JOINT EUROPEAN TORUS

JET–P(92)11

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Preprint of Paper to be submitted for publication in
Plasma Physics and Controlled Fusion

JET EXPERIMENTS WITH 120 keV ^{3}He and ^{4}He NEUTRAL BEAM INJECTION AND NEUTRON DIAGNOSTIC APPLICATIONS*

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ABSTRACT

Preliminary experiments were carried out in the Joint European Torus (JET) using 120 keV helium (He) neutral beam injection (NBI). Injected power levels up to 5 MW with ^{3}He and 7 MW with ^{4}He, lasting up to 3 s were reached. The 3 s helium NBI produced efficient ion heating and similar global and local energy confinements to those obtained with deuterium (D) NBI, in both limiter and X-point plasma geometries, in L-mode and H-mode plasma regimes. The elimination of beam-plasma and beam-beam fusion reactions by replacing D NBI with He NBI extended the range for measuring ion temperatures with the JET neutron profile monitor and neutron spectrometers.

*This paper is an expanded version of material originally presented by F B Marcus et al, and by M J Loughlin et al, at the 18th EPS Plasma Physics Division Conference, Berlin. Germany, June 1991.

1. INTRODUCTION

Neutral beam injection of helium, as proposed by THOMPSON (1975) and by MARCUS et al (1990), is of interest for a variety of reasons. In particular, it should be possible to enhance the ion heating efficiency, while limiting the neutron emission and, consequently, the induced radioactivity of the machine. Compared to hydrogen or deuterium beams at the same energy, He beams should preferentially heat the plasma ions, since the critical energy is proportional to the beam ion mass. At this energy, the beam heating powers delivered to ions and electrons are equal.

Unlike deuterium beams, the helium beams do not produce beam-beam or beam-plasma D-D fusion reactions. The only neutron production is due to thermal plasma fusion reactions, as would occur in an α-particle heated reactor. Thus, the employment of monoenergetic He NBI for heating deuterium plasmas facilitates the study of plasma ion temperatures with neutron diagnostics. Since neutrons associated with beam-plasma reactions are eliminated, the axial ion temperature of the thermal plasma can be measured more easily with a neutron energy spectrometer.

The ^{3}He and ^{4}He beams are also suitable for charge exchange recombination spectroscopy (CXRS) measurements as discussed by VON HELLERMANN et al (1991). ^{3}He beams are calculated (see below) to penetrate a given plasma density better than D beams, and also offer the possibility of diagnostic measurements based on the gamma ray branch of D-^{3}He fusion reactions as used by SADLER et al (1991).

Preliminary NBI heating experiments have been carried out in JET. Argon frost pumping of He was used on the cryopanels in the neutral beam injector boxes. These are the first NBI experiments in which ^{3}He was used for heating a tokamak. Up to 5 MW of ^{3}He at 120 keV has been injected into JET. A record power of 7 MW of ^{4}He, also at 120 keV, has been injected for 3 s.

In what follows, we compare plasmas with He neutral beam injection (He NBI) to similar plasmas employing deuterium neutral beam injection (D NBI), and discuss ion temperature measurements. Further experimental observations have been reported elsewhere: on diagnostic comparisons of ion temperatures by LOUGHLIN et al (1991); on particle transport studies by JONES et al (1991) and by VON HELLERMANN et al (1991); on ICRF heating with NBI by SADLER et al (1991); and on edge diagnostics for He by CONROY et al (1991).

