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Design of an ion temperature diagnostic based on neutral beam scattering

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Small-angle neutral beam scattering will be used on the STOR-M tokamak to obtain space and time-resolved measurements of the ion temperature. Advantages of the technique and experimental considerations leading to the design are discussed. It is expected that a 20–30-keV helium beam of 35–65-A/m^2 current density together with a large area chevron channel-plate detector and automatic data handling will allow direct determination of ion temperatures at an accuracy of 10%, a temporal resolution of 40 μs, and a spatial resolution better than 1 cm.

INTRODUCTION

An analysis of the scattering method was given by Abramov *et al.* in 1970.[1] The scattered spectrum is centered around a high energy E_0, just below the beam energy E_b. The width σ of this spectrum is directly related to the ion temperature. Therefore, localized measurements of the ion temperature are relatively unaffected by attenuation of the particle flux, detection of background neutrals, and poorly known temperature and density profiles. These important advantages over passive and active charge exchange methods will allow the use of the scattering technique on future fusion devices with increased density and size.

The first experimental results, in which a tokamak plasma was probed with an 8-keV He beam were reported by Aleksandrov[2] and Berezovskii.[3] In the present approach a 20–30-keV beam will be used along with high counting performance and automatic data acquisition to facilitate the determination of temperature profiles.

The broadening of the initial narrow spectrum by the scattering process is expressed in the differential count rate $d\Gamma$ of particles in the energy interval dE scattered at an angle θ into a solid angle $d\Omega$,

$$\frac{1}{\sqrt{E}}\frac{d\Gamma}{dEd\Omega}=C_0\frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{E-E_0}{\sigma}\right)^2\right], \quad (1)$$

where

$$\sigma=\sin\theta\sqrt{2\gamma E_b T_i}, \quad (2)$$

$$E_0=[1-\gamma(\sin\theta)^2]E_b, \quad (3)$$

$$C_0=\tfrac{1}{2}(2\pi\epsilon_0)^{-2}Z_b^2Z_p^2eJS_dD_bn_i(\sin\theta\sqrt{E_b})^{-5}, \quad (4)$$

and J is the beam equivalent current density, γ is the mass ratio of beam to plasma particles, S_d is the detector active area, and D_b is the beam diameter. For Eq. (1) to be valid it is required that $E_b \gg kT_i$.

A description of various experimental conditions to be chosen was given by Berezovskii.[3] We will focus on the effects of a further broadening of the Gaussian distribution of Eq. (1) by the beam divergence and the source characteristics. Since the total count rate over the spectrum $\Gamma_{tot}=C_0\sqrt{E_0}\,d\Omega$, is proportional to $(\sin\theta)^{-5}$, θ has to be restricted to small values. Consequently, the length l of the scattering volume (the intersecting region of the beam and line of sight) becomes quite large and a precise evaluation of the obtainable spatial resolution is needed. Finally, available data on the value of the loss factor for electron exchange during scattering[4,5] are incorporated.

I. EXPERIMENTAL CONSIDERATIONS

The broadening σ_θ of the scattered spectrum by a beam divergence with standard deviation s_θ can be expressed as

$$\frac{\sigma_\theta}{\sigma}=\frac{\sigma}{T_i}\frac{s_\theta}{\theta}. \quad (5)$$

A similar expression can be derived for the energy spread s_E of the source:

$$\frac{\sigma_E}{\sigma}=\frac{E_0}{\sigma}\frac{s_E}{E_b}. \quad (6)$$

The combined effects of Eqs. (1), (5), and (6) on the energy spread s of the measured spectrum is

$$s^2=\sigma^2+\sigma_E^2+\sigma_\theta^2 \quad (7)$$

and the contribution of beam imperfections can therefore be corrected for.

