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A STRETCHED BETATRON

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Abstract

A betatron of novel geometry is under development at UCI. Electrons are injected into an elongated magnetic mirror. The Larmor radius is 6 cm. The distance between mirrors is 80 cm. We seek to show that the total charge capacity of such a mirror trap is simply proportional to its length. The electron trajectories are helical with an axial period of 40 ns and an azimuthal period of 3 ns. The 40 ns axial period simplifies the use of both electrostatic and magnetic inflectors. A field emission injector (70 kV, 15 amp, 50 ns) allowed us to trap about 10 nC and contain it for about 10 μs. A 15-fold increase in the injected current led to radial loss of electrons in about 100 ns with no significant increase in the amount of charge trapped. Diagnostic methods are varied. A directional X-ray detector permits localization of beam spill. Electrostatic antennas detect radiation associated with collective motion of the electrons. A gate coil allows controlled opening of the magnetic trap. As the electrons are gated out they are collected to yield a direct measurement of trapped charge. Present work seeks to establish the mechanism of electron loss and to study the effect of asymmetries in fields and conducting boundaries.

Introduction

We have demonstrated trapping, confinement, acceleration and extraction of electrons in an Astron-like betatron. A high quality beam is required if the accelerated electrons are used, e.g., to drive a free electron laser. We have concluded that a tangential injector for the betatron is essential for achieving a low emittance beam. Our previous attempts to inject tangentially into a modified betatron have failed. The electrons did not trap - they always hit the injector after a few turns. The success of the vacuum injection in the Astron[1] project prompted us to try a similar configuration for a betatron. In the Astron vacuum experiments, although no field reversal was achieved, current of more than 1 kA was confined for about 200 ms. By using an inflector to facilitate trapping and an elongated geometry we believe that both high current and high beam quality is attainable. Our betatron has both solenoidal and toroidal fields of the same magnitude. The system accelerates ~ 10 nC of electrons to ~ 1 MeV in 200 μs. The electrons are confined on orbits of 5.5 cm radius between magnetic mirrors 80 cm apart. The injection energy is 70 kV. The injection current is 10 to 20 amps for ≈ 50 ns.

Experimental Apparatus

An overall scale diagram of the injector, field coils and vacuum chamber are shown in Fig. 1.

The toroidal vacuum system consists of two concentric glass pipes. The ends of the pipes are sealed with O-rings to Lexan end flanges. This forms an annular vacuum space. The inner surface of this glass is sputtered with gold to prevent surface charging. Access to the chamber is through a total of seven 1.125" ports (not shown) in the plastic end flanges. The base pressure is 2×10^{-5} torr. Use of a charcoal cold finger gives a base pressure of 2×10^{-6} torr.

Magnetic Fields

Magnetic fields provided are solenoidal, toroidal, an inflector field to trap electrons and an ejector field to extract them. The solenoidal field is obtained from windings set in a groove machined into the outside of an 8 1/2" O.D. lucite tube. The doubled winding density at the ends of the solenoid provide a mirror ratio of up to 30%.

The betatron condition requires that B_z at the electron orbit be half of B_z averaged across the orbit. To arrange this we place a 2 1/8" ID G-10 tube filled with powdered iron on the symmetry axis. The effective μ is about 5, and the corresponding equilibrium orbit radius is about 5.5 cm. Saturation occurs at 800-900 gauss applied magnetic field. The energy limit is thus about 1 MeV. The toroidal field is obtained from 47 turns of #10 AWG wire threaded between the inner glass tube and the flux concentrator's G -10 tube.

The inflector is a single turn coil placed in side the vacuum system; its radius is 7.2 cm and it is positioned as close as possible to the point of injection. It is energized during injection to reduce the mirror field close to the injector. Turning off the inflector traps electrons in transit at the time of turn-off.

The ejector field comes from two like windings in opposite sense at the ends of the solenoid. The coil near the injector adds to the main field. The coil near the target opposes the main field. Energizing the ejector shifts the electron orbits towards the target. Ejection takes less than 1 μs.

