

UKAEA-CCFE-CP(20)69

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Excitation of elliptical and toroidal Alfvén Eigenmodes by ^3He -ions of the MeV-energy range in hydrogen-rich JET plasmas

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Abstract

Elliptical (EAE) and toroidal Alfvén eigenmode (TAE) instabilities have been observed in hydrogen-rich JET discharges of the D -(^3He)- H ion cyclotron resonance heating (ICRH) scenario, which is characterized by strong absorption of radio frequency waves at very low concentrations of the resonant ^3He -ions. In the experiments, core localized TAEs with a frequency $f_{\text{TAE}} \approx 280$ kHz were detected. Following the phase with TAE excitation, EAE modes at higher frequencies $f_{\text{EAE}} \approx 550$ -580 kHz with mode numbers $n=1, 3, 5$ were seen. These high frequency modes indicate that a MeV range population of trapped energetic ions was present in the plasma. The experimental evidence of existence of the MeV-energy ^3He -ions able to excite the AEs is provided by neutron and gamma-ray diagnostics as well as fast ion loss measurements. The ICRH modelling code calculations confirm the acceleration of ^3He -ions to MeV energies. The MHD analysis results are consistent with the experimental data showing that the MeV ^3He ions are resonant when interacting with TAE and EAE modes. This experiment demonstrates the efficient plasma heating mimicking the conditions representative for the ITER plasmas and contribute to the understanding of fast-ion interaction with MHD modes.

1. Introduction

Ion cyclotron resonance range of frequencies (ICRF) heating is a powerful instrument to obtain bulk ion and/or electron heating in a variety of plasmas. In this work we used an extremely efficient ICRF absorption scheme, which relies on the presence of three ion species in the plasma, so-called “three-ion scenario” [1]. It is very effective technique for fast-ion generation that has been demonstrated on Alcator C-Mod, AUG and JET [2,3]. In our case, it is D -(^3He)- H three ion ICRH scenario. Hydrogen and deuterium are target plasma species with different fundamental ion-cyclotron frequencies ω_{ci} and a small amount of ^3He -ions is minority of resonant ions as its charge-to-mass ratio satisfies the relation $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$, i.e. $1/2 < 2/3 < 1/1$. In this ion heating scenario the left-hand polarized component of the RF electric field E_+ , which is rotating with ions, is strongly enhanced in the vicinity of the mode conversion

(MC) layer and in this region an intense wave damping occurs by ${}^3\text{He}$ -ions that satisfies the resonance condition $\omega \approx \omega_{ci} + k_{\parallel}v_{\parallel}$.

The elliptical and toroidal Alfvén Eigenmode (as apt EAE and TAE) instabilities we observed in the hydrogen-rich discharge with up to 4.4 MW of ICRH power (P_{ICRH}) applied at $f = \omega/(2\pi) \approx 32.5$ MHz at toroidal field in the plasma centre $B_T(0) = 3.1$ T and the central plasma density $n_{e0} \approx 4 \times 10^{19} \text{ m}^{-3}$. The H -ion cyclotron resonance lays at $R_{IC} \approx 4.3$ m is outside the JET vessel. The D -ion cyclotron resonance placed at $R_{IC} \approx 2.15$ m, while the MC layer is in the plasma centre $R_0 = 2.96$ m (figure 1). It is important to emphasise that concentration of ${}^3\text{He}$ -ions was very low ($X[{}^3\text{He}] < 1\%$) in this discharge.

An illustration of the time evolution of several plasma parameters during this JET pulse is found in figure 2. The ratio n_H/n_H+n_D measured at the plasma edge varied during the heating period from $\sim 90\%$ to $\sim 70\%$. One can see that from the beginning of the ICRF heating the plasma energy efficiently growing up with a rate $\Delta W_P/\Delta P_{ICRH} \approx 0.18$ MJ/MW. Since the ICRH power was coupled with asymmetric $+\pi/2$ antenna phasing, launching waves predominantly in the direction of the plasma current, a population of energetic ${}^3\text{He}$ ions was generated in the plasma, resulting in the long sawtooth periods (“monster sawtooth”). In the monster sawtooth period $t \approx 10 - 10.4$ s the core localized TAEs with a frequency $f_{TAE} \approx 280$ kHz and a weak EAEs at $f_{EAE} \approx 560 - 570$ kHz were observed. Following the phase with TAE excitation, strong EAE modes at higher frequencies $f_{EAE} \approx 550-580$ kHz with mode numbers $n=1, 3, 5$ were seen in period $t \approx 10.6 - 10.8$ s (figure 3). These high frequency modes indicate that a MeV range population of trapped energetic ions is present in the plasma interacting with the modes.

The experimental evidence of the existence of the confined MeV-energy ${}^3\text{He}$ -ions able to excite the AEs and their loss due to the instabilities obtained with neutron and gamma-ray diagnostics as well as escaped fast ion measurements is provided in the next chapter. The MHD analysis results are presented in chapter 3. The paper is completed with a summary and conclusions.

2. Observation of the confined and lost MeV-energy ${}^3\text{He}$ -ions

JET is equipped with an excellent set of diagnostics to study confined and escaped fast ions. Gamma-ray spectrometry [4] routinely used for the fast-ion studies in JET is based on measurements of gamma-rays, which are born as a result of nuclear reactions between confined fast ions and the main plasma intrinsic low-Z impurities in JET (Be and some C). This diagnostic provides information on the fast-ion tail in the MeV-energy range. In these

experiments, gamma-ray energy spectra were recorded by a collimated $LaBr_3$ scintillation detector with a vertical line-of-sight through the plasma centre [5]. The DD neutron rate is monitored with a calibrated set of fission chambers [6]. The fast ion lost detector (FILD) [7] allows detection of lost ions at a single position outside the plasma, and provides information on the lost ion pitch angle, $\theta = \cos^{-1}(v_{\parallel}/v)$, between 35° and 85° ($\sim 5\%$ resolution) and its gyro-radius ρ_{gyr} between 3 and 14 cm ($\sim 15\%$ resolution) with a time resolution of 2 ms. The grid (ρ_{gyr}, θ) on the scintillator plate calculated using EFIT equilibrium. FILD is in vessel ~ 28 cm below the mid-plane of the JET torus. The light emitted by the scintillator due to fast ion strikes is transported through a guide tube and a coherent fibre bundle to a charge-coupled device (CCD) and a photomultiplier (PMT) array.

