A NOVEL TRAPPING SCHEME IN THE MODIFIED BETATRON ACCELERATOR*

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Summary

The previously reported 'self-trapping' of an electron ring in the modified betatron results from current flowing in the diode during a secondary pulse that follows the main pulse.[1,2] A similar shift is produced by a current carrying conductor that is oriented along the toroidal magnetic field B_θ. Because 'self-trapping' is not very versatile, a new trapping scheme is being developed. In this scheme, an induction electric field is applied to a gap in the torus. Preliminary experimental results show that the equilibrium radius of the ring r_{eq} can be shifted by several centimeters.

Introduction

Following the successful experiments with multikiloampere electron beams injected into the NRL modified betatron,[3] the research effort has focused on efficient trapping and confinement of the ring as a prelude to acceleration. In these studies, a 0.5-1.0 MeV, 1-4 kA beam is injected along the 1-3 kG applied toroidal magnetic field B_θ from a diode located inside the 1.026 m major radius torus. The observations have confirmed the importance of B_θ in controlling the minor radius of the beam and are in agreement with the theoretical predictions concerning high current equilibria in the modifed betatron.[4,5]

The dynamics of high current equilibria in the modified betatron are dominated by the forces due to the self-field images of the beam. At the matching value of the betatron magnetic field B_z, the forces due to the images, the Lorentz force $ev_\theta \times B_z$ (where e is the charge on the electron and v_θ is the toroidal velocity) and the centrifugal force are in balance, and the beam does not drift poloidally. After one revolution around the major axis, the beam returns to the injector and strikes the back of the cathode. However, in the high current regime, if the betatron field is less than the matching value, the equilibrium position r_{eq} shifts radially inward, and the beam drifts poloidally about the equilibrium position. The poloidal displacement can easily be adjusted to be sufficient so that the beam does not strike the injector after one turn. For a wide range of parameters, the poloidal drift trajectory is closed, and the beam returns to the injector after a poloidal oscillation (bounce) period. This drift motion has been observed and confirmed with several different diagnostic techniques and is in very good agreement with theory. To achieve trapping, the equilibrium position must be shifted radially inward during the poloidal bounce period so that the beam does not strike the injector.[6]

Within a narrow range of parameters, 'self-trapping' is observed with $\approx 80\%$ efficiency. 'Self-trapped' rings with circulating current of 2-3 kA remain for $\approx 4\mu sec$ ($\approx$ 200 revolutions around the major axis). Confinement for 10 μsec is observed at 1 kA.

'Self trapping' results from the localized magnetic field associated with current flowing in the cathode stalk during a second pulse that follows $\approx 200 nsec$ after the main injection pulse.[2] This afterpulse occurs because the diode is not matched to the pulse forming line of the injector. Because plasma closure has reduced the diode impedance at the afterpulse, a 1-4 kA current may flow although the applied potential is only $\approx 150kV$. Thus, the magnetic forces are larger than the electric forces and the net component produces a radial inward shift of the beam.

This explanation is supported by experiments with a current carrying conductor,i.e. a kicker coil, that is oriented along B_θ. When a short cathode stalk is used and the kicker is not energized, the afterpulse does not significantly affect the beam. However, when the kicker is energized, the shift is similar to that produced by a long cathode stalk with afterpulse. The observed poloidal drift trajectories agree well with calculated orbits.[2]

The use of a kicker coil for trapping avoids the disadvantage of 'self trapping', namely that the conditions for trapping cannot be adjusted independently from the injection conditions. However, such a coil is unattractive. It must be driven with a sufficiently long pulse so that the radius of the poloidal drift trajectory can be reduced by acceleration, and the coil represents another obstacle that the beam must avoid. Therefore, a new trapping scheme is being developed. In this scheme, an induction electric field is applied to a gap in the torus. During the poloidal bounce following injection, the beam is accelerated by this applied field and r_{eq} is shifted. A preliminary experiment to test this scheme has been performed.

