FAST ION GENERATION AND ITS EFFECT ON ETB FORMATION IN THE U-3M TORSATRON

V.V. Chechkin, L.I. Grigor'eva, E.L. Sorokovoy, Ye.L. Sorokovoy, A.A. Beletskii, A.S. Slavnyj, P.Ya. Burchenko, A.V. Lozin, S.A. Tsybenko, A.P. Litvinov, A.Ye. Kulaga, Yu.K. Mironov, V.S. Romanov, D.V. Kurilo

Institute of Plasma Physics, NSC "Kharkov Institute of Physics and Technology", 061108, Akademicheskaya Str. 1, Kharkov, Ukraine

In the l=3 U-3M torsatron with RF produced and heated plasmas, a two-temperature ion energy distribution arises with a minor group of suprathermal ions. It is shown that a possible mechanism of fast ion generation is cyclotron heating and/or acceleration of ions by a strong RF field in the local Alfven resonance layer $N_{\|}^2 \approx \varepsilon_1$ with an additional RF field enhancement due to the coupling resonance. The observed spontaneous ETB formation is preceded by an accumulation of high energy ions in the plasma and synchronized with their burst-like outflow to the divertor. On this basis, it is believed that it is fast ion orbit loss that results in formation of a layer with E_r shear and $E \times B$ velocity shear accordingly at the plasma boundary, this, in turn, resulting in a damping of turbulence and turbulence-induced anomalous transport.

PACS: 52.50.Qt; 52.55.Dy,He

1. INTRODUCTION

An appreciable number of ions with energies considerably exceeding the mean thermal energy of the bulk ions can arise in the plasma of stellarator-type devices, including heliotrons/torsatrons (see, e.g., [1,2]). Apart from mechanisms of fast ion generation, studies of their confinement in stellarators is of interest as these particles undergo neoclassical transport in the l.m.f.p. regime, in particular, $1/\nu$ regime typical for reactor-scale devices [3].

In a middle-size device, the Uragan-3M (U-3M) torsatron (l=3, m=9, R=1m, $\bar{a} \approx 0.12$ m, $\iota(\bar{a}) \approx 0.3$, B_ϕ = 0.7 T), with RF produced and heated plasmas, a two-temperature ion distribution in perpendicular energies develops (T_{i1}~50…80eV, T_{i2}~250…400eV at $\bar{n}_e \sim 10^{12}$ cm^{-3}, $T_e(0) \approx 600$ eV). Also, there is a minor group (<1%) of suprathermal ions (STI) with energies >1000 eV. With this, the hotter ions and STI (hereinafter, fast ions) experience neoclassical diffusion in the $1/\nu$ regime ($\nu_i \sim 2\times 10^2$ c^{-1} < $\varepsilon_t^{3/2}\, \upsilon_{Ti}\, \iota/R$). Studies of mechanisms of fast ion generation and of their confinement in U-3M is of specific interest for the following reasons.

1. Alfven waves with $\omega \lesssim \omega_{ci}(0)$ are used for plasma heating. The closeness of ω to ω_{ci} and strong radial non-uniformity of the plasma can result in specific mechanisms of wave excitation and absorbtion in the plasma with occurrence of fast particles.

2. An open natural helical divertor is realized in U-3M. Hence, an opportunity is offered to judge on confinement and loss of fast ions by comparing their behaviour in the confinement and divertor regions.

3. A spontaneous transition to the improved confinement regime is observed in U-3M. It is of interest to find out the effect of fast ions on the transition and to compare their confinement in various phases of the transition.

2. FAST ION BEHAVIOUR IN THE CONFINEMENT AND DIVERTOR REGIONS IN VARIOUS PHASES OF DISCHARGE

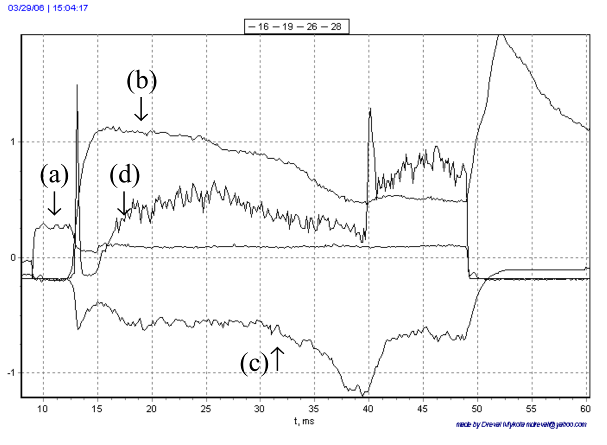

Fig. 1. Time evolution of (a) RF antenna current (envelope); (b) line-averaged electron density, $\bar{n}_e$*; (c) CX neutral flux* Γ_n *with perpendicular energy 1350 eV (directed downward); (d) fast ion component (>500 eV) in the divertor flow on the ion* ∇B *drift side,* I_i

