Efficient generation of energetic ions in multi-ion plasmas by radio-frequency heating

Ye.O. Kazakov[1], J. Ongena[1], J.C. Wright[2], S.J. Wukitch[2], E. Lerche[1], M. Mantsinen[3,4], D. Van Eester[1], T. Craciunescu[5], V.G. Kiptily[6], Y. Lin[2], M. Nocente[7], F. Nabais[8], M.F.F. Nave[8], Y. Baranov[6], J. Bielecki[9], R. Bilato[10], V. Bobkov[10], K. Crombé[1], A. Czarnecka[11], J. Faustin[12], R. Felton[6], M. Fitzgerald[6], D. Gallart[3], L. Giacomelli[7], T. Golfinopoulos[2], A. Hubbard[2], Ph. Jacquet[6], T. Johnson[13], M. Lennholm[6], T. Loarer[14], M. Porkolab[2], S. Sharapov[6], D. Valcarcel[6], M. Van Schoor[1], H. Weisen[15], JET Contributors[16] and the Alcator C-Mod Team[2]

[1] *Laboratory for Plasma Physics, LPP-ERM/KMS, TEC Partner, Brussels, Belgium*
[2] *Massachusetts Institute of Technology, Plasma Science and Fusion Center, Cambridge, USA*
[3] *Barcelona Supercomputing Center (BSC), Barcelona, Spain*
[4] *ICREA, Pg. Lluis Companys 23, 08010 Barcelona, Spain*
[5] *National Institute for Laser, Plasma and Radiation Physics, Bucharest, Romania*
[6] *Culham Centre for Fusion Energy (CCFE), Culham Science Centre, Abingdon, UK*
[7] *Istituto di Fisica del Plasma, CNR, Milan, Italy*
[8] *Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal*
[9] *Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*
[10] *Max-Planck-Institut für Plasmaphysik, Garching, Germany*
[11] *IPPLM, EUROfusion Association, Warsaw, Poland*
[12] *EPFL, Swiss Plasma Center (SPC), Lausanne, Switzerland*
[13] *KTH Royal Institute of Technology, Stockholm, Sweden*
[14] *IRFM, Association EUROfusion-CEA, Saint-Paul-Lez-Durance, France*
[15] *EUROfusion Programme Management Unit, Culham Science Centre, Abingdon, UK*
[16] *See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17–22 October 2016)*

We describe a new technique for efficient generation of high-energy ions with electromagnetic ion cyclotron waves in multi-ion plasmas. The discussed 'three-ion' scenarios are especially suited for strong wave absorption by a very low number of resonant ions. To observe this effect, the plasma composition has to be properly adjusted, as prescribed by theory. We demonstrate the potential of this technique on the world-largest plasma magnetic confinement device JET (Joint European Torus, Culham, UK) and the high magnetic field tokamak Alcator C-Mod (MIT, USA). The obtained results demonstrate efficient acceleration of ^{3}He ions to high energies in dedicated hydrogen-deuterium mixtures. Simultaneously, effective plasma heating is observed, as a result of the slowing-down of the fast ^{3}He ions. The developed technique is not only limited to laboratory plasmas, but can also be applied to explain observations of energetic ions in space plasma environments, in particular, ^{3}He-rich solar flares.

Accepted version of the paper published in *Nature Physics (2017)*
http://dx.doi.org/10.1038/nphys4167

In magnetized plasmas, charged particles gyrate around the magnetic field lines with their characteristic cyclotron frequencies $\omega_{cs} = q_s B/m_s$, where q_s is the particle's charge, m_s is the particle's mass, and B is the local magnitude of the magnetic field. A variety of strong wave-particle interactions is possible when the wave frequency is close to the particle's cyclotron frequency or its harmonics[1-3]. Ion cyclotron resonance heating (ICRH) is a powerful tool used in toroidal magnetic fusion research. In recent decades, several efficient ICRH scenarios were identified theoretically and verified experimentally[2-4]. In brief, this technique relies on external excitation of fast magnetosonic waves in the plasma, using specially designed ICRH antennas located at the edge of the device (see Fig. 1a). Antennas consist of a series of metallic straps that carry radio-frequency (RF) currents at a given frequency delivered by an external generator. The radially varying toroidal magnetic field then determines the location of the ion cyclotron layers $\omega = p\omega_{ci}$ ($p = 1, 2,\ldots$), in the vicinity of which the RF power can be efficiently absorbed by ions.

The electric field of the excited fast waves can be decomposed as a sum of the left-hand polarized component E_+, rotating in the sense of ions, and the oppositely rotating right-hand component E_-. Wave absorption by non-energetic ions is evidently facilitated by the presence of a sufficiently large E_+ near the ion cyclotron resonance. To illustrate this, we note that fundamental cyclotron heating in single-ion plasmas is ineffective since E_+ almost vanishes at $\omega \approx \omega_{ci}$.

The choice of plasma composition, namely the number of ion species and their relative concentrations, allows to control the radial dependence of the ratio E_+/E_-. In two-ion plasmas with one main ion species and a few % of minority ions with q_i/m_i different from that for the main ions, RF power absorption at the minority ion cyclotron frequency is strongly enhanced[5,6]. These minority heating scenarios benefit from the enhanced E_+ in the vicinity of the ion-ion hybrid (IIH) cutoff-resonance pair, located close to the minority cyclotron resonance[2]. If the IIH layer is not present in the plasma, as is the case at very low minority concentrations in two-ion plasmas, the RF power absorption by minorities is very limited. On the other hand, at minority concentrations significantly above the optimal value of a few %, the IIH pair is located too far away from the minority cyclotron layer, thus reducing again their absorption efficiency. Instead, such plasmas are typically used for localized electron heating through mode conversion (see ref. 7 for more details).

