EXCITATION OF RADIAL OSCILLATIONS IN THE BEAM OF THE SYNCHROCYCLOTRON BY THE PERIPHERAL CEE*

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Measurements of the characteristics of operation of the University of Rochester peripheral Cee show that the Cee may be used not only in the normal manner to stochastically accelerate the internal beam but also in a manner which induces radial oscillations in the coasting beam. These measurements verify the proposal of Wormald[1] by fitting the Dee cutoff frequency, the Cee frequency and the magnetic field gradient to the well known function for radial oscillations in a cyclotron. Other evidence for this regenerative mode of operation are the fact that the energy of a polarized proton beam obtained by scattering the internal beam from a carbon target is reduced by an amount determined by the Dee cutoff frequency, and that its energy spread is also reduced. The pion beam intensity obtained when the Cee is operated in this regenerative mode is nearly independent of the voltage on the Cee whereas in the accelerating mode it is approximately linearly dependent on the voltage. Details of the characteristics of operation are presented.

Introduction

The University of Rochester synchrocyclotron produces about a 5-μa, 240 MeV internal beam with about a 2% duty cycle. The Dee voltage is about 15 KV and is modulated 200 times per second between 26.8 and 18.8 megacycles by means of a rotating condenser. The magnet pole is 130" in diameter and has a maximum field of 16.8 Kgauss.

By now nearly all synchrocyclotrons have installed a peripheral Cee in order to increase the duty cycle by stochastically accelerating the beam into the target as proposed by Keller and Schmitter.[2] We have built such a Cee primarily following the modulation scheme of Suzuki.[3] The Cee electrodes are of aluminum, 1 1/2" above and below the median plane, covering an azimuthal angle of 45° and covering the radial extent from 55 3/8" to 62 5/8". (Targets are placed at 58 1/2" where $n = 0.2$). The Cee is operated at about 4 KV r.m.s. with a 4CW10,000A driving a shorted transmission line and 50 Ω load in a system similar to the Harvard system.[4]

When using the Cee to accelerate the beam stochastically, the Dee r.f. voltage is turned off while the beam is circulating at a radius just inside the target position, at a corresponding Dee frequency of 20.1 mc. The Cee is then modulated between about 20.2 mc and 19.6 mc to accelerate the beam on out to the target radius. A second way to modulate the Cee was first discussed by J.R. Wormald from experience on the Liverpool synchrocyclotron.[1] They found that the internal beam strikes the target even if a frequency gap of 0.7 mc is maintained between the point where the Dee cuts off and the Cee turns on. They proposed that the Cee is inducing radial oscillation in the coasting beam but did not have conclusive evidence for this proposal. We have observed this same effect and present evidence here that this is indeed the correct explanation.

Measurements

Duty Cycle - Coarse Structure

Our method of modulating the Dee r.f. voltage and the Cee r.f. voltage in this regenerative mode is shown at the top in Fig. 1. As in the accelerating mode the Dee r.f. voltage is turned off at about 20.1 mc leaving the internal beam circulating at a radius slightly smaller than the target position. The Cee r.f. voltage is modulated from about 19.5 to 18.9 mc with superimposed sawtooth sweep, 100 Kc, and 500 Kc sine waves. The coarse structure of the duty cycle is shown at the bottom of Fig. 1 as obtained from the secondary pion beam counted in a 400 channel analyzer operated in the multiscaler mode. The coarse duty cycle (defined as $\langle \text{intensity} \rangle^2 / \langle \text{intensity}^2 \rangle$ is greater than 90%. The small spike of prompt beam may be reduced or increased by slight adjustments in the Dee cutoff frequency. No periodicies of the 100 Kc or 500 Kc modulations are observed in the beam intensity

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as long as both frequencies are present.

