CLM-P697

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Preprint

PLASMA ION TEMPERATURE MEASUREMENT FROM BALMER ALPHA CHARGE-EXCHANGE RADIATION DURING NEUTRAL INJECTION

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1983

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ABSTRACT

Measurements are presented of Balmer Alpha line profiles from plasma ions which have been neutralized by charge exchange with injected neutral hydrogen beams in DITE tokamak. Doppler broadening of the Hα line is interpreted in terms of the ion temperature and line profiles are compared with neutral particle energy spectra in the regime where the plasma is transparent to the transport of neutrals from the core to the boundary. An asymmetry in the CX line profile is interpreted in terms of plasma rotation during neutral beam injection. The advantage of this method over conventional neutral analysis is seen in the context of the diagnosis of large, hot and dense tokamak plasmas.

(Submitted for publication in Nuclear Fusion Letters)

One of the main techniques for estimating plasma ion temperatures in tokamaks relies on the use of neutral particle analysers (NPAs) to measure the energy spectra of neutrals produced by charge exchange in the hot plasma core (CX neutrals) [1]. For moderate values of line-averaged density, the plasma is transparent to CX neutrals and energy spectra measured at the plasma periphery reflect accurately those in the core. However in large, hot and dense plasmas relevant to devices approaching the size of feasible tokamak reactors the plasma becomes increasingly opaque to the passage of neutrals; thus a CX neutral spectrum measured at the periphery of these devices does not reflect conditions in the core but instead, is more representative of conditions closer to the edge of the plasma.

In order to avoid future difficulties in diagnosing ion temperature in large tokamaks an alternative method has been tested on DITE tokamak [2]. The method relies on measuring the optical spectrum of Hα radiation produced in the reaction

$$\underline{H}^0 + H^+_{th} \rightarrow \underline{H}^+ + H^*_{th} \rightarrow H\alpha \text{ photon} \qquad \ldots (1)$$

where the underlined particle refers to a fast injected neutral and the asterisk to an excited n = 3 thermal which then decays through photon emission. The cross-section for process (1) has been measured by Williams et al. [3] and, at the injection energy of DITE (30keV), approximately 3% of CX neutrals are formed in the n = 3 state. For a 1keV atom, the transit distance before emission is of order a few millimetres; thus the Hα radiation is localised at the intersection of the optical viewing cone and the injected neutral beam. Observations of this type may therefore be used to determine plasma ion temperature (by Doppler broadening of the Hα line) and bulk plasma motion (by a net

Doppler shift of the line) averaged over the volume of the intersection region. Earlier measurements of plasma rotation and ion temperature have been made on PDX tokamak [4] for H_e^+ (n = 2 → 1) λ304Å CX radiation where the use of a modulated diagnostic neutral beam allowed discrimination against background plasma light.

Experiments have now been made on DITE tokamak to demonstrate the measurement of ion temperature by the method described above. Limiter discharges with a minor radius of 26cm, $T_e(0)$ = 600eV, $\bar{n}_e = 3 \times 10^{13}$ cm^{-3} and I_p = 130kA and B_ϕ = 2T were used. At this density, the plasma is transparent to CX neutrals [1]. In these experiments, the plasma was heated by three tangential injectors, supplying 1.2MW to the plasma in a 50ms pulse. The measurement geometry is shown in Fig. 1; the spectrometer used was a 50cm holographic grating instrument equipped with a vibrating mirror which enabled the Hα (λ_o 6563Å) emission line to be scanned once every 10ms before, during and after the neutral injection heating pulse. The spectrometer resolution was $\Delta\lambda_I$ = 0.6Å, small compared with the measured line widths.

