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Influence of Neutral Beam Injection Direction on Fast Ion Distribution Function in Large Helical Device (LHD)

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Effective ion heating and good fast ion confinement are essential for ignition. Therefore the influence of various types of plasma heating on fast ion distribution function in various configurations of magnetic field should be studied. To study distribution of fast ions in LHD plasma a new Angular Resolved Multi-Sightline Neutral Particle Analyzer (ARMS-NPA) has been developed [1-3]. It scans plasma by 20 sightlines and can provide detailed information about angular and radial distribution of fast particles. In this paper the influence of co- and counter-Neutral Beam Injection (NBI) on angular distribution of suprathermal particle tail is shown (Fig.1). Measurements were made for different directions of magnetic field in inward- (R=3.6m) and outward-shifted (R=3.9m) magnetic axis position. Dependence of width of suprathermal ion tail angular distribution during co- or counter- NBI was measured for different magnetic field strength and demonstrated in current work. The simulation results of fast particle orbits are shown as well in order to explain the experimental results.

Keywords: fast ion heating, neutral particles, angle resolved measurements, fast particle flux simulation, diagnostic, fast particle orbits, energy resolved measurements, angular distribution function, ion distribution.

1. Inroduction

Fast ion distribution plasma may suffer significant changes under various plasma heating mechanisms in different magnetic field configurations and plasma parameters. Therefore, as effective ion heating and good fast ion confinement are essential for ignition, fast ion distribution function should be studied properly. For this purpose numerous diagnostic tools have been developed on modern fusion devices and on LHD in particular. LHD plasma has a very complex 3D shape that complicates diagnostics and investigations of fast particle distribution function.

One of recently developed is Angular Resolved Multi-Sightline Neutral Particle Analyzer (ARMS-NPA) scanning plasma by 20 sightlines and being upgraded currently up to 40 sightlines. Among previously used NPAs on LHD for angular resolved measurements of fast particles there was only one “multi-sightline” Silicon Detector based NPA (SD-NPA) with 6 scanning chords [4]. However, the angular resolution of SD-NPA was not enough for profound investigations of fast particle angular distribution in a single plasma discharge and for studying of such an effect as predicted by theory existence of fast particles loss-cone regions in helical plasma.

The key feature and unique advantage of ARMS-NPA is the possibility to make detailed time-, angular- and energy-resolved measurements of fast particle distribution in plasma in a single plasma discharge.

First experimental results demonstrated the possibility of loss-cone existence in LHD plasma [3,5]. Same time, as comparisons of fast particle population in plasmas shifted in and out in major radius are important in the suprathurmal ion confinement studies, investigations of fast particle angular distribution has been started in inward-shifted (Rax=3.6m) and outward-shifted (Rax=3.9m) magnetic axis position configurations in [3]. As Neutral Beam Injection is widely used for fast particle heating and considered to be one of the heating mechanisms in future fusion devices as well, it is important to study how does direction of neutral beam particles influence on fast ion distribution in different plasma conditions and different magnetic axis positions.

In this paper experimental results of fast particle angular distribution obtained by ARMS-NPA are shown for inward-shifted (Rax=3.6m) and outward-shifted (Rax=3.9m) magnetic axis positions for co- and counter-injected NB for every case of magnetic axis position. Experimental results are compared with theoretical predictions based on fast ion orbit calculations.

2. Experimental Setup

The position of ARMS-NPA on LHD versus NB injectors and ICRF antennas is shown on Fig.1. For investigation of influence of NBI direction on angular

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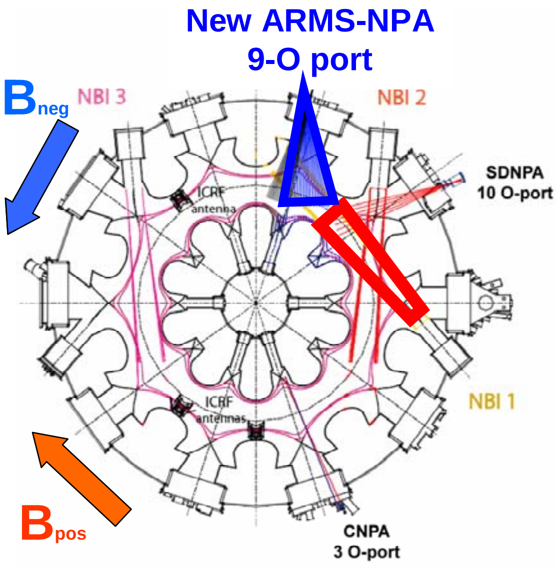

Fig.1 ARMS-NPA location on LHD (blue) versus NBI#1 (red).

distribution of fast particles NBI#1 was used with the energy of injected particles equal to 180keV. In the case with positive magnetic field (marked by orange on Fig.1) NBI#1 serves as counter-injector and in the case with negative magnetic field (marked by blue on Fig.1) as co-injector.

