Characteristics of main research directions investigated at the institute and the achievements 2010−2014

Institute	Institute of Plasma Physics of the CAS, v. v. i.

The object of the Institute of plasma Physics, ASCR, v.v.i. is research and applications of the fourth state of matter - plasma. The research comprises both the experimental and theoretical study of artificial man-made plasmas in a broad range of temperatures, densities and life-times ranging from relatively cold discharge plasmas with temperatures below 40,000 K (energies in the 1 eV order) to very hot laser plasma with temperatures in tens of millions K (energy above 1 keV), plasma densities of several orders of magnitude lower than atmospheric pressure (tokamak discharges) to density comparable with one of solid phase (initial phases of laser plasma). By the lifetime, the plasmas studied can be categorized as nearly-stationary thermal (equilibrium) plasmas (in plasma torches), quasi-stationary discharge plasmas with several hundred millisecond lifetime (COMPASS tokamak discharges) and non-stationary, highly non-equilibrium plasmas with a lifetime of 1 µs or less (pulsed plasma systems and laser plasma). IPP is also developing new necessary diagnostic methods and searching for new possibilities of plasma utilization. Further on, IPP acquires, processes and disseminate scientific information, provides scientific expert assessments, opinions and reccomendations, In close collaboration with universities IPP performs doctoral studies and educates new researchers. IPP has five scientific research departments (Tokamak, Impulse Plasma Systems, Laser Plasmas, Thermal Plasmas, Material Engineering) and one application research laboratory (TOPTEC) in Turnov. Their scientific results in 2010 – 2014 are described as follows:

TOKAMAK Department

COMPASS operation and diagnostics

In 2010 – 2013, most of the effort has been devoted to commissioning of COMPASS, its auxiliary systems, and new diagnostics. Afterwards, the main emphasis was put on development of relevant operational scenarios. The test operation of COMPASS started in April 2009, routine scientific exploitation began in 2012. The main results are optimization of plasma parameters at all intended plasma scenarios, installation and commissioning of two Neutral Beam Injectors for additional heating with the total power of 2×300 kW and achievement of high confinement mode (H-mode, reference scenario for the ITER tokamak) with different types of ELMs. In the reported period, many spatially or temporally highresolution diagnostic systems have been gradually added in order to address requirements of the scientific program, focused mainly on H-mode edge plasma physics, scrape-off-layer physics and plasma-wall interaction. Besides others, the extension and optimization of advanced diagnostics include high-resolution core and edge Thomson scattering system, edge microwave reflectometer, beam diagnostics, and infrared camera. The COMPASS tokamak focuses on the edge tokamak plasma studies, issues related to plasma instabilities, and interaction of plasma and materials of the first wall. COMPASS is capable of solving some of the fundamental questions of the fusion research and the ITER project.

Edge plasma studies

In the period 2010-2014, we used, among others, the unique capability of locally developed ball-pen probe in combination with Langmuir probes. The fast moving (reciprocating) manipulators and wall-embedded fixed probes yield plasma characterisation with extremely high spatial (2 mm) and temporal (10^{-6} s) resolution, required for measurement of edge turbulence of plasma density, electron temperature and plasma potential. We used the probes also for the ELM transient events; not only to study them but also in order to understand their mitigation. The plasma heat deposition inside millimetre-wide gaps between divertor tiles was studied numerically using earlier experimental results from our unique sandwich probe. We used the benchmarked simulation code for prediction of the ITER divertor, as well as dedicated

JET divertor melting by ELM transients. The so-called Near SOL feature likely caused accidental melting of the JET ITER-like-wall. This triggered large experimental campaign on COMPASS (proposed by the ITER Organization) and on other tokamaks worldwide (under the ITER ITPA leadership), with important consequence for ITER inner wall limiter re-design action. Concerning the Lower-Hybrid heating systems, we focused on studies of electrons accelerated by the antenna, which can cause dangerous hot spots on the inner wall. Last, but not least, COMPASS tokamak was used for testing of material samples. ***Core physics studies***

The recent core physics studies of the COMPASS team focus on two topics: quasi-coherent modes and runaway electrons. Multiple quasicoherent electromagnetic modes with steadystate frequency and different nature and location were measured in the COMPASS tokamak with Co-NBI in both L- and H-mode plasmas. Two campaigns on Runaway electron (RE) studies were performed within MST2 EUROfusion project on the COMPASS tokamak in 2014, increasing considerably our expertise in the field and strongly motivating for further RE studies. Within these campaigns a set of new scintillation detectors were installed, a database of RE-relevant waveforms and diagnostics data has been built and data from Cherenkov and HXR detectors were validated.

Theory and modelling

Theoretical research has been motivated by experiments on COMPASS as well as on tokamaks world-wide. Nevertheless, certain long-term topics are clearly present. In the reported period, the traditional wave-plasma interaction modelling covers mainly electron cyclotron (EC), electron Bernstein wave (EBW), and lower-hybrid (LH) ranges. Our own simulation codes have been extensively employed for studying EBW emission, heating and current drive on spherical tokamaks and stellarators. Non-linear LH wave-particle interactions have been studied by extending existing codes. A new code for simulating LH grill coupling has been developed. 2D and 3D Particles-in-Cell codes have been developed or extended and successfully used to study scrape-off layer plasmas. Significant contributions have been made in the resonant magnetic perturbation theory and modelling, in particular for study of the heat transport and consequences of divertor footprint generation. Edge turbulence has been studied by fluid codes. The team also contributed to the Integrated Tokamak Modelling Task force, particularly in the field of free-boundary equilibrium modelling. Transport scenario modelling, including auxiliary heating, was used to estimate the COMPASS performance.

Participation in the JET programme

The Tokamak department contributes to the JET work programme since 2001, with a clearly increasing trend of the activities. Traditional SOL plasma and turbulence expertise was complemented by pedestal, H-mode and ELMs studies. Expertise in IR camera thermography, SXR tomography and Thomson scattering diagnostics was added to the portfolio of the team, oriented traditionally to various types of electrostatic probes. Additionally, experimental SOL and edge plasma studies were complemented by modelling activities in this area, e.g. in support of the recent JET divertor lamella melting experiment, or by development of the semi-kinetic model of electron velocity distribution function near the JET divertor targets. Modelling of processes in front of JET LH and ICRH antennas is one of the traditional topics systematically addressed from the early days of our JET involvement till now. Regarding core plasma studies, the range of activities evolved around the central point of application of fast tomography reconstruction algorithms based on Minimum Fisher Regularization technique to bolometry, neutron and recently also to soft X-ray tomography. The tokamak department contributed also within JET EP2 project participating on delivery of the system of ex-vessel radiation hard Hall probes.

ITER collaboration

The Tokamak department is involved in many ITER relevant studies partly described above. These studies focus on providing data necessary to further precise the ITER scalings or detailed studies of physical processes directly influencing the ITER construction (e.g. heat loads studies at divertor and during RMP, magnetic sensor development, etc.) or operation (runaway electron studies, disruption current asymmetries, role of isotopes, etc.). Besides that, the department has some special direct involvements/contract with the ITER organization.

Impulse Plasma Systems

The research team of the Department of Pulse Plasma Systems (IPS) investigates a nonequilibrium plasma generated by various types of pulse high-voltage electrical discharges in gases, liquids and gas/liquid environments. The physical and chemical processes intentionally initiated by such discharges were studied in dependence on the type of discharge, pulsed power, and the nature and the chemical composition of the surrounding environment in order to achieve specific effects.

Plasma chemistry induced by electrical discharges in liquids

The research was focused especially on the chemistry of plasma/liquid interactions induced by air plasmas in contact with aqueous solutions, common to plasma systems interacting with living matter, in which plasma typically occurs in humid air and touches a wet surface (biofilms, cell tissue, skin). Various types of discharge plasma/liquid systems were used and studied such as plasma jets, corona discharges, dielectric barrier discharges and spark driven electrospray. For the first time the formation of peroxynitrite (ONOOH) in plasmatreated water was experimentally proved and its rate of formation was quantitatively determined through kinetic analysis of the post-discharge reaction between H_2O_2 and nitrite ions in plasma-treated water. Importance of this study was also in using phenol as a chemical probe of the chemistry of reactive oxygen and reactive nitrogen species in plasma treated water. Mechanisms of bacterial inactivation induced by plasma in water was also studied. The focus was particularly on the effects of the reactive species generated by the air plasma on the bacterial cell membrane integrity. Peroxidation of cell membrane lipids by the reactive species (mainly OH radicals) produced by plasma was determined as an important pathway of bacterial inactivation. Moreover, it was found that the bacteria have entered the *viable-but-non-culturable* (VBNC) state during the plasma treatment. Important results were also obtained in the research on plasma-catalytic processes induced by discharges in water. It was determined that tungsten as material of discharge electrodes may significantly affect plasmachemical processes induced by electrical discharges in liquids.

Physics and biological effects of focused shock waves in water

The multichannel pulsed-electrohydraulic discharge generator with cylindrical ceramic-coated electrodes developed at IPS department in previous years was used as a source of focused shock waves and their biological effects were studied *in vitro* and *in vivo* on different cancer cells and tumors using various animal models. Shock waves were generated either as a single wave or as two successive (tandem) shock waves with time delay of 10 μs between the waves. The research was performed in cooperation with 1st and 2nd Medical Faculty of Charles University Prague and Medical Faculty of Palacký University Olomouc. *In vitro* experiments showed that increasing exposure of cells by tandem shocks leads in cell membrane perforation at low number of applied shock waves (up to 100 to 200 double shocks) to total damage (fragmentation) of the cells at a higher number of shocks. *In vivo* experiments proved that focused tandem shocks waves are capable to cause localized lesions at a predictable location deep within soft tissue in the focus without damaging tissue located in front of the focal point. Consequently*, in vivo* experiments performed with B16 melanoma, T-lymphoma and R5-28 sarcoma cell lines on mice and rats showed that tandem shock waves can significantly delay growth of tumors (typically about two times). The first clinical tests of focused shock waves are under preparation in collaboration with the First Medical Faculty of Charles University Prague.

Physics, kinetics and diagnostics of streamer discharges in gas phase

By combining a wide range of complementary diagnostic techniques, fundamentals of lowtemperature, non-equilibrium plasma reaction mechanisms and energy transfer processes underlying the onset and propagation of ionizing streamer fronts were studied. Significant effort was dedicated to the development of relevant real-time control and experimental approaches allowing advanced optical diagnostics (ICCD microscopy, emission spectrometry, laser based diagnostics) with high spatial and temporal resolutions on single streamer discharge at atmospheric pressure as well as at low pressures and at controlled gas temperatures. By applying optical diagnostics at different timescales, from nanoseconds to microseconds, the IPS team obtained important results related to evolution of molecular metastables, atomic species and molecular ions produced by streamer head electrons. Obtained experimental results were complemented by numerical modeling and simulation approaches. General kinetic model was developed to predict the evolution of individual vibronic levels governed by various collisional processes.

Fast high-current capillary discharges

The research uses CAPEX/CAPEX-U machines that routinely lase on Ar^{8+} ions on the wavelength 46.9 nm. The laser radiation was focused by multilayer mirror manufactured according to our design. It was found that nanostructuring can be made in the regions, where local fluency is smaller than ablation threshold. However, it was also proved that a prolongation of laser pulse can significantly enhance the engraving efficiency of nanostructures. Up to the present three types of nanostructures have been tested:

spontaneously appearing “laser induced periodic surface structures” (LIPSS), and Fresnel diffraction patterns, as well as artificially created interference patterns; for this last one a new type of XUV “direct writing” interferometer was developed (patented Applied Gadget) with two ellipsoidal focusing mirrors. This lab has been one of the branches of the UNESCO International Centre for Dense Magnetized Plasma.

Laser Plasma Department

The Laser Plasma Department (LPD) focuses its activities on investigations of laserproduced and lasing plasmas. LPD is operating as a joint laboratory of IPP and the Institute of Physics ASCR, v.v.i. Its key experimental facility is the terawatt iodine laser system, unique in EU by its infrared wavelength of 1315 nm. Auxiliary femtosecond beam lines make it possible to realize unique pump-probe experiments and to study the processes of interaction of intense radiation with targets with sub-picosecond temporal resolution. The very high energy of the iodine laser, and the nanosecond duration of its pulse makes PALS enjoying great interest of LASERLAB-EUROPE and EURATOM Keep-in-Touch activities.

PALS research programmes

The PALS research programme covers a broad range of activities, from fundamental research of processes in laser-produced plasmas up to applications of laser-produced plasmas in science and technology. The PALS laboratory was the first where a new original plasma acceleration scheme called Laser-Induced Cavity Pressure Acceleration (LICPA) was validated. The method makes it possible to obtain superfast macroparticles at the energetic efficiency of acceleration by an order of magnitude higher compared to conventional ablative laser experiments. The accelerated plasma bunches can be highly useful in in high energy-density physics, nuclear physics and or inertial confinement fusion. Laser-produced high-pressure shocks may be used for igniting laser inertial fusion. The main goal of the experiments on shock wave generation conducted at the PALS laboratory is to study the effect of laser-generated fast electrons on the efficiency of shock wave generation. The collected experimental data confirmed the dominant contribution of fast electron energy transfer to the ablation process and shock wave generation. Substantial progress in the shock wave studies has been achieved by replacing the nanosecond diagnostic beam of the iodine laser driving the laser interferometer at PALS by a synchronized sub-picosend beam of the auxiliary titanium-sapphire laser. That was possible owing to precise synchronization of both laser systems, and redesigning completely the laser interferometer for PALS in collaboration with IPPLM Warsaw.

Laser plasma jet generation

A simple method of plasma jet generation based on using a flat massive target irradiated by a partly defocused high-power laser beam has been investigated at PALS since 2009. Those works opened up entirely new possibilities both in the laboratory simulations of astrophysical jets and the Herbig-Haro objects observed in cosmic outer space, and in using laser plasma jets for various applications in science and technology. The goal of astrophysically motivated investigations of laser-induced radiative shocks was to extend the preliminary study of the shock time and space resolved photometry using high-speed photodiodes to different wavelength ranges. In the experimental setup used the infrared PALS laser was exploited for generating both a shock wave in xenon and a delayed XUV probing pulse. In these experiments clear and unambiguous images of the shock wave have been obtained. Advanced XUV spectroscopy was an integral part of fast all interaction experiments at PALS. One of the goals of spectroscopic measurements was to develop diagnostics of suprathermal electrons.

Laser interaction with targets

A high-energy laser beam interacting with a solid target generates fast protons and highly charged heavier ions, which can enter mutual fusion reactions or produce fusion reaction in targets. The ion projects at PALS were aimed at improving the parameters of accelerated proton streams by exploiting various sophisticated targets. It has been shown that non-linear effects occurring in thin nanostructured targets induce strong resonant absorption and selffocusing of the laser beam. These two effects increase the plasma temperature and density, which results in higher ion yield. In another series of ion experiments CD_2 targets were used, which resulted in generation of a high number of accelerated deuterons entering mutual D-D fusion reactions. Particular attention was devoted to boron-doped hydrogen-enriched silicon targets.

Theoretical studies and modelling

LPD theoreticians have been studying interaction of electromagnetic waves with plasmas and various types of plasma-based radiation sources. These studies include also modelling performed for the JET tokamak shots in the ITER-like-wall environment and the fast electron generation studied by analysing the data from the Tore Supra tokamak shots. Computer simulations of pinching capillary discharge resulted in a design of new laboratory source optimised for the generation of monochromatic radiation with the wavelength of 2.88 nm with a substantially increased brightness. Soft X-ray emission from a capillary discharge with nitrogen, argon and carbon dioxide fillings as a possible source of XUV radiation in the “water window” region was investigated.

Application activities

Studies were aimed at improving the precision of measurements of characteristics of high power laser beams. That included, among others, the development of laser beam diagnostics based on low-cost silicon detectors. For reliable acquisition and transfer of large amounts of diagnostic data in extremely high-frequency-perturbed environment a qualitatively new type of control and data transfer system have been designed and tested, based on purely optical paths including optical power lines. A large-aperture composite bimorph deformable mirror with an original control system for adaptive correction of wave fronts of high-power laser beams has also been designed, tested and patented.

Department of Thermal Plasmas.

The research activity of the Department of Thermal Plasma is concentrated on the investigation of generators of thermal plasmas, diagnostics of electrical discharges producing thermal plasma, study of interaction of thermal plasma with gas, liquid and solid materials, and investigation of physical and chemical processes in several technologies based on thermal plasma processing of materials. Special attention is devoted to study of plasma and plasma jets generated in a world unique type of plasma generator with water stabilized electric arc, and investigation of applications of this type of plasma generator in various plasma processing technologies. Plasma generated in water stabilized arc is characterized by extreme parameters, not achievable in other discharges, especially high temperature, high plasma enthalpy as well as high exit plasma velocity. Besides permanent research of sources of steam plasma with the water stabilized arc, several plasma processing applications using this torch have been investigated, namely plasma pyrolysis and gasification of organic materials and waste, plasma cutting of materials, removal of organic pollutants from water, and plasma spraying.

Generation of thermal plasma in arc plasma torches and research of thermal plasma jets.

Investigation of properties of liquid stabilized arcs and plasma jets generated in this type of arc is main topic of research of plasma generators. The main goal of experimental study as well as theoretical modeling is improvement and further development of plasma torches with water stabilized arc. The research includes also development of diagnostic methods for study of high enthalpy, high velocity plasma jets. Special attention is paid to the stability of the jet flow as well as to the cathode and anode effects. The development of a new type of plasma torch with improved principle of arc stabilization have been made in cooperation with the industrial partner ProjectSoft, a.s.. The hybrid water/argon plasma torch WSPH for plasma spraying, based on the patented principle of combination of water vortex stabilization of arc with gas stabilization, was developed and introduced on the market.

Pyrolysis and gasification of organic waste materials for production of hydrogen and high quality syngas.

Extremely high enthalpy steam plasma, generated in hybrid water/argon plasma torch, is used in the research of gasification of various types of organic materials like waste biomass, waste plastics, low quality coal and pyrolytic oil from thermal treatment of waste tires. The plasma gasification reactor PlasGas with hybrid plasma torch is one of the largest research reactors with complete process diagnostics and exact reaction products analysis. Plasma aided reactions of materials with water, carbon dioxide and oxygen are studied. The main goal of the research is determination of conditions leading to production of synthesis gas with high content of hydrogen and CO and minimum tar presence. Theoretical research is devoted to calculation of composition of reaction products for various materials and oxidizing media, and to modeling of interaction of plasma with treated materials inside the reactor. Measured compositions of produced syngas are close to ideal theoretical composition calculated as thermodynamic equilibrium composition of mixture of all input components. The composition of syngas could be easily controlled by addition of reaction admixtures like CO_2, water, or oxygen. The process can be used also as energy storage.

Removal of organic pollutants from water in water-stabilized arcs.

In plasma torches with water stabilized arc, the arc column is surrounded by water wall created by inner surface of water vortex. In typical geometry of the torch the inner radius of water vortex is 3-10 mm, and the arc column with a centerline temperature up to 30 000 K is in direct contact with water. Water flows around the arc plasma and chemical processes in the water volume are stimulated by strong UV radiation and strong heat transfer, as well as by processes at the plasma-water interface. The experiments are being performed for analysis of potentials of this type of arc discharge for treatment of polluted water The experiments with degradation of organic pollutants confirm almost 100% efficiency of organic pollution degradation.

Theoretical modeling of water stabilized arc discharges and plasma jets.

The principal aim of theoretical modeling and computations was better understanding of processes and properties of water stabilized and water/gas arcs and description of processes of interaction of plasma jets generated in plasma torches with these types of arc with materials in plasma processing applications. Theoretical investigation in recent years was concentrated on some special problems of thermal plasma and arc modeling – description of turbulence effect, description of radiation transfer within the arc including reabsorption phenomena, and effect of used methods of numerical solutions of model equations on computed results. Modeling of thermal plasmas is based on description of processes by a system of MHD equations where plasma properties described by thermodynamic and transport coefficients are also calculated.

Department of Materials Engineering

The ME Department of IPP went through three important changes in the 2010-2014 period, namely new laboratory of plasma technology, upgrade of characterization instruments and staff generation exchange.

New Laboratory of Plasma Technology

The new Laboratory of Plasma Technology (LPT) was opened in March 2012. The LPT houses two major research facilities related to plasma processing of materials the Water Stabilized Plasma (WSP) spraying facility and Spark Plasma Sintering (SPS) equipment. The WSP facility went through a major technological upgrade. It is equipped with the new HybridWSP gun, innovated at IPP, and also with comprehensive diagnostics of the plasma spraying process. The unique H-WSP gun further expands the already great versatility of the original WSP gun (adjustable from high-enthalpy low-density plasmas to lower enthalpy higher density plasmas generated in gas stabilized guns). The H-WSP maintains the highest plasma enthalpy available worldwide and overcomes shortcomings of the original WSP plasma jet. The SPS system represents first such piece of equipment in the Czech Republic. The concurrent application of pulsed electric current, elevated temperature, and pressure permits preservation of beneficial fine-grained microstructures, formation of special functional graded materials (FGM), etc. In the current state, both of the facilities – Hybrid-WSP and SPS – as well as their combination significantly broaden the possibilities of special materials preparation, i.e. materials tailored to specific applications.

Major upgrade of characterization equipment

The DME has a new analytical SEM with energy-dispersive spectrometer (EDS), electron backscatter diffraction (EBSD), and in-situ bending stage. There is a new X-ray diffractometer with a high temperature chamber up to 1600 °C, collimators for local surface mapping, and other top auxiliaries. There is a new Differential Scanning Calorimeter (up to 1800 °C), new particle size analyzer, and so on. There is also a new imaging and diagnostic system (SprayCam) for measuring particle distributions and trajectories during their injection in the thermal spray process.

Major research results

Research at the DME is focused around three major topics: materials for fusion applications; fundamental research and development of new classes of materials prepared by the unique processing equipment, i.e. H-WSP and SPS; materials tailored for specific application. These three topics are often interrelated and various specific projects typically involve more than one area.

1) Fusion materials. Through participation in the EURATOM/EUROfusion programs, the DME has established a significant position in the fusion community. The DME has a unique opportunity of exposing real material samples to fusion-relevant tokamak plasma (the Compass tokamak at IPP). Since tungsten is a “hot” candidate material for tokamaks and plasma spraying is considered a viable processing route, the DME extensively studied Wbased FGM and the results were well received in the fusion community. Besides plasma spraying, several other processing techniques were also explored, including SPS. Finally, a comprehensive assessment of the advantages, drawbacks and limitations of each technique, as well as their suitability for the fabrication of plasma facing components for fusion devices, was performed.

2) New materials and FGM. The DME work proved that plasma spraying itself can be used to make FGMs (gradient or sandwich type) or in combination with post treatment. Several novel techniques, combining primary WSP spray deposits with additional treatment represent interesting ways of producing FGM, such as: i) nanostructured surface layer continuously transitioning into the as-sprayed deposit; ii) boronized steel surface that is well anchored into the steel body; iii) multilayered ceramics/metal sandwiches, exhibiting several interesting properties, such as very limited or no gas permeation trough the part. Special FGMs reducing stress concentration between dissimilar materials were prepared by combining PS and SPS. Other FGM include special thermal barriers, FGM with nanolayers, etc.

3) Tailored materials. PS and SPS can be used for synthesis of materials with special physical properties. A photocatalytical ceramics based on TiO2 + Cr2O3 were prepared by WSP. Free-standing shells were produced by WSP for adaptive optical mirrors based on PZT feedstock powders (Pb(ZrTi)O3). Plasma sprayed ceramics based on titanates MTiO3 (M = Mg, Ca or Ba) and their mixtures exhibit interesting properties potentially useful for fabrication of dielectrics, etc.

Cooperation

The ME team maintains an active cooperation with many domestic and international universities and research institutions, either bilaterally or in research consortia. DME is a member of the “Centre of Excellence” project supported by Czech Science Foundation. It brings together scientists from 4 Institutes of ASCR and 2 Universities and focuses on complex investigation of ultrafine-grained (UFG) materials, FGMs, etc. The DME also participates in the

“Competence Centre of surface treatment” supported by Technology Agency of the CR, which focuses on the development of novel thermal barrier coatings for jet engines (together with Brno University of Technology and Honeywell International s.r.o.). Internationally, there are several research institutions in the world that have been long term research partners of the ME Department. Among them are Center for Thermal Spray Research (Stony Brook, NY, USA), University of Limoges (France), Forschungszentrum Juelich (Germany), Argonne National Laboratory (IL, USA), Tampere University of Technology (Finland), Fraunhofer Institutes in Dresden (Germany), or University West (Trollhattan, Sweden). Within the last five years, the ME team has become a strong partner in European Fusion Development Agreement (EFDA) and EUROfusion programmes that are related to materials for fusion applications.

TOPTEC

Thin films

Demands on development capabilities of Thin films group, driven by research projects and customers, expanded to UV and IR antireflection coatings, coatings for high power lasers and ferroelectric coatings with electro-optical and electromechanical coupling. In order to design such coatings, the Thin film department underwent modernization through investment into measurement equipment, deposition equipment and new design and analysis software. Part of the activities was focused on development of software packages which unite technological and user interfaces of different coating machines. Significant problems solved during development of antireflective coating in projects EUREKA! Infrasens and a resort grant of Ministry of internal affair HDES were: adhesion on different surfaces of elements made from germanium, sulfides, selenides and phosphides, light scattering of thick infrared films and absorption in LWIR spectral range. Dielectric mirrors on Zerodur and copper substrates for high power lasers in the 900-1000 nm spectral range were developed for HiLASE project.

Fine Mechanics

Development and manufacturing of non-contact tonometer with cooperation of the Czech metrological institute and Korean company Huvitz Co, Ltd, was realized. The “flapper” is an optomechanical device developed for calibration of non-contact tonometers for evaluation of intraocular pressure. It was redesigned and manufactured within TOPTEC facility. The functionality and stiffness of important parts were analyzed using FEM. Flapper setup consists of approx. 85 parts, most of them designed and manufactured in high precision. The device is a unique instrument which is used for calibration of all tonometers produced by Huvitz company.