Spectral scans of the Hα radiation are shown in Fig. 2 where, in order to improve the signal-to-noise ratio on the measurements, six spectral scans (in a 70ms window) were averaged before the injection pulse and three scans (in a 40ms window) were averaged during the injection pulse. Both profiles show a narrow, intense central component and, during injection, enhanced 'wings' appear on the line. The narrow central part of the line is emission from recycling hydrogen in the relatively cool plasma boundary and the line wings are produced by thermal Doppler broadening of the core radiation. It can be seen that the wings are not symmetric about the line centre, the blue shifted wing being the more intense; this effect can be ascribed to a bulk plasma motion. In Fig. 2 the shift is $\Delta\lambda = (1.1 \pm 0.3)$Å, implying a velocity, $v_{rot} = (6 \pm 2) \times 10^6$ cm s^{-1}, in the direction of the toroidal axis.

Figures 3(a) and 3(b) allow comparison of optical and NPA data taken at the same times before and during neutral beam injection phases of the same discharge. Here, optical data have been plotted in the log I versus $(\lambda^*)^2$ (proportional to energy) plane where $I(\lambda^*)$ is the Hα intensity at wavelength $\lambda^* = \lambda - \lambda_o$. It can be seen that faint optical wings are present before beam injection; these can be interpreted in terms of electron impact excitation of the neutral H atom population (central density n_o) to the n = 3 level [5]. An estimate of the photon flux ratio, R, of the background-to-CX components during injection is given by,

$$R \simeq \frac{\langle\sigma v\rangle_e \, n_o}{n_b \, \sigma^* \, v_b} \; \frac{V_B}{V_{CX}} \qquad \ldots (2)$$

where n_b and v_b are the beam density and velocity, σ^* the cross-section for (1), V_B and V_{CX} are the volumes of plasma in the line of sight and intersecting the beam respectively and $\langle\sigma v\rangle_e \simeq 2 \times 10^{-9}$cm^{3}s^{-1}[5]. During injection (t = 180ms) the NPA signal indicated $n_o \simeq 6 \times 10^7$ atoms cm^{-3} implying R $\simeq$ 0.2. The value of n_o may be higher than this value due to the location of limiters and gas feed point near the observation region. Thus we expect a background Hα contribution of ~ 20% to the measured signal. Clearly by using beam modulation techniques this contribution could be reduced in future experiments; however, its presence here allows measurement of the ion temperature during the ohmic phase of the discharge.

To analyse the line, a bigaussian form for the line shape is assumed

$$I(\lambda^*) = I_E \exp - \left(\frac{\lambda^*}{\lambda_E}\right)^2 + I_{CX} \exp - \left(\frac{\lambda^* - \Delta\lambda}{\lambda_{CX}}\right)^2, \qquad \ldots (3)$$

and has been fitted by the least-squares criterion to the data in Fig. 3(a). Here I_E and I_{CX} are peak intensities from edge and core regions and

$$\lambda_i^2 = \frac{2e\ T_i\ \lambda_o^2}{mc^2} \qquad \ldots (4)$$

where i = E refers to the edge and i = CX to the core components. As Fig. 1 shows, the measurement region contains a relatively large path-length of plasma in the line of sight along which the Hα emissivity and temperature vary; thus the results are biassed to a particular major radius $\langle R \rangle$ along the line of sight where

$$\langle R \rangle = \frac{\int R\ \varepsilon\ d\ell}{\int \varepsilon\ d\ell} \qquad \ldots (5)$$

and the Hα emissivity is given by $\varepsilon = n_b\ n_i\ \sigma^*\ v_b$. A beam attenuation code was used to compute n_b at several hundred points in the crossed beam space and experimental T_i profiles from the NPA (Fig. 4) were used to evaluate eq (5). Results are shown in Fig. 5 plotted as a function of $R_\perp$, the tangent radius of the line of sight; in this work $R_\perp$ = 1.17m giving $\langle R \rangle$ = 1.285m (r/a = 0.43) and $\langle R \rangle$ 1.25m (r/a = 0.3) for ohmic and injection heating conditions respectively.

