OCT 18 1963

CEAL-1006

CONF-114-19

MASTER

THE EXTERNAL ELECTRON BEAM
of the
CAMBRIDGE ELECTRON ACCELERATOR

F.W.Brasse, G.E.Fischer,
M.Fotino, K.W.Robinson

Facsimile Price \$ 1.60

Microfilm Price \$.80

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

September 1963

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
and HARVARD UNIVERSITY

CAMBRIDGE ELECTRON ACCELERATOR

CAMBRIDGE 38, MASSACHUSETTS

PATENT CLEARANCE OBTAINED. RELEASE TO
THE PUBLIC IS APPROVED. PROCEDURES
ARE ON FILE IN THE RECEIVING SECTION.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

CAMBRIDGE ELECTRON ACCELERATOR

HARVARD UNIVERSITY
42 OXFORD STREET
CAMBRIDGE 38, MASS.

CEAL-1006

F. W. Brasse*
G. E. Fischer
M. Fotino
K. W. Robinson

September 27, 1963

THE EXTERNAL ELECTRON BEAM OF THE CAMBRIDGE
ELECTRON ACCELERATOR

Paper presented at the International
Conference on High Energy Accelerators
at Dubna, USSR, August 1963

22-27

Abstract

The beam extraction method of the Cambridge Electron Accelerator uses a single current strip, located at the inside of the aperture of the circulating beam, as its essential element. The magnetic field of the current strip acts both as a non-linear regenerator to increase the frequency of the radial betatron oscillations to a resonance, and as a deflector when the electrons jump to the other side of the strip. Results of measurements of the extraction efficiency and the characteristics of the extracted beam are given, and compared with values predicted by calculations.

* On leave from Deutsches Elektronen-Synchrotron, Hamburg, Germany

THE EXTERNAL ELECTRON BEAM OF THE CAMBRIDGE
ELECTRON ACCELERATOR

Introduction

In order to obtain a slow extracted electron beam from the Cambridge Electron Accelerator, it is necessary to use some form of resonant extraction system. A Piccioni type of extraction system is not feasible for electron accelerators as the Bremsstrahlung loss in any absorber greatly exceeds the collision loss. The fluctuation in the Bremsstrahlung loss would result in only a small fraction of the beam being extracted through a channel with practical energy acceptance.

The betatron frequencies of the Cambridge Electron Accelerator are about 6.4 for both radial and vertical oscillations. This makes it possible to use very simple resonant extraction system. A single focusing element may be used to bring radial betatron frequency to the 6.5 resonance, and cause the oscillation amplitudes to grow sufficiently rapidly that most of the particles jump to the other side of a current strip septum. Due to initial

value of 6.4, the vertical betatron frequency will not approach the 6.0 resonance, and the amplitude of the vertical oscillations will not be significantly increased.

In order that the beam may be extracted over a long period of time, it is necessary that the focusing element be non-linear, so that the circulating particles may be gradually brought into the region of the aperture in which the focusing element is effective.

In the Cambridge Electron Accelerator it has been possible to achieve the function of non-linear focusing element and septum magnet by a single current strip. The direction of current is such that the magnetic field of the strip deflects the electrons away from the strip. The magnetic field of the single current strip has a non-linear focusing effect in the horizontal plane, with the maximum focusing effect occurring at the edge of the strip.

In the operation of the beam extraction system, the electrons are caused to slowly fall out of synchronism with the radiofrequency system by reducing the voltage. The particles then move inward toward the current strip due to radiation loss or the increasing magnetic field. As the electrons move into the region of the strip, the radial oscillations grow rapidly such that a large fraction of the electrons jump to the outside of the current strip without striking it. On the outside of the current strip the particles are deflected away from the principal orbit, such that

at the next straight section they are well separated from the aperture of the circulating beam. At this point there is a second magnet which bends the particles radially outward, such that they emerge from the synchrotron at the third straight section beyond the current strip.

Components of Extraction System

The arrangement of the beam ejection system is shown in figure 1. The current strip is located in a straight section ahead of a radially defocusing magnet. The construction of the current strip is shown in figure 1. It consists of a copper strip one mm wide and 5 cm high. The top and bottom are slotted to restrict the current to the center 1.5 cm of height. The length of the current strip is 61 cm. The strip is mounted on stainless steel water cooling tubes. It is insulated from the cooling tubes by a layer of epoxy about 0.1 mm thick. The resistance of the current strip is .97 milliohms, and the inductance with leads is about 2 microhenries. The current required for extraction of 6 Gev electrons is 3150 amperes, and the power dissipated in the strip is about 750 watts.

The cross section of the second ejector magnet is shown in figure 1. The magnet has an iron core made up of laminations .18 mm thick. The magnet is excited by a single turn coil within the aperture, arranged so as to produce very little field outside the magnet. The coil is formed of copper conductor, pierced for water cooling. The aperture available for the extracted

beam is 2.5 cm wide and .8 cm high. The length of the magnet is 61 cm. The inductance of this magnet with leads is about 5 microhenries, and the resistance is 0.83 milliohms. The field and current required for 6 Gev operation are 8540 gauss and 5500 amperes.

In order to reduce the heating in the ejection magnets, the current is pulsed on at the end of the acceleration cycle when the beam is extracted. In order to obtain an extracted beam up to one millisecond long, the current must have a flat top one millisecond long. A pulser has been developed to produce a current pulse with a 0.5 millisecond rise time, a one millisecond flat top, and an exponential decay of about two milliseconds.

