LATENT FIELDS IN A BEAM-PLASMA SYSTEM

A.V. Agafonov
P.N. Lebedev Physical Institute of RAS, Moscow, Russia
E-mail: agafonov@sci.lebedev.ru

In a beam-plasma systems embedded in a magnetic field "paramagnetic" states of the beam can be realized with increased to the axis of the system or varied along the system full magnetic field under the condition of conservation of magnetic flux. Magnetic field concentrates near the axis, and this modification is latent as the field out of plasma channel changes insignificantly in comparison with the given external field. Radial focusing of the beam is ensured by electrostatic field of an ion pivot. If the external magnetic field changes in longitudinal direction then the value of magnetic field from the region of beam injection can be transferred along pre-axis region of the system. 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 like a diamagnetic and force the magnetic field out of its volume [1]. Under the condition of conserved magnetic flux in a cross section it leads to decreasing of the full magnetic field inside of the beam and to increasing of the full field outside. The direction of forced magnetic field (inside or outside in radial direction in cylindrical geometry) can be changed if instead of usual geometry (a beam inside a cylindrical chamber) the coaxial geometry is used (inverse magnetic isolation diode, for example) [2, 3]. For the last case the field is forced out large radii (large volume) to smaller ones (small volume) and the full field inside the area near the internal electrode (the anode) can essentially exceed the external field. All velocity components of particles and size of the beam will be changed if the external field will be varied in axial direction. The distribution of the full magnetic field will not differ significantly from the case of axially homogeneous external field because of large influence of beam space charge. An additional external focusing is necessary to reach large change of the full magnetic field without loosing the beam on electrodes of the system.

Such type of conditions (combined focusing fields) can arise during the transportation of the beam in the plasma of comparative density embedded in external longitudinal magnetic field (plasma filled diode or plasma channel, for example). This type of meta-stable states of the beam-plasma system resembles above mentioned state of electron beam in vacuum inside the inverse magnetic isolation coaxial diode with "additional" radial focusing by electrostatic field. Right analogy with this vacuum state consists in the presence of a radial focusing field created by an ion pivot: the role of internal electrode plays pre-axis ion pivot, arising when a space charge of the beam pushes out plasma electrons from its volume. As the result the full magnetic field can be increased to the axis of the beam-plasma system embedded in a constant longitudinal magnetic field and can exceed the initial external field many times [4-6].

Several peculiarities arising due to the combination of external, beam's and plasma's fields cannot be observed in vacuum systems. Beam electrons are confined 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 and spatially inhomogeneous plasma density. This combined focusing opens new possibilities of beam-plasma manipulations.

The longitudinal magnetic field created by the beam pierces the external one. This effect 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 can "capture" the field from the area of generation or injection and tries to "drag" it through external magnetic field. All these possibilities can be modified by spatially inhomogeneous plasma density. It will be noted that this modifications are latent. They are concentrated inside rather narrow area near the axis of the system whereas the field upper of plasma channel changes insignificantly.

To demonstrate the effects of "dynamical diamagnetism" different distributions of external magnetic field and of plasma density were considered by means of computer simulation performed by electromagnetic PIC code KARAT [7].

2. THE MAIN RESULTS

2.1. LATENT CHARACTER OF "DYNAMICAL DIAMAGNETISM"

The latent character of modified fields will be shown for simple geometry in Fig.1. Plasma column of diameter of 1.5 cm fills the chamber in longitudinal direction. Fig.2 show initial distribution of plasma density. The density increases from 5×10^{13} cm^{-3} up to 2×10^{15} cm^{-3} at the distance of 4 cm and then decreases to the end of the chamber to the same value of 5×10^{13} cm^{-3}. To simplify simulations at the first step, plasma ions are considered as a background, i.e. having infinite mass. Electron beam is injected to the chamber from the left to the right. The current of the beam increases to 100 kA for 1 ns, stays constant at this level for 9 ns and then decreases to zero for 5 ns. Fig.3 shows the form of injected beam current (b,2 E), and beam (b,1 A) and plasma electron (g,1 A) currents reaching the end of the chamber in the bounds of initial plasma channel radius.