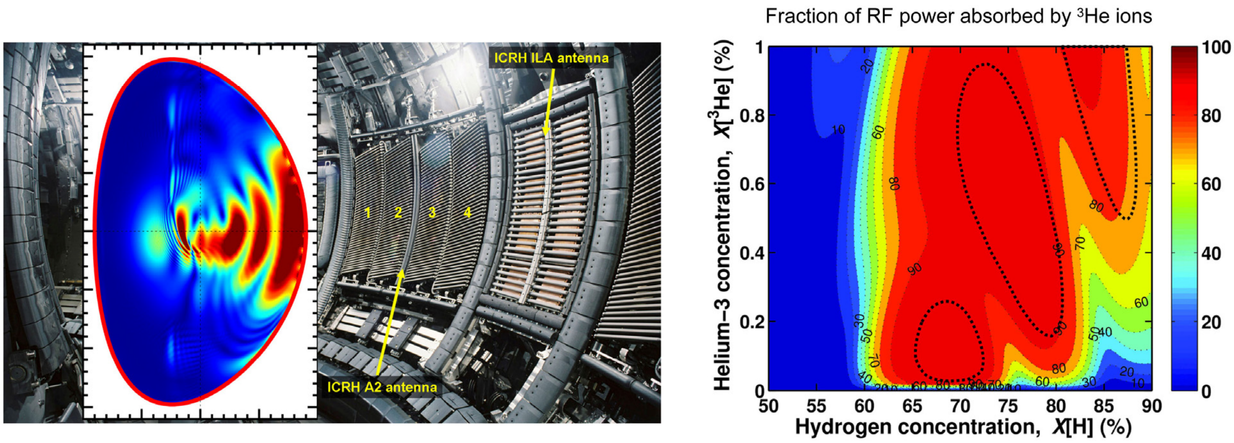

Figure 1 | A new technique for fast-ion generation in magnetized multi-ion plasmas. The goal of our study is to validate that in properly chosen multi-ion plasmas electromagnetic ion cyclotron waves can be effectively absorbed by a very low number of resonant ions ($\omega \approx \omega_{ci}$). This technique opens the possibility of high-efficiency generation of energetic ions in magnetized plasmas. **a,** Inside view of the world-largest magnetic confinement fusion device, Joint European Torus, showing different ion cyclotron resonance heating (ICRH) antennas at the edge. The insert shows an example of the computed RF electric field pattern in a cross-section of the JET plasma. **b,** 'Three-ion' scenarios require resonant ions with a (Z/A) ratio in between that of the two main ions, essentially following the 'sandwich' principle $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$. The figure shows the fraction of RF power absorbed by ^{3}He minority ions for the D-(^{3}He)-H three-ion scenario as a function of H and ^{3}He concentrations. The computations were made by the TOMCAT code for the parameters of the JET experiments discussed in this paper (B_0= 3.2T, f=32.5MHz, $n_{e0} = 4\times10^{19}\ \mathrm{m}^{-3}$, $T_0 = 4$ keV, $k_{\parallel}^{(\mathrm{ant})} = 3.4\ \mathrm{m}^{-1}$). The zones within the dotted lines correspond to a single-pass absorption larger than 50%. The code predicts wave absorption by a tiny amount of ^{3}He ions (~0.1–0.2%) in H-D plasmas with H concentrations in the range 70-80%, in agreement with Eq. (2).

There is, however, an elegant way to use mixture plasmas to channel RF power to ions: simply add a third ion species with a cyclotron resonance layer close to the IIH cutoff-resonance pair. Under these conditions, a new IIH pair appears in close proximity to the cyclotron resonance of the third ion species, even if their concentration is extremely low! For this heating scheme to work, the Z/A value of the resonant ions should be 'sandwiched' between that of the two main plasma ions

$$(Z/A)_2 < (Z/A)_3 < (Z/A)_1, \qquad (1)$$

where Z_i and A_i are the charge state and the atomic mass of ion species i. We use indices '1' and '2' for the main ions with the largest and lowest cyclotron frequencies, respectively, and index '3' for the absorbing minority. Depositing nearly all RF power to a very small number of minority ions is maximized in plasmas with main ion concentrations[8,9]

$$X_1^* \approx \frac{1}{Z_1}\frac{(Z/A)_1-(Z/A)_3}{(Z/A)_1-(Z/A)_2},\ X_2^* \approx \frac{1}{Z_1}\frac{(Z/A)_3-(Z/A)_2}{(Z/A)_1-(Z/A)_2}, \tag{2}$$

where $X_i = n_i/n_e$. Heating minority ions at higher concentrations is equally possible; plasma mixtures with $X_1 \gtrsim X_1^*$ are more optimal in this case[10]. The method can also be extended to plasmas containing more than three ion species by adapting slightly the plasma composition. For proof-of-principle demonstration, we select a plasma mixture composed of two hydrogen isotopes, H ions with (Z/A)=1 and the heavier D ions with (Z/A)=1/2, and ^{3}He ions with their unique (Z/A)=2/3 as a resonant absorber. Equation (2) predicts that ^{3}He ions should efficiently absorb RF power in H-D or H-^{4}He plasmas, if the hydrogen concentration is ~ 67%. This is supported by modeling with the TOMCAT code[11], using plasma parameters relevant for the JET experiments described below. Figure 1b shows dominant RF power absorption by a small amount of ^{3}He ions, down to concentrations $X[^3\mathrm{He}] \approx$ 0.1-0.2%. Plasma heating with the three-ion D-(^{3}He)-H scenario at higher $X[^3\mathrm{He}] \approx$ 0.5–1% is equally possible. We note that the recipe for the plasma composition given by Eq. (2) is valid for fast magnetosonic waves, excited at the low magnetic field side and propagating towards regions with increasing B, as in most of present-day fusion machines.

Efficient plasma heating with three-ion ICRH scenarios: A series of dedicated experiments were performed on the Alcator C-Mod tokamak[12] (MIT, USA; major radius R_0=0.67m, minor radius a_{pl}=0.23m) and on the world-largest magnetic fusion device JET (Joint European Torus, Culham, UK; $R_0 \approx$3m, $a_{pl} \approx$1m). The goal of these studies was to demonstrate that indeed a small amount of ^{3}He ions can efficiently absorb RF power in H-D mixtures. The Alcator C-Mod experiments were run at high central electron densities $n_{e0} \approx (2–3)\times10^{20}$ m^{-3} and very high toroidal magnetic field B_0 = 7.8T at a plasma current I_p = 1.2 MA. In the JET experiments, $n_{e0} \approx 4\times10^{19}$ m^{-3} and B_0 = 3.2T, I_p = 2.0MA were used. Accordingly, ICRH frequencies $f=\omega/2\pi$ =78.0–80.0 MHz (Alcator C-Mod) and f=32.2–33.0 MHz (JET) were chosen to locate the ^{3}He cyclotron resonance in the plasma center in both devices. The Alcator C-Mod plasmas were heated with 4–5 MW of ICRH power only. In JET plasmas, 3.2 MW of neutral beam injection (NBI) was added prior to applying ~4 MW of ICRH.

