Annex 3

SUMMARY OF PROFESSIONAL ACCOMPLISHMENTS
in English

Presenting a description of scientific achievements and accomplishments,
in particular those defined in Article 16 paragraph 2 of the Act of 14 March 2003.

Dr Maryna Chernyshova

Institute of Plasma Physics and Laser Microfusion (IPPLM)
Warsaw, 2019

Table of contents

I. Personal data

Name and surname: Maryna CHERNYSHOVA

Place of employment: Institute of Plasma Physics and Laser Microfusion
Department of Nuclear Fusion and Plasma Spectroscopy
23 Hery Street
01-497 Warsaw, Poland

II. Diplomas and degrees held

2005	PhD degree in Physics specialization: Solid State Physics Institute of Physics, Polish Academy of Sciences, Warsaw PhD thesis title “Magnetic and magneto-optical properties of ferromagnetic semiconductor structures EuS-PbS” scientific advisor: Prof. Tomasz Story
1996	Master’s degree in Physics and Engineering direction: Physics, specialization: Theoretical Physics Faculty of Physics, Donetsk State University, Donetsk, Ukraine Master’s thesis title “Amplitude of Spin Wave Dispersion in Spin Density Formalism” scientific advisor: Dr. Andrej Kuchko

III. Current and previous employment in research units and gained scientific experience

01.01.2016–currently	Supervisor of the X-ray workshop and cleanroom facility at IPPLM that is used for production of GEM-based gas detectors
01.01.2014–currently	Head of the X-Ray Radiation Diagnostics Laboratory at IPPLM
01.01.2013–currently	Manager of a 5-person team at IPPLM employed to research and develop gas detectors in the context of plasma diagnostics
2013–currently	Numerous participations in experimental campaigns at JET tokamak, Culham, United Kingdom
2014–2016	Numerous visits to CERN Centre (Geneva, Switzerland) as part of the RD51 collaboration aimed to exchange experience and knowledge related to gas detectors. Total duration of visits amounts one and a half month.
2005–2006	Three months (in total) scientific internship at the Faculty of Physics of University of Ferrara, Italy

1.03.2005–currently	Adjunct researcher, Institute of Plasma Physics and Laser Microfusion (IPPLM), Warsaw, Department of Nuclear Physics and Plasma Spectroscopy
2003–currently	Participation in numerous measurement sessions at synchrotron research facilities in Germany, France, Sweden, Spain and Italy
2000–2005	PhD studies, Institute of Physics, Polish Academy of Sciences, Warsaw

IV. Bibliometric indicators according to the Web of Science database

•	total number of publications	– 122
•	aggregated impact factor of all scientific publications that are on the list of Journal Citation Reports (JCR)	– 136.105
•	total number of citations	– 874
	without self-citations	– 544
•	Hirsch Index of published manuscripts	– 14

V. Scientific achievement being the basis for the habilitation procedure

V.i. Title of the scientific achievement

As an achievement within the meaning of Article 16, paragraph 2 of the Act of 14 March 2003 on Academic Degrees and Academic Title and on Degrees and Title in Art (Journal of Laws No. 65, item 595, as amended), I present a series of the following single-subject publications as a Habilitation Thesis entitled:

Research and development of Gas Electron Multiplier (GEM) based gas detectors and their application in diagnostics of X-ray radiation emitted by tokamak plasma

V.ii. Publications forming part of the scientific achievement

H-1. **M. Chernyshova**, T. Czarski, W. Dominik, K. Jakubowska, J. Rzadkiewicz, M. Scholz, K. Poźniak, G. Kasprowicz, W. Zabołotny, „Development of GEM gas detectors for X-ray crystal spectrometry”, *Journal of Instrumentation* 9 (2014) C03003.

H-2. T. Czarski, **M. Chernyshova**, K.T. Poźniak, G. Kasprowicz, A. Byszuk, B. Juszczyk, A. Wojeński, W. Zabołotny, P. Zienkiewicz, „Data processing for soft X-ray diagnostics based on GEM detector measurements for fusion plasma imaging”, *Nuclear Instruments and Methods in Physics Research Section B* 364 (2015) 54-59.

H-3. T. Czarski, **M. Chernyshova**, K.T. Poźniak, G. Kasprowicz, W. Zabołotny, P. Kolasiński, R. Krawczyk, A. Wojeński, P. Zienkiewicz, „Serial data acquisition for the X-ray plasma diagnostics with selected GEM detector structures", *Journal of Instrumentation* 10 (2015) P10013.

H-4. **M. Chernyshova**, T. Czarski, K. Malinowski, E. Kowalska-Strzęciwilk, K. Poźniak, G. Kasprowicz, W. Zabołotny, A. Wojeński, P. Kolasiński, D. Mazon, P. Malard, „Conceptual design and development of GEM based detecting system for tomographic tungsten focused transport monitoring", *Journal of Instrumentation* 10 (2015) P10022.

H-5. **M. Chernyshova**, K. Malinowski, T. Czarski, A. Wojeński, D. Vezinet, K.T. Poźniak, G. Kasprowicz, D. Mazon, A. Jardin, A. Herrmann, ASDEX Upgrade Team, Eurofusion MST1 Team, „Gaseous electron multiplier-based soft X-ray plasma diagnostics development: Preliminary tests at ASDEX Upgrade", *Review of Scientific Instruments* 87(11) (2016) 11E325.

H-6. **M. Chernyshova**, S. Jednoróg, K. Malinowski, T. Czarski, A. Ziółkowski, B. Bieńkowska, R. Prokopowicz, E. Łaszyńska, E. Kowalska-Strzęciwilk, K.T. Poźniak, G. Kasprowicz, W. Zabołotny, A. Wojeński, R.D. Krawczyk, P. Linczuk, P. Potrykus, B. Bajdel, „GEM detectors development for radiation environment: neutron tests and simulations", *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments, Proc. SPIE* 10031 (2016) 100313X.

H-7. **M. Chernyshova**, T. Czarski, K. Malinowski, E. Kowalska-Strzęciwilk, J. Król, K.T. Poźniak, G. Kasprowicz, W. Zabołotny, A. Wojeński, R.D. Krawczyk, P. Kolasiński, I.N. Demchenko, Y. Melikhov, „Development of GEM detector for tokamak SXR tomography system: Preliminary laboratory tests", *Fusion Engineering and Design* 123 (2017) 877-881.

H-8. **M. Chernyshova**, K. Malinowski, Y. Melikhov, E. Kowalska-Strzęciwilk, T. Czarski, A. Wojeński, P. Linczuk, R.D. Krawczyk, „Study of the optimal configuration for a Gas Electron Multiplier aimed at plasma impurity radiation monitoring", *Fusion Engineering and Design* 136 (2018) 592-596.

H-9. **M. Chernyshova**, K. Malinowski, E. Kowalska-Strzęciwilk, T. Czarski, P. Linczuk, A. Wojeński, R.D. Krawczyk, „Development of GEM detector for plasma diagnostics application: simulations addressing optimization of its performance", *Journal of Instrumentation* 12 (2017) C12034.

H-10. K. Malinowski, **M. Chernyshova**, T. Czarski, E. Kowalska-Strzęciwilk, P. Linczuk, A. Wojeński, R. Krawczyk, M. Gąska, „Simulation of energy spectrum of GEM detector from an x-ray quantum", *Journal of Instrumentation* 13 (2018) C01018.

H-11. **M. Chernyshova**, T. Czarski, K. Malinowski, Y. Melikhov, G. Kasprowicz, E. Kowalska-Strzęciwilk, P. Linczuk, A. Wojeński, R.D. Krawczyk, „2D GEM based imaging detector readout capabilities from perspective of intense soft X-ray plasma radiation", *Review of Scientific Instruments* 89 (2018) 10G106.

H-12. T. Czarski, **M. Chernyshova**, K. Malinowski, K.T. Poźniak, G. Kasprowicz, P. Kolasinski, R. Krawczyk, A. Wojeński, P. Linczuk, W. Zabołotny, A. Jardin, D. Mazon, K. Jakubowska, G. Boutoux, F. Burgy, S. Hulind, D. Batani, „Measuring issues in the GEM detector system for fusion plasma imaging", *Journal of Instrumentation* 13 (2018) C08001.

H-13. **M. Chernyshova**, K. Malinowski, T. Czarski, E. Kowalska-Strzęciwilk, P. Linczuk, A. Wojeński, R.D. Krawczyk, Y. Melikhov, „Advantages of Al based GEM detector aimed at plasma soft–semi hard X-ray radiation imaging", *Fusion Engineering and Design* (2019) https://doi.org/10.1016/j.fusengdes.2019.01.153.

V.iii. Discussion of the scientific objective and results achieved, including their usage

V.iii.1. Introduction

Current energy generation methods are not able to meet long-term global needs [1], and environmental pollution from fossil fuel combustion and nuclear waste complicates the already difficult environmental situation in the world. Therefore, one of the most important tasks of the present civilization is to research and develop new "clean" energy sources.

One such alternative energy production method is based on nuclear fusion, i.e. on the fusion reaction of lightweight nuclei, for which a fusion reactor is currently being developed, in which fusion energy on industrial scale is expected to be obtained through controlled fusion.

However, it is very difficult to implement controlled thermonuclear fusion under terrestrial conditions and this has not yet been achieved. It is well known that for this purpose it is necessary to create a structure in which, heated to huge temperatures ($\approx 10^8$ K) and then becoming a high-temperature plasma, nuclear fuel will be confined and maintained in a high-density state for a long time (as is the case with the Sun and other stars that are natural fusion reactors). In stars, high-temperature plasma is confined and maintained by powerful gravitational forces, while on Earth the most promising are two directions: the so-called inertial and magnetic confinement. In the case of inertial confinement, intensive laser beams or streams of charged particles act spherically onto the surface of a capsule filled with fusion fuel (a mixture of deuterium and tritium). In case of the capsule's implosion, the fuel is compressed and heated to the temperatures required to initiate and support the reaction. Under magnetic confinement, taking advantage of plasma's good conductivity, the magnetic field serves as a trap to prevent hot plasma from escaping from a closed, controlled volume.

Despite lengthy and costly research, the development of an efficient fusion reactor has proved to be a much more complex task than the development of a nuclear fission reactor. Currently, the most promising solution is a reactor based on magnetic confinement, and the largest project to date is ITER (*International Thermonuclear Experimental Reactor*), under construction at Cadarache (France). The main efforts of scientists are now aimed at investigating the plasma-chamber wall interaction, developing materials with low induction activity to be used as wall elements, as well as creating technologies that will make the reactor economically viable.

One of the tasks associated with the study of the interaction of plasma with the surface of the chamber walls that are in contact with plasma, is to study the process of the formation and behaviour of plasma contamination. One has to note that plasma contamination can cause many instabilities and may even lead to the disruption of the plasma chord. Therefore, the problem is not only to maintain high-temperature plasma, but also to prevent and monitor contaminations. Success in mastering a controlled thermonuclear fusion reaction depends on solving these problems.

Regarding experimental reactors (tokamaks) of today and of the nearest future, the choice of materials is limited to those based on carbon, beryllium and tungsten. These materials have various structures, which allows for their optimal selection, taking into account the characteristics of the reactor and the operating conditions of the specific component of the first wall. Of a particular interest here is tungsten, which is to be used as divertor material in the ITER reactor.

Basic information on impurities is obtained by studying linear emission of impurities. The solution of most contamination problems depends to a decisive degree on the knowledge of the dynamics of impurities emission in time and space (in the cross-section of the plasma chord). This leads to an understanding of the impact of impurities on plasma confinement and discharge scenarios and should enable better assessment of plasma status and optimisation of discharge parameters for future fusion reactors.

X-ray spectroscopy used for this purpose is a recognized, effective and powerful tool in plasma diagnostics. Measurement of such radiation (in the 0.1-20 keV range) is a standard way of obtaining valuable information on particle transport and MHD (MagnetoHydroDynamics) phenomena.

This Habilitation Thesis presents the development of the elaborated plasma imaging technology in the area of soft X-ray radiation (SXR), designed to monitor the radiation of impurities.

The search for new technologies in the field of plasma diagnostics entails the increasing demands on the radiative stability of the used materials due to development and usage of fusion facilities, where the study of processes occurring during the interaction of radiation with matter has become particularly important. This problem also applies to diagnostic components whose materials are exposed to thermonuclear fusion products. Currently, a new X-ray imaging detection technology is required for tokamaks such as ITER. X-ray detectors that are being used in existing equipment may rapidly degrade due to large neutron fluxes characteristic for the tokamak environment, as observed during fusion tests on the TFTR equipment in the USA during the experimental campaign on deuterium-tritium mixture [2].

Despite the relatively wide use of semiconductor detectors to record SXR radiation (generally ionising radiation), gas detectors are promising candidates that are suited much better for use in future fusion reactors given their resistance to neutron radiation. Several new gas detectors, that are commonly called MicroPattern Gaseous Detectors (MPGDs), have been proposed and developed in this field. The most promising representative of this class is the detector called Gas Electron Multiplier (GEM) [3], [4], which is characterized by high amplification factor of the primary charge that is originated from photon absorption. As a result, the interest in GEM-based detectors is growing steadily, and the possible use of GEM detectors now goes beyond the area of high energy physics. The main advantages of GEM technology are the compactness of the detector, good temporal and spatial resolutions, the ability to discriminate against photon energy and better neutron resistance compared to existing systems. All this makes such a detection system a potentially better candidate for soft X-ray measurements in the ITER and DEMO reactors.

