X-RAY SPECTROSCOPY AT TEXTOR

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At TEXTOR, an X-ray spectrometer in a Johann mount is utilized to measure the X-ray spectra of He-like elements with intermediate Z. Up to now, the spectra of He-like argon have been investigated. The spectra have been modeled with the most recent atomic data using physically relevant parameters only. Good agreement has been found both in modeling the experimental spectra and in the determination of the plasma parameters, such as ion temperature and plasma motion and electron temperature. The deviations between the theoretical and experimental spectra are below 7% for all lines; the precision of the plasma parameters obtained by X-ray spectroscopy agrees with the accuracy of the standard diagnostics at TEXTOR.

In addition, the abundance of Li-/He-like ions, as well as the H-/He-like ions, has been measured. For the higher densities, the abundance approaches the coronal expectation. Larger deviations to the coronal limit have been found with neutral beam injection. The system is now being upgraded for spatial resolution.

KEYWORDS: *X-ray spectroscopy, He-like ions, ionic abundance*

I. INTRODUCTION

From the beginning of tokamak experiments for thermonuclear fusion, X-ray spectroscopy has been one of the first diagnostics to determine the ion temperature in the plasma core.[1] There, the plasma temperature is high enough that the main plasma components and impurities from low-Z elements such as carbon or oxygen are fully ionized. In the typical temperature range of present-day tokamaks, intermediate-Z elements, e.g., the elements of the iron group, are ionized up to the He- or H-like states. The line emission of these ionization stages is in the range of soft X-rays. Just after the first publication on X-ray spectroscopy on fusion plasmas, it has been proposed to apply X-ray spectra to the measurement of the electron temperature[2] and the plasma composition.[3] In the following 25 yr since the publication of Refs. 1, 2, and 3, X-ray spectroscopy has been developed into a powerful tool for plasma diagnostics (see Ref. 4 and further references therein). Nevertheless, due to the development of charge exchange recombination spectroscopy (CXRS), the importance of X-ray spectroscopy for ion temperature measurements decreased temporarily. But, the dimensions of the next generation of devices such as ITER are too large for the neutral beams to penetrate to the plasma center. Therefore, X-ray spectroscopy has regained interest as a basic diagnostic for the parameters of thermonuclear plasmas. For ITER, X-ray spectroscopy will be the preferred diagnostic for the plasma ion temperature and plasma motion.

II. EXPERIMENTAL TECHNIQUES

In the X-ray range, photons impinging on a surface penetrate the material. The reflection of the X-rays on surface structures such as gratings is rather small, and classical optical instruments tend to be inefficient. But, fortunately, the diffraction at the lattice planes of high-quality crystals is wavelength selective. X-ray diffraction on crystals was first demonstrated by Friedrich et al.[5] A more practical interpretation of X-ray scattering on lattice planes was given by Bragg.[6] Bragg scattering on lattice planes is similar to the reflection of light on surfaces, but it differs in an important point: It is highly wavelength sensitive. "Bragg reflection" occurs only if the Bragg condition $n \cdot \lambda = 2d \cdot \sin\alpha$ is fulfilled. Here, n is the order of diffraction, λ the wavelength of the X-ray, d the spacing between the lattice planes, and α the angle of diffraction. The spectral width of the reflection is determined by the "rocking curve," which is an intrinsic property of the crystal.

Bragg reflection is now frequently utilized to build X-ray spectrometers with high spectral resolution. On

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TEXTOR, an X-ray spectrometer in a Johann[7] mount is used, where a cylindrically bent crystal focuses the spectral lines onto a linear detector. As Johann spectrometers do not require entrance slits, efficient instruments can be built, although the total reflectivity of a crystal is rather low. Compared to the spectrometers in the visible and vacuum ultraviolet spectral range, X-ray spectrometers are narrow band instruments but with the advantage that the spectral resolution is high and that the reflection properties of the crystals can be calculated quite accurately. On TEXTOR, two Johann spectrometers with mutually inclined planes of dispersion are used to measure either two spectral lines or the two polarization components of the same line simultaneously. The principle layout of the instrument is shown in Fig. 1.