2. ION HEATING, GLOBAL POWER BALANCE AND LOCAL TRANSPORT

To investigate the relative heating efficiency of He and D NBI, in Fig. 1 we compare two consecutive discharges which were programmed to be similar except for the NBI heating species. The parameters of both discharges were 3.6 MA, 2.5 T, double-null D-shape with 2.7 MW of 80 keV D NBI for 3.5 s. JET has two beam boxes with 8 positive ion neutral injectors (PINI) in each. In the experiments reported here, one box operated with D at 80 keV, the other with He at 120 keV. Discharge #22975 had an additional 3.7-5.1 MW of 120 keV ^{4}He injected from 13.0 s to 13.5 s, and discharge #22976 had an additional 4.3 MW of 80 keV D during the same time interval. The average heating powers during the 0.5 s interval were the same. The plasma stored energies from diamagnetic loop measurements, central ion temperatures from CXRS using beryllium impurity ions, and NBI heating powers for both discharges are compared in Fig. 1. Discharge #22975 entered the H-mode regime at 13.14 s and discharge #22976 at 13.25 s. In both discharges, the H-mode transition occurred at the same time as a sawtooth crash. Discharge #22975 had a further sawtooth crash during the NBI heating, causing a drop in ion temperature. The incremental confinement time of the plasma was 0.6 s for the ^{4}He injection and 0.5 s for the D injection case. The ion temperature was higher in the ^{4}He injection discharge, which could be the result of the higher critical energy of ^{4}He ions. However, since the sawteeth and H-mode transition times are different in the two discharges, the conclusion that ion heating is more efficient with ^{4}He NBI must be regarded as preliminary.

The combination of ^{3}He NBI and D NBI was able to produce a hot-ion H-mode regime in double-null divertor plasmas, as in the discharge #23275. When 4.7 MW of 120 keV ^{3}He NBI and 10.5 MW of 80 keV D NBI were used simultaneously to heat a low density deuterium plasma, a hot-ion H-mode was produced with an axial ion temperature of 25 keV (Fig. 2). The H-mode regime was entered 0.6 s after the start of NBI heating. At somewhat higher plasma densities, for example in discharge #23272 (not shown), the stored energy and the energy confinement time, measured with the diamagnetic loop, were respectively 8 MJ and 1 s. These results are comparable to those obtained by NBI with pure D, as reported by TANGA et al (1990).

Helium injection should result in beam deposition profiles giving efficient central plasma heating at high density, due to the monoenergetic nature of the beams. Neutralized deuterium beams have 1/2 and 1/3 energy components, with power fractions depending on the extraction voltage; these lower energy components have poorer penetration than the full energy component. Fig. 3 shows calculations from the code NFREYA, developed by FOWLER et al (1979), of the NBI power deposition per PINI versus the plasma major radius, in a plasma with a flat density profile for the maximum allowed energy for each beam species. This maximum energy depends on power supply connections, type of injector, and bending magnet constraints. The total injected power per PINI is different for each beam species and energy. Experiments with 155-160 keV ^{3}He beams are planned in JET.

A problem associated with He injection is that He neutrals with electrons in a metastable state are formed during beam neutralization. These metastables ionize at the plasma edge and could cause localized limiter or dump plate heating, leading to impurity generation and enhanced plasma radiation. The most recent calculations by HOEKSTRA, DE HEER, MORGENSTERN et al (1991) indicate that about one tenth of the beam particles are in a metastable state. In Fig. 4, the ^{3}He NBI power and the total radiated power from the plasma are plotted for the 5 MA discharge #23252, with its edge defined by the belt limiter. The global D-D fusion neutron rate of the target plasma is also shown, and will be discussed in the next section. A ^{3}He beam with an injected power of 4-5 MW lasting for 3 s did not produce a significant increase in the plasma radiated power, relative to the level due to ohmic heating, indicating that the fraction of the beam in the metastable state was small.

Localized limiter heating from direct impact of metastables ionized in the edge was below the detection level of a CCD camera viewing the appropriate limiter impact zone. This indicated that less than 10 % of the injected helium beam atoms were in the metastable state. However, surface probe measurements by CONROY et al (1991) showed that some metastables were ionized at the plasma boundary. The global energy confinement time of 0.53 s in discharge #23252 was similar to that found for deuterium neutral beam injection in 5 MA belt limiter defined plasmas, as discussed by LOMAS et al (1990), which indicated that no major degradation of plasma parameters was caused by metastables.

A time-slice analysis of sawtooth-averaged local transport was carried out for discharge #23252, using the methods discussed in HAMNEN et al (1990). An effective thermal conductivity, χ_{eff}, of between 0.5 and 1.0 m^2/s in the region $0.3 < r/a < 0.8$ was obtained. This range for χ_{eff} values is similar to that of comparable discharges with deuterium neutral beam injection, for example discharges #8848 and #8865 (not shown). Detailed particle transport studies are not presented here: they have been separately reported by JONES et al (1991), and by VON HELLERMANN et al (1991).

