Formation of a High-Current Electron Beam in Modified Betatron Fields

H. Ishizuka, G. Lindley, B. Mandelbaum, A. Fisher, and N. Rostoker
Department of Physics, University of California, Irvine, California 92717
(Received 2 February 1984)

An electron beam with a current exceeding 200 A has been generated and sustained by continuous injection of electrons into a rising toroidal and vertical magnetic field. There is a large mismatch between the electron energy and the vertical field. When the vertical field reaches a certain strength, accelerated beam electrons hit the outer wall of the torus, destroying the beam. By control of this vertical field the lifetime of the beam is extended yielding an electron energy of ~ 1 MeV.

PACS numbers: 52.75.Di, 29.20.Fj

The production of a multikiloampere electron beam in a betatron has recently attracted interest.[1-6] In order to focus an intense beam against the space-charge electric field, a modified betatron[1-5] employs a toroidal magnetic field in addition to the betatron (or vertical) field. In this paper we report the results of the formation of a high-current beam in a modified betatron and discuss the beam's characteristic features. The schematic of the experimental apparatus is shown in Fig. 1 and the major parameters are given in Table I.

The vertical field is produced by a pair of air-core coils, 62.5 cm in radius and 64 cm apart, and a center solenoid, 42 cm in diameter and 120 cm long, provides part of the toroidal electric field. Usually the center solenoid is connected in series with the vertical field coils in which case the betatron flux condition, $\langle B\rangle/B=2$, is met near the minor axis of the torus. The one-turn accelerating voltage is typically 150–250 V. The toroidal magnetic field, produced by a set of coils wound closely to the glass torus, is much stronger than the vertical field. Injection of electrons is accomplished by applying negative voltage to a heated cathode, which is normally located 1 cm from the outer wall of the torus.

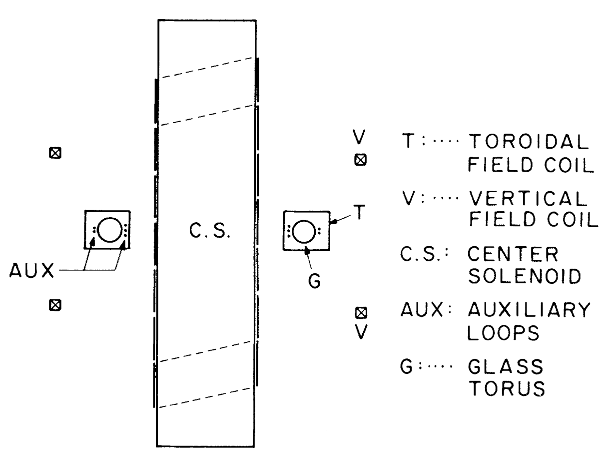

FIG. 1. Schematic cross section of apparatus.

A typical sequence of operation is shown in Fig. 2. The toroidal magnetic field [Fig. 2(a)] is fired prior to the vertical field [Fig. 2(b)] and the injection voltage. When the vertical field attains a certain value the beam forms. This formation is revealed by a drastic reduction in the injection current [Fig. 2(c)] and the beginning of a beam current measured by a Rogowski loop wound around the torus [Fig. 2(d) shows two traces of the beam current]. The beam current increases up to a peak value, then decreases gradually, and finally vanishes abruptly. When the beam vanishes a burst of x rays is detected as shown in Fig. 2(e). The beam is created only if the toroidal magnetic field is larger than a few kilogauss and the emission from the injector is greater than approximately 3 A. It should be noted that the beam life suffers little change if the toroidal magnetic field is reversed, indicating that the vertical component of the field produced by the toroidal field coils is sufficiently small. The life and parameters of the beam are nearly independent of the strength of the toroidal field above approximately 3 kG. The beam characteristics are similar for both types of injectors (tangential and nondirectional) and with the accelerating gap in the screen liner either open or shorted.

In conventional circular accelerators the vertical field B, the orbit radius R, and the momentum p of a particle with charge e are related by $p=eBR$. This is not the case with a high-current beam. In Fig. 3, open circles show the vertical field at the start of the beam as a function of the injection voltage. When the injector cathode is located 1 cm from the outer wall of the torus, the beam is formed at 40 G (50 G) for an injection voltage of 10 kV (40 kV). On the other hand, $p=eBR$ gives $B=8.5$ G (17.2 G) for 10-keV (40-keV) electrons which take a gyroradius of 0.4 m. Closed circles in Fig. 3 indicate the vertical fields at the end of the beam. The

TABLE I. Major parameters of the experiment.