It is seen in Fig. 1 that the density $\bar{n}_e$ passes 3 phases in its evolution over the RF pulse: (1) density rise at the beginning of discharge (~3…4 ms); (2) density decay (tens ms) which is terminated by edge E_r bifurcation toward a more negative value and ETB formation [4]; and (3) the H-like mode phase where $\bar{n}_e$ stops decaying and even can rise. At the phase (1), the flux Γ_n (c) exhibits a short-time rise (maximum at $\bar{n}_{e1} \approx 1.2\times 10^{12}$ cm^{-3}), indicating a rise of fast ion content in the confinement volume. Synchronously with Γ_n , a burst of fast ion outflow to the divertor occurs in the phase (1) (d) as indicated by the current I_i to the U= +500 V -biased collector of an electrostatic charged particle energy analyzer mounted in the divertor flow on the ion ∇B drift side. In the phase (2), a repeat Γ_n rise (c) evidences an improvement of fast ion confinement in this phase. This is consistent with a rise of temperature T_{i2} [4] and a current I_i reduction (d). The Γ_n rise and I_i decay last until the E_r bifurcation. With this event the start of Γ_n drop and a sharp burst of fast ion outflow to the divertor similar to that in phase (1) are synchronized, evidencing a rise of fast ion loss at the start of phase (3). Such a change of confinement regime occurs at the density $\overline{n}_{e2} \approx 1.4\times 10^{12}\,\mathrm{cm}^{-3}$ which is close to $\overline{n}_{e1}$. The relation $\overline{n}_{e1} \approx \overline{n}_{e2} \sim 10^{12}\,\mathrm{cm}^{-3}$ holds independent of RF power and operating gas (hydrogen) pressure provided the bursts of fast ion outflow occur in the phases of density rise and decay.

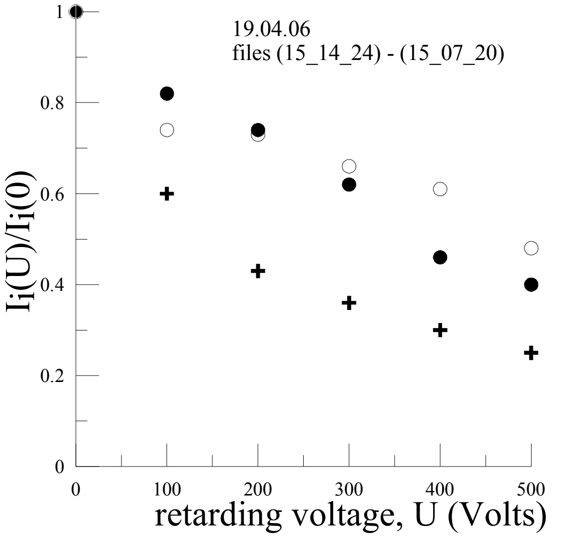

Fig. 2. $I_i(0)$-normalized ion current I_i versus retarding voltage U plots measured in the I_i maxima in the phases (1) (○) and (2) (●) and at the end of phase (2), before the I_i burst (✚)

It follows from Fig. 2 that the $I_i(U)/I_i(0)$ plots taken in the I_i maxima in phases (1) and (2) are similar. In both cases, the contribution of ions with energies eU>500 eV amounts 40-50%, while in the phase of $\overline{n}_e$ decay where the accumulation of fast ions in the plasma is observed (the rise of Γ_n) this contribution does not exceed 23%.

The closeness of $\overline{n}_{e1}$ and $\overline{n}_{e2}$ values and their practical independence on the heating power and operating gas pressure with B_ϕ fixed suggest an idea that the accumulation of fast ions in the plasma and their burst-like outflow to the divertor are governed by one mechanism and connected with dispersion properties of the plasma column. This suggestion is validated by a resonance character of plots shown in Fig. 3. A possible explanation of these plots is the effect of local Alfven resonance, $N_\parallel^2 \approx \varepsilon_1$, in an essentially non-uniform plasma resulting in cyclotron heating/acceleration of ions in the thin resonance layer in combination with an additional RF field enhancement due to the coupling resonance between the exciting antenna and plasma column. Note that other plasma parameters also exhibit a resonance B_ϕ dependence [5,6].

