CONFINEMENT OF THE 0.5…4.5 keV PLASMA IONS IN LOW DENSITY DISCHARGES OF THE U-3M TORSATRON

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Dependences of the charge exchange (CX) fluxes of neutral are investigated via neutral particle analyzers (NPA) in the U-3M torsatron. Fast (≤0.5 ms) decay of the vertical and tangential CX fluxes has been observed after turning off RF heating power. According to these measurements, the U-3M energy confinement time of the 0.5…4.5 keV ions is less than 0.5 ms in the low density (n_e=(1…4)·10^{12} cm^{-3}) discharges. No difference between confinement of the ion energy component parallel to the magnetic field and confinement of the perpendicular to the magnetic field one was observed in U-3M. Evidently, an ion cooling through CX collisions with neutrals sustain the main channel of the 0.5…4.5 keV ion energy loss in the U-3M torsatron.

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INTRODUCTION

Neutral atoms and molecules substantially affect plasma confinement in small and medium size fusion devices. Neutrals can introduce plasma cooling and additional viscosity which dominates the neo-classical ion viscosity in the gas fueling region [1, 2]. Furthermore, according to those studies, the neutral flux can modify or even determine the edge radial electric field, plasma rotation and plasma confinement. An influence of neutrals can determines ion energy confinement in the small-size torsatron U-3M. The U-3M plasma volume is about 0.3 m^3 and its chamber volume is about 70 m^3. The hydrogen pressure feeding level used in U-3M discharges is about 10^{-5} Torr. In the case when all hydrogen will be ionized and accumulate in the confinement region the plasma density should achieve a value about 10^{14} cm^{-3}. This density is two orders of magnitude higher than practically achieved densities in U-3M discharges. Evidently, substantial flux of the neutrals with mean free path longer than U-3M plasma size from large U-3M vacuum vessel should sustain main channel of the ion energy loss via the charge exchange (CX) collisions in the low density discharges of U-3M. According to set of previous articles [3-6], confinement of fast ions in U-3M was considered as collisionless. The electron-ion and ion-ion collision times are longer than the neoclassical confinement time of these ions, thus the confinement of the 0.5…4.5 keV ions is collisionless, if we are not taking into account CX collisions. Due to substantial difference in confinement of trapped and passing ions the confinement time of energetic ions with major part of the energy perpendicular to the magnetic field lines is significantly shorter than the confinement time of the ions with major part of the energy parallel to the magnetic field in the collisionless stellarator plasma. We can estimate the role of the CX ions cooling by the comparison of the parallel ion energy and perpendicular ion energy confinement times. If these times are comparable, then CX cooling is dominant channel of the ion energy loss and U-3M confinement cannot be considered as the collisionless.

In this paper, the evidence of extremely short parallel ion energy and perpendicular ion energy confinement times is shown in low density U-3M discharges. These times are shorter that temporal resolution of the NPAs and less than 0.5 ms.

1. EXPERIMENTAL SET-UP

"Uragan-3M" is a small size torsatron with l/m=3/9, R_0=1 m major radius, $\bar{a}$≈0.12 m average plasma radius and toroidal magnetic field B_0≤1 *T*. The whole magnetic system is enclosed into 5 m diameter vacuum tank. The low density discharges (n_e=(1…4)·10^{12} cm^{-3}) under consideration are induced by RF antennas [7, 8]. The U-3M is equipped with two CX neutral particle analyzers (NPA) [8]. Magnetic mass separators, reflection dumpers have been added in present NPAs set-up in contrast to the used in previous work [8]. A tangential neutral flux from almost whole U-3M cross-section is measured by one of the NPA for parallel ion energy studies. The perpendicular ion energy distribution is measured along the vertical lines by the other NPA. A radial shift of the NPA line of sight was varying from the inner conductor wall *R*=85…86 cm to the geometrical centre of the U-3M winding of *R*=100…101 cm, corresponding to the half-plasma radius ρ≈0.5 [8]. Due to strongly three-dimensional geometry of the torsatron magnetic field lines, parallel and perpendicular CX fluxes are coupled. However, present set-up is reasonable for qualitative comparison of these fluxes behaviors. The NPA signals integration time is 0.1 ms, and its sampling rate is about 50 kS/s.

