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Electron Transport in the Stellarator Diode

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Abstract

In the stellarator diode system on the torsatrons Uragan-3M and Uragan-2M dependences of emission current I_{em} on the magnetic field B strengths were measured. It is shown that the electron transport in the stellarator diode can be varied by changing the applied radial electric field. Numerous scalings of electron transport were measured. Transitions between different confinement modes were observed.

Keywords:

torsatron, stellarator diode, toroidal charged-electron plasma, electron transport, radial electric field, confinement time scaling, condition of transition between scaling

1. Introduction

Stellarator diode system [1-4], Fig. 1, is a very convenient object to study an influence of externally applied radial electric field, E_r, upon pure electron transport and to control such field independently of the usual machine parameters. In it E_r is applied between the charged toroidal electron cloud, formed by thermionic emitter and confined in the trap, and the anode (a metallic vacuum chamber surrounding the toroidal magnetic flux surfaces). Besides an external E_r there exists a radial electric field formed by the toroidal charged electron cloud itself. The degree of suppression of thermionic emission in the system characterizes the confinement of electrons on the magnetic flux surfaces. The electron transport is mainly due to collisions of electrons with neutral particles of the residual gas.

The magnetic field, B, dependence of electron confinement in the stellarator diode system can be obtained by measuring of the emission current, I_{em}, [4, 5]: $\tau_e \propto 1/I_{em}$. In experiments to determine the conditions for applying the stellarator diode method (to map vacuum magnetic surfaces), the dependence of $I_{em\,min} \propto B^{-0.87}$ (B=0.02–0.1 T) [2] was measured on the Auburn Torsatron (l=2). On the Uragan-3M torsatron two scalings were found [3], $I_{em\,min} \propto B^{-0.84}$ and $I_{em\,min} \propto B^{-0.67}$, but at much stronger magnetic fields. Good agreement was also found between the measured electron diffusion coefficient and the neoclassical transport coefficient of the equivalent tokamak for good magnetic surfaces on the Compact Auburn Torsatron [4]. However, there it was a dropping of the radial

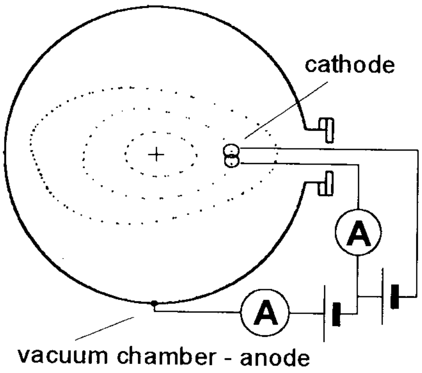


Fig. 1 A simplified model of the stellarator diode system.

Corresponding author's e-mail: ipp@ipp.kharkov.ua electric field term when the particle flux is determined.

Above described and, in particular, the presence of a space charge layer on the magnetic surfaces has stimulated us to carry out experiments on the Uragan-3M (U-3M) and Uragan-2M (U-2M) torsatrons to study electron transport as a function of minor radius, E_r, moreover to define the dependence of the electron-cloud confinement time on B in the stellarator diode system. A clearer picture of this process in a toroidal geometry may contribute to a better comprehension of much more complex plasmas of interest in thermonuclear research.

2. Experimental Methods and Setup

To study the electron transport (τ_e) in the stellarator diode, the electron current to the anode (I_{em}) as a function of B was measured at different anode bias voltages, U_a. The applied E_r is defined as $E_r = U_a/(a_{ch} - r)$, where a_{ch} is minor radius of the metallic vacuum chamber and r is the average radius of the magnetic flux surface.

In the experiments on U-3M and U-2M, the thermionic cathode (the cathode current is $I_c \cong 0.65-0.8$ A) produces a toroidal electron cloud density in the range $n_e \cong 5\times10^{11}-1\times10^{13}$ m^{-3}. A small hot cathode arranged on an alumina rod (insulating sleeve).

