

Recent Results from CX Diagnostics at Ioffe Institute Tokamaks

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Abstract

An overview of recent results obtained by Charge-eXchange (CX) diagnostics at Globus-M spherical tokamak and TUMAN-3M tokamak with circular plasma cross section is the subject of this paper. The operation principle and parameters of CX diagnostics apparatus are given. The CX energy spectra and ion temperature obtained during the ohmic and auxiliary plasma heating at Globus-M and TUMAN-3M tokamaks are presented. The bulk ion heating and fast ion confinement are discussed.

1. CX diagnostics

The CX diagnostics at both plasma machines employs the Neutral Particle Analyzers (NPAs) of ACORD-12 type [1,2]. NPA operating principle is based on the ionization of neutral particles emitted by plasma in the gas stripping cell with the subsequent analysis of the resulting secondary ions in electric and magnetic fields.

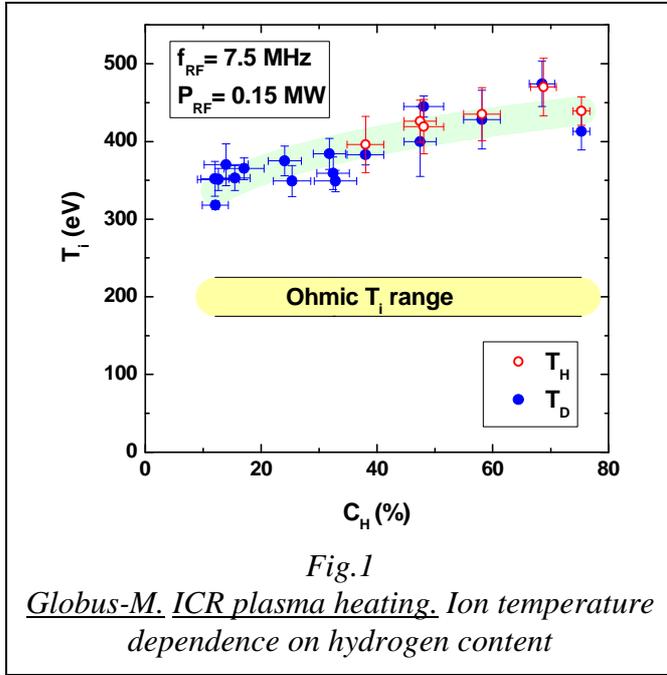
The analyzers provide the mass-resolved CX energy spectra measurements, supplying information about plasma Hydrogen/Deuterium (H/D) composition, ion temperature, and non-maxwellian ion distribution tails that appear during auxiliary plasma heating. The main ACORD-12 parameters are as follows:

Energy range	0.2-70 keV	Energy dynamic range (E_{\max}/E_{\min})	~ 7
Channel energy width	9-30 %	N ₂ stripping pressure	(1-4) $\times 10^{-4}$ Torr
Number of detectors	6x2 (H and D)	Detector type	Channeltrons
Mass suppression (H/D)	10^{-3}		

The NPAs are installed perpendicularly to the plasma column. Unfortunately the absence of appropriate NPA scanning systems and the arrangement of tokamak ports prevent the measurements in tangential direction on both plasma machines. Such measurements are important in the case of anisotropic ion distribution typical for the auxiliary plasma heating. To solve this problem a special technique based on reflection of particles from the metallic mirror was applied on the TUMAN-3M tokamak. This metallic reflector was installed at the NPA entrance, which permits the plasma observation along the tangential direction.

2. Globus-M experiments

ICR heating. On spherical tokamaks the Ion Cyclotron Range (ICR) plasma heating has some specific features such as: 1) simultaneous existence of several IC harmonics; 2) low efficiency of Radio Frequency (RF) power absorption due to large wave length in comparison with IC zone widths; 3) low efficiency of cut-off barriers.



At Globus-M a doubling of ion temperature was observed during the ICR heating experiments in mixed H-D plasma ($P_{RF} = 0.15-0.3$ MW, $f_{RF} = 7.5$ MHz, $B_{tor} \sim 0.4$ T). It was shown that ion heating can be carried out in a wide range of plasma ion composition $C_H = n_H/(n_H+n_D) = 10-70\%$ [3]. An increase of ion heating efficiency with H-content rising was detected (Fig.1).