Crystal and X-ray Optics

Crystal and X-ray Optics group focused on close cooperation with industry and universities. In the field of crystal optics, new processes to realize atypical plate retarders with an inner hole were developed. These were used for quantum optics experiments (Palacky University). In addition, research team concentrated on measurement techniques for orientation of oversized Sapphire crystals (HIC Service) as well as drilling techniques of quartz crystals with non-standard size precision (Krystaly HK). Crystal elements for measurements of inner stress relicts in float glass were further developed (Newte Teplice). In the field of X-Ray optics, we cooperated with Rigaku Praha. Further activities involved development of new types of miniature mandrels for galvanic replication of X-ray objectives and advancement of Lobster-eye type X-ray objectives for cosmic application.

Aspherical Optics

The most prestigious projects solved within Aspheric Optics department are two paneuropean space projects. PROBA3 is an ESA technology demonstrator mission, when formation of two flying satellites will be tested. The part of this mission is ASPIICS project, a solar coronagraph telescope. Within the project, TOPTEC team was responsible for optical design and tolerancing of the telescope in Phase B. Recently, the team focuses on tasks connected to Phase C/D, where both optics (11 elements) and mechanics are going to be produced, assembled, tested and delivered. The second ESA project is METIS (Coronagraph onboard the Solar Orbiter mission - optical elements). METIS is a solar coronagraph telescope, imaging solar corona in three different spectral regions from ultradeep UV up to VIS. Involvement of TOPTEC in the

METIS Phase B project was evaluated by ESA as highly successful and TOPTEC was addressed for cooperation in phases C and D. During 2014 (C,D phase) the mirrors structures for M0, M1 and M2 mirrors were redesigned with respect to specified loads (shock loads during the launch, thermal loads etc.). Also the technology of manufacturing of mirror structures was developed.

Optoelectronic systems and detectors

The Cherenkov radiators were developed for testing new sensitive photon detectors - thick gaseous electron multipliers. The design of radiators was made by Zamax© software, where problems with simulation of source and propagation of Cherenkov radiation were solved. All designed radiators were used in particle beam tests of detectors at CERN, Switzerland. The modified folded Jamin interferometer, insensitive to the rotation and translation of its two optical elements, was designed, constructed and tested. The interferometer sensitivity and accuracy is completely satisfactory. It enables measurement of a change of 10^{-6} in the refractive index in standard mode. The interferometer will be installed at Ring Imaging Cherenkov detector at the experiment COMPASS at CERN. A new original method for online segmented mirror alignment monitoring was developed and applied at Cherenkov detector COMPASS RICH-1 at CERN. Both mechanical and optical hardware were designed and produced in collaboration with INFN Trieste, Italy and Technical University of Liberec, the Czech Republic.

Adaptive Optics and Diffractive Optical Elements, Systems and Optoelectronics This research combines optics, electronics, the use of nonlinear electro-optic materials and coherent light sources – lasers. A work has been done in the research and development deformable mirrors based on composite layered structures with piezoelectric materials. The optimization of geometric parameters of a deformable mirror that consists of a nickel reflective layer deposited on top of a thin lead zirconate titanate (PZT) piezoelectric disk was designed and analyzed. Overall performance of optical system in real-world operating is severely deteriorated by the presence of vibrations. For that reason a research focus was devoted to the development of methods for the adaptive suppression of noise and vibrations using a single piezoelectric actuator shunted by a negative capacitance circuit. Last but not least, research on optical and dielectric properties of nonlinear electro-optic single crystals (i.e. ferroelectric) was performed. Presence of ferroelectric domains and domain walls represents a useful way of controlling the optical properties of single crystals using electric fields. Therefore, the interaction of electric field with charged domain walls in ferroelectrics was theoretically addressed and a general expression for the force acting per unit area of a charged domain wall carrying free charge was derived. Analysis of stability of several domain patterns with charged and neutral domain walls was performed. Results of this analysis offer simple and useful tools that can be profitably used in construction of nonlinear electro-optic devices made of ferroelectric single crystals. An important part of our research includes the development of unique measurement tools, e.g. frequency-shifted digital holography.

Measurement and characterization methods

The group dealing with measurement focused on two major activities. One activity was connected to industry demands, which were represented e.g. by a project for welding process visualization, where an instrument for characterization of very rapid processes in extreme condition of electric arc was developed. The second activity was represented by monitoring research of new techniques used in precise metrology for optical surface shape of aspheric and freeform elements. Very precise measurement of aspheric surfaces was based on multiwavelength absolute interferometry enabling us to measure surfaces with departure from the best fit sphere in order of hundreds of light waves. The measurement of freeform shapes was significantly more complicated, since the specular reflections could not be easily controlled. For that, multiwavelength digital holographic interferometry was developed. This method uses wide spatial frequency spectrum of illumination beam in order to suppress the specular effect.

Research Report of the team in the period 2010–2014

Institute	Institute of Plasma Physics of the CAS, v. v. i.

Scientific team	Tokamak

The scientific work of the Tokamak department staff focused on several main directions during the evaluated period. In the period 2010 – 2013 most of the effort has been devoted to putting of COMPASS into full operation including commissioning of all the auxiliary systems and many new advanced diagnostics. Afterwards, the main emphasis was put on successful development of (ITER-) relevant operational scenarios, namely, High confinement mode (H-mode) with different types of Edge Localize modes (ELMs) instabilities.

In parallel, however with an increasing tendency, the effort was devoted to the development of the scientific programme of the Department with a focus on ITER relevant problems. The new programme benefits from the existing edge plasma expertise of the team acquired already on the CASTOR tokamak, however, many new topics and key problems identified within the EURATOM and EUROfusion programme were addressed (see below).

The report is organized as follows:

1. The COMPASS tokamak operation
    a. Tokamak and auxiliary systems commissioning
    b. Diagnostics development and commissioning
    c. Plasma scenario development
2. Scientific programme
    a. Edge plasma studies on COMPASS and other devices
    b. Core physics studies on COMPASS and other devices
    c. Theory and modelling activities
    d. Participation in exploitation of the JET tokamak
3. ITER collaboration

1. The COMPASS tokamak operation

1a Tokamak and auxiliary systems commissioning

The COMPASS tokamak was installed, new systems built, and put in operation in the period of 2006 – 2011, i.e. part of the COMPASS commissioning phase still belongs to the reported period. The first plasma was achieved in 2008 and test operation started in April 2009. Two Neutral Beam Injection heating systems – NBI, each of 300 kW, were installed in 2010. The auxiliary systems for a routine tokamak operation were automatized and optimization of plasma break-down and position control was performed. All intended plasma scenarios were developed (circular and D-shaped plasma, L-mode, H-mode with different types of ELMs). Routine scientific exploitation of the infrastructure began in 2012.

The main results from the commissioning period and machine operation development are:

- Installation and commissioning of two Neutral Beam Injectors (NBI). The beam energy is 40 keV and the total power 2x300 kW. The NBIs were manufactured at the Budker Institute, Novosibirsk, Russian Federation and transported to IPP Prague together with their power supplies.
- Optimization of plasma parameters in the COMPASS tokamak
- Plasma stabilization with ITER-relevant plasma cross-section by means of feedback control
- Achievement of high confinement mode (H-mode), which will be a reference scenario for the ITER tokamak
- Development of new operation scenarios – with the H-mode (high plasma confinement mode) and various types of ELM-type (Edge Localized Modes) instabilities, high and low density regimes (e.g. runaway electron generation), etc.
- Tests of new systems to be employed in future physics programme (new power supplies for resonant magnetic perturbations, power supplies for fast vertical plasma movement to enable controlled induction of edge instabilities etc.)

1b Diagnostics development and commissioning

In the reported period many spatially or temporally high-resolution diagnostic systems have been gradually added in order to address the requirements of the planned scientific program of the COMPASS tokamak focused mainly on H-mode edge plasma physics, Scrape-off-Layer (SOL) physics and plasma-wall interaction. Besides other diagnostics, the extension and optimization of several advanced diagnostics include:

- High Resolution Core and edge Thomson scattering system;
- Edge microwave reflectometer;
- Beam diagnostics;
- Infrared camera.

Thomson scattering diagnostic

The High-resolution Thomson scattering (HRTS) diagnostics for measurements of the electron density and temperature profiles at both the plasma core and edge plays the key role among the newly designed and installed diagnostics on the COMPASS tokamak. It is based on two 30 Hz Nd:YAG (1064nm) lasers of energy about 1.5 J each. The lasers can be fired independently allowing different regimes of the TS measurement (30 Hz at 3 J, 60 Hz at 1.5 J, custom shift at 1.5 J). Scattered photons are collected by the core and edge optics and transmitted via optical fibres to the fivechannel polychromators. The design of polychromators has been prepared in a close collaboration with CCFE. The plasma observation covers the top half of the plasma and consists of 24 spatial points at the plasma core with resolution of 5-8mm and of 32 spatial points at the plasma edge with resolution of 2-4-5 mm (mapped to outer midplane). The measured electron density and temperature profiles provide important information on plasma confinement, e.g. in H-modes, pedestal width and height can be derived from measured HRTS profiles.

Reflectometry

The next advanced diagnostic, which has been developed for COMPASS, is the broadband FM-CW reflectometry system designed to study fast transient events in the pedestal region (density profile measurement) as well as properties of plasma turbulence. The system currently consists of the two O-mode reflectometers in K and Ka bands, but is easily extensible to cover the range of 18–90 GHz (four O-mode reflectometers in K, Ka, U and E bands and one X-mode reflectometer in Ka band). A quasi-optical band-combiner, developed in the Institute for Radiophysics & Electronics of the National Academy of Sciences of Ukraine, Kharkov, combines the five different beams into one transmitting beam. The same combiner splits them from the receiving beam. An FPGA ramp generator can be operated in two types of frequency modes, the ultra-fast sweeping (<20 μs) and the fast frequency hopping, both interleaved during the same discharge. This advanced hybrid configuration uses fast frequency synthesizers developed in the IPFN/IST Lisbon.

In addition, a new 16-channel radiometer, operating alternatively in three frequency bands (Ka-band 26.5 – 40 GHz, E-band 60 – 90 GHz, and IF-band 1.5 – 15 GHz), has been designed and constructed for COMPASS. The system is able to detect normal Electron Cyclotron Emission (O1 or X2) or oblique Electron Bernstein Wave emission. Primarily the system was designed for the investigations of EBW-XO conversion as the over-dense plasma can be produced in COMPASS. In the second stage, the radiometry system will be utilized for the conventional ECE temperature profile measurements.

Beam diagnostics

Beam-based diagnostics at COMPASS are represented by the Beam Emission Spectroscopy (BES), Charge eXchange Resolution Spectroscopy (CXRS) and Neutral Particle Analyzer (NPA). BES, developed in a close collaboration with the Wigner institute of Hungarian Academy of Science, uses accelerated Lithium atom beam. The Lithium beam with current of several mA and energies up to 100keV has been constructed for the COMPASS tokamak and equipped with deflection plates at frequencies up to 400 kHz allowing fast background noise measurements. Line radiation coming from the excited lithium atoms is detected by both the CCD camera for slow (~10ms) and by the array avalanche photodiodes for fast (~ s) measurements. The spatial resolution of density measurement is approximately 1-2 cm. During the reported period, the system was fully commissioned and became a routine technique for the determination of electron density and density fluctuation profiles on COMPASS.

CXRS, the second beam diagnostic, uses one of the heating neutral deuterium beams (NBI) installed on COMPASS (<12A, 40keV) to induce the charge-exchange line radiation of highly ionized carbon (C VI line at 529nm). Such a high-resolution spectroscopy represents a powerful tool for the measurement of plasma rotation as well as ion temperature using the Doppler shift of the emitted spectral lines and their Doppler broadening, respectively. The spectral analysis, based on the 0.67m CzernyTurner McPherson 207 spectrometer equipped with the newest model of

ANDOR's EMCCD cameras, iXon Ultra888, provides both space (0.5-5 cm) and time (10 ms) resolved toroidal plasma rotation and ion temperature profiles.

Furthermore, in collaboration with the Ioffe Physical-Technical Institute, St Petersburg, Russia, the 24-channel Neutral Particle Analyzer (NPA) has been put into operation in order to measure the energy distribution function of the flux of fast hydrogen and deuterium atoms simultaneously in a single discharge. NPA has been absolutely calibrated in the energy ranges of 250 eV – 40 keV (for hydrogen) and 400 eV – 40 keV (for deuterium atoms), which is compatible with expected tails of the ion distribution function during the NBI heating and the first measurements have been performed during the reporting period.

1c Plasma scenario development

In the reported period, the COMPASS commissioning was successfully finished and the main operational scenarios are regularly achieved by the tokamak operation team:

- discharges in hydrogen and deuterium;
- plasmas with circular, elliptic, and diverted cross-section (different triangularities);
- Ohmic as well as NBI heated discharges;
- both L-mode and H-mode discharges, incl. Type-I and Type-III ELMy H-mode.

2. Scientific programme

The COMPASS tokamak focuses on providing the possibility of unique experimental setups for the fusion community, mainly, within EURATOM and, later, EUROfusion consortium, especially in the field of edge tokamak plasma studies, issues related to plasma instabilities and interaction of plasma and materials of the first wall of the reactor. It is equipped with a comprehensive diagnostic set and it is capable of solving some of the fundamental questions of the fusion research and the ITER project. The main studied topics during the reporting period are described below.

2a Edge plasma studies on the COMPASS tokamak and other devices

Studies of plasma boundary and plasma interaction with materials have been one of the main topics of the research programme of the Institute of Plasma Physics ASCR for several decades. The research focused mainly on fundamental characterisation of the tokamak edge plasma accessible by electric probes.

In the period 2010-2014 we used, among others, the unique capability of locally developed ball-pen probe. In combination with Langmuir probes, fast moving (reciprocating) manipulators and wall-embedded fixed probes, they all yield plasma characterisation with extremely high spatial (2 mm) and temporal (10^{-6} s) resolution of plasma density, electron temperature and plasma potential, as required for measurement of edge turbulence. We used the probes also for the ELM transient events; not only to study them but also in order to understand their mitigation limiting their destructive effects by increasing ELMs frequency. Using earlier experimental results from our unique sandwich probe, we studied numerically the plasma heat deposition inside millimetre-wide gaps between divertor tiles; benchmarked simulation code we later used for prediction of the ITER divertor, as well as dedicated JET divertor melting by ELM transients. Found first on JET, the so-called Near SOL feature likely caused accidental melting of the ITER-like-wall. This triggered large experimental campaign on COMPASS (proposed by the ITER organization) and other tokamaks worldwide (under the ITER ITPA leadership), with important consequence for ITER inner wall limiter re-design action. Concerning the LowerHybrid heating systems, we focused on studies of electrons accelerated by the antenna, which can cause dangerous hot spots on the inner wall. Last, but not least, COMPASS tokamak was used for testing of material samples.

Systematic measurements of plasma potential using ball-pen probes

The ball-pen probe (BPP) for direct measurements of the plasma potential in magnetized plasma was developed in IPP Prague in 2004. BPP inserted into the magnetized plasma measures directly the plasma potential without any additional power supplies or electronics. Moreover, a combination of BPP and common Langmuir probe (LP) provides the value of the electron temperature by the difference between the plasma and floating potential, thus providing uniquely high time resolution. The swept BPP can also provide the values of the ion temperature using the exponential part of the I-V characteristic above the plasma potential.

The ball-pen probe is capable to operate during ELMs as well as it has been demonstrated on COMPASS and ASDEX Upgrade. It was used for investigation of the fine filamentary structures inside the ELMs and calculation of the electron temperature, parallel heat flux, and radial particle flux. Therefore, the ball-pen probes were directly mounted into the divertor tiles on COMPASS as well. Thus, combination of BPP and LPs (in floating and saturated regimes) provides the continuous measurements of the electron temperature and parallel heat flux in the divertor region during whole discharge.

Edge Localized Mode control by magnetic perturbations and vertical kicks

The external magnetic perturbations (MP) and vertical kicks of plasma are promising tools for ELM control in ITER. COMPASS has been equipped by both these systems with an aim to use its edge plasma diagnostics and flexible operation for better understanding of the underlying physics.

In 2014, the magnetic perturbation coil system of COMPASS (including new power supplies) was put into a routine operation. The coil system generates an n=2 toroidal mode number and consists of three rows of loops: below, and above midplane. These loops were connected in an even parity configuration. Setups using only off-midplane (even or odd parity) or only on-midplane coils are possible and planned to be exploited in 2015. The experiments performed in 2014 focused mainly on the study of plasma response in L-mode, which can provide a valuable insight into the mechanism of plasma response.

COMPASS is equipped with 104 diagnostic saddle loops which cover the whole vacuum vessel, enabling measurements of the distribution of the plasma response field. Moreover, having full coverage across poloidal and toroidal direction enabled investigation of the phase shift of the response field, or of other forms of non-linearities in the plasma response. These measurements have been investigated and compared with a single-fluid, resistive MHD code MARS-F. Qualitative agreement has been found, however, to obtain also a quantitative agreement we plan to model the response with quasilinear MARS-Q code in 2015.

In addition, a clear strike point splitting was observed in COMPASS during MP application using a divertor array of 39 Langmuir probes and fast cameras in VIS range.

In particular, we studied the penetration of perturbation using a slow ramp-up of the RMP current.

We also exploited the tangle distance method for calculation of the heat fluxes in divertor footprints developed previously by our team. We used it to calculate the heat fluxes and compare them with experimental observations on MAST. We also used the method to estimate the power fluxes to the divertor and the upper wall panels in ITER due to magnetic perturbations. We performed a detailed phase scan of the coils, which can be used for optimizing the coil phases with respect to allowable power fluxes. We found that in some cases the power fluxes exceed tolerable values, however the calculations were done with a simplified ITER wall geometry and we intend to perform a more detailed study using the exact 3D ITER wall specification.

In addition, a new system for vertical kick generation (including a new power supply) has been developed at COMPASS. The first experiments showed a possibility to generate ELMs due to fast vertical movement of plasma. Detailed experiments are planned for 2015 including comparison with a non-linear MHD code JOREK in order to better understand the underlying physics.

Plasma deposition inside divertor gaps

Measurement of plasma deposition inside gaps compared with numerical simulations and particle and power fluxes in the vicinity of gaps between divertor tiles were studied using an inhouse 2D particle-in-cell code (later 3D). Millimetre-scale effects (ion Larmor radius smoothing and electric potential generation) yield heat flux redistribution with a direct effect the risk of local melting. The effect of changes in the orientation of the gap with respect to the magnetic field direction was studied for optimising the total ion flux falling into the gap. The power load falling onto the protruding part of a gap edge due to misalignment was also investigated for ITER transient plasma conditions and the temporal evolution of the whole divertor monoblock temperature due to this transient, high heat flux was also calculated.

Simulations showed that the power flux falling on a protruding element, almost perpendicular to the parallel power flux, is mitigated on a distance less than 2 ion Larmor radii (~millimetres). The experimental data confirmed the numerical predictions obtained from our 2D self-consistent numerical code. In the case of toroidal gaps, we have a quantitative and qualitative agreement. However, in the case of poloidal gaps, it is only qualitatively acceptable. The 2-sided deposition is confirmed, with the correct order of magnitude. This set of experiments confirmed, nevertheless, our understanding of the plasma deposition in tile gaps.

The power load falling onto the protruding part of a gap edge due to misalignment was also investigated for the ITER transient plasma conditions. The temporal evolution of the whole monoblock temperature due this transient, high heat flux was also simulated. However, we realized that 2D simulations cannot assess precisely fluxes falling onto the 3D geometry of the gap crossings. For this purpose, a new full 3D PIC code have been developed at the department. The code was successfully benchmarked and used also to simulate the underlying physics of a Katsumata probe. The preliminary 3D gap simulations revealed, contrary to 2D simulations, the presence of electrons in the plasma shadow of poloidal gaps as a direct consequence of the 3D geometry of a gap crossing.

The plasma deposition into gaps has been investigated experimentally with measurements in different devices in FZ Julich (Germany): the TEXTOR tokamak and the toroidal device TOMAS. In both, we have commissioned and installed the sandwich probe and performed experiments. We have tested different working gases (Ar, O_2, H, so varying the ion Larmor radius) for each gap orientation, parallel and perpendicular to the (small) magnetic field, all modelled with the PIC code.

Next, the PIC simulations of the power deposition in gaps with misaligned edges have been performed and compared with results of dedicated experiments on COMPASS using a specially designed inner wall limiter. This experiment was directly proposed by the ITER Organization for COMPASS and it was performed under ITER ITPA leadership.

Moreover, in October 2014, IPP Prague signed a contract with ITER IO for an Assessment of the power deposition in the castellated ITER divertor by 2D PIC simulations.

Evidence of existence of double power decay-length in SOL – consequences for the ITER design

Even though spatial distribution of heat fluxes, found to decay as $q_{||}=q_{0e}r/\square$, have been measured during last decades, recently its precise scaling has come back to an interest as it directly determines the optimum shaping of the ITER limiter in order to avoid local overheating; if not properly shaped, the beryllium panels would likely melt or debond from the base. In 2012 on JET, such unfortunate melting was observed, caused likely by a surprisingly steep gradient of the parallel heat flux observed within 1 cm outside the separatrix. Therefore, several extensive campaigns on COMPASS directly proposed by the ITER Organization (and later on TCV, DIII-D and C-mod) have been performed. In all devices we found unequivocally such a new feature - Near SOL. After a detailed study of this feature at COMPASS supplemented by results from other devices the ITER Organization accepted a change of design of some of the high-heat flux first wall panels.

The so-called heuristic drift-based model was found to be capable to predict the Near SOL width for these experiments, providing value of approx. 3mm for ITER. Additional possible mechanism (caused by non-ambipolar currents) to explain the existence of the near SOL were studied at COMPASS using the limiter embedded probes, however, found to be too weak,

We have also constructed a scaling predicting the Main SOL gradient in limiter plasmas for ITER ($\square$~50 mm), based on large amount of data from a progressively build tokamak ITER-ITPA database (JET, COMPASS, Tore Supra, DIII-D, C-Mod, HL-2A, EAST, TEXTOR, FTU; half of them processed by our team).

Geodesic Acoustic Modes; Flows in edge plasmas and their relation to L-H transition

Geodesic Acoustic Modes are supposed to play a key role in the L-H transition and are also assumed to be responsible for differences in LH threshold for different isotopes. Due to high flexibility of COMPASS operation and suitable diagnostic equipment, such a study has been started there in 2014 (within Enabling research EUROfusion project).

First observation of quasi-coherent modes, consistent with GAMs, has been detected in the plasma edge region of COMPASS tokamak (D plasmas): radially localized oscillations of plasma potential with frequency approx. 30 kHz (i.e. in the range expected for GAMs from theory) have been observed inside the separatrix using the electrostatic probes on both the top and LFS reciprocating manipulators; the mode exhibits a high level of coherence in potential (floating and Ball-pen probe) between the two reciprocating probes and non-linearly interacts with local turbulent oscillations.

The top probe proofed a presence of the density oscillations (observed in the ion saturation current) associated with the mode.

When the plasma column is shifted upwards with respect to the mid-plane (i.e. the Li-beam path is effectively bellow the mid-plane), the Li-BES shows coherent density fluctuations in the confined region with frequency 29-35 kHz as well. The frequency of this mode varies radially as expected for GAM oscillations. A crosscoherence as high as 70-80% is seen between the Li-BES signals and the floating potential measured by the Langmuir probes at the LFS reciprocating manipulator.

Moreover, magnetic component of the mode was detected, showing its poloidal, and radial components. The magnetic component has also a high coherence with local measurement of potential using the LFS Ball-pen probe. The mode numbers are under study, n = 0 is possible. Next, the detailed study of GAM behaviour in different isotope plasmas will be performed in 2015-16.

Turbulent transport and ion temperature measurement in the plasma edge/SOL

The ExB analyzer has been successfully used for measurements in the scrape-off layer. It has been observed that ions are divided into two distinct populations with temperatures 5 eV and 20-30 eV respectively. The low temperature component corresponds to Franck-Condon ionization energies, suggesting a relation recycling. The second is likely to correspond to hot ions coming from the separatrix. When the density is increased, recycling seems to dominate transport. Ion temperature of filaments measured by the Retarding Field Analyzer in front of the separatrix (20 eV) coincides with the hot ion populations, which suggests that for high density the large filaments are cooled much earlier than for low density. This relevant for erosion considerations and filament modelling.

Characterization of electromagnetic feature of ELM structure

In the COMPASS tokamak, the commissioning of the U-probe, similar to the one operating in RFX-mod, was completed during 2014. The probe head allows simultaneous measurements of electrostatic and magnetic fluctuation with high temporal resolution suitable for the identification of EM features of the ELMs filaments; in particular it allows the direct measurement of the current density associated to filaments. The probe head was inserted at different radial positions in the SOL of D-shaped diverted discharges in Ohmic H-modes with the clear presence of different types of ELMs in order to monitor the filamentary ELM structure.

2b Core physics studies on COMPASS and other devices

Studies of quasi-coherent modes

Multiple quasicoherent electromagnetic modes with steady-state frequency and different nature and location were measured in the COMPASS tokamak with Co-NBI at frequencies 5 kHz $< f <$ 250 kHz. Modes were observed in both low and high confinement (L- and H-modes) plasmas. Lower frequency modes with $f <$ 50 kHz were identified as low m tearing and kink MHD modes, while higher frequency modes with 50 kHz $< f <$ 250 kHz were considered as having Alfvénic nature. Unexpectedly, such modes were only observed in the H-mode, both in NBI-assisted and Ohmic, so the mode driving force is not yet clear. Using the linear MHD code KINX, we identified the observed mode with a ballooning structure is as Beta induced Alfvén Eigenmode (BAE) with m, n < 5, while an antiballooning mode is initially identified as Toroidal Alfvén Eigenmode (TAE) with m, n < 9.

Study of Runaway electrons on COMPASS

In 2014, two campaigns on Runaway electron studies at COMPASS tokamak were performed within MST2 EUROfusion project, increasing considerably our expertise in the field and strongly motivating for further RE studies. Within these campaigns a set of four new scintillation detectors and fast valve were installed, a database of RErelevant waveforms and diagnostics data has been built and data from Cherenkov and HXR detectors were validated. The study will continue in 2015-16 in order to characterize the RE beam, its generation and termination, influence of RMP and vertical kicks, etc.

