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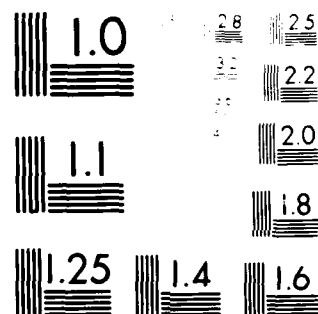
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**GRAD-B DRIFT OF AN ELECTRON BEAM
IN THE HIGH CURRENT BETATRON**

BY HANS S. UHM

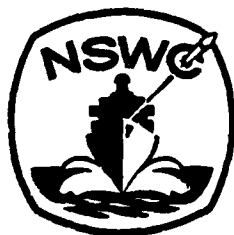
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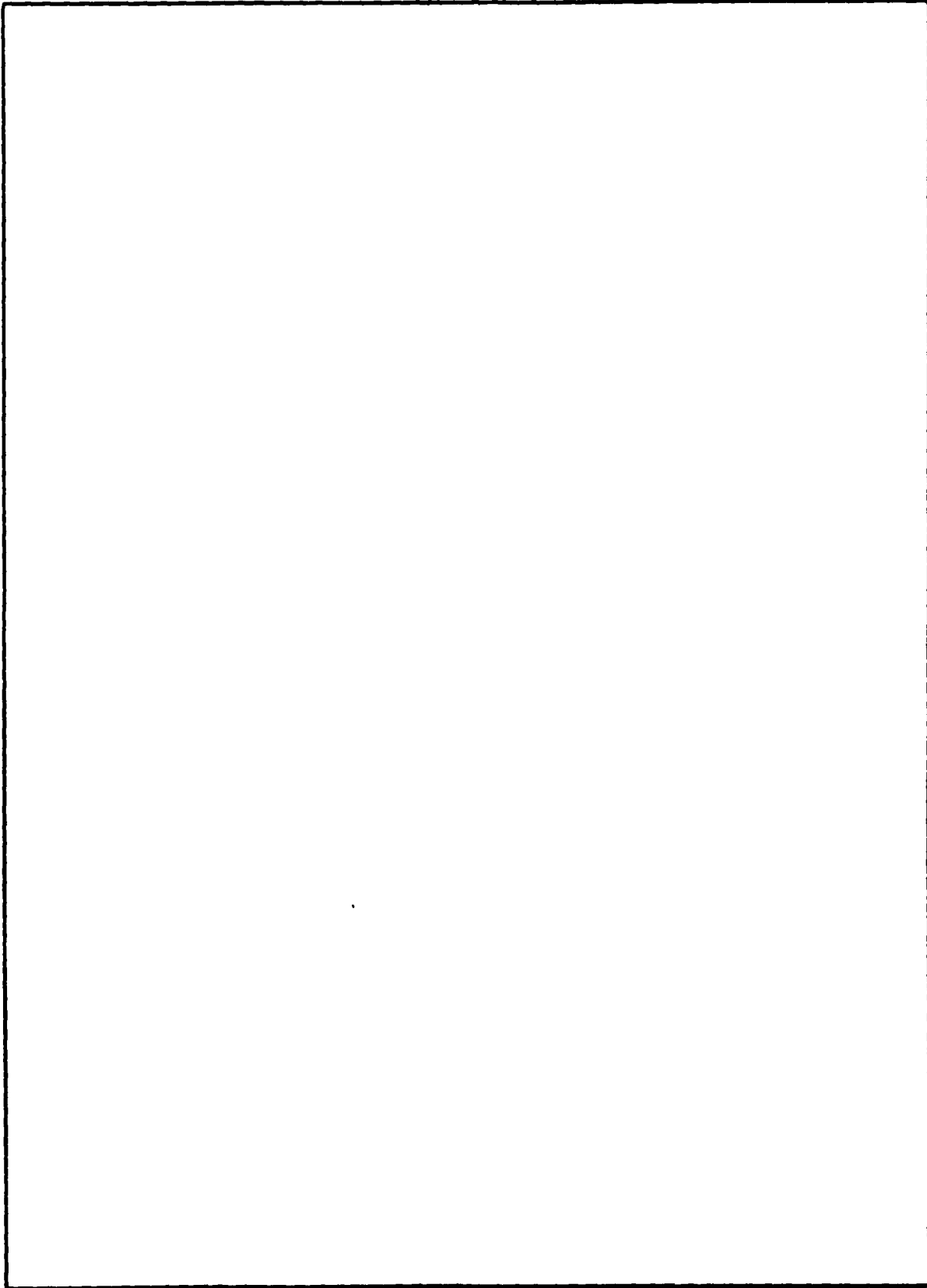
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INTRODUCTION