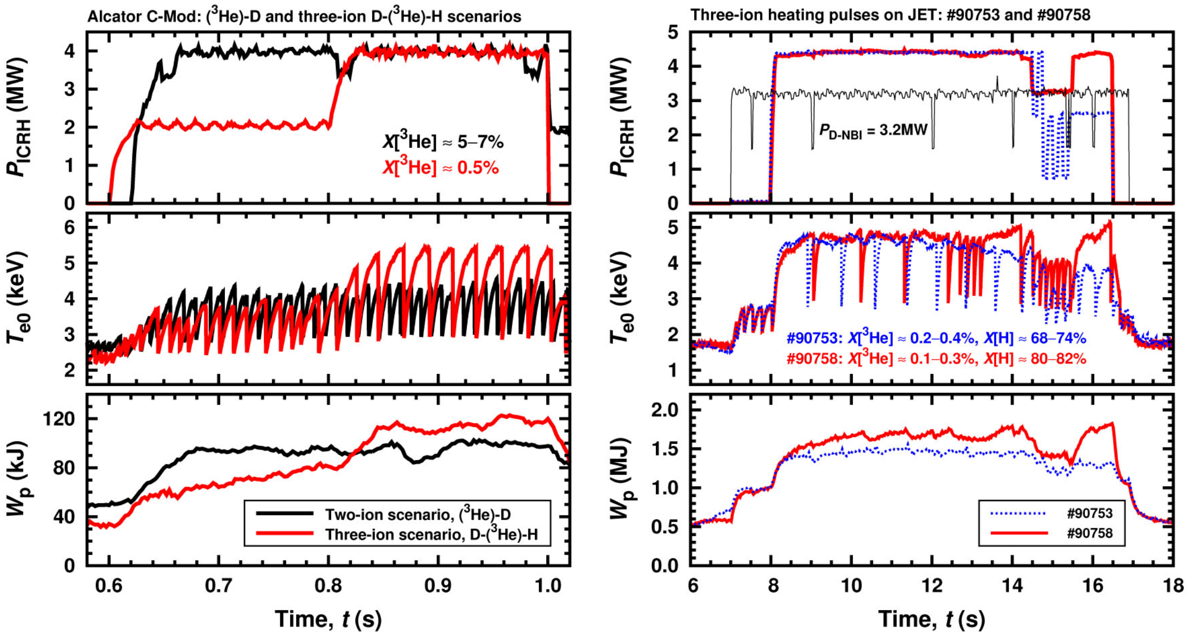

Figure 2 | Illustration of the performance of the D-(^{3}He)-H three-ion ICRH scenario on Alcator C-Mod and JET tokamaks. a, Alcator C-Mod three-ion heating pulse (#1160901009, $X[^3\text{He}] \approx 0.5\%$, red) and (^{3}He)-D pulse (#1160823003, $X[^3\text{He}] \approx 5\text{–}7\%$, black). **b,** JET three-ion heating pulses #90753 ($X[\text{H}] \approx 68\text{–}74\%$, $X[^3\text{He}] \approx 0.2\text{–}0.4\%$, blue) and #90758 ($X[\text{H}] \approx 80\text{–}82\%$, $X[^3\text{He}] \approx 0.1\text{–}0.3\%$, red). While a few % of ^{3}He is needed for minority heating in H or D majority plasmas, strong wave absorption in H-D plasmas is achieved with about ten times less ^{3}He.

Figure 2 shows the time evolution of the central electron temperature T_{e0} and plasma stored energy W_p in response to the applied ICRH on Alcator C-Mod and on JET. These results confirm our earlier predictions (Fig. 1b) for the efficiency of ^{3}He absorption at concentrations of a few per mille (‰) in H-D plasmas. The optimal ^{3}He concentration for this scenario in C-Mod plasmas was approximately $X[^3\text{He}] \approx 0.5\%$. In JET, even lower ^{3}He concentrations ~ 0.2% were successfully applied.

In JET experiments, the edge isotopic ratio H/(H+D) was varied between 0.73 and 0.92 and the ^{3}He concentration between 0.1% and 1.5% to assess the sensitivity of ICRH on the detailed plasma composition. The core hydrogen concentration was estimated from the measured edge H/(H+D) ratio as $X[\text{H}] \approx 0.9 \times \text{H/(H+D)}$, accounting for the presence of impurities in the plasma and additional D core fuelling from the D-NBI system. We find efficient plasma heating for a fairly broad range of the isotopic ratio (see also supplementary Figs. S5 and S6). In particular, central plasma heating with $\Delta T_{e0}/\Delta P_{ICRH} > 0.5$ keV/MW was observed for H/(H+D) ≈ 0.78–0.91 mixtures at ^{3}He concentrations below 0.5%.

Figure 2a also includes the evolution of T_{e0} and W_p for ^{3}He minority heating in the Alcator C-Mod D plasma with $X[^3\mathrm{He}] \approx$ 5-7% (pulse 1160823003). Compared to this (^{3}He)-D scenario, the three-ion heating scenario in C-Mod showed a larger increase in the plasma stored energy ($\Delta W_p/\Delta P_{ICRH}$ = 22 kJ/MW vs. 14 kJ/MW).

