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DETERMINATION OF THE ELECTRONIC TEMPERATURE IN THE TORSATRON TJ-I UPGRADE BY THE TWO FILTERS

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700320
TJ-I TOKAMAK
TORSATRON STELLARATORS
X-RAY DETECTION
ELECTRON TEMPERATURE
PLASMA DIAGNOSTIC
BERYLLIUM
FILTERS

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I. INTRODUCTION

In a fusion device photons in the region of the soft x-ray are emitted due to intrinsic processes involving the working gas (electron-electron collisions, electron-ion collisions, electron and ion collisions with the vessel walls, and synchrotron radiation) and to processes related to the presence of impurities (line transitions).

It is of great interest to know which is the main source of the soft x-ray emission in a given plasma. Once the source is known it is possible to estimate different plasma parameters like Te, ne or Zeff [1, 2] or to change the total flux by modifying plasma conditions.

In a wide range of fusion plasma conditions, most of the soft x-rays are produced via electron-ion collisions and assuming maxwellian distribution the total flux can be related to the electron temperature. Frequently, deviations from maxwellian distribution like the produced by relativistic effects and synchrotron radiation are of low importance but, on the other hand, line transitions and emission from runaway electrons may sometimes be important.

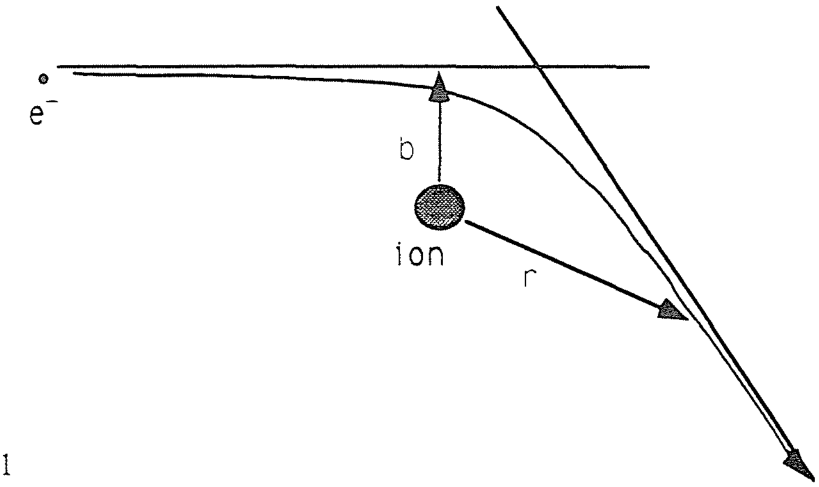


Figure 1

When x-ray are produced as a consequence of the acceleration experienced by the electrons in the neighborhood of ions (see figure 1) and isotropic emission is assumed, Maxwell equations lead the following expression:

$$\frac{dW}{d\omega} = \frac{e^2}{6\pi^2 \varepsilon_0 c^3} \left[\int_{-\infty}^{\infty} a e^{i\omega t} dt \right]^2 \qquad (1)$$

this is, the emitted energy per unit frequency $\left(\frac{dW}{d\omega}\right)$ varies with the square of the Fourier transform of the acceleration, ***a*** .

Depending on initial and final conditions (electron initial velocity, impact parameter, electron final state), the quantum-mechanical treatment of the ion-electron interaction process gives the following expressions for the emitted energy per unit frequency and stereoradian [1], **j(ω)**:

a) Bremsstrahlung (free state, final electron energy greater than zero)

$$j(\omega) = 2.4 \times 10^{-16} n_e n_i Z^2 T^{-1/2} e^{-\hbar\omega/T} \bar{g} \tag{3}$$

being n_e and n_i the electron and ion densities respectively, Z the ion atomic number, T the electron temperature and $\bar{g}$ the gaunt factor which slightly deviates from unity in a great deal of situations.

b) Recombination (bound state, final electron energy lower than zero).

$$j(\omega) = 2.4 \times 10^{-16} n_e n_i Z^2 T^{-1/2} e^{-\hbar\omega/T} \left[G_n \frac{2Z^2 R_y}{Tn^3} e^{Z^2 R_y / n^2 T} \right] \tag{4}$$

where **n** is the principal quantum number of the final electronic state, R_y is the Rydberg constant and G_n are the gaunt factors for each of the **n** possible values.

Taking the ratio between (3) and (4) equations and neglecting the gaunt factors we obtain:

$$\frac{Rec.}{Brem.} = \frac{2Z^2 R_y}{Tn^3} e^{Z^2 R_y / Tn^3} \tag{5}$$

Solving equation (5) it is found that recombination radiation will be dominant (Rec./Brem. > 1) when:

$$T < 2.85\left(Z^2 R_y / n^3\right)\ \mathrm{eV} \tag{6}$$

Typical values for oxygen and hydrogen are T < 2480 eV and T < 39 eV respectively. Electron temperatures between these two values are the most usual in small and intermediate size fusion machines as well as at the plasma periphery of the bigger devices. This means that impurities, such as oxygen, emit via recombination radiation while hydrogen does it via bremsstrahlung.

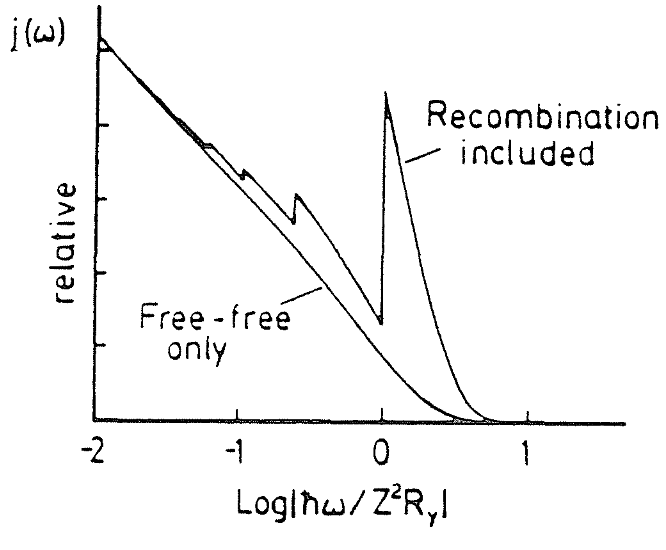


Figure 2. Comparison between bremsstrahlung and recombination radiation.

