Spatial structure of temperature and outward convection of suprathermal perpendicular ions in the TJ-II stellarator

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INTRODUCTION. The ion suprathermal component has been investigated during recent years, either in electron cyclotron emission heated (ECRH) or neutral beam injection (NBI) heated plasmas of the stellarator TJ-II, using passive emission spectroscopy and a luminescent probe (LP). The main findings concerning their temperatures, relative population and relevance to the ion power balance can be found in [1, 2].

The main goal of the present work is to study the spatial dependence of the suprathermal proton temperatures in the direction perpendicular to the main magnetic field and the convection velocity for different plasma conditions. This is done to shed light on the origin and generation mechanisms of this suprathermal component in ECRH plasmas, since a complete interpretation of the generation mechanisms remains undone. The differences between the perpendicular and parallel ion temperatures of the suprathermal component are obtained comparing spectroscopic with luminescent probe measurements.

In order to improve our experimental high-resolution Doppler spectroscopy set-up [3], a fiber bundle with a fix number of channels have been upgraded with a direct optic coupling to increase the spatial resolution. In addition, the spatial calibration has been improved by incorporating a diffuser with flat response over a broad spectral range (220-800 nm).

We study the spatial structure of suprathermal temperature and convection velocity profiles under different ECRH schemes and power levels, studying the trend of the average temperatures and convection velocities as a function of the electron density. The paper is organized as follows. First, we describe the experimental procedure. Second, we present typical profile results under different conditions and finally we depict the regular trends found in the experimental raw data.

EXPERIMENTAL. Previous works [1, 3] carried out in the TJ-II stellarator described a technique for measuring the thermal and suprathermal ion temperatures using high-resolution Doppler spectroscopy. The perpendicular thermal proton temperatures obtained using this method agree fairly well with the thermal temperatures obtained with a neutral particle analyzer (NPA) [4]. The spectral method involves detecting and analyzing the wavelength displacement of Balmer H_α emission, which reflects the velocity of the emitting neutral along the line-of-sight. Low energy neutrals, which are collisionally in thermal equilibrium with thermal protons, are detected together with fast neutrals, the latter being formed by charge-exchange between colder neutrals and energetic protons. The H_α spectral emission line recorded by the spectrometer for each line of sight is fitted by a sum of three Gaussians, as explained in [1]. From this, we associate the narrowest Gaussian with cold neutrals from the periphery and the next broadest Gaussian with the thermal component because of its closeness to the temperature measured by the NPA. In this work, we focus on the behaviour of the temperature and magnitude of the broadest Gaussian, which we take to come from the suprathermal proton population.

For this purpose two diagnostics have been upgraded: the high spectral resolution spectrometer [3], by collecting the plasma emission with direct optics without any fiber bundle and programing the spectral data acquisition with flexible number of spatial channels (19 to 29) and maximum light collection and the luminescent probe detector using a faster phosphor and higher digitalization speed [5].

RESULTS AND DISCUSSION. We focus our study on the proton suprathermal distribution covering different plasma situations, where a spatial peak structure appears in some data. Profiles observed in ECRH plasmas with different gyrotron set-ups are included as well as profiles obtained during the NBI phase. The study of these features and its dependence with heating and density are highlighted here. For instance, Fig. 1 displays typical plots, which represent the broad variety of T_{sp} and convective velocities profiles observed. In the first case, we select discharges heated by both gyrotrons, the first one corresponding to a low density case with on-axis heating for both gyrotrons with a power of 240 kW. In the second raw, we select discharges heated off-axis by only gyrotron 1. Notice the clear structure of peaks exhibited by both curves of T_{sp} and convective velocities and for the latter more marked for some off-axis heating conditions with a single gyrotron.

Another important point concerning the perpendicular suprathermal ions is to quantify whether its population is relevant with respect to the thermal one and what is the spatial dependence of its ratio. To answer these questions we display the profiles of this ratio for the same discharges presented above (Fig. 2).