2c Theory and modelling

Theoretical research within the Tokamak department has typically been motivated by experiments, either from COMPASS or from tokamaks world-wide. Nevertheless, certain principal, long-term topics are clearly present. In the reported period, the traditional wave-plasma interaction modelling covers mainly electron cyclotron (EC), electron Bernstein wave (EBW), and lower-hybrid (LH) ranges. Our own simulation codes have been extensively employed for studying EBW emission, heating and current drive on spherical tokamaks and stellarators. Non-linear LH wave-particle interactions have been studied by extending existing codes. A new code for simulating LH grill coupling has been developed. 2D and 3D Particles-in-Cell codes have been developed or extended and successfully used to study scrape-off layer plasmas. Significant contributions have been made in the resonant magnetic perturbation theory and modelling, in particular for study of the heat transport and consequences of divertor footprint generation. Edge turbulence has been studied by using and development of fluid codes. The team also contributed to the integrated tokamak modelling (ITM) taskforce, particularly in the field of free-boundary equilibrium modelling. Transport scenario modelling, including auxiliary heating systems, was used to estimate the COMPASS performance.

Electron Bernstein waves and free-boundary modelling

Electron Bernstein waves (EBWs) are the only waves in the electron cyclotron (EC) range that can propagate in a typical spherical tokamak plasma, where the EC frequency is much lower than the electron plasma frequency. This makes the usual ordinary and extraordinary EC waves are cut off. EBWs have an electrostatic nature and their propagation depends strongly on the plasma configuration. We continued the development of an EBW coupling ray-tracing code, AMR (Antenna, Modeconversion, Ray-tracing) and coupled this code with a Fokker-Planck code. These codes enabled to carry out a systematic research on EBW emission and EBW heating and current drive. Most notably, EBW heating and current drive prospects for present (NSTX) and future (MAST-U, NHTX) spherical tokamaks have been assessed. We show that EBWs can be absorbed at almost any radius and that the current drive efficiency is comparable to EC waves. The same ray-tracing code was successfully used to explain experimental observations of EBW heating and current drive on the WEGA stellarator. Off-axis power deposition and the outward shift of the absorption maximum produced by increasing the magnetic field can only be explained by the presence of a hot electron component, which permits wave absorption at the second harmonic near the plasma periphery. Moreover, the simulations also reproduced the current density reversal at the plasma centre for low magnetic fields and showed that this reversal is destroyed when larger magnetic fields are employed.

The team contributed to the European Integrated Modelling taskforce (ITM), primarily in the field of free-boundary equilibrium. A modern free-boundary equilibrium code, FREEBIE, is continuously being developed in a close collaboration with CEA Cadarache. The code was ported to the ITM platform and benchmarked against other codes.

Transport codes development and exploitation

Transport codes have been applied to predict COMPASS performance and also to interpret experimental data. The ASTRA code was self-consistently coupled to the Monte-Carlo neutral beam injection (NBI) code FAFNER, which enabled to estimate the effects of NBI heating on COMPASS. These simulations showed that NBI can significantly increase the ion temperature and thus enable regimes that were not accessible on COMPASS-D with only the electron cyclotron heating. A novel rapid tokamak simulator, METIS, was used to model COMPASS discharges using experimental data. METIS simulations can be used, for example, to calculate unknown quantities or to validate scaling laws.

Modelling of probes in plasmas – Particles-In-Cell modelling

Particles in cell (PIC) codes development is an active and strong area of the department. The in-house SPICE code has been gradually upgraded: The geometry is fully 3D now; The Poisson solver has been redesigned; Various physical phenomena have been amended. SPICE has been actively used to calibrate and interpret numerous probes, such as Langmuir, ball-pen, tunnel or Katsumata. Simulations of the Katsumata probe explained experimental observations of an electron transport into the tube due to an E × B drift. An exponential fit to the simulated I–V characteristics gives the correct ion temperature.

Quasi-neutral PIC code (QPIC) represents another PIC code that has been used and developed by the team. It has been primarily designed and applied to study fast electrons, produced be lower-hybrid grills. Secondary electron emission and collision operators were added to the QPIC code, which was then used to analyse the Tore-Supra experiments.

Magnetic perturbation modelling

One of the most important questions concerning the use of resonant magnetic perturbation (RMPs) as an ELM control mechanism is the role of plasma response. Significant progress has been made in the past years in this area. The available models now need detailed comparison of their predictions with experiments. We have been focusing on the topic of RMP-induced divertor footprints and we proved that they are sensitive to the plasma response. The magnetic field description from codes such as MARS-F is however nontrivial to precisely translate into an observable footprint shape, as the perpendicular transport must be added to the predictions based purely on the magnetic field structure - this effect is well seen in 3D transport simulations. We developed a new and fast method which takes this into account in order to be able to make more accurate predictions without relying on the time consuming transport simulations.

Another effect related to RMPs and divertor footprints are the peaks which appear when divertor heat loads are averaged over multiple RMP-mitigated ELMs. We developed a qualitative explanation of this effect based on interaction of the magnetic part of the ELM and the external RMP, and performed an analysis of results of the nonlinear MHD code JOREK in order to validate it.

2d Participation in the JET programme

The Tokamak department contributes to the JET work programme since 2001. From the overall perspective, there is a clearly increasing trend of our JET related activities as far as the number of participating scientists, total manpower as well as range of topics is concerned. This trend is naturally correlated with qualitative and also quantitative expansion of the national fusion research program after installation of the COMPASS tokamak in IPP Prague. Traditional SOL plasma and turbulence studies were gradually complemented by pedestal, H-mode and ELMs related activities. Expertise in IR camera thermography, SXR tomography and Thomson scattering diagnostics was added to the portfolio of the tokamak team, traditionally oriented toward various types of electrostatic probes. Additionally, experimental SOL and edge plasma studies were complemented by modelling activities in this area e.g. in support of the recent JET divertor lamella melting experiment, or by development of the semi-kinetic model of electron velocity distribution function near the JET divertor targets. Modelling of processes in front of JET LH and ICRH antennas is one of the traditional topics systematically addressed from the early days of our JET involvement till now. Regarding core plasma studies, the range of activities evolved around the central point of application of fast tomography reconstruction algorithms based on Minimum Fisher Regularization technique to bolometry, neutron and recently also to soft X-ray tomography. The tokamak department contributed also within JET EP2 project participating on delivery of the system of ex-vessel radiation hard Hall probes. Further, just a few highlights from the above non-exhaustive list will be mentioned in more detail.

JET divertor lamella melting – explanation of the heat flux distribution by PIC model

The JET divertor lamella melting experiment demonstrated that tungsten melting in the divertor by transient events (ELMs) can be performed without any large consequences on the core plasma behaviour by exposing a spatially misaligned lamella in the JET divertor to high heat fluxes. More than 150 ELMs indeed melted consecutively the divertor lamella. We observed shallow melt layers to move away from the strike-point region, accumulating on sides, following JxB forces as expected from the model (in both qualitative and quantitative aspects). Most importantly, we observed only a single small event of material splash out from the melt. Overall, the tungsten release stayed negligible and did not cause any problem for the discharge. However, intensive data-processing and modelling is still required in order to make predictions for ITER, where melting can happen if Type-I ELMs get unmitigated but on a 1000x larger area. Prior to this experiment a complete numerical study was made by the Tokamak Department staff (Dejarnac, Podolnik, Komm et al.) using particle-in-cell (PIC) technique to have an estimate of which flux will be falling on the spatially misaligned lamella. PIC calculations predicted a smoothing effect of the power flux falling on the protruding surface perpendicular to magnetic field lines due to the Larmor gyration of the ions.

It was shown that the probes tend to underestimate the flux by at least an order of magnitude because of measurement difficulties during the ELM peak, where the floating potential drops significantly to more negative values, making the probes nonoperational during that short period of time (< 0.5 ms). The inter-diagnostic consistency was improved with a better analysis/interpretation of IR data in the postexperiment processing in home-labs.

Experimental data (surface temperature measured by IR) were reproduced when taking into account heat propagation in the complex 3D geometry of the lamella, short time-scales of the ELMs within the MEMOS modelling (Bazylev), together with the finite Larmor effects (Dejarnac) and W vapour shielding, for both L-mode and Hmode discharges. This was done after the experiment, when we continued the analysis in our home-labs. We believe that we reached a stage where we understand the underlying physics that governs the main melting phenomena involved in this experiment.

Development of the SXR tomography algorithms

Soft X-ray (SXR) data analyses from JET using tomography was recently a very fruitful topic, in particular due to increasing interest of plasma modellers in transport of tungsten in the JET ILW configuration. Some interest was also linked to studies of plasma bremsstrahlung during different sawtooth crashes and to studies of SXR due to runaway electrons after plasma disruptions. The work has also direct synergetic effect with COMPASS programme (studies of SXR and bolometric tomography) and the WEST project in IRFM CEA Cadarache (project of the new SXR system). In the tomographic analyses at JET, we apply our algorithm MFR based on Tikhonov regularisation constrained by minimisation of Fisher information and preferential smoothness along magnetic flux surfaces. The algorithm proves to provide robust and reliable results even for the SXR diagnostic set-up at JET, which is far from ideal due to several reasons:

- The horizontal SXR camera has rather low spatial resolution, with only 15 detectors
- The horizontal SXR camera spectral sensitivity differs from other two cameras (ie the foil filter thickness is different as well as the semiconductor sensitive volume)
- The SXR cameras observe different cross-sections of the JET plasmas (ie they are located in different JET octants)

Our work demonstrated clearly that tomography based on Minimum Fisher Regularisation (MFR) can substantially contribute also to tritium transport studies, when combined with the ratio method and applied on the neutron profile monitor data from the tritium puffs in the JET TTE campaign.

Development of Hall sensors for fusion applications

Use of various configurations of flux loops for measurement of magnetic field in fusion devices is inherently limited by the pulsed operation of these machines. A principally new diagnostic method must be developed to complement the magnetic measurements in true steady state regime of operation of future fusion reactors. One of the options is the use of diagnostics based on Hall sensors. The system of two sets of three 3D ex-vessel Hall probes was designed, installed, and commissioned on JET within EP2 project. The aim of this JET upgrade is to test ITER candidate steady state magnetic sensors under fusion neutron spectrum during JET DT campaigns and also to improve the magnetic reconstruction by improving spatial resolution of exvessel magnetic field monitoring. The Tokamak Department team participated on high level commissioning of the system and on the evaluation of its long-term performance. A set of six 3-dimensional combined probes, consisting of 3 Hall sensors and 3 coils each arranged perpendicularly to each other, were designed, manufactured, and delivered to JET by MSL, Ukraine. The procurement included also the control electronic circuits that serve for various purposes including biasing of the Hall probes, amplification of the output voltage, in-situ autocalibration, monitoring of temperature inside each probe head, etc.

Measured evolutions of magnetic field components were compared to the results of modelling achieving a very good agreement. In order to assess the long term stability of performance of Hall sensors installed on JET, we compare the VH (T=0 ºC) normalized by the initial value of this voltage and multiplied by 100 for each of the three Hall sensors contained within the probe 52. Practically all values of VH (T=0 ºC) for all 3 Hall sensors contained within the probe 52 are within ± 0.1% boundaries with respect to initial values. Certain desensitization trend, amounting to approximately 0.05 %, of sensitivity is observed only for toroidal sensor during the first months of its operation on JET. Such trend is observed also for a few additional Hall sensors in other probe heads, however, upon closer inspection it was concluded that this decrease can be rather attributed to non-ideally compensated temperature dependence (slight nonlinearity) than to temporal degradation of sensors properties.

3. ITER collaboration

The Tokamak department is involved in many ITER relevant studies partly described above. These studies focus on providing data necessary to further precise the ITER scalings or detailed studies of physical processes directly influencing the ITER construction (e.g. heat loads studies at divertor and during RMP, magnetic sensor development, etc.) or operation (runaway electron studies, disruption current asymmetries, role of isotopes, etc.).

Besides that, the department has the following direct involvements/contract with the ITER organization:

- Support in design and analysis to ITER Diagnostic Division in design of edge and core Thomson scattering system including participation in Conceptual Design review (contract)
- “Plasma heat load simulations with self-consistent local electrical fields in the vicinity of the ITER tungsten divertor monoblock gaps” (contract)
- Development and testing of magnetic sensors for ITER

Research Report of the team in the period 2010–2014

Institute	Institute of Plasma Physics of the CAS, v. v. i.

Scientific team	Pulse Plasma Systems

The research team of the Department of Pulse Plasma Systems (IPS) continued investigating a nonequilibrium (low-temperature) plasma generated by various types of pulse high-voltage electrical discharges in gases, liquids and gas/liquid environments. The physical and chemical processes intentionally initiated by such discharges were studied in dependence on the type of discharge, pulsed power, and the nature and the chemical composition of the surrounding environment in order to achieve specific effects. Four main topics were studied in the period 2010-2014 with the goal of potential utilization of electrical discharge plasma in different applications (environmental, biological, medical). These topics were 1) Plasmachemistry induced by electrical discharges in liquids and gas/liquid environments, 2) Physics and biological effects of focused shock waves in water, 3) Physics, kinetics and diagnostics of streamer discharges in gas phase, 4) Soft X-ray emission of fast high-current capillary discharges. The main results achieved in the frame of each topic are following:

1) Plasmachemistry of electrical discharges in liquids and gas/liquid environment

The IPS team is considered among the world's best in the area of research on plasma chemistry induced by electrical discharges in liquids. Currently, the chemistry of plasma/liquid interactions, especially of air plasmas in contact with water, are of great interest to the nonthermal plasma community, especially to that focused on the biomedical applications of plasma. Various types of plasmas were shown efficient in inactivation of a number of microorganisms (bacteria, spores and viruses) and new successful or potential applications of plasmas in medicine have been demonstrated, such as the treatment of skin diseases and dental cavities, plasma-assisted blood coagulation, and many other applications, which led to establishing of the new research field - so called *plasma medicine*. However, despite successful results, the detailed mechanisms of plasma-induced microbial and living tissue interactions are not well understood. Characterization of physical, chemical and biological processes induced in electrical discharge plasmas and understanding their formation mechanisms present very important research topics in plasma physics and in related research on mechanisms of plasma interactions with living cells and tissue.

During last 5 years the research team of IPS published several highly cited publications related to this topic and was involved in number of international activities. The research was focused especially on the chemistry of plasma/liquid interactions induced by air plasmas in contact with aqueous solutions, common to plasma systems interacting with living matter, in which plasma typically occurs in humid air and touches a wet surface (biofilms, cell tissue, skin). Various types of discharge plasma/liquid systems were used and studied such as plasma jets, corona discharges, dielectric barrier discharges and spark driven electrospray. The success of the research performed at IPS on this topic is well represented by one of the most recent papers *Aqueous-phase chemistry and bactericidal effects from an air discharge plasma in contact with water: evidence for the formation of peroxynitrite through a pseudo-second-order post-discharge reaction of H_2O_2 and HNO_2* published by P. Lukeš, E. Doležalová, I. Sisrová and M. Člupek (all from IPS) in journal *Plasma Sources Sci. Technol.* **23** (2014) 015019 , which has been selected by the journal's Editors in the exclusive collection "*Highlights of 2014*". Highlights are selected based on outstanding research and impact on the low-temperature plasmas community and represent the breadth and excellence of the work published in 2014. Previously the formation of peroxynitrite (ONOOH) and its role in biocidal effects of air plasma was proposed by many authors, however, its experimental evidence was just speculative since ONOOH is rather difficult to measure directly due to its short lifetime and fast disproportionation in the plasma/liquid systems. In our work for the first time the formation of peroxynitrite in plasma-treated water was experimentally proved and its rate of formation was quantitatively determined through kinetic analysis of the post-discharge reaction between H_2O_2 and nitrite ions in plasma-treated water. Importance of this study was also in using phenol as a chemical probe of the chemistry of reactive oxygen (ROS) and reactive nitrogen species (RNS) in plasma treated water. By detection of specific hydroxylated and nitrated products of phenol formed upon reaction with NO_2•, NO• and OH• radicals and NO^+ ions the chemical reactions mediated in plasma treated water by peroxynitrite have been identified.

In the same work and also in another paper *Formation of ROS and RNS in water electro-sprayed through transient spark discharge in air and their bactericidal effects* published in journal *Plasma Proc. Polym*. **10** (2013) 649-659 we have demonstrated strong contribution of ONOOH to bactericidal effects induced by air plasma in treated water. Productions of H_2O_2, nitrites, nitrates, peroxynitrites, pH changes, and the extent of oxidative stress induced by plasma in selected bacteria were evaluated. Acidified nitrites interacting with H_2O_2 (as precursor of ONOOH in plasma treated water) were determined as the most important bactericidal ROS/RNS agents in plasma-treated water. In this work, which was published in the frame of joint collaboration with colleagues from Comenius University, Bratislava, our team participated by performing and processing the results of all chemical and microbiological analysis. This paper belongs among the most cited papers in the journal *Plasma Proc. Polym*. (18 citations SCOPUS within the first 18 months after publishing).

We have also studied in detail mechanisms of bacterial inactivation induced by plasma in water. We focused particularly on the effects of the reactive species generated by the air plasma on the bacterial cell membrane integrity. We have determined that peroxidation of cell membrane lipids by the reactive species (mainly OH radicals) produced by plasma is an important pathway of bacterial inactivation. Moreover, we have determined significant differences between bacteria assay using the conventional culture-based techniques and fluorescent LIVE/DEAD staining. Our experiments indicate that treatment of the bacterial suspension with the plasma was highly effective (7-logs) when assayed by conventional CFU counting, which was the opposite of the slight reduction (less than 1-log) observed when assayed by fluorescent staining. We proposed that the bacteria may have entered the viable but non culturable (VBNC) state during the plasma treatment. We proposed that the bacteria did not grow colonies because of inadequate resuscitation or transformation of DNA strands and inhibition of the replication process by the plasma treatment. The results of this work were published in the journal *Bioelectrochemistry* (http://dx.doi.org/10.1016/j.bioelechem.2014.08.018).

In addition to the chemistry of ROS and RNS produced by electrical discharge plasma in aqueous solutions, important results were also obtained in the research on plasma-catalytic processes induced by discharges in water. It was determined that tungsten as material of discharge electrodes may significantly affect plasmachemical processes induced by electrical discharges in liquids. Tungstate ions released from the tungsten electrode by erosion in the discharge were shown to form highly oxidative peroxotungstates through the catalytic reaction with H_2O_2 produced by the discharge in water. Previously attention was paid mainly to the iron/stainless steel electrodes, from which the released Fe(II)/Fe(III) ions may initiate Fenton's reaction with hydrogen peroxide plasmachemically produced by the discharge in water. In this work tungstate ions released from tungsten discharge electrode were shown to play a dominant role in the decomposition of H_2O_2 produced by the discharge in water. Using dimethysulfoxide (DMSO) as the chemical probe it was determined that tungsten participated in the degradation of DMSO through the tungstate-catalyzed oxidation by H_2O_2, in addition to the oxidation of DMSO by OH radicals. Results of this work significantly contribute to better understanding of the processes associated with plasma generated in water and they were published as an invited paper in the journal *Plasma Sources. Sci. Technol*. in special issue devoted to Plasma with Liquids (Lukeš P. et al: The catalytic role of tungsten electrode material in the plasmachemical activity of a pulsed corona discharge in water. *Plasma Sources Sci. Technol.* **20** (2011) 034011)

The leader of the research team Dr. Lukeš also edited and authored three chapters in the book *Plasma Chemistry and Catalysis in Gases and Liquids* (Wiley-VCH, Weinheim, 2012, ISBN-13: 978-3527-33006-5). This book provides for the first time a state-of-the-art of fundamental and applied knowledge on the elementary chemical and physical phenomena in low-temperature plasma in liquid and gas/liquid environments, mechanisms of interaction of plasma with chemical and biological content in water, and environmental and biomedical applications of plasma in water and gas-liquid environments. Dr. Lukeš worked on this book with major experts in the fields of plasma physics, plasma chemistry and plasma catalysis and as book editor and author of Chapters 6-8 was responsible for the part related to liquid phase, which makes over 40% of the total book content (168 pages from total number of 394). Dr. Lukeš had the major contribution to the Chapters 6-8. Topics of these chapters were: Elementary chemical and physical phenomena in electrical discharge plasma in gas-liquid environments and in liquids (Ch. 6), Aqueous-phase chemistry of electrical discharge plasma in water and in gas-liquid environments (Ch. 7, Biological effects of electrical discharge plasma in water and in gas-liquid environments (Ch. 8). Currently, SCOPUS reports 13 citations of the book and 16 citations of Chapters 6-8.

In addition to published journal works (see ASEP database for the full list), the research team presented the results of its work in number of international conferences during the 2010-2014, including one plenary lecture (PSE2014) and 8 invited lectures, given by Dr. Lukeš (http://www.ipp.cas.cz/Staff/detail?id=lukesp#invited), which demonstrates high recognition of the quality of the research work and achievements of the IPS team in the research of plasmachemical processes in liquids. Since 2013 the IPS team is also a member of the new European network project *COST Action TD1208: Electrical discharges with liquids for future applications*. Dr. Lukeš is one of the leaders (Working Group 2) and member of Management Committee of this COST Action. In the frame of this project our laboratory is frequently hosting researchers of STSM program (Short Term Scientific Mission), which is also reflecting high level of expertise of IPS team in the research of plasmachemical processes in liquids and high interest in collaboration of research institutions from EU plasma community (e.g. INP Greifswald, University of Bologna, etc.).

Our collaborations span also outside of Europe. In 2012, Dr. Petr Lukeš was 6 months as the Visiting Professor at Kumamoto University, Kumamoto, Japan with research group of prof. Hidenori Akiyama. This stay promoted research collaboration between the Institute of Plasma Physics AS CR and Kumamoto University, which continues further in the frame of joint research project supported by Academy of Sciences of the Czech Republic and in the framework of the International Bioelectrics Consortium. The outcome of this collaboration is so far two research papers focused on the plasmachemical processes induced by pulsed electrical discharges in water under high pulse repletion rates. It was found that pulse repetition rate of input power significantly influenced properties and plasmachemical activity of pulsed discharge in water. By varying the pulse repetition rate, two distinct modes of discharge plasma in water were determined (streamer and bubble mode). The first was characterized by the formation of streamer channels in water. The second mode was formed typically above 500 Hz, when the formation of streamer channels in water was suppressed into aggregate of very fine gas bubbles surrounding the electrode tip. Thermal processes played likely an important role in the formation of plasma in water with higher pulse frequency. The efficiency of both chemical and biocidal processes induced by plasma in water decreased significantly using higher pulse repetition rates. These results were published in the joint paper *Effects of pulse frequency of input power on the physical and chemical properties of pulsed streamer discharge plasmas in water* by Ruma, Lukeš P., Aoki N., Špetlíková E., Hosseini S.H.R., Sakugawa T., Akiyama H. This paper was selected as the front cover image of Volume 46, Number 12, 27th March 2013 issue of the *J. Phys. D: Appl. Phys.* The second joint paper is Ruma, Hosseini S.H.R., Yoshihara K., Akiyama M., Sakugawa T., Lukeš P., Akiyama H.: *Properties of water surface discharge at different pulse repetition rates*, published in *J. Appl. Phys*. 116 (2014) 123304. The researchers from IPS had major contribution in these works on performing the chemical and biological analysis of plasma-induced effects in water.

2) Physics and biological effects of focused shock waves in water

Multichannel pulsed-electrohydraulic discharge generator with cylindrical ceramic-coated electrodes developed at IPS department in previous years was used as a source of focused shock waves and their biological effects were studied *in vitro* and *in vivo* on different cancer cells and tumors using various animal models. Shock waves were generated either as a single wave or as two successive (tandem) shock waves with time delay of 10 μs between the waves. The research was performed in cooperation with medical institutions in the Czech Republic (1st and 2nd Medical Faculty of Charles University Prague; Medical Faculty of Palacký University Olomouc). *In vitro* experiments were performed with erythrocytes, human acute lymphoblastic leukemia CEM cells and melanoma B16 cells. Increasing exposure of cells by tandem shocks resulted in higher haemolysis and cell membrane perforation at low number of applied shock waves (up to 100 to 200 double shocks; depending on the cell type, fluid medium and vial position in the focus) and total damage (fragmentation) of the cells at a higher number of shocks. It was proved *in vivo* that focused tandem shocks waves are capable to cause localized lesions at a predictable location deep within soft tissue in the focus without damaging tissue located in front of the focal point. Tandem shock waves were focused on rabbit’s liver and tight muscle and targeted lesions induced by shock waves were examined by magnetic resonance imaging (MRI). The lesions in the tissue were clearly identified by MRI as a dark spot of hematoma surrounded by a bright area of edema with the size of approximately twice (~ ø 5 mm) the focal (- 6 dB) area of the tandem shock wave generator (~ ø 2.5 mm). This larger size was attributed to the changes in the acoustical properties of the treated tissue with an increasing number of applied shocks. Subsequent histological examinations of injured tissue showed a very sharp boundary between the injured necrotic tissue and the surrounding healthy tissue.

In vivo tumor growth delay experiments were performed with B16 melanoma, T-lymphoma and R5-28 sarcoma cell lines. Syngeneic inbred female C57B16 strain mice, outbred rats SD/CUB (SpragueDawley strain) and Lewis strain rats were used as experimental animal models. Tumors were transplanted into flanks or thighs of model animals. The growth of tumors exposed to tandem shock waves (240 or 600) was significantly delayed (typically about two times) compared to controls. A higher number of tandem shocks (> 400 to 600) resulted in hemorrhaging and tissue damage of exposed tumors. Additional delay prolongation of tumor growth was obtained by combined treatment with cisplatin, which reduced the growth of tumor three times compared to controls. The reason for enhanced cytotoxicity of cisplatin was most likely due to increased permeability of cancer cell membranes induced by tandem shock waves allowing a higher dose delivery of cisplatin into the cells. Consequently, it was shown that tandem shocks can initiate cavitation-induced sonochemical reactions in tumor. Using sonosensitive porphyrin based drug Photosan the *in vivo* effect of tandem shock waves on tumor growth was significantly enhanced. Porphyrins preferentially accumulate in malignant tissue and in contrast to anticancer drugs (such as cisplatin) they are nontoxic in the absence of light or ultrasound. Their synergistic effect is thought to be associated with cavitation, which induce sonochemical excitation of porphyrins and lead into the formation of the cytotoxic singlet oxygen. Thus, in the case of tandem shock waves it was suggested that the enhancing effect of Photosan on tumor growth delay was likely a result of sonodynamic effect of cavitation induced by tandem shock waves *in vivo*.

