Direct observation of suprathermal ion production in ECRH modulation experiments in the TJ-II stellarator

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INTRODUCTION. The existence of a significant population of suprathermal ions in TJ-II stellarator plasmas heated by ECRH has been demonstrated previously [1]. This was accomplished by analyzing data from two spectroscopic systems [2] and a luminescent probe (LuP) [3]. In order to understand more deeply the mechanisms causing this suprathermal population, we have performed a slow modulation experiment of ECRH power in TJ-II with the purpose of studying the time evolution of the suprathermal ion population and its behavior relative to other plasma properties. We have taken advantage of the fact that the TJ-II ion luminescent probe (LuP) has been recently configured to detect individual ions: from the energy distribution we determine the suprathermal ion temperature, T_{sp}, and (uncalibrated) density, both with moderate time resolution [4]. The goal of the experiment is to determine whether that suprathermal ion heating is a direct product of ECRH, or if a less direct process, e.g. heating via collisions with electrons, is responsible.

EXPERIMENT. TJ-II is a four-period, low magnetic shear stellarator with major and averaged minor radii of 1.5 m and ≤0.22 m, respectively. Central electron densities and temperatures up to 1.7×10^{19} m^{-3} and 1 keV respectively are achieved for plasmas created and maintained by ECRH at the second harmonic (f = 53.2 GHz, $P_{ECRH} \leq 500$ kW).

For this experiment we have operated one of the gyrotrons at a power of 250 kW during the whole discharge. The second gyrotron (with 200 kW full power) was modulated on and off at a low frequency of 10 Hz: the gyrotrons were focused either on axis or off axis. The behavior of the most relevant monitors during a typical discharge of this sequence is shown in Fig. 1(a), whereas an expanded view of the same traces in a single cycle –the central one–, is shown in Fig. 1(b). The plotted traces are, from top to bottom: line-averaged electron density (microwave interferometer, in blue), hard X-ray monitor (black), electron cyclotron emission (red), soft X-ray monitor (with a Be filter of 50 μm, brown), C v line emission (227.1 nm, green) and a unfiltered visible-near-UV photodiode monitor (PD, blue). All of them clearly show the effect of the ECRH modulation, although trends vary with diagnostics (e.g. the photodiode shows a rise with ECRH power while the interferometer shows a density pump-out).

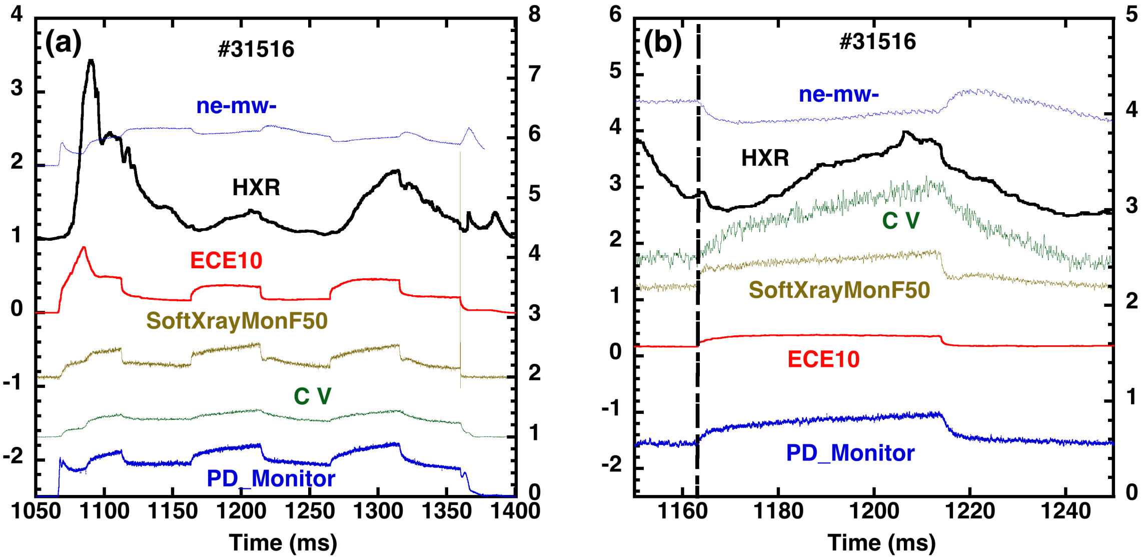

Fig. 1. a) Plots of the overall discharge monitors, where one of the gyrotrons was pulsed three times, and b) expanded view of one of the cycles and time behavior of standard diagnostic traces.

