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RECENT REBATRON STUDIES

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The Rebatron Concept

The rebatron[1] is a high-current compact accelerator concept which differs from the modified betatron[2,3] and the stellatron[4]. In the latter devices, the acceleration mechanism is the relatively slow betatron mechanism. In the rebatron, there is rapid acceleration of the electrons as the beam repeatedly passes through a small (few centimeters long) high-gradient accelerating gap, the beam being recirculated through the gap in a single toroidal beam line of major radius ~ 1m). Whereas the betatron acceleration typically boosts the electron energy by < 1 keV per revolution, in the rebatron the electron gains > 2 MeV per pass so that the beam attains a given final energy rapidly (in a few μsec) in a few revolutions, as compared to thousands of revolutions needed in a 50 MeV betatron. Hence the name REBATRON (Rapid Electron Beam Acceleration device). The rapid acceleration eases the problem of growth of beam instabilities and makes fractional synchrotron losses small.

Confinement of high-current beams in vacuum requires longitudinal magnetic fields and additional vertical (or "betatron") field can be used for bending a beam in a circular arc. The difficulty of matching the vertical magnetic field to the electron energy (which, in the rebatron changes by ~ 2 MeV at each successive recirculation of the beam) is overcome in the rebatron by applying an $l = 2$ torsatron field which gives a large bandwidth for mismatch tolerance between electron energy and the vertical field. The beam can thus be made to recirculate through the high-gradient accelerating gap in a single toroidal beam pipe of reasonably small radius (~ 10 cm). The $l = 2$ torsatron field can be generated by two wires wound helically on the torus, the wires carrying currents flowing in the same direction. This produces a strong focusing transverse magnetic field and a zero order longitudinal field. The rebatron is similar to the racetrack induction accelerator of Roberson et al.,[5] which uses the strong focusing $l = 2$ stellerator field, as produced by four helically wound wires, with currents flowing in opposite directions in the neighboring wires, for producing a finite bandwidth in the presence of externally applied vertical and logitudinal magnetic fields.

In summary, the rebatron discussed here is a high-current circular accelerator in which the entire current recirculates in the same toroidal beam line, undergoing rapid acceleration as it repeatedly passes through a high-gradient accelerating gap, the beam confinement being achieved by a strong focussing $l = 2$ torsatron field and a rapidly rising, localized, vertical magnetic field (Fig. 1). Preliminary estimates are that ultra-high electron currents can be accelerated to energies approaching 1 GeV in such a compact device of major radius 1 m.

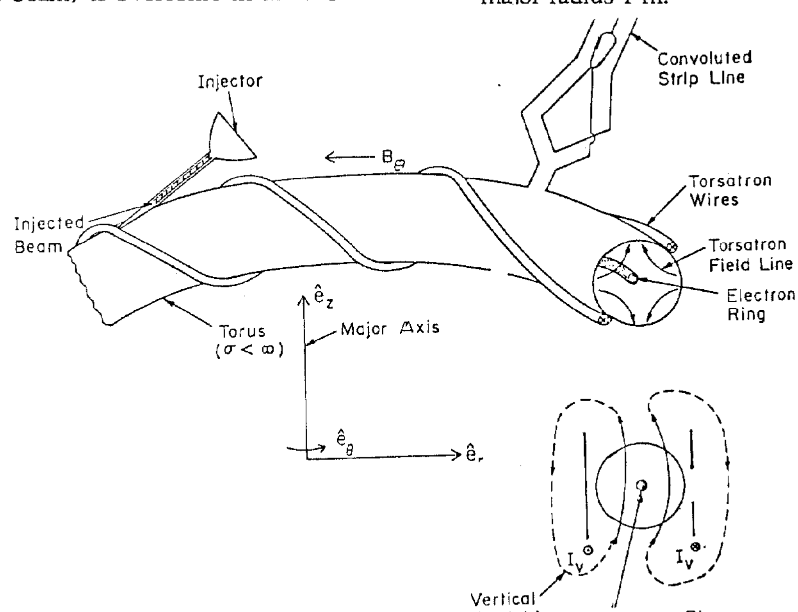

Fig.1 Schematic of a rebatron. Lower right insert shows cross section of vertical field producing coaxial lines.