II. IMPURITY EFFECT ON THE SOFT X-RAY EMISSION.

The presence of impurities manifests in equations (3) and (4) through Z and **n** parameters [3, 4]. Impurities increase both, the number of the interactions (via Z) between electrons and ions and the number of available quantum levels.

In figures 3 and 4 the effect of impurities like oxygen and iron in a hydrogen plasma is shown. Figure 3 shows the emission spectrum corresponding to a deuterium plasma at 0.24 keV of temperature and 2% of oxygen impurity. The straight line represents the resultant spectrum and dashed lines show the different contributions. Bremsstrahlung from the 2% of oxygen is predominant in the low energy range of the spectrum, while in the high energy range oxygen recombination radiation becomes the most important process.

Deuterium bremsstrahlung is always of less importance at this temperature. It can also be seen line transitions both, from the O^{+6} and O^{+7}, which coexist at this temperature.

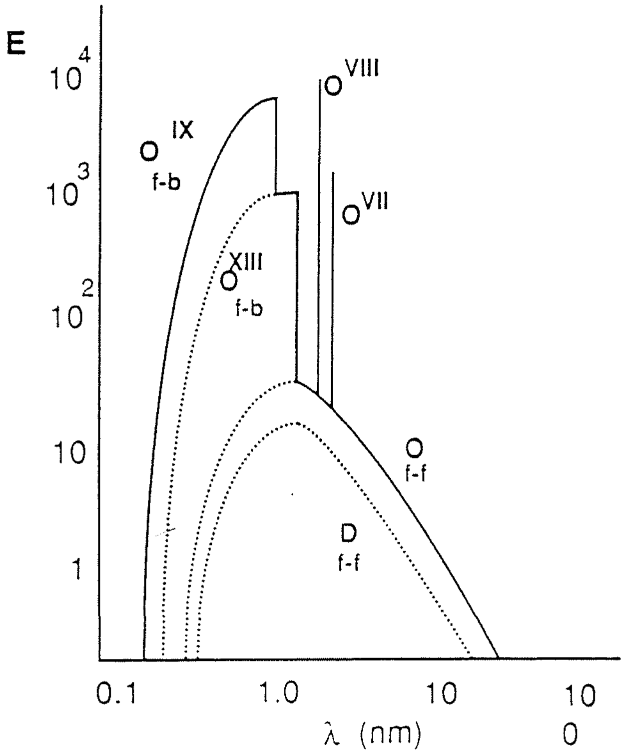


Figure 3. Emission spectrum for an deuterium plasma with 2% of oxygen. Bold line is the actual spectrum and dashed lines represent some contributions to the final spectrum.

Figure 4 represents the variation of the enhancement factor (ζ_z) with Te. ζ_z is the ratio between the total radiated energy of oxygen, iron or helium plasmas and the radiated energy of hydrogen plasma at the same electron temperature and density. Therefore ζ_z includes both, the increment of bremsstrahlung due to the Z^2 dependence and recombination radiation, which is practically absent in hydrogen (except when Te ≤ 39 eV). This figure has been calculated assuming coronal equilibrium [4].

As can be seen ζ_z takes values up to 10^3 and 10^4 at Te ≈ 0.5 keV for oxygen. This means that an oxygen concentration of 1% in a hydrogen plasma produces over ten times more radiation than the hydrogen plasma itself.

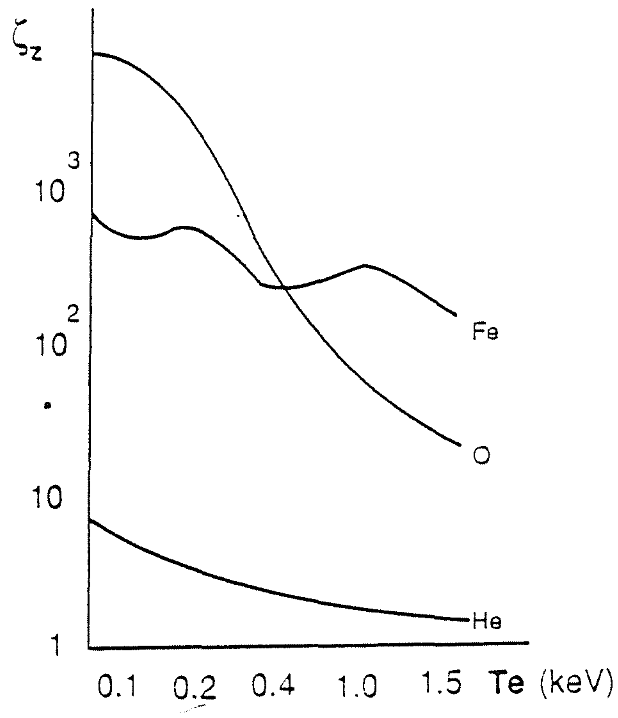


Figure 4. The enhancement factor ζ_z of the continuum radiation over that for hydrogen as a function of Te for He, O, and Fe are shown.

This all bring us to the conclusion that in real fusion plasmas, where oxygen and other impurities are always present, the main contribution to x-ray radiation involve impurities, principally recombination processes.

