Description of the main research directions investigated by the institute

The main research directions of the Institute correspond to the organizational structure. Scientific departments are further subdivided into groups by specific topics. However, synergic collaborations among the departments is supported and encouraged by the Institute leadership and results in collaboration of e.g. Tokamak and Material Engineering dept. on development of materials for fusion applications, TOPTEC center with other departments on development of advanced optical diagnostics, etc.

Below we describe the main research directions studied in the individual scientific departments:

Tokamak department

Research in the Tokamak department (TOK) is **pursued in topics that are directly linked to the international long-term efforts in mastering thermonuclear fusion as an energy source**. Experimental research in the department is based on use of the national experimental facility, the COMPASS tokamak as well as on the other European facilities within the EUROfusion consortium[1]: JET, ASDEX Upgrade, and TCV. Theory and modelling effort is focussed on support and interpretation of existing experimental activities within the department as well as within EUROfusion, on development and validation of numerical codes, and on physical foundation of understanding and developments for future devices COMPASS Upgrade, ITER, and DEMO. Diagnostic developments address diagnostics enhancement on COMPASS, design and construction of systems for COMPASS Upgrade and ITER, and developments for DEMO. Technology R&D activities are represented by designs and developments of systems for COMPASS Upgrade tokamak.

The scientific focus of the Tokamak team is mainly in the following fields:

- L-H transition and H-mode studies (L-H threshold, transport barriers, Zonal flows and Geodesic-acoustic modes, etc.)
- Physics of tokamak edge and SOL plasma (pedestal characterization, Edge Localized Modes, pedestal scaling, SOL profiles, flows, divertor plasma parameters, etc.)
- Heat flux and power exhaust (plasma-wall interaction, heat loads and their scaling, impurity seeding, detachment, etc.)
- Tokamak core plasma (scenarios optimization, Alfven modes studies)
- Runaway electrons (RE beam generation, control, and mitigation)
- Disruption studies (toroidal asymmetries, sideway forces, etc.)
- Diagnostics development for future fusion devices (Hall sensors for ITER and DEMO)

The team has established an extensive and growing collaboration with with Czech as well as many prominent foreign organizations and universities, incl. ITER Organisation, EUROfusion laboratories, Princeton Plasma Physics Laboratory in USA, etc.

[1] EUROfusion is European Consortium for the Development of Fusion Energy.

The Tokamak Department operates the COMPASS infrastructure[2], which consists of the tokamak device with a divertor configuration and its auxiliary systems. COMPASS represents one of the key facilities in the joint European effort within the EUROfusion consortium. The infrastructure provides also an open access for a wide user community: scientists from international laboratories as well as students from national and foreign universities. Thus, the TOKAMAK team enhances education in the field of high-temperature magnetized plasma physics.

Since 2017, the team focuses on the project *"COMPASS-U: Tokamak for cutting-edge fusion research"* the main objective of which is the design and construction of a new unique high-magnetic field tokamak that will replace the present COMPASS tokamak. This activity enhances the team competences in the field of physics and engineering of the tokamak construction. The new device will highly enhance the capabilities of the infrastructure. The COMPASS-U tokamak will be, after its commissioning, exploited as a consortium device of the EUROfusion consortium. In addition, the US Department of Energy has also expressed an interest in collaboration on this project, which resulted in the signature of a Collaboration Agreement in 2019. DoE is already funding several teams in the Princeton Plasma Physics Laboratory as well as several other universities, which work on the design of some of the systems and diagnostics for COMPASS-U.

Laser plasma department

The Laser Plasma Department (LPD) concentrates its effort on experimental and theoretical studies and applications of plasma generated by laser beams with very high power (in the order of TW). The laser beams are focused on solid or gaseous targets and the achieved power densities of the focused beams lie between 10^{14} W/cm^2 to $3x10^{16}$ W/cm^2. The experimental research of laser-produced plasma is mainly carried out at a terawatt iodine laser facility, being currently one of the largest in Europe, known since 2000 as the Prague Asterix Laser System (PALS), of which Institute of Plasma Physics is the main operator. The PALS laser system is simultaneously a key experimental facility of the PALS Research Centre, a joint research laboratory of the Institute of Plasma Physics and the Institute of Physics. One of the main activities of the LPD team is the operation of the PALS laser system serving as a user facility providing open access to national and international users; we provide the technical, logistic, and scientific support to the users.

The research is focused mainly on the study of high-energy density phenomena related to inertial confinement fusion studies, such as shock ignition scheme, laser plasma instabilities – their generation and mitigation of their effect, hot electron generation, etc., and laboratory astrophysics as a strong magnetic field generation. Most of the research was performed in collaboration with external users. The laboratory astrochemistry studies are performed in collaboration with Jaroslav Heyrovský Institute of Physical Chemistry; the LPD team participated mainly in the laser-generated plasma related issues such as characterization of fundamental plasma parameters. The LPD research also focuses on the laser wakefield

[2] The infrastructure is included as *"COMPASS – Tokamak for Thermonuclear Fusion Research"* in the Roadmap of the Large Research Infrastructures of the Czech Republic, which is a strategy document presenting the policy-making approach of the Czech Republic to the large research infrastructures. In the international context, the Roadmap is equivalent to the Roadmap of European Strategy Forum on Research Infrastructures (ESFRI), being the Czech contribution to the landscape of research infrastructures constructed and operated in Europe and worldwide.

acceleration of electron bunches; the main scope represents the research of alternative acceleration and electron bunch injection schemes. The non-Hermitian quantum physics focuses on the study of fundamental nature of non-Hermitian description of various phenomena in atomic and molecular physics.

The LPD team also devotes a large effort to the development and upgrade of the PALS laser system and its various diagnostics. Within the last period, the following enhancements have been completed: a precise synchronization of the kJ-level PALS laser system and femtosecond Ti:sapphire laser system, implementation of 3-frame polaro-interferometer for sub-picosecond probing of the plasma density and generated magnetic field, a high-magnification pinhole camera and also an array of magnetic dipole spectrometers for hot electron energy and temperature measurements.

TOPTEC department

The Regional Centre for Special Optics and Optoelectronic Systems (Turnov OPToElectronic Centre - TOPTEC) was put into operation in 2013 and partly succeeded the Optical department of the Institute of Plasma Physics of the CAS, v. v. i. in Turnov (formerly known as the Optical Development Workshop AS CR). The Centre continues a more than 50-year-long tradition of research and development of optics in Turnov. At present, the TOPTEC Centre is the only R&D facility that focuses on ultra-precision and special optics in the Czech Republic. The main objective of TOPTEC is the research and development in the field of aspheric and free-form optics, precision measurement, thin film layers, and the application of the results in the industrial sector.

The research and development focuses on the following areas:

- Optical systems and crystal optics;
- Optical elements and manufacturing processes;
- Nonlinear optics and electro-optical materials;
- Optical measurement methods and metrology;
- Fine mechanics;
- Thin film layers, spectroscopy and hyperdimensional imaging.

TOPTEC carried out several development projects financed from the Operational Programs (OP) or from the National Sustainability Program (NSP) in the past years.TOPTEC is also a part of the network of Application centres of the Czech Academy of Sciences. Therefore, the focus of the Centre is more application-oriented compared to the other departments of the IPP. Application centres are characterized by very close cooperation with industry in the Czech Republic and the world, and TOPTEC is among the top in both the terms of quantity and quality. TOPTEC is a co-investigator of four European Space Agency (ESA) projects and actively cooperates with the leading companies in the optical industry and related branches such as OHB, AIRBUS, LEONARDO, MICOS, ELCOM, Applic, Meopta, Rigaku, FEI, TESCAN, Varroc, Preciosa, Siemens, Crytur, Asphericon, etc..

The research directions of the Centre are oriented towards the field of super-precise and special optics. The main areas of TOPTEC focus are:

a) The design, optimization and construction of modern optical systems using optoelectronic elements, systems are controlled and monitored by the computer. Development of computer assisted alignment procedures.
b) Research and development of processes for the processing of optical glass, ceramics and metallic materials, i.e. research of polishing processes, grinding processes, glass moulding processes as well as processes of ion beam figuring aimed to atomic surface layer etching meant for fine corrections of the surface shape of the elements.
c) Research and development of thin films for antireflection and superreflection purposes, such as application-specific layer systems used in optics for high performance lasers are developed
d) Research of measurement and analytical methods for use in the measurement of the shape of optical surfaces, as well as for precise spectroscopy, hyperdimensional analysis, or measurement of refractive index distribution, or surface quality analysis, and many others.
e) Material research focused mainly on ferroelectric and other non-linear optoelectronic materials, or the use of new materials for the manufacturing of thin layers with unique properties.

The TOPTEC centre managed to gradually built a young high-quality scientific team with an international experience from leading world research centres (EPFL, Switzerland; CERN Switzerland; Lund University, Sweden, ITO, Germany, etc.).

Material Engineering department

Research of the Materials Engineering Department (ME) is focused around two main areas. They are often interrelated and various specific projects typically involve more than one area as will be described in the next section.

One research area is focused on materials for fusion applications. Nuclear fusion is considered to be one of the future sources of sustainable energy. Development of suitable materials for fusion devices, in particular for plasma facing components, is among several critical issues that need to be solved urgently to make fusion as an energy source feasible.

The other research area focuses on fundamental research and development of new classes of materials prepared by powder processing equipment that is operated by the ME team members. There are three kinds of powder processing equipment available at IPP. One of them is the hybrid water stabilized plasma torch (WSP-H) that is used for plasma spraying of powders and liquid feedstock material. Plasma spraying of liquid feedstock either in the form of suspensions or precursor solutions is an emerging route of plasma spraying. It has recently become the dominant research direction of those in the ME team focused on the area of plasma spraying.

The second powder processing equipment is the radio-frequency inductively-coupled plasma torch (RF-ICP), which was acquired during the evaluation period. The RF-ICP torch uses the principle of electromagnetic induction to ionize gas atoms as they pass through the centre of a copper coil, thus creating the plasma jet. The plasma spraying process therefore runs in a controlled atmosphere. This allows to avoid undesirable reactions, such as oxidation of metals, and at the same time opens up the possibilities of reactive spraying with suitable atmosphere.

The third powder processing equipment is the spark plasma sintering (SPS), also called field-assisted sintering machine (FAST). Its primary advantages over conventional sintering techniques are significantly shorter processing times and/or lower sintering temperatures, which permits preservation of beneficial fine-grained structures that are sensitive to thermal exposure. Mechanical alloying has become an integral part of the powder-processing route before the final SPS sintering step. For example, the research of tungsten-based micro-alloys (e.g. W-Cr) is based on utilization of mechanical alloying followed by SPS. Recently, research of high-entropy alloys (HEAs) has been also successfully started and uses the same powder-processing route.

All of the three powder processing techniques are also used to prepare new classes of multicomponent materials that are tailored for specific application (e.g. environmental barrier coatings, functionally graded materials for fusion devices, dielectric coatings etc.). In general, the ME team members are also involved in complex characterization of materials. Different kinds of material samples are analysed as part of either fundamental research projects or application-relevant case studies. Development of characterization routines is inseparable part of ME team effort as conventional techniques often do not work for our multiphase materials or standard testing conditions are not relevant for intended applications

Pulse Plasma System department

The Pulse Plasma Systems (PPS) department focuses on investigation of a non-equilibrium plasma generated by various types of pulse high-voltage electrical discharges in gases, liquids and gas/liquid interfaces.

The physical and chemical processes intentionally initiated by such discharges are studied under various conditions and different pulsed power in order to achieve specific effects and utilize electrical discharge plasma in different applications (biological, medical and environmental). The main research topics are focused on plasmachemical processes, plasma physics and biocidal effects of atmospheric discharges in gases and liquids; physics and biological effects of focused shock waves produced by electrical discharges in water. The team is highly qualified in design, operation and diagnostics of different high pulse power devices, including investigation of fast transient phenomena, emission spectroscopy diagnostics as well as of detail analysis of plasmachemical products of electrical discharges in gases and liquids, organic compounds and transient chemical products of electrical discharge plasma in water.

The team is equipped with a variety of pulse power supply and analytical instrumentation for generation and diagnostics of electrical discharge plasma in gases and liquids such as high voltage pulse power generators of electrical discharge plasma in gases and liquids with nanosecond to microsecond pulse duration (up to 150 kV, 1-500 Hz, 0.1-5 J/pulse); fast time resolved system of data acquisition and processing, spectrometric systems with gated intensifiers and instrumentation for chemical, physical and biological analysis (HPLC, GC/MS, UV-Vis spectrometry, RT-PCR, etc.).

Plasma Chemical Technologies department

The Department of Plasma Chemical Technologies (PCT) was established in March 2018 and partly succeeded the work of Thermal Plasma (TP) department, which was terminated at the same time. This change was also motivated by the recommendation of the last evaluation panel to focus more on the plasma chemical technologies connected to the waste treatment and to put lower priority on development of the plasma torch itself. Such a change, however, required also a significant change in the team structure and a generation exchange, which included also the new department head. The focus of the new department moved more towards the use of plasma torches for chemical processing applications, namely, plasma-assisted gasification, pyrolysis and destruction of organic and waste materials. At the same time, the new head of the Department of Plasma Chemical Technologies Dr Michal Jeremias, coming from the research areas of waste processing, CO_2 capture, utilization and storage (CCUS), electricity, heat and alternative fuels generation through pyrolysis and gasification technologies, guaranteed a closer inclination to the plasma treatment and plasma chemistry topics.

The PCT team focuses on the following topics: the investigation of physical and chemical processes in several thermal plasma processing technologies for materials, the study of plasma-assisted gasification, pyrolysis and destruction of organic and waste materials, and investigation of generators of thermal plasmas together with diagnostics of electrical discharges producing thermal plasma.

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, wooden pellets, polyethylene, polypropylene, waste plastics, low-quality coal, pyrolytic oil from thermal treatment of waste tires and refuse-derived fuel. The plasma gasification reactor PlasGas with hybrid plasma torch is one of the largest experimental reactors in the world with complete process diagnostics and detailed reaction products analysis. Plasma aided reactions of solid, liquid and gaseous substances with water, carbon dioxide and oxygen are studied.

The new research directions under the newly formed department include plasma-assisted reforming and pyrolysis of methane, natural gas and (waste) plastics to produce so-called blue, amber or green hydrogen (blue hydrogen is produced from fossil fuels while capturing and storing the CO_2 produced, green hydrogen is produced from renewable sources, turquoise (blue-green) hydrogen is made from the splitting of hydrocarbons to produce hydrogen and high-priced carbon structures as a by-product).

Another extensive research is done in a unique reactor, where steam plasma serves as a source of energy and active species for the decomposition of extremely stable fluorinated gases. The main goals of the research are the determination of conditions leading to the production of synthesis gas with a high content of hydrogen and CO and minimum tar presence, and production of the high amount of hydrogen together with high-quality carbon powder.

The experimental research is supported by activities in the field of theory and modelling devoted to the calculation of the composition of reaction products for various materials and oxidizing media, and modelling of the interaction of plasma with treated materials inside the reactor.

Both the experimental and theoretical study of the arc plasma torches and plasma jets is also performed, however, at a lower priority now. We are interested in the processes near the electrodes of the electric arcs, which strongly influence the overall performance and lifetime of the plasma torches. Modelling of the behaviour of the plasma in the arcs together with specific phenomena such as mixing of species in water-argon thermal plasma also belong to the scope of the PCT team.

Research activity and characterisation of the main scientific results

The research activities of the team cover a compact scope of topics in the area of plasma physics, listed above, that are addressed both experimentally and by theory and modelling, both at the COMPASS tokamak, the national infrastructure, and at several fusion research devices abroad, namely tokamaks included within the EUROfusion consortium. Thus, majority of the activities is conducted in a close international collaboration. Furthermore, the Tokamak Dept. team traditionally provides expertise in the development of plasma control and data acquisition systems and the development of diagnostics. The achievements reported bellow include activities where the IPP CAS Tokamak Dept. team had a key role or key contribution without which the results would not be obtained. The individual presented outputs are grouped according to the relevant tokamak physics field.[1]

I. L-H transition and H-mode studies

High confinement mode (H-mode) is the main envisaged scenario for ITER and future thermonuclear reactors. Despite the fact that it has been discovered more than three decades ago, many of its aspect are still evading sufficient level of understanding, which complicates predictions for future machines.

Multimachine scalings of input power required for access to H-mode have been put forward, however, studies on COMPASS and ASDEX Upgrade have demonstrated additional dependence on geometrical factors, which are not included in the scalings.

H-mode is attractive because of its improved confinement, which is manifested by appearance of narrow region in the edge plasma, where turbulence and related transport of particles and energy is strongly reduced. This region features steep gradients of both plasma density and temperature, hence this region is called the pedestal. The height of the pressure pedestal is a key parameter for predictions of fusion power in future machines. While dedicated numerical models have achieved partial predictive capability of the pressure pedestal, they rely heavily on the experimental observations from a number of tokamaks, which help to identify the main underlying physics phenomena driving the pedestal build up.

Transition to high confinement by turbulence suppression

The spontaneous transition to the high confinement mode (H-mode) was extensively studied in the COMPASS tokamak in order to test the leading theories of the underlying suppression of turbulent fluxes. Turbulence suppression mechanisms such as zonal flows and their sub-branch, geodesic acoustic modes (GAM), were extensively studied by means of electrostatic probes as well as magnetic pick-up coils [19] in collaboration with leading experts prof. C. Hidalgo from CIEMAT, Spain and A. Melnikov from Kurchatov Institute and MEPhI, Russia. The observations of GAM behavior under neutral beam injection led to theoretical developments in collaboration with prof. Elfimov and his team from University of Sao Paulo, Brazil [39]. The measurement by ball-pen probes of the Reynolds stress [49] responsible for the generation of such zonal flows motivated by the collaboration with C. Hidalgo led to the initiation of collaboration with prof. George Tynan (Uni of California, USA) on the design of a

[1] Please note that the related publications referred bellow by the numbers use the list of selected publication outputs supplied with the evaluation materials.

new probe head for measurements of potential vorticity (PV) mixing related to zonal flow generation.

The phenomena of limit cycle oscillations between the state of turbulence suppression and high turbulent fluxes which typically accompany the transition to H-mode was studied in the COMPASS tokamak in collaboration with Daniel Refy and Sandor Zoletnik from the Wigner RCP institute in Hungary [65]. Dr. Peter Manz (IPP Garching, Germany) collaborated on the advancement of the first-principles-based theory of the scaling of the limit cycle oscillation frequency; an article comparing this scaling to a multi-machine database is in preparation.

The dependence of the power threshold for the transition to H-mode on the plasma parameters in the scrape-off layer was studied in the scope of the ITPA PEP-39 working group.

The electrostatic code HESEL by the Technical University of Denmark was used for simulating turbulent fluctuations in the edge of the COMPASS tokamak which were then compared to probe measurements and used for scaling studies in the scope of MST1[2].

Related publications: [19], [39], [49], [65]

Pedestal studies

Within the framework of MST1 and JET, cooperation on the topics relevant to edge plasma physics studies was established. Edge plasma research related to plasma performance has direct implications for present day tokamaks as well as for the reactor scale device, which make it relevant and of huge importance. Pedestal studies which help to understand the behaviour of the edge transport barrier, which has major effects on plasma energy confinement, were conducted in collaboration with MST1 devices and the JET tokamak. Results from the COMPASS tokamak contributed to the scalings of the main pedestal parameters performed on leading experimental devices (ASDEX Upgrade, JET, DIII-D) [25]. The impact of pedestal shift between the electron temperature and density pedestal profiles on the stability of the edge transport barrier on JET tokamak was studied in collaboration with IPP CAS [27]. Recently, new cooperation with JET has been established related to the pedestal stability analysis, which has a potential of unravelling key aspects of plasma behaviour crucial for the determination of pedestal structure on reactor scale devices.

