SYLWESTER KALISKI INSTITUTE OF PLASMA PHYSICS AND LASER MICROFUSION

Attachment 3

The development and application of spectroscopic diagnostics in plasma impurities and plasma-wall interaction research in the context of the future fusion reactor

Dr. Monika Kubkowska
Summary of Professional Accomplishments

WARSAW 2019

Contents

1. Personal data

Monika Katarzyna Kubkowska
ORCID ID: 0000-0003-1320-7468

2. Titles and degrees obtained

PhD: 2007, Warsaw University, Faculty of Physics
title of the PhD thesis: Investigation of selected electronic states of Na_2, Li_2, Zn_2 and ZnKr molecules with the use of laser and classical spectroscopic methods
scientific supervisor: Dr. Paweł Kowalczyk, Associate Professor

MSc: 2003, Warsaw University, Faculty of Physics
title: Experimental and theoretical studies of Zn resonance line wings (λ = 213.8 nm) broadened by Kr
scientific supervisor: Dr. Teresa Grycuk, Assistant Professor

BSc: 2001, Warsaw University, Faculty of Physics
title: Van der Waals interaction spectroscopy
scientific supervisor: Dr. Teresa Grycuk, Assistant Professor

3. Information about employment

Since 1.04.2011 – Head of Nuclear Fusion and Plasma Spectroscopy Department at the Institute of Plasma Physics and Laser Microfusion (IPPLM)
1.10.2010 -31.03.2011 – acting Head of the Physics and Laser Plasma Fusion Technology Department, IPPLM
Since 1.01.2008 – Assistant, Laser Plasma Division, IPPLM
1.06-31.10.2007 – Assistant in the Laser Plasma Division, IPPLM

4. Indication of the achievement resulting from art. 16 sec. 2 of the Law of 14 March 2003 on academic degrees and academic title, and on degrees in the field of art (Journal of Laws of 2017, item 1789) constituting the basis of the habilitation procedure.

4.1. Title of the scientific achievement

The development and application of spectroscopic diagnostics in plasma impurities and plasma-wall interaction research in the context of the future fusion reactor

4.2. List of publications constituting the basis of the habilitation procedure (listed in order of appearance)

[H1] **M. Kubkowska**, P. Gasior, M. Rosinski, J. Wolowski, M.J. Sadowski, K. Malinowski, E. Skladnik-Sadowska, Characterisation of laser-produced tungsten plasma using optical spectroscopy method, European Physical Journal D 54, 463 (2009)

[H2] **M. Kubkowska**, E. Skladnik-Sadowska, K. Malinowski, M. J. Sadowski, M. Rosinski, P. Gasior, Research on laser-removal of a deuterium deposit from a graphite sample, Journal of Physics: Conference Series 508, 012015 (2014)

[H3] **M. Kubkowska,** P. Gąsior, E. Kowalska-Strzęciwilk, E. Fortuna-Zalesna, J. Grzonka, L. Ciupinski, Investigation of the irradiation effects on laser-removal and surface morphology of mixed material sample, Journal of Nuclear Materials, 438, S750 (2013)

[H4] P. Gasior, M. Bieda, **M. Kubkowska**, R. Neu, J. Wolowski, ASDEXUpgrade Team, Laser induced breakdown spectroscopy as diagnostics for fuel retention and removal and wall composition in fusion reactors with mixed-material components, Fusion Engineering and Design 86, 1239 (2011)

[H5] S. Almaviva, L. Caneve, F. Colao, P. Gąsior, **M. Kubkowska**, M. Łepek, G. Maddaluno, Double pulse Laser Induced Breakdown Spectroscopy measurements on ITER-like samples, Fusion Engineering and Design 96-97, 848-851 (2015)

[H6] S. Almaviva, L. Caneve, F. Colao, G. Maddaluno, N. Krawczyk, A. Czarnecka, P. Gasior, **M. Kubkowska** and M. Lepek, Measurements of deuterium retention and surface elemental composition with double pulse laser induced breakdown spectroscopy, Physica Scripta T167, 014043 (2016)

[H7] **M. Kubkowska**, E. Skladnik-Sadowska, R. Kwiatkowski, K. Malinowski, E. Kowalska-Strzęciwilk, M. Paduch, M.J. Sadowski, T. Pisarczyk, T. Chodukowski, Z. Kalinowska, E. Zielinska, M. Scholz, M., Investigation of interactions of intense plasma streams with tungsten and carbon fibre composite targets in the PF-1000 facility, Physica Scripta, T161, 014038 (2014)

[H8] **M. Kubkowska**, "Study of plasma-wall interactions using pulsed lasers," Proc. SPIE 10808, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2018, 108084A

[H9] N. Krawczyk, J. Kaczmarczyk, **M. Kubkowska**, L. Ryć, Comparison of silicon drift detectors made by Amptek and PNDetectors in application to the PHA system for W7-X, Nukleonika 61(4), 409-412 (2016)

[H10] **M. Kubkowska**, A. Czarnecka, W. Figacz, S. Jabłoński, J. Kaczmarczyk, N. Krawczyk, L. Ryć, Ch. Biedermann, R. Koenig, H. Thomsen, A. Weller and W7-X team, Laboratory tests of the Pulse Height Analysis system for Wendelstein 7-X, Journal of Instrumentation 10, P10016 (2015)

[H11] N. Krawczyk, Ch. Biedermann, A. Czarnecka, T. Fornal, S. Jablonski, J. Kaczmarczyk, **M. Kubkowska**, F. Kunkel, K. J. McCarthy, L. Ryć, H. Thomsen, A. Weller and the W7-X team, Commissioning and first operation of the pulse-height analysis diagnostic on Wendelstein 7-X stellarator, Fusion Engineering and Design 123, 1006-1010 (2017)

[H12] **M. Kubkowska**, A. Czarnecka, T. Fornal, M. Gruca, N. Krawczyk, S. Jabłoński, L. Ryć, H. Thomsen, K. J. McCarthy, Ch. Biedermann, B. Buttenschön, A. Alonso, R. Burhenn, W7-X team, First Results from the Soft X-ray Pulse Height Analysis System on Wendelstein 7-X stellarator, Fusion Engineering and Design 136, 58-62 (2018)

[H13] N. Krawczyk, **M. Kubkowska**, A. Czarnecka, S. Jablonski, M. Gruca, T. Fornal, L. Ryć, H. Thomsen, G. Fuchert and the W7-X team, Electron temperature estimation using the Pulse Height Analysis system at Wendelstein 7-X stellarator, Fusion Engineering and Design 136, 1291-1294 (2018)

[H14] **M. Kubkowska**, A. Czarnecka, T. Fornal, M. Gruca, S. Jabłoński, N. Krawczyk, L. Ryć, R. Burhenn, B. Buttenschön, B. Geiger, O. Grulke, A. Langenberg, O. Marchuk, K. J. McCarthy, U. Neuner, D. Nicolai, N. Pablant, B. Schweer, H. Thomsen, Th. Wegner, P. Drews, K.-P. Hollfeld, C. Killer, Th. Krings, G. Offermanns, G. Satheeswaran, F. Kunkel, and W7-X team, Plasma impurities observed by a pulse height analysis diagnostic during the divertor campaign of the Wendelstein 7-X stellarator, Review of Scientific Instruments 89, 10F111 (2018)

[H15] **M. Kubkowska**, B. Buttenschön, A. Langenberg and the W7-X team, W7-X plasma diagnostics for impurity transport studies, Problems of Atomic Science and Technology, No. 6, Series: Plasma Physics (118), 312 (2018)

[H16] **M. Kubkowska**, T. Fornal, J. Kaczmarczyk, H. Thomsen, U. Neuner, A. Weller and the W7-X team, Conceptual design of the multi-foil system for the stellarator W7-X, Fusion Engineering and Design 123, 811-815 (2017)

Most of the articles which I listed above originated in the framework of the national and international cooperation under the European fusion programme EURATOM, in 2009-2013 under the EFDA (European Fusion Development Agreement), and in 2014-2019 as the part of the EUROfusion consortium (www.euro-fusion.org). The programme is performed by 30 research organisations and universities from 26 European Union member states as well as Switzerland and Ukraine.

The complete list of my scientific papers published together with the information about my academic achievements, scientific cooperation and the popularization of science, can be found in the Attachment 6.

4.3. Scientific purpose of the above-mentioned papers with the description of main results and their application

Nowadays, there is a global need for sustainable low-carbon sources of electricity, and fusion is one of the technologies with the potential to meet this demand. The scientific and technological challenges facing society are still enormous, but the fusion programme performed in Europe and all over the world brings us closer to the first fusion power plant year by year. In such a device, the energy is obtained from a huge amount of heat from the fusion reactions, which originated from connection of light elements, resulting in heavier atoms and high-energy particles[1]. On Earth, nuclear fusion is developed in two variants: with magnetic and inertial confinement of plasma. In both cases, the selection of appropriate materials for the walls of the device that would maintain plasma is a very important issue that determines the working time of the reactor and discharge quality.

Studies of plasma-wall interaction (PWI) in thermonuclear devices is one of most important tasks in the fusion programme, especially in the magnetic confinement version [1]. Fundamental processes occurring during plasma-wall interaction, which change and modify the surface morphology and contents, are presented in fig.1. In thermonuclear devices like tokamak or stellarator, as a result of plasma interaction with inner wall material, impurities are released into the vessel which can lead to the discharge break or even damage of the components of the device. In addition, physical and chemical sputtering lead to erosion of plasma-facing components (PFCs) and the contamination of plasma, which also transports the impurities into deposition areas. With the passage of time these processes are also changing because the particles interact with the already modified surface. For safety reasons, inside the

---

[1] Main fusion reactions of hydrogen isotopes:
$D + T \rightarrow n(14.1\ \mathrm{MeV}) + {}^{4}He(3.5\ \mathrm{MeV})$
$D + {}^{3}He \rightarrow p(14.7\ \mathrm{MeV}) + {}^{4}He(3.67\ \mathrm{MeV})$
$D + D \rightarrow T(1.11\ \mathrm{MeV}) + p(3.02\ \mathrm{MeV})$
$D + D \rightarrow {}^{3}He(0.82\ \mathrm{MeV}) + n(2.45\ \mathrm{MeV})$

vacuum vessel of fusion devices, there is a permitted limit of fuel which must be well controlled by measurements. Due to this fact, monitoring the behaviour of impurities inside plasma as well as diagnostics for fuel and co-deposits removal are crucial [2]. PWI studies are a key issue for the proper operation of ITER (currently under construction) – the first experimental fusion reactor which will demonstrate the scientific and technological feasibility of fusion, or for DEMO – the first demonstration fusion power plant. The Fusion Roadmap document [3-4] created by the European fusion community shows how important the PWI research is. This document is divided into missions where PWI and the study of the behaviour of plasma impurities play a crucial role.