III. Te ESTIMATION FROM EMITTED SOFT X-RAY FLUXES

It is worthwhile to notice that in equations (3) and (4) the radiation dependence on frequency is the same. This exponential variation comes from the assumption of a maxwellian distribution for the electron energy. On the other hand, the absolute value of the emitted energy varies both with frequency and temperature.

The estimation of plasma electron temperature from the observed x-ray emission is based on this exponential dependence:

$$j(\omega) \propto e^{-\hbar\omega/T_e} \tag{7}$$

Te is directly obtained in a logarithmic diagram (plotting ln (j(ω) versus $\hbar\omega$) from the spectrum slope (1/Te). There are two experimental techniques to obtain Te, both of them making use of the former equation but developing in different ways. Their results are, however, complementary.

P.H.A. (Pulse Height Analysis)

The soft-x-ray emission spectrum can be obtained with a Si(Li) detector and a multichannel analyzer. Resolutions in photon energies of 3.75 eV may be achieved with standard commercial electronics.

Figure 5 shows a typical soft x-ray P.H.A. spectrum [1]. The expected exponential behaviour is observed together with non maxwellian emissions. At about 2.5-3 keV a sharp rise in the spectrum occurs. This is due to a combination of line transitions and recombination radiation from impurities in the plasma. Above this feature, from 3 to 6 keV, the spectrum shows again the exponential decay but now at a higher absolute level. This may be attributed in part to the additional recombination contribution, although a nonthermal electron component may also be present.

This technique has an important drawback: the overlapping of the electrical pulses generated by different photons (pile up). Due to the low signal level provided by the Si(Li) detector it is necessary high amplification. This amplification increases the electronic time response and only low fluxes can be measured, around $3x10^4$ pulses per second. Therefore, to obtain an accurate spectrum it is necessary to accumulate spectra from a number of discharges and therefore the calculated T_e is an averaged value.

Summarizing, this method gives a high resolution in frequencies and allows to detect non exponential contributions to the spectrum, but it cannot give punctual T_e values, due to the poor temporal resolution.

Two-Filters Method

This method makes use of two identical surface-barrier detectors looking at the same plasma region through filters of different thicknesses. Electron temperature is deduced from the ratio of the soft-x-ray fluxes transmitted through the two filters (see figure 6).

Depending on the flux level and the type of detectors used, temporal resolution may be of the order of 1 ms. So, it is possible to monitor the T_e evolution during a single discharge. However, its resolution in frequency is very poor, it is reduced to only two points. This diagnostic is, therefore, blinded to possible deviations of the spectrum shape from the exponential decay. Then, relative calibrations (for example, using Thomson Scattering (TS) or PHA) must be done in order to perform reliable absolute estimations of the electron temperature.

Figure 5. Typical P.H.A. emission spectrum showing the effect of impurities.

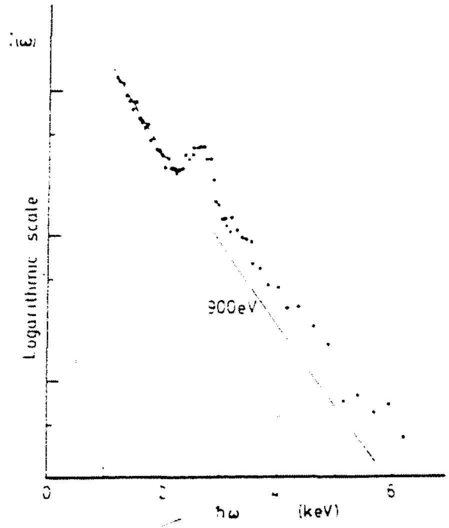
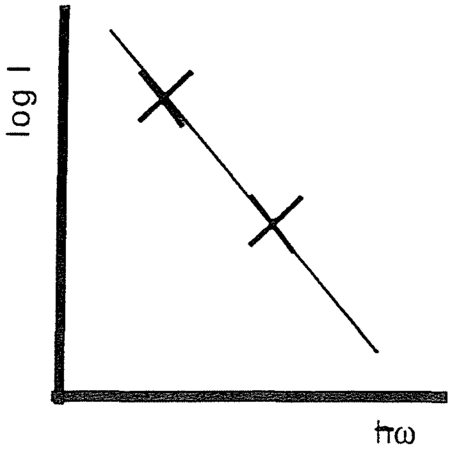


Figure 6. Schematic representation of a spectrum obtained by the two-filters method.



TWO-FILTERS METHOD

Figure 7 shows the basic diagram for this diagnostic. Both detectors are looking at the plasma through different filters and are focused at the same region with the aid of two collimators. Beryllium filters are one of the most suitable because of the low beryllium Z value. Other adequate materials for x-ray filters are CH_2, Al and Ni [6] (see figure 8) [5].

The filter cut-off energy (Tc) increases with filter thickness. The total detected intensities are calculated by integrating (3) and/or (4) equations over all the frequencies taken into account the filters effect. The resulting equation can then be fitted over the electron temperature of interest. As an example, the continuum emission from a hydrogen plasma through a beryllium filter for the interval 0.1 keV < Te < 1 keV, can be written as:

$$p \cong 2.4\times10^{-16}\, n_e n_i \left(T_e\right)^{\pm\frac{1}{2}} e^{-\left(T_c/T_e\right)^{\alpha}} \quad ; \quad \frac{keV}{cm^3\ sr\ s} \qquad (8)$$

where:

- Tc is the filter cut-off energy (in keV)
- α is a fitting parameter, which depends on the kind of impurities present in the plasma.
- The exponent is +1/2 when bremsstrahlung dominates and -1/2 when recombination radiation is the most important process.

