Fast Particle Loss-Cone Measurements by Angular Resolved Multi-Sightline Neutral Particle Analyzer (ARMS-NPA) in Large Helical Device (LHD)

Evgeny A.VESHCHEV, Tetsuo OZAKI, Pavel R. GONCHAROV, Shigeru SUDO and LHD Experimental Group

National Institute for Fusion Science (NIFS)

322-6 Oroshi-cho, Toki-shi, Gifu-ken, 509-5292JAPAN

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The possibility of the fast particles loss-cone regions on the helical devices has been predicted theoretically[1]. However the loss-cone region could not be measured so far by existing diagnostics. In order to check it experimentally the novel 20-sightline ARMS-NPA has been created on LHD. Two LHD ports were reserved to make a scan of plasma in horizontal plane. One port is for scanning of mostly tangentially emitted plasma and another one is for precise scan of perpendicular region in horizontal plane. In order to observe as wider as possible range of pitch angles, first multi-sightline measurements were made at the tangential port. Obtained data demonstrated the systematic decrease of fast particle population in the sightlines near perpendicular direction (from 95 to 100 degrees pitch-angle range) which can not be explained by the influence of the geometrical factor[2]. The assumption of the loss-cone presence in the perpendicular region of LHD plasma was made[2]. However tangential port appeared to be not sufficient for scanning of perpendicular region and only the edge part of possible loss-cone region could be observed. Same time it was complained that observed effect was not due to the loss-cone but due to the edge effect of diagnostic. To clarify the situation with possible loss-cone region the additional chamber of NPA was installed at perpendicular port. In this paper the experimental results obtained by horizontal scan of plasma column in perpendicular region are presented. Precise fast particle angular distribution in horizontal region and loss-cone region are shown evidently for the first time. Experimental data are compared with theoretical estimations.

Keywords: fast particles, fast ions, loss cone, neutral particles, ion distribution, distribution function, charge exchange, ion confinement, NPA.

1. Introduction

Investigation of fast ion distribution and confinement of fast particles under different plasma conditions is important for successful operation of future fusion reactor. Compared with tokamaks, studying the fast particle confinement properties in heliotrons is more complex mainly due to more complex magnetic configuration. Such a complex 3D geometry, e.g. of the Large Helical Device (LHD), may lead to appearance of additional types of confined particles (such as helically trapped particles), additional confinement effects (presence of loss-cones of fast particles in helical plasma predicted by theory[1]) and may result in more complicated drift motions.

A variety of neutral particle analyzing diagnostics have been developed on modern fusion devices for studying fast ion confinement properties in plasma. Attempts to measure experimentally loss-cone region and to study angular distribution of fast particles in plasma were made before by a combination of horizontally scannable Diagnistic Neutral Beam (DNB) and Neutral Particle Analyzer (NPA) [3] on the Compact Helical System (CHS) [4,5]; on LHD for this purpose the 6 chord Silicon Detector-based Neutral Particle Analyzer (SDNPA) [6] have been developed. However angular resolution of these diagnostics is not sufficient for fast particle loss-cone measurements (even for the case of 6 chord SDNPA) – either a long-time discharge or a sequence of several discharges with the same plasma conditions are required in order to make precise scan of plasma.

The necessity in the fast particle diagnostic with significantly improved angular resolution has appeared. A novel Angular Resolved Multi-Sightline Neutral Particle Analyzer (ARMS-NPA) scanning plasma column by 20 chords has been developed and installed on LHD [7,8]. Recently it was upgraded up to 40 channels due to installed additional diagnostic chamber and can provide fast particle measurements in a wide range of angles in horizontal direction. The main advantage of this system is

author's e-mail: veshchev.evgeny@lhd.nifs.ac.jp

the possibility to make time, energy, and angle-resolved measurements of charge exchange neutral particles in a single plasma discharge. This feature makes the new diagnostic a very helpful and powerful tool intended to contribute to the understanding of fast ion behavior in such a complex helical plasma geometry like the one of LHD.

The results of work presented in this paper are considered to be an extension of the investigations started in manuscript [2] which demonstrated the possibility of the loss-cone existence in LHD plasma.