The injector is derived from a Russian design[2] and is shown to scale in Fig. 2. It uses a combination of Pierce cathode and ceramic drift tube to focus the electron beam. Reliable ignition is obtained by the use of Thornel graphite fibers as the emissive material.[3] The operating voltage is between 50 and 100 kV. We apply a 70 kV 150 ns pulse. The injector current rises to 10-20 amps before the impedance collapses at about 75 ns. The cathode fibers are replaced every few thousand shots.

Power Supplies

At present the toroidal and solenoidal field coils are connected in series. They are driven by a 46 μF capacitor charged resistively. A 15 μF capacitor is charged from the same supply to drive the ejector winding. Both circuits use ignitron switches. The injector is driven by a 200 ohm 150 ns Blumlein line delivering 70 kV. The line is pulse charged with a grounded grid thyratron and pulse transformer circuit.

Two circuits have been used to power the inflector. Initially we used a 50 ohm 150 ns Blumlein line delivering a square 10 kV pulse. This traps electrons effectively when a simple solenoidal field is used. It will not work when the toroidal field is added. A simple sine wave of 6 ns half cycle and 600 A peak amplitude will trap electrons when mixed fields are used.

Diagnostics

Charge collecting targets are the basic quantitative diagnostic. They are placed in the path of the electrons to measure injection efficiency. The integrated current signal is easily interpreted and noise is no problem. Trapped charge is measured by placing a target just outside the trap region. Energizing the ejector winding drifts the electron orbits and within at most a few axial transits all the trapped charge finds the target. These measurements are more noisy, but with care can be used for any time after 2-5 μs following injection.

A directional X-ray detector is used to monitor electron loss processes. It consists of a sodium iodide scintillator with a PMT. The injector is equipped with a capacitative voltage monitor and transformer current monitor. The gold lining of the chamber is isolated from the injector and so the ground return currents can be measured. Noise pickup has so far prevented the measurement of magnetic fields due to the trapped electrons.

Observations

Trapping and acceleration are achieved with a purely solenoidal field when the Blumlein line is used to drive the inflector with a 200 amp 10 ns full time pulse. 15-20 nC are trapped for 2 μs. X-rays indicate electron spillage during the first 50-100 μs of acceleration. The losses then become small until the accelerating field peaks at about 200 μs. During the field peak an abrupt dump spills most of the trapped electrons. Ejecting the charge onto a graphite target shows .5-1 nC just before the dump (Fig. 3). On some occasions the X-ray signals were cyclic with a period of about 1 μs. The orbit period is about 3 ns, the axial period is about 40 ns. Electrons have not been trapped in this mode when using the 6 μs 600 A sinusoidal inflector drive signal.

When the toroidal field is connected in series with the solenoidal field trapping is best achieved with the 600 A 6 μs sinusoidal drive to the inflector. The injector must be fired near the end of the inflector pulse. Electrons are still spilled during acceleration but the loss seems smaller than before and the dump at field peak is less complete. Ejection before dump reveals about 10 nC trapped at 200 ns (see Fig. 4). Roughly 15 nC are trapped for 100 ns (Fig. 5). Some earlier work involved independent control of solenoidal and toroidal fields. In general it seems easier to trap electrons when the toroidal field is rising. Trapping on a falling toroidal field is possible but more difficult.

The entire system operates without difficulty at .5 Hz. Higher rep rates could be easily used but for heating problems in the injector. With the addition of a ceramic insulator to the injector ten Hz seems practical.

