LBL-15206

CONF-821123--34

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the 7th Conference on the Application of Accelerators in Research and Industry, Denton, TX, November 8-10, 1982

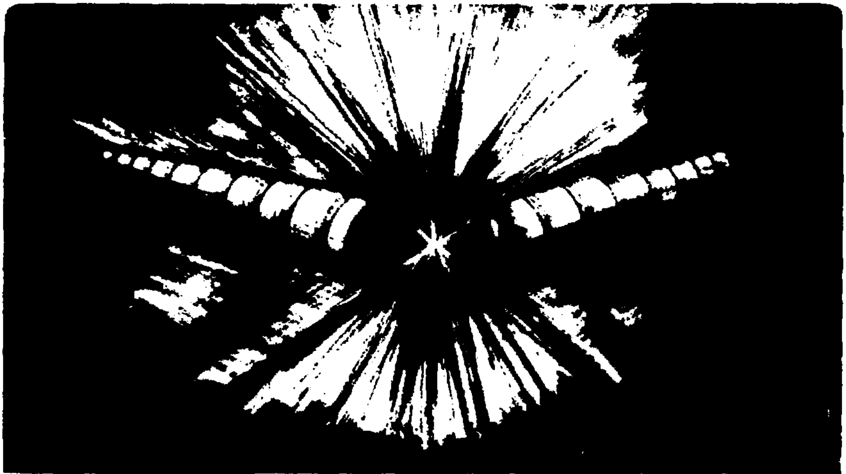
BETATRONS WITH KILOAMPERE BEAMS

Jack M. Peterson

November 1982

LBL--15206

DE83 005857



MASTER

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

LBL-15206

BETATRONS WITH KILOAMPERE BEAMS*

Jack M. Peterson

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

November 1982

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It has been reproduced from the best available copy to permit the broadest possible availability.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. [illegible] necessarily state or reflect those of the United States Government or any agency thereof.

*This work was supported by the Defense Advance Research Projects Agency under Contract No. N60921-81-LT-W0031 and the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

DISTRIBUTION OF [illegible]

BETATRONS WITH KILOAMPERE BEAMS*

J.M. Peterson
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

I. Summary

Although the magnetic-induction method of acceleration used in the betatron is inherently capable of accelerating intense particle beams to high energy, many beam-instability questions arise when beams in the kilo-ampere range are considered. The intense electromagnetic fields produced by the beam, and by the image currents and charges induced in the surrounding walls, can produce very disruptive effects. Several unstable modes of collective oscillation are possible; the suppression of any one of them usually involves energy spread for "Landau damping" and careful design of the electrical character of the vacuum chamber. The various design criteria are often mutually incompatible. Space-charge detuning can be severe unless large beam apertures and high-energy injection are used. In order to have an acceptably low degree of space-charge detuning in the acceleration of a 10-kilo-ampere electron beam, for example, an injection energy on the order of 50 MeV seems necessary, in which case the forces due to nearby wall images can have a larger effect than the internal forces of the beam. A method of "image compensation" was invented for reducing the net image forces;[1] it serves also to decrease the longitudinal beam impedance and thus helps alleviate the longitudinal instability as well. In order to avoid the ion-electron collective instability a vacuum in the range of 10^{-8} torr is required for an acceleration time of 1 millisecond. A multi-ring betatron system using the 50-MeV Advanced Test Accelerator at LLNL as an injector was conceptually designed.

II. High-Intensity Beam Phenomena

For accelerating beam currents in the kilo-ampere range a relatively low-impedance method of acceleration is required. The magnetic induction method of acceleration, which characterizes the betatron, is inherently a low-impedance system and is better suited to accelerating kilo-ampere beams than the radio-frequency-cavity method. Furthermore, the "weak-focussing" magnetic guide field structure, which typically is used in betatrons, is advantageous because its relatively large optical dispersion is beneficial in applying Landau damping to the control of collective beam instabilities.