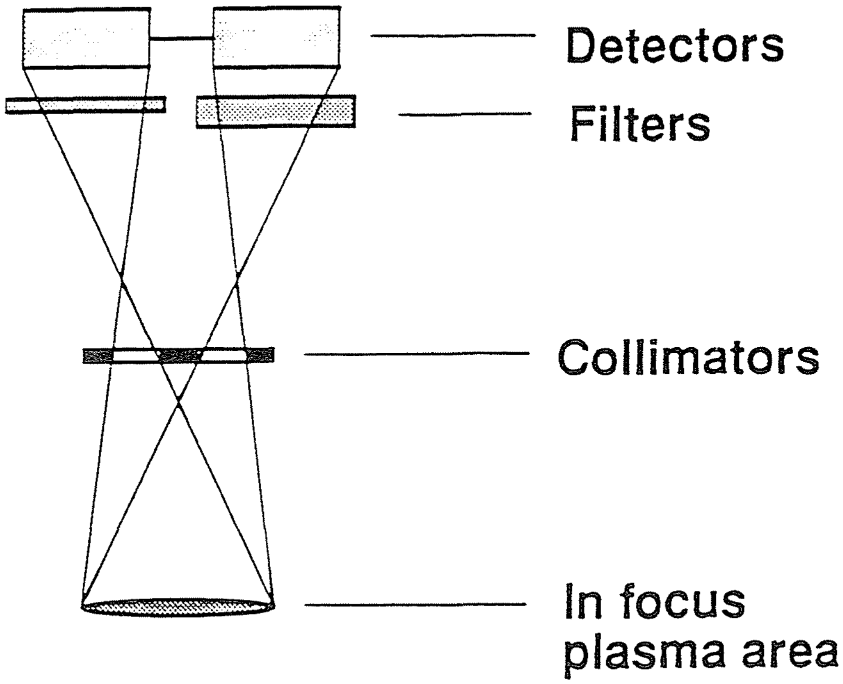


Figure 7

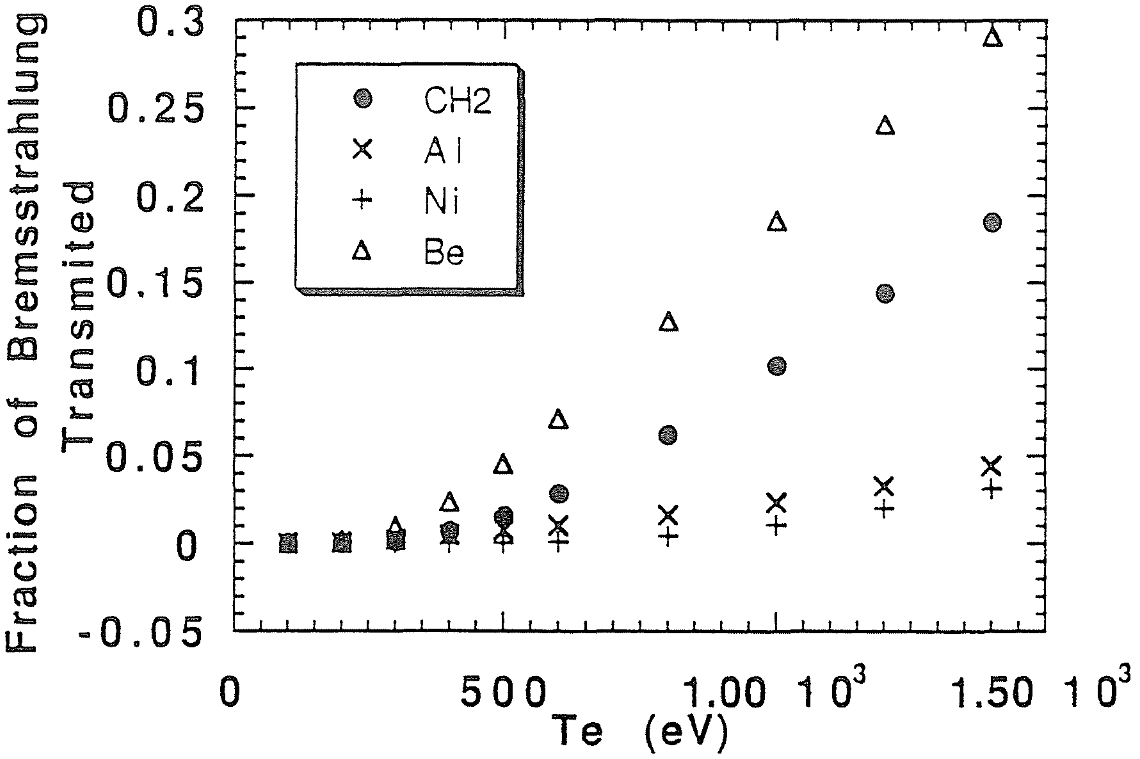


Figure 8.

In practice, filters may reduce the in focus area since the emission from cold plasma areas is composed primarily by low energy photons and these photons are filtered. An extreme case occurs when all the photons except those from the plasma center are filtered. In this situation there is no need for collimators.

This diagnostic is specially convenient for low temperature plasmas where line transitions are of less importance: only a small fraction of atoms have enough energy to populate energetic atomic levels. As an example we are showing the effect of two impurity lines: 2.3 keV Mo - Lα line and 5.5 keV Fe - Kα line, on the emission spectra of two hydrogen plasmas with the same contamination levels.

Figures 9 and 10 show measured spectra from W VII A Stellarator as well as two simulated spectra. In figure 9 plasma temperature is 500 eV. There, the 2.3 keV emission is almost unseen and 5.5 keV emission is not observed al all. On the contrary, these two lines are clearly seen in the spectrum of figure 10 from a 600 keV plasma.

Filters may play another important role in this diagnostic. It is sometimes possible to eliminate these undesired line transitions by choosing adequate filter thicknesses, though a detailed knowledge of plasma impurities is needed. This fact is shown in figure 10 where the 0.9 keV Fe - L line has been cut by a 164 µm Be filter while it is clearly observed in figure 9, where a 9 µm Be filter is used.