3. NEUTRON DIAGNOSTICS WITH He NBI HEATING

He NBI does not produce the beam-beam and beam-plasma fusion reactions that occur with deuterium beams, so that the total neutron production is reduced without detriment to efficient plasma heating. As shown in Fig. 4, the neutron emission during 5 MW of ^{3}He NBI was much larger than during ohmic heating alone, and was comparable to the emission from 1.3 MW of D NBI at 80 keV. The increase in the global neutron emission rate during He NBI was entirely due to an increased fusion rate of thermal deuterium ions.

The elimination of beam-produced D-D reactions allows an improved measurement of the ion temperature with neutron spectrometers, since the broadening of the neutron spectrum is entirely due to the thermal ion motion. The time-of-flight neutron spectrometer measurement of the axial ion temperature was 2.9 ± 0.8 keV in discharge #23252. The axial ion temperature at the end of the ^{3}He NBI was 3.0 ± 0.2 keV from CXRS. The latter measurement was made possible by adding a low-power deuterium beam observable by the CXRS viewing optics. The electron temperature was sawtoothing between 2.8 and 3.2 keV, a relatively small amplitude. Sawteeth were also observed on other diagnostics. The electron and ion temperatures are expected to be nearly equal, given the relatively high plasma density and low temperature of this discharge. Thus, the various temperature measurements are in good agreement.

The ion temperature can also be deduced from the neutron emissivity, which was measured by the JET Neutron Profile Monitor as described by ADAMS et al (1989). The profile monitor consists of two heavy concrete, fan-shaped, multi-collimator cameras. One has 10 horizontal channels and the other has nine vertical channels (eight are used here). Each channel has a NE-213 scintillator coupled to a photomultiplier, and a pulse shape discrimination unit set to distinguish the neutrons from the gamma rays. The raw data are corrected for neutron back-scatter and attenuation from material in the sight line, small angle scattering in the collimator, detector live-time, efficiency and viewing solid-angle.

The neutron profile monitor data of discharge #23252 were integrated over 8 to 11 s to obtain good statistics, and the 2-D emissivity profile was then derived by tomographic analysis, as discussed by MARCUS et al (1991), and is shown in Fig. 5. The axial neutron emissivity was 1×10^{13} n / m^3s. The local neutron emissivity depended only on the ion temperature and the deuterium ion density. The average ionic charge of the plasma Z_{eff} was measured to be 1.5 ± 0.1 from both CXRS and visible bremsstrahlung and the measured time-averaged axial electron density was 6×10^{19} m^{-3}. The CXRS measurements indicated that the axial ratio of deuterons to electrons was 0.8 to 0.95. The lower value was consistent with the amount of He injected during the 3 s period, which could have provided 20 % of the electrons when volume averaged. The calculated axial deuteron density was therefore 4.8×10^{19} m^{-3}, and the 3 s averaged axial ion temperature based on axial neutron emissivity was 2.6 keV, within the error bars of the other measurements (CXRS and neutron energy spectrometry). At an ion temperature of T_i = 2.6 keV, the neutron emissivity varies as $n_D^2 T_i^4$, so errors as large as 20 % in axial neutron emissivity and 10 % in deuteron density lead to less than 10 % errors in the inferred axial ion temperature.

Since the neutron emissivity profile was averaged over many sawteeth, the deduced ion temperature was affected by ion redistribution from sawtooth crashes. Both the neutron line-of-sight integrals and the resulting emissivity were peaked on-axis, although there was some off-axis structure due to the effects of sawtooth crashes. The full-width half-maximum of the emissivity profile was 0.7 m, compared to the wider profile with 1.1 m from tomography for the sawtoothing ohmic discharge #15119 (also a 5 MA discharge) analyzed by ESPOSITO et al (1991). Both discharges had a similar sawtooth repetition period of about 0.1 s. The narrower width of discharge #23252 indicates that the effect of sawteeth was not very large in this discharge and that their effect on the temperature and neutron emissivity was not significant.

4. NEUTRON SPECTRA WITH MIXED He AND D NBI HEATING

The neutron energy spectra recorded by the JET time-of-flight and ^{3}He ionization chamber neutron spectrometers are generally due to separate contributions from thermal, beam-beam and beam-plasma fusion reactions when beam heating with deuterium beams is employed. The normalized spectra for the separate contributions have been calculated by VAN BELLE and SADLER (1986). Depending on the precise conditions, analysis of the measured spectra can yield the ion temperature or the deuterium concentration, as shown by JARVIS et al (1990). LOUGHLIN et al (1989) demonstrated the self-consistency of the technique when they showed that the results are independent of the line-of-sight selected.