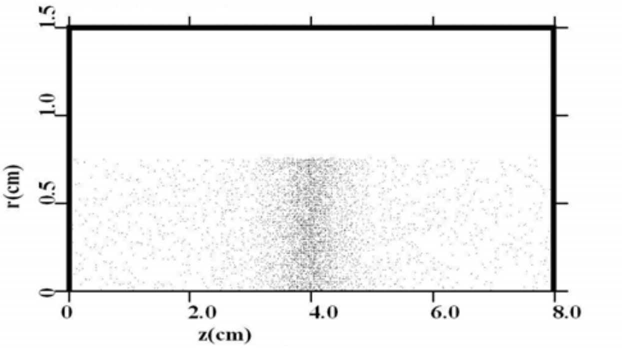

Fig.1. Configuration of considered system

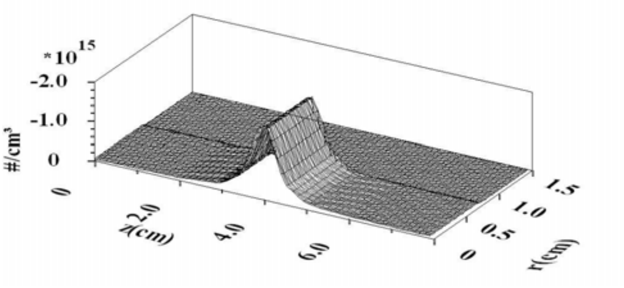

Fig.2. Initial distribution of plasma density

The energy spread of injected electrons is uniform from 400 to 500 keV. The system is placed inside uniform external longitudinal magnetic field of 10 kGs.

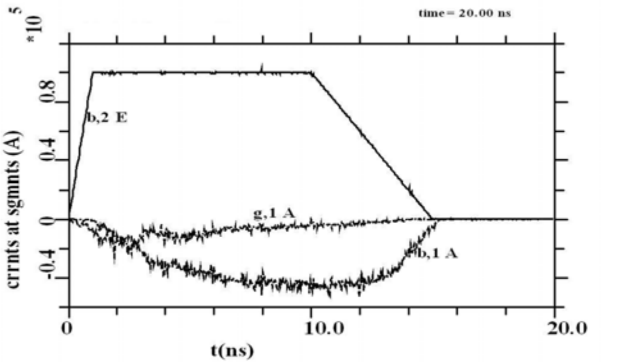

Fig.3. Dynamics of beam and plasma electron currents

Due to the effect of "dynamical diamagnetism" and picked out plasma distribution the full magnetic field concentrates near the axis in the middle of the system. The longitudinal and radial distributions of the full magnetic field for three sections are shown in Fig.4,5 at the moment t = 10 ns. It will be noted that: 1) the value of amplified magnetic field equals approximately 200 kGs and exceeds the value of external field 20 times; 2) the value of the full field outside of plasma channel was changed insignificantly; 3) the density of electromagnetic energy inside small area near the peak reaches approximately to 9×10^7 J/m^3; 4) the given field structure is maintained after the end of beam injection at all events for 10 ns (see Fig.3 and Fig.6). Fig.6 show the similar longitudinal distribution of the full field at the moment t = 20 ns.

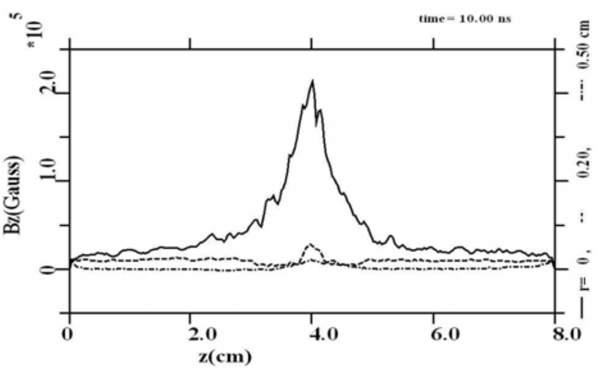

Fig.4. Longitudinal distribution of the full magnetic field at 3 radial coordinates at t = 10 ns