2. Experimental Setup

The 20 chord ARMS-NPA has been installed on LHD to measure theoretically predicted existence of loss-cone region and to study fast ion distribution in plasma under different discharge scenarios. The first position of ARMS-NPA on LHD was chosen in such a way to measure as much as wider range of pitch angles.

Local pitch-angles along all the 20 sightlines and corresponding normalized radii are shown on Fig. 1 by blue and green color. Green color curves correspond to the sightlines at which the significant reduce of fast particle population has been observed, probably due to the loss-cone of fast particles near perpendicular direction. As it can be seen from Fig.1, such position allows one to scan mainly tangentially emitted particles from plasma.

Therefore, in order to confirm the existence of the loss-cone in the central region, the additional diagnostic chamber has been prepared for detailed scan of the perpendicular plasma region. Two sets of NPA, 20 sightlines each, have been prepared and were named as ARMS-T (tangential) and ARMS-P (perpendicular) NPA.

Two diagnostic position versus LHD plasma column are shown on Fig.2. Local pitch-angles along all the 20 sightlines for the ARMS-P NPA are shown on Fig.1 by black and red color. Running a few steps forward, red colored curves correspond to the sightlines with significantly reduced fast particles population probably due to the loss-cone region. Experimental results with detailed scan of perpendicular region from ARMS-P NPA will be demonstrated in the third part of the paper.

It can bee seen from Fig.1 that pitch angle range between the ARMS-P scanning sightlines and magnetic axis is from 75 to 95 degrees and from 95 to 150 degrees for ARMS-T NPA. In addition to that, the detector of ARMS-P NPA can be rotated that allows one to change diagnostic plane and make the radial scan of plasma.

Unfortunately at the moment fast particle measurements can be performed by only one of two

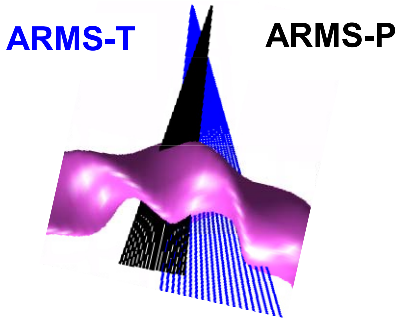

Fig.2 Top view of ARMS-T and ARMS-P diagnostic sightlines versus LHD plasma column.