Currently, the work focuses on the development of diagnostics for monitoring the first wall composition, removal (cleaning of PFCs) of deposited layers from the tokamak's or stellarator's wall, as well as the development of new materials which will be resistant to high thermal loads and characterized by low erosion at the same time. This issue requires additional R&D in several directions, such as cleaning the inventory of a fusion device (ITER) from accumulated tritium, mitigating the retention by proper choice of wall materials and operational scenarios as well as developing methods to quantify the amount and location of retained tritium inside the fusion device. While preparing for ITER, JET (Joint European Tokamak) located in Culham, England has been upgraded with a new ITER-like Wall (ILW), whereby the main plasma-facing components, previously made of carbon (C), have been replaced by beryllium (Be) in the main chamber and tungsten (W) in the divertor. The tritium inventory with such choices of facing materials is expected to be dominated by co-deposition with beryllium and the remaining carbon, with a minor contribution from T retention in the bulk of the W tiles. The experiments during the last campaigns demonstrate that the long-term retention rate with the ITER-like Wall exhibits a significant decrease compared to the carbon wall references. Nevertheless, further investigations of the long-term retention under different plasma scenarios are required. The material deposition determines not only the long-term T retention by co-deposition but also the production of dust and flakes by disintegration of the deposited layers. Tritium might be transported to remote areas of ITER where actual removal techniques are not efficient. Thus, in situ characterisation of deposited layers (tritium quantity and surface distribution, thickness, composition) and deposition layer detritiation are of major importance for fusion device operation. Laser-based methods combined with optical spectroscopy during discharges and laser-induced breakdown spectroscopy (LIBS) between discharges could provide in situ data on the amount of material deposition and on fuel retention. A tile removal is unnecessary, and the method is compatible with tritium, beryllium and neutron activation.

Another important aspect in the research on controlled fusion is the study of the behaviour of plasma impurities in the device, especially in different experimental conditions. Knowledge about the transport of impurities in plasma is extremely important for the proper operation of the fusion device. It is also significant for the development of numerical models to simulate the phenomena occurring in the reactors. Taking into account the above-mentioned, it is required that power which reaches the divertor plate should be low enough to not cause the impurity transport to the plasma center. Nowadays, various scenarios are developed to reduce the amount of impurities originating from the components of the tokamak (stellarator), e.g. by the injection of additional gas, but they are still under development and require tests at real fusion machines. The information about diffusion and convection coefficients which describes the quality of the discharge and its stability is also important in this field.

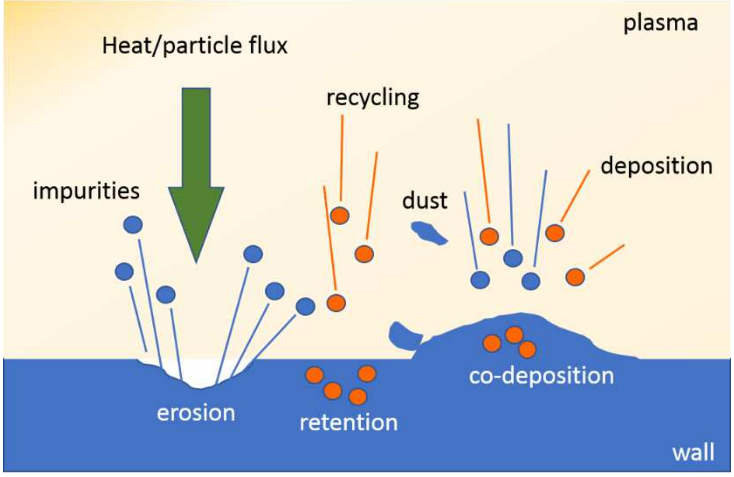

Fig. 1. Fundamental processes during plasma-wall interaction in fusion devices.

Currently, in two areas of research being performed in magnetically confined fusion covering the tokamak and the stellarator, both above-mentioned subjects are explored: plasma-wall interaction and impurity transport studies. For this purpose, a set of diagnostics is developed from which spectroscopic methods are the most promising ones because they can provide much valuable information and bring us closer to the day of the first thermonuclear power plant.

I divided the description of my scientific achievement, which is the basis for starting the habilitation procedure, into two chapters correlated with the main areas of research that I performed after the doctoral degree:

- a chapter dedicated to plasma-wall interaction studies together with the development and application of spectroscopic diagnostics for monitoring sample composition, and
- a chapter dedicated to the development of soft x-ray diagnostics for impurity behaviour studies in fusion devices.

4.3.1. Spectroscopic diagnostics in plasma-wall interaction studies

Study of plasma-wall interactions (PWI) with the application of laser pulses or plasma streams generated by liner devices like plasma focus with materials are very useful in laboratory conditions. One of the methods, which I have applied and developed over the recent years in PWI, was the laser-induced breakdown spectroscopy (LIBS) technique, which is a unique method for determination of the material content [5]. However, the application of laser pulses is arguable in terms of simulating the impact of the heat loads on the surface damage due to usually significantly higher power density and considerably shorter interaction time (from hundreds of kW and hundreds of ns to tens of GW and several ns for fibre and Nd:YAG systems respectively), lasers can be used both for maintenance and diagnostics commonly associated with PWI. The LIBS method is an analytical technique used routinely for the analysis of the elemental composition of the investigated sample. In this method, as a result of laser pulse interaction with the sample surface, first, the heating, melting, evaporation and ionization of the material take place. The analysis of the collected LIBS spectra can provide information about plasma parameters (electron temperature and density) and plasma content (which corresponds to the sample content).

The paper [H1] presents the application of the optical spectroscopy with combination of ion diagnostics and optical microscopy for determination of plasma content and surface morphology changes after interaction with laser pulses for given power density. This type of interaction can simulate the instabilities observed in fusion devices which occur during sudden heat deposition onto the wall. There are many kinds of instabilities, among which the most popular are: Edge Localised Mode (ELM), sawteeth or Vertical Displacement Event (VDE). They can occur when some parameters exceed their limit value and lead to cooling the edge plasma or even break the discharge. Each of these instabilities characterise the time and deposition power density. Application of laser pulses or plasma streams due to their wide range of parameters in PWI studies is very useful especially in the laboratory, for simulation of plasma interaction with first wall material in fusion reactors. The paper [H1] describes the results of spectroscopic investigation of laser-produced tungsten plasma. Tungsten is one of very few possible materials for in-vessel components in the future thermonuclear reactors. Therefore, each and every investigation of its properties and behaviour is very important, and in particular the characterisation of its evaporation processes from the inner wall of a tokamak chamber is needed. Tungsten has high thermal and mechanical resistance, in particular a high sputtering threshold, low fuel retention and it does not create a co-deposition, which is the reason why it is meant to be used as a material for the divertor in ITER tokamak. In the described experiment, the Nd:YAG laser system delivering energy of 0.5 J in 3 ns at the fundamental harmonic (1063 nm) was used to deliver power density at level of 10^9 - 10^{10} W/cm^2 at the sample surface. The main parameters of a plasma plume, like the electron temperature (T_e) and electron density (n_e), were estimated using the calculated Saha-LTE spectrum from the NIST database. The spectroscopic measurements have been complemented by results of ion diagnostics, namely ion collectors and an electrostatic ion energy mass analyser. The spectra collected by the ion energy analyser showed that the plasma included tungsten ions up to W^{+6} and the signals from the ion collector allowed to estimate the average ion energy as of 4.6 keV. Such information is significant for the fusion reactor operation because ions generated during the PWI can disturb the discharge and affect the impurity transport. In addition, structural changes in target surface after irradiation with laser pulses were also investigated in this work by means of an optical microscope. The investigation of the target surface shows that in case of application of high power density melting of tungsten is visible while at lower power density only the changes in surface morphology are observed. These results are important again from the power plant point of view because some material droplets can penetrate the plasma as a result of melting, which is dangerous and can lead even to damaging internal components.

In paper [H2] I presented the application of laser pulses for the removal of co-deposits from TEXTOR (Tokamak EXperiment for Technology Oriented Research) tokamak elements. This device was located in FZJ Juelich in Germany and was closed at the end of 2013. In the experiment described in [H2] a deuterium-deposited graphite sample (Toyo Tanso, IG-430U) cut out from a TEXTOR toroidal limiter, which was earlier exposed to a series of discharges performed with the pure deuterium filling, was investigated. Historically, TEXTOR tokamak was a metallic device with a stainless steel wall; however, due to erosion and release of high Z elements to the plasma (like iron, nickel or chromium), low Z materials have been considered for the first wall, mainly made of carbon and used as so-called plasma limiter elements. The main advantages of carbon composites, such as good thermal conductivity, resistance to short-and a long-term thermal stress, low fragility, no melting but sublimation, whereby the element retains its shape even under high thermal loads, lead to carbon being considered a material for the divertor in the ITER tokamak. That is why the investigation of carbon played a crucial role then. Unfortunately, due to the carbon chemical erosion, which results in accumulation of fuel, and also the fact that high thermal loads caused by disruption can lead to crushing of the material and generate the dust, only tungsten is foreseen as a material for the ITER divertor.

In the paper [H2] the application of nanosecond Nd:YAG laser (3.5 ns, 0.5J@1065nm) for fuel retention and fuel removal has been shown. However, it strongly depends on the laser wavelength and energy. The analysis shows that the fuel is retained in the material (carbon) and penetrates up to some depth. In this particular experiment, deuterium line was observed in spectra obtained from about 50 laser pulses with a power density of 0.7-1 × 10^9 W/cm^2, which corresponds to 150 µm in depth, and was confirmed by the material analysis. One of the disadvantages of a nanosecond laser as a tool for co-deposits removal, is a potential damage of the sample surface, but this requires energy in the pulse above 0.1 J (it also should be taken into account, however, that the spot of the laser treatment is very small). During the interaction of ns-laser pulses with materials craters are created, so this method, especially for fuel removal, is not appropriate as a diagnostics for tokamaks or stellarators as the internal components of the device would be damaged. Experimental results revealed the problem with fuel removal as well as the removal of co-deposited layers. The studies performed show that the application of ns-laser pulses is adequate for monitoring fuel content in the wall as well as diagnostics for co-deposits removal (applied proper laser parameters which do not cause the damage of the surface). This conclusion contributed to the new experiment in which Yb:fibre laser with lower energy in pulse (1mJ) and longer pulse duration (100-150 ns) but with higher repetition rate up to 100kHz was applied. In [H3] the aluminium sample with mixed material layer of tungsten, aluminium and carbon deposited with the use of PVD method (sputter deposition) prepared by the Institute of Electronic Materials Technology (IEMT) in Warsaw, was investigated. The analysis of this kind of sample can provide information about the efficiency of laser removal (treatment) of co-deposits from tokamak walls. In this case, the aluminium substrate was used as a proxy for beryllium[2] (which could not have been used in our laboratory due to its toxicity) while the mixed material layer together with the aluminium oxide layer simulate materials deposited during the discharges. In case of the experiment with the Yb:fiber laser, several values of power densities were used to find the thresholds for the

---

[2] Thermal conductivity of both materials, Al and Be, is relatively close (18.5 % larger for Al) also in comparison with other metals e.g. Mg, Fe, Cu, Ga, etc., the difference in the thermal diffusion is larger (~65% larger for Al). Moreover, it should be noted that both elements tend to form different crystal structures – face-centred cubic for Al and hexagonal for Be. Hardness and the Young module are significantly higher for Be. The conducted research allows to determine that the aluminium is the closest substitute for beryllium in terms of research aimed at investigating materials for PFC in fusion reactors, and that is why it was mainly used in laboratory experiments.

removal of the mixed material and ceramic aluminium oxide layers. It was found that only for the highest power density the aluminium substrate has been uncovered (the 150 μm of diameter spot in the centre of the crater) while for the lower power densities, below 10^6 W/cm^2, the ceramic layer has not been damaged, and only the mixed material layer has been removed. It means that the threshold for the removal of aluminium oxide layer is at level 10^6 W/cm^2. The application of the Yb:fiber laser presented in [H3] proves to be more effective and does not lead to substrate damages as well as does not create macroscopic dust.

