APPLICATION OF ELECTRODE-DRIVEN SHEAR FLOWS FOR IMPROVED PLASMA CONFINEMENT

A.D. Beklemishev, P.A. Bagryansky, V.V. Prikhodko

Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia, E-mail:bekl@inp.nsk.su

In open magnetic configurations (open traps, SOL) it is possible to control the plasma potential along magnetic field lines via external electrodes. This is a possibility for direct drive of shear flows and suppression of instabilities if there is a sufficient electrical contact of plasma with electrodes (such contact occurs across the Debye sheath and is not particularly good even in 100eV plasmas). In contrast to the ITB shear flows, the governing equations in this case are strongly dissipative: the same electrical contact (line-tying) that allows control of the plasma potential negates conservation of energy and enstrophy for long-wavelength perturbations. Thus, the electrode-driven shear flows are not particularly good for simulation of ITB physics. We show that nevertheless they can allow achievement of improved-confinement regimes in open traps. Due to their dissipative nature the generated flow layers possess structural stability that can be used for fast saturation of flute modes of different origin. Theoretical analysis is compared with experimental data from the gasdynamic trap in Novosibirsk, the GDT.

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1. INTRODUCTION

Shear flows have attracted a lot of attention due to their apparent ability to suppress turbulent transport processes. Especially important role they play in formation of internal transport barriers (ITBs) in tokamaks [1]. However, in ITBs the shear flows are self-consistent with the background turbulence, i.e., they are simultaneously generated by the turbulence and modify it as well. It makes analysis of the process difficult. There is a temptation to model the shear flows while breaking the interconnection with the turbulence. It can be done by creating a direct flow drive via electrodes placed in contact with the plasma.

One aim of this note is to show that while possessing certain similarities, the physics and nonlinear dynamics of electrode driven shear flows is very much different from the traditional analysis of ITBs. The main difference is in strong dissipation of long-wavelength modes due to line-tying to the electrodes. This causes large-scale quasi-stable vortex structures to dominate the flow pattern, while the small-scale turbulence just fills in the gaps and provides flattering.

The second aim is to demonstrate possible and actual uses of electrode-driven shear flows. Surface insulation requirements usually lead to such experimental setups when the metal electrodes are separated by narrow vacuum gaps. The main potential difference across the magnetic field has these junctions of electrodes as a source, while the electrodes themselves provide energy and enstrophy sinks due to line-tying. As a result, the generated flow structures are very well defined spatially at the electrode junctions, and it is difficult to shift them elsewhere. The flow width provides an external saturation scale for convective modes. The flute-like instabilities with transverse scales exceeding the flow width are nonlinearly saturated at low levels.

Analytic analysis and computer simulation of electrode driven flows in presence of finite-Larmor-radius (FLR) effects and curvature-driven flute modes is in agreement with experimental data of vortex-confinement regimes in the gasdynamic trap in Novosibirsk. As predicted, the plasma exhibits steadily rotating saturated small-amplitude modes *m=1* or *m=2*, and a good (experimentally indistinguishable from classical) transverse confinement. But this happens only when the flow layer exists due to applied potentials. Without it or below the predicted threshold the plasma decay time decreases dramatically due to flute convection and high radial losses.

2. THE FLOW LAYER

In the simplest possible MHD model with a straight uniform field, uniform density, and a straight thin junction between electrodes the vorticity equation can be derived from the current closure condition. In the normalized form it can be written as

$$\partial_t \Delta\varphi + \{\varphi, \Delta\varphi\} - \Re^{-1}\Delta^2\varphi = \varphi - \theta(x) \, . \tag{1}$$

The right-hand side represents currents that escape to the electrodes along field lines, while $\theta(x)$ is the step-like function, representing the applied potential at the *x=0* electrode junction. Here the potential φ is normalized to the applied potential, φ_0, the time is normalized to τ and all dimensions to *d*, where

$$\begin{aligned} d^4 &= L\rho_*^3 \left(e\varphi_0/T_e\right)\left(env_*/J_{oi}\right), \\ \tau &= d^2 B/c\varphi_0, \end{aligned} \tag{2}$$

L is the plasma length, J_{oi} is the ion current density to the electrodes, $v_* = \sqrt{T_e/m_i}$, and ρ_* is the ion Larmor radius in electron temperature. While using the standard electrode model, we also assumed that the applied potential is less than the electron temperature. Otherwise the right-hand side would become exponential, and the ratio of the electron temperature to the applied potential would appear as parameter of the equation.

