Alpha-Tail Production with Ion-Cyclotron-Resonance Heating of ^{4}He-Beam Ions in JET Plasmas

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Third-harmonic ion-cyclotron-resonance heating of ^{4}He-beam ions has produced for the first time on the JET tokamak high-energy populations of ^{4}He ions to simulate 3.5 MeV fusion-born alpha (α) particles. Acceleration of ^{4}He ions to the MeV energy range is confirmed by γ-ray emission from the nuclear reaction ^{9}Be$(\alpha, n\gamma)$ ^{12}C and excitation of Alfvén eigenmodes. Concomitant electron heating and sawtooth stabilization are observed. The scheme could be used in next-step tokamaks to gain information on trapped α particles and to test α diagnostics in the early nonactivated phase of operation.

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In magnetic fusion based on the reaction $\mathrm{D} + \mathrm{T} \rightarrow {}^4\mathrm{He}\ (3.5\ \mathrm{MeV}) + n\ (14\ \mathrm{MeV})$, the reactivity of deuterium-tritium (DT) plasma has to be sustained by heating provided by fusion-born alpha (α) particles (i.e., ^{4}He ions) with a birth energy of 3.5 MeV. The development of the magnetic fusion concept requires a thorough investigation of α-particle production, heating, and transport in order to predict with confidence the α-particle behavior in a reactor. The most successful device yet found for magnetic fusion is the tokamak, where the plasma is confined in a toroidal vacuum vessel by the magnetic fields generated by external field coils and the current in the plasma. Behavior of α particles has previously been studied on the TFTR [1] and JET [2] tokamaks. In these full-scale DT experiments the heating of plasma electrons by α-particles was demonstrated [3,4], the possibility of α-driven Alfvén eigenmodes was investigated [5–7], and α particles were measured with an array of different diagnostics [8–11].

This Letter reports the development of a technique to produce MeV-energy ^{4}He ions accelerated by ion-cyclotron-resonance heating (ICRH) in nonactivating helium plasmas on JET. This technique permits the experimental simulation of trapped MeV-energy α particles without the complications of a full-scale DT campaign. It could be of a special importance for next-step tokamak reactors in order to gain information on the trapped α particles and to test α diagnostics in an early nonactivated phase of operation.

Earlier, energetic ions accelerated by ICRH have used to simulate α particles, even though the interaction with ICRH waves preferentially increases the perpendicular energy of the ions and thus results in the formation of an anisotropic high-energy part (i.e., tail) in the fast ion distribution with a large number of trapped ions. ICRH-accelerated fast ions have usually been hydrogen, deuterons, or ^{3}He ions, while information on fast ^{4}He ions and their effects on the plasma is sparse. The technique, reported in this Letter, allows the acceleration of ^{4}He ions with ICRH to simulate trapped α particles and their effects in a quasi-steady-state plasma regime where heating by fast ^{4}He ions is the dominating heating process. This method for α-tail production was developed during recent experiments in ^{4}He plasmas on JET. These ICRH experiments were carried out at a magnetic field B of 2.2 T with the third harmonic ^{4}He ion cyclotron resonance, $\omega \approx 3\omega_c(^4\mathrm{He})$, in the plasma center. This scheme is unique in its suitability for accelerating ^{4}He ions as compared with other candidate scenarios. For example, the $\omega \approx \omega_c(^4\mathrm{He})$ scenario is not suitable for this purpose since the wave electric field component E_+ giving rise to absorption becomes small at the resonance in a ^{4}He plasma, while for $\omega \approx 2\omega_c(^4\mathrm{He})$ and $\omega \approx 4\omega_c(^4\mathrm{He})$ strong central absorption takes place by low-concentration residual hydrogen present in the vessel. Furthermore, at higher harmonics multiple resonances exist in the plasma, which complicates the analysis of the experiments. The choice of $\omega \approx 3\omega_c(^4\mathrm{He})$ was supported by earlier

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observations of third harmonic ICRH acceleration of deuterons in D plasmas [12–14]. Up to 8 MW of ICRH power, $P_{\rm ICRH}$, was applied at a frequency $f = \omega/(2\pi)$ of 51 MHz using waves with a symmetric toroidal mode number spectrum.

