

## Study of fast ion losses during NBI heating on Globus-M tokamak

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### Introduction.

In 2012-13 years the experiments on auxiliary heating plasma with the use of a Neutral Beam Injection (NBI) with energy increased up to 24 – 30 keV were carried out on Globus-M tokamak. Such plasma parameters as electron density, isotope composition and plasma horizontal and vertical position were varied in order to study the energy transfer from NB to plasma and to optimize the NBI heating. The study of ion component behavior was performed using two Neutral Particle Analyzers (NPA) of ACORD type [1]. One of them (ACORD-12 NPA) was placed perpendicularly to the plasma column and used for ion temperature measurements. The maximal ion temperature increase  $\Delta T_i \sim 200\text{--}600$  eV in comparison with ohmic temperature level were obtained during the deuterium injection to deuterium plasma when the plasma was shifted to the central column of the tokamak ( $\Delta R \sim 1.5$  cm). In the case of non-shifted plasma the ion temperature increase was significantly lower  $\Delta T_i \sim 100\text{--}200$  eV. A better fast ion confinement during NBI heating of shifted plasma was indicated by measurements of intensity of 2.45 MeV neutron flux, where it was about 1.6 times higher in comparison with the case of non-shifted plasma. To explain the effects mentioned above the study of fast ion losses was performed.

### Study of losses using the analysis of fast ion spectra.

To study the fast ion losses the measurements of Charge-eXchange (CX) atomic fluxes emitted by plasma were used. The spectra of CX atoms were recorded using the second NPA (ACORD-24M) placed tangentially to the plasma column with impact parameter equal to impact parameter of NBI. The energy range of the NPA is 0.3-70 keV, energy resolution  $\Delta E/E = (10\text{--}25)\%$  and time resolution  $\geq 200\text{ }\mu\text{s}$ .

The spectra obtained with time resolution of 3 ms for both cases of shifted and non-shifted plasma are presented in the figure 1. Several features should be emphasized. First, the fluxes of CX atoms are significantly higher in the case of shifted plasma. Second, the slopes of these two spectra in the energy range  $(1/2E_{NBI} - E_{NBI})$  are different. Third, in the

both cases the spectra have such a complex shape, which is not possible to explain by slowing down of three energy components of injected particles ( $E_{NBI}$ ,  $1/2E_{NBI}$ ,  $1/3E_{NBI}$ ).

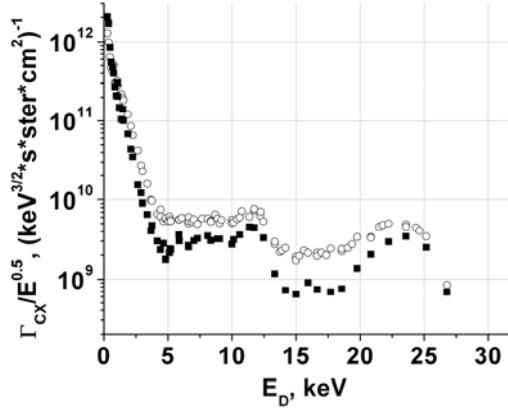


Fig. 1. Spectra of fast and thermal particles recorded at 25 ms of NBI. Time resolution 3 ms. Empty dots – discharges with the shifted plasma (##30143-50, ##30580-81), squares – discharges with non-shifted plasma (##30135-41, ##30571-77).

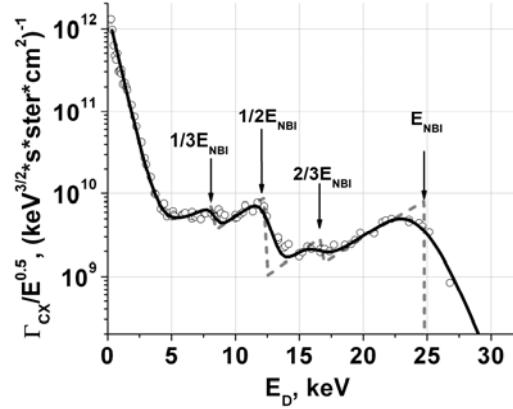


Fig. 2. Spectra of fast and thermal particles in the discharges with shifted plasma. Empty dots – recorded spectra; dashed gray line – calculated slowing down spectrum and Maxwell spectrum of thermal particles, black curve – calculated spectra with taking into account the energy resolution of ACORD-24M NPA.

According to the solution (1) of Fokker – Plank equation [3] there is no concavity expected in the shape of spectra within the energy range of ( $1/2 E_{NBI} – E_{NBI}$ ), while such a concavity was observed on the recorded spectra.

$$\frac{dN}{dE} \propto \sqrt{E} \cdot (E - E_{crit})^{v-1}, \text{ where } v = \frac{\tau_{se}}{3\tau_l}, \quad (1)$$

$\tau_l$  – particle losses time,  $\tau_{se}$  – time of particle slowing-down on electrons,  $E_{crit}$  – critical energy ( $E_{crit} \approx 10$  keV).

To explain the shape of spectra two assumptions should be made. First, there is the fourth energy component in injected particle spectra with  $E = 2/3 E_{NBI}$ . Second, there are significant particle slowing-down losses creating negative slope on the spectra in energy range of ( $1/2 E_{NBI} – E_{NBI}$ ). The approximation of measured spectrum (shifted plasma) with taking into account two assumptions is shown in the figure 2.

