Simulation of Angle and Energy Resolved Fluxes of Escaping Neutral Particles from Fusion Plasmas with Anisotropic Ion Distributions

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Multidirectional diagnostics employing high resolution atomic energy spectrometers [1,2] are being used to study the ion component heating mechanisms and fast ion confinement in helical plasmas. Since the natural atomic flux source is not localized in contrast to pellet charge exchange [3,4] or diagnostic neutral beam methods [5], the correct interpretation of such measurements in a complex toroidally asymmetric geometry requires a careful numerical modeling of the neutral flux formation and the knowledge of the charge exchange target distributions, relevant cross-sections and the magnetic surface structure. The measured neutral flux calculation scheme for LHD geometry was given in [6] and the influence of the geometry effect on the interpretation of measured data was shown. In the current work angular dependence of fast ion distribution function is taken into account. Experimental signals for all 20 channels of the Angular-Resolved Multi-Sightline Neutral Particle Analyzer (ARMS-NPA) were simulated for different cases of fast ion distribution functions. Calculation results are shown for heating-induced fast ion distribution tails obtained from Fokker-Planck modeling. The behavior of calculated and experimental ion spectra from NBI is discussed.

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

1. Introduction

Multi-directional neutral particle analyzer beside high resolution energy spectra of fast particles can provide the information about their angular distribution during scan of plasma column in tangential direction. Vertical scan of plasma column by multi-directional diagnostic can provide information about the radial distribution of fast particles. Such measurements are required for the understanding of the fast ions behavior in plasma, for checking of the fast particle loss-cone presence, for studying if the heating mechanisms, etc. Such information is important for the fast particle confinement and ignition of the future fusion reactor. For this purpose the novel ARMS-NPA has been developed [1] which can measure plasma in vertical and tangential directions. As the magnetic field geometry of LHD has a very complex 3D structure, simulation of the experimental signal of the flux of fast particles is required with taking into account the attenuation of fast particles on the way to the detector due to the charge-exchange, and the influence path length of the particle along every scanning chord in order to understand how does geometry of measurements influences in the angular fast particle distribution. The difference in the geometry of measurements can be clearly seen on the illustration of the vertical cross-section plane of every detector sightline on Fig.1. Detector 1 corresponds to the most tangential direction and detector 20 is the direction close to the perpendicular one. The sheaf of sightlines was adjusted in such a way that all the channels to observe as closer as possible to the central region of plasma.

2. The Calculation Scheme.

The escaping neutral flux formulation has been made in [6] for passive diagnostics and the atomic flax can be written as:

$$\Gamma(E,\vartheta) = e^{\int_{\rho_{\min}}^{1} \frac{Q^{-}(\rho')d\rho'}{\lambda_{mfp}(E,\rho')}} \frac{\Omega S_a}{4\pi} \int_{\rho_{\min}}^{1} g\left(E,\vartheta,\rho\right)\times$$

$$\times\left[Q^{+}(\rho) e^{-\int_{\rho_{\min}}^{\rho} \frac{Q^{+}(\rho')d\rho'}{\lambda_{mfp}(E,\rho')}} - Q^{-}(\rho) e^{-\int_{\rho_{\min}}^{\rho} \frac{Q^{-}(\rho')d\rho'}{\lambda_{mfp}(E,\rho')}} \right] d\rho$$

where $Q^{+}(\rho) = dX/d\rho > 0$ and $Q^{-}(\rho) = dX/d\rho < 0$ on the two intervals between $\rho = 1$ and $\rho = \rho_{\min}$.

In order to check the geometry influence simulation of experimental signal was made for the isotropic Maxwellian plasma ion energy probability density uld be