For a high-harmonic ICRH scheme such as $\omega \approx 3\omega_c(^4\mathrm{He})$, 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. Here $v_\perp$ is the ion velocity component in the direction perpendicular to B. In order to ensure significant third harmonic absorption, ^{4}He neutral beam injection (NBI) with energy E_b in the range of 70–120 keV and ρ in the range of 1.4–2.2 cm were added to ICRH. NBI was applied before ICRH to provide a steady beam ion population with which the ICRH waves can interact. A relatively low NBI power (typically $P_{\rm NBI} < 2.2$ NW) was used in order to seed ^{4}He ions with high ρ for effective acceleration to high energies. $P_{\rm NBI}$ was stepped down typically 1.5 s before the ramp-down of ICRH to provide an ICRH-only phase for comparisons.

Clear differences in the global plasma characteristics were observed as E_b was increased from 70 to 120 keV (Fig. 1), which increased the ^{4}He single-pass damping (estimated using the Wentzel-Kramers-Brillouin approximation [15] and integrating rays across the midplane) from 0.8% to 1.5% at the application of ICRH. The total stored plasma energy $W_{\rm DIA}$, measured by a diamagnetic loop, and the electron temperature T_e, deduced from electron cyclotron emission (ECE) heterodyne data at a normalized minor radius $r/a \approx 0.25$, are significantly higher with 120 than with 70 keV beams. We can also see that in the ICRH-only phase $W_{\rm DIA}$ and T_e are smaller than with combined NBI and ICRH. With 70 and 120 keV beams, we estimate from the plasma response that ≈50% and 85% of $P_{\rm ICRH}$, respectively, are absorbed in the main plasma. Consequently, the discharge with 120 keV beams goes to an ELMy H mode with improved energy confinement, while the other discharge stays in the L mode. The power losses could be due to parasitic edge absorption, e.g., at the $\omega \approx \omega_{c\rm H}$ 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 $W_{\rm DIA}$ and T_e were observed, consistent with a decrease in the ICRH damping strength as the number of energetic ions at the resonance decreased.

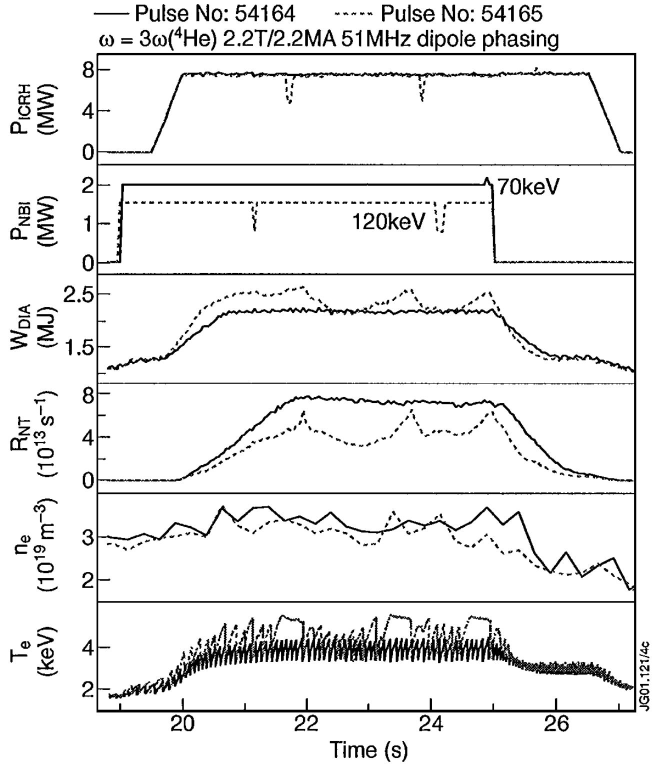

FIG. 1. Overview of two discharges with $\omega \approx 3\omega_c(^4\mathrm{He})$, one with 70 keV and the other with 120 keV beams. The difference in $P_{\rm NBI}$ is due to technical constraints and favors the 70-keV beam case in terms of ^{4}He single-pass damping.

