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A SCHEME FOR FORMING HIGH POWER ION RINGS IN COMBINED STATIC AND PULSED MAGNETIC FIELDS

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INTRODUCTION

There exists a hope to realize proposed by Christofilos the "Astron" concept [1] employing compact ion rings with ion energy $\mathcal{E}_i \gtrsim 0.5$ GeV and current $I_i \sim 10$ MA. Such rings can be formed by adiabatic compression in pulsed magnetic field [2]. It is, however, clear that this method cannot provide high efficiency and repetition rate and leaves little chance of utilizing the benefits of superconductivity.

Therefore it seems interesting to consider in this context a method of compression in static magnetic field [3], also suggested by Christofilos for electron rings (and independently by Laslett and Sessler [4]). Just as during compression in a pulsed magnetic field [2] the field reversal factor of a statically compressed ring

$$\xi = - B_Z^{self}/B_Z^{ext} , \qquad (1)$$

defined through B_Z values at the axis, increases inversely proportional to the ring major radius, R . Since compression in static magnetic field is not accompanied by energy gain a preliminary acceleration of particles is needed. For this purpose another idea, proposed in connection with electron ring accelerator development, the spatial betatron concept[5], can be employed.

PRINCIPLE OF OPERATION

A simplified scheme of the device is shown in Fig. 1. A low energy ion ring 1 is generated by injecting an annular beam through a cusp of magnetic field with immediate charge neutralization. The magnetic field is formed by a superposition of pulsed magnetic field created by currents in coils 2, and static field of solenoids 3,4. Under the action of a moving magnetic mirror, formed by successively switching on the coils 2, the ions gain the energy and at the same time are pushed along the axis of solenoids 3,4 into a stronger static magnetic field. The winding of the solenoids should be tailored so as to ensure an approximate constancy of the ring major radius over the betatron section. Under certain conditions (the absence of dense plasma being a crucial

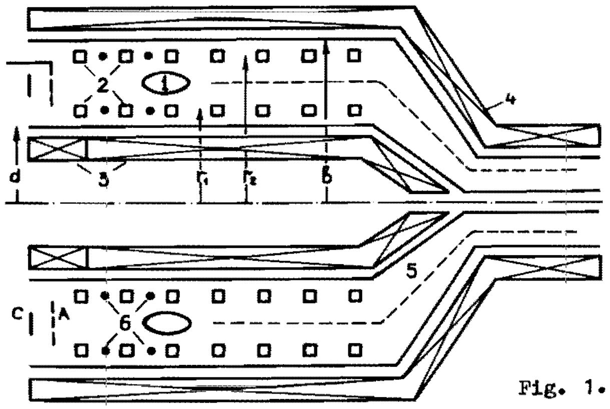

Fig. 1.

one) the neutralizing electrons are locked inside the ion ring thus being accelerated by the induction electric field and acquiring rotational velocity opposite to that of ions.

On the attainment of the final energy the ring enters the static compression region 5. During compression the kinetic energy of particles is partially transferred to the self-magnetic field. Besides this, the ring electrons intensely radiate synchrotron light. Due to radiation damping of transverse oscillations electrons form a thin cord inside a thicker ion ring resembling Budker's relativistic stabilized beam [6]. Owing to a strongly non-linear character of the cord self-fields an effective suppression of otherwise unstable transverse modes may be expected.

The following features make the discussed scheme look attractive: the pulsed magnetic field is spatially localized in a small-volume moving mirror and has a lower strength compared to static field; the ring is compressed and being kept in final state without contribution from the pulsed field.

Let us consider the consecutive stages of the scheme operation in more detail.

ION-ELECTRON RING GENERATION

Results, achieved in the course of the Ion Ring Experiment [7] show feasibility of forming high-quality charge-neutralized proton rings by injection through a cusp-like magnetic field. With the injection energy $\mathcal{E}_{i0} \sim 1$ MeV a total number of protons

$N_i \sim 10^{17}$ may be expected in a ring of major radius R = 1÷2 m and minor half-sizes $a_r \simeq 5$ cm, $a_z \simeq 10$ cm.