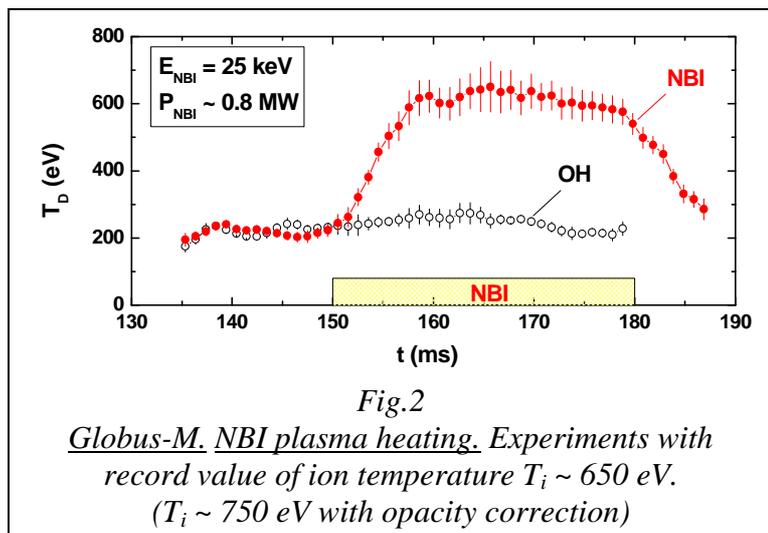
Due to a weak signal at high energies the measurements of CX flux above

5 keV was complicated. However using the measurements of 4 keV CX flux decay after ICR termination, the maximum energy of accelerated H-ions could be estimated from the formula:

$$\tau = t_{se}/3 \ln[(1+(E_0/E_{cr})^{3/2})/(1+E_{fin}/E_{cr})^{3/2}], \quad (1)$$

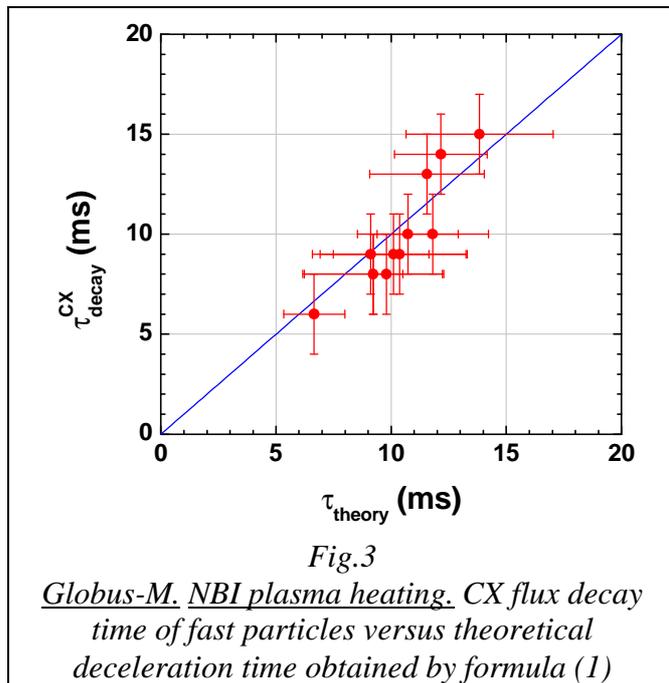
where τ is the time of particle deceleration from energy E_0 to energy $E_{fin} = 4$ keV; t_{se} is the slowing down time on electrons; and E_{cr} is the critical energy [4]. It was found that the maximal energy of H-ions was $E_0 \sim 15$ keV.

NB heating. One of the features of Neutral Beam Injection (NBI) on spherical tokamaks lies in the low magnetic field B_{tor} and the tight aspect ratio R/a (for Globus-M $B_{tor} \sim 0.4$ T,



$R/a = 1.5$). The NBI on this plasma devices is characterized by large gyro-radius of beam ions

r_L in comparison with plasma dimensions (for Globus-M $r_L \sim 3-5$ cm, $a = 0.24$ m). This can lead to enhanced particle losses and can reduce the efficiency of NB heating.

