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LASER EXTRACTION OF AN ELECTRON BEAM FROM A MODIFIED ELONGATED BETATRON ACCELERATOR

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Abstract

The Modified Elongated Betatron Accelerator (MEBA) that was developed at UCI has demonstrated injection, trapping and confinement of about 10^{12} electrons. The electrons have been accelerated to about 1 MeV. They occupy an annular region 80 cm long with a 6 cm radius and a thickness of about 0.5 cm. We propose to contract this annular beam from 80 cm to a few centimeters by moving the magnetic mirrors. Then the beam will be extracted by means of a laser-initiated channel to guide the beam across the magnetic field. This will be accomplished with a gas puff valve to inject benzene gas and a KrF laser. In this paper, we describe the necessary modifications of the accelerator to accomplish laser extraction of the beam.

Introduction

An electron beam can be guided across a magnetic field without deflection by means of a laser ionized channel. If the line density of the beam electrons is N_b, and a channel is formed with N_i low energy electrons, the N_i low energy electrons will all be expelled from the channel if $N_b > N_i$. A low energy electron sees the electric field of the other low energy electrons, the electric field of the beam electrons and the electric field of the ions. The beam electrons see their self electric and magnetic fields, which almost cancel if the beam is relativistic. When the low energy electrons are expelled, the beam electrons see only the field of the ions, which is $2\ N_i\ e/R$, where R is the channel radius. If

$$2\ N_i\ e/R > B \quad ,$$

where B is the external magnetic field that the beam transverses, the beam will follow the ion channel and have little or no deflection due to B. Electron beam guiding with a laser ionized channel has been demonstrated experimentally [1] and injection and extraction of an electron beam in a modified Betatron has been proposed by this method. [2]

This paper examines the possibility of extraction from an operating elongated form of a modified Betatron (MEBA) [3] (see Fig. 1). Extraction is considerably more difficult using laser initiated channels than injection because the magnetic fields are small at injection. After acceleration, the magnetic fields in a Betatron are much larger. For example, in the MEBA, the field at the beam is about 100 gauss just after injection at 50 KeV and about 450 gauss after acceleration to 1 MeV. The total number of electrons accelerated is about 10^{12}.

The accelerator is illustrated in Fig. 1. The electrons occupy an annular volume 80 cm long, 6 cm in radius, and 0.5 cm thick. Prior to extraction, the annular beam can be deformed into a ring by moving the magnetic mirrors. Then the line density of the ring would be $N_b = 10^{12}/(2\pi \times 6) = 2.7 \times 10^{10}$/cm. Assuming a beam and channel radius of 1 cm:

$$2\ N_b\ e/R = B = 26 \text{ gauss} \quad .$$

This is an upper bound to the magnetic field that could be crossed by the laser channel method. The beam must be moved into a region with a magnetic field that is smaller than this value prior to extraction. In the balance of this paper we show how this can be accomplished.

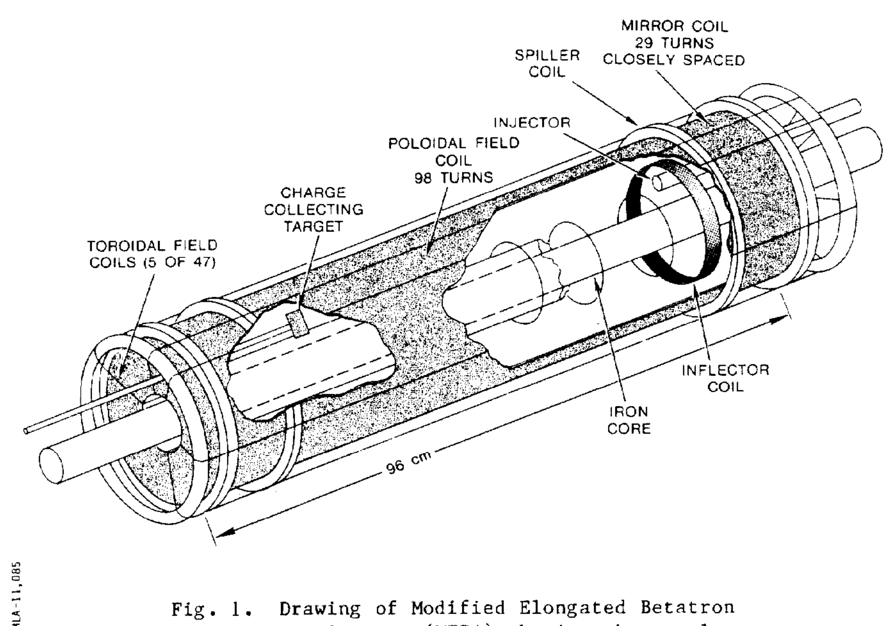

Fig. 1. Drawing of Modified Elongated Betatron Accelerator (MEBA) showing the accelerator magnetic field geometries and charge diagnostic.

