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EQUILIBRIUM AND DESTRUCTION OF A REB IN A MAGNETIC GUIDE

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Summary

A REB with a relatively small ν/γ (320 keV, 0.75 kA and 1.0 MeV, 1 kA) is injected into an axial magnetic guide in the injection system of ERA device of IPP-Nagoya. The beam surface envelope reveals an outstanding spatially periodic structure in the uniform field and the wave length and the REB parameters in the guide are found to be well consistent with the values predicted with a particular kind of the equilibrium model, proposed by Diament a few years ago. A rapid destruction of the REB during the passage through a magnetic hump and with an abrupt change of the surrounding metal wall radius is observed and discussed briefly.

Introduction

The study of charged particle, in which space charge effect plays a significant role in their propagation behavior, has already a long history over several tens of years.[1] Recently a new way of producing a very intense beam far beyond the Alfven limit was developped and the characteristic features of such dense beam including its equilibrium with or without external fields and the instabilities as nonneutral plasma have been considered in detail, related to the various fields of the application, especially the ion collective acceleration, the inertial fusion, the high power microwave production, etc.[2]

The stable transport of the intense beams with the focusing elements (the guiding magnetic field, for example) is one of the subjects of principal concerns. Mahaffey et al. reported surface ripples on magnetically confined electron beams and analysed their properties in the nonrelativistic[3] and the relativistic limits,[4] in the framework of the rigid rotor equilibrium.[1] In the course of the study on the ERA device in IPP-Nagoya,[5] a similar ripple was observed in the electron beam propagating in the magnetic guide between the cold emission electron gun and the injection port, through which the beam was injected into the ERA compressor field. It was found that the wave length of the ripple, the equilibrium radius and other properties of the beam were far from the values predicted theoretically with the rigid rotor model cited above. Here the experimental results and the analyses of the electron beam in the injection system of the ERA are reported with stress on the importance of the self-consistent structure of the equilibrium and the effect of the conducting & surrounding.

Experiment

The experiment to generate the electron flow is depicted schematically in Fig. 1. The electron gun consists of a Marx (600 kV or 2 MV) and a vacuum diode. Stainless-steel needles are attatched on the top of the cathode shank over the circular area of 1 cm radius. A stainless-steel mesh anode and an anode-cathode spacing of 1 cm result in 0.75 and 1.3 kA beams of 0.32 and 1.0 MeV for two Marx voltages. The beam duration is about 100 ns and the other parameters are listed in Table I, where E_0 the mean kinetic energy of the electrons, I_b the total beam current passing through the anode, ν the Budker parameter, V_z the mean axial velocity of the particles, $\Omega^2 = -\omega_p^2/2$, ω_p the electron plasma frequency of the beam with the electron mass relativistically modified, and a is the beam radius.

A series of two coils supplies with the magnetic guiding. One of the coils is located inside a housing of a stainless-steel drift tube and operated pulsively to give minimum perturbation to the compressor field. The other one wound outside the tube produces a stationary field. An auxiliary coil is placed in the intermediate region between two coils to reduce a hump in a magnetic field due to the mismatching of the two fields. The axial field distributions are shown in Fig. 2, where the field is normalized with B_0 = 0.154 T. The curve (a) is for the field by the stationary current and (b) and (c) are for the combinations of the stationary and the pulsive ones without and with the auxiliary coil, respectively. D is the distance from the anode.

Fig. 3 shows the intensities of the propagating electron beam in fields for the case of the 600 kV Marx. The currents were measured by a Faraday cup at their peak values. In the region of the constant magnetic fields (D = 0 ∿ 25 cm) the beam intensity shows the remarkable structure fixed spatially with a periodicity of 7 ∿ 8 cm. Entering into the pulsive field through a hump, the beam is suffering a reduction of the intensity. The result measured for 1 MeV beam is given in Fig. 4 for comparison. The beams are well reproducible and the spatial structure observed should not be due to any instability or some other stochastic mechanisms.

Discussion

The experimental results stated above cannot be explained with the model frequently adopted so far, where the laminer flow and the constant angular velocity in every layer were assumed. The following formula for the wave length of the periodicity, using the rigid rotor model in the limit of small amplitude,

$$\lambda = \frac{2\pi v_z}{\omega_c\sqrt{1-\left(\frac{\omega_p}{\omega_c}\right)^2}} \qquad (1)$$

where all symbols have the usual meanings, gives values of about 10 cm for E_0 = 320 keV and 17 cm for 1 MeV, which are not consistent with the observation.