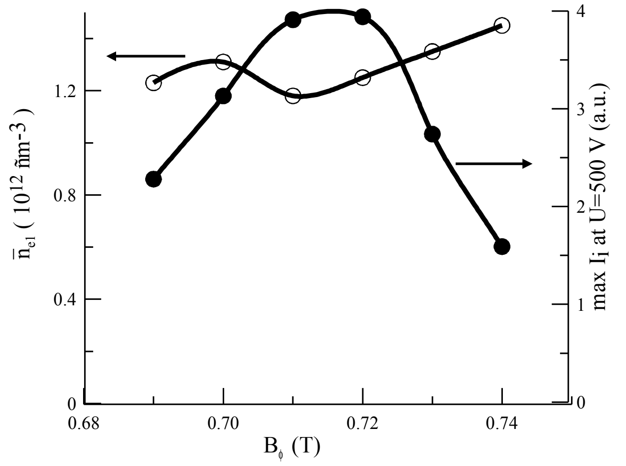

Fig. 3. Density $\overline{n}_{e1}$ (○)and current I_i in its maximum in phase (1) (●) as functions of B_ϕ.

3. EDGE POTENTIAL AND ITS FLUCTUATION

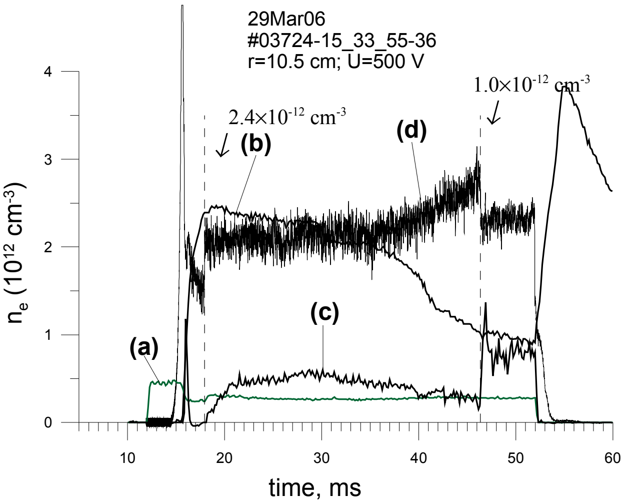

Fig. 4. Time evolution of (a) RF antenna current (envelope), (b) density $\overline{n}_e$, (c) current I_i (U=500 V) and (c) edge floating potential, V_f. Vertical dotted lines indicate 1st and 2nd V_f bifurcations

As is seen in Fig. 4, first, a short-time potential increase occurs in phase (1), then it is followed by the above mentioned burst of fast ion outflow to the divertor (maximum at $\overline{n}_{e1} \approx 1.1\times10^{12}\,\mathrm{cm}^{-3}$). Afterwards, a state sets in with a reduced fluctuation level, which is terminated at $\overline{n}_e \approx 2.4\times10^{12}\,\mathrm{cm}^{-3}$ by the first bifurcational transition toward a higher potential V_f (in the chosen radial location of the Langmuir probe) and a higher fluctuation level. With this, the rise of density is slowed down and an $\overline{n}_e$ decay starts (phase (2)) which lasts until the second bifurcation at $\overline{n}_{e2} \approx 1.0\times10^{12}\,\mathrm{cm}^{-3}$ toward a lower potential and a lower fluctuation level.

It follows from comparison of Figs 5(a) and 5(b) with Fig. 4 that regimes with a stronger negative E_r and E_r shear accordingly occur after the burst-like fast ion outflow *before* the first bifurcation, in phase (1), and *after* the second bifurcation, in phase (3). In both phases, (1) and (3), a lower level of fluctuation is observed, this, in turn, resulting in reduction of the anomalous transport at the plasma boundary and in observed slowing down of the density decay or even density rise (see, also, [4]).

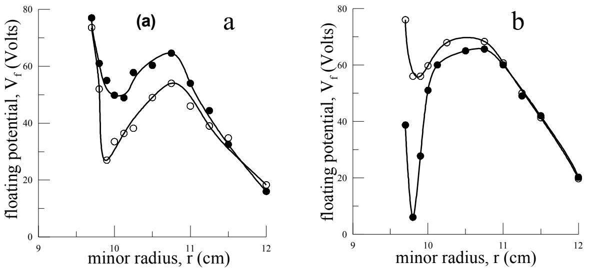

Fig. 5. Equilibrium component of floating potential V_f of a movable Langmuir probe versus minor radius r just before the bifurcation (○) and right after it (●) in the: a) phase (1), b) phase (3)

4. SUMMARY AND DISCUSSION

1. A possible explanation of the effect of fast ion generation could be cyclotron heating and/or acceleration of the ions by a strong RF field arising in the layer of non-uniform plasma where the local Alfven resonance condition, $N_{\|}^2 \approx \varepsilon_1$, is fulfilled in combination with an additional RF field amplification due to the coupling resonance between the exciting antenna and the plasma column.

