Proposal for Beam Extraction from a Modified Betatron Accelerator Using a Toroidal Electric Field

C. A. Kapetanakos, E. Drakakis, Z. Xenidi, and D. Karabourniotis
Institute of Plasma Physics, University of Crete, Iraklion, Crete, Greece
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A technique is proposed for extracting the beam from the modified betatron accelerator. Briefly, after the acceleration is completed, the beam is forced to drift vertically by applying a rapidly rising toroidal electric field. Following the crossing of the septum, the beam enters the extractor, which is either helical or straight. In the latter case the electrons are guided to target by a plasma lens.

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The modified betatron accelerator (MBA) is a high-current, recirculating, induction accelerator with high effective accelerating gradient. Its improved current carrying capability is due to the addition of a toroidal B_θ field [1] and a strong focusing twisted quadrupole [2,3], to the vertical B_z field of the conventional betatron.

The research program to develop the MBA at the Naval Research Laboratory (NRL) lasted approximately a decade and furnished valuable information on the various critical physics issues of the concept [4]. During the last phase of its operation, the trapped electron current in the device routinely exceeded 1 kA and the peak energy exceeded 20 MeV. All the electron rings in the NRL device were formed by an injected electron beam of energy, typically, between 0.5 and 0.6 MeV. A smaller MBA at the University of California, Irvine [5], also obtained interesting results. However, the majority of electron rings in the Irvine device were formed by runaway electrons and not by an injected beam.

As a result of the two additional magnetic fields, the extraction of the beam from the MBA is more difficult than from the conventional betatron. Currently, the extraction of the beam from the MBA is the most important unresolved critical physics issue of the concept.

In 1988, an extraction scheme was reported by the NRL research staff [6] that is based on the excitation of the cyclotron resonance. The hardware for this extraction technique was designed and fabricated but never tested experimentally [4]. The reason is that it requires a beam with low transverse velocity because the aperture of the agitator is very limited. However, the beam in the NRL device had substantial transverse velocity. As a result, the NRL research staff pursued, for a brief period of time, some alternate extraction approaches that did not require beams with low transverse velocity. Although the NRL work on the extraction of the beam from the MBA furnished some interesting results [4], it did not provide a viable extraction technique.

All the NRL effort on beam extraction, as well as some recent work at Irvine [7], is based on magnetic agitators (kickers). Typically, the magnetic agitators are relative high inductance L coils that require substantial current to produce the desired magnetic disturbance. Therefore, they have to be driven by low characteristic impedance Z_0 lines. Since the rise time of the pulse depends on the ratio L/Z_0, it is difficult in general to achieve very short (of the order of few nanoseconds) rise-time magnetic disturbances at manageable voltages.

This limitation impacts on the efficiency of extraction, because, when the electron ring occupies the entire length of the torus, the beam losses during extraction are proportional to the ratio τ_r/τ_0, where τ_r is the rise time of the pulse that creates the magnetic perturbation and τ_0 is the electron transit time around the torus, i.e., $2\pi r_0/c$, where r_0 is the major radius of the electron ring, and c is the velocity of light.

The rise-time limitation is greatly alleviated by replacing the magnetic with an electric agitator. Since the main contribution to the inductance of such an agitator comes from the switch and since its capacitance can be kept low, both the inductive L/Z_0 and the capacitive term Z_0C can be kept small at reasonable values of Z_0.

This paper reports on a novel beam extraction technique from the MBA using a large aperture electric agitator.

Description of technique and results.—Just before the end of the acceleration cycle, the strong focusing field is crowbarred and the external field index n is brought to near zero by pulsing a coil that is located at the midplane and in the inner side of the outer wall of the vacuum chamber. With the electron beam at or near the minor axis, an electric field is rapidly applied to a gap of the vacuum chamber, as shown in Fig. 1. At the gap the electrons gain energy and the mismatched beam drifts downward with a speed of several centimeters per revolution. After a few revolutions the beam enters the extractor, which, typically, is a short helical pipe. For some applications the helical extractor may be replaced with a straight pipe that carries a plasma lens [8,9].

