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THE EXTERNAL ELECTRON BEAM FACILITY AT THE CAMBRIDGE ELECTRON ACCELERATOR

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Summary

The development of the resonant extraction technique has made possible the slow extraction of the internal beam from alternating gradient synchrotrons. An electron beam was extracted from the 6 Gev Cambridge Electron Accelerator in 1963, using this technique.[1] Measurements of intensity and emittance confirmed the design calculations on the components of the extraction system. During 1964, the external beam facility was developed to a point where it is in routine use for high energy physics experiments. Some modifications were made to the components of the extraction system and a more complete study was made of its performance. Seventy per cent of the circulating beam is extracted with spill times up to 1 millisecond. Two beams are derived from the extracted beam and are transported by achromatic transport systems to different points on the experimental floor. Each transport system was designed in such a way as to minimize the radiation hazard which could be produced by the intense electron beam.

The Extraction System

The Extraction Mechanism

The current strip and ejection magnet (see below) are located inside the equilibrium orbit in straight sections 4 and 5 of the accelerator, see Fig. 1. At high energy when one wishes to extract the beam, the current strip and ejection magnet are pulsed on and the beam is made to approach the strip slowly by applying a beam bump[2]. The magnetic field of the current strip acts as a non-linear focusing element increasing the horizontal betatron frequency from the normal 6.4 to the half integral resonance at 6.5. The radial oscillations grow so rapidly that a large fraction of the electrons jump the current strip without colliding with it. An electron which has jumped the strip is now deflected further inward away from the equilibrium orbit and into the aperture of the ejection magnet where it is deflected outward leaving the accelerator through a special exit vacuum chamber in magnet 6.

The Current Strip and Ejection Magnets

The mechanical design of the first version of the current strip and of the ejection magnet has been described previously[1] and only the basic design parameters are given here.

The current strip is a water cooled copper conductor 24" long, 0.6" high and 0.035" thick. It can be pulsed to a maximum current of 3000 amps with a 20% duty cycle. Due to thermal and radiation damage to the epoxy insulation, the original design of current strip suffered from local overheating which caused it to rupture. It was replaced by an improved all metal design[3] which has proven to be completely satisfactory.

The ejection magnet is a septum magnet with a single turn coil within the aperture, arranged so as to produce little field outside the magnet. The length of the magnet is 24" and it has a useful aperture 1" wide and 0.3" high. The maximum design current is 5500 amps with a 20% duty cycle. Both the ejection magnet and the current strip are capable of being remotely positioned inside the straight section vacuum tanks of the accelerator.

The Pulsers

The synchrotron is operated over a wide range of peak energies, 600 Mev to 6 Gev. The ejection magnet and current strip pulsers must, therefore, be capable of producing current pulses with a similar range of amplitudes, the maximum current being 5500 and 3000 amps respectively. The pulses must have one millisecond flat tops to allow beam extraction times of this order and should have short rise and fall times to minimize power dissipation in the magnets.

The pulsers which were originally designed for this application, employed banks of high power transistors switching current between storage inductors and their loads[1]. The advent of high power silicon controlled rectifiers made possible the construction of the simpler lumped circuit discharge line pulsers which are presently used. Figure 2 shows the circuit of this type of pulser. The current step up transformers are placed close to their loads while the other components are outside the synchrotron tunnel. To prevent the A.C. coupling of the transformers giving rise to a current in the extraction magnets during injection, the circuit is arranged so that the resonant charging current also passes through the transformer and load, see Fig. 2. The pulse shape can be adjusted by varying the coupling between the coaxial air cored inductors in the discharge line. Power is supplied to the discharge lines from voltage stabilized power supplies.

Performance of the Extraction System

The efficiency of the extraction system and the emittance of the extracted beam were measured over the energy range 1 to 6 Gev. The effect of varying the fields and positions of the current strip and ejection magnet were also studied. After leaving the accelerator the electron beam was focused by two quadrupole magnets on to glass microscope slides placed 40 feet from the exit point. Darkening of the glass by radiation made beam size clearly visible when viewed by a television camera and quantitative information was obtained from photometric measurements. The beam was transported in a vacuum pipe which was an extension of the accelerator vacuum system and contained a beam position monitor[4] and an RF cavity current monitor. A Faraday cup acted as a beam stopper and a total current monitor.

The extraction efficiency was measured to be 70 % at all energies and independent of spill time up to the maximum possible of one millisecond. Under typical operating conditions this gives a beam of approximately 10^{12} electrons/sec with an overall duty cycle of 3 %. The horizontal and vertical emittance of the extracted beam was calculated from the measured relationship between beam spot size and quadrupole lens strength. The vertical emittance is largest at low energies, about 0.7 mm-milliradian total area at 1 Gev, and decreases with increasing energy to about 0.2 mm-milliradian at 6 Gev.