Ion temperatures derived from optical data were $T_i(0.43) = (310 \pm 60)$eV and $T_i\ (0.3) = (570 \pm 100)$eV for ohmic and injection phases respectively, in reasonable agreement with NPA profile data.

The relatively large error bars in the derived values of ion temperature reflect the signal-to-noise ratio of the Hα measurements. This noise originated mainly in the detector; typically a dynamic range of 120 : 1 was achieved for the narrow spectral component and $\simeq$ 40 : 1 for the wings alone. No attempts were made here to maximise the spectrometer performance although this could be done in future experiments by increasing the etendue, improving the detector performance (by using a multichannel analyser), or using a more intense neutral beam. One advantage of this optical method over neutral particle analysis can be seen by referring to Figs 3(a) and (b). It is clear that the Hα technique is sensitive to the wing radiation (from which T_i is derived) at energies as low as ~ 1-2 T_i whereas with the NPA technique, one has to use ~ 2-6 T_i to evaluate the temperature. This latter constraint is due to the relatively large edge signal in the NPA data; the optical data, having relatively less edge signal is therefore less likely to be affected by slowed down beam ions in the tail of the distribution. Thus more precise values of Ti should be obtained. The same consideration also applies to the measurement of rotation velocity.

In principle profile information on T_i and v_{rot} could be extracted from a series of observations made at different values of $R_\perp$ since, as Fig. 5 shows, $\langle R \rangle$ is strongly dependent on $R_\perp$. One practical possibility here might be to multiplex several different optical lines of sight and image the light on different parts of the spectrometer slit. In this context it would be desirable to use a spectrometer capable of resolving both spatially and spectrally. Alternatively, the measurement volume in the plasma could be reduced to dimensions in the order of centimetres by the use of a collimated diagnostic neutral beam which, itself, could be modulated to allow rejection of the background plasma light. Such an experimental arrangement could facilitate the measurement of radial profiles of T_i with a high degree of localization. By making absolute rather than relative measurements of the Hα CX signal strengths, it should also be possible to estimate local values of the neutral density (with a knowledge of n_i and n_b). Moreover, by observing CX impurity spectral lines [4], absolute impurity abundances in the centre of the plasma could be determined in a similar way.

The author thanks the DITE Group for assistance, in particular J.W.M. Paul, J. Hugill, P.J. Lomas and S.J. Fielding for discussions and T.S. Green for loan of the grating spectrometer.