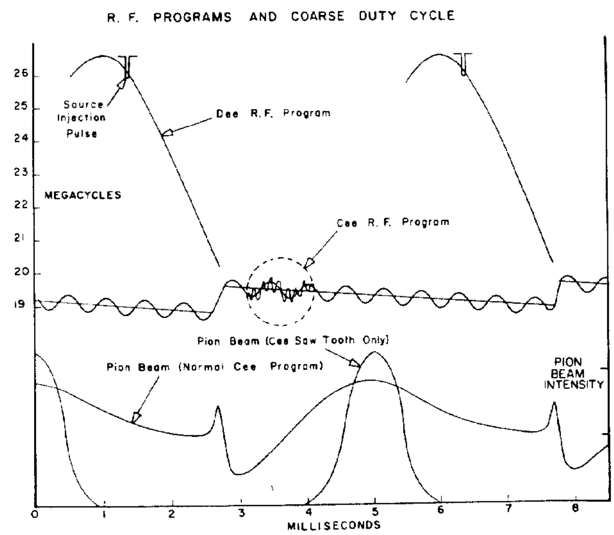

Fig. 1. Dee and Cee r.f. modulation program in the regenerative mode of operation and the coarse duty cycle of the beam intensity.

Duty Cycle - Fine Structure

Figure 2 shows the fine structure in the time distribution of the pion beam as obtained with a scintillation telescope and a time to pulse height converter. The characteristic period using the Cee in the regenerative mode is 52 nsec corresponding to a frequency of 19.2 mc. This is lower than either the Dee cutoff frequency (20.1 mc) or the circulation frequency at target radius (19.6 mc) and is evidently the resonant frequency of radial oscillations of the circulating beam. This frequency is given by the expression:

$$f_r = f_{Dee}(1-n)^{1/2}$$

where f_{Dee} is the beam circulation frequency or Dee frequency at the time of turning off the Dee r.f. voltage and n is the magnetic field index at the radius of the coasting ($n = -\frac{dB/B}{dr/r}$). Under the conditions of Fig. 2 (and Fig. 1):

$$f_r = 20.1(1-0.09)^{1/2} = 19.2 \text{ mc}$$

in agreement with the measured characteristic period. The Cee increases the width of the fine structure peaks only slightly; from 9 to 11 n sec.

Intensity

With nearly optimum duty cycle the $\pi+$ beam intensity is actually greater than the prompt beam intensity (about 120%) while the $\pi-$ beam intensity is less (about 60%). This difference may indicate that the Cee either walks the internal proton beam into or away from the target depending on the relative azimuthal position of the Cee and target. In the $\pi+$ case the Cee is in a position which also would be optimum for a magnetic regenerator, i.e. 90° "downstream" from the target. The magnetic regenerator was not in the cyclotron at the time of these measurements. In the accelerating modes intensities of only about 50% of the prompt beam are observed in both cases. The pion beam intensity obtained when the Cee is operated in the regenerative mode is nearly independent of the voltage on the Cee whereas in the accelerating mode it is approximately linearly dependent on the voltage. The regenerative mode is evidently more efficient in use of the available power.

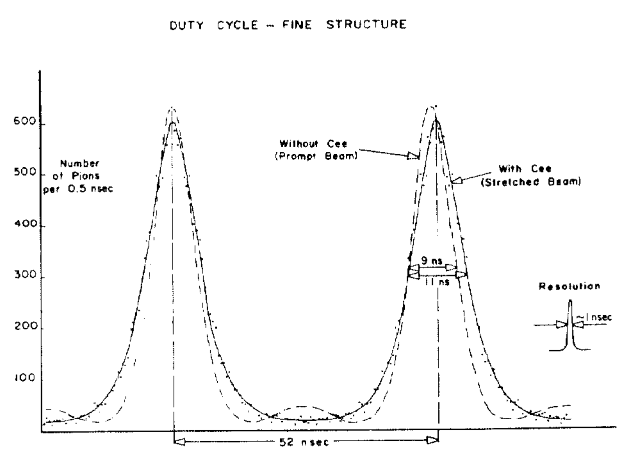

Fig. 2. Fine structure of the beam intensity with and without the Cee.

f_{Cee} vs. f_r

The proposal that the Cee induces radial oscillations may be verified in a direct manner. The frequency of the Cee at maximum pion beam intensity, f_{Cee} , may be measured as shown in Fig. 1 using the sawtooth modulation only. The frequency of radial oscillation, $f_r = f_{Dee}(1-n)^{1/2}$ may independently be determined from measurements of f_{Dee} and n . (The dependence of n upon radius in our machine is known from magnetic field measurements.[5] The radius of the coasting internal beam may be measured as a function of f_{Dee} by measuring the Dee frequency at the time the internal beam strikes a target at a known radius) A plot of f_{Cee} vs. f_r is shown in Figure 3 for measurements over a range in f_{Dee} of 20.9 to 19.7 mc. This corresponds to a range in radii of 50.5 to 58.1 inches and a range in n of 0.06 to 0.14. The actual measurements are represented by circles on Figure 3. The shaded band represents the combined measuring uncertainties and possible systematic errors on each axis. Agreement is close between the predicted and measured values.

