Conceptual design and development of GEM based detecting system for tomographic tungsten focused transport monitoring

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ABSTRACT: Implementing tungsten as a plasma facing material in ITER and future fusion reactors will require effective monitoring of not just its level in the plasma but also its distribution. That can be successfully achieved using detectors based on Gas Electron Multiplier (GEM) technology. This work presents the conceptual design of the detecting unit for poloidal tomography to be tested at the WEST project tokamak. The current stage of the development is discussed covering aspects which include detector’s spatial dimensions, gas mixtures, window materials and arrangements inside and outside the tokamak ports, details of detector’s structure itself and details of the detecting module electronics. It is expected that the detecting unit under development, when implemented, will add to the safe operation of tokamak bringing the creation of sustainable nuclear fusion reactors a step closer.

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KEYWORDS: Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); X-ray detectors; Nuclear instruments and methods for hot plasma diagnostics; Data acquisition concepts

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1 Introduction

X-ray spectroscopy is an established, successful and powerful tool for tokamak plasma diagnostics which utilizes soft X-ray (SXR) radiation of magnetic fusion plasmas allowing extraction of valuable information on particle transport and MagnetoHydroDynamic (MHD) phenomena, like sawteeth, snakes, magnetic islands, etc., leading to effective monitoring of the tokamak plasma properties.

The aim of this work is to design a new diagnostics for poloidal tomography focused on the metal impurities radiation monitoring, particularly tungsten emission, by means of SXR measurements. Being a main candidate for the plasma facing material in ITER and future fusion reactor for some time [1], tungsten has recently started to be used as such in many machines. This also includes the WEST project [2], where an actively cooled tungsten divertor is being implemented. Inevitably, this forced creation of the ITER-oriented research programs aiming to effectively monitor the impurity level of tungsten in plasma. However, due to the interaction between particle transport and MHD activity the situation is even more complicated as such impurities might accumulate in plasma [3]. This effect could lead to a plasma disruption, especially, in case of long pulse tokamaks. Therefore, an appropriate diagnostic tool has to be developed which will not just monitor the level of impurity but will also reconstruct its distribution. It is worth noticing that the tomography system under development will also allow energy discrimination of the photons, that is not available in most current SXR tomographic systems exploiting Si diode detectors. Combining both spectral information on plasma radiation and good spatial resolution of its detection should allow recovering fundamental information in order to estimate the level of the plasma contamination and consider its effects on plasma scenarios. For this purpose, an SXR tomographic diagnostics with energy discrimination has been extensively considered for a while [4].
Detection system based on Gas Electron Multiplier (GEM) technology [5] with energy discrimination capability has been recently proposed to be used as an SXR tomographic system for ITER-oriented tokamaks and is under development by our group [6–9]. Detectors built with this technology will satisfy the main constraints on dimensions, X-ray spatial position and required energy sensitivity imposed on any X-ray detector for tokamak plasma in ITER and/or DEMO. In addition such detectors will offer large detection area matching the aperture of the single window of the spectrometer, good spatial resolution, high signal to noise ratio, detection stability for a wide range of photon rates, capability of photon energy discrimination, and sustainability to neutron radiation. It has been shown that the multichannel proportional gas detectors configured in a multistep structure are capable of providing sufficient detection characteristics [6, 10–12].

Within this work the GEM-detector based SXR tomography is proposed to monitor the impurity level in SXR region with the determination of tungsten distribution in focus. Control of this element will be crucial for achieving the appropriate operating parameters of the whole reactor. The array of two GEM detectors is expected to discriminate the energy of SXR photons together with their position reconstruction in vertical and horizontal locations enabling energy-resolved poloidal plasma tomography. Controlling tungsten impurities in the plasma center should be based on the analysis of the characteristic radiation of L/M lines emitted by tungsten (the highest intensity of radiation emitted from the plasma center) [13]. The main aim of the new X-ray diagnostics is to provide the monitoring of the radiation emitted by highly ionized metal impurities focusing on the emission of W lines in the region of 2–4 keV. The W$^{46+}$ emission line is positioned at ~2.4 keV from the hottest region of the tokamak plasmas [14, 15].