The analysis of gamma-ray spectra recorded during the period of TAEs and EAEs excitation shows that identified gamma-ray peaks are related to the 3He nuclear reactions: $^9Be(^3He, n\gamma)^{11}C$ and $^9Be(^3He, p\gamma)^{11}B$. These reactions become intensive and can be detected with the diagnostics in JET, if energies of 3He -ions $E_{3He} > 0.9$ MeV. The analysis of the gamma-ray spectra has been made with a special deconvolution code DeGaSum [8] developed for fusion plasma studies. Response functions of the spectrometer were calculated with Monte-Carlo code MCNP [9], using the detector line-of-sight model. Figure 4 shows experimental spectrum, the identified gamma-ray lines and the re-convoluted spectrum demonstrating the quality of the analysis. Gamma-rays with energies $E_\gamma = 2.13, 4.44$ and 7.29 MeV are related to transitions in the excited nucleus $^{11}B^*$ and $E_\gamma = 2.00, 4.32, 6.34, 6.48$ and 6.91 MeV in the $^{11}C^*$. Using the obtained intensities of gamma-ray lines and known partial cross-sections of the nuclear reactions we reconstructed energy distribution functions of 3He -ions in the Maxwellian approximation (figure 5a). The effective temperature of ions in the TAEs period of the discharge (8.0 - 10.3s) is $T_{3He} \sim 1$ MeV and it is ~ 0.7 MeV in the period of the EAE appearance (10.3 – 14s). So, during the excitation TAEs and EAEs the 3He -ions are extremely fast having energy in the MeV-range, which make them potentially responsible for triggering the modes.

The calculations of the 3He -ion heating with the ICRF modelling code PION [10] have been made. The 3He -ion tail temperatures as a function of the square root of normalized poloidal flux is presented in figure 5b. It is seen that the 3He -ion tail temperature in the plasma centre is at ~ 1 MeV and this is in the good agreement with the central line-integrated gamma-ray spectra measurements.

In addition, we established that the neutron rate in this ICRH-only hydrogen-reached plasma discharge is anomalously high (figure 6). It is seen that during the both first and second monster sawteeth, during very efficient plasma heating, neutron rate grows dramatically. To

compare the thermal DD neutron rate, which is expected, with experimental one the TRANSP calculations were made. Since the ratio n_D/n_H+n_D was growing in the sawteeth period, the calculations were done for 6 periods averaged ratios in each time-bin. Figure 7 shows comparison of the TRANSP calculations, including the uncertainty band related to the deuterium concentration variation, and measured neutron rate. One can see that measured rate up to ~ 4 times higher than expected with $T_i = T_e$. One of the possible sources of the anomalous rate increase could be a knock-on effect [11]. The gamma-ray measurements confirm the MeV-energy tail of ${}^3\text{He}$ -ions accelerated due to ICRH, hence the Coulomb and nuclear $d\text{-}{}^3\text{He}$ scattering could generate supra-thermal deuteron distribution thereby greatly enhancing $D(d,n){}^3\text{He}$ reaction rate. Also, ${}^3\text{He}$ -ions with $E_{3\text{He}} > 0.9$ MeV can give rise additional neutrons due to the nuclear reaction ${}^9\text{Be}({}^3\text{He},n){}^{11}\text{C}$. Indeed, neutron energies up to 10 MeV have been detected with high-resolution neutron spectrometer TOFOR during fast-ion studies with ${}^3\text{He}$ -minority ICRF heating on JET [12]. Depending on Be concentration, a contribution up to $\sim 10 - 50\%$ to the total neutron yield from the ${}^9\text{Be}({}^3\text{He},n){}^{11}\text{C}$ reaction was found.

In figure 6 one can see sharp transient spikes of the neutron rate at time of the monster sawtooth crashes. We can suggest that 10-20% of neutron rate increase could be caused by D -ion acceleration by the sawtooth reconnection electric field. Following the approximation [13] and results [14] the relative change of kinetic energy, W , of 4-keV D -ions due to reconnection can be $\Delta W/W \sim 0.03$. In the keV-energy range the cross-section of the $D(d,n){}^3\text{He}$ reaction [15] has a steep slope and the sawtooth reconnection W changes can lead to the reactivity increase $\sim 20\%$ and it could account for the observed effect. It should be note that only a fraction of ions can pass through the reconnection layer (because the reconnection is asymmetric), hence the expected reactivity growth is smaller. Also, there is an additional way to generate extra neutrons in the sawtooth crashes. It could be caused by a massive escape of the MeV ${}^3\text{He}$ -ions due to the crash. Since the modern JET has beryllium wall (so named the JET ITER-like wall), the ${}^9\text{Be}({}^3\text{He},n){}^{11}\text{C}$ reactions give rise neutrons [12].

The fast ion losses detected with FIELD indicate that escaped ${}^3\text{He}$ -ions are very energetic laying in the MeV-energy range. Indeed, the footprint of losses shown in figure 8a demonstrates that ions lost in the period of TAEs $t = 9.94 \text{ s} - 10.34 \text{ s}$ have the gyro-radius of in the range $\rho_{gyr} > \approx 10 \text{ cm}$ with pitch-angles $\theta \approx 60^\circ - 66^\circ$. The energy of ions is related to the gyro-radius as

$$E_i = \left[\frac{\rho_{gyr}(cm) B_{FIELD}(T)}{14.45} \right]^2 \frac{Z_i^2}{A_i}, \quad (1)$$