Related publications: [25], [27]

II. Physics of tokamak edge and SOL plasma

The properties of plasma in the edge and scrape-off layer (SOL) determine the plasma interaction with components of the first wall and divertor. One of the key challenges for future reactors is to maintain the impacting plasma particle and heat fluxes below the material limits of plasma-facing components, in order to avoid their damage. This is especially challenging in case of Edge Localised Modes (ELMs), quasi-regular instabilities, which accompany the high confinement mode. At high densities in the core, the profile of plasma density in the SOL ceases to have an exponential nature and develops so-calles "shoulder", which can result in undesired increase of particle fluxes to the components of the first wall. However, the conditions required for appearance of this phenomena are not yet sufficiently well understood.

[2] WP MST1 is an acronym for Work Package Medium Sized Tokamaks of the EUROfusion Work Plan

ELM energy fluence and ELM Te measurements

The ELM energy fluence measured by IR camera on the divertor of the JET, ASDEX Upgrade and MAST tokamak were recently published and compared with the model prediction (T. Eich at al.). The experimental data from JET, ASDEX Upgrade, MAST are in a good agreement with the prediction in the scale 1:1 - 3:1. The comparison is obtained mainly for large Type-I ELMs with high ELM energy fluence in the range of 0.1 - 1 MJ/m^2 on JET and ASDEX Upgrade (IR measurements) with ITER-like geometry. Here, the COMPASS tokamak with ITER-like geometry plays an important role because its ELM energy fluence is expected much smaller than for JET or ASDEX Upgrade. We have used the new system of divertor probes to determine the ELM energy density by integration of the parallel heat flux over the single ELM event at different positions on divertor. We have found that the resulting values of ELM energy fluence on the COMPASS divertor are also in a good agreement with the model prediction in a range 1:1 up to 3:1. The results were presented during ITPA meeting and also published in Nuclear Fusion journal. We would like to stress that the experimental data from JET, ASDEX Upgrade are based solely upon conditionally-averaged IR camera measurements, while the COMPASS data are obtained for single ELMs using fast probe measurements of parallel heat flux. These results contribute to the scaling of the peak ELM energy fluence towards the ITER prediction.

Related publications: [14, 26, 46]

Shoulder formation study in SOL

Shoulder formation is a broadening effect of the plasma density profile at the Scrape-Off Layer (SOL) which has an impact on edge filamentary structures and consequently on the particle flux to the first wall. This effect was systematically studied and confirmed on a large tokamak like JET or ASDEX Upgrade and recently on COMPASS tokamak as well. We have performed systematic measurements and a study of the density and electron temperature upstream profiles and its characteristic decay length accompanied by the divertor collisionality values. It was found on ASDEX Upgrade, JET as well as COMPASS that the broadening of the density profile “shoulder formation” is visible only if the value of the normalized divertor collisionality Λ_{div} exceeds 1. The COMPASS measurements confirmed that the shoulder formation is not connected with the size of tokamak and it gives a nice prediction for other new fusion devices like ITER, COMPASS-U.

Related publications: [6], [13]

III. Heat flux and power exhaust

The power handling capabilities of future plasma-facing components (PFCs) depend on the distribution of heat fluxes on their surface. Localized elevated heat fluxes, e.g. due to exposed leading edges of the PFCs can lead to complete destruction of the component. After intensive experimental and modelling effort, it was decided that PFCs in ITER will adopt shaping to hide such leading edges. The COMPASS team played an important role in this process.

Should the tungsten PFC be heated close to melting temperatures, an intensive thermionic emission arises, which drives equally large replacement current in the molten layer on top of the PFC. This current is responsible for motion of the liquid via jxB force. The magnitude and orientation of the current then determines whether the liquid is pushed outside the zone of elevated heat flux which might lead to bridging of the individual PFCs etc. Experiments with melting of deliberately misaligned PFCs and related modelling are currently one of the literally hot topics in tokamak research.

One of the perspective ways to reduce high impacting heat loads in future reactors is the regime of so-called detachment, where a majority of energy carried by plasma particles is converted into radiation. This is achieved by injection of impurities in the divertor region. The amount of impurities needed to achieve this regime as well as undesired consequences on plasma confinement are currently an area of intensive research in the fusion community. The material limits of the ITER's plasma-facing components are rather strict and the predictions toward DEMO are even less favourable, the search for alternative solutions is ongoing. A promising way is the use of liquid metal PFCs which would not suffer from melt damage and erosion. However, their compatibility with plasma operation in the desired regimes is yet to be fully demonstrated.

Detachment studies

Studies of detachment at COMPASS were effectuated as a complementary research within EUROfusion MST1 High Level Topic 18 (2017-18) and later within HLT14 (2019-2020). The objective of these experiments was to achieve partial detachment, which is relevant for ITER and future thermonuclear reactors, and to study the heat flux footprint at the divertor targets. This regime was achieved by injection of impurities into plasma – nitrogen, neon and argon. A second series of experiments was focused on the development of a real-time system for heat flux control, using nitrogen injection as actuator and combined array of Ball-pen and Langmuir probes as a sensor. In these experiments, it was demonstrated that this system can significantly reduce the heat fluxes (up to factor 4). These activities were carried out in close contact with activities at tokamaks ASDEX Upgrade (Germany) and TCV (Switzerland). M. Komm is the scientific-coordinator of the relevant MST1 topic.

Related publications: [24], [26]

Thermionic current modelling (cooperation within WP PFC[3])

The objective of this activity was to simulate the thermionic emission from hot tungsten surfaces in tokamak-relevant plasma conditions. The most important outcome of these simulations was the magnitude of the escaping thermionic current released into the plasma. This current drives a replacement current in the plasma-facing component and subsequently causes a motion of molten tungsten liquid layer due to jxB force. As such, our modelling

[3] WP PFC is an acronym for Work Package Plasma Facing Components of the EUROfusion Work Plan

provided an important input to the modelling of the molten layer motion done by MEMOS code (performed at KTH Stockholm). Altogether, this modelling aimed at reproduction of experimental observations obtained in dedicated experiments with misaligned tungsten lamellas in tokamaks JET and ASDEX Upgrade. This goal was successfully achieved.

Related publications: [42], [57] and

Thorén E., et al.: MEMOS 3D modelling of ELM-induced transient melt damage on an inclined tungsten surface in the ASDEX Upgrade outer divertor. Nuclear Materials and Energy 17 [December] (2018) 194-199.

Krieger K., et al.: Investigation of transient melting of tungsten by ELMs in ASDEX Upgrade. Scripta. T170 [December] (2017) 014030.

Modelling of rough surfaces & sputtering (cooperation within WP PFC)

Rough surfaces and sputtering represent a relatively new activity, which was developed in 2019. The objective was to simulate plasma interaction with non-planar surfaces, in order to mimic the realistic conditions in tokamak plasma-facing components. Since the surface morphology of real PFCs is typically rather complex, with a number of different spatial scales combined together, we started with a simple approximation of sinusoidal "wavy" surface. For the first time, 3D3V particle-in-cell simulations were employed to handle such a problem. The aim of the study was to characterize the profile of electric potential in the vicinity of such surface, so that it could be used in ERO code (used at FZ Juelich, Germany) to simulate sputtering from such a surface. First batch of simulations was completed but the integration within ERO is not yet functional.

Related publications:

A. Eksaeva et al. Surface roughness effect on Mo physical sputtering and re-deposition in the linear plasma device PSI-2 predicted by ERO2.0. Nuclear Materials and Energy 19 [May] (2019) 13-18.

Modelling of power deposition profiles on divertor monoblocks in ITER

The objective of this activity was to provide predictive modelling of the spatial distribution of heat fluxes on the surfaces of divertor monoblocks in ITER. 2D3V particle-in-cell simulations were employed to achieve realistic profiles, which include the effect of the sheath electric field. The results were then compared to a much simpler ion orbit model, which did not include such E fields. It was verified that the E fields do not play a significant role in most studied cases, so the ion orbit code could be used for a much broader study. This work was effectuated within a contract with ITER Organisation.

Related publications: [12], [18]

Scaling of L-mode heat flux for ITER and COMPASS-U divertors

This research follows up the 2016 experimental paper [47] (and its theoretical interpretation [Halpern et al.]) where we empirically scaled and predicted heat fluxes in low-power limiter plasmas. Similarly, here we performed 550 experiments in Low confinement mode divertor plasmas on five tokamaks and collected a consistent database in which we searched for multi-parameter dependencies (physics understanding of which is an open task). This yielded predictions of extreme heat loads in future tokamaks ITER (10 MW/m^2) and COMPASS Upgrade (20 MW/m^2), implying challenging requirements on their divertor heat shields even in low power L-mode plasmas.

Related publications: [47] and

Halpern, et al. Plas. Phys Contr. Fus. 58 084003, 2016

COMPASS team activities under WP PFC on WEST tokamak

Within the period 2016-2019, we were involved in the scientific exploitation of the WEST tokamak (CEA, France) under the EUROfusion Work Package Plasma Facing Components. Numerical predictions of power deposition in WEST divertor tiles using in-house particle-in-cell simulations were first performed (2016-2018), followed by a strong active participation in all WEST experimental C3 & C4 campaigns with subsequent data analysis (2018-2019). This includes the scientific coordination of one particular out of five WP PFC WEST experiment in C3 by one of our staff member (2018-2019), successful tests of the Langmuir probes which were designed, constructed and delivered in-kind to the WEST team by our department, the supervision of all the C4 campaigns experiments (4) by our colleague promoted to WP PFC sub-project leader for WEST experiments, a presentation on WEST highlight at the 2019 WP PFC annual meeting and co-authoring several scientific publications and abstracts for participation in future international conferences.

Liquid metal divertor module tests on COMPASS

Power exhaust experiments with a liquid metal divertor module based on the capillary porous system (CPS) technology were performed in the tokamak COMPASS. The power handling performances of two metals (Li and LiSn alloy) were tested for the first time under ELMy H-mode conditions in a tokamak divertor. No damage of the CPS mesh and good exhaust capability were observed for both metals in two separate experiments up to 12 MW/m^2 of deposited perpendicular heat flux and local peak energy fluence at the module ~15 kJ.m^{-2}. No droplets were ejected from the CPS surface, no contamination of the core and SOL plasmas by Sn was observed.

Modelling of power deposition profiles on misaligned lamellas for tungsten melting experiments on JET & ASDEX Upgrade

The objective of this activity was to simulate plasma interaction with shaped plasma-facing components in tokamaks in order to obtain a spatial distribution of the impacting heat fluxes. These were mainly influenced by ion gyration, since the spatial scale of the gaps between lamellas and their misalignments was comparable to the ion Larmor radius. The distribution of heat fluxes was then compared with IR measurements in tokamaks JET and ASDEX Upgrade, where dedicated experiments with misaligned lamellas were performed (with the aim of achieving melting of tungsten). The ultimate goal was to verify which physics processes are governing the heat flux distribution. Surprisingly, it turned out that the sheath electric fields in the vicinity of the surfaces play only a minor role in this process.

Related publications: [5], [9], [20]

IV. Tokamak core plasma

The core plasma has been in a spotlight of fusion research since its dawn. Many of the important problems of plasma confinement and transport have been resolved, however, new experimental findings and issues bring new challenges also in this field. One of them is the phenomenon of the internal transport barrier, which can greatly improve the density in the plasma center and thus increase the fusion power. This regime has been observed on some tokamaks, however, the understanding of conditions required for its access are still far from being fully understood.

Another issue related to core plasma is the interaction with intrinsic or deliberately introduced error fields. The objective of the later is to partially relax the gradients in the pedestal region and prevent ELM crashes, which represent a substantial danger for the plasma facing components of future reactors. Mitigation and suppression of ELMs has been studied on a number of tokamaks with mixed success – which means that ELM mitigation and suppression without compromising the plasma confinement remains an important topic for ITER.

Optimization of q profile in ramp-up in hybrid scenarios, Confinement time analysis, MHD analysis

The hybrid tokamak scenario is so far the one that delivers the best performance and is thus an attractive mode of operation for ITER. JET (Joint European Torus) upcoming D-T operation[4] hybrid scenarios can be modelled by the fast integrated code METIS [1]. METIS combines scaling laws, e.g. for global and pedestal energy or density peaking, with simplified transport and source models, whilst retaining a very accurate 1D representation of the current sources and diffusion. METIS can be tuned to match JET-ILW high performance experiments, including baseline and hybrid.

By adjusting the dependencies of the scaling laws (eg. the dependence on W sources on input power) we manage to reproduce an entire JET pulse (simultaneous evolution of

temperatures, densities, radiated power and stored energy). Our approach can guide experiment development by providing trends in predictions in a wide range of conditions. The investigation focuses on the possible shaping of the safety factor profile during the ramp-up phase of hybrid discharges.

We are able to reproduce precisely the hybrid pulses of the previous JET Deuterium campaign and derive them into a family of simulations by varying parameters in a small range around the experimental data. In particular, this allows us to explore a complete range of shapes of safety factor profiles by adjusting the timing of the heating, current and density ramp-up.

In our approach, care is given to the stationarity of the safety factor profile and the possibility to reproduce Deuterium performances in D-T experiments. The experimental MHD stability (eg. NTMs, fishbones) of the pulses is considered.

Related publications:

F. Jaulmes, et al. presentation at 2018 EU-US TTFM

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[4] experiments with the deuterium – tritium mixture as the working gas

Interaction of plasma with 3D magnetic perturbations

Interaction of plasma with 3D magnetic perturbations (MPs, foreseen as one of the methods to control ELM instabilities at ITER), was studied in collaboration with leading experts. With dr. Yueqiang Liu from the CCFE in the UK, the electromagnetic response of plasma to MPs was modelled by MARS-F code and compared to its direct experimental measurements by the rich magnetic diagnostic system at COMPASS [33]. The dynamics of ELMs [41, 60], the divertor heat fluxes consequent to the application of MPs on ITER [31], and the plasma response to MPs in ASDEX Upgrade [54] were simulated in a broad international team of developers and users of the non-linear MHD code JOREK and the fluid and kinetic neutral transport code EMC3-EIRENE.

Error fields due to MPs were also studied as a potential trigger of disruptions through locking of magnetic islands. The experiments in COMPASS have directly contributed to the multi-machine scalings (and the ITPA database) of the critical MP amplitude and predictions for ITER, in collaboration with P. de Vries from the ITER Organization [29] and with dr. Park and dr. Logan from PPPL. Extensive studies of the n=1 MPs generated at the HFS by the unique set coils at COMPASS were conducted as high-priority experiments in close collaboration with dr. Alberto Loarte and dr. Yuri Gribov from ITER. The results contributed significantly to an internal memorandum to the ITER management regarding the applicability of Top and Bottom Error field correction coils.

Related publications: [19], [29], [31], [33], [39], [41], [49], [54], [60], [65]

V. Runaway electrons

Runaway electrons (RE) present one of the major concerns for future fusion devices, ITER and beyond, since the uncontrolled localized RE losses can compromise the integrity of tokamak device and its further operation. Runaway electrons can emerge within a tokamak plasma either at low density, during the discharge start-up phase or as a result of rapid plasma termination, associated with sudden cooling causing a significant electric field induction. A strong and motivated team focused on runaway electron studies grew within the Tokamak Dept. during the reported period. The team activities cover intense experimental work on COMPASS as well as on other European tokamaks that is supported by detailed modelling.

Thanks to the cooperation between IPP Garching (Germany) and IPP CAS, it was possible to arrange long term loan of the room temperature solid-state pellet injector that is a key device in the investigation of runaway electron radiation and interaction with solid materials within a framework of Czech Science foundation project GA18-02482S.

COMPASS team members are heavily involved in JET (Joint European Torus - UK) runaway electron experiments program in terms of diagnostics coordination and analysis of experimental data. Some of the data were published in overview papers [56,62] and more publications are currently under preparation. IPP CAS physicists also actively participate in the EUROfusion MST1 (Medium Size Tokamaks) research activity dedicated to runaway electron studies, where COMPASS tokamak belongs to complementary MST1 devices since 2014. Under this activity, ten experimental campaigns targeting several runaway electrons related topics were held with the presence of groups of international experts. At present, one of the IPP CAS scientists is involved in the coordination of the scientific programme across all European MST1 machines since 2016.

Regarding runaway electron beam control, there is an ongoing cooperation and exchange of ideas with the team from University of Rome Tor Vergata that is by far the most successful in pursuing runaway control on European devices, to which this cooperation has also partly contributed [22,44].

Within the International Tokamak Physics Activity (international coordination of fusion research in support for ITER), multiple collaborations were initiated in 2019, ranging from diagnostics to interaction of runaway electrons and instabilities and also the generation of runaway electrons during the discharge initiation.

The colleagues from NCBJ Swierk (PL) that developed a detector of runaway electrons based on Cherenkov radiation regularly participate in the COMPASS experiments and the detector is a very useful tool for analysis of lost runaway electrons.

Numerical simulations and modelling collaborations with Chalmers University (Sweden), IPP Garching (Germany), CEA (France), EPFL (Switzerland) and Budapest University of Technology and Economics (Hungary) within the E-TASC (EUROfusion task - Theory and Advanced Simulation Coordination) modelling project become more intense thanks to a joint project that started in May 2019.

Via the collaboration with FNSPE CTU detector group, we are also in touch with the modern pixel particle detector developers that are closely connected to CERN and other particle physics laboratories.

Related publications: [22], [44], [56], [62], and

Carnevale D. et al., Runaway electron beam control. *Plasma Physics and Controlled Fusion*. 61, 1 (2019), 014036. ISSN 0741-3335

VI. Disruption studies

Understanding of abrupt terminations of plasma discharge, called disruptions, plays an important role in the design of future fusion devices as they induce large thermal and electromagnetic loads on vacuum vessel (VV) and might compromise the structural integrity of tokamak. Intolerable thermal loads might be mitigated by shattered pellet injection (SPI). Assessment of electromagnetic loads strongly depends on understanding of the vessel current distribution within VV structure during disruptions. The COMPASS size allows non-destructive operation without disruption avoidance or mitigation techniques which enables unique dedicated disruption experiments. Moreover, COMPASS is equipped with an extensive set of magnetic diagnostics and provides a unique opportunity to study vessel currents distribution in poloidal and toroidal direction as well as plasma current asymmetries.

Vertical Displacement Events experiments

Intentionally induced vertical displacement events (VDEs), i.e. disruptions caused by uncontrolled vertical movement of the plasma column were studied experimentally in detail on COMPASS. On request of the ITER Organization, two special divertor tiles have been installed on COMPASS in order to directly measure the current flows during VDEs. The aim of the experiment is to better understand current pattern distribution within the vessel structure and the divertor and to test the model of asymmetric toroidal eddy currents (ATEC). It is suggested that Halo current is limited by ion saturation current.

Studies of sideways forces during plasma disruptions on COMPASS tokamak

One of the critical issues for ITER is the sideways forces on its vacuum vessel during disruption. Current predictions of the sideways force for ITER vary by a factor of 50 with the upper estimate (80 MN) well above the design value (48 MN). These studies contribute to the Joint Experiment (JEX) ITPA MDC-25 "Sources and Scalings of Nonaxisymmetric Sideways Disruption Forces for ITER", which is led by IPP CAS and conducted under the umbrella of ITER. Other institutions participating in the JEX include General Atomics (USA), QST (Japan), IPP Garching (Germany), EPFL (Switzerland), CCFE (UK), Consorzio CREATE (Italy).

SPI experiments (JET)

Shattered pellet injection is a method used to mitigate disruption loads. A Shattered Pellet Injector (SPI) has been installed on the JET tokamak and SPI impact on current quench time has been studied. Its dependence on Ne fraction in D_2+Ne discharges has been revealed while no dependence on pre-disruptive current has been found. A decrease of forces acting on the vessel and lower magnitudes of plasma current asymmetry have been observed compared to unmitigated disruption. This effect is comparable to Massive Gas Injection (MGI) mitigation.