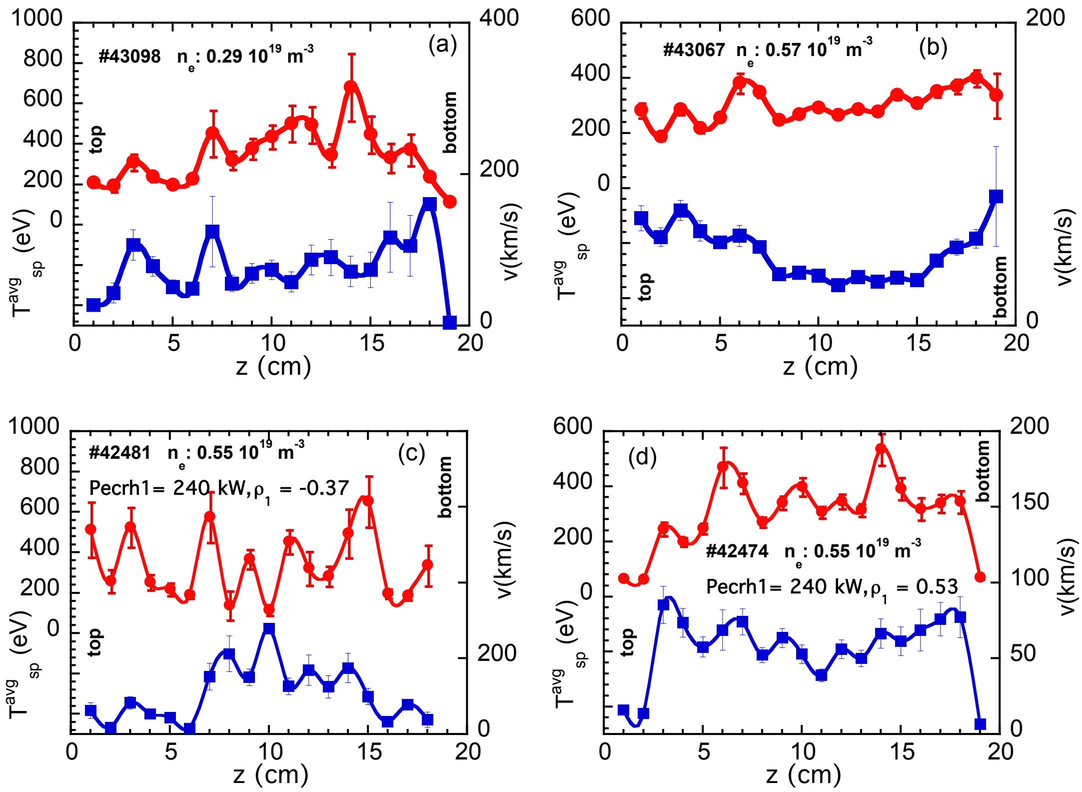

Fig. 1. Display highlighting different behaviors of T_{sp} (red full points) and convective velocity (blue squared points) profiles for different ECR heated plasmas: a) a low-density case with 480 kW ECRH power; b) Relative high-density case with the same power; c) and d) two cases with half ECRH power. z is vertical coordinate in [3].

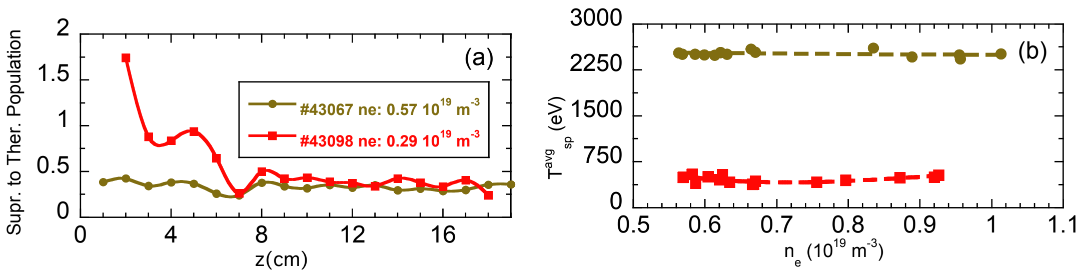

Fig. 2. a) Ratio of perpendicular suprathermal ion to thermal ion populations for two discharges as a function of radial position and b) Comparison between the perpendicular averaged temperature of suprathermal ions and those with more parallel velocities detected by the LP.

