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ABSTRACT

The RF-pinch has been observed during ^{3}He minority heating in JET, in the diamagnetic energy, fast ion energy content, sawtooth period, Alfvén eigenmode excitation and γ-emission, when altering the antenna phasing. The results of simulations with the SELFO code are consistent with the measurements.

INTRODUCTION

During ICRH high energetic anisotropic tails of the resonant ion species are produced [1]. The energy of the tails are determined by the balance between power absorbed by the wave field, power transfered to the background plasma and transport of the energetic ions. The latter is due to both collisional transport, and wave-particle induced transport, the so called RF-pinch [2]. An experimental study of the RF-pinch is possible by its an-tisymmetric dependence on the parallel wave number, which can be altered by changing the phase between the current in the antenna straps. In hydrogen the RF-pinch has been indirectly observed through the effect on sawtoothing, line integrated proton distribution function and triggering of Alfvén eigenmodes [3]. Further, tomografic reconstruction of γ-emission [4] is consistent with an RF-pinch of trapped ions and a detrapping of these ions into co-current passing orbits [5]. Here experimental observations of the RF-pinch during minority ^{3}He heating in a ^{4}He plasma are presented (see also [6]).

For one toroidal wave mode in the ICRF, wave-particle interactions will transport the resonant ions along characteristics in the space of invariants of motion in an axisymmetric torus; energy E, magnetic moment μ (or $\Lambda = B0\mu{=}E$) and canonical toroidal angular momentum P_ϕ, see figure 1. For increasing energy, Λ approaches $\Lambda_{res} = nZeB = (m\omega)$ asymptotically, corresponding to the motion of the trapped ion turning points towards the resonance, see figure 1. The motion in P_ϕ corresponds to the RF-pinch, which is a motion of the trapped ion turning points across the magnetic flux surfaces. Depending on the sign of the toroidal mode number n f the pinch can transport ions outwards or inwards. If the turning points meet in the mid plane the orbit will be detrapped into a passing one. For high energies this transition exclusively produce co-current passing orbits [7, 8]. The coordinate system is choosen such that the negative toroidal mode numbers travel in the co-current direction and produce the inward pinch. They are the dominant components of the mode spectra obtained by the $+\pi{=}2$ antenna current phasing in JET.

ANALYSIS OF EXPERIMENTAL RESULTS

Experiments has been conducted in a ^{4}He plasma with a ^{3}He minority concentration of 1-2%. The cyclotron resonance is located at $R{\sim}2{:}82m$ with B_0 = 3.45T and f = 37.3MHz. In the Pulse No's: 54243 and 54239 with $-\pi/2$ and $+\pi/2$ phasing, respectively, the density and ICRH power were the same (see figure 1), while the diamagnetic energy, sawtooth behaviour, TAE activity (fig.2) and g emission (fig.3), all show clear differences between the two pulses. These pulses have been analyzed using the SELFO code [9, 10], which solves the distribution function, using the FIDO code [11], and the wave field, using the LION code [12, 13], in a self-consistent manner.

The differences in diamagnetic energy comes from the differences in thermal energy and fast ion energy content. Both terms are caused by the increase in confinement of high energetic ions heated by the inward pinch, which allows for a higher tail energy producing more power transfer to the electrons by collisions, compared to the decrease in confinement for the outward pinch. The longer sawtooth period with the $+\pi = 2$ antenna phasing (see figure 1) is consistent with the stabilizing effect of fast ions inside the $q = 1$ surface [14]. The fast ion perpendicular energy content is calculated by SELFO to be 0:43MJ for Pulse No: 54239 and 0:34MJ for PulseNo: 54243, whereas in the experiments ~0.5MJ and ~0.3MJ were measured, respectively. The discrepancy in the differences between the two pulses is probably caused by wall losses in the simulation of Pulse No: 54239 that prohibits the long time scale detrapping into co-current passing orbits to reach steady state.

In order to trigger Alfvén eigenmodes a sufficiently strong radial gradient of fast ions satisfying the resonance conditions is required [15]. In Pulse No: 54239 both TAE and EAE modes were observed, while no AE modes were observed Pulse No: 54243, which is consistent with the larger pressure gradient in Pulse No: 54239 calculated with the SELFO, see figure 2.

The emission of γ's from $^{12}C(^3He,p\gamma)^{14}N$ reactions has been measured with 19 lines of sight spanning a mesh over the poloidal cross section (see fig.3). The measured γ's in Pulse No: 54243 are consistent with an energetic population of trapped ions with their turning point close to the cyclotron resonance, channel 13 and 14. These ions also produce γ's on the LFS, channel 15, 16, ..., but the intensity decreases with increasing $|v(R)| = \sqrt{1 - B(R)\mu/E}$. In the simulation 79% of the ions with energies above 2MeV were trapped, see figure 4. In Pulse No: 54239 the g-emission was stronger and shifted towards the LFS. This is consistent with the increased confinment of energetic ions and the RF-induced detrapping into co-current passing orbits that are shifted towards the LFS by the ÑB and curvature drift [5]. For this pulse the simulations produced more ions above 2MeV than in Pulse No: 54243, and 73% of them were passing, see figure 4. Among ions above 500keV, ˘ 50% were passing for both pulses. This is due to a combination of the subdominant component of the toroidal mode spectra that produces an outward pinch for a subset of the distribution function in Pulse No: 54239 (see figure 4) [5], and the Doppler shifted absorbtion that reduces the wave field strength at the resonance and thereby reducing the absorption by ions with less Doppler shift [10].

