The Harwell 110 in synchrocyclotron modification scheme

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ABSTRACT

Modifications to the Harwell synchrocyclotron have been made with the objects of increasing the accelerated beam currents, improving the extraction efficiency and broadening the field of use of the machine. The means adopted have been to install a 30 kV, high repetition rate rf system operating on three frequency ranges to allow acceleration of protons, deuterons, α-particles and $^3He^{++}$, a calutron ion-source, regenerative beam extraction and improved neutron time-of-flight facilities.

Though there are still some problems regarding acceleration of α-particles and $^3He^{++}$, internal beams up to 10 μA protons and 40 μA deuterons have been obtained. The extraction efficiency is low as yet, largely because of poor internal beam quality, the reasons for which are discussed.

1. INTRODUCTION

The Harwell 110-in Synchrocyclotron first came into operation in 1949 as a proton accelerator capable of producing 1 μA of internal beam at energies up to 165 MeV. It was used without major modification until the beginning of 1968. The 110-in diam. magnet with a basic pole gap of 12 in operated at a central field of 16 200 G. A 7 kV rf system with a single 180° dee was modulated between 25 and 20·1 MHz at a repetition frequency originally 100 Hz but later increased to 200 Hz. Simple 'open' ion-sources of both filament and cold cathode type were used.

Despite the low intensity of the external beams ($\sim 1{\cdot}6 \times 10^{-5}$ μA unpolarised and $\sim 1{\cdot}6 \times 10^{-6}$ μA polarised) which were produced by scattering from internal targets into a magnetic channel, much useful research was carried out in a number of fields. A unique feature of the machine[1] was the pulsed electrostatic beam deflector, which enabled single turn vertical deflection of the complete proton bunch onto an internal target, providing a short burst neutron source (time resolution variable from 10 ns to 2 ns *FWHM*) for time-of-flight work at energies from the keV region up to 140 MeV, using a 27 m flight path.

In the early 1960's it became clear, however, that advantage could be taken of advances in cyclotron technology. Results achieved with the Orsay synchro-cyclotron demonstrated the possibility of obtaining a significant increase of internal beam intensity by the use of higher dee voltages and frequency modulation rates to combat space charge limitation and of decreasing the radial betatron amplitudes of the internal beam.

Consequently a proposal was made that the Harwell machine should be modified by:

(a) providing a 30 kV rf system operating at repetition frequencies up to 1600 Hz on three separate frequency bands, allowing acceleration of protons, deuterons, α-particles and $^3He^{++}$;
(b) installing a calutron ion-source to obtain good initial beam centring and to make optimum use of the higher dee voltage;
(c) installing a regenerative extractor;
(d) improving the neutron time-of-flight facilities to make use of the expected performance improvements.

The magnetic field was to be left unchanged apart from changes in shimming where it was found necessary. It was estimated that in this way an increase of at least a factor of ten in internal beam might be obtained and an extraction efficiency of 10% was hoped for.

