A PROPOSED SYSTEM FOR MULTI-CYCLE INJECTION OF POSITRONS AND ELECTRONS INTO THE 6-GeV CAMBRIDGE ELECTRON ACCELERATOR

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Summary

The design of a system for accumulating counter-rotating beams of positrons and electrons, up to 0.1 A, in the CEA ring is discussed. Beams of this intensity are required if the CEA is to be used successfully as a colliding beam facility. Repeated, single turn, off-axis injection will be used at a repetition rate of 60 c/s. After each injection at 135 Mev,all particles will be accelerated to an energy in the 2 to 3 GeV range and then decelerated back to the injection energy. During the cycle, sufficient radiation damping of betatron and synchrotron oscillations is achieved to allow more particles to be injected without losing a large fraction of the particles injected in preceding cycles. Incoming particles are inflected by a septum magnet located off the equilibrium orbit while the path of the circulating beam is displaced towards the septum throughout the interval required for single turn injection.

The current that can be accumulated depends on the number of particles injected per cycle and the lifetime of the circulating beam. Injection of a positron beam is more difficult than injection of an electron beam because of the smaller current and larger emittance associated with the source. When the horizontal phase space is used for injection, the half-life of the circulating beam is estimated to be 90 s if the average gas pressure is 5.10^{-8} torr. The positron source is expected to deliver 0.4 mA with an energy spread of 2.5 MeV and an emittance of (2.5 π mrad. cm)[2]. We expect to be able to inject 0.1 mA of this current each cycle and have a considerable margin for error in arriving at our design estimate of 100 mA.

Beam Storage in a Synchrotron

At the Cambridge Electron Accelerator the possibility of using the existing synchrotron for storing counter-rotating electron and positron beams was investigated and found feasible for beams up to 4 GeV energy and with intensities sufficient to provide colliding beam experiments.[1,2,3] The method which is to be used to fill the ring with positrons and electrons was first indicated and tried by Ado, et. al.,[4] who stored an electron beam in a 280 MeV electron synchrotron. Electron storage rings are normally filled at energies high enough so that there is sufficient radiation damping between injection pulses; however, we propose to inject particles at a relatively low energy, and damping will be obtained by accelerating the particles to high energies and decelerating again. Figure 1 shows how the excitation of the ring magnets varies over the cycle. The radiation damping at high energies causes the beam, after it has been decelerated to injection energy, to have a reduced size and allows further off-axis injection without loss of previously injected beam. The advantage of this method is that filling the ring is possible at a high repetition rate with a small and inexpensive injector.

In such a cycling operation the damping times for synchrotron and betatron oscillations decrease with the third power of the peak energy. For the CEA they have been calculated[5] assuming 60 c/s operation and a minimum energy of 130 MeV. With a peak energy of 3 GeV, betatron oscillations are damped with a time constant of 51 ms giving a reduction in betatron oscillation amplitudes in one cycle by a factor of 0.7. At 2.5 GeV this factor becomes 0.81 and at 2 GeV it is 0.92. Synchrotron oscillations are damped at twice the rate of betatron oscillations.

However, the oscillations are not able to decay completely because of the quantum nature of the synchrotron radiation which excites synchrotron and betatron oscillations. These two effects give rise to an equilibrium horizontal width of circulating beam. When the energy is held constant the width is proportional to the energy. The equilibrium beam size at injection depends also on the adiabatic antidamping and on the voltage program of the radio-frequency cavities during the acceleration cycle.

The peak energy of the cycle is determined by the conflicting requirements of large damping ratios and a small equilibrium beam size. If we set a limit of 10^{-4}/cycle for the rate of beam loss due to particles passing out of the accelerator aperture and assume a constant radiofrequency voltage throughout the cycle, we find that the necessary horizontal aperture varies from 1.1 inches for a peak energy of 2.5 GeV to 0.8 inch for 2 GeV. Smaller apertures can be tolerated if the radio-frequency voltage is increased when the beam is at the higher energies. With an available horizontal aperture of 2.6 inches in the CEA, the optimum peak energy is believed to be between 2.5 and 3 GeV.[3]