2. NPA SIGNALS IN OLD NPA SET-UP

In previously used NPA set-up, long enough decay of measured signal was observed after turning the RF power off. This long decay was improperly qualified as a long enough confinement time of the energetic ions [4, 7]. An example of such CX flux decay in old set-up in the sweeping NPA mode of operations [8] is shown in Fig.1. The 0.1 ms integration time was used in this experiments [8] in contrast to results of Ref. [4, 7] where long integration time in addition to NPA diagnostic error cause the long confinement time. Due to extremely low cross-section of the hydrogen atoms striping by the nitrogen in a energy range below 100 eV [8], the NPA signal in minima of the analyzing energies should be equal to zero.

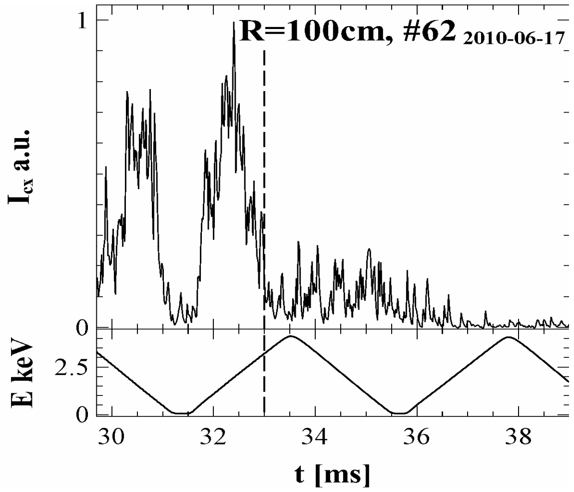

Fig. 1. NPA signal (top frame) and analising energy (bottom frame) in old NPA set-up. Dashed line marks the RF generator switching off time

Observed in these minima NPA signal is not related to the CX flux and represent an NPA diagnostic error. During U-3M discharge a level of the NPA signal in energy minima is low and this level is order of magnitude lower the NPA signal level in medium energies. It allows us to analyze CX energy distributions in the main U-3M discharge [8]. In contrast to the main discharge the signal after RF power switching off is not correlated with the analyzing energy and its level is high in the zero energy stage. This is direct evidence that the NPA signal after RF switching off was not related with the CX flux in pervious NPA set-up.

3. CX FLUXES DECAY

Vertical CX flux decays in present NPA set-up and NPA mode with fixed energy, are shown in Fig. 2.

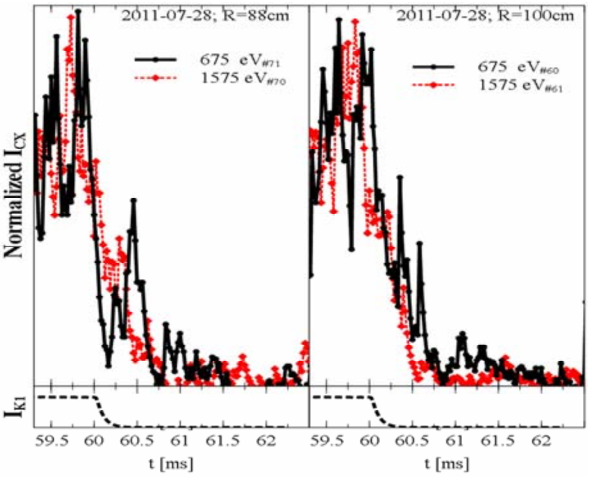

Fig. 2. Normalized CX fluxes from plasma periphery and geometrical chamber centre (top frames); NPA line of sight positions and the energy of CX flux are marked in legends. RF power (bottom frames)

Such fast decay of the CX flux is always observed in all low density discharge conditions and all CX energies (0.4…4.5 keV) and in all NPA line of sight positions (ρ=0.5…1.2). Same fast decay of the parallel to the magnetic field CX flux was observed in all discharge conditions and for all measurable CX energies. The 675 eV CX flux decay in discharges with different magnetic fields is demonstrate (Fig. 3) this fast decay.

