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DYNAMICS OF AN INTENSE ELECTRON RING IN A MODIFIED BETATRON FIE--ETC(U)

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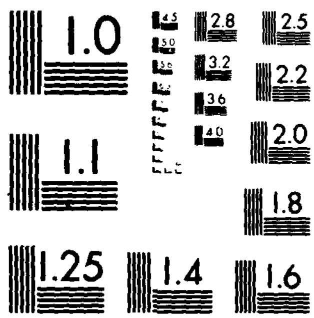

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The dynamics of an intense electron ring confined in a modified betatron magnetic field is considered. The analysis assumes that the electron ring is located near the center of a conducting torus and includes self fields, induced fields from the walls surrounding the ring and toroidal effects. It has been found that the geometric center of the ring can perform circular motion around the minor axis of the torus. Based on this analysis, a scheme is proposed for the injection of an intense electron beam into a modified betatron accelerator.

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CONTENTS

DYNAMICS OF AN INTENSE ELECTRON RING IN A MODIFIED BETATRON FIELD

I. Introduction

The modified betatron accelerator consists of a conventional betatron [1] magnetic field configuration in addition to a strong toroidal magnetic field. It has been shown [2,3] that the modified betatron has orbit stability properties that are considerably superior to those of the conventional betatron.

From space charge considerations alone, the total number of electrons (current) that can be contained in the modified betatron field greatly exceeds the number that can be contained in a conventional betatron configuration. If N_{mb} is the maximum number of electrons that can be stably confined in a modified betatron and N_{cb} is the corresponding number for a conventional betatron, it can be shown that for $B_\theta >> B_z$

$$N_{mb} = \tfrac{1}{2} \left(\frac{B_\theta}{B_z}\right)^2 N_{cb} , \qquad (1)$$

where B_z is the betatron or vertical field and B_θ is the toroidal magnetic field. The maximum electron current that can be confined in a modified betatron is

$$I = 2.1 \left(\frac{r_b}{r_o}\right)^2 \gamma^3 \left(\frac{B_\theta}{B_z}\right)^2 \text{ [KA]} , \qquad (2)$$

where r_b and r_o are the minor and major electron ring radii respectively and γ is the relativistic factor. It is apparent from Eq. (2) that for injection energies in the MeV range, extremely high currents (in the tens of kiloampere range) can be confined in the modified betatron for very modest values of r_b , r_o and B_θ.

In addition to its beneficial effect on the stability of the orbits, the toroidal magnetic field improves the stability of the ring with respect to several unstable modes, including the negative mass [4,5] the precessional instabilities [5,6] and the transverse wall resistive instabiltiy [5].

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In the previous work [2] it has been assumed that the walls of the toroidal vacuum chamber were far away from the ring and thus the effect of the image forces neglected. Furthermore, the analysis was done in cylindrical geometry and thus toroidal effects were ignored. In this paper we examine the dynamics of an intense electron ring confined in a modified betatron field near the center of a conducting torus. The analysis includes self fields, induced fields from the wall and toroidal effects. It has been found that the geometric center of the electron ring can perform circular motion around the minor axis of the torus. The center of the orbit coincides with the axis of the torus only if the electrons in the ring have the appropriate canonical angular momentum (injection energy).

The present analysis suggests ways to inject and trap an electron beam in a modified betatron accelerator. Briefly, the electron beam is injected as shown in Fig. 1 along an open magnetic field line and is allowed to drift toward the center of the torus, away from the injector insert that is located near the wall. When the beam approaches the center, a set of coils is energized. This changes slightly the external field index and the electron beam can be trapped on a stable orbit around the center of the minor cross-section of the torus. The most important predictions of the present theoretical work have been verified by a computer simulation.

II. Electron Ring Dynamics

Our model is based on the configuration shown in Fig. 2. The electron ring is assumed to have a circular cross section with minor radius r_b. The center of the cross section of the beam is located at $r = r_o + \Delta r$ and $z = \Delta z$. The beam is enclosed in a toroidal chamber of infinite conductivity with minor radius $a \gg r_b$ and major radius $r_o \gg a$.

