The University of Birmingham Radial-Ridge Cyclotron

W. B. Powell

It was my intention to make remarks similar to Dr. Richardson's on the simplicity of the formulas which can be used to guide the design and construction of small sector-focused cyclotrons, and so I will be very brief.

My colleague (P. J. Waterton) and I started only a year ago when the magnet from the 37-in. cyclotron at the Cavendish Laboratory at Cambridge was brought to Birmingham. We wanted to get it operating again with a large beam current as quickly as we could. We decided not to have spiral ridges because we felt that these would be more awkward to achieve quickly; so flat radial-ridge, three-sector construction was adopted (Fig. 6).

In the calculations we also concern ourselves with arcs of circles, but I think I can claim that our formulas become even more simple; we don't need to bother about a spiral angle. The shape of an orbit is specified by the angle between the particle trajectory as it crosses a step and the tangent to a circle, where

$$\tan \alpha = \frac{1}{\sqrt{3}} \frac{\Delta H}{H} .$$

The circumstances are illustrated in Figure 7, where the magnetic field is approximated by the square wave $(H + \Delta H)$ on the hills and $(H - \Delta H)$ in the valleys.

The axial focusing force expressed in terms of an average field index, n, is given by

$$n = \frac{6}{\sqrt{3}\,\pi} \left(\frac{\Delta H}{H}\right)^2 .$$

This expression gives the angular frequency of the particles,

$$\omega = \frac{He}{m_o} \left[1 - \frac{1}{2} \left(\frac{v}{c}\right)^2 + \frac{6}{\pi} \frac{\Delta H}{H} \gamma + \left(\frac{2\sqrt{3}}{\pi} - 1 \right) \left(\frac{\Delta H}{H}\right)^2 \right] .$$

The expression contains the angle γ obtained by increasing the extent of the high field region by shimming the sides of the sectors. By varying γ, isochronism can be maintained.

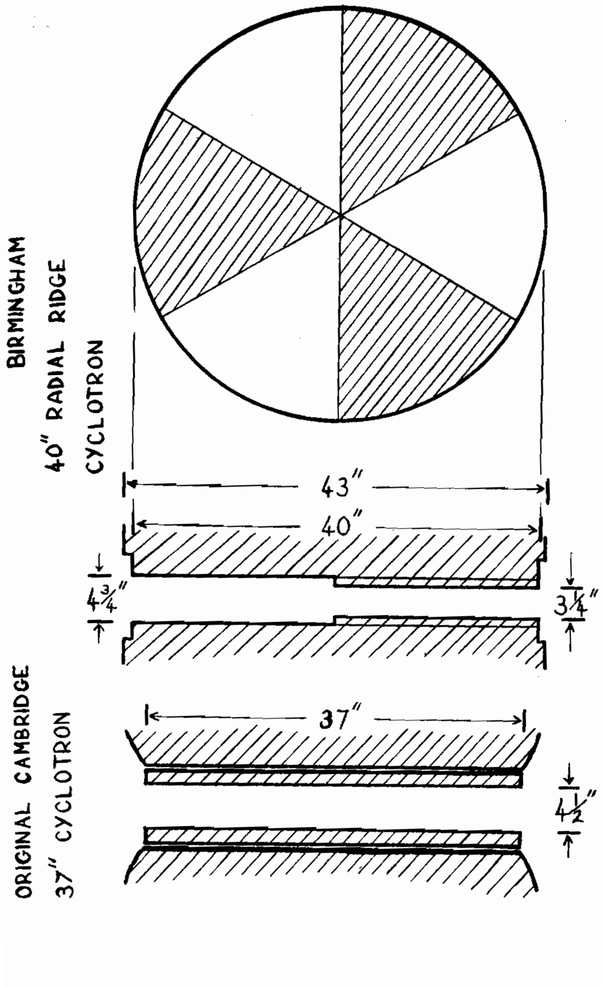
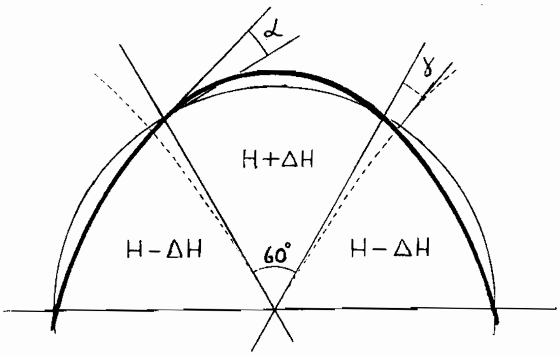


Fig. 6. Pole tip configuration of Birmingham radial-ridge cyclotron.



$$\mathrm{TAN}\,\alpha = \frac{1}{\sqrt{3}}\frac{\Delta H}{H} \qquad n = \frac{6}{\sqrt{3}\pi}\left(\frac{\Delta H}{H}\right)^2$$

$$\omega = \frac{He}{m_0}\left[1-\frac{1}{2}\left(\frac{v}{c}\right)^2+\frac{6}{\pi}\frac{\Delta H}{H}\gamma+\left(\frac{2\sqrt{3}}{\pi}-1\right)\left(\frac{\Delta H}{H}\right)^2\right]$$

Fig. 7. Basic Formulae for Particle in the square-wave approximation to the magnetic field.