In order to choose the proper laser beam parameters for the removal of co-deposits in fusion devices, the information about the wall composition is very important. While studying this subject together with my collaborators, I used the LIBS technique to diagnose fuel retention and to determine the investigated sample content, this time in metallic samples. The paper [H4] describes the results obtained for two kinds of samples: real-machine ASDEX Upgrade (AUG) strike-point tiles and calibrated C:W:Al samples prepared by the Institute of Electronic Materials Technology, Warsaw (IEMT), by sputtering were used as targets for laser irradiation. The choice of the components in these samples was aimed at investigating the spectroscopic response of various mixes of ITER-relevant materials (with Al as the Be analogue). Both types of samples contained hydrogen isotopes on their surface. In case of the AUG samples, it was the result of plasma operation, and in case of the IEMT samples, it was the result of hydrogen contamination in the production process.

In the first case, AUG samples were investigated—with 4 and 200 μm of tungsten coatings on graphite substrates produced by PVD (physical vapor deposition) method. The presence of a deuterium line in LIBS spectra was recorded only for the first two laser shots in series for both types of samples. For the samples with thin coating, most tungsten was removed during the first 5 shots. In the spectra of the subsequent laser shots, the tungsten lines become less significant due to the removal of the layer while carbon lines which are below the detection level (~10^{18} C/cm^2 for these irradiation conditions) for the first two shots became dominant. For the sample with 200 μm tungsten coating, it was observed that the metallic layer preserved for even more than ~500 laser pulses which suggests that removal rate for thick layers is lower. The results showed that the layer with fuel (deuterium) in case of metallic samples (from AUG) is much thinner and weakly depends on the thickness of the tungsten layer, which is different compared with the results obtained in [H2] with carbon samples. The qualitative results of IEA were fully consistent with those obtained for LIBS.

A second type of materials investigated in [H4] were samples provided by the IEMT which contained thin mixed materials layers consisting of C:W:Al of depth from1 to 3 μm.
One of the goals of this investigation was to measure spectroscopic signals corresponding to carbon, tungsten and aluminium for different mixtures of these components. For this purpose the concept of the “synthetic contents coefficient” (S_{cc}) was developed. The synthetic contents coefficient was the indicator of the contents of the spectroscopic signal corresponding to a given element in the overall spectroscopic signal of all plasma components. The obtained values of the coefficient were correlated with the ratio of the components in the mix, although the dependence does not seem to be straightforward (see figure 4 in [H4]). The standard deviation of the coefficients was in most cases lower than 10%, which suggests that the measurement method and its parameters were reliable. The results also indicate that the coefficient for aluminium was most sensitive to changes in the mix, and probably the matrix

effect depends more heavily on the ratio Al:W than Al:C. On the other hand, the surprisingly low coefficient for the sample with C:W:Al in ratio 1:1:1: may be attributed to the lowest thickness of the layer. Another experimental aim was to investigate the behaviour of the Balmer Hα line during subsequent laser shots at samples with different material mixtures. As it had been expected, hydrogen line was quickly decreasing in intensity for all types of layers. The shapes of the fitting curves presented in figure 5 in [H4] are very similar for all mixes, although, the fluctuation of datapoints, especially for the sample Al:W:C with ratio 3:1:2 is visible. It could suggest that LIBS diagnostics for measuring the contents of the hydrogen isotopes during the laser removal process may be relatively insensitive to the material mix of the layer in which the retention takes place. The fluctuations observed for this sample may result from the local chemical nonuniformity of the layers which consist of materials with various hydrogen retention capabilities. To construe the results, one should also bear in mind, that the total amount of the released hydrogen depends also on the removal rate of the layer. Nevertheless, the main conclusion from the performed experiment is that the fuel removal does not depend strongly on mixed material layer, which is an important result from the developing of detritation methods point of view for the future fusion devices. It is worth adding that the examined mixed-material layers (containing carbon) are also interesting due to the Wendelstein 7-X stellarator in Germany launched in 2015, which in the first operational phase was equipped with a carbon limiter, and currently – with a carbon divertor.

Understanding and investigation of wall erosion processes, fuel retention and impurity transport in plasma are one of the main critical issues, especially for ITER or W7-X, and for the development of a fusion reactor. It should be noticed that, up to now, many studies have been performed for the tiles removed from the tokamaks or stellarators (so-called post-mortem analysis) or for the calibrated samples simulated only the wall of the fusion reactor. During the progress of the research, the work has started to focus also on developing diagnostics in real machines, which will not require the removal of samples [2, 7]. This is because in the future, the access to the samples will be limited due to the use of actively cooled components and safety requirements. That was one of the reasons to proposed the LIBS method as a diagnostic for retention and wall content monitoring in the fusion devices. Currently, the LIBS-based system mounted on a robotic arm is tested and demonstrates its performance in a realistic environment in the FTU tokamak under the EUROfusion project „WP18-MST2-A: Implementation of Laser Induced Breakdown Spectroscopy (LIBS) using the Multi-Purpose Deployer". If the application of the LIBS method in the laboratory is not so complicated, it is a real challenge in real tokamak or stellarator environment. In the fusion device, it requires a proper design of the optical paths, laser and acquisition systems together with a robotic arm.

In order to improve the sensitivity of the LIBS method as an in-situ diagnostic of the tokamak wall, in papers [H5-H6] together with my collaborators, I proposed the application of the dual-pulse LIBS (DB LIBS) technique. It is based on two coaxial pulses, temporally separated by delays between 100 ns up to ms for improving the detection limits and sensitivity of the LIBS signal with respect to the standard configuration with a single pulse (SP LIBS). Although the mechanisms leading to the analytical improvements of double-pulse excitation in LIBS still need further investigation, an overall agreement exists on the main role in signal enhancement to be played by the re-excitation of the material ablated in the first laser pulse by the second laser pulse, with consequent higher plasma temperature and electron density in the second plasma (the second pulse mainly re-excites the reflected plume originating from the first pulse). In fusion applications, LIBS provides a non-contact method to determine the chemical content of the surface regions of plasma-facing components. However, the power density of the laser beam is considerable (10^7 – 10^{11} W/cm^2 for ns LIBS) and the area of interactions is limited to a spot of a submillimeter diameter. This results in ablation of down to about 10^{13} atoms from the surface. In spite of the tiny amount of the released material, LIBS ensures detection limits in range of 1 – 100 ppm as it is facilitated by high initial electron temperature (T_e> 15 000 K) and electron density ($n_e > 10^{18}$ m^{-3}). By applying consecutive laser pulses, depth profiles for the different elements on stratified deposited layers on the first wall and divertor components of the next step fusion devices can be extracted. To this end, the ablation rate of these layers has to be known accurately. Studies, which successfully confirmed this possibility, were reported in [H4] for obtaining retention depth profiles of H isotopes in mixed material layers.

The experiment described in [H5] has been performed at IPPLM laboratory together with Italian colleagues from ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development, Frascati, Italy). As investigated samples, round shaped tungsten samples, with a diameter of 25 mm and a mixed W:Al:C (Al as proxy for Be) superficial layer, co-deposited with deuterium (D) by vacuum arc deposition method, were used. In the first step of the experiment, the choice of a proper time window of spectra observation in correlation with the delay between two laser pulses in DP LIBS was important. The window suitable for signal maximization was chosen in the temporal range where conditions close to LTE (Local Thermal Equilibrium) could be assumed, in particular, the detection window was a set with gate delay of 450 ns after the first laser shot and gate width of 500 ns. The interpulse delay was fixed at 300 ns. These parameters have been chosen studying the plasma evolution with kinetic series of 20 DP laser shots delayed at step of 50 ns, in order to temporally discriminate the signal coming from the first laser pulse from that from the second one. To get the elemental composition of the surface layer in the DP-LIBS experiments the so-called Calibration Free LIBS (CF-LIBS) method has been applied. By using this method, the relative elemental concentration can be determined without prior knowledge of the sample composition. For the CF-LIBS method the electron density and temperature evaluations are accurately determined for each laser shot, using Stark broadening analysis and Saha-Boltzmann plots assuming LTE, optically thin plasma (no reabsorption) and stoichiometric ablation. In the CF procedure, the concentration of emitting species is related to the interception of the Boltzmann plot which is proportional to the logarithm of the species concentration multiplied by the experimental factor which is a priori unknown. In order to remove the unknown factor, one can use the normalization relation on the species concentration of the sample, which simply states that the sum of concentrations of all species in the analysed sample must be equal to unity. By applying this procedure to a mixed sample, the number density (particles/cm^3) of each species can be calculated. If the absolute photon efficiencies (ablated atoms per number of emitted photons) are known and the transmission of all optical components is taken into account, the absolute D (T) content can be obtained from the measured intensities. The same is possible if the ablated mass could be measured by monitoring the crater dimensions.

In both papers [H5-H6], the electron density has been calculated from the Stark broadening of the ionic emission lines, and the plasma temperature was calculated from the Bolzmann plot of the stronger and not-saturated atomic and ionic lines. The correctness of the CF method application was suggested by the laser power density (~ 3 GW cm^{-2}) being sufficient to guarantee a stoichiometric ablation of the sample surface. The application of the CF method to the experimental results by using the inferred temperature and density values led to the pattern of atomic concentrations reproducing in a satisfactory way the values found by EDX (Energy Dispersive X-ray) analysis carried out in two zones of the sample far from the laser spots.

In [H5] for estimating the concentration of deuterium and hydrogen (the resolution of the spectrometer is not sufficient to resolve the Hα and Dα lines well) the relative concentrations between H, D and C, of which the concentration is known from the CF application, validated by EDX measurements, was considered. From the ratio between the integrated line intensity of CII and H + D, the concentration ratio between carbon ion and H + D was calculated to 75.7. At the measured plasma temperature and density, the ratio between the ion and atom carbon populations was about 19. Therefore, being the total carbon atomic concentration 75%, the one of H + D was about 1.8%. Trying to separate the contribution of H and D results in a D content of 0.95%, slightly larger than the H one and compatible with the decrease of the initial deuterium concentration in the sample. The application of DP LIBS methods showed that elements at level around 1% can be detected, nevertheless in the next experiment a spectrometer with higher wavelength resolution was applied.