Theory

Trapping by rapidly accelerating the beam with an inductive electric field applied to a gap in the torus is non-invasive. The scheme makes use of the dependence of r_{eq} on γ. Linear theory predicts that a change in the in the ring energy $\delta\gamma$, will produce a shift in the ring equilibrium position δr given by

$$\frac{\delta r}{r_o} = \frac{\delta\gamma/\gamma_o}{1 - n - n_s\,[r_b^2/a^2]}, \tag{1}$$

where $\delta r = r_{eq} - r_o$, B_{zo} is the betatron field at the minor axis, n_s is the self-field index, r_b is the beam minor radius, and r_o(a) is the chamber major (minor) radius. This expression is valid near the minor axis. However, away from the minor axis, non-linear expressions for the external fields and self-field images must be used. The non-linear equations yield the curves plotted in Fig. 1. These show the energy parameter at the diode γ_D versus r_{eq} when $B_{zo} = 30G$. The various curves correspond to different currents and are labelled in units of I/β where I is the beam current in kA. It is seen that when $I \approx 1kA$ and $r_{eq} \approx 105cm$, a change in γ by 0.1 will produce a shift of ≈ 7 centimeters.

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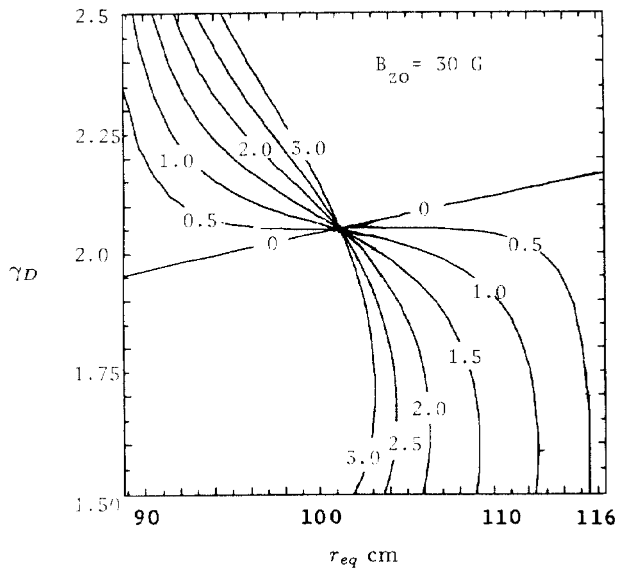

Fig. 1. γ_D versus r_{eq} for various values of I/β where I is in kA.

The normalized energy of the ring γ is less than γ_D because energy must be provided to establish the self-fields of the ring. The change in γ that occurs during injection of the beam is [7]

$$\langle\gamma\rangle - \gamma_D = \Delta\gamma = -\left(2\nu - \frac{\nu}{\gamma_c^2}\right)\left[\frac{1}{4} + ln\frac{a}{r_b} - \left(\frac{\Delta}{a}\right)^2\right], \quad (2)$$

where ν is Budker's parameter $= I/17\beta$ (I in kA), $\langle\gamma\rangle$ is the average gamma of the ring, and Δ is the displacement of the ring centroid from the minor axis.

When the accelerating potential is applied to the gap, γ increases, but there is also a significant increase in velocity and current because β is less than unity. Thus, the self field flux Φ^s increases and produces a diamagnetic back-emf at the gap. The rate of change of γ that is associated with the change of accelerating flux $d\Phi^{acc}/dt$ and the change in the self field flux $d\Phi^s/dt$, for a fixed position in the transverse plane, is given by

$$m_oc^2\frac{d\gamma}{dt} = ec\beta\frac{\partial A}{\partial t} = \frac{ec\beta}{2\pi r_o}\left(\frac{d\Phi^{acc}}{dt} - \frac{d\Phi^s}{dt}\right)$$

$$= \frac{ec\beta}{2\pi r_o}\left[V_{gap} - \frac{d[LI]}{dt}\right], \quad (3)$$

where $L \approx \mu_o r_o[ln(8r_o/r_b) - 1.75]$ is the beam inductance, and the change in Φ^s is proportional to a change in velocity $\delta\Phi^s = LI(\delta\beta/\beta) = LI(\delta\gamma/[\gamma(\gamma^2-1)]$.

