OPERATION OF THE REGENERATIVE EXTRACTION SYSTEM ON THE UNIVERSITY OF BIRMINGHAM 40-INCH CYCLOTRON

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(Presented by W.B. Powell)

The peeler-regenerator system, which is based on the ideas of Tuck and Teng and of Le Couteur[1], was worked out in detail for the Birmingham 40-inch cyclotron[2] by E.A. Finlay[3]. Since the system has been in operation for only a short time, and at present departs slightly from the computed arrangements, it has not yet been possible to make a detailed comparison between theory and experiment; however, there is good qualitative agreement with Finlay's work.

In this system particles near the extraction radius enter the peeler and regenerator, which are less than 180° apart. They receive an outward deflection in the peeler and an inward deflection in the regenerator. This action, with a suitable choice of values, stops them precessing round the cyclotron centre and causes them to penetrate further into the peeler and regenerator. In the linear system, to which the present case approximates, the deflection is proportional to the depth of penetration and, consequently, the turn separation in the region between peeler and regenerator also increases linearly. The entrance to the extraction channel is placed at a suitable radius near the point of maximum turn separation. Accompanying the spread in orbit centres in the direction of the channel (the r direction) is a compression of orbit centres at right angles to this (the r' direction).

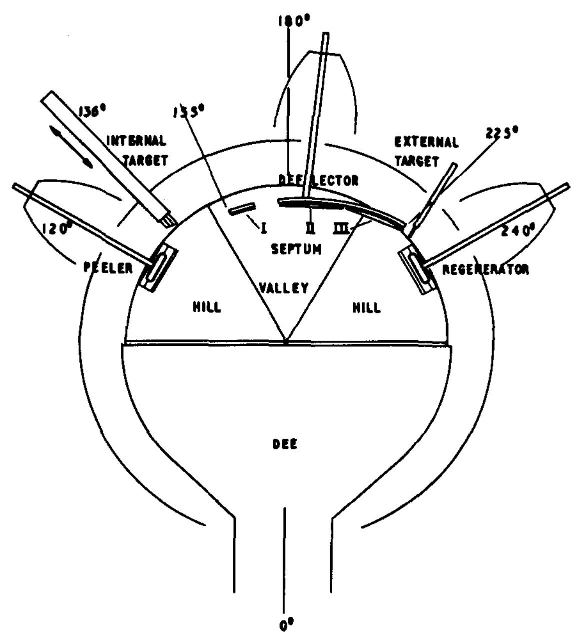

Fig. 1 Arrangement of peeler, deflector and regenerator.

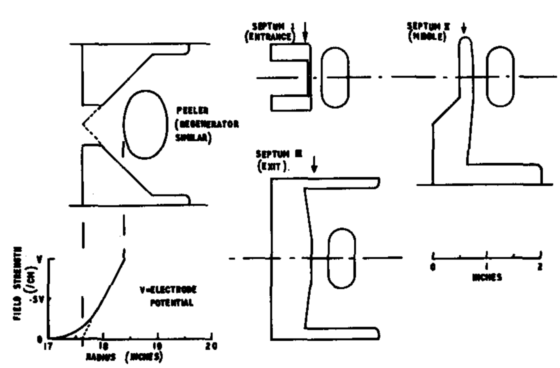

Fig. 2 Sections through peeler and deflector channel.

Present arrangements

The peeler and the regenerator, shown in Fig. 1 and Fig. 2, are electrostatic devices operating with negative and positive potentials respectively. They are sited on either side of the deflector in the centre of a hill, and their main action begins at a radius of 17.6 inches. They are 4 in. long and a potential of V kilovolts corresponds to a strength[1)] of 0.01 V. The centre of the entrance to the deflector channel is at 17.6 in. radius and its width increases from 0.2 to 0.3 in., the exit being at 20 in. radius. At 3 in. from the entrance there is a 3 in. gap to accommodate the ion source tube. The septum, which has a 1.25 in. long V-slot and is 0.062 in. thick near the entrance, is split into three parts, and the current to each can be measured. Figure 3 shows one of the dee-box cover plates with the peeler, deflector, and septum in position. The insulators are similar to those used on the cyclotron at the University of Illinois. Values for the average magnetic field and the vertical and horizontal oscillation frequencies are given in Fig. 4.