The effects of the ECRH power modulation of one of the gyrotrons on the modulated behavior of detected pulses originated from the suprathermal ion populations are depicted in Fig. 2.

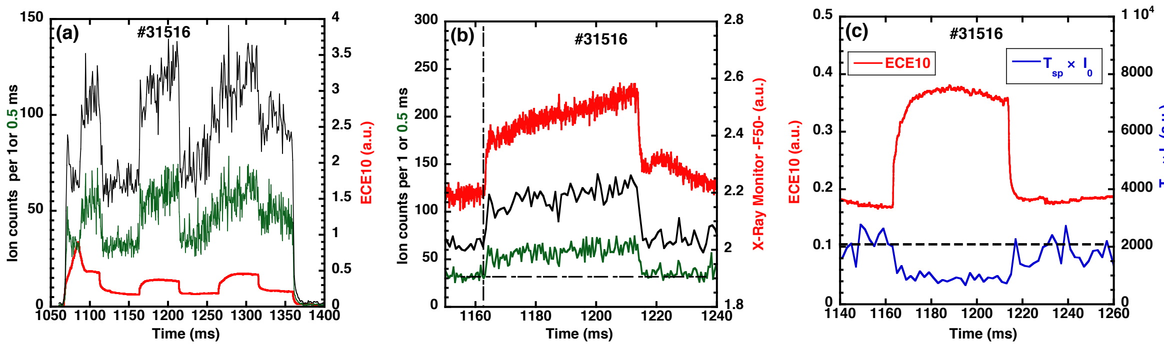

Fig. 2. The behavior of the suprathermal ions in comparison with relevant traces of the discharge: a) Global view of the ion counting rate for two pulse integration time (1 and 0.5 ms); b) An expanded similar view for the central pulse and comparison with X-ray monitor (filter 50 μm) and c) Global effect of the modulation on the ECE trace and the product $T_{sp} \times I_0$ representing the total energy content in the ion suprathermal component.

In Fig 2(a), we depict the modulation as seen in a central ECE channel and the suprathermal ion pulses counted within an interval of 1 ms (black trace) and 0.5 ms (green trace); similar plot but with an expanded view is shown in Fig. 2(b), but the reference discharge trace for the modulation is that provided by the response of a soft X-ray monitor with a 50 mm Be filter.

This SXR shows a rise time very similar to that of the LuP operating in the counting mode as can be seen from that figure, being the only signature of the TJ-II discharge that exhibits that time behavior in this power modulation experiment. We must highlight that a soft X-ray monitor with lesser filter thickness and therefore being sensitive to a less energetic range of the electron distribution function does not respond to the microwave power modulation as fast as that depicted in Fig. 2(b). This double observation effect of the modulation on both electron and ion signatures suggest direct coupling of the power to both types of energetic particles, either electrons and ions, since it does not seems reasonable that the collisional electron-ion coupling is fast enough for the densities of these populations to explain the suprathermal ion heating as been caused from this mechanism. Instead, a parametric decay process, as has been suggested by Gusakov [5] seems more likely.

The main results of this pulsed experiment are shown in Figs. 3(a), 3(b) and 3(c), where we show how the suprathermal temperature, T_{sp}, and y-intercept (I_0) behave when the gyrotrons are operated either on axis or off axis. We see from inspecting these plots that the modulation on the suprathermal ions is clearly smaller when both gyrotrons are both focused off axis, results depicted in Fig. 3(c).

