LONGITUDINAL DIAMAGNETIC EFFECTS IN BEAM-PLASMA SYSTEM EMBEDDED IN AN EXTERNAL MAGNETIC FIELD

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High-current electrons beams generated in an external magnetic field in vacuum behave as a diamagnetic and force a magnetic field out of its volumes in radial direction. Under the condition of conservation of a magnetic flux the magnetic field inside of the beam decreases and increases outside. In the beam-plasma systems embedded in a magnetic field (plasma filled diodes or a beam in a plasma channel) another state of the beam with the total magnetic field increased to the axis can be realized. Radial focusing of the beam is ensured by electrostatic field of an ion pivot and azimuthal self magnetic field. If the external magnetic field changes in longitudinal direction then the value of magnetic field from the region of beam injection is transferred along near axis region of the system. It looks like a “magnetic needle” and resembles “frozen field” effect but the physics is different. Different beam-plasma systems were considered by means of computer simulation. Computer simulation was performed using electromagnetic PIC code KARAT.

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1. INTRODUCTION

High-current electron beams in an external longitudinal magnetic field behave as a diamagnetic and force a magnetic field out of its volume. It leads to decreasing of the full magnetic field inside of the beam and to increasing of the field outside if the wall chamber conductivity is high enough. The last condition corresponds to the conservation of the magnetic flux in the cross section of the chamber. For charged beams a degree of the diamagnetism cannot exceed 100% [1]. The equilibrium with closed magnetic field lines, i.e. with different directions of full magnetic field inside and outside of the beam was called E-layers (project “Astron”) [2, 3]. Such equilibrium was created experimentally only under condition of electrostatic neutralisation of a beam space charge [4]. The coaxial chamber with additional potential difference between the electrodes can be used to create charged E-layer [5]. From another side, to reach essentially increasing of the full magnetic field, an inverse diode with magnetic isolation can be used [6]. For both last examples the voltage plays a role of the beam ions space charge neutralising.

Another type of the equilibrium can be created when a high-current electron beam is injected in the plasma with comparative density placed in a longitudinal magnetic field (plasma filled diodes, plasma channels). This type resembles two above-mentioned states with additional electrostatic field. Right analogy with these vacuum states consists in the presence of a radial focusing field in an ion pivot. In this case the role of internal electrode plays near axis ion pivot. The pivot arises when a space charge of the beam pushes out plasma electrons from its volume. As the result full magnetic field increases to the axis of the beam-plasma system embedded in a constant longitudinal magnetic field and exceeds this initial external field several times [7, 8]. Several peculiarities arise because the combination of the external beam and plasma fields cannot be observed in vacuum systems. Beam electrons are confined always inside plasma column if the density of the plasma exceeds the density of the beam, but it is not enough for current neutralisation. This situation practically does not depend on the value of the external magnetic field and allows using spatially inhomogeneous external magnetic field. Very interesting effect arises in this case. The longitudinal magnetic field created by the beam pierces the external one. It looks like a “magnetic needle”. Actually, it can be considered as a transformation of the usual transverse diamagnetic effect in the axially homogeneous system to the axially inhomogeneous one. The beam “captures” the field in the area of generation or injection and tries to “drag” it through external magnetic field. To demonstrate the effect different external magnetic field configurations were considered by means of computer simulation performed by electromagnetic PIC code KARAT [9].

Following results are presented for the geometry of the plasma filled diode shown in Fig. 1. Such diodes are used to produce high-current low-energy electron beams for surface material modifications [10-12]. An electron beam is generated in the thin double-layer near the cathode formed just after the beginning of an accelerating voltage pulse. The relatively low applied voltage is localized in this layer making possible the beginning of the explosive emission from the cathode surface.