A direct comparison of the heating performance of the three-ion discharges was not possible for the JET discharges discussed here. It can however be assessed comparing the measured thermal plasma energy to the one derived from a so-called scaling law. These scaling laws predict the energy confinement value for a given plasma experiment as a function of specific engineering parameters (I_p, B_0, n_e, …)[13] and result from a statistical analysis of data collected from multiple tokamaks worldwide. Here, we use the well-established ITERL96-P and IPB98(y,2) scaling laws for the energy confinement time τ_E (Eqs. (24) and (20) in ref. 13) for L-mode and H-mode tokamak plasmas. τ_E is the characteristic time during which the plasma maintains its energy if the heating power is suddenly switched off[1]. Under stationary conditions it is given by the ratio of the stored plasma energy divided by the total heating power. The Supplementary Information (Figs. S1–S4) shows the results obtained for L-mode JET discharges heated with different ICRH minority scenarios, including the ratios $\tau_E/\tau_{E,\,scaling}$. From the definition of τ_E given above, it follows immediately that $\tau_E/\tau_{E,\,scaling}$ is equal to the ratio of the corresponding stored energies. For the three-ion heating pulse #90758 (Fig. 2b), we obtain $\tau_E/\tau_{IPB98(y,2)} \approx$ 0.85–0.88 and $\tau_E/\tau_{ITERL96\text{-}P} \approx$ 1.43–1.48. This compares very well to $\tau_E/\tau_{E,\,scaling}$ values for the excellent (H)-D minority heating scenario in JET plasmas (Fig. S1).

Efficient generation of high-energy ions: Energetic ions play a crucial role in fusion plasmas[14]. Indeed, the success of magnetic fusion relies upon good confinement of energetic alpha particles (^{4}He ions with birth energies 3.5 MeV). This is required to sustain high plasma temperatures and for economical operation of a fusion reactor[1]. However, these energetic ^{4}He ions can also trigger instabilities that degrade the plasma performance. To mimic the behaviour of fusion-born alphas, but without actually using D-T plasmas, ICRH has been extensively used in the past.

For fundamental ion cyclotron absorption the acquired ion energies scale with the absorbed RF power per particle[15]. Since three-ion scenarios allow minimizing the number of resonant particles down to ‰ levels, rather high-energy ions can be generated. For plasma densities and ICRH power levels available in the JET and C-Mod experiments, self-consistent power deposition computations with the codes AORSA[16], PION[17] and SCENIC[18] predicted acceleration of ^{3}He ions to energies of a few MeV.

Figure 2b shows fast repetitive drops in T_{e0} (so-called 'sawtooth' oscillations) with a period of ~0.2 s during the NBI-only phase of JET pulses #90753 and #90758 (t = 7-8 s). Extended sawtooth periods up to ~1.0 s are seen when ICRH is applied on top of NBI. Similarly, in the three-ion Alcator C-Mod discharge in Fig. 2a, the sawtooth period increases from ~0.13 s during the 2 MW ICRH phase to ~0.23 s during the 4 MW phase. The observation of long-period sawteeth is a first indication of the creation of energetic ions by ICRH, as the presence of fast ions in a plasma is well-known to have a stabilizing effect on sawteeth[19,20].

An independent confirmation of accelerating ^{3}He ions to high energies is provided by gamma-ray emission spectroscopy on JET[21,22]. Figure 3a displays the gamma-ray spectrum for pulse #90753 during t = 8–14 s (P_{ICRH} = 4.4 MW), recorded with the $LaBr_3$ spectrometer[23]. The observed lines originate from ^{9}Be(^{3}He, $p\gamma$)^{11}B and ^{9}Be(^{3}He, $n\gamma$)^{11}C nuclear reactions between fast ^{3}He ions and beryllium (^{9}Be) impurities. These impurities are intrinsically present in JET plasmas with the ITER-like wall. The reported plasmas were contaminated with ~0.5% ^{9}Be, as estimated by charge exchange measurements.

The observation of the $E_\gamma \approx 4.44$ MeV line implies immediately the presence of confined fast ^{3}He ions with energies > 0.9 MeV[21]. Alpha particles, born in concurrent ^{3}He-D fusion reactions, also contribute to the gamma-emission at this energy through ^{4}He+^{9}Be reactions. Figure 3a also shows a number of characteristic gamma lines at $E_\gamma > 4.44$ MeV, originating from transitions between higher excited states of ^{11}B and ^{11}C nuclei (products of ^{3}He + ^{9}Be reactions). The excitation efficiency for such high-energy levels increases by a factor of 10 when the energy of the projectile ^{3}He ions increases from 1 MeV to 2 MeV[24]. For comparison, we also display the γ-spectrum recorded in JET pulse #91323, in which ^{3}He ions (≈ 2%) were heated as a minority with up to 7.6 MW of ICRH in an almost pure H plasma (see supplementary Fig. S3). Figure 3a clearly shows higher gamma-count rates for the three-ion pulse #90753 (X[^{3}He]≈ 0.2–0.3%), although a factor of two less ICRH power was injected into the plasma.

In JET, we further enhanced the efficiency for fast-ion generation by changing the configuration of ICRH antennas from dipole to $+\pi/2$ phasing. The phasing defines the dominant $k_\parallel$ and the spectrum of emitted waves, where $k_\parallel$ is the wavenumber parallel to B. The $+\pi/2$ phasing launches waves predominantly in the direction of the plasma current with typical values $k_\parallel^{(\mathrm{ant})} \approx 3.4\ \mathrm{m}^{-1}$, which is two times smaller than for dipole phasing ($k_\parallel^{(\mathrm{ant})} \approx 6.7\ \mathrm{m}^{-1}$). Since the width of the absorption zone scales with $|k_\parallel|$, reducing it has the