Integrating and assuming $\delta\gamma << \gamma$ and $V_{gap} = V_g sin(\pi t/\tau)$ where τ = trapping pulse duration, one obtains

$$\delta\gamma = \frac{2}{\pi}\frac{\tau}{\tau_o}\frac{eV_g}{m_oc^2}\left[1 + \frac{2L\nu}{\mu_o r_o\gamma^3}\right]^{-1}, \quad (4)$$

where $\tau_o = 2\pi r_o/\beta c$. When $\gamma_D \approx 2.1$, $I \approx 1.5kA$, a=15.3 cm, and $r_b \approx 1cm$, $\gamma \approx 1.6$ and $2L\nu/(\mu_o r_o\gamma^3) \approx 0.3$, i.e., $\delta\gamma$ is reduced by $\approx 25\%$ by the beam diamagnetism. It is seen that a penalty results for 'low' energy injection.

Experiment

The NRL modified betatron has been described in detail previously.[8] For the present experiments, the principal parameters are listed in Table 1. The betatron field is 'crowbarred' prior to injection and decays with an 'L/R' time constant of several msec so that B_z is quasi-static during the times of interest. Circulating current is measured by Rogowski coils located at two azimuthal positions. The transverse motion of the beam is monitored by three diagnostics: magnetic probes monitoring the poloidal self field of the beam, x-rays emitted when the beam hits a Ta target, and open-shutter photography of the beam interacting with a thin polycarbonate film target that spans the minor cross section of the torus. The film target is 2 microns thick and is coated with carbon to reduce electrostatic charging.

Table 1. Experimental Parameters

Injection energy	0.5-1.0 MeV
Injection current	0.4-3.0 kA
Major radius	1.026 meter
Minor radius	15.3 cm
Injection radius	1.10 m
Toroidal field	3 kG
Betatron field	20 - 80 G
vacuum field index	0.35-0.55
pressure	4 x 10^{-6} Torr

To accelerate the electron ring, the flux linked by the ring orbit must increase. This can be accomplished by driving a current around the torus or by changing the flux in a pulse forming line (PFL) that is coaxial with the toroidal chamber. Such a PFL is under development and is shown in Fig. 2. In the mean time, a preliminary test of the trapping scheme has been performed using a planar Blumlein PFL that has been connected to the chamber. This PFL has an impedance of 5Ω/section, a capacitance of 36 nF/section, can be charged up to 18 kV, and produces a pulse of 0.25 μsec duration. A typical waveform is shown in Fig. 3.

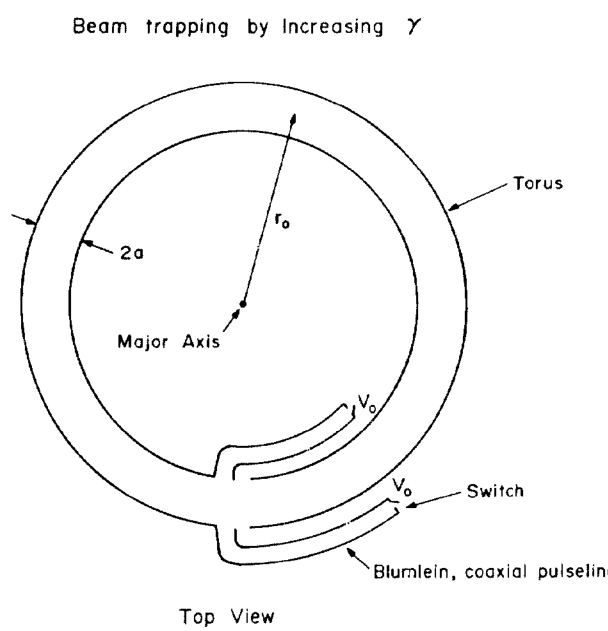

Fig. 2. Schematic of a pulse forming line that is coaxial with the torus.