CEE FREQUENCY vs. FREQUENCY OF RADIAL OSCILLATION

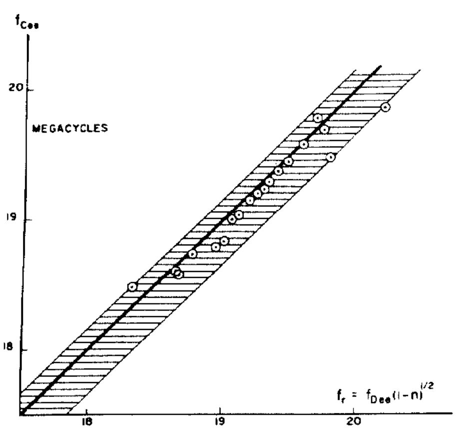

Fig. 3. The Cee frequency at maximum beam intensity versus the frequency of radial oscillation calculated from the Dee cutoff frequency and the magnetic index.

Energies

One further measurement demonstrates that when the Cee is operating in the regenerative mode only f_{Dee} affects the energy of the internal beam: This energy is :

$$T/E_o = \frac{1.52B}{f_{Dee}} - 1$$

with B in Kilogauss, f_{Dee} in mc and E_o is the rest mass. For four settings of f_{Dee} the energies calculated from the above formula reduced by the average energy loss in the target are plotted in Figure 4 against experimental energies determined from range measurements. The calculated energies are very sensitive to small uncertainties in B and f_{Dee} but they are in agreement with the measured energies. One differential range curve with the Cee is shown at the bottom of Figure 4 as also is the range curve of the prompt beam. The energy spread with the Cee in the regenerative mode is only 3/4 as wide as the spread without the Cee. This is due to the fact that the usual radial oscillations in the internal beam do not contribute to the energy spread. The intensity of the scattered external proton beam with the Cee in only about 60% of that without it even though the circulation of the internal beam is in the same sense as for the π+ case which gave over 100%.

CALCULATED vs. MEASURED PROTON BEAM ENERGIES

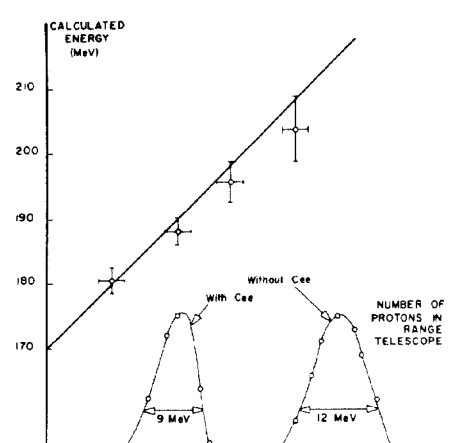

Fig. 4. -TOP- Four proton beam energies calculated from the Dee cutoff frequency, the magnetic field, and the energy loss in the target versus the experimentally measured energies.
-BOTTOM- Experimental range curves plotted in terms of energy with and without the Cee.

Concluding Remarks

Operation of the Cee in the regenerative mode has been useful, especially for high duty cycle pion beams. With the regenerative mode the scattered proton beam is somewhat more monoenergetic but double energy peaks will be produced if the Cee is inadvertantly modulated in both the regenerative and acceleration modes simultaneously. It is not known whether the regenerative mode is compatible with an extraction system for the internal beam since this cyclotron does not have such a system. The compatibility may depend on the relative azimuthal position as in the case of ordinary magnetic regenerators. It would be of interest to investigate the dynamics of the circulating beam being perturbed by the various components of the electric field but this has not been done. The results may indicate that a radial component is more effective than the azimuthal field of the present configuration.

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