The Injection System

Figure 2 shows the relative locations of the electron linac, the converter, the positron post-accelerator and the synchrotron. The electron linac has a dual role. Either it provides electrons for injection in the counter-clockwise direction or it generates positrons at the converter for subsequent injection in the opposite direction. The location of the linac, radial to the ring, simplifies the transport systems and will enable switching from positron to electron injection in a few seconds. The final steering element of each of the transport systems is a septum magnet which adjusts the angle of the incoming beam for minimum betatron oscillation amplitude at the septum. These magnets are displaced from the equilibrium orbit of the stored beam,which is not affected magnetically because of the shielding action of the septum. At the time of injection,the orbit of the circulating beam is displaced towards the septum and afterwards it is returned to its normal position. This change in the position of the equilibrium orbit prevents the newly injected beam from being lost on the septum after several more turns around the accelerator.

Present plans call for filling no more than half the circumference of the ring with positrons or electrons. The injection pulse length is therefore less than 0.38 μs, leaving almost another 0.38 μs for turning the orbit distortion on or off. In principle this distortion could have a considerably longer switching time since it is necessary for the beam to go around the synchrotron several times before the more recently injected beam is at the right betatron phase angle to strike the septum. However, if the orbit switching time is fast, a larger distortion can be used resulting in a smaller betatron oscillation amplitude for the newly injected beam. The reason for wanting a fast switching time stems from the magnitudes of the damping factors. Oscillations induced when particles are injected are not attenuated to equilibrium beam size in one cycle, although they will have become incoherent during this period. If the orbit distortion is made large enough, the septum becomes the limiting aperture for the circulating beam but part of the beam that has not reached the equilibrium size strikes the septum and is lost. This loss can be kept quite small if the orbit distortion exists only for the time beam is being injected.

Figure 3 illustrates injection in the horizontal aperture. Figures 3 (a) to 3 (c) represent the beams immediately before, during, and one turn after an injection pulse. The diagrams on the left are for real space; the Y-axis indicating the vertical direction and the X-axis the horizontal. The diagrams on the right represent horizontal phase space. For simplicity, the momentum spread in the beams has been neglected. Fig. 3(a) shows the stored beam just before the orbit distortion is turned on and more beam is to be injected. The inner shaded region is beam that was injected many damping time constants ago. In the physical space diagram it contains 99.995% of the circulating beam. Surrounding this core is beam which was injected on recent cycles and has not come to equilibrium. Fig. 3 (b) shows the beams at injection after passing through the septum magnet. The orbit distortion has been applied and a little of the incompletely damped beam has been lost. The positron beam being injected is shown filling the aperture of the septum magnet (emittance of the electron beam will be much smaller). Beam falling outside the septum is not correctly steered and most of it will be lost, as will any beam traversing the septum magnet but lying outside the ellipse indicating the acceptance of the CEA. Only the beam occupying the hatched portion of the phase space diagram can be captured. In fig. 3 (c), one turn after injection, the orbit distortion has been removed and the beam just captured has betatron oscillation amplitudes which are smaller than the distance between the equilibrium orbit and the septum. As the coherence of these oscillations is lost and radiation damping has had time to have some effect, we arrive back at fig. 3 (a) ready for another injection pulse.

Septum Magnets

The septum magnet planned for the electron beam has an aperture 1 inch square. The septum is 0.02 inches thick and carries a current of 320 A. The bending strength is 1.2 kG-inch. The septum magnet in the positron path will be similar but with a somewhat larger bending strength.

Production of a Rapidly Switched Orbit Distortion

The orbit distortion required is shown in figure 4. The three bends are produced by ferrite window magnets which have a rectangular aperture of 4¼ inches in the horizontal direction and 1¼ inches in the vertical. These magnets do not limit the CEA aperture.

The magnets are placed in accelerator straight sections #23,26 and 31. Straight sections #23 and 31 are separated by a betatron phase angle 384° and a bend at either one can be very nearly cancelled by a bend at the other. The inclusion of a third magnet allows complete cancellation of the distortion around the ring except between sections #23 and 31. This distortion has a suitable amplitude at the two septum magnets in straight sections #25 and 29.

The single-turn ferrite magnets are to be driven from coaxial cable, pulse-shaping circuits. The lines will be charged to 15 kV and each switched by a hydrogen thyratron.

