On the Magnetic Compression of Electron Beams in E.B.I.S. or E.B.I.T.

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Abstract

Conditions for compression of a laminar non-relativistic dense beam by an inhomogeneous magnetic field B are investigated theoretically and numerically. A generalized Brillouin regime is defined in which an efficient beam compression may proceed according to the scaling Br = const, provided the field undergoes slow variations: adiabaticity condition. The initial density profile and radial velocity are found critical for subsequent laminarity.

I. INTRODUCTION.

A large electron density in the beam of an E.B.I.S. or E.B.I.T. is of paramount importance to obtain a large number of multiply charged ions. Adiabatic magnetic compression starting for example at the gun exit or further downstream in a Brillouinlike beam is a way to reach this goal. It will be shown in section II that numerical simulations refering to actual devices indicate an unfavorable Br^2 = const scaling law. Furthermore "beam scalloping" easily occurs depending on initial conditions and beam geometry. It appears then worthwhile to investigate magnetic compression both theoretically and numerically. An important requirement is the laminarity of the electron flow. Since the whole analysis deals with electron trajectories, laminarity is defined by nonintersecting trajectories.

II. IDEAL BRILLOUIN BEAM AND MAGNETIC BEAM COMPRESSION

We need to use an electron beam in Brillouinlike conditions (≈ 0.5 mm envelope beam radius, constant beam profile all along the beam section, 3000 Gauss axial magnetic field) and to increase by 100 the current density, using magnetic compression in Brillouin mode (Br = const in a rigid rotator beam) up to 3 Tesla axial magnetic field (Fig.1).

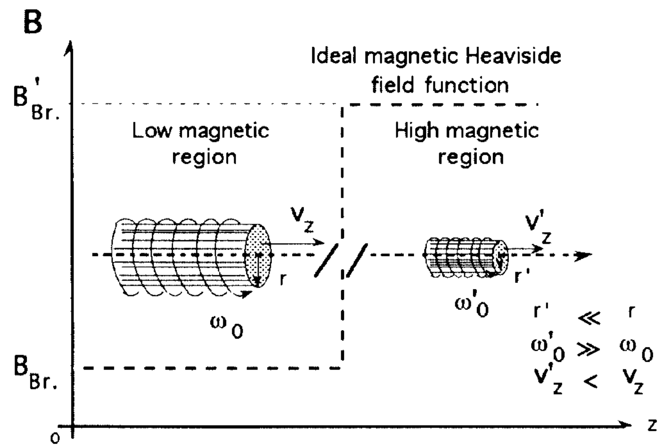

Fig. 1

In our E.B.I.S. design and with the beam conditions at 3000 Gauss, the computed trajectories (2D-axisymetric Thomson-CSF-TTE code with space charge) lead to a Br^2 = const (Fig. 2) beam compression scaling (constant flux) instead of the expected Br = const law (Brillouin mode).

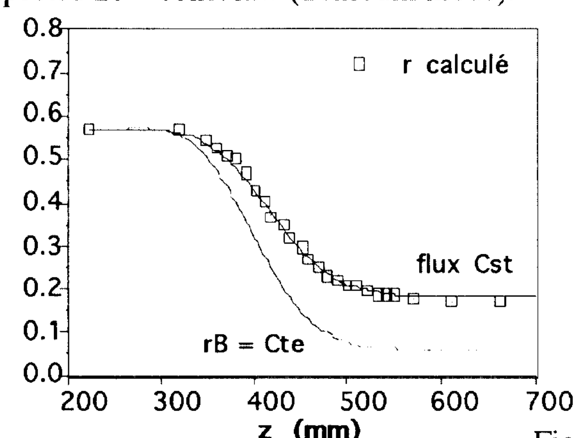

Fig. 2

Beam enveloppe when the magnetic field increases from 3000 Gauss to 3 Teslas. Squares are computed values. Vertical scale in millimeters.

We then investigate the better way to reach high current density beam, with a special emphasis on initial beam conditions. Two simulations were performed starting with a perfect Brillouin beam (0.5 mm, 10 kV, 0.054 A, 386 Gauss, constant current density). We used a 2D-Thomson code and alternatively a Runge-Kutta procedure integrating the equations of motion. It appears immediately a beam envelope scalloping (Fig. 3) corresponding to the inhomogeneous magnetic field structure (a gradient of the radial magnetic component is associated with any axial magnetic field component rise).