It can be shown from the linearized equations of motion [10] that when the current in the stellarator windings and the external field index n are equal to zero, the beam centroid drifts vertically with a speed $\Delta\dot{z}$ that is given by

$$\Delta\dot{z} = -\frac{\Omega_{z0}}{\Omega_{\theta 0}}\frac{c}{\beta_{\theta 0}}\frac{\delta\gamma_0}{\gamma_0}, \tag{1}$$

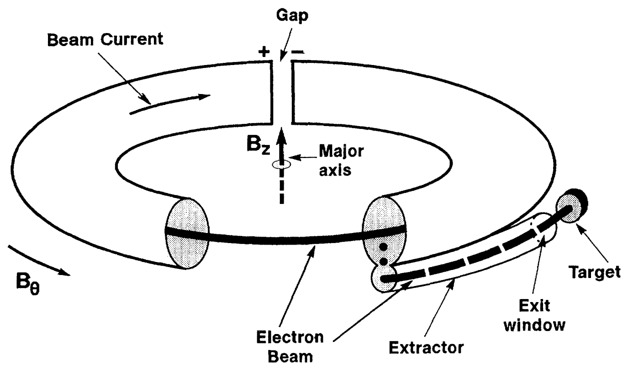

FIG. 1. Schematic of the proposed extraction scheme.

where Ω_{z0} is the cyclotron frequency of the vertical field on the minor axis, $\Omega_{\theta 0}$ is the cyclotron frequency of the toroidal field on the minor axis, $\beta_{\theta 0} = v_{\theta 0}/c$, $v_{\theta 0}$ is the toroidal velocity of the reference electron that is located at the beam centroid, $\delta\gamma_0$ is the normalized energy mismatch of the reference electron at the beam centroid, and γ_0 is its normalized energy. Since $\beta_{\theta 0} \simeq 1$ and $\Omega_{z0}/\gamma_0 \approx c/r_0$, Eq. (1) becomes

$$\Delta\dot{z} = -\frac{c^2}{r_0\Omega_{\theta 0}}\,\delta\gamma_0 . \tag{2}$$

For fixed r_0, the vertical speed of the beam's centroid depends only on $\Omega_{\theta 0}$ and $\delta\gamma_0 = NV_{\rm gap}/m_0c^2$, where N is the number of passes through the gap, $V_{\rm gap}$ is the voltage of the gap, and m_0 is the rest mass of the electron.

Results from the numerical integration of orbit equations for the beam centroid are shown in Fig. 2. The various parameters for the run are listed in Table I. The electric field at the gap was computed using Eqs. (17)–(20) of Ref. [11]. Since the extraction of the beam occurs at a relatively high value of γ, the induced fields from the wall of the vacuum chamber are very small and have been neglected. Figure 2(a) shows the projection of the orbit in the $\theta = 0$ vertical plane. The small deviation to the right is due to the small bounce motion of the centroid. In this run, when the beam approaches the septum the deviation is approximately 2 mm, and, as expected, it decreases with increasing $V_{\rm gap}$.

Figure 2(b) shows the transverse velocity of the centroid as a function of time. There are two components. The vertical drift that increases with each passage of centroid through the gap and the speed of the fast motion around the guiding center. When the beam crosses the septum, the combined normalized vertical speed is less than 1.5%. Finally, Fig. 2(c) shows the vertical position of the beam as a function of time. When the beam approaches the wall of the vacuum chamber, its vertical displacement is 6.25 cm per revolution (~23 nsec), which is more than sufficient to avoid the septum.

Results from the numerical integration of orbit equations for a higher value of γ_0 are shown in Fig. 3. The various parameters for this run are also listed in Table I. Reasonable vertical displacements per revolution are obtained for a Blumlein charging voltage $V_0 = 150$ kV, although the toroidal field was increased from 3.4 to 8 kG. As a result of higher bounce frequency ω_B, N, and τ_0, the vertical deviation has increased from 2 to 8 mm. Since $\omega_B \sim r_0^{-2}$, while $\tau_0 \sim r_0$, a larger r_0 reduces the deviation for fixed γ_0.