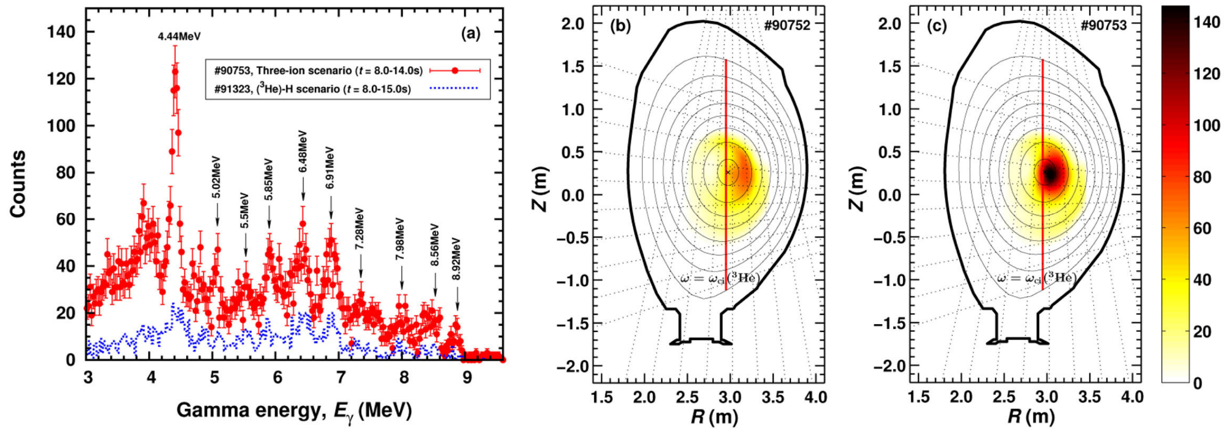

Figure 3 | Gamma-ray emission from ^{3}He + ^{9}Be nuclear reactions, proving the presence of energetic ICRH-accelerated ^{3}He ions. a, Gamma-ray spectra measured in JET pulse #90753 (three-ion scenario, $X[^{3}\mathrm{He}] \approx 0.2$–$0.4\%$, red) and in pulse #91323 ((^{3}He)-H scenario, $X[^{3}\mathrm{He}] \approx 2\%$, blue). The error bars represent the square root of the number of counts in each channel of the spectrum and arise from the underlying Poisson statistics of the gamma-ray detection process. **b,c,** The JET plasma cross-section and 19 lines-of-sight of the neutron/gamma camera. The reconstructed high-energy gamma-ray emission ($E_\gamma = 4.5$–9.0 MeV) visualizes the population of the confined energetic ^{3}He ions ($E[^{3}\mathrm{He}] > 1$–2 MeV). Pulses #90752 (b) and #90753 (c) had a nearly identical plasma composition ($X[\mathrm{H}] \approx 70$-75%, $X[^{3}\mathrm{He}] \approx 0.2$-$0.3\%$) and RF heating power ($P_{\mathrm{ICRH}} = 4.2$ MW), except for the ICRH antenna phasing. A factor-of-two increase in the γ-ray emissivity was observed in pulse #90753, in which 2 MW of RF power was coupled to the plasma with $+\pi/2$ phasing (see text for more details).

advantage of increasing the absorbed RF power per ion. Furthermore, the $+\pi/2$ phasing allows to exploit the RF-induced pinch effect, beneficial to localize the energetic ions towards the plasma core[25].

The result is clearly visible in Figs. 3b,c, showing the 2D tomographic reconstruction of the $E_\gamma = 4.5$–9.0 MeV gamma-ray emission[21] for two comparable three-ion heating pulses #90752 and #90753. Both had a similar edge H/(H+D) ratio, varying from ~0.84 at the beginning of the pulse to ~0.75 at the end ($X[\mathrm{H}] \approx 68$–76%), and $X[^{3}\mathrm{He}] \approx 0.2$–$0.3\%$. In pulse #90752 (Fig. 3b), all ICRH power was applied using dipole phasing, while in pulse #90753 (Fig. 3c) about half of ICRH power (2.0 MW) was launched with $+\pi/2$ phasing. Energetic ^{3}He ions are more centrally localized and the number of gamma-ray counts increases by a factor of two in pulse #90753. The period of the sawteeth oscillations also increases from ~0.54 s to ~0.78 s.

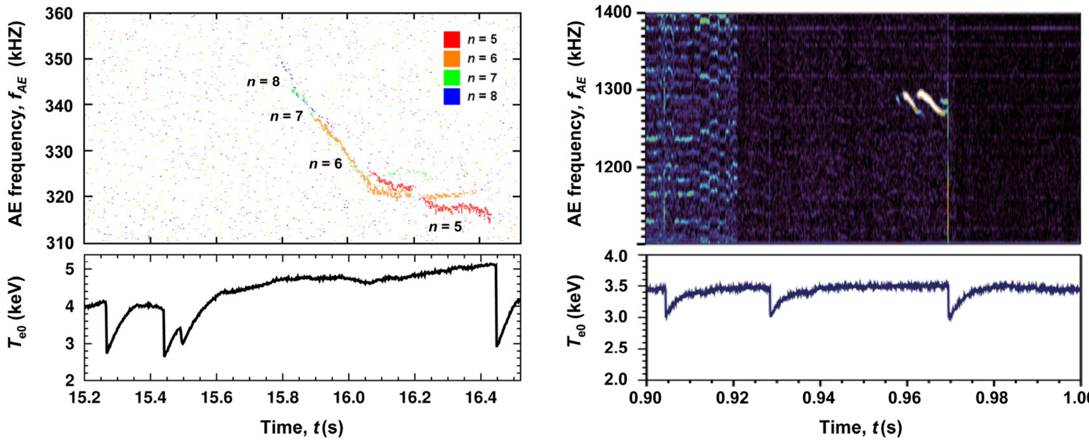

Figure 4 | Excitation of Alfvénic eigenmodes in magnetic fluctuation spectrograms, another proof of the presence of ICRH-accelerated fast ions. a, JET pulse #90758 and **b,** Alcator C-Mod pulse #1160901023. The evolution of the central electron temperature T_{e0} is also plotted in the bottom part of the figures.

We also observed excitation of Alfvén eigenmodes (AE) in JET plasmas with frequencies ≈320–340 kHz in pulses, where $P_{ICRH} \geq 2$ MW was delivered with $+\pi/2$ phasing. These instabilities are excited if a sufficiently large number of energetic ions with velocities comparable to the Alfvén velocity is present in the plasma. Figure 4a shows the AE dynamics for JET pulse #90758 (previously shown in Fig. 2b), with a sequential excitation of modes with mode numbers from $n = 8$ to $n = 5$. The MHD code MISHKA[26] yields eigenfrequencies $f_{AE}^{(0)} \approx 285 - 295$ kHz for $n = 5$–7 modes in the plasma frame. Even closer correspondence to the observations is obtained, when plasma rotation due to NBI ($f_{rot} \approx 5$kHz measured at $R \approx 3.25$ m) is taken into account $f_{AE}^{(lab)} = f_{AE}^{(0)} + n f_{rot} \approx 320$kHz . Further analysis of the conditions for energetic ions to interact with the $n = 5$ AE mode yields ^{3}He ions with energies ≈ 1.5–2.5 MeV.