The self-magnetic field, steeply rising during the ring roll-up, can excite coherent radial oscillations of the ions. To minimize the oscillation amplitude the self-field should satisfy the betatron condition at the ring radius. For an axially stretched layer shielded by inner and outer conducting cylinders of radii d and b, respectively, this condition holds at the radius

$$R = \sqrt{db}\,. \tag{2}$$

After the pulsed field is triggered off, electrons captured into the ring exhibit radial drift in cross fields E_θ and B_z. In the case of dynamical compression [2] this drift does not lead to any consequence since its velocity practically equals to that of radially compressing ion ring. In our case the electron drift causes significant radial polarization of electrons and ions. If the filling gas pressure is sufficiently high, the ring ions produce enough plasma to maintain its charge neutrality. A more promising situation arises when after the ring formation a further influx of electrons is stopped. Then the drift motion of trapped electrons gives rise to radial electric field E_r which in its turn causes electrons to drift azimuthally with an increasing speed v_e directed opposite to the velocity of ions v_i so that they contribute to the total current.

In intense ring radial polarization is small compared to both the major ring radius and its minor dimensions $a_{r,z}$. Assuming $R_i = R_e = R$ and excluding E_r from equations of radial balance we get expressions for canonical momenta of single-charged ions and electrons, respectively:

$$M_i = R^2 \left[B_z \frac{(v_i - v_e)p_i}{v_i p_i + v_e p_e} - \frac{1}{2}\bar{B}_z \right]$$

$$M_e = R^2 \left[\frac{(v_e - v_i)\, p_e}{v_i p_i + v_e p_e} B_z - \frac{1}{2}\bar{B}_z \right] \tag{3}$$

with $p_{e,i}$ being the azimuthal mechanical momenta. In an axially symmetric system M_i is a good invariant whereas M_e may change due to synchrotron radiation loss (which is most intense in the end of compression phase).

As follows from eqs (3), the magnetic field at the orbit B_Z and its mean value over the area encircled by particles $\bar{B}_Z$ should vary as

$$B_Z = B_{Zo}\left(\frac{v_i}{v_i - v_e} - \frac{P_e}{P_{io}}\right), \quad \bar{B}_Z = \bar{B}_{Zo} - 2B_{Zo}\frac{P_e}{P_{io}} \qquad (4)$$

in order to keep the ring radius constant. Therefore a decrease in B_Z is needed to compensate for the rising polarization field E_r at the early stage of acceleration. Additional coils 6 (Fig. 1) serve for this purpose.

A sharp increase in the ring current due to electrons being accelerated leads, on the one hand, to shrinkage in minor dimensions (approximately by a factor of $\sqrt{c/|v_{io}|} = 4{\div}5$) and on the other hand to a possible stopping of particles in self-magnetic field. As the absence of dense plasma has been assumed, the pinching of electron current upsets local charge neutrality and the Coulomb repulsion stabilizes the electron motion. To prevent the ion current from decay a requirement

$$\nu_i \equiv \frac{e^2 N_i}{m_i c^2 2\pi R} < \frac{|v_i|}{|v_i| + |v_e|} \qquad (5)$$

should be met, which imposes a restriction on injection energy and initial ring radius. For a number of protons $N_i = 10^{17}$ and $\mathcal{E}_{io} = 0.5$ MeV from (5) follows a limitation $R > 0.8$ m.

SPATIAL BETATRON

The adiabatic motion of the ring is governed by equations (4) and condition of axial balance

$$B_r = -\frac{R}{2}\cdot\frac{\partial \bar{B}_Z}{\partial z} = 0. \qquad (6)$$

After a short period of time when the first term dominates in expression (4) for B_Z the magnetic field and its average should satisfy the betatron condition, which may be formulated as a requirement to the total time derivative

$$\left(\frac{\partial}{\partial t} + v_Z\frac{\partial}{\partial z}\right)(\bar{B}_Z - 2B_Z) = 0 , \qquad (7)$$

where v_Z is axial velocity of moving magnetic mirror.