The measurements to be described were obtained with 11 MeV deuterons at dee voltages between $28\frac{1}{2}$ and $21\frac{1}{2}$ kV. These conditions correspond to between 200 and 250 particle revolutions and to turn separations of 0.045 to 0.034 in. at full radius. In no case was the component of turn separation, caused by the dee voltate, sufficient to clear the septum entrance.

<u>Peeler-Regenerator Characteristics</u>

Preliminary tests were made in the linear region with the peeler and regenerator at 16.75 in. from the region of field fall-off. A target which could measure turn separations and also vertical oscillation amplitudes greater than 0.125 in. was placed at 180° azimuth and 16.55 in. radius. According to the linear theory, with $\nu_r > 1$, the peeler alone should introduce some turn separation, but the regenerator alone should not. This tendency, together with the other predictions of the theory, was confirmed but in general the measured turn separations were too large, probably because of off-set orbits and spurious beams. The increase in amplitude of vertical oscillations with strong regenerators and weak peelers is clearly shown in the measurements of Fig. 5. They also show that a peeler on its own will introduce a small increase in vertical amplitude. It was confirmed that the vertical oscillations were quickly

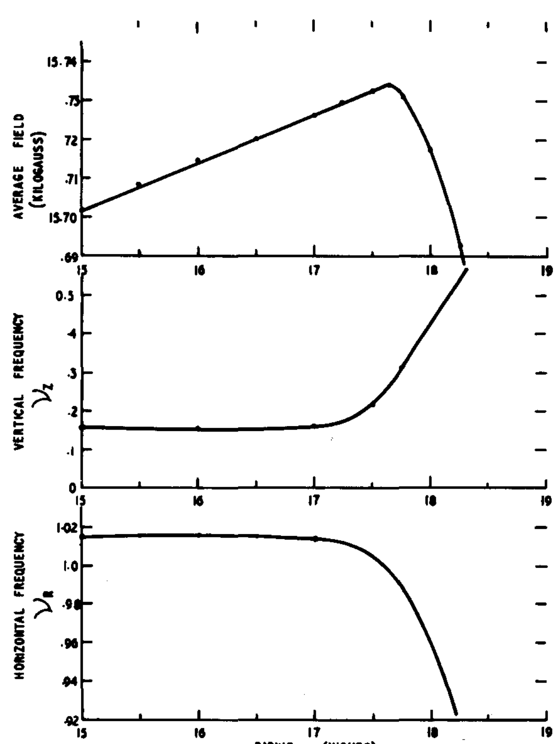

Fig. 4 Average magnetic field and vertical and horizontal oscillation frequencies versus radius.

Fig. 3 Photograph of dee-box cover, with the peeler, deflector and septum in position.

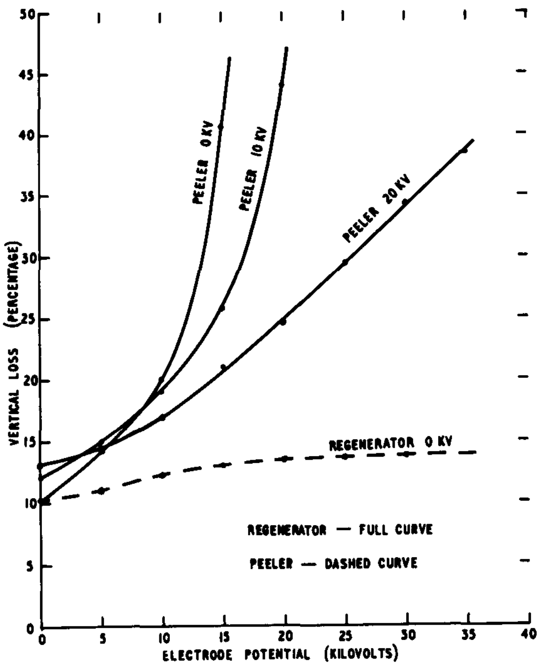

Fig. 5 Percentage of total beam with vertical amplitudes greater than 0.125 versus peeler and regenerator voltages.