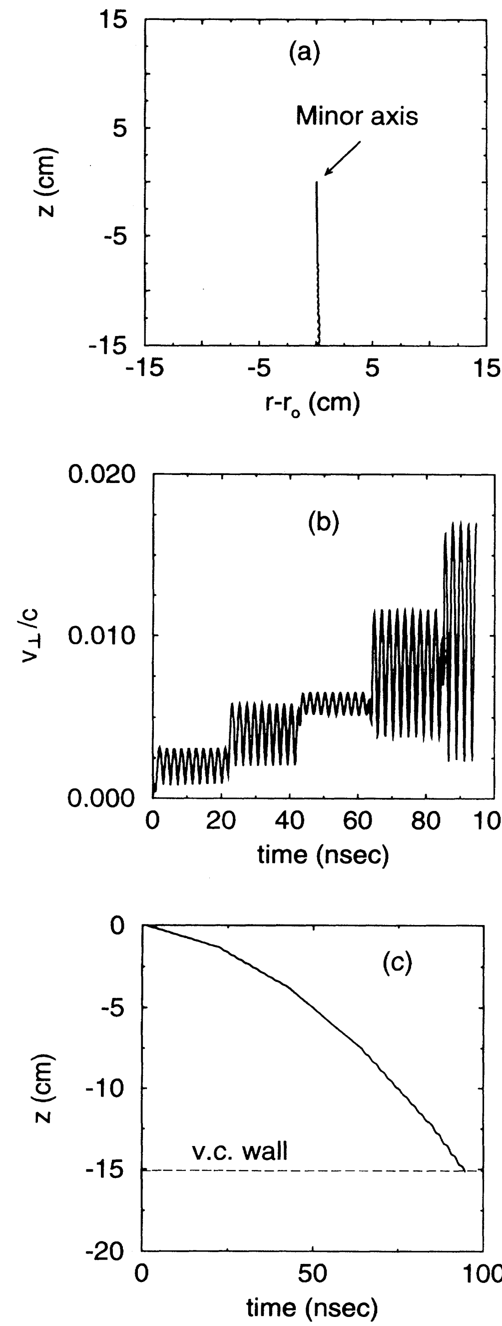

FIG. 2. Results from the numerical integration of orbit equations for a low energy ($\gamma_0 = 20$) beam.

TABLE I. Parameters of the runs shown in Figs. 2 and 3.

	Fig. 2	Fig. 3
Major radius r_0	1 m	2 m
Torus minor radius a	15 cm	15 cm
Peak vertical field B_{z0}	340 G	2130 G
Toroidal magnetic field $B_{\theta 0}$	3.4 kG	8 kG
External field index n	0.01	0.01
Gap voltage V_{gap}	-0.2 MV	-0.3 MV
γ_0 when V_{gap} is turned on	20	250
Blumlein charging voltage V_0	0.1 MV	0.15 MV

After a few revolutions the beam enters the extractor, a helical pipe that is terminated at an exit window. For most applications a short extractor will be sufficient. When further focusing of the electron beam is desired, the helical extractor may serve as the housing of an active or passive plasma lens. For these applications that require a straight beam, the electrons may be guided to the target by an ion channel that is formed by a laser beam. The ion channel may eliminate the need for additional coils to cancel the components of magnetic field that are transverse to the axis of the extractor. It should be noticed that in this case the ion channel is located entirely within the extractor and therefore there is no need to puff gas in the vacuum chamber, an important drawback of the original extraction technique [8].

Generation of rapid electric field.—The localized electric field of the gap can be generated by either close-ended or open-ended transmission lines. A typical example of a close-ended line is the toroidal pulse line [12] that is similar to the radial line initially employed by Pavlovskii *et al.* [13] and analyzed by Eccleshall and Temperley [14]. A typical example of an open-ended line is the toroidal Blumlein transmission line that is shown in Fig. 4.

A basic difference between the two lines is that in the case of the open-ended line the magnetic field of the beam diffuses out of the vacuum chamber immediately after injection, while in a close-ended line the magnetic

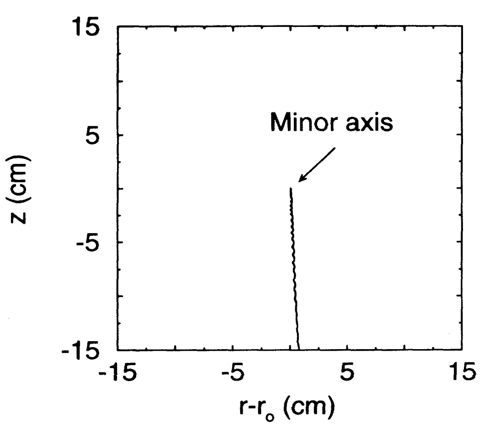

FIG. 3. As in Fig. 2(a) but for higher energy ($\gamma_0 = 250$).

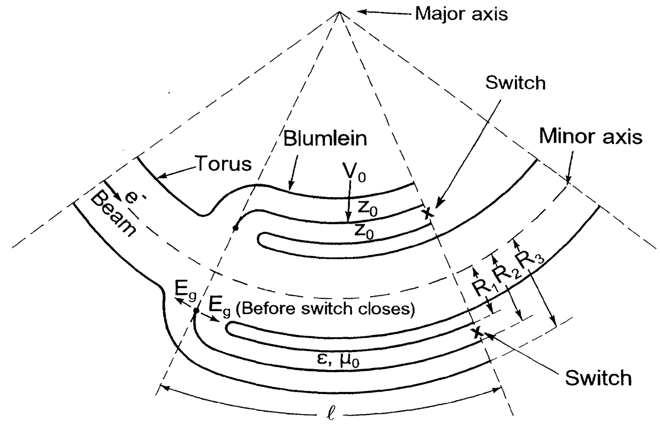

FIG. 4. Schematic of cross sectional view of the toroidal Blumlein line. The electric fields at the gap are depicted after charging of the line but before the switch closes.

field of the beam diffuses out of the vacuum chamber within two to three magnetic field loop times $\tau_{00} = (\mu_0 a \Delta a/\rho)[\ln(8r_0/a) - 2]$, where a is the minor radius of the torus, Δa is its thickness, and ρ is the resistivity of the chamber's wall. For the existing MBA, τ_{00} is approximately 40 μsec. In the presence of strong focusing the rapid loss of additional confinement from the induced field of the beam in an open-ended line is not very important.