Information on confined ^{4}He ions was obtained with a gamma-ray (γ-ray) spectrometer. Gamma-ray energy spectra were measured in the energy range 1–28 MeV using a calibrated bismuth germanate scintillation detector, located in a well-shielded bunker viewing the plasma tangentially at about 30 cm below the plasma magnetic axis. Figure 2 shows the γ-ray spectra for discharges in Fig. 1. The peaks at the γ energy of 4.44 MeV are due to γ emission from the nuclear reaction $^9\mathrm{Be}(\alpha, n\gamma)\,^{12}\mathrm{C}$ between ICRH-accelerated ^{4}He ions and intrinsic beryllium impurity ions present in JET plasmas. While this reaction has been proposed earlier as a diagnostic for fusion-born α particles [16], the present experiments are the first to demonstrate its feasibility for this purpose. Because of the dependence of its cross section on the α-particle energy E_α (i.e., a resonance at $E_\alpha \approx 2$ MeV and a number of

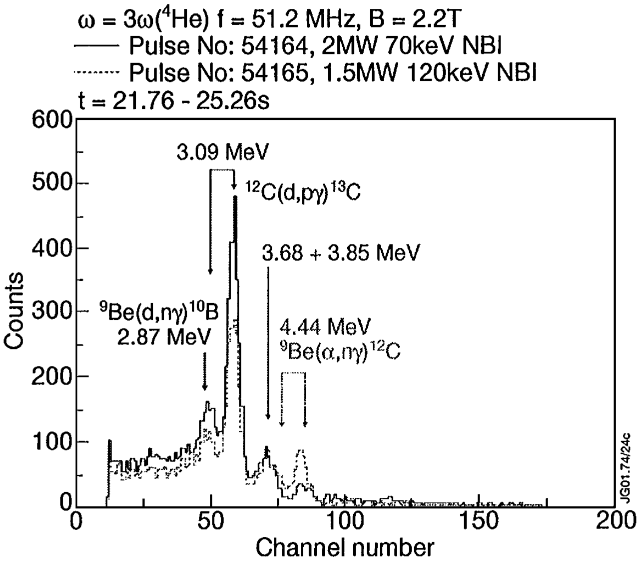

FIG. 2. Gamma ray spectra for the two discharges in Fig. 1.

resonances at $E_\alpha \geq 4$ MeV), this reaction is sensitive to the high-energy part of the α distribution.

The spectra in Fig. 2 were analyzed with the GAMMOD code [17], based on experimental data for γ reactions, calculated response functions for the γ-ray spectrometer and a $^{9}\mathrm{Be}/^{12}\mathrm{C}$ impurity density ratio of 1.5% (which is in the range of 0.1%–2% suggested by visible, VUV, and XUV spectroscopy). The GAMMOD analysis shows that when E_b was increased from 70 to 120 keV, the number of α particles with $E \geq 2$ MeV increased approximately by a factor of 5. Without beams, no fast ^{4}He ions are observed in the γ-ray spectrum.

Further evidence for the α-tail production comes from multiple toroidal and elliptical Alfvén eigenmodes (TAEs and EAEs) detected with magnetic pickup coils in the frequency ranges of 150–200 and 37–420 kHz, respectively, in discharge with 120 keV beams (Fig. 3). No AEs are observed with 70 keV beams and identical P_{ICRH}. Earlier, AEs have been found [18,19] to be a good indicator of the presence of high-energy ions with velocities comparable to the Alfvén speed v_A in the plasma. The modes in Fig. 3 have amplitudes at the plasma edge up to $\delta B \approx 10^{-6}$ T and dominant toroidal mode numbers of $n = 4$–7. The envelope of the EAE frequency follows the Alfvén scaling with density, $f \propto n_i^{-1/2}$, while the fine structure correlates with the sawtooth activity. The EAEs disappear and the TAEs emerge before the "monster" sawtooth crash at $t \approx 21.94$ s. No significant adverse effects of AEs on the plasma confinement are observed. Analysis with the ideal MHD code MISHKA1 [5] gives frequencies consistent with the measured ones, e.g., $\omega/\omega_A = \omega R_0/v_A(r/a = 0) = 1.08$ for the $n = 6$ EAE, which corresponds to $f = 385$ kHz and agrees well with the measured frequency. The computed EAEs are localized in the central plasma ($r/a \approx 0.3$–0.6) and are associated with the $q = 1$ surface. The fine structure in the time evolution of their frequency is likely to be due to relaxations of the $q = 1$ surface in time in the presence of sawteeth. Around the calculated mode location, the dimensionless fast ion pressure gradient $|R_0 \nabla \beta_{\mathrm{fast}}|$, which is a measure of the energetic ion instability drive, is estimated to be in the range of 0.03–0.1 and thus close to values expected in next-step tokamaks. However, since for a given n_e and ion temperature T_i, the ratio of thermal ion Landau damping in ^{4}He plasma to that in 50:50 DT plasma is as small as $\approx(5/2)^{5/2}\exp[-(15\beta_i)^{-1}]$ where β_i is the thermal ion beta of ^{4}He plasma, AEs are excited more easily by energetic ^{4}He ions in these ^{4}He plasmas than in DT plasmas.