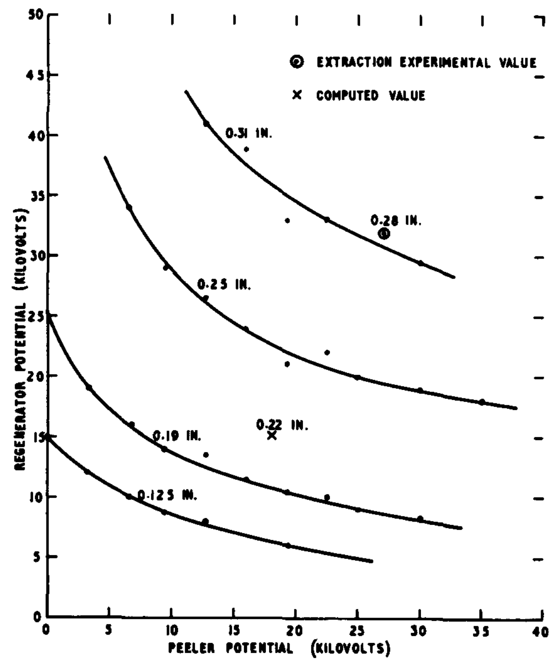

Fig. 6 Turn separations for different peeler and regenerator values, measured at extraction radius.

established and that thereafter their amplitude remained constant as the target was withdrawn.

A further set of measurements was taken with the peeler and regenerator at the extraction radius of 17.6 in. and the target at 17.5 in., 0.1 in. beyond the radius of the last turn at 180° azimuth. There was now less spurious beam. In comparison with the linear region there were two outstanding differences caused by the peeler-like action of the field fall-off. A turn separation was obtained using the regenerator alone, and the amplitude of vertical oscillations was greatly reduced. The graph of Fig. 6 shows the turn separations measured for various combinations of peeler and regenerator voltages. A computed value is given for comparison, and also an experimental point obtained more recently under extraction conditions using the deflector electrode and septum as targets (the value has been normalised to 180° azimuth).

A few measurements made with the peeler and regenerator at 17.8 in. radius show that turn separations up to 0.5 in. can be obtained without any loss of beam and indicate that the optimum radius for extraction may be a little further out.

Extraction

The search for an external beam was begun when it was only possible to hold 45 kV on the deflector. The orbit centres were varied by changing the ion source, dee and dummy-dee positions, and the deflector voltage was slowly raised. With a deflector voltage of 50 kV and the initial orbits off-set by approximately 0.375 in. at 260°, a small external beam was detected. This off-set, which is almost certainly not the optimum, remained unchanged throughout the measurements.

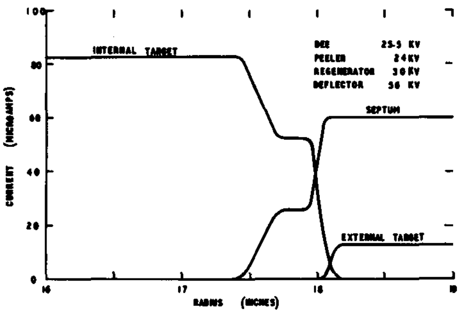

Fig. 7 Current to internal target, septum and external target versus internal target radius. (Double beam condition). Averaged for a number of runs. Part of septum current is deduced from measurements made with zero deflector voltage.