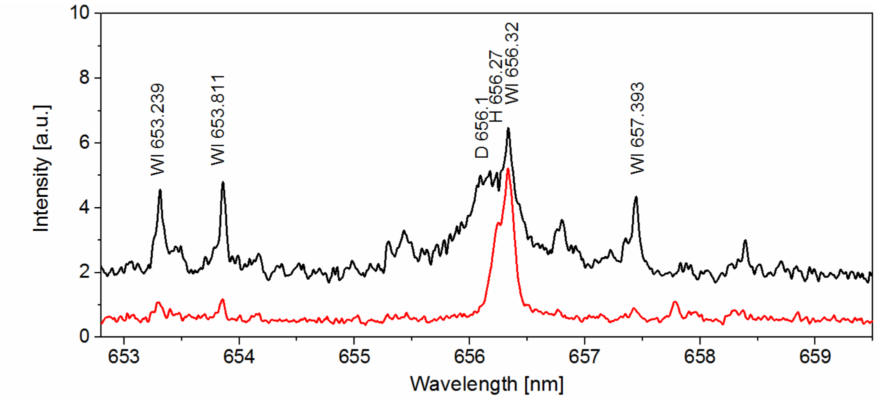

Fig.2. Comparison of SP (red) with DP (black) LIBS spectra in the deuterium (Dα) and hydrogen (Hα) emission [H6-H7].

In the experiment presented in [H6], round-shaped molybdenum samples, with a diameter of 25 mm coated with 1.5–1.8 µm thick mixed W–Al (Al as proxy for Be) layer which contained deuterium co-deposited in the superficial layer by using vacuum arc deposition method, were used. It is worth adding that the time interval between manufacturing and using the samples was of about 2 years. During this time, the samples were stored in the atmosphere. The initial amount of deuterium was at a level of a few at. percent which correspond to less than 10^{18}D/cm^2. When the DP-LIBS experiments were performed the D concentration significantly decreased due to spontaneous gas release from thin layers. In the experiment two detection systems: the first with a wide spectral coverage and moderate resolution (Me5000 with iStar iCCD, λ/Δλ = 4000), and the second with a high spectral resolution over a narrow spectral region centred on the emission of a specific trace element (hydrogen) (ISA 550 Jobin–Ivon, λ/Δλ = 50 000), were applied. The example of collected spectra in SP and DP LIBS is presented in fig. 2. The SP-LIBS signal intensity was found to be lower than the corresponding DP-LIBS. Linear emissions from the ablated superficial layer were identified, with a higher signal to nose ratio (S/N) in the DP-LIBS spectra with respect to the SP experiment. As it had been already mentioned, in order to get the elemental composition of the surface layer, the CF method was applied. Similarly to the results presented in [H5], also this time thanks to the application of CF procedure it was possible to obtain concentrations in good agreement, within the experimental errors, with those obtained from preliminary RBS (Rutherford Back Scattering) measurements. With the calculated plasma density and average temperature, the deuterium concentration was estimated to be about 1.5% (atomic), in satisfactory agreement with the nominal concentration found with SIMS.

It is worth adding, that in the described CF method, the identification of all sample components (based on spectral lines) is required, which corresponds to the application of broad wavelength range spectrometer. Only this can determine the percentage of individual elements with good accuracy. The content of tungsten and aluminium, determined in the first phase of the analysis, allowed determining the deuterium concentration by the detailed analysis of the spectrum collected in a narrower wavelength range but with higher resolution.

The application of laser pulses in plasma-wall interaction studies was described in my next paper [H7] where I presented erosion and deposition regions in fusion devices, mechanisms of material transport and main problems with PWI. The paper contains exemplary results of PWI laboratory studies using laser pulses for laser-removal of deposits from mixed materials samples using the high power density Nd:YAG laser and/or high average power but lower power density Yb:fiber laser. A description of the Laser Induced Breakdown Spectroscopy (LIBS) diagnostics, which is a potential candidate for monitoring the layer composition and fuel retention of fusion device walls is also presented.

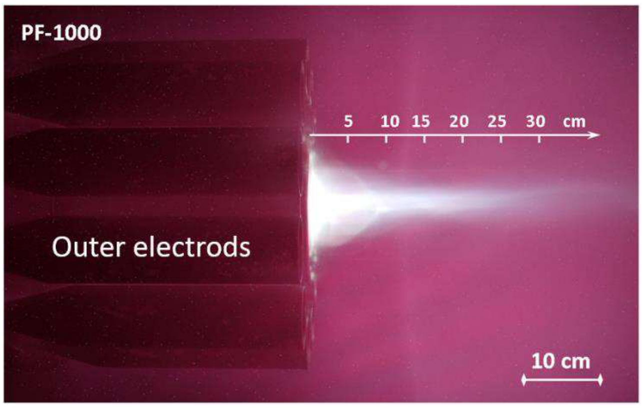

Fig. 3. A photo of the PF-1000 discharge in deuterium showing generated plasma streams range along the z-axis.

Besides lasers, linear generators of plasma streams, like plasma focus devices can be applied in PWI studies. In the paper [H8] I showed that plasma-focus device PF-1000 [8-9] located at IPPLM in Warsaw can be used for such studies in the fusion programme. A large PF-

1000 dense plasma-focus facility belongs to the Z-pinch class devices. Figure 3 presents the photo of plasma streams generated during the discharge with dimensions. Depending on target location on z-axis of the device, materials can be subject to various thermal loads, including the depositing of electrode material on the surface. In experiments described in [H8], tungsten and carbon fibre composite (CFC) samples were exposed to dense plasma streams, which consist of thermal plasma flow and fast deuterons and ions. To generate plasma streams containing significant admixtures of tungsten ions, which could simulate the tokamak plasma and interactions with materials foreseen for the first wall in thermonuclear devices upon the front of the Cu inner electrode, a central 50 mm-diameter tungsten insert was placed. Experimental studies of plasma discharges were carried out by means of different diagnostic techniques, and in particular with the optical emission spectroscope, soft x-ray pin diodes, 16-frame laser interferometer and neutron counters. Based on the spectroscopic measurements, it was possible to determine the contamination of plasma streams emitted from the PF-1000 and the main plasma parameters. Based on the calculated density and taking into account the velocity of the deuterons of the order of 10^5 m/s, the energy density of the interaction with the targets has been estimated to be in the range between 1 and 3 MJ/m^2. Interferometric measurements allowed determining the time after which the maximum number of electrons was observed in the area close to the target surface. This number could be treated as an indicator of plasma stream interaction with the target. In the described experiments, the higher number of electrons was observed for the CFC target, which is in line with expectations because this material is more erosive than tungsten. This observation confirms the decision related to ITER that carbon is not good as a divertor material. The work related to PWI studies at PF-1000 was performed within the strategic research project "Technologies supporting the development of safe nuclear power" financed by the National Centre for Research and Development (NCBiR), research task „Research and development of techniques for the controlled thermonuclear fusion", Contract No. SP/J/2/143234. In the framework of this project, I was a coordinator of the 1st goal related to the study of interaction of plasma streams generated by plasma-focus with solid targets. The detailed report of his project can be found in the monography [10].

In connection with my work, in 2017 I was asked to give an invited talk at the international conference PLASMA-2017 - International Conference on Research and Applications of Plasmas (http://plasma2017.ipplm.pl/2013-01-02-07-40-52), which took place in Warsaw (title: Study of Plasma-Wall Interactions using pulsed lasers and plasma focus devices).

4.3.2. Development and application of soft X-ray diagnostics for the stellarator Wendelstein 7-X

Parallel to work related to PWI studies, I also focused on the development and design of spectroscopic diagnostics for the stellarator Wendelstein 7-X (W7-X) which is located in Greifswald in Germany. Stellarators in comparison with tokamaks are much more complicated from the construction point of view, which results from the requirement that the plasma is stabilized by the external magnetic field formed by special coils. There are four types of stellarators from the magnetic field point of view: torsatron, heliotron, heliac and helias. Currently, the largest operating superconducting stellarator is the W7-X, which was commissioned at the end of 2015. Its scientific programme is focused on the demonstration of steady-state operation under plasma conditions relevant for a fusion power plant. This requires special technologies and technical challenges in the design process but also physics development. It is worth adding that stellarators are also listed in the document related to the European fusion roadmap [3-4], and one of the missions describes their role in the fusion programme. The W7-X will be the first fully optimized stellarator which belongs to HELIAS (HELIcal-axis Advanced Stellarator) line [11]. During the first operational phase, the plasma was limited by the 5 carbon inboard limiters, while during the second phase, W7-X was equipped with carbon divertor.

Since the beginning of my work at the Institute of Plasma Physics and Laser Microfusion I have been involved in a project related to the design and development of two spectroscopic diagnostics for the W7-X: the pulse height analysis system (PHA) and multi-foils system (MFS). At the beginning, the work was performed in the framework of the bilateral agreement between IPPLM and IPP Greifswald and was focused on studying literature. In 2011, already as a project manager, I started to recognize the apparatus which would meet the requirements set by IPP-Greifswald. The conceptual design of the PHA system was based on the results of simulation performed by the simple 1D code named RayX [12]. The difficulty in the project was the selection of appropriate detectors that could collect spectra in a wide energy range, enabling identification of both light (whose spectral lines are below 1 keV) and heavier plasma impurities (above 4-5 keV). To this end, the PHA system dedicated for the W7-X has been divided into 3 channels that can record spectra integrated along the line-of-sight through the plasma centre. Taking into account the expected plasmas impurities in W7-X and IPP requirements, finally silicon drift detectors (SDD) have been chosen for collection of soft X-ray spectra.

The investigation of silicon detectors available on the market led to the selection of two of them: one produced by Amptek (USA) and the second – by PnDetector (Germany) companies. The paper [H9] presents the comparison of two silicon drift detectors considered for a soft X-ray diagnostic system for W7-X. Both of them were equipped with the cooling system based on Peltier (single- or double-stage) and field-effect transistor (FET) located in different places in the detector chip. The nominal energy resolution given by the producers for both detectors was also similar and amounted to 135eV for energy equal to 5.9 keV. The detectors were tested in the IPPLM laboratory, including the analysis of their technical parameters. The obtained results indicated that the SDD from PnDetector is slightly better. The measurements of the fluorescence spectra showed that its average energy resolution is even better that that given by the producer and is about 123.6 eV for Fe line (for low counting rate). Moreover, technical parameters of PnDetectors, such as single-stage Peltier element, FET integrated on the chip, and active area size (10 $mm^2 \times 450\ \mu m$) were arguments for choosing them. The most important advantage of PnDetector company was the fact that during this time they had in their offer the detectors covered by thin Polymer window which was suitable for measurements of low energy range spectra (from 350 eV). Taking all these into account, detectors from PnDetector have been chosen for the PHA system dedicated for W7-X.

In my next paper [H10] I presented laboratory tests of the PHA system which was connected to the W7-X diagnostic port in the middle of 2015. The main purposes of this system are identification of the impurities and study of their behaviour in different plasma conditions, estimation of impurity concentration, estimation of electron temperature and the average effective charge, Z_{eff} (combined with simulation to extract free-bound radiation from continuum spectrum). The quality of the acquired spectra is determined by sufficient counting statistics in the individual channels. In order to have the possibility to reduce or increase photon flux of radiation that reaches the detectors, the system has been equipped with pinholes of changeable size (piezo-slits). The intensity of radiation must be at the sufficient level to guarantee the condition at which the electrical signals from individual quanta do not overlap (no "pile-up" effect) either in the detector or in the electronics following the detector. The input count rate (ICR) is the parameter which has a big impact on observed spectra. With the increase of the number of collected photons, energy resolution decreased and also pile-up effect started to be significant. In the paper [H10] I presented a conceptual design with the detailed description of main components of the PHA diagnostic.

