EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(01)08-01

M.J.Mantsinen, M.-L.Mayoral, V.Kiptily, S.Sharapov, A.Bickley, M.de Baar, L.-G.Eriksson, T.Hellsten, K.Lawson[2], F.Nguyen, J.-M.Noterdaeme, E.Righi, A.A.Tuccillo, M. Zerbini, and JET EFDA Contributors

Alpha Particle Physics Studies on JET with ICRH-accelerated ^{4}He Beam Ions

Alpha Particle Physics Studies on JET with ICRH-accelerated ^{4}He Beam Ions

M.J.Mantsinen[1], M.-L.Mayoral[2], V.Kiptily[2], S.Sharapov[2], A.Bickley[2],
M.de Baar[3], L.-G.Eriksson[4], T.Hellsten[5,6], K.Lawson[2], F.Nguyen[4],
J.-M.Noterdaeme[7], E.Righi[8], A.A.Tuccillo[9], M. Zerbini[9],
and JET EFDA Contributors

EURATOM-UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 4XB, United Kingdom.
[1]*Helsinki University of Technology, Association Euratom-Tekes, Finland*
[2]*Association Euratom-UKAEA, Culham Science Centre, Abingdon, UK*
[3]*FOM-Rijnhuizen, Ass. Euratom-FOM, TEC, Nieuwegein, NL*
[4]*Association EURATOM-CEA, CEA-Cadarache, Saint-Paul-Lez Durance, France*
[5]*Euratom-VR Association, Swedish Research Council, Stockholm, Sweden*
[6]*EFDA-JET CSU, Culham Science Centre, Abingdon, UK*
[7]*Max-Planck IPP-EURATOM Assoziation, Garching, Germany*
[8]*EFDA CSU-Garching, Garching, Germany*
[9]*Associazione EURATOM-ENEA sulla Fusione, CR Frascati, Frascati, Rome, Italy*
**See Annex of J. Pamela et al., "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in Proceedings of the
7th IAEA TCM on Energetic Particles,
(Gothenburg, 8-11 October 2001)

ABSTRACT
JET experiments with ^{4}He plasmas have provided a unique opportunity for alpha particle physics studies. Dedicated experiments have been performed adding ICRH power to ^{4}He neutral beam injection in order to produce high-energy ICRH-accelerated ^{4}He ions to simulate fusion-born alpha particles. The third-harmonic ^{4}He scenario, with the $\omega \approx 3\omega(^4He)$ resonance in the plasma centre, was chosen in order to avoid complications, such as cold-plasma cutoff for wave propagation and central hydrogen damping which occur for waves tuned to the fundamental and second-harmonic ^{4}He resonance, respectively. Up to 7.5MW of ICRH power was applied at a frequency of 51MHz and a magnetic field of 2.2T.

Clear evidence for a ^{4}He tail and its effects on the plasma was obtained using low-power (1.5MW) ^{4}He beams with the highest available energy (120keV) and with the most central power deposition. The use of the high-energy ^{4}He beams maximised the ICRH damping strength on ^{4}He and the ICRH power per ^{4}He beam ion was large enough to produce a significant ^{4}He tail. The ^{4}He ions with energies above ^{2}MeV were detected using gamma-ray emission from the nuclear reaction $^9Be(\alpha,n\gamma)^{12}C$ between ICRH-accelerated ^{4}He beam ions and ^{9}Be which is one of the impurity species in JET plasmas. This reaction has been proposed earlier as a diagnostic for fusion-born alpha particles [1]. The direct measurement of high-energy alpha particles (although not fusion-born), together with other alpha particle observations in these experiments, are discussed in detail. These include the first excitation of Alfvén eigenmodes by alpha particles on JET, heating of the background plasma, triggering of H-mode as well as indications for sawtooth stablisation by alpha particles. [1] V. Kiptily, Fusion Techn. **18**, 583 (1990).

1. INTRODUCTION
Experiments have been carried out for the first time on JET with the 3rd harmonic ion cyclotron resonance heating of ^{4}He beam ions in order to produce a high-energy population of ^{4}He ions for simulating 3.5MeV fusion-born alpha particles. The successful acceleration of ^{4}He beam ions to the MeV energy range has been confirmed by measurements of gamma ray emission from the reaction $^9Be(\alpha,n\gamma)^{12}C$ and excitation of Alfvén eigenmodes, and is consistent with the observed heating of the background electrons and sawtooth stabilisation.