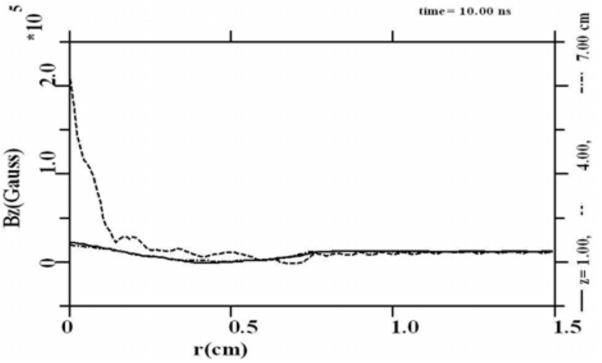

Fig.5. Radial distribution of the full magnetic field at 3 longitudinal coordinates at t = 10 ns

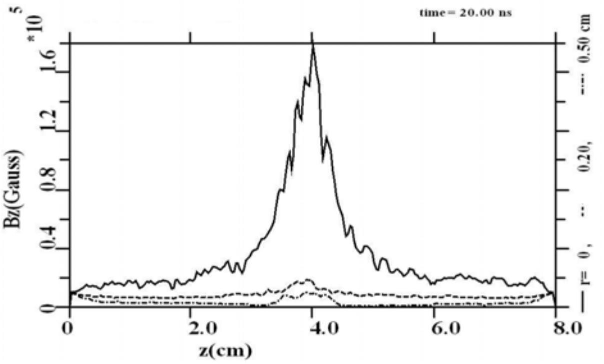

Fig.6. Longitudinal distribution of the full magnetic field at 3 radial coordinates at t = 20 ns

The motion of beam particles is rather complicated. Fig.7 shows projections of two particles trajectories on the transverse plane for the time interval of 1 ns.

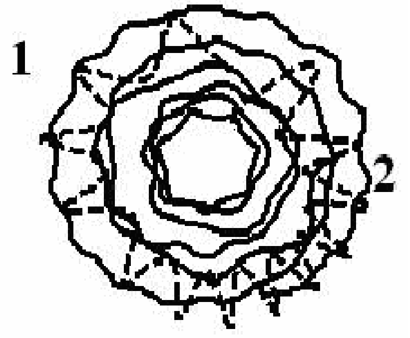

Fig.7. Transverse plane projection of 2 particle trajectories

2.2. INFLUENCE OF LONGITUDINAL PLASMA GRADIENT ON MAGNETIC FIELD DISTRIBUTION

To confirm the main influence of plasma ions on the effect discussed above the results for the same geometry, the same beam parameters and the same external magnetic field but with different signs of plasma gradient are given below. In the first case initial density of the plasma increases along the chamber from 5×10^{12} to 1×10^{14} cm^{-3}, in the second case it decreases from 1×10^{14} to 5×10^{12} cm^{-3}.

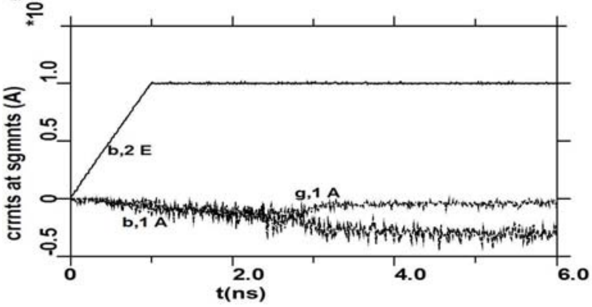

Fig.8. Dynamics of beam and plasma electron currents

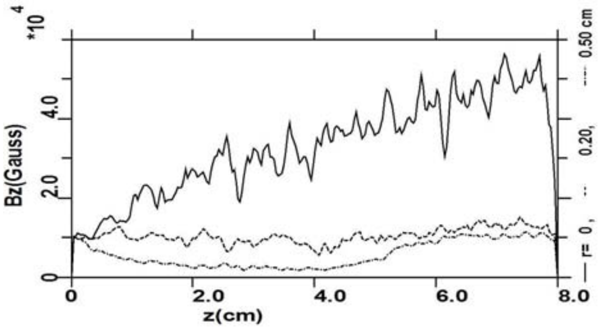

Fig.9. Longitudinal distribution of the full magnetic field at 3 radial coordinates for the case of positive gradient of plasma density