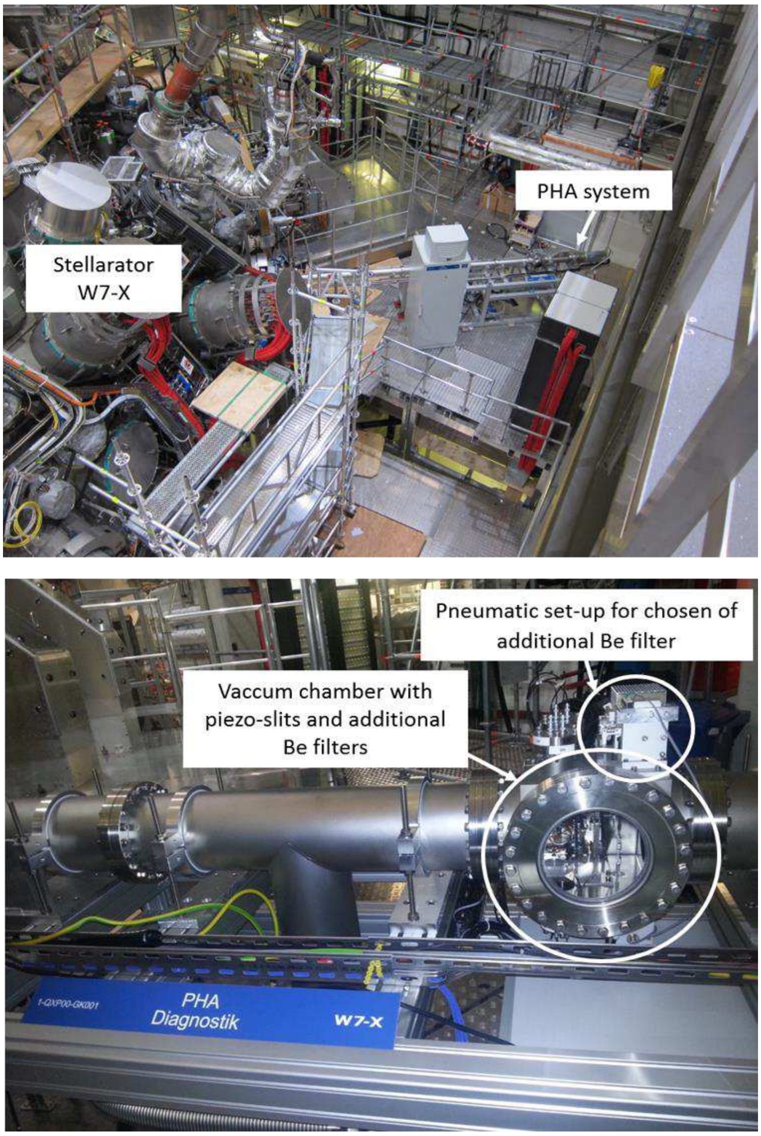

Fig. 4. A photo of the PHA diagnostic installed at W7-X.

The system consists of 3 energy channels with Silicon Drift Detector (SDD) to acquire spectra in the energy range from 0.6 to 19.6 keV (assuming 1/e transmission). The 1st and 2nd PHA channels are equipped with SDD detectors from PnDetector (type SDD-10-130) covered with an 8 µm Beryllium (Be) window, while the 3rd channel is equipped with SD3 detector with a polymer window and aluminium light protection, to cover the energy range starting from about 350eV. The application of the additional filter allows to record spectra in the chosen energy range. The energy calibration of the registered spectra is done by the measurements of fluorescence spectra of well-known materials like Fe, Cu, Cr exited by mini X-ray tube integrated in the PHA system. After laboratory tests and calibration, the system was delivered to IPP in Greifswald. With its commissioning, I was appointed as a PHA Responsible Officer at IPP. Figure 4 presents the location of the diagnostic around the W7-X. It is worth noticing that the PHA system was one of the first diagnostics that was launched during the first operational phase of the W7-X. Before delivering good-quality X-ray spectra (determined by statistics), a series of tests of the developed diagnostics were performed. The main results are presented in [H11]. It turned out that factors influencing the quality of collected spectra included: peaking time parameter which defines the shape of the trapezoidal digital filter used in the DSP (digital signal processor), pinhole size which defines the number of photons and pile-up effect. After many attempts and tests of the PHA settings, at the end of W7-X first experimental campaign, OP1.1, the 1st PHA channel was optimised. The recorded spectra from hydrogen-plasma experiments were sufficient to perform an analysis of the intrinsic impurities.

The first physical results I included in the paper [H12] where example of observed spectra with identified impurities lines presented. The least expected elements were sulphur and chlorine, whose presence was also confirmed by other diagnostics, like VUV HEXOS spectrometer. It is worth adding that the material analysis (energy-dispersive X-ray, EDX) of limiter tails, before and after the exposure to W7-X plasma, confirms the presence of both chlorine and sulphur on the surface. The source of these elements in W7-X is still unclear but probably it could be this way because of the PVC element left behind e.g. a protection cap on a bolt. Besides S and Cl, in the spectra also argon and neon He- and H-like lines were identified. These elements were injected into the W7-X plasma for study of plasma confinement time and impurity behaviour. Figure 5 presents examples of observed spectra for discharges with and without argon gas-puff with identified impurities lines. Observation of He- and H-like impurity lines is of great importance in the impurity transport studies, and in particular for modelling of processes occurring in plasma. In addition, besides the information about plasma composition, the analysis of the PHA spectra can also deliver information about electron temperature (T_e) (from the Bremsstrahlung radiation), which was the main subject of the paper [H13]. It should be noted that the obtained values of T_e correspond to average along the PHA line of sight value. To compare the calculated numbers with other delivered by other diagnostics, e.g. from Thomson Scattering (TS) system, values obtained from PHA spectra must be corrected to correspond to plasma centre. In [H13] the results obtained from experimental spectra were compared with the T_e from simulations using RayX code [12], which is based on coronal equilibrium of impurities in hydrogen plasma. The obtained values showed good agreement between simulation based on TS data and PHA data analysis within the error bars. Any differences can result from quality of the collected PHA spectra (determined by statistics), which leads to higher uncertainties in bremsstrahlung radiation or from the accuracy of TS profiles. The PHA system and the electron temperature calculated from the observed spectra are very good for verification of the central T_e value delivered by TS diagnostic because the central temperature should not exceed the value obtained by the PHA.

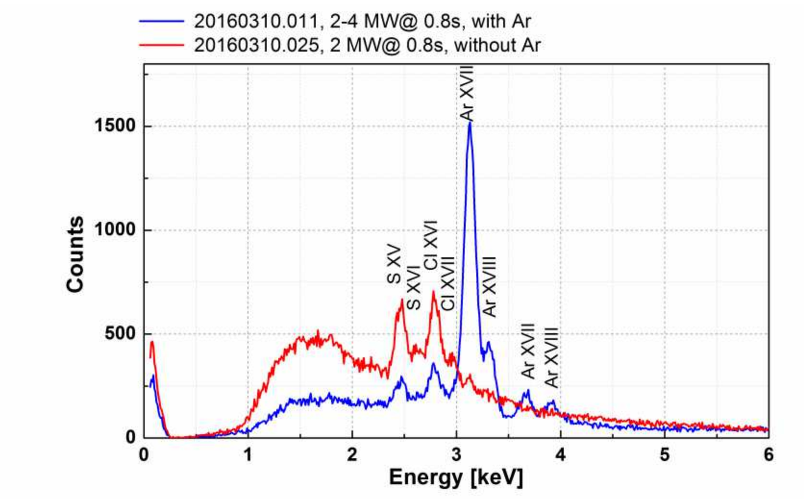

Fig. 5. A PHA spectra for discharges with (——) and without (——) Ar-puff collected during the W7-X first experimental campaign [44].

The first experimental campaign at the W7-X was mainly devoted to the integral commissioning of plasma start-up and operation, using an electron cyclotron resonance heating (ECRH) system and an extensive set of plasma diagnostics, as well as, conducting physical research, including the assessment of the power balance and the time of plasma maintenance. It should be noted that due to the complexity of the magnetic field configuration in the stellarator the source of impurity transport differs from this in tokamak due to pressure anisotropy [13-14]. In stellarators, the electrons and ions are often in different collisional regimes. The core radial electric field connected with temperature and density profiles has an impact on plasma conditions. Understanding the processes of particle interaction in plasma is crucial for the stellarator's proper operation; that is one of the reasons why the selection of diagnostics for monitoring impurities in the plasma is a very important task. The PHA system belongs to the so-called core plasma diagnostics and has been in operation since the beginning of W7-X operation.

During the next W7-X experimental campaigns, OP1.2a and OP1.2b, it was possible to optimize the other two PHA channels, and additionally, thanks to the application of additional beryllium filters with different thicknesses, to choose different energy range of observation for each channel. In [H14] I described the optimisation process of the detectors with an example of collected by all 3 PHA channels spectra from W7-X divertor campaign. Moreover, I presented the method of intensifying calibration of the PHA spectra and calculation of its emissivity in (W/m^3eV)]. The method is based on a diagnostic geometry, the influence of filters, the detector efficiency, and the efficiency of electronics (dead time) defined theoretically by exponential function (equation 5 in [H14]). The conversion of photons to emissivity (or intensity in (ph/cm^3s)) allows then to calculate the impurity concentration or the cross-calibration of other diagnostic systems (e.g. spectra delivered by X-ray Imaging

Crystal Spectrometer which observes the same as PHA, He-like ion lines). During the OP1.2 phase, the new laser blow-off (LBO) system was successfully installed at the Wendelstein 7-X stellarator and commissioned. The system allows performing impurity transport and confinement studies by the injection of different tracer ions into the plasma edge situated on a glass target holder mounted on the multi-purpose manipulator. The PHA diagnostic was one of the first systems which confirm proper operation of the laser blow-off system by the observation of injected impurity lines. This confirmed proper functioning of the LBO system. In addition, in spite of the lower time resolution of the PHA system in comparison with other diagnostics, it was possible to observe the exponential decay time of the injected elements (see fig. 7 in the [H14]), which corresponds to impurity transport time. I would like to add that during the last W7-X experimental campaign in 2018, the temporal resolution was improved by the proper settings of the PHA system. The collected spectra (registered with the time of 60 ms) allow for even more accurate study of the decay times of impurities. These results are still under analysis.

