WPS1-CPR(18) 20030

T Fornal et al.

Choice of the detectors for light impurities plasma studies at W7-X using C/O Monitor system

Preprint of Paper to be submitted for publication in Proceeding of 30th Symposium on Fusion Technology (SOFT)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Choice of the detectors for light impurities plasma studies at W7-X using 'C/O Monitor' system

Tomasz Fornal*[a], Ireneusz Książek[b], Monika Kubkowska[a], Jacek Kaczmarczyk[a], Rainer Burhenn[c] and W7-X team[c]

[a]Institute of Plasma Physics and Laser Microfusion, Hery 23 St., 01-497 Warsaw, Poland
[b]Institute of Physics, Opole University, Oleska 48 St., 45-052 Opole, Poland
[c]Max-Planck-Institut fürPlasmaphysik, Wendelsteinstrasse 1, 17491 Greifswald, Germany

The 'CO monitor' is a dedicated spectrometer for the measurements of line intensities of carbon, oxygen, boron and nitrogen. Its main purpose is to deliver with high time resolution constant information about the indicated elements, so it is constructed with high throughput and low spatial resolution. This paper presents the consideration about an application of detector type for this system. The considered options are like Multi Channel Plates (MCP), CCD cameras, Multi Strip Gaseous Chambers (MSGC) and the Gas Electron Multipliers (GEM) detectors. For the experimental campaign OP2 the CCD cameras are the main candidates as a detection system for the 'CO monitor' purpose due to their high sensitivity and the fact, that they are commercially available. Nevertheless, all other detector types are taken into account for the latter experimental operation when the deuterium plasmas will be investigated, and the neutron yield is expected.

1. Introduction

In magnetically confined fusion plasmas, the measurement of the impurities and its behaviour is a very essential task. Monitoring of their content delivers information about e.g. plasma composition, overheating, energy radiated from plasma, etc. During the experimental campaigns OP1.1 and OP1.2 (Operational Phases 1.1 and 1.2) on the Wendelstein 7-X stellarator (W7-X), there were many diagnostic systems [1] dedicated for the measurement of impurity content in the plasma (e.g. X-ray radiation pulse-height analyser - PHA[2], VUV grating spectrometer - HEXOS[3] or XICS/HR-XIS[4][5]). The CO Monitor system is a new dedicated diagnostic for the W7-X stellarator which is already designed and is going to be build and planned to be installed before the next experimental campaign OP2. This device is dedicated equipment for the observation of Lyman-α lines of light impurities such as carbon (VI – 3.4nm), oxygen (O VIII – 1.9nm), boron (B V – 4.9nm) and nitrogen (N VII – 2.5nm). Real time, fast monitoring of those lines would deliver an information about wall conditioning (oxygen), overheating of plasma facing components (carbon) and the quality of boron layer (boron). The possible malfunction of vacuum system will be indicated by monitoring of oxygen and nitrogen. For the proper machines operation this knowledge is essential, and their constant monitoring would help to improve the optimisation of the W7-X as well as the future fusion devices.

The system consists of two vacuum chambers with crystal or multilayer mirrors as dispersive elements selected for reflection of particular photon wavelengths corresponding to the respective ions. The chambers are positioned at the elongated AEK30 port, horizontally one over another with their line of sight crossing at the main magnetic axis of the W7-X (see Fig. 1.).

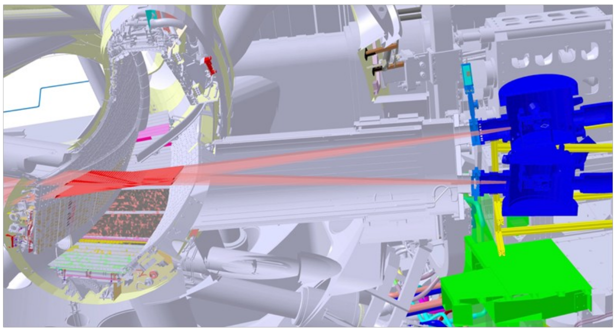

Fig. 1. CO Monitors lines of sight crossing at the main magnetic axis.