Studies of electromagnetic loads during plasma disruptions for COMPASS-U tokamak

The COMPASS-U tokamak will operate at high magnetic field (up to 5 T) and high plasma current (up to 2 MA), therefore, strong electromagnetic loads on its vacuum vessel and plasma facing components are expected during disruptions. Modelling studies are being conducted in collaboration with Consorzio CREATE (Naples, Italy) in order to address the disruption induced forces in the COMPASS-U tokamak. CREATE provided a number of codes (CREATE-L, CARIDDI, CarMa0NL) and related training and support. The modelling is done by the Tokamak Dept. team.

<u>Related publications:</u>

V. V. Yanovskiy, et al. Comparison of approaches to the electromagnetic analysis of COMPASS-U vacuum vessel during fast transients. *Fusion Engineering and Design* 146 (2019): 2338-2342.

N. Isernia, et al. Cross-validation of analytical models for computation of disruption forces in tokamaks. *Plasma Physics and Controlled Fusion*, *61*(11), (2019), 115003.

VII. Diagnostics development for future fusion devices

Future fusion devices, like ITER and DEMO, set new demands on the diagnostics systems. This is given namely by the presence of high heat and neutron loads as well as by the request of a reliable and long lasting operation. Therefore, a world-wide strong effort is dedicated to development of new diagnostic systems. Within our team, the development of Hall sensors and the design of Thomson scattering diagnostics are addressed.

Hall sensors and DEMO relevant research

Research in the area of development of non-inductive types of magnetic sensors for fusion reactors is one of the strategic priorities of the Tokamak department of IPP CAS since the beginning of this century. Systematic long term R&D [17] and encouraging results of study of properties of in-house developed Hall detectors based on bismuth sensitive layer [52] resulted in interest of ITER International Organization (IO) to apply these sensors on ITER reactor as a set of 60 Outer Vessel Steady State (OVSS) magnetic sensor units. These sensors will provide key information on plasma position and shape and will be one of the critical diagnostic systems for ITER operation. Memorandum of Understanding (LGA ref. 2015-M-8) between ITER IO and IPP on Technical and Scientific Cooperation was signed early in 2015. Two months later, Collaborative Service Contract ITER/CT/15/4300001165 on the collaboration on the development and fabrication and commissioning of the tangential (PBS 55.A5) and normal (PBS 55.A6) ex-vessel steady-state magnetic sensors for ITER was signed between ITER IO and IPP CAS. Scope of the activities of IPP CAS within this contract for the period of 2015 – 2024 (according to the latest amendment) included all key development, validation, testing and manufacturing activities necessary for the delivery of the OVSS diagnostic complex to ITER. First stage of the project was concluded by the Final Design Review meeting in December 2016. Since 2017, manufacturing stage of the contract was lunched where IPP CAS is managing a set of international subcontracts with industrial partners for delivery of various components and services associated with the deployment of OVSS diagnostic on ITER. Installation of the sensors on ITER is envisaged in 2021. In parallel, IPP CAS was actively pursuing basic R&D in this area by exploring new materials and technology concepts of Hall sensors usable even in the more demanding environment of the future demonstration fusion energy reactor DEMO within the EUROfusion Work Package Diagnostics and Control (WPDC) since 2015 [4].

Related publications: [4], [17], [52]

Collaboration on Design of the ITER Core Thomson scattering Diagnostic

The team of our diagnosticians was involved in an ITER Organization contract on designing the "core plasma Thomson scattering" (CPTS) diagnostic system for the ITER tokamak. The COMPASS team participated in the preparations of the Conceptual Design Review and supported definition of specifications of the CPTS system for the Procurement Arrangement between ITER IO as a customer and F4E as a supplier. The team was deeply involved in definition of all requirements on the CPTS systems and its interfaces with other systems. In the design, the Tokamak team contributed with its expertise, especially in fibre bundle arrangement and laser beam path design, but also in other issues, based on the experience with Thomson scattering diagnostic development and operation on COMPASS.

Related publications:

R. Scannell, et al. Design advances of the Core Plasma Thomson Scattering diagnostic for ITER. *Journal of Instrumentation* **12** November (2017) C11010.

P. Bílková, et al. Scaling Thomson scattering to big machines. *Journal of Instrumentation* **11** 3 (2016) C03023.

Research activity and characterisation of the main scientific results

Laser plasma department focuses on the research of the interaction of high-power laser radiation with matter, both experimental and theoretical, by means of numerical simulations. The Department operates a large research infrastructure PALS (Prague Asterix Laser System) which is a part of the joint laboratory of IPP and the Institute of Physics, CAS, "Research Centre PALS", where the experimental part of the department research is performed. Furthermore, as PALS is an open access facility, the scientific and technical staff provides a full scientific, technical and logistic support to the users' experimental projects conducted at the PALS facility in the frame of open access. Since 2018, the department is undergoing a transformation from a solely user-service providing department to a scientific department with its own research programme, the main research topics being the inertial confinement fusion, laser-driven plasma-wave-based particle accelerators, and the application of laser and XUV pulses in non-Hermitian quantum physics; the third topic is both theoretical and experimental. However, during the evaluated period, the research agenda of LPD was mostly driven by the open-access-user research projects. Therefore, the scope of research in which the department members were involved was quite broad and included research on inertial confinement fusion, high energy chemistry (astrochemistry), proton-boron (beam-target) fusion, electromagnetic pulse generation, etc. Within the following activity review, we will report mainly on the research conducted in collaboration with external (international and national) users.

INERTIAL CONFINEMENT FUSION (SHOCK IGNITION SCHEME)

Shock ignition scheme belongs to the most promising candidate for the inertial fusion ignition. The group is involved into this research mainly via external user´s access to PALS Research Infrastructure in the frame of Laserlab or Eurofusion projects (ILIL INO, Pisa, Italy, IPPLM, Warsaw, Poland, HZDR, Dresden, Germany, CELIA, Bordeaux, France, Sorbonne University, Paris, France, York University, York, UK) and in collaboration with Institute of Physics and Czech Technical University – Faculty of Nuclear Sciences and Physical Engineering.

Generation of hot electrons represents one of the most important issues in the shock ignition scheme. Hot electrons have, in fact, a double role in the shock ignition. If their energies are higher than approximately 100 keV, they can preheat the fuel, making its compression more difficult. On the other hand, if they have energies below 100 keV, they are unable to penetrate deeper into the target; in this case, they may increase the shock pressure and help to the compression. Due to this fact,the hot electrons have to be very accurately characterized. This was done via highly spatially and spectrally resolved X-ray emission of the interaction region of PALS laser pulse with a target, this region was imaged by a quartz crystal on the CCD detector. Moreover, it was also observed that there is a significant delay (200 ps) between the laser pulse peak and the peak of suprathermal electron yield [1].

Another experiment performed at PALS at 1315 nm (1ω) and 438 nm (3ω) showed an increase of hot electron generation rate and a decrease of the role of collisional absorption. Significant laser absorption is caused by parametric instabilities which are responsible for hot electron generation. It was observed that the pressure increase was larger than 250 % for 1ω frequency with a co-action of hot electron compared to 40 % when 3ω was used. This experiment showed that pre-plasma strongly degrades the plasma scale length which leads to decreasing the fast electron energy contribution to shock pressure [2, 3]. In the absence of long pre-plasma, the increase in the laser energy leads to significant generation of fast electrons by resonance mechanism [4]. However, for 3ω, the experiment indicated that the laser energy conversion into the energy of fast electrons is very small – the fraction of fast electron energy did not exceed a few tenths of a percent of laser energy both in the absence and in the presence of pre-plasma [5].

Other series of experiments performed at PALS was focused directly on the study of parametric instabilities. It was observed that Stimulated Brillouin Scattering (SBS) is more effective in degradation of laser-plasma coupling than Stimulated Raman Scattering (SRS), reducing the energy available for the generation of shock wave. SBS causes a laser reflection at the level of 3 – 15 % of the incident laser energy; whereas the backward SRS up to 0.2 % (according to the plasma scale length). SRS is mainly driven by beam speckles with high local intensity. These experiments also indicated that hot electrons are predominantly produced by SRS or Two plasmon decay (TPD) [6,7,8,9].

Successful demonstration of inertial confinement fusion requires a very high degree of uniformity of laser irradiation. Several smoothing techniques, which were applied during last decades, have dramatically improved our control on laser implosions and laser-plasma interactions. However, an issue of nonuniformity at very early times being called laser-imprint problem was not solved up to now; such a nonuniform laser beam profile may affect the compression uniformity at later times and in particular influence the development of the Rayleigh-Taylor instability. Due to the importance of this issue, several experiments performed at PALS used the low-density foams, considered as promising candidates for the beam smoothing, in order to study their influence on the laser-plasma interaction. A foam layer on the front-side of aluminum target was used; moreover, the double focal spot was used to simulate large, high-power laser beam nonuniformities. It was observed that the collision between two shocks originated from each of two spots occured. This indicated that the presence of the foam does not necessarily smooth out the large scale nonuniformities, but it may induce a higher local pressure being deleterious for ICF as well. In this experiment a prism laser beam splitter was used for generation of two foci (30 – 100 μm in diameter and separation of 100 – 200 μm. For the study of their influence, there were used two kinds of targets: simple aluminum foil as a reference (10 μm in thickness) and double-layer target – 50 μm thick foam on 10 μm thick aluminum [10].

All the experiments mentioned above used a random phase plate (RPP) inserted into the laser beam path to reach a certain level of the laser beam smoothing. However, the effects of laser beam nonuniformities – speckles – can be enhanced when the RPP is not used, i.e. when the laser is focused into a tight focus. The nonlinear interaction of the laser pulse peak with a preplasma can be easily studied at PALS due to temporal profile of the PALS laser pulse (having a low contrast). When the laser beam is focused it can reach an intensity of 10^9 W/cm^2 about 2 ns before the arrival of the peak intensity. Several performed experiments revealed that observed values of maximum ion energy and hot electron temperatures do not correlated with any of laser-produced plasma models. Such phenomena can be a result of occurrence of various non-linear phenomena as the self-focusing of the laser beam causing the local increase in the laser intensity. Furthermore, the plasma-generated ion current fluctuations also indicated that the instability associated with non-linear laser-plasma interaction occurred [11]. Non-linear interaction of laser beam with the plasma can also lead to formation of multi-temperature plasma and emission of ion bursts. This may be also accompanied by SRS powered in beam speckles. When used deuterated polyethylene targets, the produced plasma generated proton beams with energies up to 4.5 MeV (for PALS laser intensity according to various scaling laws, the energy shall be as low as 1 MeV). This difference can be caused by self-focusing of the laser beam causing the increase in laser intensity. Furthermore, the nonlinear nature of the interaction (e.g. speckle self-focusing) was indicated also by observation that deuterons were accelerated up to 3 MeV, which is enough to initiate DD fusion reaction [12]. The observed values of maximum proton energies and electron temperatures suggest that the laser intensity is reaching the relativistic intensity level through the laser beam self-focusing. The ponderomotive self-focusing of the most intense speckles with intensity above 2 – 3 x 10^{16} W/cm^2 can be also responsible for these effects; it has been expected to occur at plasma densities relevant for SRS and TPS processes. Under such conditions, the produced hot electrons can penetrate the target foil and create at the rear surface a hot plasma. Maximum energy of forward accelerated protons reached value of about 5 MeV also backward accelerated protons reached energies up to 5 MeV. Electron energies reaching 2 – 3 MeV with cut-off energy of 5 MeV were also observed. From deuterated polyethylene, there were observed backward accelerated deuterons with energies up to 2 MeV [12].

In the compression phase of inertial confinement fusion, the composition of the outer fuel pellet layer – the ablator – plays also the important role for successful generation of strong shock wave. Ablative plasma energy transfer into a massive aluminum target, using different atomic number ablators (Z = 3.5 – 73: CH, Mg, Cu, Ag, Ta), was studied at PALS being operated at 438nm wavelength and energy = 130 J. The efficiency of the plasma energy transport to the target was determined via crater volume measurement. During this experiment, there was found that the growth of the thermal emission with increasing atomic number of the ablator leads to a decrease of the ablative plasma pressure. The ablator thickness was chosen in the way to be completely evaporated by laser pulse: CH – 0.5 µm, Mg – 0.3 µm, Cu – 0.21 µm, Ag – 0.17 µm, and Ta – 0.1 µm. The crater is formed as a result of phase transformation (melting and evaporation) of the target material behind the shock wave front. The duration of the PALS pulse is considerably (100 – 200 x) shorter than the decay time of the crater producing shock wave. Therefore, the crater volume is determined with a high accuracy by the energy transferred to the material behind the shock wave front during the laser pulse [13].

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ELECTROMAGNETIC PULSES

Besides energetic charged particles (electrons, protons, ions), X-rays, a laser generated plasma is also source of strong electromagnetic pulses (EMP) with frequencies up to GHz range. Such strong electromagnetic pulses can malfunction, damage or even destroy electronic devices used as detectors for plasma diagnostics; the research of EMP radiation shielding, the novel ways of directions in electronic device protection or electromagnetic compatibility. The research of the EMP generation is also held in collaboration with PALS international users (mainly within the frame of Laserlab and Eurofusion projects) and Czech Technical University (Faculty of Electrical Engineering) and Institute of Physics (including ELI Beamlines department).

During various experiments at PALS, it was observed that for short pulse laser-matter interactions the main contribution to EMP should be associated with discharge currents flowing through the target holder and for long pulse lasers (duration of hundreds of ps), such an EMP contribution should be strongly inhibited. However, at PALS, it was observed that discharge current is also observed for laser pulses with a duration of 350 ps [1,2]. Duration of return (neutralizing) target current and EMP is much longer than the duration of laser-target interaction. During experiments it was observed that laser energy affects the low frequency spectrum 0 – 600 MHz of target current pulse. The higher the laser energy, the higher the spectral intensity. The frequency spectrum of the target current is influenced by the geometry of the interaction chamber as well as of the target holder and target (having characteristic resonant eigenfrequencies). It was found that eigenfrequency of the target chamber at PALS corresponds to about 260 MHz (in agreement with Comsol 3D EM simulations). Target holder, acting as an antenna, emits frequency about 850 MHz or 1,5 GHz [3]. The total number of electrons needed to neutralize the target (measured using the inductive target probe mounted in the target holder) within the first ten nanoseconds after the interaction with the laser reaches a value of 10^{14} electrons [2].

Experiments focused on the plasma evolution (studied by the femtosecond interferometry or by the gated four-frame soft X-ray camera) proved that the duration of active post-plasma on the target can reach tens of nanosecond [3]. Both the duration and spatial distribution of the plasma interacting with the target has an impact on the EMP emission by the target holder including its directionality. The EMP was observed by means of a horn antenna having a detection bandwidth of 0.8 – 18 GHz; whereas the emitted EMP was limited up to 3 – 4 GHz. These frequencies include the resonant frequencies of equipment being bombarded by hot electrons which are neutralized. As the laser generated plasma expands into the interaction chamber, dimensions of the expanding plasma after a certain period become comparable to EMP wavelengths being in a range of 0.1 – 3 m. Within this period, the expanding plasma fills the interaction chamber and affects the EMP because the space-variable plasma frequencies match the EMP frequency bandwidth. Thus, the plasma causes strong distortion of the transient EMP inside the chamber through the reflection, absorption and transmission of EMP. The time-resolved analysis of antenna signals observed within the interaction chamber indicated that the direct transmission of EMP into the entire cavity of the interaction chamber is disrupted by the expanding plasma [3].

Experiment with laser pulse-solid hydrogen ribbon interaction (in collaboration with ELI Beamlines and Low Temperature Laboratory of CEA in Grenoble) 62 μm in thickness and 1 mm in width, showed, in comparison with grounded solid target (polyethylene), the shorter plasma active phase (2 ns of plasma expansion); the energy carried by EMP was also significantly lower in this case. It was found that the solid hydrogen exhibited a rise time of 1.7 ns and a duration of 17 ns, whereas polyethylene had a rise time of 21 ns and duration 115 ns [4].

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STRONG MAGNETIC FIELD GENERATION

Strong magnetic fields play an important role both in astrophysics and inertial confinement fusion where they may influence the hot electron transport. Our group collaborate on this topic (mainly as user-based activity in the frame of infrastructure open access) with Institute of Plasma Physics and Laser Microfusion (IPPLM) in Warsaw (Poland). The spontaneously generated strong magnetic fields generated by PALS laser are studied by means of complex polaro-interferogram (2-frame interferometer in the setup in which one arm serves for the study of magnetic field and the second arm to study plasma density at the same time), developed in collaboration with IPPLM, relating on probe laser polarization rotation by Faraday effect. The generated magnetic fields may reach up to 1kT field strength. It was observed that the magnetic field strength increases with target material atomic number; in later phases of plasma expansion in particular for heavier targets there was observed on-axis double maximum magnetic field [1]. Furthermore, experiments showed that fast electrons are of crucial importance for the formation of strong magnetic fields; plasma magnetization results from the kinetic processes related to fast electrons in the plasma corona. Such a kinetic magnetization is quite effective in the examined parameter range. The generated magnetic field is of about one order of magnitude higher than by the Biermann battery mechanism (effect of action of crossed density gradient and temperature gradient) [2]. Capacitor coil targets represent the other option for magnetic field generation. In this case, the maximal magnetic field strength, approximately 315 T, was reached in the time 170 ps after the laser pulse peak. (In this measurement, the probe beam passed through a single loop equipped by TGG crystal (having large Verdet constant: 60 rad T^{-1} m^{-1}) [3]. The third option, which was tested at PALS, for strong magnetic field generation used ”snail-shaped“ targets. In this case, the magnetic field is generated by surface electric current and return currents induced by grazing incidence (and multiple reflections) of laser pulse. The maximal magnetic field of about 40 T was observed at time 368 ps after the laser pulse peak [4].

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LABORATORY ASTROCHEMISTRY

In collaboration with Jaroslav Heyrovsky Institute of Physical Chemistry and Institute of Biophysics, the research is focused on the study of generation of prebiotic molecules from primordial chemical components. Within these experiments, PALS laser usually with energy 100 J or 150 J is focused into a 15-liter gas cell (filled by specific gas mixtures). By means of laser induced dielectric breakdown (LIBD), the plasma (representing the lightning, meteorite or comet impact) or few centimeter-size fireball is generated; under these conditions, the delivered energy triggers the chemical reactions. One experiment dealt with a gas mixture CH_4+N_2+H_2O, such an atmosphere is expected in early Titan or Earth. Within this experiment, several intermediate compounds formed during the various stages of the LIDB plasma chemical evolution were investigated, using optical emission spectroscopy (OES) with temporal resolution [1]. For the detailed role of water, the deuterated water (D_2O) in a gas mixture was also used to separate several of the produced isotopomers of acetylene, which were then quantified using the Fourier Transform Infrared Spectroscopy (FTIR) technique. The FTIR showed a significant increase in the intensity of acetylene isotopomers C_2H_2, C_2HD, C_2D_2 and HCN (although no DCN isotopomer, which was not found in the mixture), as well as HDO, H_2O, CH_4, CO and CO_2. Other experiment was focused on the role of formaldehyde in the prebiotic molecules´ formation. Nowadays, formamide and hydrogen cyanide are generally considered as key molecules in prebiotic synthesis; they were also detected in interstellar and interplanetary regions. Other molecules as formaldehyde are far more abundant in the space; several studies indicated that formaldehyde may play the role of important intermediate in prebiotic synthesis. The experiment performer at PALS used a HCHO $+N_2$ mixture. It was found that glycine and sugar ribose were detected as products of chemical reactions triggered by laser generated plasma [2]. Theoretical calculations also showed that prebiotic relevant species (as e.g. formamide) can be alternatively created by shock synthesis due to dust-grain-grain collisions in interstellar or circumstellar regions. Formamide can be created by mutually collisions of isocyanic acid (HNCO) containing icy grains [3]. Furthermore, the glycine can be also generated after the shock compression. Moreover, the research is further focused, in the context of observation features obtained by future ESA probe ARIEL dedicated to exploration of exoplanet atmospheres and asteroid impacts into their atmosphere, on exploration of meteor spectral features observed in Earth atmosphere. PALS laser system was used, in this case, as a terawatt driver of LIBS (laser-induced breakdown spectroscopy) method to acquire the spectra of the real meteorites in order to obtain the meteorite mineral composition; the comparison with a conventional methods for composition analysis and the sky-overview meteor spectrum camera was performed [4].