The results of this extensive and highly interdisciplinary research work are very encouraging and promising for potential use of focused tandem shock waves in tumor therapy, e.g. for potentiation of cytotoxic effects of cytostatic drugs on tumors. The results of this research were published in several journal papers* and were presented at international conferences including two invited lectures. Moreover, the first clinical tests of focused shock waves are under preparation in collaboration with the First Medical Faculty of Charles University Prague. *[1] Lukeš et al.: Focused tandem shock waves in water and their potential application in cancer treatment, *Shock Waves* **24** (2014) 51-57; [2] Lukeš et al.: Generation of focused shock waves in water for biomedical applications, in: *Plasma for BioDecontamination, Medicine and Food Security, Series NATO Science for Peace and Security Series – A: Chemistry and Biology, Chapter 31*, Springer, 2012, p. 403-416; [3] Beneš et al.: Biological effects of tandem shock waves demonstrated on magnetic resonance, *Bratislava Medical Journal* 113 (2012), 335-338; [4] Zeman et al.: Účinek rázové vlny na kostní cement a její potenciální využití v ortopedii, *Ortopedie* 6 (2012), 100-102. IPS team contributed to these results by performing all physics and generation of shockwaves.

Since 2011, the IPS research group also became a member of prestigious International Bioelectrics Consortium (IBC). In 2005, the consortium was established by Old Dominion University, USA; Karlsruhe Institute of Technology, Germany and Kumamoto University, Japan in order to develop broad international research collaboration on bioelectrics. These three institutions belong to the world leaders in the research on biological effects of pulsed electrical field (PEF). Since 2005 the IBC expanded its target activity from PEF to other fields including biological effects of nonthermal plasma, shock waves and pulsed electromagnetic radiation. At present, thirteen additional American and European institutions are members of the IBC including the Institute of Plasma Physics AS CR.

In the frame of IBC began close cooperation of the IPS research team with Kumamoto University concentrated on the research of physical mechanisms of interactions of focused shock waves in water generated by shock wave generator developed at IPP. Pressure field generated by shockwaves at the focus was determined using fiber optic probe hydrophone (FOPH) and analysis of shock wave propagation in water was performed using high speed framing camera at Kumamoto University. Using these diagnostics a very unique data were obtained. The FOPH measurements of the shock wave profile revealed much higher peak pressure at the focus (372 MPa) compared to the values we have measured by polyvinylidene fluoride (PVDF) pressure sensors in our previous work (typically ~ 50 MPa). The reason for such great differences was in the much smaller diameter of the active area of the FOPH (100 μm) than PVDF (1,000 μm). Therefore, FOPH can much more accurately capture the pressure variation within the focal extension for fine focus with smaller than 1 mm^2 area. It was determined that the peak amplitudes of the positive pressure wave rapidly decreased with lateral distance from the focus, indicating a very narrow focal area. The pressure amplitude dropped to the half value at a distance of less than 0.25 mm from the axis. The shock wave propagation through the focal area in water visualized by a high-speed camera showed that by focusing the primary diverging cylindrical pressure wave propagating from the cylindrical discharge electrode was transformed into an approximately conical converging shock wave at the focus area. The shock front was visible in the shadowgraphs as two lines intersecting on the axis of symmetry of focusing parabolic reflector. The experimentally determined speed of propagation of intersection point of shock wave front in axial direction was 2.17 ± 0.1 km/s.

These results were compared with the shock wave propagation in tumor tissue. We have studied *in vivo* effects of focused shock waves induced in the syngeneic sarcoma tumor model using the TUNEL assay, immunohistochemical detection of caspase-3 and haematoxylin-eosin staining. This study was performed in collaboration with the Institute of Animal Physiology and Genetics AS CR and the First Faculty of Medicine of Charles University in Prague. In tumors treated with shock waves, a large area of damaged tissue was detected which was clearly differentiated from intact tissue. Localization and a cone-shaped region of tissue damage visualized by TUNEL reaction apparently correlated with the conical shape and with the direction of shock wave propagation determined by high-speed shadowgraphy. A strong TUNEL reaction of nuclei and nucleus fragments in tissue exposed to shock waves suggested apoptosis in this destroyed tumor area. However, specificity of TUNEL technique to apoptotic cells is ambiguous and other apoptotic markers (caspase-3) that we used in our study did not confirmed this observation. Thus, the generated fragments of nuclei gave rise to a false TUNEL reaction not associated with apoptosis. Mechanical stress from high overpressure shock wave was likely the dominant pathway of tumor damage.

The results of this work were published in joint paper *In vivo effects of focused shock waves on tumor tissue visualized by fluorescence staining techniques* which is *in press* in the journal *Bioelectrochemistry* (http://dx.doi.org/10.1016/j.bioelechem.2014.08.019). The contribution of IPS team to the result of this work was 50%. Another paper published on physics of focused shock waves in water by IPS research team was *Shock waves generated by an electrical discharge on composite electrode immersed in water with different conductivities* by Stelmashuk V. and Hoffer P. in *IEEE Trans. Plasma Sci*. 40 (2012) 1907-1912. Physics of electrical breakdown in cavitation bubbles produced by focused shock waves in water was the topic of another four papers published by Dr. Stelmashuk in journals *J. Phys. D: Appl. Phys., Phys. Plasmas* and *IEEE Trans. Plasma Sci*. in 2014.

3) Physics, kinetics and diagnostics of streamer discharges in gas phase

The IPS team has been also at the forefront of research related to filamentary streamer discharges in gaseous phase. Various atmospheric-pressure streamer-based discharges have become important in numerous environmental applications, material treatment technologies, and aerodynamic and biomedical applications. Therefore continuous effort is required in order to understand and determine basic streamer parameters produced under various conditions through the state-of-the-art experimental measurements and numerical modelling. On the other hand, red-sprite transient luminous events (TLEs) are large streamer events propagating vertically in the upper atmosphere surpassing altitudes from ~35 km to ~85 km above sea level characterised by very different pressures
(between ~8.9 and ~0.16 torr) and gas temperatures (between -10 and -75 °C). Investigation of TLEs based on plasma-induced emission is, compared with laboratory discharges, much more difficult because of their stochastic nature (as in the case of cloud-to-ground lightning events) and very long observational distances (typically hundreds of kilometres between the place of the TLE occurrence and diagnostic instrumentation). To this end, laboratory red-sprite TLE analogue experiments are important for better understanding of both the fundamentals of TLEs and their associated phenomena (heating or NO_x production). In order to address challenges associated with typical streamer characteristics (e.g. high propagation velocity exceeding the velocity of electron drift, small streamer channel radius with respect to its length and enhanced mean energy and density of free electrons in the streamer head compared with the streamer channel), we have developed several original approaches allowing advanced study of streamer discharges on nanosecond to microsecond timescales with spatial

resolution of several micrometers. By combining a wide range of complementary diagnostic techniques, fundamentals of low-temperature, non-equilibrium plasma reaction mechanisms and energy transfer processes underlying the onset and propagation of ionizing streamer fronts were studied. Obtained experimental results were complemented by numerical modeling and simulation approaches.

Significant effort was dedicated to the design and development of three new discharge reactors suitable for implementing in situ diagnostics based on laser techniques with high spatial and temporal resolutions on single streamer discharge at atmospheric pressure as well as at low pressures (to simulate the laboratory analogue of the TLE's discharges) and at controlled gas temperatures (cooling/heating circuit allows stabilising gas temperature between -70°C and + 50°C). We have built one dielectric (discharges at high pressures and controlled gas temperatures down to -70 °C) and two stainless-steel reactor chambers (discharges at high pressures at ambient temperature, and at low pressure and controlled gas temperatures down to -70 °C), all suitable of implementing the emission and LIF based diagnostics on a single streamer filament produced in various DBD gaps (from 1-2 mm to 5-10 cm) at required pressures. Furthermore, both stainless-steel reactors allow mounting pair of high reflectivity mirrors necessary for implementing CRDS diagnostics (the two mirrors form optical cavity after the alignment with the streamer filament passing perpendicularly through the cavity axis). At the end of 2014, the LIF optical ports were upgraded in order to start with implementing and testing techniques based on stimulated Raman scattering (allowing to monitor rotational/vibrational distributions of ground electronic states of diatomics).

Development of relevant real-time control and experimental approaches allowing advanced optical diagnostics (ICCD microscopy, emission spectrometry, laser based diagnostics) of discharges on timescales from nanoseconds to milliseconds was recognised as a crucial step (spatio-temporal stability of generated micro-discharges and precise timing of diagnostic instrumentation) whose solution determined quality of further experimental works. We developed and successfully tested an approach to control the generation of micro-discharges on the ns time-scale. Controlled generation of triggered streamer micro-discharges is based on the power supply superimposing the AC HV driving waveforms with a fast (ns risetime) positive HV pulse. The applied AC high voltage waveforms were amplitude modulated to give several consecutive sine-wave cycles fired at a fixed repetition frequency producing required high-voltage AC ON/OFF periods. By monitoring simultaneously HV, current and emission waveforms associated with triggered micro-discharges, we have verified that achievable temporal stability is about 1 ns in a wide range of pressures (0.1-760 torr) by selecting suitable (pressure and gap dependent) amplitudes and ratios of AC and pulse HV waveforms. Achieved temporal stability is more than sufficient for the ICCD (minimum gate width of 2ns) and/or laser (pulse duration of 5 ns) based diagnostics however it also significantly improves quality of sub-nanosecond diagnostics (fast photomultipliers) because triggered micro-discharges develop under the same conditions (not guaranteed in the case of simple AC or simple pulse excitation). Furthermore, we developed methodology to obtain radial distributions of electronically excited species produced during the streamer propagation by applying Abel inverse transform to projected luminosities of single streamers. The approach is based on projected luminosities processed by Abel inverse transform procedure assuming cylindrical symmetry of the streamer channel (analytical method based on coaxial Gaussian functions was verified by numerical Hankel-Fourier method).

Application of LIF/CRDS techniques on a single streamer micro-discharge with high spatial and temporal resolutions allowed quite significant qualitative step forward. Implementation of the LIF diagnostics (realised during 2011-2013) focused on tracking OH and NO species in ground electronic state, electronically excited N_2(A^3 and B) molecule, ground electronic state of N_2 (X) ion, ground 3 + 2 electronic states of atomic oxygen and nitrogen (TALIF). Measurements were performed on discharges produced at selected pressures (10, 50, 100, 200, 400 and 760 torr). In the case of OH, NO, N_2(B^3) and N_2^+(X^2) we utilised standard excitation -detection schemes to detect the lowest (v=0) vibrational level of a given state. Concerning the OH detection, the laser (excitation) wavelength was set to 282.05 nm which nearly coincides with Q_{11}(J=1.5) rotational line of the (1,0) band at 282.07 nm. After pumping the single rotational level of the OH(A^2 ,v=1) electronic state, the excitation energy becomes quickly redistributed due to fast rotational relaxation processes and, partly due to vibrational relaxation. Consequently, at atmospheric pressure, observed fluorescence spectrum is usually characterised by a Boltzmann rotational distribution and emission originating from both OH(A^2 ,v=0)) metastables we have developed an

and OH(A^2□,v=1) vibronic states. In the cas e of N_2(A^3
alternative excitation-detection scheme which is particularly suitable for highly transient (streamer) discharges and we succeeded to detect the lowest eleven vibronic N_2(A^3 □) levels at different pressures in timescales ranging from 50 ns up to 200 microseconds after the streamer event. This temporal range evidences quite high sensitivity of our LIF-OPO setup and allows exploring wide range of phenomena associated with filamentary streamers (e.g. vibrational relaxation during early afterglow or quenching by atomic species during late afterglow). Implementation of the CRDS (cavity ring-down spectroscopy) diagnostics (realised during 2013) is based on CRD-Optics (Los Gatos Research) components (two high reflectivity (99.995%) mirrors, center wavelength 635 nm, bandwidth 610-670 nm), two Quartz-Coated Mirror Mounts and two home-made adaptors (allowing quick mount of the cavity on both ss reactors). Concerning light source for injecting photons into the cavity, we used OPO laser tuned to specific wavelengths. Methodology tested is based on sampling variation of the ringdown time constant at wavelength corresponding to absorption peaks of tracked species (623 and 662 nm for NO_3, and 643 nm for NO_2). Time-resolution and detection limits of the technique is limited by ring-down time of empty cavity (approx. 3 microseconds in our case) and by the laser pulse duration. Implementation of techniques based on stimulated Raman scattering (during 2014) was realised by employing 2nd harmonic output of the Nd-YAG fundamental wavelength at 532 nm, purified by the laser clean-up transmitting filter. Raman signal (Stokes component) from N_2/O_2 observed through steep edge filter allowing measurements of low frequency Raman shifts (down to 100 cm^{-1}).

Determination of basic discharge regimes and parameters including overall energy balance, and determination of reactive species (radicals, metastables) concentration, time-evolution and spatial distributions in plasmas ignited at atmospheric pressures and at pressures relevant for the TLE's has been of fundamental importance for our work. The build-up and decay of UV–vis–NIR emission produced by a single triggered streamer discharge under various conditions was inspected (ICCD images and PMT waveforms) simultaneously with voltage/current waveforms allowing recognition of principal pre-breakdown/streamer/glow phases including estimation of the fraction of the total energy deposited during each distinct phase. ICCD spectrometry with time resolution of 2 ns was used to study temporal evolution of radiative species in N_2, N_2-O_2, Ar streamers with/without He/H_2O admixtures. Optical emission intensity waveforms of important electronic states of diatomic molecules (N_2, N_2^+, NO) and atoms (Ar, He, N, O) were also studied with sub-nanosecond time-resolution (approx. 200 ps) during single streamer micro-discharge evolution. Detailed numerical roto-vibrational analysis of dominant diatomic systems observed in emission was performed employing numerical models of emission spectra. Obtained waveforms were associated with principal processes occurring during streamer evolution, e.g. electron impact excitation and ionization, resonant energy transfer reactions, vibrational relaxation or quenching due to atomic species. Special attention was paid to study emission produced by atomic oxygen and helium lines, and to their potential use for the E/n measurements. Detailed analysis of N_2 triplet emission systems was performed and vibrational distributions/rotational temperatures of excited states under specific discharge conditions were obtained.

Extension of diagnostic tools related to E/N measurements in streamer micro-discharges is of general importance for the streamer related research community. The simplest way to obtain information on the E/N is based on comparing the emission intensities of selected radiative transitions with different excitation thresholds. In the case of nitrogen containing streamers, the method based on the ratio of FNS/SPS emission intensities has been frequently utilized. The method requires the evaluation of the reliable dependence of excitation rates on E/N (e.g. by using the BOLSIG+ solver), and FNS/SPS ratios determined experimentally can be reduced to E/N by well-established procedures. However, the use of the FNS/SPS ratio method is, in the case of streamer discharges, by no means trivial. It has been proved that in the case of a propagating streamer, the self-enhanced electric field in the streamer front and emission waveforms of both the FNS and the SPS system are mutually shifted. When integrating FNS and SPS emissions from both regions, due to the limited spatiotemporal resolution of spectrometric detectors, radiation acquired from the Emax region becomes outweighed by the stronger contribution from the region behind the streamer head. The registered FNS/SPS ratio then characterizes the lower E/N occurring behind the streamer head rather than the Emax itself. This issue has been addressed in collaboration with colleagues from MU Brno, Greifswald and Paris. Further discrepancies arise due to various kinetic schemes behind the FNS/SPS ratio method, including the assumption of the exclusive excitation of N_2/N_2^+ molecules from the ground electronic state by electron impact processes and selection of collisional quenching channels (with appropriate rate constants) of radiative states by N_2/O_2 molecules. We have demonstrated, that for low reduced fields, E/N < 200 Td

, the excitation rate of the N_2^+(B^2□) is not controlled by electron impact ionization from the ground electronic state of N_2. The direct consequence of this (and the core of our proposal) is that for lower fields the excitation from the N_2^+(X^2□) state b ecomes a comparable or even dominant process which must be, in general, included into the kinetic scheme. Furthermore, other two possible probes for testing E/n were demonstrated and proposed: (i) vibrational N_2(C^3□) distributions created by electron impact obtained from the SPS, and (ii) the ratio of intensities of the N^I or O^I near-infrared atomic lines with respect to the FNS and SPS molecular bands (particularly suitable for sprite streamers or other TLE forms).

Description of the fundamental physical and chemical processes occurring during streamer discharge evolution through experiments, modelling and simulations has allowed obtaining further insight. General kinetic model was developed to predict the evolution of individual vibronic levels governed by various collisional processes (during 2011-2013). Vibrational kinetics of exited states was described by a set of coupled differential equations (0-D model). Numerical solution allows predicting evolution of individual levels for specific initial conditions (pressure, temperature, gas mixture) and is being used to make comparison with experimental findings (obtained through the LIF and emission diagnostics). Simplified model was used to simulate both shape and amplitude of the LIF pulse (during 2012). Basically the LIF pulse decay can be well fitted by the three-exponential decay with parameters depending on the vibrational level, total pressure and gas composition. Decoupling individual threeexponential decay components allows determination of rates of quenching processes and corresponding quenching rate constants. The procedure was successfully tested for example on v=4-6 vibrational levels of the N_2(B^3 □) electronic state providing excellent agreement with published data and we are working on fixing quenching rate constants for v=7-12 vibrational levels of the N_2(B^3□) electronic state (poorly known or not published). Modelling dominant excited/radiative states was performed and results compared with experimental observations in case of Ar streamers during 2013. Namely, kinetic model describing temporal evolution of Ar multiplet transitions occurring in the NIR spectral range has been developed. It takes into account electron impact excitation from the Ar ground and metastable states. This model was used to explain quite efficient population of $2p'_1$, $2p'_4$, $2p_5$ and $2p_9$ terms (in Paschen notation) observed experimentally during Ar streamer propagation period. In the case of nitrogen (or N_2+O_2), the kinetic scheme is (completed during 2014) based on assumption of vertical quenching of triplet states of nitrogen (justified in the literature). Obtained results emphasised importance of N_2(a^1□, A^3□, B^3□ and C^3□) state populations for predicting optical emissions produced by streamers under various conditions. The actual kinetic scheme accounts for selected electron impact ionization, excitation and dissociation processes, collisional-radiative cascades and most important energy transfer processes (vibrational relaxation, quenching by atoms, resonant energy transfer and pooling reactions. The N_2(A^3□, B □ and C^3□ states are considered including their 3 vibrational structure, other electronic states of nitrogen and oxygen are considered as electronic states without internal vibrational structure. Very good agreement experiment-model was achieved for in the case of the A evolution of individual vibrational levels of the A ^{3}□ and C^3□ states at various pressures. Furthermore, □ state, we have been able to provide, for the first time, experimental vibrational distributions and populations of first eleven vibrational levels of N $_2$(A^3□) metastables under streamer 3 discharge conditions.

In the course of the last few years, we have definitely improved spatiotemporal resolutions of the diagnostic instrumentation by employing ICCD microscopy which triggered research focused on radial distributions of radiative species within the streamer head and channel. By applying optical diagnostics at different timescales, from nanoseconds to microseconds, we have obtained important results related to evolution of molecular metastables, atomic species and molecular ions produced by streamer head electrons. The results of the group were continuously reported on international congresses including two invited lectures given by the PI (Dr. Šimek) and published in international journals including one comprehensive invited topical review (Šimek M.: Optical diagnostics of streamer discharges in atmospheric gases, *Journal of Physics D-Applied Physics* **47** (46), (2014) 463001).

Two bilateral cooperations have been established with the team of Istituto de Astrofisica de Andalusia, (IAA-CSIC Granada, Spain) and the Istituto di Metodologie Inorganiche e dei Plasmi (CNR, Bari, Italy). Cooperation with the IAA-CSIC group focuses physics of transient luminous events, especially so called "Red Sprites". During the last period, several joint papers have been published, e.g.: A. Luque, F.J. Gordillo-Vázquez and M. Šimek: Spectrum of Sprite Halos, *J. Geophys. Res.* 2011, **116**, A09, 319 and Gordillo-Vázquez F.J., Luque A., Šimek M.: Near infrared and ultraviolet spectra of TLEs, *J. Geophys. Res.* **117** (2012) A05329. The contribution of IPS team to both results of this work was 50%. Cooperation with the CNR group addresses development of various laser-based diagnostics focused on streamer based discharges. For example, paper G. Dilecce, P.F. Ambrico, M. Šimek and S. De Benedictis: LIF diagnostics of hydroxyl radical in atmospheric pressure He-H_2O dielectric barrier discharges, *Chem. Phys.* 398 (2012) 142-147 (20 citations WOS within the first 2 years after publishing) and G. Dilecce, P.F. Ambrico, M. Šimek and S. De Benedictis: OH density measurement by time-resolved broad band absorption spectroscopy in an Ar–H_2O dielectric barrier discharge, *J. Phys. D: Appl. Phys.* 45 (2012) 125303 make significant contribution to OH detection in atmospheric DBD based discharges utilised in field of plasma medicine research. The contribution of IPS team to both results of this work was 30%.

4) Soft X-ray emission of fast high-current capillary discharges

The research direction of pulsed high-current capillary discharges was primarily focused on generation and application of coherent extreme ultraviolet (XUV) radiation. The research started on CAPEX machine with Ar-filled capillary that lase on Ne-like argon ions (Ar^{8+}) on the wavelength 46.9 nm. One of challenges for discharge-based coherent sources is to achieve lasing on shorter wavelength (optimally at 13 nm, which is attractive for micro-electronics-motivated nano-lithography). There are basically two approaches: the first is to continue in the row of excitation-pumped transitions of Ne-like or Ni-like ions (Pd, Ag, Cd, In, Sn), the second changes the excitation pumping to recombination one. Both these approaches have been tested.

The first approach was published in the paper *A potential environment for lasing below 15 nm initiated by exploding wire in water* in *Laser and Particle Beams* **28** (2010), 1, 61-67 by K. Kolacek et al. which summarizes our idea of “capillary with liquid walls” filled with Ag vapour that is created by Ag wire explosion in liquid (water) and that should lase at 13.9 nm. The proximity-wall-stabilized plasma channel is extremely stable and its walls are ever fresh (without any metallic deposition). The model of wire explosion (inclusive melting and boiling phase transitions, thermal diffusion, and variable conductivity at originally skinned and gradually diffusing driving current) was developed and compared with measurement of the discharge current and with side-on and end-on monitoring of H-alpha line emission. Analysis of H-alpha line profile is used for diagnostic of water-vapour layer around the wire. The differences between model and reality are attributed to the fact that the pressure dependence of material constants was neglected in the first approximation. The above mentioned model of wire explosion was further improved including water evaporation around the plasma channel (K. Kolacek et al. *EUV radiation of pulse high-current proximity-wall-stabilized discharges*, X-Ray Lasers 2010, Proc. 12th IC X-Ray Lasers 2010, Gwangju, Korea, 263-268). This method of extraction of XUV radiation from water-filled chamber into vacuum is protected by patent-pending application 2009-805. Another lasing media using Zn and Ag wires were also tested, however, further experiments were stopped, because they were extremely technically as well as time demanding.

The second approach was based on recombination pumping scheme. In the most common case the population inversion is achieved on Balmer-alpha transition of hydrogen-like ions. Here two conditions have to be fulfilled: first, during discharge-pinching the plasma channel has to be heated so much that abundance of fully stripped ions is created; second, as soon as the first condition is fulfilled, plasma has to be so rapidly cooled that fully stripped ions recombine to hydrogen-like ions and during this recombination and de-excitation process the population inversion (most probably on Balmer-alpha transition) is created. In the beginning we tested the first step with nitrogen filling of the capillary that should lase at 13.4 nm. According to X-ray signal the pinching process was not efficient enough, probably due to the fact that simultaneously atomic and molecular nitrogen ions are created that (due to their different mass) reach the discharge axis in different times. Therefore, with a glass model of the capillary we spectroscopically tested effect of an increased pre-pulse that should dissociate and ionize the primary nitrogen filling as much as possible (J. Schmidt et al., *Pre-pulse current measurement of the* *fast high-current capillary-discharge experiment*, Proc. 2010 IEEE Power Modulator and High Voltage Conf., Atlanta, GA, USA, 2010, pp.573-575). Then a detail simulations (Hübner J. et al., *Dynamics of pre-ionized fast capillary discharge,* Scripta **161** (2014) 014047) were done showing that sufficiently fast plasma cooling can be achieved by plasma expansion, if the driving current half-period is ~100 ns. This was achieved by capillary shortening down to 90 mm (O. Frolov et al., *EUV radiation from nitrogen capillary discharge*, Internat. J. Mod. Phys. **32** (2014), 1460329). Recent measurements (J. Schmidt et al., *XUV source based on the fast high-current capillary-discharge system*, IEEE Int. Power Modulator and High Voltage Conf., Santa Fe, NM, USA, to be published) show dependence of time-curves of XUV radiation on filling pressure. The absence of lasing is ascribed to large ablation of capillary walls in high-current regime and this problem will be solved in future.