where B_{FILD} is magnetic field at the location of the FILD scintillator plate, which in the presented case, $\approx 2.38\text{T}$. Therefore, escaping ${}^3\text{He}$ -ions have energies $E_i > \approx 3.6\text{ MeV}$ in the TAEs period. However, losses due to the monster sawtooth crash (figure 8b) at $t \approx 10.4\text{ s}$ aligned along the $\theta \approx 68^\circ$ are related to ${}^3\text{He}$ -ions in the broader energy range $E_i > \approx 1.8\text{ MeV}$ ($\rho_{gyr} > \approx 7\text{ cm}$). It is quite difficult to separate the CCD footprint loss contributions related TAEs, ST and EAEs because of a finite $\Delta\rho_{gyr}$ and $\Delta\theta$ resolution and a rather weak light emissivity of FILD in this discharge. However, we obtained a reasonable quality footprint integrating the scintillator light emission in the whole interested period $t = 10\text{ s} - 10.8\text{ s}$ (figure 9a). Selecting the large gyro-radius area related to high-energy ions, as shown in figure 9a ($\rho_{gyr} \approx 11\text{ cm} - 13.5\text{ cm}$, $\theta \approx 60^\circ - 66^\circ$), we produced a waveform of losses, which is presented in figure 9b. This waveform demonstrates increase of the loss rate during TAEs ($t \approx 10\text{ s} - 10.4\text{ s}$) with a sawtooth crash peak at $\approx 10.4\text{ s}$. Also, two strong peaks of losses related to EAEs excited in the periods $t \approx 10.6\text{ s} - 10.7\text{ s}$ and $t \approx 10.7\text{ s} - 10.8\text{ s}$.

Using the data presented in figure 9a, we obtained a pitch-angle distribution of lost ions with $\rho_{gyr} = 13\text{ cm}$ related to energies $E_i \approx 6\text{ MeV}$ of ${}^3\text{He}$ -ions (figure 10). One can see that maximum of the distribution is at $\theta \approx 64^\circ$. It is important to note that the major radius at the ion bounce reflection and the pitch-angle θ of the grid are related by

$$R(\theta) = R_{FILD} \sin^2\theta, \quad (2)$$

where $R_{FILD} = 3.825\text{ m}$ is radial position of the FILD scintillator in the vessel. We calculated orbits of escaping ${}^3\text{He}$ -ions with pitch-angle $\theta = 64^\circ$ back-in-time from the FILD scintillator plate (figure 11). The orbits with gyro-radii $\rho_{gyr} = 10\text{ cm}$ and 13 cm have the turning points at 2.90 m and 2.85 m consequently, i.e. they are in the vicinity of the MC layer, the region where an intense wave damping occurs by ${}^3\text{He}$ -ions.

3. Results of MHD analysis

In these experiments core localized TAEs (“tornados”) with frequency $f_{TAE} \approx 280\text{ kHz}$ were observed. Following the phase with excitation of TAEs, strong EAEs at higher frequencies $f_{EAE} \approx 550\text{-}580\text{ kHz}$ with mode numbers $n=1, 3, 5$ were seen. The high frequency modes indicate that the MeV range ${}^3\text{He}$ -ions in the plasma are interacting with the modes via $\omega = n\omega_\phi - p\omega_\theta$ resonance (here ω , n are the frequency and toroidal mode number of AE, ω_ϕ and ω_θ are toroidal precession drift and bounce frequencies of the hot ions, and p is integer). For moderate bounce angle the strongest wave-particle energy transfer is expected for values of p close to $p = 0$ [16]. Calculations of ω_ϕ and ω_θ were performed for unperturbed ${}^3\text{He}$ -ion orbits with the HAGIS code [17].

The TAE resonance condition analysis shows (figure 12) that the mode with frequency and toroidal number $f=280\text{kHz}$, $n=3$ could be excited by ${}^3\text{He}$ -ions in the energy range 3 – 4 MeV. In the case of EAEs $n=3$, $p=[-2,-1,0]$, the strongest wave particle interaction is expected ion energies of $E_{3\text{He}} \approx 6$ MeV to excite the modes with 560kHz (figure 13a). However, for EAEs with $n=1$, the resonance map shows that the modes with 560kHz are much more difficult to excite and only $p = -2$ appearing at these energies (figure 13b).

During the studied discharge, we did not measure the q -profile with MSE diagnostics. Nevertheless, for the MHD analysis, the EFIT equilibrium has been used, which was reprocessed with pressure constraint, giving good agreement with MHD spectroscopy on the ECE diagnostic data, i.e. MHD markers $q = 1.5$ at 3.37 ± 0.05 m; a weak $n=3$ mode, which gave us the position of $q=4/3$ ($q \approx 1.33$ at 3.32 ± 0.05 m); sawteeth indicated that $q=1$ at 3.15 ± 0.05 m. Figure 14 depicts the q -profile provided by the pressure-constrained EFIT.

The linear MHD code MISHKA [18] identified a core localised $n=3$ EAE with frequency 539 kHz, giving agreement within $\sim 5\%$ of measured values, however the ideal MHD EAE solution was obtained only for the radial positions inside the $q \approx 1.33$ surface, where the EAE gap in the Alfvén continuum closes. The calculated EAE electrostatic potential is presented in figure 15 together with orbits of lost ${}^3\text{He}$ -ions with gyro-radii 10 cm (a) and 13 cm (b) that was calculated back-in-time from the FILD scintillator plate (figure 11). The loss orbits with $\rho_{\text{gyr}} \approx 10$ cm – 13 cm are crossing inside $R = 3.3$ m and therefore interact with the ideal MHD EAE. Non-ideal effects are required to resolve mode beyond $R = 3.3$ m. It is important to note that calculated orbits are related to ions with the pitch-angle $\theta = 64^\circ$ that have the bounce reflections in the region of the MC layer. Hence, the MHD analysis gives the mode locations, which are consistent with the experimental observations.