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SOFT X-RAY RADIATION INTERACTION WITH MATTER

The interaction of intensive femtosecond XUV and X-ray radiation from free-electron lasers (FEL) with various material was also (main contribution of the IPP group members represents numerical studies) studied. The interaction of XUV radiation with ruthenium thin films was studied. Ruthenium is considered as a perspective material to be used for XUV mirrors at FELs. Its interaction with ultrafast XUV laser radiation is still not well understand. The single-shot damage studies of ruthenium thin films revealed that the weakest point for its damage is the surface roughening [1]. The damage formation is mostly affected by ultrafast heating of the lattice by hot electrons; it is not very sensitive to the initial stage of material excitation [2]. X-ray mirrors usually have overcoating made from B_4C layer. The X-ray induced damages of B_4C coated bilayer materials under various irradiation geometries (experiments were performed at FEL SACLA) for 10 keV linearly polarized X-ray pulses at both grazing incidence and normal incidence [3]. The other experiment performed at LCLS revealed ultrafast phase transition (as short as 300 fs being shorter than one oscillation of the lattice at room temperature) in bismuth single crystal induced by hard X-ray pulses. The subsequent analysis indicated a non-thermal origin of lattice disordering process [4]. Ultrafast ionization of solid by intensive femtosecond XUV FEL pulses leads to a change of complex refractive index on ultrashort timescale. The performed numerical simulations predict the temporal kinetics of XUV pulse induced electron cascades; thus they allow to yield temporally and spatially resolved information on the induced changes (simulations are in a good agreement with experiments done at FERMI and LCLS) [5].

Theoretical investigations concerned on the study of ultrafast thermal or non-thermal processes in semiconductors; including study of discrimination between them by observation signatures [6]. Electron-phonon (electron-ion) coupling rates in semiconductors driven out of equilibrium were studied. Transient change of optical coefficients reflects the band-gap

shrinkage in covalently bonded materials, i.e. heating of the atomic lattice. Simulations also indicated that the Fermi´s golden rule can break down describing material excitation on femtosecond time scales [7]. Response of group III-V compound semiconductor (AlAs, AlP, GaAs, GaP, GaSb) to FEL radiation identifying their damage threshold was theoretically studied. All but AlAs III-V compounds exhibited a phase transition into a metal disordered state of lower density than the solid phase. AlAs showed two possible phases: low density and high-density liquid [8]. X-ray/XUV excitation of GaAs showed ultrafast relaxation; this study was enabled by extension of XANT code in which band-specific effects of suppression of collisional processes in GaAs were included (theoretical studies were compared with available experimental data) [9]. Silicon surface modification triggered by femtosecond XUV photon pulses from SACLA FEL were investigated in the vicinity of damage thresholds. The aim of this study was to establish connection to microscopic theoretical approaches which can help better illustrate physical mechanisms of damage processes [10].
Further studies were focused on the improvement of diagnostic methods used at FELs. One of the important parameters for FEL experiments is knowledge of the pulse duration or even the whole temporal intensity profile. Two different methods based on cross-correlation of the FEL pulses with an external optical laser were experimentally tested at FERMI. These methods possibly also allow single-shot measurements [11]. The transient optical properties can be used for diagnostics of electronic and structural transitions occurring in irradiated semiconductors [12]. Furthermore, as the commonly used materials (as Si_3N_4) in the XUV and soft X-ray region for precise characterization of intense FEL laser pulses do not work efficiently in the hard X-ray regime, the new materials as SnO_2 were tested for pulse diagnostics at LCLS for photon energies of 5 keV and 9 keV [13]. The reason for inefficiency of standard materials is the fact, that the impact of hard X-ray photon is followed by series of electron cascading processes.

X-ray FEL pulses enable diffractive structural study of protein nanocrystals. However, nanocrystal electronic form factor may be modified during ultrashort X-ray pulse interaction due to photoionization and the following electron cascade; thus, the minimization of the radiation damage effect is a major concern to ensure reliable reconstruction of the molecular structure. A radiation damage free diffraction may be achieved with atomic spatial resolution by using X-ray parametric down-conversion and ghost diffraction with entangled photons of X-ray and optical frequencies [14]. Further, the numerical simulation of ultrafast soft X-ray methyl iodide photodissociation showed that spectral signatures allow to map the time-dependent dynamics of ultrafast photoinduced bond breaking [15]. Other theoretical studies were focused on the ultrafast proton migration and isomerization in acetylene and its ions. Theoretical studies showed that there is a large potential barrier (> 2 eV) for isomerization; this implies picosecond or longer isomerization timescales. However, recent experiments at femtosecond X-ray FEL suggested sub-100 fs isomerization; being in contrast with these theoretical results which did not revealed sub-100 fs isomerization. Hence, it was proposed to perform a careful interpretation of structural information being obtained from a widely utilized Coulomb momentum imaging method [16].

The interaction of intensive femtosecond soft X-ray pulses with carbon forms. The response of amorphous carbon coating and C-60 fullerene thin films to XUV and soft X-ray FEL radiation showed remarkable difference in damage thresholds being 0.15 eV/atom and 0.9 eV/atom for C-60 fullerene and amorphous carbon, respectively. The damage threshold of fullerene is significantly lower due to a low cohesive energy of fullerene crystal [17]. Soft X-ray pulses of a duration of 52.5 fs were applied to induce graphitization of polycrystalline diamond through thermal and non-thermal solid-to-solid phase transition. This experiment found that the phase transition measured via cross correlation with an optical pulse of duration of 32.8 fs appears on a time scale similar to 150 fs, which is in a good agreement with the developed theory [18]. Furthermore, the interaction of femtosecond X-ray (9.8 keV) pulses with graphite revealed ultrafast non-thermal changes lasting up to 300 fs in its structure [19]. Theoretical study of diamond bulk irradiated with FEL laser pulse (6.1 keV, 5 fs) showed disordering on sub-100 fs time scale and the diamond transition to warm dense matter state. Simulation results compared with SACLA experiment showed qualitative agreement [20].

Besides, there was proposed and theoretically studied that the use of Hanbury-Brown and Twiss (HBT) technique can increase the resolution power of standard X-ray imaging techniques (as phase contrast imaging) can be enhanced [21].

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SWIFT ION INTERACTION WITH MATTER

Members of the LPD team have also significantly contributed, mainly by numerical simulations, to a study of the interaction of swift heavy ions with various materials.

Swift heavy ions leave a damaged trail while penetrating through a solid. Recrystallization was identified as the dominant mechanism governing the formation of detected tracks. Structural changes and their formation threshold were studied in dielectric crystals, such as Al_2O_3 [1] MgO, YAG [2] and forsterite [3], exposed to irradiation with 167 MeV Xe ions decelerating in the electronic stopping regimes. Numerical simulations [4] demonstrated that despite similar ion energy losses and initial excitation kinetics of the electronic systems and lattices, significant differences occur among the final structures of ion tracks in these materials. No tracks appeared in MgO, whereas discontinuous distorted (disordered) crystalline track similar to 2 nm in diameter were observed in Al_2O_3 and continuous amorphous tracks were detected in YAG (track structures were confirmed by high resolution TEM data). Moreover, it was found that the track radius depends on the ion energy loss and velocity; thereby on the ion penetration depth. Simulation showed dependencies of the track radius and structure on the ion energy and its energy losses. It was also found that the position of the maximal damage produced by ions in a solid does not coincide with the Bragg peak of its electronic stopping [3].

During the passage of Au ions through LiF crystal, the point defect halos, created due to decays of self-trapped valence holes, appear in nanometric vicinities of the Au ion trajectories. These defects were observed experimentally for 0.28 GeV and 2.2 GeV Au ions in LiF by absorption spectroscopy. Both kinds of ions have approximately the same electronic stopping power. The usual concept of velocity effect is that a slower ion produces larger structure changes due to a higher density of the deposited energy However, the opposite was observed for the defect halo, revealing a larger radius and larger defect concentration for an ion having higher velocity [5].

A technique for the monitoring of transient states of the electronic system of materials irradiated with swift heavy ions was proposed; this method is based on spectroscopic measurements of photon emission triggered by radiative decay of holes from different inner shells of ionized target atoms. Since a hole in each shell of each element decays with its own characteristic time, it potentially allows the extraction of femtosecond time-resolved information [6].

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LASER WAKEFIELD ACCELERATION

The research on laser wakefield acceleration focuses both on numerical particle-in-cell (PIC) simulations and experimental studies performed at the local 25 TW (i.e. 15 TW on target) Ti:sapphire laser system available at the PALS laboratory (operated by the Institute of Physics). The experimental effort aims at the production of stable electron beams for secondary radiation pulses, namely the betatron radiation, which can be used as a diagnostic tool for the large-size plasma generated by the PALS laser system. The experiment, focused on the production of stable electron beams, used dried air; stable (in energy) electron beams with an energy of 17 MeV and absolute energy spread of 13 MeV (FWHM) were generated [1].

The numerical PIC simulations are devoted to the study of electron beam injection mechanism and trapping into the accelerating plasma wave. Several optical injection schemes were proposed to test if the stable electron bunches can be obtained with fundamental parameters approaching those of conventional accelerators: orthogonal collision with perpendicularly polarized laser pulses (one injection pulse [2] or two injection pulses [3]) which can be useful especially for long accelerating plasma stage; the injection laser pulse will propagate only through a short plasma length (in contrast to colliding laser pulses). The energy of the generated electron bunch reaches more than 600 MeV in 3 mm of plasma length with a relatively low energy spread (<4%). Furthermore, it was found that the dark current can be controlled by the laser pulse negative chirp [3]. The studies of the accelerating bubble dynamics, aimed at exploring the possibilities for improvement of the performance stability of a laser wakefield accelerator, were conducted for two optical injection schemes: perpendicular injection and the pre-pulse/main pulse sequence. In the latter case, the injection of electron bunches is triggered by a preceding laser pulse weaker than the main pulse but intensive enough to create its own bubble. This injection scheme is also promising in the way that it possibly allows to obtain much higher charge in the trapped electron bunch [4]. For a precise study of the betatron radiation emitted by electrons accelerated in the plasma wave, an algorithm to obtain betatron radiation spectrum, the particle trajectory tracking routine was developed and implemented into the EPOCH PIC code; the calculation of the spectrum uses Lienard-Wiechert potentials of accelerated charge [5].

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BEAM-TARGET FUSION

Another concept in nuclear fusion is represented by beam-target fusion. The research performed in collaboration with external international users, the Institute of Physics (including ELI Beamlines department) and the Czech Technical University (Faculty of Electrical Engineering) is mainly focused on deuterium-deuterium (DD) scheme and aneutronic proton-boron (PB) scheme.

For the DD scheme, a neutron yield of 4.1×10^8 was reached when the deuterated polyethylene target was used. Moreover, when the laser accelerated deuterons (from a deuterated polyethylene target) interacted with the secondary deuterated polyethylene target, the neutron yield increased to 2.0×10^9 neutrons per shot. Furthermore, it was estimated that 2×10^4 deuterons with energies in a range of 0.5 – 2 MeV had bombarded the secondary target [2].

The PB fusion scheme represents a promising clear energy source due to its aneutronic nature. Several theoretical and experimental studies reported a resonance peak occurring at 0.675 MeV proton energy in the fixed target reference frame with the maximum cross section at 1.2 barn; the second resonance peak is observed at 0.16 MeV having the maximum cross section of about 0.1 barn. The fusion reaction generates three alpha particles with a broad energy spectrum strongly peaked at 4 MeV. Previous experiments performed at PALS showed a yield of 10^9 alpha particles per steradian per shot. However, new experiments using the boron-nitride 0.5 mm thick targets produced by Micro-Nano Facility of the Fondazione Bruno Kessler in Trieste exhibited a yield of 2.8×10^{10} alpha particles per steradian per shot; this represents the world record of the alpha particle yield in PB fusion. Furthermore, the observed spectral end-point was 10 MeV, much higher than the expected end-point (6.7 MeV) at 0.675 MeV proton energy and 7.3 MeV for 1.5 MeV protons, i.e. at common conditions; this means that more energetic protons were generated during laser-plasma interaction [3].

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PROTON ACCELERATION

In 2015, a unique experiment was conducted at PALS in collaboration with the Institute of Physics (including ELI Beamlines department and Low Temperature Laboratory of CEA in Grenoble). Within this experiment focused on proton acceleration, the target consisted of a solid hydrogen ribbon kept at a temperature of 10 K with electron density of 5.36×10^{22} cm^{-3} (1 mm wide, thickness of 62 µm; in fact, the solid hydrogen ribbon had a controllable thickness 20 – 100 µm depending on the used nozzle). Laser pulse interacted with the target surface at normal angle of incidence. The laser pulse delivering 500 J in 300 ps generated protons with the energy up to 1.4 MeV and a maximum flux of 6×10^{14} protons in the energy range of 0.1 –

1 MeV which represents about 30 J, i.e. 5% conversion efficiency [1,2]. As expected, the Thomson parabola detector did not show any other elemental contribution, in contrast to commonly used proton acceleration from metal or plastic foils. Thus, the solid hydrogen represents a promising source of extremely pure energetic protons, which can be used e.g. in proton therapy.

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NON-HERMITIAN QUANTUM PHYSICS

This topic is studied in collaboration with the Institute of Physics, and Technion in Israel. Our particular interest consists in phenomena involving metastable quantum systems (atoms, molecules, or quantum dots). A metastable quantum system possesses a finite lifetime (either per se, or due to its interaction with the laser) and decays into fragments (due to ionization, dissociation, spontaneous emission). Importantly, quantum dynamics of such metastable systems often gives rise to counter-intuitive physical features, which can be adequately theoretically interpreted only by means of the non-hermitian quantum mechanics (NHQM); they are known as exceptional points (EP). Powerful formalism of the NHQM often enables even to predict striking, unexpected, qualitatively new phenomena which cannot be discovered otherwise. The peculiar features of EPs can have influence on the phase transitions in excited states [1]. We have investigated the NHQM theory of spontaneous emission. More explicitly, we have formulated, in a self-contained and foundational manner, the so-called complex scaling method for the case of photons escaping from a model atomic system due to spontaneous emission [2]. This work opens for us the possibility to further investigate NHQM phenomena in the context of quantum optics, optionally in the presence of an external driving laser. An additional contribution [3] deals with the general theory of quantum measurement, in particular with the Heisenberg uncertainty relations associated with the so-called weak measurement scheme involving two non-commuting observables. Another work [4] contributes a mathematical inequality which can be useful for statistical analysis of data, namely, for estimating the covariance.

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Research activity and characterisation of the main scientific results

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 often even contradictory. The development is further complicated by the requirement of using low activation elements only. 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 Eurofusion program, our team has established a significant position in the fusion community and in the internationally coordinated research activities. A marked advantage of the ME team 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 (mainly by WSP-H and SPS, recently also by RF-ICP), other samples are obtained from various cooperating laboratories.
In the frame of the integrated research coordinated by the Eurofusion program, tungsten-based materials are being developed for prospective application in selected components of fusion facilities, such as divertor regions. Divertor regions are exposed to the highest heat fluxes. Tungsten is a highly suitable candidate material from the point of view of its favourable interaction with tokamak plasma. Tungsten possesses high resistance to sputtering, high melting point, good thermal conductivity and low tritium retention. On the other hand, it also exhibits several drawbacks that complicate the potential fabrication of plasma facing components (PFCs), such as low machinability, intrinsic brittleness at lower temperatures, thermal expansion coefficient mismatch with the planned structural steels and susceptibility to oxidation at elevated temperatures. Plasma spraying is among alternative preparation methods being studied. The main problem with standard atmospheric plasma spraying (APS) is the susceptibility of tungsten to oxidation. A suitable solution to this problem is to perform the plasma deposition in vacuum, inert or even reducing atmosphere. The recently acquired radio-frequency inductively-coupled plasma torch (RF-ICP) enables plasma spraying of powders in controlled atmosphere. The RF-ICP technology is available both at the laboratory (as in IPP) and industrial scales, enabling later upscaling of research results to the target applications.
The research has focused on i) preparation of functionally graded materials (FGMs), where a smooth transition to either steel (as a construction material) or copper (with its high thermal conductivity) is provided, and their comprehensive characterization for advanced PFC design, ii) optimization of tungsten coating adhesion on various substrates with the help of laser surface texturing. The graded layers could be used either as full-fledged plasma facing surfaces or as bonding interlayers for mitigating stress concentration. Tungsten-steel composites and graded layers were further prepared by hot pressing and SPS. Besides comprehensive characterization of the macroscopic properties of the composites, novel methods to characterize the thermal and mechanical properties of the individual phases were

developed. Pilot experiments with preparation of W-based FGMs using plasma transferred arc cladding were also carried out.

SPS was used extensively for the development and preparation of tungsten-based materials with improved properties. Self-passivating W-Cr alloys for fusion applications are primary examples of this effort by the ME team. Self-passivating tungsten-based alloys form a durable protective oxide surface layer in the fusion reactor during loss of cooling situation accompanied with oxygen intake. A promising W-10Cr-1Hf alloy was successfully prepared by SPS powder metallurgy method in combination with mechanical alloying. Thermal testing of the samples (in cooperation with Forschungszentrum Juelich) under conditions simulating steady-state operation of the fusion reactor showed good phase and microstructural stability of the prepared alloy. However, during exposure to conditions simulating fusion-relevant loss of cooling situation, undesirable changes of microstructure and physical properties were observed. The obtained results are currently used for further optimization these alloys. For the protective performance of W-Cr alloys, both the chemical homogeneity and correct phase composition are important. Our study on controlling the carbide formation and chromium depletion in the W-Cr alloy during SPS focused on these two aspects. The ME team described the sintering conditions of W-Cr alloys that prevent depletion of solid solution by chromium. Mechanism of the complex chromium-rich phase formation was explained using detailed calorimetric measurements, XRD analysis and available phase diagrams predicted by Calphad method.
Another important direction was the study and development of SPS tungsten for prospective use in divertor regions of tokamaks, where mechanical properties and irradiation resistance are of key importance. In particular, microstructure and purity play a major role in these aspects. An extensive study of the effects of starting powder properties and sintering conditions (including temperature, time and lining foil material) was undertaken, focusing also on the role of carbon and oxygen impurities and their interaction. This helped to develop a fine-grained material which showed comparable or better mechanical performance at various temperatures than ITER-qualified reference tungsten. Neutron irradiation of these materials was performed at SCK (Belgium).
A significant attention was also paid to the interaction of tungsten-based fusion materials with low-Z elements that will be present in fusion plasma, i.e. hydrogen isotopes and helium. The interaction may happen in the form of plasma exposure (either in a tokamak or in a laboratory plasma with fusion-relevant parameters) or through diffusion. Plasma-material interaction studies at the Compass tokamak at IPP involved thin coatings and bulk W with so-called helium fuzz. Arcing was identified as the main erosion mechanism. The performance of various SPS W grades in thermal shock type heat flux tests, using laboratory deuterium plasma, was studied in collaboration with Forschungszentrum Juelich and the behaviour was correlated with the grain structure and SPS processing conditions. In both of these studies, deuterium uptake was investigated in collaboration with the Nuclear Physics Institute of the CAS.
Furthermore, several less common nitride coatings were explored as potential hydrogen permeation barriers, the role of which is to block the permeation of hydrogen isotopes in a fusion reactor. Besides evaluating their permeation barrier capability, comprehensive characterization of other application-relevant properties was performed, in several instances for the first time.