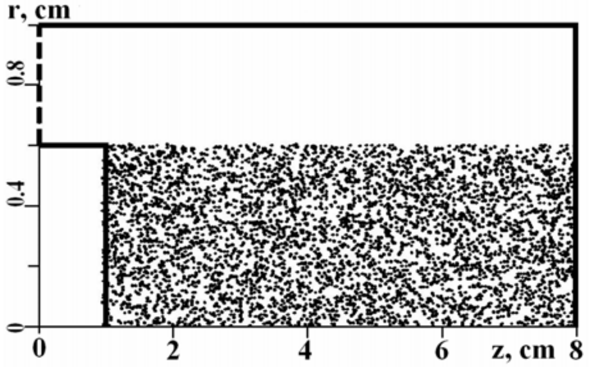

Fig1. Configuration of the diode

The space between 0.6 cm radius cathode and 1 cm radius anode fills plasma with 3×10^{13} cm^{-3} density and 0.6 cm radius. The plasma is homogeneous in radial and axial directions. The applied voltage rises to 100 kV in 1 ns and stays constant at this level. It is supposed that an emission of a beam begins immediately after the accelerating field arises. A time delay between the beginning of the voltage pulse and emission of the beam does not influence essentially on the final results. To simplify simulations at the first step, plasma ions are considered as a background, i.e. ions have infinite mass. The current of the beam is defined as a current limited by space charge under the condition of zero accelerating field at the cathode surface.

2. THE MAIN RESULTS

2.1. THE DIOD WITHOT AN EXTERNAL FIELD

Fig. 2 shows the dynamics of the beam current emitted from the cathode (b, 1 E), the beam (b, 1 A), and the plasma electron (g,1 A) currents to the cathode. Beam (b, 2 A) and plasma electron (g, 2 A) currents reaching the anode in the bounds of initial plasma channel radius are given in Fig. 3. The beam current on the anode is about 15 kA and exceeds Alven current $I_A = 17\beta\gamma \approx 11$ kA. The average density of the beam electrons is about 5×10^{12} cm^{-3}.

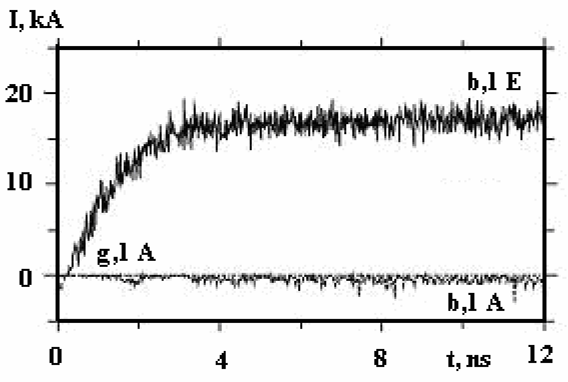

Fig. 2. Dynamics of currents at the cathode

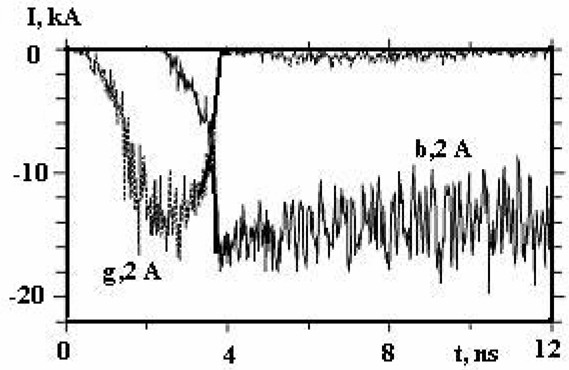

Fig. 3. Dynamics of currents reaching the anode

Self longitudinal magnetic field of the beam fluctuates at the level of tens Gauss.

2.2. THE DIOD IN HOMOGENEOUS FIELD

Fig. 4 and Fig.5 show initial (t = 0 ns) and final (t = 12 ns) distributions of the longitudinal magnetic fields. The magnetic field influence weakly on the beam dynamics and the value of the beam current reaching the anode is similar to the previous case (see Fig. 3). Magnetic field at the axis of the diode equals approximately 7 kGs (Fig. 5) and several times exceeds the external one (2 kGs). Here it is necessary to note, that the modification of the magnetic field concentrates near the axis, and this modification is latent if the field out of plasma channel changes insignificantly in comparison with the given external field.

