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High resolution compact X-ray spectrometer with large spherical crystals for ion temperature measurements

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Middle- and high-Z impurities, due to their strong radiation potential, substantially contribute to the power losses in present tokamak devices. Investigations of impurity behavior in such plasmas belong therefore to the most important tasks in present experiments on the way toward the fusion reactor. Besides that the present and future large tokamaks require new techniques for the measurement of the ion temperature (T_i) in the plasma core since the standard methods become more difficult with increasing plasma dimensions and electron temperature (T_e). Charge exchange (CX) diagnostic, for example, can not be used for the determination of the central temperature when the mean free path for the neutral CX is much smaller then plasma diameter. Alternatively, the method of T_i determination from a measurement of the neutron yield becomes insensitive for higher T_i values. In this situation, the T_i determination from the line Doppler broadening occurs as a one of the most suitable methods. Since T_e in present devices reaches the level of several keV the line radiation is predominately emitted in the x-ray region between 0.1 and 2.5 nm. This work presents a compact X-ray spectrometer with spherically bent crystals of Johann type. The spectrometer is mounted on the tokamak ASDEX Upgrade (AUG).

The device

The scheme of the device is shown in Fig.1. The diffraction element here is a large , spherically bent crystal of Johann type (l=35 mm, R=500 mm, where l and R are the length and crystal curvature radius, respectively). Such a crystal is chosen because it allows larger areas and thus higher sensitivity and spectral resolution compared to toroidally bent one [1]. It is made of high purity quartz, which make it quite resistive to high neutron fluxes in thermonuclear devices. The crystal is placed on a fused quartz substrate by means of “optical contact” technique avoiding the presence of glue layer of undefined thickness. The diffraction crystal plane is inclined to the mechanical surface (the angle depends from the crystal used). The spectrometer is made in asymmetric Rowland geometry. The position of the detector can be varied in order to fulfill the Bragg diffraction criteria ($2 \cdot d \cdot \sin\theta = n \cdot \lambda$) for the chosen crystal. With a proper set of crystals the instrument covers the energy range between 3.2 and

13.1 keV, which is sufficient for the measurement of He-like spectra for the elements between Ar and Kr. Presently, the crystals for measurement of Ar and Fe are available. Their performances are given in Table 1. Resolving power ($\lambda/\Delta\lambda$) of the instrument is given by

$$\lambda/\Delta\lambda = tg\,\theta\cdot(\Delta\theta_{diff}^2 + \Delta\theta_{geom}^2)^{(-1/2)} \qquad (1)$$

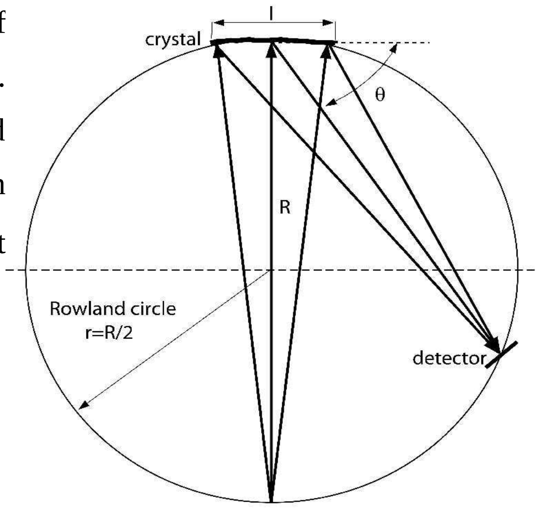

Fig. 1*: Schematic of the spectrograph made in asymetric Rowland geometry.*

The $\Delta\theta_{diff}$ is the crystal rocking curve. The two crystal diffraction measurements gave the value of $2.5\cdot10^{-4}$ rad. The $\Delta\theta_{geom}$ is the measure of the geometrical aberration and can be calculated with the following equation:

$$\Delta\theta_{geom} = 1/8\cdot(l/R)^2\cdot ctg(\theta-\varepsilon) \qquad (2)$$

Here, ε is the angle between mechanical surface and diffraction plane of the crystal. For the one used for measurement of He-like Ar (θ=68.1°, ε=21.9°), $\Delta\theta_{geom} = 5.8\cdot10^{-4}$ rad.