Two computed radius envelope electron beam in inhomogenous magnetic field with space charge with Brillouin injection conditions:

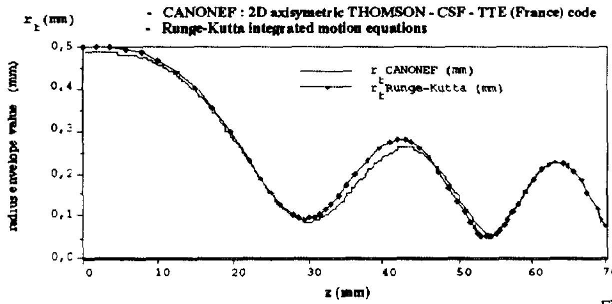

Fig. 3

When analysing accuratly the motion of an electron in an axisymetric magnetic structure with space charge (beam charge density), trochoïdal trajectories are found with conspicuous beam translaminarities (Fig. 4).

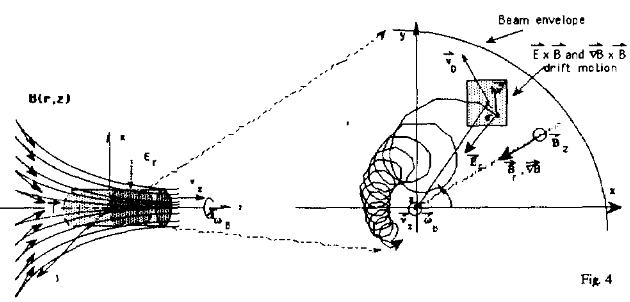

Fig. 4

We can explain these results using the transverse reduced effective potential energy leading to extented laminar flow expressions (low magnetic fields up to high magnetic fields).

III. A GENERALIZED BRILLOUIN REGIME

In a uniform magnetic field parallel to the beam, the socalled Brillouin flow corresponds to the limit:

$$\omega_p^2 = \frac{\Omega^2}{2}\,,\ \omega = \omega_B = \frac{\Omega}{2}\ \textit{(Larmor frequency)}\,,$$

where ω is the angular velocity around the beam axis, ω_p is the plasma frequency and Ω is the gyro frequency of the electrons. The beam then behaves like a rigid rotor: perfectly laminar flow. Now, Busch's theorem holds, i.e., for every electron trajectory

$$\omega = \frac{d\varphi}{dt} = \frac{e}{2\pi m r^2}\left(\Phi - \Phi_0\right).$$

Φ is the magnetic flux through a disk centered on the beam axis with radius is r, the distance of the electron to the axis . Φ_0 is a constant of the motion which vanishes in the Brillouin regime. Now in a non uniform field with azimuthal vector potential A_φ, assuming an homogeneous compression and an almost constant longitudinal velocity v_z (this is close to reality), a radial electric field is

$$E_r = -\frac{m}{e}\frac{W_0}{r}\,,\ \text{where } W_0 = \int_0^r \omega_p^2(r')\, r' dr'.$$

In the case $\Phi_0 = 0$, a transverse reduced effective potential energy is

$$E_{eff} = \left(\frac{eA_\varphi}{m}\right)^2 - 2W_0 \ln\!\left(\frac{r}{r_0}\right).$$

This potential has a minimum at r_{min} such that

$$r_{min}^2 = \frac{\Omega(0,z)}{\dfrac{d^2\,\Omega(0,z)}{dz^2}}\left(1 - \sqrt{1 - \frac{8\,W_0}{\Omega^3(0,z)}\frac{d^2\,\Omega(0,z)}{dz^2}}\right),$$

which in the "superadiabatic" limit

$$\frac{8\,W_0}{\Omega^3(0,z)}\frac{d^2\,\Omega(0,z)}{dz^2} << 1\,,$$

reduces to

$$r_{min} = \frac{2\sqrt{W_0}}{\Omega(0,z)}\,,\ \text{i.e. } B(0,z)\, r_{min} = \text{const.}$$

A laminar flow (generalized Brillouin regime) is obtained when every electron trajectory follows the bottom of such a potential valley (line C Fig. 5).