As one can see, all parameters, except the very large Reynolds number, $\Re$, can be normalized away, i.e., the flow patterns are universal for all applied potentials and plasma parameters (if the boundary conditions also scale properly or are at infinity).

If we neglect the fluid viscosity completely, and consider the time evolution of a straight (along the electrode junction) flow, its radial profile is self-similar in form, while its width decreases with time as $x \sim 1/\sqrt{t}$, as shown in Fig. 1. During period of order one, the width and velocity reach values of order one, and there is an onset of instability.

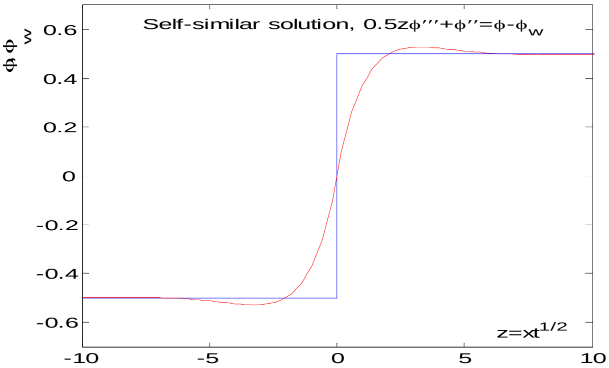

Fig. 1. Plasma potential profile during initial evolution stage

(The flow with inflection points is always unstable, but for slow flows in the beginning the instability simply has no time to develop, as the growth rates are small.) The instability is of the Kelvin-Helmholtz type, developing sequence of vortices along the flow layer. The vortex sizes are again of order one. In the nonlinear stage vortices form two chains on both sides of the junction and move along with the flow. Although the flow layer becomes chaotic, namely, the vortices slightly fluctuate in size and form, there is definitely no self-similarity in scale as in turbulent models with viscous dissipation only. One mode clearly dominates, while everything else amounts to intermittent fluctuations. This dominant mode is shown in Fig.2. The net result of the instability is appearance of convective momentum transport across the flow, so that its width can no longer decrease (while the velocity cannot increase) and stays of order one.

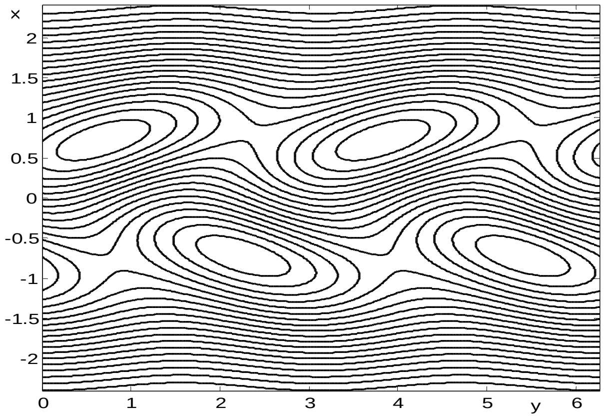

Fig. 2. Dominant flow-pattern in the co-moving reference frame. Central flow is to the right

If the fluid viscosity cannot be neglected, there appears a stationary straight flow, in which the flow width is determined by viscous transport of momentum. Its profile is very similar to the self-similar one, again with many inflection points. However, it is unstable only if its width is less than one. The critical Reynolds number is about 80. (Since it enters in width in the power ¼, it is consistent with order one.)

Thus, simulation of a flow along a straight electrode junction shows that it is not straight but structurally stable, and its saturated width is of order one in normalized variables, if the Reynolds number exceeds 80.