For extraction, it is necessary to use the leading pulse to power the gap. Since the duration of the leading pulse is the same for either line and since for the same charging voltage the amplitude of the pulse in the Blumlein is twice the amplitude of the pulse in the Pavlovskii line, the Blumlein has been selected as gap driver.

For simplicity, we limit the discussion to a coaxial, cylindrical Blumlein. For such a line it can be shown that when the beam is not matched to the line, the voltage at the gap V_{gap} is given by

$$V_{\text{gap}} = 2(V_0 - I_b Z_0), \tag{3}$$

where I_b is the beam current and Z_0 is the characteristic impedance of the line

$$Z_0 = \frac{1}{2\pi} \ln\left(\frac{R_3}{R_2}\right)\sqrt{\frac{\mu_0}{\epsilon}}, \tag{4}$$

where the radii R_2, R_3 are defined in Fig. 4, and $\epsilon = \epsilon_r \epsilon_0$ (ϵ_r is the relative permittivity of the dielectric medium filling the pulse line). If $m_0 c^2 \delta\gamma_0$ is the required energy mismatch, the length of the line is given by

$$\ell = \frac{\delta\gamma_0 m_0 c^3 \tau_0}{4\sqrt{\epsilon_r}[V_0 - I_b Z_0]}, \tag{5}$$

where τ_0 is the period of revolution around the torus.

For $m_0 c^2 \delta\gamma_0 = 1$ MeV, $\tau_0 = 23$ nsec, $V_0 = 0.1$ MV, and $\epsilon_r = 81$, Eq. (5) gives $\ell = 1.9$ m. Shorter lines are possible using higher permittivity dielectrics, such as titanate composites. The term $I_b Z_0$ has been neglected because the waves induced by the injected beam have decayed when the Blumlein is activated.

For $Z_0 = 1.5\ \Omega$ and $R_1 = 16$ cm, where R_1 is defined in Fig. 4, Eq. (4) and the relation $R_2^2 = R_1 R_3$ give $R_2 = 20$ cm and $R_3 = 25$ cm. Therefore the radius of strong focusing windings will be approximately 26 cm; i.e., they will be located 11 cm away from the wall of the vacuum chamber. It should be noticed that a toroidal coaxial pulse line with $Z_0 = 0.84\ \Omega$ was constructed and tested successfully at NRL [12]. The computed rise time of the line was 5 nsec. However, the measured rise time was $\sim$10 nsec. The difference was attributed to the resistive phase of the switch and is related to the low operating voltage. This explanation is consistent with the observation that the rise time increased to 20 nsec for charging voltages below 15 kV. Because of substantially higher operating voltage in the proposed pulse line the resistive phase of the switch should not be present, and thus its rise time is expected to be a few nsec. This rise-time value may be further reduced to subnanosecond by applying pulse sharpening techniques.

A 5 nsec rise time results in a ratio $\tau_r/\tau_0 = 5/23 = 22\%$. If such beam losses are not tolerable, pulse sharpening techniques may be necessary. In contrast, beam losses associated with voltage ripple are not expected to be significant, because a ripple with amplitude δV will change the vertical position of the electrons by $\delta z = \Delta z(\delta V/V_{\text{gap}})$. Since a $\delta V/V_{\text{gap}} \approx 1\%$ is easily achievable for a carefully designed line, δz is only 0.6 mm for the results shown in Fig. 2.

Following injection, the beam will induce oscillations in the line with amplitude $I_b Z_0$. For $I_b = 1$ kA and $Z_0 = 1.5\ \Omega$ the amplitude will be limited to 1.5 kV. Furthermore, these oscillations will decay rapidly and, therefore, we do not expect they will adversely impact the dynamics of the beam.

The beam extraction efficiency in the MBA can be enhanced by forming an electron ring that partially fills the torus. This allows raising of the electric field while the electrons are away from the gap, and thus beam losses are avoided. Obviously, this approach is of interest only if the beam expansion during acceleration remains small. Initial calculations indicate that this is the case over a wide range of parameters [15].

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