This paper is organized as follows: section 2.1 describes briefly the overall concept of the detecting system for plasma radiation diagnostics listing major requirements which should be realized in such system. Section 2.2 explains the layout of the tomographic detecting unit in the experimental environment of the WEST tokamak. The design of both detectors for tomographic detecting unit is explained in section 2.3. Finally, the concept of the processing electronics and data acquisition is summarized in section 2.4.

2 GEM technology based SXR monitoring system

2.1 Concept of the detecting system for plasma radiation diagnostics

The concept of the detecting system is based on the requirements imposed by needs of impurity distribution studies. As the system is dedicated to monitor tungsten impurity and to study slow MHD activity, the following requirements on time resolution have been set: the detecting system should be able to resolve at least 1 kHz impurity transport scale, and it should pick up the slowest MHD activities at 10 kHz (tearing modes, sawtooth crashes). It is worth mentioning that such temporal resolution sets high limits on the detecting electronics. Concerning the spatial scale, it was estimated that resolution of 1 cm is satisfactory to obtain good tomographic image that will contain accurate information about the magnetic axis, sawteeth inversion radius, and the impurity gradients distribution.

Figure 1 presents the block diagram illustrating the main signal/data path for the elaborated detecting system. The main principle of the gas detector operation is based on the registration of
an effect of interaction of ionizing radiation with gas adapted to photoionization. For SXR detection application, X-ray photon, which penetrates the detector window, could be absorbed in the gas volume placed between the cathode and the following electrodes with an electric field up to a few kV/cm. It is sufficient to prevent the recombination of created ion-electron pairs and to further separate these charges: electrons drift towards the following electrode and readout plane, while ions drift to the cathode. As the number of the originated primary electrons is too low to be measured directly (reasonable signal to noise ratio is impossible to be achieved) GEM technology [16] is proposed for the effective signal amplification with the GEM foil [11, 17] as a charge multiplier step.

A major problem in tokamak plasma imaging is a high level of noise signals in the detector and electronics. This noise can result in misinterpretation of SXR data leading to achievement of non-physical parameters for high-temperature plasma. Suitable discrimination of noise signals in a high intensity stream of photons should be one of the most important tasks for such diagnostics. Another challenge for imaging is the tokamak plasma irregularities in the measured profiles of plasma, so X-ray detection systems for future fusion reactors should demonstrate a high dynamics and offer relatively easy calibration in the time between the discharges. The GEM structure allows one to construct a gas detector of relatively high charge amplification and operating at radiation flux of up to $10^{11} \text{m}^{-2}\text{s}^{-1}$. The pulse-height dynamic range of such a detector can be expanded to 2 orders of signal magnitude above the common electronic noise level, with very low probability of discharges induced by heavily ionizing background.

![Figure 1](image.png)

**Figure 1.** Signal/data flowing path block-scheme of the proposed detecting system.

The possibility of using several GEM foils in cascade for charge amplification permits much larger gains than single stage detectors before discharge breakdown. The electric field through all electrodes is chosen in such a way that it provides the efficient electron transparency up to the readout plane. In this way the multiplied primary electrons reach the readout plane forming the initial signal which is acquired through the electronics module. Firstly, it is shaped and amplified
by low noise charge sensitive amplifiers on the analog front-end (AFE) boards and then is digitized through analog-to-digital converters (ADCs) with $\sim125$ MHz sampling frequency [18]. It is then treated with the processing electronics in order to obtain position and energy reconstruction of the absorbed photon (see figure 1) by analysis of the cluster structure: pulse-heights are recorded on the readout plane allowing the precise measurement of the primary ionization position and photon energy discrimination [19]. The proposed detecting system should be able to resolve incoming radiation with 1 ms integration time for real time processing and down to $\sim100\mu$s for offline spectra processing.