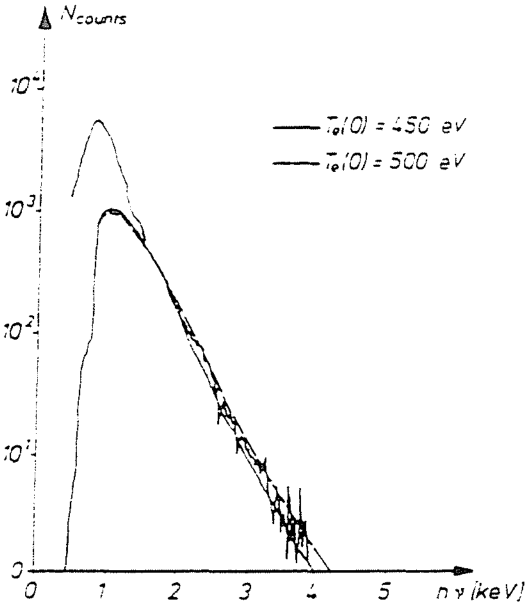


Figure 9 Measured and calculated spectra using a 9 µ m Be filter.

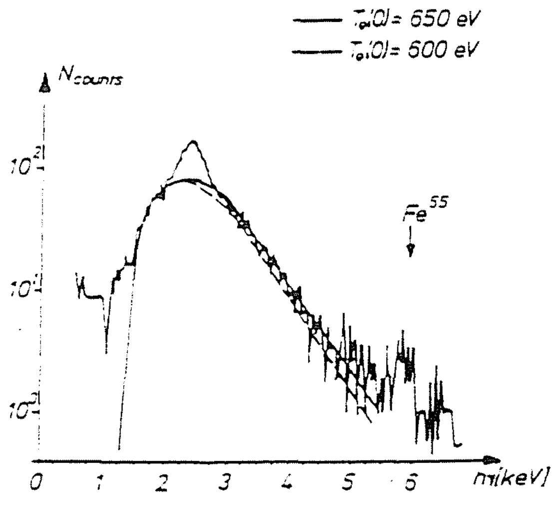


Figure 10 Measured and calculated spectra using a 164 µ m Be filter.

Electron temperature may be obtained from the ratio ***R*** (Te) of detector intensities (P_1 and P_2). From equation (8) it follows that:

$$R(T_e) = \frac{P_2}{P_1} \cong e^{-\left(A/T_e\right)^{\alpha}} \quad ; \quad A = \left(T_{c1}{}^{\alpha} - T_{c2}{}^{\alpha}\right)^{1/\alpha} \tag{9}$$

The parameter α is calculated for each sort of atom present in the plasma assuming coronal equilibrium (see Table 1). When the main part of the emitted intensity involves only one sort of ion its corresponding α value is introduced in equation (9). Otherwise, the value of α must be an averaged value (α_{eff}).

Table 1.

atom	α
H	0.79199
O	0.81612
Fe	0.82138

In figure 11 are plotted different R(Te) values calculated [4] for several impurity ions as a function of the plasma electron temperature. As it can be seen, the influence of type of impurity is of no importance until Te reaches 700 eV. Therefore, at low Te values the α variations for different ions are negligible.

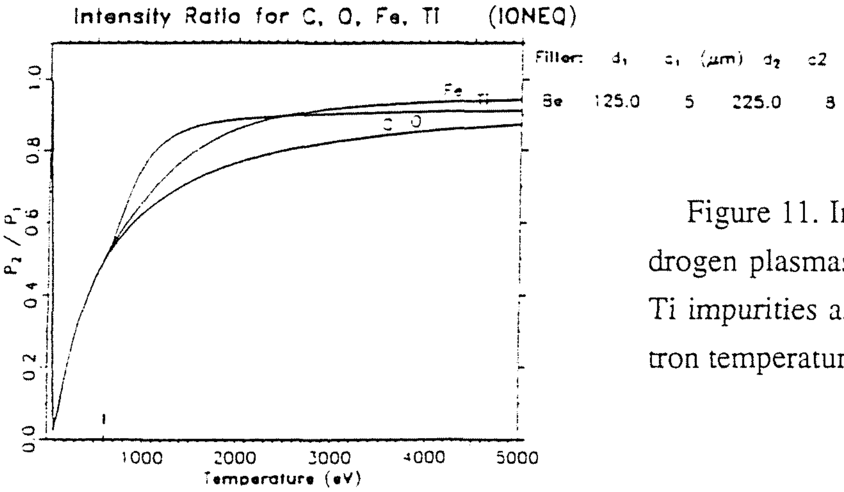


Figure 11. Intensity ratio for hydrogen plasmas with C, O, Fe and Ti impurities as a function of electron temperature.

IV. ELECTRON TEMPERATURE DIAGNOSTIC FOR THE TJ-I Upgrade

The TJ-I Upgrade is a low aspect ratio torsatron ($R_0 = 60$ cm, $< a > = 10$ cm, $B_0 = 0.5$ T, $\ell = 1$, $m = 6$) under construction at CIEMAT to be in operation by autumn 92. In the first period of operation, plasmas of 40 ms will be sustained with 100 kW ECRH (2^{nd} harmonic 28 GHz). This device has been designed to have moderate magnetic configuration flexibility which will modify both, shape and plasma center position [7].

Electron temperature of TJ-I Upgrade plasmas will be estimated from the soft-x-ray emission by the two-filters method. Two surface barrier silicon detectors (on loan from A. Weller, IPP Garching) will be installed at an upper port of the vacuum vessel. In figure 12, a front view of the TJ-I Upgrade with a scheme of the Te diagnostic is shown.