For discharges with line-averaged electron densities of the order $0.6\text{x}10^{19}$ m^{-3} (#43067) the ratio is almost flat and in the range 20 to 40%. However, it can be higher and peaked for particular cases such as discharge #43098. In Fig. 2(b), we compare the average temperature of perpendicular ions, measured by the spectral method with the temperature of more parallel ions detected by the LP. The latter have a temperature that is a factor 4-5 higher than perpendicular ones.

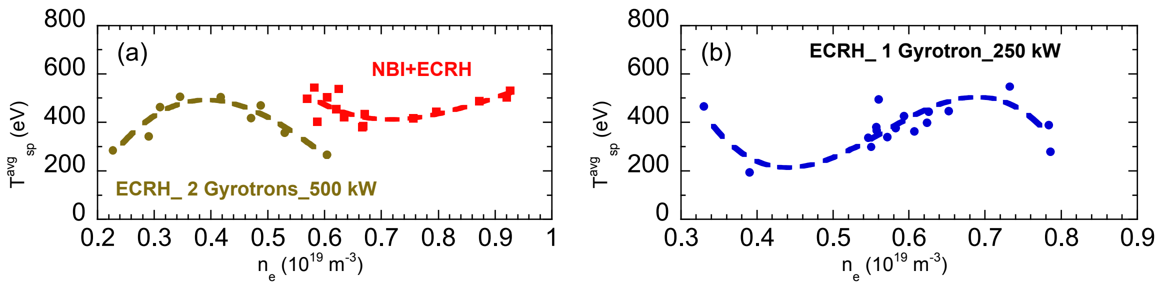

Fig. 3. Dependence of chord-integrated suprathermal temperatures, averaged over all line-of-sights, versus line averaged density under different heating scenarios: a) Plasma discharges heated by the maximum ECRH power, two gyrotrons with total power of 500 kW (full brown points) and ECRH initiated discharges followed by NBI, but superimposing one or two gyrotrons for keeping density control during the NBI phase (full red squares); b) Similar plot but for discharges heated by a single gyrotron with a power of around 250 kW (full blue points).

It should be noted that the value of T_{sp} averaged over all lines-of-sight (T_{sp}^{avg}), shown in Fig. 3, exhibits a smooth and systematic behavior with line-averaged-density. It reaches its maximum at a density that scales inversely with ECRH heating power: 0.4x10^{19} m^{-3} for the high power discharges (500 kW), Fig. 3(a), while close to 0.7x10^{19} m^{-3} for the low power set (250 kW) plotted in Fig. 3(b). The red squares of Fig. 3(a) correspond to the NBI phase of discharges where we superimposed one or two gyrotrons off-axis to produce controlled and flat densities in that NBI phase. The same density range cannot be achieved with ECRH only because of density cut-off limit.

In conclusion, the perpendicular suprathermal temperatures are typically between 8-10 times higher than the thermal ones and a factor 6 smaller than the suprathermal ion component, detected by the luminescent probe that correspond to more parallel ions. Perpendicular T_{sp} exhibit systematic peaks at some particular chords, which are more pronounced for some specific conditions, Fig. 1(c). A similar peaked behavior is also observed in its convection velocity profile. Systematic behavior of averaged perpendicular T_{sp} with electron density, are reported. These empirical observations that contribute to a more complete suprathermal database need to be complemented with a more theoretical approach that could account for these observations.

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