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SELF-FIELD COMPENSATION OF HIGH-CURRENT REB TRANSPORTED BY GRADIENT DRIFT IN AZIMUTHAL MAGNETIC FIELD

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The research on the basic physical factors influencing the compensation of self-fields of a high-current electron beam transported in azimuthal magnetic field using gradient drift was conducted. The magnetic field was produced by the current carrying conductor placed on the beam axis. The beam self-field compensation is provided by the plasma produced by the electron beam when it is injected into some rarified gas. It was shown, that under conditions of the experiments carried out by the authors, the transversal magnetic field considerably reduced the electron beam compensation degree. On the whole, the obtained results confirm the general concepts of the physical processes occurring in the beam-produced plasma when the beam is injected into some rarified gas. So, when solving some technical tasks associated with effective transport of a high-current relativistic electron beam (REB), the parameters of the electron beam and those of the transport channel are to be matched carefully.
KEY WORDS: high-current relativistic electron beam, beam-self-field compensation, gradient drift, transport, azimuthal magnetic field.

The works on development of super-high-power X-ray generators built on multi-modular principle stimulate searching for methods of highly efficient terawatt electron beam transport and convergence [1]. The only method of megavolt electron beam transport with currents of $\approx 10^6$ A that has been put into practice to present day is electron gradient drift in azimuthal magnetic field produced by the current in the linear conductor located on the transport channel axis [2]. To compensate the beam self-fields a background gas at the pressure of a few Torr was used with which the transport channel was filled. To implement high-performance beam transport, and, especially, to converge several megampere beams into one, very high degree of their self-magnetic fields compensation is required.

A great deal of theoretical and experimental works have been devoted to the studies on efficient transport of high-current electron beams in gases, however, most of them have been carried out for the cases when the electrons are injected into gas when the applied magnetic field is absent or it is longitudinal. Rather few works have been devoted to the study of the beam self-field compensation using Grad-*B* drift [2, 3].

Analysis of the obtained results shows, that despite sufficiently complete conception of the physical events providing self-field compensation processes of electron beams transported in a neutral gas, the experimental results very largely depend on the experiment conditions (characteristics of electron beams and transport channels, diagnostics employed, and so on).

As is well known, when a relativistic electron beam is injected into gas, a back current arises in the beam-produced plasma, thus compensating the current of the injected beam. The compensation degree is determined by the value of the plasma-produced current I_p, flowing in the beam created plasma channel:

$$I_p \sim \sigma E_Z, \tag{1}$$

where σ – plasma conductivity, E_Z – electric field produced in the beam front region due to the beam current I_p built-up, $E_Z \sim \frac{\partial I_b}{\partial t}$. Plasma conductivity σ is determined by the kind of the chosen gas Z, its density n, density of the beam created plasma n_e, plasma electron temperature T_e, and so on. As applied to the beam transport in azimuthal magnetic field being transversal both to the beam and to the plasma back current, the low-ionized conductivity of plasma $\sigma_{H_\perp}$ can be written as:

$$\sigma_{H_\perp} = \frac{\sigma}{1+(\omega_H \tau)^2}, \tag{2}$$

where $\omega_H = \frac{eH_\varphi}{m_e c}$ – cyclotron frequency rate of electrons in magnetic field; σ – plasma conductivity without applied magnetic field; τ – effective time between collisions of electrons and gas atoms. Thus the transversal magnetic field causes additional reduction of the plasma conductivity.

Another substantial parameter that determines the beam current compensation degree is its front steepness. Apparently, high value of $\partial I_b/\partial t$ became a determining factor to provide effective transport for a megampere beam [2].

The third significant factor for efficient propagation of the beams whose currents exceed their Alfven limit tens times is a correctly chosen structure for the drift chamber. As long as the beam-created plasma conductivity has its finite quantity, a portion of the back current can flow down the drift chamber walls if the latter is made of metal. In this case the back current distribution is determined by the ratio of full impedance of plasma channel and that of the chamber, and some actions should be taken to increase the impedance of the out-of-beam circuit. It should be noted, that the beam-induced electric field as well as the plasma conductivity have rather a complex spatial structure, which is determined by the radial heterogeneity of the conductor-produced azimuthal field and of the beam density, as well as by the cycloidal character of the beam electrons' trajectories when the beam is transported. Besides, the plasma finite conductivity results in non-ideal compensation of the beam self-magnetic field, which is imposed on the external field.