4. Summary and conclusions

The EAE and TAE instabilities were observed in hydrogen-rich, $n_H/n_{H+n_D} \sim 70\text{-}90\%$, JET discharges of the D -(${}^3\text{He}$)- H three-ion ICRH scenario, which has demonstrated a strong absorption of radio frequency waves at very low concentrations ($<1\%$) of the resonant ${}^3\text{He}$ -ions. In the experiments, core localized TAEs with a frequency $f_{\text{TAE}} \approx 280$ kHz were observed. Following the phase with TAEs excitation, EAEs at higher frequencies $f_{\text{EAE}} \approx 550\text{-}580$ kHz with mode numbers $n=1, 3, 5$ were seen. These high frequency modes indicate that a MeV range population of trapped energetic ions was present in the plasma interacting with the modes via $\omega=n\omega_\phi - p\omega_\theta$ resonance. The experimental evidence of the existence in the plasma of the MeV-energy ${}^3\text{He}$ -ions, which are able to excite the AEs, is provided by neutron and gamma-

ray diagnostics as well as fast ion loss measurements. It was found that the anomalous DD neutron rate in the ICRF-only heated plasma was provided by a population of energetic deuterons formed via knock-on effect: $D(^3He, ^3He)D_{\text{knock-on}} \Rightarrow D(D_{\text{knock-on}}, n)^3He$. Gamma-ray diagnostics showed that some neutrons are also generated in the nuclear reaction $^9Be(^3He, n)^{11}C$, which takes place with 3He -ions in the MeV-range. The fast ion loss detector indicated that the MeV 3He -ion losses related to the core localized TAEs ended with a spike associated with a monster sawtooth, after which the losses correlated with the EAE modes were observed. The analysis of FILD data indicates that the lost 3He -ion energies exceed 2 MeV. The MHD analysis results are consistent with the experimental data showing that the MeV 3He ions are resonant, when interacting with TAE and EAE modes.

These experiments are mimicking the conditions representative for ITER plasmas and contribute to both the understanding of fast-ion interaction with MHD modes and the understanding of the impact of energetic ions on the plasma turbulence, in particular, the impact of alphas in ITER [19].

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053 and from the RCUK Energy Programme [grant No EP/T012250/1]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ukaea.uk. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Captions

Fig.1. Resonant layers in the “three-ion” scenario experiment with the central toroidal magnetic field $B_T(0) = 3.1$ T and $f = 32.5$ MHz.

Fig.2. Waveforms and signals of some key quantities of the “three-ion” scenario discharge #91304 at $B_T(0) = 3.1$ T, $I_p = 1.8$ MA with $P_{ICRH} \approx 4.5$ MW at $f_{ICRH} \approx 32.5$ MHz; T_{e0} – the central electron temperature, W_p – the plasma energy and $H/(H+D)$ – a relative concentration of hydrogen.

Fig.3. Magnetic spectrograms of TAEs (the upper figure) and EAEs (the bottom figure) exited during the period $t = 9.8 - 10.8$ s in the discussed JET discharge.

Fig.4. Results of gamma-ray spectrum analysis. The upper figure: spectrum recorded during $t = 8.0 - 10.3$ s (black); the bottom figure: gamma-ray spectrum deconvoluted with DeGaSum [8]; gamma-ray energies related to the reactions ${}^9\text{Be}({}^3\text{He}, n\gamma){}^{11}\text{C}$ (grey) and ${}^9\text{Be}({}^3\text{He}, p\gamma){}^{11}\text{B}$ (black). The re-convoluted spectrum is shown in the upper figure in red.

Fig.5. (a) - energy distributions of ${}^3\text{He}$ -ions obtained from gamma-ray spectra recorded in the periods of the discharge 8.0-10.3 s (black line) and 10.3 – 14 s (red line); (b) – the PION calculation results the radial dependence of the ${}^3\text{He}$ -ion tail temperature as a function of the square root of normalized poloidal flux s .

Fig.6. Waveforms and signals of the discharge discussed in the paper; $D/(H+D)$ – a relative concentration of deuterium.

Fig.7. Neutron rate measured during the discharge and calculated by TRANSP in 6 time slots with D-ion densities averaged over the time slot.

Fig.8. Footprints of losses in the discharge #91304 recorded with CCD camera: (a) in the period 9.94s – 10.34s during the TAEs; (b) during the monster sawtooth crash 10.39s – 10.41s.

Fig.9. (a) footprint of losses in the discharge #91304 recorded with CCD camera in the period 9.94s – 10.79s during the TAEs, the monster sawtooth crash and EAEs; the yellow line shows the area used for making a waveform presented in figure (b): waveform of losses related to the scintillator areas designated in figure 9a, which show a strong correlation with appearance of the TAE and EAE modes in the discharge.

Fig.10. The pitch-angle distribution of lost ions with $\rho_{gyr} = 13$ cm obtained from the FILD footprint data presented in figure 9a.

Fig.11. Orbits of ${}^3\text{He}$ -ions with gyro-radii 10 and 13 cm and pitch-angle 64° calculated back-in-time from the FILD scintillator plate; these parameters are related to the footprint presented in figure 9.

Fig.12. A resonance map $\omega = n\omega_\phi - p\omega_\theta$ for TAEs with frequency $f = 280$ kHz and toroidal number $n = 3$.

Fig.13. A resonance map $\omega = n\omega_\phi - p\omega_\theta$ for EAEs with frequency $f = 560$ kHz and toroidal numbers: (a) $n = 3$ and; (b) $n = 1$.

Fig.14. q-profile used for MHD analysis.

Fig.15. The mode electrostatic potential shows location of the EAE modes. Orbits of ${}^3\text{He}$ -ions with gyro-radii 10 cm (a) and 13 cm (b) and pitch-angle 64° calculated back-in-time from the FILD scintillator plate (see figure 11).

Figures

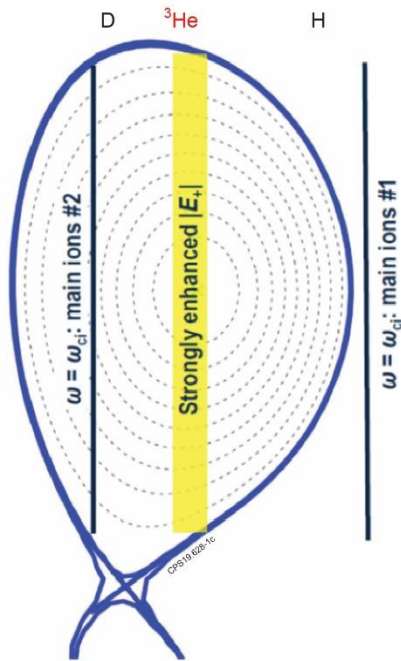


Figure 1.