On most experiments, X-ray spectroscopy is performed on He-like ions, as He-like ions are the most abundant over a large range of the plasma temperature. To fit best to the range of the plasma temperature for a specific experiment, different impurities ranging from silicon for small tokamaks up to krypton for the next generation of large fusion devices such as ITER can be chosen. From a practical point of view, He-like ions are ideal to determine plasma parameters: On one hand, the X-ray spectra are complicated enough to contain a lot of information on the surrounding plasma, and on the other hand, two electron systems can be calculated with high accuracy and the spectra can be modeled precisely. With the spectra, the ion temperature and the plasma rotation, as well as the electron temperature and the plasma composition, can be measured. The ion temperature and the plasma motion broaden and shift the spectral lines by the Doppler effect. The electron temperature is calculated from the line ratios between the singlet resonance line and the Li-like satellites, which are populated by dielectronic recombination of He-like ions, as well as by the relative intensities between singlet and triplet lines. The abundance of Li-like ions is obtained from Li-like satellites, which are populated by electron collisions with the electrons on the closed inner shell. H-like ions can be estimated from the contributions of the H-like ions to the He-like lines due to recombination. All this information is obtained from a narrow spectral range, with $\Delta\lambda/\lambda \sim 2\%$; therefore, the variation of the detection efficiency along the spectrum is rather small. The ratio in the intensities of the different lines can be obtained with high precision, and the accuracy of the measurement depends mainly on the quality of the theoretical data. Because of these unique properties, X-ray spectra are also useful to measure the plasma parameters of hot solar and stellar objects, such as solar flares or stellar X-ray sources. In these applications, the spectra provide the only information on the plasma properties, and therefore, benchmarking under controlled conditions is required.

The measurements on well-diagnosed plasmas such as on TEXTOR are dedicated not only to the determination of the plasma parameters, but they are also benchmark experiments and sensitive checks of the theoretical data.

III. THEORETICAL CONSIDERATIONS AND RESULTS

On TEXTOR, argon has been used for the test impurity, as it is easily applied to the plasma by gas injection

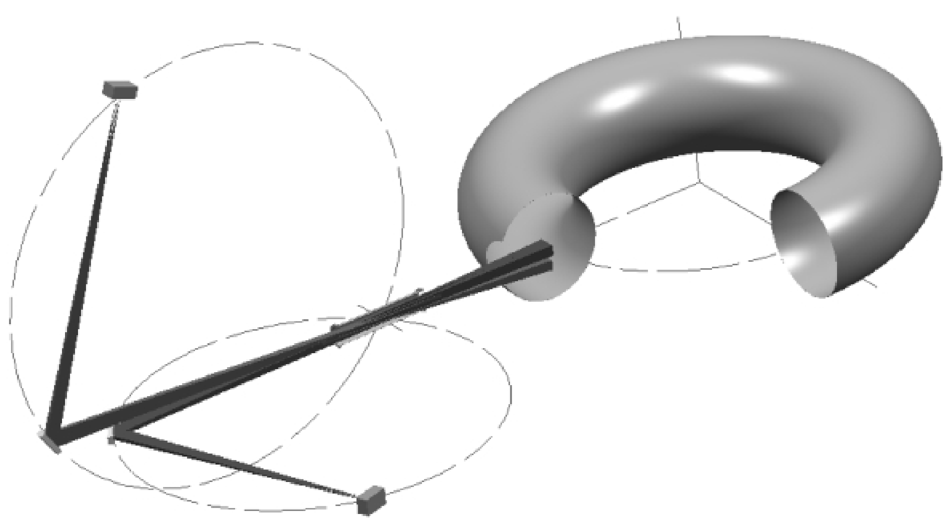


Fig. 1. Schematic of the X-ray spectrometer at TEXTOR. The instrument consists of two Bragg spectrometers in a Johann mount; the dispersion planes of the two spectrometers are perpendicular. The vertical spectrometer is sensitive to horizontal polarization of the X-rays, the horizontal spectrometer for vertical polarization. The two spectrometers observe the same volume of the plasma.

systems without long-term accumulation and it is well adapted to the range of electron temperature. A typical spectrum is shown in Fig. 2.