3. THE VORTEX CONFINEMENT

The most interesting question is how this inherently unstable but dissipative flow layer interacts with convective instabilities across it. This interaction was extensively studied due to its practical importance for plasma confinement. In particular, the following simplified set of equations, governing the two-dimensional plasma dynamics on open field lines, has been studied analytically and numerically [2]:

$$\partial_t \Delta\varphi + \{\varphi, \Delta\varphi\} = \varphi - \varphi_w + \Re^{-1}\Delta^2\varphi + \nabla\{\nabla\varphi, P\} + \kappa\{P, r\},$$

$$\partial_t P + \{\varphi, P\} = \nu\Delta P \,. \tag{3}$$

It is supposed to describe the nonlinear drift-interchange modes in presence of a hot-ion species that provides the pressure, P. Two new terms in the right-hand side describe the collisionless ion viscosity (drift-FLR effects) and the curvature drive of the flute instability, respectively.

If the collisional transverse diffusion remains small, the flow layer still evolves into two moving chains of quasi-stationary vortices on both sides of the central flow-layer as shown in Fig. 3. The transverse-to-parallel ratio of vortices is influenced by the FLR ion viscosity term, $\nabla\{\nabla\varphi, P\}$, i.e., vortices become elongated along the flow. But the most important effect is the nonlinear saturation of curvature-driven interchange modes. The flow width provides a new transverse scale that limits plasma convection across it. If the applied potential exceeds the saturated amplitude of the interchange mode the vortex chains do not overlap and the transverse transport remains small.

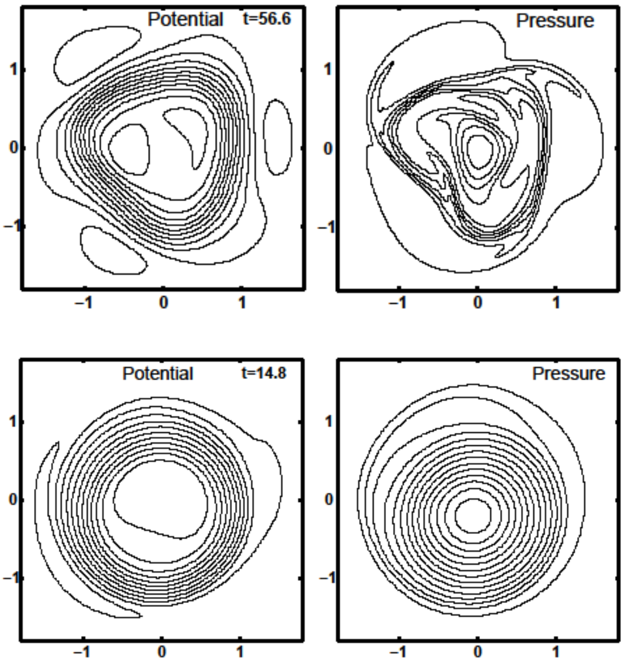

Fig. 3. Simulation of vortex confinement without (first row) and with (second row) FLR effects

Recent GDT experiments largely confirmed the above theoretical picture. When the biasing potentials of order T_e are applied at the edge of the plasma column, the transverse confinement improves to values only slightly below classical diffusion.

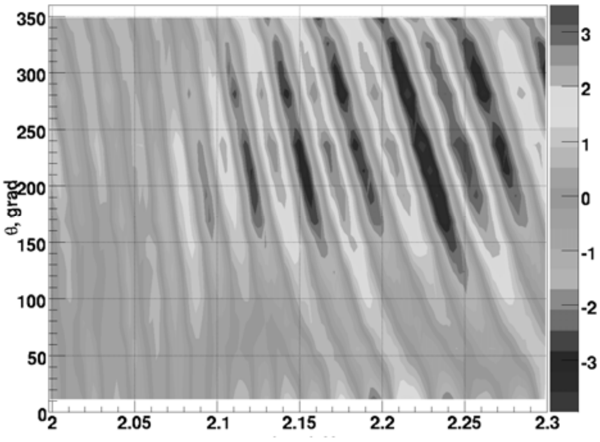

Fig. 4. Diagnagnetic signal in angular position vs. time coordinates; " vortex confinement" in GDT

Saturated rotating $m=1$ or $m=2$ modes are seen on a variety of diagnostics. In particular, the magnetic probes at the edge demonstrated that in confinement regimes with applied electrode potentials the discharge exhibits saturated rotating flute modes (Fig.4).