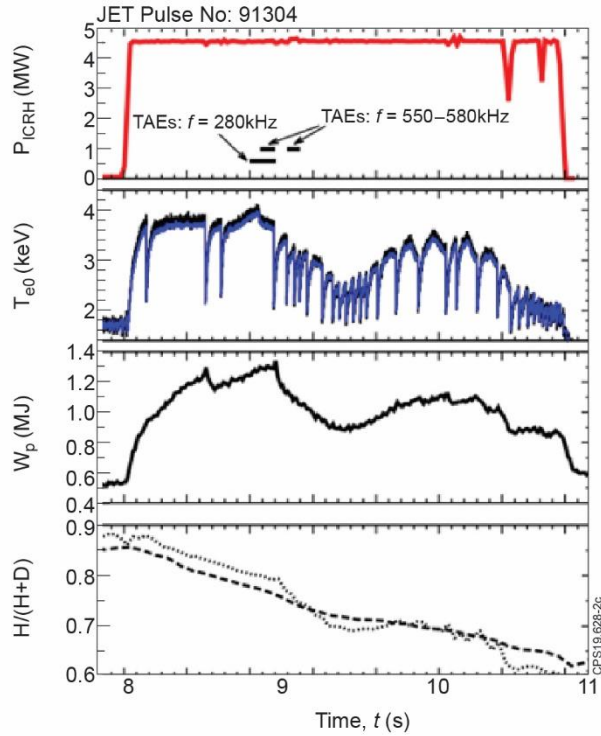


Figure 2

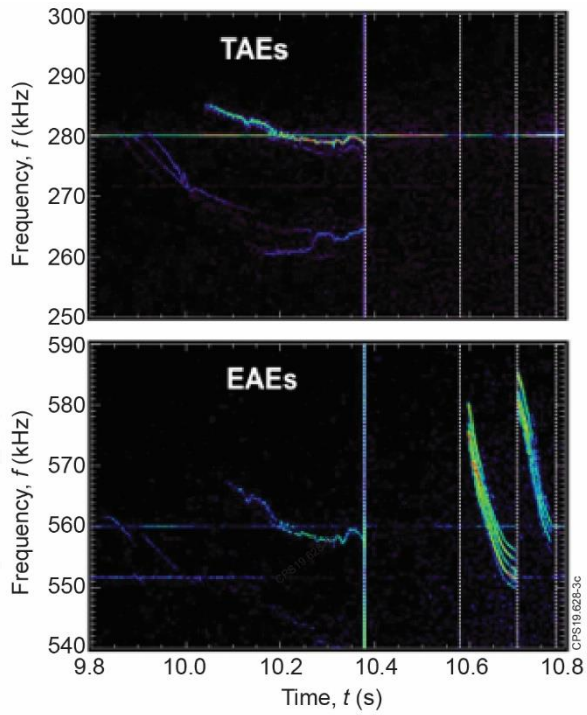


Figure 3

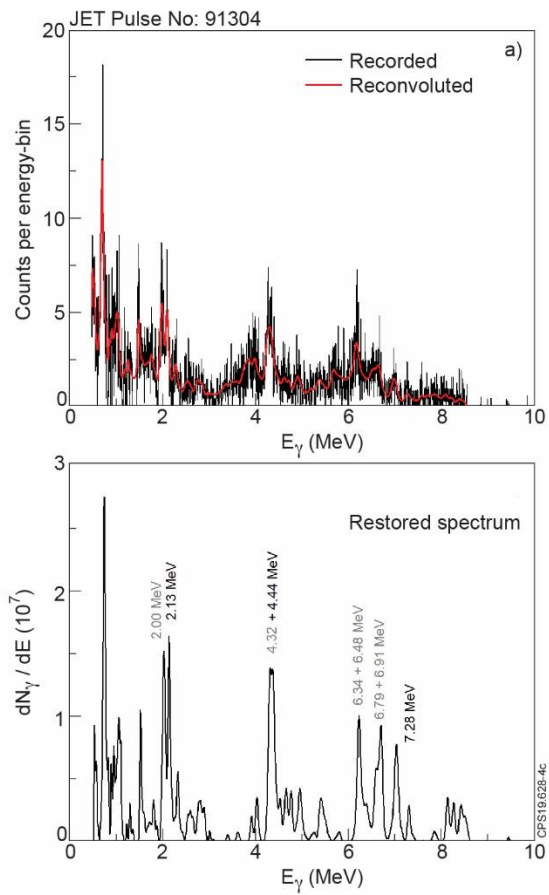


Figure 4

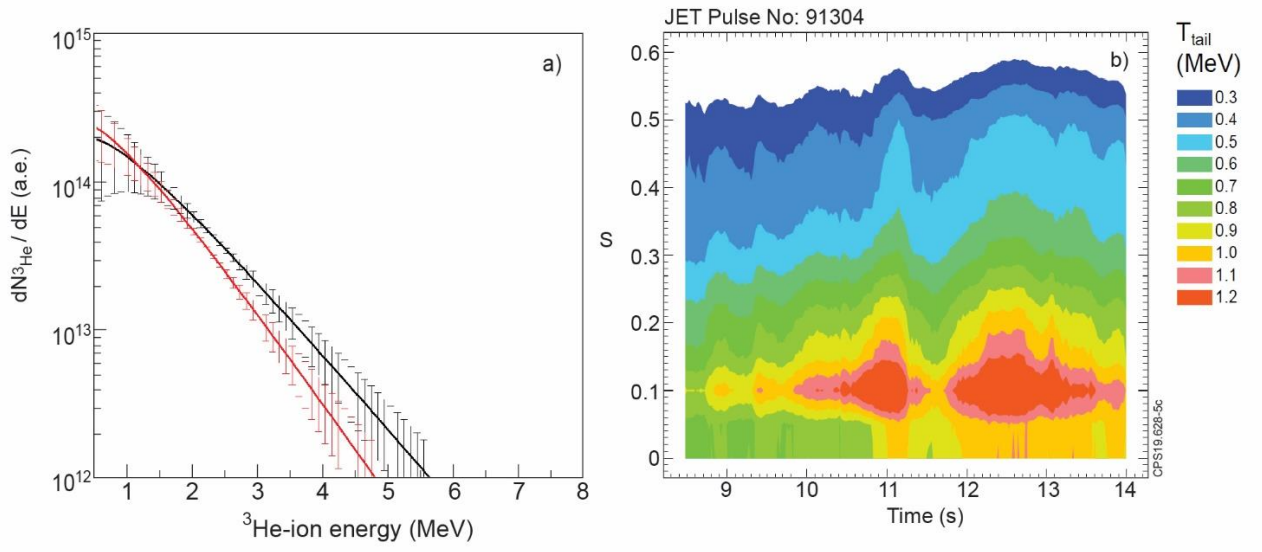