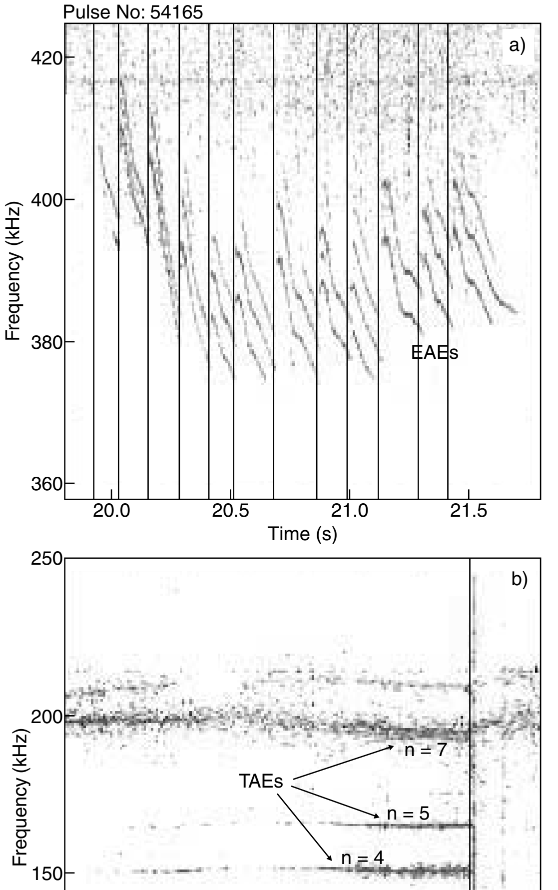

FIG. 3. Magnetic fluctuation spectrograms showing (a) elliptical and (b) toroidal Alfvén eigenmodes. The vertical lines indicate the sawtooth crashes. Note the different axes.

The T_e trace in Fig. 1 shows that sawteeth are more stabilized in discharge with 120 keV beams accelerated with ICRH. The sawtooth period τ_{saw} as a function of the fast ion energy W_{fast} is shown in Fig. 4a in quasi-steady-state conditions with 1.5 MW of 120 keV beams and various P_{ICRH}. With identical P_{ICRH} and 70 keV beams, up to 40% smaller W_{fast} were obtained. The highest W_{fast}'s contribute up to 30% ± 10% of W_{DIA} and correspond to an average beta of fast ions $\langle\beta_{\mathrm{fast}}\rangle = 2\mu_0\langle p_{\mathrm{fast}}\rangle/B^2 = 4\mu_0 W_{\mathrm{fast}}/(3VB^2)$ of up to 0.3% ± 0.1% (V is the plasma volume). Since the main increase in W_{fast} is near the central $\omega \approx 3\omega_c(^{4}\mathrm{He})$ resonance and inside the $q = 1$ surface located around $r/a \approx 0.5$, the increase in τ_{saw} with W_{fast} appears to be consistent with the stabilizing effect of fast ^{4}He ions on the internal $n = 1$ kink mode [20]. Sawteeth with longest τ_{saw} trigger magnetic perturbations with toroidal n and poloidal m mode numbers equal to $n = 2$, $m = 3$, or $n = 3$, $m = 4$. These modes typically exist for 1–2 s after sawtooth crashes, during which they degrade the plasma performance (cf. W_{DIA} in Fig. 1).

The ECE $T_e(r/a \approx 0.25)$ also increases with W_{fast} (Fig. 4b), indicating effective power transfer from fast ^{4}He to electrons. As $T_e(r/a \approx 0.25)$ increases from about 3.6 to 5.4 keV, T_i measured with an x-ray crystal spectrometer around the same radial location increases from