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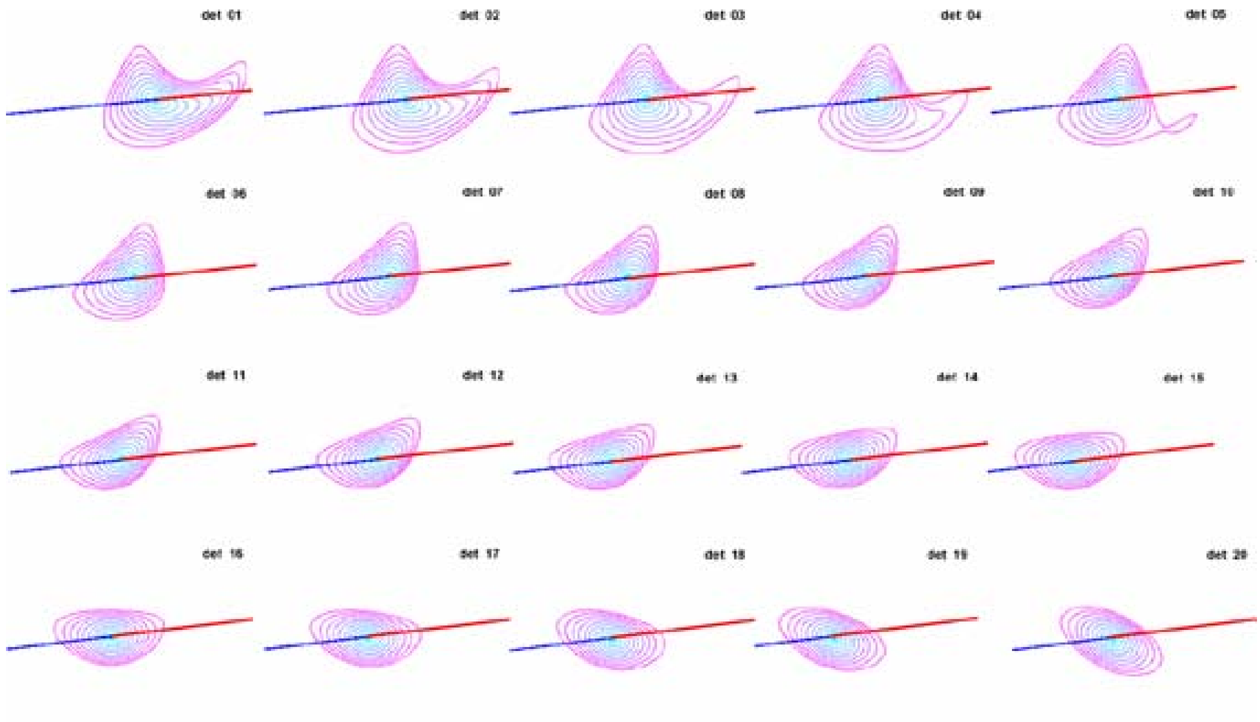

Fig.1 Vertical cross-section plane of every ARMS-NPA sightline. Red color of the line correspond to the scanned part of plasma close to the LHD center. Blue color is the part of sightline close to the detector. Detector 1 corresponds to the most tangential direction and detector 20 is the direction close to the perpendicular one.

function:

$$f_i^{(M)}(E,\rho) = \frac{2\sqrt{E}}{\pi^{1/2} T_i^{3/2}(\rho)} \exp\left(-E/T_i(\rho)\right)$$

It has already been shown that the geometry effect may influence on the fast particles spectra [6] but not as significantly as in experiment. That could be due to the not significant difference of the compared magnetic configurations Rax = 3.6m and Rax = 3.53m. Thus the new calculations were made for much more different magnetic axis configurations (Rax = 3.6m and Rax = 3.9m) for all 20 sightlines. The results of simulation can be seen on the Fig.2. Both cases demonstrate angular anisotropy due to the geometry influence and in both cases fast particle population is reduced in perpendicular region.

3. Experimental Results

Angular resolved measurements were made for both magnetic axis configuration (Rax = 3.6m and Rax = 3.9m). Angular resolved spectra plotted on Fig.3 Both cases demonstrate angular anisotropy and both cases demonstrate the reduceing of fas particle population in perpendicular direction. In order to understand if such a behavior of fast particle spectra is due to the geometry effect, it must be subtracted from experimental data. The geometry of measurements influences only on the relative values of fast particles but not on the shape of spectra, thus for the geometry effect subtraction it will be enough to divide experimental spectra along every sightline by relative values obtained from calculation results.