In the meantime our Ar^{8+} discharge laser was gradually optimized. As the first step in this optimization a clean (debris-free) and reproducible (laser energy fluctuations within ±10% interval) working regime was achieved. Then spherical multilayer focusing mirror was designed and manufactured (superpolished substrate in the TOPTEC Turnov, multilayer coating in the Institute of Scientific Instruments AS CR Brno). With this mirror our first ablation experiments were performed (K. Kolacek et al., *Nanostructuring of solid surface by extreme ultraviolet Ar^{8+} laser*, Laser and Particle Beams **30** (2012), 1,
57-63): the sagittal focal spot was as large as 375x125 μm, and the bottom of the crater ablated into PMMA was covered by a laser-induced periodic surface structure with periodicity ~2.8 μm. When the surface of PMMA was covered by a grid with small (7.5x7.5 μm) windows, the clearly developed twodimensional diffraction patterns (with periodicity spanning down to ~125 nm in the pattern-centre) were imprinted into PMMA behind each window.

Later-on a smaller Marx generator was put in operation and a repetitive regime with repeating frequency 1 Hz was tested, but with 0.03 Hz is at present used (J. Schmidt et al., *Repetitive XUV laser based on the fast capillary discharge*, Proc. SPIE X-Ray Lasers and Coherent X-Ray Sources: Development and Applications, San Diego, USA, 2011, pp. 814015-1 to 6). Simultaneously, the laser energy was slightly increased, which caused that the local fluency in the centre of laser beam was higher than the ablation threshold not only for PMMA, but also for GaAs. It turned out (K. Kolacek et al. *A new method of determination of ablation threshold contour in the spot of focused XUV laser beam of nanosecond duration*, Proc. of SPIE **8777**, 87770N (2013)) that nanostructuring appears only in the desorption region. It is known that for femtosecond pulses the desorption regime (local fluency is smaller than ablation threshold) has small particle-removal-efficiency (~10%) that abruptly jumps to ~100% efficiency in the ablation regime. However, we found that for nanosecond pulses this is valid for difficult removable material (like e.g. GaAs) only. For easily removable material (like PMMA) the desorption efficiency gradually rises with local fluency up to 90-95% and transition to ablation regime is very smooth. This is a positive message for nano-structuring, but negative one for local fluency evaluation from the morphology of craters (that was proposed and used earlier).

Due to our ablation-oriented work we had to improve our knowledge about our laser beam (J. Schmidt et al., *Beam characteristics of CAPEX XUV laser*, Proc. SPIE X-ray lasers and Coherent X-ray sources: Development and Applications, **8849** (2013), 884917-1 to 7): the divergence of laser beam was measured to be 2.27 mrad for 400 mm long capillary and 1.87 mrad for 232 mm long capillary. The larger divergence for longer capillary is probably due to longer path of the periphery beams along the transverse density gradient inside the capillary. The pre-pulse changes can modify even the beamprofile from hollow to nearly flat-top one. Due to better understanding of pinching process (gained mainly at our work with nitrogen filled capillary) we increased the energy of our laser up to ~40 mJ per pulse, which is the peak value in the XUV region in the world. That energy enabled us to measure attenuation of Al filters, to calibrate our detector (vacuum photodiode), to develop a new detector with extremely high saturation (working as energy monitor at each shot) and to demonstrate this high pulse-energy by massive ablation plums released from various materials (Cu, Al, Au, Si, Au-coated PMMA) during impact of laser pulse (O. Frolov et al., *Ablation plume induced by laser EUV radiation*, 14^{th} Int. Conf. X-Ray Lasers 2014, Fort Collins, USA, 2014, to be published). It was shown that these ablation plumes are clouds of photoelectrons and neutral excited (i.e. radiating) atoms and molecules. A more precise study revealed: first that incoherent radiation of pre-pulse elevates the substrate surface (Au-coated PMMA) and second that laser-generated radiating atoms or molecules form two groups propagating from the target surface with initial velocities ~1100 and ~500 m/s. However, both these groups are rapidly de-accelerated reaching after ~1 μs by turns velocities ~300 and ~100 m/s (K. Kolacek et al., *Interaction of* *extreme ultraviolet laser radiation with solid surface: ablation, desorption, nanostructuring*, The 20th Int. Symp. High Power Laser Systems and Appl., Chengdu, China, 25-29 August 2014, to be published).

Recently a new type of interferometer has been designed (K. Kolacek et al. *Interferometer for extreme ultraviolet region,* Patent PUV 2013-27549 (2013), K. Kolacek et al. *An extreme ultraviolet interferometer suitable to generate dense interference pattern*, Proc. of SPIE **9206**, 92060D-1 to 10) that works in extreme ultraviolet region and that is intended for direct imprinting of densest possible (for given wavelength) interference pattern into a substrate. The interferometer belongs to the wavefront division category: each of its two aspheric mirrors reflects approximately one half of incoming laser beam and focuses it into a point image. Both focused beams have to intersect each other, and in the intersection region an interference pattern is generated. The closer the intersection region is to the above-mentioned point images, the smaller the interference field is, but simultaneously the smaller the fringe-pitch is. During manufacturing process a multilayer coating of both mirrors had to be individually solved.

In the last year two kinds of samples have been irradiated for external customers. The first one (from Laboratory of Magnetism, University of Bialystok, Poland) was an ultrathin sandwich Pt-Co-Pt, in which XUV radiation induces reversible or irreversible (depending on fluency) changes of magnetic properties. For that a smooth attenuation of laser pulse energy had to be developed. The second one (from Institute of Laser Technology/Institute of Laser Engineering, Osaka, Japan) was a SiC sample as a test material for the first wall of laser fusion thermonuclear reactor. Currently, we are the only lab that can produce on this material some visible footprints by one shot. The same irradiation of new and better prepared samples (SiC, Mo, W, …) is requested and is under preparation.

Our laboratory is a branch of the UNESCO International Centre for Dense Magnetized Plasma (ICDMP) and Dr. Kolacek is the chairman of Council of the ICDMP Foundation and a member of the ICDMP International Scientific Committee. Recently we were integrated into COST activity MP 1203 focused on diagnostics and applications of coherent EUV and soft X-ray radiation.

Research Report of the team in the period 2010–2014

Institute	Institute of Plasma Physics of the CAS, v. v. i.

Scientific team	Centre TOPTEC

Simulation of optical diagnostic tool in coating machines
Performance analysis and simulation of an optical diagnostic tool on vacuum coating machines used by Preciosa a.s. company. Study was focused on finding behaviour and limits of present optical path and electronic detector under various deposition condition including errors in alignment of optical elements and witness chip. The optical diagnostic tool was designed more than 20 years ago thus Preciosa a.s. company decided to replace it by modernized version. Study also contains design of new optical path which would be suitable for new optical diagnostic tool.

Result: Study: RIV/61389021:_____/13:00427433 - Simulace optické soustavy depozičního monitoru

Development of new optical diagnostic tool for Preciosa a.s. company.
New diagnostic tool was developed as replacement to old optical monitors for endpoint detection during vacuum deposition of multilayer decorative coatings in production of Preciosa a.s. company. Requirements for new optical monitors were quite strict – robust, error-free, unattended operation in rapid production environment, optical parts and configuration should be reused and it has to be integrated into PLC controlled machine. Final device provides simultaneous measurement of transmission a reflection at three wavelength in or to provide robust diagnostic of an actual film thickness. In order to fit new optical monitoring system into old chassis, it was separated to three cooperating modules (source, transmission and reflection) connected by dedicated digital link. Master module (source) provides protocol-based connection to main PLC (OMRON) which controls vacuum deposition machine.

Result: Instrument and software for diagnostic and end-point detection of vacuum deposition process.

Vertical Gradient Freeze Gallium Phosphide based optics for infrared sensors
EUREKA! project no. 3869 INFRASENS was aimed to develop the process and methods for manufacturing of optical elements and optical systems from VGF GaP material. Optical systems can gain interesting advantages by using GaP elements. GaP provides optical designer new material with different dispersion of refractive indices necessary to compensate chromatic aberration and thermal effects. Compared to other material in the same class (transparency from VIS to LWIR) it excels in mechanical and chemical resistance. Our research center participated in the project as a developer of manufacturing processes and techniques, thin film antireflection coatings and optical system design and integration. Manufacturing processes were

affected by toxicity of byproducts of polishing and grinding, therefore an isolated workspace with an efficient ventilation and filtration system was build. Strong emphasis was placed on development of polishing and grinding slurries with inhibition properties on production of toxic byproducts.

Result: Proven technology / pilot plant : RIV/61389021:_____/12:00379795 - Galium Fosfor připravený technologií vertikálního chladícího gradientu jako základní materiál pro optiku infračervených senzorů

Hyperspectral Detection of dangerous Substances (HDES)

HDES development project is a joint project, supported by Ministry of the Interior of the Czech Republic in program of security research, focused on development of simple and affordable infrared hyperspectral imager for fire brigades in order to remotely detect dangerous substances on site. Research centre is responsible for development of hyperspectral detection principle in LWIR spectral region, design and production of optical system and development of detection algorithms. Optical system is already designed and manufactured. Cost analysis proved that cooled infrared imaging array would account for more than 80 % of target cost of the system which was not acceptable. That was the reason for choosing uncooled focal plane array (FPA) as an imager. Uncooled imager imposes great stress on a throughput of optical system as to minimize noise in acquired data. Optical system provides images of the scene in spectral range 8-14 μm with spectral resolution 4 cm-1, field of view (FOV) 20°×10° (H×V). The design employs aspherical surfaces to achieve specified performance and fully exploits availability of SPDT production method. All respective optical elements are optimized to simplify manufacturing process and ensure required precision of assembly.

Results:

Study. Design of infrared hyperspectral optical system. Prototype of the optical system. Jan Václavík ; Radek Melich ; Pavel Pintr and Jan Pleštil, “High-throughput optical system for HDES hyperspectral imager", Proc. SPIE 9442, (2015)

Dielectric mirrors with high damage threshold for HiLASE project

Development of high-reflective coating with high damage threshold for aluminum and ceramics mirrors. Mirrors employed metal Cu-Cu2O layers combined with TiO2-SiO2 dielectric stack. Coating was designed to take advantage of the fact that future optical elements for HiLASE project will be probably made from copper. Coatings successfully passed first testing.

Results: Design of high reflectivity thin film stack made of Cu, Cu2O, TiO2 and SiO2 layers. Samples of mirrors using such coating

Flapper (2012)

Flapper is a shortened term for an optomechanical device developer for calibration of non-contact tonometers for evaluation of intraocular pressure. As a R&D project with cooperation of the Czech metrological institute and Korean company Huvitz Co, Ltd, the flapper was redesigned and manufactured in TOPTEC. The functionality and stiffness of important parts were analyzed using FEM. Flapper setup consists of approx. 85 parts, most of them were designed and manufactured in high precision.

Result: Apparatus for calibration of non-contact tonometers
Special precision mechanics parts for Laser System (2013-2014)
On the basis of cooperation with the Institute of Physics, technological design and manufacturing of fine-mechanics parts for laser system was carried out. Total number of 356 parts for Lens Array system, 348 parts for Mirror Array system and 95parts form Pinhole systems were manufactured, most of them in high precision.
Results: 4xLens Array system, 4x Mirror Array system, 2x Pinhole system

Welding Process Visualization Instrument
Instrument for welding process visualization was developed and built in TOPTEC Centre under a contract with Air Products. The instrument employs three principles which lead to the state where the welding process can be recorded without an influence of wide spectral noise coming from accompanying welding arc. First and undoubtedly most important feature of the instrument, it is necessary to suppress the overall illumination of the welding arc so it (the welding process itself) can be recorded. Because of the high optical power of the suppressed welding arc stronglysuppressing filter system has to be used. After this filtration there is consequently no useful light which still keeps information about the welding process. Therefore, new, additional, illumination is required. This illumination has to be of high optical power and its wavelength is chosen in such spectral region that it would pass through the used filter system and would be inside of a sensitivity region of fast recording camera. An overall instrument configuration consists of two modular parts. First part – illumination – is used to produce laser light with maximal optical power of 15 W with the central wavelength @828.6 nm. Second part– recording – consists of a fast camera and a filter system. The filter system is made of one edgepass filter (long pass @800 nm), one laser line filter (central wavelength @830 nm, FWHM 10 nm) and a neutral density filter (suppression ratio of the neutral density filter is chosen with respect to the welding current, i.e. to the optical power of welding arc). The fast recording camera can record more than 500 FPS. The instrument can be used in three different configurations: "sideway" configuration, opposite side configuration and "shadow" configuration in order to visualize different parameters of the welding process. These visualized characteristics allow engineers to produce very precise analyses of welding process in order to improve efficiency and quality of customers welding processes. Optical monitoring system is also perfect source of highly appreciated educational movies and pictures for training a new welding personnel not only in welding school but also at universities and in companies around the world. *Results:* Instrument for visualization of welding process; software for controlling and evaluation of visualized processes

Measurement instruments for aspherical and free form optical surfaces The project Measurement instruments for aspherical and free form optical surfaces supported by TA CR is aimed at R&D of systems and technologies for measuring of the shape of aspherical and free form optical surfaces. The project started in 2013 and it will run until 2016. Within the project, intended measuring systems will be constructed regarding the contemporary requirements of the industry. In the course of development, the latest design of the optical system are applied and modern optoelectronic elements used. Crucial pursuit embracing all planned activities is to shift the overall concept of devices in accordance with modern trends from the idea of very precise and robust optomechanical construction to the idea of smart solution where the compensatory and calibration principles will be applied. This will be established by development of very efficient software, based on implementation of advanced mathematical and physical principles, which will assume the fundamental role while pursuing the achieving the required precision and repeatability. The objectives of the project can be divided into two subgroups: 1) The first one is a development of a non-contact measurement device for measuring spherical, flat and mild- aspherical optical surfaces (department from best sphere up to 200 lambda) up to diameter of 100 mm with measuring time of maximum one minute. 2) The second subgroup is covered by aims that will lead to production of a device which is able to measure more complex aspherical or free form surfaces. The device will also enable the user to measure positions of precise optical components mounting. This part will mostly entail research and development of a prototype.

Results till 2014:

Research reports: Mechanical and optical design of the aspherical interferometer Utility model “Device for shape measurement of optical surfaces, particularly slightly diffusely reflecting“

Utility model “Extension of non-null interferometer measuring range with use of spatial light modulator and optimization of computer generated diffractive pattern”.

METIS (Coronagraph onboard the Solar Orbiter mission - optical elements) - Phase B (2012-2013)

The project is financed from PRODEX (Programme for the Development of Scientific Experiments) which is one of the scientific programs of European Space Agency. METIS is going to be one of ten main experiments on Solar Orbiter satellite. METIS is a solar coronagraph telescope imaging solar corona in three different spectral regions - in a HeII spectral line at 30.4 nm, in HI spectral line at 121.4 nm and in visible polarized light at 590 - 650 nm. A structure and dynamics of solar corona will be imaged in angular range of 1.4 to 3.0 solar radii. Centre TOPTEC was responsible for design and manufacturing of the samples of two main mirrors (M1 and M2) of METIS telescope. Both mirrors were designed as annulus shaped with an outer diameter of 218 mm and inner diameter of 128 mm for M1. Mirror M2 has 125 mm outer diameter and 88 mm inner diameter. Both mirrors surface shape was planned to be a mild asphere with departure of approx. 40 mm from the best fit sphere, therefore it was necessary to apply sub-aperture grinding and polishing techniques that TOPTEC is equipped with. Most challenging within this project was to reach the optical qualities of the mirrors that stands in their surface form (120 nm PV) and microroughness (0.3 nm) together with their total weight that is demanded as < 1kg for both mirrors in total. The choice of the mirror material – SiSiC, together with above mentioned parameters, was also a challenge for the optical manufacturing.

Results:
T Vít, R Melich, J Václavík, V Lédl, Design of Precise Lightweight Mirror, Applied Mechanics and Materials, 2013
Metis Phase B Final report on design and manufacturability - documentation for PI
Samples of SiSiC mirrors structures.
Samples of super-polished ZERODUR surfaces

METIS (Coronagraph onboard the Solar Orbiter mission - optical elements) - Phase C/D (2013-2014)

Involvement of the TOPTEC into the METIS Phase B project was evaluated by the METIS consortium and ESA as highly successful and TOPTEC was addressed for cooperation in phases C and D, (where C represents the final design of the coronagraph and D represents the production of flight pieces). During 2014 the mirrors structures for M0, M1 and M2 mirrors were redesigned with respect to specified loads (shock loads during the launch, thermal loads etc.). Also the technology of manufacturing of mirror structures and of grinding and polishing of the optical surfaces were developed and tested. New procedure for evaluation of the image quality based on the results of numerical simulations as well as new technology procedure of acid etching of Zerodur structures were developed.

Results:
Tomáš Vít, Radek Melich and Paolo Sandri, Numerical simulation of deformation and figure quality of precise mirror, Proc. SPIE 9442, Optics and Measurement Conference 2014, 94421F (January 7, 2015), 94421F-94421F-8, doi:10.1117/12.2176336, Design and test reports
Structural models (parts) of M0, M1, M2 mirrors
Test samples of M0 mirror
Technology of acid etching of Zerodur structures
Procedure for evaluation of the image quality based on the results of numerical simulations

PROBA3 - ASPIICS - Phase B (2012-2013)

The project is financed by PRODEX (Programme for the Development of Scientific Experiments) which is one of the scientific programs of European Space Agency.PROBA-3 is a technology mission of the European Space Agency (ESA), devoted to the in-orbit demonstration of formation flying techniques and technologies. In phase B, PROBA-3 implemented a coronagraph (called ASPIICS, “Association de Satellites Pour l'Imagerie et l'Interferometrie de la Couronne Solaire”) that both demonstrates and exploits the capabilities and performance of formation flying. ASPIICS is distributed on two spacecrafts separated by 140m with the external occulting disk hosted by one spacecraft and the telescope (optical camera included) on the other one. ASPIICS will perform high spatial resolution imaging of the solar corona from the coronal base (1.04 solar radii) out to 3 solar radii.
TOPTEC centre was responsible for simulation and tolerance analysis of the telescope optical system. The coronagraph telescope.

Results:
Documentation of provided studies for the Principal Investigator (PI):
P3-IPP-AN-7001_FMEA
P3-IPP-IID-7001_IIDB
P3-IPP-LI-7001_DPL_DML_DPML
P3-IPP-LI-7002_CIDL
P3-IPP-LI-7003_IHT
P3-IPP-PL-7002_Cleanliness_Plan
P3-IPP-PL-7003_AIT
P3-IPP-RP-7002_FEM.docx
P3-IPP-RP-7003_IDR

PROBA3 - ASPIICS - Phase C/D (2014)
The project is financed by PRODEX (Programme for the Development of Scientific Experiments) which is one of the scientific programs of European Space Agency.
PROBA-3 is a technology mission of the European Space Agency (ESA), devoted to the in-orbit demonstration of formation flying techniques and technologies. In phase B, PROBA-3 implemented a coronagraph (called ASPIICS, "Association de Satellites Pour l'Imagerie et l'Interferometrie de la Couronne Solaire") that both demonstrates and exploits the capabilities and performance of formation flying. ASPIICS is distributed on two spacecrafts separated by 140m with the external occulting disk hosted by one spacecraft and the telescope (optical camera included) on the other one. ASPIICS will perform high spatial resolution imaging of the solar corona from the coronal base (1.04 solar radii) out to 3 solar radii.
TOPTEC centre is responsible for approval of telescope optical system design, its manufacturability and realization of opto-mechanical components of the coronagraph telescope.

Results:
Documentation of provided studies for the Primary Investigator (PI):
P3-TOP-TN-14001 Manufacturability of coronagraph optical system design at TOPTEC facility
P3-TOP-TN-15001 Achievable microroughness of PROBA3 coronograph optical glass elements

Optical insert surfaces for intraocular lens molding used in opthalmology (2013 - 2014)
R&D project with MEDICEM Institute. Development of the technology of intraocular lens production, material testing (numerical), research of the lens shape. *Resuls*: Technical report, molds

High power modules for fiber laser pumping (2014)
R&D project with SQS Vláknová optika supported by TAČR. The aim of the project is to design novel high power laser pumping module and to develop technology for press molding of precise free-form optical elements.

Results:
Annual report
Molds for molding of the optics
Samples of molded optical elements

Advanced optical systems using aspheric surfaces (TA03010843; TAČR; 20132014)

In accordance with objectives of the Advanced optical systems using aspheric surfaces project complete technology for aspheric surfaces production was developed in the year 2013 and 2014. This technology covers the area from the optical design draft, product documentation manufacturing, CNC grinding by various types of instruments with different roughness for required surface quality, subaperture CNC polishing in various modes of tool movement with achieving PV shape accuracy of about 200 nm and the surface microroughness of about 1 nm Sq, up to process or final shape, microroughness and surface defects evaluation.

Results:
Project TA03010843 report for year 2013 and 2014
Samples of aspherical surfaces with high precision surface form and minimized slope error

Nanofibers and nanoparticles abrasives as the basis for a new generation of tools for ultra-fine polishing (TA03010609; TAČR; 2013-2014)

In accordance with objectives of the Nanofibers and nanoparticles abrasives as the basis for a new generation of tools for ultra-fine polishing project polishing process testing methodology and methodology for experimental samples evaluation based on shapes and surface micro-roughness changes monitoring was defined. Moreover a variety of polishing slurries containing nanoparticles tests and nanofiber polishing tools tests were performed too.

Results:
Project TA03010609 report for year 2013 and 2014
Samples of nanofiber based polishing pads and polishing slurries

Cherenkov radiators

The Cherenkov radiators were developed for testing of new sensitive photon detectors - thick gaseous electron multipliers (TH-GEM). The design of radiators was made by Zemax© software, where problems with simulation of source and propagation of Cherenkov radiation were solved. Different types for various purposes were designed and produced. Hemispherical radiator can focus radiation to narrow ring. Long radiator can produce very large amount of photons, proportional to the radiator length, due a specific property of Cherenkov radiation. Particle beam, going in direction of a cylinder axis, produces Cherenkov photons, falling to the cylinder surface in critical angle, so photons are completely reflected. All radiators were used in particle beam tests of TH-GEMs at CERN. Completely new, different type of radiator, using aspherical surface, was designed too. It can be produced by new machining technologies. It consists of significantly smaller amount of fused silica, and can focus Cherenkov radiation to sharp ring of required properties. *Result*: Study, design and produced radiators.

Folded Jamin interferometer for measurement of gas refractive index

The modified folded Jamin interferometer, insensitive to the rotation and translation of its two optical elements was proposed, constructed and tested. It is relatively simple and vibration-insensitive. An incoming He-Ne laser beam is split by a polarizationsensitive partial beam-splitter coating on the second surface of a plane-parallel plate. One of the resulting beams is reflected by a high-reflectance coating on the first surface. Two parallel beams of equal intensity with orthogonal polarizations are generated by this beam-splitter coating. The first beam passes through a closed quartz pipe (evacuated or gas-filled); the second beam passes outside this pipe through the measured gas. Both beams are reflected by a retro-reflecting prism, and they pass through the same quartz disk on the end of the pipe, so the phase difference between the two beams is only induced by the refractive-index difference. Quadrature encoder measurement allows the measurement of the absolute value of the gas refractive index (with respect to the vacuum). The interferometer sensitivity and accuracy is completely satisfactory. It enables measurement of a change of 10-6 in the refractive index. This measurement can be further improved by a factor of 100 using the appropriate software. A completely automatic driving system is foreseen. The interferometer is placed inside a stainless steel chamber to protect the He-Ne laser from the external magnetic field, and is directly connected to the COMPASS RICH-1 vessel. The pressure and temperature control detectors inside the chamber verify that the gas conditions are the same as those inside the RICH vessel. The majority of these mechanical parts was produced at INFN Trieste, Italy, all optical parts and mechanics of interferometer holder were designed and produced at TOPTEC.

Results: Study, design, interferometer.

On-line mirror misalignment measurement system CLAM

The segmented mirrors at large size gaseous Cherenkov detector must be very accurately aligned so to form a focused image of Cerenkov photons in the detector photon detection area. Any misalignments distort the image and thus directly affect the detector resolution. A new original method was applied for on-line mirror alignment monitoring. The rectangular grid, placed near the focal plane of the mirror wall inside the detector vessel, is illuminated by high luminosity LEDs. The image of the grid, reflected by the spherical mirrors, is monitored by digital camera. Image processing techniques are adopted to analyze the position of the grid image, deformed by a reflection on individual misaligned spherical mirrors. It was checked that the sensitivity of the monitoring method is sufficient 0.1 mrad, and that the information about measured misalignments can be included in the particle identification algorithm at COMPASS experiment at CERN.

Both mechanical and optical hardware was designed and produced with collaboration with INFN Trieste, Italy and Technical University of Liberec, Czech Republic. The significantly largest part of work was concerning about the algorithm design and software for misalignment reconstruction and it was made at TOPTEC. Similar system, based on our research, will be applied at FIAR accelerator DESY, Germany. *Results:* Study, design and development of CLAM system.

Adaptive optics and vibration control

A considerable amount of scientific activities have been devoted to the research and development of composite systems with piezoelectric and electrostrictive materials. The structure of the developed composite systems is based on layered “sandwich” structure of optical, elastic and piezoelectric materials. These systems then form fundamental operational elements of two types of devices: (i) deformable mirrors for the spatial correction of the wavefront in adaptive optics systems and (ii) active vibration absorbers and active acoustic metamaterial for temporal control of transmitted vibrations and noise in noise and vibration shielding systems. The temporal and spatial control of the deflection of the developed systems is achieved by means of the interaction of composite piezoelectric structures with electric fields produced by feedback electronic systems. Our research activities are focused on (i) design of optimal geometrical parameters of the piezoelectric composite structures, (ii) development of electronics and control algorithms, (iii) measurement of spatial and temporal dependences of the piezoelectric composite structures, and (iv) finite element method simulations of developed mechatronic and optoelectrical systems. Several results have been achieved with a close cooperation with “Thin films” and “Metrology” research groups.