After the successes connected with the commissioning, operation and delivering first results obtained by the PHA diagnostic, in 2018 I was invited to give a talk entitled "W7-X plasma diagnostics for impurity transport studies" at the international conference International Conference and School on Plasma Physics and Controlled Fusion (ICPPCF-2018), which took place on 10-13 September in Kharkov, Ukraine. In paper [H15] I described the main W7-X diagnostics for impurity transport studies with some exemplary results obtained from recent experiments., in particular PHA system, VUV spectrometer HEXOS (High-Efficiency XUV Overview Spectrometer) and X-ray imaging spectrometers, XICS and HR-XIS (high resolution), which are devoted for measurements of spatio-temporal impurity emissivity of highly ionized ions with high temporal resolution. The PHA and HEXOS spectrometers measure spectra in very broad energy ranges while XICS being an imaging crystal spectrometer, delivers spectra in very narrow energy ranges but with higher energy resolution (it observes resonant line with satellites). All these systems are complementary and enable the verification of the results. Both spectrometers, PHA and HEXOS, can provide information for impurity decay time (transport time) study on atomic number Z. While PHA spectra consist of He- and H-like ion lines, in the HEXOS spectra of lower ionised spectral lines are observed. Thus, delivering decay time in dependence of Z, requires operation of these two diagnostics.

Another diagnostic design for the stellarator W7-X, in which I am a Responsible Officer, is a multi-foil system (MFS) which is based on the foil-absorption technique used for the estimation of the intensity of X-ray radiation and electron temperature of plasma. This diagnostic is currently in conceptual phase and has already passed the so-called conceptual design review at IPP, Greifswald. Details of this system I described in [H16]. The MFS is planned to be installed for the next W7-X campaigns OP2 (stellarator with water cooled CFC divertor, steady-state operation). Foreseen detectors will run in current mode and will be based on 40 silicon semiconductor detectors configured in a 5 × 8 matrix (5 rows and 8 columns). The detectors along a row monitor five different view cones across the plasma delivering information about the spatial distribution of the radiation. These cones of view are defined by the positions and dimensions of pinholes. The detectors along a column monitor the same plasma area, with each detector fitted with a beryllium filter of different thickness. This set-up permits the collection of X-ray spectra as a function of energy. The resulting spectra do not have the energy resolution high enough to reveal the spectral emission line structure (as is the case of a PHA system), but give the possibility to determine the slopes of spectra which are directly related to the electron temperatures of the plasma. The reconstruction of the energy spectra based on the experimental data can be performed by the deconvolution method which is an inversion method for solving integral equations. In general, the MFS system is intended for the measurement of soft X-ray in the range of 1–20 keV. The principal purpose of this system is to provide independent measurements of T_e for different plasma locations.

4.3.3. Summary of the scientific achievements constituting the basis of the habilitation procedure

In series of papers [H1-H16] I presented the development and application of spectroscopic methods for plasma-wall interaction together with impurity transport studies in the context of the future fusion power plant. These are selected articles from all my scientific achievements in which I asses my contribution as significant and important. I believe that these papers present the most important results of my research, which contributed to the development of thermonuclear fusion.

In the field of plasma-wall interaction studies I described the application of laser pulses, within the proper selection of their parameters, both in fuel and co-deposits layer removal [H2-H4], as well as for simulation of PWI in the laboratory [H1-H4, H7-H8]. Furthermore, I demonstrated the possibility of using the laser-induced breakdown spectroscopy (LIBS) method as a diagnostic for monitoring the surface composition of internal components in fusion devices [H4-H6]. The proposed double-pulsed LIBS technique was already tested at the FTU tokamak mock-up, and in 2019 will be installed FTU for final tests. In the future there are plans for the installation of LIBS diagnostic at JET and maybe even at ITER. Plasma-wall interactions in fusion devices have a huge impact on plasma behaviour (impurities behaviour) which can result in breaking the discharge and stopping the fusion reactions. Knowledge about plasma impurities behavior is very important for the determination of the operating regime and for the development of new models which are needed for optimization processes of the fusion reactor's functioning.

The set of papers [H9-H15] presents a series of articles concerning the development of the soft X-ray pulse height analysis (PHA) diagnostic for the W7-X stellarator, from the origin of the concept, through selecting detectors and components [H9], laboratory tests [H10], installation at W7-X, commissioning [H11], and finally, the first physical results confirmed also by other W7-X diagnostics [H12-H15]. The next system designed, which is planned to be installed at W7-X in the nearest future, is a multi-foil system (MFS) which will be a complementary diagnostic devoted to electron temperature profile determination. This parameter is very important from the impurity transport studies point of view. The concept of the MFS system including all IPP requirements has been presented in [H16].

I think that my greatest achievement in my scientific work is the application of the LIBS method as a diagnostic for monitoring fuel retention and co-deposits composition in fusion devices. LIBS technique is a well-known technique; however, adapting it to the tokamak or stellarator is challenging especially given the fact that it requires a lot of things which must be taken into account such as distances in optical system which collect LIBS signals, robotic arm which must deliver laser pulses to a selected place inside the device, etc. Among other candidates' methods, LIBS offers the possibility of non-contact real-time measurements of contents of different components in a sample under analysis. This specific feature is very convenient in the perspective of in-vessel fusion device monitoring of the fuel retention in plasma-facing components. Moreover, flexibility of the method allows for a distant observation of the laser induced plasma and transmission of the signal to detectors with the use of fibers.

My second greatest achievement is the installation of PHA system at W7-X and operating the system during the first experimental campaigns. I treat it as my personal success that as the project manager I have enabled my group's participation in such a big project as the W7-X programme. The PHA system at W7-X for which I am a Responsible Officer is a well-recognized diagnostic as designed, developed and operated by Polish scientists.

4.4. Description of other scientific and research achievements

4.4.1. Information about scientific work before receiving the PhD degree

In 1998, I started my studies at the Faculty of Physics at Warsaw University (WU), where after two years I managed to pursue the Optics specialization. In 2001 under the supervision of Dr. Teresa Grycuk, Assistant Professor, I defended my BSc thesis, which dealt with the spectroscopy of van der Waals interactions. I continued my work on spectroscopy of intermolecular interactions. In the academic years 2001/2002 and 2002/2003, I received scholarships for scientific achievements. In 2003 I completed my MSc studies and defended the thesis entitled "Experimental and theoretical studies of Zn resonance line wings (λ = 213.8 nm) broadened by Kr" which concerned the determination of far-range parts of interaction potential of the ZnKr molecule. In the thesis, I applied the classical absorption spectroscopy method using high resolution Rowland spectrometer.

In the same year, I started my PhD studies in the Optics Division at the Institute of Experimental Physics, WU, under the supervision of Dr. Paweł Kowalczyk, Associate professor. Then, I dealt with the use of two spectroscopic methods: laser polarization labeling and a classical one, for studying several excited electronic states of homo- and hetero-nuclear diatomic molecules.

In the framework of my PhD thesis, it was the first time when the $6^1\Pi_u$ electronic state correlated with the (3^2S+4^2F) atomic asymptote of Na_2 molecule was examined experimentally. The potential determined became the basis for the verification of existing theoretical calculations.

The next examined exited electronic state was $C^1\Pi_u$ state of Li_2 molecule correlated with ($2^2P_{1/2} + 2^2P_{3/2}$) atomic asymptote. In this case, I identified 30 vibrational progressions in the band system of lithium dimer (26 of them in $^7Li_2$ and 4 in $^6Li_7Li$), in their parts corresponding to low υ' values in the C state. In this way over 1000 transitions were assigned in the $C\leftarrow X$ system, spanning the range from $\upsilon' = 0$ to $\upsilon' = 21$ and from $J' = 1$ to $J' = 47$. Thus, the experimental potential curve provides some reliable information concerning the molecular potential for about 57% of the well depth. Furthermore, the experimental analysis also revealed a slight breakdown of the Born–Oppenheimer approximation for the Li_2 isotopomers. Since the Li_2 $2^1\Sigma^+_u$ state correlated with ($2^2S_{1/2} + 3^2S_{1/2}$) asymptote corresponds to a double-well potential, it can be represented only by the potential energy curve built by a fully quantum-mechanical procedure such as the IPA (Inverted Perturbation Approach) method. In that case the recorded spectra provided wave numbers of lines transformed to energies of 263 rovibrational levels of the $2^1\Sigma^+_u$ state in the range $30 \leq \upsilon' \leq 50$, $3 \leq J' \leq 34$ (all of them corresponding to the $^7Li_2$ isotopomer).

The second spectroscopic method which I applied was based on the analysis of spectral line wings shape which allows the determination or verification of the shape of the electronic potential curves involved in the considered transition. For Zn_2 dimmer I determined long-range part (10-25Å) of interatomic potentials of two electronic states, ^11_u and $^10^+$, correlated with $Zn(4^1P_1) + Zn(4^1S_0)$ asymptote. The oscillator strength *f* for the absorption transition to these states was also derived experimentally from the careful analysis of the self-broadened resonance 213.8 nm line of Zn. It was found that although the interatomic interactions at such long distances are dominated by the resonance potential of the form C_3/R^3 resulting in the Lorentzian line shape, the parameter C_3 and thus oscillator strength significantly decrease with R decreasing. The obtained value seemed to be the most accurate experimental result as yet and showed that the best theoretical values for this quantity were overestimated. It suggested that the long- range behaviour of the potential energy curves observed there for the first time, represented the effective potentials including dominating resonance interactions and a possible slight contribution of the dispersion interactions as well as the R-dependent spin-orbit interaction.

The results of research work performed in the framework of my PhD studies were presented in 7 scientific papers [16-22]. Moreover, the results were presented at international conferences, among others: the 17th International Conference on Spectral Line Shape in Paris (2004), the International Conference on Laser Probing in Argonne (2004) and the FAMO workshop organized in 2004 in Jurata. I also presented my results at the XXXVII (2003) and XXXIX (2005) Congresses of Polish Physicists. During my doctoral studies, I also delivered didactic lectures for students of the Faculty of Physics at Warsaw University.

In October 2007, I defended my PhD thesis entitled: "Investigations of selected electronic states of Na_2, Li_2, Zn_2 i ZnKr molecules by the use of laser and classical spectroscopic methods".

4.4.2. Information about scientific work after obtaining the PhD degree not included in the habilitation

I started working at the Institute of Plasma Physics and Laser Microfusion (IPPLM) in 2007 where from the beginning I focused on the application of spectroscopic methods in the investigation of plasma produced by laser pulses. The studies performed concerned the simulation of plasma-wall interaction in fusion devices with different materials foreseen as candidates for the first wall. They were focused on the research on plasma generated by the pulsed lasers, its main parameters (electron temperature and density) as well as the research on morphology changes of treated surfaces. The main task of my work can be summarized as optimization of laser removal process of co-deposited layer from the inner components of fusion devices, including fuel removal. The detailed study had a much wider character, which resulted from the complexity of this issue and the advanced state of fusion research, and required conducting multi-parametric experiments allowing for the multi-aspect analysis of phenomena occurring during laser-target interactions.