In recent years, there have been numerous investigations in the high current betatron accelerators,¹⁻³ in connection with generations of intense high energy electron beams. In a conventional betatron accelerator, a toroidal configuration of electrons is confined in a betatron (or mirror) magnetic field. As shown in Fig. 1a, in the present high current betatron accelerator,^{1,2} an additional focussing magnetic field in the azimuthal direction is applied, thereby considerably enhancing the current limitation. However, in the present article, we investigate the equation of motion of the center of mass coordinates for electron beam, with particular emphasis on the grad-B drift⁴ caused by the variation of the azimuthal magnetic field with the radial coordinate r .

As shown in Fig. 1a, the equilibrium configuration consists of a relativistic electron ring located at the midplane of externally imposed mirror field $B_{er}(r,z)\hat{e}_r + B_{ez}(r,z)\hat{e}_z$. In addition, the applied azimuthal magnetic field $B_{e\theta}\hat{e}_\theta$ with the mirror field acts to confine the ring both axially and radially. Here, $\hat{e}_r$, $\hat{e}_\theta$, and $\hat{e}_z$ are the unit vectors along the cylindrical coordinates r , θ , and z , respectively. The equilibrium radius of the ring is denoted by R_0 , and the minor dimensions of the ring is denoted by $2a$ (radial direction) and $2b$ (axial direction). The minor dimensions of the ring are much smaller than its major radius R_0 . The electron composing the ring gyrate in the external mirror field with azimuthal velocity $\beta_b c = (\gamma_b^2 - 1)^{1/2} c / \gamma_b$ in the positive θ -direction. The associated ring current produces a self magnetic field $B_s(\chi)$, which tends to compress the minor dimensions of the ring both axially and radially. The electron ring is assumed to be partially neutralized by a positive ion

background with a fractional charge neutralization f . The excess electrons forms the electrostatic field which tends to increase the minor dimensions of the ring.

For the convenience of future analysis, we define $x = r - R_0$. Shown in Fig. 1b is the configuration and coordinate system of the minor dimension. The center of mass coordinates of electron beam are denoted by (X, Z) . The electron density profile is assumed to be

$$n_b^0(x, z) = n_b U[1 - (x - X)^2/a^2 - (z - Z)^2/b^2], \quad (1)$$

where $U(x)$ is the Heaviside step function and n_b is the electron density at the center of mass coordinates (X, Z) . The self electric and magnetic fields produced by beam itself exert the transverse force^{5,6}

$$\vec{F}_s = -\gamma_b m [\omega_r^{s2} (x - X) \hat{e}_r + \omega_z^{s2} (z - Z) \hat{e}_z], \quad (2)$$

on the beam electrons. Here ω_r^{s2} and ω_z^{s2} are the radial and axial betatron frequency-squareds of the self field defined by

$$\omega_r^{s2} = \frac{b}{a+b} \omega_p^2 [\beta_b^2 - (1 - f)], \quad (3)$$

$$\omega_z^{s2} = \frac{a}{a+b} \omega_p^2 [\beta_b^2 - (1 - f)],$$

and $\omega_p^2 = 4\pi n_b e^2 / \gamma_b m$ is the plasma frequency-squared for beam electrons.