The idea of the 'CO Monitor' diagnostic system is that the design of the system is characterized by its simplicity and is dedicated directly for the fast measurement of selected lines with their high temporal resolution. Its design is based on the Johann geometry providing an energy resolved spectrum in contrast to monochromators. This offers the opportunity to observe the full spectral line. Thus, the measured line radiation can be corrected by the background level (visible in the far wings of the line) simultaneously. Due to the clear separation of lines in this spectral range, the spectral resolution can be poor. While the detectors will not be positioned tangentially to the Rowland circle, the line shapes are not going to be investigated (see Fig. 2.).

To obtain maximum possible count rate, the volume of observed plasma in the plasma centre is quite large and equals approximately 10 cm height which determines the intensity as well as radial resolution and 50 cm width for broader energy range detection. This reduces the spatial resolution but simultaneously increase the amount of photons reaching the detectors what enable to increase the time resolution of the system.

author's email: tomasz.fornal@ipplm.pl

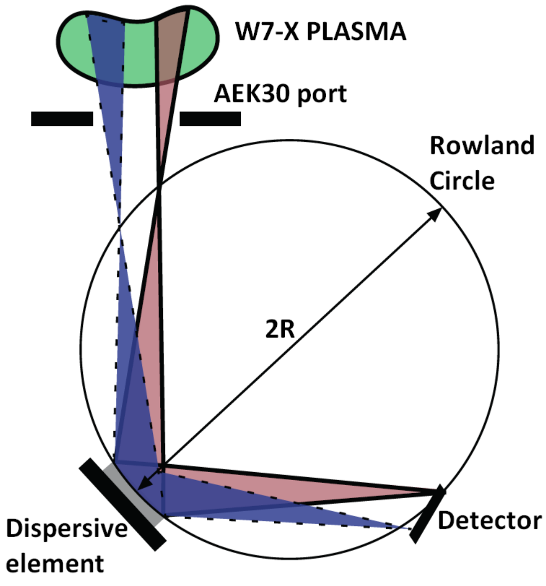

Fig. 2. CO Monitor system principle based on Johann geometry.

For the proper operation of the CO Monitor spectrometer and to obtain a reliable data about the plasma composition, choosing the right detector type is really crucial. Several types of detectors were considered for this application which need to face with particular requirements associated with the purpose of the detector and the conditions in the W7-X as well. Therefore, the 'CO monitor' system was designed in a such way (by appropriate adjustment systems), that it is possible to apply their different types.
In the next sections the detailed characteristics of requirements as well as considered options for the detectors are described.

2. General requirements for the detector

For the magnetically confined fusion plasmas in the stellarator type fusion device which is Wendelstein 7-X, the proper detecting system application of interesting ions observation have to be installed. For light impurities observation in the XUV/soft X-ray range with hot plasmas experiments, the proper detection systems need to be applied. Due to that fact, that system has to cope with some requirements, and the detector should fulfill certain properties.

Due to the fact, that the 'CO monitor' system will possess high throughput and high time resolution (1ms) the detector system should provide the fast measurement and fast processing of the data collected during experiment. Such information should be delivered constantly with its best accuracy in order to obtain high throughput. Moreover, such detector ought to have relatively high sensitivity in the wavelength range of the observed lines. In the case of 'CO monitor' high spatial resolution of the detector is not required since only the lines intensities will be investigated, not their shapes.

For the observation of narrow band of C, B, O and N elements by a spectrometer based on the Johann geometry with bended dispersive elements, it is essential that the detector should have appropriate detection area. Its length should be sufficient to cover the line profile of the spectral line (30 mm) and its height should be associated with the height of dispersive element (20 mm).

What is very important, the quantum efficiency of the detector ought to be as high as possible in order to get signal to noise ratio order of at least 10 at integration time order of ms. The sensitivity of some of the detectors (e.g. Multichannel Plates) changes over time of its operation (like on KT4 on JET [6]). It is not crucial in case of qualitative measurements but for obtaining quantitative information the system would require frequent recalibration or cross-calibration with other spectrometer.