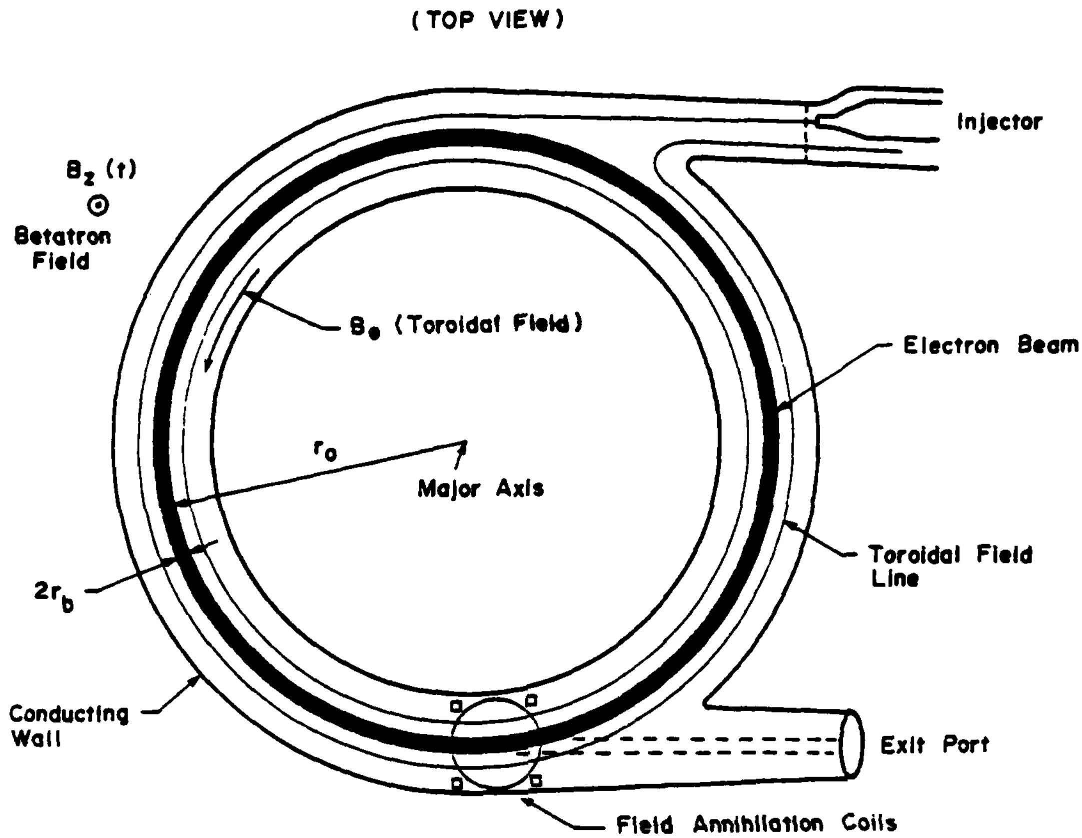

Fig. 1 — Schematic of the modified betatron

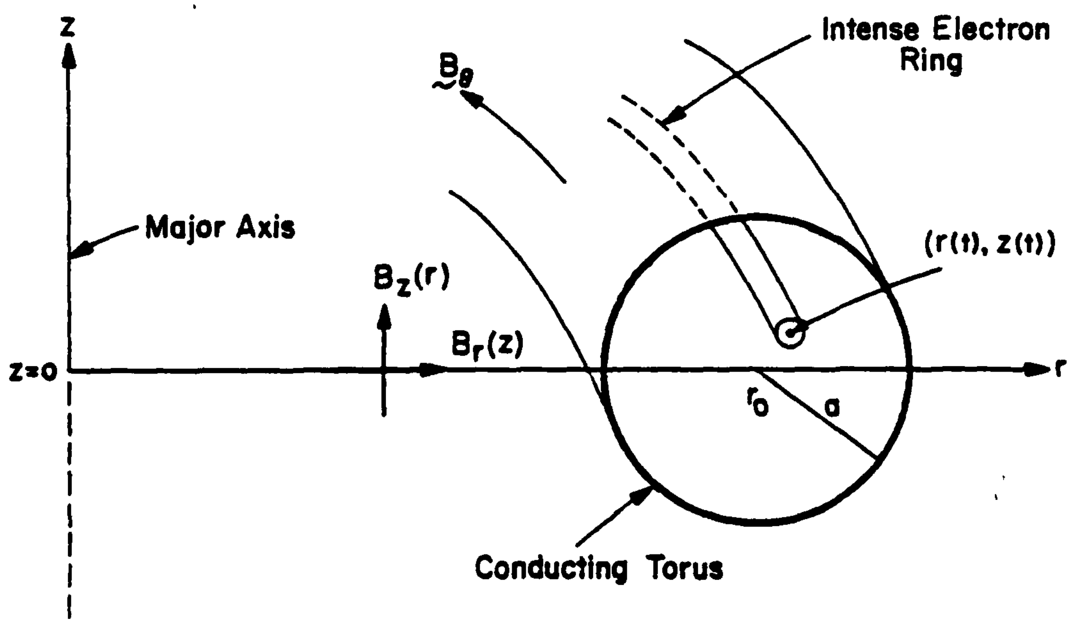

Fig. 2 — System of coordinates used in the analysis

The externally applied fields, associated with the modified betatron accelerator, expanded about (r_o, o) are

$$B_z = B_{oz}\,(1 - n(r-r_o)/r_o),$$

$$B_r = -B_{oz}\, nz/r_o$$

and

$$B_\theta = B_o\,(1-(r-r_o)/r_o), \qquad (3\ a,b,c)$$

where B_{oz}, B_o are constant and n is the external field index. Besides the external fields, the forces acting on the center of the beam located at $(r_o + r, \Delta z)$, are the electric and magnetic forces that are due to the induced charges and currents on the surface of the toroidal chamber. Because of toroidal effects these induced charges and currents arise even when the beam is centered in the chamber. For a constant density profile beam that rotates with constant angular velocity, the induced fields at the center of a displaced beam are

$$\underset{\sim}{E}_{ind} = -2\pi|e|n_o r_o \left[\left(\frac{r_b^2}{a^2}\frac{\Delta r}{r_o} + \frac{1}{2}\frac{r_b^2}{r_o^2}\ln\frac{a}{r_b}\right)\hat{e}_r + \frac{r_b^2}{a^2}\frac{\Delta z}{r_o}\hat{e}_z\right],$$