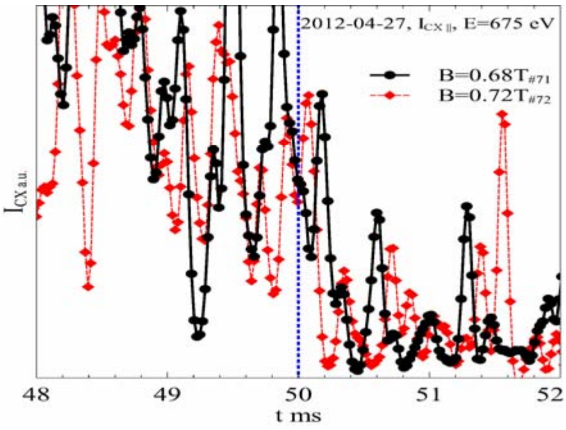

Fig. 3. Tangential 675 eV CX fluxes in discharges with different magnetic field; doted line is marked end of RF

A level of parallel CX flux is at least order of magnitude lower than the level of the perpendicular one. It explains a noisy character of the observed signal in 0.1 ms integration time set-up, as well as non-systematic noise due to the NPA photomultipliers noise. Absence of any correlations of the parallel NPA signal bursts after the decay stage in set of similar U-3M pulses demonstrates, that these bursts can-not be associated with CX flux.

The CX flux from a plasma $\Gamma_{cx}(E,R)=\int\xi(E,R,z)dl$ depends on molecular and atomic hydrogen concentrations n_0 and n_{H2} respectively: $\xi\approx n_i(E)\left(n_0\sigma^0_{cx}(E)+n_{H_2}\sigma^1_{cx}(E)\right)$, where $\sigma^0_{cx},\sigma^1_{cx}$ are cross sections of the hydrogen ion charge exchange on hydrogen atom and molecule respectively. In general, CX flux decay can be determined by ions cooling and by a modification of the concentration of the neutrals (conversion to molecules in particular). Energy dependence of $\sigma^0_{cx},\sigma^1_{cx}$ [9] and ratio of this cross-sections are shown in Fig. 4.

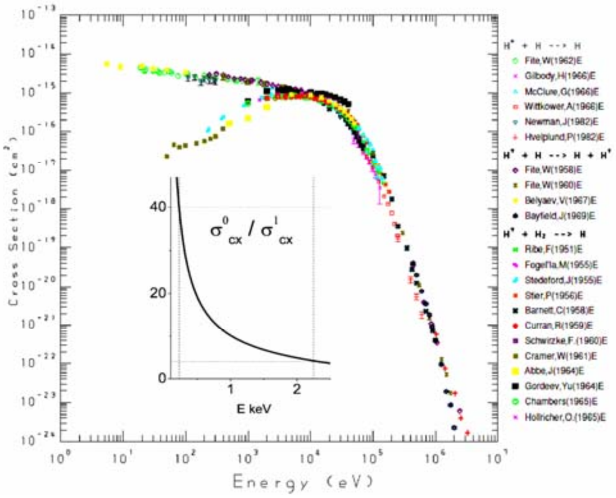

Fig. 4. Atomic and molecular CX cross-sections and their ratio (in a central inset)

According to these data, the ratio of atomic and molecular cross-sections is order of magnitude lower at 225 eV than at 2.25 keV. If substantial modification of the molecular and atomic concentrations ratio takes place during the decay stage of the discharge, then decay times of CX flux of these two energies should be significantly different. Experimental comparison of the CX fluxes under consideration (Fig. 5) does clearly show that no difference in their decay times is recognizable.