This diagnostic has been designed to be able to estimate central and average electron temperatures, therefore radial resolution must be variable. On the other hand, and due to the flexibility in magnetic configuration of plasmas, the whole system must be poloidaly tiltable, to follow plasma center position. This later characteristic will also enable to obtain the radial profile of Te in a series of reproducible discharges.

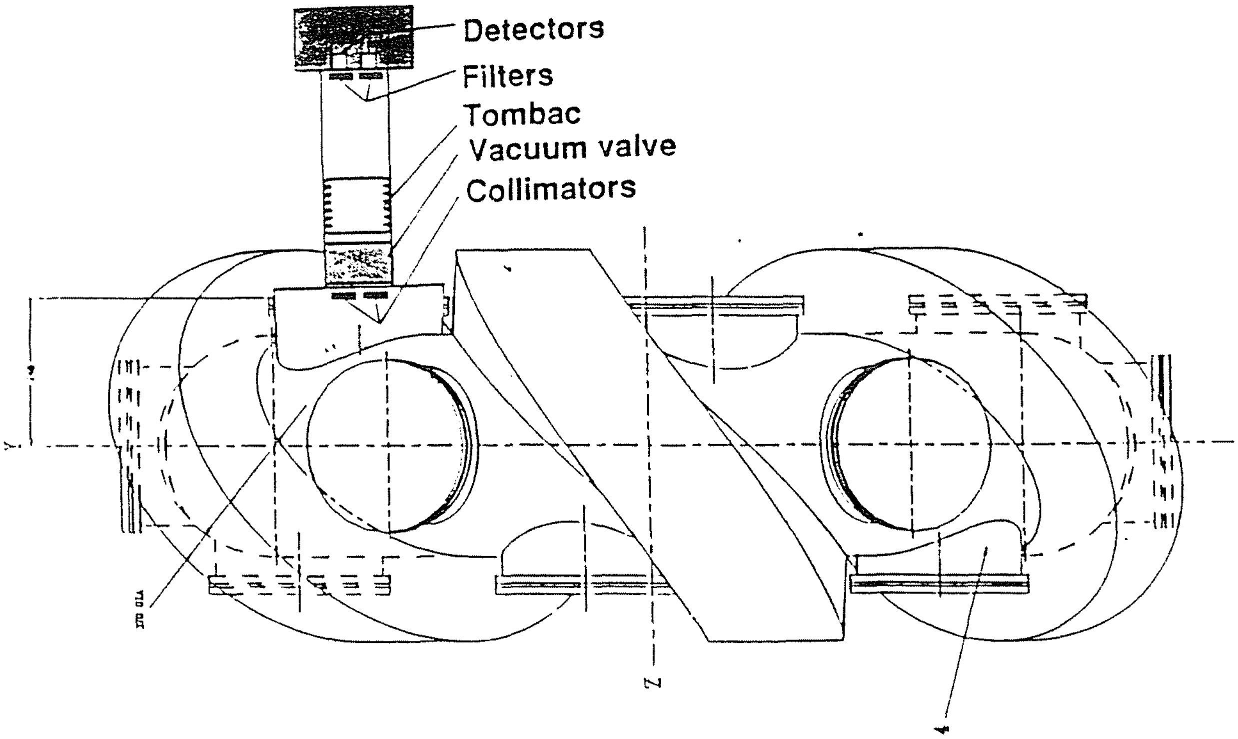


Figure 12. Front view of the Te diagnostic layout at the TJ-I Upgrade. (schematic).

DETAILED DESCRIPTION.

As mentioned above, the diagnostic will be attached to an upper port of the vacuum vessel of the TJ-I Upgrade. At that toroidal position (θ = 10°), the corresponding plasma poloidal cross sections are shown in figure 13. The magnetic flux surfaces displayed here have been calculated for the design parameters (current in hard core Ihc = 280 kA and in the vertical fields Ivf1 = -49 kA and Ivf2 = 122 kA).

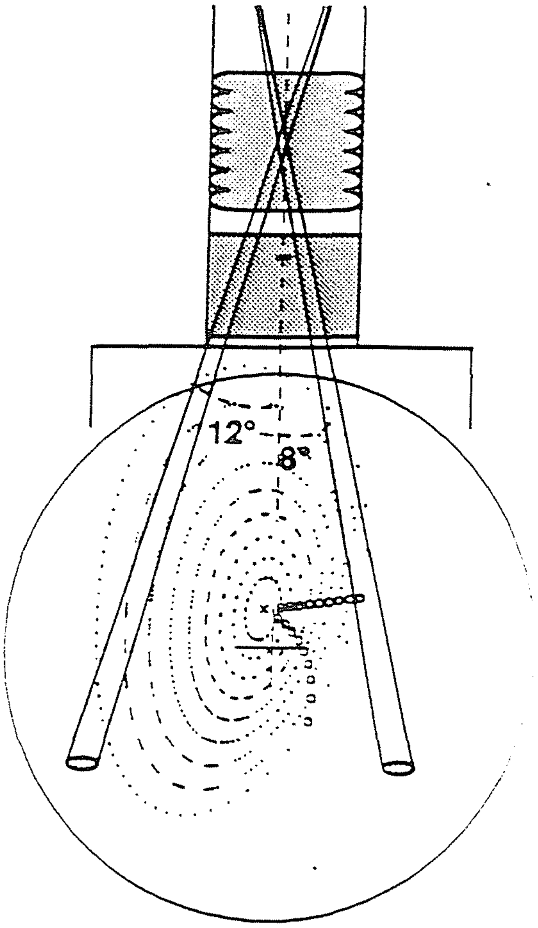


Figure 13. Magnetic configuration at the toroidal section θ = +10° and limiting viewing chords.

Also the limiting chords and the chords widthness (radial resolution) are displayed. It can be seen that the whole system has to be tilted from -12° to +8° poloidaly in order to cover the full plasma cross-section.

