EFDA–JET–CP(09)06/38

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** See annex of F. Romanelli et al, "Overview of JET Results",*
(Proc. 22 nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

Preprint of Paper to be submitted for publication in Proceedings of the
36th EPS Conference on Plasma Physics, Sofia, Bulgaria.
(29th June 2009 - 3rd July 2009)

1. INTRODUCTION

Ion Cyclotron Radio Frequency (ICRF) heating is one of the main techniques proposed for auxiliary plasma heating at ITER [1]. ICRF heating can produce fast ion populations with energies reaching up to several MeV. In this paper, we study fast deuterons accelerated by 3^{rd} harmonic ICRF at JET. We present theoretical predictions of the fast deuterium distribution function (f_d) and benchmark these with measurements using neutron emission spectroscopy.

2. 3RD HARMONIC ICRF

Fast ion populations from RF heating at a harmonic of the cyclotron frequency can be of very non-Maxwellian shape [2]. This is a result of the properties of the RF diffusion coefficient, D_{RF}, (i.e., the strength of the heating), which is given by:

$$D_{RF} \propto \left| E^{+} J_{n-1}\left(\frac{\rho_L}{k_\perp}\right) + E^{-} J_{n+1}\left(\frac{\rho_L}{k_\perp}\right) \right|, \tag{1}$$

where E^{+} and E^{-} are the strengths of the co- and counter-rotating electric fields, respectively; J_m is the m^{th} Bessel function; n is the harmonic number; ρ_L is the Larmor radius of the resonating ion and $k_\perp$ is the perpendicular wave number. Since the 0^{th} Bessel function is the only that is finite for a zero argument, fundamental ICRF heating ($n = 1$) is the only scheme that works for cold resonating ions as $\rho_L \propto v_\perp$. For harmonic ICRF, the strength of the heating increases with the energy of the resonating ions. For this reason, a seed of fast ions from 3MW Neutral Beam Injection (NBI) heating is used in the experiment studied here to improve the efficiency of 3rd harmonic ICRF.

At a specific energy, here denoted E^*, ρ_L becomes comparable to the wavelength and the resonating ions start to gyrate out of phase with the wave. E^* depends on the ratio $\rho_L/k_\perp$ and scales as B_T^2/n_e. A typical D_{RF} is shown in Fig.1(a), where E^* is indicated with a vertical dashed line. Examples of simulated distribution functions at different power levels are shown in Fig.1(b). Of special interest are two qualitative features of f_d. First, since the efficiency of 3^{rd} harmonic RF increases rapidly with energy, it preferentially heats a small population of particles to high energies. This results in f_d being almost flat for ions between 0.5-1.5MeV. Second, at E^*, D_{RF} goes to zero and no ions are expected to be accelerated further, regardless of the power of the RF heating. Therefore, a cut off in f_d is expected closely below E^*.

3. EXPERIMENTAL

Two sessions, with 18 successful discharges, using 3rd harmonic ICRF heating where run at JET during 2008. In this paper, Pulse No: 74937 is studied. The plasma was in L-mode with a central electron density, *n*e, varying from 2"≈1019 to 4"≈1019 m-3. The magnetic field, BT, was 2.2 T and the plasma current, IP, was 2.0 MA. The heating started at $t = 11$ s with 3MW of NBI; at $t = 12$ s, an additional 3MW of ICRF at 52MHz was applied, giving an on-axis 3^{rd} harmonic resonance at a major radius of 3.0m. The neutron energy spectra where measured with the time-of-flight spectrometer TOFOR [3], which is positioned in the roof laboratory at JET and views the plasma core vertically from above. The response function of TOFOR is calculated in detail with Monte

Carlo simulations and is used to in the analysis of TOFOR data; to first order, neutrons with E_n = 2.5MeV result in a flight time of 65ns and 14MeV result in 27ns

The fast deuterium distribution function can be derived from neutron emission spectra of the DD reaction by analyzing the kinematical energy shift of the product neutron. For reactants at thermal energies, the emission is well approximated by a Gaussian centered at E_n = 2.5MeV. Reactants at higher energies result in broad spectra with a width that is related to the reactant energies. In Fig.2, simulated spectra from monoenergetic deuterons reacting with thermal bulk plasma are shown, here called $\delta-$spectra. In the simulation shown, E_d was 0.5, 1.5 and 3.0MeV. This results in neutron energies reaching up to 3.5, 4.8 and 6.2MeV respectively. A neutron spectrum from an arbitrary f_d can be obtained by superimposing several $\delta-$spectra with their individual weights proportional to the level of f_d at the corresponding energy. Equivalently, folding the sum spectrum with the TOFOR response function and fittingto the data, with the weights as free parameters, f_d can be derived from the t_{TOF} spectrum. 15 $\delta-$spectra, with E_d from 150keV to 3.0MeV, where used in the analysis presented here. A pitch angle of 90±10^o was assumed when calculating the $\delta-$spectra since ICRF heating accelerate ions in the direction perpendicular to the magnetic field. A 5keV temperature of the bulk plasma was assumed.