Vacuum chamber (glass torus)	
Major radius	40 cm
Minor radius	5 cm
Liner	Stainless steel 12 mesh/inch
Vacuum	$\sim 10^{-7}$ Torr
Electron injector (thermionic electron source)	
Filament	4-cm-long stranded wire
Type	Tangential (Kerst type) or nondirectional (Ref. 7)
Voltage	0–40 kV
Pulse width	0–400 μs
Emission current	4 A (typically)
Toroidal magnetic field	
Rise time	100 μs (0 to peak)
Max. field	12 kG
Axisymmetry	< 1% on the minor axis
Vertical magnetic field	
Rise time	100 μs (0 to peak)
Max. field	0.5 kG
Field index	0.2–0.8

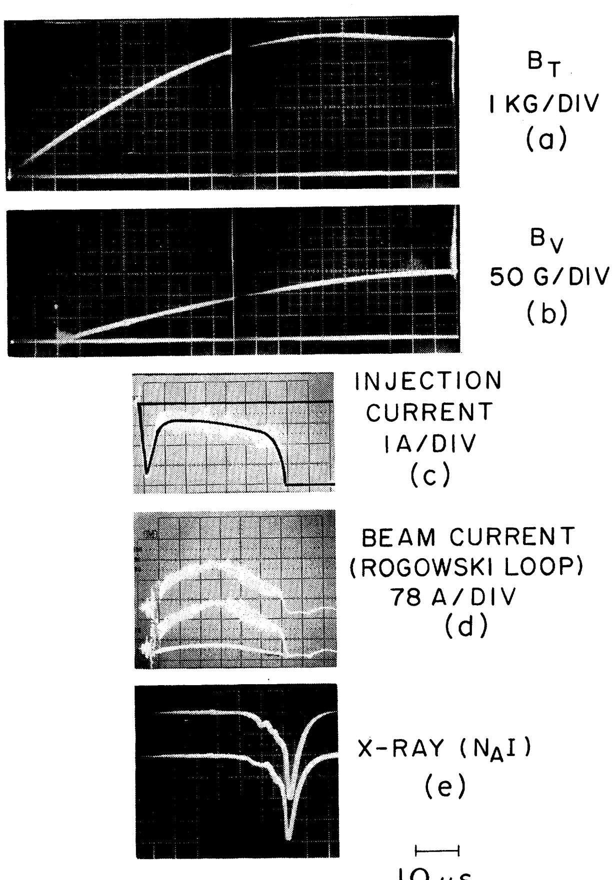

FIG. 2. Typical oscilloscope traces.

final electron energy is estimated by means of the x-ray absorption method, which gives $p \approx 0.5eBR$.

Measurements with a wire probe show that the electrons are located near the minor axis of the torus in the early phase of beam life but move outward with time. A plane probe placed at a radial position between the injector and the outer wall of the torus detects an electromagnetic charge of $\sim 1\ \mu$C just before the beam hits the outer wall. The sources of the x rays produced by the beam are located with collimated x-ray detectors. These detectors reveal successive small bursts of x rays from

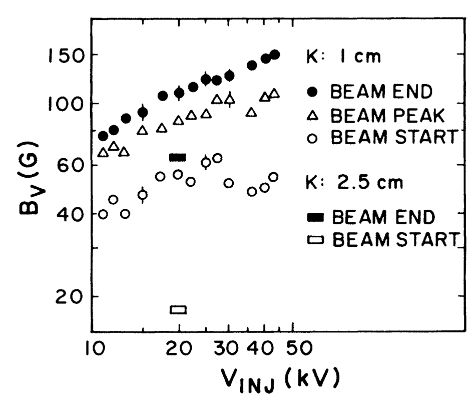

FIG. 3. The vertical field at the start, peak, and end of the beam vs the injection voltage. The injector cathode is located 1 or 2.5 cm from the outer wall of the torus.

the electron injector after the beam current reaches its peak and before the beam is finally lost. The final x-ray burst comes from both the injector and the outer wall of the torus.

The circulating electron ring is observed to last only as long as the injection is continued. If the injection is turned off, the electron beam is lost and the x-ray burst appears in a short time. It should then be questioned whether the electron beam consists of initially trapped electrons or newly injected electrons which are supplied into the ring to replace lost electrons. To answer this, we compare the final electron energy inferred from x-ray absorption data with the calculated energy an electron would gain if it was trapped when the beam current was first observed and then accelerated by the magnetic induction. Agreement is found between the measured electron energies and the calculated energies, indicating that the electrons remain in the beam from beginning to end. We also observe temporal coincidence between the small x-ray signals, which occur after the peak beam current, and the unintegrated Rogowski-loop output signal. This unintegrated signal gives the number of electrons lost by the beam per unit time. The ratio between the x-ray signals and the unintegrated Rogowski-loop signals becomes greater with time, showing that electron energy is a monotonically increasing function of time.

