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REGENERATIVE BEAM EXTRACTION FOR THE BERKELEY 88-INCH CYCLOTRON*

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Abstract

The electro-static regenerative beam extraction system for the Berkeley 88" cyclotron is described. Results of the orbit studies using the modified general orbit code are shown. The design features of the regenerator with a 3 section electro-static deflector are given. The results obtained from the machine tests are summarized.

1. Introduction

For the positive ion isochronous cyclotron, a number of beam extraction methods are proposed, namely: turn separation by energy gain and precession, the nonlinear resonance, and regenerative extraction. The original beam extraction method for the Berkeley 88" cyclotron was investigated by Garren et al.,[1] using turn separation from energy gain and precession. The beam extraction based on this study was accomplished by Grunder et al.[2] The beam could be accelerated through $\nu_r = 1$ and $\nu_r = 2\nu_z$ resonances. About 50% extraction efficiency and 0.5% energy spread has been achieved. Later developments improved further from the above figure.[3] One may improve the system by using a beam with narrow rf phase (single turn extraction); but it requires an accurate instrumentation and it reduces greatly the duty cycle. Extraction by the nonlinear resonance is rather difficult for the variable energy machine.

The successful operation of the electro-static regenerative system for the Birmingham 40" cyclotron,[4] led to an investigation of regenerator beam extraction for the 88" cyclotron. This method was originally developed for synchrocyclotrons by Tuck, Teng[5] and LeCouteur.[6,7,8] In this method turn separation is obtained from the resonance excitation of the radial motion by the gradient harmonics. Since the turn separation does not depend, in principle, on the energy gain, a low dee voltage can be used for the cyclotron. Also the energy spread of the extracted beam can be improved.

This paper describes the investigation of regenerative beam extraction for the 88" cyclotron. In the following section, general considerations and numerical integration results are presented. In Sect. 3 preliminary operating features of the system are summarized. Finally future developments are discussed.

2. General Considerations and Computer Studies

The Berkeley 88" cyclotron is a 3 sector A.V.F. variable-energy cyclotron designed to accelerate protons up to 60 MeV, deuterons up to 65 MeV, and heavier ions up to comparable energies.[9] A plan view of the pole face and the original extraction system is shown in Fig. 1. The entrance of the deflector starts at 3° azimuth and ends at 108°. The maximum deflector voltage held is given by $VE = 1.5 \times 10^3$ kV^2/cm.

For a given dee position and external beam line, the following restrictions are imposed.

1) The maximum deflector strength should not be more than in the original system, namely: $VE = 1.5 \times 10^3$ kV^2/cm^3. Therefore the entrance of the deflector should be located near 3°, unless the regenerator action makes possible a reduction of the required deflector strength. This eliminated a possible use of the peeler, because a peeler should be located inside the dee.

2) When we fix the position of the entrance of the deflector near 3°, the regenerator should be located near 60-90° for good turn separation at the entrance of the deflector.

3) Since we are considering the use of only the regenerator, the radial position of the regenerator should be started at about $\nu_r = 1$ and we should be inside the $\nu_r = 2\nu_z$ resonance.

4) Since the 88" cyclotron is a variable energy machine, it is preferable to use an electrostatic device rather than magnetic bump for the regenerator.

Following the above requirements, computer studies were made by the General Orbit code,[10] including acceleration and the action of the regenerator. The cross section of the regenerator electrodes are similar to the Birmingham system,[4] which is shown in Fig. 2. The effects of the 3/4" open slot is shown in Fig. 3. When the particle enters the regenerator, the action of the regenerator is introduced as an impulse at each Runge-Kutta step, to change the radial and the vertical momentum.

Analytical studies indicated the worst position of the regenerator is at about 60° azimuth, and the best is at about 120° for the 88" cyclotron.[11] Therefore a comparison is made for the two cases at 60 and 90 azimuth. The ν_r and ν_z values of 65-MeV α particles are shown in Fig. 4. We took the starting radius of the regenerator (end of the tail) at 37.7" average radius, a 6° long regenerator, a voltage of 240 kV at the electrode spacing of 3 cm. Turn separation is plotted in Fig. 5, showing clearly that the position at 60° is worst. Therefore the main study is made for the regenerator at 90° azimuth. A regenerator 36° long is chosen for a reasonable maximum voltage and electrode spacing of 3 cm.