To verify the first assumption concerning the  $2/3 E_{NBI}$  energy component the experiment on injector energy spectrum determination was carried out with the use of ACORD-24M NPA. In this experiment deuterium NB was injected to the tokamak chamber filled the deuterium gas. During the injector pulse a toroidal magnetic field was turned on. Some part of injected particles were ionized in the gas, confined by toroidal field, neutralized and entered the

NPA. Measured spectrum of such particles is shown in the figure 3. The presence of  $2/3E_{NBI}$  energy component, associated with of  $\text{HD}^+$  ions, is clearly seen in the figure. Unfortunately it is not possible to estimate the quantity of the particles with this energy because of particle spectrum distortion during transfer from the injector to the NPA.

The possible reasons of significant fast ion losses (figure 1, 2) have been studied. First, the parameter  $v$  characterizing the amount of slowing-down losses was estimated. It has been done using approximation of measured spectra by the superposition of four solutions of Fokker – Plank equation (1). It was obtained that  $v \sim 5$  for the case of shifted plasma and  $v \sim 7$  for the case of non-shifted plasma. These values could not be explained by charge-exchange losses. It was found earlier that the typical value of  $v$  for CX- losses in the plasma with similar density is of the order of 1 [2]. Moreover, by means of approximation the particle direct losses were estimated by the level about 50% for both cases. Such the level of direct losses is normal for Globus-M tokamak [2].

During the analysis of measured spectra the increase of particle number in the shifted plasma discharges has been noted. The spectra approximation gave the value of this increase as large as 1.3 times. The increase of particle number can be partially explained by changes in the CX- target. Probably because of the plasma shift the profile of plasma neutrals has changed and this could result in increase of CX- signal. In favor of this assumption the particle number in the thermal spectra measured by ACORD-12 NPA was about 1.3 times higher in the discharges with shifted plasma.

#### *The influence of sawtooth oscillation on fast ion losses.*

The most probable reasons of enhanced slowing-down losses were the sawtooth oscillations which took place during NBI. To find the possible correlation between the sawtooth oscillations and slowing-down losses the time evolutions of plasma parameters, including the CX-flux evolution, have been examined. The period of sawtooth oscillations was about 1.5 – 2 ms, therefore the measurements with fast time resolution of CX-fluxes were performed.

The regime with non-shifted plasma and strong sawtooth oscillation has been studied. With the use of ACORD-24M NPA the CX fluxes have been measured with time resolution equal to 300  $\mu\text{s}$ . It became possible after installation of new electronics on CX- diagnostics complex. Oscillograms of plasma density and SXR signal, on which sawtooth oscillations were clearly seen, are presented in the figure 4. The neutral particle flux with energy equal to 26.6 keV (close to  $E_{NBI}$ ) is also presented on the figure. The neutral flux was strongly

modulated during sawtooth oscillations and the value of the flux has significantly decreased after the start of the oscillations. This result shows that sawtooth oscillations can be the reason of enhanced slowing-down losses of ions.

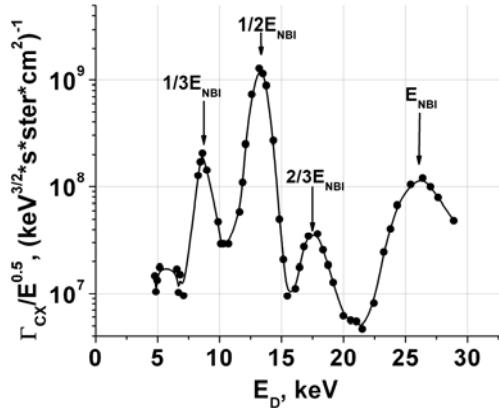


Fig. 3. Energy spectra of deuterium NB injected to the Globus-M chamber filled with deuterium gas and switched on toroidal magnetic field recorded with use of ACORD- 24M NPA.

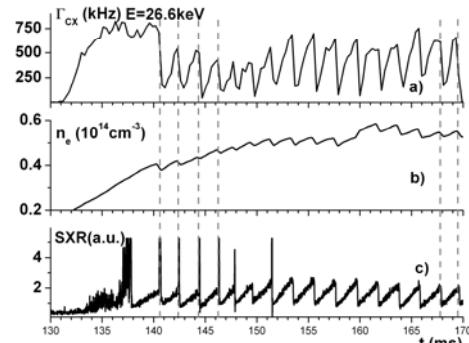


Fig. 4. Temporal correlation of CX flux with sawtooth oscillations (#30376):  
 a) Neutral particle CX flux with energy equal to 26.6keV.  
 b) Linear averaged plasma density.  
 c) Soft X-ray signal.

During the analysis of the injected particle spectra it has been obtained that the particle losses are lower in the case of shifted plasma. It is expected that this effect can be explained such a way: the influence of oscillations on particle confinement became weaker when the plasma is shifted. The mechanism of this phenomenon is not clear at this moment and it is the subject of further research.

#### Conclusion.

The losses of fast ions have been studied in the discharges with various plasma horizontal shifts. The analysis of experimental spectra of fast CX atomic fluxes has been performed. The presence of the energy component with  $E = 2/3 E_{NBI}$  has been found. Significant slowing-down losses have been detected. Modulation of neutral particle flux by sawtooth oscillation has been observed. The assumption of the influence of sawtooth oscillation on fast particle confinement has been made.

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- [1] A.B. Izvozhikov, et al, Tech. Phys., 37 (1992) 201
- [2] F.V. Chernyshev, et al., Plasma Phys. Reports, 7 (2011) 553
- [3] W.W. Heidbink , et al., Nucl. Fusion, 4 (1994) 535