From $(\nabla \times \vec{B})_z = 0$, we obtain $\partial B_{e\theta} / \partial r = -B_{e\theta} / r$ and the symmetry about the $z = 0$ plane implies $(\partial B_{e\theta} / \partial z)_0 = 0$. Thus, $B_{e\theta}(r, z)$ is approximated by

$$B_{e\theta}(r, z) = B_{e\theta}(R_0, 0)(1 - x/R_0). \quad (4)$$

Making use of Eqs. (3) and (4), one can obtain the transverse equations of motion

$$\ddot{x} + \omega_c^2(1 - n)x + \omega_r^2(x - X) = \omega_g(1 - x/R_0)\dot{z} ,$$

$$\ddot{z} + \omega_c^2nz + \omega_z^2(z - Z) = -\omega_\theta(1 - x/R_0)\dot{x} , \quad (5)$$

for beam electrons. In Eq. (5), $n = -[R_0/B_{ez}(R_0,0)][(\partial/\partial r)B_{ez}(r,0)]_{R_0}$ is the external field index of the mirror field, dot ($\cdot$) denotes the time derivative d/dt , and $\omega_c = eB_{ez}(R_0,0)/\gamma_b mc$ and $\omega_\theta = eB_{e\theta}(R_0,0)/\gamma_b mc$ are the electron cyclotron frequencies of the axial and azimuthal magnetic fields, respectively. Note that in Eq. (5), the terms proportional to x/R_0 are contributed by the variation of the azimuthal magnetic field with r .

SINGLE PARTICLE ORBIT IN EQUILIBRIUM STATE WITH $(X,Z) = (0,0)$

In this case, Eq. (5) can be simplified by

$$\ddot{x} + \omega_r^2x - \omega_\theta\dot{z} = 0 , \quad (6)$$

$$\ddot{z} + \omega_z^2z + \omega_\theta\dot{x} = 0 ,$$

where $\omega_r^2 = \omega_c^2(1 - n) + \omega_r^2$ and $\omega_z^2 = \omega_c^2n + \omega_z^2$ are the radial and axial betatron frequency-squareds for external and self fields. In obtaining Eq. (6), use has been made of the fact that $|\omega_r^2| \sim |\omega_z^2| \sim \omega_\theta^2$ for a high current betatron. With the usual assumption that x and z have solutions of the sinusoidal form

$$x = c\sin(\omega t + \alpha), \quad z = d\cos(\omega t + \alpha) , \quad (7)$$

it can be shown that Eq. (6) reduces to

$$d/c = (\omega^2 - \omega_r^2)/\omega\omega_\theta , \quad (8)$$

and the dispersion relation

$$(\omega^2 - \omega_r^2)(\omega^2 - \omega_z^2) = \omega_\theta^2 \omega^2, \quad (9)$$

which gives the eigenfrequencies $\omega = \omega_b^\pm$ defined by

$$2(\omega_b^\pm)^2 = \omega_r^2 + \omega_z^2 + \omega_\theta^2 \pm [(\omega_r^2 + \omega_z^2 + \omega_\theta^2)^2 - 4\omega_r^2 \omega_z^2]^{1/2}, \quad (10)$$

where the two sign ($\pm$) represent fast (+) and slow (-) oscillation states. The necessary and sufficient condition for stable single particle orbit is given by

$$(\omega_r^2 + \omega_z^2 + \omega_\theta^2) > 2|\omega_r \omega_z|, \quad \omega_r^2 \omega_z^2 > 0, \quad (11)$$

which is identical to the previous result⁷ obtained for the plasma betatron.

CENTER OF MASS ORBIT. Neglecting momentum spread, Eq. (5) can be averaged over the beam cross section. After some straightforward algebra, we obtain the transverse equation of motion for the center of mass coordinates

$$\ddot{X} + \omega_c^2(1 - n)X = \omega_\theta [\dot{Z} - (X\dot{Z} - \omega_\theta a^2 \eta/2)/R_0], \quad (12)$$

$$\ddot{Z} + \omega_c^2 n Z = -\omega_\theta [\dot{X} - X(\dot{X} - \omega_\theta b \zeta)/R_0],$$

where η and ζ are the form factors of the nonlinear terms with order unity. However, these form factors depend on the oscillation state of individual electron motions.