Figure 14 shows the detailed scheme of the diagnostic. Here, detectors (**D**), their respective filters (**F**) and a pair of fixed diaphragms (**F D**) are placed in an aluminum case. Both are silicon surface-barrier detectors. They are based on the measurement of the current produced in the Au-Si (n-type semiconductor) interphase when x-ray radiation passes through. Each absorbed photon produces electron-hole pairs, one each 3.76 eV. A bias voltage makes electrons and holes to move in opposite directions, generating an electrical current proportional to the absorbed x-ray flux.

Detectors case will be attached to the chamber port (**C P**) by means of a robust mechanical adapter. It consists mainly of a rigid tube (**R** T), a flexible tombac (**F** T), a high vacuum valve and a non standard transition flange. Attached to the inner part of the rigid tube there is a telescopic tube (**T T**) which can be folded in vertical direction. At its lower end, there is the collimators holder (**C H**) whose position can be known with an accuracy of 0.1 mm. Collimators (C) will serve to define the plasma region of interest. Moving them up and down (up to approximately 100 mm), both spatial resolution and flux densities at the detectors surface may be modified. This flexibility is quite convenient in order to assure that signal levels are acceptable under a variety of plasma heating conditions.

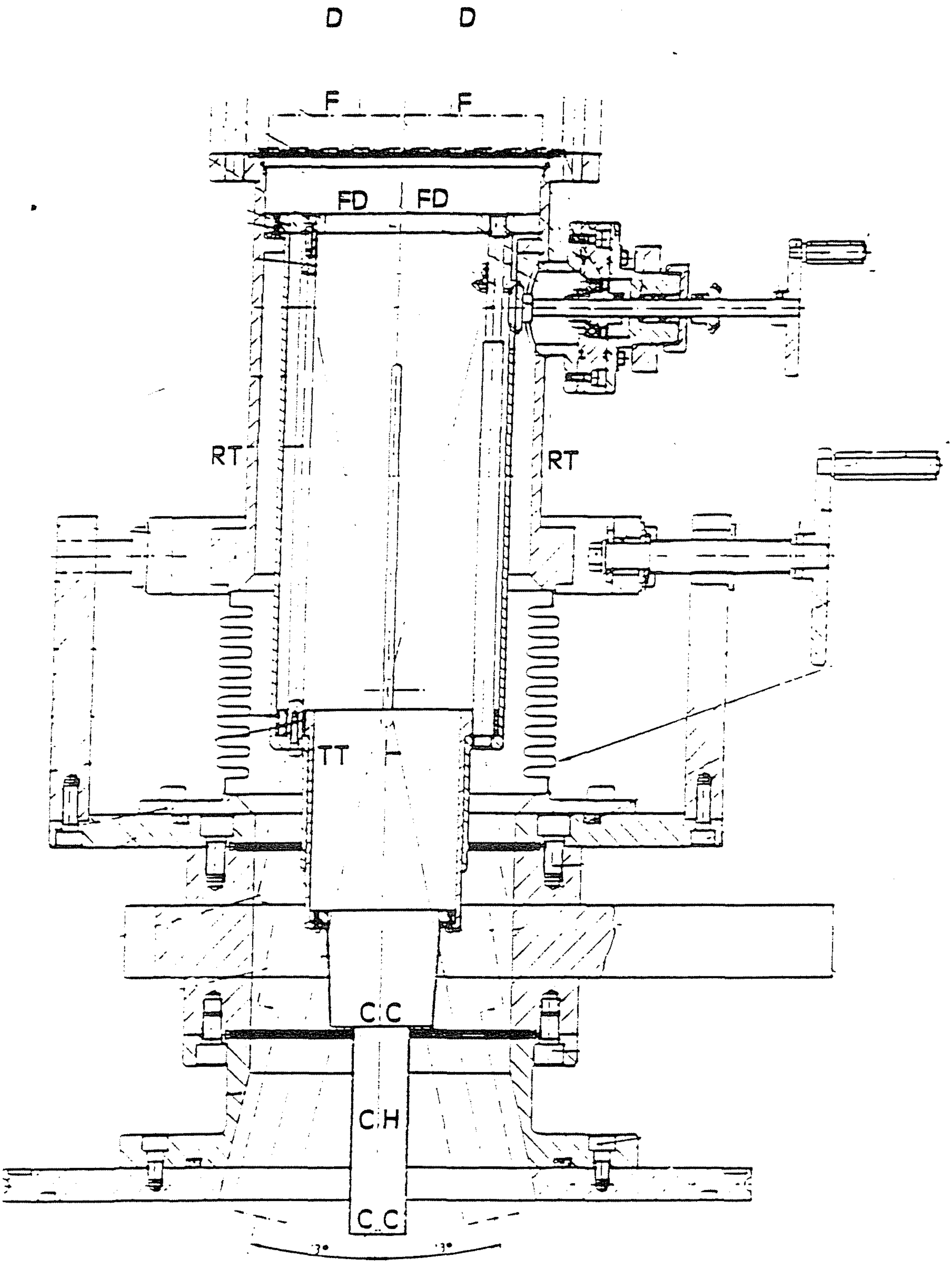


Figure 14. Detailed scheme of the diagnostic.

The flexible tombac will permit to tilt the whole system poloidaly in order to scan the full plasma cross-section in a shot to shot basis; as indicated in the figure, maximum inclination enabled is 13°.

For the selected magnetic configuration shown in figure 13, distances between detectors and collimators, detectors and plasma center, collimators widthness and spatial resolution have been calculated to optimize density fluxes at detectors surface and to minimize the total size. These parameters are listed in table 2, assuming a filter thickness of 50 µm (T_C = 2.5 keV).

