ION TEMPERATURE MEASUREMENT IN JET USING NEUTRON SPECTRA

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1. INTRODUCTION

The use of neutron spectrometry as a tool for the determination of ion temperature of DD plasmas is based on the well known relation /1/

$$\Delta E = 82.5 \sqrt{T_i} \text{ (keV)} \quad (1)$$

relating the width of the 2.45 MeV neutron line FWHM to the ion temperature T_i. This method suggests the use of a high energy resolution spectrometer: in our measurement we have been using a ^3He ionisation chamber, based on the reaction n + ^3He --→ T + p + 764 keV, which was shown to have an energy resolution of FWHM = 42 keV for 2.45 MeV neutrons. Unfortunately, the detector has a high sensitivity to thermal and epithermal neutrons (the ratio between the thermal and 2.45 MeV reaction cross sections being 4×10^3) and this puts severe limitations on the useful count rate of the detector. This problem has been reduced by careful positioning of the detector (Fig.1) in a well shielded (2 metres thick concrete) roof laboratory (20 metres away from the machine midplane). The neutrons coming from a vertical port of the torus reach the detector through a collimator set in the floor of roof laboratory.

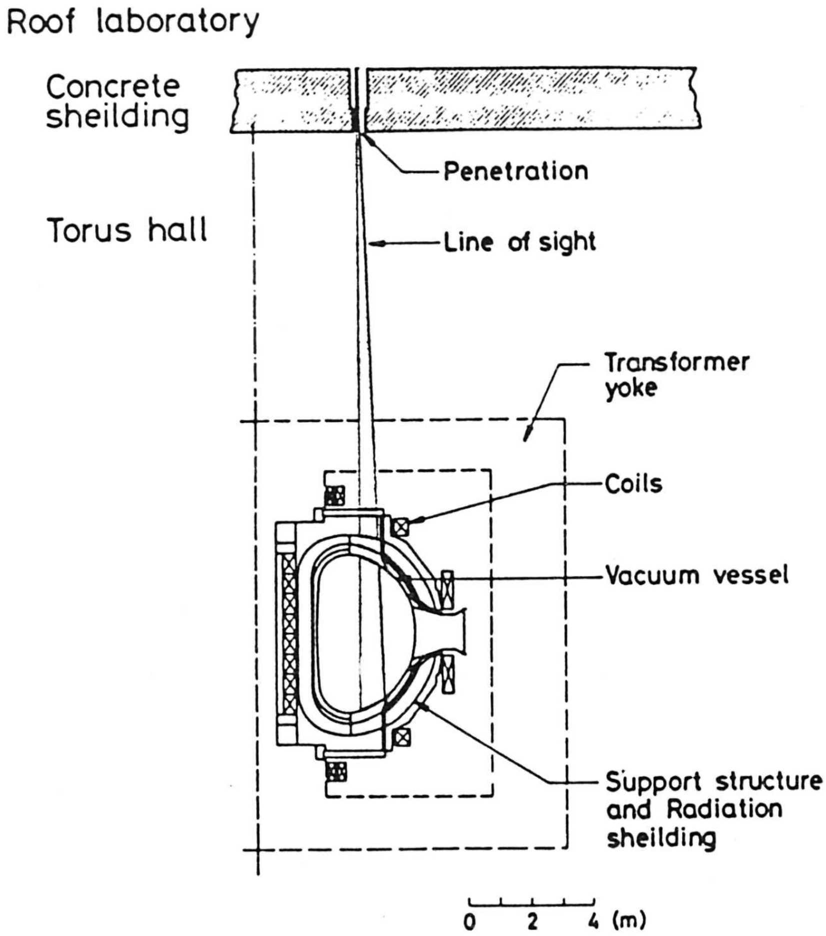

Fig.1 : Schematic layout of the line of sight arrangement.