Thermal (Doppler) broadening of a plasma emission line is given by the relation

$$(\Delta\lambda/\lambda)_T = 2.44\cdot10^{-3}\cdot(T[keV]/A)^{1/2} \qquad (3)$$

where A is the atomic mass of the emitter. Introducing the spectrometer resolution on the place of $(\Delta\lambda/\lambda)_T$ one gets the minimal ion temperature (T_{app}) that can be measured with the device . The detector is a CCD camera (DO420-BR-DD, ANDOR Technology. Ltd.) with the maximum of quantum efficiency of the chip between 1 and 10 keV and the pixel size of 26 μm. The whole instrument is very compact with radius of Rowland circle of 0.25 m and total weight of about 10 kg. The spectrometer is mounted on the middle upper port in sector 2 of AUG (see Fig. 2) with the line of sight approximately going through the center of the poloidal cross-section.

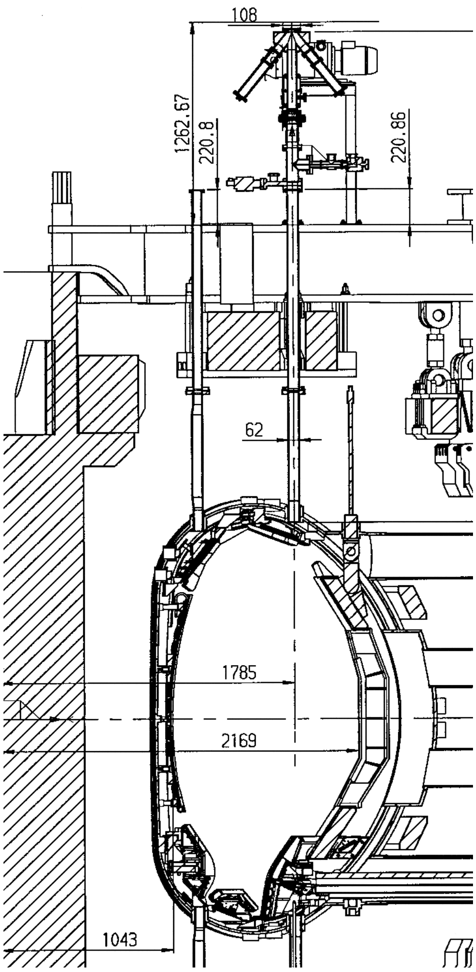

Fig. 2*: Scheme of the spectrometer mount on AUG.*

***Table 1**: Characteristics of presently available diffraction crystals*

Line	λ (nm)/E(kev)	Cut	2·d (nm)	θ (°)	λ/Δλ	D (mm/nm)	T_{app} (keV)
He-like Ar	0.395 / 3.14	$(1\ 0\ 0)_2$	0.425	68.1	5000	2770	0.32
He-like Fe	0.185 / 6.7	$(2\ 3\ 0)_1$	0.195	71.4	5000	7890	0.38

Spectroscopy of He-like Ar and Fe

The observation of characteristic x-ray emission lines from He-like charge states is a well established method for diagnostic of hot plasmas. The spectrum of such ions is dominated by four lines labeled according to Gabriel [2]: the resonance line *w*, the intercombination lines *x* and *y* and the forbidden line z. They originate from transitions between the *1s2l* levels and the ground state $1s^2$ [3]. These parent emission lines frame the lines of satellite transitions of the type $1s^2sl$-$1s2l2l'$ that result from the radiative stabilization of doubly excited Li-like states. Detailed information about the above mentioned transitions ones can be found in [4].