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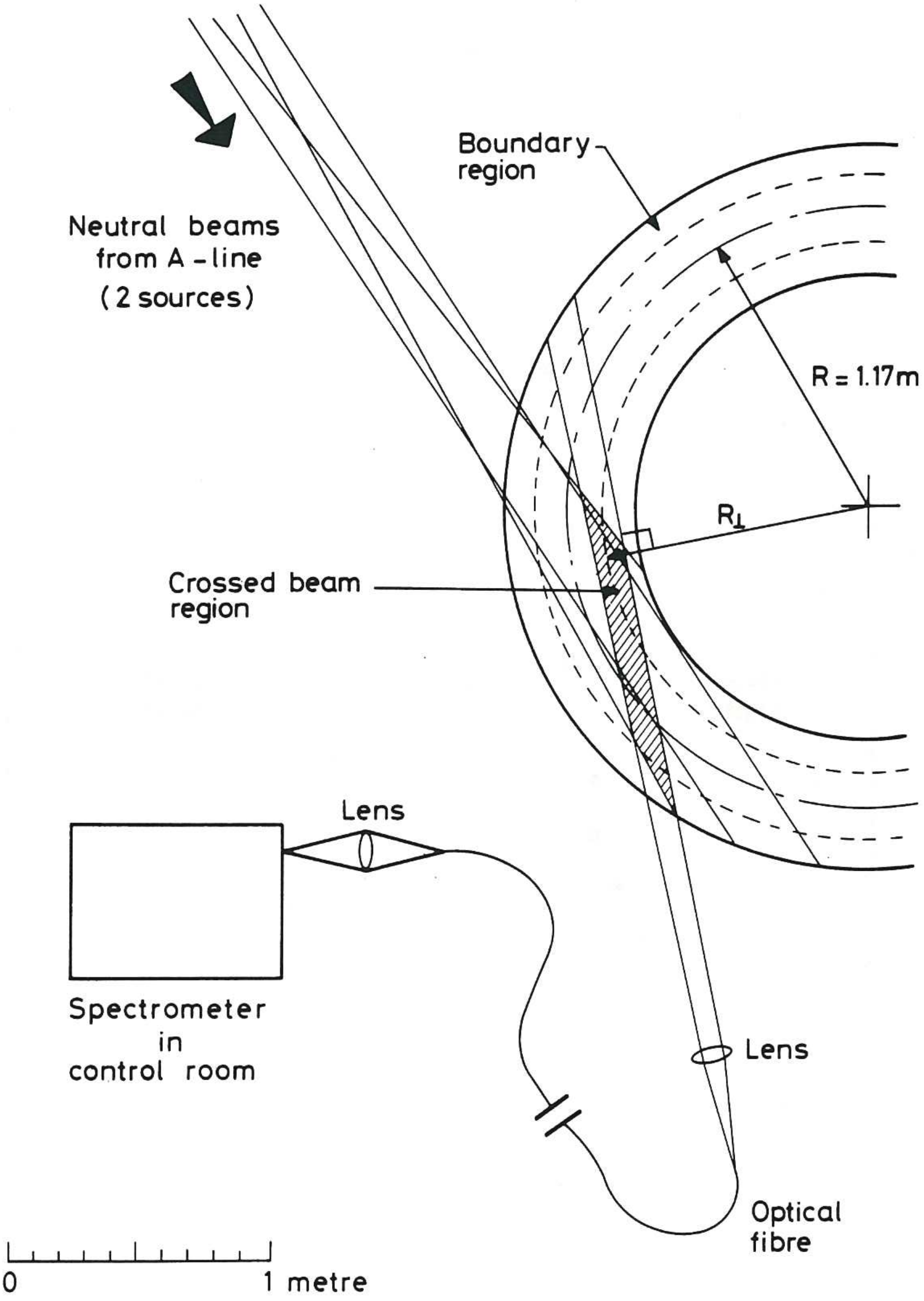

Fig.1 Measurement geometry used to measure CX Hα radiation in DITE tokamak showing position of injected neutral beam (A-line) and optical viewing cone. The crossed-beam is shown hatched. Hα light was collimated by the lens and transmitted to the remote spectrometer via a light fibre.