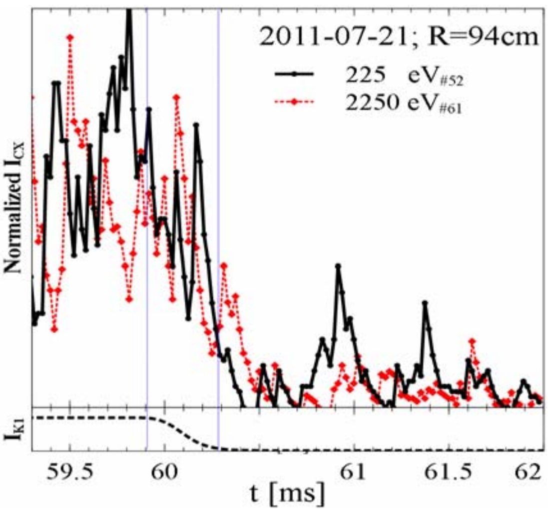

Fig. 5. Normalized 225 eV and 2.25 keV CX fluxes (top frames); RF power (bottom signal)

Therefore, the ratio of the molecular and atomic concentrations is constant during the 0.5 ms decay time of the CX fluxes and the decay is caused by the fast ion cooling.

Thus, the decay time of perpendicular (ρ=0.5…1) and tangential (from almost whole cross-section) CX fluxes after switching off RF power is shorter that 0.5 ms. The U-3M energy confinement time of the 0.5…4.5 keV ions is less than 0.5 ms in the low density (n_e=(1…4)·10^{12} cm^{-3}) discharges. This time is substantially shorter than the energy confinement time according to U-3M stellarator scaling [7]. Evidently, an ion cooling through CX collisions with neutrals sustain the main channel of the 0.5…4.5 keV ion energy loss in the U-3M torsatron.

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УДЕРЖАНИЕ ИОНОВ ПЛАЗМЫ 0.5…4.5 кэВ В МАЛОПЛОТНЫХ РАЗРЯДАХ ТОРСАТРОНА У-3М

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Зависимости потоков нейтралов перезарядки измерены с помощью анализаторов нейтральных частиц в торсатроне У-3М. Быстрое (≤0.5 мс) время спада вертикального и тангенциального потоков нейтралов перезарядки наблюдалось после выключения мощности ВЧ-нагрева. Согласно этим измерениям время удержания энергии 0.5…4.5 кэВ ионов в У-3М меньше, чем 0.5 мс в низкоплотных (n_e=(1…4)·10^{12} cm^{-3}) разрядах. В У-3М не было обнаружено разницы между удержанием компонентов ионной энергии параллельной и перпендикулярной магнитному полю. По-видимому, остывание ионов посредством актов перезарядки с нейтралами является основным каналом потери энергии 0.5…4.5 кэВ ионов в торсатроне У-3М.

УТРИМАННЯ ІОНІВ ПЛАЗМИ 0.5…4.5 кеВ У РОЗРЯДАХ ТОРСАТРОНА У-3М З МАЛОЮ ГУСТИНОЮ

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Залежності потоків нейтралів перезарядки виміряні за допомогою аналізаторів нейтральних частинок у торсатроні У-3М. Швидкий (≤0.5 мс) час спаду вертикального і тангенціального потоків нейтралів перезарядки спостерігався після виключення потужності ВЧ-нагріву. Згідно цим вимірам час утримання енергії 0.5…4.5 кеВ іонів в У-3М менший, ніж 0.5 мс у розрядах з малою густиною (n_e = (1…4)·10^{12}cm^{-3}). В У-3М не було виявлено різниці між утриманням компонент іонної енергії паралельної та перпендикулярної магнітному полю. Мабуть охолодження іонів за допомогою актів перезарядки з нейтралами є основним каналом втрати енергії 0.5…4.5 кеВ іонів у торсатроні У-3М.