# FAST TRAPPED PARTICLE MOTION IN URAGAN-2M STELLARATOR WITH EMBEDDED MAGNETIC MIRROR

*V.E. Moiseenko*[1], *V.V. Nemov*[1], *V.N. Kalyuzhnyi*[1], *O. Ågren*[2]

[1]*Institute of Plasma Physics NSC "Kharkov Institute of Physics and Technology", Kharkov, Ukraine;*
[2]*Uppsala University, Ångström Laboratory, Uppsala, Sweden*

The magnetic configuration of a stellarator with an embedded magnetic mirror is arranged in the Uragan-2M experimental device by switching off one toroidal coil. The motion of particles magnetically trapped in the embedded mirror is analyzed numerically with use of motional invariants. It is found that without electric field the particle quickly drift out of the mirror. Sufficiently small radial electric field can make the drift trajectories closed that substantially improve particle confinement. It is remarkable that the improvement acts both for positive and negative charges.

PACS: 52.65.Cc

## INTRODUCTION

In the proposal for a fusion-fission hybrid [1, 2] a plasma neutron source is used. The neutrons are generated in D-T fusion reactions between the hot sloshing tritium minority ions and the deuterium of the background warm plasma. For plasma confinement a special stellarator machine is used (Fig. 1). It contains an embedded magnetic mirror with lower magnetic field. In this mirror the hot sloshing tritium ions, which are created with neutral beam injection or ion cyclotron heating, are trapped. The necessary mirror ratio for the magnetic mirror is not high Π=1.5…2 [3]. The mirror is not long: its length is of the order of the stellarator major radius.

The magnetic configuration of a stellarator with embedded mirror may be arranged in the Uragan-2M experimental device since in addition to the helical coils it has coils for the toroidal field. Switching off one toroidal coil or lowering the electric current in the pair of neighboring coils results in appearance of the magnetic mirror with the mirror ratio about 1.5. Under certain conditions, a system of nested magnetic surfaces can exist in such a combined magnetic trap [4].

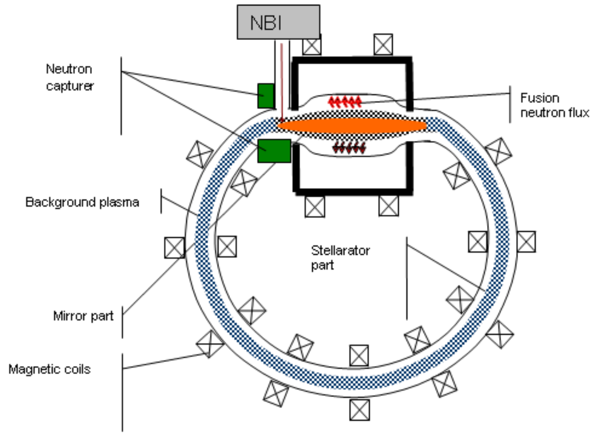

*Fig. 1. Sketch of fusion neutron source*

The aim of the present study is to investigate the trapped ion motion in the mirror part of the device. The investigation is based on Biot-Savart calculations of the magnetic field of the device and the analysis of the parallel adiabatic invariant $J_{||}$.

## MOTIONAL INVARIANTS

Certain factors stipulate existence of motional invariants for a trapped particle in the mirror part of the stellarator. The first important factor is that the motion is in static electric and magnetic fields. Neglecting collisions, the total energy of the particle

$$\varepsilon = \frac{m\mathrm{v}^2}{2} + e\varphi = const \qquad (1)$$

is then conserved. Here v is the particle velocity, φ is the electric potential.

The particle motion is adiabatic, and the Larmor radius of the particle is small compared with the scale of the magnetic and electric fields variation. Under such conditions, the magnetic moment of the particle is conserved

$$\mu = \frac{m\mathrm{v}_\perp^2}{2B} = const. \qquad (2)$$

Here $\mathbf{v}_\perp = \mathbf{B}\times\mathbf{v}\times\mathbf{B}/B^2$, $\mathbf{B}$ is the magnetic field.

The motion of the trapped particle is mainly the bouncing between the reflection points. The bouncing is accompanied by the slow drift perpendicular to the magnetic field owing to the magnetic field gradients and action of the electric field. The motion of the particle is quasi-periodic, and the parallel adiabatic invariant

$$J_{||} = \int\limits_{\mathrm{v}_{||}^{*2}>0} \mathrm{v}_{||}^{*} dl = const \qquad (3)$$

is conserved. The integration in (3) is performed along the magnetic field line, at which the particle gyro-center is at current time moment, between the reflection points where the 'virtual' parallel velocity

$$\mathrm{v}_{||}^{*} = \sqrt{\frac{2}{m}(\varepsilon - \mu B - e\varphi)} \qquad (4)$$

turns to zero. This velocity $\mathrm{v}_{||}^{*}$ is the parallel velocity which have a similar particle with the same energy and magnetic moment at the different positions at the magnetic field line.