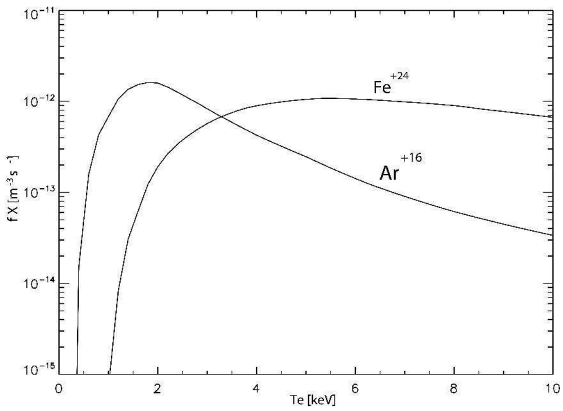

***Fig. 3**: Product of fractional abundance (f) and photon emission coefficient (X) for He-like Ar and Fe, w-lines.*

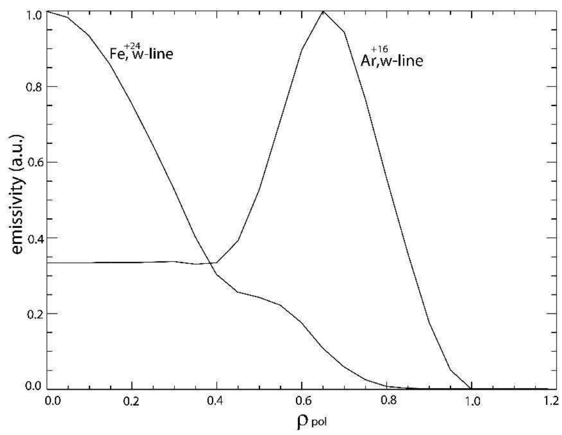

***Fig. 4:** Radial emissivity distribution of He-like Ar and Fe, w line in the AUG discharge #21269.*

Argon is frequently employed in fusion devices, since it can easily be injected in controlled quantities and efficiently pumped out. It can serve as a tracer for plasma diagnostic. Furthermore Ar is used as a coolant of the plasma edge in the divertor region in present tokamak machines. The emissivity of the resonance He-like Ar line is significant in the temperature range between 1 and 4.5 keV (see Fig. 3), which covers wide range of central T_e in medium size tokamaks. Iron is present as a intrinsic impurity in almost all present tokamaks. Besides that it can be introduced in a machine by means of laser blow-off system. For T_e > 2 keV the He-like charge state becomes well excited and isolated resonance w line at 0.185 nm appears, suitable for Doppler broadening measurements. The radial emissivity distribution of Fe and Ar w lines in an AUG improved H-mode discharge is shown on the Fig. 4. The emissivities are calculated in approximation of corona equilibrium using the following equation:

$$\epsilon = \int c\, n_e^2\, f\, X\, dl \qquad (4)$$

Here, *c* is the concentration of emitting element in the plasma, *f* is the fractional abundance and *X* is the photon emission coefficient of the certain transition. The last two quantities were taken from ADAS database. The integration is performed along the spectrometer line of sight *l*. The same formula is used for the determination of unknown concentration of an emitting species if the emissivity ε is known.

The Fig. 5 shows time-integrated spectrum of the AUG discharge #21356 (B_t=-2.4 T, I_p= 0.8 MA, q_{95}=4.3, n_e=4.5·10^{19}m^{-3}, T_{e0}=2.0 keV). The total amount of about 10^{18} Fe particles was injected in the discharge by means of laser blow-off. Vertical dashed lines on the upper diagram sign the calculated positions of *x*, *y*, and *w* lines from He-like Fe. The quite week *x* and *y* and somewhat more intensive *z* line are visible in the spectrum. One of the reasons for low line intensities here is a quite low electron temperature. The f·X at this temperature reach only about 20% of maximum value (see Fig. 3). Unfortunately, in the experiments performed up to now there were no discharges with T_e high enough for the substantial ionization of Fe to the He-like charge state. The lower diagram at Fig. 5 presents the w line from He-like Fe measured with a laboratory x-ray source. This spectrum is used for the determination of the apparatus function (e.g. T_{app}) of the instrument as well as for the wavelength calibration.

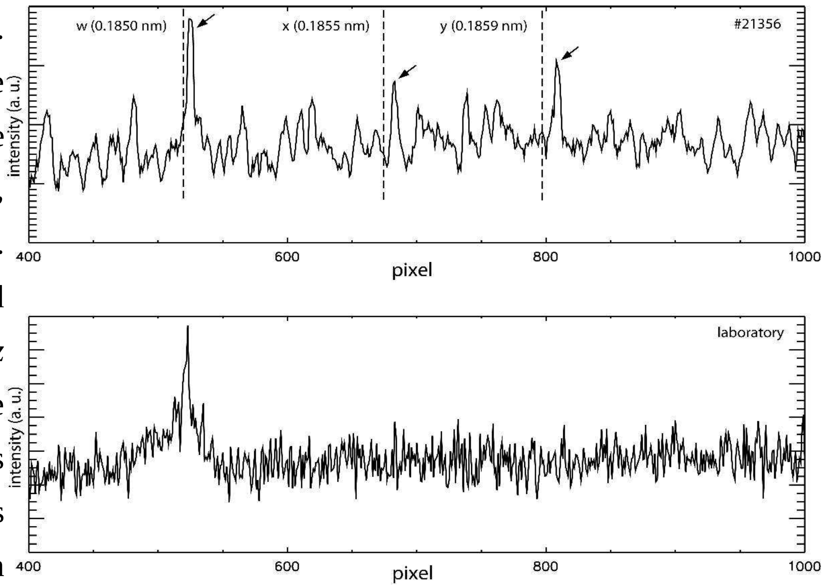

Fig. 5*: The spectrum of the AUG discharge #21356 (up) and w-line from He-like Fe measured with a laboratory x-ray source (down).*

The instrument is the result of EFDA project on development of an ITER relevant x-ray crystal spectrometer (EFDA Reference: TW5-TPDS-DIARFA).

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