Injection Timing

The approximate timing of the injection pulse (to within one turn) will be derived from a peaking strip, which senses the correct magnetic field strength in the synchrotron for the energy of the injector. The exact timing, within a single turn, for the injector and the orbit distortion magnets will be determined from a clock running at the orbital frequency of 1.3 Mc/s. The clock will be driven from the radio-frequency system of the synchrotron.

Estimate of Beam Intensities

Because the emittance of the positron beam is much larger than that of the electron beam, we will fill the ring with positrons first, taking advantage of the full vertical aperture. After the ring is filled, vertical electrostatic fields around the ring will displace the positron equilibrium orbit vertically and allow electrons to be injected and to avoid the positron beam.

The total positron current possible is given by the product of the current injected per cycle and the lifetime of the beam. These two factors are not entirely independent.

Beam Intensity Injected per Cycle

The most relevant information concerning the yield from a positron source similar to the one we intend to use is given by Amman, et. al., for the linear accelerator installed at Frascati. By scaling the measured numbers in their report, we estimate for the CEA positron linac a positron current of 0.4 mA within an energy spread of 2½% at 135 MeV and an emittance of $(2.5\ \pi\ \text{mrad. cm})^2$.

Knowledge as to the acceptance of the CEA at 135 MeV is less certain. At present with an injection energy of 35 MeV, it appears that the horizontal aperture into which we can inject is appreciably less than the 2.8 inches that could be expected from the "good field region" of the synchrotron magnet. However, it has been shown that it is possible to expand the beam to a width of 2.6 inches after acceleration to near 130 MeV and still retain the beam for the rest of the acceleration cycle. We hope this value will apply when injecting with the new linac. If we assume this aperture, a peak energy of 2.5 GeV, an orbit distortion of 0.65 inches during injection and the numbers given earlier for the positron source, we calculate an injection efficiency of 25%.[7] The result gives an injected beam current per cycle of 0.1 mA.

Beam Lifetime During Multicycle Filling

The most important source of beam loss during multicycle filling is single Coulomb scattering in the vertical plane, off the residual gas. A calculation[8] of the lifetime with corrections for scattering off bound electrons and for bremsstrahlung gives a value of 210 s for an average gas pressure of 5.10^{-8} torr at an injection energy of 135 MeV. In addition to these losses we have the loss of 10^{-4} per cycle due to the limitation of the horizontal aperture and the consequent scraping off of the Gaussian tail of the horizontal equilibrium beam distribution. An overall lifetime of 90 s or 5400 cycles together with an injected current of 0.1 mA per cycle leaves a comfortable margin for error if we require 100 mA circulating current.

Use of the Vertical Betatron Phase Space

The largest uncertainty so far has been the available horizontal aperture in the CEA at injection. If the aperture turns out to be considerably smaller than the 2.6 inches we have assumed, our margin dwindles quickly. However, provided the equilibrium width of the circulating beam is not larger than we expect, a reduction of 1 inch in the horizontal aperture is required to reduce the injection efficiency by a factor of ten.

We have considered using the vertical aperture for injection as an alternative. A magnet, placed above the median plane is used for the final horizontal steering of the incoming beam, but the lower horizontal iron magnetic return path is made as thin as possible (0.016 inches) and forms a shielding septum for the circulating beam. The orbit distortion is now made in the vertical direction.

The lifetime due to single scattering is of course much smaller. The overall lifetime is estimated to be 65 s and the injection efficiency is down to 3%. Thus it seems that currents of up to only 45 mA could be accumulated this way. It is to be noticed, however, that this number will increase linearly with an improvement in the vacuum.