Figure 5

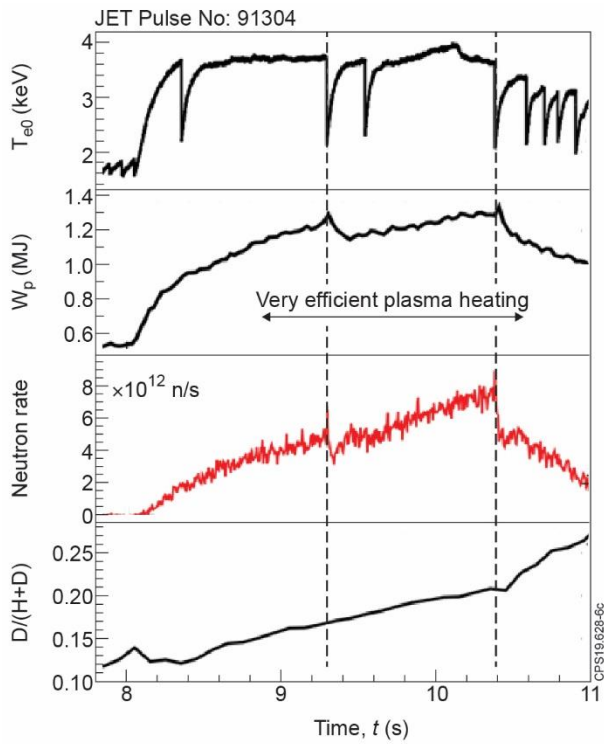


Figure 6

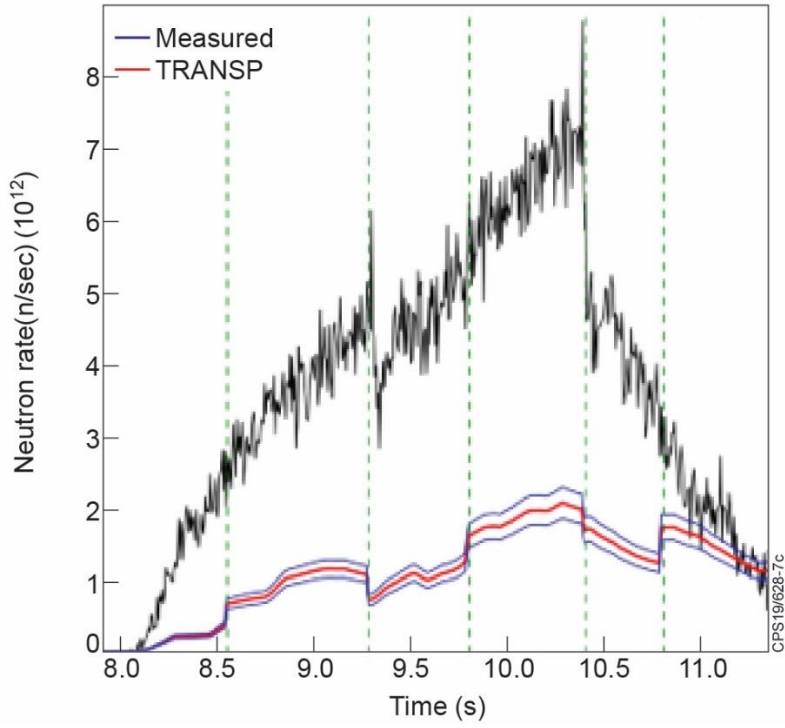


Figure 7

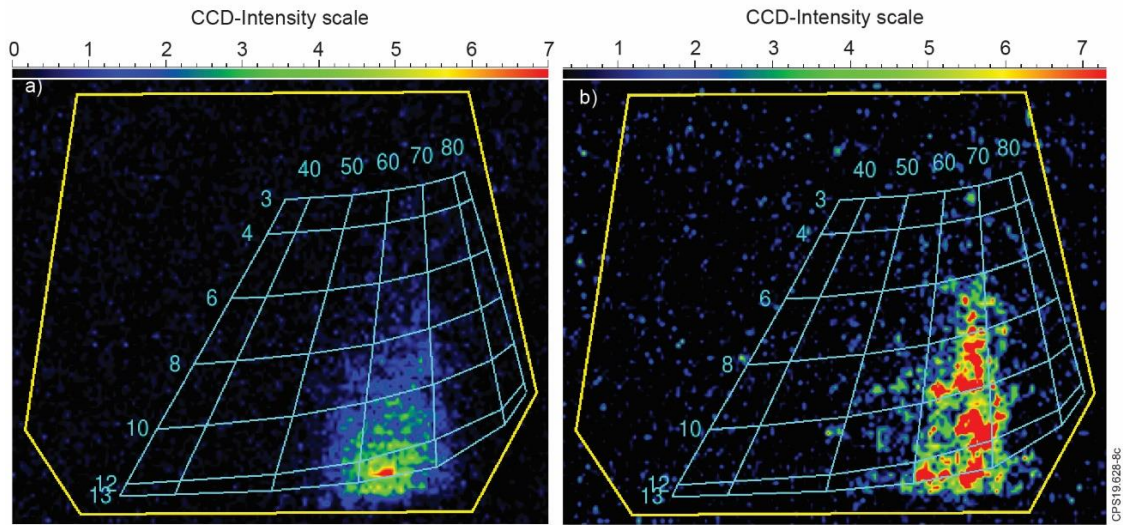


Figure 8