Figure 4a also shows a time delay before the appearance of AE's, following a sawtooth crash. For the series of shots we studied, we find on average a time delay of ~ 0.5 s and 0.7 s for the $n = 6$ and $n = 5$ modes, respectively. Having long-period sawteeth favours the observation of AE's under these conditions. Similar AE activity was also detected in the Alcator C-Mod experiments during sawteeth with a period of ~ 40 ms. As shown in Fig. 4b, AE's at frequencies $f_{AE} \approx 1270 - 1300$ kHz ($n \approx 12$) were observed 30 ms after the sawteeth crash. Interestingly, the normalized frequency ratio $f_{AE}/f_A(0) \approx 0.56$–0.61 is similar for the AE modes observed on both devices. Here, $f_A(0) = v_A(0)/2\pi R_0$, with $v_A(0)$ the on-axis Alfvén velocity. This further highlights the similarity of the three-ion heating experiments on the two devices.

How many 'three-ion' scenarios exist? These novel scenarios allow a large flexibility in the choice of the three ion components. Table 1 summarizes the (Z/A) values for fusion-relevant ion species. The isotopes of hydrogen have Z/A =1 (protons), 1/2 (D ions) and 1/3 (T ions). Fusion plasmas can also contain ^{4}He and light impurity species, released in plasma-wall interactions. In the core of high-temperature plasmas, those ions (^{4}He, ^{12}C, ^{16}O, etc.) are typically fully ionized with Z/A=1/2, just as the D ions. We also note the isotope ^{3}He, which has a unique Z/A=2/3. Other ion species like $^{9}Be^{4+}$, $^{7}Li^{3+}$, $^{22}Ne^{10+}$, etc. have a Z/A ratio in the range 0.43 and 0.45 and bring extra possibilities. Among these, beryllium is of particular importance. Plasmas in JET and the future tokamak ITER naturally contain a small amount of ^{9}Be impurities. Since $(Z/A)_{T} < (Z/A)_{9Be} < (Z/A)_{D}$, ^{9}Be ions can efficiently absorb RF power and transfer most of their energy to D and T ions during their collisional slowing-down, a feature particularly attractive for a fusion reactor[10]. As another example of three-ion technique, we mention the observed parasitic off-axis absorption of ICRH power by ^{7}Li impurities in TFTR D-T plasmas[27]. Low-temperature plasmas offer an even larger variety of scenarios since light ion species are not necessarily fully ionized.

Table 1: (Z/A) ratio for different ion species in fusion plasmas.

Ion species	T	^{9}Be, ^{7}Li, ^{22}Ne	D, ^{4}He, ^{12}C, …	^{3}He	H
$(Z/A)_{i}$	1/3	≈ 0.43–0.45	1/2	2/3	1

Relevance for space plasmas: As discussed above, ion species with Z/A = 1/2 are nearly identical to D ions from the wave propagation point of view. Therefore, helium ions (Z = 2, A = 4) can replace D. According to Eq. (2) and Fig. 2b, hydrogen plasmas additionally including 10–17% of ^{4}He ions are optimal for effective RF power absorption by a small amount of ^{3}He ions.

The presented experimental results provide also an additional insight in the understanding of the ^{3}He-rich solar flares[28-30], known for the past four decades. These events are characterized by an anomalously large abundance ratio $^{3}He/^{4}He \sim 1$ in the energy range ~ 1 MeV/nucleon, compared with a typical value of $^{3}He/^{4}He \sim 5\times10^{-4}$ in the solar corona. The proposed theoretical models to explain anomalous ^{3}He-enrichment generally rely on selective energy absorption by the ^{3}He ions via wave interaction mechanisms making use of ^{3}He unique charge-to-mass ratio.