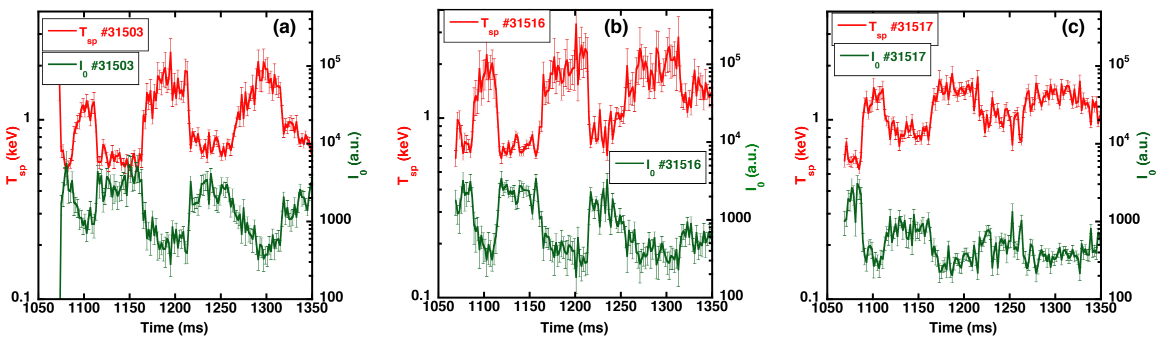

Fig. 3. Plots of the behavior of the suprathermal ion temperature (T_{sp}) and y-intercept (I_0) during the ECRH pulsed experiment for different tuning of the ECRH: a) (on-on), b) (on-off) and c) (off-off) of unmodulated and modulated gyrotrons, respectively.

The type of plasma that we have during the two phases of the modulated experiment can be seen in the Fig. 4 where we depict the Thomson scattering profiles during the phase with two gyrotrons, Fig. 4(a), and with a single one, Fig. 4(b). Notice the significant asymmetries between the high field ($\rho < 0$) and low field side ($\rho > 0$) of TJ-II plasmas. In Fig. 4(c), we show the T_e continuous time evolution during two ECRH modulated pulses for three representative type of discharges used in this experiment. This T_e was obtained from a set of X-ray detectors using the filtered signal ratio method [6].

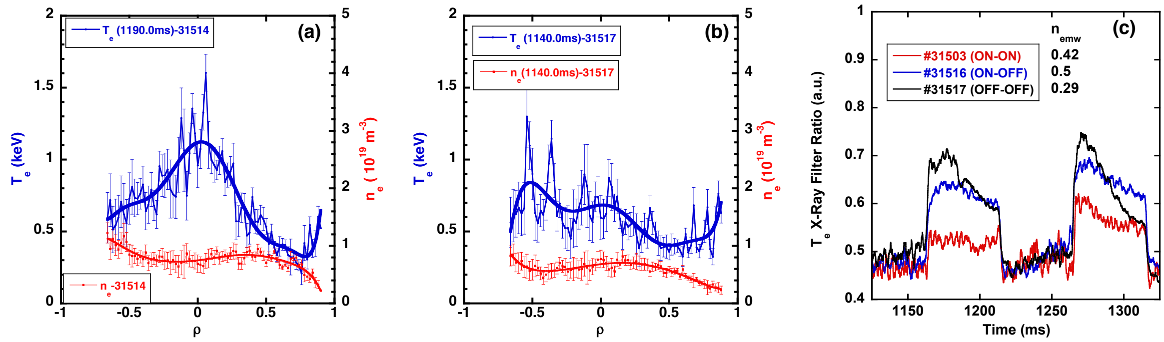

Fig. 4. a) and b) Electron temperature and density profiles measured by Thomson scattering during the two phases of the discharge: with two gyrotrons (left) and with solely one (right), respectively; c) Electron temperature evolution during three modulated discharges with the "continuous" and modulated gyrotrons focused either on axis or off axis.

In conclusion, we have shown the time behavior of the suprathermal ion population generated by the ECRH in TJ-II and measured by a luminescent probe operating in the ion counting mode with energy discrimination by means of its pulse amplitude analysis. The rise and decay time of both rate count and suprathermal temperature exhibit a rise and a fall time as fast as that shown by thermal T_e related traces such as ECE and soft X-ray monitors, and different than the time behavior of hard X-rays. These features suggest that the suprathermal ions are directly related to the ECRH power and not to the intermediate heating by electrons neither thermal nor suprathermal. We believe the fast T_{sp} decay is to be due to the fact that although there is an ion heating during the square modulation of the second gyrotron, the total energy of that component decreases with respect to the plasma heated by a single gyrotron, see Fig. 2(c), consequence of the degradation of confinement with power exhibit by any plasma component (electrons, ions, etc.) in fusion relevant plasmas.

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