A typical plot of current distrubution versus internal target radius is shown in Fig. 7. It will be seen that nearly all the internal beam strikes the septum (most of it on the first three inches). It is inferred from this curve, and also from a measurement of current striking the deflector with the voltage off (to remove emission currents), that only about 1% of the internal beam hits the deflector. The plateau in the curves of the current to the internal target and to the septum is at too small a radius for the $\nu_r = 2\nu_z$ resonance and occurs because at this time the internal beam was split into two separate components. The larger component (which gives rise to the external beam) is of reasonable quality while the other component is poor with centres off-set by an inch or two. It appears that the off-set beam was caused by unstable components near the centre which were later captured into a stable orbit. The steep di/dr characteristic as the target is finally withdrawn is more likely to arise from the compression of orbit centres in the r' direction, referred to earlier, than from a high quality beam. While the energy spread is not at present known, it could be quite large.

With the above arrangement a 25% extraction efficiency for the 'on centre' component was achieved with a maximum deflected beam of 45 μA. During the extraction process the beam was less than 0.125 in. high and accurately on the median plane. The spot size at the end of the deflector channel was about 1 mm high and 3 mm wide.

By varying the centre trimming coils it was found that the extraction efficiency was sensitive to changes in the value of the central magnetic field (the iron gives a decrease of 100 gauss over the first 3 in.) and to the height of the median plane at the centre. Suitable adjustments caused the off-set beam to disappear and brought the overall extraction efficiency to 37%. .It has not yet been possible to explore this situation in detail, but the changes involve only a few tens of gauss and result in an increase in the value of the central field bump.

The above conditions gave the best results so far obtained. With a dee voltage of 25 kV and an extraction efficiency of 37% the ion source current was slowly increased. For external currents up to 40 μA there was no noticeable change in efficiency, but above this level there was a small decrease. Because of misalignments certain carbon components in the machine become excessively hot at high currents and it has not been possible to run at maximum output, nevertheless an external beam in excess of 60 μA has been obtained.

To assess the accuracy required in setting various controls each was varied until the external current fell to half value on either side of tune. The surprisingly wide range permitted is shown in Table I; in fact, the only control with a relatively sharp tuning characteristic is the deflector voltage.

Table I

Typical Tuning Characteristics.

Range of Controls to Halve External Beam

Central Magnetic Field		15.7 k.gauss ± 18 gauss
Harmonic Coils at 5 inch radius.	Amplitude	36 gauss ± 36 gauss
	Azimuth	$260^\circ\ {}^{+\ 60^\circ}_{-\ 100^\circ}$
Harmonic Coils at 13 inch radius.	Amplitude	12.5 gauss ± 25 gauss
	Azimuth	$120^\circ \pm 40^\circ$
Dee Voltage		24.5 kV $^{+\ 4\ kV}_{-\ >\ 4.5\ kV}$
Peeler Voltage		24 kV ± 17 kV
Regenerator Voltage		30 kV $^{+\ 30\ kV}_{-\ 17\ kV}$
Deflector Voltage		54.5 kV $^{+\ 6\ kV}_{-\ 4.5\ kV}$

Voltage Breakdown Characteristics

The three high voltage electrodes and the first three inches of the septum are copper, and the rest of the surroundings at earth potential are of carbon.

There is nothing very unusual about the behaviour of the two negative electrodes. The deflector will hold 65 to 70 kV without a beam and a little over 55 kV with one; this corresponds to a voltage field strength product of 0.6×10^4 kV^2 cm^{-1}. The equivalent figures for the peeler are 70 kV without a beam and 50 kV with one. There has been no requirement for voltages higher than this, but the performance gives the impression that they could be obtained if desired. The deflector, on the other hand, gives the impression that it would be difficult to obtain significantly higher voltages with the present arrangement.

The behaviour of the regenerator with a positive potential is dramatic. With air pressures above about 1.5×10^{-5} mm Hg it is impossible to hold voltages in the region of 4.5 kV because the emission current is too high for the power supplies. At higher voltages and below this critical pressure there is no difficulty and the characteristics are quite similar to an electrode at negative potential. The situation is shown in Fig. 8, in which the emission current is plotted against voltage for a range of pressures; the absolute values are not too reliable because the emission currents varied between runs. The current peak which is just over 1 mA at