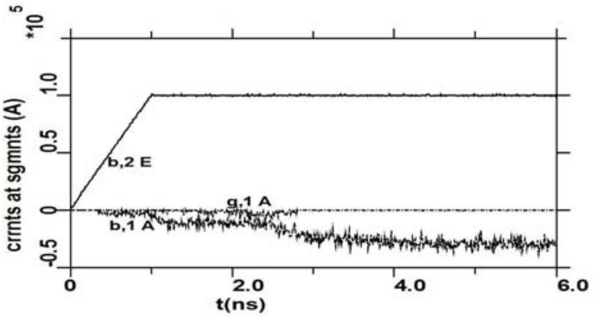

Fig.10. Dynamics of beam and plasma electron currents

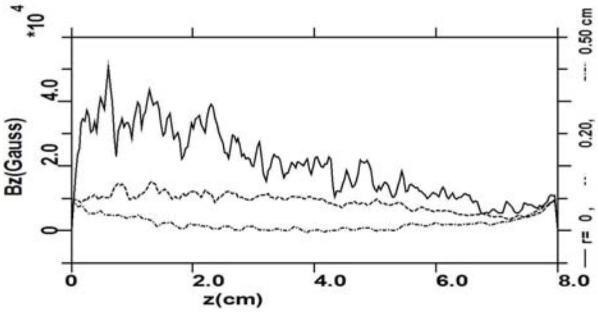

Fig.11. Longitudinal distribution of the full magnetic field at 3 radial coordinates for the case of negative gradient of plasma density

Fig.8 and Fig.10 shows the forms of injected beam current (b,2 E), and beam (b,1 A) and plasma electron (g,1 A) currents reaching the end of the chamber in the bounds of initial plasma channel radius for these two cases.

Final distributions of the full magnetic field at the moment t = 6 ns are shown in Fig.9 and Fig.11. It is obvious from Fig.9 and Fig.11 that the form of the full magnetic field at the axis follows the profile of plasma density. Essential modification of the initial magnetic field concentrates near the axis as for previous case.

2.3. “DYNAMICAL DIAMAGNETISM” IN PLASMA FILLED DIODES

Qualitative result of magnetic field modification does not depend on the case of transportation or of generation of electron beam. Following results are presented for the plasma filled diode about the same geometry but for lower energy of electrons. Such diodes are used to produce high-current low-energy electron beams for surface material modifications [8-10]. 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.

Plasma column of 3×10^{13} cm^{-3} density and of 0.6 cm radius fills 7 cm gap between the cathode and the anode. Plasma is homogeneous in radial and axial directions. The applied voltage rises to 100 kV for 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. As above to simplify simulations plasma ions are considered as the background.

In comparison with the transportation of the beams considered above where the energy and the current of the beam can be defined independently the difference consists in the current of the beam is defined as limited by space charge under the condition of zero accelerating field at the cathode surface and depends as on the voltage as on the plasma density.

First of all it is reasonably to consider the diode without an external magnetic field. Fig.12 shows the dynamics of beam current emitted from the cathode (b,1 E), beam (b,1 A), and 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.13. 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}. Self longitudinal magnetic field of the beam fluctuates at the level of tens Gauss.

The external longitudinal magnetic field of 2 kGs influences weakly on the value and the behavior of beam and plasma electrons currents reaching the anode. It is similar to the previous case (Fig.13). But the final distribution of the full magnetic field is changed drastically (see Fig.14).