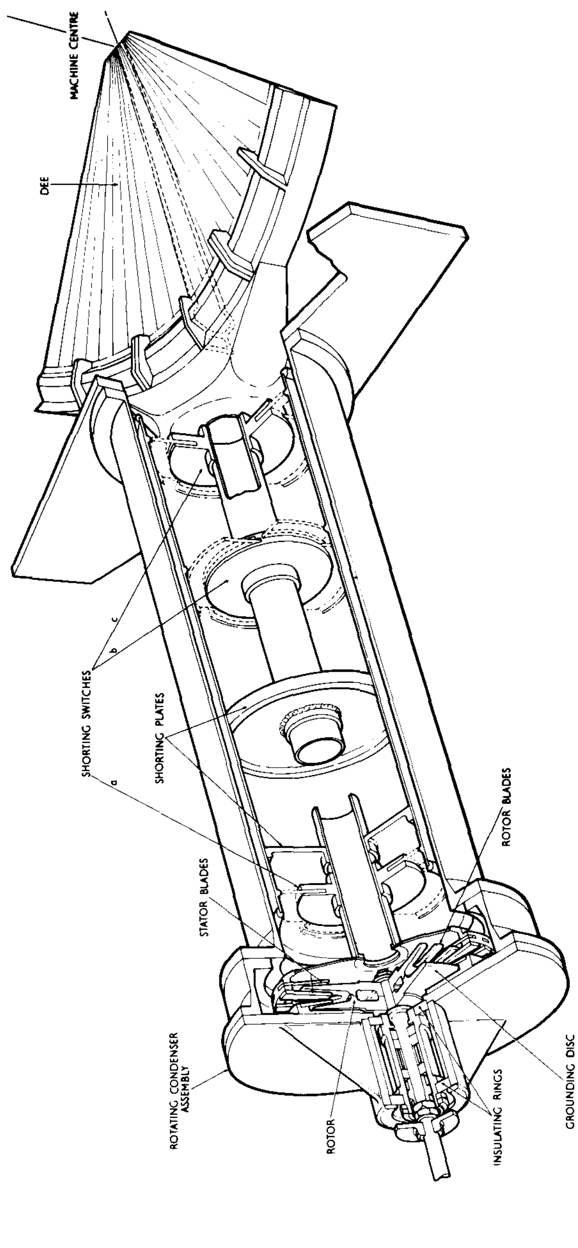
This proposal was accepted in 1966 and the machine was closed down at the beginning of 1968 for implementation of the scheme. Operation recommenced in December of that year. Performance has not yet been optimised in all respects, but the progress made so far allows a considerable fraction of running time to be devoted to experimental work.

2. THE NEW RF SYSTEM

The rf system is an oscillator driven half-wave resonant line with the dee at one end and a rotating capacitor at the other. To allow operation over the three frequency bands the concentric portion of the line is constructed in re-entrant form. The full length is used for the deuteron and α-particle band and the other two bands are obtained by closing shorting switches between the inner and outer sections. A schematic representation of the system is shown in Fig. 1.

The rotating capacitor which provides the frequency modulation has a single bank of 32 radial blades with a blade/space ratio of ~1/2 and rotates within a 32 section stator of similar profile with a rotor-stator gap of 0·11 in. No attempt has been made to control the shape of the frequency sweep by shaping the blades in any special way. The rotor and the stator blades are manufactured from chromium-copper alloy. The rotor is held near ground potential by the capacity between a fixed grounding plate and a rotating disc mounted on the rotor shaft, the gap being 0·014 in. The form of frequency sweep obtained is shown in Fig. 2.

The dee is a light copper structure and, as shown in Fig. 1, it is severely cut-back from the normal 180° shape. The dee tips, which are not shown in the figure, maintain 180° to a radius of 5 in and the dee is then cut back at 49°, until at full radius it subtends ~90° at the machine centre. This was done to simplify the design problems of the modulation system by reducing



NEW RF SYSTEM FOR HARWELL SYNCHRO-CYCLOTRON

Fig. 1. Rf system (schematic view)

the dee capacity to a minimum and to allow the maximum amount of space within the magnet gap for other apparatus. It was realised from the outset that such a scheme could generate considerable off-centring forces on the particle orbits, but it was thought that such effects could be mitigated by a suitably designed radially and azimuthally varying magnetic field perturbation.
A subsequent computer study of this problem showed that any such hope could not be realised, and the present dee shape has unfortunate consequences on the internal beam quality, as will be discussed later.

The main engineering difficulties have been associated with the rotating capacitor, as might be expected. Particular problems have been:

(a) Voltage breakdown across the grounding gap, traced to misalignment and distortion of the plates.
(b) Oil leakage through the bearing seals into the vacuum system, also leading to voltage breakdown. This has been largely cured by replacing