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Beam Dynamics and Results

In the local cylindrical coordinate system $\hat{e}_\rho$, $\hat{e}_\phi$, $\hat{e}_s$ shown in Fig. 2, the components of the $l = 2$ torsatron magnetic field are given by

$$B_\rho = B_\rho^{(0)} + B_{\rho+}^{(1)} + B_{\rho-}^{(1)} , \qquad (1a)$$

$$B_\phi = B_\phi^{(0)} + B_{\phi+}^{(1)} + B_{\phi-}^{(1)} , \qquad (1b)$$

$$B_s = \frac{1}{1 + (\rho/r_0)\cos\phi} \left[B_s^{(0)} + B_{s+}^{(1)} + B_{s-}^{(1)} \right], \qquad (1c)$$

where

$$B_\rho^{(0)} = B_0 \sum_{m=1}^{\infty} A_m^{(0)} m x_0 I'_{2m} (mx) \sin\psi \qquad (2a)$$

$$B_\phi^{(0)} = B_0 \sum_{m=1}^{\infty} A_m^{(0)} 2m \frac{x_0}{x} I_{2m} (mx) \cos\psi \qquad (2b)$$

$$B_s^{(0)} = B_0 \left\{ 1 - \sum_{m=1}^{\infty} A_m^{(0)} m x_0 I_{2m} (mx) \cos\psi \right\} \qquad (2c)$$

with

$$\psi = 2m \, (\phi - \alpha \, s \,) \qquad (3)$$

are the zero order field components produced by the helical windings in a straight (cylindrical) configuration and the terms with superscript (1) in equations (1a), (1b) and (1c) are the first order toroidal corrections, proportional to ρ_0 / r_0 , and are explicitly given in refs. [1,6]. The remaining terms are defined as follows:

$$A_m^{(0)} = K'_{2m} (m x_0) \, C_m \qquad (4a)$$

$$C_m = \frac{2 \sin 2m \, \delta}{2m \, \delta} \qquad (4b)$$

$$B_0 = \frac{8\pi \, I}{cL} \qquad (4c)$$

$$x_0 = 2 \, \alpha \, \rho_0 \qquad (4d)$$

$$x = 2 \, \alpha \, \rho \qquad (4e)$$

$$\alpha = \frac{2\pi}{L} \qquad (4f)$$

where I is the current flowing in the windings, $2\delta\rho_0$ is the width of the current carrying conductor, r_0 is the major radius of the torus, and $I_n (x)$, $K_n (x)$, $I'_n (x)$ and $K'_n (x)$ are the Bessel functions and their derivatives. In a toroidal device the period should satisfy the relation $2\pi r_0 / L = N$ where N is an integer. In addition to the torsatron field, the rebatron accelerator includes a "betatron" or vertical magnetic field described by the linearized equations

$$B_z = B_{z0} \left[1 - nx / r_0 \right] \qquad (5)$$

$$B_r = - B_{z0} \, ny / r_0 \qquad (6)$$

where B_{z0} is the betatron field at the reference orbit, i.e., at $x = y = 0$, and n is the external field index. We find that the first two non-zero terms in the expansions describe the field for $\rho / a \leqslant 0.5$ to better than 95% accuracy.

We have numerically integrated the relativistic equations of motion using Eqs. (1) to (6). The accelerating gap is 2 cm wide and the electric field is limited to a 0.6 radian wide toroidal sector. The accelerating voltage has been taken as 2 MeV. In our computer runs, an external toroidal field $B_s^{ex} = -6kG$ was also applied in addition to the field generated by the torsatron windings. Figs. 3(a) and 3(b) show the electron energy (γ) as a function of time and orbit projected on the minor cross section of the torus when the current in the torsatron windings is taken to be -250 kA so that the torsatron field strength factor ϵ_t is -0.8, where $B_s^{ex} \epsilon_t = B_0 x_0 K'_2 (x_0)$. The betatron field was held constant at 118 G with $n = 0.50$. Torus major radius was 100 cm and the toroidal chamber minor radius was $a = 10 \, cm$ while the winding minor radius was $\rho_0 = 12 \, cm$. The parameter α was taken as 0.1 cm^{-1}, so that $N = 10$. The injection energy was $\gamma = 7$, the matching energy for $B_{z0} = 118G$. We see that the particle remains confined for over 14 recirculations and attains γ of approximately 65 before it hits the chamber wall. The total time the electron remains in the system is an order of magnitude greater than when the torsatron field is absent, demonstrating the substantial improvement of confining properties of the system by the addition of torsatron field.

To achieve very high energies ($\approx 1 GeV$), the fixed betatron field is replaced by a local vertical magnetic field that varies rapidly with time. The synchronism of the vertical field with the electron energy need not be exact (because of the large bandwidth resulting from the torsatron windings) until γ approaches a value for which the matched vertical field equals in magnitude the torsatron field. The rapidly varying vertical field can be generated by two coaxial, cylindrical lines that carry current in the opposite directions and which are concentric with the torus (see inset Fig. 1). By splitting the outer line into two, as shown, the index of the vertical field can be controlled. With such an arrangement, we were able to attain easily a γ of 1,650 in our computer simulations with a rapid increase of the applied vertical field to approximately 28 kG. Figs. 4(a) and 4(b) show the orbit of an electron in the transverse plane and the increase in γ as a function of time for this high energy mode of the rebatron with torus major radius of 100 cm.