As a simple example, we consider the fast oscillation state for single particle electron orbit. That is

$$x = X + c \sin(\omega_b^+ t + \alpha), \quad z = Z + d \cos(\omega_b^+ t + \alpha). \quad (13)$$

Thus, after a straightforward algebraic manipulation, we obtain

$$\langle \dot{x}\dot{z} \rangle = X\dot{Z} + a^2(\omega_r^2 - \omega_b^2)/4\omega_\theta, \quad (14)$$

where the bracket $\langle \rangle$ represents the average over the beam cross section. From Eq. (14), we identify,

$$\eta = (\omega_b^2 - \omega_r^2)/2\omega_\theta^2. \quad (15)$$

Similarly, the form factor ζ is given by

$$\zeta = 4(\omega_b^2 - \omega_z^2)/3\pi\omega_\theta^2, \quad (16)$$

for the fast oscillation state corresponding to Eq. (13). In reality, the single particle electron orbit is the linear combination of the fast and slow oscillation states, thereby considerably complicating the form factor determination.

When the betatron field is sufficiently large, satisfying the ratio $\rho = \omega_c^2 R_0 / a\omega_\theta^2 \gg 1$, then Eq. (12) can be simplified by

$$\ddot{X} + \omega_c^2(1 - n)X = \omega_\theta \dot{Z}, \quad (17)$$

$$\ddot{Z} + \omega_c^2 nZ = -\omega_\theta \dot{X},$$

which is an identical form to Eq. (6). Assuming that $X = \xi_x \sin(\Omega t + \alpha)$ and $Z = \xi_z \cos(\Omega t + \alpha)$, one can show that the general solution is the linear combination of the fast (+) and slow (-) oscillation states with the eigenfrequency $\Omega = \Omega_b^\pm$ defined by $2(\Omega_b^\pm)^2 = \omega_c^2 + \omega_\theta^2 \pm [(\omega_c^2 + \omega_\theta^2)^2 - 4n(1 - n)\omega_c^4]^{1/2}$. The center of mass orbit can then be expressed as

$$X^2 + \Omega^2 \{ \omega_\theta / [\Omega^2 - (1 - n)\omega_c^2] \}^2 Z^2 = \xi_r^2, \quad (18)$$

for either fast or slow oscillation state. In this regard, we note from Eq. (18) that the center of mass orbit for the slow oscillation

state is hyperbolic [$n(1 - n) < 0$] or elliptic [$n(1 - n) > 0$], depending on the external field index.

GRAD-B DRIFT MOTION WITH SMALL BETATRON FIELD. When the betatron field is small, so that the betatron focussing terms are less than the nonlinear $B_{e\theta}$ terms (i.e., $\rho \ll 1$), then Eq. (12) can be approximated by

$$\begin{aligned}\ddot{X} - \omega_{\theta} \dot{Z} &= -\omega_{\theta} (\dot{X}Z - \omega_{\theta} a^2 \eta / 2) / R_0, \\ \ddot{Z} + \omega_{\theta} \dot{X} &= \omega_{\theta} X (\dot{X} - \omega_{\theta} b \zeta) / R_0.\end{aligned}\tag{19}$$

Equation (19) has been previously investigated by Ferrari and Zucker⁸ for the single particle orbit calculation in the plasma betatron. The result is given by

$$\begin{aligned}X &= X_0 + \xi_x \sin(\omega_{\theta} t + \alpha) + \dots \\ Z &= Z_0 + \xi_x \cos(\omega_{\theta} t + \alpha) + v_g t + \dots,\end{aligned}\tag{20}$$

where X_0 and Z_0 are constants determined from the initial values, the symbol (...) represents the higher order oscillation terms and

$$v_g = -\omega_{\theta} (\xi_x^2 + a^2 \eta) / 2R_0,\tag{21}$$

is the grad-B drift velocity in the z-direction.