Angular resolved spectra plotted Fig.4 represent experimental data of angular distribution of fast particles after the geometry effect subtracting for Rax = 3.6 m and R_{ax} = 3.9 m correspondingly. Both cases still demonstrate angular anisotropy. Fast particle population in Rax = 3.6m configuration measured along four perpendicular sightlines are plotted on Fig.5 and demonstrate reducing of spectra. The case of R_{ax} = 3.9 m in addition to the reducing of the fast particle flux in perpendicular direction (Fig.103) still demonstrate the drop of fast particle population in the region of the 8th channel. Such a behavior can be due to the presence of the loss-cone region.

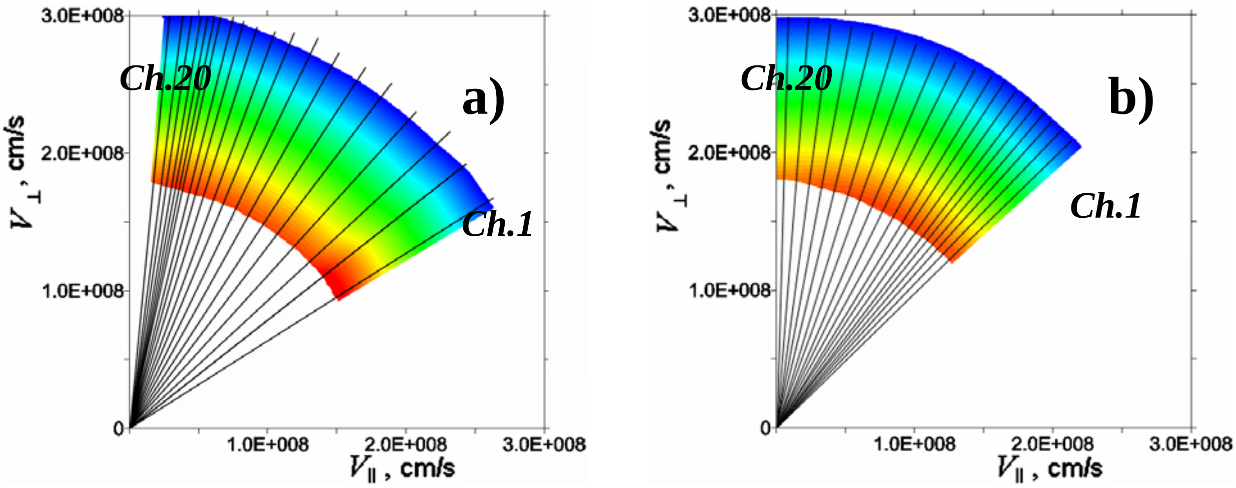

Fig.2 Calculated angular resolved spectra of fast particles a) for Rax = 3.6 m magnetic axis position and b) for Rax = 3.9 m magnetic axis position.