The spectra consist of the lines in the He-like system, the resonance line *w*, the intercombination line *y*, and the two forbidden lines *x* and *z*. The notation is chosen after Gabriel,[8] who compared the spectra of solar flares to laboratory spark plasmas. Associated to these lines, satellite lines of Li-like ions are observed. These Li-like satellites are doubly excited, i.e., the ion is in an unstable state above the ionization limit, which can decay either to the ground state of the Li-like ion by emission of photons or to the He-like ion by emission of an electron.

For the description of the spectra, we make use of the relatively low density of the plasmas for magnetic fusion. In this low density limit, most of the time the ions are in the ground state. They can be excited to higher states by electron collisions and decay spontaneously by emission of photons or, for doubly excited states, also by emission of electrons. Collisions between electrons and excited states can be omitted, which simplifies the calculations considerably. For extended plasmas in the low density limit, the distribution over the different ionization stages depends on the rates for ionization and recombination and therefore on the electron temperature only. This equilibrium is the "coronal equilibrium," as these conditions were found for the first time in the corona of the sun. Deviations from coronal equilibrium can occur by transport processes in a plasma and by additional recombination processes, such as charge exchange recombination with hydrogen atoms.

The intensity of the lines excited by electron collisions is proportional to

$$I_{\mathrm{He,Li}} = n_e \times n_{\mathrm{He,Li}} \times X(T_e) \ , \quad (1)$$

where n_e, $n_{\mathrm{He,Li}}$ are the densities of the electrons and the He, or Li-like impurities, respectively. $X(T_e)$ is the rate coefficient for excitation by electrons, which depends on the electron temperature.

The upper Li-like states are populated either by excitation of Li-like ions or by dielectronic recombination. During the process of dielectronic recombination, a He-like ion captures a free electron. Energy conservation during the capture process of a free electron requires that an electron from the closed He-like shell is moved to an excited level. The ion is then in a doubly excited state, with excitation energy larger than the ionization energy of the Li-like ion, and decays either by radiative decay to the Li-like ion or by emission of an electron. Compared to the lines in the He-like system, the wavelength of the satellite lines is shifted to lower energies, as the potential of the core is shielded slightly by the "spectator" electron. The shielding and hence the wavelength shift is smaller for higher levels of the spectator electron.