2. EXPERIMENTAL IMPLEMENTATION
The experiments were carried out at a magnetic field of 2.2T with the 3rd harmonic ^{4}He ion cyclotron resonance, $\omega \approx 3\omega_c(^4He)$, in the plasma centre. This scenario is better suited for accelerating ^{4}He ions than the other candidate scenarios, i.e. $\omega \approx 3\omega_c(^4He)$ for which the wave electric field component E_+ giving rise to absorption becomes very small at the resonance in a ^{4}He plasma, and $\omega \approx 2\omega_c(^4He)$ for which strong central absorption takes place by low-concentration residual hydrogen present in the vessel. The choice was supported by earlier observations of 3rd harmonic ICRH acceleration of deuterons in deuterium plasmas [1-3]. Up to 8MW of ICRH power was applied at a frequency $f = \omega/(2\pi)$ of 51MHz and mainly waves with a symmetric toroidal mode number N spectrum with a peak around $|N| \approx 26$ were used.

For a high-harmonic ICRH scheme such as $\omega \approx 3\omega_c(^4He)$, ICRH absorption at the ion cyclotron resonance is a finite Larmor radius effect. Thus, the wave absorption by the resonating ions increases with the ratio of the ion Larmor radius, $\rho = v_\perp / \omega_{ci}$, to the perpendicular wavelength of the fast wave until a maximum is reached which typically occurs at ion energies in the MeV range. In order to ensure significant high-harmonic absorption, ^{4}He neutral beam ions with energy E_b in the range of 70-120keV and ρ in the range of 1.4-2.2cm were added to ICRH. NBI was applied before ICRH to provide a steady beam ion population with which the fast waves can interact. A relatively low NBI power (typically < 2.2MW) was used in order to seed ^{4}He ions with high ρ for effective acceleration to high energies. NBI power was stepped down typically 1.5s before the ramp-down of ICRH to provide an ICRH-only phase for comparisons.

3. GLOBAL PLASMA CHARACTERISTICS

Clear differences in the global plasma characteristics were observed as E_b was increased from 70 to 120keV. As can be seen in Fig. 1(a), the total plasma stored energy W_{DIA} measured by the diamagnetic loop and the electron temperature T_e at a normalised minor radius $r/a \approx 0.25$ deduced from electron cyclotron emission (ECE) are significantly higher with 120 than 70keV beams. We can also see that in the ICRH-only heating phase W_{DIA} and T_e are smaller than with combined NBI and ICRH. With 70 and 120keV beams, we estimate from the plasma response to the applied ICRH power that about 50% and 85% of the input ICRH power, respectively, is absorbed in the main plasma. Consequently, the discharge with 120keV beams goes to the ELMy H mode, while the other discharge stays in the L mode. The power losses could be due to parasitic edge absorption, for example, at the $\omega \approx \omega_{cH}$ resonance located at the high-field-side plasma edge. In these discharges, beams with the most central deposition were used. With off-axis NBI, smaller increases in W_{DIA} and T_e were observed, consistent with a decreasing ICRH damping strength as the number of energetic ions at the resonance decreases.

4. EXPERIMENTAL CONFIRMATION OF FAST ^{4}HE IONS

Information on confined ^{4}He ions was obtained with a gamma-ray spectrometer. Gamma-ray energy spectra were recorded by a calibrated bismuth germanate scintillation detector, located in a well-shielded bunker viewing the plasma tangentially at about 30cm below the plasma magnetic axis. The gamma rays were recorded in the energy range of 1-28MeV. Figure 1(b) shows the gamma-ray spectra recorded during discharges in Fig. 1(a). The peaks at a gamma ray energy of 4.44MeV are associated with gamma ray emission from the reaction $^9Be(\alpha,n\gamma)^{12}C$ between ICRH-accelerated ^{4}He ions and beryllium impurity ions that are typically present in JET plasmas. The reaction $^9Be(\alpha,n\gamma)^{12}C$ has been proposed earlier as a diagnostic for fusion-born alpha particles [4]. Due to the dependence of its cross-section on the alpha-energy E_α (i.e. a resonance at $E_\alpha \approx$ 2MeV and a number of resonances at $E_\alpha \geq$ 4MeV), this reaction is a sensitive measure of the high-energy part, the tail, of the alpha-particle distribution function.