Dielectric ceramic coatings

Dielectric ceramic coatings were prepared by plasma spraying with the aim of potential application of these coatings in electrical industry. Their dielectric strength was studied as a function of their microstructure. Dielectric ceramic $CaTiO_3$ with perovskite structure was sprayed by WSP technology. For the first time, unique preparation method of this dielectric material based on reactive suspension plasma spraying was also successfully developed by the ME team. Most of the characterization work was carried out by the ME team as well. Some special electrical measurements were done in cooperation with the Czech Technical University. Conventional plasma spraying of $(Ba,Sr)TiO_3$ samples for comparison was done at the Center for Thermal Spray Research (Stony Brook University, USA).
Barium titanate was plasma sprayed using water stabilized plasma (WSP) and hybrid WSP-H torches. The best dielectric properties were obtained using WSP, WSP-H and conventional GSP plasma torches (in descending order) which is given by undesirable susceptibility of barium titanate to formation of oxygen vacancies under reductive plasma conditions. Vacancy clustering at Ba and Ti positions was demonstrated by positron anihilation spectroscopy (carried out at the Charles University) and by linking to porosity evaluated by small angle neutron scattering (carried out at the Nuclear Physics Institute of the CAS). The WSP coatings prepared by the ME team showed even from the world-wide perspective cutting edge electric properties fully comparable to coatings sprayed by supersonic plasma spraying.

Unique coatings prepared by liquid plasma spraying

The ME team developed and optimized plasma spraying of suspensions and solutions with the unique Hybrid Water-Stabilized Plasma (WSP-H) torch. The feedstock material is injected into the plasma in the form of liquid. Deposited coatings possess qualitatively different microstructure than coatings prepared from conventional coarse and dry powders. High enthalpy of the plasma generated by the WSP-H torch enables unique combination of extreme throughputs and efficient deposition of the liquid feedstock. Coatings tailored to various applications were prepared by careful selection and optimization of liquid plasma spraying parameters. For example, highly porous YSZ ceramic coatings with extremely low thermal conductivity as well as almost fully dense, hard and wear-resistant alumina coatings have been successfully prepared. Reactive suspension plasma spraying can effectively deposit for example calcium titanate dielectric coating. The WSP-H torch was proved to be a powerful tool and well suited for the plasma spraying of liquids and has gained considerable attention in the thermal spray community.
Relation between microstructure of liquid feedstock plasma sprayed coatings and the deposition conditions was evaluated. Results enabled deposition of coatings of various ceramics (e.g. YSZ, YAG, alumina or titania) with controlled microstructures, which allows optimization of materials properties of the coatings for various applications (e.g. thermal barriers, wear resistant layers, etc.). The suspensions for the plasma spraying were obtained thanks to the close collaboration with Treibacher Industrie AG (Austria), Fujimi (Japan) and Wroclaw University of Science and Technology (Poland). Wear resistance measurements were carried out at the University of West Bohemia. The knowledge gained for spraying of single-layers was used for successful deposition of multilayered thermal barrier coatings which were proven to be durable both in conventional thermal cycling test (cooperation of IPP and University West, Sweden) and during extreme laser-rig test carried out by the National Research Council Canada.

The ME team used the novel concept of liquid plasma spraying to deposit Silver-Doped Hydroxyapatite Coatings from suspension. Bioactive ceramics coatings with nanometric structure were prepared. For the first time recorded, silver nanoparticles were introduced into the coatings via transformation of a silver-containing precursor. Aside from strengthening the bioactivity through the nanostructure, the silver particles will enhance the antibacterial properties and thereby increase the success rate of the bone and dental implants surgeries. The suspension for the experiments was supplied by Brno University of Technology. Wear resistance measurements were carried out at the University of West Bohemia and the bioactivity measurements are currently being done at the Institute of Microbiology of the CAS.
Solution precursor plasma spraying (SPPS) presents a modern route to deposit coatings from the liquid feedstocks. Unique ability of SPPS to intermix different precursors on the atomic scale was employed to deposit Cr-doped Al_2O_3 (technically, synthetic ruby) by high-enthalpy WSP-H torch. Homogeneous distribution of Cr atoms in Al2O3 resulted in reversible thermochromic behavior, i.e. coloration of the coating directly indicates its temperature, which greatly increases coatings functionality. This was the first time, a successful deposition of thermochromic coating by the SPPS method was reported. The thermochromic measurements were done at the Faculty of Chemical Technology, University of Pardubice.
Build-up mechanisms leading to growth of various types of microstructures when plasma spraying liquids with high-enthalpy WSP-H torch were identified. It was clearly demonstrated that the coating microstructure is generally controlled by
morphology of individual deposited splats which is influenced namely by formulation of the suspension and mean trajectory of the fragmented suspension droplets in the plasma jet, both influencing the size, flattening ratio and thermal history of deposited splats. Saturation of lateral growth of the cauliflower-like (columnar) microstructure was observed.
Recently, the ME team focused also on the so-called “hybrid spraying” that combines conventional plasma spraying of dry powders with concurrent plasma spraying of liquids. The hybrid spraying takes advantage of the WSP-H torch high enthalpy as it can process two streams of dry powders and one stream of liquid at the same time. It combines high powder feeding rates with the additional microstructure variability that is brought about by spraying the liquid feedstock. This experimental work is done in cooperation with University West (Sweden).
It is worth mentioning, that the group (all from the ME team) headed by Dr. Musalek was awarded the Werner von Siemens Award 2018 for the most important fundamental research result. The Award was given for their research in the area of suspension and solution plasma spraying. There have been several best paper awards of our students at international conferences and invited talks of the ME team members at renowned workshops TS4 2017 (Niskayuna, USA) and TS4 2019 (Montreal, Canada), ETSA 2018 workshop in Pilsen (Czechia) and ATSC 2018 conference in Singapore.
A completely new liquid feeder was developed by the ME team members for the use in our high-throughput suspension/solution plasma spraying experiments. Thanks to informal research cooperation on liquid spraying of potentially bioactive materials with the Swinburne University of Technology (Australia), the University placed an order for the newly developed feeder. It resulted in further improvement of the gravimetric feature of the feeder, followed by manufacturing and delivery of the IPP’s gravimetric liquid feeding unit called “Lisquid” to Swinburne University.

Coatings prepared by atmospheric plasma spraying of dry powders

Many different thermal barrier coatings (TBCs) were plasma sprayed by the WSP-H torch in the frame of the Competence Centre (2014-2019) supported by the Technology Agency of the Czech Republic. The coatings were subject to thermal cycling (done in-house at IPP), burner rig tests (carried out at Brno University of Technology), and CMAS (calcium-magnesium-alumino-silicate) attacks. Comparison with the benchmark TBCs prepared by standard atmospheric plasma spray torch (APS sprayed at Honeywell) led to a surprising conclusion that some of the coatings prepared by WSP-H torch performed better in these tests.
Fatigue Performance of TBCs was also tested in cooperation with Czech Technical University in Prague. Testing was carried out for TBC samples deposited on industrially relevant Hastelloy X substrates. Samples were tested after each step of the TBC deposition process and also in the as-sprayed condition and after annealing. Obtained results showed that each stage of the TBC manufacturing process as well as the simulated in-service heat exposure may significantly influence the fatigue properties of the TBC coated part. All heat-treated samples showed enhanced fatigue performance.
Note on industry relevance of the WSP-H plasma spraying system.
The ME team members are convinced that the WSP-H plasma spraying system is a highly competitive product with unique properties for both dry and liquid feedstock materials. Together with the Czech company called ProjectSoft HK a.s. marketing of the integrated H-WSP system to the international thermal spray community has been done over the last five years. However, the marketing effort of the ProjectSoft HK lead to one sold WSP-H system to a Japanese customer. Other than that, several Czech SMEs turn to the ME team of IPP for development of a special coating each year.

Novel materials prepared by SPS

A promising group of novel multicomponent material systems are the so-called high-entropy alloys (HEAs), where at least four respective elements are mixed in approximately even atomic content while retaining a single-phase microstructure stabilized by the high configurational entropy of the mixture. Two projects with different Czech partners (including the Charles University, institutes of the CAS and one R&D company) were financed by the Czech Science Foundation in the field of HEAs. The ME team contribution focused on HEAs preparation by powder metallurgy route with the use of SPS and on material characterization. As an example, a homogeneous HfNbTaTiZr high-entropy alloy was successfully processed via powder metallurgy route. The HfNbTaTiZr HEA is biocompatible. Spark plasma sintering of gas atomized powder was used for the powder compaction at sintering temperatures ranging from 800 to 1600 °C. Microstructure, lattice defects, porosity and mechanical properties of the compact samples were used to optimize sintering conditions to obtain a fully dense, homogeneous, single-phase bcc material with considerable flexural strength and ductility.
Another example of a novel material are semi-heusler/light metal composites prepared by spark plasma sintering. Spark plasma sintering of powders of semi-Heusler ferromagnetic compound and pure titanium resulted in the formation composite with small precipitates and intermetallic phases at the interfaces. Various experimental methods were used to fully characterize the microstructure. Electron microscopy with X-ray spectroscopy revealed a position and chemical composition of individual intermetallic phases. This study proves that powder metallurgy followed by spark plasma sintering is an appropriate technique to prepare bulk composites from very dissimilar materials. This work was carried out within the Centre of

excellence supported by the Czech Science Foundation. The ME team focused on material preparation, SEM characterization, and mechanical testing.
Novel high entropy alloys based on CoCrFeMnNi with in-situ formed oxide dispersion were prepared by a combination of ball milling and SPS in collaboration with the Institute of Physics of Materials. Thanks to the oxide dispersion, the alloys featured significant grain refinement, improved strength at both low and high temperatures and improved creep resistance. The processing and microstructural effects on the mechanical behavior were elucidated. The ME team focused on material preparation, and SEM characterization.
The SPS was also employed to prepare ternary carbide Ti3SiC2, a member of the MAX phase family. A powder mixture of Titanium, Titanium Carbide, and Silicon Carbide was prepared using a planetary ball mill. As a result, samples with high phase purity were obtained in a relatively short sintering process. Moreover, this approach is unique as the preparation of Ti3SiC2 from the above-mentioned starting materials has not been reported earlier in the scientific literature. These research findings will be published in 2020.
A new pioneering project started in 2019 in collaboration with the Charles University. It aims on exploring alternative - non-conventional - applications of SPS. Firstly, the SPS is being used for an in-situ annealing treatment to achieve optimal phase composition in aerospace high strength lightweight Ti-based alloy Ti5553. Secondly, specialized biomedical Ti-Nb-Zr-O alloy was prepared by high-temperature sintering as enhanced diffusion during SPS allows alloying of complicated alloys from elemental powders.

Applied research and development - the research for practice

The ME team participated for example in the following small application projects:

- Development of ceramic thermal spray coatings for carbon/carbon composite materials for a Czech SME.
- Development of a protective coating on a prototype part for shielding block in a nuclear power plant for UJP PRAHA a.s.
- Special self-supporting thin-walled ceramic tubes prepared by WHS-H plasma spraying for DEPRAG CZ a.s. and other SMEs
- Development of alumina protective coatings for key components (e.g. molybdenum stirrers) of glass furnaces for KAVALIERGLASS, a.s.

The ME team carried out several on-demand material analyses (XRD phase analyses and microstructural observations) of real-life specimens each year for different small and medium enterprises based in Czechia.
One Czech patent “A method of preparation of nanometric metallic silver particles and a device for implementation of this method” was registered in 2017. The patent is related to solution plasma spraying by WSP-H torch. Two utility models were also registered in 2018. One utility model is called “A semi-automatic device for measurement of surface tension of solutions” and the other “A semi-automatic device for measurement of surface tension of suspensions”.

Research activity and characterisation of the main scientific results

In the period 2015-2019, the scientific program of PPS team continued in the research of non-equilibrium plasma generated by pulse high-voltage electrical discharges in gases, liquids and gas/liquid environments. Compared to the previous period 2010-2014, the research activities have been reduced to two main topics: 1) Chemistry and physics of plasma/liquid interactions; 2) Physics, kinetics and diagnostics of streamer discharges in gas phase. The main results achieved in the frame of these topic are following:

1a) Chemistry of plasma/liquid interactions

The research of the chemical processes induced by electrical discharge plasma in liquids was focused on the characterization of the reaction mechanism and the diagnostics of key transient and long-lived chemical species produced by discharge plasma at gas/liquid interfaces and in plasma produced chemically reactive liquids. The knowledge of plasma chemical processes at gas/liquid interface is of great importance for the understanding of fundamental mechanisms of interaction of the plasma formed species with the condensed liquid phase such as the penetration of the plasma-formed radicals into the liquid through the plasma-liquid interface and the effects of the radicals from the plasma on the bulk phase reactions in the liquid. Also, to what extent the chemistry at the gas/liquid interface is governed by the gas phase discharge and what are the key factors that determine the mass transfer of plasma chemical species from the gas into the liquid. Among these processes, the oxidative properties of reactive oxygen species (OH•, O•, $O_2^{\bullet -}$, ozone, hydrogen peroxide) and nitrogen species (nitric oxide and its derivatives formed with water, peroxynitrite) are of the utmost interest. There are also possible synergistic effects of the above-mentioned processes. The consequences are: first, highly reactive chemical species in plasma deriving from oxygen and nitrogen are transferred to the liquid, and second, many of these chemical species are not stable in the liquid and subsequent reactions can be initiated in the plasma-treated liquid, giving rise to new transient species and lead to the final more stable species. These secondary aqueous-phase post-discharge chemical reactions play very important role and can last in plasma-treated liquids (also called as *plasma activated water* - PAW) for significant periods of time after the solution's exposure to the plasma (minutes to hours). Because of the complexity of the reactions, detailed characterization of these processes is one of the key research issues, and of great interest to the nonthermal plasma community, especially to that focused on the biomedical applications of plasma, but also in the environmental applications of plasma and the use of plasma in agriculture applications.

During the last 5 years, the PPS team published several highly cited publications related to this topic and was involved in a number of international activities. 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 research was focused especially on a) diagnostics and characterization of the aqueous-phase chemistry produced in water by air plasma, b) diagnostics and characterization of the aqueous-phase chemistry of reactive chlorine species initiated in saline solutions by He/O_2 plasma, c) chemistry of discharge plasma directly in liquid and d) plasmachemistry in organic liquids.

Aqueous-phase chemistry produced in water by air plasma

Research of aqueous-phase chemistry produced in water by air plasma continued in the line of our previous successes in this field, specifically on the diagnostics and the characterization of the chemical processes induced by air plasma in chemically reactive liquids, namely on the chemistry of peroxynitrite (ONOOH). In collaboration with colleagues from Comenius University, Bratislava, Slovakia (CU) we evaluated specificity and possible interferences of analytical methods commonly used for detection of nitrites and ozone in aqueous solutions treated by air plasma. Griess assay was determined suitable for nitrites detection, H_2O_2 did not affect specificity of this assay. Indigo blue assay was strongly affected by OH radicals from acidic decay of peroxynitrite and was not specific for O_3 detection. This work provided important guidelines to the diagnostics of nitrites and ozone in PAW. The PPS team performed chemical analysis and evaluated results on plasma-induced effects in plasma-treated liquids with the focus on the specificity and possible interferences of analytical methods of nitrites detection in PAW.

With the same CU team and with the INP Greifswald, Germany (INP), we also examined the use of the 2,7-dichlorodihydrofluorescein diacetate (H_2DCFDA) fluorescent dye to detect peroxynitrite in aqueous solutions treated by air plasma. The diagnostic selectivity of H_2DCFDA to reactive oxygen and nitrogen species in PAW was examined by using various scavengers. The highest sensitivity of the H_2DCFDA dye was to peroxynitrite, however, it was very high also to hypochlorite. This work provided important guidelines to the diagnostics of peroxynitrite in PAW. The PPS team performed chemical analysis and evaluated the results of plasma-induced effects in PAW with the focus on the specificity and possible interferences in ONOOH detection.

In collaboration with colleagues from Bologna University, Italy (BU), we assessed biocidal effects of PAW on two pathogens typically associated with nosocomial infections (*Candida albicans* and *Staphylococcus aureus*). We demonstrated high antimicrobial activity of PAW, though lifetime of this activity was limited and strongly related to the concentration of the peroxynitrite as the key antimicrobial agent formed in water treated by air plasma. This work provides new insights into biocidal effects induced by PAW and possible applications of PAW as an innovative antimicrobial agent in healthcare associated infection control. The PPS team performed chemical analysis and evaluated results of a study on plasma-induced effects in liquids treated by air DBD plasma performed in the frame of a stay of Dr. Laurita from BU in Prague.

Formation and chemistry of reactive chlorine species in saline solutions

Important results have been obtained by the PPS team in the research of the chemistry of oxygen atoms at plasma/liquid interface. In collaboration with colleagues from Ruhr University Bochum, Germany, we demonstrated experimentally for the first time that oxygen radicals from plasma produced above the water surface penetrate into the water through the plasma-liquid interface. We proved that O atoms could directly promote chemical reaction at the gas/liquid interface and in bulk liquid. Transfer mechanism of O radicals and their bulk phase reactions were analyzed using chemical probe phenol in the plasma treated liquid and the reactivity of O radicals showed similar properties to those of OH radicals. These findings are important in understanding of oxidative effects induced in water by plasma. The PPS team performed all chemical analysis and evaluated data on plasma-induced effects in water treated by a He plasma jet constructed for this work.

Further, we used the same He/O_2 plasma jet to promote reactions of plasma-generated oxygen atoms with chloride anions at the gas-liquid interface. For the first time, we made quantitative analysis and evaluated the kinetics of subsequent post-discharge chemical processes of oxychlorine species in plasma treated saline solution. We detected three new Cl-species: hypochlorites $HOCl/OCl^-$, chlorites ClO_2^-, and chlorates ClO_3^-. The final pH of plasma treated saline was typically 10. The produced total hypochlorite was in direct proportion to the initial NaCl concentration, supporting the idea of a direct reaction of Cl^- with O atoms. The post-discharge processes led to the disproportionation of hypochlorite into different oxidation states of chlorine with formation of ClO_3^- as the final product. This work was fully made in our laboratory and it is important for understanding of chemical effects induced by plasma in liquids containing chlorides. It also reveals important consequences on the role of oxychlorine compounds in plasma medicine, including generation of reactive chlorine dioxide and singlet oxygen in situ in the liquid phase.

Chemistry of discharge plasma directly in liquid

In addition to the chemistry of reactive oxygen, nitrogen and oxychlorine species produced by electrical discharge plasma in contact with aqueous solutions, important results were also obtained in the research on discharge plasma directly in liquid. In collaboration with colleagues from INP Greifswald, Germany (INP) we have shown that discharge plasma is effective in degradation of pharmaceuticals known to be problematic substances for conventional water purification technologies. In this work, we used microsecond pulsed corona discharge plasma in a reactor of a wire-cylinder electrode geometry. Seven compounds from different important substance groups (analgesics, antiepileptic drugs, hormones and antibiotics) including two which are on EU watch list of emerging pollutants, were decomposed by plasma. This work demonstrated potential of plasma technology in water treatment. With the same INP team, we have also shown for the first time that depending on the electrode material, ground electrode corrosion and associated catalytic processes can strongly influence the liquid chemistry associated with plasma. So far these effects were considered only with erosion of high voltage electrodes directly subjected to the discharge plasma. Stainless steel ground electrodes possessed the highest effect due to Fenton promoted chemistry. These results are important in the evaluation of plasma processes in liquid. In this joint research, the PPS team performed chemical analysis and evaluated the results on plasma-induced effects in water.