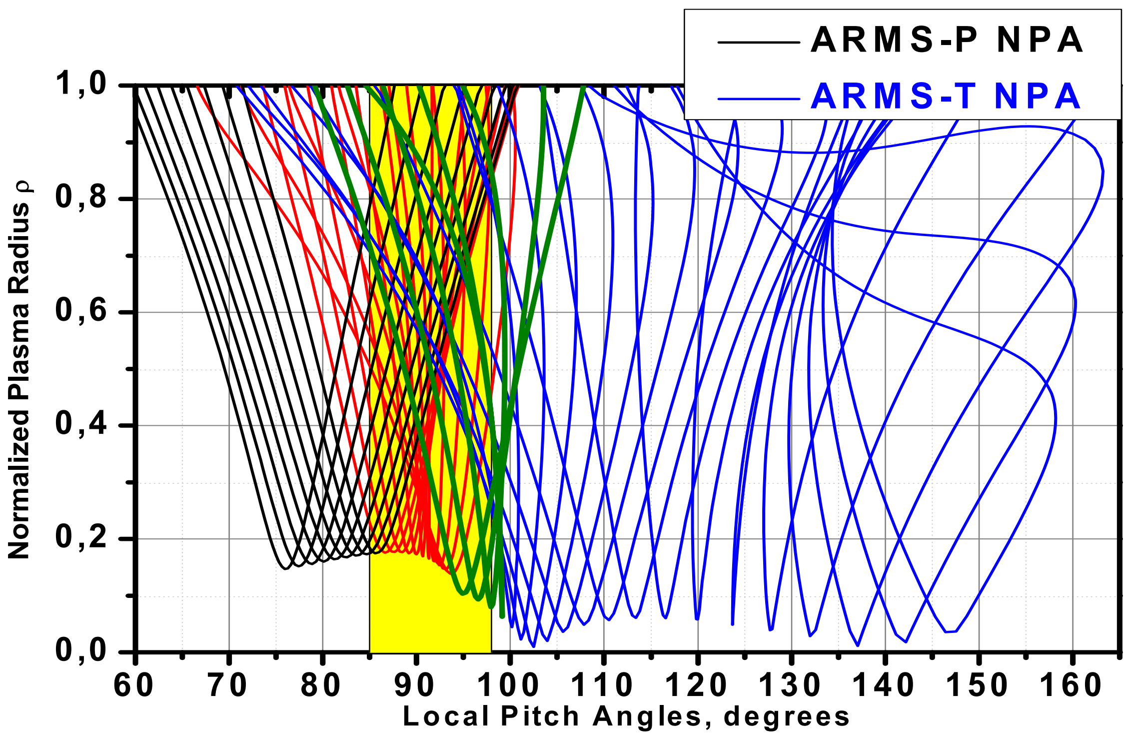

Fig.1 The sheaf of pitch-angles along the sightlines of ARMS-T NPA (blue and green colors) and of ARMS-P NPA (black and red colors)

diagnostic chambers either by ARMS-P or by ARMS-T. Further upgrade and additional data acquisition is required in order to perform simultaneous scan of plasma from tangential to perpendicular direction by both diagnostic chambers (40 sightlines). However, their joint operation would provide the data demonstrating the possibility of fast loss-cone in the perpendicular region marked by yellow color on Fig.1.

3. Experimental Results.

The spectrum of fast particles measured by one of the diagnostic sightlines (e.g. sightline No3) is shown on Fig.3 with the scale of colors corresponding to the measured flux of fast particles.

The set of such spectra along all sightlines for the case of ARMS-T forms the angular distribution of fast particles as it is shown on the Fig.4. For visual illustration of the flux dependence on the direction of the sightline the slope θ of every spectrum was assumed as the angle between the sightline and magnetic axis. The 1st channel directed in the most tangential direction was broken in the

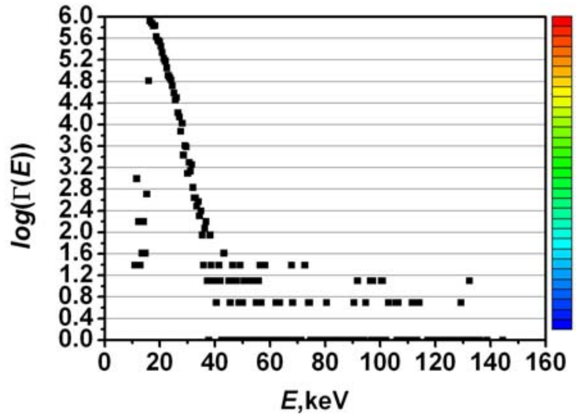

Fig.3 Energy spectrum measured along one of the 20 sightlines (e.g. sightline #3).

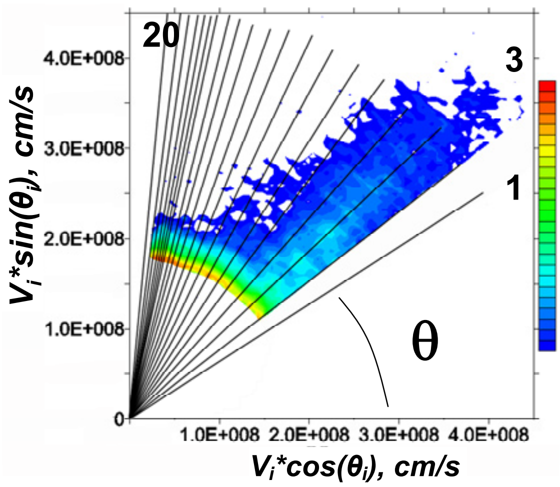

Fig.4 Energy spectrum measured along 19 sightlines (i is index of the sightline, θ is the angle between the sightline and magnetic axis).

very beginning of experimental campaign. This spectrum was measured during operation of tangential Neutral Beam Injector (NBI#1). The suprathermal energy tail at the tangential sightlines is caused by high-energy NBI particles.