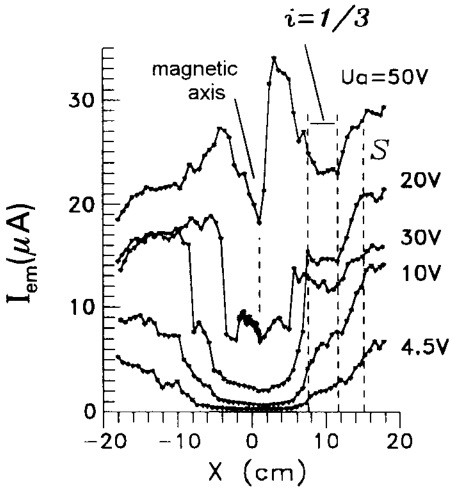


Fig. 2 Electron emission current to anode versus cathode location along the major radius in equatorial midplane of the Uragan-3M torsatron (B=0.15 T; $\bar{B}_\perp/B$=-0.1%; the rotational transform $\iota(0)\approx0.1$, $\iota(a)\approx0.33$; $p\approx(2.7-5.3)\times10^{-4}$ Pa; x=0 is the geometrical axis; $x>0$ is the outer side of torus; S is the separatrix location). The parameter is the anode voltage U_a.

On the U-3M torsatron [6] (l=3, m=9, R=1 m, a_{ch}=0.19 m, average radius of the last closed magnetic surface $a\approx0.125$ m) the experiments were performed at B=0.15–0.76 T with the residual gas pressure $p=(2.7-5.3)\times10^{-4}$ Pa.

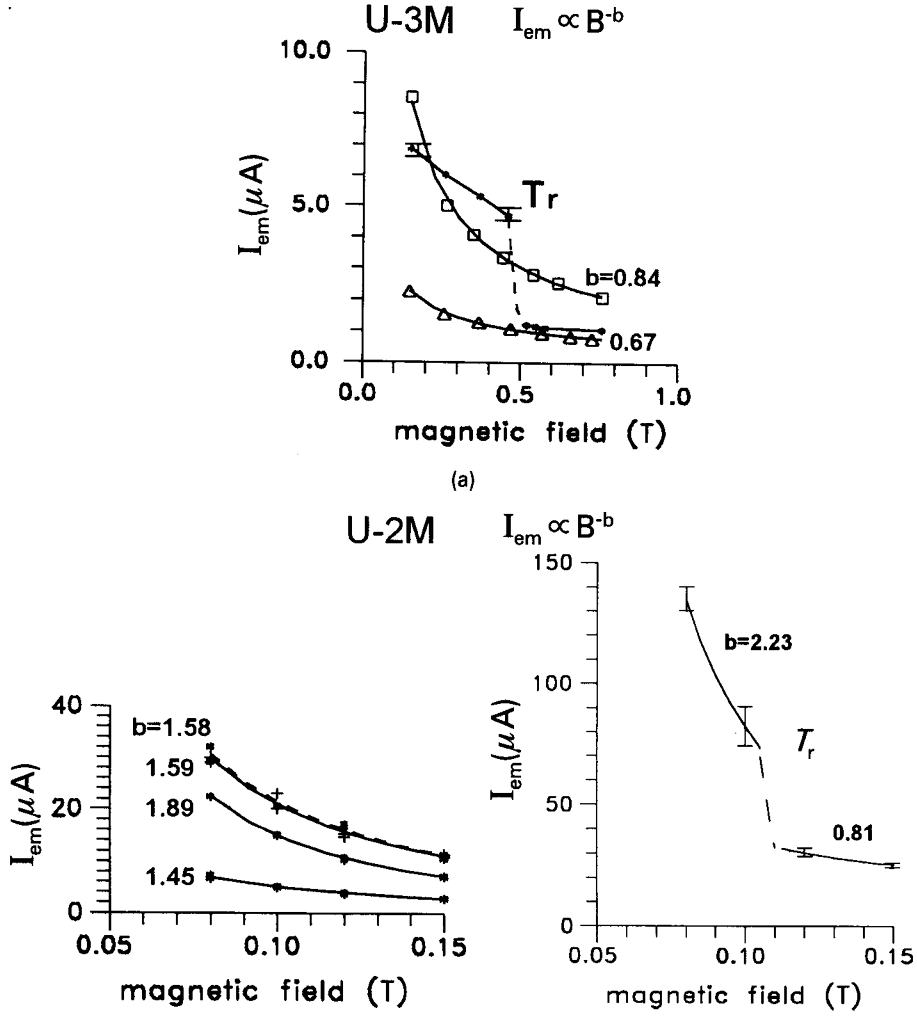
The experiments on the U-2M torsatron with an additional toroidal magnetic field [7] (l=2, m=4, R=1.7 m, a_{ch}=0.34 m, $a\approx0.2$ m) were performed for the B=0.08–0.15 T range and with $p=(2.7-5.3)\times10^{-3}$ Pa. In this device, parameters a, R and p are greater than those in the U-3M torsatron.