RESULTS

In JET Pulse No: 74937, the neutron rates for the NBI only period reached 5×10^{14} s^{-1}. Adding 3MW of ICRF resulted in neutron rates peaking at 7×10^{15} s^{-1}, which is an enhancement of a factor 14 due to an increase in the heating power by a factor of 2. The high neutron rates provided TOFOR data of high quality. Examples of data from combined ICRF + NBI heating are presented in Fig.3(a). Events with t_{TOF} down to 45ns are seen, which is evidence of neutrons with energies around 5MeV, or equivalently of deuterons with energies of 2MeV (Fig.2). f_d was found with the method described above; in FIG 3a, the fitted summation spectrum, after folding with the TOFOR response function, is shown (solid blue) as well as examples of folded $\delta-$spectra at E_d = 0.1, 0.5, 1.0, 1.5 and 2.0MeV (solid black). The resulting f_d is shown in Fig.3(b) (points with error-bars) together with a calculated f_d (solid line), obtained by integrating the Fokker Planck equating [4] with a D_{RF} as shown above. As seen, a large population of deuterons with E_d > 1MeV is created. This is the reason for the exceptionally high neutron rates observed; at energies above 1MeV, the DD reactivity exceeds the DT reactivity.

During Pulse No: 74937, the core electron density varied by a factor of two (Fig.4(a)); as a result, this is reflected in a time varying E^* (Fig.4(b), solid line). The time evolution of the cut-off in f_d was fitted from the TOFOR data (Fig.4(b), points with error bars). It is striking to see how the main features of the theoretical prediction of f_d are well in agreement with that derived from TOFOR data. Especially the location of E^*, which is correctly modeled within 10%, as seen in Fig.3 and Fig4(b)). Depending on the plasma parameters, all discharges in the 3rd harmonic heating experiment showed similar shapes of f_d, i.e., flat between 0.5 and 1.5MeV and with a drop in the range 2 to 3MeV.

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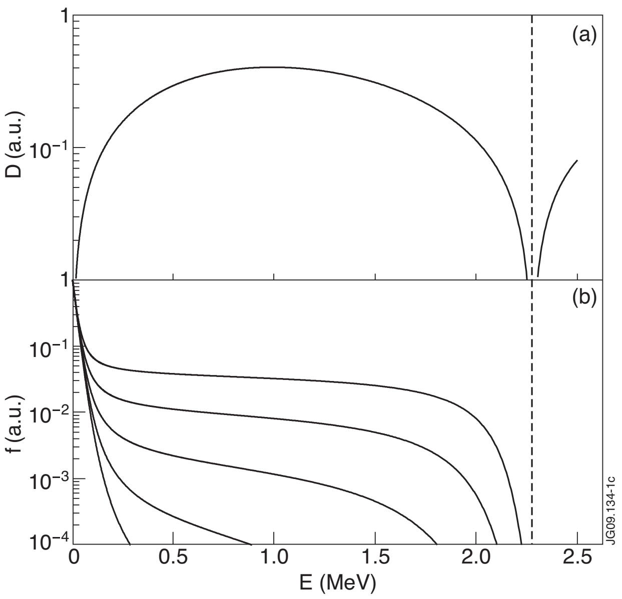

Figure 1 (a) Example of RF diffusion coefficient for the 3rd harmonic ion cyclotron resonance. (b) Examples of simulated distribution functions from 3rd harmonic ICRF at different power levels.

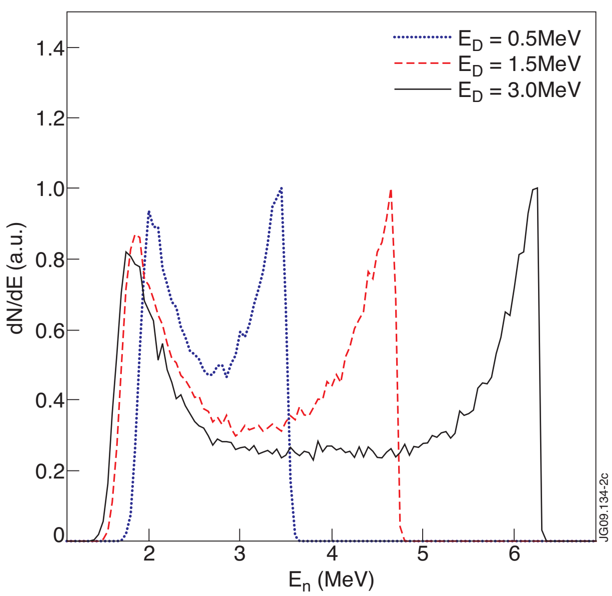

Figure 2 Simulated neutron energy spectra from mono-energetic deuterium distributions.