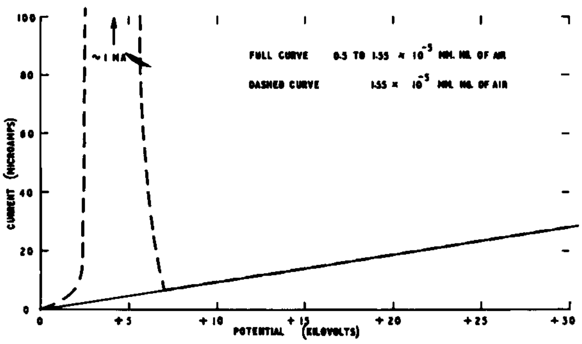

Fig. 8 Emission current versus regenerator voltage for various pressures

the critical pressure increases rapidly thereafter, but at pressures only a little above the critical point it is possible, with the existing power supplies (which are designed for a maximum load of 1 mA), to break through to the high voltage region by switching on quickly.

The use of a 10 mA, 10 kV power supply permitted a visual observation of the regenerator operating under high current conditions; a glow discharge was seen close to the electrodes. It seems that the phenomenon is due to oscillating electrons which in the regenerator geometry could have path lengths of hundreds of metres and at electrode potentials of a few kV have a maximum ionization probability. The characteristics of the discharge with hydrogen gas are similar except that the critical pressure is higher. Under operating conditions the detailed behaviour of the regenerator is complicated by the release of gas caused by local hot spots and normal breakdown, but recovery is immediate and 70 kV can be held without a beam and 50 kV with one. In a brief attempt to place a positive voltage on the deflector it was not possible to break through the glow discharge, although the pressure was only 5×10^{-6} mm Hg.

Conclusion

This investigation has shown that electrostatic peelers and regenerators may be used in cyclotrons under normal operating conditions. For internal target work they can be used to spread the beam over a larger area, and for extraction they are particularly suitable for those conditions in which flexibility and sharp changes in field values are more important than strength.

In the immediate future attempts will be made to improve on the present extraction efficiency of 37% by optimising the internal beam position and the alignment of the deflector channel. It is hoped to follow this with extraction experiments on the axially injected beam.

Acknowledgments

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We are greatly indebted to E.A. Finlay who in addition to his earlier calculations also designed the deflector and the extraction power supplies. We are grateful to the members of the Physics Department who made the components, and to P.B. Moon and W.E. Burcham for their encouragement throughout the project.

References

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2. A.J. Cox et al., Nucl. Instr. and Meth., 18-19, 25 (1962).
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DISCUSSION

BLOSSER : The curves which you showed for ν_r and ν_z were unusually smooth. Would you comment on how the curves were computed, and whether you feel the field is really as smooth as the curves would indicate?

POWELL : I would think the curves are fairly accurate, but there are certain small variations. The curves were calculated from some magnetic field measurements done on the iron with the calculated trimming coil fields added. A number of terms in the Smith and Garren formulas were used.

ZUCKER : Your slide shows that the regenerator potential is much more effective for extraction than the peeler potential. Why is that?

POWELL : The magnetic field itself behaves like a peeler. Hence, in principle there is a setting at which you can use just the magnetic field as peeler. This, I think, is entirely the principle used in FM cyclotron extraction. What perhaps I should point out is that with this system you can vary the regenerative action of the magnetic field at will, and you can adjust in detail the orbit slope at the entrance to the deflector.

RICHARDSON : I understand you have done some work with negative ions. Could you comment on this.

POWELL : Well, we did accelerate negative deuterons mainly to see if it was possible. We found that we had to cut down the size of the aperture in our hooded ion source to about 1/8" diameter. We had to work at rather high gas pressures and when we did this we got an estimated d.c. output of about 100 mA of negative ions, which was reduced to about 25 mA on the first turn. Gas pressures at this time were not particularly good, of the order of 9×10^{-6}, and because the deuterons travel slowly gas stripping was severe. We got serious gas stripping as we moved out, and reached only a little beyond half radius before current had dropped off to below 1 mA. We are now building a negative ion source with axial injection and hope to keep the pressure rather low to avoid gas stripping.