3. Scanning Experiments

The increase in the potential difference between the emitter and the anode at the scanning by the emitter along R changes the character of electron confinement, starting at the edge of the confinement volume in U-3M (at $U_a>20$ V), Fig. 2. An abrupt change in the electron confinement at U_a=20 V corresponds to $E_r\approx2.2\times10^2$ V/m ($E_r\approx2.3\times10^2$ V/m at U_a=30 V). The average radius of the characteristic change in electron confinement at U_a=20 V remains practically the same as the magnetic field strength increases from B=0.15 T to B=0.4 T. The results of radial scans in the U-2M torsatron shown that the confinement volume shrinks around the magnetic axis, starting also at the edge, as U_a increases (when $E_r\geq E_{cr}\approx2.3\times10^2$ V/m, E_{cr} is the critical electric field). In spite of the increasing level of the minimum emission current, the character of electron confinement near the magnetic axis does not change up to $U_a\approx100$ V at B=const. The rise of the minimum emission current as U_a increases at $E_r<2.3\times10^2$ V/m shows that the electron flow increases continually without the change of a transport law.

4. Magnetic Field Dependence of Emission Current

Stellarator diode measurements of electron confinement versus B in the U-3M torsatron have given two scalings (Fig. 3(a)): the $I_{em}\propto B^{-0.84}$ curve (open squares, I_c=0.7A, U_a=55 V, I_{em}=8.6 μA at B=0.15 T); the $I_{em}\propto B^{-0.67}$ curve (triangles, I_c=0.8 A, U_a=30 V, I_{em}=2.25 μA at B=0.15 T). The thermionic cathode was located near the magnetic axis ($r\approx0.5\times10^{-2}$ m) in regime of the magnetic configuration with $\bar{B}_\perp/B$=1% (see [6]). Here and henceforth the experimental data in the figures are shown with points only. The solid lines are the best fit lines. These scalings have resulted from variations in the hot cathode current and in U_a. Independent variations of the cathode current and



(a)

(b)

(c)

Fig. 3 A plot of emission current to anode versus magnetic field strength and scalings. Parameters are I_c, U_a, thermocathode position r (see the text).

a) The Uragan-3M torsatron: $\bar{B}_{\perp}/B = 1\%$, $\iota(0) \approx 0.24$, $\iota(a) \approx 0.43$; $p \approx 3.2\times10^{-4}$ Pa.

b) The Uragan-2M torsatron: $B = 0.1$ T, steady-state regime with $k_{\varphi} = 0.295$ and $\bar{B}_{\perp}/B = 1.85\%$, half-period of magnetic field, $\iota(0) \approx 0.31$, $\iota(a) \approx 0.4$; $p \approx (2.7-5.3)\times10^{-3}$ Pa.

c) Transition between two scalings in the Uragan-2M torsatron.

U_a made it possible to find the transition between the two scalings of emission current. It is clearly seen in Fig. 3(a) (T_r curve). The transition occurs at $E_r = E_{cr} \approx 2.3\times10^2$ V/m and $B_{tr} \approx 0.47$ T for the following initial parameters of the diode: $I_c = 0.7$ A; $U_a = 30$ V; $I_{em} = 6.8$ μA at $B = 0.15$ T.

The scalings $I_{em} \approx B^{-1.45}$ (average radius of electron injection $r \approx 3.1\times10^{-2}$ m, $I_c = 0.69$ A, $U_a = 50$ V), $I_{em} \approx B^{-1.59}$ ($r \approx 8\times10^{-2}$ m, $I_c = 0.75$ A, $U_a = 55$ V) and $I_{em} \approx B^{-1.58}$ ($r \approx 8\times10^{-2}$ m, $I_c = 0.7$ A, $U_a = 55$ V) were obtained in the U-2M torsatron at $E_r \leq 2\times10^2$ V/m, Fig. 3(b). In U-2M the residual gas pressure stipulates the electron — neutral frequencies, ν_{en}, an order of magnitude higher than that in U-3M. The scaling (Fig. 3(b)) $I_{em} \propto B^{-1.89}$ ($r \approx 5\times10^{-2}$ m, $I_c = 0.71$ A, $U_a = 80$ V) and the curve in Fig. 3(c) with a transition between the two scalings ($I_c = 0.71$ A, $r \approx 8\times10^{-2}$ m, $U_a = 80$ V) were found at $E_r \geq 2.6\times10^2$ V/m. The best fit lines give the scaling $I_{em} \propto B^{-2.23}$ for the upper part of the transition curve and the scaling $I_{em} \propto B^{-0.81}$ for the lower part. The transition occurs at $B_{tr} \approx 0.105$ T. The dependences shown in Fig. 3(b), (c) are mainly due to different n_e