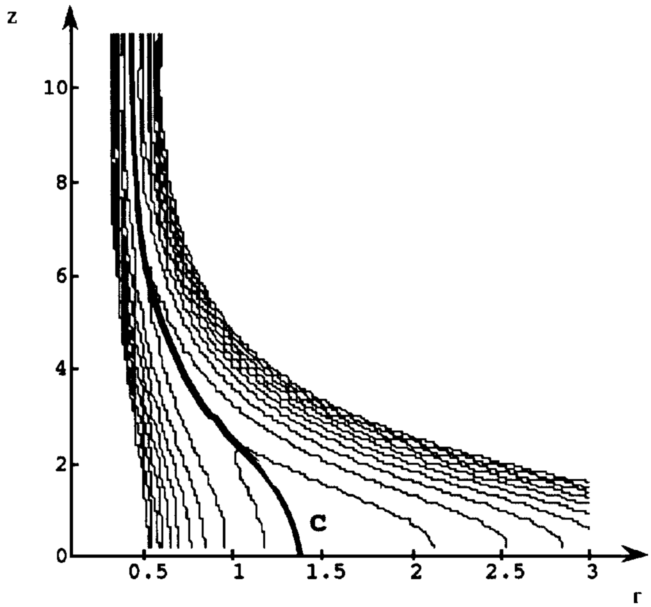

Fig. 5

The corresponding requirements are:

i) $$r_0 = r_{min}(z{=}0),$$

$$\omega_0(r_0) = \frac{e}{2m} B_z\left(\frac{r_0}{\sqrt{2}}\right),$$

$$n(r_0) = \frac{\varepsilon_0 m}{e^2} \frac{\Omega^2(0,0)}{2}\left(1 - \frac{r_0^2}{\Omega(0,0)} \frac{d^2\Omega(0,0)}{dz^2}\right)$$

and since

$$\Omega^2(r_0,0) = \Omega^2(0,0)\left(1 - \frac{r_0^2}{2\Omega(0,0)} \frac{d^2\Omega(0,0)}{dz^2} + \dots\right).$$

The Brillouin matching $\omega_p^2 = \frac{\Omega^2}{2}$ holds only on the beam axis .

ii) the ratio of initial radial vs longitudinal velocities has to be carefully optimized.

These initial beam conditions (longitudinal and angular beam velocity for each beam radius) added to the $\Phi_0 = 0$ Busch condition allow a favourable compression mode of electron beams in inhomogeneous axisymetric magnetic fields (Fig. 6).

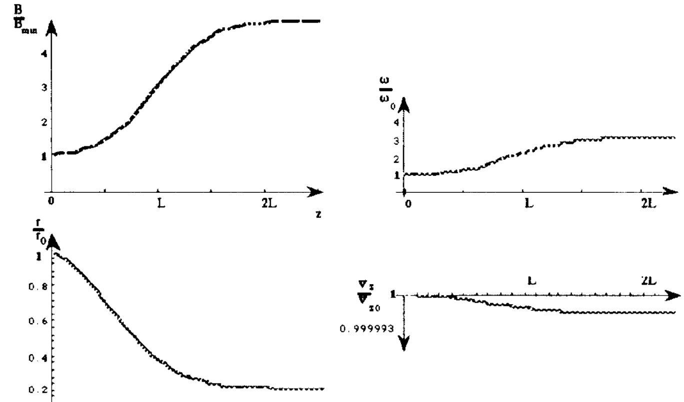

Fig. 6

III. CONCLUSION

Although the better way to transport electron beams with space charge in a constant magnetic field is to use a constant profile density beam in the Brillouin regime (rigid rotator conditions), the laminarity of such a beam is not conserved along an increasing field. Looking then for laminarity conservation, we have shown that suitable conditions are $\Phi_0 = 0$ for every electron trajectory at the initial field increase, a parabolic density beam profile, an inhomogeneous rotating beam and an adiabatic magnetic field increase.

References:

R.C. Davidson, in: The Physics of Nonneutral Plasmas, Addison Wesley (New-York, 1990)

J.D. Lawson, in: The Physics of Charged-particle Beams, Oxford (England, Oxford, 1977) § 2

L. Brillouin, Phys. Rev. 67 (1945) 260

E.D. Donets, IEEE Trans. Nucl. Science 23 (1976) 897

R.E. Marrs, M.A. Levine, D.A. Knapp and J.R. Henderson, Phys. Rev. Lett. 60 (1988) 1715

H. Busch, Annalen der Physik 81 (1926) 974

E. Durand, Electrostatique et Magnétostatique, Masson (France, Paris, 1953)

G. Giardino, Etude de réalisation d'une sources d'ions du type super EBIT, Doctorate thesis Université Paris 7 (France, Paris, 1992)