The procedure is as follows: With the ratio of the areas of the thermal and beam-plasma contributions to the spectrum and the width of the thermonuclear peak as adjustable parameters, the contributions are summed and convoluted with the detector response function, and a best-fit to the measured spectrum is sought. The beam-beam contribution is usually known to be small enough to be neglected. Examples of the shapes of the different types of spectra are shown in Fig. 1 of LOUGHLIN et al (1989). The width of the thermonuclear peak determines the ion temperature.

At ion temperatures below 15 keV, the shape of the neutron energy spectrum from the fusion of thermal ions is distinguishable from the beam-plasma spectrum. When He and D NBI are used simultaneously instead of NBI by deuterium only, the measurement of the ion temperature from the neutron spectrum is more accurate when the relative thermonuclear fraction is enhanced. Ion temperatures were obtained for discharges in which the thermonuclear yield represented more than 50 % of the total neutron yield. Measurements using this technique are compared in Fig. 6 to those from charge exchange spectroscopy and show good agreement.

5. CONCLUSIONS

In preliminary experiments, He NBI has produced both H-modes and also, if combined with D NBI, hot-ion H-modes. The global neutron emissivity is decreased, relative to discharges heated with NBI by deuterium, because of the reduction of D-D beam-plasma and beam-beam fusion, and dilution with the injected He. The global and local energy confinements were similar within error bars to those obtained with D NBI. The central ion temperature was higher with He NBI than for equal power D NBI in two discharges that were programmed to be identical except for the heating species. Good agreement was found between neutron and other diagnostic measurements of ion temperatures.

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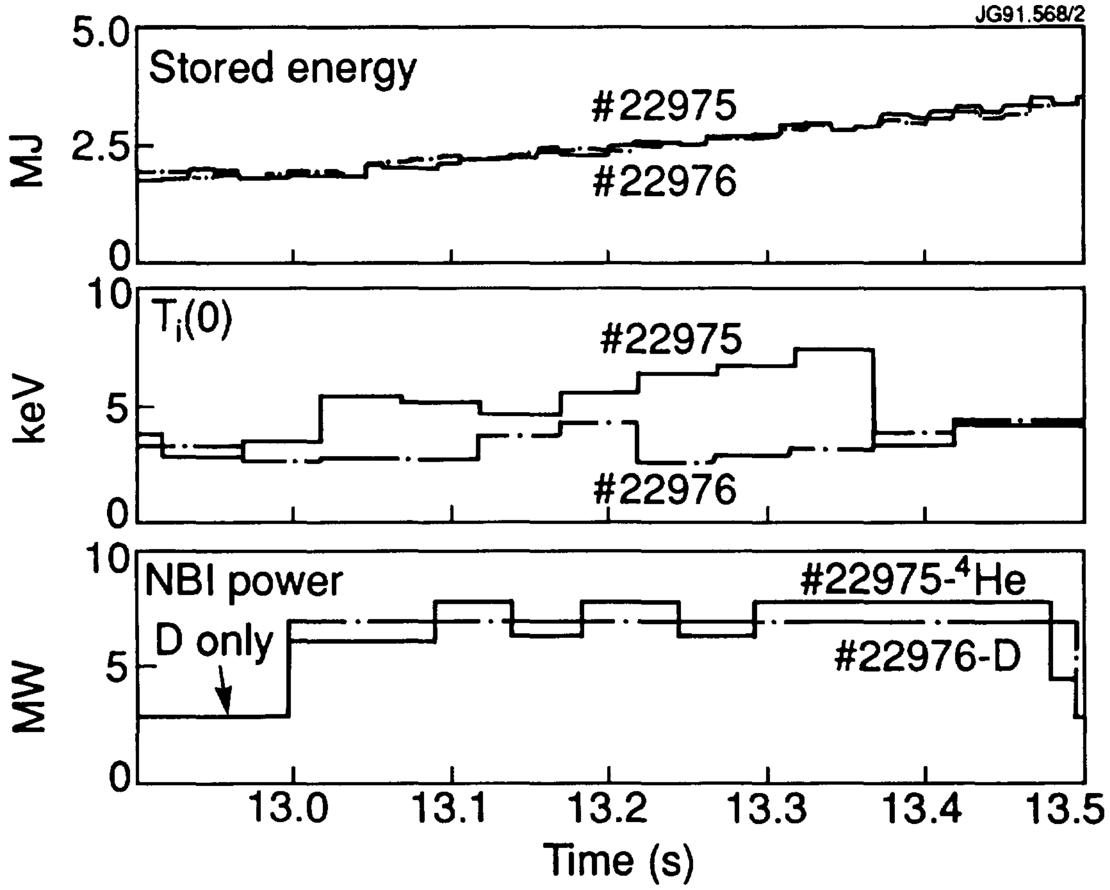