Even though the single particle orbit of beam electrons in a high current beam is stable [see Eq. (11)], the center of mass coordinates exhibits a drift motion for a small betatron field. As shown in Eq. (21), the grad-B drift velocity can be fractional percents of the speed of light in the present experimental parameters of a high current betatron. However, in the time varying betatron field, the external focussing terms [terms proportional to ω_c^2 in Eq. (12)]

together with this grad-B drift motion give a finite displacement⁸ of the center of mass coordinates (X,Z) from their equilibrium values $(0,0)$. In this regard, it is required to determine an appropriate time profile for the betatron field, thereby reasonably confining an electron beam near its equilibrium orbit.

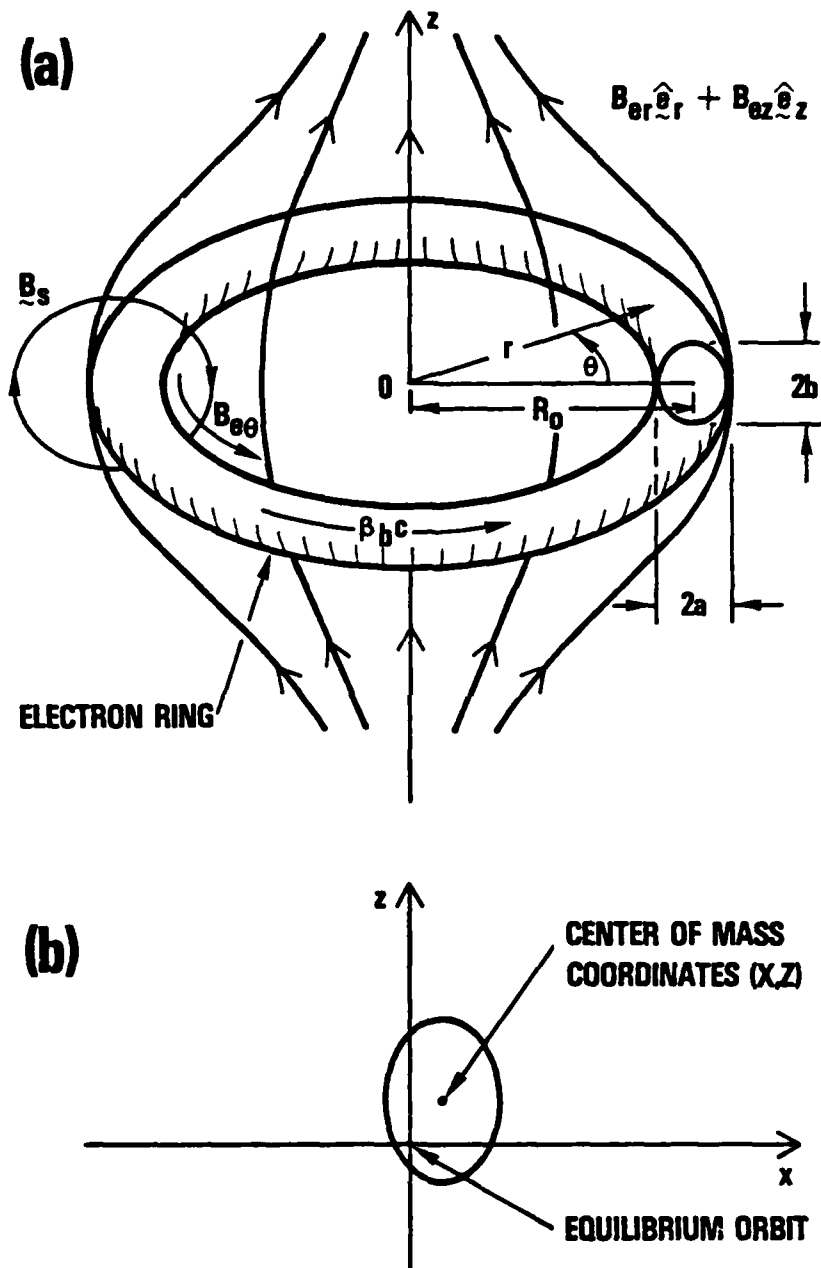


FIGURE 1 CONFIGURATION AND COORDINATE SYSTEM.
(a) OVERVIEW AND (b) CROSS SECTION OF THE MINOR DIMENSION.

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