and (4 a,b)

$$\underset{\sim}{B}_{ind} = -2\pi|e|n_o\beta_o r_o \left[\frac{r_b^2}{a^2}\frac{\Delta z}{r_o}\hat{e}_r - \left(\frac{r_b^2}{a^2}\frac{\Delta r}{r_o} - \frac{r_b^2}{r_o^2}\{1 + \tfrac{1}{2}\ln\frac{a}{r_b}\}\right)\hat{e}_z\right],$$

where n_o is the beam density, $\beta_o = v_o/c$ and v_o is the azimuthal velocity to be defined shortly.

It is conventient at this point to define a reference particle located at $r = r_o$ and $z = o$ that is in perfect unperturbed circular motion around the major axis. If the electron beam is itself centered at (r_o, o), the orbit of the reference particle is governed by the external and induced fields at (r_o, o). Note that because of toroidal effects the induced fields do not vanish at (r_o, o). Using the fields in (3) and (4) it can be shown that the azimuthal velocity of this reference particle is

$$v_o = \frac{r_o \Omega_{oz}/\gamma_o}{1 + 2(\nu/\gamma_o)(1 + \ell n\ a/r_b)} , \qquad (5)$$

where $\Omega_{oz} = |e|B_{oz}/m_o c$, $\gamma_o = (1 - v_o^2/c^2)^{-1/2}$, $\nu = |e|^2 N_{mb}/(2\pi m_o c^2 r_o)$

is Budker's parameter, $\nu/\gamma_o = \gamma_o^{-1}(\omega_b r_b/2c)^2$ and $\omega_b^2 = 4\pi|e|^2 n_o/m_o$.