From the point of view of physical environment of the detector, it has to be taken into account, that the equipment is going to work in the magnetic field reaching the level of 75-100 mT. The magnetic field, unlike in many other MCF experiments (e.g. JET, ASDEX), will be switched-on constantly for hours (or days). Moreover, in the future experiments which will be performed also with deuterium plasmas – the particular increase of neutron yield is predicted. The neutrons can distort the measured signal by direct hitting the detection area and cause some damage of the detector electronics as well as the detector itself.

Taking into account all the above it was essential to find the most suitable option for the detector that will be applied for the 'CO monitor' diagnostic system.

The detailed consideration on the selection of the detectors has been performed and is described in detail in the further section.

3. Detection systems under considerations

For the measurements of lines in the wavelength range of interest, there are several options possible to be applied. First of them are the Multichannel Detectors (MCD) which are commonly used on other machines e.g. in KT4 diagnostic at Joint European Torus (JET). These are composed of Microchannel Plates (MCP) connected to a phosphor screen image intensifiers. The basic principle of operation [7] consists in multiplication of photoelectrons emitted by the incoming radiation. Once the VUV/XUV photons reaches the MCP, it produces the photoelectrons that are multiplied in the microchannels. Depending on the voltage applied to the MCP, the particular amplification of emitted photoelectrons (even up to 10^4) is achieved. An obtained electrons are subsequently accelerated and focused on the luminofor (phosphor plate), in which they are converted into the visible light. An additional accelerating voltage is applied between the MCP and phosphor plate.

However, there are some drawbacks that needs to be taken into account. First of all, the system based on the MCPs have to be constantly under high vacuum (approx.10^{-6} mbar). MCP detector is very sensitive to the level of

author's email: tomasz.fornal@ipplm.pl

vacuum and can work properly only in high vacuum condition. If the MCP is operated at insufficient vacuum it can be associated with malfunction, shortened lifetime or even damage of the detector. This requires some additional safety systems based on the voltage cut off if the pressure suddenly increases and/or individual pumping systems dedicated directly for achieving the proper vacuum level for the MCDs operation (e.g. HEXOS [8]). Another disadvantage of MCDs, like an experience obtained by the KT4 diagnostic system on JET shows, is that the sensitivity of the MCDs decreases over time even several times [6]. Due to that fact, for the long operation purposes the calibration process needs to be cyclically repeated. Moreover, it was observed that after very high energy discharges at JET the sensitivity of the system decreases rapidly and recover to the previous level of sensitivity after several hours.

Another option is to use the commercially available CCD cameras, which is very well known and developed technology. This solution is commonly used in many other plasma diagnostic systems e.g. X-ray crystal spectrometer at Large Helical Device (LHD) [9]. In our case, one of the considered option is the Andor Newton SO DO920P camera [10], which assures high linear response (better than 99%) in the energy range of interest. An advantage of such solution is its availability and high sensitivity in the area of interest varying from the 60 to 90% (see Fig.3).

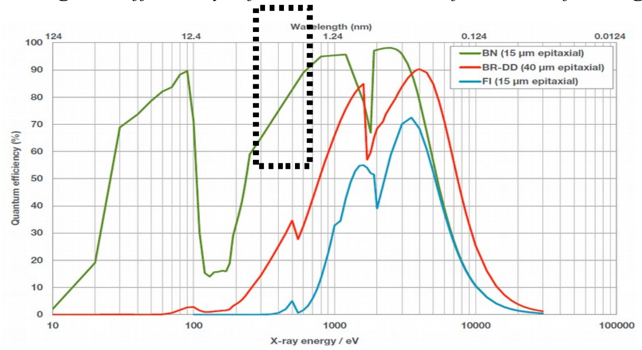

Fig. 3. Efficiency of the CCD in the function of energy [10].

Another essential advantage is a high time resolution of such equipment. The latest available models assure time resolution better than 1 ms which fulfills the requirements of its application in the 'CO monitor' system.