Diament proposed an equilibrium of a laminer flow of charged particles confined magnetically in a circular conducting drift tube.[6] The only assumption used is that the all particles have the same axial velocity over the whole radius of the beam and the effects originated by the self-electrostatic and magnetic forces of the beam, including the fields from the surrounding walls, are taked into consideration with complete self-consistency. The beam radius a is no longer a free parameter, but a parameter a/R is determined by the known system parameters, such as the applied magnetic field and the geometry of the surrounding structure with the total beam current and the kinetic energy γ of the particles. With the numerical values in the experiment stated above, the external field B_z, for example, is given by a/R, as indicated in Fig. 5, where the equi-total current contours are also shown, for the slow mode of the beam rotation. With this figure it can be seen the equilibrium should be attained for the values of the parameters: B_0 = 0.154, I_b = 0.8 kA, a = 8 mm and the radius of the drift tube

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r_0 = 2.75 cm. These are close to the observed currents and radii shown in Table I. The most significant feature concluded from the Diament's model is a large reduction of the particle kinetic energy by the space charge effect. According to the model, although the angular velocity of the bulk rotation of the beam is nearly constant over the whole radius, γ should by reduced to 1.37 ($V_z = 2.05 \times 10^8$ m/s) and 2.45($V_z = 2.74 \times 10^8$ m/s) for the 600 kV and the 2 MV Marx respectively. These reductions of the axial velocity are considerably larger than in the case of the rigid rotor and just result in the wave length of the spatial perturbation λ = 7.8 and 14 cm, using the formula, for each case, that is a very excellent agreement with the experiment. The non-linear effect of the rippled structure could be seen from the experimental values, but any definitive description does not seem possible. As the conclusion, the Diament's model is a good candidate of the equilibrium which is realized in the experiment described.

The 320 keV beam loses the intensity rapidly in the pulsive field if the hump of the field is large, while the 1 MeV one is kept at almost constant level. The reason of the 320 keV beam destruction has not been understood completely, however, the parametric pumping by the hump and the sudden change of the surrounding wall radius to 15 mm (from 27.5 mm) and the succeeding particle loss of particles by colliding with walls could be one of the principal mechanisms. On this line numerical tracings of the particle orbits were studied and the results are shown in Fig. 6. It is evident that the calculation can only partly explain the experiment. Some alternatives of the loss mechanism such as the instability of the beam are under study, being expected a better agreement with the measurements.

The authors are grateful to Y. Kubota for his assistance in the experiments.

Reference

1) See for example a review book by Davidson and the references cited therein: Theory of Nonneutral Plasma, R. C. Davidson, Benjamin, Mass. 1974.

2) The most up to date informations are given by the reports presented at the topical conferences held recently such as the 2nd International Topical Conference on High Power Electron and Ion Beam Research and Technology, Cornell University, Ithaca, N.Y. Oct. 3-5, 1977.

3) R. A. Mahaffey et al: Phys. Rev. Lett. 35 1439 1975.

4) R. A. Mahaffey: Phys. Fluids 21 518 1978.

5) S. Kawasaki et al: IEEE NS - 20 280 1973
A. Miyahara et al: IPPJ-T-11, Institute of Plasma Physics, Nagoya Univ. Japan 1973.

6) P. Diament: Phys. Rev. Lett. 37 168 1976.

Table I. Beam characteristics of 600 kV and 2 MV Marx generators.

	Marx generator	
	600kVtype	2MV type
E_0 (MeV)	0.32	1.0
I_b (kA)	0.75	1.3
a (cm)	1.0	1.0
ν/γ_0^3	0.013	0.0036
$(\lvert\Omega\rvert a/V_z)^2$	0.042	0.0081
B_c (T)	0.09	0.09

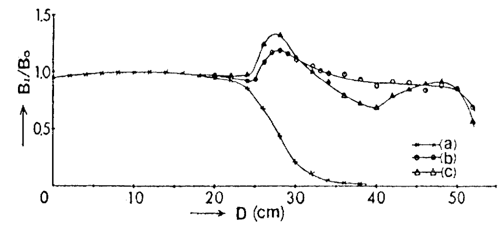

Fig. 2. Axial distribution of the guiding magnetic field normalized by B_0 = 0.154 T, where D is distance from the anode, (a) is for the field by stationary current and (b) and (c) are for the combinations of the stationary and the pulsive ones with and without the auxilialy coil, respectively.