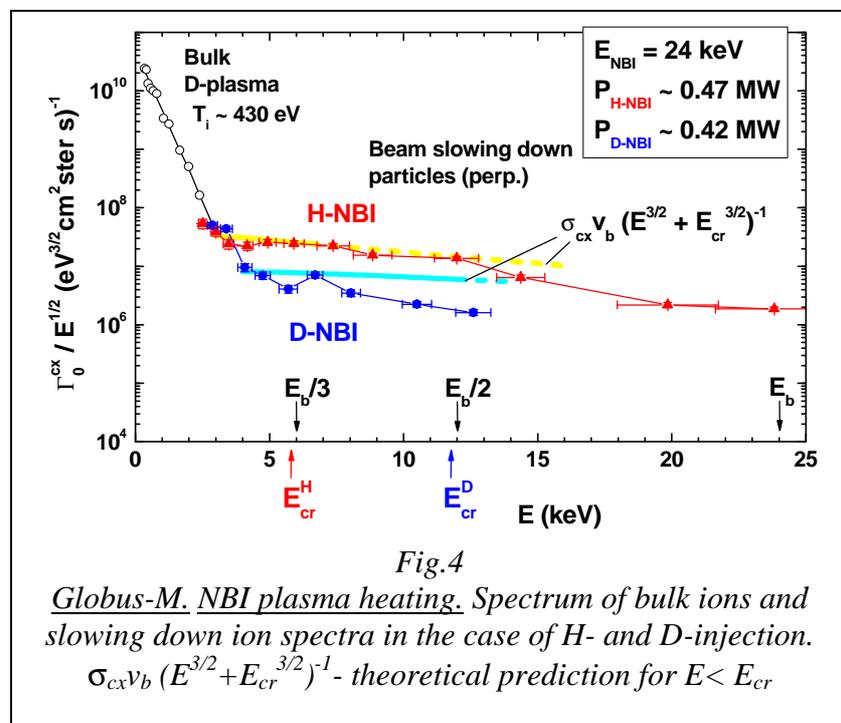


In spite of such complication about 3 times increase of ion temperature was obtained during Co-NBI experiment [5] ($P_{NBI} = 0.4-0.8$ MW, $E_{beam} = 22-29$ keV) (Fig.2). The record ion temperature value of $T_i = 650$ eV was achieved in low density plasma ($(1-2) \times 10^{19} \text{ m}^{-3}$). The measurements in the moderate density plasma ($(3-5) \times 10^{19} \text{ m}^{-3}$) give the value of $T_i = 430$ eV. However it was shown that due to plasma opacity the central T_i value could be as high

as 750 eV for low density and 700 eV for moderate density.

The beam ion deceleration time given by formula (1) was compared with the one obtained from the measurements of fast particle flux decay after NBI termination (Fig.3). A good agreement with theoretical prediction was found.

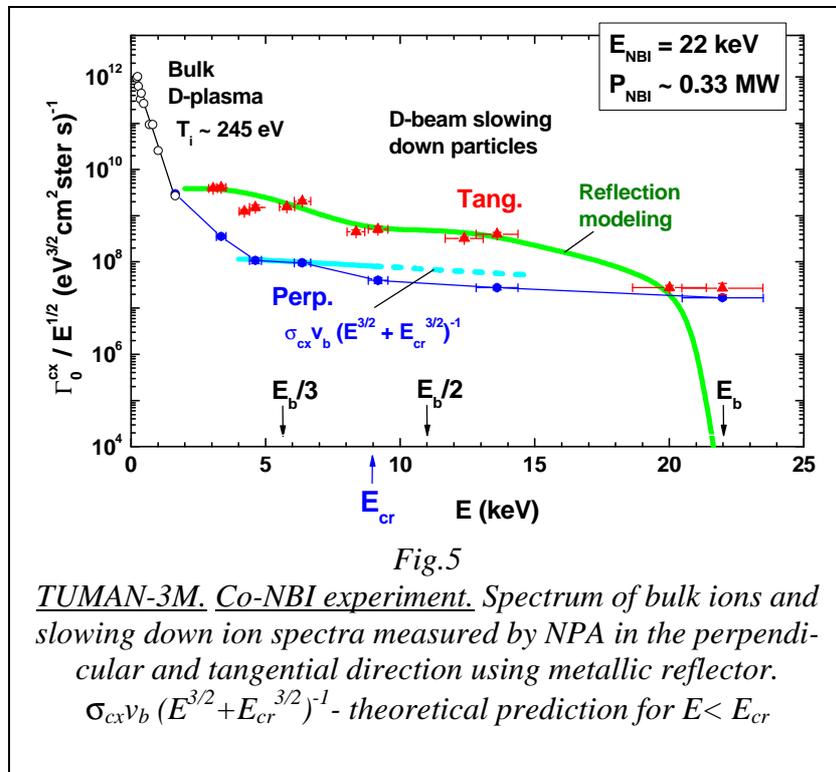
The beam slowing down spectra measurements were performed in a suprathermal energy range $E = 3-30$ keV [6]. The comparison of H- and D-NBI displays a higher population of beam slowing down ions in the case of H-NBI (Fig.4). The performed



particle trajectory simulations partly explain this difference due to first orbit losses and CX losses.

3. TUMAN-3M experiments

The NBI at the TUMAN-3M tokamak has the similar specific features as at Globus-M because of low toroidal field ($B_{\text{tor}} \sim 0.7$ T), which can lead to fast particle losses.



metallic reflector at the angle coinciding with the angle of NBI. On the contrary, neither significant increase of ion temperature nor appearance of suprathermal particles was observed during Counter-NBI, which is consistent with the tendency of orbital loss enhancement for counter-injected particles.

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In spite of this about a doubling of ion temperature was obtained during Co-NBI heating experiment ($P_{\text{NBI}} = 0.2-0.5$ MW, $E_{\text{beam}} = 18-25$ keV) [7]. A rise of high energy ion tail was noted from the CX flux measurements both in tangential and perpendicular directions (Fig.5). The tangential measurements were performed using the