To find the best condition, corresponding to the best energy resolution, a turn separation of 0.25", and a reasonable vertical amplitude, we

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tried several radii for the regenerator position. One of the best results for 65-MeV α particles is shown in Fig. 6. A quarter of the 1/2" square radial phase space is separated by 0.04" at 39.0" radius, at 3° azimuth. Individual particles have turn separation of 0.2". An improvement of the energy spread is clearly shown, but the wide rf phase (60°) of the internal beam may make a continuous overlapping of the phase space, and the energy spread of the external beam may be 100-200 keV, full width half maximum. The average vertical amplitude is increased by about 30% at 39.0" radius. For a stronger regenerator, or a larger radius, the turn separation and the energy resolution is improved, but the vertical amplitude is increased further. For stable vertical motion the change of ν_z should be slower than Fig. 4. A higher energy gain makes the change of ν_z fast during regeneration, and therefore it is better to use a lower dee voltage for stable vertical motion. The result for 130-MeV α particles is more or less the same as 65-MeV α, except the radius of the regenerator should be about 0.2" smaller. This is because the field falls off faster. The voltage of the regenerator for 130-MeV α is at about 60 kV.

For the design of the electro-static deflector channel, the CYBOUT code[12] was used, with the channel entrance at 3°, 9°, and 21°, using the initial conditions from the regenerated beam. We can see from Fig. 6 that there is a large x' spread at 3° and this causes a reduction of acceptance for the deflector channel. At 21°, the turn separation will be bigger, and the acceptance better, but it requires a higher electric field gradient for the deflector channel than the strength given $\nabla E = 1.5 \times 10^3$ kV^2/cm. Finally a compromise is made at 9° and a flared channel shape is used: $E = (150\text{-}33\ \theta^2)$ kV/cm for 130-MeV α particles, with the entrance of the channel at 38.9". If we had the entrance of the channel at 3°, the electric field could be $E = (135\text{-}35\ \theta^2)$ kV/cm. Therefore, if we could put the regenerator at about 60° and the channel at 3°, we could gain a considerable reduction in deflector voltage compared to the extraction without regenerator, for which case $E = (160\text{-}35\ \theta^2)$ kV/cm.[1]

For the different energy beams, the shape of the channel is different from the case of 130-MeV α particles due to the difference in the flutter and the shape of the fringe-fields. Therefore, a 3 section deflector is proposed to match these cases.

The position of the virtual source for the radial and the vertical motion are approximately the same as for the original deflector, and therefore the optics of the external beam may not be changed.

3. Preliminary Results from Experimental Testing

To check calculations on turn separation produced by a regenerator, a model regenerator was constructed by the 88" cyclotron engineering group. The regenerator was 24" long, curved to match the 130-MeV α particle equilibrium orbit, and had an electrode spacing of 2.5 to 3.0 cm. This was the same size as the proposed final regenerator. The model was simplified mechanically to allow a preliminary test without a deflector. The regenerator was located at 90° azimuth (the center of a valley) with a starting radius adjustable from 36.5-38.0". A Δr probe at 3° azimuth was used to obtain turn separation measurements in the cyclotron. One of the results of these measurements is given in Fig. 7. Current collected by the outer electrode of the Δr probe indicates that the necessary 0.2" turn separation was obtained.

The final design of the 3 section electrostatic deflector with the regenerator is shown in Fig. 8. The regenerator is located at 90° azimuth and the radial position can be changed from 36.9-37.9". The spacing of the electrodes is 2 to 3 cm. The deflector extends from 9° to 117° azimuth. The septum has a 4" V slot. The position of the regenerator and the deflector channel can be changed remotely from the control room. The mechanical details of the design of the system are described in a separate paper by D. Elo et al.[13] One positive high voltage supply for the regenerator and three negative high voltage supplies for the 3 section deflector are of the Cockcroft-Walton type using silicon rectifiers and 100 kc oscillator for the primary.[14]

The extraction studies are made with and without the regenerator. The deflector voltage required is less with the regenerator on than it is off. Since the deflector channel is moved 6° downstream in this new system, the regenerator must be used to extract the highest energy particles—above 100-MeV α particles. The primary study is made for 65-MeV α particles with and without the regenerator for comparison. The result of the extraction study is summarized in Table I. For around 50 kV dee voltage the quality of the extracted beam is about the same and the extraction efficiency is slightly lower with the regenerator. A part of the loss seems to be in the vertical direction. The deflector voltage is slightly lower with the regenerator, even though the radius of the channel is smaller in that case. For around 20 kV dee voltage, which is the lower limit of the operating voltage given by the ion source and the center region, the extraction efficiency is much higher with the regenerator. But the acceleration is more difficult due to requirements of isochronism. A satisfactory trim coil solution for the isochronous condition up to 37.5" average radius was obtained from a computer calculation using the "linear programming method",[15] and the outer 2 trim coils of the 17 were adjusted to match regenerator requirements. This low dee voltage run may have considerable importance for a future higher energy machine. Twenty kV dee voltage at 65-MeV α particles is about the same as 60 kV dee voltage for 100 MeV protons, as far as the number of turns is concerned. So a regenerator with a single dee at 60 kV could be used to give enough turn separation for 100 MeV protons to enter an electro-static channel in an 88" cyclotron, and to ease the requirement for deflector strength. In such a design one would also want a larger diameter machine to make deflection easier.