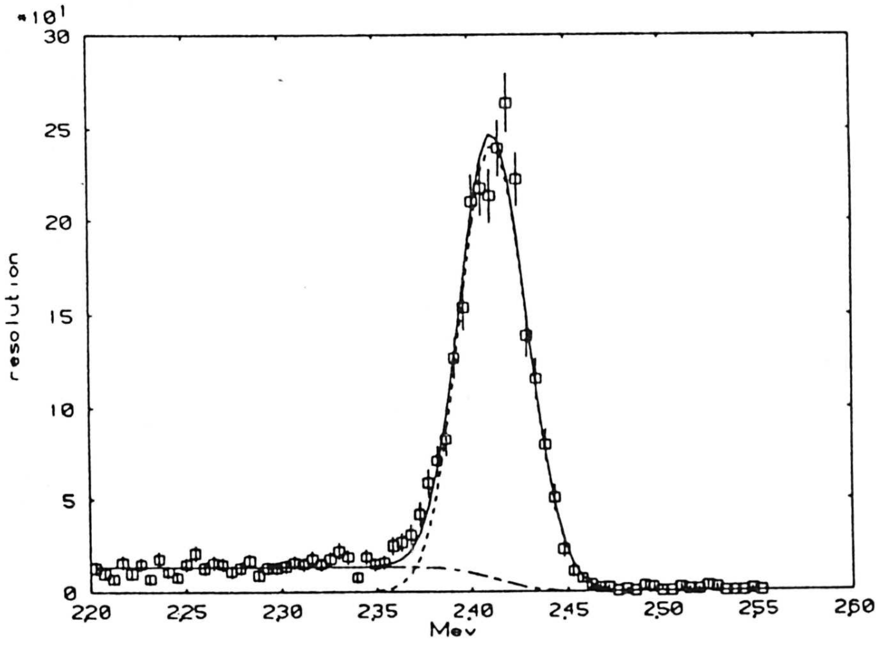

Fig.2: Measured ^{3}He response function: the dashed lines refer to the two terms in eq.(3).

This paper has been organised as follows. First a description of the instrument calibration by means of a monoenergetic neutron source is given. The data analysis procedure is then presented, in which particular emphasis has been put on the reliability limits of the temperature measurement: in particular, it has been found that the number of counts needed to obtain a given percentage error in temperature is 3 times higher compared to that found in previous estimates /2/. Finally, we present results from 4.0 MA, 3.4 T ohmic plasmas: the axial ion temperature on a single discharge basis is given and the resulting uncertainty discussed.

2. CALIBRATION OF THE INSTRUMENT

The ^{3}He gridded ionisation chamber /3/ was calibrated using a Van de Graaff 3 MV accelerator. The reaction used was

$$p + T \rightarrow n + {}^3He + Q \qquad (2)$$

with Q=-764 kev; the detector was normally oriented relative to the incoming neutrons, which were emitted in the forward direction with an energy E_n=(2421+10)KeV. The dispersion in energy is almost entirely due to kinematics, the detector subtending a finite angle with respect to the target. The measurement was performed in an open geometry in order to minimise the presence of back-scattered neutrons. The resulting resolution function is shown in Fig.2, where the continuous line refers to the function

$$R(E) = A_1 \exp\{-(E-A_2)^2/2A_3^2\} + A_4 \{\tfrac{1}{2}[1-\mathrm{erf}(\frac{E-A2}{\sqrt{2}A3})]\} \qquad (3)$$

where the second term takes into account the so-called wall-effect, due to the fact that the tracks of most of the protons produced in the detector are terminated by the walls resulting in a lower amount of ionisation. A simple analysis based on the statistics of ion pair production plus electronics Gaussian noise would yield a FWHM of the Gaussian term of the order of 20 keV: the experimental value ΔE=42 keV at 2.45 Mev and its observed steep increase with energy are then closely related to the increase of particle range with energy. Hence ΔE and the amplitude of the wall-effect part (designated by h hereafter) should be considered related and not independent parameters like in the parametrisation (3). Figures of merit of the response function are:

(a) excellent energy resolution, ΔE=42keV;

(b) existence of a low-energy tail, due to the wall-effect; this tail, though being 5% of the Gaussian peak height, plays an extremely significant role in the final temperature determination.