To carry out a detailed experimental research into the influence of these factors upon the beam being transported is rather difficult. The first attempt to study the mentioned factors and their influence on the beam transport was made using computer simulation, see reference [3].

The purpose of this work is experimental verification of the general principles that are to be taken into consideration when transporting megampere beams using electron gradient drift in the applied azimuthal magnetic field.

EXPERIMENTAL FACILITIES

The accelerator-produced electron beam, having parameters: electron energy $E_e \approx 700$ keV, beam current amplitude $I_b = 90 \div 100$ kA, pulse duration at the FWHM $t_p \approx 100$ ns, was injected into a metal drift tube with 97-mm inner diameter, see Fig. 1. The tube was made three-sectioned, so that the length of the transport channel could be varied from 300 to 1000 mm. Rogowsky coils have been mounted at the entry of the first section and in the connecting flanges of the subsequent sections to register the drift tube net current along the tube axis. A copper wire with diameter of 5 mm meant for azimuthal magnetic field generation was placed on the transport channel axis. The wire was fed by a current pulse from the remote (from the diode output window) tube end, so it was short-circuited to the drift tube walls by three thin spokes made from stainless steel. At the drift tube entry the beam had an annular cross-section whose outer diameter was ≈ 50 mm.

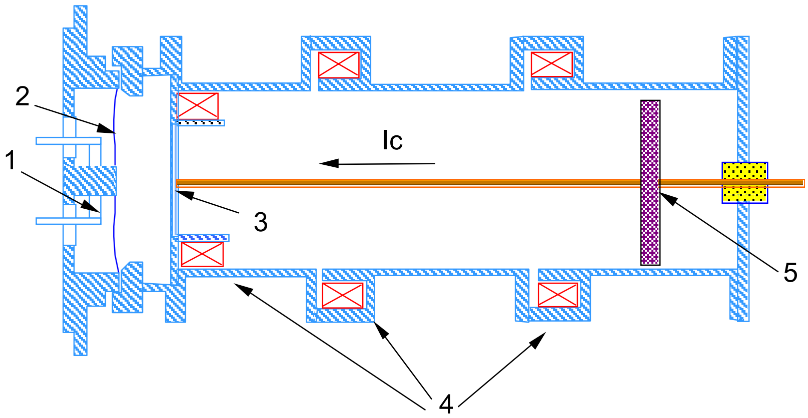


Fig. 1. Schematic drawing of the metal drift chamber. *1* – cathode; *2* – anode window foil; *3* – spokes; *4* – Rogowsky coils; *5* – calorimeter.

To form an annular beam a double diode provided with three rod-hole-transitions, meant to supply the ring cathode with the accelerating voltage impulse, was used. As long as the current strength in each of the convolutes (30 ÷ 35 кA) did not suffice to provide their effective self-isolation from the leakage currents, the diode total current was shared among the current of the beam injected into the drift chamber and the electron current leakage to the anodes. That is why the current of the beam injected into the drift chamber ranged from 40 to 60 kA. A graphite calorimeter was employed to measure the current value of the beam injected into the transport channel. The beam current I_b was determined from the calorimeter readings by formula:

$$I_b = I_d \cdot \frac{q}{Q}, \tag{3}$$

where I_d – the diode current measured with Rogowsky coil; q – the beam energy measured with the calorimeter; $Q = \int U_d(t) \cdot I_d(t)\, dt$ – the diode energy input; $U_d(t)$ – voltage impulse applied to the cathode. Besides, the problem of the electron kinetic energy loss at the beam propagation in the transport channel was studied separately, both experimentally and by computer modeling. With the length of the transport channel being less than 400 mm, guide conductor current less than 40 kA, and background gas pressure less than 100 Torr, the particle energy losses were no more than 5 % and were not taken into consideration since they were within the measurement errors. When measuring the beam current with the beam transport length of up to 1m and at thicker background gas density, an appropriate correction for energy loss was made. The current compensation degree f_m was defined as the ratio of the drift tube net current I_{net} measured with the Rogowsky coils to the current I_b calculated by formula (3).