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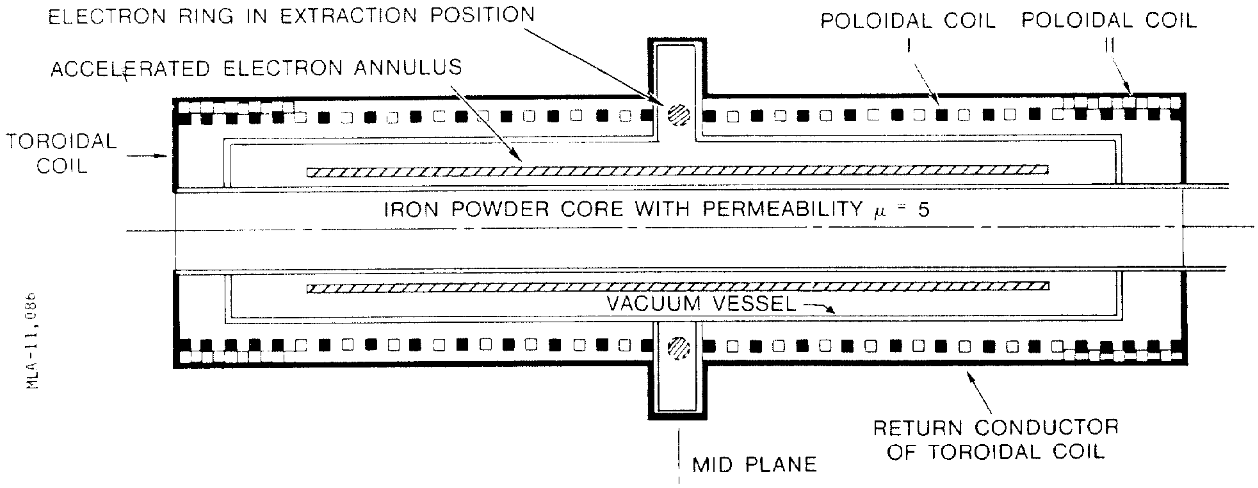

Fig. 2. Schematic diagram of MEBA accelerator with auxiliary coils for bunching and extraction.

Magnetic Field Calculations

A schematic diagram of the MEBA accelerator with auxiliary coils for bunching and extraction is given in Fig. 2. Poloidal coil I provides the poloidal and mirror fields. Poloidal coil II serves to move the mirror point inward and bunch the beam. Calculations of B_z versus z measured from the midplane are shown in Fig. 3; B_z is calculated at the radius R = 6 cm where the beam is located. The effects of both poloidal field coils is to 1) increase the field as required for acceleration, and 2) move the mirror for bunching. Thus, the beam begins as a long annulus after initial trapping and becomes a ring at the end of the acceleration and compression process. The iron powder core with permeability $\mu = 5$ is designed to accommodate the Betatron condition $\bar{B}_z = 2\, B_{zo}$, where B_{zo} is the field at the orbit and $\bar{B}_z$ is the average field inside the orbit. This condition is required to keep the beam radius constant at R = 6 cm. It is satisfied if $(R_o/R_c)^2 = \mu = 5$, where R_o = 6 cm is the beam radius and R_c is the radius of the iron powder core.

The magnetic field B_z in the vicinity of the midplane is plotted in Fig. 4. With increasing radius, the magnetic field must decrease and eventually pass through zero and change sign. Because the poloidal coil is quite long, the external field is weak and the field B_z passes through zero at $R \cong 19$ cm. In order to extract the ring beam by the laser method, the beam must be expanded into the weak field region. The beam can be expanded by increasing the current in a coil which increases the field inside the electron orbit. Therefore, $\bar{B}_z/B_{zo} > 2$; the Betatron condition is violated so that the orbit radius will increase as well as the electron energy.

We have thus far considered only the poloidal magnetic field and dealt with it by expanding the beam into a weak field region where the laser extraction method can be effective. There is also a toroidal field $B_\phi \cong B_z$ in the vicinity of R = 6 cm. However, beyond the return conductor of the toroidal coil $B_\phi = 0$. B_ϕ is parallel to the electron orbit and does not change the orbit until the beam leaves its circular trajectory to be extracted.

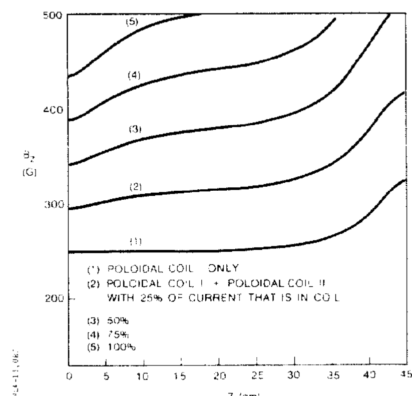

Fig. 3. Axial magnetic field at the location of the electron beam for increasing values of poloidal field II (mirror compression field).