The conservation of these 3 invariants determines an approximate drift surface in space.

## CALCULATION METHOD AND PARAMETERS

In the numerical experiments, one of the 16 toroidal field coils of Uragan-2M is switched off. Its central plane is at azimuthal position at $\varphi=\pi/32$. The ratio of currents in the helical and toroidal coils was chosen so that the ratio of the toroidal magnetic field created by helical winding to the total toroidal field at the toroidal axis $K_\varphi=0.24$ for the case that one coil is not switched off.

For this magnetic configuration Biot-Savart calculations are performed. For 9 different starting points, magnetic field lines making 250 turns around the vertical axis are computed. Their footprints at the plane $\varphi=\pi/32$, where switched off coil is located and a magnetic well is created, are shown in Fig. 2.

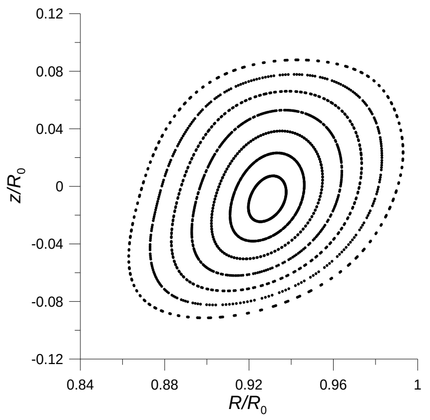

*Fig. 2. Magnetic surfaces of Uragan-2M with switched off toroidal coil. The coordinates are normalized by the torus major geometrical radius $R_0$=170 cm*

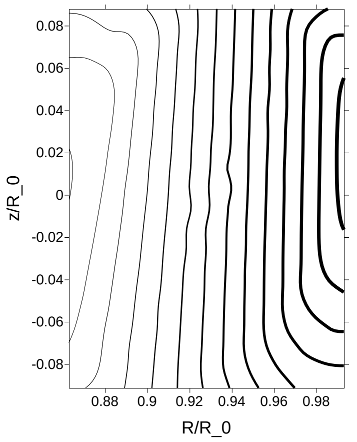

*Fig. 3. Contours of $\bar{J}_{\|}$ for $\bar{\varepsilon}$ =0.8 and A=0. Fatter line corresponds to bigger $\bar{J}_{\|}$ values*

The seven inner flux lines form nested magnetic surfaces. They are surrounded by a chain of magnetic islands, and also ergodic layer appears.

For the parallel invariant calculations the following normalized quantities are introduced.

$$\bar{\varepsilon} = \frac{\varepsilon}{\mu B_0}, \ \bar{\varphi} = \frac{e\varphi}{\mu B_0}, \ \bar{B} = B/B_0, \ \bar{l} = l/R_0. \quad (5)$$

Here $B_0$ is the normalizing constant for the magnetic field. In this notation, the normalized parallel invariant is

$$\bar{J}_{\|} = \int\limits_{p>0} \sqrt{p}\,d\bar{l} \quad (6)$$

with $p = \bar{\varepsilon} - \bar{\varphi} - \bar{B}$. The relation of the normalized parallel invariant to the parallel invariant is given by formula

$$J_{\|} = \sqrt{\frac{2\mu B_0}{m}} R_0 \bar{J}_{\|}. \quad (7)$$

The magnitude and distribution of the electric potential in the plasma column ought to be suggested. Since the hot ions are in minority, it seems reasonable to suggest that the electric potential does not vary along the magnetic surface. This assumption is applicable to the region of nested magnetic surfaces only, and the consideration must be restricted to this area. The distribution of the electric potential is assumed to be parabolic

$$\bar{\varphi} = A\bar{r}^2. \quad (8)$$

Where $\bar{r} = \langle r \rangle / \langle r \rangle_{last}$ is the normalized radius and $\langle r \rangle_{last}$ is the average radius of the last closed magnetic surface.

## CALCULATION RESULTS

The results of calculation of drift surfaces, i.e. surfaces of constant $\varepsilon$, $\mu$ and $J_{\|}$, are mapped to the surface $\varphi=\pi/32$.

For these particular calculations the trapping of the particle occurs if $0.7<\bar{\varepsilon}<0.9$, and lower value of $\bar{\varepsilon}$ corresponds to deeper trapping.