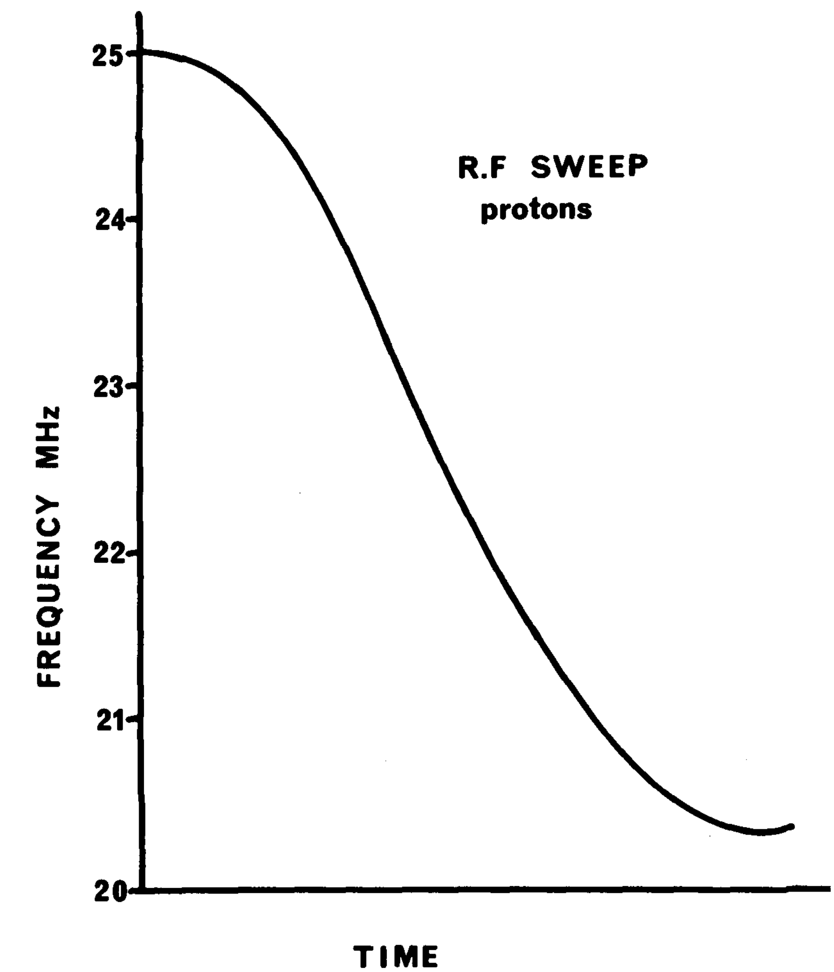


Fig. 2. Frequency sweep

the seals until specimens with adequate performance have been found.

(c) Damage to the bearings by stray rf currents, somewhat alleviated by improving the bearing insulation.

(d) Voltage breakdown at high repetition rates (typically 1400 Hz, ~2600 rpm). This is believed to be caused by a mechanical resonance.

The system has run for two periods in excess of 1000 h between overhauls, though a considerable increase of bearing noise is apparent towards the end of such a period.

The frequency ranges obtained at present are:

Protons	25·014–20·323 MHz
Deuterons and α-particles	12·599–11·484 MHz
$^3He^{++}$	17·249–14·609 MHz

The upper limits are adequate, but the lower limits are very slightly too high to allow the synchronous radius to expand through 48 in, the designed extraction radius. A new stator giving a slightly higher capacity change will shortly be installed, enabling the full frequency swing to be attained.

A Colpitts oscillator, using a BW165 triode, supplies rf power to the resonator without adjustment over the three frequency bands. A d.c. coupled anode modulator allows a range of voltage modulation patterns to be imposed over the frequency sweep. This feature has not yet been exploited except to turn down the rf voltage during the unwanted portion of the sweep. Without modulation, voltage remains constant to within ~10%. At proton frequencies the maximum attainable dee voltage has so far been limited to slightly over 20 kV by voltage breakdown at the rotor. At lower frequencies the rotor voltage is relatively lower and over 30 kV has been reached.

3. ION-SOURCE AND MACHINE CENTRE

The decision to use a calutron source was based on the known performance of such devices in isochronous machines and in the Orsay synchrocyclotron. The present source is of the filament type, with a ¼ in outside chimney diameter and an ⅛ in internal diameter. The puller electrode is connected electrically to the live dee, as is the usual practice. The design is shown in Fig. 3. An ⅛ in thick tantalum filament operates at ~350 A, 5 V, and the arc is pulsed over the acceptance period with ~2 A at 400 V, the length and timing of the pulse being adjustable. The slit dimensions are set by interchangeable tantalum plate collimators, the usual slit size being 0·25 in × 0·08 in. One novel feature is the rigid attachment of the puller to the ion-source body by a boron nitride insulator, electrical contact to the dee being made by a sliding spring contact. This method ensures positive location of the puller with respect to the slit, but any adjustment must be made with the source withdrawn from the cyclotron.