In this work, a new type of detection system based on GEM technology was proposed for soft X-ray measurements in the ITER reactor-oriented research. *Research and development work on diagnostic systems that use this type of detectors constitutes the basis of this Habilitation Thesis describing the achievements of the Habilitation Candidate*. Along with the research work, adjustment, modernization and optimization of the detectors themselves, the aim was also to solve a number of scientific and technological problems related to the usage of such detectors in research that is carried out on modern fusion systems. These detectors are planned to be used to monitor plasma impurity in research projects and scientific programmes to support the construction of the ITER experimental reactor and ultimately achieve an effective fusion reaction.

The presented Habilitation Thesis covers important examples of development and implementation of gas detectors and it is based on a set of selected publications describing different stages of both research and practical application in research centres of the developed detectors based on GEM technology. This Habilitation Thesis is organized as follows. Chapter V.iii.2 summarizes the achievements in the development and application of GEM-based detectors for bent crystal spectrometer of the Johann type at JET tokamak in Culham (UK). Chapter V.iii.3 discusses the results of the design and development of a system of two detectors for direct recording of plasma radiation (so-called poloidal tomography), and its future application at WEST tokamak in Cadarache (France). Chapter V.iii.4 focuses on advances in the development of detectors for two-dimensional imaging of plasma radiation, presenting comprehensively examining various scientific and technological aspects.

Before describing the main part of the Habilitation Thesis, I would like to point out that all aspects of the presented research concerning gas detectors, which have been the subject of my research since 2010, have been developed by me, i.e.: determination of research goals, development of the concept and design of these detectors, organization and implementation of laboratory or tokamak measurements, interpretation of the results of experimental research supported by numerical simulations and preparation of publications. The Habilitation Candidate emphasizes that the results of the research have contributed to the progress in the field of MPGD detectors and tokamak tests using X-ray radiation and are an important contribution to the development of scientific discipline. In addition, the research carried out has made it possible to obtain funding for new research topics in the field of plasma physics.

V.iii.2. Development of GEM-based gas detectors for spectrometer on JET tokamak (related to [H-1, H-2, H-3])

Tokamak plasma X-rays come from continuous radiation (e.g., bremsstrahlung) and linear radiation. In particular, on the JET tokamak, in addition to continuous radiation, intense linear one is emitted by highly ionized tungsten and nickel impurities that escaped from structural materials during plasma discharge. Therefore, the main purpose of such a detection system is to measure the spectra of X-rays, with high resolution, coming from characteristic lines of impurities present in the plasma of tokamak and to ensure the monitoring of this radiation. This measurement is very important as it can provide accurate information on key plasma parameters such as impurities concentration, ion temperature and toroidal rotation velocity [5], [6].

In fusion devices with magnetic confinement of plasma, high-resolution diagnostics of SXR radiation is applied in specific energy ranges of photons. Therefore, two independent measurement paths were prepared for high resolution bent crystal spectrometer on the JET tokamak to monitor plasma emission spectra. Each of the measurement paths was designed to monitor plasma emission spectra in certain ranges of photon energy, which correspond to specific orders of diffraction of used crystals [**H-1**].

The first diagnostic channel was designed to monitor the radiation emitted by tungsten ions, mainly W^{46+} with an energy of about 2.4 keV, observed in the first order of diffraction (the most intense W radiation is in the energy ranges of ~250 eV and ~2.5 keV photons [7], [8]). This measurement channel allows simultaneous recording of continuous radiation emitted in narrow ranges of energy defined by the spectrometer geometry and corresponding to the first three orders of diffraction.

The second measurement channel was dedicated to monitoring the radiation emitted by nickel ions Ni^{26+} with an energy of about 7.8 keV observed in the second diffraction order. This detection channel also enables the recording of continuous radiation with photon energies suitable for the first, second and third order of diffraction, and intensities determined by the electron temperature of the plasma.

In order to record characteristic emission lines of impurities and continuous radiation in a wide range of energy, this spectrometer required two independent detection systems with high counting speed and very good spatial resolution in one dimension, suitable for spectrometer parameters. In addition, it was important to obtain an energy resolution of the detection technique used, which would allow the identification of photons from different reflection orders. It should be noted that this was not possible for the previous detection system used on the KX1 spectrometer. The information extracted from all spectral diffraction orders (the continuous radiation spectrum) should also have allowed a better estimation of the plasma state.

During realisation of this research programme focused on the development of future ITER reactor, in particular on materials for the plasma face components and the divertor (ITER-Like Wall programme), and therefore, on the observation of the level of tungsten contamination, a new technique of detection of impurities was proposed. The technique was developed by a team of researchers of which the Habilitation Candidate was a member, actively participating in the tasks on the design, construction, testing and application of two gas detectors based on the Triple-GEM cascade technology [9-10], [**H-1**]. In addition, the Habilitation Candidate coordinated the work of the team of scientists within the IPPLM.

Triple-GEM-based detection modules have been designed and built to meet the requirements of SXR radiation monitoring on the JET tokamak [6], [11]. The following requirements were used during the design: large detection area (suitable for large plasma volumes and spectrometer geometry), high SXR photon conversion factor in the drift/conversion area of the detector, good signal-to-noise ratio provided by the high amplification of the detector charge and satisfied energy resolution (20-30%). X-rays monitoring required also good spatial resolution (appropriate to the characteristics of the spectrometer), time resolution corresponding to plasma dynamics and high repeatability and measurement stability at high radiation intensities. This work required the participation of the Habilitation Candidate in simulations of gas mixtures to determine the performance of the detector, planning and conducting laboratory tests, optimizing the mechanical structure of the detector, participating in many discussions on the selection of parameters of the electronics module, etc.

GEM technology enables separation of gas amplification structure and readout electrode [12]. An additional advantage of such a structure is that only a fast electron component of avalanches in gas drifts in the direction of the readout electrode strips, which significantly reduces the effect of the spatial charge caused by positive ions. After the gas amplification stage, the next structure is the electrode that reads the signal from the stripes in order to position and energy-sensitive measurement of the diffraction profile appropriate for the specific SXR energy range. Each strip of the electrode is assigned to an acquisition electronics channel, together those form an electronic system.

The signals generated on the strip electrode contain all the information necessary to evaluate the energy and to reconstruct the position of the absorbed photons [**H-2**, **H-3**]. Due to the diffusion of the charge during the drift and amplification stages, the final electron cloud in the induction gap already spreads onto several readout strips. Such a group creates a cluster for a given single quantum absorption event of incident radiation. Therefore, an important measurement issue is the determination of the charge and position of the cluster (i.e. the energy and position of the photon), through its identification by means of a developed data processing algorithm.

Within this work the Habilitation Candidate took part in the preparation of the procedure of data acquisition and processing, the development of algorithms determining the energy and position of photon, which are crucial for obtaining correct physical results. It should be noted that the preparation of appropriate algorithms for obtaining physical parameters and checking the results produced by the electronics module is necessary during the development of the diagnostic tool. Therefore, I actively participated also in the next stage of development of the acquisition system, namely the preparation and verification of the physical correctness of the results of the so-called serial data acquisition, which was developed for the purposes of laboratory research [**H-3**] and in which all signal samples exceeding the trigger level were independently recorded for each measuring channel. This allowed the system to increase throughput, which resulted in an increase in the detector's measurement performance. In addition, the effect of the developed acquisition procedure resulted in obtaining of a correct distribution of the cluster charge value, which directly corresponds to the energy spectra of the X-ray source.

In the course of this work, during laboratory tests, the Habilitation Candidate studied the operation of detectors with an ^{55}Fe radiation source. Typical energy distributions were obtained for the whole detector operating at a gas charge amplification above 10^3 with an energy resolution (FWHM) of 23%. I confirmed the linear dependence of the cluster charge on the photon energy in the energy range corresponding to iron isotope source line with the energy of about 5.9 keV and in the range of plasma radiation selected by diffraction on a crystal with a width of ~20 eV by means of the KX1 spectrometer.

I also verified the stability of the detector during short-term exposure to rapid changes in X-ray flux intensity using an X-ray generator. For this purpose, I used a sequence of 20-second exposures separated by a few minutes interval of time. Such a time structure corresponded to the time sequence of the detector's operation on the JET tokamak. These tests were dictated by the dependence of the GEM detector amplification on the charge accumulated on the dielectric in the GEM film holes, since the time constant of charging the Kapton depends strongly on the density of current flowing locally through the GEM film. Decrease of the amplification gain at low intensity measured in the direction of decreasing radiation intensity indicated that the GEM film charging processes caused by avalanche current in the gas determined the detector's susceptibility to radiation intensity variation. The results of my measurements of the evolution of the amplification of the detector charge showed a relatively good stability of the amplification in the range of the spectrometer radiation intensity.

After laboratory tests and preliminary tokamak results, and after optimization of the final mechanical construction of the detectors, they were installed on the KX1 spectrometer on the JET tokamak (in 2013 I managed and supervised the installation of both final detectors).

The purpose of processing the signals obtained from the detectors was to measure the energy and position distribution of photons for the exposure time of 10 ms. The GEM detectors developed with a significant involvement of the Habilitation Candidate, are being actively used in data acquisition and measurements of plasma contamination radiation and determination of plasma parameters on the JET tokamak.

The results obtained for the plasma discharge recorded by the detector in the first measurement channel (W lines) are shown in the Figure 1. Since for bent crystal spectrometer the distribution of the charge position of the cluster also corresponded to the energy defined by crystal diffraction, it was crucial to use the energy resolution capability of the detectors used to distinguish between first and second orders of diffraction for tokamak plasma diagnostics [13], [14].

The performance of the final detection systems has been tested by a team, with a significant participation of the Habilitation Candidate, on the JET tokamak in standard operation mode. It has been shown that the *on-line* system separates the continuous and linear X-rays from the different diffraction orders and provides the energy spectra for each readout channel. This innovative functionality of the developed X-ray diagnostics enabled precise analysis of spectra corresponding to different ions of plasma contamination.

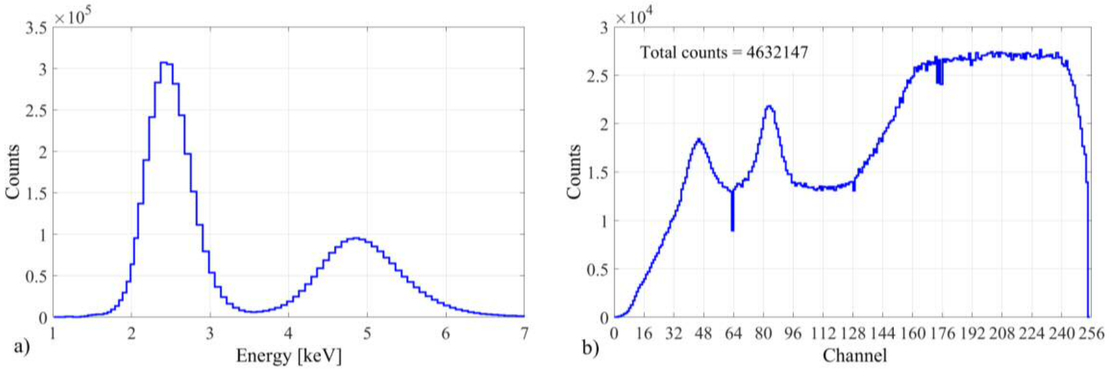


Figure 1. Characteristics of plasma radiation imaging for JET tokamak discharge: (a) energy spectrum accumulated over time, (b) position distribution accumulated over time.

Figure 2 illustrates how the tungsten monitoring system works during a plasma discharge on the JET tokamak. The time dependency of the energy spectrum of radiation is accumulated for all readout strips/detector channels for 10 ms exposure time (Figure 2 (a)). The two lines are clearly visible at 2.4 keV and 4.8 keV, relating respectively to the first (lines of characteristic radiation of the W^{46+} ion and other W ions of similar ionisation as well as continuous radiation) and the second order of crystal diffraction (continuous radiation). Figure 2 (b) shows the time evolution of the number of photons for each measuring channel during 20 seconds of the plasma discharge. It should be noted that these data have been processed in real time as part of individual histogramming (energy distributions and positions of registered photons) for each channel.

