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Conceptual design of Light Impurity Monitor for Wendelstein 7-X

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Abstract. As plasma impurity ions can significantly influence the properties of a fusion plasma by dilution and enhancement of the radiation losses, the process of monitoring of their concentrations is one of the most important tasks. A Light Impurity Monitor is needed for monitoring the contamination of the stellarator plasma by carbon, nitrogen, boron, and oxygen impurities, which are indicators for the overload of the plasma facing components, leakage of the vacuum vessel, or wall condition, respectively. Their concentration will be estimated on the basis of emission intensities of their hydrogen-like ions. In this paper a conceptual design of such a spectrometer is presented, including the description of the geometry, the acquisition system and safety systems.

Key words: plasma spectroscopy • stellarator • soft X-ray

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Introduction

A stellarator is a magnetic confinement plasma device in which the total magnetic field is produced exclusively by external coils, without the need for an externally induced toroidal net current in the plasma, as is the case in tokamaks. This makes the stellarator a suitable design for a continuous operation mode. The downside is that the field is no longer axially symmetric as in tokamaks. The field lines of the confining magnetic field must exhibit a helical twist along the axis of the torus, and the coils of discrete external magnets necessarily have a complicate three-dimensional geometry, resulting in a toroidal change of the plasma shape. The higher transport generally predicted by a neoclassical theory for three-dimensional (3D) devices had been reduced by optimization of the magnetic field topology, which should finally be demonstrated by the Wendelstein 7-X (W7-X) project. Quasi-continuous operation with maximum pulse lengths of 30 min is planned.

Unlike in most present pulsed experiments, where the toroidal magnetic field is switched on only during the pulse duration of several seconds, in W7-X the field is planned to be switched off only for the maintenance periods (at the end of working weeks). This means that the field might be switched on for a week without access to the machine during this time. Therefore, it would be necessary to employ such a technical equipment for the diagnostics, which is not damaged or distorted by operation in a strong static magnetic field. The equipment should be shielded without disturbing the confining field by large amounts of ferromagnetic materials, or located at a larger distance in the region of lower magnetic field.

The second specific feature of the W7-X design is the high power of the microwave radiation applied as one of the main heating system (ECRH – electron cyclotron resonance heating, 10 MW at 140 GHz). Because of the long time duration of the pulse (up to 30 min) care has to be taken of non-absorbed microwave stray radiation, which may cause overheating and eventually even destruction of sensitive components, even at low but nonzero absorption.

Monitoring of intrinsic plasma impurities is one of the most important tasks in magnetic confinement plasma diagnostics. As the main impurity species are expected to be low Z elements originating from the plasma-wall interaction with plasma facing components, the spectral lines of interest are transitions of hydrogen or helium-like ionization states of these ions. One of the most intensive lines is the Lyman-α transition emitted by hydrogen like ions. The wavelengths of this emission are in the soft X-ray or extreme ultraviolet (EUV) regions and are strongly absorbed by materials of any kind (even gases). Therefore, the spectrometer has to be kept in vacuum and only extremely thin filters or detector windows are allowed in the line of sight.

The impurity level in fusion plasma is a very important plasma parameter. Radiative energy losses due to radiation of impurities belonging to the discrete or continuous spectrum may severely affect the power balance of the plasma. In many experiments, accumulation of plasma impurities during the discharge is observed [5, 6, 8], leading to enhanced radiation losses which eventually result in a radiative instability. Rapid changes of the impurity level may indicate the onset of plasma instabilities (e.g. ELMs – edge localized modes, sawteeth etc.) or malfunctioning of the plasma device [7] (local overload, leakage etc.). An increase of the carbon level is usually associated with a higher heat load on plasma facing in-vessel components. The boron level reflects the quality of the boron layer commonly used as a coating of the vessel wall. An increase in the nitrogen concentration in plasma may be a result of leakages in the vacuum system. The concentration of oxygen reflects the wall conditions.

Monitoring of impurities by measurements of their hydrogen-like ion emission is therefore an important element of the safety concept for plasma devices. Consequently, it is necessary to construct a fast and sensitive monitoring system.

Several possibilities of technical realization of such a system exist. It can be realized on the basis of flat crystal Bragg spectrometers [1, 4, 7, 8], curved dispersive elements in Johann geometry [2, 3] or even without a dispersive element, based on the absorption in different foils [10].