Further work was focused on the assessment of effects of the input pulse power parameters (pulsed duration) on plasmachemical processes induced by electrical discharge plasma in the liquid, this means, whether the plasmachemical reactions can be varied with the pulse duration. More specifically, whether with a shorter pulse length, a plasma with a higher mean electron energy can be produced, allowing to initiate or to give higher yield of high-energy electrons driven reactions. Discharge pulse duration was varied from µs- to ns-range with voltage amplitudes up to 150 kV, and the effects of the input pulse power parameters on plasmachemical processes induced by electrical discharge plasma in liquids were determined. It should be noted that the research on nanosecond discharges in liquid is very challenging and in many aspects rather limited. Only a few laboratories in the world have successfully worked in this field before us, and so far with a rather low voltage amplitude (order of 10-20 kV). Recent development of the nanosecond pulsed generators technology allowed to generate streamer discharges in water of nanosecond pulse duration with significantly higher pulse energy. We have initially collaborated on this research topic with the team of prof. J. Kolb from INP Greifswald, Germany and then, in the year 2015, we bought our own nanosecond pulse power generator from FID Technology GmbH (5 ns pulse duration, voltage up to 150 kV, pulse frequency 1-100 Hz, impedance load 50 Ohm). With this generator, we are able to generate stable pulsed nanosecond discharge in liquid in the streamer mode and maintain it for a long time in a wide range of voltages (with breakdown voltage close to 50 kV, however, for plasmachemical experiments optimized conditions we use voltages > 100 kV).

Using this setup, we were able to obtain a number of unique results on the physics and chemistry of nanosecond discharge produced directly in water. Plasmachemical production of hydrogen peroxide and OH radicals by nanosecond discharge in deionized water was measured under various conditions and compared to that of microsecond pulse duration range. Energy efficiency of hydrogen peroxide production by nanosecond discharge (about 1.5 g/kWh) was found very similar with the energy yields determined for H_2O_2 production by the microsecond discharge. OH radical production by nanosecond discharge was proved using phenol as a chemical probe, however, electronically excited radiative state of the OH (A-X) was not detected in emission spectrum of nanosecond discharge in water. This was in contradiction with the results obtained for OH radical production in water analyzed with microsecond discharge. This indicates that plasmachemical production of hydrogen peroxide by the discharge with the nanosecond pulse duration might be driven by the same mechanisms as by the discharge with longer pulse duration, i.e. processes critical for H_2O_2 formation in plasma channel are occurring in the shorter time scales than in the range of nanoseconds. However, for the formation of OH radicals, some other process than a direct electron excitation of water molecules might be important and could take place on longer time scales. OH radical production by nanosecond discharge in water was further proved using the chemical probe phenol. Results of this work were presented by Dr. Lukeš in invited and plenary lectures at IEEE conferences. These processes were further explored using spectroscopic diagnostics, which is described in the section 1b) Physics of plasma/liquid interactions.

Plasmachemistry in organic liquids

We also investigated fundamental plasmachemical processes initiated by pulsed discharge plasma in organic/dielectric liquids combined with the diagnostics of discharge plasma characteristics in these liquids. Experiments with organic liquids were performed with C6-C10 homologues of pure aliphatic alkanes (specifically *n*-hexane, *n*-heptane, *n*-octane, *n*-nonane and *n*-decane) and in mixtures with alcohols (methanol, ethanol) and/or with small addition of water. Unsaturated products with double and triple carbon bonds and products containing both types of unsaturated carbon bonds were the major products determined in all hydrocarbons mixtures exposed to the plasma. Acetylene, methane and molecular hydrogen were the major gaseous products. A large number of heavier saturated aliphatic hydrocarbons of different C7-C19 alkane isomers was formed in minor amounts. No carbonaceous products were detected. Primary plasmachemical reactions were driven by highly energetic electrons from plasma leading to the alkane fragmentation and hydrogen abstraction. Thermal decomposition reactions of alkanes were negligible. Dehydrogenation of alkanes was the major reaction pathway of plasmachemical conversion induced by nanosecond discharge leading to unsaturated hydrocarbons of lower molecular weight (C2-C4) and molecular hydrogen. This process can take place either through direct cleavage of carbon-hydrogen bond or hydrogen abstraction from alkyl radicals formed in the discharge due to alkane fragmentation (varying from methyl to specific alkyl radicals). Recombination reaction between alkyl radicals led to the formation of heavier hydrocarbons.

The leader of the research team Dr. Lukeš also edited and authored one chapter in the book *Bioelectrics*, Chap.3: *Special Electromagnetic Agents: From Cold Plasma to Pulsed Electromagnetic Radiation* (Springer 2017, ISBN 978-4-431-56093-7, p. 109-154) and he was a co-author of the review paper and roadmap on plasma-liquid interactions (*Plasma Sources Sci. Technol*. 2016, 25, 053002). This paper provides comprehensive overview of the state-of-the-art of plasma–liquid interactions and identifies key research challenges in this field regarding diagnostics and modelling of physical and chemical processes at the plasma–liquid interface and in the bulk liquid. These processes play an important role in many research areas and this review, prepared by major experts in this field, established itself as a key reference in the research of plasma-liquid interactions (> 500 citations in WoS). Dr. Lukeš as an expert on diagnostics of chemical processes induced by plasma in liquids contributed to this paper by writing the texts focused on the liquid phase diagnostics. Additionally, he gave a number of invited lectures including plenary on this topic which demonstrates the high recognition of the quality of the research work and achievements of the PPS team in the research of plasmachemical processes in liquids.

1b) Physics of plasma/liquid interactions

Research on physics of plasma/liquid interactions was mainly focused on the characterization of fundamental phenomena associated with nanosecond pulsed streamer discharge in water. Using the ns-pulsed generator described above, we studied physics, kinetics and diagnostics of streamer discharges in liquid water. Experimental works focussed on interferometric measurements of pressure waves and the electric field, measurements based on Schlieren images, ultrafast emission spectrometry and the measurement of electrical characteristics. We have developed fast time resolved system diagnostics for data acquisition and processing of electrical and optical signal with sub-nanosecond time scale duration. Basic morphologic and emission characteristics of the nanosecond discharge produced in deionized water were performed.

We have been able to associate, for the first time ever, characteristic emission spectra with the ICCD microscopic images of most important phases of the streamer nanosecond discharge evolution in liquid water. We have shown that the nanosecond discharge in liquid water is characterised by many isolated primary (mostly 2–4 channels) and secondary micro-filaments which create a tree-like structure similar to the corona discharges in air. An inception of a few isolated micro-discharges is followed by an approximately linear initial expansion of luminous discharge filaments, with propagation velocity of luminous front of ~10^5 m/s. After the initial expansion and branching of primary filaments, the length of the luminous filaments collapses.

Time-averaged as well as time–resolved emission spectra were acquired in the 250-850 nm spectral range. The spectrum was dominated by a broadband UV-vis continuum emission and three weak NIR atomic lines corresponding to H_α at 656 nm, O^I at 777.1 nm and O^I at 844.6 nm. On the other hand, the typical profiles of the H_β line and OH (A-X) regularly observed in microsecond underwater discharges were not observed in the case of ns discharge. The time–resolved spectra showed delay in emission of hydrogen and oxygen. During the first 20 ns a large continuum radiation was dominating the spectra profile, most likely caused by ionized water molecules. We concluded that the initial emission is likely caused by the bound-free and free-free radiative transitions only, while the H_α and OI emissions occur later. This implied that these species might be formed due to charge exchange reactions of atomic ions with water molecules in the cooler shell of plasma and subsequent dissociative recombination. The free electron density estimated from the broadening of the Hα line profile was of the order of 10^{18}–10^{19} cm^{-3}. To the best of our knowledge, no other studies have been reported that deal with time-resolved optical characteristics of underwater nanosecond HV discharges correlated with reflected HV pulses. Our results indicate that the discharges generated due to the reflected pulses were very likely generated in the non-relaxed environment.

Bound-free/free-free radiative transitions might be the most important emission characteristics of the nanosecond discharge initiation mechanism, which does not involve the formation of vapour bubbles, in liquid water. Bound-bound (atomic) emission (by hydrogen and oxygen) occurs much later during subsequent discharge initiated by reflected HV pulses, and probably indicates (together with the Stark and pressure broadening) the discharge mechanism with participation of bubbles. The study findings have strong implications for the fundamental understanding of initiation of nanosecond discharges in liquid water.

Pressure fields developing around nanosecond discharges produced in deionized water by fast rise-time positive high-voltage pulses (+100 kV, duration 10 ns) on a point electrode were investigated by means of laser interferometry with high spatial resolution (0.75 microns). Unique results characterizing pressure fields developing due to the propagation of a single discharge filament were obtained. The peak pressure of 500 MPa was at the shock front with radius of 2 microns, with the generating filament invisible at early stage.

Shadowgraph images evidenced three distinct events. The first one, subcritical (no-discharge) event, is characterised by periodic perturbations of the index of refraction which depart from the anode surface and are pulled away with the speed of sound as an expanding envelope defined by the shape of the anode tip. The second one, dark or non-luminous discharge event, is characterised with the onset of few isolated very tiny tree-like structures growing from anode tip. Depending on the HV amplitude, the initial structures occur with a delay of 2-3 ns after the onset of the HV pulse and subsequently expand with an average velocity of 1-2 x 10^7 cm/s, creating very dense bush-like structures made of thin hair-like filaments in a few nanoseconds. The third one, luminous discharge, follows (nearly simultaneously) the dark discharge event and unveils much simpler tree-like morphology determined by the extension of non-luminous bush-like structures. Characteristic dimensions of observed events range from about 1 micron (typical diameter of non-luminous filaments) to tens of micrometres (characteristic diameters of luminous filaments). The extension of dark/luminous filaments depends on the amplitude of primary HV pulse and number of subsequent reflections. Furthermore, we have addressed a possible role of microbubbles developing in the anode region due to the periodic HV pulses and verified that the UV-vis-NIR spectrometric signatures of the luminous phase notably change when replacing non-degassed DI water with the degassed one. The results of the work on nanosecond pulsed discharges in water described above have been published in several papers in journals *Plasma Sources. Sci. Technol*. and *J. Phys. D: Appl. Phys*.

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

Experimental works focussed on the spatial and temporal evolution of single streamer filament developing in pure nitrogen and N_2-O_2 mixtures at reduced pressures. ICCD images of the streamer formation and propagation in a volume DBD geometry were captured with the time resolution of 50 ps by employing the technique of kinetics series with a progressive increase of the ICCD gate-width. We showed that during the initial phase, an avalanche slowly builds up in the anode region with a subsequent formation of the cathode directed streamer. Spectra of this phase were acquired with different spatial and temporal resolution. In particular, spatially resolved spectra with 100 ps effective gating enabled evidencing distinctive spectral characteristics of different phases.

The N_2(A,v=0-10) vibrational kinetics in nitrogen-oxygen mixtures was studied by LIF technique under DBD streamer discharge conditions at low pressures. In pure nitrogen, the observed evolution of the N_2(A) LIF signal during the decaying streamer channel period evidences a fast initial relaxation of high vibrational levels towards the v=2 and 3 levels, followed by a delayed increase of terminal v=0 and 1 levels. In nitrogen-oxygen mixtures, however, the efficient quenching of higher N_2(A,v) levels by oxygen significantly inhibits vibrational relaxation towards the lower and terminal levels, causing much lower populations of the v = 0-3 levels. Obtained results show that with the addition of oxygen, the evolution of the N_2(A,v) vibrational distribution is effectively terminated during the collisional-radiative cascade inhibiting the energy pooling mechanism which is effective in pure nitrogen. We also focused on the OES and LIF studies of streamers in N_2+O_2 mixtures with a variable percentage of O_2. The goal of this study was the determination of quenching rate constants of the N_2(B) and N_2(A) states for various vibrational levels (these results have been presented and got 'Best Poster Award' at the 18^{th} International Symposium on Laser Aided Plasma Diagnostics 2017).

In cooperation with MU Brno, complementary TALIF experiments were performed to fix the dynamics of N atomic species under triggered streamer conditions using the IPP reactor and setup. For this purpose, frequency-trippled dye laser at Masaryk University was used. In order to get spatially resolved data perpendicularly to the discharge, the fluorescence signal was measured by means of the ICCD camera. The measurement of absolute atomic nitrogen concentration was enabled by the TALIF calibration by krypton. The dependence of atomic nitrogen concentration on the delay after the discharge was measured in pure nitrogen and these measurements were realized for a wide range of pressures. Outcomes of this study provide absolute densities of N radicals and their evolution in time including radial expansion in the centre of the discharge gap.

We have developed a detailed kinetic scheme to study discharges in mixtures of molecular gases. We have compiled state-to-state vibrational kinetics, including e-V, V-V, V-T and e-E(V) transfers, of the ground and electronically excited species in the case of nitrogen and N_2-O_2 streamers. The scheme contains about 10^4 processes considered for 229 species. We performed a series of test case simulations for a wide range of pressures (10-760 Torr) and for pure N_2 and synthetic air. The results of these extensive simulations were compared with selected experimental results and published as an invited paper in the ‘Special issue on chemical kinetics in non-equilibrium plasmas‘ in J. Phys. D: Appl. Phys. We believe that this extended scheme should become a standard for simulations of physical and chemical kinetics of streamer discharges in molecular gases.

In cooperation with MU Brno, substantial theoretical efforts were also focused on electric field determination in air plasmas from the intensity ratio of two nitrogen spectral bands. The primary aim was to quantify the overall uncertainty of the theoretical dependence for the intensity ratio and identify the main sources of these uncertainties. We have performed sensitivity analysis (SA) based on Elementary Effects Method, for the N_2/O_2 plasma kinetics model composed of 617 reactions finding a minimal set of reactions to which is the intensity ratio sensitive. Subsequently, we have utilized Monte-Carlo-based uncertainty quantification supported by comprehensive bibliography research to provide a confidence band for the electric field obtained from the theoretical dependence. Outcome of this extensive study was published as a sequence of three papers in Plasma Sources Sci. Technol. The main benefit and practical utility of this work is that utilized sensitivity analysis framework is very general and is capable of identifying those inputs to which a numerical model is insensitive. In particular, it is very efficient for the reduction of kinetic schemes. The SA framework was presented and won the Best Oral Presentation Award at the 23rd International Symposium on Plasma Chemistry 2017.

Research activity and characterisation of the main scientific results

The research activity of the team of Thermal Plasma Department (2015-2018) and Department of Plasma Chemical Technologies (2018-2019) was focused on the investigation of physical and chemical processes in several technologies based on thermal plasma processing of materials, the study of plasma-assisted gasification, pyrolysis and destruction of organic and waste materials, and investigation of generators of thermal plasmas together with diagnostics of electrical discharges producing thermal plasma.

Characteristics of the leading research topics of the team are given below.

1. Gasification and pyrolysis of organic waste materials for the production of hydrogen and high-quality syngas

This is the main topic of the department during the evaluation period, with the highest number of outputs, including articles in impacted journals and chapters in books of prestigious publishers.

A large number of results from gasification experiments is summarized in [1]. Treated materials were wood sawdust, wooden pellets, pyrolytic oil, refuse-derived fuel (RDF), sunflower seeds skins, lignite, polyethylene pellets and waste plastics. These experiments verified the possibility of production of high-quality syngas with a high content of hydrogen by treatment of different materials in steam plasma. For all materials, the produced synthesis gas is characterized by high purity and very high content of hydrogen and carbon monoxide, which is substantially higher than hydrogen and CO content, obtained by conventional non-plasma as well as plasma processes. High quality of the produced gas is given by extreme parameters of the used plasma – composition of steam plasma, very high temperature and extremely low plasma mass flow rate in connection with high enthalpy. Measured compositions of the produced syngas were close to ideal theoretical composition calculated as thermodynamic equilibrium composition of a mixture of all input components. Measurements also revealed very low concentrations of tar which is substantially lower than tar content in the gas produced by other gasification processes. The composition of syngas could be easily controlled by the addition of reaction admixtures like CO_2, water, or oxygen. The process can also be used as 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 beneficial as well.

The specific case of RDF gasification, which was of high interest for industrial partners, is described in detail in [2]. A comparative analysis of the syngas characteristics and process yields was done with different types of gasifying agents. The syngas compositions were compared to the thermodynamic equilibrium compositions, and the performance of the single-stage plasma gasification of RDF was compared to that of similar experiments with biomass and the performance of a two-stage plasma gasification process with RDF. The temperature range of the experiment was from 1400 to 1600 K. For all cases, medium calorific value syngas was produced with lower heating values up to 10.9 MJ/Nm^3, low levels of tar, high levels of CO and H_2 and with composition in good agreement with the equilibrium composition. The carbon conversion efficiency ranged from 80% to 100% and maximum cold gas efficiency and mechanical gasification efficiency of respectively 56% and 95%, were registered. Overall, the treatment of RDF proved to be less performant than that of biomass in the same system.

Compared to a two-stage plasma gasification system, the produced syngas from the single-stage reactor showed more favourable characteristics. At the same time, the recovery of the solid residue as a vitrified slag is an advantage of the two-stage set-up.

Series of experiments with methane reforming for syngas production is presented in [3]. It was shown that the output H_2/CO ratio could be adjusted by choice of feed rates of input reactants in the range of 1.1–3.4. Depending on experimental conditions the conversion of methane was up to 99.5%, the selectivity of H_2 was up to 99.9%, and minimum energy needed for the production of 1 mol of hydrogen was 158 kJ/mol. Effect of conditions on process characteristics was studied. Comparison of measured data with results of theoretical computations confirmed that the reforming process produces gas with the composition which is close to the one obtained from the thermodynamic equilibrium calculations. Relations between process enthalpy, the composition of produced syngas and process characteristics were determined both theoretically and experimentally.

Low-quality coal, lignite, was studied with the aim of its gasification [4]. The efficiency evaluation of the thermal decomposition process was performed. Energy balance of the process was carried out as well as an influence of the lignite particle size and the addition of methane on the synthesis gas composition. The ratio H_2/CO was in the range of 1.5–2.5 depending on the experimental conditions.

The wooden particles gasification was studied theoretically in [5]. To investigate this process of gasification in detail with possible impact on performance, a numerical model has been created using ANSYS FLUENT program package. Results for molar fractions of CO for three different particles diameters obtained by the modelling (0.55, 0.52 and 0.48) at the exit are a relatively good approximation to the corresponding experimental value (0.60). The numerical results reveal that the efficiency of gasification and syngas production slightly decreases with increasing diameter of the particles. Computed temperature inhomogeneities in the volume of the reactor are most vital for the largest particle diameter and decrease with decreasing size of the particles.

Comprehensive studies regarding plasma gasification and plasma waste treatment, including examples of experimental results and practical utilization, were presented as book chapters [6, 7].

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2. Decomposition of perfluorinated compounds and fluorinated ozone-depleting substances in thermal plasma jets

A large number of experiments dealing with the decomposition of perfluorinated compounds (PFC) and fluorinated ozone-depleting substances was carried out in a unique newly built plasma reactor. This research was performed in the frame of the Czech Science Foundation (CSF) project No. GC17-10246J and in close cooperation with partner institutions in Taiwan: National Taiwan University (NTU) and Institute of Nuclear Energy Research (INER).

Fluorinated compounds, widely used substances in semiconductor manufacturing, represent a potent source of global warming effect with direct global warming potential much higher than that of carbon dioxide, methane or nitrous oxide. These gases are exceptionally chemically stable, and thus very high temperature as generated by thermal plasma torch is adequate for their destruction. Compared to conventional methods, thermal plasma offers higher efficiency of decomposition as it enables reaching sufficiently high temperature and enthalpy.