3. DATA ANALYSIS

Let f(E) be the spectrum of the neutrons incident on the detector: the measured spectrum is then

$$S(E) = \int_{-\infty}^{+\infty} R(E,E')\ f(E')dE' \qquad (4)$$

where R(E,E') is the detector response function. Now, since R was measured only at a few energy points, the following assumption has been made:

$$R(E,E') = R(E-E') \qquad (5)$$

i.e. translational invariance is assumed in the energy range we are interested in: this assumption is not strictly justified, but is an adequate approximation. For Ohmically heated plasmas f(E) can be well represented by a Gaussian described by three parameters, namely: amplitude, variance $\sigma^2(\sim T_i)$ and peak position E_p. It can be shown that σ^2 and E_p are related (see /1/); however, both have been left independent because of the uncertainty in the calibration of the MCA with respect to the peak position (the differential energy calibration being very good though). Optimum values are obtained by best-fitting the folded spectrum S(E) to the experimental data. The usual technique consists of a χ-square minimisation procedure. However, since in our measurement the number of counts per bin falls below 20, χ-square ceases to be a good statistics. Following Cash /4/ we introduce the so-called C-statistics

$$C = 2 \sum_{i=1}^{N} (e_i - n_i \ln n_i) \qquad (6)$$

where e_i=predicted counts and n_i=measured counts. The C-statistics immediately follows from an application of the principle of maximum likelihood to a Poisson distribution. The reliability of the C-statistics(as opposed to the χ-square) was confirmed by means of numerical simulation in which case it proved to be able to give correct estimates in cases with n_i<10 counts per bin.

Let us now turn to the reliability of the determined T_i value and in this context determine how-many counts are needed to obtain T_i with a relative uncertainty $\Delta T_i/T_i$. The analysis based on the use of a purely Gaussian resolution function gives the following answer /2/:

$$\frac{\Delta T_i}{T_i} = \sqrt{\frac{2}{N}} \left\{1 + \frac{R^2}{W^2}\right\} = \sqrt{\frac{2}{N}}\, \alpha \qquad (7)$$

where R=intrinsic detector resolution FWHM, W=input spectrum FWHM: eq.(7) is valid provided $\Delta R/R$ is negligible, which we have verified to be the case. Unfortunately in our case R is not Gaussian, and a further analysis is necessary. This has been achieved using the fitting procedure on synthetic data which were generated folding R with a given input spectrum (obtaining a smooth output spectrum) and superimposing random noise using a simple Monte Carlo technique generating Poisson statistics. A plot of $\Delta T_i/T_i$ against the total number of counts from 2.2 to 2.6 Mev, the energy range used in our fitting code, was produced; assuming (7) to be still valid, results can be rephrased in terms of some R' (or equivalent gaussian FWHM). The following value has been obtained

$$\alpha = 1.81 \pm .01 \qquad (8)$$

to be compared to α=1.08 yielded by a 42 keV-wide pure Gaussian. Furthermore, for fixed N=3500 counts, $\Delta T_i/T_i$ against T_i was computed in the range from 1 to 10keV, the result being that $\Delta T_i/T_i$ stays constant: this means that the value α given by (8) is independent of temperature. The fact that the relative uncertainty in T_i does not improve with increasing T_i is important, though disappointing from an experimental point of view. The increase of the effective resolution with W is due to the fact that more tail events need to be included in the response function at higher values of W, effectively pushing up the second moment of the detector resolution function.

In practice, given $\Delta T_i/T_i = 10\%$, we calculate the number of counts needed in both cases:

N = 220 counts	(pure Gaussian)
N = 660 counts	(true resolution)

Thus, the presence of a low-energy tail h of magnitude only 5% of the Gaussian peak in the resolution function implies that three times the number of counts are needed in order to obtain the same $\Delta T_i/T_i$; considering the count rate limitations of the ^{3}He ion chamber, this puts severe limits on the time resolution attainable with such a device on a Tokamak discharge time-scale.