The source is inserted axially through an 8 in diam. hole in the upper magnet yoke and pole face in a similar manner to that used in the Berkeley 88 in Cyclotron.[2] The feed tube is 2¼ in diam. and 10 ft long, and is located at the pole face in a system of rotatable steel plugs which also serve to shim the centre field. Further shim steel is incorporated in the feed tube. Positional movement is obtained as at Berkeley by rotation of the plugs, using an epicyclic gear-train mounted above the magnet. Azimuthal or radial motion of the source with respect to the machine centre is provided and the source may also be rotated about its own axis. Collisions between the source

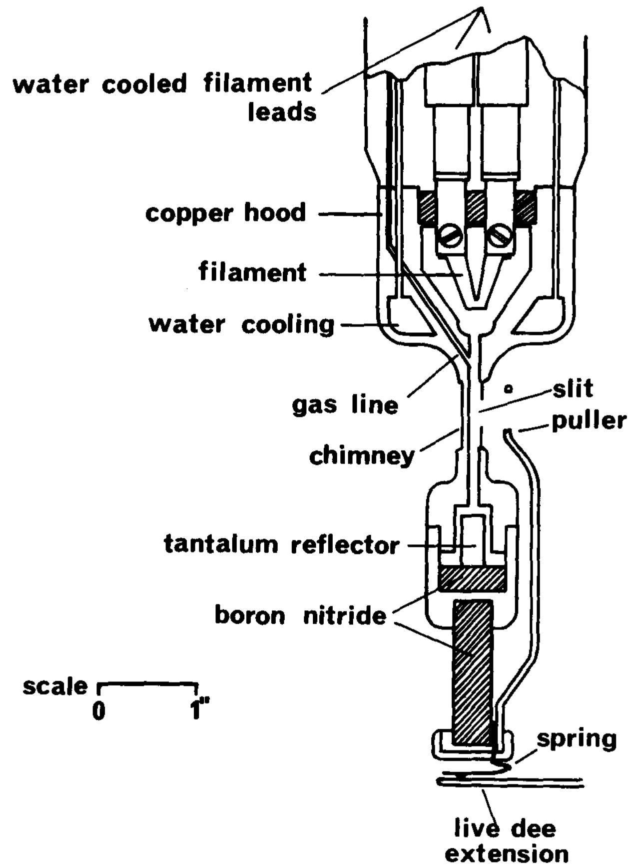


Fig. 3. Hot cathode calutron ion-source

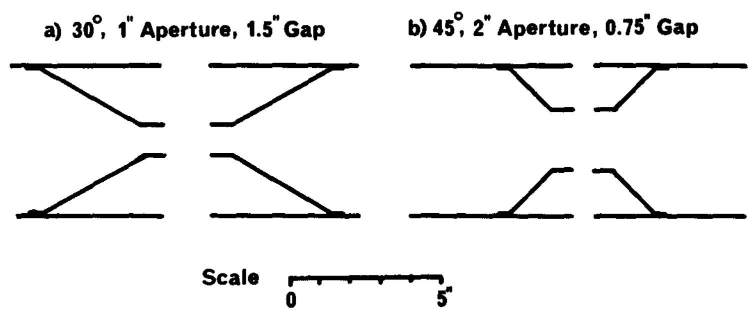


Fig. 4. Alternative dee tip geometries

and the dee structure are prevented by the interaction of a model of the source with a mask above the driving mechanism, and remote position indication is provided.

The dee tips, which clip on to the live and dummy dee, determine the electrical field configuration out to 5 in radius. So far, the design shown in Fig. 4(a) has been used with a central aperture of 1 in, a dee-dummy dee gap of 1·5 in and a 30° cone angle. Measurements of the vertical extent of the beam suggest that the cones may be clipping the beam in the region of space charge limitation to a total vertical extent of little more than 1 in. The large gap was chosen to allow easy movement of the source during the initial stages of performance measurements, but must lead to inefficient acceleration during the first few turns. An alternative geometrical arrangement [Fig. 4(b)] with 2 in aperture, ¾ in gap and 45° cone angle will shortly be tried.