Fig. 3 shows contours of $\bar{J}_{\|}$ for the case of zero electric field. The drift surfaces are not closed in this case. This is because of the toroidal drift that forces the particle to drift in vertical direction.

When a positive electric field is applied, the drift surfaces become bended (Fig. 4). With $A$=0.05 a small region exists at the inner part of the torus where the surfaces are closed. With $A$=0.1, closed drift surfaces occupy the major part of the plasma column.

Fig. 5 displays $\bar{J}_{\|}$ contours in case of negative electric field. The picture is similar to the previous case with the only difference that the closed trajectories are shifted outward of the torus.

Fig. 6 shows the case of deeper and shallower trapped particles. As it could be seen from the pictures, the trapping level does not significantly influence on the character of the particle orbits.

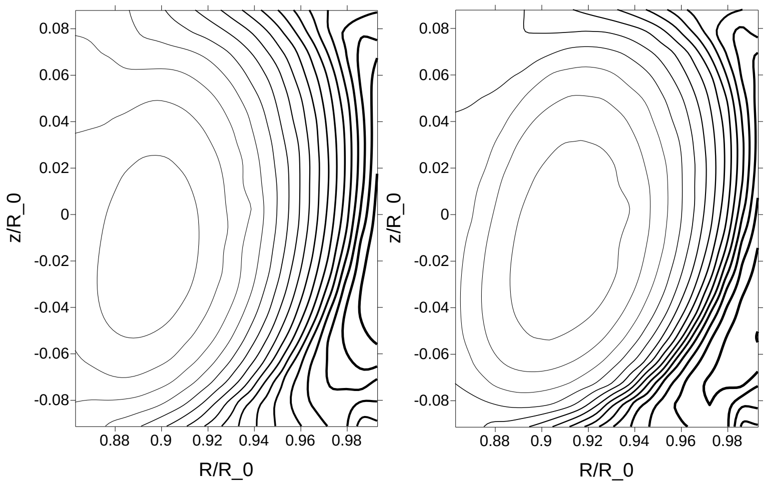

Fig. 4. Contours of $\bar{J}_{\parallel}$ for $\bar{\varepsilon}$ =0.8. A=0.05 at left chart and A=0.1 at right one

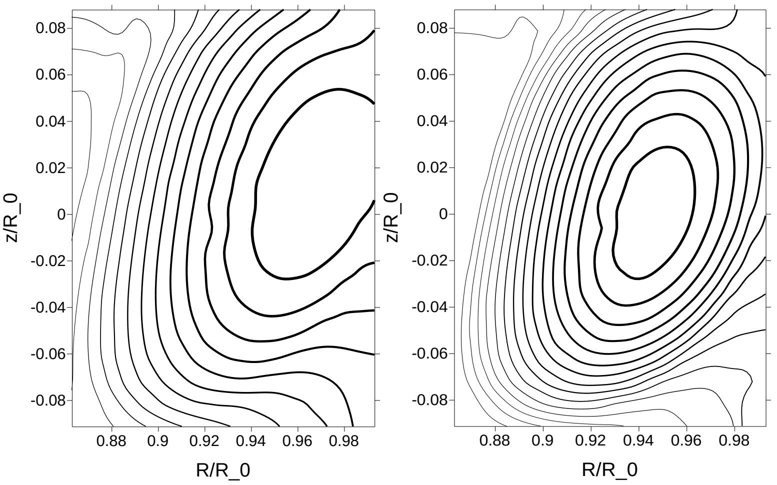

Fig. 5. Contours of $\bar{J}_{\parallel}$ for $\bar{\varepsilon}$ =0.8. A=-0.05 at left chart and A=-0.1 at right one

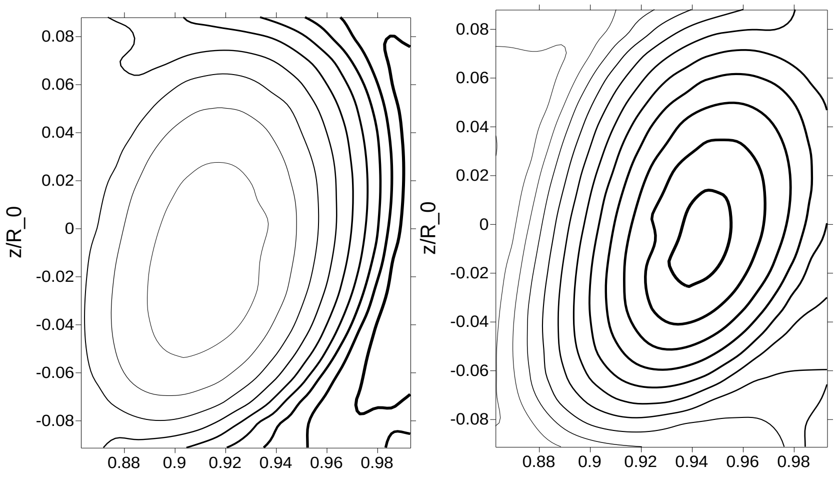

Fig. 6. Contours of $\bar{J}_{\parallel}$ for $\bar{\varepsilon}$ =0.7 and A=0.1 at left chart and $\bar{\varepsilon}$ =0.9 and A=-0.1 at right one