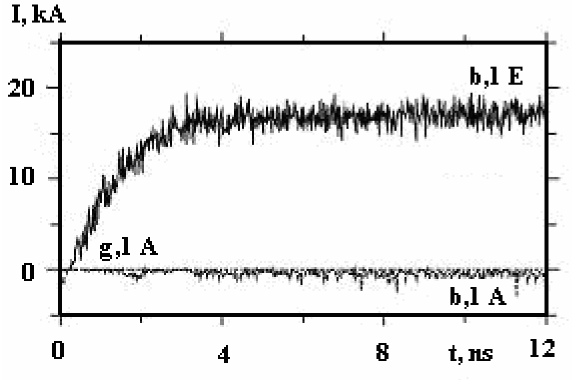

Fig.12. Dynamics of currents at the cathode

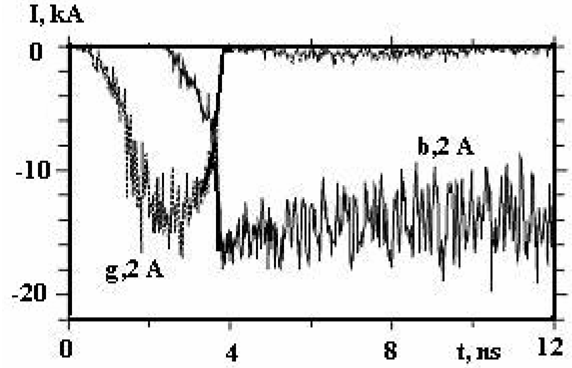

Fig.13. Dynamics of currents reaching the anode

Magnetic field is concentrated at the axis of the diode approximately homogeneously in longitudinal direction and equals approximately 7 kGs 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 also and this modification is latent also as the field out of plasma channel changes insignificantly in comparison with the given external field.

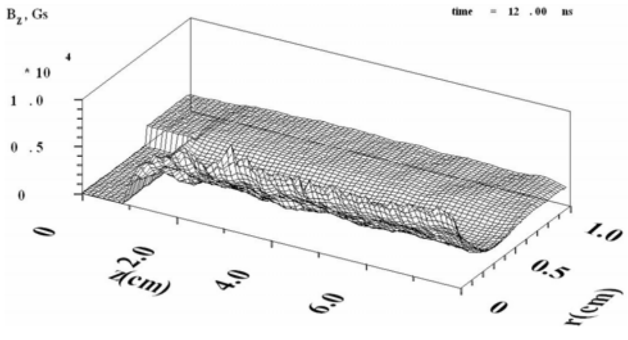

Fig.14. Final distribution of magnetic field

2.4. "DYNAMICAL DIAMAGNETISM" IN PLASMA FILLED DIODES WITH MAGNETIC FIELD GRADIENT

Let us consider the case when only the cathode of the diode is placed inside the magnetic field and the magnetic field is absent in the most part of the diode but plasma density is homogeneous in radial and longitudinal directions. Fig.15 shows the initial distribution of external magnetic field. The final distribution of the full magnetic field at the moment t = 12 ns is shown in Fig.16.

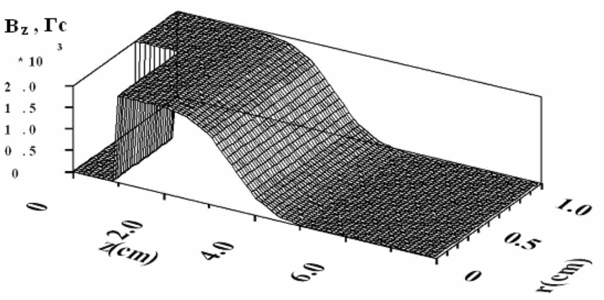

Fig.15. Initial distribution of magnetic field

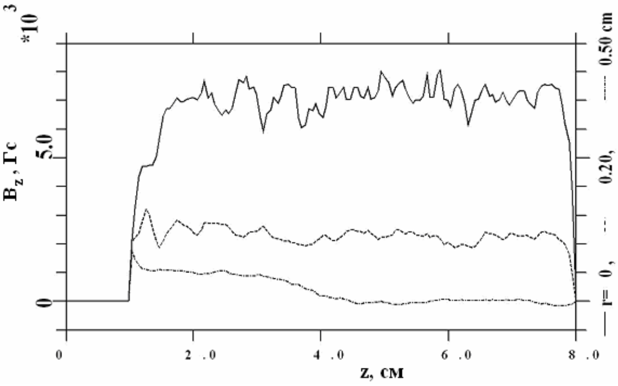

Fig.16. Longitudinal distribution of the full magnetic field at 3 radial coordinates

It will be noted that the beam has concentrated the field not only near the cathode but this concentrated field was transported by the beam along pre-axis region of the diode into the area of zero external magnetic field. Note that the full field has kept about zero value out of plasma column (Fig.17).