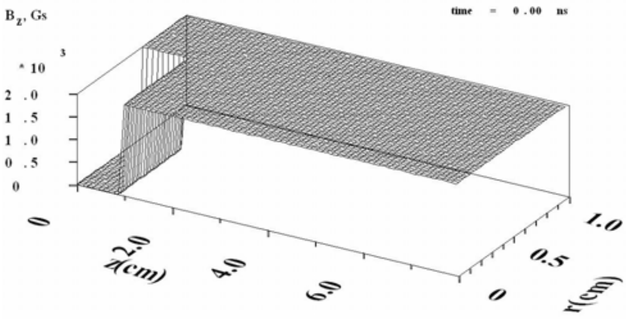

Fig. 4. Initial distribution of magnetic field

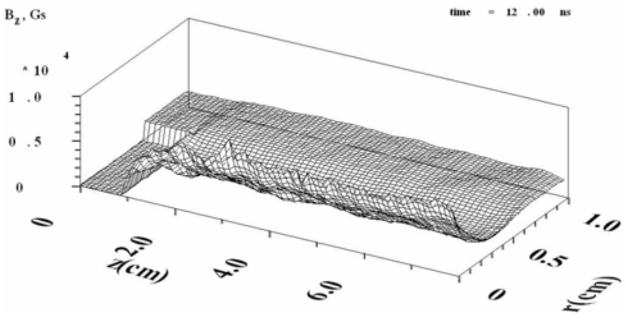

Fig. 5. Final distribution of magnetic field

2.3. THE DIOD WITH PLASMA DENSITY GRADIENT IN THE HOMOGENEOUS FIELD

To confirm the main influence of plasma ions on the effect discussed above the results for the diode with plasma gradient are given in this section. Initial density of the plasma decreases from 3×10^{13} cm^{-3} near the cathode to 3×10^{12} cm^{-3} near the anode (Fig. 6). Initial distribution of the magnetic field is chosen similar to the previous case (see Fig. 4). Fig. 7 shows the final distribution of the full magnetic field at the moment t = 12 ns.

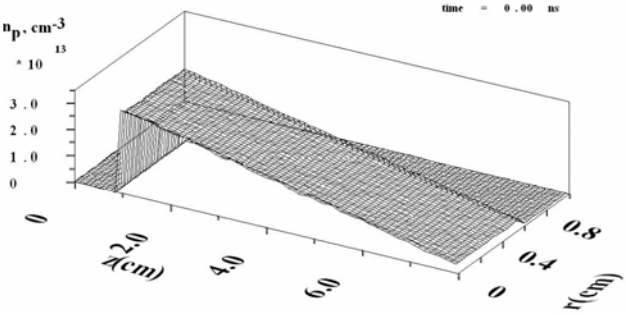

Fig. 6. Initial distribution of plasma density

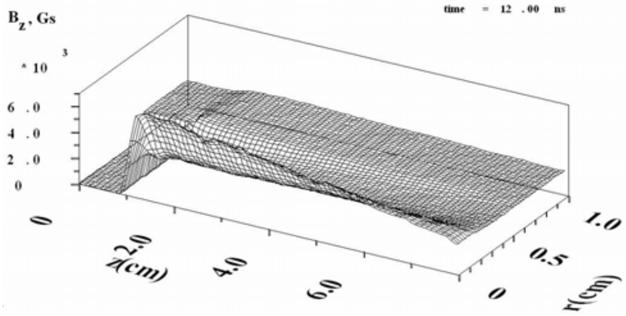

Fig. 7 Final distribution of magnetic field

It is obvious from Fig. 6 and Fig. 7 that the form of the full magnetic field at the axis follows the profile of the plasma ion density. Essential modification of the initial magnetic field concentrates near the axis.

Beam current reaching the anode decreases to approximately 8 kA due to decreasing the plasma density to the anode in comparison with previous cases.

3. CONCLUSIONS

The new effect of the transportation of a magnetic field by a high-current electron beam from the area of the beam generation or injection through an external magnetic field inside a plasma channel was demonstrated be means of computer simulation.