The spectra in Fig. 1(b) have been analysed with the GAMMOD code [5], based on experimental data for gamma reactions, calculated response functions for the gamma spectrometer and a ^{9}Be/^{12}C impurity ratio of about 1.5% which is in the range suggested by visible, VUV and XUV spectroscopy for this ratio. A Maxwellian energy distribution is used to describe the line-averaged ICRH-accelerated fast ion distribution function. The analysis shows that when E_b was increased from 70 to 120keV, the number of alpha particles with $E \geq 2$MeV increased. With 120keV beams an effective ^{4}He tail temperature of 1.1±0.4MeV is deduced. Without beams, no traces of fast ^{4}He ions are observed in the gamma ray spectrum.

Further evidence for the alpha tail production comes from multiple toroidal and elliptical Alfvén eigenmodes (TAEs and EAEs) detected with magnetic pick-up coils in the frequency ranges of 150-200 and 370-420kHz, respectively in discharge with 120keV beams. The modes have amplitudes at the plasma edge up to $\delta B \approx 10^{-6}$T and dominant toroidal mode numbers of n = 4–7. The TAEs emerge (cf. Fig 2) and the EAEs disappear before the 'monster' sawtooth crash at t ≈ 21.94s. The envelope of the EAE frequency follows the Alfvén scaling with density, $f \propto n_i^{-1/2}$. No AEs are observed with 70keV beams and identical ICRH power. Analysis with the ideal MHD code MISHKA1 gives a normalised frequency $\omega / \omega_A = \omega R_0 / v_A(r/a = 0) = 1.08$ (R_0 is the major radius and v_A is the Alfvén speed) for the n = 6 EAE, which corresponds to f = 385kHz and agrees well with the measured frequency. The EAEs are localised in the central plasma (r/a ≈ 0.3-0.6) and are associated with the q = 1 surface.

Figure 3 shows the ECE T_e at r/a ≈ 0.25 as a function of the fast ion energy content W_{fast} in quasi-steady-state conditions with 1.5MW of 120keV beams and various ICRH powers. Here, W_{fast} has been obtained from the measured total plasma diamagnetic stored energy by subtracting the thermal contribution, which has been estimated from the measured background densities and temperatures. Note that W_{fast} thus obtained contributes up to 30±10% of W_{DIA} and corresponds to a volume average beta of fast ions, $\langle\beta_{fast}\rangle$, of up to 0.3±0.1%. The increase of T_e with W_{fast} shown in Fig. 3 indicates effective power transfer from fast ^{4}He ions to electrons. As W_{fast} increases from 170 to 500kJ, T_e at r/a ≈ 0.25 increases from about 3.6 to 5.4keV, which is significantly more than the ion temperature increase from 2.4 to 2.9keV measured with a X-ray crystal spectrometer around the same radial location. Thus, electron rather than ion heating dominates, as expected.

The T_e trace in Fig. 1(a) shows that sawteeth are more stabilised in discharge with 120keV beams accelerated with ICRH. As E_b was increased from 70 to 120keV, W_{fast} increased from ≈300 to ≈500kJ. Since the main increase in the ICRH-driven fast ^{4}He population is expected to be near the $\omega \approx 3\omega c$ (^{4}He) resonance and thus inside the q = 1 surface, the observed longer sawtooth period with 120keV beams appears to be consistent with the stabilising effect of fast ions on the internal n = 1 kink mode [6]. Sawteeth with the longest periods trigger long-living magnetic perturbations with the toroidal n and poloidal m mode numbers equal to n = 2, m = 3 or n = 3, m = 4. These modes typically exist for 1-2s after 'monster' sawtooth crashes, during which they decrease the plasma performance dramatically [cf. W_{DIA} in Fig. 1(a)].

5. OBSERVATIONS OF OTHER FAST ION POPULATIONS

For alpha-particle physics studies, the presence of fast ions other than ^{4}He ions is undesirable. If such ions are observed, it is necessary to quantify their characteristic energies and densities and to compare them with those of fast ^{4}He ions. Two different types of fast ions other than ^{4}He could potentially exist in the present experiments: residual ^{3}He ions remaining from earlier experiments and heated by the second harmonic ^{3}He resonance, and deuterons accelerated via the $\omega \approx 3\omega_{cD}$ resonance which coincides with the $\omega \approx 3\omega_c(^4\text{He})$ resonance. The thermal deuterium concentration D/^{4}He at the plasma edge, as deduced from visible spectroscopy, was about 25%.