4. EXPERIMENTAL RESULTS

The analysed data refer to a cluster of six identical ohmically heated discharges. These were chosen for having long flat-top (~5 sec.) and for the plasma being formed under almost the same experimental conditions. Main parameters of the plasma were I=4.0 MA, B=3.4 T, $n_e = 3\times10^{19}m^{-3}$ and neutron yield $Y \simeq 10^{14}$n. We were able to collect some 250 counts per discharge over the whole flat-top, so that we actually measured a time averaged temperature. With such a low number of counts, one expects from the previous numerical analysis $\Delta T_i/T_i$ to be 16%. The results of the measurement are presented in TABLE I: the dispersion in the values of T_i is seen to be due only to the rather poor statistics, and the experimental errors are in excellent agreement with those predicted. Hence, our single-discharge results

TABLE 1: Single discharge line-averaged ion temperatures (kev)

3.01 ± .48
2.90 ± .47
3.08 ± .47
2.08 ± .39
2.69 ± .44
2.36 ± .35

are reliable in a statistical sense: T_i is within $\pm\Delta T_i$ with 68% probability. It is worth noticing that in this measurement systematic errors do not play any significant role so that the total uncertainty is seen to be almost entirely statistical in nature. A more precise result is obtained summing up the six spectra together, thereby obtaining a 1300 counts statistics: the result is (see Fig.3)

$$T_i = (2.73 \pm .18)\text{keV} \tag{9}$$

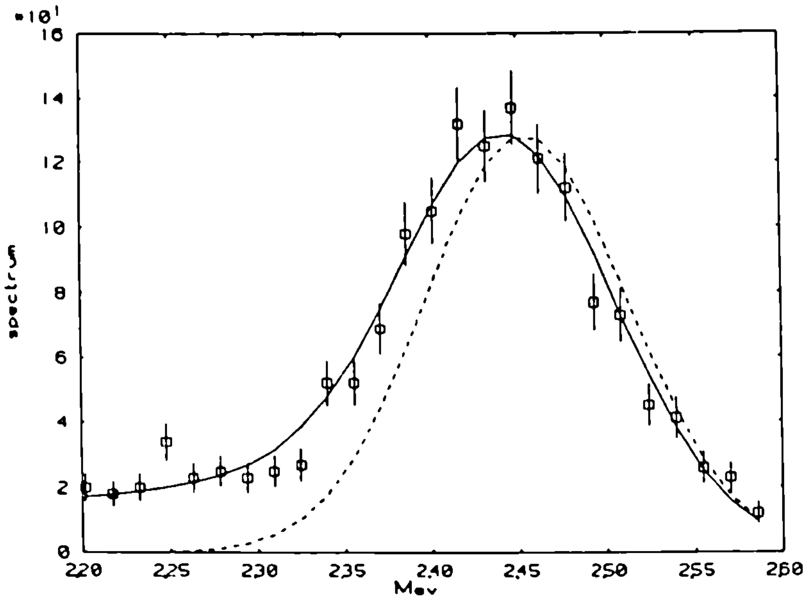

Fig.3: Neutron spectrum summed over six discharges: the continuous line is the best-fitted curve and the dashed line is the corresponding input Gaussian spectrum.

The excellent quality of the fit indicates that the assumption of Maxwellian ion velocity distribution is justified.

Finally, a correction factor is needed in order to obtain the axial ion temperature from our line-averaged reading; numerical studies (with flat ion density and peaked ion temperature profiles) show that the correction factor is

$$\beta = 1.08 \pm .01 \tag{10}$$

5. CONCLUSIONS

Reliable ion temperature measurements have been obtained on a single-discharge basis; the present level of uncertainty (16%) is well within the limits of other ion temperature diagnostics. The overall uncertainty in the measurement is dominated by the statistical uncertainty; systematic corrections are apparently small.

6. REFERENCES

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