Even with the relatively favorable type of accelerator many high-intensity phenomena make it difficult to accelerate kiloampere beams to high energy. However, there is cause for optimism in achieving such intensities because other circular induction accelerators — namely, electron-ring compressors, which are essentially betatron-type structures — have operated in the kilo-ampere, tens-of-MeV range in experiments in Berkeley and Livermore and in Germany and Russia. This experience gives us confidence that the high-intensity phenomena are basically understood and that these results can be scaled to higher intensities and higher energies.

There are many known undesirable effects associated with high-intensity beams in circular accelerators. These effects include:

(a) detuning due to space-charge forces,
(b) longitudinal collective instabilities,
(c) transverse collective instabilities, and
(d) ion-electron collective instabilities.

The forces that cause detuning and drive all of these instabilities are forces produced by the beam itself. They are called "space-charge" forces although in general they include forces due to electric and magnetic images induced by the beam in the walls of the vacuum chamber.

The Laslett incoherent space-charge limit[2] for a continuous (unbunched) electron beam can be written in the form

$$I_{incoh}^{(Amp)} = \frac{ec \quad b(a+b)\ \beta^3\gamma^3\ \Delta(\nu^2)}{4\ r_e R^2 \left[1 + \epsilon_1 \frac{b(a+b)}{h^2}(1+\beta^2\gamma^2) + \epsilon_2 \frac{b(a+b)}{g^2}\beta^2\gamma^2\right]}$$

where e is the electronic charge, c the velocity of light, b the beam half-height, a the beam half width, β the beam velocity in units of c, γ the beam energy in units of the electronic rest mass, $\Delta(\nu^2)$ the allowable shift in the square of the vertical betatron tune, r_e the classical electron radius, $2\pi R$ the perimeter of the orbit, ϵ_1 the electrostatic image coefficient (typically 0.2), h the half-height of the vacuum chamber, ϵ_2 the magnetostatic image coefficient (typically 0.4), and g the magnetic half-gap. Figure 1 is a graph of this space-charge limit versus beam energy for typical beam geometries. It shows that to accelerate a 10-kilo-ampere electron beam a 50 MeV injection energy is required and a vacuum chamber with an aperture on the order of a meter in height in order to keep the image forces to an acceptable level. The space-charge forces here are image dominated to a degree that has never been experienced in any existing accelerator.

It may be surprising to find that the forces due to the electric and magnetic images in the walls can have a stronger effect on the beam that the internal forces of the beam itself. This is due to the strong cancellation of the electric and magnetic internal forces and the typical lack of such cancellation in the image forces. The net force on an electron due to the internal electric and magnetic fields of a straight beam is

$$f_{net} = e\,\vec{\varepsilon}_{int} + e\vec{v} \times \vec{B}_{int} = e\,\vec{\varepsilon}_{int}(1 - \beta^2) = e\,\vec{\varepsilon}_{int}/\gamma^2$$

where ε_{int} is the internal electric field strength, and B the internal magnetic field. Thus the internal electric and magnetic forces cancel to a high degree in the relativistic domain. At 50 MeV, e.g., the internal forces cancel to 1 part in 10^4. In toroidal geometry the degree of cancellation is not quite as great as in linear geometry but is still quite strong if the major radius of the toroid is much larger than the minor radius.

* Supported by the Defense Advanced Research Projects Agency.

1. A. Faltens, "Image Compensation", LBL internal report, LBID-548, Aug. 1981.

2. L.J. Laslett, Brookhaven National Lab report BNL-7534, 1963.

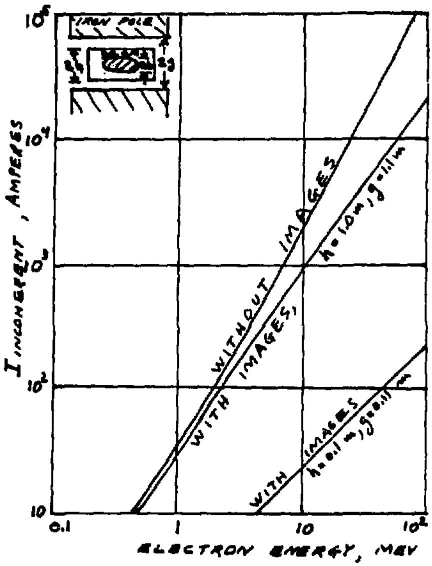


Fig. 1. Incoherent space-charge limit for case $a = b = (5 \times 10^{-3}\ R/\beta\gamma\nu)^{1/2}$ (m), R = 5 meters, and allowable tune shift $\Delta\nu = 0.25$.