While no significant populations of fast ^{3}He ions were detected with gamma spectrometry or the high-energy Neutral Particle Analyser (NPA) [7], fast deuterons were detected with both diagnostics. However, the neutron yield R_{NT}, which is mainly due to reactions between fast and thermal plasma deuterons, starts to increase in time significantly later than W_{DIA} and T_e at the application of ICRH power [Fig. 1(a)]. Furthermore, AEs appear at t = 19.9s and thus before the increase in R_{NT} and hence before the formation of the fast deuteron population. Thus, these modes are indeed driven by fast ^{4}He ions.

The analysis of the gamma-ray spectra in Fig. 1(b) shows that that the deuteron tails have effective temperatures of about 0.3MeV, giving rise to emission through the reaction $^{12}\text{C}(\text{d},\text{p}\gamma)^{13}\text{C}$ with the carbon impurity. However, the fast ^{4}He density is about 16 and 25 times higher than that of fast deuterons with 70 and 120keV beams, respectively. The measured stronger ^{4}He tails are consistent with modelling with the PION code [1]. According to PION, 4 He damping dominates, and deuteron absorption < 1 MW is sufficient to give rise to the measured neutron rates.

CONCLUSIONS

Experiments have been carried out for the first time on the JET tokamak in ^{4}He plasmas with ICRH power added to ^{4}He NBI at the third harmonic ^{4}He ion cyclotron resonance. High-energy ^{4}He ions have been observed using the reaction $^9\text{Be}(\alpha,\text{n}\gamma)^{12}\text{C}$ and contribute up to 30±10% of the total plasma diamagnetic stored energy. The effects of high-energy ^{4}He ions have been quantified, including excitation of Alfvén eigenmodes, heating of the background plasma and sawtooth stabilisation. The adopted ICRH scheme allows the experimental simulation of MeV-energy alpha particles without complications of a full-scale DT campaign. It could be used on next-step tokamak reactors to gain information on alpha particles in the early, non-activated phase of their operation.

ACKNOWLEDGEMENTS

This work has been performed under the European Fusion Development Agreement.

REFERENCES

[1]. L.-G.Eriksson, et al., Nucl. Fusion 38, 265 (1998).
[2]. R.Koch et al., Plasma Phys. Control. Fusion 37, A291 (1995).

[3]. J.-M.Noterdaeme et al., in RF Power in Plasmas (13 th Topical Conference, Annapolis, Maryland, 1999) AIP, New York, 1999, p. 92.
[4]. V.G.Kiptily, Fusion Techn. 18, 583 (1990).
[5]. V.G.Kiptily, et al., Proc. 6 th Int. Conf. Advanced Diagnostics for Magnetic and Inertial Fusion, Villa Monastero, Varenna, 2001.
[6]. F.Porcelli, Plasma Phys. Control. Fusion 33, 1601 (1991).
[7]. A.A.Korotkov, A.Gondhalekar, and R.J.Akers, Phys. Plasmas 7, 957 (2000).