The central magnetic field shape is set by adjusting the vertical position of the shim plugs in the upper pole and introducing a corresponding 8 in diameter flat steel shim on the lower pole. It has been found that great care must be taken in adjusting this shimming to obtain an adequately flat and undisplaced magnetic median plane in the central region. Three sizes of central field bump have been tried, corresponding to ⅛ in, 1/16 in, and 1/32 in shimming top and bottom of the

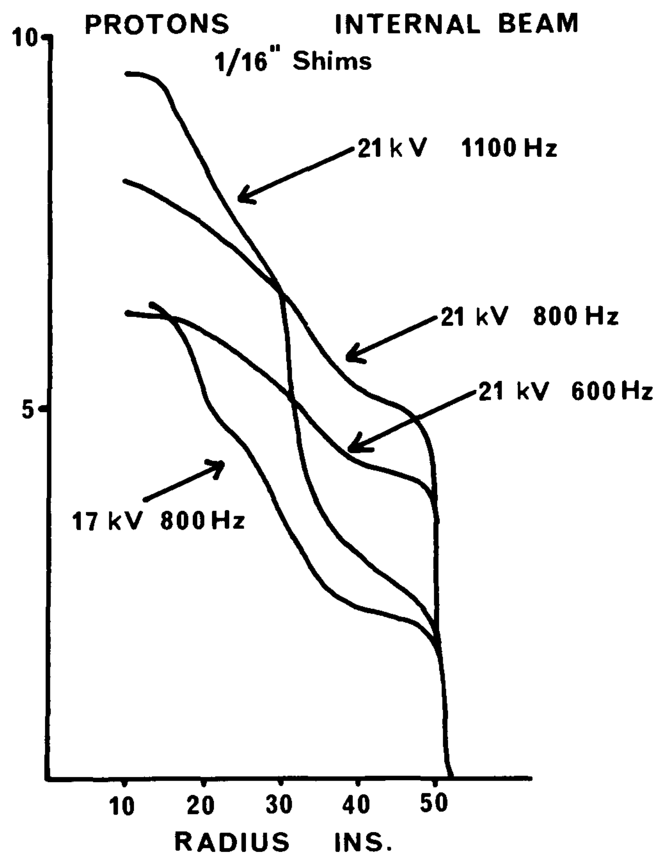


Fig. 5. Variation of internal beam with radius

12 in pole gap. The highest accelerated beam intensities have been attained with 1/32 in shimming, which corresponds (for protons) to a K value varying from 2·5 at 1 in radius to 1·5 at 5 in radius.

4. INTERNAL BEAM PERFORMANCE

As mentioned earlier, the cut back dee was expected to degrade the internal beam quality, and calculations indicated that radial oscillations up to several inches amplitude would be generated. This conclusion has been borne out in practice; consequently no effort has been made as yet to assess the initial beam quality produced by the source and central geometry. Measurements have been concentrated on determining the intensity and quality at larger radii.

Using an insulated probe target, measurements of beam intensity vs radius have been made, mainly for protons and deuterons, over a range of dee voltages and repetition frequencies. Some typical results are shown in Fig. 5. The shape of the frequency modulation law and the form of the magnetic field fall-off with increasing radius results in a stable phase bucket which decreases in size up to an intermediate radius between 20 in and 30 in and then expands again. This is reflected in the way the intensity falls off with radius. As would be expected, the effect decreases as the dee voltage is raised or the repetition frequency lowered.

Fig. 6 shows the variation of beam intensity at intermediate radii as a function of dee voltage. The rapid fall of beam at low dee voltages may be attributed to phase space reduction, increased space charge losses and less efficient extraction from the source. The highest beam intensities recorded at large radius have been 9 μA of protons for a dee voltage of ~22 kV at 1000 Hz and 40 μA of deuterons for ~35 kV at 1400 Hz. It seems reasonably certain that a considerable increase of proton beam would be possible if the full dee voltage were available.