The extracted beam has an inherent energy spread which, because of the momentum vector of the exit trajectory, increases the overall horizontal emittance at the exit point. The energy spread is dependent on the process used to initiate beam extraction. Using a high energy beam bump, the energy spread is small (less than $\pm$ 0.05%) at energies below 5 Gev and the horizontal emittance is 4 mm-milliradian. Between 5 and 6 Gev the energy spread increases to $\pm$ 0.1% and the overall horizontal emittance is 8 mm-milliradian. If RF turnoff is used to initiate beam extraction the energy spread at 6 Gev is $\pm$ 0.3%.

Both the efficiency and the overall horizontal emittance are a function of the power level at which the current strip is operated. Increasing the current in the strip gives a higher extraction efficiency at the expense of an increased horizontal emittance.

Beam Transport Systems

The layout of the transport systems of both electron beams is shown in Fig. 1. The beam spot size at the experimental target and the location of the target and the beam line, were determined by the particular requirements of each experiment. A long beam extraction time implies a time dependent energy spread (1 millisecond spill time gives $\pm$ 0.5% energy spread) and, therefore, the transport systems were required to be achromatic. The beams are transported in vacuum up to and including the experimental target. This vacuum system is directly coupled to the accelerator and is pumped by two pumping stations identical to the accelerator pumping stations. Numerous beam position monitors[4] are installed along the transport system and small steering adjustments, $\pm$ 1 milliradian are made with coils mounted on the vacuum pipe. The magnetic elements of the system are 72" x 10" x 2" bending magnets and 16" x 4" diam. quadrupole lenses. The magnets are operated up to 19.2 Kgauss giving a deflection of 183 milliradian at 6 Gev. The quadrupole lenses throughout both beam transport systems are operated with approximately 100" focal length which requires 9.2 Kgauss/in at 6 Gev.

The beams pass through the well shielded target area of the accelerator, across the relatively poorly shielded experimental floor and are absorbed in heavily shielded beam catchers. If a power supply for any of the magnetic elements in the system failed or was incorrectly set, the electron beam could strike a vacuum pipe, quadrupole lens etc., producing a severe radiation hazard on the experimental floor. The transport systems were designed in such a way as to overcome this problem.

Beam (8) transport system consists of nine quadrupole lenses and three bending magnets, cf Fig. 1. Quadrupoles Q3 to Q7 make the system achromatic to first order and they are powered in series from one power supply. Q1 and Q9 are horizontally focusing and Q2 and Q8 are vertically focusing, each pair being connected in series. The three bending magnets are also connected in series as one unit. As a result of powering the magnets and lenses in this way, one cannot change the beam location or beam size on the experimental floor without producing a corresponding change earlier in the transport system. Therefore, by limiting the possible beam size and range of positions inside the target area, one can prevent the beam hitting an object on the experimental floor. A water cooled slit, 20 radiation lengths thick, was placed at Q5 as shown in Fig. 1. The size and location of the slit was determined from a computed error analysis of the transport system. Two larger slits were added further downstream to absorb scattered electrons from the primary "safety slit". The above system has been operating for six months over a range of energies from 1 to 6 Gev, focusing the beam to a spot 1 mm high and 3 mm wide at the target.

Beam (7) transport system contains 6 quadrupoles and 2 magnets bending in the vertical plane. This beam is used as an electron or a photon beam for the same experimental program. To produce the photon beam a converter is placed ahead of magnet M.a, which deflects the electron beam downwards into a beam stopper and a beam collimator is placed ahead of M.b, which acts as a scrubber. When operating as an electron beam the magnets are not powered and the quadrupoles focus the beam onto the target. As in beam (8) radiation safety is secured by grouping appropriate lenses in series and by having a limiting slit between them.

Trickle Beam

A second experiment on the latter beam line requires a weak electron beam of approximately 10^8 electrons/sec. This magnitude of current can be extracted by a Piccioni type system. If when the beam in the accelerator is bumped onto an internal photon target, the ejection magnet (placed close to the equilibrium orbit) is powered, about 0.1% of the degraded electrons are extracted. This "trickle beam" is transported by the same transport system which is arranged to focus it beyond the beam catcher onto the target of the downstream experiment.