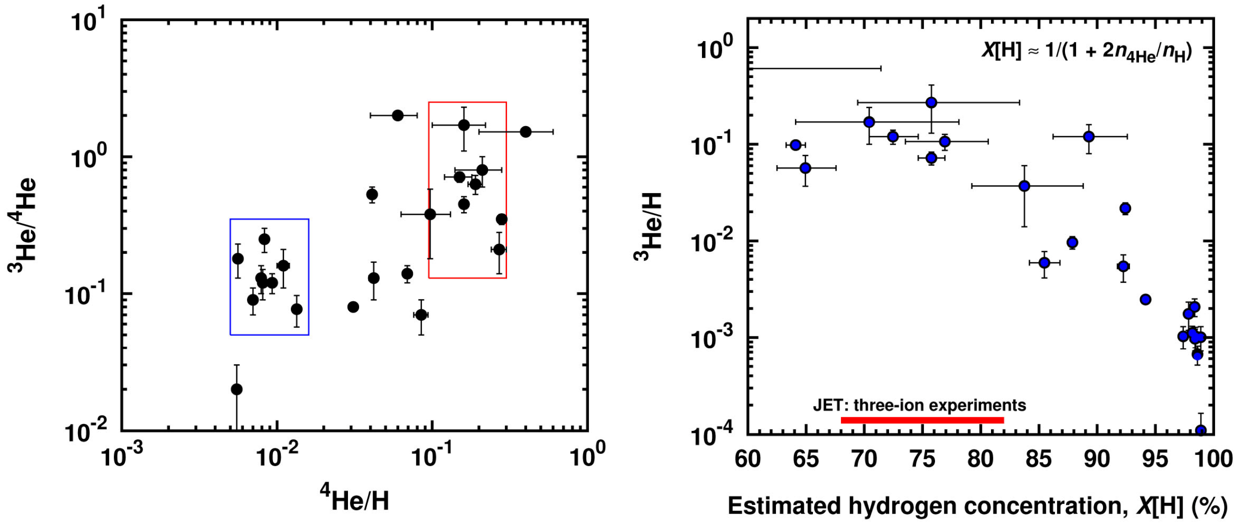

Figure 5 | Three-ion ICRH scenarios also explain some of the observations of energetic ions in space environments, in particular, ^{3}He-rich solar flares. **a,** ^{4}He/H and ^{3}He/^{4}He ratios for ^{3}He-rich solar flares. Data taken from Table I and Fig. 2 of ref. 32, including the original error bars. The data cloud within the red line corresponds to a n_{4He}/n_H ratio very similar to our theoretical predictions for a hypothetical three-ion ^{4}He-(^{3}He)-H scenario at work in space plasmas (see text for more details). **b,** The ratio $n_{3He}/n_H = (n_{3He}/n_{4He})\times(n_{4He}/n_H)$ versus hydrogen concentration estimated from $X[H] \approx 1/(1 + 2n_{4He}/n_H)$ for the same dataset (ref. 32). A large ^{3}He enhancement for the events at $X[H] \approx 70$-75% is seen. The error bars for n_{3He}/n_H are directly taken from Table I of ref. 32. The error bars for the estimated H concentration are computed using the relation between X[H] and n_{4He}/n_H, and taking the maximum and minimum values of n_{4He}/n_H for a particular ^{3}He-rich event.

Fisk suggested pre-heating of ^{3}He ions via *electrostatic* ion cyclotron waves in H-^{4}He plasmas, followed by a second-stage acceleration process[28]. Crucial in his model for the wave absorption by ^{3}He ions is also having a plasma mixture, consisting of H and ^{4}He ions. On the other hand, Reames highlights in his review (ref. 30) that the ^{3}He-rich events are associated with streaming 10–100 keV electrons. He suggests that such electron beams might be a source for *electromagnetic* ion cyclotron waves. The advantage of this explanation is that electromagnetic waves can directly accelerate ions to MeV energies, without the need of a secondary process, which is a serious simplification compared to the theory by Fisk. Roth and Temerin developed a single-stage model for the resonant acceleration of ^{3}He ions to high energies, utilizing electromagnetic ion cyclotron waves in H plasmas[31]. Their study resembles closely the (^{3}He)-H minority heating in tokamaks. Figure 3a, showing the γ-ray spectrum for JET pulse #91323, confirms generation of MeV-range ^{3}He ions with this scenario in a fusion hydrogen plasma.

Figure 3a also illustrates that a significantly larger number of high-energy ^{3}He ions was generated using the D-(^{3}He)-H three-ion scenario under similar conditions. Thus, we hypothesize that resonant absorption of *electromagnetic* waves by a small amount of ^{3}He ions in H-^{4}He plasmas (i.e. effectively the three-ion ^{4}He-(^{3}He)-H scenario) can be another effective mechanism for ^{3}He acceleration in space plasmas. This proposal then combines in one scenario the advantages of the theories of Fisk and Temerin-Roth. We recall that in JET experiments efficient RF power absorption by ^{3}He ions was observed in H-D plasmas with X[H] ≈ 68%–82% (see Fig. 2b and supplementary Figs. S5 and S6). Equivalent H-^{4}He mixtures with the same H concentrations should have a $n_{4\mathrm{He}}/n_\mathrm{e}$ ratio in the range between 0.11 and 0.24.

Figure 5a summarizes the ^{4}He/H and ^{3}He/^{4}He ratios for a number of observed ^{3}He-rich solar flares, taken from Table I and Fig. 2 of ref. 32. Remarkably, our estimates are consistent with the data points at $n_{4\mathrm{He}}/n_\mathrm{H} \approx 0.1$–$0.3$. This becomes even clearer if the same dataset is plotted as a function of the estimated hydrogen concentration $X[\mathrm{H}] \approx 1/(1 + 2n_{4\mathrm{He}}/n_\mathrm{H})$ and using the measured number of energetic ^{3}He ions normalized to the number of protons, $n_{3\mathrm{He}}/n_\mathrm{H}$ as an indicator for the efficiency of ^{3}He acceleration. Figure 5b shows a large ^{3}He enhancement for events with X[H] ≈ 70–75%, thus providing additional support for our hypothesis.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

References

[1] Ongena, J. *et al.* Magnetic-confinement fusion. *Nature Phys.* **12**, 398–410 (2016). http://dx.doi.org/10.1038/nphys3745

[2] Adam, J. Review of tokamak plasma heating by wave damping in the ion cyclotron range of frequency. *Plasma Phys. Control. Fusion* **29**, 443–472 (1987). https://doi.org/10.1088/0741-3335/29/4/001

[3] Porkolab, M. *et al.* Recent progress in ICRF physics. *Plasma Phys. Control. Fusion* **40**, A35–A52 (1998). https://doi.org/10.1088/0741-3335/40/8A/004

[4] Noterdaeme, J.-M. *et al.* Physics studies with the additional heating systems in JET. *Fusion Sci. Tech.* **53**, 1103–1151 (2008). http://www.ans.org/pubs/journals/fst/a_1749

[5] Lerche, E., *et al.* Optimization of ICRH for core impurity control in JET-ILW. *Nucl. Fusion* **56**, 036022 (2016). https://doi.org/10.1088/0029-5515/56/3/036022

[6] Van Eester, D. *et al.* JET (^{3}He)–D scenarios relying on RF heating: survey of selected recent experiments. *Plasma Phys. Control. Fusion* **51**, 044007 (2009). https://doi.org/10.1088/0741-3335/51/4/044007

[7] Mantsinen, M.J. *et al.* Localized bulk electron heating with ICRF mode conversion in the JET tokamak. *Nucl. Fusion* **44**, 33–46 (2004). https://doi.org/10.1088/0029-5515/44/1/004

[8] Kazakov, Ye.O. *et al.* On resonant ICRF absorption in three-ion component plasmas: a new promising tool for fast ion generation. *Nucl. Fusion* **55**, 032001 (2015). https://doi.org/10.1088/0029-5515/55/3/032001

[9] Kazakov, Ye.O. *et al.* Fast ion generation and bulk plasma heating with three-ion ICRF scenarios. *AIP Conf. Proc.* **1689**, 030008 (2015). http://dx.doi.org/10.1063/1.4936473