Technical objectives of the diagnostics

The purpose of the Light Impurity Monitor is to perform fast monitoring of intensities of the Lyman-α lines in the spectra of hydrogen-like ions of boron (at 4.9 nm), carbon (at 3.4 nm), nitrogen (at 2.5 nm), and oxygen (at 1.9 nm), with a high throughput and a high temporal resolution. All line intensities ought to be measured simultaneously with highest possible time resolution (in the order of milliseconds). The spectrometer will be fixed at the above mentioned wavelengths, and the line of sight through the plasma will not be changed for the whole operation time of the W7-X experiment. In this way it would be possible to study long time scale changes of impurity densities obtained at different conditions (wall conditions, heating power etc.). Such a device could also serve as a fast indicator of the overload of in-vessel tiles or the appearance of sudden leakages. For these purposes the high spectral resolution is not required, because the spectral lines are well separated. This spectrometer is not suitable for studies of the spectral line shapes.

Such a dedicated spectrometer had been developed e.g. for the ASDEX-Upgrade experiment [7] and consists of flat crystals playing the role of dispersive elements, combined with a grid collimator at the entrance beamline, operating as a monochromator. This design allows for a high throughput and accurate measurement in the central part of the spectral line (line core) intensity, but excludes the ability of a simultaneous measurement of the background continuum radiation level at wavelengths far from the line wings.

A general outline

In order to avoid the problem of continuum measurements it was decided that the Light Impurity Monitor for W7-X will be constructed in the so-called Johann geometry with cylindrically bent crystals or multilayer mirrors (MLM). In this type of spectrometer the dispersive element is bent and placed tangentially to the so-called Rowland circle (see Fig. 1). If the curvature radius of the dispersive element is equal to the diameter of the Rowland circle, the spectrum of plasma radiation with interception points on this circle will be focused on this circle again. This geometry, associated with the use of a position sensitive detector, allows for a simultaneous measurement of intensities in the line core (i.e. central part of the spectral line) and the far line wings, the latter reflecting the continuum level. By introducing a complicated crystal bending (e.g. spherical or toroidal) one may also obtain information about the spatial distribution of the radiation, but this option was omitted here for simplicity.

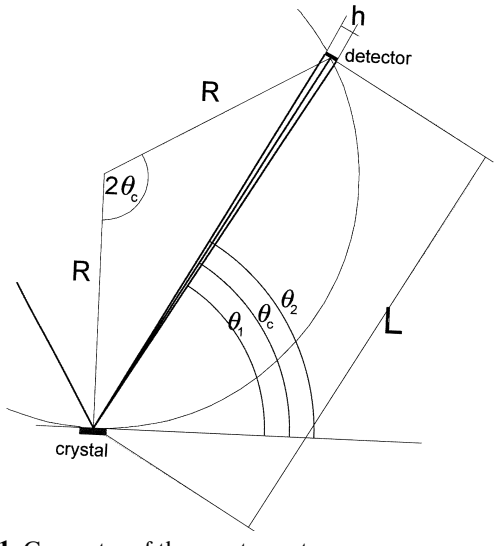

Fig. 1. Geometry of the spectrometer.

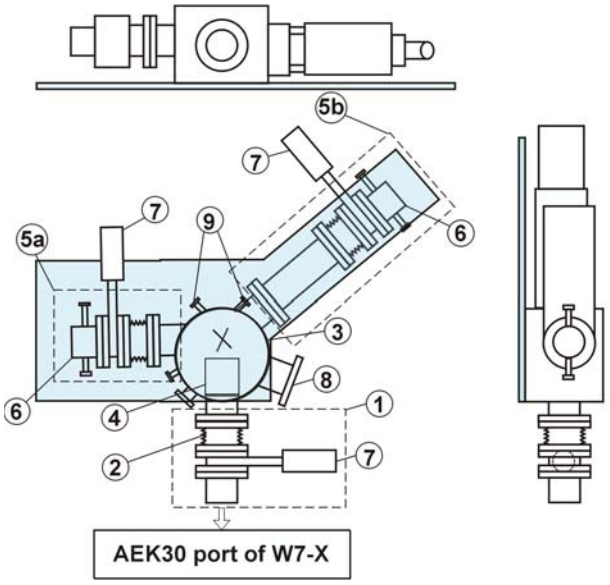

Fig. 2. Schematic drawing of the carbon-oxygen part of the spectrometer: 1 – the input arm; 2 – the electrical insulation and a microwave shielding; 3 – the crystal chamber; 4 – the variable aperture with a slit; 5a – the oxygen channel output arm; 5b – the carbon channel output arm; 6 – the detector chamber; 7 – vacuum gate valves; 8 – the connection to vacuum system; 9 – crystal (or MLM) angle adjusting screws.