Nevertheless, due to the fact, that the sensitivity of considered CCD camera model is quite high also in the region of visible light and the reflectivity of dispersive elements does not exceed 5%, the system would suffer from the high background noise level that can occur during the operation. Also some possible heat loads on the inner wall of stellarator during operation can cause the sudden increase of background noise level significantly which in extreme case would saturate the detector and blind the system. In the latter phases of W7-X operation when the Deuterium plasmas is going to be investigated, some neutron field level may appear. It is difficult to estimate the neutron resistivity and how long the detectors based on the CCD cameras withstand such conditions. The solution for that hazard would be an implementation of neutron shielding housing for each of the detectors as a protection against the neutrons. Such solution is successfully applied as a protection of neutron-sensitive equipment e.g. at ASDEX-U.

An alternative for the detectors based on semiconductor sensors can be gas detectors in a type of proportional counter. One of such, position sensitive, gas detector is Multi Strip Gaseous Chambers (MSGC) which is applied e.g. at ASDEX experiment. The detection system based on proportional counter has been successfully applied in the similar diagnostics – KS6 at JET. The sensitivity of such kind of detectors depends on its construction in the energy range of interest.

The basic principle is that the incident photons reaching the chamber ionizes the working gas which the chamber is filled with – usually Argon with small admixture of quenching gas (e.g. methane). The primary electrons are accelerated in HV electric field and by avalanche amplification creates the electrical signal proportional to the deposited photon energy. Low energy photons (e.g. in the visible range) have too little energy to ionize the gas and high energy photons, because of much lower cross-section than XUV photons, can pass through the detector with low probability of any collision inside the chamber. That allows to construct the detector with selective range of energy photons under observation. Moreover, its sensitivity does not decrease over time, thus it was successfully used as a reference diagnostic e.g. on JET [6]. The main factor which determines the efficiency of the detector is transmission of the detector window (thin foil) which separates the gas filled chamber of the detector from the vacuum area of 'CO monitor' diagnostic system. Such window would be composed of a thin Mylar foil with 0,9µm thickness with 100 nm of Aluminium coating preventing emerging of the space charge on the foil surface (see Fig. 4).

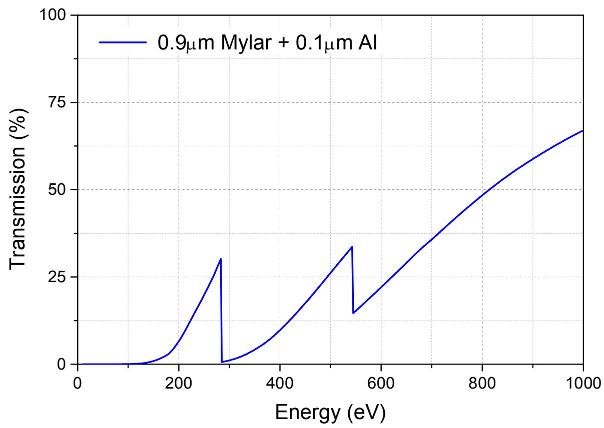

Fig. 4. Transmission of the 0,9µm Mylar foil with 0,1µm Al coating [11].

Nevertheless, due to the relatively high pressure gradient (approx. 1 atm) between the gas chamber and the vacuum area of the CO monitor, there exist a risk of leakage or even an accident associated with uncontrolled rupture of

author's email: tomasz.fornal@ipplm.pl

the window. That would result in sudden increase of the pressure in the CO monitor vacuum and leakage of the counter gas into the plasma vessel. In order to avoid such hazard, a dedicated safety system with a feedback between the main gate valve and vacuum gauges need to be installed. Moreover, the MSGC detectors are characterized by quite low amplification factor (approx. 100), and dynamic range which could result in necessity to frequent adjusting the incoming radiation flux by means of the variable aperture.

In order to solve those issues, the gas electron multipliers (GEM) detectors could be proposed [12]. As they are offering at least two stages of amplifying they are characterized by much higher amplification and dynamic range. GEM detectors also do not suffer from neutron impact as MCP or CCD cameras, that is why it is considered to be applied especially in the latter phase of operation.

Nevertheless, beside the presence of a gas as a working medium and the pressure difference issue that was mentioned as drawbacks of typical proportional counter, the construction of the GEM detectors is much more complicated hence much more expensive.