3. Experimental Results

Experimental angular-resolved fast particle spectra are shown on Fig.2. Spectra on Fig.2a) and 2b) correspond to co- and counter-injected NBI#1 regimes correspondingly with inward-shifted (Rax=3.6m) magnetic axis position. Spectra on Fig.2c) and 2d) correspond to co- and counter-injected NBI#1 regimes correspondingly with outward-shifted (Rax=3.9m) magnetic axis position. The colored scale units of every picture correspond to the ln(Γ(E)), where Γ(E) [counts] is the flux of fast particles detected by diagnostic.

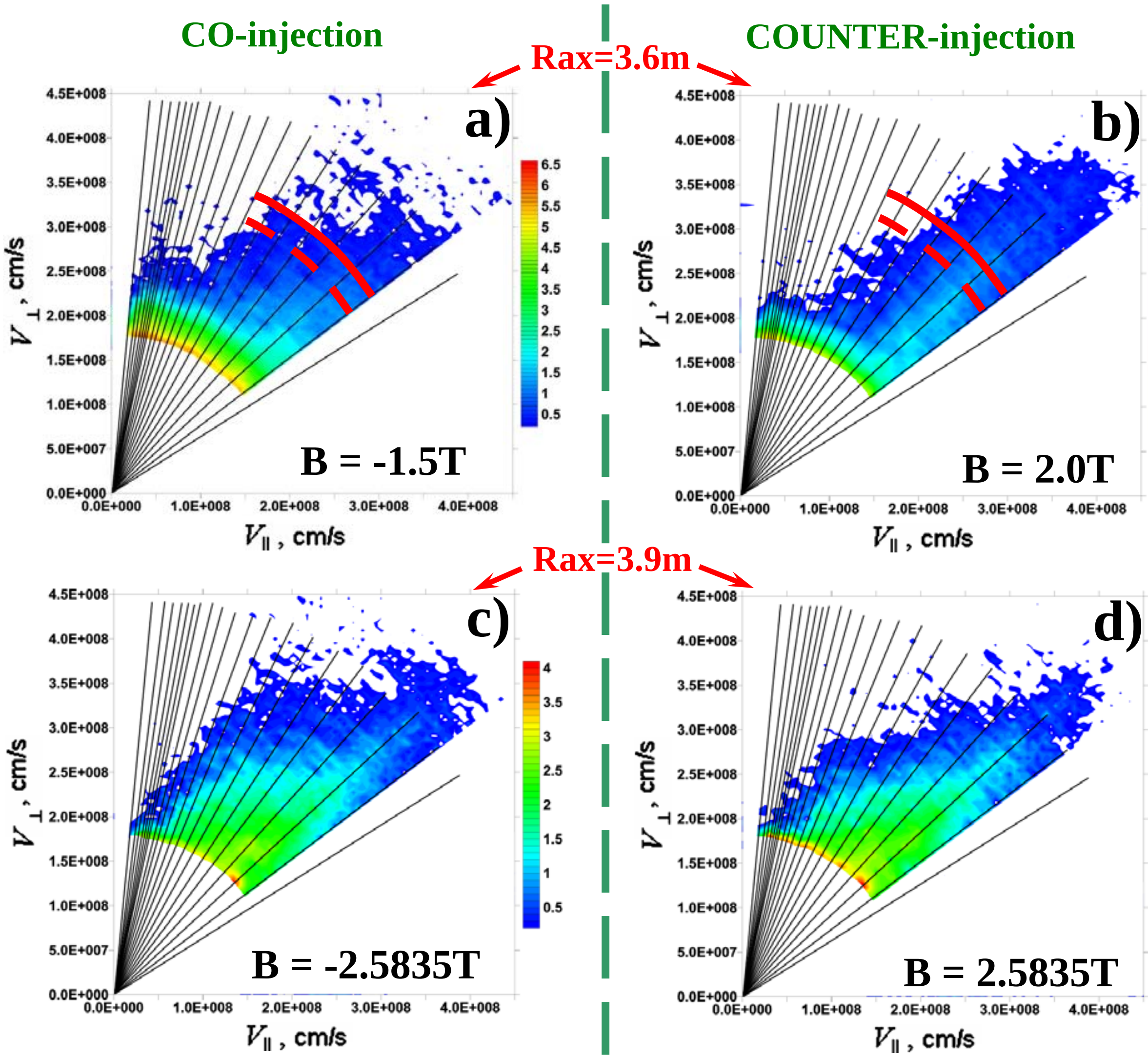

Fig.2 Comparison of experimental fast particle angular distribution in co- and counter-injected NBI#1 regimes for Rax=3.6m and R=3.9m magnetic axis positions

Let's compare spectra obtained in co- and counter-regimes, *i.e.* compare Fig.2a) with Fig.2b) and compare Fig.2c) with Fig.2d). From these comparisons one can notice that angular distribution of high-energy tail from NBI#1 is wider during co-injection for both outward- and inward magnetic axis positions.