Results:

A. V. Kruchenko, K. Nováková, and P. Mokrý, “Optimization of electrode geometry and piezoelectric layer thickness of a deformable mirror,” EPJ Web of Conferences, vol. 48, p. 11 (2013). (RIV/61389021:_____/13:00423845)

P. Psota, V. Lédl, R. Doleček, P. Mokrý, V. Kopecký: Measurement of Vibration Mode Structure for Adaptive Vibration Suppression System by Digital Holography, Proceedings of the Joint UFFC, EFTF and PFM Symposium. Prague : IEEE-UFFC, s. 215-217 (2013) (RIV/61389021:_____/13:00423598)

K. Nováková, P. Psota, R. Doleček, V. Lédl, P. Mokrý, J. Václavík, P. Márton and M. Černík: Planar acoustic metamaterials with the active control of acoustic impedance using a piezoelectric composite actuator, Proceedings of the Joint UFFC, EFTF and PFM Symposium, Prague, p. 317-320 (2013) (RIV/61389021:_____/13:00423591) K. Novakova, P. Mokry, J. Vaclavik, 'Application of piezoelectric macro-fibercomposite actuators to the suppression of noise transmission through curved glass plates', IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 59(9), 2004-2014 (2012) (RIV/61389021:_____/12:00382829)

J Václavík, P Mokrý, Measurement of mechanical and electrical energy flows in the semiactive piezoelectric shunt damping system, Journal of Intelligent Material Systems and Structures 23 (5), 527-533 (2012)

M. Kodejška, M.; Mokrý, P.; Linhart, V.; Václavík, J. & Sluka, T. (2012), 'Adaptive vibration suppression system: an iterative control law for a piezoelectric actuator shunted by a negative capacitor', Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on 59(12), 2785-2796.

M. Černík, P. Mokrý, 'Sound reflection in an acoustic impedance tube terminated with a loudspeaker shunted by a negative impedance converter', Smart Materials and Structures 21(11), 115016 (2012). (RIV/61389021:_____/12:00382830)

J. Vaclavik, P. Mokry, M. Kodejska, Wall-plug efficiency analysis of semi-active piezoelectric shunt damping systems, Journal of Vibration and Control (Impact Factor: 4.36). 09/2014; 1077546314548910. DOI: 10.1177/1077546314548910

K. Steiger, P. Mokry, Finite element analysis of the macro fiber composite actuator: macroscopic elastic and piezoelectric properties and active control thereof by means of negative capacitance shunt circuit, Smart Materials and Structures (Impact Factor: 2.45). 01/2015; 24. DOI: 10.1088/0964-1726/24/2/025026

P Mokrý, P Psota, K Steiger, J Václavík, R Doleček, V Lédl, M Šulc, Noise suppression in curved glass shells using macro-fiber-composite actuators studied by the means of digital holography and acoustic measurements, AIP Advances 5 (2), 027132 (2015)

Crystal optics and electro-optic systems based on nonlinear optical materials A lot of research efforts have been made in the research and development of electrooptic systems based on nonlinear optical materials. Our research focus has been devoted to the study of optical and dielectric properties of ferroelectric, ferroelectric semiconductors and other nonlinear optical materials. The developed nonlinear optical systems are based on the use of ferroelectric materials with ferroelectric domain walls. Several research outcomes of international importance have been achieved in the in the fields of: (i) understanding the response of charged and neutral domain walls to electric fields in ferroelectric semiconductors, (ii) interaction of ferroelectric domain walls with crystal lattice defects, (iii) numerical computation of optical properties near ferroelectric domain walls, (iv) development of methods for optical observation of ferroelectric domain walls. several results have been achieved with a close cooperation with “Metrology” research group. *Results:*

MY Gureev, P Mokrý, AK Tagantsev, N Setter, Ferroelectric charged domain walls in an applied electric field, Physical Review B 86 (10), 104104 (2012) (RIV/61389021:_____/12:00382300)

P. Mokry, K. Steiger, P. Psota, R. Dolecek, P. Vojtisek, and V. Ledl, Digital Holographic Interferometry as an Experimental Instrumentation for Measurements of Macroscopic Properties of Polydomain Ferroelectrics, Proc. SPIE 9442, Optics and Measurement Conference 2014, 9442:94420V, 2015. (doi:10.1117/12.2178485)

Research Report of the team in the period 2010–2014

Institute	Institute of Plasma Physics of the CAS, v. v. i.

Scientific team	Materials Engineering

The Materials Engineering Department (ME) of IPP went through several important changes in the 2010-2014 period. These important changes represent one group of results and will be therefore described alongside with scientific results. Although the changes definitely brought several major improvements to research performance at the ME Department, they also had a temporary negative influence on the number of scientific publications during the course of their implementation. However, the number of publications went up in 2014.

<u>New Laboratory of Plasma Technology</u>

The first major improvement was the opening of the new Laboratory of Plasma Technology (LPT) in March 2012. The new LPT houses two major research facilities related to materials processing - the Water Stabilized Plasma (WSP) spraying facility and Spark Plasma Sintering (SPS) equipment.

The Spark Plasma Sintering system was installed during the course of 2012 and represents first such piece of equipment in the Czech Republic. Its primary advantage over conventional sintering techniques lies in the concurrent application of pulsed electric current, temperature and pressure. This allows for shorter processing times and/or lower temperatures. Besides obvious economical impact, this also permits the formation and preservation of beneficial fine-grained structures that are sensitive to thermal exposure.

The original premises for the WSP spraying facility were located some 15 kilometres away from the main institute building and had several drawbacks adversely affecting research of the team. A new location has been found fairly close to the institute. During several month of reconstruction at the new location, the WSP spraying facility went through a major technological upgrade before moving to the new location. The WSP spraying facility is now fully comparable with similar spraying facilities abroad. Besides the spraying system itself, it is also equipped with comprehensive diagnostics of the process. Since 2013 it is also equipped with the new Hybrid-WSP gun, innovated at IPP, that combines water vapour and argon gas stabilization of plasma arc. This unique H-WSP gun further expands the already great versatility of the original WSP gun. Its hybrid water/gas stabilization offers the possibility of adjusting plasma jet parameters within a wide range from high-enthalpy low-density plasmas typical for liquid stabilized guns to lower enthalpy higher density plasmas generated in gas stabilized guns. The hybrid-WSP gun maintains the highest plasma enthalpy available on the market and overcomes shortcomings of the original WSP gun. Namely, gas flow in the cathode part protects a cathode tip and thus a consumable graphite cathode used in water-only stabilized plasma guns could be replaced by a fixed tungsten cathode.

In the current state, both of the facilities – Hybrid-WSP and SPS – as well as their combination significantly broaden the possibilities of special materials preparation, i.e. materials tailored to specific applications.

Major upgrade of characterization equipment

Secondly, the fleet of materials characterization equipment went through a major upgrade. The team has a new analytical SEM with energy-dispersive spectrometer (EDS, since 2010), electron backscatter diffraction (EBSD, since 2012), and in-situ bending stage (2014). There is a brand new X-ray diffractometer (since 2012) with a 1D detector, high temperature chamber up to 1600 °C in inert gas or high vacuum, collimators for local surface mapping, open Eulerian cradle for texture determination, rotating sample holder for stress tensor determination, and XYZ stage for measurements on samples of various shapes. There is a new Differential Scanning Calorimeter (since 2013) for measurement up to 1800 °C and a new particle size analyser (2014) measuring from 20 nm to millimetres. There is also a new imaging and diagnostic system (SprayCam, 2013) specifically targeted for the thermal spray. This system is designed for viewing and measuring particle injection distributions, trajectories, and velocities as the particles enter the plasma jet, ensuring reliable and more consistent coatings.

Staffing of the team

Finally, a gradual generational change took place over the last five years. Three respectable team members retired and many talented and perspective young researches joined the ME department as full time employees. Some of them came from the Czech Technical University in Prague, with which close ties are maintained. A number of doctoral and PhD students from CTU and other universities spend several years within the ME team as they worked toward the fulfilment of their degree. Three current team members received their PhD in the 2010-2014 period within the IPP-CTU collaboration. Since summer 2012, there is also a new head of the ME department and a new head of the Laboratory of Plasma Technology. The new departmental head had been part of the team for 9 years in 2012. The new head of the LPT is a person that has worked for the industry and proved to be a great asset in managing the daily routines of the LPT.

Cooperation

The ME team maintains a lively and active cooperation with many domestic and international universities and research institutions. There are close contacts with Czech Technical University in Prague, Institute of Chemical Technology in Prague, University of West Bohemia in Pilsen, Research Center Rez, Nuclear Physics Institute ASCR and Brno University of Technology, to name a few. The ME team participates in one Project for promotion of excellence in basic research (Centre of excellence) supported by Czech Science Foundation. The project (2014-2018) brings together six departments from four Institutes of ASCR and two Universities to form Multidisciplinary research centre for advanced materials. The centre focuses on complex investigation of ultrafine-grained (UFG) materials (prepared by advanced methods, such as severe plastic deformation and plasma technologies), functionally graded materials (prepared by plasma spraying and spark plasma sintering), coated light metal-based composites, and functional materials with martensitic transformation. Several members of the team also participate in the Competence Centre (2014-2019) called “Research center of surface treatment” supported by Technology Agency of the Czech Republic. One work package of this centre focuses on the development of novel thermal barrier coatings for jet engines and the main partners are Brno University of Technology and Honeywell International s.r.o. There are several running bilateral projects as well. Both the Centre of Excellence as well the Centre of Competence are quite prestigious in the Czech Republic.

Internationally, the ME Department is well recognized as a strong research partner. There are several research institutions in the world that have been long term research partners of the ME Department. Among them are Center for Thermal Spray Research (Stony Brook, NY, USA), University of Limoges (France), Forschungszentrum Juelich (Germany), Argonne National Laboratory (IL, USA), Tampere University of Technology (Finland), and Fraunhofer Institute in Dresden (Germany).

Recently a fruitful cooperation was established with the thermal spray laboratory in University West (Trollhattan, Sweden) that resulted in several joint publications. Within the last five years, the ME team has become a strong partner in European Fusion Development Agreement (EFDA) and EuroFusion programmes that are related to materials for fusion applications (e.g. plasma facing compoments). Several recently published papers are a positive outcome of this cooperation.

Major research results

Research at the ME Department is focused around three major topics. One topic, which is becoming more and more important within the ME team, are the materials for fusion applications. The other two topics focus on fundamental research and development of new classes of materials prepared by the unique materials processing equipment (H-WSP and SPS) that is operated by ME team members. These two processing techniques are utilized to prepare new classes of usually multicomponent materials that are tailored for specific application (e.g. functionally graded materials, dielectric coatings etc.). These three major topics are often interrelated and various specific projects typically involve more than one area. Fusion materials. The research and development of suitable materials for future tokamaks (ITER and mainly DEMO) is crucial for successful operation of these devices which bring the promise of a cleaner and sustainable large-scale energy source for the future. In such environments, the materials and components will be subject to harsh conditions, i.e. thermal, mechanical, chemical, and irradiation loading, while the materials requirements are quite complex and sometimes even contradictory. There is only a limited number of elements that these materials could contain to be allowed in a fusion reactor. The currently available materials are at their limits and there is a strong worldwide R&D effort to improve their structure, properties and performance. Through participation in the EURATOM - EFDA and later the Eurofusion programmes, our team has established a significant position in the fusion community and in the internationally coordinated research activities. A marked advantage of IPP-ME lies in the availability of three much needed assets in one place – the facilities for materials processing, a comprehensive range of characterization equipment and the Compass tokamak (operated by Tokamak Department of IPP). The latter brings the possibility of exposing real material samples to fusion-relevant tokamak plasma, which is a great advantage, not readily available elsewhere. Some of the tested materials are prepared by the processing equipment available at IPP (namely H-WSP and SPS), other samples are obtained from various laboratories.

Plasma sprayed W-based coatings for fusion applications. In the frame of the integrated research coordinated by the European Fusion Development Agreement (EFDA), tungsten-based materials are being developed for prospective application in selected components of fusion facilities, such as divertor regions. Tungsten is a suitable candidate material from the point of view of interaction with tokamak plasma, however, has limitations in difficult machining, brittleness and only moderate thermal conductivity. Plasma spraying is among alternative preparation methods being studied. The research has focused on i) mapping of oxide formation during spraying and exploration of methods to suppress it, ii) preparation of functionally graded materials, where a smooth transition to either steel (as a construction material) or copper (with its high thermal conductivity) is provided, iii) optimization of tungsten coating adhesion on various substrates. The graded layers could be used either as full-fledged plasma facing surfaces or as bonding interlayers for mitigating stress concentration.

Besides plasma spraying, several other processing techniques were also explored. These included laser cladding, hot pressing and spark plasma sintering. The studies involved basic characterization as well as optimization of the techniques. With the SPS technique, tungsten compacts were prepared from starting powders of various sizes (down to submicron size) and at different temperatures, and the effect of the resulting grain size on thermal and mechanical properties was evaluated. Finegrained tungsten is expected to have better mechanical properties and better resistance to neutron and ion irradiation; the ability of SPS to preserve these fine grains is thereby utilized. In a particular case of tungsten-steel composites and FGMs, formation of Fe-W intermetallic phases was observed. These were identified by a combination of x-ray diffraction, EDS and EBSD and their thermal and mechanical properties were characterized – to our knowledge, for the first time. This can serve as a basis for assessment of the role of these intermetallics in future performance of such materials in fusion environment as well as for further process optimization. Finally, a comprehensive assessment of the advantages, drawbacks and limitations of each technique, as well as their suitability for the fabrication of plasma facing components for fusion devices, was performed. The results are reported to EFDA for potential use in designing various tokamak components. A significant part of the activities was also devoted to studying the plasma-material interaction, involving both tokamak and fusion-relevant laboratory plasma. In the Compass tokamak, the erosion of tungsten, steel and nickel coatings by a deuterium plasma was studied. The results indicate only localized erosion in small spots, probably related to unipolar arcing, without any large-area material loss. Deuterium enrichment of a thin surface layer was also observed. A complex characterization of the changes induced in tungsten materials by laboratory plasma, simulation various scenarios of fusion reactor conditions, was performed. Various loading conditions included steady-state and pulsed deuterium plasma, laser pulses, helium preexposure, etc. This was done in collaboration with the Dutch Institute for Fundamental Energy Research (DIFFER) and the Institute of Plasma Physics and Laser Microfusion (IPPLM) in Warsaw. The exposure was done in these laboratories, while the characterization was performed at IPP. The samples included tungsten processed by conventional powder metallurgy, SPS and WSP and the role of particular microstructures in their response was evaluated. A new project called "Interaction of hydrogen isotopes with candidate fusion materials" supported by Czech Science

Foundation has started in 2014. The ME team is joined by researchers from Nuclear Physics Institute ASCR to explore some outstanding issues that are faced by plasma facing components.

Functionally graded materials. Single materials are often unable to meet properties required for certain high-tech applications. One possible solution is the use of "tailored" functionally graded materials (FGM). FGMs are defined as materials with changing microstructure and/or composition and/or properties across the material's volume. These changes are designed on purpose to cope with different requirements at different parts of the fabricated component. However, wider application of FGMs depends on availability of suitable production techniques. In our work it was proven that thermal spraying (TS) in general can be used to make both basic types of FGMs, i.e. one with a continuous gradient of properties or the "sandwich" type. TS itself or in a combination with an additional treatment, such as laser glazing, annealing, etc. is a very efficient and flexible technology of FGM manufacturing. Using the unique WSP gun then extends the limits or constrains mentioned in the literature for "classical" plasma spraying with gas stabilization. WSP application allows production of relatively thick deposits – coatings or free-standing bodies – in a reasonably short time with the multiple powder feeding set-up, inherent to WSP. Several novel techniques, combining primary WSP spray deposits with additional treatment represent interesting ways of producing FGM, such as:

i) nanostructured surface layer continuously transitioning into the as-sprayed deposit (this result was achieved solely by the ME team)
ii) boronized steel surface that is well anchored into the steel body; (about 30% of activities were carried out by members of CTU in Prague)
iii) multilayered ceramics/metal sandwiches, exhibiting several interesting properties, such as very limited or no gas permeation trough the part or increased strength, etc. (this result was achieved solely by the ME team) Utilization of WSP in FGM production could help to broaden present limited application fields to new ones, such as various free-standing "tailored" parts for gas management, for higher temperature utilization, materials for fusion devices, etc.

The above mentioned result i) was transformed into a patent application filed with Czech industrial property office. The patent called "Process for preparing multilayer ceramic coating and multilayer ceramic coating prepared in such a manner" was granted in 2013. Suitable ceramic powder of eutectic composition is plasma spraying by WSP to a base metal substrate. The WSP ceramic coating is completely amorphous. The surface of the applied amorphous ceramic coating is then heated by WSP gun for a short time to a temperature ranging from 940 to 1200 °C, while the temperature of the bottom side of the coating that contacts the base metal is maintained below 250 °C. The obtained multilayer ceramic coating consists of three continuous layers. The surface layer consists of splats with nanocomposite structure with crystal grains of average size ranging from about 10 to about 60 nm formed by a single phase of a solid solution of tetragonal ZrO_2 oversaturated with Al_2O_3. The layer contacting the base metal substrate consists of the splats with amorphous internal structure and a middle transient layer has both the splats with the internal nanocomposite structure and splats with the amorphous internal structure. There is a twofold increase of abrasion resistance of such multilayer ceramic coating that makes the coating the most abrasion resistant of all oxide ceramic coatings prepared by plasma spraying. This result is a world priority and was achieved solely by the ME team.

Another important result was achieved in the field of advanced composites and graded layers. The approach combines plasma spraying and spark plasma sintering. Graded layers, whose main purpose is to reduce stress concentration compared to a sharp interface between dissimilar materials, were prepared by plasma spraying and spark plasma sintering. The application fields include thermal barriers (Ni-10Al + Cr_2O_3 layers) and plasma-facing components for fusion reactors (steel + tungsten layers). A complex characterization of their structure, thermal and mechanical properties on both macro- and microscopic level was performed, including the identification and characterization of newly formed phases at the interface. This result was achieved in cooperation with CTU in Prague; ME team contributed the materials preparation and basic characterization, while CTU contributed fatigue testing and fractography; residual stress measurement was performed jointly.

Special microstructure of plasma sprayed coatings that includes pores, voids, and microcracks is responsible for their unique properties, especially anisotropy, nonlinearity, hysteresis and inelasticity. It is very important to understand the mechanical response of plasma sprayed ceramic coatings to mechanical and thermal loading. Such understanding is essential for selecting suitable coatings for particular applications. Samples of plasma sprayed alumina were subjected to four-point mechanical bending and thermal loading was provided by heating the samples, while stresses were generated by thermal mismatch between the coatings and substrates. In both cases, cyclic loading was applied. Non-linear behaviour and significant hysteresis were observed, indicating inelastic phenomena taking place. Unique results of this work helped identify relevant structural features and possible mechanisms underlying this inelastic behaviour. Failure mechanisms and significance of individual microstructural elements was also assessed. During this work, several important characterization methods were developed or improved/refined. These include the bonded specimen technique for tracking localized deformation, in-situ observation of crack propagation, detailed quantification of pore and cracks for modelling the thermal conductivities and Young’s moduli, combination of several methods of adhesion/cohesion testing, etc. Large part of the experimental work was done by ME team members R. Musalek and M. Vilemova during their PhD studies at CTU; several articles were co-authored by their formal coadvisor at the University.

The SPS was also used for post-treatment of plasma sprayed ceramic material and it proved to be a suitable technique for controlled crystallization and further compaction of as-sprayed deposits. The as-sprayed amorphous deposits of eutectic ceramic material were transformed into almost fully dense mostly crystalline material with negligible open porosity. The two major phases in sample sintered at 1150 °C, gamma alumina and tetragonal zirconia, are present in the form of nanocrystallites with average size 5.2 nm and 21 nm respectively. The post-treated material is very well sintered resulting in significantly improved cohesion between splats. Therefore interfaces and cracks between splats in the post-treated sample do not present a viable path for failure propagation under mechanical loading unlike interfaces in assprayed deposits. The improved splat cohesion results in more than a threefold increase of flexural strength in the post-treated samples. Hardness values of 1075 HV1 in the post-treated sample are increased by about 30% when compared to values of 830 HV1 in the as-sprayed material. This result was achieved solely by the ME team.

Ceramics with special physical properties – dielectric, piezoelectric, and photocatalytic. Plasma-based technologies (i.e. plasma spraying and spark plasma sintering) can be used for synthesis of materials with special physical properties. Using a water-stabilized plasma gun (WSP) a photocatalytically active ceramics based on a combination of TiO_2 and Cr_2O_3 were prepared. Variable ratio of both components leads to materials with variable photoactivity and with changing hardness and wear resistance while maintaining good mechanical cohesion of the coating layers. Plasma sprayed self-standing shells were produced for adaptive optical mirrors based on PZT feedstock powders ($Pb(ZrTi)O_3$). The original phase of PZT feedstock decomposes during spraying into several other phases, but a thermal post-treatment allows recrystallization leading to the desirable piezoelectric composition. Plasma sprayed ceramics based on titanates $MTiO_3$ (M = Mg, Ca or Ba) and their mixtures exhibit interesting properties potentially useful for fabrication of dielectrics.

Study of the influence of dopants on the photocatalytic activity of the plasma-sprayed titanium oxide layers. Plasma spray technique enables creation of coatings or freestanding parts from various materials. The main result of this study was that plasma sprayed TiO_2 is oxygen-deficient and the stacking faults in the crystal lattice of TiO_{2-x} influence the electrical and optical properties of the deposits. Doping of the starting powders was studied in detail to enhance the photocatalytic efficiency by the effect of dopants. Physical mechanisms playing a role in the TiO2 interaction with foreign atoms (Fe, N, Al) were described. Mechanically rigid coatings and free-standing parts utilizing the mentioned combinations of materials were prepared. Furthermore, it was demonstrated that the ferroelectric ceramics $BaTiO_3$ after interaction with a hot plasma jet forms a deposit, in which OH groups are bonded. After activation with ultraviolet light, the OH groups are able to enhance the photocatalytic efficiency. The work was done in collaboration with researchers from the Institute of Inorganic Chemistry ASCR. The team of IIC ASCR participated in the research by measuring the photocatalytic activity/efficiency and by producing

Rutile TiO_2 and eskolaite Cr_2O_3 powders were mechanically mixed and fed into the plasma jet simultaneously at different ratios. Photocatalytic decomposition of butane on the coatings was studied using visible light together with a setup typically used for UV-light tests. All coatings are relatively efficient photocatalysts for butane decomposition. Moreover, the coatings have good mechanical properties governed predominantly with Cr_2O_3 content as the harder component. It was shown that WSP spray process leads to robust photocatalytically active coatings. The work was done in collaboration with researchers from the Institute of Inorganic Chemistry ASCR. The team of IIC ASCR participated in the research mainly by measuring the photocatalytic activity/efficiency and XPS.

At the end of 2014, a self-adjustable powder injecting equipment was developed for Hybrid-WSP to increase the efficiency and repeatability of the H-WSP spraying process. The development was carried out within a joint project of IPP ASCR (ME Department) and ProjectSoft HK a.s. The project called “Precise powder feeding mechanism for water stabilized plasma WSP spray technology” is supported by the Technology Agency of the Czech Republic. The new equipment ensures a high degree of reproducibility of plasma sprayed products, efficient use of spray materials, and user friendly operation of the whole WSP system. Integrating the new equipment into the H-WSP spray system has resulted in a highly competitive product with unique properties and also in efficient optimization of the plasma coating technology. ProjectSoft HK has already begun marketing the new integrated H-WSP system to the international thermal spray community.

Finally, testing and evaluation phase of using H-WSP system for solution plasma spraying was successfully concluded. The H-WSP system turns out to be highly suitable for solution plasma spraying thanks to its high enthalpy plasma jet. Therefore the H-WSP will be routinely used for suspension plasma spraying in the coming years.

Research Report of the team in the period 2010–2014

Institute	Institute of Plasma Physics of the CAS, v. v. i.

Scientific team	Thermal Plasma

Characteristics of main results achieved by the team in the evaluated period. In the description of the result achieved in collaboration with other teams, the share of the team in its creation must be clearly specified (i.e. what specific activity the team contributed to the result). Maximum length of 10 pages.

The research activity of the Department of Thermal Plasma is concentrated on the investigation of generators of thermal plasmas, diagnostics of electrical discharges producing thermal plasma, study of interaction of thermal plasma with gas, liquid and solid materials, and investigation of physical and chemical processes in plasma processing of materials.

Special attention is devoted to study of plasma and plasma jets generated in a world unique type of plasma generator with water stabilized electric arc and applications of this type of plasma generator in various plasma processing applications. The water stabilized arc (Gerdien arc) has been intensively studied in recent years at IPP; IPP is known as the only laboratory where this type of arc is investigated, and where a DC arc plasma torch, based on this patented principle, have been developed. Plasma generated in water stabilized arc are characterized by extreme parameters, especially high temperature (up to two times higher than in common gas stabilized arc torches), plasma enthalpy which is one or two orders higher than in gas torches, and exit plasma velocity, again several times higher than gas torches. Besides permanent research of sources of steam plasma with the water stabilized arc, which resulted in recent years in a design and realization of new type of the plasma torch for industrial applications, several plasma processing applications using this torch have been investigated, namely plasma pyrolysis and gasification of organic materials and waste, plasma cutting of materials, removal of organic pollutants from water, and plasma spraying. This research is concentrated on utilization of extreme plasma characteristics typical for water stabilized arcs. In the following text the main results achieved in this field are described.

Development of plasma torches with water/gas stabilized arc.

The development of a new type of plasma torch with improved principle of arc stabilization have been made in cooperation with the industrial partner ProjectSoft, a.s., in the project supported by the grant agency TAČR in the years 2011 – 2013. The hybrid water/argon plasma torch WSPH for plasma spraying, based on the patented principle of combination of water vortex stabilization of arc with gas stabilization, was developed and introduced on the target in cooperation with a US company as a dealer. Due to the special plasma characteristics the hybrid torch provides unique performance characteristics in plasma spraying, namely extremely high plasma temperatures and spraying rates. The second type of the plasma torch - the torch for reactor applications, based on the principle of the hybrid water/gas stabilization, have been developed and it is now used for IPP research of plasma pyrolysis and gasification of organic materials.