2. The resonance character (with respect to B_ϕ and $\bar{n}_e$) of generation of fast ions and their sharp burst-like outflow to the divertor region (Fig. 3) are combined with indications of transition to an H-like mode (Figs 4,5). In view of these experimental data, a scenario can be suggested where non-ambipolar fast ion orbit loss should be responsible for formation of a layer with an initial small E_r shear at the boundary (so-called “ion galo” [7]) in the phase (2). As the number of fast ions increases with the total density decreasing, a critical ion collision frequency is achieved when E_r exhibits a hard bifurcational transition to a more negative value [8]. The observed time of potential jump, $\lesssim$10 ms, is consistent with a theoretical estimation of the bifurcation time, $\tau_{tr} \sim \varepsilon_t^2 \iota^2 \nu^{-1}$ [9]. A reverse process, i.e., H-L-like transition, takes place at the end of phase (1)-start of phase (2) with an obvious hysteresis by density (Fig. 4) which is typical for hard bifurcational transitions [9].

REFERENCES

1. T. Seki et al. // *15th Int. Stellarator Workshop, Madrid, 2005. Paper IT-21.*
2. H. Okada et al. // *15th Int. Stellarator Workshop, Madrid, 2005. Paper P2-26*
3. G. Grieger et al. //*Phys. Fluids B*. 1992, v. 4(7), p. 2081.
4. V.V. Chechkin et al. //*Plasma Phys. Control. Fusion*. 2006, v. 48, p. A241.
5. N.I. Nazarov et al. // *Fizika Plazmy*. 1989, v. 15, p. 1027 (in Russian).
6. V.V. Chechkin et al. //*Nucl. Fusion*. 1996, v.36, p. 133.
7. R.D. Hazeltine //*Phys. Fluids B*. 1989, v.1, p. 2031.
8. K.S. Shaing and E.C. Crume, Jr. //*Phys. Rev. Lett.* 1989, v. 63, p. 2369.
9. K. Itoh, S.-I. Itoh //*Plasma Phys. Control. Fusion*. 1996, v. 38, p. 1.

ГЕНЕРАЦИЯ БЫСТРЫХ ИОНОВ И ЕЁ ВЛИЯНИЕ НА ФОРМИРОВАНИЕ КТБ В ТОРСАТРОНЕ У-3М

В.В. Чечкин, Л.И. Григорьева, Э.Л. Сороковой, Е.Л. Сороковой, А.А. Белецкий, А.С. Славный, П.Я. Бурченко, А.В. Лозин, С.А. Цыбенко, А.П. Литвинов, А.Е. Кулага, Ю.К. Миронов, В.С. Романов, Д.В. Курило

В 3-заходном торсатроне У-3М при ВЧ создании и нагреве плазмы образуется двухтемпературное распределение ионов по энергиям с небольшим количеством сверхтепловых ионов. Вероятным механизмом генерации быстрых ионов являются циклотронный нагрев или ускорение сильным ВЧ полем в слое локального альфвеновского резонанса при дополнительном усилении ВЧ поля вследствие резонанса связи. Спонтанное образование КТБ предваряется накоплением высокоэнергичных ионов в плазме и синхронизуется с их резким выбросом в дивертор. На этом основании считается, что образование на границе плазмы слоя с широм E_r, вызывающим подавление турбулентности и связанного с нею аномального переноса, обусловлено орбитальными потерями быстрых ионов.

ГЕНЕРАЦІЯ ШВИДКИХ ІОНІВ ТА ЇЇ ВПЛИВ НА ФОРМУВАННЯ КТБ В ТОРСАТРОНІ У-3М

В.В. Чечкін, Л.І. Григор’єва, Е.Л. Сороковий, Є.Л. Сороковий, О.О. Білецький, О.С. Славний, П.Я. Бурченко, О.В. Лозін, С.А. Цибенко, А.П. Литвинов, А.Є. Кулага, Ю.К. Миронов, В.С. Романов, Д.В. Курило

У 3-західному торсатроні У-3М при ВЧ створенні та нагріві плазми виникає двотемпературний розподіл іонів за енергіями з невеликою кількістю надтеплових іонів. Можливим механізмом генерації швидких іонів є циклотронний нагрів або прискорення сильним ВЧ полем у шарі локального альфвенівського резонансу при додатковому підсиленню ВЧ поля внаслідок резонансу зв’язку. Спонтанне створення КТБ випереджується накопиченням високоенергійних іонів в плазмі і синхронізується з їх різким викидом в дивертор. На цій основі

вважається, що створення на границі плазми шару з широм E_r, що викликає придушення турбулентності і пов'язаного с нею аномального переносу, зумовлено орбітальними втратами швидких іонів.