Writing $\gamma = \gamma_o + \delta\gamma_o$, $r = r_o + \Delta r$ and $z = \Delta z$ where $|\delta\gamma_o/\gamma_o|$,

$|\Delta r/r_o|$, $|\Delta z/r_o| << |$, the azimuthal ring velocity correct to lowest order is independent of Δz and is given by

$$v_\theta = v_o + \frac{\delta\gamma_o}{\gamma_o}\frac{c}{\gamma_o^2} + \frac{\nu}{\gamma_o}\frac{c/r_o}{\gamma_o^2}\ \ell n\left(\frac{a}{r_b}\right)\ \Delta r. \qquad (6)$$

Using the external and induced fields in (3) and (4) together with the expression for v_θ in (6) we find that the temporal evolution of the center of the electron ring is governed by the equations

$$\ddot{\Delta r} + \tilde{\omega}_r^2\ \Delta r = \frac{\Omega_{o\theta}}{\gamma_o}\ \dot{\Delta z} + \xi\left(\frac{\Omega_{oz}}{\gamma_o}\right)\frac{\delta\gamma_o}{\gamma_o}\ c , \qquad (7a)$$

and

$$\ddot{\Delta z} + \tilde{\omega}_z^2\ \Delta z = -\frac{\Omega_{o\theta}}{\gamma_o}\ \dot{\Delta r} , \qquad (7b)$$

where

$$\tilde{\omega}_r^2 = \frac{\Omega_{oz}^2}{\gamma_o^2}\ (\alpha - n^* - n_s r_b^2/a^2),$$

$$\tilde{\omega}_z^2 = \frac{\Omega_{oz}^2}{\gamma_o^2}\ (n^* - n_s r_b^2/a^2) ,$$

$\alpha = (1 - \frac{\nu}{\gamma_o}\ \ell n\ \frac{a}{r_b})\ \xi^2$, $\xi = \left(1 + \frac{2\nu}{\gamma_o}(1 + \ell n\ \frac{a}{r_b})\right)^{-1}$, $n^* = n\xi$ is the modified external field index and $n_s = 2\frac{\nu}{\gamma_o}\left(\frac{c}{\Omega_{oz} r_b}\right)^2 = \omega_b^{\,2}/(2\gamma_o \Omega_{oz}^{\,2})$ is the self field index. For $B_{o\theta} \gg B_{oz}$ the motion of the electron ring in the (r,z) plane is slow compared to the gyration period about the major axis. Hence, using the orbit equations in (7), the equations describing the slow time evolution of the electron ring center are reduced to

$$\ddot{\Delta r} = -\omega^2(\Delta r - \Delta r_o), \qquad \text{and} \qquad \ddot{\Delta z} = -\omega^2 \Delta z, \tag{8 a,b}$$

where

$$\omega^2 = \left(\frac{\bar{\omega}_z \bar{\omega}_r}{\Omega_{o\theta}/\gamma_o}\right)^2 = \left(\frac{B_{oz}}{B_{o\theta}}\right)^2 \left(\frac{\Omega_{oz}}{\gamma_o}\right)^2 (\alpha - n^* - n_s r_b^{\,2}/a^2)(n^* - n_s r_b^{\,2}/a^2), \tag{9}$$

is the oscillation frequency of the ring in the (r,z) plane and

$$\Delta r_o = \frac{\xi c \delta\gamma_o/\gamma_o}{(\alpha - n^* - n_s r_b^{\,2}/a^2)\ \Omega_{oz}/\gamma_o}, \tag{10}$$

is the radial displacement of the center of the orbit for stable oscillations, i.e., $\omega^2 > o$. If $\omega^2 > o$ the orbit of the ring in the (r,z) plane of the toroidal chamber is stable (closed), while for $\omega^2 < o$ the orbit is unstable (open). Figure 3 shows the quantative behavior of ω^2 as a function of $n_s r_b^{\,2}/a^2 = 2(\nu/\gamma_o)(c/\Omega_{oz} a)^2$ and denotes the conditions necessary for stable and unstable orbits to exist.