First measurements of angular resolved fast particle distribution were made by ARMS-T. It was found that in most cases the systematic decrease of fast particle distribution has been observed near the perpendicular direction (at the sightlines from the 17th to the 20th) as it can be seen at Fig.5. The spectra of Fig.5 were measured in R_{axis}=3.6m B=2.75T magnetic axis configuration during injection of just perpendicular NBI#4. It was expected that injection of perpendicularly directed particles in the inner-shift configuration, like the R_{axis}=3.6m one, will lead to reducing of the loss-cone region. However the flux near perpendicular region is still significantly smaller than at other sightlines. Structure of

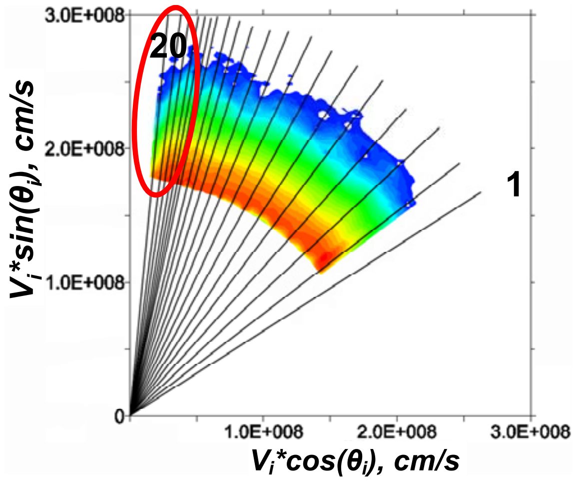

Fig.5 Experimental result of angular distribution of fast particles for Rax=3.6m obtained by ARMS-T during operation of the perpendicular NBI#4.

magnetic field in LHD device has very complicate shape, therefore the possibility of the geometry of measurements influence on the measured flux was evaluated. For this purpose the expected fast particle spectra were calculated in [2]. The calculation results demonstrated that geometry of measurements may influence on the measured flux of fast particles, however can not completely explain the reduced fast particle population near perpendicular region. It was supposed that it can be explained by the loss-cone region existence near perpendicular region [2].

As it was mentioned in Part 2 of this manuscript, in order to check the existence of the loss-cone region in the perpendicular region, the additional diagnostic chamber providing detailed scan of perpendicular region was installed on LHD.

The very first experimental data from ARMS-P were obtained recently and are shown on Fig.6. Data obtained by ARMS-P demonstrate substantial reduction in fast particle population at the sightlines scanning perpendicular region of plasma column. More clearly and quantitatively this effect can be seen on Fig.7, where distributions of 20keV and 30keV particles are compared. I can be seen that confinement of particles with higher energies is significantly reduced in perpendicular region.

Thus ARMS-P NPA allows one to observe the loss-cone region more clearly than before. In ARMS-T case only the edge side of this region was measured and it wasn't clear how fast particles are distributed in perpendicular region and how large is this loss-region.

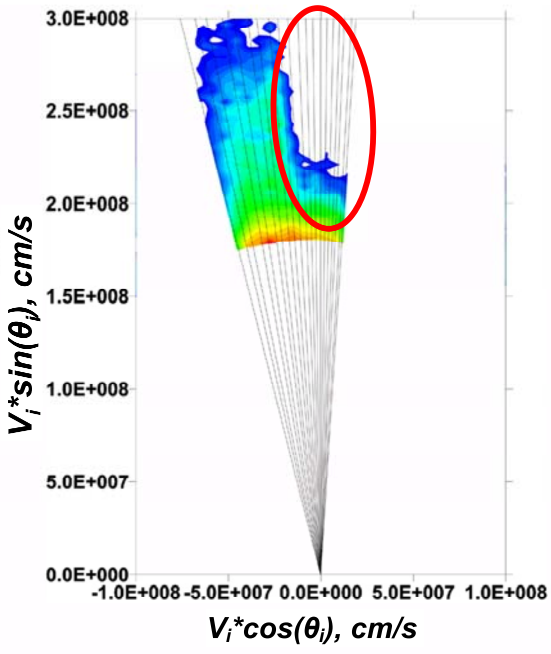

Fig.6 Experimental result of angular distribution of fast particles for Rax=3.6m obtained by ARMS-P during operation of the perpendicular NBI4.