The flux condition for beam formation to occur is not severe. The electron ring is formed provided $1.2 \lesssim \langle B \rangle / B \lesssim 3$ on the minor axis of the torus. For $\langle B \rangle / B < 2$, the strength of the vertical field at the start of the beam is nearly independent of $\langle B \rangle / B$. For $\langle B \rangle / B > 2$, the beam starts at a higher vertical field for higher values of $\langle B \rangle / B$; however, neither the beam current or the final electron energy is strongly dependent on the value of $\langle B \rangle / B$. Also these beam parameters are not sensitive to the radial position of the injector over the range 1–3 cm from the outer wall of the torus. If the injector is moved inward within this range, a lower value of the vertical field is required to maintain the beam (see data points for $K = 2.5$ cm in Fig. 3) but the beam current and final electron energy remain nearly the same. In contrast, both the beam current and the final electron energy vary almost linearly with the injection voltage. Empirically the final electron energy is found to be roughly twenty times the injection voltage and the peak beam current in amperes is approximately five times the injection voltage in kilovolts (open triangles in Fig. 4).

Further increase in the beam current and electron energy is achieved by proper control of the vertical field over time. Auxiliary loops shown in Fig. 1 are activated by discharge of a capacitor bank resulting in extended beam life and increased beam current, as plotted in Fig. 4. The best result is obtained when (i) the vertical field is reduced from its origi-

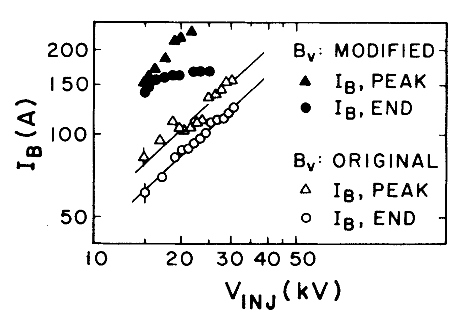

FIG. 4. Injection-voltage dependence of the beam current. $I_{b,\text{peak}}$ is the peak value of the beam current. $I_{b,\text{end}}$ is the beam current at the time of disruption.

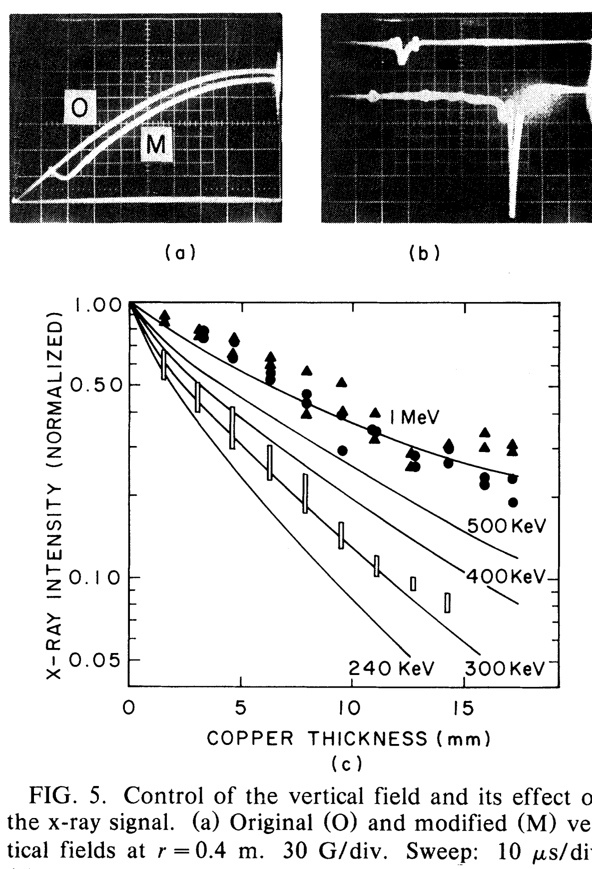

FIG. 5. Control of the vertical field and its effect on the x-ray signal. (a) Original (O) and modified (M) vertical fields at $r = 0.4$ m. 30 G/div. Sweep: 10 μs/div. (b) X rays for the original (upper trace) and modified (lower trace) vertical fields. The injector cathode is located 2.5 cm from the outer wall. Sweep: 10 μs/div. (c) X-ray absorption data. Rectangles for original and circles and triangles for modified vertical fields.

nal strength and (ii) the modification is initiated shortly after the beginning of the beam current. The increase of the beam current is partly due to the longer period before the beam reaches its peak. At the same time, the trapping is apparently improved, possibly as a result of the transient changes in the strength and/or the index of the vertical field. Figure 5 demonstrates the effect of field control on the final electron energy. The original and modified vertical fields in Fig. 5(a) yield the upper and lower traces of the x-ray signals shown in Fig. 5(b), respectively. X-ray absorption data for cases with and without the field modification are shown in Fig. 5(c). With copper plates as the absorber the solid curves are calculated for bremsstrahlung generated from a thick target[8] bombarded by monoenergetic electrons. From this figure, the final electron energy reaches ~ 1 MeV with the modified vertical field.