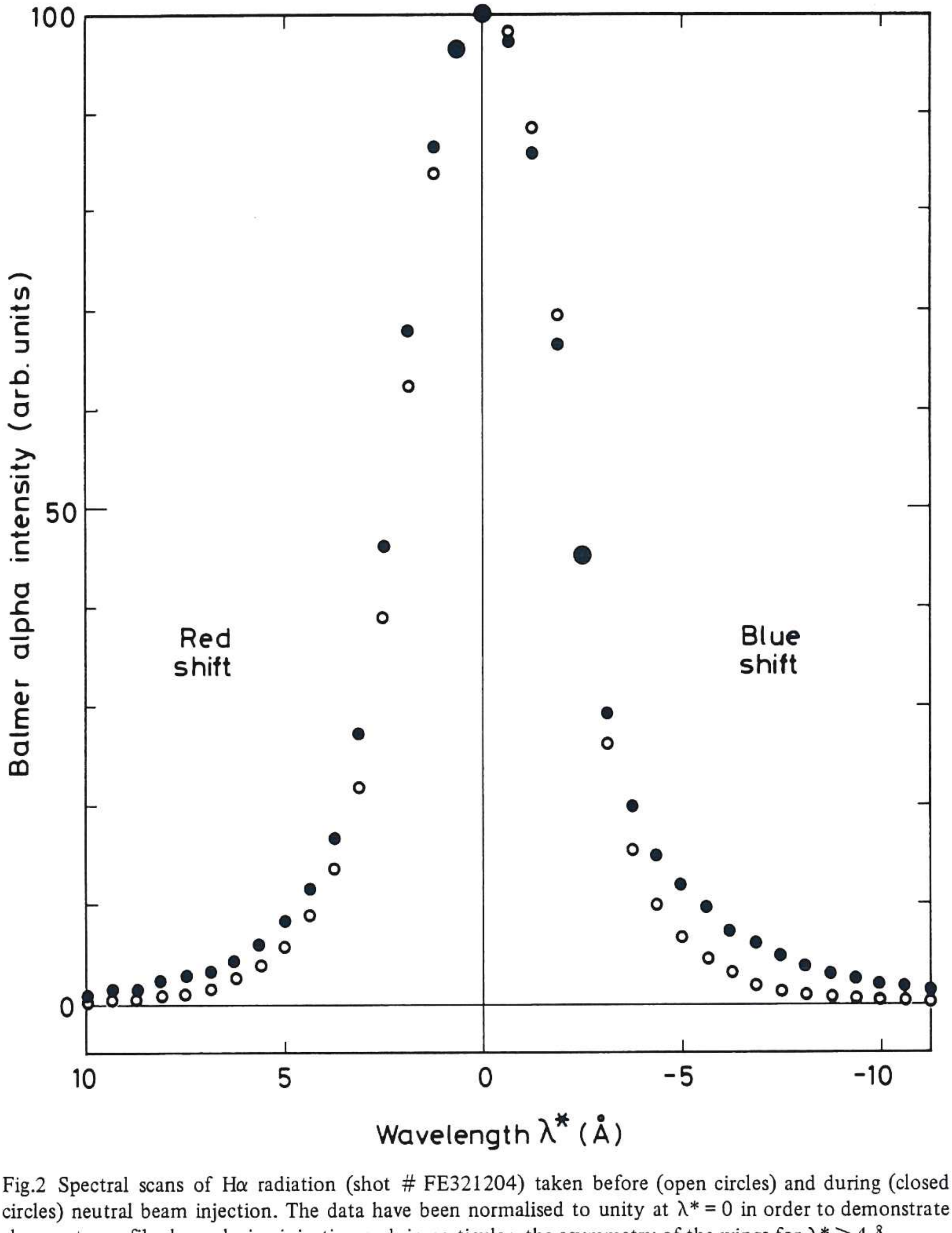

Fig.2 Spectral scans of Hα radiation (shot # FE321204) taken before (open circles) and during (closed circles) neutral beam injection. The data have been normalised to unity at $\lambda^* = 0$ in order to demonstrate changes to profile shape during injection and, in particular, the asymmetry of the wings for $\lambda^* \geqslant 4$ Å.