Fig. 1. Stored plasma energies, central ion temperatures, and NBI heating waveforms for discharges #22975 (with He NBI added to a constant 2.7 MW of D NBI) and #22976 (with D NBI only) with equal total NBI powers.

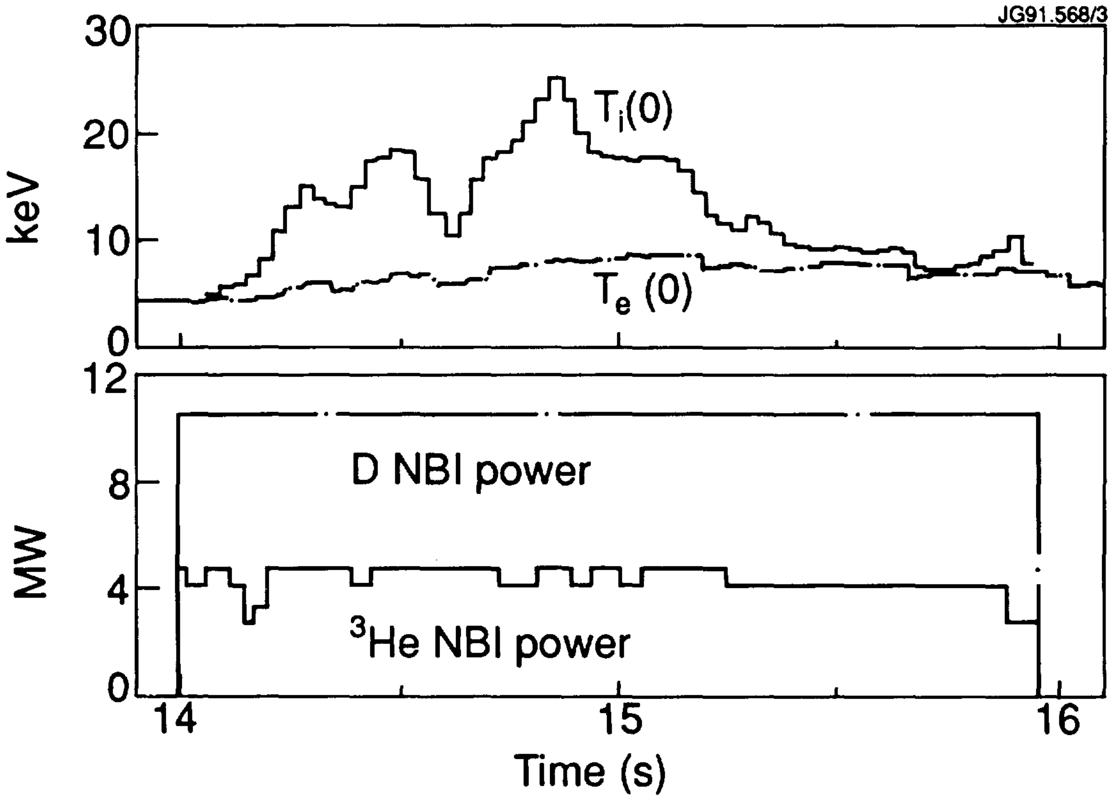

Fig. 2. Ion and electron temperatures and NBI heating waveforms for discharge #23275.