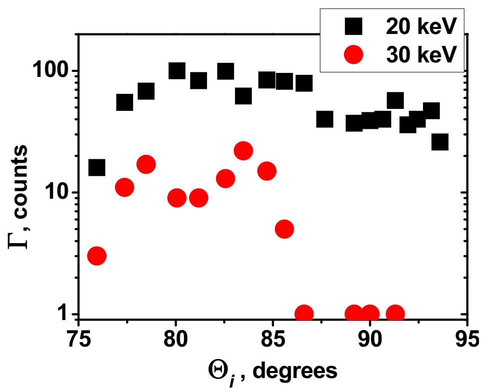

Fig.7 Angular distribution of 20keV(black squares) and 30keV (red circles) protons. (*i* is index of the sightline, *θ* is the angle between the sightline and magnetic axis).

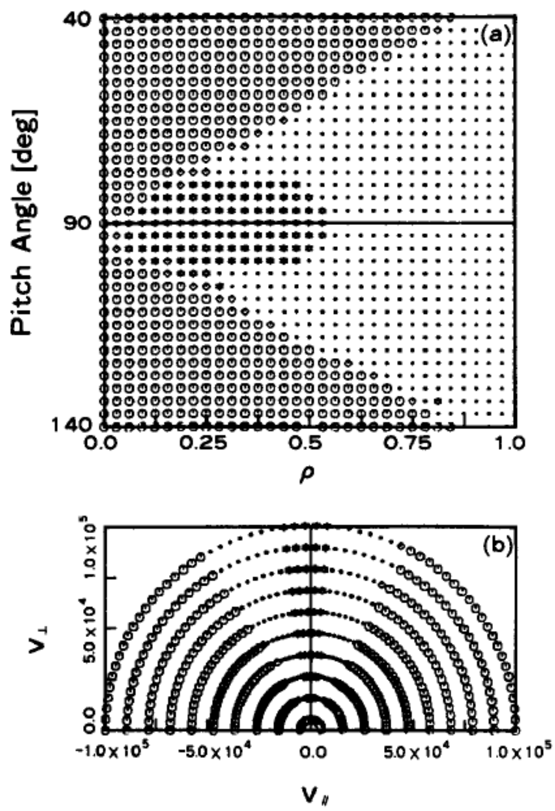

Fig.8 Numerical results of the loss region in both (a) configuration and (b) velocirt space at ρ = 0.5 outside the torus in the case of φ = 0. Results are obtained by solving the drift equations.

Accordingly, ARMS-P NPA data confirm data obtained by ARMS-T and allow one to study loss-cone behavior in different plasma regimes. The sightlines at which the significant reduction of fast particle population was observed are marked by red color (11 sightlines of ARMS-P) and green color (4 sightlines of ARMS-T), and the range of the possible fast particle loss-cone region in LHD plasma is marked by yellow on Fig.1. Therefore, experimental data correspond to theoretical predictions about the existence of the loss-cone region in the perpendicular region of helical plasma as it was described in the manuscript [1] and shown on the Fig.8. These calculations were made with assumption that a particle is considered to be lost beside last closed magnetic flux surface.

4. Conclusion

Possibility of the fast particle loss-cone region existence in the perpendicular region was confirmed by experimental data obtained from upgraded ARMS-NPA. The detailed scan of fast particle angular distribution in a wide range of angles is possible during joint operation of ARMS-T and ARMS-P diagnostics. New ARMS-NPA system is promising to become an excessively helpful tool in investigations of the fast particle distribution function and the confinement of fast particles due to the possibility to make angle- energy- and time dependant measurements simultaneously.

5. References

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