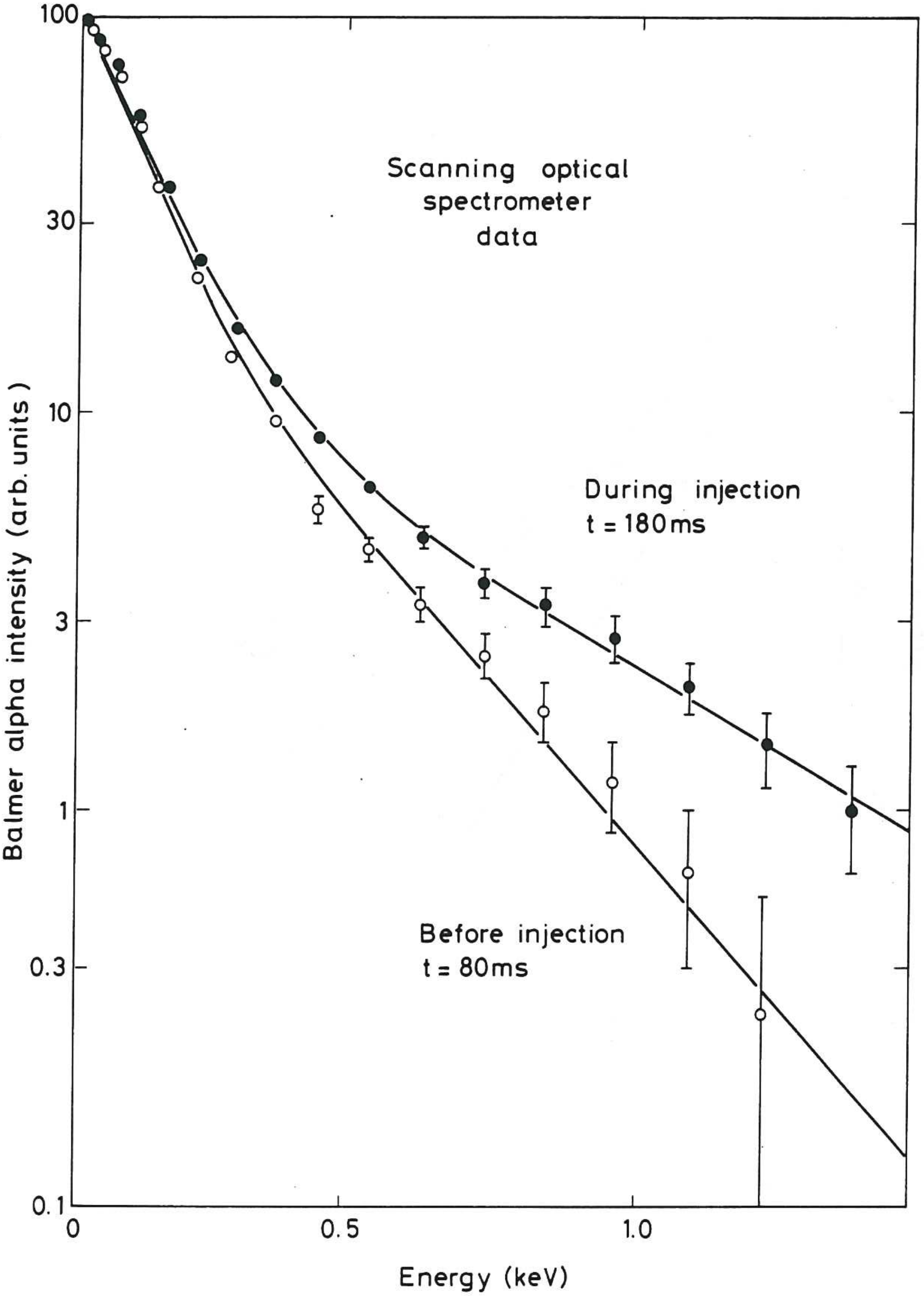

Fig.3 (a) Points: Optical Hα emission data taken before (t = 80 ms) and during (t = 180 ms) beam injection with a time resolution of 10 ms plotted in the log (intensity) versus energy plane (shot # MY321771); solid lines: least-squares fit of bigaussian form. Data have been normalised to same peak height to show changes in the profile; the injection-case points were scaled by 0·51 with respect to the points obtained before injection.