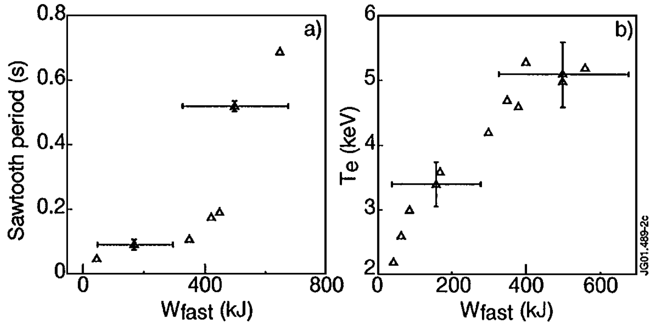

FIG. 4. Sawtooth period (a) and ECE $T_e(r/a \approx 0.25)$ (b) as functions of the fast ion energy $W_{\mathrm{fast}} = 2(W_{\mathrm{DIA}} - W_{\mathrm{th}})/3$ for discharges with $\omega \approx 3\omega_c(^4\mathrm{He})$ and 1.5 MW of 120 keV beams. Here W_{th} is the thermal stored plasma energy deduced from measured plasma densities and temperatures.

2.4 to 2.9 keV. Thus, electron heating is the dominating heating process, as expected. We estimate that in these discharges fast ^{4}He ions provide up to about 80%–90% of the total heating power to the thermal plasma.

For α-particle physics studies, the presence of fast ions other than ^{4}He ions is undesirable. 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 $\omega \approx 3\omega_{c\mathrm{D}}$ resonance which coincides with the $\omega \approx 3\omega_c(^4\mathrm{He})$ resonance. The thermal deuterium concentration, D/^{4}He at the plasma edge, as deduced from visible spectroscopy, was about 25%. The high-energy neutral particle analyzer (NPA) [21] was used to assess the presence of fast ^{3}He ions. No significant populations of fast ^{3}He ions were observed in the energy range of 0.3–1.1 MeV. No fast ^{3}He was detected with γ spectrometry either. The presence of fast deuterons was inferred from γ-ray spectrometer and high-energy NPA measurements. However, the neutron yield R_{NT}, which is mainly (up to 90%) due to reactions between fast and thermal deuterons, starts to increase in time significantly later than W_{DIA} and T_e at the application of ICRH (cf. Fig. 1). Furthermore, EAEs in Fig. 3 appear at $t = 19.9$ s and thus before any significant increase in R_{NT} and hence before the formation of the fast deuteron population. Thus, the available data indicate that these modes are indeed driven by fast ^{4}He ions.

The γ-ray spectra in Fig. 2 shows that the deuteron tails give rise to emission mainly through the reaction $^{12}\mathrm{C}(d,p\gamma)^{13}\mathrm{C}$ with the carbon impurity. Since the cross section of this reaction at the lowest energy resonance at $E_d \approx 0.9$ MeV is of the same order as that of $^9\mathrm{Be}(\alpha,n\gamma)^{12}\mathrm{C}$ at $E_\alpha \approx 2$ MeV (130 and 250 mb, respectively) while the $^9\mathrm{Be}/^{12}\mathrm{C}$ impurity density ratio is in the range of 0.1%–2% as discussed earlier, only a small number of fast deuterons are required to account for the observed γ emission due to $^{12}\mathrm{C}(d,p\gamma)^{13}\mathrm{C}$. According to GAMMOD, the fast ^{4}He density is about 16 and 25 times higher than that of fast deuterons with 70 and 120 keV beams, respectively. We conclude that the main contribution to W_{fast} is not from D but from fast ^{4}He ions. The measured stronger ^{4}He tails are consistent with modeling with PION code [12]. According to the calculations by PION, ^{4}He damping dominates, and deuteron absorption <1 MW is sufficient to give rise to the measured R_{NT}.

To summarize, experiments have been carried out on the JET tokamak in ^{4}He plasmas with ICRH added to ^{4}He NBI at the third harmonic ^{4}He ion cyclotron resonance to explore for the first time quasi-steady-state plasmas with significant heating by fast ^{4}He ions. Fast ^{4}He ions have been observed using the reaction $^9\mathrm{Be}/(\alpha,n\gamma)^{12}\mathrm{C}$, thus demonstrating the feasibility of this reaction for diagnosing fast ^{4}He ions, and contributing up to 30% ± 10% of the total plasma diamagnetic energy. The effects of fast ^{4}He ions have been quantified, including excitation of AEs, heating of the background plasma and sawtooth stabilization. No significant adverse effects of AEs on plasma confinement have been observed. The adopted scheme could be used in next-step tokamak reactors in order to gain information on trapped α particles and to test the α-particle diagnostics in an early nonactivated phase of operation.

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