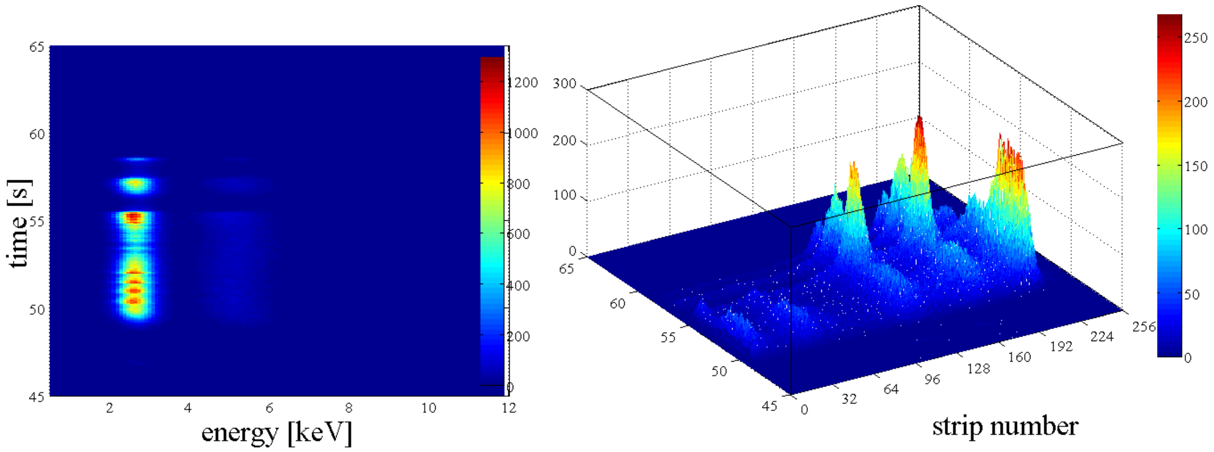


Figure 2. Time dependence of photon energy distribution for all channels (a) and corresponding time dependence of photon intensity (b) for individual detector channels during the discharge on JET tokamak with time resolution of 10 ms (exposure time). Both parts of the figure represent the total X-ray spectrum from all diffraction orders.

The data obtained from the developed detectors correlated well with the plasma process. The supplied detection system has identified, for the first time, diffraction profiles corresponding to different spectral orders of crystal reflection for KX1 diagnostics, thus providing accurate information on the emission of continuous and characteristic radiation from plasma contamination. These results indicate that the developed Triple-GEM detectors are an innovative scientific and research tool of high utility and importance for plasma radiation measurements in the SXR range. This was also confirmed by the results of the work presented in [14]. The development of the issues discussed above can be found in publications [**H-1**, **H-2**, **H-3**] as well as in the following publications [13], [9], [10], [15].

The work of the Habilitation Candidate on detectors for KX1 diagnostics was acknowledged by the Director of the Institute of Plasma Physics and Laser Microfusion. This work won an Award of II degree in the competition for outstanding scientific achievements for "Significant participation in the launch of KX1 diagnostics on JET and the provision of data essential for the development of nuclear fusion, on the basis of which it is possible to determine the concentration of tungsten and nickel in plasma".

V.iii.3. Design, development and production of GEM-based gas detectors for direct recording of plasma radiation in difficult tokamak conditions (related to [H-4, H-5, H-6, H-7, H-8, H-9, H-10])

The aim of this part of the Habilitation Thesis is to present a diagnostics that was design and constructed under the direction of the Habilitation Candidate, for poloidal tomography dedicated to monitor SXR radiation of metal impurities (tungsten emission) in stationary/long discharge conditions.

The problem of metal impurities also applies to the WEST project [16] in which an actively cooled tungsten divertor is implemented. Because of the coupling between impurities transport and MHD activity, which can lead to accumulation of impurities in the plasma [17], this is particularly dangerous in the case of long-term tokamak impulses (target discharges on the WEST tokamak). Therefore, an appropriate diagnostic tool is required to monitor the level of impurities and to reconstruct their distribution.

In the framework of this Habilitation Thesis, a GEM-based detection system for the ITER-oriented WEST tokamak has been proposed as a dedicated SXR radiation tomography system with energy differentiation. The proposed diagnostics is in the final stage of preparation by the research team under the supervision of the Habilitation Candidate [**H-4**-**H-10**], [18-21]. Detectors based on this technology were designed to meet the requirements of dimensional limitations, to be sensitive to the spatial location of X-rays and their energy (i.e. the basic features required of any tokamak plasma X-ray detector), to offer a sufficiently large detection area matched to a dedicated diagnostic port, to have good spatial resolution, high signal-to-noise ratio, photon energy estimation capability and neutron resistance. It should be emphasized that the developed tomography system will allow distinguishing the energy of photons; such information has been inaccessible to the former tomography system on the WEST tokamak. Combining spectral information about plasma radiation with good spatial resolution of detection will provide basic information about the state of the plasma.

The proposed tomography based on GEM detectors will be used for impurities studies, especially tungsten. The control of this element will be crucial in order to obtain appropriate parameters for the whole device. Control of tungsten contamination in the centre of the plasma should be based on an analysis of the characteristic *L/M* line radiation emitted by tungsten (the most intense central plasma radiation). Therefore, the main objective of the new X-ray diagnostics was to ensure monitoring of radiation emitted by highly ionized metal impurities, focusing on emission in the range of 2-4 keV.

It is expected that the system of two GEM detectors, located in the vertical and horizontal ports [**H-4**], will register the energy of SXR photons together with the reconstruction of their location, i.e. enabling poloidal plasma tomography with the resolution of energy. The detectors are positioned to cover the maximum total viewing angle available for each port in order to achieve both optimal spatial resolution and optimal internal structure of the detection chamber. Numerous physical, technical and logistical problems had to be solved, taking into account the space limitations and operating conditions of the detection system, such as high ambient temperature, expected magnetic field distributions, etc. In addition, as the viewing angle for both ports is quite large (~25° and ~32°), the parallax effect had to be taken into account. Therefore, the Habilitation Candidate optimized the drift gap of the inner chamber of the detector to minimize the shift in the visible position of plasma radiation observed for two different viewing lines (tomographic lines) [21]. As part of that work, I designed the structure of the detectors, in particular the horizontal detector with a curved detection surface in order to take into account the parallax effect. Due to the very limited space inside the vertical port, it was decided that the vertical detector would remain flat.

Since the system is designed to test tungsten impurities and MHD activity, the following time resolution requirements have been set: the detection system should be capable of achieving a transport range of impurities with a resolution of at least 1 kHz and should record the slowest MHD activity at 10 kHz. With regard to the spatial scale, I estimated that the resolution of 1 cm for the entire plasma volume is satisfactory to obtain a good tomographic image that will contain accurate information about the magnetic axis, the inversion radius of the sawteeth and the gradient distribution of the impurities.

In accordance with these requirements, the Habilitation Candidate developed a conceptual design of the detector’s detection chamber. The chosen design of the triple GEM cascade allowed achieving high total gas multiplication with very low probability of spontaneous discharges. Due to the strongly reduced effect of space charges in the sequential amplification process, high efficiency could also be achieved. The quantum detection performance has been adapted to the energy of interest by simulating the photon absorption performance of different gas mixtures and detector window materials. The expected efficiency of detection of the *M* line of W X-rays (2.4 keV) was ~20%.

In the meantime, in order to support the ongoing design and construction phases, as well as the design and development of processing electronics and the completion of the final detection system for poloidal tomography, a significant research was conducted by the Habilitation Candidate to study the basic characteristics of the detector and the final preparation of the detector for the foreseen experimental conditions by means of tests using a model detector (with a similar configuration) and simulation of the detector signals. In this way, I examined the detector’s operation on many levels.

For example, the time required to achieve stable GEM performance for different gas mixtures was checked [**H-7**]. Once these conditions were reached, the basic parameters of the GEM detector were monitored, such as effective amplification (electron multiplication) and energy resolution as a function of the high voltage applied to each GEM foil, HV_{GEM}. The exponential dependence of amplification has been met for almost the entire HV_{GEM} range, excluding the highest values used in a gas mixture containing CF_4, where the detector operation went beyond proportional mode. In the paper [**H-4**], the Habilitation Candidate confirmed good linearity of detector response for ^{55}Fe source emission and Zr and Cu fluorescence lines. Reliable detector performance was achieved with an energy resolution depending on the mixture used: a higher content of the Ar component leads to a lower resolution, similar to that of a lower gas flow.

In order to meet the requirement of ensuring good spatial resolution of the plasma image (i.e. to work as a proper tomographic diagnostics), specific requirements had to be imposed on the structure of the readout anode of the detector. For this purpose, in order to adjust the size of the readout anode to the size of the cluster generated by the photon absorption charge, the Habilitation Candidate conducted measurements of the size of the cluster estimated by means of the one-dimensional Triple-GEM strip detector [**H-7**]. The corresponding cluster size has been estimated to be no more than 2 mm for both gas mixtures (Figure 3). This result helped me to determine the strip size for the final detector by optimizing the number of independent electronic channels while meeting the requirements for good spatial plasma resolution.

In addition to the different gases and sensor performance at different HV_{GEM} values, I also investigated the geometry of the GEM film holes and its impact on detector's performance [**H-8**]. In addition, I measured the effective electron gain in order to find the optimal distribution of the electric field for which the gain is maximized. For this purpose, two GEM prototype detectors having either double conical or cylindrical holes in GEM films were constructed with my significant involvement and were subject to my extensive testing in order to achieve an optimal electric field for each prototype. The results showed that optimal field distribution maximizes charge generation for each GEM hole geometry. However, the relative energy resolution is another factor defining the final choice of the electric field distribution: it must be also optimised. It was possible to demonstrate that optimal gain and resolution occur at different voltages. For energy resolution, both its optimum value and the regular shape of the spectrum were achieved when the electric fields between the electrodes of the detector were very similar, as opposed to the amplification ratio. In this situation, optimal extraction and collection

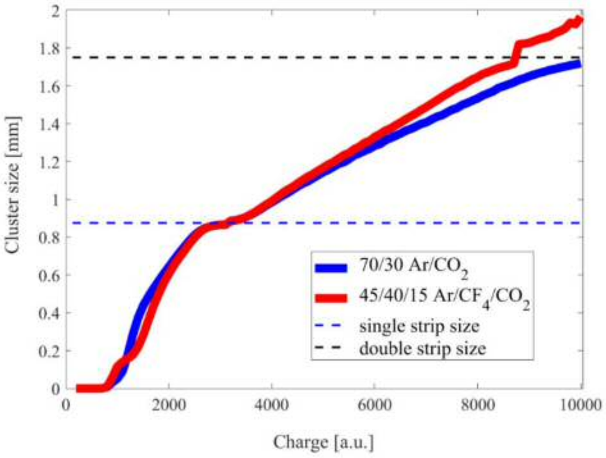


Figure 3. The dependence of the cluster size on the generated load for 0.8 mm wide strips.

performance resulted in better shape and linearity of the spectrum. The situation of the sensor with cylindrical holes was similar but less pronounced. This tendency was taken by me into account in the selection of further detector parameters.

The GEM technology allows building a gas detector with a relatively high gain operating steadily at radiation fluxes up to 10^{11} cps^{-1} m^{-2}. However, due to the requirement of energy discrimination in tokamak applications, the detector should operate in proportional mode with a stable, relatively low gas gain (~10^3) over a wide dynamic range to prevent discharges and saturation of the spatial charge. To verify these limitations, the Habilitation Candidate examined the detection capability of two GEM hole geometries using a copper anode X-ray tube emitting photons with ~8 keV energy (*K* Cu line). The detector was exposed to a collimated beam perpendicular to its window and the effective electron amplification as a function of the absorbed photon flux was determined (Figure 4).

The result of these tests was quite significant in terms of application of the GEM detector in plasma physics. For double conical holes, it was found that the effective amplification is stable over a wide range of photon fluxes, which is compatible with [22]. High voltage HV_{GEM} resulting in high gain of the ~10^4 detector provides almost constant effective gain for fluxes below 0.1 MHz/mm^2. While reducing voltage and therefore also gas amplification, it significantly increases the stable range of effective amplification. With low electron multiplication, ~10^3, this parameter remains constant almost up to 1 MHz/mm^2. This behaviour is closely related to the amount of spatial charge accumulated in the path of its multiplication. For an ion yield level more than ~20 (greater than ~10^3 fC/cm^3) [23] of ions drifting back onto the arriving electron, the external electric field begins to distort significantly.

In the case of cylindrical holes, the effective gain is constant, within the error range, up to 0.07 MHz/mm^2 and then increases, but not as rapidly as in the case of double conical holes.

Therefore, such a geometry may be more suitable for the recording of high-dynamic intense plasma radiation. Due to the use of the detector in plasma conditions, the functioning of the detector with as little as possible gas amplification can be beneficial in order to extend the stable operating range.

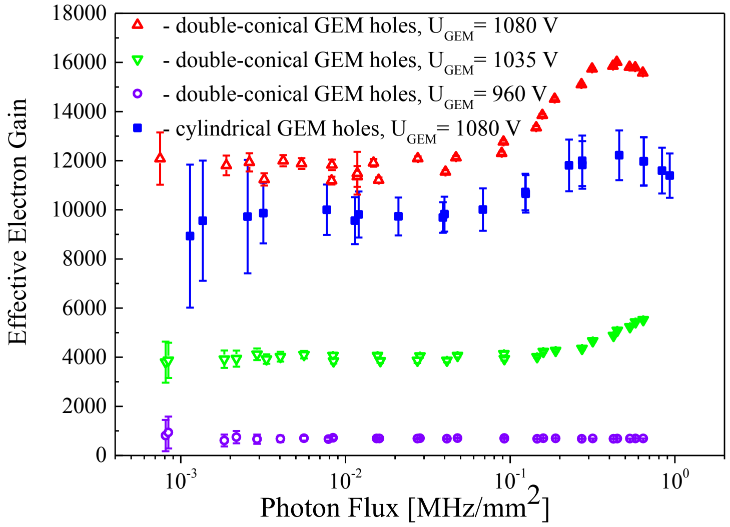


Figure 4. Effective electron amplification as a function of photon flux for double conical and cylindrical GEM foil holes.