and T_e in the toroidal electron cloud, which are dependent on r, I_c and U_a, that is $I_{em}=F(r, U_a, 1/I_c)$. The maximum error ~ 15% usually corresponds to emission current measurements before the transition (the left-hand side of the transition curve, Fig. 3(a), (c)). The major portion of error in I_{em} current measurements is attributed to a low-frequency amplitude modulation of I_{em}.

From the analysis of the transition curves (Fig. 3(a), (c)) it is evident that the main parameters determining the transitions are r, E_{cr}, B_{tr}, ν_{en}. They can be combined into the dimensionless ratio

$$\frac{r\nu_{en}B_{tr}}{E_{cr}} = \text{const.}\,, \qquad (1)$$

characterizing probably of the transition between two laws of electron transport. This ratio turns out to look like the resonance condition in the ordinary plasma, if the spin of the $E \times B$ flow equals the electron-neutral collision frequency ν_{en}, $(1/r)(E \times B)/B^2=\nu_{en} \rightarrow r\nu_{en}/V_E=1$ ($V_E=(E \times B)/B^2$), and the internal electric field of plasma is replaced by applied E_r.

One can see that the applied external $E_r \geq E_{cr}$ is the necessary but not sufficient condition for detecting the transition. The $I_{em} \propto B^{-1.89}$ scaling curve (Fig. 3(b)) is an example of that. It does not show any transition. The analysis of results performed after this series of experiments has revealed that the transition should not take place in the range of magnetic field strengths under study. At $E_r \geq E_{cr}$ the transition takes place if $B=B_{tr}$. For the stellarator diode parameters corresponding to this curve ratio (1) allows one to predict the transition at $B_{tr} \approx 0.16$ T. Rough estimations of ν_{en} show that in our case const. ≈ 0.01 in ratio (1) and these collision frequencies can correspond to the left-hand edge of the "plateau" regime of the neoclassical transport of electrons. The last might be responsible for the scaling laws $\tau_e \propto B^{0.81}$ and $\tau_e \propto B^{0.84}$. The exactness and the versality of ratio (1) must be confirmed in future experiments.

5. Summary

The transport of a charged electron plasma has been studied in the toroidal stellarator diode system on the U-3M and U-2M torsatrons for a wide range of variations in ν_{en}, U_a and B, *i.e.*, when the process is controlled by $E \times \mathbf{B}$ fields. In the stellarator diode system the emitting cathode produces a toroidal cloud of electrons whose subsequent transport mainly depends on the magnetic configuration and on the applied radial electric field. The hysteresis in the I-V characteristic (see [1, 3] also) is an evidence of electron transport bifurcation (E_r is changed, B=const.). It is shown that the electron transport in the stellarator diode can be varied by changing the applied radial electric field (numerous scalings of electron transport were measured).

If $E_r \geq E_{cr}=(2.3-2.6) \times 10^2$ V/m is applied, then the measured dependences of I_{em} on B show the following scaling laws: 1) $\tau_e \propto B^{0.67}$ and $\tau_e \propto B^{0.84}$ (U-3M torsatron); 2) $\tau_e \propto B^{0.81}$ and $\tau_e \propto B^{2.23}$ (U-2M torsatron). Transitions are observed between these levels of transport. At $E_r \leq 2 \times 10^2$ V/m the scaling law for the electron transport from the toroidal pure electron cloud changes from $\tau_e \propto B^{1.45}$ to $\tau_e \propto B^{1.89}$ (U-2M torsatron). The last result can be helpful for an adequate explanation of the experimental data on the transport in a pure electron plasma with similar parameters [8].

Another, most important result of this investigation is that at $I_{em} \propto B^{-1.89}$ a much higher electron current is transported to the anode than in the case of $I_{em} \propto B^{-1.45}$, Fig. 3(b).

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