One of the advantages of the GEM-based detector is the possibility to separate the amplification stage from the readout electrode. Thus, the shape of the flat readout electrode does not influence the amplification process. This ensures a large degree of freedom in construction of the readout structure that matches both optimal detection position resolution and signal to noise ratio that is of high importance for tomographic application and operation in the tokamak environment conditions. Within this work the readout anode plane of one-dimensional rectangular pixels array will be used.

The detector will be operated in the gas flow mode. It has been demonstrated that multi-stage GEM detectors can provide long-term stable operation when filled with inert gas mixtures [12, 20, 21] something that is usually an issue when safety is concerned.

3 Concept of the detecting unit layout in experimental environment of the WEST tokamak

In order to verify the principle of the proposed diagnostics the installation of the developed unit is planned in a poloidal section of the WEST project. The system would be able to discriminate different impurities, together with tungsten being the dominant contributor in the WEST project, through line emissions with different energies according to the detector energy resolution. Other impurities (coming mainly from the heating systems, e.g., copper, iron) will be present but their concentration will be much less than concentration of W. The expected conditions of the core electron temperature and density in the WEST project are $5\text{ keV}$ and $\sim 8 \times 10^{19} \text{ m}^{-3}$, respectively. The flexibility of the system under development will allow adjusting to different conditions during real life measurements, therefore, simulations of photon intensity and spatial distributions for expected plasma conditions are not crucial for the diagnostics design. Nevertheless, the non-distant acquisition achieved in Tore Supra (former WEST project) with silicon barrier diodes provided already indication about the number of photons arriving on the detector which helps in the design and optimization of the diagnostics [22].

In considered set-up, see figure 2, detectors are optimally positioned to cover total viewing angle available for each port as big as possible. Such configuration allows achieving optimal spatial resolution as well as optimal internal sensitive volume structure. Numerous physical, technical and logistical issues are to be resolved, taking into consideration spatial constraints and external operating conditions for the detecting system, such as extreme temperature, present magnetic field distributions.

The proposed arrangement of the detecting system is presented in figure 2. Due to the upper divertor in the WEST project case, the vertical detector has to be positioned inside the port aiming
to visualize as large part of the plasma surface as possible. As a result of this, the vertical detector (and part of its amplification electronics) must be installed in a cooled glove finger keeping the detectors working temperature at 25–27°C. The absence of extra constraints on the horizontal port allows installation of the horizontal detector outside of the port. Nevertheless, as the system under development is a tomography system, both detectors must be kept at the same constant temperature as temperature strongly influences the response of the detectors requiring, therefore, the horizontal detector to be cooled as well.

The magnetic field from the neighboring coils could have undesired impact onto the charge propagation/diffusion within the sensitive detecting volume and, therefore, could affect an operation of the GEM detector. Therefore the direction and magnitude of the magnetic field has to be taken into consideration while positioning detectors and, if required, detector has to be shielded using mu-metal. Initial preliminary estimations of detector external operating conditions for the vertical port arrangements presented in [7] were utilized in this design.

Having taken into considerations all mentioned above constraints, a preliminary conceptual study of installation of the detecting system was conducted identifying necessary parameters for all
main and auxiliary parts: solid angle of detection, schematic diagram of glove finger systems and facilities, He buffer with high transmission coefficient for SXR radiation, details of internal system, supportive systems, etc. This study showed that integration is viable and, in particular, there will be enough space for the vertical detector within the glove finger to be inserted inside the port and the required temperature tolerance will be achievable. It was estimated that the distance between the vertical detector and a pinhole should be 473 mm with sufficiently small ∼0.3 T [7] magnetic field at this position. The necessary simulations of magnetic field influence on the detector electron avalanches are in progress using combined MAGBOLTZ and GARFIELD tools. Preliminary results demonstrated a small, about 0.3 mm, electron avalanche deflection in 0.3 T uniform magnetic field rising for a single GEM structure [23]. Further simulations considering a full magnetic field map expected at the detector position are necessary in order to conclude whether the magnetic field shielding or photon position correction is required. The requirements for the horizontal detector are less strict and it will be positioned at 442 mm away from a pinhole to fulfil the spatial plasma radiation resolution and to keep the identical analogue amplification electronics as for vertical detector.