EXPERIMENTAL RESULTS

Fig. 2 shows the azimuthal magnetic field influence on the current compensation degree of the propagated beam. The figure represents the beam current compensation degrees f_m depending on the background gas (air) density for the cases when the beam is injected into the drift chamber and the magnetic field is absent (round dots), and when 35-kA current impulse is transmitted along the drift chamber axis (triangles).

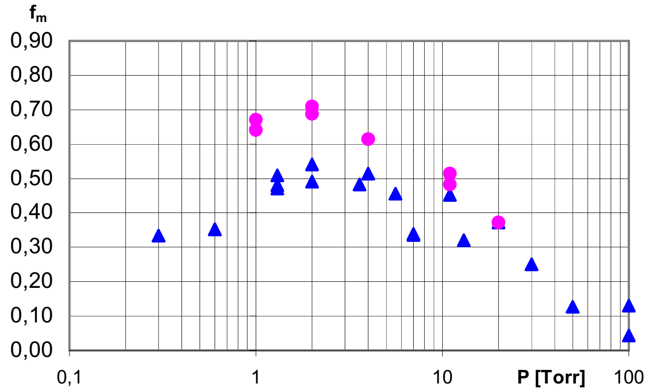


Fig. 2. Dependence of the beam current compensation on the background gas (air) pressure.

Azimuthal magnetic field is absent. Transport channel length – 40 cm.

In presence of azimuthal magnetic field generated by the conductor current of 35 kA. Transport channel length – 75cm.

In the range of the background gas optimal pressures of 1-4 Torr the magnetic field is evident to decrease the degree of the beam current compensation by about 28%.

As the analysis of the obtained results has shown the major spread in values of the beam current compensation from pulse to pulse causes spread in the beam front rise time. Therefore, further experiments on the influence of $\partial I_b/\partial t$ of the injected beam on the value of the back plasma current induced by that beam were performed. Technical potentiality of the electron accelerator allowed to change the diode current build-up rate from 0.3 to 1.7 kA/ns.

Dependence of the beam current compensation f_m on the rise time of the diode beam current is shown in Fig. 3. Experiments were carried out with the drift chamber length of 40 cm, the guide conductor current of 35 kA, and the air pressure in the tube – 2 Torr. As indicated in the figure $\partial I_b/\partial t$ of the beam is an important factor that essentially influences the degree of the electron beam current compensation in plasma, at the same time according to proportion (1) in the current rise range of 0.5÷1.7 kA/ns a linear increase of the beam current compensation is observed.

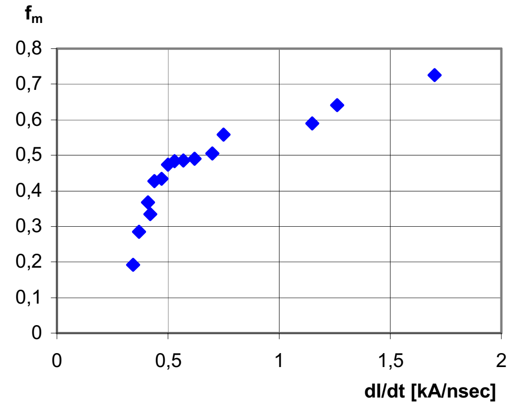
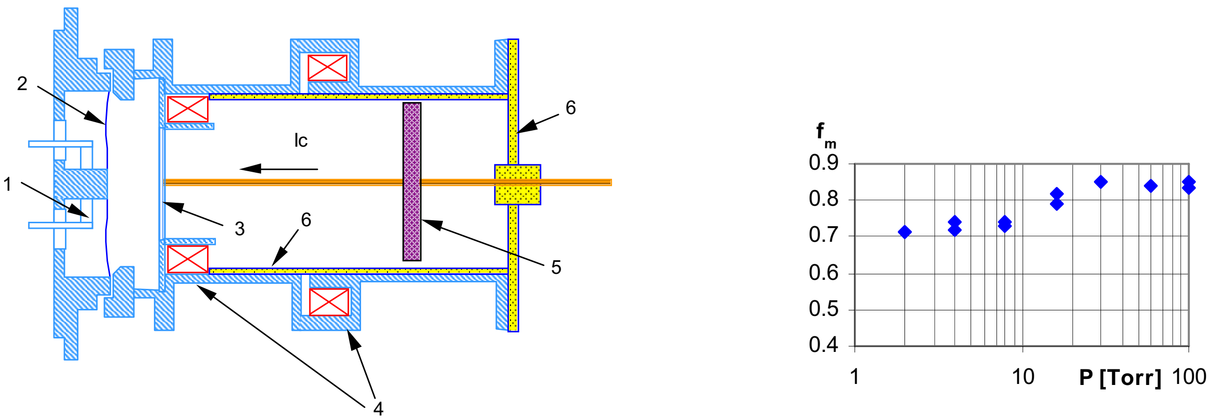