Taking into account the restrictions of space available in the vicinity of the AEK30 port of W7-X it was decided that the spectrometer will consist of two independent devices, each covering two spectral channels (double spectrometer): one device for carbon and oxygen, the other for boron and nitrogen. They will be placed one over the other in front of the AEK30 port.

A schematical drawing of the carbon-oxygen spectrometer is presented in Fig. 2. The second spectrometer (nitrogen-boron) has similar design and very similar dimensions. Both spectral channels of each of the double spectrometers share the common input beamline (part 1 in Fig. 2), which is attached to the AEK30 port. The beamline will be equipped with a gate valve separating the spectrometer from the plasma vessel. It will include an electric insulation from W7-X and some kind of a microwave shielding protection (e.g. a cooled mesh), with a temperature sensor connected to the safety feedback system. The main gate valve will be closed if the shielding mesh would overheat due to excessive levels of ECRH stray radiation.

The next part of the double spectrometer, the crystal chamber, is shown in part 3 of Fig. 2. It will contain two crystal holders, one over the other. These holders should make it possible to perform small changes of the crystal angles during the adjustment phase, and to keep the crystals at fixed positions afterwards. In order to protect the detection system from saturation, each channel should be equipped with a variable horizontal aperture (part 4 in Fig. 2), that would reduce the effective height of the dispersive element (MLM or crystal). In order to measure the pressure inside the crystal chamber a set of vacuum gauges will be attached to this device, consisting of a Penning gauge for high vacuum measurement (which has been experimentally proven to operate correctly in strong magnetic fields), and a capacitor type one (insensitive to magnetic field), which should be attached to the safety feedback loop.

Both crystal chambers – the one for carbon-oxygen, as well as the one for boron-nitrogen – will be attached to one common vacuum system, equipped with a high efficiency turbopump (element 8 in Fig. 2). The pumps have to be placed in regions where $B < 5$ mT, because otherwise they could be damaged (in case of Light Impurity Monitor the distance is more than 3 m). Magnetic shielding of pumps and gauges is difficult to achieve without a distortion of the confining magnetic stellarator field.

The output arms of the two spectral channels will be attached on both sides of the crystal chamber (elements 5a and 5b in Fig. 2), fixed at the appropriate angles. The connection between the crystal chamber and the output arm should allow some adjustment of the angle and detector position during the alignment phase.

An additional gate valve at the end of each output arm, placed in front of the detector – a position sensitive proportional counter – will disconnect the detector in case of a serious leakage or bursting of the counter foil. In order to protect the crystal chamber and the plasma vessel from a steady increase of the contamination level by a possible small leaking of the counter gas, the valve separating the detector compartment should be closed between the measurement sessions. The volume between each detector and the corresponding valve in front of it will additionally be connected to a separate vacuum system (independent from the one connected to the crystal chamber), equipped with an efficient turbomolecular pump and monitored by a capacitor-type gauge. In case of any serious increase of the pressure (e.g. burst of the window) all gate valves should be closed together with the valves blocking the counter gas supply line (in- and output).

The detector

In the process of selecting the detector for the spectrometer it is necessary to take into account its sensitivity, dynamic range and the time resolution. It is also important to take into account vulnerability to other kinds of radiation (hard X-ray, neutrons etc.) and the price. Based on the experience gained during the soft X-ray spectroscopic studies at JET and ASDEX-U experiments, a modified multistrip proportional counter had been chosen as the radiation detector.