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REFERENCES

1. A.V. Agafonov, V.S. Voronin, K.N. Pazin, A.N. Lebedev. High-Current Electron Beam Transportation in Magnetic Field// *JTF*. 1974, v. 44, p. 1909-1916 (in Russian).
2. N.C. Christofilos. Astron Thermonuclear Reactor// *Proc. of the 2^{nd} United Nations International Conference on Peaceful Uses of Atomic Energy*. Geneva: United Nations, 1958, p. 279-290.
3. N.C. Christofilos. Minimum-B properties of Relativistic Electron Coils// *Phys. Fluids*. 1966, v. 9, p. 1425-1427.
4. M.L. Andrews, H. Davitian, H.H. Fleschmann, et al. Generation of Astron-type E-layers using Very High-Current Electron Beams // *Phys.Rev.Lett.* 1971, v.27, p. 1428-1431.
5. A.V. Agafonov. Charged E-layer // *Plasma Physics*. 1976, v. 2, p. 57-62 (in Russian).
6. A.V. Agafonov. High-Current Electron Beam Equilibrium of Θ-pinch Type in an Inverse Magnetic Isolation Coaxial Diode // *Plasma Physics*. 1982, v. 8, p. 925-930 (in Russian).
7. A.V.Agafonov, V.P. Tarakanov. Paramagnetic States of High-Current Electron Beams in a Beam-Plasma Systems// *Problems of Atomic Science and Technology. Series "Plasma Physics" (12).* 2006, N 6, p. 169-171.
8. A.V .Agafonov, V.P. Tarakanov. Computer Simulation of Low-Energy High-Current Electron Beam Dynamics in a long Plasma Diodes// *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"(49).* 2008, N 3, p. 136-138.
9. V.P. Tarakanov. *User's Manual for Code KARAT* / Springfield, VA, Berkeley Research Associates Inc. 1992, p. 127.
10. G.E. Ozur, D.S. Nazarov, L.B. Proskurovsky. Generation of Low Energy High-Current Electron Beams in the Gun with Plasma Anode*//Izvestija VUZ'ov. Physics.* 1994, N 3, p. 100-107.
11. A.V. Agafonov, V.A. Bogachenkov, E.G. Krastelev. High-Current Low-Energy Electron Beam Generation in a Plasma System// *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations" (47).* 2006, N. 3, p. 49-51.
12. A.V. Agafonov. Low Impedance Plasma Systems for Generation of Low Energy High-Current Electron Beams// *Physics of Elementary Particles and Atomic Nuclei Letters*. 2006, v. 3, N 7(138), p. 19-26.

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ПРОДОЛЬНЫЕ ЭФФЕКТЫ ДИАМАГНЕТИЗМА В ПУЧКОВО-ПЛАЗМЕННОЙ СИСТЕМЕ ВО ВНЕШНЕМ МАГНИТНОМ ПОЛЕ

А.В. Агафонов

Сильноточные электронные пучки во внешнем магнитном поле ведут себя как диамагнетик, вытесняя магнитное поле из своего объема. При условии сохранения магнитного потока это сопровождается уменьшением результирующего магнитного поля внутри пучка и увеличением его снаружи. В пучково-плазменной системе в магнитном поле (плазменный диод или плазменный канал транспортировки) возможно другое равновесное состояние пучка, в котором результирующее магнитное поле растет ближе к оси системы. Радиальная фокусировка пучка обеспечивается электростатическим полем ионного остова и собственным азимутальным магнитным полем, в то время как продольное магнитное поле имеет дефокусирующий характер. Если внешнее магнитное поле меняется вдоль оси системы, то пучок захватывает и переносит вдоль оси поле из области инжекции. Этот эффект выглядит внешне как «магнитная игла» и напоминает эффект «вмороженности» поля, но отличается по физике. При численном моделировании с помощью электромагнитного кода КАРАТ рассмотрены различные пучково-плазменные системы.

ПОДОВЖНІ ЕФЕКТИ ДІАМАГНЕТИЗМУ В ПУЧКОВО-ПЛАЗМОВІЙ СИСТЕМІ У ЗОВНІШНЬОМУ МАГНІТНОМУ ПОЛІ

О.В. Агафонов

Потужнострумові електронні пучки у зовнішньому магнітному полі поводяться як діамагнетик, витісняючи магнітне поле зі свого обсягу. За умови збереження магнітного потоку це супроводжується зменшенням результуючого магнітного поля усередині пучка і збільшенням його зовні. У пучково-плазмовій системі в магнітному полі (плазмовий діод або плазмовий канал транспортування) можливо інший рівноважний стан пучка, у якому результуюче магнітне поле росте ближче до вісі системи. Радіальне фокусування пучка забезпечується електростатичним полем іонного кістяка і власним азимутальним магнітним полем, у той час як подовжнє магнітне поле має дефокусуючий характер. Якщо зовнішнє магнітне поле міняється уздовж вісі системи, то пучок захоплює і переносить уздовж вісі поле з області інжекції. Цей ефект виглядає зовні як «магнітна голка» і нагадує ефект «вмерзлості» поля, але відрізняється по фізиці. При чисельному моделюванні за допомогою електромагнітного кода КАРАТ розглянуто різні пучково-плазмові системи.