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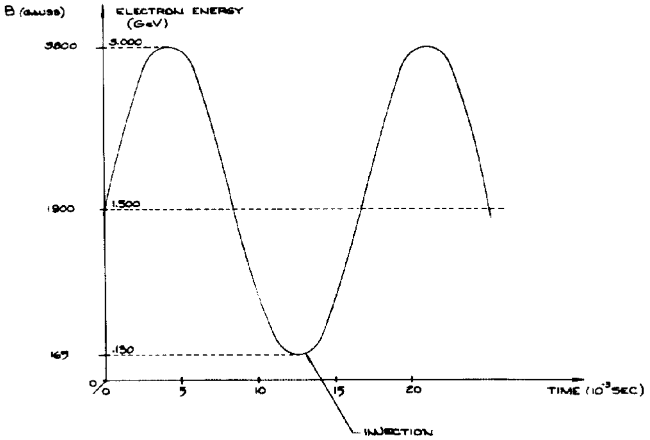

Fig. 1. Synchrotron magnet excitation for multi-cycle injection.

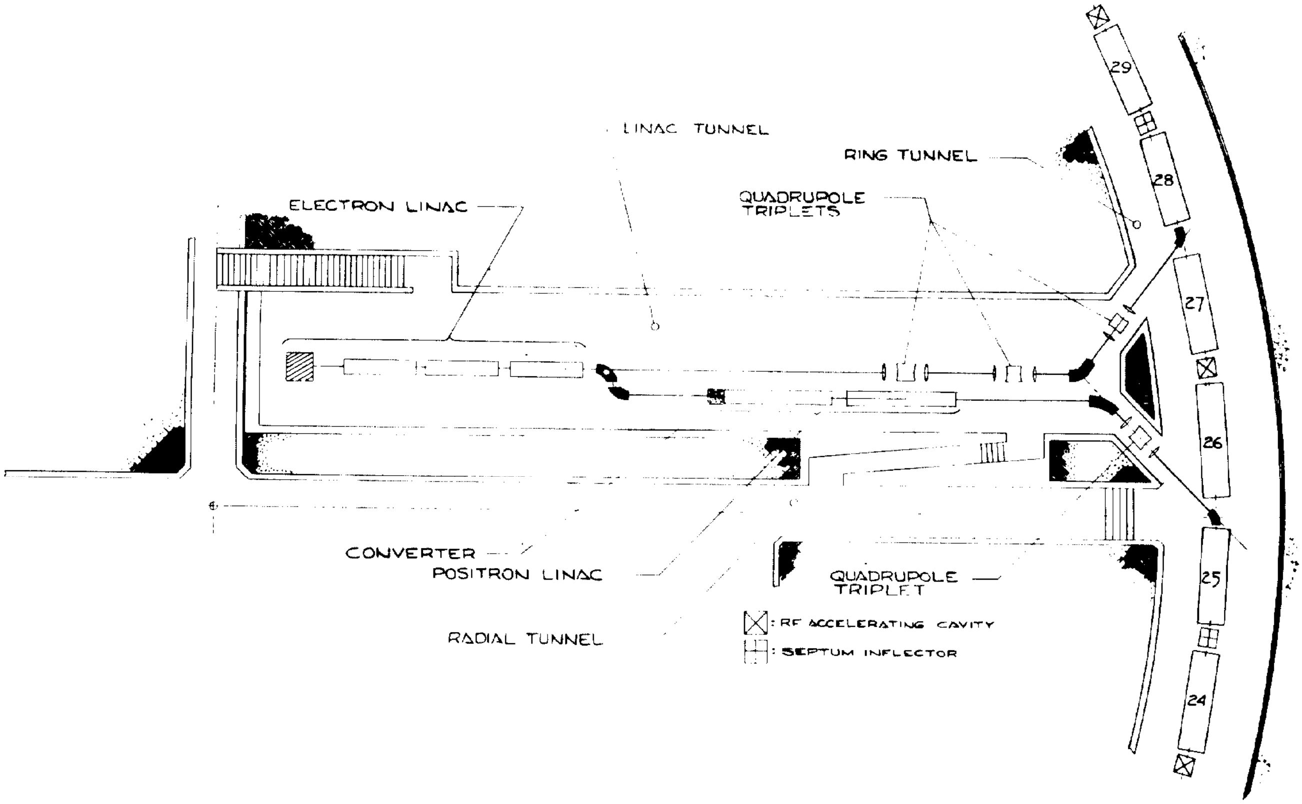

Fig. 2. Plan showing the relative locations of the electron linac, positron accelerator and the Cambridge Electron Accelerator ring.