The design would be based on the counter working at ASDEX-U experiment [7]. The active area of the detector has a length of 4 cm and a height of 3 cm. It consists of a multistrip structure (150 nm gold on a 20 nm titanium layer) placed on a substrate made of glass. Anodes (8 μm width) and cathodes (400 μm width) are alternating (296 μm separation distance), providing very short drift channels for gas ions and therefore extending the regime of operation to higher count rates (up to 1 MHz). It is planned that after the modification of the readout system the detector would be replaced by a position sensitive one with 40 channels, each with 1 mm width. The great advantage of this detector is its simplicity, low noise level and immunity against serious damage by neutrons and other types of high energy radiation. Measures would be taken in order to reduce the background intensity induced by neutron radiation.

The critical point of this type of detector (in case of the soft X-ray detection) is the counter window, which is subject to the atmospheric pressure of the counter gas on one side and the spectrometer vacuum on the other. This requires a compromise in foil thickness with respect to mechanical properties of the foil on one hand and reduction of the intensity associated with high absorption in this energy range on the other hand. The window is usually made of a very thin polymer foil (mylar, polyethylene) covered by thin aluminium layer (10–100 nm). Consequently, there always exists a certain risk for leaking or a foil burst, so the spectrometer system has to be equipped with an appropriate set of valves, pressure gauges and feedback systems, in order to protect the spectrometer itself and the main plasma vessel from contamination with the counter gas and air. The estimated quantum efficiency of this detector, equipped with a mylar window (1.5 μm thick) and filled with P10 gas, varies from 1.5% for the carbon line through 14 and 15% for the nitrogen and oxygen lines, respectively, up to 37% for the boron line.

Alternative soft X-ray detectors of semiconductor type (photodiodes or CCD) arrays seem to be too sensitive to low energetic quanta, i.e. visible and infrared radiation, and may be easily damaged by neutrons. Furthermore, the sensitivity of such detectors might not be stable in longer time scales (of the order of tens of years).

Other types of position sensitive detectors considered for this purpose were multichannel plate detectors. They have strong limitations concerning vacuum and can easily be destroyed in case of an accidental pressure increase.

Another interesting alternative consists of gas electron multipliers (GEMs). It is a new and a very promising technology, but still in a R&D phase as far as the soft X-ray detection is concerned.

The Rowland circle radius

Using a proportional counter as a detector, we have to face the problem of high absorption at the detector window. By mounting the detector tangentially to the Rowland circle, the absorption length within the foil increases according to $d/\sin(\theta)$ where d is the thickness of the foil and θ is the incidence angle with respect to the surface of the detector window. Moreover, the absorption area inside the detector corresponding to certain photon energy smears out over several spectral channels, thus reducing the spectral resolution. Therefore the detector was placed perpendicularly to the ray of the central wavelength reflected from the crystal. The spatial resolution of the detector, although slightly reduced, should still be sufficient to resolve the spectral line without the need to analyze the line profile.

Such orientation leads to slightly unfocussed imaging of the line wings (in the order of 5%) and a distorted line shape, but still allows for a reliable measurement of the total line intensity and its temporal evolution.

For projected wavelength range $<\lambda_1,\lambda_2>$ being simultaneously measured by a detector with the length h and the lattice spacing d the required radius of the Rowland circle (see Fig. 1) for the perpendicular (non-tangential) detector position is given by

$$R = \frac{h}{4\sin(\theta_c)\tan\left(\frac{\theta_2 - \theta_1}{2}\right)} \tag{1}$$

where: R – is the Rowland circle radius; h – is the length of the detector; θ_1, θ_2 – are the Bragg angles, corresponding to low and high wavelength limits λ_1 and λ_2 defined by the detector length; θ_c – is the central angle defined as $\theta_c = [(\theta_1 + \theta_2)/2]$, $\theta_{1,2} = \arcsin(\lambda_{1,2} / 2d)$.

Dispersive elements

When using gratings in the soft X-ray/EUV wavelength range, a sufficient reflectivity can only be obtained at grazing incidence angles, leading to small acceptance angles and thus to small plasma volume contributing to plasma intensity. This may be improved by using crystals which can be operated at higher Bragg angles, but only few types of crystals are suitable for this energy range. Due to recent progress in MLM technology products of good quality are available, with a much higher reflectivity, but a low resolution (which nevertheless may be acceptable in the present case) for the selected wavelength, even if the wavelength falls into the soft X-ray/EUV region. The stability of a multilayer mirror and its tolerance to irradiation by neutrons remain an open question. Nevertheless, experience acquired in the soft X-ray plasma spectroscopy measurements in the Culham Science Centre [9] indicates, that the stability of multilayers can be sufficient for our purpose.