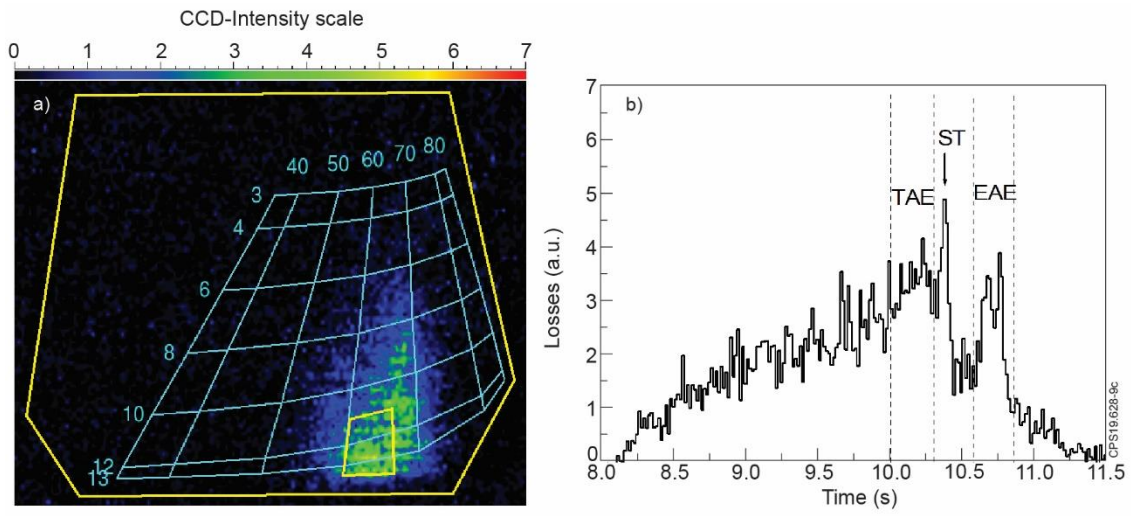


Figure 9

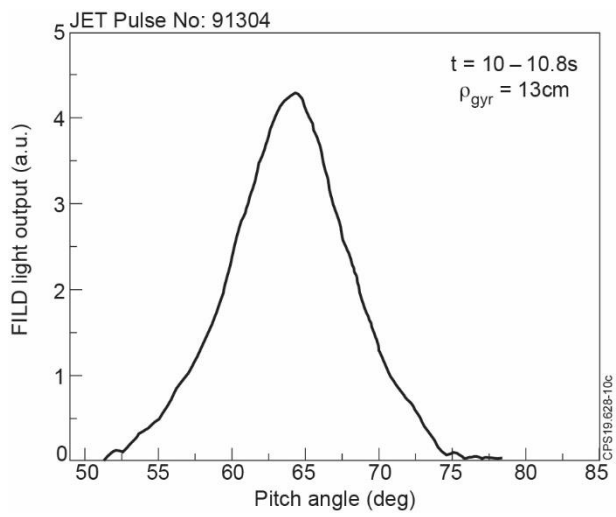


Figure 10

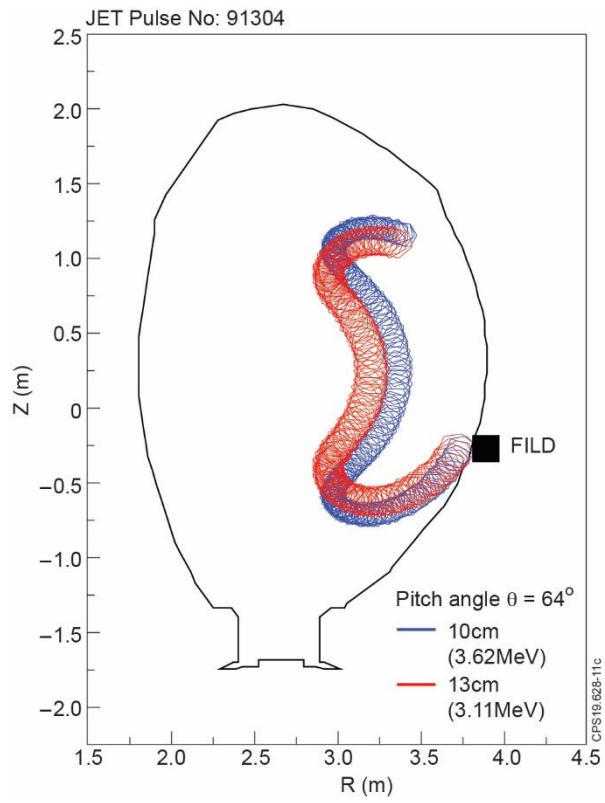


Figure 11

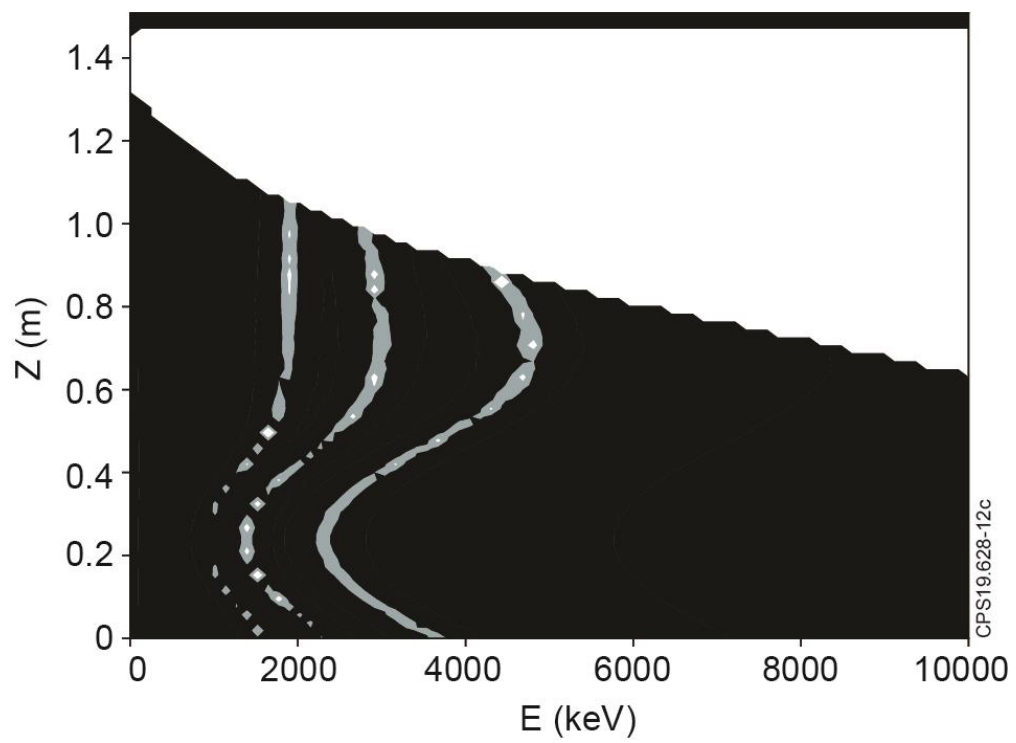