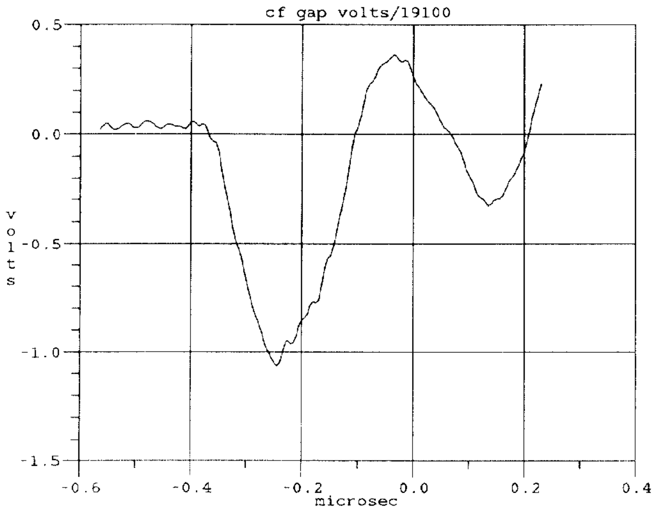

Fig. 3. Typical voltage waveform applied to the gap in the torus (time origin is arbitrary).

To test the trapping scheme, shots were fired with zero and 14 kV applied to the gap. Results are shown in Figs. 4 and 5. The circulating current at two azimuthal positions are shown in each frame of Fig. 4. It is apparent that the duration of the current is substantially longer in the presence of the accelerating voltage (right frame). The poloidal trajectory of the beam obtained by the open-shutter camera technique is displayed in Fig. 5. The injection position is indicated by the arrow, and the major radius is situated to the right of each picture. The results show that the trapping scheme effectively shifts the beam away from the injector.

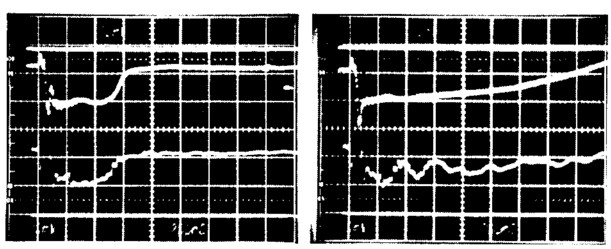

Fig. 4. The circulating ring current at two azimuthal positions versus time (200 nsec/div); left: without gap voltage, right: with 14 kV gap voltage.

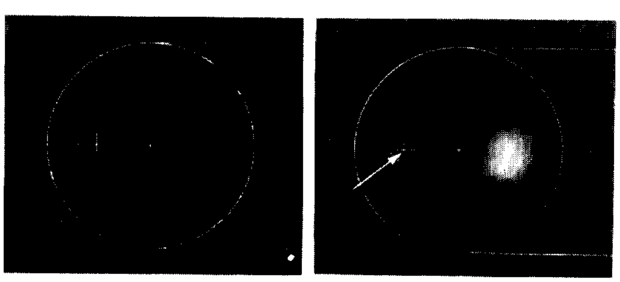

Fig. 5. The poloidal trajectory of the beam. Circle outlines the cross section of the torus; the major axis is to the right. Left: without gap voltage, right: with 14 kV gap voltage.

The displacement of the beam is sensitive to the timing and amplitude of the applied gap potential. Therefore, this scheme offers a way to trap the beam that is independent of the injector and is non-invasive. Following refinement of the apparatus by installing a coaxial Blumlein PFL, experiments to improve the confinement time and accelerate the beam will commence.

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