My scientific work at IPPLM was performed mainly in the framework of the European fusion programme supported by the European Communities under the contract of Association between EURATOM and IPPLM, and was carried out, firstly, within the framework of the European Fusion Development Agreement (EFDA), and currently it is carried out within the framework of the EUROfusion Consortium. Part of my work was also performed within the strategic research project 'Technologies supporting the development of safe nuclear power' financed by the National Centre for Research and Development (NCBiR), research task 'Research and development of techniques for the controlled thermonuclear fusion', contract number SP/J/2/143234. I mainly carried out my research in cooperation with other scientific units, both domestic and foreign. Most of the work performed on the PF-1000 plasma-focus device was carried out in collaboration with researchers from the Institute for Nuclear Studies (IPJ), and after the National Center for Nuclear Research (NCBJ), mainly with the group of Prof. Marek Sadowski. Thanks to this collaboration, I had an opportunity to participate in the experiment at RPI-IBIS facility and got some experience on other plasma generator [23]. The works performed at PF-1000 device were mainly devoted to the study of free propagating plasma streams in different experimental conditions and their interaction with various materials [24-28] for thermal load studies.

I also participated in the number of experiments which were devoted to laser pulses interaction studies with different materials. The main results can be found in refs. [29-33].

Dust generation in the interaction of plasma-facing components (especially those covered with deposits) with pulsed laser beams is not only a phenomenon associated with laser ablative fuel removal but also can simulate the effects of transient heat loads on the wall of thermonuclear reactors. Due to this fact, in 2012 I performed an experiment related to the investigation of dust parameters (grain size, initial velocity) influence on their fuel content. Another issue was the dependence of the dust parameters on the laser power density. The research included CCD observation of the dust generation process and collection of the dust particles in aerogel catchers provided by VR, Sweden. The work was performed under EFDA task WP12-IPH-A03-2-08. As the target, the ALT-II TEXTOR limiter sample covered with a thick co-deposit was used. In subsequent experimental series, the aerogel collectors were installed at distance from a part of centimeter (0.2 cm) to 1.5 cm from the irradiated area. The sample was irradiated with 5 to 10 laser shots in vacuum (5×10^{-5} mbar) or in oxygen atmosphere (10 and 100 Pa). The frame of the CCD observation varied from 10 μs to 1 ms. After the experimental series at the IPPLM, the aerogel collectors with accumulated dust were sent for further analysis to VR in Sweden. A CCD observation of the dust particles confirmed that they reach the aerogel surface from which they can be reflected, but on the other hand, most often they were absorbed. Based on the length of the tracks the velocity of dust particles was assessed at 100 m/s in vacuum and at 10-50 m/s in O_2 atmospheres depending on pressure. The main objective of this task was to catch the generated dust in to the aerogel as a potential candidate of dust catcher in fusion devices. The results confirmed that aerogels are good particle catchers [34-35]; however, the material itself still required further investigation, especially in the real tokamak or stellarator environment to check if they resist high temperature.

In the framework of other EFDA tasks (WP09-DTM-01-WP 1.1, Divertor Erosion Monitor study, WP09-DTM-01-WP 1.3, Review of the spectroscopic diagnostics foreseen in

ITER, WP09-DTM-01-WP 2.1, Study of periodic dust mobilization from hot surfaces with the use of laser scanning method) I participated in the analysis of application of laser-based techniques as diagnostics for ITER. Independently on advanced and flexible components, laser technology offers the advantage of a few methods with countless variants to measure the quantities of interest which in case of ITER divertor are displacement, deformation, thickness/distance difference and vibration with time and spatial resolution depending on the method, variant and parameters of the used equipment. Among other methods, multi wavelength speckle interferometry appeared to be the best developed and the most convenient one e.g. for ITER. In spite of many uncertainties and problems which are likely to be faced during the device final design and installation, the method may be expected to give enough power and flexibility to reach the goal.

As the solution for dealing with vibrations, application of vibration sensors and/or algorithms of digital signal processing should be considered. For reducing the negative influence of deposits on the behavior of the system fiber laser as a cleaning tool can be considered and tested.

Aging effects studies of fuel retention performed together with ENEA, Frascati on mixed materials samples (W:Al:C) were also very important. This type of experiments was previously carried out only for carbon deposits. For this reason, research on mixed materials samples were repeated after about 8 months with the use of single- and double-LIBS method for estimation of fuel content (hydrogen isotopes). In the experiments pure tungsten samples with deuterium layer were also used and the results showed that intensity line of Deuterium was almost at the same level as it was during the first experiment while for the mixed materials layer, intensity of deuterium Balmer alpha line was almost invisible – it was at noise level. It meant that the level of deuterium in the second investigated samples was below the detection limit which was calculated to 10^{16} at/cm^2. The observed behaviour of deuterium suggested that external layer has an impact of fuel retention and especially mixed material layer composed of tungsten, aluminium and carbon accelerates the release of trapped gases and prevents the accumulation of gases originated from the atmosphere (mainly water vapor, which is the main source of hydrogen). This can be explained by the low susceptibility of the W:AI:C layer to the adsorption of water and hydrogen molecules, which prevents the molecules from penetrating the layer and escaping from the substrate. If the particles presented in the substrate reach (due to diffusion) the layer, the probability of their release is greater than their return to the substrate. Furthermore, the thermonuclear fuel (i.e. deuterium) from the W: AI: C layer can be removed (by evaporation / desorption) even before the layer itself is removed, which was confirmed by measurements using material engineering methods. This can have very important consequences for the development of fuel removal techniques from the walls of the thermonuclear reactors. This creates the possibility of incomplete removal of the surface layer, which can then serve as a screen against the penetration of the fuel into the solid base material.

In the experiment performed together with ENEA-Frascati colleagues, samples from COMPAS tokamak (Prague, the Czech Republic) (deuterium), were investigated. The samples consisted of thin layer of tungsten and stainless steel (100nm) deposited by PVD method on the graphite substrate and were irradiated by deuterium plasma. The spectroscopic analysis showed that such layer was removed in one laser pulse using 25 J/cm^2 energy density.

Application of DB-LIBS method allowed us to obtain a better SNR (Signal to Noise Ratio) ratio than in SP-LIBS. Moreover, the DP-LIBS technique allowed for the precise adaptation to spectral lines observation that corresponds to various elements (presented in the sample) and ions with different charge stages.

I would like to mention that at the beginning of my work at IPPLM, I participated in the data analysis of results which were aimed at high-intensity proton beam generation driven by a short laser pulse of relativistic intensity using 100TW-laser located in LULI in France. The effect of laser intensity, the target structure and the laser wavelength on the proton beam parameters and laser-protons energy conversion efficiency were examined [36-37]. It has been shown that SLPA (skin-layer ponderomotive acceleration) makes it possible to produce collimated dense proton beams of extremely high intensities and current densities, which are significantly higher than those produced by TNSA (target normal sheath acceleration) at similar laser intensities.

The experiments I carried out as part of my PhD studies provided so many results that even after defending my PhD thesis I continued further analysis. The results obtained have been presented in refs. [38-39], in which, among others, the correction of the interaction potential coefficients for the self-broadened Zn (213.8 nm) and Cd (228.8 nm) lines was presented.

Parallel to the PWI research, I was involved in the work related to the Wendelstein 7-X stellarator programme [40-43]. In the framework of activities related to the development of the plasma diagnostics, I was also involved in the discussion related to data analysis which were of great importance after commissioning the W7-X and performing the first experimental campaign [44-45]. In my opinion, one of my achievements in this field was the contribution to the article published in Nature Physics in 2018 [14], in which the magnetic configuration effects on the W7-X and on impurity transport was presented. In this paper, also the results provided by the PHA system were included, namely, based on the continuum radiation (excluding free-bound radiation), the estimated value of the effective charge Z_{eff} presented in fig. 5 in [14].

I would like to add that I am also involved in the design and development of the W7-X diagnostic devoted to monitoring of light impurities like oxygen (O), carbon (C), boron (B) and nitrogen (N), historically named ‘CO monitor’. The system will consist of 4 independent spectrometers located in two vacuum chambers and will observe Lyman-lines of B (4.9 nm) C (3.4 nm), N (2.5 nm) and O (1.9 nm) [46]. Currently, the project has already passed the Detailed Design Review and has entered the executive stage. It will be installed at W7-X in 2020 and the first operation is foreseen in the course of the next experimental campaign at W7-X at the beginning of 2021.

As the head of the Department of Nuclear Fusion and Plasma Spectroscopy at IPPLM, I also participated in the first discussion on the tomographic system for tokamak WEST in Cadarache in France. It will based on gas electron multiplier detectors (GEM) which are developed at IPPLM [47-48].

To sum up, during all the years after completing my PhD studies, I performed research connected with the subject of the scientific achievement which I indicated as the basis for initiating my habilitation procedure. The IPPLM laboratories and equipment allowed me to fully understand and control the LIBS technique and to learn more about the physical processes occurring during the interaction of nanosecond laser pulses with various materials. As a result, together with my collaborators I could propose the LIBS method as a diagnostic for monitoring the wall erosion, material deposition and the associated fuel-retention in fusion devices. Furthermore, my contribution in the design and development, manufacture, installation, commissioning and finally, operation of the PHA system at W7-X, enabled me to get extensive experience. Moreover, I managed to build a research team that allows me to achieve my goals.

4.4.3. Organizational and educational achievements

In 2011, at the Faculty of Physics in Warsaw University of Technology, I got a ten-hour lecture on thermonuclear energy, and in 2012 I got a thirty-hour lecture entitled 'Introduction to plasma physics and thermonuclear energy'. In both cases, I developed a script to make students easier understand the issues described during the lecture. In 2013, at the Faculty of Power and Aeronautical Engineering in Warsaw University of Technology, I gave a thirty-hour lecture dedicated to fusion energy. During many years of work at IPPLM, I also conducted student internships.

In June 2018, I was selected as a member of IPPLM Scientific Board, and on the first meeting I was appointed a Scientific Board Secretary and I performed this function until 2013. This year, I was again selected for the IPPLM Scientific Board member where I was appointment a Vice-chair which function I have been performing until today. At the beginning of 2009, I became a member of the Plasma Physics Section of the Polish Academy of Science (PAS) Committee of Physics, where I was selected the Secretary and held this position until 2013. In the same year I was selected a member of the Plasma Physics Section Board, this time under the auspices of the Polish Physical Society. In 2007, I was a member of the Local Organizing Committee of the international conference "34th European Physical Society Conference on Plasma Physics", which took place in Warsaw (2-6.07.2007). In 2008, I took part and represented IPPLM in the XXII Science Picnic organized by Polish Radio and the Copernicus Science Center, (14/06/2008) in Warsaw. In 2009, I was a co-organizer of the 8th Annual Meeting of the EU-PWI Task Force, 4-6 November 2009, in Warsaw. In 2011 and 2013, I was the secretary of the Local Organizing Committee of the international conference "International Conference on Research and Applications of Plasmas" PLASMA-2011 and PLASMA-2013, while in 2015 I was the Chairwoman of the Local Organizing Committee of this conference.