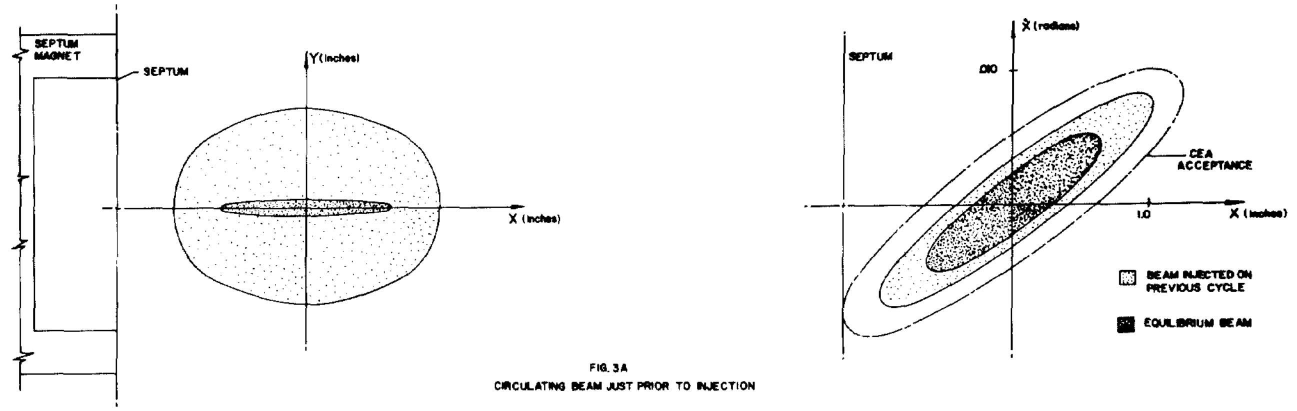

FIG. 3A
CIRCULATING BEAM JUST PRIOR TO INJECTION

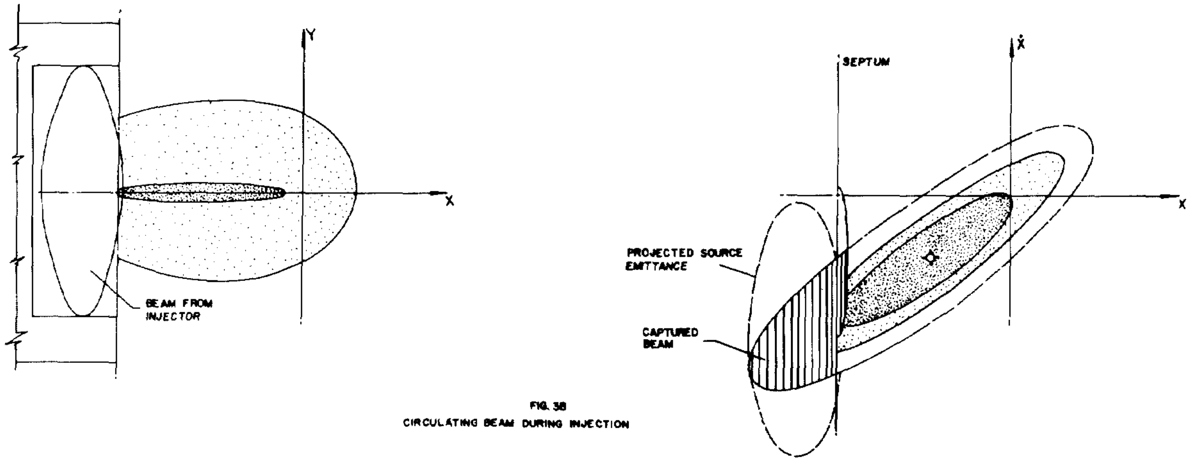

FIG. 3B
CIRCULATING BEAM DURING INJECTION

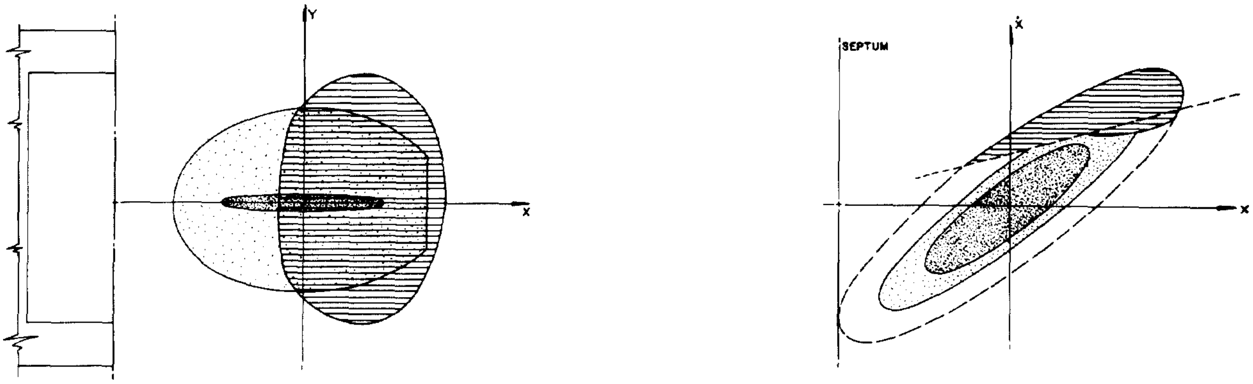

Fig. 3. Beam cross-sections at the septum magnet during injection. The drawings in the column