In addition to the laboratory tests, the Habilitation Candidate planned and conducted the tokamak tests of a model detector that was introduced to the experimental conditions of the operating ASDEX Upgrade (AUG) device for the first preliminary GEM-based diagnostic tests. The aim was to take into account the challenges related to the operation of the detector in an arduous radiation environment [**H-5**].

The experiments were conducted in two phases. In the first phase, the detection system was exposed only to background radiation (neutron, gamma and hard X-ray (HXR)). In this phase, the detector had no direct view of the plasma and was placed close to HXR diagnostics. It has been tested both without and with neutron shielding. Then, in the second phase, the system was moved to SXR, where in addition its detection surface was exposed to SXR photons, through a direct view of the central plasma.

In the first phase, a reasonable correlation between the signal from the GEM detector and the HXR radiation was observed. For most discharges, the detector's behaviour in this position was consistent with the HXR data from the nearest diagnostics. Then SXR measurements were performed for many AUG tokamak discharges for different plasma scenarios. Since the signal on the active surface of the GEM detector was unchanged in the toroidal plasma direction (due to the toroidal symmetry of the tokamak), I decided to divide the active surface of the detector in this direction into three equal parts. Only the middle part had a direct view of the plasma through the beryllium filter. The other two parts were protected either from SXR radiation or from SXR and neutrons at the same time. The signal from the two shielded areas was then used to determine the background for the signal from the central uncovered area. Figure 5 contains the data for the *L*-mode discharge, for which the signal from the GEM detector is fundamentally different from the strong background radiation.

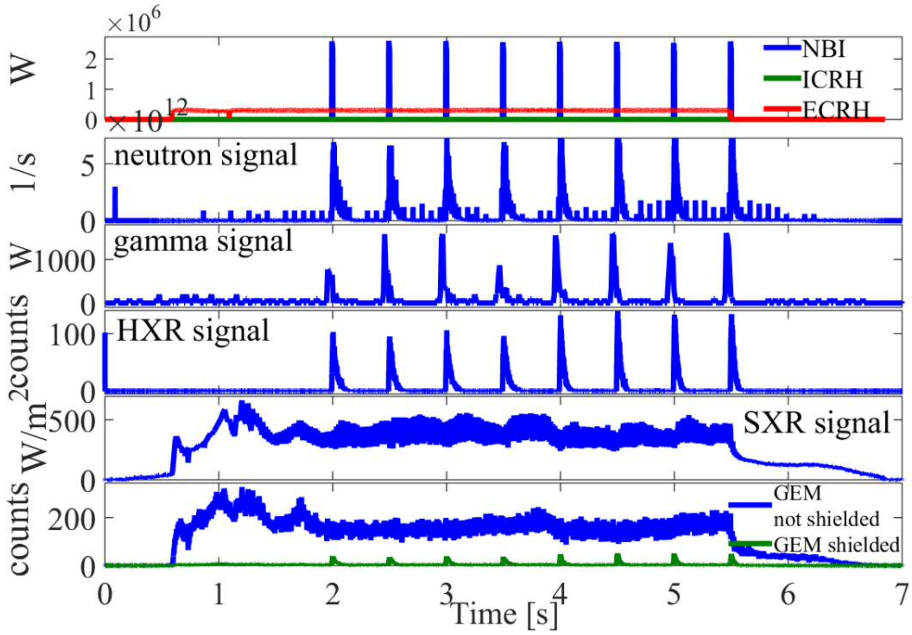


Figure 5. Signals from the GEM detector (bottom) collected for the #33464 discharge on the AUG tokamak and shown with selected radiation profiles and plasma heating. The signal for the exposed part of the detector is standardised by subtracting the background radiation (depending on the shielded part).

As in the first phase, identical GEM signal behaviour was observed in areas with and without neutron shielding. The signals from the areas with and without neutron shielding are presented at the bottom section of Figure 5. As expected, the behaviour of the central uncovered part with subtracted background was similar to that of conventional SXR diagnostics on AUG, while the signal from SXR and neutron protected areas was similar to HXR/gamma temporal dependencies. This observation was consistent with other discharges for low heating power.

The obtained spectral results indicated that the observed low energy shoulder in the detector spectrum can be interpreted as a contribution from high-energy photons. Such high energy photons may also induce emission from some elements present in the elements of the gas detection chamber or in its immediate vicinity, causing characteristic fluorescence lines that contribute to the spectrum observed. In the SXR area, the main candidate, among the detector chamber materials, may be copper in GEM foils with $K_{\alpha 1}$ line of 8.05 keV (the line at 8 keV was observed in the spectrum for the entire detection area at the very beginning of the discharge at a lower SXR photon flux).

Since the neutron beams from the plasma cause a mixed field of radiation that accompanies the transmission of neutrons through the environment, the Habilitation Candidate planned and conducted additional laboratory tests of the detector's operation under the influence of neutron fluxes from ^{241}Am-Be source [**H-6**]. Their aim was to check the elements of the detection system which, as a result of neutron interaction, could become a source of electromagnetic radiation of various origins, such as gamma, X-rays, etc. Thus, by placing a neutron source near the detector window, the spectrum of an uncovered (non-removable casing) radioactive source was measured, which showed a peculiarity at about 8 keV, overlapping with a monotonically decreasing "tail" (that was also observed for the data from the AUG tokamak), created under the influence of illumination. In order to prove the origin of this peak, various tests were performed, the results of which confirmed that the peak was originated from Cu fluorescence in the detector chamber and was most probably caused by gamma radiation from a neutron induced activation reaction of aluminium (^{27}Al(n,γ)^{28}Al), the source casing material. The total attenuation of these gamma rays by means of a lead shield effectively removed the observed peak, indicating its non-neutron origin in the detector chamber.

It is worth mentioning that before and after irradiation of the detector, background radiation was recorded without any radioactive source in order to check its possible changes. The background intensity after irradiation turned out to be about four times higher than at the beginning of the tests. This number relatively characterised the neutron induced radioactivity of the detector materials, which was not significant in comparison with the detector signal intensity during exposure on the whole detector surface. On the other hand, however, during the irradiation process, the background signal may also come from the own gamma rays emitted by the radioactive source. Thus, secondary products from the neutron reaction may be important, contributing to the neutron detector signal.

In order to estimate the possible influence of neutron flux on the regular GEM detector signal and to understand the mechanism of neutron interaction with detector materials, I have initiated and developed a simulation methodology using the GEANT4 toolkit [24]. As a result of the simulations, the intensity of the most common emerging radiation in the function of neutron energy, which accompanies the neutron interactions, was obtained. It was found that the most frequent nuclear reactions induced by neutrons are as follows (n,γ), (n,p), (n,d), (n,α), (n,n'). Basically, for all particles, their number increases with the neutron energy, with a clear interaction starting at about 0.1 MeV of the neutron energy. Since the generated particles can continue to interact with the materials of the detector and the gas, they can eventually create high-energy electrons inside the detector before they leave the detector or are absorbed in its chamber. In fact, they can be additionally dissipated by the materials of the detector and the gas, ionizing neutral atoms and losing energy. These interactions produce low energy electrons (~1-10 keV) that can be trapped in the detector and recorded as a regular signal, which is undesirable when GEM detectors are used for SXR diagnostics.

Therefore, a further simulation of the evolution of the reaction products was carried out and the spectra of energy of the formed particles for neutrons with energy of 2.45 MeV, inseparably connected with the deuterium plasma, were calculated [**H-6**]. In terms of charged particles, the expected response of the detector is quite predictable, so simulations of the final detector signal, which can be recorded, were conducted for gamma rays, for two energies: 0.6 and 1.33 MeV, and three interactions of interest for the operation of the GEM detector: photoelectric effect, Compton scattering and the effect of the creation of electron-positron pairs. All effects are produced by high-energy electrons inside the detector. Tracking all the interactions in the detector that cause the appearance of the electron finally in the drift/conversion gap, the energy distributions of electrons were obtained and is shown in Figure6 (a). The electrons of the presented energy distribution can be completely trapped in the drift gap of the detector and recorded as a regular signal, which can be mistakenly considered as SXR photons of different energies. The origin of primary electrons for the used experimental system on AUG tokamak is illustrated on Figure6 (a) in the function of energy of the absorbed photon. In addition to air in the front of the detector window, the main materials contributing to the signal were copper and the detector's working gas.

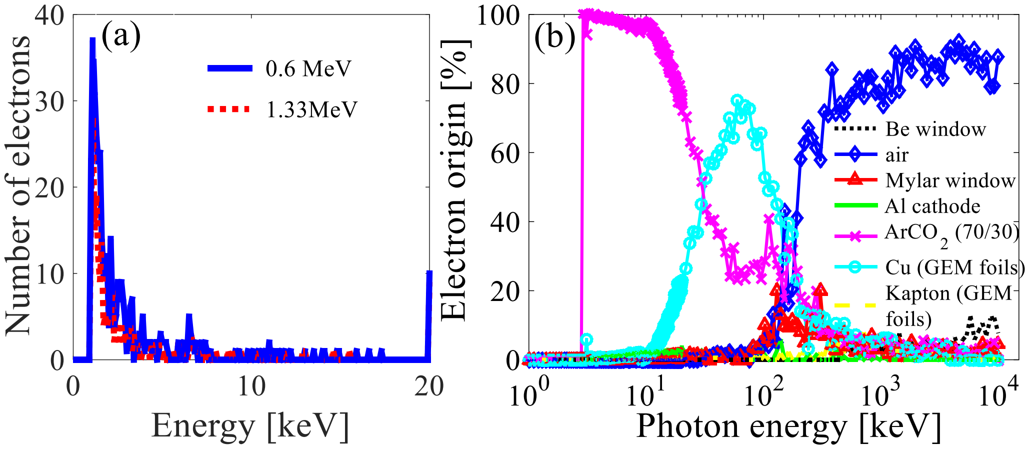
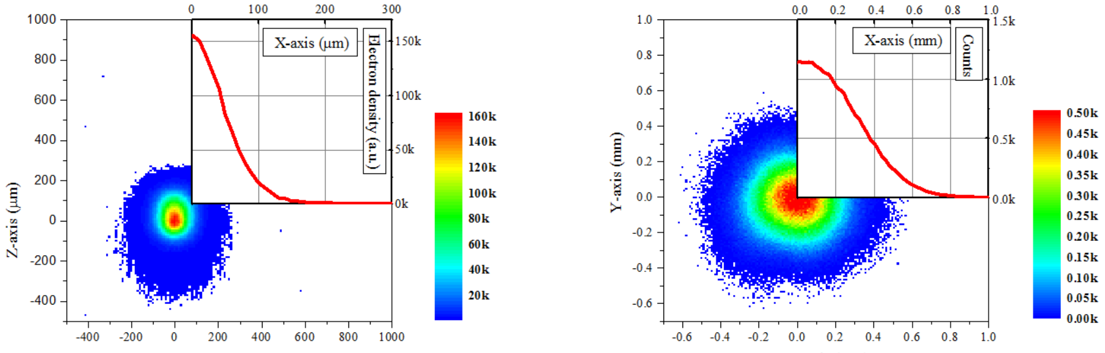


Figure6. (a) Simulated spectra of produced electrons that have appeared in the detector drift gap for photons of 0.6 and 1.33 MeV energies. (b) Contribution of various basic materials/gases present during the experiment on the AUG tokamak in the formation of the electron in the drift gap in the function of energy of the absorbed photon.

The simulations coordinated by me were used not only to consider the interaction of incident radiation with the detector elements, but also to optimise the design of the inner chamber of the detector and its performance [**H-9**]. For example, the study of the influence of the arrangement of electrodes allowed me to choose the distances between them, which maximize the transmission of electrons and provide the optimal electric fields used. Based on the numerical results obtained, optimal values of electric fields were selected for the middle value of applied voltage on the GEM foil and simulations of triple GEM avalanches were performed for different detector's electrode geometries. Basic detector parameters were acquired from the obtained data: electron multiplication factor, electron energy distribution, electron time distribution and radial distribution of electron signal in the readout plane.

The total evolution of electric charges in the GEM detector, from the drift area to the readout electrode, has been simulated. The original electron cloud, representing the electrons produced in the drift gap, forms an asymmetrical shape resembling a drop as it moves towards the first GEM foil, as shown in Figure7 (a). This is due to the fact that the distribution of the total charge is created by fast moving electrons in front and slower ions in the rear. An example of the obtained distribution of electron clouds in the readout plane, i.e. after passing through the entire triple GEM detector, is shown in Figure7 (b). Based on this simulation and experimental results I chose the appropriate width of the readout electrode for the final detector.



a) b)

Figure7. (a) Cross section of the primary electron cloud forming the shape of droplets, where positive *Z-axis* values indicate the first GEM foil. The insert shows the density of the electrons in function X for $Z = 0$. (b) Top view of the electron cloud in the readout plane. The insert shows the number of electrons formed in 100 electron avalanches as a function of the distance from the centre of the cloud.