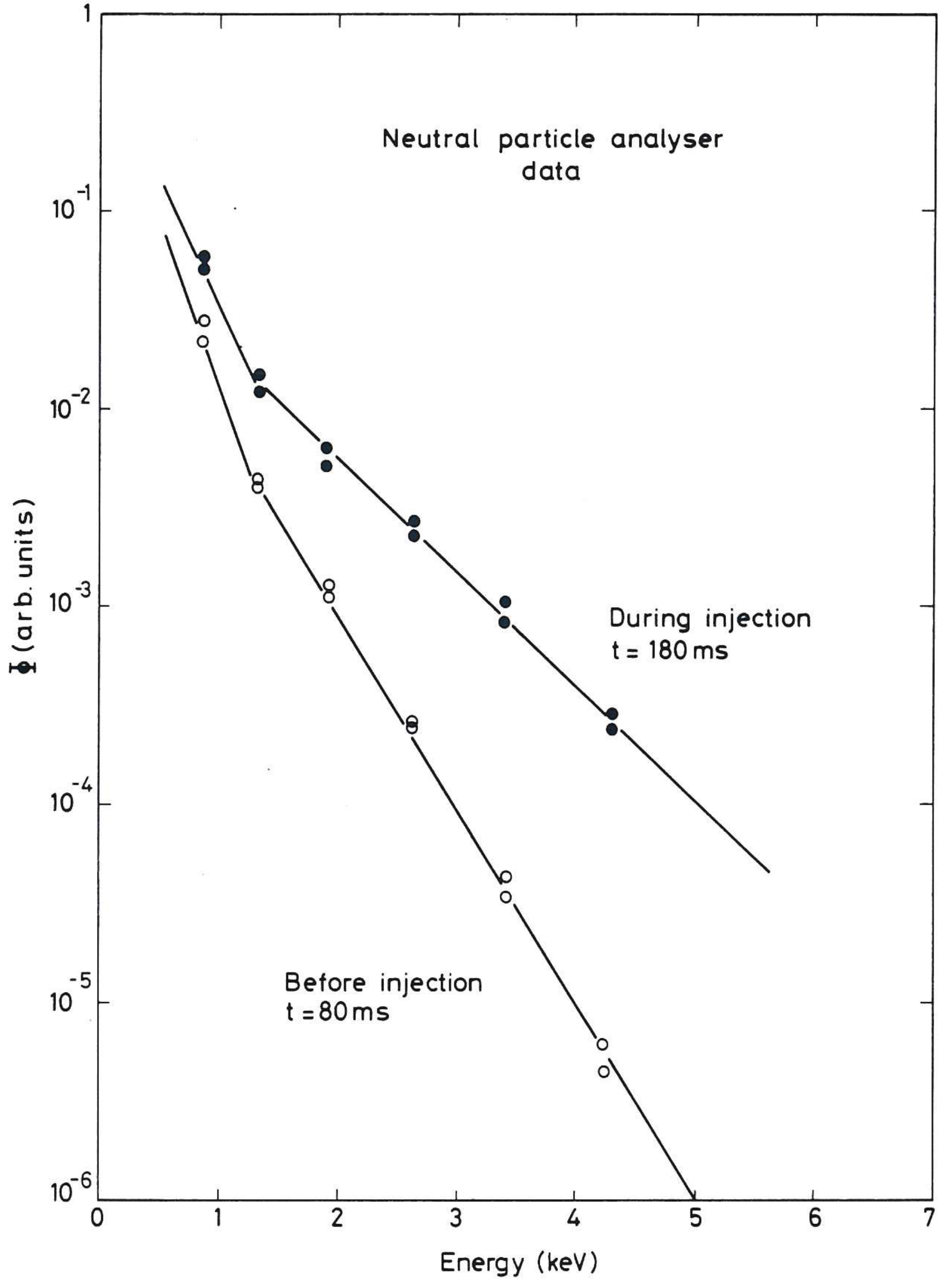

Fig.3 (b) Conventional Neutral Particle Analyser spectrum: semi-logarithmic plot of detector count rate, Φ, against particle energy; data were collected at same times in same discharge as in 3(a) but with a time resolution of 20 ms. Fitted central ion temperatures in the thermal part of energy spectrum (1·3 – 4·3 keV) are (450 ± 50)eV and (763 ± 50)eV for ohmic and neutral injection phases of the discharge.