We applied N_2 stabilized direct current-plasma torch to generate steam plasma for an efficient abatement of model fluorinated substances (CF_4, C_2F_6, CHF_3, NF_3, and SF_6) [1]. The effect of arc power of the plasma torch, gas flow rate and the concentration of fluorinated compounds on their destruction efficiency was tested. Determined destruction and removal efficiency can be ordered with respect to the treated chemical substance in the following way: $NF_3 > C_2F_6 > CHF_3 > SF_6 > CF_4$. Removal greater than 99.99% level of the most persistent gas, i.e., CF_4 was attained at 16 kW torch power and inlet concentration of 1% for feed rate 50 slm. For C_2F_6 abatement, it was found that steam addition is essential to prevent CF_4 by-product formation even though this addition reduces destruction and removal efficiency. The general trend observed at 10 kW torch power showed that destruction efficiency increases with increasing inlet gas concentration. The only exception is SF_6 that exhibit the opposite tendency for any applied torch power. The dependence of residual concentrations of the abated gases on the feed rate to the torch power ratio was evaluated to assess the energy efficiency of the abatement process.

We also used water-argon stabilized DC plasma torch for efficient abatement of the most persistent PFC, i.e., CF_4, and to observe a dependence of destruction and removal efficiency on operational conditions, including the concentration of CF_4, input arc power of the plasma torch and influence of an additional gas [2]. The experiments were carried out at 20 kW and 40 kW of torch power in the concentration range 1–20% of CF_4 in mixture with both nitrogen and argon and total feed rate 50 L/min. The mixture with argon exhibit considerably higher destruction efficiency than that with nitrogen. The highest destruction efficiency was attained in the mixture CF_4/argon at 40 kW of torch power. Among other gases (CO_2, O_2, H_2) added to CF_4, only hydrogen exhibited a positive effect on destruction performance. It was found an optimal feed rate of additional hydrogen corresponding to the maximum of destruction efficiency.

Other results and more detailed analysis of PFC destruction in water-argon thermal plasma reactor were presented in conference proceedings [3, 4]. These experimental data and also theoretical studies dealing with this topic are currently being prepared to publish in impacted journals.

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3. Diagnostics and modelling of the water-argon arc plasma jet

Various aspects of the physics of the thermal plasmas generated in hybrid water-argon plasma torch have been investigated. Both experimental and theoretical studies of the processes in the arc plasma as well as in the freely expanding jet were carried out. The aim of this research is closely related to the applications as described above. Understanding of different details of the generated plasma may play a crucial role in the optimization of its operation in plasmo-chemical reactors.

Detailed investigation of the anode area of the water-argon plasma torch using optical methods was carried out [1 - 3]. For our measurements, we used a high-speed camera and a high-voltage probe [1]. The results are in agreement with a model of plasma generated by a hybrid plasma torch and with spectroscopy measurements. The results describe the movement of the anode arc attachment in detail and provide experimental data on average plasma electrical conductivity in hot anode areas. Both the measurements of the mean electrical conductivity and the procedure for quantitative comparisons of anode erosion can also be used in other types of plasma torches.

We also found out that the anode erosion decreases along with ambient pressure, and it is lower when a diffuse anode arc attachment is present as opposed to a constricted anode attachment [2]. The sources of plasma fluctuations inside and around the plasma jet are mainly the movement of the anode arc attachment and turbulent vortices. The average speed of the anode arc attachment increases with decreases in ambient pressure. On the contrary, the average period of the restrike process, or the distance between the exit nozzle and the average attachment's position, decreases with reductions in ambient pressure. We report ambient pressure values for the transition between a constricted and diffuse anode arc attachment and the transition between subsonic and supersonic plasma flow.

Simultaneous optical, spectroscopic, and electrical measurements allowed to monitor the movement of the arc attachment along the anode surface together with its restrike [3]. Temporal evolution of temperature during one cycle of the restrike mode is obtained in three different axial positions in the plasma column. Resulting temperature profiles show how the position of the arc attachment influences the plasma properties.

Modelling of this water-argon arc plasma, including the abovementioned anode region, was performed in cooperation with Brno University of Technology and with Tohoku University in Japan [4, 5]. The calculations showed that the most critical processes determining properties of the arc are the balance of the Joule heat with radiation and radial conduction losses from the arc. Local thermodynamic equilibrium conditions are satisfied in the arc column with the 2 mm radius. Comparison between the simulations and experiments shows good agreement with the current-voltage characteristics, radial velocity and temperature profiles, as well as with the other related numerical simulation. Calculations also reveal inhomogeneous mixing of argon and oxygen-hydrogen species with the argon species prevailing near the arc axis.

Except for the arc plasma, the processes downstream the plasma flow, in the freely expanding plasma jet of the water-argon plasma torch, have been studied both theoretically [6] and experimentally [7]. CFD simulations of the jet issuing into ambient nitrogen gas with three different mixing models were compared based on the temperature, velocity and nitrogen concentration profiles in the resulting flow field. It was found that the use of approximate mixing rules can significantly influence the calculated flow of a plasma jet [6]. Experimental results are based on the comparison of the water-argon plasma torch and air plasma torch and especially on comparison of their plasma jets which are studied using optical emission spectra [7]. Results include temperatures obtained from emission lines of atoms, ions and diatomic molecules in various distances along the axes of the plasma jets. Understanding of temperature distributions is complicated mainly in the downstream turbulent regions of the jets. Several standard features are found during the comparison of emission spectra and corresponding temperatures. It is shown that the Boltzmann plot of rotational lines of OH can serve as a good thermometer in the downstream regions of both jets. It should be emphasized that this research is significant for the plasma chemical applications because the studied regions are critical for the processes of interaction of plasma flow with treated materials.

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[4] Jeništa J., Steam torch plasma modelling, Plasma Chem. Plasma Process. (2017) 37 (3), 653-687
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4. Other interesting results

Members of the team participated in the research carried out in collaboration with partner teams and institutions. Our experience and experimental equipment were used to obtain very interesting results, which then led to several publications.

Experimental characterization of the gliding arc discharge, which was further used for degradation of Verapamil hydrochloride, was performed together with colleagues from the University of South Bohemia in Ceske Budejovice and Czech Technical University in Prague [1]. Our contribution consisted in plasma discharge characterization by means of optical emission spectroscopy. The emission spectra of atoms (O, N, Cu, Na) were observed mainly in the discharge region of the gliding arc. Going down the flow, at a distance of 10 mm only the molecular emissions (OH, N_2, N_2^+) were detected. Farther than 10 mm from the electrodes emission spectra more or less disappeared. It is evident that the discharge produces relevant active species like O or OH radicals, which play key role in Verapamil degradation reaction.

A detailed description of the control system of the hybrid water-argon plasma (WSP-H) torch was presented as a book chapter [2]. The chapter contains short introduction of the plasma torch, description of basic components of the control system and principles of their operation. Special care is given to the water supply part of the system, which has been uniquely designed in our laboratories.

Member of our team P. Ondáč made a significant contribution in data processing from time-resolved ICCD imaging showing initial propagation of positive nanosecond discharge in liquid water [3]. The technique of time-resolved ICCD imaging microscopy turned out to be suitable method for discharge filament visualisation in various time delays after the discharge onset. After processing of hundreds of images, it was possible to estimate the average propagation velocity of the discharge. We can say that the nanosecond discharge in liquid water is characterized by many isolated primary and secondary micro-filaments and creates a tree-like structure similar to the corona discharges in air.

Another team member M. Hlína performed experimental characterization of the thermal plasma flow used for suspension and solution plasma spraying [4]. Plasma properties were measured by enthalpy probe connected to a mass spectrometer. It was obvious that the injection of ethanol substantially increases the available enthalpy content presumably due to the prevailing exothermic reactions (combustion) of ethanol (or products of ethanol decomposition such as methane) with entrained air. On the contrary, available enthalpy was decreased for the water injection where endothermic processes (such as water evaporation) dominate. During the injection of mixture of water and ethanol (1:1) both of these phenomena compensated and provided enthalpy comparable to the state without any liquid injection.

Collaboration with Institute of Thermomechanics led to the experimental characterization of the thermal plasma source for energy conversion [5]. A laboratory scale thermal plasma source for magnetohydrodynamic or magnetocumulative generator was developed. The thermal plasma was created from combustible stochiometric mixture of hydrogen and oxygen by spherical implosion of convergent detonation wave. Resulting high velocity plasma was observed by capturing emitted light by hi-speed camera to determine plasma velocity and also spectroscopically in order to estimate the plasma temperatures.

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5. Research for practice

Cooperation with industrial partners leads to the practical and commercial utilization of the results of our research. In the years 2015-2019 following work was done in the frame of contracts and projects with commercial companies:

- Since 2018 we have a cooperation with ExxonMobil in the project dealing with thermal plasma pyrolysis of methane and natural gas for hydrogen and carbon black production. Several targeted experiments were performed in our laboratories, and up to now, we prepared two confidential reports summarizing the research.
- The cooperation with Millenium Technologies and Millenium Plasma should lead to the building of commercial plasma plant for energetic utilization of waste and syngas production.
- In the frame of TACR project NCK MATCA (National Centre of Competence: Materials, Advanced Technologies, Coatings and their Applications) we have close cooperation with the company HVM Plasma, to test various plasma sources for plastic waste processing.

We also continue the successful collaboration with the company ProjectSoft, which leads to the introduction of the water-argon plasma torch developed in our laboratories as a commercial product, used mainly for the plasma spraying application

Research activity and characterisation of the main scientific results

The TOPTEC Centre is a part of the network of application centres of the CAS. Therefore, the focus of the Centre is more application-oriented compared to the other workplaces of the CAS institutes. Application Centres are characterized by very close cooperation with industry in the Czech Republic and abroad, and TOPTEC ranks among the top both in terms of quantity and quality. The Centre is a co-investigator of four European Space Agency (ESA) projects and actively cooperates with top companies in the optical industry and related branches such as OHB, Airbus, Leonardo, Micos, Elecom, Applic, Meopta, Rigaku, FEI, Tescan, Varroc, Preciosa, Siemens, Crytur, Asphericon, etc.
The research directions of the Centre are oriented towards the field of super-precise and special optics. Significant, well-recognizable R&D directions of TOPTEC are:

- Design, optimization, and construction of modern, compter controlled and monitored optical systems using optoelectronic elements. Development of computer assisted alignment procedures.
- Research and development of processes for the processing of optical glass, ceramics and metallic materials, i.e., research of polishing, grinding, and glass moulding processes, as well as processes of ion beam figuring aimed at atomic surface layer etching intended for fine corrections of element surface shape.
- Research and development of thin films for antireflection and superreflection purposes, such as application-specific layer systems used in optics for high performance lasers.
- Research of measurement and analytical methods for use in measuring the shape of optical surfaces, as well as in precise spectroscopy, hyperdimensional analysis, measurement of refractive index distribution, surface quality analysis, and many others.
- Material research focused mainly on ferroelectric and other non-linear optoelectronic materials, or the use of new materials for the manufacturing of thin layers with unique properties.

The TOPTEC Centre currently features a high-quality scientific team with international experience from leading world research centres (e.g., EPFL, Switzerland; CERN Switzerland; Lund University, Sweden; ITO, Germany).
The quality of its research activities can be documented by regular publication of achieved results in prestigious international journals focused on optics and related topics, e.g., Scientific Reports, Journal of Applied Physics, Physical Review B, Applied Optics, or Applied Physics Letters. The Centre is also an established investigator of grant projects under the Czech Science foundation (four projects in total, in two ongoing projects where TOPTEC is the main investigator and co-investigator). The Centre also participates in the Freeform Project under the Horizon 2020 program focused on reference algorithms and metrology for aspheric and free-form lenses. Recently, we have been working on ERC CZ, which is a program aimed at unsuccessful applicants of ERC who got very high ranking but their projects were not recommended for funding. The Centre also solves projects of the Technology Agency of the Czech Republic and the Ministry of Education, Youth and Sports as well as projects of the Ministry of Industry of the Czech Republic and the Ministry of the Interior of the Czech Republic.

TOPTEC Laboratories provide extensive instrumental, machine, and analytical infrastructure which enables the implementation of complex research and development tasks at various Technology Readiness Levels. The necessary mechanical parts for use in optical systems, alignment aids, mounting clamps, or measurement setups is also developed and manufactured within the Centre.

The long-term strategy of TOPTEC focuses on achievement of excellence in selected key areas such as the development of complex optical surface treatment technology, the transition from simple optical elements to complex optical systems, hyperdimensional analysis, advanced spectroscopy, or development in the field of infrared optics. Inevitably, there is constant drive towards increasing competencies in the area of precision and special metrology.

In 2019, the Centre got funding for a new PRESO project, which is oriented towards fundamental research in selected areas in cooperation with leading industrial partners, i.e. Crytur CZ and Asphericon GE.

For each activity, the main aims, running projects, achieved results, and other details are provided further in the text.

Optical Systems and Crystal Optics

The Optical Systems and Crystal Optics group of the TOPTEC team focuses on the research, development, and production of optical systems and studies crystal optical elements. The team designs complex optical and optoelectronic systems which are subsequently analysed regarding, e.g., tolerance totals, concerning, for instance, the manufacturability of individual components, dilation, or nonhomogeneity of refractive index. The systems designed and completed by the Centre often feature optoelectronic parts or crystal optical components. Atypical crystal elements and those characterized by a high degree of manufacturing difficulty are realized directly in the department´s laboratories.

Activities

Numerical Simulations

The team´s strength lies in its deep knowledge of complex optical simulations. Their standard tools include the commonly used Code V or Zemax optical design software as well as customized in-house developed programs, and they are able to simulate all types of crystal optical elements from both known and atypical crystal materials. The field of X-ray optics requires a simulation of all the produced parts and systems, primarily for the tolerance calculations carried out when designing these high-precision elements.

Experiments

The group participates in designing and conducting experiments at the TOPTEC Centre and oversees the development of experimental equipment used in crystal and X-ray optics. Great emphasis is also laid on the modernization of the existing unique in-house built equipment.

Prototype Manufacturing

The Optical Systems and Crystal Optics group closely cooperates with other groups of the TOPTEC Centre in designing and fabricating all known types of crystal optical elements, including those imposing atypical requirements, primarily from silicon dioxide and perovskite birefringent crystals. Other products include high-precision phase wafers for adjusting the polarization position of light, including achromatic elements, precise uniaxial and biaxial polarizers, professional narrow-band filters for wide spectrum ranges, and Babinet, Soleil, Berek and Šolc compensators. In addition to the optical elements, it is possible to deliver their casing as well.

Research

The research of the Crystal and X-Ray Optics group focuses on the following areas:

- construction and installation of astronomical satellite and ground segment devices;
- design and realization of systems for optical diagnostics;
- analysis and production of unique crystal optical elements;

Main results

- Patent: Optical element - patent document number: 306085. The optical element for information panels (Variable Traffic Signs). The team developed highly optimized complex optical structures for several purposes of panels of Eltodo a.s. company. Freeform elements were used and many paremeters, like geometry, mixing of colors from RGB LED, resistance again ghost solar reflections, irradiation characteristics were variables of the model.
- Patent: High-power laser beam mirror converter - patent document number: PV 2018-708. The mirror converter for a high-power laser beam was developed on the basis of a joint project called "Laser process optics of a new generation" with the company LaserTherm, spol. s r.o. The whole laser head optics in a standard laser head was replaced by copper segmented freeform mirror which is possible to cool with running water and due to simplified construction the 50 kW continual power in NIR lasers for machining is possible.
- Patent: An optical system for producing a structured beam – patent document number 18305552.4-1020. Nondiffractive beams have unique properties regarding it divergence and self restoration of the beam if part is lost. The nondiffractive beam has vast field of applications – a spin off company based on this IP is going to be set up. The license has been already sold to - Aircision, Netherland. The patent is owned by CERN 50% and IPP 50%.
- Patent: A device for monitoring a quality of moving linear textile material at an operating unit of a textile machine – patent document number EP2687838B1, The patent protects unique construction of optical system mechanical construction of micro illumination system and optical sensing system the patent is owned by Rieter 50% and IPP 50%.

Currently, the group finished two major phases of space projects in cooperation with the European Space Agency (ESA):

- NEOSTEL (Near Earth Object Survey TELescope) ‘Fly-Eye’ telescope optics - demonstrator. NEOSTEL is a ground based telescope for sky surveillance and automatic searching for potentially dangerous objects in the proximity of the Earth. The group designed, developed and manufacturedf polygonal aspheric elements of the Fly-Eye telescope, a system for the rough alignment of the telescope by means of laser beams, and a thermally compensated active optics low beam divergence autocollimator with a 700 mm-diameter for the final alignment of the telescopeIn cooperation with SQS Nova Paka The team designed and developed an optical system for high-power fibre laser pumping. the part of the result was design, optimization, and tolerance analysis, as well as for prototype construction 2 freeforms were used.

- Phase B and C of development of Optical System of the Coronagraph ASPIICS (Association de Satellite Pour l'Imagerie et l'Interferometrie de la Couronne Solaire) for the PROBA-3 Mission. Engineering models of optical systems, final design and simulations, documentation, etc was done.
- In cooperation with LaserTherm s.ro. of the team designed and developed two new high power laser heads. The team created analysis of thermall stress in the optics, tested surface resistance to high light intensity damage, which resulted in the minimization of the, number of head elements by means of complex optical surface shapes – freeforms.
- The team developed new collection optomechanical system with highly efficient transfer of light energy to the spectrogrf of 2m Perek telescope at Astronomical institute of CAS.
- Opto-mechanical design, tolerance analysis and delivery of CADs for 14 element neutron imaging objective - Paul Scherrer Institut
- A study and design of a solution for increasing the light efficiency an optical element in a matrix for traffic information panels, the team deliverd Design and prototzpe production and charcterization measurement of optical power, results report" for ELTODO, a.s.
- Development of the absolute illumination measurement system and its realization; realization of calibration device, mathematical physical analysis, design of the wide field objective, construction for ELCOM, a.s.
- Design status of ASPIICS, an externally occulted coronagraph for PROBA-3Renotte, E., Alia, A., Bemporad, A., Zender, J., Zhukov, A.Proceedings of SPIE - The International Society for Optical Engineering, 2015, 9604, 96040A

Cooperation

The group closely cooperates with research departments of the Institute of Plasma Physics of the CAS in Prague and with research institutions across the Czech Republic (e.g., Palacký University of Olomouc, University of Defence in Brno, Faculty of Mathematics and Physics of Charles University in Prague, Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague, Brno University of Technology, Technical University of Liberec, Institute of Physics of the ASCR, Czech Aerospace Research Centre in Prague, Rigaku Prague, Rieter Ústí nad Orlicí, Newte Teplice), as well as with international ones (ESA, OHB, CGS, Siemens, Wroclaw University, and others). Thanks to the extensive cooperation with the abovementioned institutions, we are able to deliver great results when solving problems in this field of optics. We also cooperate with a wide range of foreign organizations such as the European Organization for Nuclear Research (CERN) in Geneva and the National Institute for Nuclear Physics (INFN) in Trieste, Italy.

Optical Elements and Machining Processes

The Optical Elements and Machining Processes group is the largest group in the TOPTEC Centre. Apart from researchers and engineers, it also employs a number of technologists and laboratory specialists. The main focus lies, first, in research and development of machining processes for ultraprecise aspheric and free-form production with suppressed mid spatial frequencies, minimal subsurface damage, and reasonable processing time, and, secondly, in the ability to manufacture a variety of materials from very soft glassy materials to very hard crystal-like materials.

Activities

The main activity of the Optical Elements and Machining Processes group is to study processes producing high-quality optical surfaces whether in terms of shape quality, microroughness, spatial mid frequency suppression, or so-called ‘cosmetic’ purity. These processes include both classical machining and modern CNC subaperture methods. An additional activity is the fabrication of spheric, aspheric, as well as free-form optics focusing on high quality of elements or their uniqueness for optical systems with high requirements, e.g., for astronomical or laser application. The dimensions of the fabricated prototype items range from units of millimetres to approximately 450 mm. The shape precision achieved on these surfaces reaches fractions of light wavelengths. The resulting microroughness may reach as low as tenths of nanometres.