The extraction of this weak electron beam has forced the development of ultra-sensitive RF cavity beam position monitors. These position monitors are rectangular cavities operating in the TM 210 mode on the third harmonic (1.4 KMHz) of the accelerator radio-frequency. They utilize the fact that the extracted electron beam maintains its R.F. structure and they are three orders of magnitude more sensitive than the tuned position monitors[4] in Beam (8).

Future Development

With an increasing number of experiments being planned using electron beams it is becoming necessary to extract further beams from the accelerator. The presently used extraction system is limited in that it can only be usefully applied at this one location in the accelerator. Alternative extraction systems are being studied. At the present time it would appear that a possible system will consist of a combined current strip and ejection magnet, in one straight section, situated on the outside of the equilibrium orbit.

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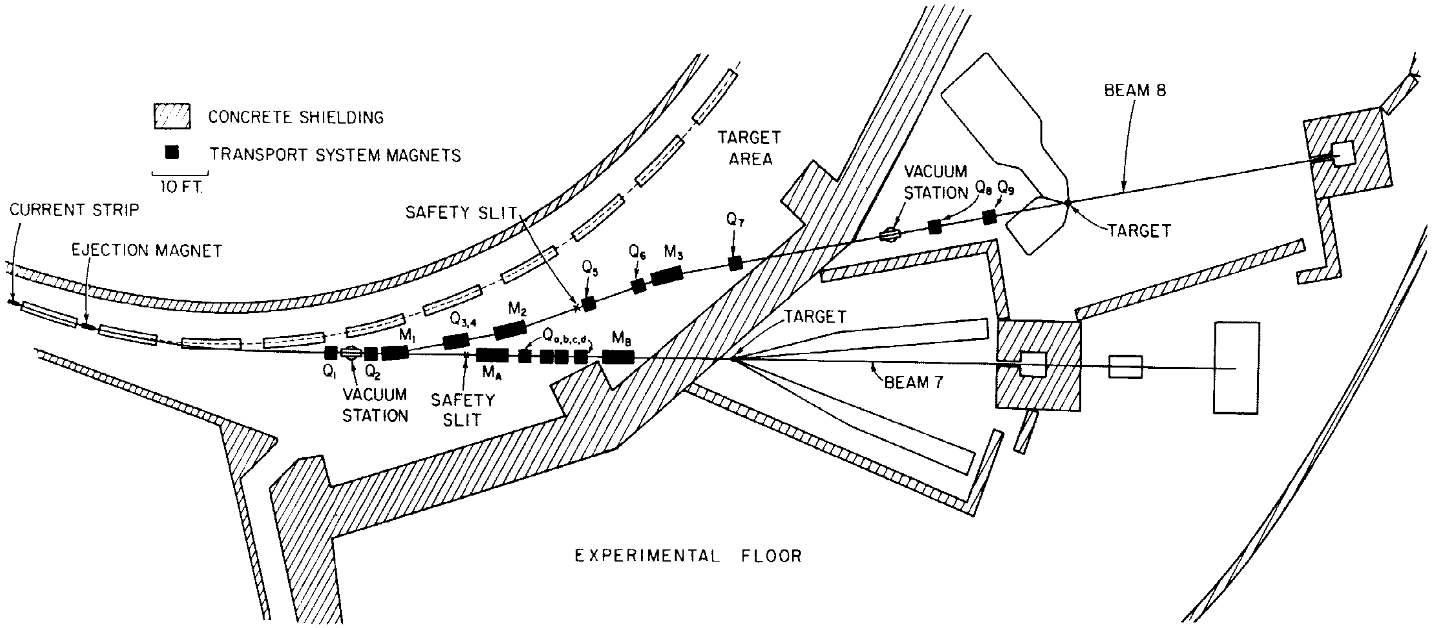

Fig. 1. Part of the target area and experimental floor of the CEA showing the overall layout of the external electron beam facility.

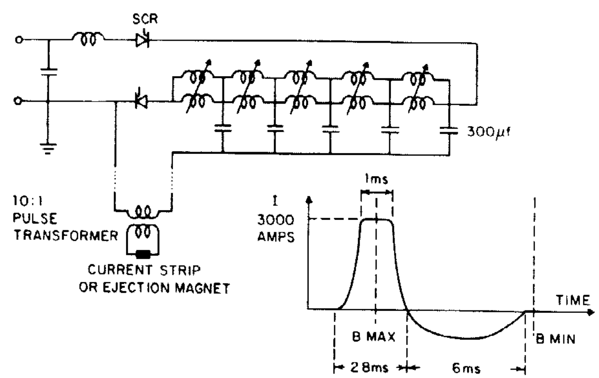

Fig. 2. Schematic diagram of ejection magnet and current strip pulsers showing typical current pulse.