Toroidal effects are proportional to ν/γ_0, which in turn is proportional to $N_{mb}/(\gamma_0 r_0)$. Hence, in the limit that $N_{mb}/(\gamma_0 r_0) \to 0$ toroidal effects can be neglected. In this case the coefficients α and ξ are approximately equal to unity and Eqs. (9) and (10) become

$$\omega^2 = \left(\frac{B_{oz}}{B_{o\theta}}\right)^2 \left(\frac{\Omega_{oz}}{\gamma_o}\right)^2 \left(1 - n - n_s r_b^{\,2}/a^2\right)\left(n - n_s r_b^{\,2}/a^2\right), \tag{11}$$

and

$$\Delta r_o = \frac{c\ \delta\gamma_o/\gamma_o}{\left(1 - n - n_s r_b^{\,2}/a^2\right)\ \Omega_{oz}/\gamma_o}.$$

When $n = n_s = 0$, Eq. (11) gives $\omega = o$ and the electron ring drifts vertically at a constant speed. This drift is due to the curvature of the magnetic field lines.

Equation (8) together with the expression for ω^2 gives insight into a possible method of drift injection and trapping of an intense electron ring in a modified betatron field configuration. The basic idea is to drift the electron ring towards the center of the chamber by initializing the parameters of the system so that $\omega^2 < 0$. The ring is then on an unstable orbit and would eventually drift, pass the center and strike the wall. If however, the parameters of the system are changed in time so that $\omega^2 \geq 0$ as the ring approaches the center, the orbit becomes stable and the ring would oscillate around the point $(\Delta r_o, 0)$. To assure that Δr_o is sufficiently small compared to the minor radius of the chamber, i.e., $|\Delta r_o| << a$, the injection energy mismatch, $\delta\gamma_o m_o c^2$, must be small.

The various stages of the drift injection and trapping in the modified betatron are shown in Fig. 4. The family of curves indicate the possible electron ring trajectories in the (r,z) plane. The direction is indicated by arrows. The only difference between Figs. 4 a,b and c is the value of the external field index. If the external field index were varied continuously in time the beam trajectory in the (r,z) plane would be a spiral orbit converging about the center, (r_o, o). A convenient way to change the electron ring trajectory from unstable to stable and thus to achieve trapping of the beam is by changing the external field index when the drifting beam approaches the center of the torus.

It should be noticed than in Eq. (7) the nonlinear terms $\frac{\Delta r}{r_o} \frac{\Omega_{o\theta}}{\gamma_o} \Delta\dot{z}$ and $\frac{\Delta r}{r_o} \frac{\Omega_{o\theta}}{\gamma_o} \Delta\dot{r}$ have been omitted. These terms have their origin in the gradient of the toroidal magnetic field. The ratio of $\frac{\Delta r}{r_o} \frac{\Omega_{o\theta}}{\gamma_o} \Delta\dot{z}$ to the linear term $\tilde{\omega}_r^2 \Delta r$ in Eq. (7a) is $\frac{\Delta\dot{z}}{\tilde{\omega}_r r_o}$. In general, this ratio is considerably lower that unity, but when $\omega_r^2 \to o$, these nonlinear terms cannot be neglected.