For the oxygen channel the reflectivity of TlAP crystal is appropriate, for all other channels MLMs are foreseen. All selected crystals and multilayers as well as the matched curvatures are listed in Table 1.

The data acquisition and control system

A schematic drawing of the data acquisition and control system is presented in Fig. 3. Since it is planned that the

Table 1. Geometrical characteristics of the spectrometer

Channel number	1	2	3	4
Emitter	B V	C VI	N VII	O VIII
Line wavelength (nm)	4.859	3.373	2.478	1.890
Wavelength range (nm)	4.69–5.21	3.09–3.51	2.25–2.65	1.86–2.00
Crystal	MLM	MLM	MLM	TlAP
2d (nm)	10.50	8.26	5.05	2.59
Incidence angle (deg.)	27.56	24.10	29.39	47.09
Rowland circle radius (mm)	750	890	450	340
Cylindrical curvature	1500	1780	900	680

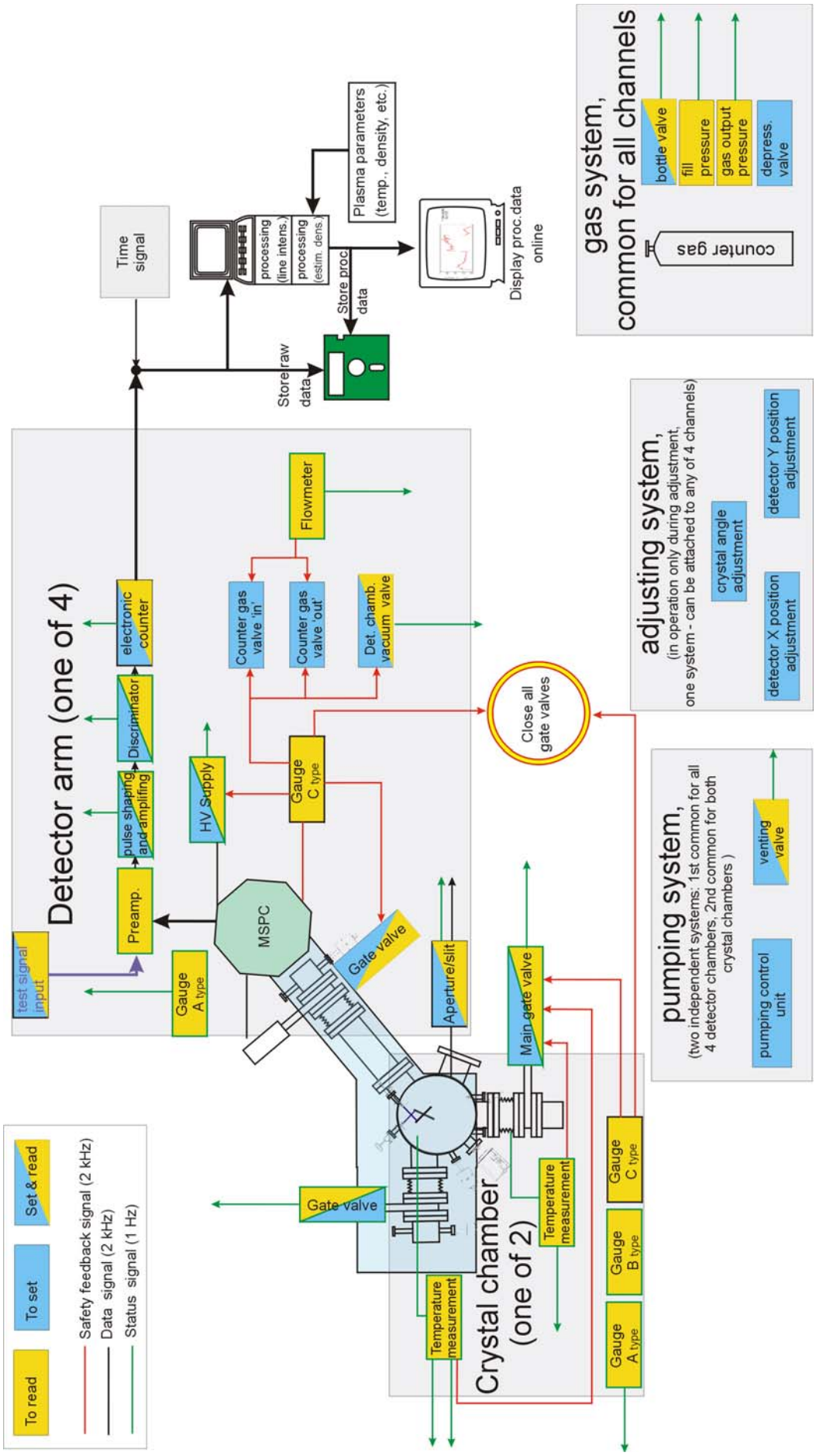

Fig. 3. A schematical drawing of the data acquisition and control system.

magnetic field would be switched off only on weekends, the access to the spectrometer would be restricted. Therefore the major part of the control systems has to be operated remotely. Apart from signals defining the registered intensities – such as the number of counts per detector channel or position of the slit (defining the input aperture) – which have to be monitored with high time resolution (on the order of 2 kHz or better), it is necessary to acquire also several signals defining spectrometer settings (e.g. position of valves, shaping electronics and discriminator parameters, gas flow, vacuum level etc.). Those signals, defining the status of the system, can be stored with low time resolution (on the order of 1 Hz or lower).

An important part of the data acquisition is the safety feedback loop. Because of the complexity of the safety system, it will be controlled via the data acquisition system by computer. Sensors included into the system are: the capacitor-type vacuum gauges in front of the detector and in the crystal chambers, temperature sensors (as indicators for the existence of a certain microwave stray radiation level) placed in crystal chambers and in the microwave shielding element, and flowmeters in the counter gas supply lines.

The Light Impurity Monitor is designed for monitoring the impurity concentrations, which may be calculated from the spectral line intensity. Therefore, it is necessary to subtract the measured continuum radiation (which can be derived from the intensities in both far wings of the measured spectral line) from the intensity in the line core. The temporal evolution of the line intensity should be available in quasi real-time during the plasma pulse.