on the left are projections in the plane perpendicular to the normal equilibrium orbit. The diagrams on the right are of the radial betatron oscillation phase space.

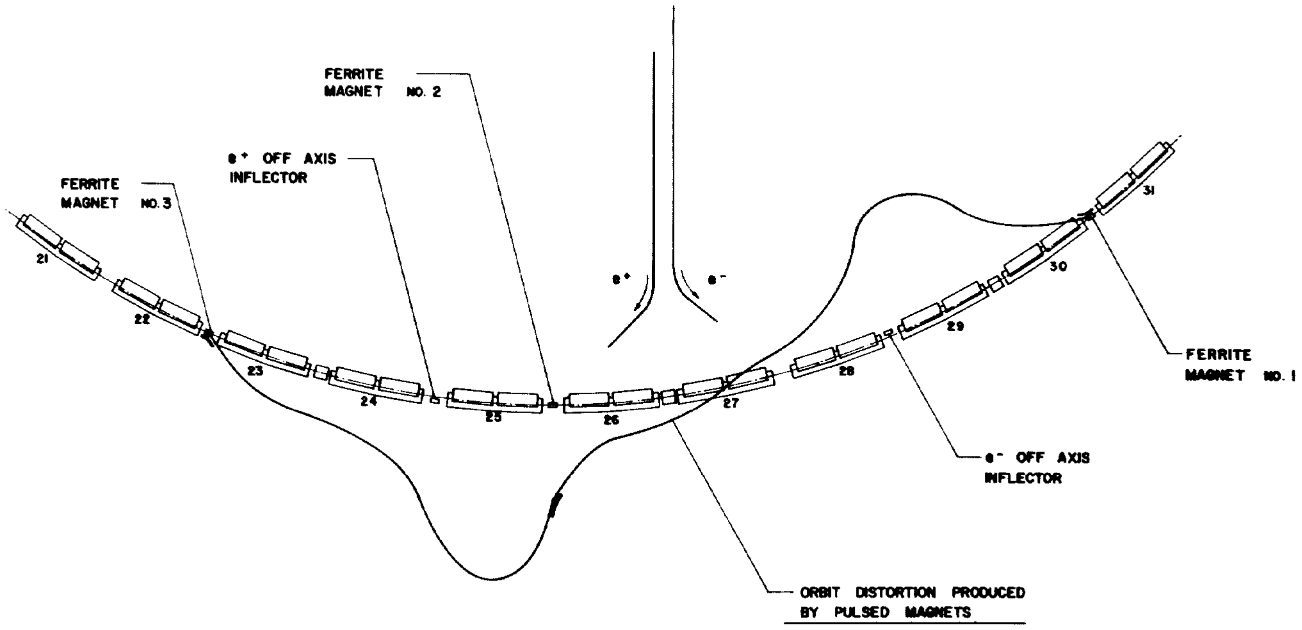

Fig. 4. Schematic diagram showing the production of a local orbit distortion for multi-cycle injection.