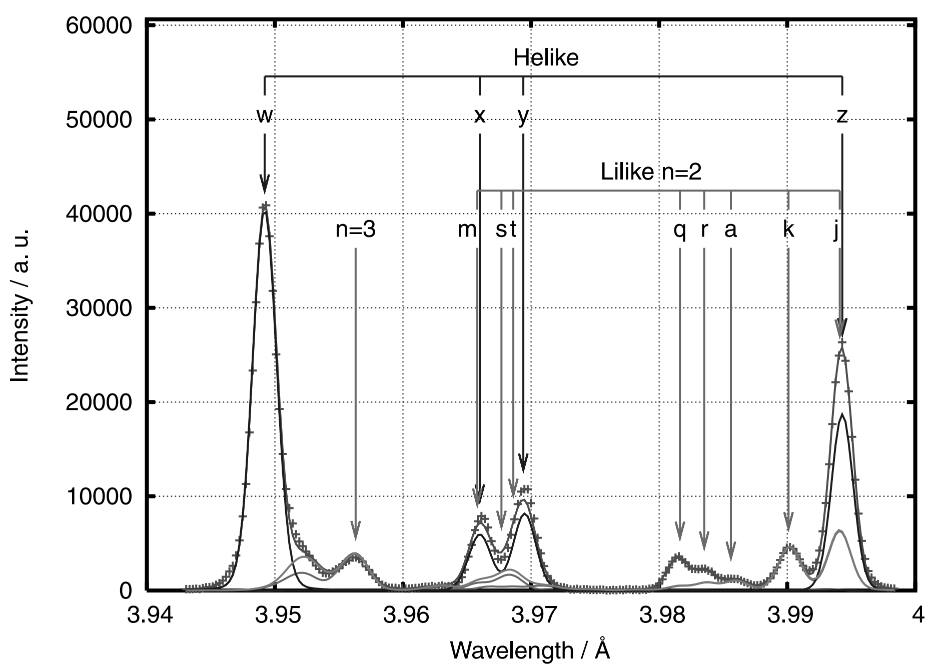


Fig. 2. Spectrum of He-like argon from a discharge at TEXTOR with heating by injection of neutral beams. The points are measured by the horizontal spectrometer; lines are model calculations fitted to the experimental points. The lines are indicated due to Gabriel.[8] Spectra are obtained by integration over the line of sight. For the integration, the profiles of the electron temperature and density are taken from the ECE radiometers and the HCN-laser interferometer at TEXTOR, respectively.

The intensity of a satellite line populated by dielectronic recombination is proportional to

$$I_s = n_e \times n_{He} \times F_2 \times f(T_e) \ , \tag{2}$$

where n_e, n_{He} are the densities of the electrons and He-like ions, respectively; F_2 is a constant that is specific for a certain transition; and $f(T_e)$ is a function of the electron distribution.[9] It has been shown that in most of the discharges on TEXTOR, the distribution function of the electrons is a Maxwellian distribution.[10]

Except for atomic properties, the ratio between the intensity of a He-like line excited by electron collisions and a Li-like satellite line resulting from dielectronic recombination depends on the electron temperature only; it is independent of the densities of the electrons and the impurities. This ratio is therefore a sensitive and robust means to determine the electron temperature. In Fig. 3, the electron temperature on TEXTOR, as measured by X-ray spectroscopy, is compared to the measurements of the electron temperature by microwave diagnostics using the electron cyclotron emission (ECE).

The accuracy of both measurements is comparable. Even though both the spatial resolution and the temporal resolution are much higher for the ECE measurements, the long-term stability of the X-ray spectroscopy is higher than for the other electron temperature diagnostics on TEXTOR.

The ion temperature and the plasma motion as measured by the broadening and the shift of the spectral lines due to the Doppler effect are shown in Fig. 4 and compared to the measurements by CXRS. Both methods provide comparable accuracy, but both have specific restrictions. X-ray spectroscopy requires addition of tracer impurities, which may increase the radiation losses in the plasma center. The CXRS usually relies on intrinsic impurities such as carbon or oxygen, but it requires a neutral beam, which may heat the plasma.

For the determination of the relative abundance of different ionization stages in the plasma center, X-ray spectroscopy is the only precise diagnostic method. The rates for the excitation of the resonance lines in the He-like ion and for inner-shell excitation of Li-like ions are similar. Therefore, the ratio between the resonance line w and a Li-like satellite populated by electron collisions depends on the ratio between the densities of He- and Li-like ions. The weak contribution due to dielectronic recombination can be taken into account by careful modeling of the spectra.

For TEXTOR, the ratio between the Li-/He-like ions is shown in Fig. 5. The experimental ratio is normalized to the coronal equilibrium, which is expected for highly charged ions in extended plasma columns. The deviations can be attributed to the diffusion of the ions to the hot plasma center and to additional recombination processes. The deviation is larger for low densities, as both the diffusion and the recombination due to charge exchange increases for low density plasmas. For higher densities, the ratio of Li-/He-like ions approaches the coronal equilibrium. The diffusion coefficient is similar as described previously in the gas injection experiments.[11] It verifies the assumptions on the charge exchange corrections, which have been used for the