Similar γ-emission profiles as in Pulse No: 54239 has also been observed in a reversed shear plasma with an internal transport barrier, Pulse No:54081 with $+\pi/2$ phasing, $B_0 = 3{:}42T, f = 37.4MHz$, $n_e = 2.6 \times 10^{19}\ m^{-3}$ and $T_i = 7keV$ (see fig.3). Due to the very low concentration of reminescent 3 He ion the power per particle and the energy of the tail is higher, and the RF-induced detrapping becomes stronger than in Pulse No: 54239 (see fig.4).

CONCLUSIONS

The RF-pinch has been observed in the differences between pulses with an inward and outward pinch. The diamagnetic energy, fast ion energy content and sawtooth period indicate a significant increase in the confinement of fast ions with the $+\pi/2$ phasing. Both EAE and TAE modes were observed with the +π/2 phasing, but neither were observed with the −π/2 phasing. The γ-emission is shifted towards the LFS by the RF-induced detrapping into co-current passing orbits. Simulations with the SELFO code reproduces the measured fast ion energy content, produces differences in the ion pressure gradients for the two phasing consistent with measured TAE and EAE emission, and produces RF-induced detrapping into co-current passing orbits consistent with measured γ-emission.

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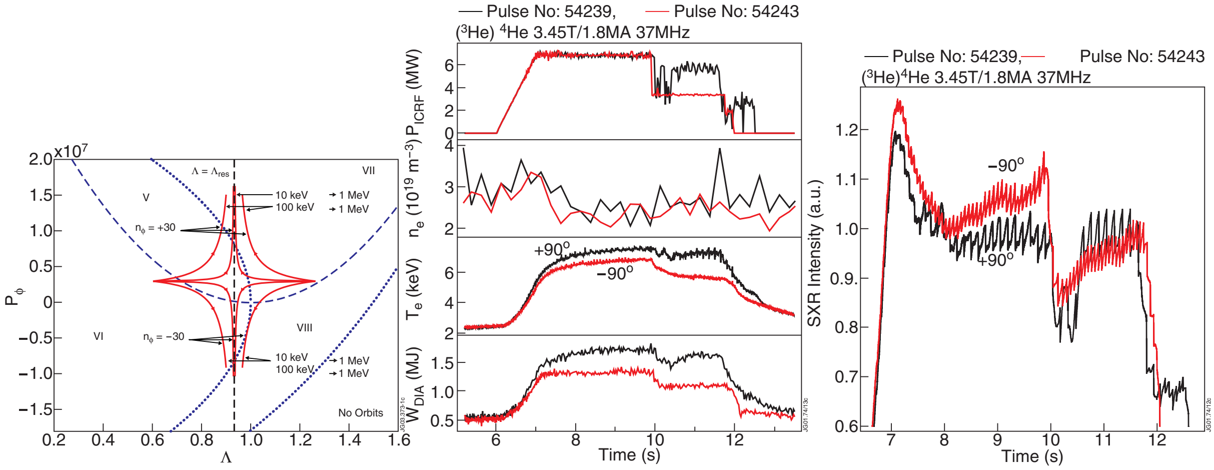

Figure 1: To the left, characteristics in (E, Λ, $\tilde{P}_\phi$) space projected on the (Λ, $\tilde{P}_\phi$)-plane, were $\tilde{P}_\phi = P_\phi/m$ [5]. In the middle, experimental parameters from JET Pulse No: 54243 and Pulse No: 54239. To the right, the sawteeths behaviour measured by SXR.

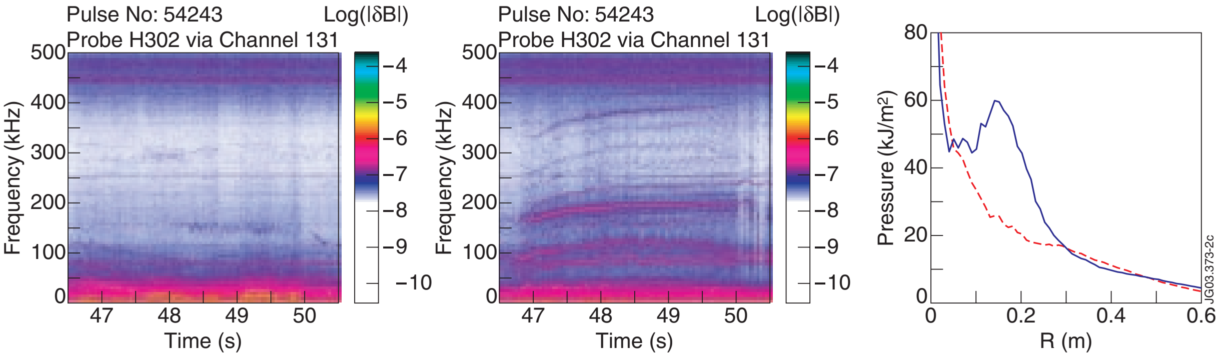

Figure 2: The two figures to the left shows AE modes in Pulse No: 54243 and Pulse No: 54243 [16]. TAE's are at 150-250kHz and EAE's are at 325-450kHz. To the right, the pressure of resonant ions calculated with SELFO for Pulse No:54243 (solid line) and Pulse No: 54243 (dashed line).

