Steep gradients in plasma confined at convex-concave magnetic field lines

M.M. Tsventoukh[1,3], G.V. Krashevskaya[2], A.V. Kaziev[2]

[1] Lebedev Physical Institute of the Russian Academy of Sciences, Moscow

[2] National Research Nuclear University MEPhI, 31 Kashirskoe schosse, Moscow, Russia

[3] email: elley@list.ru

The formation of large stable plasma gradients, e.g. in form of internal transport barriers, being of a strong both practical and fundamental interest. Normally the larger the gradient the larger the transport, and any deviation due to collective plasma behavior is of great interest.

We have predicted theoretically that there is a strong stabilizing action against convective (flute-interchange) perturbations when plasma is confined by magnetic field of alternating-sign curvature – i.e. with convex–concave field lines [Tsventoukh 2014 *Nucl. Fusion* **54** 022004]. The calculations that have been done for simple combinations of axisymmetric mirrors and cusps according to the kinetic stability criterion, give strongly centrally peaked stable plasma pressure profiles instead of shallow ones.

Connection of the convex and concave field line parts results in a reduction of the space charge that drives the unstable $\boldsymbol{E} \times \boldsymbol{B}$ motion, as there is an opposite direction of the particle drift in a non-uniform field at convex and concave field lines. The pressure peaking arises at the minimum of the second adiabatic invariant J that takes place at the 'middle' of a tandem mirror–cusp transverse cross-section. Recall that there has been proposition by Arsenin [see 1983 *JETP Lett.* **37** 637 and 1986 *JETP Lett.* **43** 346] that there is a plasma interchange stability due to the alternating-sign curvature.

The simple ideal MHD description gives a strong variation in the stable pressure profile due to the strong variation in the specific volume $\int dl/B$: the critical profile being $p_{MHD} \propto (\int dl/B)^{-5/3}$. However, we have found that there is a strong variation in the stable pressure profile at regions of almost equal specific volume – near min $\int dl/B$, with curvature of alternating sign – with appropriate combination of the convex and concave field line parts.

We have performed an experimental investigation of the plasma confinement at magnetic confinement device of the alternating-sign curvature [Tsventoukh *et al* 2015 *Nucl. Fusion* **55** 062001].

For the experimental research of this effect, a compact magnetic confinement device has been modified by adding of the external current coil to fulfil the field-line curvature requirements. The critical convectively-stable plasma pressure profiles calculation in this experimental geometry and the probe measurements of the spatial plasma distribution in the new magnetic configuration of alternating-sign curvature have been performed.

The experimental results give some support for a conclusion that there is an increase in the ion saturation current at the region near the minimum of the specific volume min $\int dl/B$. This region corresponds to the average minimum in the second adiabatic invariant, and the kinetic description predicts the stable pressure profile peaking here due to reduction of charge separation by particle drift in alternating-sign curvature.

For further experimental investigations, a stationary microwave device has been used. A mirror geometry has been created by axisymmetric coils, Langmuir and magnetic probes have been used for the measurements.

For the theory developing the effects of a finite plasma beta has been analyzed in axisymmetric equilibrium, and plasma particle kinetics effect on the plasma transport.

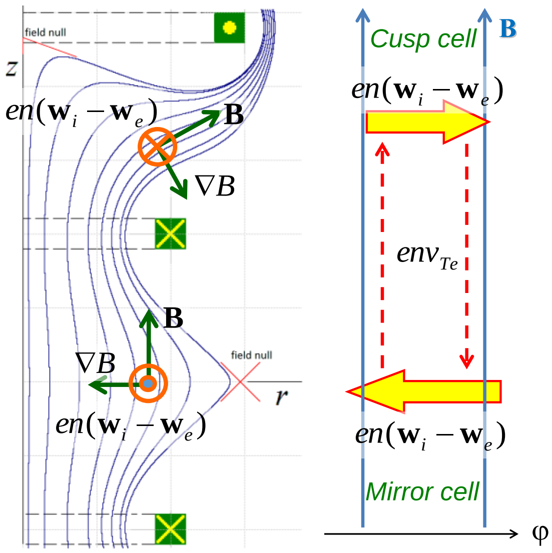

Figure 1. Sketch of the stabilization effect. Left – the magnetic field lines in r–z for a tandem system mirror–cusp, the current ring coils and the drift-current directions are depicted as well. Right – schematic side view of the short-circuiting effect for the drift currents in adjacent mirror and cusp cells, φ is the azimuthal angle.

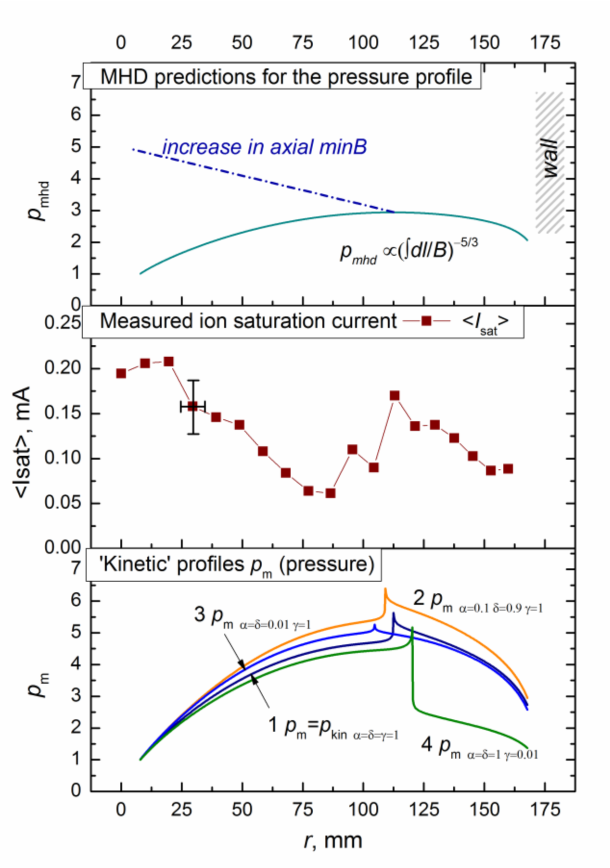

Figure 2. Comparison of measured and calculated profiles at axial position z = 150 mm. Ion saturation current values have been averaged over several pulses. Convectively-stable pressure profiles for the experimental modified Magnetor configuration: 1 – $p(\psi)$ for isotropic plasma ($\alpha=\delta=\zeta=1$), 2 – for plasma having almost empty loss cones $p_\perp > p_\parallel$ (α=0.1, δ=0.9, ζ=1), 3 – for plasma almost completely concentrated at field line minima $p_\perp >> p_\parallel$ ($\alpha=\delta$=0.01, ζ=1), 4 – for plasma in most concentrated within the loss cones $p_\perp < p_\parallel$ ($\alpha=\delta$=1, ζ=0.01), and 5 – $p \propto (\int \mathrm{d}l/B)^{-5/3}$. Curve 6 – is the dependence $r(\psi)$ for the z-level 150 mm.

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