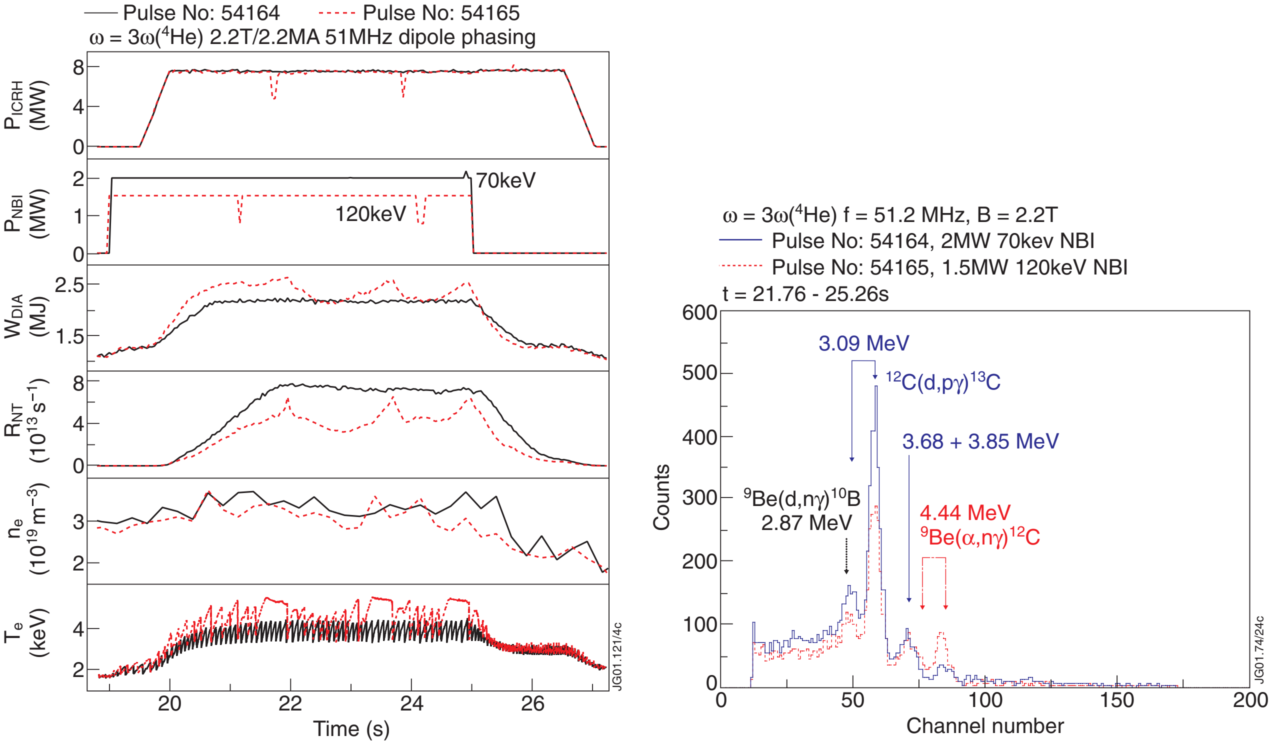

Figure 1: (a) Overview of Pulse No: 54164 and 54165 with third harmonic ^{4}He heating and with 70keV and 120 keV ^{4}He beams, respectively. (b) Gamma ray spectra for the two pulses in (a).

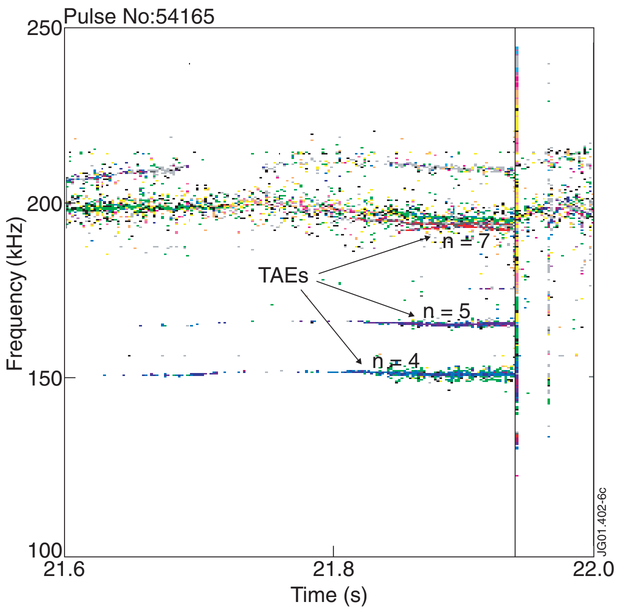

Figure 2: Magnetic fluctuation spectrogram showing toroidal Alfvén eigenmodes for Pulse No: 54165.

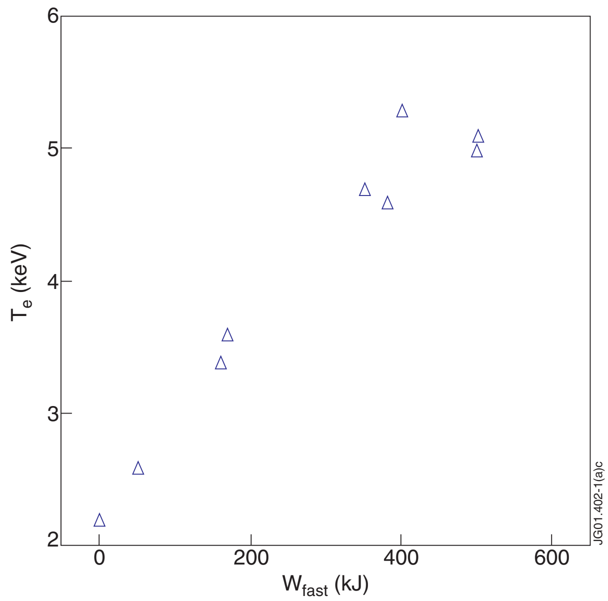

Figure 3: ECE $T_e(r/a \approx 0.25)$ as a function of the experimental fast ion energy content with $\omega \approx 3\omega_c(^4He)$ ICRH and 1.5MW of 120keV beams.