Established spatial distances allowed us to evaluate other parameters such as: the whole angle of view for diagnostics, the number of readout channels and their shape, pinhole size, and the necessity to make a bent detector. In case of pinholes, their size should be kept below 50 µm in order to reduce overlapping of neighboring tomographic lines.

Additionally, since the viewing angles for both ports are quite large (∼25° and ∼32°) parallax effect should be considered. As a result of this, a drift layer of the detector chamber is reduced to minimize a displacement in the apparent position of plasma radiation viewed along two different lines of sight [23]. Within this work a bended structure of the horizontal detector will be designed in order to eliminate the difference between the real plasma radiation position and the recognized tomographic line of sight. However, due to very limited space inside the port, the vertical detector will remain planar.

Finally, the number of tomographic lines for vertical and horizontal detectors is accepted to be 83 and 107, respectively, that allows achieving spatial resolution better than 1 cm at the equatorial plane.

4 Detector chamber conceptual design

As was mentioned in Introduction the design of position and energy sensitive X-ray detector for tokamak plasma radiation should be driven by several requirements, where among others are high charge amplification, spatial and energy resolution, high quantum detecting efficiency and detection stability for a wide range of photon rates. Since the possibility of using several GEMs in cascade for charge amplification permits much larger gains than single stage detectors before breakdown, Triple GEM (T-GEM) geometry [11] is proposed for construction of detectors for poloidal SXR diagnostics at the WEST project (figure 3). Such structure allows one to reach a high total gas gain (exceeding10⁴) with a very low discharge probability. Due to strongly reduced space charge effects in the sequential amplification process a high rate capability can be achieved. It was estimated that inter-GEM spacing and induction gap of 2 mm should produce a detecting structure that will match the operational requirements of tokamak X-ray diagnostics. One-side thin aluminized Mylar foil of 5 µm thickness was chosen as a detector window in order to minimize the low energy photon
absorption. The total active surface of the vertical and horizontal detectors is $200 \times 20 \text{mm}^2$ and $254 \times 20 \text{mm}^2$, respectively. Detailed information about the internal detector structure design will be given elsewhere.

Figure 3. Schematic structure of the T-GEM X-ray vertical detector for poloidal tomography: (1) window frame, (2) drift-gap frame, (3–5) GEM foils with frames, (6) strip plane and (7) closing plane frame.

To obtain good statistics for experimental X-ray spectra, high quantum detection efficiency is required for SXR diagnostics. Studies on the gas mixture and detector window materials were performed in order to optimize the detection efficiency for selected energies of X-rays. High photon absorption in the gas mixture is required but the absorption level is different for photons with low and high energies. Usually, one would prefer to have a compromise between having a fast gas mixture revealing a small Lorentz angle with high drift velocity/small diffusion properties, and having a high primary ionization. Mixtures of some noble gases with popular quenchers were considered. The results of quantum detector efficiency (QDE) simulations, conducted by GEANT code [24] in order to choose the most suitable gas mixture and detector window material, are represented in figure 4. Whereas high QDE should ensure good experimental conditions for measuring the W concentration in the whole plasma, the appropriate gas mixture is expected to be identified. Taking into account that the most intense emissions of W ions at ASDEX Upgrade (I-like $W^{21+}$ to Mn-like $W^{49+}$) are in the VUV to the SXR ($\sim 1.5$–$3$ keV) region covering the electron temperature range of 0.5–5.0 keV [25], as well as predictions for the WEST project [13], two gas compositions were selected. Initially, the Ar:CO$_2$ and Ar:CO$_2$:CF$_4$ mixtures with 5 mm thick conversion layer are considered to be used for application in the detector chamber. Ar:CO$_2$ mixture with the ratio of Ar(85–70%):CO$_2$(15–30%) demonstrated already stable operation for long-term measurements [21], whereas addition of CF$_4$ improves the temporal resolution of the primary detector signal [26]. The expected efficiency for M X-ray line emission of W (2.4 keV) is $\sim 20\%$.