A brief test of the beam extraction for 120-MeV α particles was made with the regenerator, and about 45% extraction efficiency was obtained. The difficulties of holding regenerator voltage at higher magnetic fields made it hard to optimize. Several ideas for electron dumps have been tested and have improved the voltage holding characteristics of the regenerator.

4. Conclusion

Using the higher dee voltage, the regenerative extraction system for the 88" cyclotron gave about the same beam quality and extraction efficiency as the original system for normal operational dee voltage. By careful shaping of the magnetic field near the extraction radius, the system can be improved further, namely by an improvement in the vertical loss. The relative position of the magnetic sectors to the dee gave a tight design limit. This reduced the acceptance of the beam into the deflector channel and prevented the use of a peeler. A low dee voltage test indicated possible uses of the regenerator in higher energy machines with a comfortable dee voltage.

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Table 1

Dee voltage	50 kV		20 kV	
Reg. voltage	32 kV	0	28 kV	0
Ent. of def.	38.8 in.	39.0 in.	38.8 in.	39.0 in.
Max. gradient	60 kV/0.25"	62 kV/0.25"	58 kV/0.25"	62 kV/0.25"
Max. extraction efficiency	~60%	~65%	55%	~30%
The best ΔE/E of ext. beam	~0.25%	~0.25%	not measured	not measured