Let's compare spectra obtained in co-injected regimes with inward (Rax=3.6m) and outward (Rax=3.9m) magnetic axis positions and spectra obtained in counter-injected ones, *i.e.* compare Fig.2a) with Fig.2c) and compare Fig.2b) with Fig.2d). From these comparisons one can notice that although total flux has been reduced in regimes with outward-shifted magnetic axis (colored scale limit is equal to 4 for Rax=3.9m against scale limit equal to 6.5 for Rax=3.6m), the high high-energy tails from NBI#1 in outward-shifted magnetic axis configuration are wider than those ones in inward-shifted magnetic axis configuration.

In order to confirm if such a difference has appeared due to increased magnetic field strength (B=2T for Rax=3.6m case against B= 2.6T for Rax=3.9m) or due to magnetic axis shift effect, dependence of fast ion angular distribution on magnetic field strength has been measured for the case of Rax=3.6m. The magnetic field strength was varied from -0.75T to -2.811T. Results of such measurements are shown on Fig.3. It shows angular distribution of fast particles with the energies of 65÷70keV as it is marked, for example, on Fig.2a) and Fig.2b) by red colored arcs. Black circles of Fig.3 correspond to the positive magnetic field direction and counter-injecting NBI#1 correspondingly. All other colored dots correspond to the negative magnetic field direction and co-injecting NBI#1. Black circles and colored dots except blue dots correspond to magnetic axis position at Rax=3.6m, blue dots correspond to slightly shifted out magnetic axis position at Rax=3.65m.

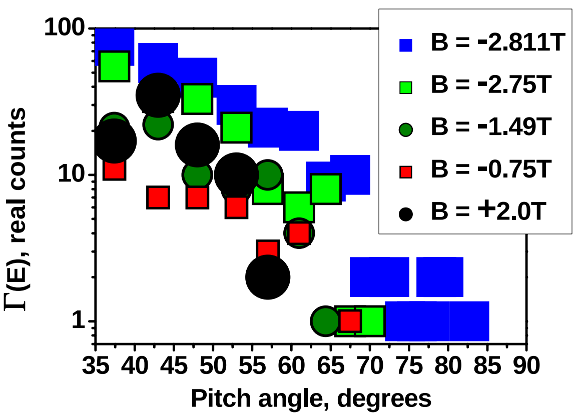

Fig.3 Angular distribution of high energy tail particles from NBI#1 (particles energies are in the range of 65÷70keV). Blue squares correspond to Rax=3.65m magnetic axis position. All other dots correspond to Rax=3.6m. Black dots correspond to positive direction of magnetic field and , accordingly, to counter-injecting NBI#1, all other dots correspond to negative magnetic field and , accordingly, to co-injecting NBI#1.

It can be noticed on the Fig.3 that although the flux of fast particles is increasing with increasing of magnetic field strength (for the case of negative magnetic field), the angular range of suprathermal ion tail remains the same (35°÷67°) degrees for the case of negative magnetic field and magnetic axis position at Rax=3.6m. However, the slight shift of magnetic axis to the outward direction (Rax=3.65m) together with increasing of magnetic field strength (B=-2.811T) leads to the broadening of angular distribution (35°÷80°) together with increasing of fast particles population.

Same time from Fig.3 it can be clearly seen that fast particles angular distribution for the case of B=2T is narrower than those ones for the case of negative magnetic field and, accordingly, co-injected NBI#1 in the whole range of scanned magnetic field strength from -0.75T to -2.811T.

Therefore, from experimental results it may be concluded that co-injecting NB is more effective than counter-injecting NB for fast ion heating on LHD.

In addition to that, outward shift of magnetic axis is more favorable than inward shift of magnetic axis for fast ion heating from the point of view of creating a broader angular distributed high energy tail from NB.

Accordingly, outward shifted magnetic axis configuration with co-injecting NBI (in our case it is Rax=3.9m, B=-2.5835T and operating NBI#1) is the most appropriate for broad heating of fast ions by tangential NBI in LHD plasma.