[10] Kazakov, Ye.O. *et al.* A new ion cyclotron range of frequency scenario for bulk ion heating in deuterium-tritium plasmas: How to utilize intrinsic impurities in our favour. *Phys. Plasmas* **22**, 082511 (2015). http://dx.doi.org/10.1063/1.4928880

[11] Van Eester, D. and Koch. R. A variational principle for studying fast-wave mode conversion. *Plasma Phys. Control. Fusion* **40**, 1949–1975 (1998). https://doi.org/10.1088/0741-3335/40/11/010

[12] Marmar, E.S. *et al.* Alcator C-Mod: research in support of ITER and steps beyond. *Nucl. Fusion* **55**, 104020 (2015). https://doi.org/10.1088/0029-5515/55/10/104020

[13] ITER Physics Expert Groups on Confinement and Transport *et al.* Chapter 2: Plasma confinement and transport. *Nucl. Fusion* **39**, 2175–2249 (1999). https://doi.org/10.1088/0029-5515/39/12/302

[14] Breizman, B.N. and Sharapov S.E. Major minority: energetic particles in fusion plasmas. *Plasma Phys. Control. Fusion* **53**, 054001 (2011). https://doi.org/10.1088/0741-3335/53/5/054001

[15] Stix, T.H. Fast-wave heating of a two-component plasma. *Nucl. Fusion* **15**, 737–754 (1975). https://doi.org/10.1088/0029-5515/15/5/003

[16] Jaeger, E.F. *et al.* Advances in full-wave modeling of radio frequency heated, multidimensional plasmas. *Phys. Plasmas* **9**, 1873–1881 (2002). http://dx.doi.org/10.1063/1.1455001

[17] Eriksson, L.-G. *et al.* ICRF heating of JET plasmas with the third harmonic deuterium resonance. *Nucl. Fusion* **38**, 265–278 (1998). https://doi.org/10.1088/0029-5515/38/2/310

[18] Jucker, M. *et al.* Integrated modeling for ion cyclotron resonant heating in toroidal systems. *Comput. Phys. Comm.* **182**, 912–925 (2011). http://doi.org/10.1016/j.cpc.2010.12.028
[19] Porcelli, F. *et al.* Model for the sawtooth period and amplitude. *Plasma Phys. Control. Fusion* **38**, 2163–2186 (1996). https://doi.org/10.1088/0741-3335/38/12/010
[20] Graves, J.P. *et al.* Control of magnetohydrodynamic stability by phase space engineering of energetic ions in tokamak plasmas. *Nature Communications* **3**, 624 (2012). http://dx.doi.org/10.1038/ncomms1622
[21] Kiptily, V.G. *et al.* Gamma ray diagnostics of high temperature magnetically confined fusion plasmas. *Plasma Phys. Control. Fusion* **48**, R59–R82 (2006). https://doi.org/10.1088/0741-3335/48/8/R01
[22] Tardocchi, M. *et al.* Diagnosis of physical parameters of fast particles in high power fusion plasmas with high resolution neutron and gamma-ray spectroscopy. *Plasma Phys. Control. Fusion* **55**, 074014 (2013). https://doi.org/10.1088/0741-3335/55/7/074014
[23] Nocente M. *et al.* High resolution gamma ray spectroscopy at MHz counting rates with $LaBr_3$ scintillators for fusion plasma applications. *IEEE Trans. Nucl. Sci.* **60**, 1408–1415 (2013). https://doi.org/10.1109/TNS.2013.2252189
[24] Coker, W.R. *et al.* An investigation of the ^{9}Be(^{3}He, *p*)^{11}B reaction at low energies. *Nuclear Physics* **A91**, 97–111 (1967). https://doi.org/10.1016/0375-9474(67)90453-8
[25] Mantsinen, M.J. *et al.* Controlling the profile of ion-cyclotron-resonant ions in JET with the wave-induced pinch effect. *Phys. Rev. Lett.* **89**, 115004 (2002). https://doi.org/10.1103/PhysRevLett.89.115004
[26] Mikhailovskii, A.B. *et al.* Optimization of computational MHD normal-mode analysis in tokamaks. *Plasma Phys. Rep.* **23**, 844–857 (1997).
[27] Wilson, J.R. *et al.* Ion cyclotron range of frequencies heating and flow generation in deuterium–tritium plasmas. *Phys. Plasmas* **5**, 1721–1726 (1998). http://dx.doi.org/10.1063/1.872840
[28] Fisk, L.A. ^{3}He-rich flares: a possible explanation. *Astrophysical Journal* **224**, 1048–1055 (1978). http://dx.doi.org/10.1086/156456
[29] Kocharov, L.G. and Kocharov, G.E. ^{3}He-rich solar flares. *Space Science Reviews* **38**, 89–141 (1984). http://dx.doi.org/10.1007/BF00180337
[30] Reames, D.V. Particle acceleration at the sun and in the heliosphere. *Space Science Reviews* **90**, 413–491 (1999). http://dx.doi.org/10.1023/A:1005105831781

[31] Roth, I. and Temerin, M. Enrichment of ^{3}He and heavy ions in impulsive solar flares. *Astrophysical Journal* **477**, 940–957 (1997). https://doi.org/10.1086/303731
[32] Ramadurai, S. *et al.* ^{3}He-rich solar flares. *Pramana – J. Phys.* **23**, 305–311 (1984). http://dx.doi.org/10.1007/BF02846573

Author contributions

All authors have contributed to the publication, being variously involved in the design of the experiments, in running the diagnostics, acquiring data and finally analysing the processed data.

Additional information

Supplementary information is available in the online version of the paper. Correspondence and requests for materials should be addressed to Ye.O. Kazakov
(yevgen.kazakov@rma.ac.be)

Acknowledgements

The support from the JET and Alcator C-Mod Teams is warmly acknowledged. 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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was also supported by the U.S. DoE, Office of Science, Office of Fusion Energy Sciences, SciDAC Center for Simulation of Wave Plasma Interactions under DE-FC02-01ER54648 and the User Facility Alcator C-Mod under DE-FC02-99ER54512.

Competing financial interests

The authors declare no competing financial interests.