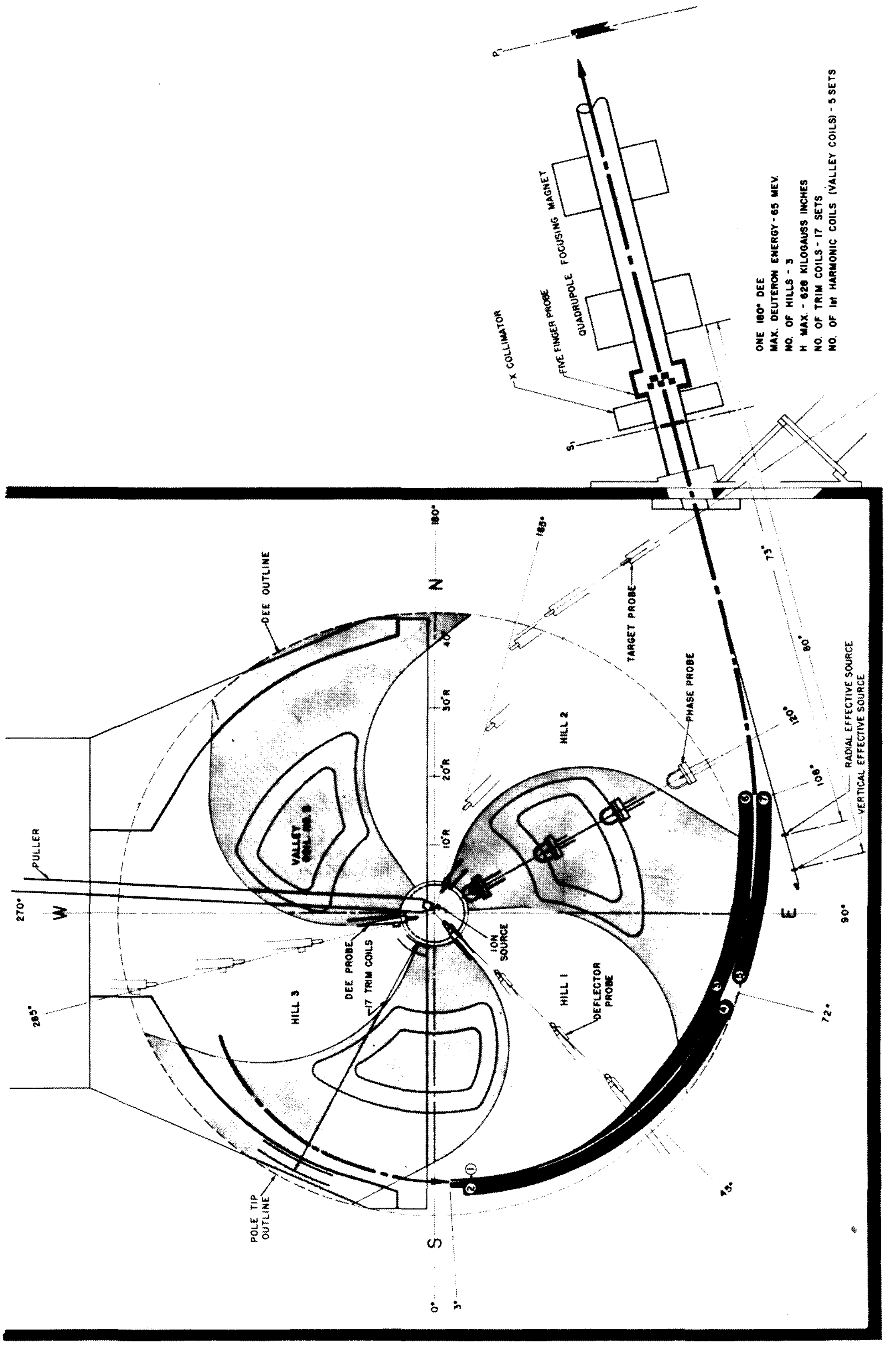

Fig. 1. A plan view of the pole face and the original extraction system.

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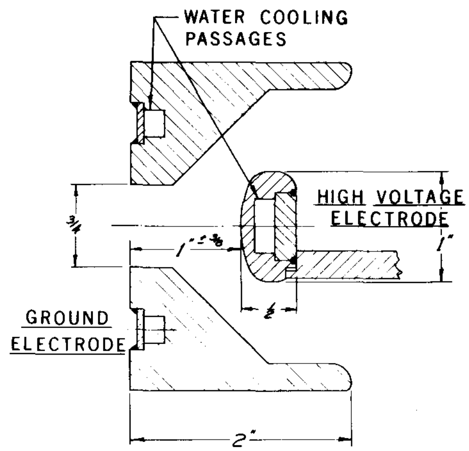

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Fig. 2. A cross section of the regenerator electrodes.

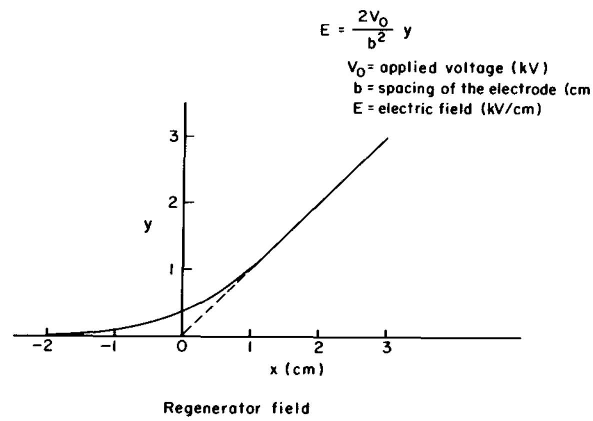

Fig. 3. Electric field of the regenerator.

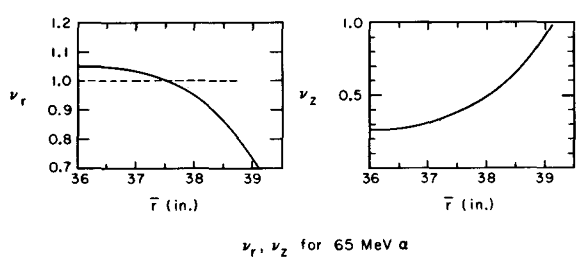

Fig. 4. ν_r and ν_z values for 65-MeV particles.

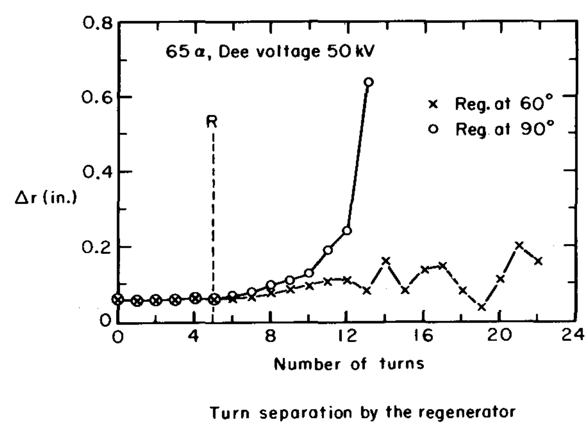

Fig. 5. Plots of turn separation by the regenerator action
Particle: 65-MeV α
Electrode spacing 3 cm
The length of the regenerator 6°
Voltage of the regenerator 240 kV
-o-o- The regenerator at 90°
x-x The regenerator at 60°