Taking into account all the previously described features of each detector type it was decided to apply CCD cameras for the OP2 due to their availability and high sensitivity in the spectral range of interest. Nevertheless, for the future application, especially for campaigns with the deuterium plasmas operation on W7-X (and hence when the neutron yield is expected), other options are considered.

4. Summary

The CO Monitor is a new diagnostic system, dedicated for investigation of the light impurities behaviour in the W7-X stellarator. The system is already designed and is going to be installed before OP2. It consists of two subspectrometers with two spectral channels each, dedicated for the measurement of particular Lyman-α lines – carbon, oxygen, nitrogen and boron. The main purpose will be the constant observation of the selected lines, with high temporal resolution (better than 1 ms) but the line shapes are not going to be investigated. Taking into account the purpose and the particular requirements that the detectors need to face with, the choice of its proper type is very essential. In this paper the discussion about the detector types that are taken under consideration for the application in the 'CO monitor' system is presented. Several types of detecting systems like CCD cameras, MCPs and gas detectors in a type of proportional counters were presented and their features were described. As the W7-X experiment is very unique, the requirements and environment condition are very specific. All the detectors have their pro and con and it is not easy to state which one will be the most suitable for our purpose. Probably the final answer will be possible only after the tests performed on-site. The main candidate for the detector type before OP 2 experimental campaign is a CCD camera which is commercially available and which sensitivity in the spectral range of interest reaches up to 90%. Nevertheless, each of the detectors are taken into consideration for the future application when the deuterium plasma experiments will be performed.

author's email: tomasz.fornal@ipplm.pl

5. Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

This scientific work was partly supported by Polish Ministry of Science and Higher Education within the framework of the scientific financial resources in the years 2014 - 2018 allocated for the realization of the international co-financed project.

6. References

[1] M. Krychowiak et al., Overview of diagnostic performance and results for the first operation phase in Wendelstein 7-X (invited), Rev. Sci. Instrum. 87 (2016) 11D304. doi:10.1063/1.4964376.

[2] M. Kubkowska et al., First Results from the Soft X-ray Pulse Height Analysis System on Wendelstein 7-X Stellarator, Fusion Eng. Des. (2017). doi:10.1016/j.fusengdes.2017.12.024.

[3] W. Biel et al., Design of a high–efficiency extreme ultraviolet overview spectrometer system for plasma impurity studies on the stellarator experiment Wendelstein 7-X, Rev. Sci. Instrum. 75 (2004) 3268–3275. doi:10.1063/1.1784557.

[4] N.A. Pablant et al., Layout and results from the initial operation of the high-resolution x-ray imaging crystal spectrometer on the Large Helical Device, Rev. Sci. Instrum. 83 (2012) 083506. doi:10.1063/1.4744935.

[5] G. Bertschinger et al., Compact imaging Bragg spectrometer for fusion devices, Cit. Rev. Sci. Instruments. 75 (2004) 3727. doi:10.1063/1.1781755.

[6] I. Książek, Private Communication, Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland, 2018

[7] J.L. Schwob et al., High□resolution duo□ multichannel soft x□ray spectrometer for tokamak plasma diagnostics, Rev. Sci. Instrum. 58 (1987) 1601–1615. doi:10.1063/1.1139408.

[8] B. Buttenschön et al., Proceedings of 43rd EPS Conference on Controlled Fusion and Plasma Physics, Leuven, Belgium, 4-8 July 2016, Vol. 40A, P4.012

[9] I. Sakurai et al., Development of a Wide Band and Compact X-Ray Crystal Spectrometer for Iron Charge State Distribution Measurement on LHD, 2 (2007) 1068. doi:10.1585/pfr.2.S1068.

[10] https://andor.oxinst.com/

[11] http://henke.lbl.gov/cgi-bin/filter.pl
[12] M. Chernyshova et al., Conceptual design and development of GEM based detecting system for tomographic tungsten focused transport monitoring, J. Instrum. 10 (2015) P10022–P10022. doi:10.1088/1748-0221/10/10/P10022.

author's email: tomasz.fornal@ipplm.pl