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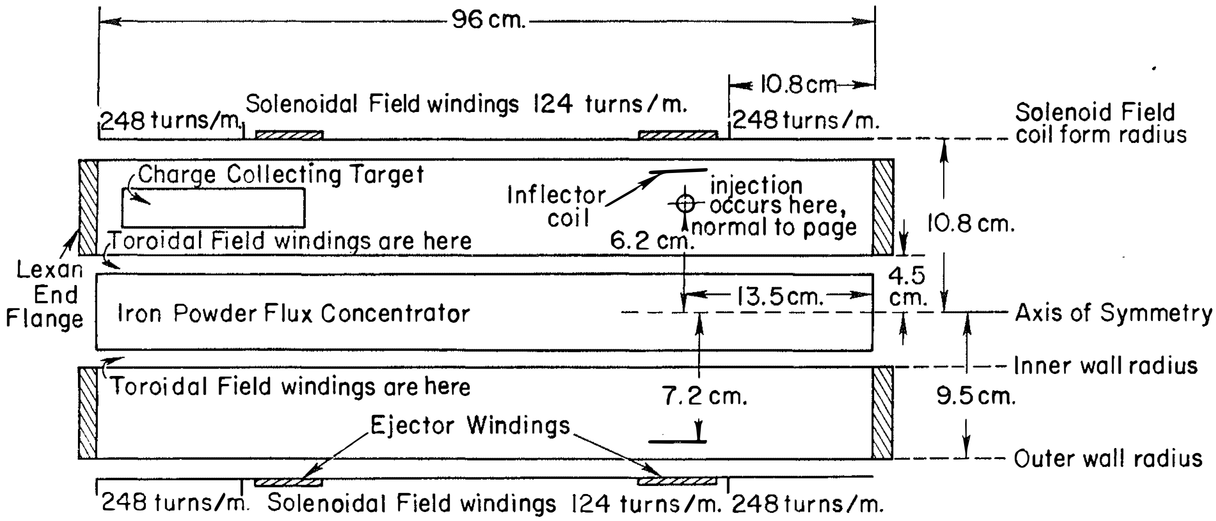

Fig. 1. The stretched betatron.

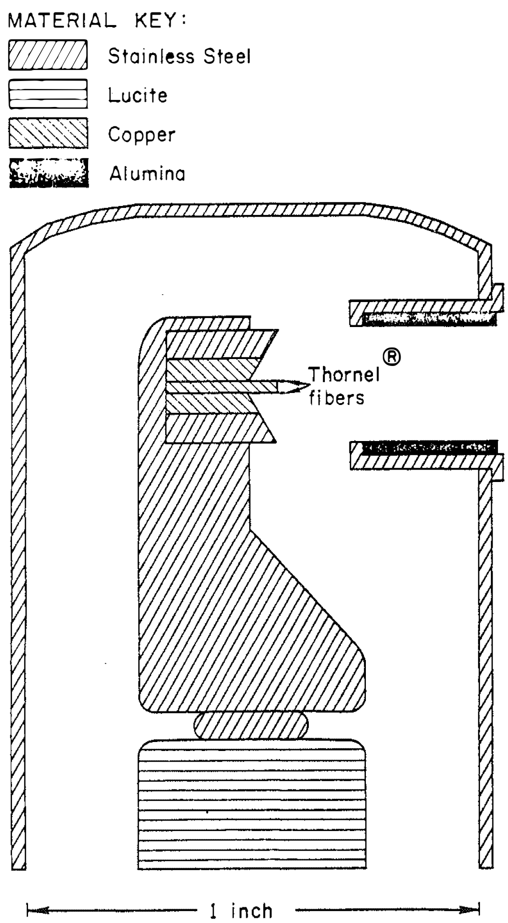

Fig. 2. Injector for stretched betatron.

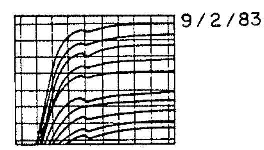

Fig. 3. Solenoidal field only.
ejection - 200 μs
5 nC/division
50 μ/division

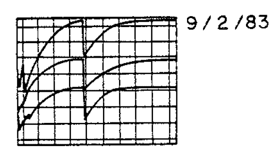

Fig. 4. Trapped charge on mixed fields.
ejection - 200 μs
5 nC/division
50 μs/division

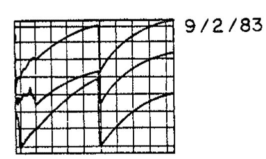

Fig. 5. Mixed fields.
ejection - 100 μs
5 nC/division
20 μs/division