One of the important operating parameters of the detector is its energy resolution. Under my supervision, in the framework of [**H-10**], simulation studies were conducted to assess the energy resolution of a triple GEM detector for a 5.9 keV X-ray quanta. The calculations were performed using the numerical tool Garfield++ in two stages. In the first stage, the conversion of photons in the drift area into multiple primary electrons (δ electrons), which are the source of electron avalanches in the GEM detector, was simulated. This allowed obtaining a distribution of the number of primary electrons generated in the drift area by quantum X using the numerical tool Heed [25].

In the second stage, the primary electrons from the resulting quantitative distribution became the source of electron avalanches propagated through the whole volume of the GEM detector. The distribution of the obtained signals produced a spectrum corresponding to a peak with energy of 5.9 keV, which allowed determining the theoretical energy resolution of the detector at the level of 16.77%. For comparison, experimental measurements of signals from the model GEM detector were also carried out. The results of the calculations were found to match well with the experimental data.

In this way, I was able to study the influence of individual elements of the detector's chamber on its energy efficiency. The knowledge gained allowed for a better understanding of experimental observations and their influence on the deterioration of recorded energy resolution, accompanying the process of recording and processing signals.

The detectors developed within the framework of this Habilitation Thesis are now completed and ready to be tested. Very preliminary and quick tests of the vertical detector (Figure8) were carried out during the last experimental campaign on the WEST tokamak in December 2018. Currently, the team under my supervision is planning to participate in the next experimental campaign on the WEST tokamak in order to comprehensively verify the operation of the vertical detector in a plasma environment. After verification, the second detector of the poloidal tomography system will be transported to the device for installation in the horizontal port, thus completing the poloidal tomography diagnostic system for monitoring soft X-rays. In the next stage of diagnostics, international cooperation will be continued, providing research topics and enabling scientists from different countries to engage in experiments. Further research on plasma produced in tokamak systems will be carried out within the EUROfusion consortium, of which the WEST tokamak is a part.

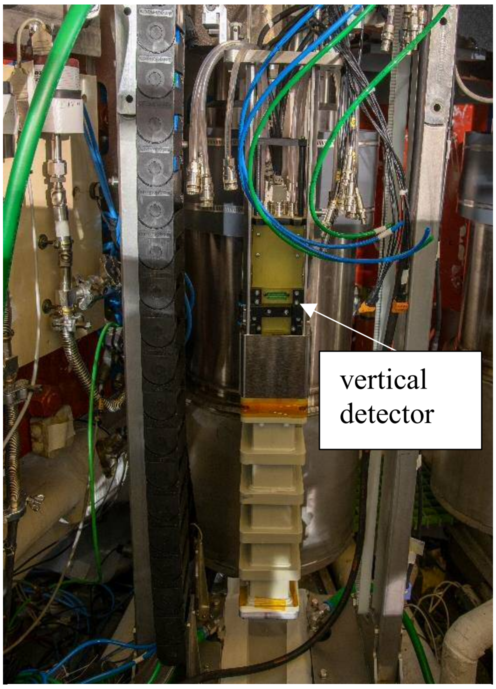


Figure8. Picture of the diagnostic system with the GEM detector before leaving the port on the WEST tokamak.

The progress of this research on the issues discussed above and the obtained results can be found in the following scientific papers [**H-4**]-[**H-10**], as well as in publications [18-20, 26-31].

V.iii.4. Work on detectors that are used to image X-ray radiation originated from tokamak's plasma (related to [H-2], [H-3], [H-11], [H-12], [H-13])

Excellent imaging capabilities for MPGD-based detectors [32] which, due to their wide application, conquer various fields (e.g. [33], [34]), can also be used for direct imaging of plasma radiation. For example, using 2D toroidal GEM-based imaging and combining it with GEM-based poloidal tomography makes possible obtaining 3D information that should be available to study the interaction between tungsten impurities and MHD activity. Combined with advanced electronics, these detectors offer excellent spatial and temporal resolution, as well as the ability to obtain a charge spectrum from which it is possible to reproduce the photon spectrum. In this way, additional 3D information can be used to determine the boundary conditions of 2D tomography, direct imaging, MHD simulation testing (synthetic diagnostics) or to use 3D tomography. The spectral resolution provided by the system can be used to determine the boundary conditions of the tungsten transport codes.

As we know, tungsten ion transport interacts with MHD activity and this interaction is a full three-dimensional phenomenon (e.g. 3D tungsten redistribution in NTM (Neoclassical Tearing Mode) or internal kink mode instabilities due to, for example, plasma rotation or off-axis ICRH (Ion Cyclotron Resonance Heating)). Proper identification of the mode and its location, as well as the spatial distribution of tungsten, would be more accurate thanks to diagnostics that guarantees obtaining of such 3D effects. In this respect, this diagnostics could be beneficial because a third detector, which would be a two-dimensional detector observing a poloidal cross-section, would provide access to the required 3D information, and would be complementary to standard poloidal tomography. It can be used both to effectively identify limits of 2D tomography in simple cases with axial-symmetric SXR emissions, as well as to validate 3D effects in a synthetic diagnostics approach, or to be used as direct 3D tomography. It must be said that the activity of W and MHD cannot be considered independent, therefore spectral resolution and 3D information are complementary if detailed physical examinations are to be carried out. Moreover, it is expected that electrons accelerated during magnetic reconnection processes, i.e. sawtooth, or during the discharge disruption caused by massive gas injections should produce a strongly anisotropic signal, to measure which a toroidal camera is excellently suited. Therefore, common use of toroidal detector with poloidal detectors would allow for better quantification of radiation anisotropy, and thus, both better quantification of the responsible electric field and better spatial location of accelerated electrons. Of course, such radiation would be visible at higher energy levels, but early observations suggest that it should be visible on SXR signals.

It should be noted that gas detectors based on GEM technology, which are developed by the research group under the guidance of the Habilitation Candidate, have additional advantages that are important for the current task, such as compactness, but a large detection area, and operational and flexible geometry, which is very important due to the limited available space around the tokamak chamber. In addition, external conditions such as magnetic field will not prevent the detector from operating effectively [35], [21]. Other advantages include ~20 ns single photon measurement time (reasonable time resolution will allow solving the problem of plasma dynamics (~100 μs)), relatively low cost, and as mentioned above, spatial separation of charge transfer/amplification and charge accumulation processes (i.e. signal readout), which allows for good 2D resolution (up to 50 μm [36]).

So far, I have conducted extensive research to optimise the response of GEM detectors. These include electrode configurations, detection chamber materials choice, geometry of holes in GEM foils, applied voltages for optimal field distribution, and gas flow rate and mixture composition. Micropattern readout is another important element of GEM detectors. It is responsible for the effective extraction of the collected charge from the electron cloud and its proper transfer to the electronic circuit. Selecting the geometry of the readout plane is important for the spatial resolution of the detector. This chapter presents the results of the Habilitation Candidate studies carried out with respect to the limits of the possibility of using several readout structures, both at intense photon flux and at maximum achievable spatial resolution, in order to determine their usefulness for plasma radiation imaging by means of GEM detector [**H-11**].

For the above tests, I used a model triple GEM detector filled with a mixture of Ar/CO_2 gases. Pixel readout structure (anode) was connected with readout electronics [28-30] which was able to deliver a signal performance of up to 2.5 MHz on a single channel.

Because the structure of readout imposes a certain number of electronic channels, in case of a large detection surface (typical for tokamak applications), a compromise should be found between good spatial resolution and unambiguity of photon position reconstruction and minimization of electronic channels number. Therefore, in this work I considered different layouts with a total detection area of ~100 × 100 mm^2, to optimize both parameters. I tested four readout geometries to study their spatial resolution and the ability to process intense photon fluxes, which are crucial for the imaging diagnostics of tokamak plasma.

The imaging of the detector signal was prepared with the participation of the Habilitation Candidate, assuming that the pixel charge of the readout, collected for the absorption of a single photon, refers to the probability of photon absorption on the associated detection surface [**H-2**, **H-3**]. Therefore, the location of a cluster was defined by the relative values of the pixel charges forming the cluster (an example with two ^{55}Fe sources is shown in Figure9).

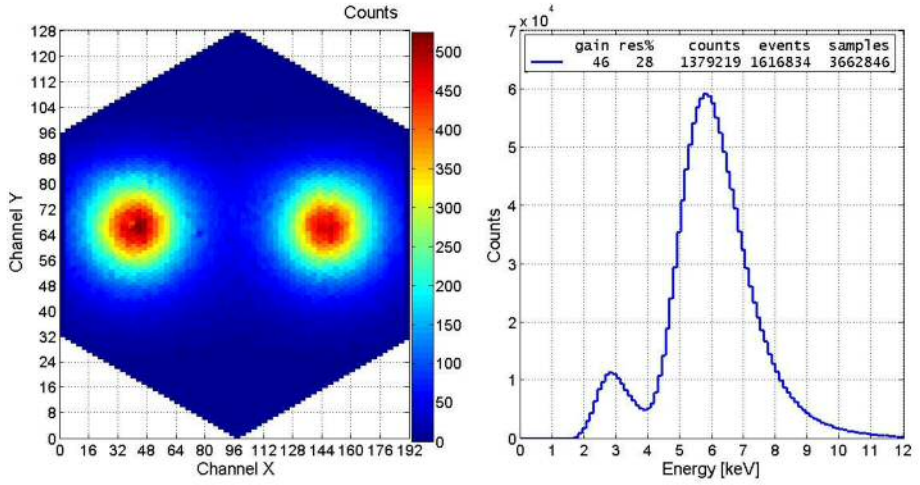


Figure9. GEM detector characteristics for two ^{55}Fe reference sources for UXV readout structure: planar distribution (left), energy spectrum (right).

In the case of intensive radiation sources such as tokamak plasma, there are events with multiple photons at the same time, which are lost during histogramming. This is due to the fact that simultaneous photons can appear in the same electronic channel, common for a group of connected pixels, even being recorded in different places on the readout plane. It is associated with the ambiguity of processing such a multi-hit event. A potential solution would be to have smaller and independent pixels for unambiguous reconstruction of the position and energy of the registered photons. This may not be practical, however, because thousands of pixels are needed for good spatial resolution even on a relatively small detection area.

In order to determine the limit values for the considered readout structures in relation to the unambiguous determination of the charge cluster produced by the photon and its position on the anode plane, this type of measurements was carried out for all readout structures [**H-11**]. The results are shown in Figure10 together with the extrapolated intensity of the X-ray generator. All readout structures were tested at the same settings of the X-ray generator. As it can be seen, a certain fraction of all registered events will be rejected from further processing. It includes ambiguous events, as irregular clusters of charges, when signals from adjacent pixels overlap in time or space, or events that cannot be resolved unequivocally (use of at least one common coordinate/channel for separate events). For independent hexagonal pixels (without interconnection), gathering information with higher performance was achieved at the cost of lower spatial resolution (another important parameter determining the imaging capabilities of the detectors, which I examined in this work).

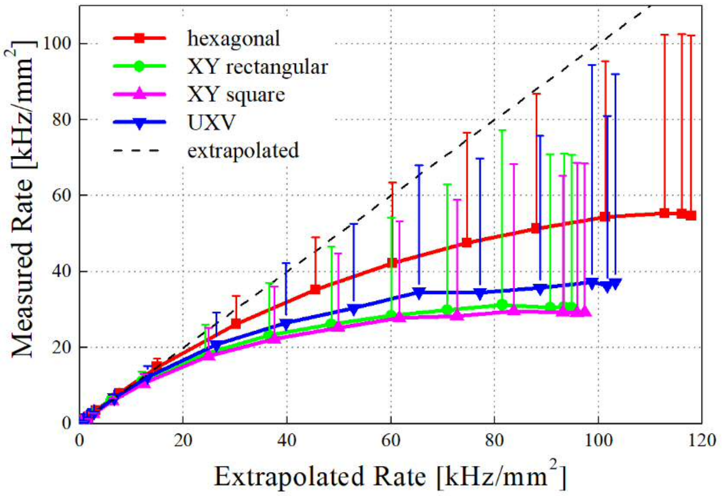


Figure10. The deviation of the photon flux measured by the GEM detector from the extrapolated flux for all the readout structures. The total number of indistinguishable events is marked as error bars. Extrapolated flux (dashed grey line) was obtained from independent verification of the linearity of the X-ray generator.

Comparison of the results for the other structures (UXV, XY with rectangular and square pixels) showed that all of them suffer to some extent (over 50%) from information loss for radiation fluxes above 60 kHz/mm^2. However, a slightly more effective detection of the measured photon flux was provided by UXV readout, which was able to handle higher throughput with good spatial resolution of the measurement.