4. Simulation Results

Obtained experimental results can be explained by fast particle orbit simulation results, which predicted that co-injection is more favorable for fast ion heating than counter-injection on LHD [5]. These simulation results from manuscript [5] can be seen on Fig.4, which shows the most outermost drift surfaces of co-injected (by red color) and counter-injected (by green color) NB particles with E=180keV. Magnetic axis radius is Rax=3.6m for both cases and magnetic field strength at the axes is B=0.5T for Fig.4a) and B=2.75T for Fig.4b).

From the Fig.4b) it can be seen that in usual LHD operating range (Bax=2.75T E=180keV) the confinement region of the counter-injected NB particles is slightly smaller than the Last Closed Flux Surface (LCFS) and the confinement region of co-injected NB particles reaches

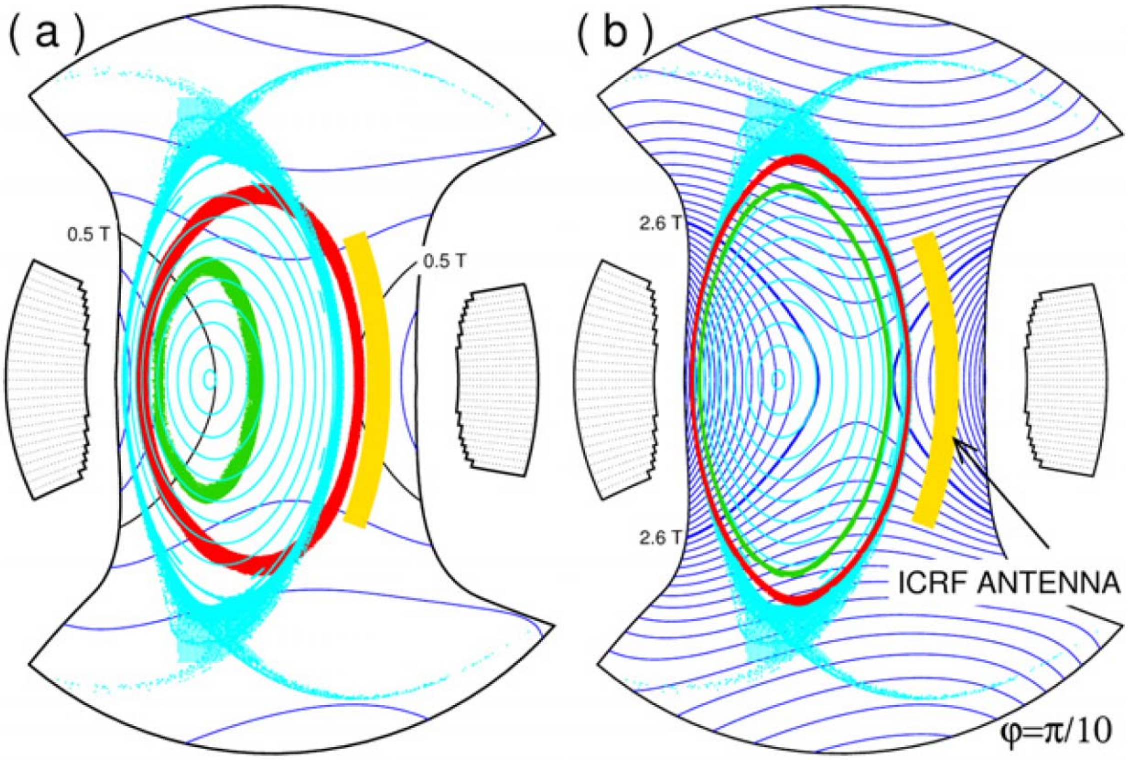

Fig.4 Relations between the magnetic surface, the outermost drift surfaces and magnetic field intensity are shown by the Poincar´e plots at the poloidal cross section of $\varphi = \pi/10$. Red (green) color dots show the almost outermost drift surface of co-NBI (counter-NBI) particle with E = 180 keV. Cyan color dots show the structure of lines of force. Position of magnetic axis is 'inward shifted' one (Rax = 3.6 m). (*a*) Low magnetic field case (Bax = 0.5 T). (*b*) Standard magnetic field case (Bax = 2.75 T).

even the boundary of the chaotic field line layer exceeding the LCFS. However, in the low magnetic field operation case, the effect of the $B \times \nabla B$ drift motion increases. The drift surface of the co-NBI can extend fairly outside the LCFS and the drift surface of counter-NBI is reduced fairly compared with the LCFS as it is shown on figure Fig.4a).

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