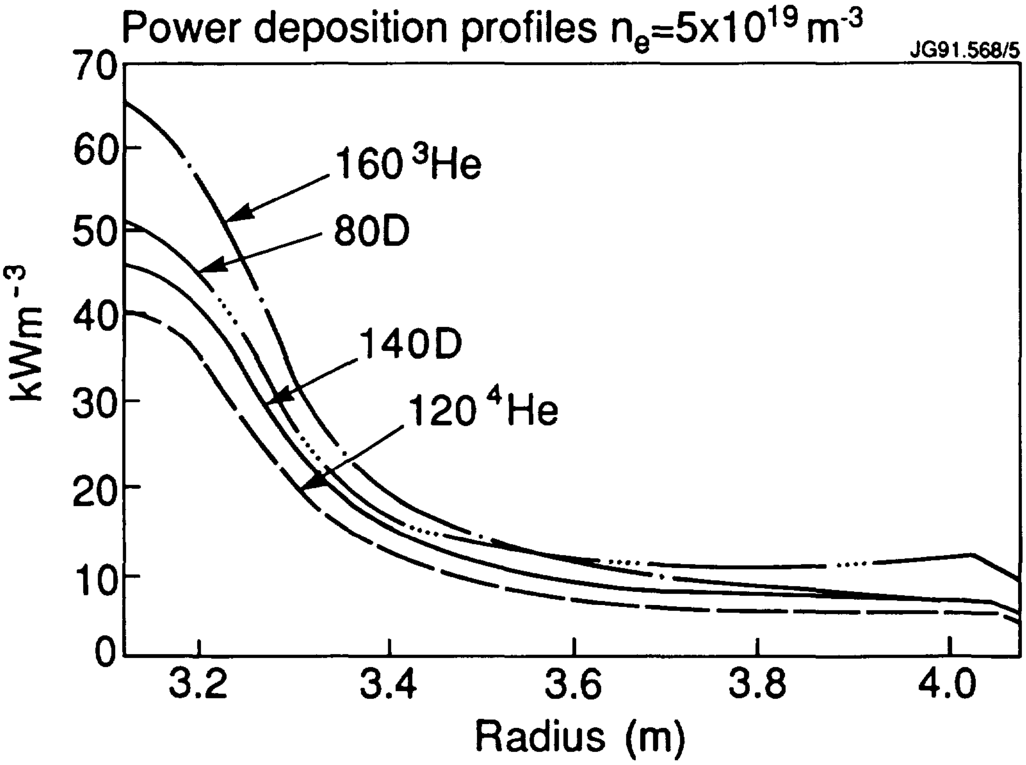

Fig. 3. Calculated NBI power deposition versus plasma major radius for 1 PINI into a D plasma assuming $Z_{eff}=1$, $T_e(0)=8$ keV, flat electron density, $N_e(0)=5x10^{19}m^{-3}$ for different NBI options.