A necessary condition for the ring centroid equilibrium in the limit $\Delta \equiv b - d \ll R$ has the form

$$n\left(1 - n + \frac{\pi^2 I R}{c\Delta^2 B_Z^{ext}}\right) - \rho^2 > 0 \qquad (8)$$

with $n = -r/B_Z^{ext} \cdot \partial B_Z^{ext}/\partial r \,|_{r=R}$, $\rho = r/B_Z^{ext} \cdot \partial B_Z^{ext}/\partial z \,|_{r=R}$ being the external magnetic field indices and I the absolute value of the ring current. It can be easily inferred from eqs (6,7) that in order to keep the value of ρ sufficiently small, both the static and pulsed magnetic field spatial gradients, taken separately, should satisfy the betatron condition [8]. This accounts for presence of two rows of fast coils with radii r_1 and r_2 in Fig. 1.

Introducing smoothed current densities i_1, i_2 in solenoids formed by inner and outer coils, respectively, the pulsed magnetic field in the long-wavelength limit can be written as

$$B_Z^{pulse} = \frac{4\pi}{c(b^2 - d^2)}\left[(b^2 - r_2^2)i_2 - (r_1^2 - d^2)i_1\right]. \qquad (9)$$

With the help of this formula it is easy to find the average field B_Z^{pulse} and voltage applied to fast coils at desired values of field gradient and the mirror velocity. When, in particular, current densities are equal $(i_1 = i_2)$, the betatron condition holds at a radius R, determined by relation

$$(R^2 + d^2)(b^2 - r_2^2) = (b^2 + R^2)(r_1^2 - d^2). \qquad (10)$$

Substituting $r_1 = r_2 = R$ into (10), which corresponds to the case of self-fields, gives the eq. (2).

STATIC COMPRESSION

Compression in static magnetic field takes place due to a large radial component of magnetic flux streaming out of the inner solenoid, which pushes the ring into an increasing field of the outer solenoid and makes the ring compress. In absence of self-field the conditions of a force-free motion along a trajectory slanted to the axis by the angle α , are

$$n = \sin^2\alpha , \quad \rho = \sin\alpha \cdot \cos\alpha , \qquad (11)$$

where n and ρ are the field indices of eq. (8). Realizability of these conditions has been shown in Ref. [4]. The self-magnetic field does not impede the compression if the inductance per a unit length of the ring is not diminishing.

The ring minor dimensions both in the betatron and compressor vary as

$$a \sim \sqrt{\frac{R}{\rho_i(v_i - v_e)}} \qquad (12)$$

If the ring does not accumulate dense plasma during compression then there exists a radial polarization electric field in which redistribution of energy between ions and electrons occurs. The electrons work against this field and each of them imparts to ions an amount of energy

$$\Delta \mathcal{E}_e \simeq \frac{R_o}{R} \cdot c\,|p_{io}| \qquad (13)$$

which can reach 0.5 GeV.

AN ILLUSTRATIVE SET OF PARAMETERS

Let the initial ring parameters be: number of protons $N_i = 10^{17}$, $\mathcal{E}_{io} = 1$ MeV, $R_o = 1.6$ m, $a_{ro} = 5$ cm, $a_{zo} = 10$ cm. To achieve the ion energy $\mathcal{E}_i = 1.05$ GeV at 10 m betatron section length and $b = 1.97$ m, $d = 1.3$ m, $r_1 = 1.5$ m, $r_2 = 1.77$ m a peak value of current surface density $i_1 = i_2 \simeq 10^6$ A/m is required. For mirror velocity $v_z = 10^4$ m/s (corresponding acceleration time is 1 ms) peak voltage at fast coils equals approximately 50 kV. At the end of acceleration phase the ring minor radius is less than 2 mm, the total kinetic energy of ions and electrons amounts to 17 MJ and 28 MJ, respectively. A higher energy gain by electrons results from a more rapid increase in azimuthal velocity and correspondingly a longer way travelled in the accelerating field.

On compressing to $R = 20$ cm the minor radius shrinks to $a \lesssim 1$ mm whereas the self-magnetic field at the ring surface rises to more than 15 MG. Some 5 MJ of electrons energy is passed to ions and approximately 25 MJ of particles total kinetic energy is spent for the self-magnetic field build-up. For holding the ring at the final radius only $B_z \simeq 0.15$ MG is required so it can be performed by the reflected from the outer shield self-field alone. The time period in which electrons lose their energy by radiation to the level, defined by equality $\nu_e/\gamma_e = 1$, exceeds 1 ms.

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