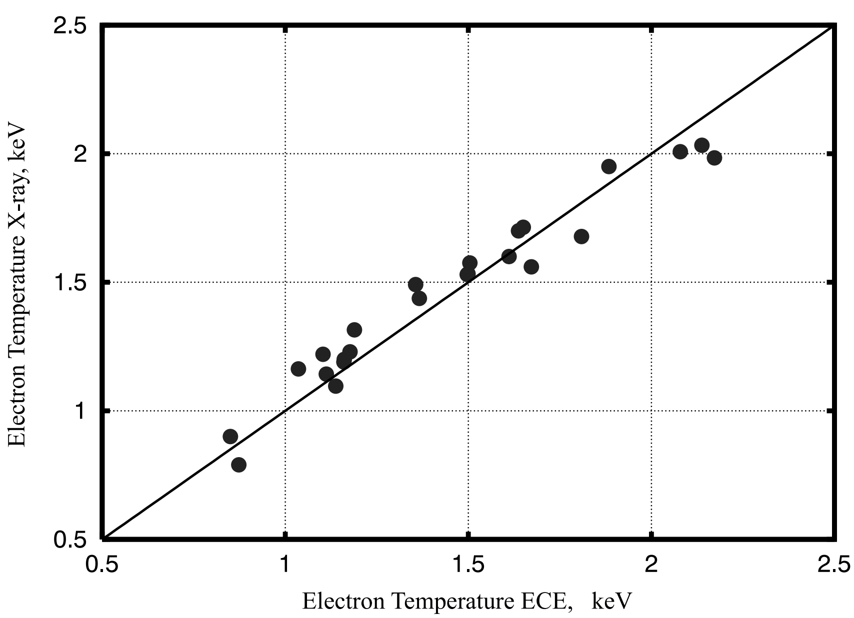
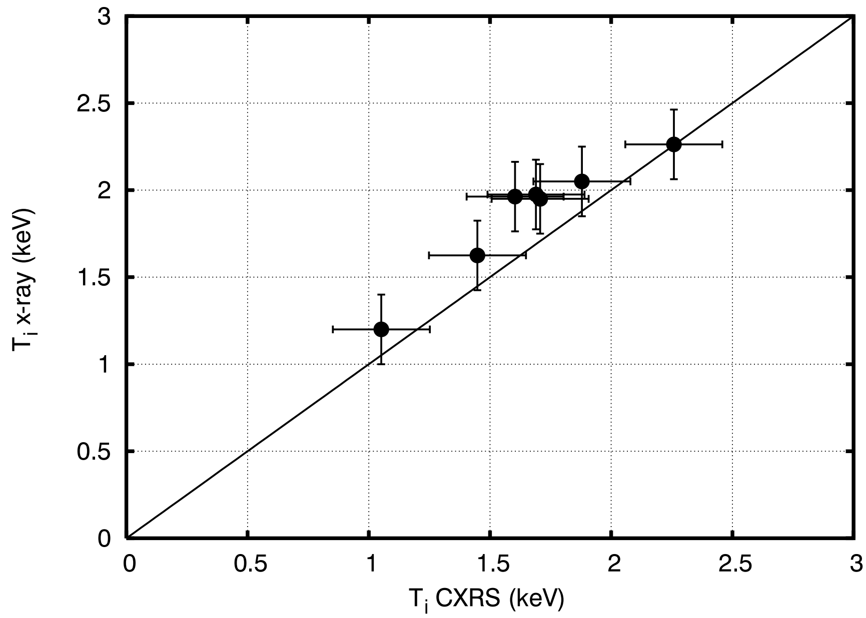
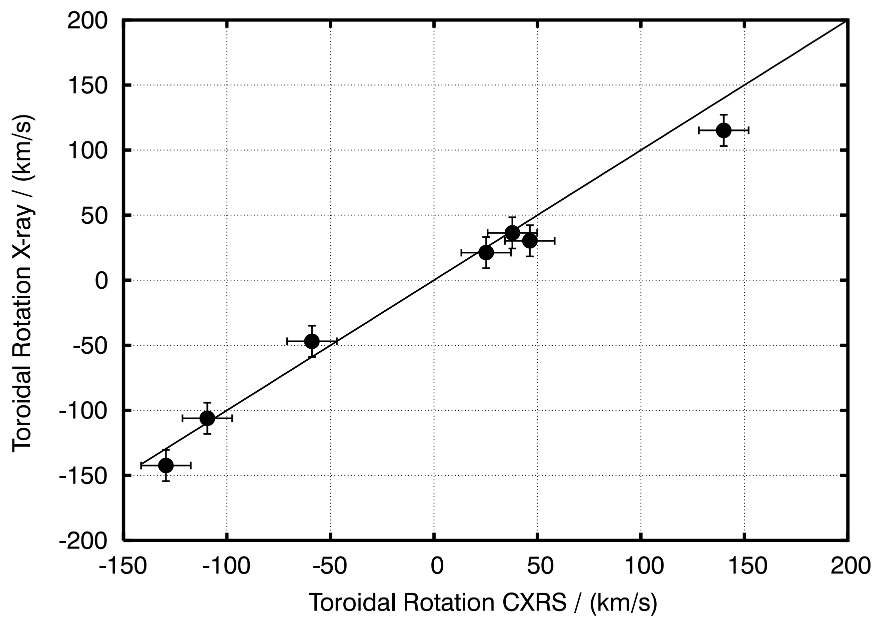