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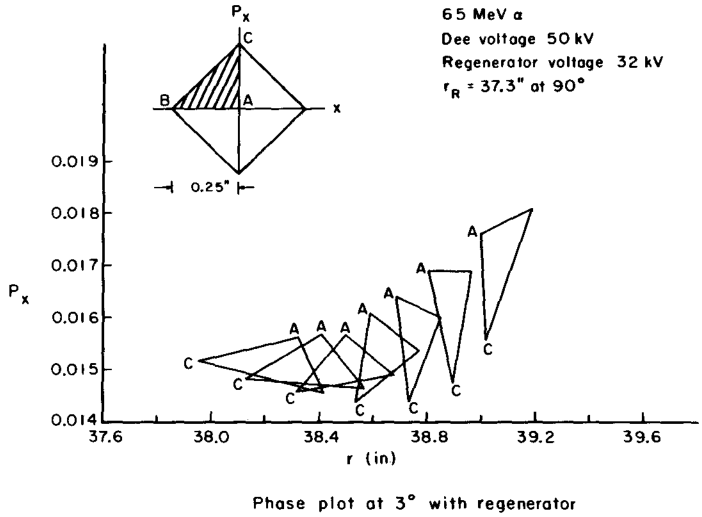


Fig. 6. A phase plot of 65-MeV α-particle by an action of the regenerator, showing the turn separation and energy resolution improvement.

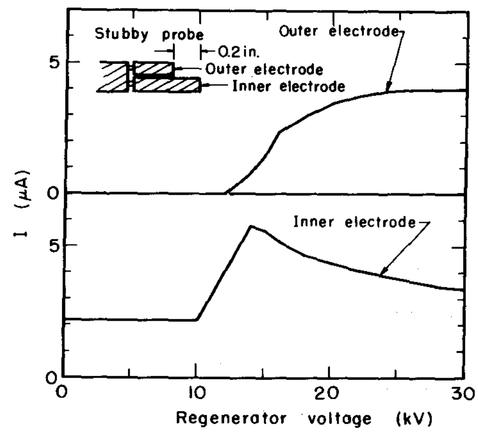
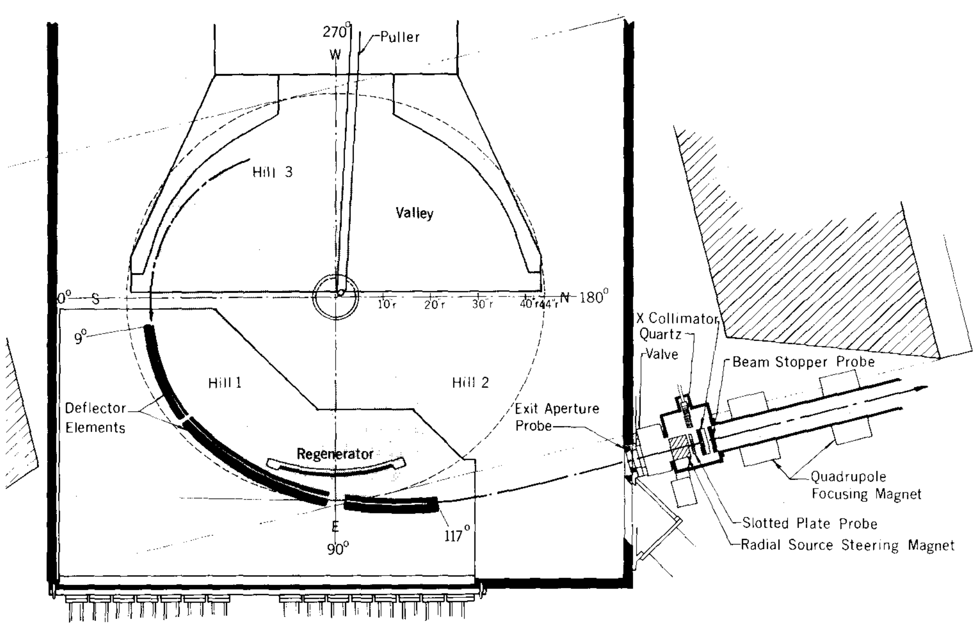


Fig. 7. A result of turns separation measurement, 45-MeV α-particles.



88" Cyclotron
Regenerative System Plan Schematic

Fig. 8. A plan view of the pole face and the new extraction system, showing the position of the regenerator and a 3 section deflector.