I would just like to mention some of the differences between this and the UCLA machine, since the pole tip diameters are virtually the same. We have not been nearly so ambitious as they, for we plan to operate with a maximum field of 19 and a minimum of 13 kilogauss, feeling that even at 19 kilogauss we shall run into some saturation difficulties. Because of saturation effects we shall not vary the energy, although we do plan to accelerate different particles, including helium-3, deuterium, and nitrogen. We shall use a single dee; to accommodate this our minimum gap needs to be over twice as wide. This is not entirely disadvantageous as our access will be better. Finally, the energy of our most relativistic particles, 32-Mev He^3, has a v/c of 0.15, whereas the UCLA value is over twice this, I think.

I should also like to describe some measurements made on the 50-in. cyclotron(1) of the Medical Research Council at Hammersmith Hospital.

Firstly, in Figure 8 (upper) two drawings illustrate the calculated paths of particles leaving the ion source. The starting time in terms of peak dee voltage is indicated and the hatched line shows the position of particles at the instant of the second voltage peak. The first sketch shows the paths when there is no feeler; consequently, the electric field strength varies with time only. After half a turn there is phase bunching, but no space bunching. In the second sketch the full dee voltage is applied to the particles immediately as they leave the source; now there is bunching in space, but no phase bunching.

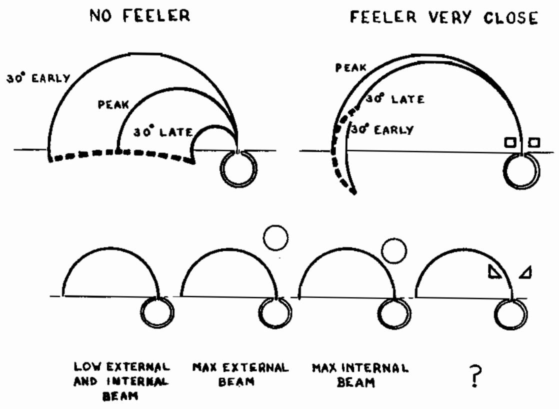


Fig. 8. Particle motion in the first half-turn and its effect on beam quality.

The point of showing these two figures is so that I can comment on the measurements illustrated schematically in the lower part of the figure. We first of all optimized the internal and external beams without a feeler; we adjusted everything we could including the dee position, the ion source, and the deflector channel - but consistently both the internal and external beams were low.

Then we put a cylindrical feeler in the dee and investigated the effect on the beam of different source-to-feeler distances. We varied everything we could and found time and again that

---

(1) J. W. Gallop et al, Proc. I.E.E. 104.B, 17 (Sept. 1957).

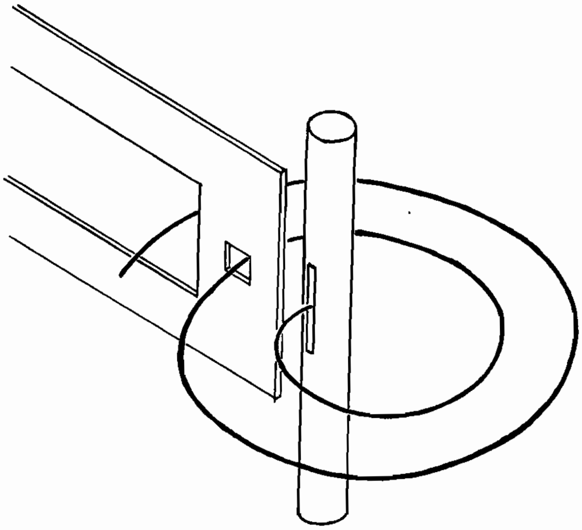


Fig. 9. Removal of unwanted beam.

with 5/8-in. separation (the dee voltage was 60 kv) we got a maximum external beam of about 150 μa. If we pushed the feeler closer to the ion source then we got bigger internal beams, but the external beam fell off considerably. We could not place the feeler very close to the ion source without intercepting beam. We did not use a slit to overcome this difficulty because the measurements we had already made seemed to show that, whilst we might have increased the internal beam in this way, the external beam would decrease further.

Numerical calculation showed that under the conditions for maximum external beam the particles were predominantly phase bunched at the start. Further calculations were in line with the experimental results, for they indicated that if phase bunching is sacrificed in order to obtain space bunching the final beam will, in fact, be more incoherent. This arises as a result of the difference in voltage gain per turn, which introduces a spread in phase and precession angle at the extraction radius. We concluded that to get large extracted beams it is important not to interfere too much with the phase-bunching condition.

In the next series of measurements (Fig. 9), we put a square slot at the first turn(2), and found that when the sides were only 5/16-in. there was no reduction in the size of the extracted beam. Also, the internal beam of about 1 ma at full radius was reduced by less than 20 percent.

With the aid of other slots, rectangular in shape, we were able to distinguish between the effects of the sides and of the top and bottom of the square slots. We found that the top and bottom of the slot removed most of the stray beam that had previously been striking the dees. (This gave a marked improvement in operating conditions). The sides of the slot removed stray beam which had previously been hitting the sides of the deflector channel, particularly along the first few inches.

On the radial-ridge cyclotron at Birmingham we plan to use a similar slot to remove unwanted beam. In addition, we shall have a long slot at earth potential running from the center to the outside of the machine. This will present a smaller aperture to the beam than the dee and in this way we hope to ensure that no beam can reach the dee.

---

(2) W. B. Powell, Nature <u>177</u>, 1045 (1956).