For proportional mode of detector operation the amount of charge collected on the readout plane corresponds to the energy of absorbed photon, where the number of liberated electrons is subject to statistical fluctuations which set an inherent limit on the achievable energy resolution. This property is used for energy discrimination in photon detection with a typical energy resolution of 17–25% for Ar:CO$_2$ gas mixtures. Energy resolution, which is dependent on the HV distribution applied, improves with both the smaller gaps between detector electrodes and higher/lower HV values on drift-transfer/induction gaps. Achievement of spectral information is highly desirable for current tomographic systems. In the frame of this work an ability to perform a tomography
Figure 4. Photon absorption percentage for different gases and proposed window materials.

Together with spectral information in a few energy bands within expected range from about 2 keV to 15 keV will be realized. In order to fulfill energy discrimination requirement, the detector should operate in the proportional mode with relatively low gas gain ($\sim 10^3$) with high dynamic range to prevent discharges and space-charge saturation. To verify the proportionality of the detector charge signal-energy correspondence, tests with different SXR fluorescence sources were performed on the model detector with the structure similar to the proposed with emission lines being excited by high intensity Amptek X-ray tube. Figure 5 summarizes the results, together with the linear fit, showing very good linearity for the proposed T-GEM structured model detector.

Figure 5. Relative charge gain values vs photon energies of fluorescence lines for different elements excited by the X-ray tube.

5 Processing electronics design and data acquisition concept

The aim of detector signals processing is to estimate energy and position distribution of the individual photons for each channel with 1 ms of real time resolution [27]. At the same time it must give
the possibility of full raw data acquisition for post-processing analysis in order to reach the tempo-
ral scale, down to 100 $\mu$s of exposure time, suitable for tearing instabilities and sawteeth studies in
tokamak plasma. The fulfillment of this requirement will result in development of a state-of-art in-
strumentation. An additional difficulty is connected with the fact, that for such temporal resolution
the bandwidth of analog electronics module should be very wide, up to 50 MHz, which requires its
rigorous and precise shielding against electromagnetic interference.

The concept of the readout electronics system is presented in figure 6. The system is based on
a concept of full modularity. Such approach gives great flexibility in systems construction where
both small and large, 1D and 2D imaging systems can be relatively quickly constructed using
standardized building blocks.

![Figure 6](image-url)

**Figure 6.** Block diagram of the system for the WEST project tomography module of the detecting electronics.

Further processing is realized using repeatable blocks which are AFE channels, ADC modules,
field-programmable gate array (FPGA) backplane and Data Concentrator Board (DCB).

The detector electronics processing unit will have near 100 measurement channels per each
detector controlled by the signal processing units. Readout channels are grouped by 16 in AFE and
ADC boards. Signals from each detector module are processed in parallel by means of the custom
FPGA processor. The system consists of:

- Detector strip board with backplane, which receives electron avalanche charge and transfers
  it to the AFE boards;
• 16 channel AFE boards, which convert charge into voltage that is transferred using symmetrical cable do the ADC modules;

• 16 channel ADC boards, which convert voltage signal from the shaper to digital value and then transfer this value to the FPGA using differential high speed LVDS links;

• The FPGA backplane modules with 4 AFE slots, which perform synchronization and preprocessing of all 64 channel data;

• DCB with PCIe switch, management FPGA and serial ports for trigger and interlocks;

• Server CPU mainboard where most of the data processing takes place;

• 800W ATX Power Supply;

• High and low voltage power supply unit (PSU);

• Temperature, humidity and pressure sensors;

• Fast feedback FPGA board with a processor.

Two identical electronics modules will be constructed for vertical and horizontal detecting systems. Detector electrodes are supplied with dedicated T-GEM PSU which is a customized version of a commercially available product.