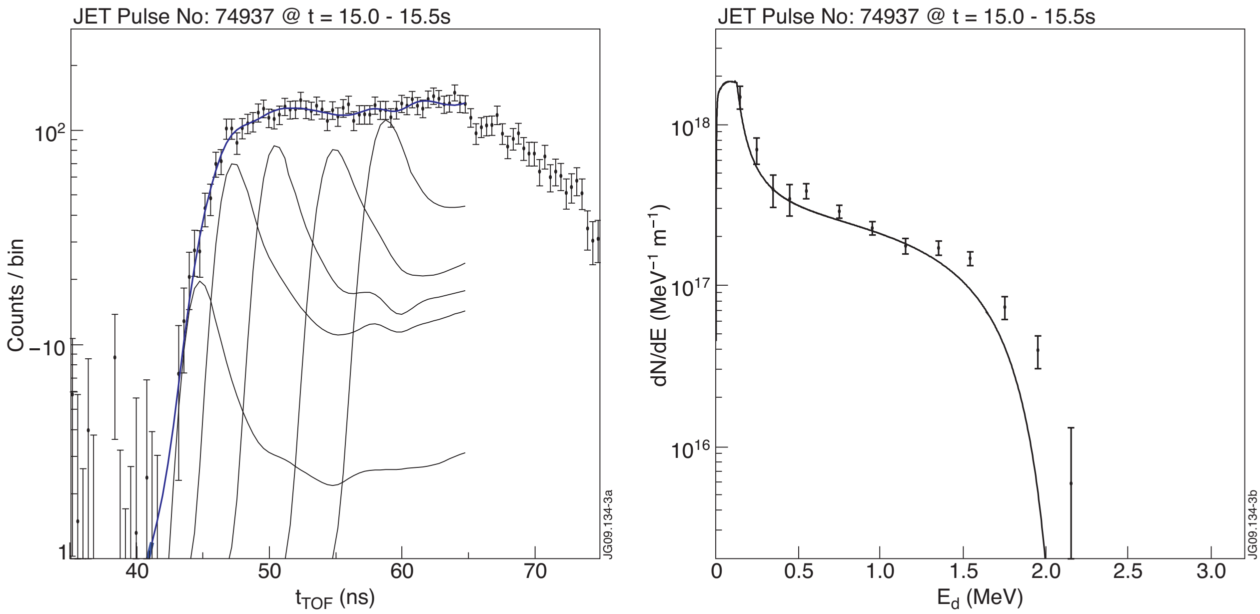

Figure 3(a) TOFOR data from the corresponding period (points with error bars). Fitted data (solid blue) and examples of δ-spectra (solid black). (b) Fast D^+ distribution function of JET Pulse No: 74937 derived from TOFOR data (points with error bars) and calculated distribution (solid line).

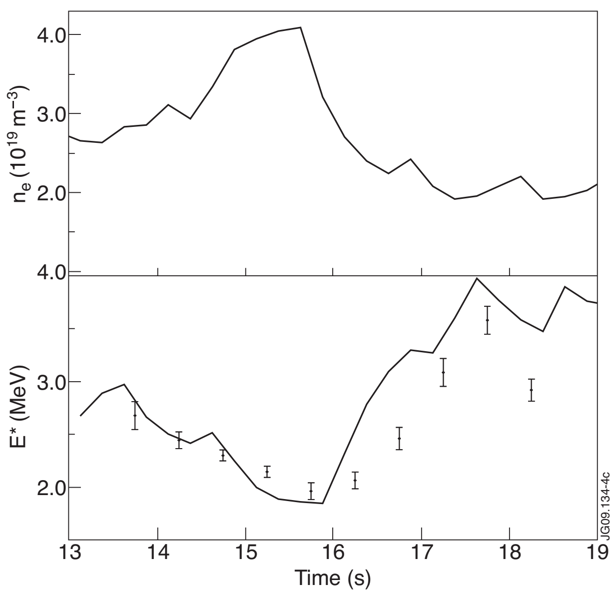

Figure 4(a) Central electron density of JET Pulse No: 74937. (b) Calculated E (solid line) and fitted from TOFOR data (points with error bars).*