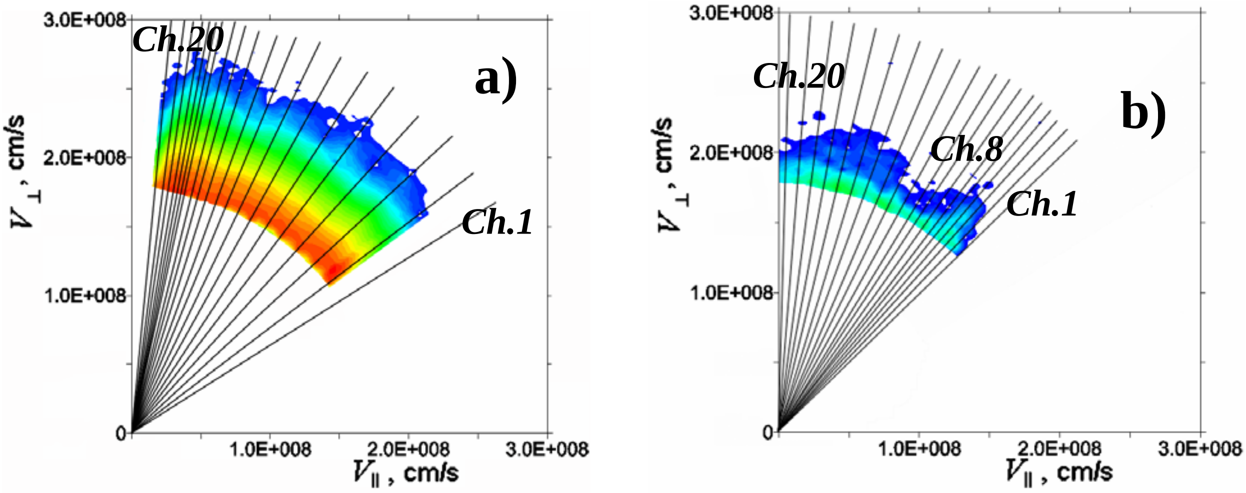

Fig.3 Experimental results of angular distribution of fast particles a) for Rax = 3.6 m magnetic axis position and b) for Rax = 3.9 m magnetic axis position.

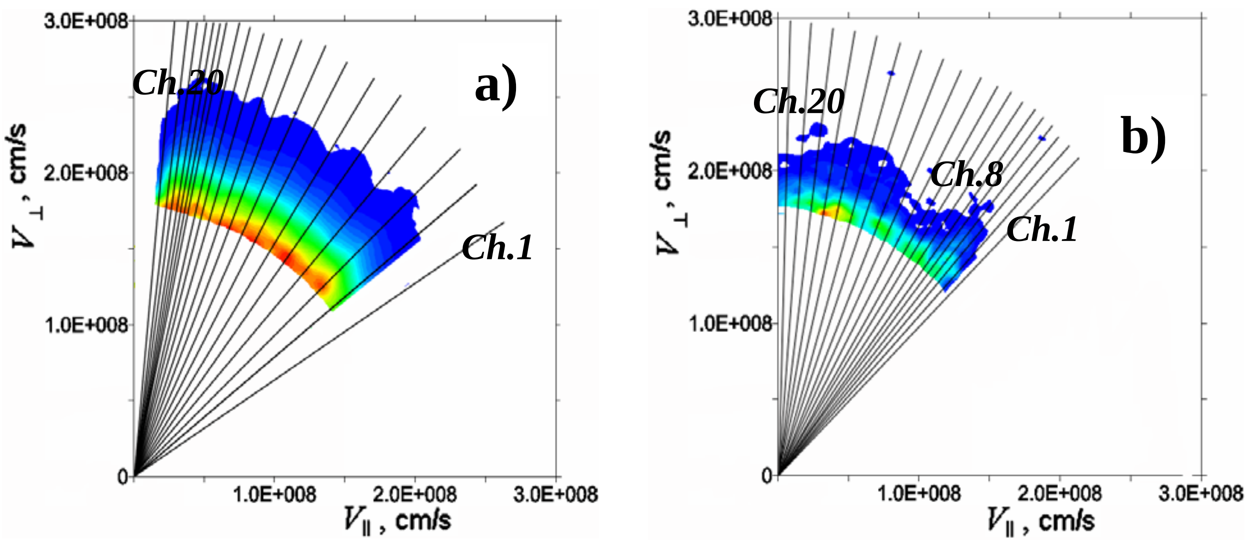

Fig.4 Experimental data of angular distribution of fast particles after the geometry effect subtracting a) for Rax = 3.6magnetic axis position and b) for Rax = 3.9 m magnetic axis position.

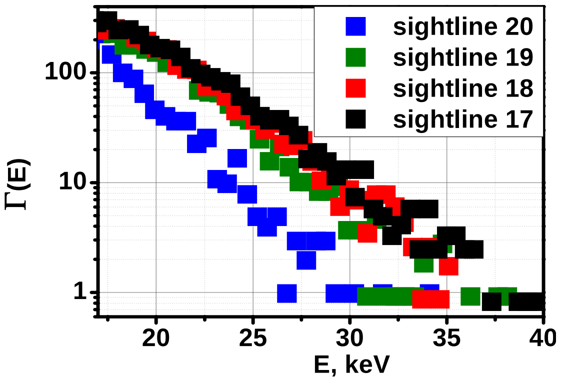

Fig.5 Fast particle spectra for four of the sightlines close to perpendicular direction (sightline 20 is the most perpendicular one) during perpendicularly-injecting NBI4 operation the case of Rax = 3.6 m B_T = 2.75T magnetic field after the geometry effect subtracting.

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