The shape the diaphragms may circular or rectangular. Rectangular shape enhance the energy flux while maintaining high poloidal resolution. Collimators radii might be up to 20 mm, in this case the whole plasma cross section is observed.

Table 2

R det (mm)	R col (mm)	D plas-col (mm)	Res (p) (mm)	Photons rate** (ph/ms, x10^{-4})	Flux (keV/ms, x10^{-4})
12.5	4.5	240-300	13.8-22	1.2-2.3	9.9-18.2
5.0*	4.5	240-300	9.4-13.8	0.5-9.1	4.0-7.3

* 5.0 mm is the poloidal effective radius (detector diameter is 25 mm).
** Assuming 0.5 the detector efficiency and 4keV the averaged photon energy.
(R det = detectors radii; R col = collimators radii; Dplas-col = distance from collimators to plasma center and Res (p) = poloidal resolution).

V. SUMMARY

The two-filter method is a diagnostic to estimate electron temperature of plasmas from the soft x-ray flux measurement. This technique allows to attain very good temporal resolution since is based on total flux measurement.

The two identical detectors are focused on the same plasma area. Each detector receives the radiation through a Be filter of adequate thickness and the ratio of the two signals gives the Te value.

Owing to this method measures total fluxes it is necessary to make a previous analysis, using for example the P.H.A. technique, to show and/or quantify possible deviations of radiation from a maxwellian distribution, as occurs when line transition and emission from nonthermal electrons take place.

Here we present the design of the diagnostic for the TJ-I Upgrade. This small torsatron is going to attain electron temperatures up to 0.5 keV and despite not very high densities are expected we think this diagnostic will be of great interest.

Much attention has been paid to confer to the system as much flexibility as possible:
a) filters of different thickness are available
b) spatial resolution is variable
c) radial profiles can be determined in series of reproducible discharges

Theoretical calculations for a standard TJ-I Upgrade discharge ($T_e = 0.3$ keV and $n_e = 10^{13}$ cm^{-3}) show that the estimated energy flux reaching the detector would be from 4.0×10^4 to 18.2×10^4 keV/ms. Assuming 0.5 as the detector efficiency the number of detected photons per millisecond would lye between 5.0×10^3 and 2.0×10^4. The expected current in the detectors range from 10^{-9} A to 5×10^{-9} A (one electron is produced every 3.75 eV of radiated energy absorbed in the detectors).

ACKNOWLEDGMENT

We have to thanks A. Weller (IPP, Garching) for borrowing us the detectors and some specific information.

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CIEMAT-725

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"Determinación de la temperatura electrónica en el torsatron TJ-IU por el método de filtros."

MEDINA, F.; OCHANDO, M. (1994) 27 pp.,14 Figs.,7 Refs.

Se ha diseñado un monitor de rayos-x para el torsatrón TJ-IU. Consiste en dos detectores de superficie de barrera de silicio enfocados a una misma región del plasma a través de dos filtros de berilio de diferente espesor. La temperatura electrónica se deduce a partir del cociente del flujo de rayos-x transmitido a través de los dos filtros.

En el diseño de este diagnóstico se ha tenido en cuenta la flexibilidad que en la configuración magnética tienen los plasmas en el TJ-IU. El diagnóstico, que se anclará a una ventana superior de la cámara de vacío, podrá desplazarse vertical y horizontalmente para cambiar la resolución del área enfocada y para permitir el barrido de toda una seccion del plasma. Pudiendose obtener de esta forma el perfil radial de la temperatura electrónica del plasma mediante sucesivas descargas reproducibles.

CLASIFICACION DOE Y DESCRIPTORES: 700320. TJ-I Tokamak. Torsatron Stellarators. X-ray Detection. Electron Temprature. Plasma Diagnostic. Beryllium. Filters.

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Instituto de Investigación Básica.- MADRID

"Determinación de la temperatura electrónica en el torsatron TJ-IU por el método de filtros."

MEDINA, F.; OCHANDO, M. (1994) 27 pp.,14 Figs.,7 Refs.

Se ha diseñado un monitor de rayos-x para el torsatrón TJ-IU. Consiste en dos detectores de superficie de barrera de silicio enfocados a una misma región del plasma a través de dos filtros de berilio de diferente espesor. La temperatura electrónica se deduce a partir del cociente del flujo de rayos-x transmitido a través de los dos filtros.

En el diseño de este diagnóstico se ha tenido en cuenta la flexibilidad que en la configuración magnética tienen los plasmas en el TJ-IU. El diagnóstico, que se anclará a una ventana superior de la cámara de vacío, podrá desplazarse vertical y horizontalmente para cambiar la resolución del área enfocada y para permitir el barrido de toda una seccion del plasma. Pudiendose obtener de esta forma el perfil radial de la temperatura electrónica del plasma mediante sucesivas descargas reproducibles.

CLASIFICACION DOE Y DESCRIPTORES: 700320. TJ-I Tokamak. Torsatron Stellarators. X-ray Detection. Electron Temprature. Plasma Diagnostic. Beryllium. Filters.

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"Determination of the electronic temperature in the torsatron TJ-I Upgrade by the two filters."

MEDINA, F.; OCHANDO, M. (1994) 27 pp., 14 Figs., 7 Refs.

A Te monitor for the TJ-IU torsatron, based on the two-filters method, has been designed. It will consist of two surface-barrier silicon detectors looking at the same plasma region through berilium filters of different thickness. Plasma electron temperature is deduced from the ratio of the soft-x-ray fluxes transmitted through the two filters.

The flexibility in magnetic configuration of TJ-IU plasmas has been taken into account in the mechanical design of this diagnostic. It will be attached to an upper port of the vacuum vessel and the whole system will be movable both, to change the spatial resolution when needed and to enable the scan of the full plasma cross-section to obtain the radial profile of electron temperature in a shot-to-shot basis.

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