Figure 12

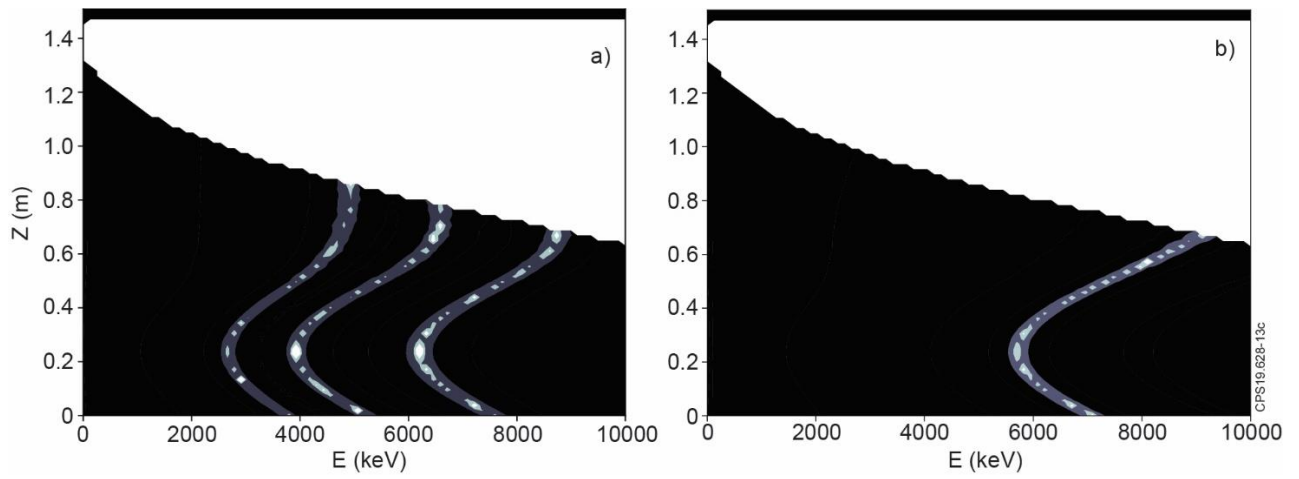


Figure 13

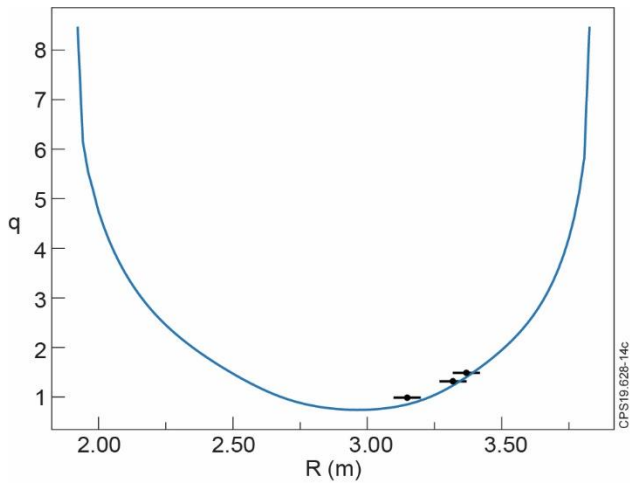


Figure 14

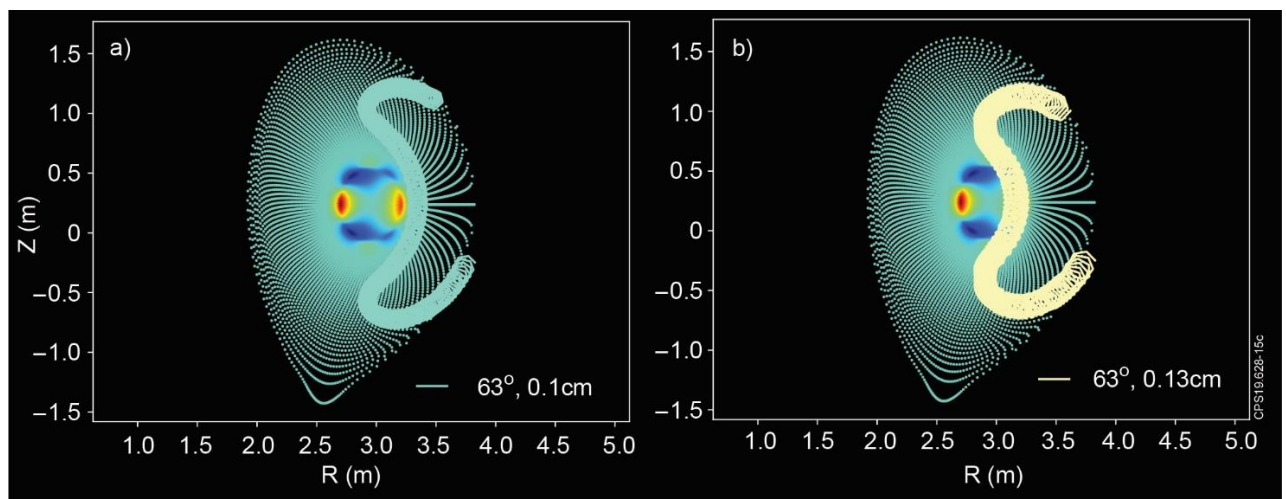


Figure 15