Measurements of internal beam structure have been made by observing the shape of the current pulse collected on the insulated target and by the time distribution of neutrons and γ-rays emitted from the target. The results are not easy to interpret, because the gross time structure depends on both radial and phase oscillations. Pulse shapes such as those of Fig. 7 have been observed, showing structure at both the phase oscillation and radial precession frequency, indicating that even at large radii the phase bucket is not filled uniformly and that there is some phase bunching of the radial oscillations. The latter is more consistent with generation of radial motion by the dee cut-back than by the ion-source. An attempt to extract values for the maximum radial oscillation amplitude as a function of machine radius gives the results shown in Fig. 8. The results are probably rather inaccurate, but if genuine the increase in amplitude for deuterons at large radii is surprising, as it would be expected that generation would have died out after ~30 in.

Calculations indicate that the amplitude of dee induced radial oscillations should be roughly proportional to phase oscillation amplitude for the dee shape in use. Some evidence for this is found by changing the timing of the ion-source pulse so that only the beginning of the acceptance period is covered. Under such circumstances, the average phase amplitude should be reduced, and the current pulses shown in Fig. 9 show a marked shift of centre-of-gravity towards later time, i.e. towards smaller radial motion.

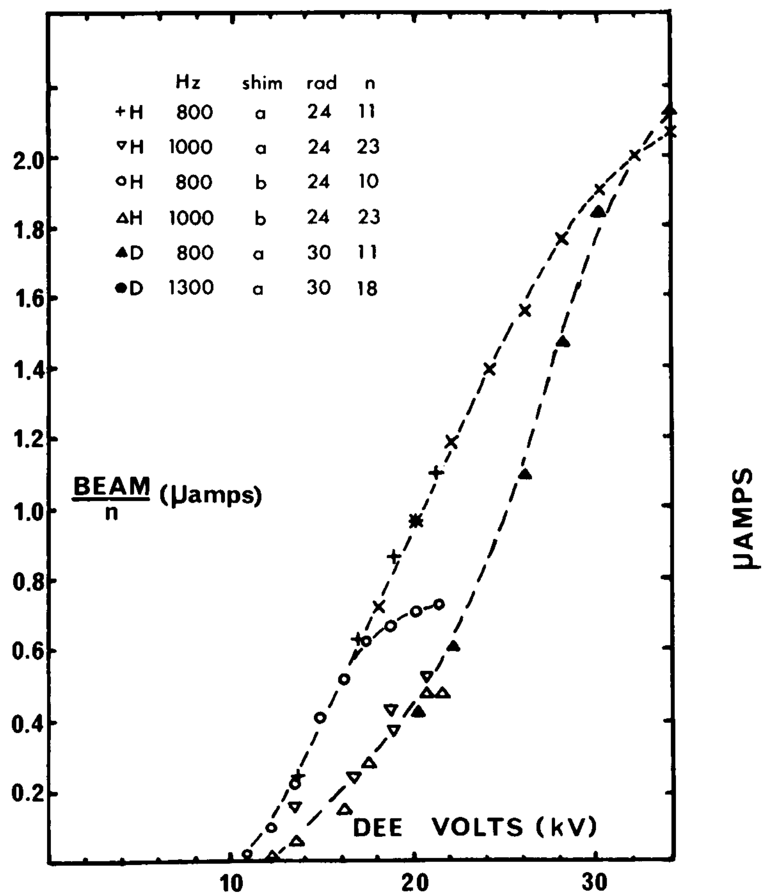


Fig. 6. Variation of internal beam with dee voltage

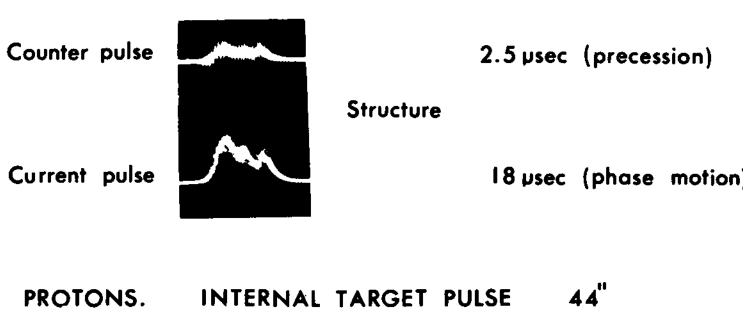


Fig. 7. Time structure of beam striking internal target

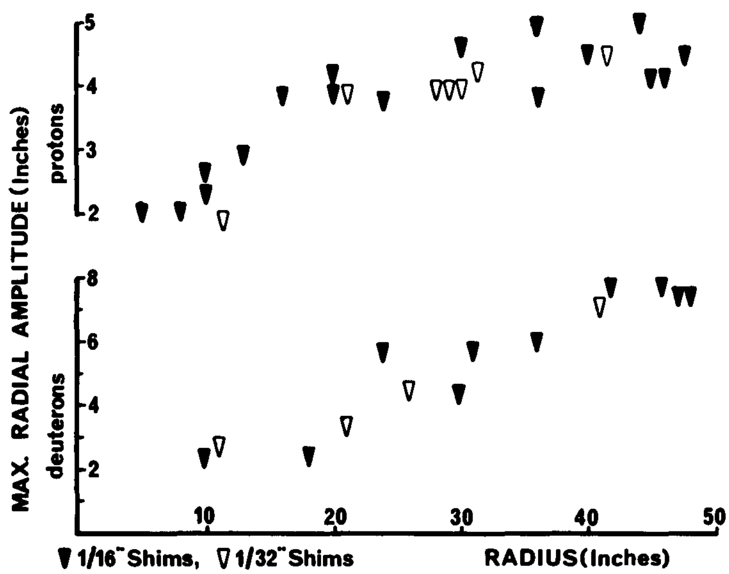


Fig. 8. Estimated maximum radial oscillation amplitude as function of radius

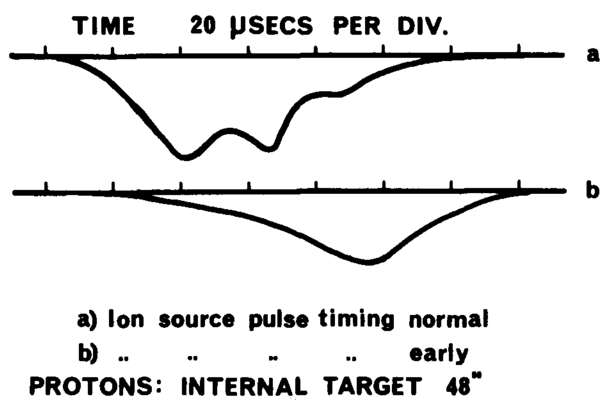


Fig. 9. Variation of time structure with ion-source timing