Since tokamak plasma is a very bright source of SXR radiation, it can produce a very intense photon flux on the detector surface, which reaches over 10^5-10^7 cps mm^{-2} depending on the heating power, impurities present in the plasma and the detector system. Considering that high spatial resolution imaging of tokamak plasma would require a huge number of pixels directly connected to the readout electronics channels, it would be more appropriate to develop a readout structure with reduced independent electronics channels. Therefore, for the purpose of plasma imaging, the structure of the UXV readout, taking into account its further development and optimization, can be considered as a promising basic configuration for the construction of anode electrodes with the required characteristics.

With the high radiation fluxes mentioned above, there is a high probability of overlapping signals in time and space, which may prevent the identification of charge clusters from the detector signals, and this means a loss of information about the energy and number of photons. In order to improve the performance of the detector, a procedure of separation of overlapping pulses for the same electronic channel has been developed with the participation of the Habilitation Candidate, so that it can be implemented in real time data processing [**H-12**]. The developed algorithm separates the superimposed signals caused by a relatively slow electronic circuit. The separation of overlapping pulses has been successfully introduced and verified for simulation experiments. The procedure is effective when the primary GEM pulses do not overlap. The expected improvement in time resolution is about ~50 ns compared to ~500 ns previously achieved for shaped detector signals. This can significantly improve the performance of the GEM detector by implementing an algorithm in the FPGA module (or by processing signals in quasi online mode).

Since plasma radiation has a very high intensity and covers a wide range, the detection section of the developed diagnostics must be adapted to the experimental environment. It should not only thoroughly examine the radiation, but ideally, it should not provide any additional parasitic signals from the interaction of detector elements with incident radiation, e.g. fluorescence emission from photon-sensitive chamber elements. Therefore, the detector components must be designed so as not to interfere with the original signal.

The X-ray spectrum from the plasma in the Soft-Semi-Hard *(*S-SH) area of the radiation consists of a wide part of continuous radiation mixed with the emission from heavy impurities. Such a spectrum usually extends above the absorption edge of the copper (~9 keV), in particular for the ITER reactor, the basic material used so far for the production of GEM films, what could lead to a parasitic fluorescence signal. Recently, very preliminary studies on the adaptation of GEM foil with reduced copper have been launched [37] based on a chromium adhesive layer. However, the energy of the Cr K_α line is 5.411 keV, reaching the target energy range of photons. In addition, the fluorescence yield of Cr layers is also high due to relatively high Z, equal to ~0.35 for Cr and ~0.5 for Cu [38] as well as the effect of photon absorption.

In this work, the Habilitation Candidate proposed aluminium as a top metallic layer of GEM foil in order to use them for tokamak plasma imaging in the S-SH X-ray range. A lower absorption coefficient of Al compared to Cu above 2 keV leads to a lower radiation effect for Al film, and in addition, the fluorescence yield of Al is less than 0.05 [38]. In one of the recent papers [**H-13**], for the first time, according to the best knowledge of the authors, the newly developed GEM aluminium foils (with an adhesive layer of Cr) proposed by the Habilitation Candidate have been pretested for use in plasma X-ray imaging in the S-SH range.

In order to compare the influence of different materials on radiation imaging, I initiated simulations of a GEM response using GEANT4 (Figure 11**)**. It was shown that the intensity of parasitic fluorescence lines varies strongly depending on the material used in the detection chamber. Despite the slightly higher absolute intensity of the Al fluorescence line compared to the Cu line, the Al line intensity is only about 3% of the gas line at 2.3 keV compared to 60% of the Cu line to the gas line at 17.4 keV.

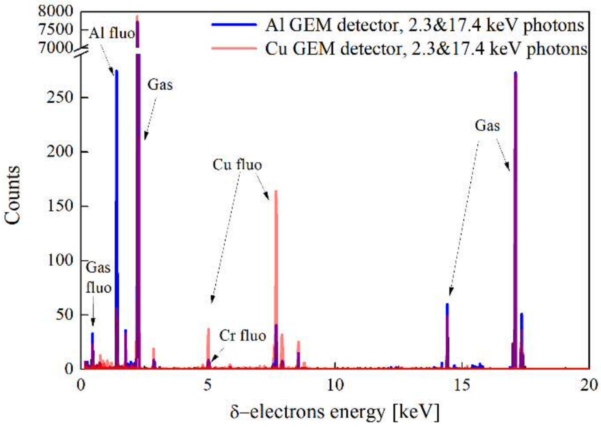


Figure 11. Simulations of δ electrons spectra for incident photons of 2.3 and 17.4 keV (*L*, *K*-edge of Mo) for Al and Cu GEM foils.

Since direct imaging imposes a perpendicular direction on incident radiation, it requires that the contribution of all unwanted signals from the interaction of detector materials with incident radiation be minimized. Therefore, I planned to test the detectors for different radiation sources (fluorescent lines) to verify the spectral performance of two detectors differing only in GEM foil material. The results of the tests, conducted with my significant participation, are shown in Figure12.

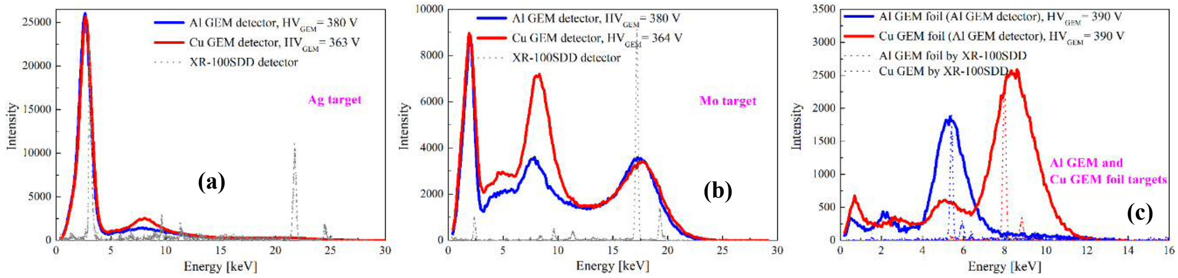


Figure12. Measured spectra for the following material targets: (a) Ag, (b) Mo, and (c) Cu GEM and Al GEM foils.

The presented dependencies (Figure12 (a-b)) show an undesirable influence of Cu material. Even with an aluminium GEM-based detector that has copper only on the readout board, Cu contributes to the overall signal (peak at ~8 keV on both drawings). The results of GEM foils irradiation are shown in Figure12 (c). The spectrum derived from Cu GEM foil exhibits a line of copper *K*- series (wide peak at ~8 keV with a Ar escape peak at ~5 keV). The measured spectra were consistent with the results of the simulation. This provided important information about the origin of the detector signal, with both the material and type of interaction been explained. This also confirmed the conclusion that Al is a more suitable material for the use in the detector for plasma imaging.

Moreover, the aspect of neutron interaction with the detection chamber material and with surrounding materials in a fusion experiment, as a source of background radiation, should be taken into account (which is a separate and broad issue) ([**H-5**], [**H-6**]). Not deviating from the subject and comparing the activation of Al and Cu by the full spectrum of neutrons produced in fusion devices, it turns out that Al material is more suitable for fusion applications also under its neutron interaction, since its active cross-section for activation is several times smaller than in the case of Cu. It also disperses several times less neutrons than Cu in almost the entire neutron range, except for 1-3 MeV, where this ratio is relatively higher (by 30-40%) than for Cu. In addition, the cross-sections of the radiation capture (n,γ), which is a very intensive reaction for thermal neutrons, are about 10 times smaller for Al than for Cu atoms.

It is worth mentioning that as part of this work, the invention in the field of electronics, used especially for the detection of soft X-rays, titled “Method and arrangement for separating overlapping impulses”, of which I am a co-author, was granted Patent No. 229625 from 07-06-2016 by the Patent Office of the Republic of Poland.

V.iii.5. Summary of the work

This Habilitation Thesis summarizes the achievements of the Habilitation Candidate in the development of a new global SXR measurement system based on GEM gas detectors. This work was initiated and is currently ongoing to support an ITER-oriented research programme, in order to develop a useful and effective detector for research in plasma physics through observation and analysis of radiation measurement. The main objective of this work was to develop, construct and study new GEM-based detectors for high resolution bent crystal spectrometer, tungsten transport tomography in ITER-oriented tokamaks and plasma radiation imaging.

The presented achievements showed that the proposed diagnostics can be used to measure SXR in tokamak plasma conditions. This diagnostics is intended to be used in future fusion reactors, as it takes into account the harshness of the operating conditions and eliminates the weaknesses of currently used SXR semiconductor detectors.

The effect of the performed work was design and production of detectors dedicated and optimized for continuous monitoring of plasma radiation emitted by highly ionized metal impurities present on the tokamak JET, W^{46+} (~2.4 keV) and Ni^{26+} (~7.8 keV). As a result, two detection modules for fast dynamic plasma imaging with SXR energy resolution and 10 ms time resolution were installed on the KX1 spectrometer. The high counting capability of the detection modules was achieved with a good position resolution. In addition, on-line separation of diffraction profiles corresponding to three orders of crystal diffraction was reached, that was not possible for the former detectors at KX1.

Then, a detection system based on GEM technology was developed for tomographic and imaging plasma diagnostics with energy discrimination of plasma radiation, which is an extremely valuable tool for monitoring transport of impurities and understanding its physics. Within the framework of this work, numerous tests and studies, both experimental and numerical, have been carried out to assess the performance of the detector, along with its detailed design and construction, in order to develop it in relation to the requirements imposed by the plasma radiation conditions and the tokamak environment. Ultimately, one of the system's detectors has been installed on WEST tokamak to verify its performance, which will be followed by the installation of a second detector for a complete poloidal tomography.

Two-dimensional GEM detectors were also developed to provide 3D information on plasma phenomena by observing the poloidal cross-section. Tests and innovative solutions have been implemented to create a new diagnostic tool appropriate to the scope of plasma physics. The design and construction of the elements of the detection chamber, as well as the exploration of the scientific results of the developed diagnostic tool were carried out with the significant participation of the Habilitaton Candidate of both the scientist and the head of the research team.

My most important achievements as a candidate for the Habilitation degree include: improvement of the radiation diagnostics technique itself in the field of plasma physics as well as increase of scientific knowledge about GEM detectors by many-sided studies of their performance at various conditions and applications. Such research required both conducting experiments and simulations to understand the mechanism of signal generation in the detector, optimise its performance, develop and test readout structures to meet the requirements of experiments at fusion reactors. In addition, experimental and numerical studies were conducted on the influence of the radiation environment on the behaviour of the detector and the effect of different geometries of GEM foils holes on the stability of the detector under the influence of intense radiation flux. Finally, a new material to be used for the production of GEM foil was proposed and tested, resulting in improved direct imaging capabilities and in a reduction of parasitic signals. At various stages of the research work, the Habilitation Candidate had to demonstrate effective planning of experimental work both in the local laboratory and on tokamaks JET, AUG, WEST, and at the same time to be a valuable collaborator in solving various issues relating the detectors themselves as well as in the development of algorithms for signal processing from both the substantive and methodological point of view. As a result of all these studies, it can be concluded that the detector based on GEM technology has contributed to eventual realization of the controlled thermonuclear fusion under Earth conditions.

VI. Discussion of other scientific and research achievements

VI.i. Activities conducted before the award of the academic degree of Ph.D.

I graduated with honours from the Faculty of Physics of the Donetsk State University in Donetsk (Ukraine) with a degree in Physics with a specialization in Theoretical Physics in June 1996. My Master's Thesis titled "Amplitude of Spin Waves Scattering in Spin Density Formalism" was successfully finished in May 1996 allowing me to obtain Master's degree. The summary of the results from the Master's Thesis were published in peer-reviewed international journal: "Scattering of spin waves by a rectilinear edge dislocation", A.N. Kuchko, M.V. Chernyshëva, Physics of the Solid State 40 No.11 (1998) 1861.

In 1996, I continued my doctoral studies at the Faculty of Physics of the Donetsk State University in the field of Theoretical Physics. I completed my doctoral studies in 2000, where I passed all the required exams with very good grades, but due to geopolitical reasons, I was forced to suspend writing of my doctoral thesis. The lack of funds to support myself during this period due to extremely difficult political and economic situation in Ukraine forced me to take up a full-time job in a private company, which resulted in a significant reduction of time that I could devote to completing and defending my doctorate. The general, very difficult economic situation, which effectively hindered access to the necessary tools, as obvious as a computer necessary to complete a doctoral thesis, contributed to the total resignation and departure from the country. As a result, the doctoral dissertation and its defence were not completed. However, the need for self-improvement and the innate attitude of finalizing the challenges faced earlier did not allow me to leave this issue open.

Therefore, after passing the qualifying exam, in April 2000 I undertook full-time doctoral studies at the Institute of Physics, Polish Academy of Sciences (IP PAS), in the ON1.2 division, i.e. the Division of Physics and Technology of Epitaxial Layers. In the years 2000-2005 I was involved in measurement of temperature and field dependence of magnetization of semiconductor three- and multilayer magnetic structures. I conducted experimental research and analysis of physical models concerning magnetic and optical properties of ferromagnetic semiconductor structures EuS-PbS. The results of these studies formed the basis for my doctoral dissertation.