The developed data processing method, unlike commonly used ones based on discriminators and analog FIFOs, uses simultaneously sampling high-speed ADCs with a fast hybrid integrator and advanced FPGA-based processing logics to estimate the energy of every single photon. Data streaming is performed via Artix7 FPGA devices. For data transmission PCI-Express interface is used, allowing fast data transfers. As was mentioned above, the system is highly modular allowing interconnecting multiple FPGA backplane boards together using high speed gigabit transceivers [9, 18].

Detector signals for each channel for the presented serial data acquisition (SDAQ) [28] are treated independently. Figure 7 presents an example of regular GEM detector digitized ADC signals with 77.7 MHz sampling frequency and 15 MHz bandwidth of AFE boards for 5 channels output. The processing channels are located close to each other in the same fashion as detector strips. For the available model GEM detector it was found that the mutual crosstalk is not distinguishable from charge distribution that affects neighboring strips. Individual channels were also tested using a known charge injected from the embedded calibrator with the resulting crosstalk at a noise level.

The SDAQ is based on an assignment of a charge value obtained within the time window for charge estimation (20 samples per signal) to a time stamp of the system clock and a given readout channel. The other two time windows are intended for evaluation of the signal offset and verification of the signal regularity on its tail aimed at multiphoton events discrimination. This procedure takes data from many channel inputs, synchronizes them and releases in chronological order through one output allowing data storage in a DDR memory, and not in the internal FPGA memory [29]. As a result, full data from each readout channel are given as a system output that
allows gaining the maximum achievable temporal resolution of detection. Indeed, the offline processing of obtained data enables to reach for the photon spectrum exposure time the intrinsic raw signal time resolution, 100–200 ns, for non-overlapped signals. Two data streams to the tokamak database are foreseen for the system — fast channel with the online processed spectra of 1 ms time resolution and slow channel for the offline spectra processing (due to huge amount of data to be transferred) with the exposure time fitted for the studied phenomena and achievable statistics [8].

6 Summary

This work presents the conceptual design of the detecting unit for poloidal tomography to be installed for first tests at the WEST project tokamak. It concerns the detectors general structure and arrangement inside and outside the tokamak ports. Both distances in relation to the pinhole positions are determined and set to 473 and 442 mm for the vertical and horizontal ports, respectively. For the internal structure of the detectors simulations for selection of the proper gas mixtures and window material were presented. Two candidates are chosen for the first tests: Ar:CO\textsubscript{2} and Ar:CO\textsubscript{2}:CF\textsubscript{4}. One-side aluminized Mylar window was accepted as a window material. A good linearity of the detector response for different photon energies was observed for the model detector. First concept of the detecting module electronics is presented with the elaborated data acquisition method allowing 1 ms of time resolution in online mode and up to 100 μs in offline mode for satisfactory data statistics.

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References

[1] R. Hawryluk et al., Principal physics developments evaluated in the ITER design review, Nucl. Fusion 49 (2009) 065012.

[2] J. Bucalossi et al., The WEST project: Testing ITER divertor high heat flux component technology in a steady state tokamak environment, Fusion Eng. Des. 89 (2014) 907.

[3] M. Sertoli et al., Modification of impurity transport in the presence of saturated \((m,n) = (1,1)\) MHD activity at ASDEX Upgrade, Plasma Phys. Control. F. 57 (2015) 075004.

[4] D. Vezinet et al., Fast nickel and iron density estimation using soft X-ray measurements in Tore Supra: preliminary study, Fusion Sci. Technol. 63 (2013) 9.

[5] A.F. Buzulutskov, Radiation detectors based on Gas Electron Multipliers, Instrum. Exp. Tech. 50 (2007) 287.

[6] J. Rzadkiewicz et al., Design of T-GEM detectors for X-ray diagnostics on JET, Nucl. Instrum. Meth. A 720 (2013) 36.

[7] D. Mazon et al., Design of soft-X-ray tomographic system in WEST using GEM detectors, Fusion Eng. Des. 96-97 (2015) 855.