Removal of biasing results in immediate loss of confinement. The characteristic width of the flow layer, frequency and threshold parameters are in reasonable agreement with predictions of the model.

4. CONCLUSIONS

In summary, we emphasize that though the electrode-driven plasma flows are unstable due to the Kelvin-Helmholtz instability, they relax to saturated states that can be effective in limiting large-scale convection.

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ПРИМЕНЕНИЕ ГЕНЕРИРУЕМЫХ ЭЛЕКТРОДАМИ СДВИГОВЫХ ТЕЧЕНИЙ ДЛЯ УЛУЧШЕНИЯ УДЕРЖАНИЯ ПЛАЗМЫ

А.Д. Беклемишев, П.А. Багрянский, В.В. Приходько

В открытых магнитных конфигурациях (открытых ловушках, SOL) можно управлять потенциалом плазмы с помощью электродов. Это позволяет напрямую возбуждать сдвиговые течения и, возможно, подавлять неустойчивости, если существует достаточный контакт плазмы с электродами (этот контакт происходит через дебаевский слой и, поэтому, не слишком хорош в плазме с температурой порядка или больше 100 эВ). В отличие от сдвиговых течений во внутренних транспортных барьерах токамаков (ITB), этот случай описывается сильно диссипативными уравнениями: тот же самый электрический контакт (line-tying), который позволяет управление потенциалом плазмы, уничтожает сохранение энергии и энстрофии для длинноволновых возмущений. Таким образом, рассматриваемая задача не может служить для моделирования внутренних транспортных барьеров. Мы покажем, что, тем не менее, рассматриваемые сдвиговые течения могут использоваться для улучшения удержания плазмы в открытых магнитных конфигурациях. Из-за их диссипативной природы генерируемые течения обладают структурной устойчивостью, что приводит к быстрому насыщению желобковых мод различной природы. Теоретический анализ сравнивается с экспериментальными данными, полученными на установке ГДЛ в Новосибирске.

ЗАСТОСУВАННЯ ЗСУВНИХ ТЕЧІЙ, ЩО ГЕНЕРУЮТЬСЯ ЕЛЕКТРОДАМИ, ДЛЯ ПОКРАЩЕННЯ УТРИМАННЯ ПЛАЗМИ

О.Д. Беклемішев, П.А. Багрянський, В.В. Приходько

У відкритих магнітних конфігураціях (відкритих пастках, SOL) можна керувати потенціалом плазми за допомогою електродів. Це дозволяє безпосередньо збуджувати зсувні течії і, ймовірно, придушувати нестійкості, якщо існує достатній контакт плазми з електродами (цей контакт відбувається крізь дебаєвський шар і тому не дуже приємний для плазми з температурою порядку або більше 100 еВ). На відміну від зсувних течій у внутрішніх транспортних бар'єрах токамаків (ITB), цей випадок описується сильно диссипативними рівняннями: той же самий електричний контакт (line-tying), що дозволяє керування потенціалом плазми, знищує збереження енергії і енстрофії для довгохвильових збурювань. Таким чином, розглянута задача не може служити для моделювання внутрішніх транспортних бар'єрів. Ми покажемо, що проте розглянуті зсувні течії можуть використовуватися для поліпшення утримання плазми у відкритих магнітних конфігураціях. Через їх диссипативну природу течії, що генеруються, мають структурну стійкість, що приводить до швидкого насичення жолобкових мод різної природи. Теоретичний аналіз порівнюється з експериментальними даними, отриманими на установці ГДП у Новосибірську.