Fig. 3. Dependence of the beam current compensation on the beam front rise time. Transport channel length – 40 cm. Axial conductor current – 35 kA. Background gas – air at pressure of 2 Torr.

Since the conductivity of the plasma produced in an azimuthal magnetic field is finite there is a portion of the back current running down the drift chamber wall. Therefore, some actions should be taken to force passage of the back current through the plasma channel produced by the beam. To verify this assertion experimentally the drift chamber inner surface was insulated with 0.8-mm thick Mylar film, see Fig. 4a; the calorimeter meant to measure the beam-transmitted energy was located 400 mm away from the anode. In that way the possibility of the beam current leakage to the drift chamber end or its sidewall was eliminated.



a b

Fig. 4. Case of the chamber insulated with plastics.
a – Scheme of the experiment with the drift chamber insulated from the back current leakage to the chamber wall. Transport channel length – 40 cm. *1* – cathode; *2* – anode window foil; *3* – spokes; *4* – Rogowsky coil; *5* – calorimeter; *6* – plastics,
b – Dependence of the beam current compensation on the air pressure in the transport channel (a).

The results of the beam compensation with 35 kA current in the axial conductor are presented in Fig. 4b showing that f_m has increased from about 0.5 (see Fig.2) to more than 0.7 within the background gas pressure range of 2-10 Torr.

In order to explain the net current decrease at the gas pressure of more than 10 Torr some further experiments ought to be conducted, since when the gas pressure was higher than 16 Torr under conditions of our experiments, erratic behavior of the electron beam resulting in high-frequency modulation of the signals from Rogowsky coils could be observed.

CONCLUSION

This work is the first try for experimental verification of general concepts about processes of self-magnetic field compensation of the electron beams transported by gradient drift in an applied azimuthal magnetic field. The obtained results rather strongly prove these principles, however, meticulous optimization of parameters for the accelerator-transport channel system is required for every specific case in order to achieve highly efficient beam transport at megampere currents.

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КОМПЕНСАЦИЯ СОБСТВЕННЫХ ПОЛЕЙ СИЛЬНОТОЧНОГО РЭП, ТРАНСПОРТИРУЕМОГО В АЗИМУТАЛЬНОМ МАГНИТНОМ ПОЛЕ ПОСРЕДСТВОМ ГРАДИЕНТНОГО ДРЕЙФА

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Исследованы основные физические факторы, влияющие на компенсацию собственных полей сильноточного электронного пучка, транспортируемого посредством градиентного дрейфа в азимутальном магнитном поле, создаваемом током в проводнике, размещенном на оси пучка. Компенсация собственных полей пучка обеспечивается плазмой, создаваемой электронным пучком при инжекции его в разреженный газ. Показано, что в условиях выполненных экспериментов, поперечное магнитное поле существенно снижает степень компенсации электронного пучка. В целом, полученные результаты подтверждают общие представления о физических процессах, происходящих в создаваемой пучком плазме при инжекции его в разреженный газ. При решении технических задач, связанных с высокоэффективной транспортировкой сильноточных РЭП, необходимо тщательно согласовывать параметры электронного пучка и канала транспортировки.

КЛЮЧЕВЫЕ СЛОВА: сильноточный релятивистский электронный пучок, компенсация собственных полей пучка, градиентный дрейф, транспортировка, азимутальное магнитное поле.