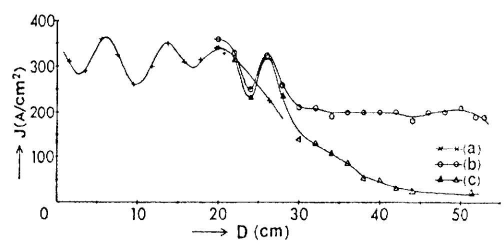

Fig. 3. Axial variation of the beam intensity for the beam energy of 320 keV in the guiding magnetic field (a), (b) and (c), where J is the beam intensity.

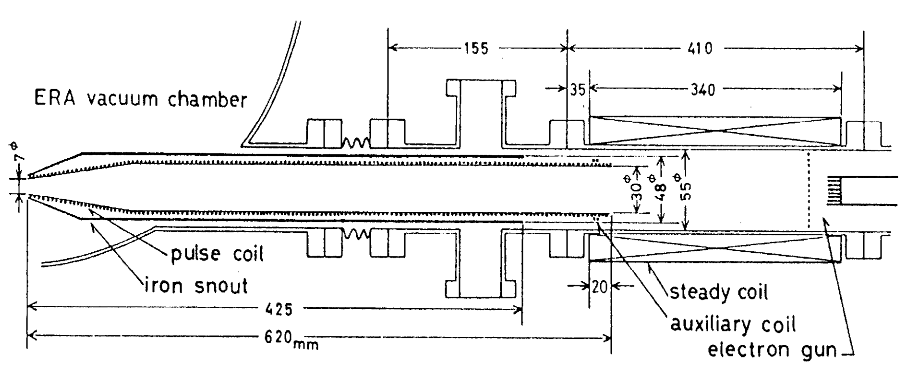

Fig. 1. Electron gun and beam transport system

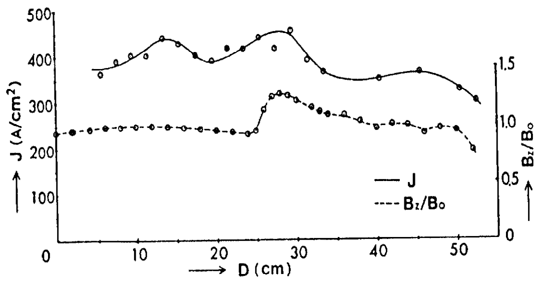

Fig. 4. Experimental results of the beam guiding for the beam energy of 1 MeV, where the solid line is the beam intensity and the dashed line is the guiding field normalized by $B_0 = 0.185$ T.

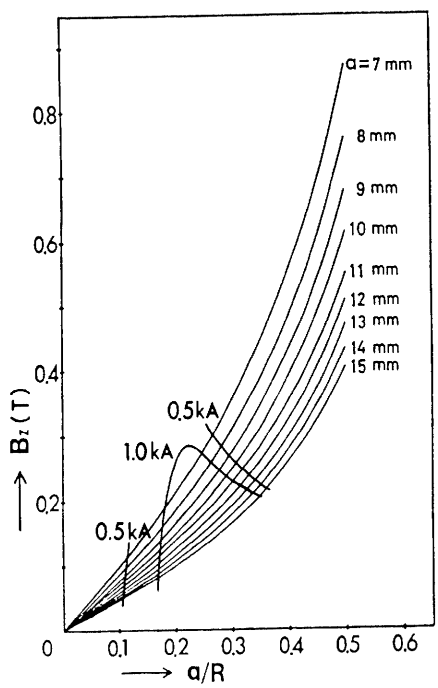

Fig. 5. External magnetic field B_z versus a/R for different equilibrium beam radii, where a is the beam radius and R is defined by

$$eaB_z/m_0c = 4a/R/\{1 - (a/R)^2\}^2.$$

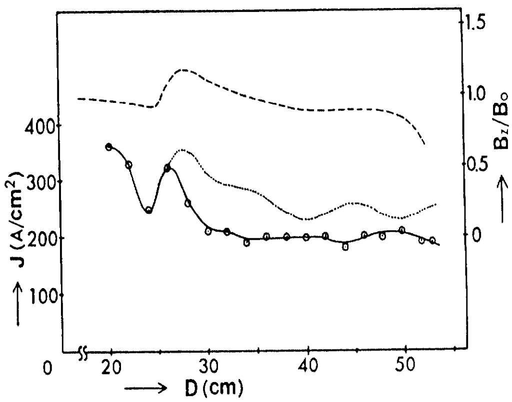

Fig. 6. Beam intensity estimated from the numerical tracing of the test particle in the guiding field (b), where particle energy is 320 keV, the dotted line is the estimated result, the dashed line is the guiding field and the solid line is the measured beam intensity.