## DISCUSSION

The study reveals poor confinement properties of the magnetic mirror created in the Uragan-2M stellarator by means of switching off one coil of the toroidal magnetic field. This mirror is handicapped, where the major deficiency is its non-uniformity of the magnetic field in the torus major radius direction.

A radial electric field can improve the situation substantially. It causes a drift of the particle in the poloidal direction which is competing with the vertical magnetic drift. Above a certain value of the electric field, the drift surfaces become closed and particle confinement improves. This value can be estimated by the formula

$$|e\varphi| \sim \mu\Delta B, \quad (9)$$

where $\Delta B$ is the variation of the magnetic field across the confinement volume. This estimate is confirmed by the above calculations. Since $\Delta B/B \sim \langle r \rangle_{last}/R_0 \ll 1$, it is sufficient with a potential variation (provided by the electric field) which is much smaller than the kinetic energy of the particle to achieve confinement. Another remarkable feature is confinement improvements for both positive and negative charges.

The estimate (9) can be interpreted as an estimate on the perpendicular energy threshold for the confinement cured by the electric field. The confinement occurs up to a certain value of the magnetic moment, and particle with larger magnetic moment will drift out.

Biased endplates is a possibility to control the plasma potential variations in a mirror machine [5]. The value of the electric potential in a toroidal device may be hard to control. It is conditioned by the requirement of ambipolarity of plasma outflux. Thus, in case if ions are hot, they drift out faster than the electrons, causing a negative plasma charge. Then the radial electric field establishes improving confinement both of ions and electrons, and diffusive processes become more important.

## REFERENCES

1. V.E Moiseenko, K. Noack, O. Ågren // *J. Fusion Energy*. 2010, v. 29, p. 65.
2. V.E. Moiseenko et al. // *Plasma Phys. Control. Fusion*. 2014, v. 56, p. 094008.
3. V.E. Moiseenko, O. Ågren // *Fusion Science and Technology*. 2013, v. 63, № 1, p. 119.
4. V.G. Kotenko, V.E. Moiseenko, and O. Ågren // *AIP Conf. Proc*. 2012, v. 1442, p. 167.
5. O. Ågren and V.E. Moiseenko // *Plasma Phys. Control. Fusion*. 2014, v. 56, p. 095026.

*Article received 10.09.2014*

---

## ДВИЖЕНИЕ БЫСТРЫХ ЗАПЕРТЫХ ЧАСТИЦ В СТЕЛЛАРАТОРЕ УРАГАН-2М СО ВСТРОЕННЫМ ПРОБКОТРОНОМ

***В.Е. Моисеенко, В.В. Немов, В.Н.Калюжный, О. Ågren***

Магнитная конфигурация стелларатора со встроенным пробкотроном может быть реализована в экспериментальной установке Ураган-2М путем отключения одной катушки тороидального магнитного поля. Движение быстрых частиц, запертых во встроенном пробкотроне, изучено численно с использованием инвариантов движения. Установлено, что без электрического поля частицы быстро покидают ловушку. Достаточно небольшое радиальное электрическое поле может сделать дрейфовые траектории замкнутыми, что существенно улучшает удержание частиц. Примечательно, что улучшение действует как для положительных, так и отрицательных зарядов.

## РУХ ШВИДКИХ ЗАМКНЕНИХ ЧАСТИНОК У СТЕЛАРАТОРІ УРАГАН-2М З ВБУДОВАНИМ ПРОБКОТРОНОМ

***В.Є. Моісеєнко, В.В. Нємов, В.Н. Калюжний, О. Ågren***

Магнітна конфігурація стеларатора з вбудованим пробкотроном може бути реалізована в експериментальній установці Ураган-2М шляхом відключення однієї котушки тороїдального магнітного поля. Рух швидких частинок, замкнених у вбудованому пробкотрони, вивчено чисельно з використанням інваріантів руху. Встановлено, що без електричного поля частинки швидко залишають пастку. Досить невелике радіальне електричне поле може зробити дрейфові траєкторії замкнутими, що істотно покращує утримання частинок. Примітно, що поліпшення діє як для позитивних, так і негативних зарядів.