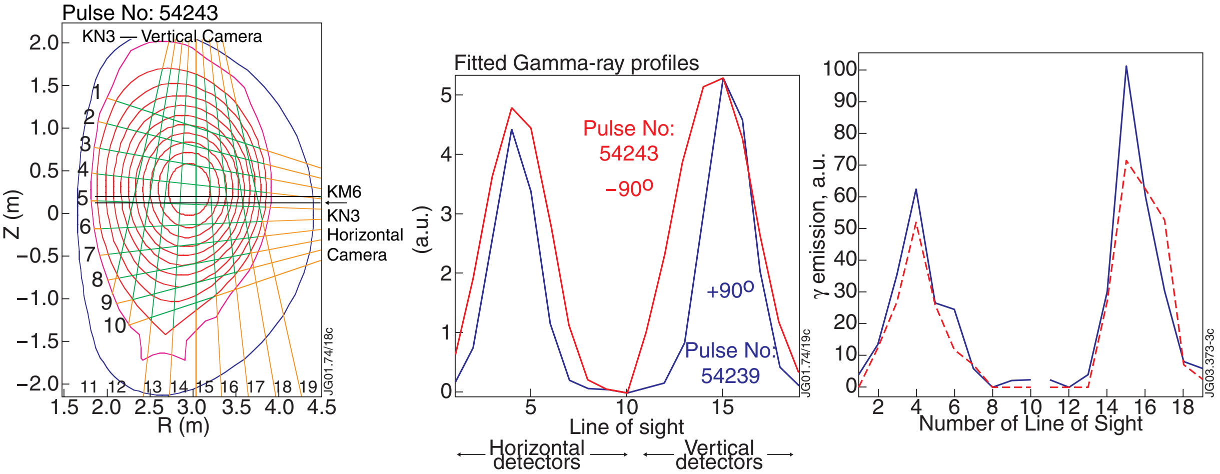

Figure 3: To the left the lines of sight though the poloidal cross section [17]. In the middle, the meassured γ-emission in Pulse No:54239 and Pulse No:54243. To the right, the meassured γ-emission in Pulse No: 54081. The magnitude of the emission in Pulse No: 54243 is normalized by a factor 4.7 compared to Pulse No:54239. The cyclotron resonances is in the core located around channel 14 in all pulses.

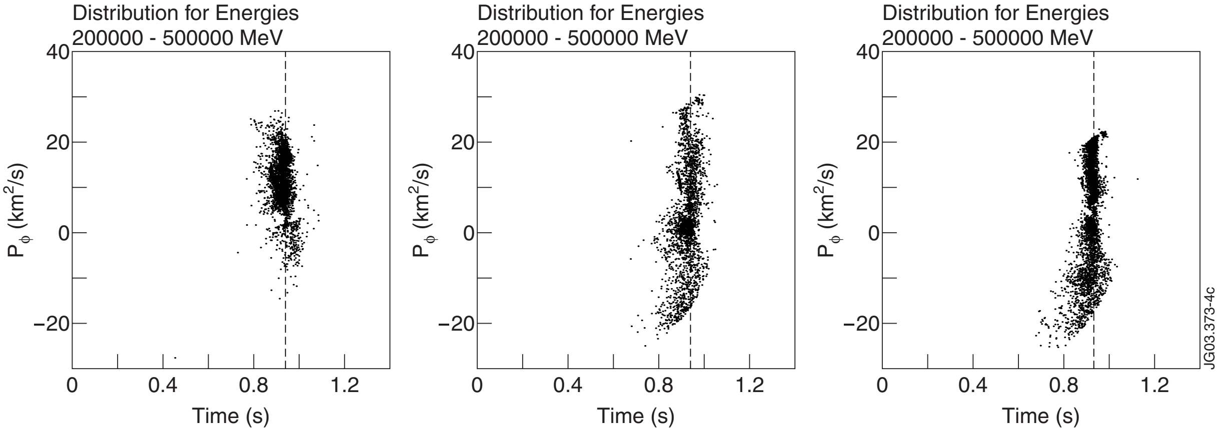

Figure 4: The distribution function of 2-5MeV ^{3}*He ions calculated with SELFO for Pulse No: 54243 (left), Pulse No: 54239 (middle) and Pulse No: 54081 (rigth) (see also figure 1). For* $P_0 < 0$ *only co-current orbits exists.*