Fig. 3. Comparison of the electron temperature of TEXTOR with the ECE measurements. Discharges with different heating methods, plasmas with ohmic heating, and heating by injection of neutral hydrogen beams are included in the diagram.



(a)



(b)

Fig. 4. Comparison of (a) the ion temperature and (b) the toroidal rotation of TEXTOR plasmas heated by neutral hydrogen beams. X-ray measurements are compared to CXRS.

determination of the diffusion coefficients. For plasmas with heating by a beam of fast neutral hydrogen, the deviation to the equilibrium is still larger, as the neutral density and hence the recombination is increased.

In the 25 yr of X-ray spectroscopy on fusion devices, both the experimental techniques and the accuracy of the theoretical data have improved significantly. Now, the X-ray spectra can be modeled with high accuracy to get the full information on a high temperature plasma.

IV. FUTURE DEVELOPMENTS AND CONCLUSIONS

Recent investigations on the properties of Bragg spectrometers have shown that the wavelength resolution can be improved if the cylindrically bent crystals in the Johann spectrometer are replaced by spherically or toroidally bent crystals.[12] This improves the wavelength resolution, as some error terms are reduced, at the same time it increases the efficiency as the X-rays are focused

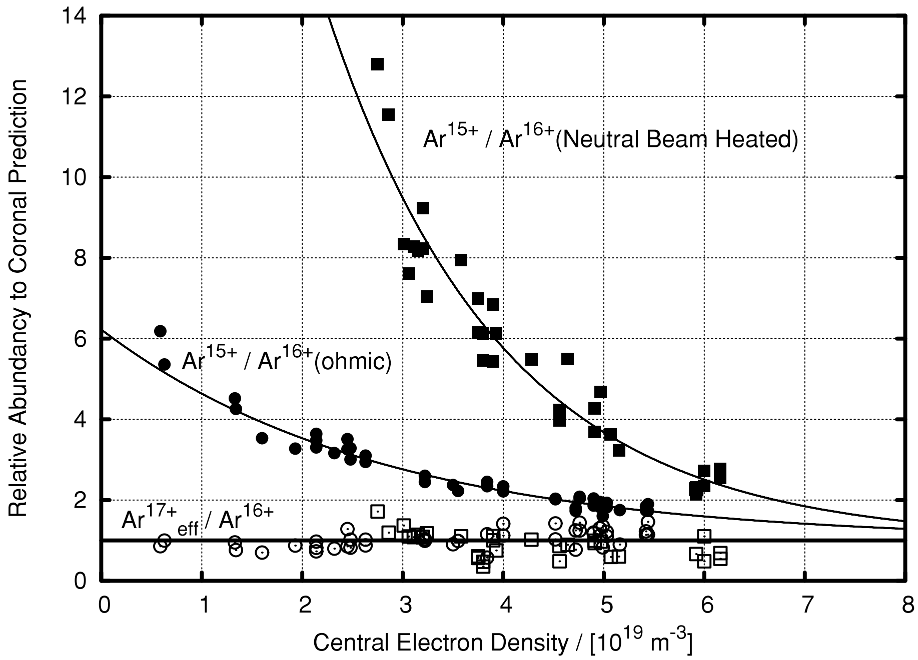


Fig. 5. Charge state distribution of TEXTOR plasmas with ohmic heating (circles) and neutral beam injection (squares). The ratios are normalized to the coronal equilibrium expectations. Full symbols are for the concentration of Li-like ions, and open symbols are for the effective concentration of H-like ions. The effective concentration of H-like ions is calculated by the contribution of recombination of H-like atoms to the He-like lines. It contains the recombination with electrons (radiative and dielectronic), as well as charge exchange recombination with neutral hydrogen. In combination with a transport model, the effective concentration provides a rough estimate of the concentration of neutral hydrogen.

onto the detector.[13] By choosing the geometry, especially the reflection angle of the crystal, focusing of the different positions within the plasma on the detector is achieved. On a two-dimensional detector, spectral resolution shows up in one dimension and spatial information in the other dimension. The design makes use of the astigmatism of reflection on spherical or toroidal surfaces to get the focus in vertical and horizontal direction at different distances from the crystal (Fig. 6).