As far as orbit stability is concerned, the maximum electron beam current that can be confined in a rebatron accelerator is estimated [1] to be given by

$$\frac{\nu}{\gamma} \leqslant \frac{\Omega_\theta^2 a^2}{8 c^2}. \qquad (7)$$

For $a = 10 \, cm$, $B_\theta = 10 \, KG$, $\gamma = 7$, this gives $\nu = 3{,}000$ or $I = 50MA$. Therefore, it is expected that the limiting beam current in a rebatron would be determined from collective instabilities rather than macroscopic stability of beam orbits.

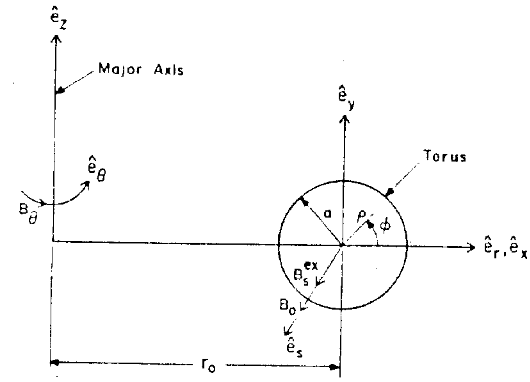

Fig.2 Coordinate system for beam dynamics.

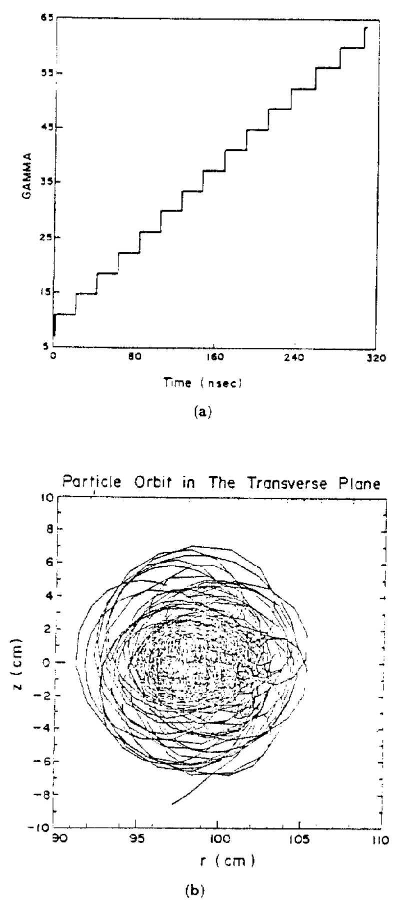

Fig.3 (a) γ of electron as a function of time with fixed vertical field and (b) electron orbit in r,z plane.

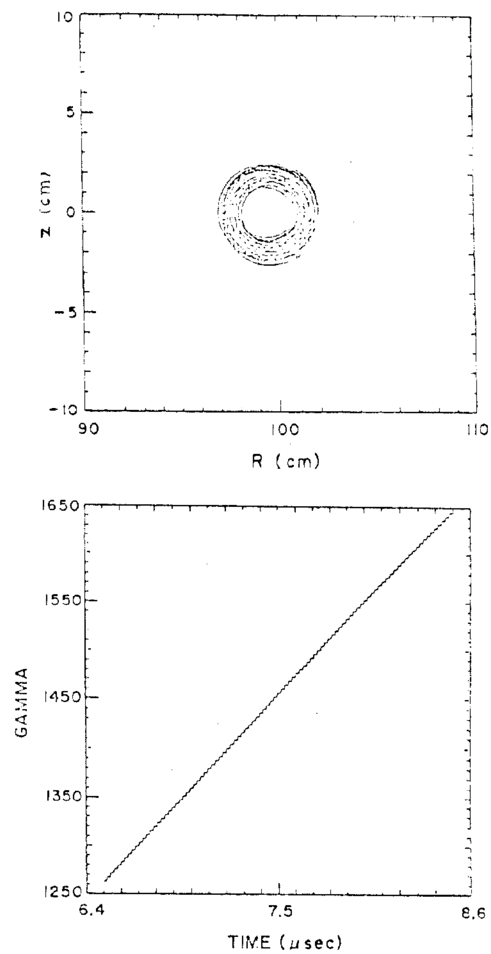

Fig.4 (a) particle orbit in the transverse plane and (b) particle energy as function of time.

Acknowledgements

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