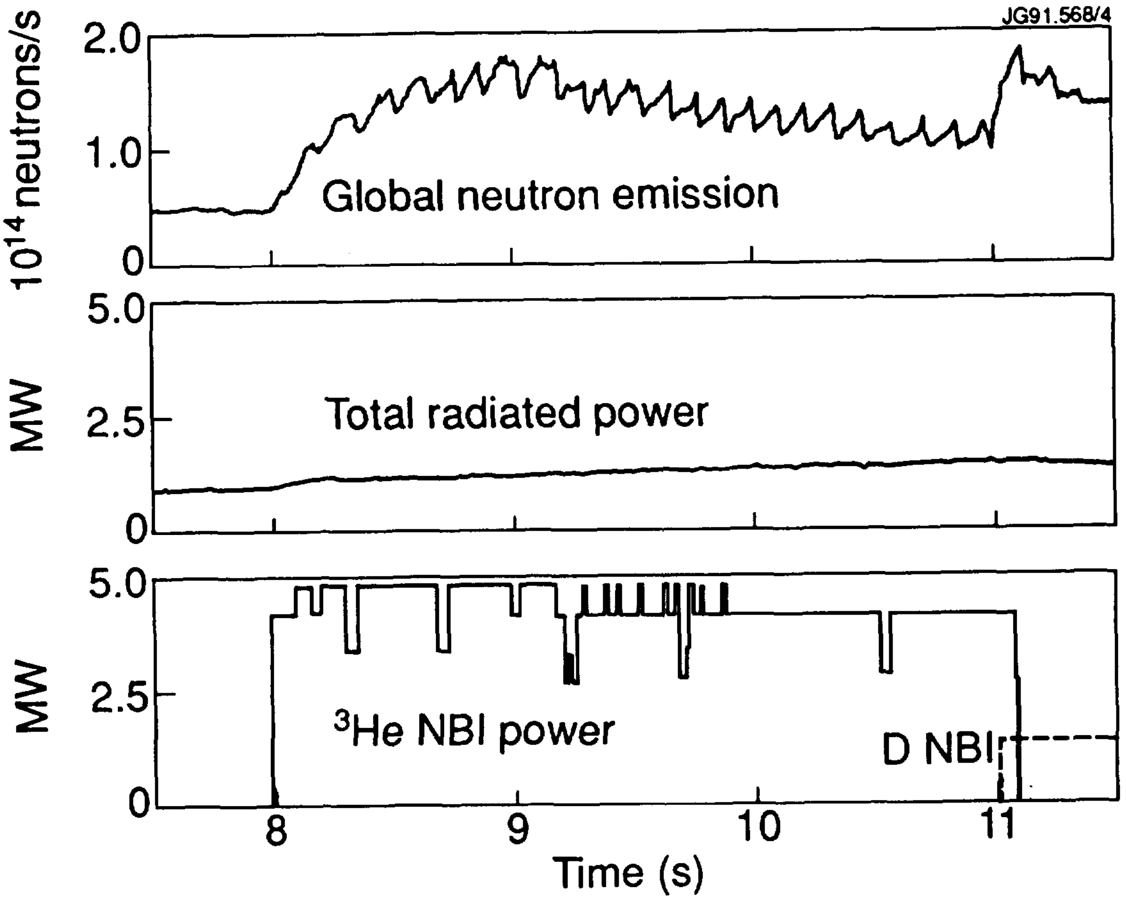

Fig. 4. Global neutron emission, radiated power, and D and He NBI waveforms for discharge #23252.