The signal processing system will include for each detector independent amplification of 40 channels, pulse shaping and discrimination of the signal. Simultaneously signals detected by one of the channels could be applied to study the pulse-height spectrum and to control and adjust the discrimination levels.

Continuum radiation measured by the detector might not only be associated with the radiation emitted within the selected wavelength region but also with higher orders of diffraction or background radiation originating from irradiation by neutrons and gamma radiation. In the case of a proportional counter such an influence can be reduced by a proper choice of an upper discrimination level, thus cutting-off high-energy pulses. However, the actual dynamic range of the detector is of course still determined by the total pulse rate, which must not exceed the maximum counting rate of the detector (which can be controlled by reducing the input aperture). Detectors will be also additionally shielded against neutrons and high energy electromagnetic radiation as far as it is possible.

The intensity measured by the Light Impurity Monitor is a result of an integration of this emissivity along a line of sight, i.e. originating from plasma layers with different temperature and density. In order to determine the impurity concentration it is necessary to know the plasma temperature and density distribution as well as the impurity transport. Based on the plasma density and temperature profiles and making some simple assumptions about the impurity transport, the impurity density can be estimated using a radiation and transport code. Such results can be obtained in quasi real-time during the plasma pulse.

In postprocessing of the dedicated experimental data, the determination of the impurity level can be improved by applying more sophisticated transport models and more precise (but time-consuming) numerical calculations.

Conclusions

The Light Impurity Monitor should be a reliable, fast and simple system for monitoring concentrations of boron, carbon, nitrogen and oxygen impurities in the stellarator plasma during the operation in a long pulse mode. These impurity species are important indicators for machine conditions, plasma-wall interaction and impurity behaviour in fusion plasmas. The spectrometer should serve as a fast monitor for these lines with a high time resolution. Consequently, a high throughput at moderate spectral resolution is one of the main design criteria. For this purpose a focusing geometry with highly reflective dispersive elements and sensitive detection system was chosen. The conceptual design of the spectrometer was presented.

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