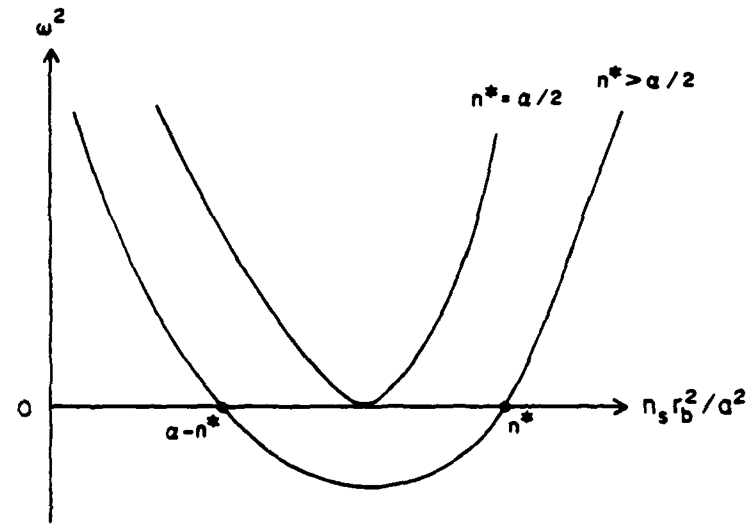

Fig. 3 — ω^2 vs. $n_s r_b{}^2/a^2$ with n^* as a parameter. At injection the beam parameters are such that $\alpha - n^* < n_s r_b{}^2/a^2 < n^*$.

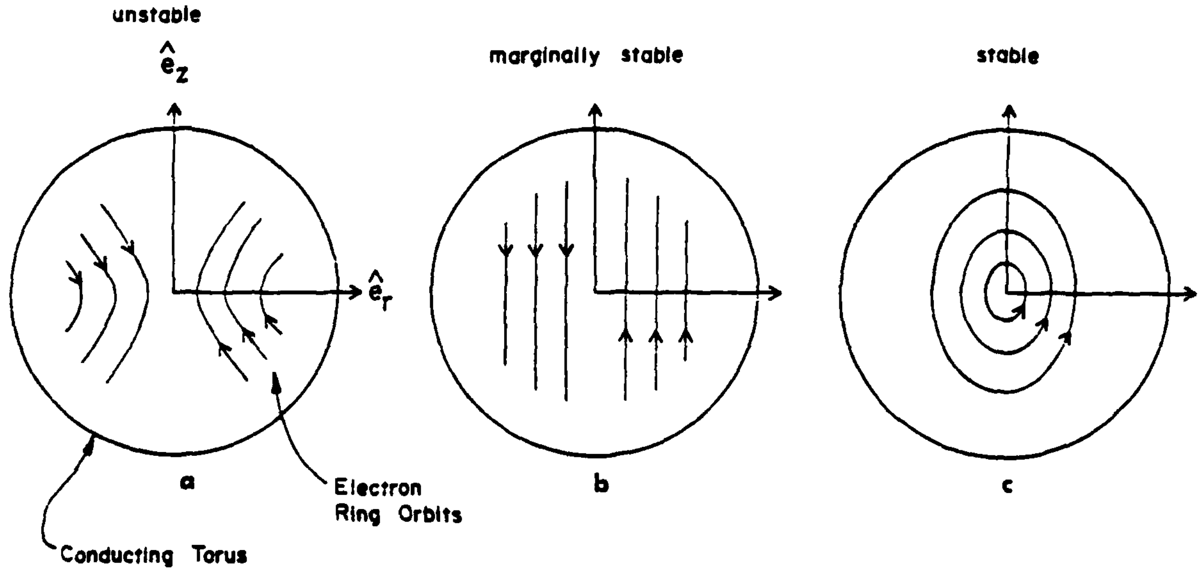

Fig. 4 — Electron ring orbits in the (r, z) plane. The ring is injected on an open orbit (a) and is trapped on a closed orbit (c).

In addition to the above terms, the nonlinear terms of the image fields have also been omitted. Therefore, the equations of motion and their solutions are not valid near the wall of the vacuum chamber. When the beam is injected near the wall it is necessary to solve the system of nonlinear equations. This work is presently in progress.

III. Numerical Simulation

The beneficial effect of the toroidal magnetic field on the stability of the orbits has been studied numerically using a particle code. The electron ring parameters are given in table I. Snap-shots of the electron ring minor cross section in a modified betatron field at $t \approx 10$, 18 and 38 nsec are given in Fig. 5a for a 10 kA electron ring. After a slight initial expansion, the minor radius of the beam remains constant. Results of the simulation for a conventional betatron $(B_\theta = o)$ are given in Fig. 5b. Although the electron ring current is only 500 A, i.e., a factor of 20 lower than in the modified betatron, the beam strikes the wall in about 4 nsec. In this time the beam propagates less than a quarter of the torus. It should be noticed that the vertical (betatron) magnetic field in the modified betatron is 53% higher than in the conventional betatron. The higher external field is required to insure radial force balance at the geometric center. Due to toroidal effects the induced fields at the geometric center of the beam are non zero even though the beam is centered in the chamber. As may be seen from Eq. (5) the external magnetic field necessary for the beam to rotate with a major radius r_o is

$$B_{oz} = B_o \left[1 + 2 \frac{\nu}{\gamma_o} \left(1 + \ln \frac{a}{r_b}\right)\right],$$

where B_o is the magnetic field required for a single particle to rotate with a radius r_o.