The main aims of the study were: experimental study of antiferromagnetic mechanisms of interactions between EuS layers through non-magnetic semiconductor PbS layers and experimental verification of the influence of ferromagnetic EuS barriers on electron structure and magnetooptical properties of EuS-PbS multilayers in various spectral areas. A number of tasks undertaken in the Ph.D. thesis were related to studies of optical properties of EuS-PbS structures. For the quantitative analysis of experimental results it was necessary to develop a physical model taking into account the basic features of magnetization of the triple layers coupled antiferromagnetically.

Essential significance for my Ph.D. work had studies of optical properties and electron structure of PbS wells with ferromagnetic EuS barriers. This task was carried out with the use of photoluminescence measurements as a function of temperature and magnetic field. The thesis undertook a particularly difficult task, namely experimental verification of the possibility of using ferromagnetic properties of EuS-PbS multilayers to control the optical properties of PbS wells. In order to obtain a complete picture of the electron structure and optical properties of EuS-PbS structures, the analysis of spectral dependence of the Kerr effect in the range of EuS absorption edges and synchrotron photo-emission measurements allowing to determine the density of electron states of EuS layers were performed. A large part of the experimental work was carried out at IP PAS in cooperation with various departments of the Institute. The cooperation with the University of Eindhoven and the HASYLAB laboratory in Hamburg were also actively utilised.

The results of my experimental research and numerical calculations were included in a dissertation entitled “Magnetic and magneto-optical properties of semiconductor ferromagnetic structures EuS-PbS” written under the supervision of Dr. hab. Tomasz Story. The Ph.D. degree in Physics of Solid State was awarded to me by the resolution of 23 June 2005 of the Scientific Committee of IP PAS.

In cooperation with IP PAS scientists during my doctoral studies, I got acquainted with the techniques of Photo Emission Spectroscopy (PES), X-ray Absorption Near Edge Structure (XANES), Extended X-Ray Absorption Fine Structure (EXAFS), Resonant Inelastic X-ray Scattering (RIXS), and actively participated in numerous synchrotron measurements (within the framework of the projects “Ge atoms buried in silicon matrix”, “XAFS studies of the local structure of Mn doped dilute magnetic semiconductors”, “Ge atom surrounding in Ge/Si heterostructures”, “Study of strains of Ge atoms bonds in Ge(n)/Si(m) superlattice by XAFS exploring polarization effects of SR", and "New materials for spintronic") at European synchrotron research facilities: HAASYLAB in Hamburg and LURE in Orsay.

The results obtained in this period (2000-2005) were published in 14 scientific manuscripts in internationally peer-reviewed journals that are listed at Institute for Scientific Information (ISI) (including 3 manuscripts as the first author). In addition, 3 annual reports were published to summarise DESY synchrotron measurements. The results were also presented at international conferences, seminars and PhD workshops.

VI.ii. Activity pursued after the award of the academic degree of Ph.D.

Shortly before the award of the Ph.D. degree (1 March 2005), I became an employee at the Institute of Plasma Physics and Laser Microfusion as an adjunct researcher. As a result of that, the area of my scientific research has moved from physics of solid state into plasma physics, a significantly different direction.

At IPPLM, the aim of my scientific work after obtaining the Ph.D. degree was to actively participate in experiments on the Plasma Focus 1000 kJ (PF-1000) and two smaller PF devices (6 and 8 kJ). The main aim of the experiments was to get acquainted with the physics of those devices whose basic design is derived from the Z-pinch concept, as well as with the use of such devices in various applications, research and technological processes. Studies of the interaction of plasma streams and radiation with the surface of different materials can be used to spray thin layers of metal on different substrates. As an effective pulsed ion source, PF is used for carbon and fullerene deposition, zirconium titanate grain deposition, surface nitriding or carbon implantation. This field of research contributed to establishing of international cooperation with the Korean Institute of Science and Technology in Seoul (Korea). For this purpose, the PF machine was adjusted to grow thin layers of Cr on silicon substrates. This material is very promising for the electronics industry since it can potentially be used as additives to thin $SrTiO_3$. It is assumed that the produced material should have certain parameters, e.g. specified purity. For this reason, the main problem that had to be solved when depositing thin layers with a PF device (with a stored energy of 1 kJ) was the elimination of impurities from the electrode material. This influence of the electrode structure on the purity of the chromium layer for the samples produced under the same deposition conditions was investigated. As a result, it allowed obtaining chromium layers free of impurities from the insulator and cathode material.

Independently, I have participated in numerous other experiments on the PF-6 device at IPPLM, related to the production of X-rays and neutrons for a wide range of applications. In neutron applications, intensive neutron scattering on light elements (mainly hydrogen) was planned to be used for the detection of illicit materials, e.g. chemical warfare agents, explosives, using PF as a mobile neutron source. This method uses very intensive neutron pulses with a duration of about 10 ns, which are generated by dense plasma devices like Dense Plasma Focus, filled with working gas in the form of pure deuterium or a mixture of deuterium and tritium. The small spatial size of the neutron beam, the high number of neutrons per single pulse and the monochromaticity ($\Delta E/E \sim 1\%$) of the neutron spectrum make it possible to use the time-of-flight (TOF) technique with variable bases of about a few meters within this method. It was shown that short TOF bases and relatively low neutron outputs are sufficient to distinguish between nuclei from different elements of the substance and to characterise the geometry of long objects in some cases.

As an effective source of X-rays generated during the compression phase of such a device operation, it can be freely used to perform rapid defectoscopic tests. One example is the testing of car tyres to detect manufacturing defects during the manufacturing process for selective quality control. The obtained results can certainly be taken as the first milestone on the way to confirming that radiography with a PF device has a number of advantages over traditional X-ray radiography and as such can be successfully used, for example, to recognise the delicate structure of a tyre.

In 2005-2006, I completed a total of three months' scientific internship at the Faculty of Physics of the University of Ferrara (Italy), within the framework of the scholarship programmes POL/07001 and POL/06002 of the IAEA "Laboratory for material testing based on Plasma-Focus". During this internship a very modern PF machine was practically completed and the first tests using it were carried out. It was a unique opportunity to advance knowledge, improve skills and get started quickly in a new field of physics, as all important aspects of the functioning and verification of the PF device were examined in a fairly short time.

This work was continued in cooperation with the Multidisciplinary Laboratory (MLab) of the Abdus Salam International Centre for Theoretical Physics in Trieste (Italy), where I conducted numerous scientific visits taking an active part in experimental research in the laboratory equipped with the PF device (8 kJ) and participated in activities related to the organization and conduction of practical classes on the PF device in MLab for participants of international workshops (Annex 4 III(C) 1-4).

Basically, my work with PF devices concerns basic research studies in the field of high-current discharge physics; experiments with deposition of thin Cr layers on Si substrates; optimization of Cr layer growth conditions for ultra-thin and pure chromium layers; development of Re implantation; participation in experiments on the use of PF device as a pulse source of X-rays for qualitative radiograms of tested materials; optimization of PF work in order to obtain effective X-ray efficiency; application of this system as an effective neutron source; neutron diagnostics. I was involved in the measurement of neutrons from fusion reactions in the PF device and in the preparation of holographic interferometry diagnostics for the measurement of plasma density distributions in the pinch and plasma streams. I was also actively involved in material testing, e.g., interaction of fast plasma fluxes with the surface of various fusion materials, such as low activation steels, tungsten, carbon composites, etc. In addition, I was involved in evaluation of modifications of surface, microstructure and phase in different classes of tungsten samples that were subject to pulsed plasma loading. This and other works on the PF devices were carried out within projects under the Coordinated Research Project (CRP) of the International Atomic Energy Agency (IAEA) and "Transnational Access to Major European Infrastructures" implemented by a team of IPPLM researchers (Annex 4, II(H), 30-34, 16).

Independently I have been and still am continuing my cooperation with IP PAS in applicability of X-ray spectroscopy for various studies: (1) study of modification of local atomic structure around Mn atoms in (Ga,Mn)As layers after annealing at moderately high temperatures; (2) study of XANES structure of modified and newly synthesized nanostructured manganese oxides; (3) combined analysis of X-ray emission results and XANES structure for L_3 edge of Cd and K edge of O in CdO layers as well as for $In_xGa_{1-x}N$ layer aimed for electron structure studies; (4) applications of X-ray spectroscopy to study the electron structure of polycrystalline cadmium disulphide; (5) observation of quantum confinement in the band of conductivity of PbS colloidal quantum dots; (6) application of XPS to explain the variability of Hall coefficient sign in thin layers of niobium covered with silicon; (7) study of magnetic anisotropy in the Co/MgO system with a gold interlayer using the XPS method; (8) influence of argon sputtering on the obtained XPS depth profiles for Si/Nb/Si samples, etc. My participation in most X-ray spectroscopy research projects has been related to discussion, analysis of experimental and theoretical results and assistance with synchrotron measurements during realization of research projects. Within the framework of this cooperation, I took an active part in numerous experimental measurements at European synchrotrons: MAX-lab (Sweden), ALBA (Spain), ELETTRA (Italy). For example, I was a co-author of the application for the beam time at ALBA synchrotron (project titled "Impact of growth conditions on the chemical and electronic structure of *p-type* ZnO:N thin films produced by ALD" submitted and awarded in 2015) as well as co-investigator in this research study. Also, I was a co-author of the application for the beam time at ELETTRA synchrotron (project titled "X-ray absorption fine structure analysis of optically active centres in Re-implanted ZnO films" submitted and awarded in 2016) as well as co-investigator in this research study. Furthermore, I was involved in organizing scientific workshops (Annex 4 III(C) 5).

In addition to the research topics discussed above, preliminary studies of rhenium implantation into silicon substrate have been started in cooperation with IP PAS. Silicon doped with rhenium, which is a transition metal, is estimated to belong to a class of materials called diluted magnetic semiconductors. Because of the half-filled shell *d*, in compounds with other elements rhenium electrons should form states strongly hybridised with states of the host element. So far, due to difficulties with the introduction of rhenium into bulk silicon, such a material has not been studied experimentally. In order to check the characteristics of such a material (especially its magnetic properties), I conducted an experiment using a PF device for rhenium implantation into a silicon substrate. It was shown that the conducted tests allowed obtaining high Re content in the Si matrix with constant concentration at the depth of at least 7 microns. However, due to contamination of the samples by copper and chromium from the materials in the PF system chamber, it was difficult to identify the source of the weak ferromagnetism of the samples produced, which could also be originated from Cr. Therefore, further testing of the samples obtained by Electron Paramagnetic Resonance (EPR) is required to resolve these issues. Despite the ambiguous result of the experiment, such production technique highlighted unique abilities of PF system to incorporate Re, which is a very difficult material to process, of such deep penetration ability and such high content in the silicon substrate throughout the entire examined depth. Further tests should be carried out in device with a chamber specifically dedicated to the implantation of Re.

In the years 2010-2013 my main task was to coordinate and realise the project "Gas Electron Multiplier Detector for X-ray Crystal Spectrometry GXS", dedicated to the development, construction and implementation of GEM detectors for X-ray diagnostics of tokamak plasma on JET tokamak (KX1 diagnostics). In the first period of the project I was its coordinator within the IPPLM team, however, in the last year of the project until its successful completion I was the deputy project leader, also directing and supervising the installation of the final detection systems on the KX1 spectrometer. Then, in the years 2011-2014, I was involved in a strategic research project sponsored by the National Centre for Research and Development (NCBR) entitled "Technologies supporting the development of a safe nuclear energy sector". My participation in the mentioned project was related mainly to Work Package 2.3 concerning the task "Development of plasma imaging technology in the field of X-rays for the purpose of diagnostics of monitoring impurity released from the walls of a fusion reactor". As part of this project (from 2013 as principal investigator of the Work Package 2.3), I was responsible for the design, development, construction and testing of two-dimensional GEM detectors for fusion applications.

In the years 2015-2016 I initiated the modernization of a cleanroom at the IPPLM, where detectors are being made, and modernization of the X-ray Diagnostics Laboratory equipping it with modern tools used for research purposes (microscope, modern electronics modules, supercomputers for computation, spectroscopic tools, high-voltage power supplies, gas systems, etc.).

In the years 2013-2018, I made active attempts to obtain funding both in international and domestic programs, preparing project proposals, and establishing international cooperation with foreign research centres by delivering papers originated from my own research. In 2013 and 2014, as part of the so-called Enabling Research Programme of EUROfusion, I submitted grant applications which were accepted for implementation and where I was the leading author and Project Leader.

I have also made several visits to CERN (gas detector laboratory) as part of the scientific exchange and established cooperation within “RD51 MPGD Collaboration”, within which I am the head of a group of scientists from the IPPLM side.

In 2014-2018, within the framework of the so-called Enabling Research projects of the EURATOM programme, the EUROfusion consortium, (WP14-ER-01/IPPLM-05 and ENR-MFE15.IPPLM-04 entitled “Development of soft X-ray GEM based detecting system for tomographic tungsten focused transport monitoring”), of which I was the project leader, I was conducting research dedicated to the development and construction of detectors for soft X-ray measurements at the WEST tokamak. Both detectors were recently finalised. The flat surface detector has been installed in the WEST tokamak port and is ready to measure plasma radiation. Currently, we expect our French collaborators to verify the data from this detector in the next experimental campaign (middle 2019). After successful validation, installation of the second detector with a curved detection surface (that is under laboratory testing at IPPLM) will be progressed aiming to achieve a working tomography system.