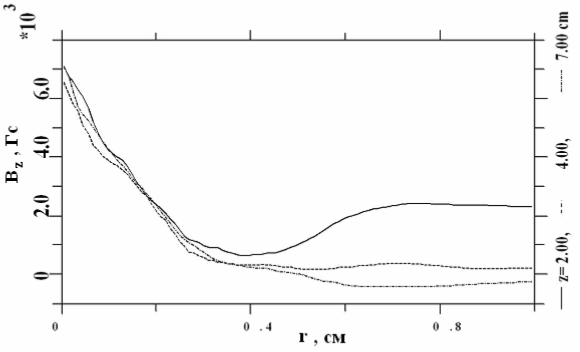

Fig.17. Radial distribution of the full magnetic field at 3 longitudinal coordinates

CONCLUSIONS

The new effect of "dynamical diamagnetism" in beam-plasma systems embedded in an external magnetic field was demonstrated by means of computer simulation. It was shown that "paramagnetic" states of the beam can be realized with increased to the axis of the system or varied along the system total magnetic field under the condition of conservation of magnetic flux. The modification of the magnetic field concentrates near the axis, and this modification is latent as the field out of plasma channel changes insignificantly in comparison with the given external field.

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СКРЫТЫЕ ПОЛЯ В ПУЧКОВО-ПЛАЗМЕННОЙ СИСТЕМЕ

А.В. Агафонов

При инжекции сильноточного пучка в плазму сравнимой плотности, находящуюся во внешнем магнитном поле, возможна реализация метастабильных состояний как с реверсом магнитного поля, так и с увеличением магнитного поля к оси системы. Радиальная фокусировка пучка обеспечивается при этом как собственным азимутальным магнитным полем, так и электростатическим полем ионного остова, образующегося после выталкивания плазменных электронов пространственным зарядом пучка. Из-за такого комбинированного удержания возникают особенности, которые невозможно наблюдать при транспортировке заряженного пучка в вакууме. В однородной в аксиальном направлении системе, находящейся в однородном продольном магнитном поле, возможно увеличение магнитного поля в приосевой области в несколько раз по сравнению с внешней, а если внешнее магнитное поле меняется в продольном направлении, возникает эффект «прокола» внешнего поля собственным магнитным полем пучка. Обращает на себя внимание латентность суммарного магнитного поля. На границе плазменного столба поле меняется слабо по сравнению с исходным, в то время как все существенные изменения происходят в приосевой области. С помощью численного моделирования по электромагнитному коду КАРАТ рассмотрены различные пучково-плазменные системы.

ПРИХОВАНІ ПОЛЯ В ПУЧКОВО-ПЛАЗМОВІЙ СИСТЕМІ

А.В. Агафонов

При інжекції сильнострумового пучка в плазму порівнянної щільності, що знаходиться в зовнішньому магнітному полі, можлива реалізація метастабільних станів як з реверсом магнітного поля, так і зі збільшенням магнітного поля до осі системи. Радіальне фокусування пучка забезпечується при цьому як власним азимутним магнітним полем, так і електростатичним полем іонного остову, що утворюється після виштовхування плазмових електронів просторовим зарядом пучка. Із-за такого комбінованого утримання виникають особливості, які неможливо спостерігати при транспортуванні зарядженого пучка у вакуумі. У однорідній в аксіальному напрямку системі, що знаходиться в однорідному подовжньому магнітному полі можливе збільшення магнітного поля в приосевій області у декілька разів в порівнянні із зовнішній, а якщо зовнішнє магнітне поле міняється в подовжньому напрямі, виникає ефект "проколу" зовнішнього поля власним магнітним полем пучка. Звертає на себе увагу латентність сумарного магнітного поля. На межі плазмового стовпа поле міняється слабо в порівнянні з початковим, тоді як усі істотні зміни відбуваються в приосевій області. За допомогою чисельного моделювання за електромагнітним кодом КАРАТ розглянуті різні пучково-плазмові системи.