[8] P. Zienkiewicz et al., Data management software concept for WEST plasma measurement system, Proc. SPIE Int. Soc. Opt. Eng. 9290 (2014) 92902B.

[9] A. Wojenski et al., Diagnostic-management system and test pulse acquisition for WEST plasma measurement system, Proc. SPIE Int. Soc. Opt. Eng. 9290 (2014) 929029.

[10] A. Kozlov, I. Ravinovich, L.I. Shekhtman, Z. Fraenkel, M. Inuzuka and I. Tserruya, Development of a triple GEM UV photon detector operated in pure CF(4) for the PHENIX experiment, Nucl. Instrum. Meth. A 523 (2004) 345 [physics/0309013].

[11] M.C. Altunbas et al., Construction, test and commissioning of the triple-GEM tracking detector for COMPASS, Nucl. Instrum. Meth. A 490 (2002) 177 [inSPIRE].

[12] K. Jakubowska et al., Development of a 1D Triple GEM X-ray detector for a high-resolution X-ray diagnostics at JET, in Proceedings of the 38th EPS Conference on Plasma Physics (2011) 716.

[13] L. Syrocki et al., Modelling of the soft X-ray tungsten spectra expected to be registered by GEM detection system for WEST, Nukleonika (2015) to be published.

[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, J. Phys. B-At. Mol. Opt. 48 (2015) 144023.

[15] A.E. Shumack et al., X-ray crystal spectrometer upgrade for ITER-like wall experiments at JET, Rev. Sci. Instrum. 85 (2014) 11E425.

[16] F. Sauli, GEM: A new concept for electron amplification in gas detectors, Nucl. Instrum. Meth. A 386 (1997) 531.

[17] F. Sauli, Development and applications of gas electron multiplier detectors, Nucl. Instrum. Meth. A 505 (2003) 195.
[18] G. Kasprowicz et al., *Fast modular data acquisition system for GEM-2D detector*, Proc. SPIE Int. Soc. Opt. Eng. **9290** (2014) 92902F.

[19] T. Czarski et al., *Data processing and analysis for 2D imaging GEM detector system*, Proc. SPIE Int. Soc. Opt. Eng. **9290** (2014) 92902I.

[20] M. Chernyshova et al., *Development of 2D imaging of SXR plasma radiation by means of GEM detectors*, Proc. SPIE **9290** (2014) 92902J.

[21] M. Chernyshova et al., *Development of GEM gas detectors for X-ray crystal spectrometry*, 2014 JINST 9 C03003.

[22] D. Mazon et al., *Soft x-ray tomography for real-time applications: present status at Tore Supra and possible future developments*, Rev. Sci. Instrum. **83** (2012) 063505.

[23] 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. SPIE Int. Soc. Opt. Eng. (2015) accepted for publication.

[24] GEANT4 collaboration, S. Agostinelli et al., *GEANT4: A Simulation toolkit*, Nucl. Instrum. Meth. A **506** (2003) 250.

[25] T. Putterich et al., *Modelling of measured tungsten spectra from ASDEX?Upgrade and predictions for ITER*, Plasma Phys. Control. F. **50** (2008) 085016.

[26] G. Bencivenni, P. De Simone, F. Murtas, M. Poli-Lener, W. Bonivento, A. Cardini et al., *Performance of a triple-GEM detector for high rate charged particle triggering*, Nucl. Instrum. Meth. A **494** (2002) 156.

[27] K.T. Pozniak et al., *FPGA based charge fast histogramming for GEM detector*, Proc. SPIE Int. Soc. Opt. Eng. **8903** (2013) 89032F.

[28] P. Kolasinski et al., *Serial data acquisition for GEM-2D detector*, Proc. SPIE Int. Soc. Opt. Eng. **9290** (2014) 92902H.

[29] A. Byszuk et al., *Fast data transmission in dynamic data acquisition system for plasma diagnostics*, Proc. SPIE Int. Soc. Opt. Eng. **9290** (2014) 92902O.