Investigation of plasma jet generated in water/gas stabilized arc

Properties of water stabilized arcs and plasma jets generated in plasma systems with this type of arc were studied. As stability of the jet flow is an important factor influencing performance characteristics of the jet in some applications like plasma spraying, special attention has been paid to investigation of characteristics of instabilities of the jet downstream of the torch nozzle exit. Instabilities of plasma jet were studied on the basis of analysis of plasma radiation fluctuations recorded by an array of high frequency photodiodes. Characteristic frequencies of jet oscillations were found and spatial distribution of amplitude of plasma fluctuations was determined. The influence of arc current ripple on plasma instabilities was investigated for two types of power supply—classical thyristor controlled unit with the frequency of the current ripple 300 Hz and the rectifier with the high frequency converter and frequency of the current modulation 30 kHz. Generation of boundary layer instability with the current modulation frequency and its harmonics was proved using fast Fourier transform, contour plots and phase portraits. It was found that the character of fluctuations of plasma jet was substantially influenced by current ripple with the frequency or its harmonics close to the frequency of oscillations generated by boundary layer instability. Spatial distribution of plasma flow instabilities was investigated using statistical image analysis of jet images obtained by high speed and fast shutter cameras.

The results of investigations of jet properties in several plasma processing technologies are described in the following paragraphs.

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M. Hrabovský, M. Konrád, V. Kopecký, T. Kavka, O. Chumak, V. Sember, A. Mašláni, Thermal Plasma Jet Generated by Gas-Water Torch: Properties and Applications, Proc. of 7th International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC), Las Vegas, 13-15.09.2011, 13 – 15.

Pyrolysis and gasification of organic waste materials in steam plasma.

Extremely high enthalpy steam plasma, generated in hybrid water/argon plasma torch, has been used for the gasification of biomass and waste: spruce sawdust, wood pellets, pure polyethylene particles, waste plastics-pieces, 89% HDPE, 10% PP, 1% PET and pyrolytic oil from thermal decomposition of waste tires (complex mixture of aromatic hydrocarbons with mole composition CH1,47). Plasma was produced by a plasma torch with DC electric arc using unique hybrid stabilization. The experiments were performed with the torch input power of 100–140 kW and the mass flow rates of gasified materials of tens kg/h. Produced plasma features extreme parameters such as very high bulk temperature (18,000 K) together with low mass flow rate (typically around 0.3 g/s H2O + 0.2 g/s Ar), and high enthalpy up to 200 MJ/kg. Plasma aided reactions of materials with water, carbon dioxide and oxygen were realized in the plasma reactor PlasGas, installed at IPP. For all materials the produced synthesis gas was characterized by very high content of hydrogen and carbon monoxide (together minimum 90%), which is substantially higher than hydrogen and CO content obtained by common non plasma as well as plasma gasification processes. High quality of the produced gas is given by extreme parameters of used plasma – composition of steam plasma, very high temperature and extremely low plasma mass flow rate in connection with high enthalpy. Measured compositions of produced syngas were close to ideal theoretical composition calculated as thermodynamic equilibrium composition of mixture of all input components. Measurements also revealed very low concentrations of tar – under 10 mg/N m3, which is substantially lower than tar content in gas produced by nonplasma gasification processes. The experiments verified possibility of production of high quality syngas with high content of hydrogen by a tretament of organic materials in steam plasma generated in hybrid stabilized arc. The composition of syngas could be easily controlled by addition of reaction admixtures like CO_2, water, or oxygen. The proces can be used also as an energy storage. Electrical energy is transferred in the torch to plasma enthalpy which is then transformed to syngas chemical energy which can be stored. Possibility of reforming of carbon dioxide is benefitial as well.

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M. Hrabovsky, M. Hlina, M. Konrad, V. Kopecky, O. Chumak, A. Maslani, T. Kavka, O. Zivny, G. Pellet, Steam Plasma-Assisted Gasification of Organic Waste by Reactions with Water, CO2 and O2, 21st International Symposium on Plasma Chemistry (ISPC 21) August 4 – 9, 2013, Cairns, Australia.

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M. Hrabovsky, M. Hlina, M. Konrad, V. Kopecky, O. Chumak, T. Kavka, A. Maslani, Mass and Energy Balances of Organic Waste Gasification in Steam Plasma, Proc. of 9th Int. Conf. on Flow Dynamics, Sendai, Japan, September 2012, 696-697.

Plasma cutting with steam plasma.

The research of plasma cutting using steam plasma jet have been performed in cooperation with the company Fronius Int. GmbH, Austria in the framework of a research project financed by Fronius. Plasma cutting torch manufactured by Fronius and utilizing water evaporation for production of steam plasma jet was used in the experiments. The goal of the research was description of processes decisive for quality and efficiency of cutting with steam plasma and comparison the characteristics of steam plasma process with the processes in common plasma cutting apparatus with gas stabilized arcs. The research was based on diagnostics of steam plasma jet and investigation of interaction plasma jet with treated material. As most decisive processes take place in the anode region of the arc, special attention was devoted to the diagnostics and description of anode region of the arc and diagnostics of arc column inside and downstream of the kerf. The Fronius supplied the torches for the experiments and cooperated in preparation of measurements. All diagnostics, evaluation of the results and analysis was made at IPP.

Arc cutting of mild steel was studied using plasmas generated in gas (nitrogen, air, oxygen) and liquid (water) media. The experiments were performed on 15mm mild steel plates using commercial equipment (Fronius) to approach real operation conditions in application areas. The studied gases were chosen according to recommendations of the world's leading manufacturers of arc cutting equipment for mild steel. Basic diagnostics used in the experiments were emission spectroscopy, high speed photography and pyrometry. Specific differences between plasma gases are discussed from the point of view of properties of the gas and the generated plasma, amount of removed material, kerf shape and overall energy balance of the cutting process. The role of exothermic reaction of iron oxidation for oxygen cutting was described. Calculation of thermophysical properties of all gases involved in the experiments was performed for temperatures from 400 to 35 000 K and for pressures 100, 200 and 300 kPa. The equilibrium thermodynamic properties were computed according to the standard formulae of enthalpy, mass density, heat capacity and sound velocity for each pressure. For calculation of the transport coefficients the Enskog–Chapman method of solution of the Boltzmann equation in the fourth approximation was applied. The potentials of facilitating the cutting process by modification of the plasma gas chemical composition and flow rate were analyzed on the basis of experimental and theoretical results.

Anode processes taking place during pilot arc and cutting phases of plasma arc cutting (PAC) were experimentally studied. The obtained results show significant role of anode attachment in both process phases. An increase in the flow rate of the plasma medium facilitates anode spot movement. In the cutting phase, the anode attachment significantly affects the kerf shape and surface morphology. Lack of its movement deeper inside the kerf leads to different heat transfer conditions at the top and bottom of the material and results in different surface roughness values. Facilitating the anode spot movement towards the plate bottom is desirable to improve the cut quality.

Optical emission spectroscopy has been used to investigate the characteristics of a plasma jet produced by a steam arc cutting torch operated in air at atmospheric pressure. A procedure has been developed for simultaneous determination of temperature and pressure in the plasma jet as well as an effective non-equilibrium factor. It is based on comparison of a few experimental and simulated spectral quantities. The existence of the shock wave structure characteristic of an underexpanded jet can clearly be deduced from the measured properties. Spectroscopic measurements were used also for diagnostics of arc plasma inside the kerf during cutting of stainless steel. Emission spectral lines of neutral iron were used to experimental evaluation of the temperature of plasma in the kerf and close under the cut plate. Complicated nature of the plasma inside the kerf, including presence of metallic vapours and departures from equilibrium, was taken into account. Hence relatively reliable results were obtained, from which it was possible to get insight into the energy balance and cutting performance of the torch. Temperature of the plasma in the kerf was substantially lower than at the nozzle exit of the torch; however the temperature drop along the kerf was small.

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Removal of organic pollutants from water in water-stabilized arc.

In plasma torches with water stabilized arc, studied and developed at IPP, the arc column is surrounded by water wall created by inner surface of water vortex. In typical geometry of the torch the inner radius of water vortex is 3-10 mm, and the arc column with a centerline temperature up to 30 000 K is in direct contact with water. Water flows around the arc plasma and chemical processes in the water volume are stimulated by strong UV radiation and strong heat transfer, as well as by processes at the plasma-water interface. The experiments were performed for analysis of potentials of this type of arc discharge for treatment of polluted water.

Azo-dye Orange II was used as a model organic compound. Water circulates around the arc in the layer depth of 1 mm at the distance of 3 mm from the centerline of high temperature arc column. Arc power at all degradation experiments was 100 kW.The centerline plasma temperature that was measured by optical emission spectroscopy is 19 000 K. Degradation of the dye took place with high efficiency so that the fast decrease of a dye concentration during first minutes of experiments was observed. The changes of dye concentration were measured by means of UV/Vis spectroscopy. Intermediates (and partially also final products) produced during dye degradation were analyzed by total carbon (TC), total organic carbon (TOC), and total inorganic carbon (TIC) measurements. The decrease of dye concentration was approximately in first three minutes even faster than in simple theoretic model providing all dye passing by the column arc is degraded by the efficiency of 100%. Observed rapid degradation of the dye can be explained by very intensive UV radiation that is emitted by the arc due to its high temperature but also some reactive species are formed through the excitation and/or ionization of the water molecules by the energetic electrons An electric field in connection with reduction/oxidation medium caused by the reactive species also plays an important role. The experiments confirmed almost 100% efficiency of organic pollution degradation.

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M. Hlina, P. Lukes, M. Hrabovsky, Phenol degradation in water whirling around DC arc, 21st International Symposium on Plasma Chemistry (ISPC 21) August 4 – 9, 2013, Cairns, Australia.

Properties of water-stabilized plasma torches in plasma spraying applications.

Plasma spraying is basic plasma processing application of torches with water stabilized arc. New type of plasma spraying system, based on principle of hybrid arc stabilization which was studied, developed and designed at IPP, is now manufactured by our industrial partner ProjectSoft. Therefore special attention has been devoted to an investigation of performance properties of hybrid plasma torch and study of processes decisive for production of sprayed coatings in steam/argon plasma jets.

Spraying tests with copper powder have been carried out for a wide range of plasma torch parameters. Copper was used as a model material, which exhibits a rather low melting point, good heat conductivity, high density and tends to oxidize under plasma conditions. In practice, copper coatings are required when it is necessary to improve material heat or electrical conductivity, e.g., heat sinks for electronic applications, surfaces of printing rolls, or for cavities for electron and proton accelerators. Analyses of particle in-flight behavior for various spraying conditions were done. At the positions where substrate is located, particles were collected in liquid nitrogen which enabled analyses of the particle in-flight oxidation. A series of spraying tests were carried out and coatings were analyzed for their microstructure, porosity, oxide content, mechanical, and thermal properties. The tests were performed with various plasma torch parameters to observe their effect. Plasma torch arc current and secondary gas flow rate have been varied as well as a powder feeding distance. An analysis of particle in-flight behavior and oxidation was made. Increased torch power led to both higher particle temperature and velocity. Increased argon flow rate led to higher particle velocities, but had only minor effect on their temperature. Thus, possibility of rather independent control of particles velocity and temperature in spraying with hybrid plasma system was verified and tested. Temperatures and velocities of the particles had a direct influence on their in-flight oxidation, shapes of the deposited splats and resulting coating properties. The oxide content in both freeflight particles and coatings decreased with increasing argon flow rate, and correlated well with particle temperature and dwell time in the jet. Structure and thermal and mechanical properties of coatings were also sensitive to the torch parameters. The obtained results will be used for further optimization and development of the plasma spraying process by the hybrid water gas torch.

Possibility of reduction of oxidation of metallic particles and coatings by shrouding of plasma jet with inert gas was investigated. Effect of shrouding on plasma spraying of tungsten and copper was studied. Tungsten-based coatings represent an example of material where oxidation during spraying is important. They can find a use in various thermal management applications, such as thermonuclear fusion. Tungsten, with its refractive nature, can provide a plasma facing surface in a Tokamak, where it would be subjected to large heat and particle fluxes, and thereby protect the underlying components. Copper, with its high thermal conductivity, represents a suitable candidate material for heat removal. Combination of these coatings offers a prospective alternative to bulk material processing, which is particularly difficult in the case of tungsten. In-flight particle diagnostics and analysis of free-flight particles and coatings was performed for spraying experiments in the open atmosphere and with argon shrouding. The application of shrouding was found to affect particle in-flight parameters, reduce the oxide content in the coatings and generally improve their properties, such as thermal conductivity. Different degree of these effects was observed for copper and tungsten. All three studied spraying parameters, i.e. torch power, argon flow rate and location of particle injection, were found to have a significant influence on the in-flight particle behavior. Their effects on particle velocity were generally more pronounced than effects on particle temperature. Evaluation of collected splats showed that for copper full melting of the particles took place for all studied conditions, while tungsten particles were completely molten only for conditions with high plasma enthalpy. The changes in particle state were reflected in properties of the resultant coatings, particularly their oxide content and thermal conductivity. Application of inert gas shrouding generally led to reduction in oxide content and improvement in thermal conductivity. This effect was more pronounced for copper than for tungsten.

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T. Kavka, J. Matějíček, P. Ctibor & M. Hrabovský, Spraying of Metallic Powders by Hybrid Gas/Water Torch and the Effects of Inert Gas Shrouding, J Therm Spray Tech (2012) 21:695-705.

Supersonic steam plasma jet generated in water stabilized plasma torch.

The specific feature of the water stabilized arcs is a strong influence of ambient pressure on arc processes. Thus effect of ambient pressure on arc characteristics and generated jet properties was studied. Conditions in the arc chamber are determined by several processes - production of steam by water evaporation, plasma formation in the arc, outflow of plasma through the exit nozzle and a water exhaust from the chamber. All these processes are influenced by the pressure at the nozzle exit and thus the effect of ambient pressure on arc characteristics and processes of production of plasma inside the plasma torch may be substantial. At atmospheric ambient pressure the plasma jet of hybrid water/gas torch is subsonic; despite of the high velocity up to 8 km/s (the sound velocity in high temperature plasma is higher). When ambient pressure is reduced, the plasma flow regime is changed from subsonic to supersonic. The supersonic jet was investigated by emission spectroscopy and high speed photography at the region of the first expansion zone with supersonic velocity and downstream of this region. For pressures between 40 and 10 kPa, the jet structure could be well seen, showing clearly the expansion region at approximately 10mm from the nozzle with lower radiation intensity, where the supersonic flow velocity and lower density and temperature of plasma are present. For pressures below 4 kPa, the jet was more diffuse and supersonic structure is not apparent in visible light.Emission spectra of OH radical were analyzed in a chamber with pressures 4 kPa and 10 kPa. In spite of high temperatures of produced plasma, OH spectra in the plasma jet were found in a large area of the jet. It was concluded that excited OH molecules can be formed by various mechanisms, mainly in the outer parts of the jet, where thermal processes are not as dominant as in the hot central region. Rotational temperatures were calculated from the measured spectra and temperature profiles were evaluated in the large area of the jet in axial positions up to 70mm from the nozzle exit. Spectroscopic temperature measurements reveald minimum of temperature at about 10mm from the nozzle, which corresponds to the expansion region observed in jet images obtained by high speed photography. For lower pressures with difusion region of jet at 4 kPa, the local minimum in the radiation intensity in this region was not visible anymore; however, rotational temperature had minimum in this position similarly as for 10 kPa. For pressures 10 kPa and higher one other local minimum of plasma temperature was found at position 48 mm, which indicates existence of the second expansion zone. For lower pressures the variations of temperature along the jet axis downstream the first minimum are smaller, which corresponds to diffuse and more uniform jet. The results will be used in future reserach of low pressure plasma processing applications of the jet, namely plasma spraying and deposition of films.

Mašláni A., Sember V., Hrabovský M., Electron number density in supersonic thermal plasma jet, IEEE Transactions on Plasma Science 39 (2011), Issue 11, part 1, p. 2840-2841.

Theoretical modeling of water stabilized arc discharges and plasma jets.

The principal aim of theoretical modeling and computations was better understanding of processes and properties of water stabilized and water/gas arcs and description of processes of interaction of plasma jets generated in plasma torches with these types of arc with materials in plasma processing applications.

Basic modeling of water stabilized arcs and hybrid plasma torches was made in the past at IPP, theoretical investigation in recent years was concentrated on some special problems of thermal plasma and arc modeling – description of turbulence effect, description of radiation transfer within the arc including re-absorption phenomena, and effect of used methods of numerical solutions of model equations on computed results.

Numerical simulation of the turbulence effect in the nozzle region and upstream from a rotating disc anode in the hybrid-stabilized water/argon arc was made. The aim of this research was to analyze through numerical simulation if plasma flow in the hybrid torch can be considered laminar or if turbulence should be considered. To check possible deviations from the laminar model, we utilized the Large-Eddy Simulation (LES) and compared our results with the laminar case. The results obtained for currents 300-600 A and for argon mass flow rates 22.5-40 slm can be summarized as follows:

(a) Turbulence is not a significant phenomenon in the discharge and near-outlet regions of the hybrid-stabilized argon-water electric arc:

(b) Turbulent effects are stronger in small regions near sharp edges of the outlet nozzle and in the transition region between hot plasma and the surrounding atmosphere in the near-outlet region with high radial temperature and velocity gradients (shear layer). From our numerical simulation, we found that heat transfer from the arc to the nozzle with and without consideration of the turbulence is nearly the same because differences in temperature and velocity fields in the vicinity of the nozzle are negligible.

(c) Comparison with available experimental data demonstrates very good agreement for radial temperature profiles.

Special attention was devoted to the description of radiation transfer in the arc, as due to very high temperatures in hybrid arc the plasma radiation play important role. Two methods of modeling radiation transport were used – partial characteristics method and net emission coefficients. Results of simulation for 300–600 A and argon mass flow rates of 22.5–40 slm reveal that a significant amount of radiation is being reabsorbed in arc fringes. Radiation losses from argon–water plasma are calculated by the partial characteristics method for different molar fractions of argon and water plasma species in dependence on temperature and pressure. Continuous radiation due to photo-recombination and “bremsstrahlung” processes has been included in the calculation as well as discrete radiation consisting of thousands of spectral lines. Broadening mechanisms of atomic and ionic spectral lines due to Doppler, resonance, and Stark effects have been considered. Oxygen and argon lines included in the calculation are O (93 lines), O+ (296), O2+ (190), Ar (739), Ar+ (2781), Ar2+ (403), and Ar3+ (73). In addition, molecular bands of O2, H2, OH, and H2O have been also implemented. Absorption coefficient as a function of wavelength has been calculated from infrared to far ultraviolet regions and the tables of partial characteristics for 1000 K–35 000 K. It was proved in our simulation that though the relative differences for the electric potential, reabsorption and the arc efficiency are somewhat high in the discharge chamber, the radial profiles of temperature, velocity and the Mach number at the exit nozzle position show lower relative difference, below 20% for both radiation models. Agreement between experiment and calculation near the nozzle orifice is very good for the radial temperature profiles.

The last study was concentrated on comparison of numerical results for the discharge and near outlet regions of the hybrid-stabilized electric arc obtained by two different numerical methods. The first of them is based on the SIMPLER (SemiImplicit Method for Pressure-Linked Equations Revised) control volume iterative method, the second one on the LU-SGS algorithm (Lower–Upper Symmetric-Gauss– Seidel). Differences in results obtained by the two methods were analyzed and the comparison with available experimental data was made. The major difference between the results using the two methods occurs in the temperature distribution in arc fringes within the discharge chamber. This fact influences the potential drop, overpressure, reabsorption of radiation and arc efficiency. The radial profiles of temperature at the exit nozzle are less influenced by the choice of numerical method. This feature is attributed mainly to different ways of upwinding and discretization of the convection terms – first-order upwind used in the first method and a combination of LU-SGS algorithm and the Roe flux differential method together with the 3rd-order MUSCL type TVD scheme in the second method. In consequence, the electric potential drop in the discharge region, arc efficiency and reabsorption of radiation calculated by the second method are higher. Nevertheless the radial profiles of temperature, velocity and the Mach number at the exit nozzle position are less influenced by temperature distribution inside the discharge chamber; comparison between Methods 1 and 2 shows relative differences below 20%.

The model calculations was made in cooperation with the Institute of Fluid Science, Tohoku University Sendai, Japan. Part of the computations was made during stay of J. Jenista in Sendai, the partners from Tohoku University partially participated on formulation of model equations and analysis of the results. At least 80% of research was made by members of IPP team.

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Computation of transport and thermodynamic properties of thermal plasma.

Modeling of thermal plasmas is based on description of processes by a system of MHD equations where plasma properties are described by thermodynamic and transport coefficients calculated under the assumption of existence of local thermodynamic equilibrium. The computations of these coefficients for conditions corresponding to water stabilized and hybrid arc discharges were made and tables of material coefficients of steam/argon plasma were created. The spectroscopic measurements revealed substantial elevation of the electron temperature at the nozzle exit compared to the gas temperature. It was therefore necessary to validate the models of plasma property functions using nonisothermal plasma composition and nonisothermal thermodynamic and transport properties. Nonisothermal calculastions were made for various H2O-Ar mixtures at the temperatures 300 K to 50 000 K and pressure 0.1 MPa. and were compared with the results calculated under LTE assumptions. The results show an inportant dependence of plasma property functions on the Te/T ratio.

Composition, thermodynamic and transport coefficients of non-isothermal H2O-Ar plasma were computed for the temperature range 300 K to 50 000 K and pressure 0.1 MPa. For rates of non isothermality (T_e / T) from 1 to 2 for various molar amounts of argon. The non-isothermal composition was calculated using the usual four equations (quasineutrality, stoichiometric balance between H, O and the given amount of Ar and nonisothermal Dalton.s law) for four basic elements (e, H, O, Ar) completed by the equations connecting complex elements with its equilibrium constants under consideration of 31 relevant components. The equilibrium constants were computed using the partition functions in which the elevated excitation temperatures were taken into account. The partition functions of atoms and its ions were computed directly from their atomic energy levels, the equilibrium constants of ions of complex species were calculated approximately, using the equilibrium values taken from thermodynamic tables and their modification by elevated ionization energies corresponding to the given excitation temperatures. The non-isothermal transport properties were calculated using the method developed by us earlier. It is based on the Chapman-Enskog method in 3th approximation which was generalized to the non-isothermal case using matrix elements of semilinearized non isothermal Boltzmann collision operator. The computations were made also for plasma in mixtures of nitrogen with Fe vapor.

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Book chapters with topics related to principal investigations at IPP.

The results of research of basic topics studied at the Department of Thermal Plasma were used in texts of chapters in books. Three chapters were written by the members of the Department in the last five years. The chapters describe water stabilized arcs, their properties and utilization of this type of arcs for generation of thermal plasma jets in dc arc torches, and methods of theoretical modeling of water stabilized torches. The last chapter is devoted to problems of thermal plasma gasification nof biomass for synthesis gas production.

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Research Report of the team in the period 2010–2014

Institute	Institute of Plasma Physics of the CAS, v. v. i.

Scientific team	Laser Plasma

The Department of Laser Plasma focuses its research activities on the interaction of high-power radiation with matter, on the investigation of laser-produced and lasing plasmas in particular. The Department is operating a large European research infrastructure called Prague Asterix Laser System (PALS), established and exploited as a joint laboratory of IPP and the Institute of Physics ASCR, v.v.i. The scientific and technical staff of the Department provides full scientific, technical and logistic support to the experimental projects conducted at the PALS laser facilities. Theoreticians of the Department carry out simulation calculations to support radiation experiments and interpret their results. In the period 2010-2015 the associates of Laser Plasma Department were authors or co-authors of 72 scientific papers in impacted journals and 115 conference contributions. The following examples illustrate the breadth of the research program of the Department and highlight the most important results having been obtained by its staff during the last five years.

Background of the experiments with high-power lasers

The key experimental facility of the PALS laboratory a single-beam terawatt iodine laser system, unique in EU by its infrared wavelength of 1315 nm, belonging at present to only four European lasers of kJ-class. During the last five years the facility has been upgraded with several auxiliary femtosecond beam lines. An auxiliary Ti:Sapphire laser system at PALS is capable of delivering compressed output pulses of energy up to 1.2 J and duration less than 40 fs, which enrich the PALS experimental capabilities by tools for femtosecond plasma probing and double-pulse experiments with synchronized femtosecond and nanosecond beams. A unique combination of the synchronized long and short pulses generated by the above lasers makes it possible to study the processes of interaction of intense radiation with targets with very high (sub-picosecond) temporal resolution. These innovations have widely extended the capability of the infrastructure to meet even the most demanding requirements of laser plasma experiments of different kind. Moreover, the current research program of the PALS laboratory takes advantage of very high energy of the iodine laser, which is capable of generating relatively large volumes (of up to several mm cubed) of hot and dense laser plasmas. Such plasmas can be exploited, for instance, for implementation of experiments in the field of inertial fusion, charged particle acceleration, or plasma-based X-ray lasers and amplifiers. Another important fact is that the nanosecond duration of the iodine laser pulse corresponds to that assumed for use in future laser fusion devices. That is why the PALS laboratory is enjoying great interest of European users both in the framework of LASERLABEUROPE consortium and so called keep in touch activities of EURATOM.

Laser-Induced Cavity Pressure Acceleration

In October 2010 Czech and Polish physicists started at PALS a highly ambitious project, the aim of which was to test a new original highly efficient plasma acceleration scheme called Laser-Induced Cavity Pressure Acceleration (LICPA). In this scheme, a plasma projectile is produced by a laser beam inside a cavity and accelerated along a guiding channel by the thermal and photon pressure created inside. The method makes it possible to obtain superfast macroparticles at the energetic efficiency of acceleration by an order of magnitude higher compared to conventional ablative laser experiments. The possibility of efficient production of intense, high-energy ion bunches in the photon pressure-driven LICPA accelerator has also been proved using particle-in-cell simulations. Borodziuk et al. [1] formulated an original idea of cavity pressure acceleration in 2009. The next paper by Badziak et al. [2] is one of the first ones of a series of more than 30 scientific papers and conference contributions devoted to the LICPA project and published in coauthorship with PALS associates in the period 2009 – 2014.