The physical interpretation of the departure from the conventional relation $p = eBR$ can be seen by examining the force balance on the minor axis of the electron ring:

$$ev_{\parallel} B \cong (\gamma m/R)(v_{\parallel}^2 + \tfrac{1}{2} v_{\perp}^2) + eE_r,$$

where E_r is the radial electric field and $\gamma m v_{\parallel}^2/R$ is the usual centrifugal force. $\gamma m v_{\perp}^2/2R$ is a force that arises because of the magnetic moment of the electron and the gradient of the magnetic field. In conventional betatrons, this term and eE_r are negligible. In the present case, because of the method of injection and the subsequent magnetic compression, $v_{\perp}^2$ is of the same order as $v_{\parallel}^2$ during the early development of the beam. The radial electric force eE_r is directed outward if the major radius of the electron ring is larger than the major radius of the torus. These two factors account qualitatively for the momentum mismatch observed at the start of the beam. When acceleration takes place B is increased as well as $v_{\parallel}$. Eventually $v_{\parallel} \gg v_{\perp}$ but the magnetic field is too large for the relation $p \cong eBR$ to be satisfied. The effect of the auxiliary loops is to decrease the magnetic field B after the beam has formed in order to correct the initial departure from this relation. Only a small departure can be tolerated, or the beam will deflect to the wall.

This work was supported by the Office of Naval Research.

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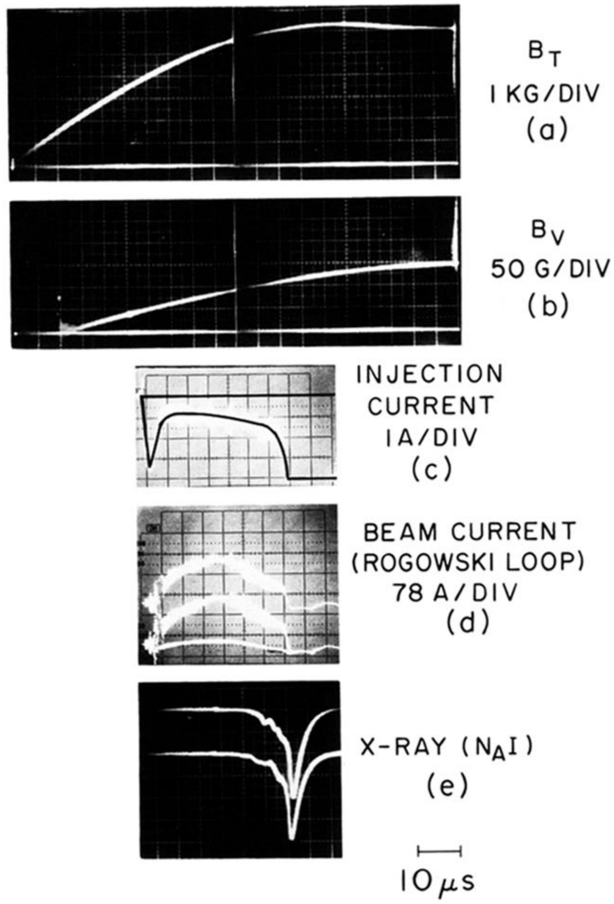

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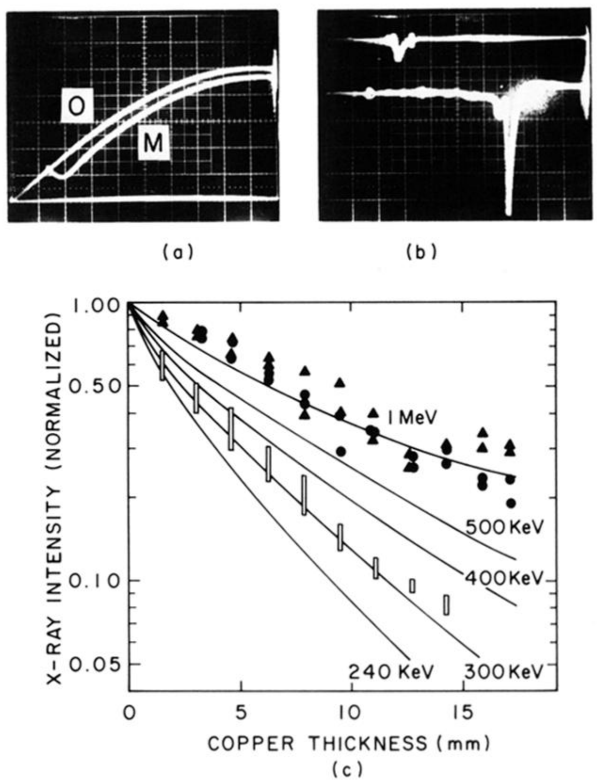

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