$$I_{incoherent} = 4.3\ \beta^2\gamma^2/D\ \text{(amp)}$$

The image factor D is:

$$D = 1 + 0.4\ \frac{b^2}{h^2}\ (1+\beta^2\gamma^2) + 0.8\ \frac{b^2}{g^2}\beta^2\gamma^2$$

If we now consider the cancellation of the electric and magnetic forces due to the image charges and currents in the walls of the vacuum chamber, we again see strong self-cancellation when the beam is suddenly injected. However, this self-cancellation of the image forces is eventually lost because of two effects: (1) the current images tend to redistribute in the walls, so that the electric and magnetic image fields lose their orthogonality, which is necessary for the γ^{-2} degree of cancellation, and (2) the current images decay in magnitude, whereas the electric images are usually frozen in position and constant in magnitude. Implicit in the Laslett space-charge formula is the assumption that all the current images have died out, except the d.c. current image in the iron pole tips.

III. Image Compensation

To alleviate the space-charge detuning problem we have invoked a new technique called "image compensation". The idea is to maintain artificially the image currents set up by the beam, both in position and in magnitude. If this could be done perfectly, the image forces would be reduced by the factor γ^2, or 10^4 in the example just considered. Thus, even approximate compensation can alleviate the space-charge detuning effect to a significant degree.

A system for producing image compensation is shown in Figure 2a. It consists of an array of copper conductors near the ceramic walls of the vacuum chamber. Each conductor is in a circuit that contains (a) a bucking voltage equal to the voltage induced by the total magnetic flux change within the circuit (so that no current flows if the beam current is zero) and (b) a controllable power supply to maintain the current in that conductor at the proper value. A circuit with three of the image conductor circuits is illustrated in Figure 2b. In this example the compensating voltages are applied at one point, which forms the accelerating gap at which the beam gains energy on each revolution. The ideal pattern of image charges and image currents is set up automatically by the injected beam. The problem is to sense departures from the ideal image current pattern and to compensate them. A system of magnetic pickups oriented so as to sense only the magnetic field of the conductors and the beam is one method that has been considered for determining when and by how much the image current pattern has to be corrected. The time constants for redistribution of image current are estimated to be in the range of milliseconds for a typical betatron system. The time constants for the decay of the image currents is typically on the order of a second. Thus the circuitry involved is not technically demanding.

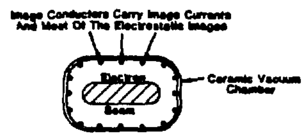


Fig. 2a. Cross Section Of Vacuum Chamber System

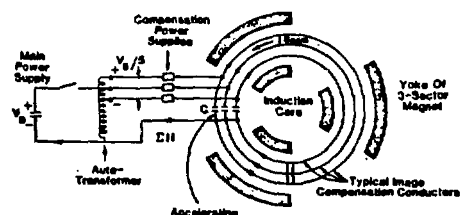


Fig. 2b

Fig. 2. Cross Section Of Vacuum Chamber System And Electrical Arrangement Of Image-Compensation And Accelerating System

XBL 822-7604

Note that the d.c. components of the image currents flow directly through the main power supply and thus directly couple the beam to the power source. The high-frequency components of the image currents must be conducted across the accelerating gap through by-pass condensers, as indicated in Figure 2b.

Another feature of the system of image conductors is that it can carry the magnetization current for the induction core as well as the image currents. Thus the system of image conductors replaces the normal betatron induction coil.