As part of my work on GEM type gas detectors, in addition to the usage of detectors to measure X-rays, I have participated in various projects under the 7th EURATOM and H2020 EURATOM Framework Programmes of the European Union, that were devoted to the design, construction and testing of GEM type detectors aimed, for example, to monitor neutrons with an energy of 2.5 and 14 MeV. My role in the task, dedicated among others to the construction of a prototype GEM detector filled with neon to detect 14 MeV neutrons using Ne activation in the drift area, was to supervise in the final stage, namely to conduct an experiment and analyse the results of the GEM detector, which was used to record beta particles. In 2013, I was also implementing a project concerning the development of new generation X-ray detectors for hot plasma measurement and imaging in the area of soft X-ray radiation in the photon range of 2-10 keV.

Apart from a very extensive work on gas detectors that has started in 2010 and that was related to the design and construction of X-ray diagnostics with the use of GEM detectors for fusion devices, whose most important achievements are the basis of this Habilitation Thesis, I was involved in various other scientific projects. Starting in 2013, as part of the European fusion research programme (EURATOM), I have conducted data analysis and actively participated in experimental campaigns on fusion devices (JET, ASDEX Upgrade), where I have deepened my knowledge and gained scientific experience. I am constantly improving my qualifications in the field of plasma physics and fusion devices by participating in training courses: “Training in the basics of vacuum technique” in 2006 in Cracow, Poland; “JET Bolometer Analysis Training” in 2014 in Culham, U.K., devoted to tomography based on data analysis of bolometer measurements on the JET tokamak; “The JET Refresher Course” in 2018 in Culham, U.K., devoted to Viewing System Operator (VSO) competence. Since 2014, after completing the training in experimental campaigns, I have been preparing tomographic reconstructions based on bolometric measurements obtained during experiments, distribution of radiation power in the divertor area and main chamber of the tokamak for discharges with different plasma scenarios. Within the scope of this issue, I perform an analysis of radiation power for the entire discharge, validation of the values of plasma radiation parameters and analysis of the sensitivity of the selection of reconstruction parameters to the result obtained.

VI.iii. Didactic work and other achievements

The duties of adjunct researcher and specifics of the scientific and research activities at IPPLM do not provide too many opportunities for didactic work with students. However, the research carried out at the Institute is of interest to a wide range of people, including undergraduate and doctoral students. As a result, in the years 2014-2015 I was a scientific supervisor of the engineering thesis “Application of GEM type gas detectors to measure soft X-ray radiation emitted from plasma” of a student of the Faculty of Physics of Warsaw University of Technology (Annex 4 III(I)). This study concerned the simulation of electromagnetic field distribution in GEM type detectors for various electrode configurations and applied voltages and was successfully defended by the candidate with a grade “Very Good” in 2015. As a scientific supervisor, I provided substantive support to student on plasma physics, GEM-related phenomena, simulation and interpretation of numerical results.

Since the beginning of 2017 I have also been the scientific supervisor of the engineering thesis of a student of the Faculty of Physics of the Warsaw University of Technology (Annex 4 III(I)) entitled "Impact of GEM foil on plasma to electric current conversion process simulation". This study is related to the simulation of GEM detector signals in a heterogeneous magnetic field, which may contribute to the optimization of the detector results. The cooperation with the student lasted until the end of 2018, but due to serious personal circumstances of the student, the work has not yet been finalised despite numerous support and thorough substantive assistance in preparing and collecting the results necessary to write an engineering thesis.

Since the beginning of this year (scientific support has been provided since 2016) I have been an assistant supervisor of a Ph.D. student at the Institute of Electronic Systems of the Faculty of Electronics and Information Technology of the Warsaw University of Technology (Annex 4 III(J)). The solution, which will be presented in the Ph.D. thesis, concerns data processing within the system for monitoring plasma contamination developed jointly by Warsaw University of Technology and IPPLM in the WEST experiment in Cadarache (France). As an assistant supervisor, I provide substantive support for the phenomena of plasma physics, phenomena related to detectors (especially GEM), interpretation and obtaining results of high quality, implementation of the work, correct planning and undertake of measurements.

My expertise in the field of gas detectors has also been utilized beneficially by two Ph.D. students pursuing Ph.D. degree at the Institute of Electronic Systems at the Faculty of Electronics and Information Technology of the Warsaw University of Technology. These studies were successfully defended in 2018.

I am the Head of the X-ray Diagnostics Laboratory at the IPPLM (since July 2014) and I am the Head of the team that works on GEM detectors (since January 2013). This leading role also involves some didactic work among my team members. In addition, in 2017, I took over the role of Group Manager from IPPLM as part of the "RD51 MPGD Collaboration" cooperation at CERN.

My contribution to the research, results and analysis in cooperation with domestic and foreign research centres resulted in quite a lot of publications, conference presentations delivered personally by me or my co-authors. The results of the research I have actively pursued has resulted into 10 oral and 17 poster contributions presented by me at international conferences and scientific symposia on plasma physics or entirely on MPGD gas detectors

(Annex 4 II(J), III(B)). Furthermore, I have had one invited paper that I delivered at the conference PLASMA 2015: International Conference on Research and Applications of Plasmas, Warsaw, 2015.

My scientific achievements have been recognized twice by the director of the IPPLM through individual awards in 2013 and 2018: Award of II degree in 2013 competition for outstanding scientific achievements with the title of distinguished work: "Significant participation in the launch of KX1 diagnostics on JET and the provision of data essential for the development of nuclear fusion, on the basis of which it is possible to determine the concentration of tungsten and nickel in plasma" , and Award under the IPPLM Director's Order No. 25/2018 of 16 November 2018 for exemplary performance of duties, demonstration of initiative in work and improvement of its efficiency, and in particular for commitment to new projects and effective management of the managed Laboratory.

I am the co-author of patent No. 229625 for the invention entitled "Method and system for separation of overlapping impulses" that has been granted on 07-06-2016.

Furthermore, I have been a regular reviewer for the following scientific journals: Czechoslovak Journal of Physics (2 manuscripts), Review Scientific Instruments (2 manuscripts), Fusion Engineering and Design (2 manuscripts). I was also appointed as a reviewer of diploma thesis for MSc degree of a student from the Institute of Electronic Systems (Faculty of Electronics and Information Technology of the Warsaw University of Technology) entitled "Fast track of charge acquisition using FPGA system" (Annex 4 III(H)).

Bibliography

1. J. Ongena, G. Van Oost, „Energy for future centuries: will fusion be an inexhaustible, safe, and clean energy source?", *Fusion Science and Technology*, 45(2T) (2004) 3-14.
2. F.H. Séguin et al., „Radiation-hardened x-ray imaging for burning-plasma tokamaks", *Review of Scientific Instruments* 68 (1997) 753.
3. F. Sauli, „The gas electron multiplier (GEM): Operating principles and applications", *Nuclear Instruments and Methods in Physics Research Section A* 805 (2016) 2-24.
4. A.F. Buzulutskov, „Radiation Detectors Based on Gas Electron Multipliers (Rreview)", *Instruments and Experimental Techniques* 50(3) (2007) 287–310.
5. K.W. Hill et al., „A spatially resolving x-ray crystal spectrometer for measurement of ion-temperature and rotation-velocity profiles on the Alcator C-Mod tokamak", *Review Scientific Instruments* 79 (2008) 10E320.
6. K.-D. Zastrow et al., „Deduction of central plasma parameters from line-of-sight averaged spectroscopic observations", *Journal of Applied Physics* 70 (1991) 6732.

7. I. Zemtsov et al., „Modelling of tungsten behavior in plasma of t-10 tokamak”, *Physics of Atomic Nuclei* 81(7) (2018) 1042-1047.
8. T. Pütterich et al., „Modelling of measured tungsten spectra from ASDEX Upgrade and predictions for ITER”, *Plasma Physics and Controlled Fusion* 50 (2008) 085016.
9. J. Rzadkiewicz et al., „Design of T-GEM detectors for X-ray diagnostics on JET”, *Nuclear Instruments and Methods in Physics Research A* 720 (2013) 36.
10. K. Jakubowska et al., „Development of a 1D Triple GEM X-ray detector for a high-resolution X-ray diagnostics at JET”, *Proceedings of the 38th EPS Conference on Plasma Physics 2011* (EPS 2011) 716.
11. R. Bartiromo et al., „JET high resolution bent crystal spectrometer,” *Review of Scientific Instruments* 60 (1989) 237.
12. S. Bachmann. et al., „Charge amplification and transfer processes in the gas electron multiplier”, *Nuclear Instruments and Methods in Physics Research Section A* 438 (1999) 376.
13. A.E. Shumack et al., „X-Ray Crystal Spectrometer Upgrade for ITER-like wall experiments at JET”, *Review of Scientific Instruments* 85 (2014) 11E425.
14. T. Nakano et al., „Determination of tungsten and molybdenum concentrations from an X-ray range spectrum in JET with the ITER-like wall configuration”, *Journal of Physics B: Atomic, Molecular and Optical Physics* 48 (2015) 144023.
15. K.T. Pozniak et al., „FPGA based charge fast histogramming for GEM detector”, *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments, Proc. SPIE* 8903 (2013) 89032F.
16. J. Bucalossi et al., „The WEST project: Testing ITER divertor high heat flux component technology in a steady state tokamak environment”, *Fusion Engineering and Design* 89(7-8) (2014) 907-912.
17. M. Sertoli et al., „Modification of impurity transport in the presence of saturated (m,n) = (1,1) MHD activity at ASDEX Upgrade”, *Plasma Physics and Controlled Fusion* 57(7) (2015) 075004.
18. D. Mazon et al., „Design of soft-X-ray tomographic system in WEST using GEM detectors”, *Fusion Engineering and Design* 96-97 (2015) 856-860.
19. P. Zienkiewicz et al., „Data management software concept for WEST plasma measurement system”, *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics, Proc. of SPIE* 9290 (2014) 92902B-1.
20. A. Wojenski et. al., „Diagnostic-Management System and Test Pulse Acquisition for WEST Plasma Measurement System”, *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics, Proc. of SPIE* 9290 (2014) 929029-1.

21. M. Chernyshova et al., „GEM detector development for tokamak plasma radiation diagnostics: SXR poloidal tomography”, *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics, Proc. of SPIE* 9662 (2015) 966231-1.
22. F. Sauli, „Development and applications of gas electron multiplier detectors”, *Nuclear Instruments and Methods in Physics Research A* 505 (2003) 195-198.
23. M. Ball et al., „Ion backflow studies for the ALICE TPC upgrade with GEMs”, *Journal of Instrumentation* 9 (2014) C04025.
24. S. Agostinelli et al., „Geant4—a simulation toolkit”, *Nuclear Instruments and Methods in Physics Research A* 506 (2003) 250.
25. I.B. Smirnov, „Modeling of ionization produced by fast charged particles in gases”, *Nuclear Instruments and Methods in Physics Research A* 554 (2005) 474.
26. D. Mazon et al., „SXR measurement and W transport survey using GEM tomographic system on WEST”, *Journal of Instrumentation* 12 (2017) C11034.
27. A. Jardin et al., „Tomographic capabilities of the new GEM based SXR diagnostic of WEST,” *Journal of Instrumentation* 11 (2016) C07006.
28. A. Wojenski et al., „Concept and current status of data acquisition technique for GEM Detector–based SXR diagnostics”, *Fusion Science and Technology* 69 (2016) 595-604.
29. A. Wojenski et al., „Multichannel reconfigurable measurement system for hot plasma diagnostics based on GEM-2D detector”, *Nuclear Instruments and Methods in Physics Research B* 364 (2015) 49-53.
30. A. Wojenski et al., „FPGA-based GEM detector signal acquisition for SXR spectroscopy system”, *Journal of Instrumentation* 11 (2016) C11035.
31. D. Mazon et al., „GEM detectors for WEST and potential application for heavy impurity transport studies”, *Journal of Instrumentation* 11 (2016) C08006.
32. S. Bachmann et al., „ High rate X-ray imaging using multi-GEM detectors with a novel readout design”, *Nuclear Instruments and Methods in Physics Research A* 478 (2002) 104.
33. A. Zielinska et al., „X-ray fluorescence imaging system for fast mapping of pigment distributions in cultural heritage paintings”, *Journal of Instrumentation* 8 (2013) P10011.
34. J.F.C.A.Veloso et al., „Energy resolved X-ray fluorescence imaging based on a micropattern gas detector”, *Spectrochimica Acta Part B: Atomic Spectroscopy* 65(3) (2010) 241-247.
35. S. Blatt et al., „Charge transfer of GEM structures in high magnetic fields”, *Nuclear Physics B Proceedings Supplement* 150 (2006) 155-158.
36. A. Bressan et al., „Beam tests of the gas electron multiplier”, *Nuclear Instruments and Methods in Physics Research Section A* 425(1-2) (1999) 262-276.
37. B. Mindur et al., „Performance of a GEM detector with copper-less foils”, *Journal of Instrumentation* 12 (2017) P09020.

Maryna Chernyshova

The applicant's signature