Of course, the focal distances depend on the angle on the crystal, and hence on the Bragg angle. The imaging properties are fulfilled for a certain Bragg angle only. For a range of a few degrees in the Bragg angles, the error in the position does not exceed a few centimeters and is tolerable.

Fortunately, crystal cuts in suitable crystal materials such as quartz, silicon, or germanium with high-reflection efficiency could be found for all important impurities.[13]

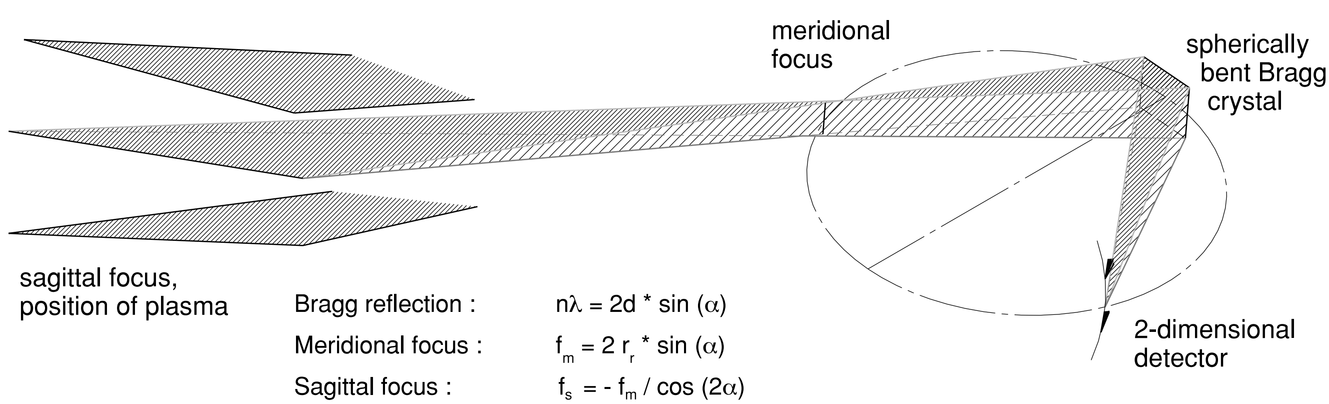


Fig. 6. Principle of an imaging Bragg spectrometer with a spherical crystal at a fusion device. The plasma is placed at the position of the meridional focus.

On TEXTOR, it is planned to install an imaging Bragg spectrometer until the end of 2004 to determine the plasma parameters and especially the distribution of different ionization stages of the impurities on several distances from the plasma center. On ITER, it is proposed to use an array of four imaging Bragg spectrometers to investigate the ion and the electron temperature profiles as well as the toroidal and the poloidal plasma rotations.

In addition to the investigations on thermonuclear plasmas, X-ray spectroscopy gains growing interest in astronomy. On the early satellite experiments, strong bursts of X-rays emerging from astrophysical objects have been found, and in the meantime, several satellite-based X-ray telescopes such as ROSAT, Chandra, and XMM have been launched. The X-ray telescopes provide not only imaging of the stellar objects but also some energy resolution. Even though the spectral resolution is lower than on the spectrometers on fusion experiments, the X-ray satellites provide important information on hot astrophysical objects. For the next generation of satellite experiments, the spectral resolution will be comparable to the ground-based X-ray spectrometers, and detailed modeling comparable to the TEXTOR experiments will be required. For these investigations, the experiments on fusion devices and especially on TEXTOR provide important tests and validations of the theoretical atomic physics data to get complete and reliable information on the hot astrophysical objects.

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