The effect of the length l of the scattering volume on the spatial resolution δx is calculated for a temperature that depends linearly on the length coordinate x within the volume. The center of the volume $(x=0)$ is denoted by index 0. An error analysis up to second order in the perturbation of T shows that σ^2 is changed to

$$\overline{s^2}\cong\sigma_0^2\left[1+\tfrac{1}{3}l^2(T_0'/T_0)^2\right]. \quad (8)$$

Considering the assumed $T(x)$ dependence, the discrepancy between $\overline{s^2}$ and σ_0^2 can be translated into an uncertainty in the position:

$$\delta x=\tfrac{1}{3}l^2(T_0'/T_0). \quad (9)$$

Since lT_0'/T_0 will be less than one, δx remains smaller than one third of the length of the scattering volume. Poloidal alignment of the scattering volume will further improve the spatial resolution.

The temporal resolution is related via the number of counts N, to the accuracy in the ion temperature[6]:

$$\Delta T_i/T_i=\sqrt{2/(N-1)} \quad (10)$$

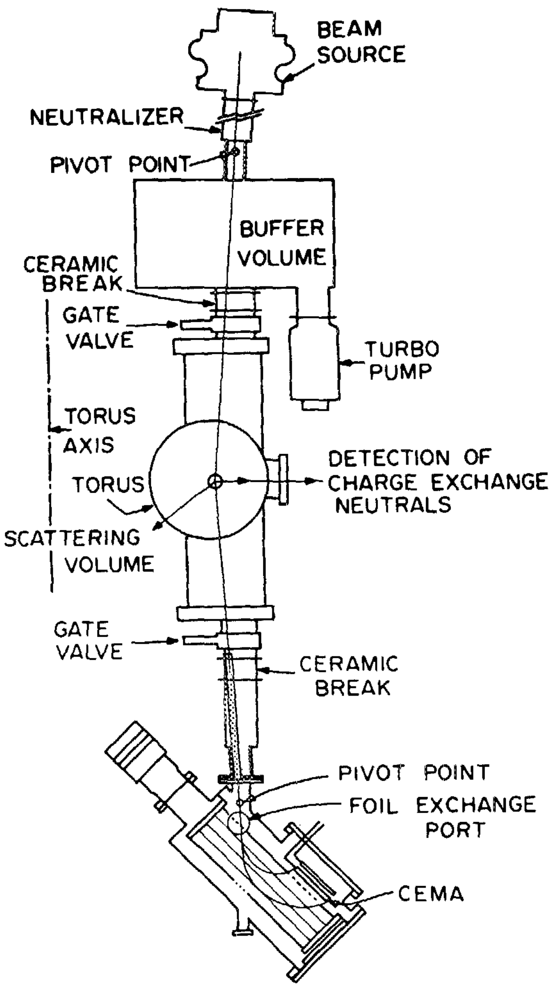

FIG. 1. Experimental arrangement.

II. EXPERIMENTAL ARRANGEMENT

Figure 1 shows the experimental arrangement. At 20 keV, the source provides a current density of $36\ \text{A/m}^2$ for a 1-cm-wide He beam in the target area. The detector, of the electrostatic deflection type, contains a stripping foil and a linear channel plate with eight anodes each having an area of $1.8\times10^{-4}\ \text{m}^2$. Taking into account the detector efficiency, the loss factor due to electron exchange during scattering and the neutral flux attenuation by the plasma, a total count rate of $5.3\times10^{6}\ \text{s}^{-1}$ is expected for a 20-keV He beam scattered at 8° by the STOR-M tokamak plasma ($T_i = 100$ eV, $T_e = 300$ eV, $n_i = 2\times10^{19}\ \text{m}^{-3}$). For a similar hydrogen beam the count rate would be much less, i.e., $1.4\times10^{4}\ \text{s}^{-1}$. The count rate due to background neutrals originating from the incident beam after double charge exchange is $2.5\times10^{4}\ \text{s}^{-1}$ for helium and $2.7\times10^{6}\ \text{s}^{-1}$ for hydrogen in the case of a 20-keV beam. It is clear that a helium beam must be chosen to obtain useful information on T_i.

The accuracy of the measurements, as calculated from the foregoing, is 10% in T_i at a temporal resolution of $40\ \mu\text{s}$ and a radial resolution of 1 cm or less.

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