In 2018, I was appointed a member of the Scientific Committee of the 14th Kudowa Summer School "Towards fusion energy", organized every 2 years in Kudowa Zdrój. Furthermore, along with the new structure of the fusion energy research programme in Europe, in 2014 I was appointed a Chairwomen of the WPS1 project: Preparation and Exploitation of W7-X Campaigns, in the consortium of EUROfusion that deals with the operation of the W7-X stellarator in Greifswald, as well as a member of the WPPFC project board: Preparation of efficient PFC operation for ITER and DEMO on IPR research. In 2018, I was appointed a member of the panel of experts in the EUROfusion consortium, which made an initial assessment of the projects submitted under the so-called 'Enabling research projects'. Since 2017, I have been a member of the "Team for scientific and technical staffs' at IFPiLM" whose tasks include conducting competitions for scientific positions and assessing the qualifications of candidates for research and technical positions at IPPLM. I am also a reviewer of scientific publications in several journals, as well as a co-author of legal and political expertise regarding the fusion area being investigated, as well as strengths and weaknesses of research on fusion energy in Poland.

The details of my scientific and educational achievements together with the description of the scientific collaboration can be found in Attachment 6.

4.5. Scientific plans for the future

Currently, I continue the subject of the work presented in papers [H1-H8] within the EUROfusion project which aims at demonstrating the LIBS method at the real fusion machine, FTU tokamak. The quantitative detection of tritium retained in the ITER in vessel components is mandatory for deciding if the machine operation must be stopped and the exceeding tritium removed. Laser Induced Breakdown Spectroscopy (LIBS) is a suitable and not invasive in situ diagnostic for detecting the retained tritium. In 2019, I will participate in the LIBS experiment which will consist of laser system and two spectrometers to collect spectra in different wavelength range: the first in a very broad range to identify all elements, and the second one in a narrow range but with high wavelength resolution to distinguish deuterium and hydrogen spectral lines. Additionally, the experimental set-up will be equipped with special nozzle which allows experiments in nitrogen, helium or argon atmosphere. The results, which will be obtained during the experiment planned for 2-3 weeks in 2019, will then be subject to detailed analysis. I hope that the successful implementation of the experiment will open the possibility of the further development of LIBS methods on larger thermonuclear devices (WEST and W7-X) and the LIBS diagnostic will be present at ITER.

In the following years, I will also continue the research described in [H9-H16], which concerns the development of spectroscopic diagnostics for the W7-X stellarator. Currently, I am dealing with the analysis of experimental data obtained from recent experiments on this device. Its aim is to investigate the behavior of plasma impurities in various experimental conditions, determine their decay time in the plasma, and thus important transport parameters (diffusion and convection). The latest results obtained in the experiment with the injection of special pellets with selected impurities, the so-called TESPEL (tracer-encapsulated solid pellet), will be presented at the 3rd European Conference on Plasma Diagnostics, which will be held in 2019 in May in Lisbon. As part of the research conducted on stellarators, in 2019 I will also take part in an experimental campaign on the LHD device (Large Helical Device) in Japan. I will participate, among others in the experiment devoted to impurity transport studies using TESPEL injection. The planned studies are aimed at comparing the expected results from the LHD system with the results already obtained in the W7-X system, as well as planning new experiments in the W7-X stellarator.

At the end of 2018 I was invited by the International Scientific Committee to give a talk at International Conference on Research and Applications of Plasmas, PLASMA-2019, which will be held in Opole. The title of my talk will be ‘Pulse Height Analysis diagnostic for impurity behaviour studies at W7-X’ (http://plasma2019.wmfi.uni.opole.pl/invited-speakers/) and will be related to possibilities, limitations, construction and use of PHA diagnostics for W7-X plasma research.

As an auxiliary scientific advisor of the PhD student Natalia Krawczyk, I am planning to finalize (in 2020 at the latest) her PhD thesis, which will be devoted to plasma research in the W7-X stellarator using the PHA diagnostic system.

References

[1] S. Brezinsek, … M. Kubkowska, et al., Nuclear Fusion, (2017) 57 (11), art. no. 116041
[2] A. Malaquias, ... M. Kubkowska, et al., Journal of Nuclear Materials, (2013) 438, pp. S936-S939
[3] F. Romanelli P. Barabaschi, D. Borba, G. Federici, L. Horton, R. Neu, D. Stork and H. Zohm, Fusion Electricity: a roadmap to the realisation of fusion energy, EFDA, 2012 ISBN 978-3-00-040720-8
[4] T. Donne, W. Morris, et al. European Research Roadmap to the Realisation of Fusion Energy, EUROfusion, 2018, ISBN 978-3-00-061152-0
[5] D. A. Cremers and L. J. Radziemski, 2013, Handbook of Laser-Induced Breakdown Spectroscopy 2nd edn (New York:Wiley)
[6] J. Roth, et al., Journal of Nuclear Materials 390–391 (2009) 1–9.
[7] V. Philipps, ... M. Kubkowska, et al., Nuclear Fusion 53 (2013) 093002
[8] M. Scholz et al. Nukleonika 51 (2006) 79
[9] F. Dabrowski, Ł. Ciupiński, M. Kubkowska, et al., International Journal of Materials Research (2016) 107 (8), pp. 729-734
[10] ‘Badania i rozwój technologii dla kontrolowanej fuzji termojądrowej. Główne osiągnięcia projektu realizowanego w latach 2011 – 2014 w ramach strategicznego projektu badawczego NCBiR: „Technologie wspomagające rozwój bezpiecznej energetyki jądrowej”, Red. U. Woźnicka, ISBN 978-83-63542-28-3, wydano nakładem IFJ PAN
[11] F. Warmer et al., Fusion Engineering and Design (2017) 123 p. 47-53
[12] S. Jabłoński, A. Czarnecka, M. Kubkowska, et al., Journal of Instrumentation 10, P10021 (2015)
[13] C.D. Beidler et al., Nuclear Fusion (2011) 5 p. 1076001
[14] A. Dinklage, .., M. Kubkowska, et al., (2018) Nature Physics, 14 (8), p. 855-860
[15] T.P. Donaldson, Plasma Phys. 20 (1978) P1279
[16] M.K. Kubkowska, et al., (2007) Chemical Physics, 333 (2-3), pp. 214-218
[17] M.K. Kubkowska, T. Grycuk, Journal of Physics B: Atomic, Molecular and Optical Physics (2007) 40 (2), art. no. 009, pp. 361-370
[18] T. Grycuk, T. Kłoda, M.K. Kubkowska, T. Kutner, Optica Applicata, 36 (4), pp. 505-510
[19] A. Grochola, M.K. Kubkowska, W. Jastrzçbski, P. Kowalczyk, Optica Applicata, 36 (4), pp. 469-473
[20] T. Kutner, M.K. Kubkowska, T. Grycuk, Journal of Molecular Spectroscopy, (2005) 233 (1), pp. 149-156
[21] M.K. Kubkowska, K. Moczadłowska, T. Grycuk, T.M. Szczęśniak, Journal of Physics B: Atomic, Molecular and Optical Physics, (2005) 38 (8), pp. 1279-1289
[22] M.K. Kubkowska, T.M. Szczęśniak, T. Grycuk, Long-Range Interactions and the Oscillator Strength for the 11u,10+u <- X10+g Transitions in Zn2, (2004) Acta Physica Polonica A, 105 (4), pp. 317-328
[23] E. Skladnik-Sadowska, K. Malinowski, M.J. Sadowski, K. Czaus, M. Kubkowska, et al. Problems of Atomic Science and Technology (2008) (6), pp. 95-97
[24] E. Skladnik-Sadowska, R. Kwiatkowski, K. Malinowski, M.J. Sadowski, V.A. Gribkov, M. Kubkowska, et al. Physica Scripta (2014) T161, art. no. 014039
[25] M. Chernyshova, V.A. Gribkov, E. Kowalska-Strzeciwilk, M. Kubkowskaet al. (2016) Fusion Engineering and Design, 113, pp. 109-118
[26] K. Jakubowska, M. Kubkowska, et al. (2011) Nukleonika, 56 (2), pp. 125-129
[27] E. Skladnik-Sadowska, K. Malinowski, M.J. Sadowski, M. Kubkowska, et al. (2011) Contributions to Plasma Physics, 51 (2-3), pp. 288-292
[28] M. Kubkowska, et al. (2010) Problems of Atomic Science and Technology, (6), pp. 202-204
[29] E. Skladnik-Sadowska, K. Malinowski, M.J. Sadowski, J. Wolowski, P. Gasior, M. Kubkowska, et al. (2009) Journal of Nuclear Materials, 390-391 (1), pp. 847-851
[30] E. Skladnik-Sadowska, K. Malinowski, M.J. Sadowski, J. Wolowski, M. Kubkowska, et al. (2010) Radiation Effects and Defects in Solids, 165 (6-10), pp. 412-418

[31] M. Kubkowska, et al. Nukleonika 57(2), 163–166 (2012)
[32] A. Czarnecka, M. Kubkowska, et al. (2013) Problems of Atomic Science and Technology, (1), pp. 258-260
[33] K. Jakubowska, M. Kubkowska, et al. (2014) Physica Scripta, T161, art. no. 014029
[34] D. Alegre, H. Bergsåker, I. Bykov, P. Gąsior, M. Kubkowska, et al. (2014) Physica Scripta, T161, art. no. 014010
[35] D. Alegre, P. Gasior, M. Kubkowska, F.L. Tabares, (2015) Fusion Engineering and Design, 100, pp. 646-651
[36] A. Szydlowski, J. Badziak, J. Fuchs, M. Kubkowska, et al. (2009) Radiation Measurements, 44 (9-10), pp. 881-884
[37] J. Badziak, S. Jabłoński, M. Kubkowska, et al. (2010) Radiation Effects and Defects in Solids, 165 (6-10), pp. 760-766
[38] T. Grycuk, M. Kubkowska, (2010) Journal of Physics B: Atomic, Molecular and Optical Physics, 43 (12), art. no. 125204
[39] T. Grycuk, M. Kubkowska, T. Szczesniak, (2012) Journal of Physics B: Atomic, Molecular and Optical Physics, 45 (24), art. no. 245005
[40] H.-S. Bosch, ... M. Kubkowska,et al. (2013) Nuclear Fusion, 53 (12), art. no. 126001
[41] R. König, ... M. Kubkowska,et al. (2014) Review of Scientific Instruments, 85 (11), art. no. 11D818
[42] H. Thomsen, ..., M. Kubkowska, et al. (2015) Journal of Instrumentation, 10 (10), art. no. P10015
[43] R. König, ...M. Kubkowska et al. (2015) Journal of Instrumentation, 10 (10), art. no. P10002
[44] M. Krychowiak, ... M. Kubkowska,et al. (2016) Review of Scientific Instruments, 87 (11), art. no. 11D304
[45] R. C. Wolf, ..., M. Kubkowska, et al. (2017) Nuclear Fusion, 57 (10), art. no. 102020
[46] T. Fornal, I. Ksiazek, M. Kubkowska, et al. Fusion Engineering and Design (2019) in press https://doi.org/10.1016/j.fusengdes.2019.03.015
[47] P. Moreau, ...M. Kubkowska et al. (2017) Fusion Engineering and Design, 123, pp. 1029-1032
[48] D. Mazon, .., M. Kubkowska, et al. (2015) Fusion Engineering and Design, 96-97, pp. 856-860

The Summary of Professional Accomplishments contains 30 numbered pages.
April 24, 2019

MKubkowska