The use of LICPA accelerator for obtaining superfast macroparticles was demonstrated at PALS in 2011 [3], when two different ways of macroparticle acceleration - "forward" and "backward" acceleration schemes - were tested and compared. The maximum measured velocity of the accelerated piece of 20 μm polystyrene foil was as high as $1x10^8$ cm/s. In [4-6] Badziak et al. summarized the results of the LICPA experiments performed at PALS. They have shown, for instance, that the ion current density and intensity of the ion flux produced in the LICPA scheme from CD_2 foil target irradiated by a 0.3-ns laser pulse of intensity 10^{14}–10^{15} W/cm^2 are by an order of magnitude higher, and the mean and maximum ion energies by a factor 4–5 higher than those found for the conventional acceleration schemes. The plasma bunches accelerated by LICPA method can be highly useful in contemporary research in high energy-density physics, nuclear physics, or inertial confinement fusion. The parameters of ion fluxes produced in the accelerator can be further increased by selection of the target thickness and optimizing the accelerator geometry. At laser intensities on the target achievable with PALS laser efficient generation of intense ion fluxes with MeV ion energies seems to be feasible. The idea of LICPA accelerator was Polish, however the experiments were conducted exclusively at the PALS iodine laser facility in Prague. They would not be possible without concentrated effort of PALS scientists and engineers, who played a dominant role at preparation and realization of the experiment, as well as at final redaction of the papers presenting the results. Besides the Polish and Czech colleagues also single physicists from other countries (France, Italy, Korea) participated at measuring the parameters of accelerated plasma streams some LICPA experiments.

Shock Wave Studies at PALS

The main goal of the experiments on shock wave generation having been conducted at the PALS laboratory since the year 2011 was to study the effect of laser-generated fast electrons on the efficiency of shock wave generation in a regime relevant to shock ignition scheme of inertial confinement fusion. Fast electrons might be dangerous in ICF scenarios, since they could preheat the fusion target and cause its premature expansion. The experiments on shock wave generation conducted at the PALS facility gave first relevant data in this field. The shock wave was produced by a laser beam at a wavelength of 438 nm with intensity of up to 10^{16} W/cm^2 in a pre-plasma created by means of a weaker auxiliary beam at a wavelength of 1315 nm. The diagnostics used permitted to evaluate the shock breakout time, quantity of fast electrons, thickness and temperature of the pre-plasma and backscattered emission inside and outside the cone of the focusing lens. The results have been compared with CHIC 2D simulations in order to infer the maximum pressure inside the target. In another experiment of that class the effect of large scale preformed plasma on parameters of laser-driven shock wave produced in a planar target was studied. Characteristics of the plasma ablated from the plastic target were measured with the use of 3-frame interferometry, ion collectors, Thomson spectrometer, X-ray spectrometer, and K imaging. The results of the above experiment were reported in [7-9]. Batani at al. in [7] showed that the laser beam can be coupled to a payload and generate a rather strong shock of ~90 Megabars even in the presence of an extended plasma corona. This was the highest pressure measured so far in this kind of experiments, showing a clear progress in approaching a shock ignition relevant regime. Even higher pressures are inferred when a much larger focal spot is used.

Gus'kov et al. in [8] report the results of study of the efficiency of laser energy transfer to solid targets irradiated by PALS laser pulses with intensities of 1–50 PW/cm^2 and duration of 200–300 ps, i.e. at conditions corresponding to those designed to generate the igniting shock wave in the shock ignition concept. The diagnostic data collected at PALS using three-frame interferometry, X-ray spectroscopy, and crater replica technique were interpreted by two-dimensional numerical and analytical modeling which included generation and transport of fast electrons. The collected experimental data confirmed the dominant contribution of fast electron energy transfer to the ablation process and shock wave generation.

Pisarczyk et al. in [9] reported the studies of efficiency of the laser radiation energy transport into the shock wave generated in layered planar targets consisting of a massive Cu plate covered with a thin CH layer. The influence of the preplasma on parameters of the shock wave was determined from the crater volume measurements and from the electron density distribution measured by 3-frame interferometry. The experimental results show that the energy transport by fast electrons plays a decisive role at the shock wave generation. In the last experiments with the first harmonic of the PALS laser radiation the ablative pressure estimates gave a shock ignition relevant value of up to 300 Mbar.

As in the preceding case of LICPA investigations, the experiments with shock waves take advantage of rich diagnostic equipment of the PALS laboratory and a unique multi-beam capability of the PALS iodine laser and its target facilities. The PALS staff was responsible for preparation of the experiment, including beam lines and diagnostics, and performing the measurements, the PALS scientists participated in processing the results and final redaction of the papers. For use at PALS a 3-frame laser interferometer was specially designed and fabricated at IPPLM Warsaw.

Femtosecond interferometry

Substantial progress in the shock wave studies has been achieved by replacing the nanosecond diagnostic beam of the iodine laser driving the laser interferometer at PALS by a synchronized sub-picosend beam of the auxiliary Ti:Sapphire laser. That was possible owing to precise synchronization of both laser systems described e.g. in [10], and redesigning completely the laser interferometer for PALS by Polish colleagues at IPPLM Warsaw. A new two-channel polarointerferometer makes it possible to measure the plasma density and even the magnetic fields spontaneously generated in laser-produced plasmas with a subpicosecond time resolution. Such a device has no match worldwide up to now. It was used at PALS for the first time in autumn 2013, at measurements of early stages of the plasma generated by laser irradiation of planar targets [11] with the aim to gain deeper insight in the processes of laser energy transformation to the shock wave in relation to the shock ignition concept. By using the new two-channel polarointerferometer, X-ray spectrometers, ion collectors, and a Thomson analyzer the electron density, magnetic field distributions and other characteristics of the ablative plasma have been determined. Also at these investigations the PALS scientists and engineers were fully responsible for the laser part of the experiment.

Plasma Jet Studies

A simple method of plasma jet generation based on using a flat massive Cu target irradiated by the a partly defocused high-power laser beam beam was suggested by Kasperczuk et al. already in 2006 [12]. The method was tested at the PALS iodine laser, the results of first experiments having been summarized by Kasperczuk et al. in [13]. That work started a long series of more than 30 publications in impacted journals and conference contributions based on the results of investigations of laser-produced plasma jets at PALS in the years 2009-2013. These works opened up entirely new possibilities both in the laboratory simulations of astrophysical jets and the Herbig-Haro objects observed in outer space, and in using laser plasma jets for various applications in science and technology, including the method of a controlled energy transport in fusion targets.

Already the very first experiments with directed plasma streams at PALS have shown that well-formed plasma jets can be produced at laser interaction with targets made of materials with high atomic numbers. The experiments described in [14] were aimed at investigation of the interaction of a laser-produced copper plasma jet with an ambient plastic plasma, and of the interaction of two plasma jets produced successively from Cu target [15]. Detailed studies of the interactions of CH-Cu and CH-Al plasmas have shown that a relatively thin plastic plasma envelope is able to compress the Al plasma streams [16,17]. As a result, smaller diameter plasma streams and higher plasma densities have been obtained. More complicated target compositions, consisting of inserts of different materials, make it possible to control the jets and produce more complicated plasma stream structures tailored for different applications [18]. For instance, a Cu-plasma pipe can serve as a nozzle for the CH plasma streams. By using heavier target materials (Ag, Ta) more complex plasma configurations have been created. In the experiment reported by Kasperczuk et al. in [19] two experimental arrangements were studied: targets with a cylindrical plastic insert fixed inside different metals like Cu, Ag, Ta, and targets with cylindrical Al, Cu, and Ag inserts placed inside a different-Z material. This approach allowed us to determine the relationship between the plasma pressure and the plasma atomic number. It has been demonstrated that the plasma pressure decreases with growing atomic number Z at lower Z only, becoming stabilized approximately at Z=47 (Ag).

Directional flows of energetic ions produced by laser-exploded foils were used also to investigate transient phenomena accompanying the plasma interaction with surfaces of solid targets (walls). In the experiments carried out at PALS, the formation of energetic plasma jets from burn-through foils of Al and Ta was optimized using three-frame laser interferometry. The interaction of the directional plasma flows with secondary targets was studied by means of X-ray imaging, high-resolution optical and X-ray spectroscopy [20, 21]. The environmental conditions in near-wall plasmas created at surfaces of plasma-exposed solids, the velocity distributions of impinging and back-scattered ions in particular, were determined via analysis of the observed space-resolved spectra of Al Ly□ and He□ groups. The validity of the ion velocity gradients derived from the Doppler effect induced shifts and splits of the spectral lines was supported by theoretical modeling based on a combination of hydrodynamic, atomic and collisional-radiative code.

All the experimental results mentioned above have been obtained exclusively at the PALS laser laboratories, the PALS research staff being fully responsible for the laser part of the experiments and for preparation of the experiments in the PALS target area. Polish colleagues from IPPLM Warsaw were responsible for laser interferometry, collaborators from the Institute of Physics and CTU in Prague for radiation spectroscopy and particle diagnostics. Theoreticians from CTU Prague, Institute of Physics and P.N. Lebedev Physical Institute of RAS provided theoretical interpretation of some of the collected experimental data.

XUV Laser Experiments

An astrophysically motivated project aimed at investigation of radiative shocks produced by the PALS laser was conducted at PALS in 2011. The goal of the project was to improve the imaging diagnostics with zinc X-ray laser at 21 nm and extend the preliminary study of the shock time and space resolved photometry using high-speed photodiodes to different wavelength ranges. In the experimental setup used the infrared PALS laser was exploited for generating both a shock wave in xenon and a delayed X-ray laser probing pulse.

Thanks to a new XUV mirror with excellent imaging quality and improved target filling procedure, allowing to use finer windows and thus increase their transparency, clear and unambiguous images of the shock wave have been obtained, some of them showing the presence of a curved ionization front. Highspeed Al-filtered diodes placed perpendicularly to the shock direction made it possible to record the plasma XUV radiation at a short distance from the initial position of the plasma boundary. No radiation was detectable at longer distances, which indicates radiative cooling of the shock. A new diagnostic based on optical fibers was implemented at different locations perpendicularly to the shock tube to measure the lifetime of the shock. Stehle et al. and Cotello et al. reported these and other results in [22] and [23], respectively. As in other experiments reported above the PALS staff, represented in the cited articles by M. Kozlova, was fully responsible for the laser part of the measurements.

Another collaborative international X-ray laser project was conducted at PALS in the beginning of 2012. The main objective of the experiment was to carry out the first measurement of the temporal coherence and associated spectral line width of the zinc XUV laser generated at PALS. As this laser is operated at a larger electron density and a larger ionic temperature than other short-pulse pumped Xray lasers, it has a large bandwidth advantageous for the development of subpicosecond XUV lasers. The measurements were performed using a unique wavefront-division, variable path-difference interferometer provided by the users team. The temporal coherence of the

Zn XUV laser operated in double-pass amplification has been measured, two slightly different values of the coherence time (0.7 ps and 1 ps) having been found. This confirms the high potential of the Zn quasi-steady state XUV laser at PALS for the generation of femtosecond amplified pulses, through seeding with high-harmonic radiation, as suggested by Kozlova et al. in [24]. More precise measurement of the temporal coherence of the 21.2 nm laser at PALS through a better control of the spatial coherence of the beam confirm that the QSS zinc XUV laser has the largest gain bandwidth over the existing XUV lasers. This large bandwidth should allow amplification of pulses with duration below 1 ps.

Advanced XUV Spectroscopy of laser-produced plasmas

Advanced XUV spectroscopy was and integral part of fast all interaction experiments at PALS. Direct X-ray spectroscopic characterization of suprathermal electron distribution inside laser-produced plasmas was the subject of another collaborative project conducted at PALS in April and May 2013. Its main goal was to develop diagnostics of suprathermal electrons by exploiting X-ray radiative properties of mid-Z tracer elements like copper and germanium. By using two spherically bent quartz crystal spectrometers and high-dispersion Johann spectrometer highresolution spectra the X-ray transitions in relatively cold dense copper plasmas have been measured. The novel features observed in the spectra were attributed to hollow ion emission from cold dense Cu plasma under the action of hot electrons [25]. The spectral lines induced by the action of suprathermal electrons in a laser-irradiated Cu target were studied, a whole set of transitions between K_a and He_a lines originating from Be-like to Ne-like Cu having been identified. The emission was modeled using the FLYCHK code, the simulation procedure used offering a basis for the development of alternative x-ray spectroscopic diagnostics for hot electrons. Detailed spectroscopic studies of the plasma produced by both the iodine nanosecond and Ti:Sapphire femtosecond lasers have been continuing at PALS up to now. As in the preceding experiments, the PALS scientists and engineers provided support for the laser part of the experiments, while spectroscopists from the Institute of Physics with a group of French collaborators were responsible for preparing and performing the spectroscopic measurements.

Charged-particle acceleration in laser-produced plasmas

Investigation of charged particle acceleration in laser-produced plasmas belongs to traditional lines of research at PALS, having been reported in several tens of scientific articles published on that subject since the PALS start in 2001. A highenergy laser beam interacting with a solid target generates fast protons and highly charged heavier ions, which can enter mutual fusion reactions or produce fusion reaction in targets of proper compositions. The experimental methods of diagnostics of accelerated ion streams are improving year on year. In the experiments performed at PALS in the period 2012-2013 the fast ion currents generated in deuterated polyethylene and graphite plasmas were studied in detail [26]. The PALS ion projects were aimed at improving the parameters of accelerated proton streams by exploiting various sophisticated targets, such as hydrogenated thin foils, or targets with nanostructured layers.

Production of heavier ions was studied by irradiating Cu targets and Au, Au/Mylar, and Mylar thin films. Ion investigations at PALS stimulated joint development of advanced measuring instruments, such as a new Thomson parabola spectrometer (TPS) with a multi-channel-plate detector, described by Cutroneo at al. in [27, 28]. It was used to record and characterize the plasma ion emission in the forward direction and to get information on the ion charge states and energy. TPS experimental spectra were compared with accurate TOSCA simulations of the TPS parabolas. Ion collectors and semiconductor SiC detectors, described by Cutroneo et al. in [29], were employed in the time-of-flight arrangement in order to measure the ion velocities as a function of the angle around the normal direction to the target surface. The ion emission from non-equilibrium plasma laser-generated on thin targets was studied in terms of energy distribution, yield, angular distribution, maximum proton energy and maximum charge states. The observed characteristics of the emitted fusion neutrons witnessed an important role of non-linear processes, including beam self-focusing, which is of high importance in experiments with highpower laser pulses of nanosecond duration.

The measurements realized at PALS demonstrated that protons with energy of up to 3 MeV can be generated by using hydrogenated foils 10 microns thick. Gold ions up to about 120 MeV and 60+ charge state were also detected. It has been shown that non-linear effects occurring in thin nanostructured targets induce strong resonant absorption and self-focusing of the laser beam. These two effects increase the plasma temperature and density, which results in higher ion yield. Accelerated deuterium ions were also detected at irradiating CD_2 targets, and D-D fusion reactions observed [30]. The objectives of the following experiment were to determine the maximum energy and yield of protons accelerated from the laser irradiation of thin targets in TNSA conditions, to check the efficiency of nanostructured targets with high absorption and low reflectivity coefficients, and to test new methods of diagnostics for on-line characterization of laser-produced plasmas. For that purpose a Thomson parabola spectrometer coupled to a multichannel plate and CCD camera was used, together with ion collectors, SiC detectors and X-ray streak camera. The D-D fusion reaction and Li_7 and Li_6 reactions with protons were monitored though the characteristic radiations emitted from the reaction events. The maximum proton energy of 4 MeV and maximum Al ion energy of up to 50 MeV have been achieved, when using advanced targets with a reduced surface reflection and an increased laser absorption coefficient. With thin hydrogenated porous targets of optimal thickness the maximum energy of accelerated protons has been enhanced up to 5 MeV.

Fast particle streams produced at the laser interaction with thin solid targets were studied also by means of the 25-TW Ti:Sapphire femtosecond laser shortly after its commissioning at PALS in 2011 [31]. The aim of that pilot experiment was to use protons streams as probe beams for diagnostics of the plasma produced by the kJclass iodine sub-nanosecond laser. The accelerated particle streams were characterized in terms of maximum energy and total yield, the proton energy spectrum having been recalculated from the recorded TOF spectra. It has been shown that proton beams produced by femtosecond lasers may serve as a prospective diagnostic tool for dense plasmas.

Proton-boron fusion experiment

The aim of the ion experiment conducted at PALS in the beginning of 2013 was to maximize the proton/ion energy and yield at target interaction of a subnanosecond laser PALS using artificial hydrogen-enriched targets. Particular attention was devoted to boron-doped hydrogen-enriched silicon targets as well as simple H-enriched ones. It was already known from earlier PALS experiments that silicon doped targets of various thickness were able to produce relatively high currents of forward accelerated protons with energy of up to 2 MeV [32]. The proton currents achieved with hydrogenated target were much higher than those measured with pure silicon ones. Picciotto et al. reported the most important result of experiments of that kind in [33]. They show that a spatially well-defined layer of boron dopants in a hydrogen-enriched silicon target allows for the production of a high yield of alpha particles of around 10^9/steradian using a nanosecond, low-contrast laser pulse with a nominal intensity of approximately 3×10^{16} W/cm^2. Possible impact of this result on future applications such as a-neutronic nuclear fusion or compact ion accelerators is unquestionable.

The laser part of the ion experiments at PALS including the laser and plasma diagnostics was fully of responsibility of the PALS scientists and engineers. Fast ion diagnostics such as Thomson Parabola Spectrometers and ion collectors and detectors were supplied by the Institute of Physics in Prague and Messina University. The special laser targets used in the experiments were fabricated at the Italian and Polish partner institutes

High-frequency plasma heating

For realization of the thermonuclear reaction it is necessary to heat the plasma in the future thermonuclear reactor to a sufficiently high temperature. One of the possibilities, which was in the reported period a subject of interest of Vaclav Petrzilka, the leading theoretician of LP Department, is the lower hybrid (LH) wave heating applied in tokamaks. In an experiment carried out at JET, reliable coupling of the LH waves to plasmas was made feasible through a dedicated gas injection system, located at the outer wall. The injected gas was ionized by LH energy dissipation in the Scrape-Off-Layer (SOL) [34, 35]. V. Petrzilka was modeling the SOL near the LH antenna, with the aim to find whether the gas injection from the tokamak top, (as also foreseen for gas injection in ITER) could also provide a good coupling of the LH waves. The results of modeling indicated that a top gas injection is not efficient enough for providing a reliable LH power launching. A gas injection system, set in the outer mid-plane, was therefore recommended in order to provide appropriate density growth and reliable coupling for an LH antenna in ITER.

Further, a series of JET tokamak shots in the ILW (ITER-like-Wall) environment was successfully modeled by EDGE2D code, in which variations of the SOL due to parasitic absorption of the LH power were implemented. The density variations during LH were measured by Li-beam, and the results were compared with the EDGE2D computations. The power needed for the code to fit the modeling results with the observed enhancement of the SOL density provides estimates of the heat flux into the hot spots from the grill mouth. For a more detailed description of the ponderomotive force effects just in front of the LH antenna (grill) a simple code was also created. However, the SOL density increase due to direct ionization of the SOL by LH waves was rather strong in the modeled shots, the ponderomotive density depletion in these shots representing a small perturbation only.

As it is obvious, the SOL density variations described above are critically dependent on the rate of the LH energy parasitic absorption in the SOL, in which the energy is carried away by the beam of fast electrons generated near the antenna by cascade Landau damping process. The fast electron generation was therefore studied on the Tore Supra tokamak by analyzing the data from the RFA (Retarding Field Analyzer) and tunnel probe in Tore Supra tokamak shots. Further, V. Petrzilka participated in analysis of the heat loads created by the older Fully-Active Modules (FAM) LH grill C3 and the ITER-like Passive-Active Modules (PAM) LH C4 grill. This effect has been studied for the PAM and the FAM by using RFA, magnetically connected to either of the two launchers, in identical plasma conditions. Infrared (IR) imaging of the hot spots on the launcher side protections, or on a magnetically connected limiter, was also used for the analysis. Both the RFA collector current and the IR hot spot temperature are consistently somewhat higher for the FAM than for the PAM, at the same power (1.4 MW) and same plasma-launcher distance (4 cm). This is in agreement with test electron modeling of the electron power flux, based on the electric field pattern computed by the ALOHA coupling code. The simulations show that the power flux is by ~30% higher for the FAM than the PAM at 1.4 MW and with density at the launcher mouth above 2×10^{17} m^{-3}. Furthermore, the power flux increases with increasing electron density in front of the launcher, which is well observed experimentally by the IR measurements. Rounding the waveguide septa reduces the electric field at the launcher mouth. Test electron simulations predict that the resulting power flux can decrease by almost a factor of eight, by rounding the waveguide septa on the PAM. Such modification may allow reducing significantly the localized power flux in the scrape-off layer. This will hopefully be tested experimentally in the forthcoming Tore Supra campaigns. Further, the results indicate one important effect, namely that the active ICRH Q5 antenna blocks the fast particle beam passing the antenna on its way from the Lower Hybrid (LH) antenna to the probe. Based on this finding, to further Tore Supra experiments will be designed, to elucidate the preliminary conclusions in more detail.

The results of the above works, obtained in collaboration with colleagues from the JET and TORE SUPRA tokamak teams, were published in 9 journal (impacted) papers and 20 international conference contributions. V. Petrzilka participated in the design and data analysis of the experiments, and in their numerical simulations and theoretical modeling.

Development and optimisation of XUV radiation sources

Computer simulations of pinching capillary discharge resulted in a design of new laboratory source optimized for the generation of monochromatic radiation with λ = 2.88 nm. The estimated output energy of monochromatic radiation 5.5 mJ/sr ($1.e^{14}$ photons/sr) corresponds well with the observed experimental value $3.e^{13}$ photons/sr. The high current XUV source driver based on water capacitors charged by MARX-FITCH generator was built and run as a water window wavelengths source. The main result is its five times higher brightness when compared with previous sources [36].

Further optimization of a nitrogen capillary plasma source of intense monochromatic radiation at 2.88 nm has been done using laboratory experiments and computer simulations. In particular, the pre-ionization of capillary discharge was studied to obtain optimal conditions for generation of XUV radiation. Exponentially damped or high-frequency alternating low currents were used before application of the main sinusoidal damped current. Systematic study of the discharge dynamics was accomplished for an alumina capillary filled with nitrogen. For comparison of the pre-ionized plasma properties predicted by MHD and RMHD codes also spectroscopic measurements on CAPEX apparatus have been carried out [37].

Free-standing grating spectrometer has been designed and built for a routine diagnostics of the radiation emitted by laser produced plasma (LPP) system and a pinching capillary discharge produced plasma (DPP) system. The pulse energy produced by the DPP source at 2.88 nm was found to by approximately by one order of magnitude higher compared to LPP. Soft X-ray emission from a capillary discharge with nitrogen, argon and carbon dioxide fillings as a possible source of XUV radiation in the “water window” region was investigated. The dependences of XUV radiation power, radiation energy per pulse, beam profile, beam divergence, source size and time-integrated spectra on capillary current were measured. Computer study of amplified spontaneous emission (ASE) at the Balmer alphatransition of helium-like carbon and nitrogen ions were performed for ablative capillary discharge. The capillary discharge evolution was modeled by NPINCH code. The spectroscopic estimations were done by means of FLY, FLYPAPER and FLYSPEC programs, used as post-processors [38-41].

Nitrogen gas-puff target experiment

The apparatus consists of an interaction chamber in which nitrogen gas was blown through special nozzle under high pressure (p ~1-10 bar). The corresponding density and plasma temperature is achieved by applying laser light (Nd:YAG) in the longitudinal direction. Results of the measurement of radiation intensity at a distance of ~ 0.5 mm from the nozzle orifice for various laser pulses (600 mJ/7 ns and 525 mJ/170 ps) were compared with theoretical calculations [42]. The nitrogen gas-puff target used in laser produced plasma soft x-ray source was studied via experiment and computer simulations. Radiography done by 13.4 nm radiation was used for estimation of spatial distribution of nitrogen mass density. The dynamics of supersonic nozzle was also simulated by 2D RMHD Z* code. Computer and experimental results correspond each other [43].

The above results have been achieved in close cooperation with two departments of the CTU in Prague: the Department of Physical Electronics (DPE) at Faculty of Nuclear Sciences and Department of Natural Sciences (DNS) at Faculty of Biomedical Engineering. Experiments with the pinching capillary discharge were done in the DPE, whereas the experiments with laser plasma XUV source were performed in the DNS. Pavel Vrba (DLP) and his doctoral student J. Hübner of the Laser Plasma Department of IPP carried out most of the computer simulations.

Diagnostics and control of high power laser beams

This activity was aimed during the period in question at improving the ability to collect sufficiently accurate characteristics of PALS high power laser beams, to predict laser beam modifications during propagation and amplification in system and to control output laser beam properties in order to tailor interaction profile to plasma experiment. The LP sub-team headed by V. Kmetik designed, developed, and realized new types of hardware for PALS laser facility upgrade. It included a laser beam diagnostics for 1.3 □m with on InGaAs detectors and development of 1.3 □m high-resolution high-fidelity laser beam diagnostic based on low-cost silicon detectors [44]. Implementation of a new hardware and an accurate simulation of beam propagation enabled us correctly interpret PALS experimental results, in particular to clarify a generation of dense, large aspect ratio laser plasma jets from planar targets [45]. For reliable acquisition and transfer of large amount of data from beam diagnostics in extremely high-frequency perturbed environment a qualitatively new type of control and data transfer system based on purely optical paths including optical power lines with opto-electronic conversion efficiency over 40% was designed and tested [46]. In order to actively control a PALS laser beam, to tailor it to experiments and to correct perturbations during amplification the sub-team investigated an adaptive correction for a high power laser beam and with partners from University and industry developed an adaptive optic system with a largeaperture composite bimorph deformable mirror and an original control system [47] registered as Invention No. 27619, 2014, Czech Patent and Industrial Property Office (V. Kmetik: Deformable mirror control device for manipulation of high power laser beam quality). The last two research items gained support by the Technology Agency of CR under grants Alfa TA01010522 2011-2014 (participant FOTON s.r.o) and Alfa TA01010878 2011-2013 (participants Faculty of Mechanical Engineering CTU, and 5M s.r.o), with V. Kmetík as a proposer.

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