The basic circuit of the pulser is shown in figure 2. During the time between pulses a current somewhat larger than the pulse current circulates through the choke and transistor bank. This choke of about 50 microhenries acts as an energy storage device for the pulser. The transistor bank consists of 288 transistors in parallel. In parallel with the transistor bank are the ejection magnet and three diodes in series. The impedance of the diodes is sufficiently high that when the transistors are turned full on, very little current circulates through the magnet. In order to pulse the magnet the impedance of the transistor bank is increased. The current then decreases in the transistor bank and rises in the magnet. When the current reaches the desired value the control circuit regulates the impedance of the transistor

bank, so as to maintain the current in the magnet constant for one millisecond. At the end of the pulse the transistor bank is again turned full on. The current then decays in the magnet and rises in the transistor bank. This type of pulser is used for both the current strip and the second ejection magnet.

After being deflected outward by the second magnet, the electrons emerge as an external electron beam at the end of magnet six. This is an open magnet so as the particles traverse the outward edge of the field there are no large non-linear effects. At the end of magnet six, the electrons are 13.4 cm from the principal orbit. There is a special vacuum chamber in magnet six which extends farther outward than a normal vacuum chamber, and has an exit port which joins to a vacuum pipe for the external beam.

Calculation of Electron Extraction

In order to design the extraction system, calculations were made on an electronic computer. Particles were started with various amplitudes and phases of radial and vertical betatron oscillations. The motions of the particles for successive turns were calculated including the current strip. The effect of the current strip is to introduce a radial angular deviation of $\theta_x = \frac{2}{\pi} \theta_M \tan^{-1}(h/x)$, and a vertical angular deviation of $\theta_y = \frac{2}{\pi} \theta_M h y / (h^2 + x^2)$, where h is the half height of the strip, x is the horizontal distance from the strip, and y is the vertical distance from the median plane, and θ_M is the deflection of a

particle at the edge of the strip. Each turn of the calculation, the equilibrium orbit was moved a small distance toward the current strip. The calculation for each particle was continued until the particle first went beyond the edge of the current strip. At low energies the movement of the equilibrium orbit is due to the increasing magnetic field, and may be as little as 3×10^{-3} cm per turn. At 6 Gev the movement due to the radiation loss is almost 1 mm per turn.

It was found that the calculated efficiency of the best design was in the range of 75 to 80%. This calculated efficiency is almost independent of the rate at which the orbits of the particles approach the current strip. Most of the loss of particles is due to hitting the current strip. A small number of particles are lost by striking the outer edge of the current strip aperture. The best efficiency was found with a strip 1.5 cm high, producing a deflection of 4 milliradians at the edge of the strip. This strip has a gradient at the edge of the strip approximately twice as large as that required to move the operating point of the radial betatron from 6.4 to the 6.5 resonance.

The calculated vertical emittance of the extracted beam is about the same as the circulating beam in the accelerator. It is largest at lower energy. At 2 Gev it is about .05 cm-milliradian total area. At 6 Gev it is less than .02 cm-milliradian.

The horizontal emittance is calculated to be about 0.2 cm-milliradian. It is almost independent of energy. There is also an energy spread in the extracted beam. At low energies, when the

orbit approaches the current strip slowly, this is less than 0.1%. At 6 Gev, when the orbit approaches the current strip rapidly, the calculated energy spread of the extracted beam is about 0.6%. This energy spread is due to the random initial phases of the radial betatron oscillations. Due to the rapid movement of the equilibrium orbits toward the current strip, the particles with different initial phases are extracted at different positions of the equilibrium orbit. Due to the momentum vector of the ejection trajectory following the current strip, this energy spread results in an increased horizontal emittance at the exit point. This may be eliminated by designing an external transport system so that the momentum vector of the ejection trajectory is cancelled.

Performance of the External Electron Beam

The equipment for the external electron beam system has been fabricated and assembled during the last two years. The principle of the extraction system was first tested by using only the current strip on April 5, 1963. The position of the extracted beam at the next straight section was observed by the darkening of glass slides between lead plates which had been inserted into a reentrant tube. The intensity of the extracted beam was estimated by the heat delivered to a water cooled lead stopper. It was found that the extraction efficiency was greater than 50% in the energy range 1.2 to 6 Gev. The position and size of the beam in the next straight section agreed fairly closely with calculations

from 1.2 to 6 Gev, although a small discrepancy in position was found at 6 Gev.

The second ejection magnet and special vacuum chamber were then installed. The electron beam was first extracted from the Cambridge Electron Accelerator on July 2, 1963. This was done at an energy of 2 Gev, since a temporary pulser for the second magnet could not be operated at a higher energy. The beam was directed into a large lead Faraday cup located in the target area, about 6 meters from the exit window. The extraction efficiency was measured to be 70%.

The size of the beam at the Faraday cup was measured with glass slides to be roughly 1 cm both vertically and horizontally. The emittance of the external beam was measured by putting a quadrupole lens at this point, and focusing the beam onto glass slides located another 6 meters beyond the original location of the Faraday cup. The total area of the emittance at 2 Gev was measured to be 0.1 cm-milliradian in the vertical, and 0.3 cm-milliradian in the horizontal. The increased area of the measured emittance as compared with the calculated values is believed to be due to scattering in the exit window, and in the horizontal to the variation of the current in the second ejection magnet.

A transport system has been designed to direct the electron beam along a presently exiting gamma beam, and to eliminate the momentum vector of the ejection trajectory. This transport system uses two bending magnets and four small quadrupoles. It is expected that the external electron beam will be operational for experiments before the end of 1963.

Acknowledgment

We wish to thank the many members of the CEA staff who contributed their efforts; in particular, the Vacuum Group under J. Hagopian and the Operations Group under G. Voss.

EJECTOR MAGNET PULSER

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to any information pursuant to this employment or contract with the Commission.