Table I.

Parameters	Modified Betatron	Conventional Betatron
Beam Energy (MeV)	2	2
Beam Current (kA)	10	0.5
Beam minor radius (cm)	1.6	1.0
Beam major radius (cm)	100	100
Torus minor radius (cm)	6.4	6.4
Vertical magnetic field (G)	122	80
Toroidal magnetic field (KG)	10	0

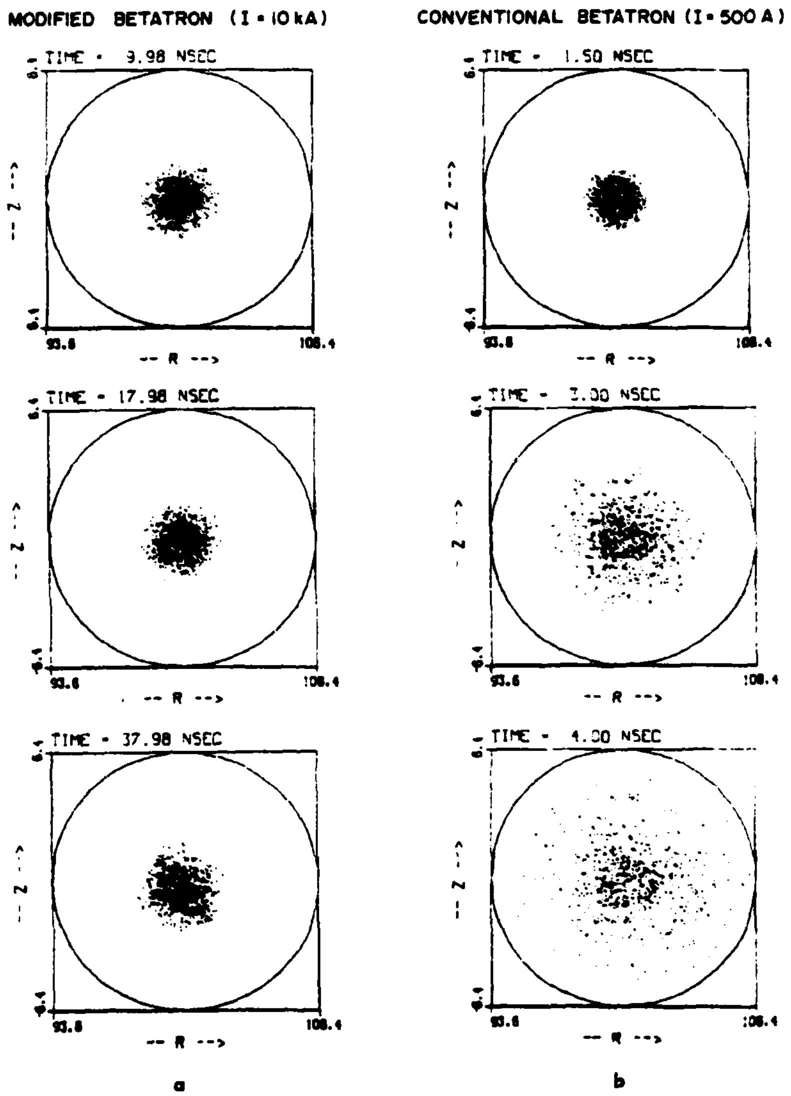

Fig. 5 — Snap-shots of the electron ring minor cross section in a modified betatron field (a) and in a conventional betatron (b) for the parameters given in Table 1. The current in the modified betatron is twenty times greater than in the conventional betatron.

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