As a result of using the method of image compensation the vacuum aperture can be reduced considerably. For example, using only a modest factor of 4 as the reduction of the image force effects, we can reduce height of the vacuum chamber by a factor of 2. The smaller vacuum chamber produces a lower longitudinal impedance, and thus the longitudinal collective instability is also alleviated by the use of image compensation. This instability typically has a lower threshold than the transverse collective (resistive wall) instability (which favors a large vacuum chamber). In summary, the method of image compensation has provided a basis for designing a betatron system for accelerating a 10-kilo-ampere electron beam to several hundred MeV. In this arrangement all of the known instabilities can be controlled with a reasonable amount of energy spread.

The ion-electron type of collective instability can be avoided through good vacuum technique. This translates to a vacuum requirement of about 2×10^{-8} torr for an acceleration time of one millisecond.

IV. High-Current Betatron Model

A high-current betatron has been designed to test the concepts that we have developed for accelerating electron beams in the kilo-ampere range. It was designed to use the 10-kilo-ampere, 50-MeV Advanced Test Accelerator at the Lawrence Livermore National Laboratory as an injector.

The proposed machine is illustrated in Figure 3. It consists of a stack of three betatron rings with a common induction core. The three beams are accelerated simultaneously to 250 MeV and extracted in a controlled sequence during the magnetic flat-top.

The magnet is divided into three 120° sectors separated by three 1.8-meter straight sections, which provide field-free regions for the injection and extraction magnets. Each system has a vertically-deflecting iron-septum magnet plus a horizontally-deflecting full-aperture kicker magnet separated by 90 degrees in betatron phase. The orbit circumference is 18.0 meters, and the bending radius is 2.0 meters. The peak magnetic field at 250 MeV is 4.18 kilogauss. The stored energy in the magnetic field is 1.0 megajoule. The height of the magnet is 2.8 meters and its radial width is 1.3 meters. The magnet weight is 260 tons.

The ceramic vacuum chamber has a vertical aperture of ± 20 cm and a horizontal aperture of ± 25 cm. The injected beam has a vertical width of ± 4.4 cm, a horizontal width of ± 19 cm, and a momentum spread of ± 3.5%.

V. Betatron Study Group

The group that studied the use of betatrons for accelerating kiloampere beam included Robert Avery, William Barletta (LLNL), Andris Faltens, Donald Kerst (Univ. of Wisconsin), Robert Kuenning, L. Jackson Laslett, Edward Lee, Jack Peterson, Andrew Sessler, and Lloyd Smith.

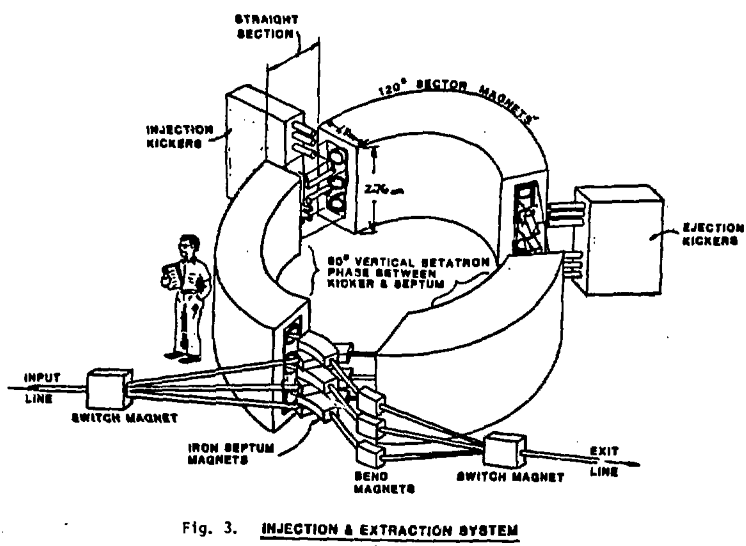


Fig. 3. INJECTION & EXTRACTION SYSTEM for 3 RING ATA ADD-ON.