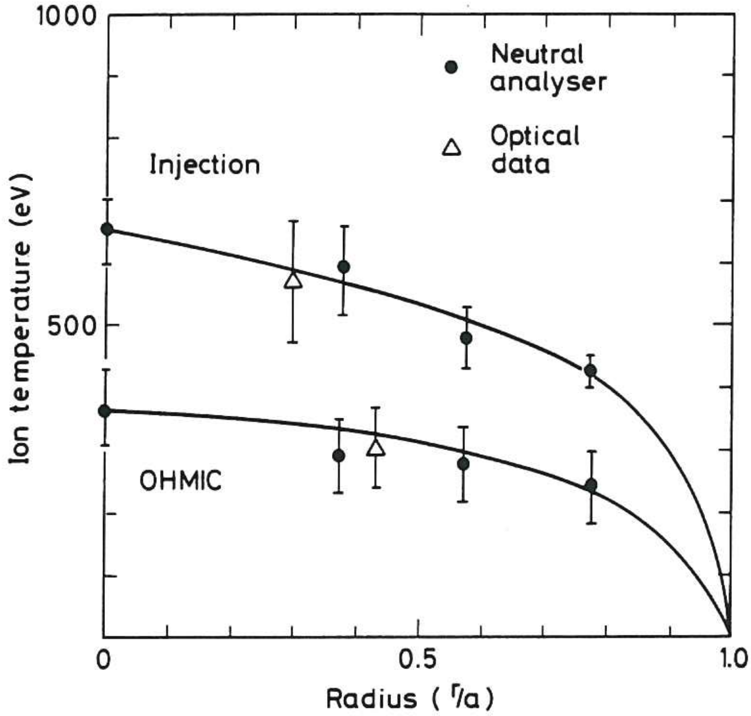

Fig.4 Measured T_i profile data for ohmic and injection discharge phases showing comparison between Neutral Analyser and Optical data.

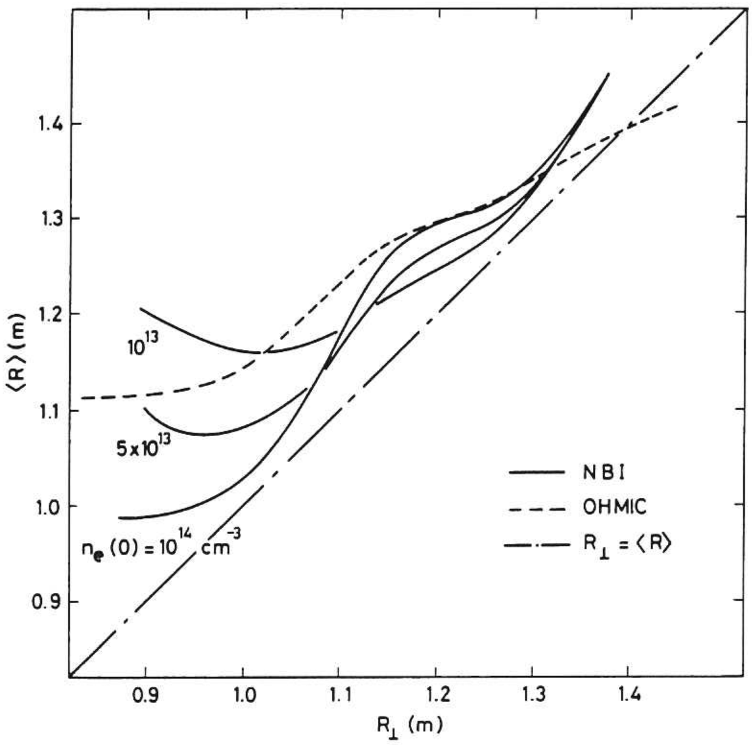

Fig.5 Plot of calculated emissivity-weighted radius, $\langle R \rangle$, for Hα CX radiation and thermal electron excited background Hα radiation as a function of $R_\perp$, the tangent radius of the observational line of sight for the beam-torus geometry relevant to these experiments.