Research in Machining Processes and Numerical Modelling

Research is run in two key areas. One of them is the generation of the basic shape of the optical surface by means of grinding or milling and the other consists in the finishing of the optical surface by polishing, iterative correction of the optical surface shape, and the finishing of the surface with the aim of achieving its maximum quality. The area of research thus includes numerical modelling of processes, optimization of kinematic modes, observation of the chemical interactions between surfaces and polishing agents, or the increasingly important suppression of CNC machining-induced medium frequencies.

Main results

- František Procháska, Ondrej Matousek, David Tomka, Jiří Beneš, Miroslava Pechociakova, "Concept of a polishing tool based on viscoelastic properties for midspatial frequencies suppression on aspheric surfaces," Opt. Eng. 58(11) 115102 (28 November 2019) https://doi.org/10.1117/1.OE.58.11.115102 (IF 1,286)
- Light-weighted anular aspheric mirrors of the METIS (Multi Element Telescope for Imaging and Spectroscopy) telescope for the ESA Solar Orbiter mission – EUROPEAN SPACE AGENCY. METIS is a coronagraph developed for the study of the structure and dynamics of the solar corona, primarily in the deep UV region. Thus the mirrors are extremely polished to the sub nm microroughness and the optical shape achieved was better than fraction of wavelength of He Ne laser. The group

developed optics and mechanics, and the whole apparatus was sucesfully launched in beginning of 2020.

- Repeatable machining process for aspherical optics used in advanced optical systems The project in cooperation with Meopta received a TECHNOLOGICAL AGENCY OF THE CR award for the best academia and industry cooperation.
- The new nanofiber material was developed and tested for ultrafine optical surface polishing Nanofibres and nanoparticles of abrasives as the foundation of a new generation of tools for ultrafine surface polishing – TECHNOLOGICAL AGENCY OF THE CR.
- New method for supperesion of creation and later elimination of medium spatial frequencies of surface structures during production of aspheric and free-form optical surfaces was developed, the key is the use of material with tuned viscoeleastic properties of tool body.
- The team developed and optimized a manufacturing technology for PbWO3 crystaline material for use in large calorimeter in CERN. Almost any prismatic element has specific shape – in several thousands of elements. Technology is suitable for semi serial s production in cooperation with CRYTUR, spol. s r. o.
- Špína M., F. Procháska a R. Melich. Scratch and dig analysis for Metis mirrors surfaces defects evaluation [online]. , 101510P- [cit. 2017-01-25]. DOI: 10.1117/12.2256634. ISBN 10.1117/12.2256634. available at: http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.2256634

Cooperation

The group cooperates closely with a broad spectrum of scientific R&D departments in the Czech Republic, both in the academic (Technical University in Liberec, Czech Technical University in Prague, Institute of Thermomechanics of the ASCR, Institute of Physics of the ASCR, Institute of Scientific Instruments of the ASCR, Medical Faculty of Charles University) and the application sphere (Meopta optika, Polpur, Diaz). As far as international cooperation is concerned, the group has participated in research activities with, among others, Technische Hoschule Degendorf, TNO Nederland, IOM Leipzig, or Durham University UK. The list of important clients requiring customized solutions include Meopta optika, Elcom, CGS, ESA, AIRBUS, Antares, SIEMENS, and RIETER. Thanks to this versatile cooperation, the TOPTEC Centre, including the Optical Elements and Machining Processes Group, has gained a European-scale reputation as a top scientific R&D centre.

Thin Film Deposition and Hyperdimensional Imaging

The Thin Film Deposition and Hyperdimensional Imaging group of the TOPTEC Centre focuses mainly on research into new ways of designing and deposition of thin layers with unique features, as well as on material and structural layer research. The group also studies methods for hyperdimensional imaging, specifically for hyperspectral imaging, computational optical imaging, application of hyperdimensional imaging in spectroscopy, etc.

Activities

Research into Losses in Thin Films

The group has been carrying out research into absorption – and losses in general – in thin film systems. The main emphasis is on colour resistance for use with high power lasers. Another line of research is concerned with absorption lines of water vapour in the infrared region and with the structure of films suppressing the impact of water vapours on optical parameters of optical surfaces.

Design of Thin Film Systems

One of the main objectives of the Thin Film Deposition and Hyperdimensional Imaging Group is the study of deposition processes and of optimum composition of thin film systems for visible and infrared regions. Special attention is paid to new approaches to achieving deposition homogeneity.

Characterization of Thin Film Systems

The methodology is based mainly on ellipsometric and spectroscopic data and numerical modelling. The group has the option to use destructive test equipment for analyses at other sites.

Development of Monitoring and Power Systems for Vacuum Deposition

The expertise of the TOPTEC Centre employees in electronics, automatic control, and measuring technology enables the Centre to develop systems for controlling non-standard deposition processes. A typical example is the development of a control system for coating deposition, where technological parameters may influence optical, mechanical, electrical, and magnetic properties.

Hyperdimensional Imaging

One of the new trends developed by the group is Hyperdimensional Imaging (combining imaging with spectral or temporal resolution), particularly in exotic spectral (infrared) and temporal (fs) regions, where the use of standard methods is problematic or impossible. This activity includes work on the so-called computational imaging, where the development of new imaging systems with alternative approach (without the use of a lens) is carried out by means of algorithms of compressed sensing.

The group performs the auxiliary activity of prototype manufacture of special thin films whether for the purpose of solving other projects of the Centre or for external customers such as universities and research centres. This area of R&D includes computations of thin film systems based on customer specifications. The design is based around the required spectral and phase characteristics or on the description of the application of the given thin film system. The design also usually undergoes a simulation of the deposition yield and can be optimized according to the character of the deposition technology. The group participates in designing and performing experiments conducted at the TOPTEC Centre, primarily by fabricating parts of experimental equipment and carrying out measurements and analyses.

Main results

- Extensive study of infrared imaging system for Thermal Infra-Red Imager - Technology Pre-Development for AIRBUS SA, Toulouse, France. The study included the instrument covering the swath of Sentinel-2 and providing TIR imagery in at least two spectral channels with moderate top of atmosphere temperature resolution (about 0.5 K) adequate for land monitoring.

- Patent: A focusing lens of a system for hyperspectral display, patent document number 27447. The patent protects intellectual property on design of focusing lens of imaging spectrometer with wide field of view and image-telecentric properties.
- Vojtíšek P., Květoň M., Richter I. : Effective spectral dispersion of refractive index modulation. Journal of Optics (2017), nr. Of paper 045603. ISSN 2040-8978 Journal of Optics (IF 1.741)
- O. Denk O., Musiienko A., Žídek K.: Differential single-pixel camera enabling lowcost microscopy in near-infrared spectral region. Optics Express 27(3), (2019) (IF 3.356)
- Žídek K., Hlubuček J., Horodyská P., Budasz J., Václavík J.: Analysis of sub-bandgap losses in TiO2 coating deposited via single and dual ion beam deposition. Thin Solid Films. Roč. 626, March (2017), s. 60-65 ISSN 0040-6090 Thin Solid Films (IF 1.879)
- Žídek K., Denk O., Hlubuček J.: Lensless Photoluminescence Hyperspectral Camera Employing Random Speckle Patterns. Scientific Reports. Roč. 7, č. 1 (2017), č. článku 15309. ISSN 2045-2322 Scientific Reports (IF 4.259)
- Vojtíšek, P., M. Květoň a I. Richter. Complex method for angular-spectral analysis of volume phase diffraction gratings recorded in photopolymers. Journal of the European Optical Society: Rapid Publications [online]. IEEE, 2016, 11, - [cit. 2017-01-25]. DOI: 10.2971/jeos.2016.16009. ISBN 978-1-4673-5996-2. ISSN 1990-2573.
- Hyper-Spectral Detection System of Dangerous Substances – result of the project of MINISTRY OF THE INTERIOR OF THE CR in program SECURITY RESEARCH. The project results in prototype of the LWIR hyperspectral imaging system, prototype of custom infrared camera, patent and utility model.

Cooperation

The group has entered into cooperation with research institutions both abroad (e.g., Fraunhofer Institute, Germany or Lund University, Sweden) and in the Czech Republic (e.g., University of West Bohemia – Faculty of Applied Sciences, Masaryk University – Faculty of Science, Technical University in Liberec – Faculty of Mechatronics, Informatics and Interdisciplinary Studies, Institute of Physics of the ASCR, Applic Ltd. Liberec, Extreme Light Infrastructure (ELI) Beamlines, Dolní Břežany, HILASE Centrum, Dolní Břežany).

Non-Linear and Electro-Optical Materials

The Non-Linear and Electro-Optical Materials group of the TOPTEC Centre combines selected activities related to the research into the properties of nonlinear optical materials and electro-optical and electromechanical materials. The main objective of this research is the discovery of new principles and natural causations and the study of physical phenomena in which optical materials react with a static or quasi-static electric field and mechanical effects. The focus is primarily on ferroelectric monocrystals and transparent ferroelectric ceramics. Sophisticated instruments for suppressing vibrations in optical systems, adaptive optics systems, and systems for generating higher harmonics are examples of relevant applications from this category.

Activities

The TOPTEC Centre performs fundamental material research in the following areas:

- Optical, dielectric and electromechanical properties of ferroelectric domain structures research using numerical simulations based on a so-called phase-field model.
- Methods for simulation of optical wave propagation in ferroelectric materials.
- Experimental methods for the characterization of refractive index distribution in nonlinear optical materials by means of digital holographic microscopy and tomography.
- Experimental methods for the characterization of domain structures in ferroelectric materials based on the measurement of nonlinear macroscopic dielectric response.
- Research, development, design, and fabrication of composite structures with piezoelectric or electrostrictive materials, development of control electronics and control algorithms for application in adaptive optics. By means of the developed mechatronic structures, the team produces deformable mirrors and systems with spatially tunable optical length. The group also deals with numerical simulations of complex systems using the final elements method. The team members have considerable experience of simulations covering static as well as dynamic response and linear as well as nonlinear systems including modal and frequency analysis.

Main results

- Denk, O., Zheng, K., Zigmantas, D., & Žídek, K. (2019). Compressive imaging of transient absorption dynamics on the femtosecond timescale. Optics express, 27(7), 10234-10246 (IF 3.669).
- Denk, O., Musiienko, A., & Žídek, K. (2019). Differential single-pixel camera enabling low-cost microscopy in near-infrared spectral region. Optics express, 27(4), 4562-4571(IF 3.669).
- Václavík, J., Kodejška, M.,Mokrý, P. „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 (IF:4.355)
- Steiger, K., Mokrý, P. “Finite Element Analysis of the Macro Fiber Composite Actuator: Macroscopic Elastic and Piezoelectric Properties and Active Control There of by Means of Negative Capacitance Shunt Circuit.” Smart Materials and Structures 24, no. 2 (February 1, 2015): 025026. doi:10.1088/0964-1726/24/2/025026. (IF 2.449)
- Mokrý P., Sluka T.: Identification of defect distribution at ferroelectric domain walls from evolution of nonlinear dielectric response during the aging process. Physical Review B. Roč. 93, č. 6 (2016), s. 064114 ISSN 2469-9950 Physical Review B (IF 3.836)

- Mokrý P., Psota P., Steiger K., Václavík J., Doleček R., Vápenka D., Lédl V. : Ferroelectric domain pattern in barium titanate single crystals studied by means of digital holographic microscopy. Journal of Physics D-Applied Physics. Roč. 49, č. 25 (2016), s. 255307 ISSN 0022-3727 Journal of Physics D-Applied Physics (IF 2.588)
- Psota P., Lédl V., Doleček R., Mokrý P., Vojtíšek P., Václavík J.: Comprehensive time average digital holographic vibrometry. Optical Engineering. Roč. 55, č. 12 (2016), č. článku 121726. ISSN 0091-3286 Optical Engineering (IF 1.082)
- Mokrý P., Sluka T.: Identification of microscopic domain wall motion from temperature dependence of nonlinear dielectric response. Applied Physics Letters. Roč. 110, č. 16 (2017), č. článku 162906. ISSN 0003-6951 Applied Physics Letters (IF 3.411)
- Utility model: Mechanism for clamping and positioning of optical elements, document number: 32598. Utility model protects intellectual property on piezoelectricaly driven mechanism for positioning of optical elements that also reduces effect of external vibrations.

Cooperation

The group maintains close cooperation with research institutions in the Czech Republic and abroad: Technical University in Liberec – Laboratory of Optical Measurement Methods, Laboratory of Intelligent Materials and Structures, Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague – Department of Optoelectronics, Fraunhofer Institute, National Taiwan University, Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland – Ceramics Laboratory, Laboratory of Electromagnetism and Acoustics, Technical University of Dresden – Institut für Angewandte Photophysik, Dresden, Germany, Ceramics Laboratory, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, CIS Institut für Mikrosensorik (Germany).

Optical Measurement Methods and Metrology

The Optical Measurement Methods and Metrology group of the TOPTEC Centre deals with the research, development, and manufacture of optical measurement systems for the measurement of the shape of the optical surfaces of glossy as well as diffusive surfaces.
The Measurement group also provides facilities and services for other teams within TOPTEC in the area of interoperation measurement or the final characteristics of optical elements and whole systems. In addition, the team studies methods of interferometry, holographic interferometry, or microscopy for the measurement of various nonstandard quantities, including refractive index distribution, vibration amplitudes, or thermal fields.

Team Structure

The team consists of several qualified researchers who have a wealth of experience of measurement method application in demanding and highly precise tests. These tests are run for internal purposes as well as for issues solved in cooperation with the industrial sector. The team is supported by four PhD students and last-year Master´s degree students, who gain practical experience here while solving selected tasks, often as part of their master´s theses.

Activities

The group develops, on a long-term basis, methods based on using holographic interferometry (HI) in digital form. HI is applied in the measurement of vibrations which have a static character or which develop dynamically in real time. The largest share of R&D focuses on the development of methods for the measurement of the geometry of optical surfaces. The main emphasis is put on the precise measurement of the optical surfaces of elements having a complex geometry such as aspheric and free-form elements.

The group also works on the area of optical surface measurement using multiwavelength interferometry and subaperture interferometry, where the team focuses on the possibilities to increase the dynamic range of measurement or on the enlargement of the size of the measured surface.

The last area where the application of HI principles is on the increase is digital holographic microscopy or digital holographic tomography, the latter being applicable even on a microscopic scale. Tomographic measurement can be applied, e.g., when studying the properties of nonlinear materials such as ferroelectrics by means of spatial visualisation of domain structures.

The group’s auxiliary activities include the development of unique measurement tools, methods, or agents. Special measurement methods and agents are the key to the design of non-standard parts, optical systems, or equipment. For active alignment support the crucial activity is the development of Shack-Hartmann (SH) sensor and computer based tracing methods. The group has also been successful in meeting a broad range of requirements in automation for systems using computer vision and in developing a variety of instruments, methods, and software tools for data processing as well as for individual component and whole system control.

Main results

- Patent: Interferometric measurement device for asphericsurfaces, patent document number 306463. The patent protects new construction of interferometric setup, which significantly increases the measurement range regarding the asphericity of the surfaces. The patent is owned by IPP 50% and Meopta 50 %.
- Lédl V., Psota P., Kaván F., Matoušek O., Mokrý P.:Surface topography measurement by frequency sweeping digital holography. Applied Optics. 56, 7808-7814 (2017) (IF 1.650)
- Mokrý P., Lédl V., Psota P., Sládek J., Steiger K., Václavík J. : Three-dimensional imaging of ferroelectric domain structure in periodically poled lithium niobate using digital holographic tomography. Applied Physics Letters. Roč. 112, č. 15 (2018), č. článku 152903. ISSN 0003-6951 Applied Physics Letters (IF 3.411)
- P. Psota, P. Mokry, V. Ledl, M. Stasik, O. Matousek, and J. Kredba, "Absolute and pixel-wise measurements of vibration amplitudes using time-averaged digital holography," Optics and Lasers in Engineering 121, 236-245 (2019) (IF 4.273).

- P. Psota, P. Dancova, G. Cubreli, V. Ledl, T. Vit, R. Dolecek, and O. Matousek, "Development and application of spatial carrier interferometry for whole field real-time investigation of temperatures in liquid media," International Journal of Thermal Sciences 145 (2019) (IF 3.476).
- Mokrý P., Psota P., Steiger K., Václavík J., Doleček R., Lédl V. and Šulc M.: Noise suppression in curved glass shells using macro-fiber-composite actuators studied by the means of digital holography and acoustic measurements, AIP Advances. 02/2015; 5(2):-. DOI: 10.1063/1.4913624 (IF 1.52)
- Psota P., Mokrý P., Lédl V., Vojtíšek P.: Image plane digital holographic microscope for the inspection of ferroelectric single crystals. Optical Engineering. Roč. 55, č. 12 (2016), č. článku 121731. ISSN 0091-3286 Optical Engineering (IF 1.082)
- Psota P., Lédl V., Kaván F., Matoušek O., Mokrý P. : Surface profilometry by digital holography. IEEE International Conference on Emerging Technologies and Factory Automation. IEEE, 2017. ISBN 978-1-5090-6505-9. ISSN 1946-0759. [22nd IEEE International Conference on Emerging Technologies and Factory Automation. Limassol (CY), 12.09.2017-15.09.2017]

Cooperation

The group closely collaborates with research sites in the Czech Republic as well as abroad: Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, LNE LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS, Meopta, Corp., Technical University in Liberec – Faculty of Mechatronics, Informatics and Interdisciplinary Studies, Institute of Scientific Instruments of the ASCR, Asphericon GMBH, Crytur Ltd., University of Eastern Finland – Institute of Photonics, CMI – Czech metrological Institute, VUTS – Textile Research Institute, Czech Technical University in Prague – Faculty of Mechanical Engineering.

Fine Mechanics

The Fine Mechanics group of the TOPTEC Centre focuses primarily on the development, design, construction, and production of mechanical elements of optical systems. The core of the group lies in its developmental prototype workshops.

Activities

Construction
The Fine Mechanics group´s focus is on development tasks in the area of constructing mechanics for optical systems. The main activity consists in analyses, design, and construction of prototype parts, and in the preparation of technical documentation. The analyses include numerical simulations required for their optimization according to selected criteria.

Numerical Simulations
The team is able to run complex numerical simulations such as linear static and nonlinear analyses, modal analyses, harmonic analysis, thermal and thermomechanical analyses,

heating and cooling analyses (including radiation and induction heating), and dynamics and kinematics of body systems. Another line or research studies approaches to numerical simulations of technological processes such as glass pressing or optical surface polishing.

Prototype Production
The Fine Mechanics group includes a prototype workshop for the production of mechanical parts of optical systems and precise moulds, as well as the production of mechanical parts of experimental setups. Thanks to the software equipment and instrumentation available, as well as to the extensive experience of the team, the commonly achieved precision of machining of complex systems and general surfaces reaches the order of units of micrometres.

Main results

- Patent: Molding of optics enhancements, patent document number: 308253. Patent protects new construction of the mould made from highly thermally resistive steel coated with NiP. This construction allow us to get quite easily complex shapes of the fimnal element and the production is cost effective.
- Veselý M., T. Vít a J. Pleštil. The mounting system of lenses in ASPIICS coronagraph [online]. [cit. 2017-01-25]. DOI: 10.1117/12.2257230. ISBN 0.1117/12.2257230. available at: http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.2257230
- Alignment of solid targets under extreme tight focus conditions generated by an ellipsoidal plasma mirror, Kumar, D., Šmíd, M., Singh, S., Nakatsutsumi, M.,Fuchs, J., Ledl V.,Matter and Radiation at Extremes, 2019, 4(2), 024402,

Cooperation

The group closely cooperates with research institutions across the Czech Republic (Technical University in Liberec, Institute of Thermomechanics of the ASCR, Institute of Physics, Medical Faculty of Charles University, etc.), as well as with international ones (Fraunhofer Institute, National Taiwan University, etc.). Thanks to the cooperation with the above-mentioned subjects, the TOPTEC Centre is able to deliver great results when responding to challenges in in the field of optics