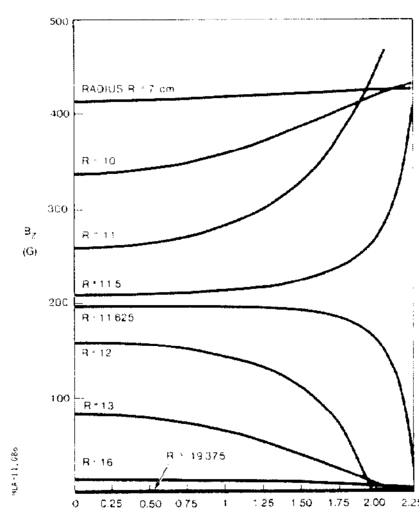

Fig. 4. Magnetic field B_z in the vicinity of the midplane of the accelerator (extraction region).

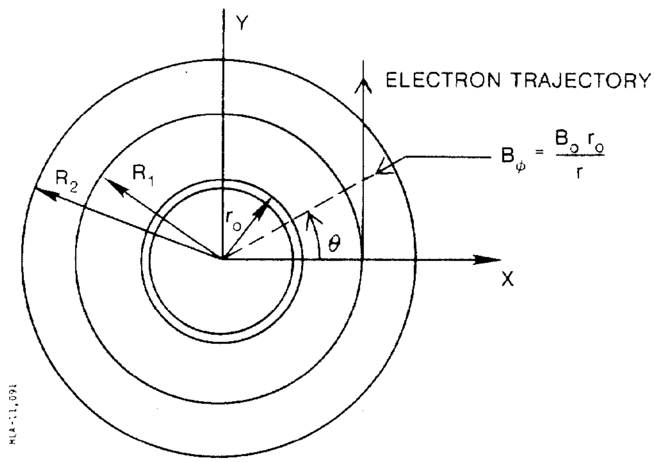

Fig. 5. Calculation of electron trajectory modification due to toroidal field by the midplane Z is illustrated r_o = initial beam radius (6 cm); R_1 = radius at which the beam is extracted (12 cm); and R_2 = radius of the toroidal return conductor (21 cm) beyond which B = 0.

Extraction at radius $r = R_1$ is illustrated in Fig. 5. The electrons move tangential to the circle $r = R_1$. Due to the toroidal field B_ϕ, the beam will be deflected in the z-direction according to:

$$\gamma_m \frac{dv_z}{dt} = \frac{e}{c} v_y \frac{B_o r_o y}{r} \frac{y}{r} \quad ,$$

$v_y = v_o \cong c$ and $y = v_y t$ so that:

$$\frac{d^2 z}{dt^2} = - \frac{\Omega_o r_o (v_y t)^2}{R_1{}^2 + (v_y t)^2} \quad .$$

The total deflection in the z-direction is:

$$\Delta z = - \frac{\Omega_o r_o}{2} \frac{R_1}{v_y} \int_{x=0}^{x=x_1} \ln (1 + x^2)\, dx$$

$$\Delta z = 1.5 \text{ cm} \quad ,$$

where

$$x_1 = \sqrt{(R_2/R_1)^2 - 1} \quad ,$$

$\Omega_o = eB_o/\gamma mc$ and B_o = 400 gauss was assumed. The trajectory is thus curved. This can be accommodated by ionizing a channel somewhat larger in diameter than the beam. Alternately, the channel can be made to approach the predicted curvature of the beam by splitting the laser beam and using several beams at slightly different angles. The toroidal field is too large to overcome with ion focusing, but the total deflection is small enough that it is tolerable and will not prevent extraction.

Discussion

When the electron ring has expanded to the weak field region, it would no longer be magnetically confined; it should be ejected symmetrically. The purpose of the laser/ionization channel is to destroy the symmetry in order to extract electrons from the ring in the form of a beam. There are other methods to do this by introducing auxiliary coils, magnetic materials, etc. These methods necessarily introduce permanent asymmetry and are not attractive for the present application because the MEBA is quite intolerant of asymmetry during the stages of injection, trapping and acceleration. In earlier experiments with the MEBA, the beam has been released after acceleration by manipulating the magnetic fields symmetrically. The beam has also been deposited on internal targets for measurements of charge, X-rays, etc. This has been accomplished with little apparent loss of electrons as long as axial symmetry was maintained. Extraction by methods which introduce permanent asymmetry has been attempted; the result was that the amount of charge trapped was greatly reduced. The virtue of the laser/ionization channel is that asymmetry is only necessary after injection, trapping and acceleration, and then only for a few nanoseconds.

Acknowledgment

We would like to express our appreciation to Ray Grandey for doing the magnetic field calculations.

The initial experiments on extraction by conventional methods were carried out at UCI. The experiment has now been relocated at Maxwell Laboratories for the laser extraction demonstration. The modifications of the magnetic field and vacuum system are underway. The KrF laser and gas puff valve systems are also available at Maxwell Laboratories.

References

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