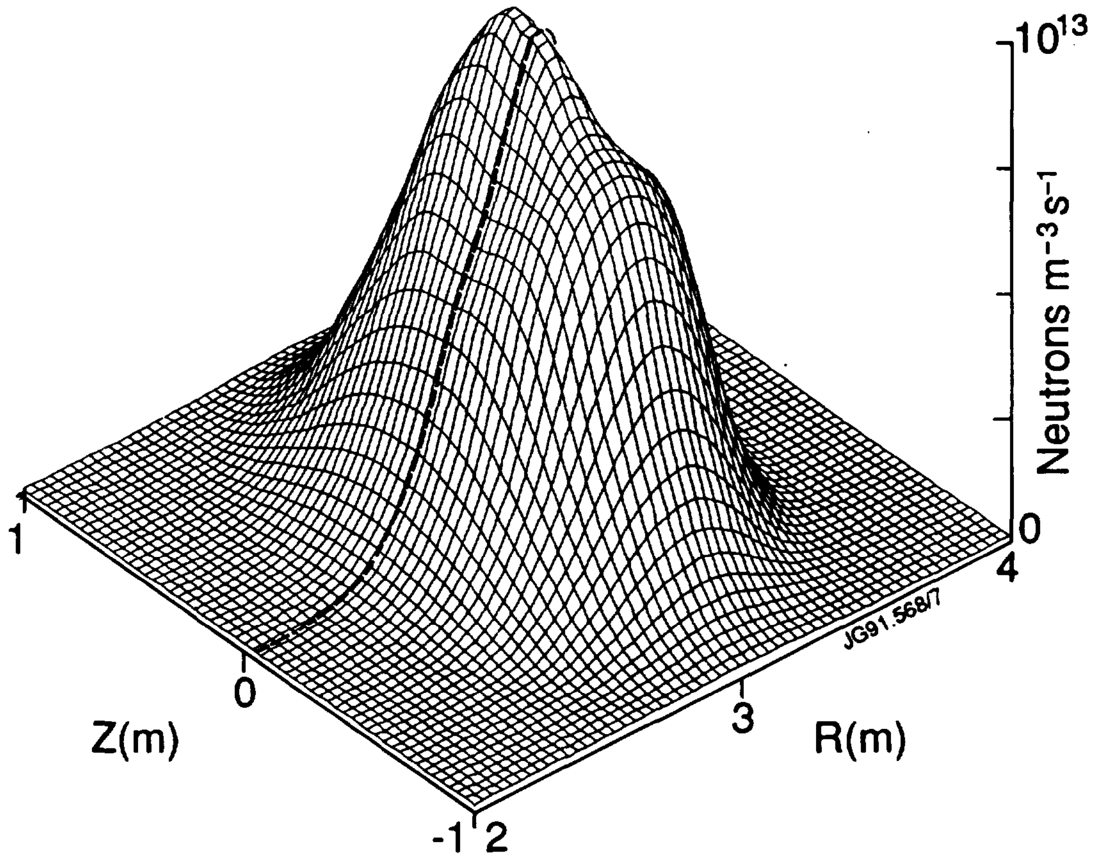

Fig. 5. 2-D neutron emissivity profile derived from tomographic analysis for discharge #23252, averaged from 8 s to 11 s.

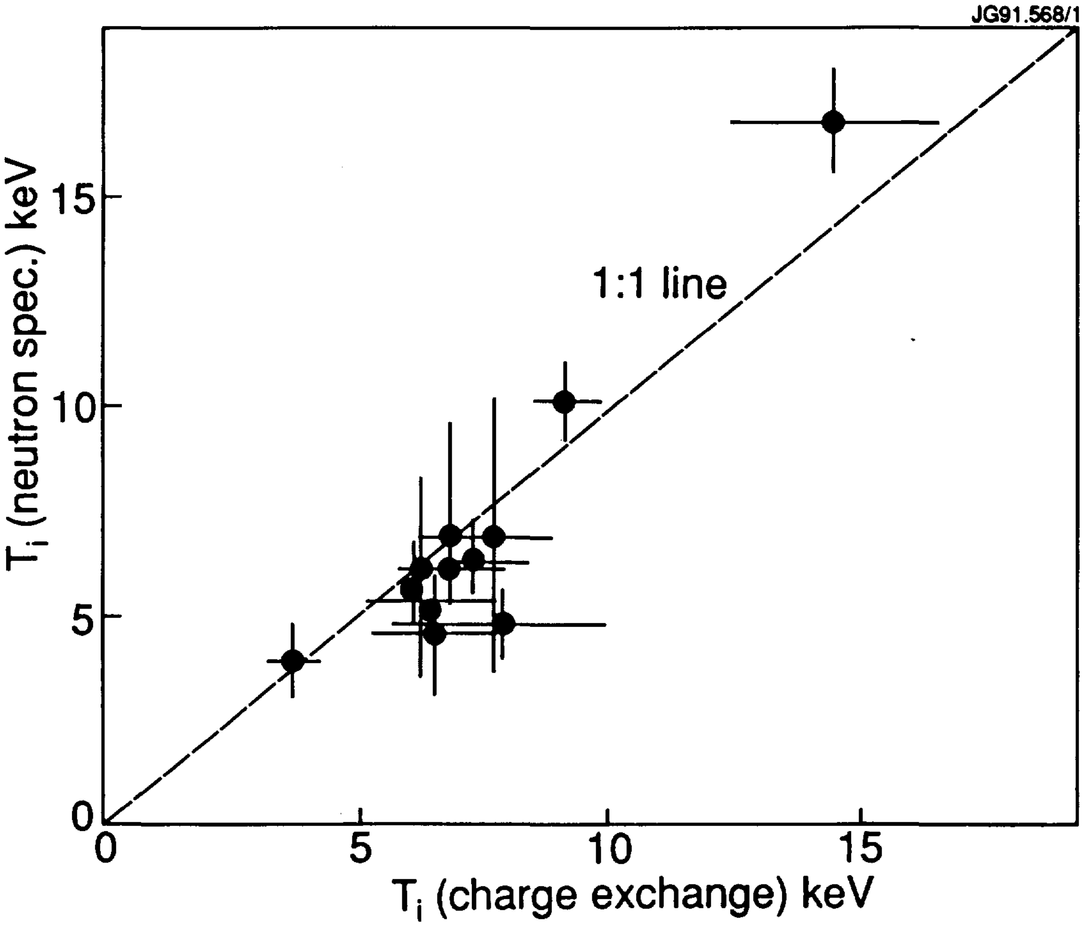

Fig. 6. Comparison of ion temperature measurements from neutron spectrometry and charge exchange spectroscopy.

ANNEX

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