Measurements of the vertical extent of the beam have been made using autoradiograph targets and also with beam clippers. At large radii, the maximum vertical extent of the beam for protons is ~0·4 in and for deuterons ~0·5 in.

Results with α-particles and $^3He^{++}$ have so far been disappointing. Contrary to experience at Orsay with α-particles, only low intensities up to ~1 μA have been accelerated. The reasons are by no means understood and further work is required.

5. BEAM EXTRACTION

The regenerative extraction system is of conventional design and follows closely that for the Orsay synchrocyclotron as described by de Kruif and Verster.[3] However, in establishing the required parameters and also in the commissioning stages, a great deal of reliance was placed on orbit calculations using the programmes written at CERN by Vogt-Nilsen.[4] Extensive magnetic survey work was required at various stages, and an automatic survey system using the difference coil technique with NMR normalisation was used.

The shape of a theoretical 'line' regenerator field bump was calculated for an extracted energy of 158·5 MeV (corresponding to 48 in radius and an unperturbed n value of 0·08) to produce 'constant phase' regeneration with the displacement node 128° from the regenerator. The required field disturbance was realised in practice by triangular section steel blocks covering 20° azimuth between 49·26 in and 53·26 in radius, the gap changing linearly from 8¾ in to 3 in. The regenerator with its associated shimming can be seen on the R.H.S. of Fig. 10.

The extraction channel was designed in 12 sections each 6 in long with a radial aperture increasing from ¾ in at the entrance to 1¾ in at the exit, and a vertical aperture increasing from 2 in to 3 in. The third and fourth sections were designed to give radial focusing. Shimming the unwanted field disturbances from channel and regenerator required six cycles of measurement and re-shimming, the final value of first harmonic at 48 in was 10·7 G. The channel with shimming is shown in Fig. 10, the channel entrance being on the left of the picture. One novel constructional feature is that the adjacent channel

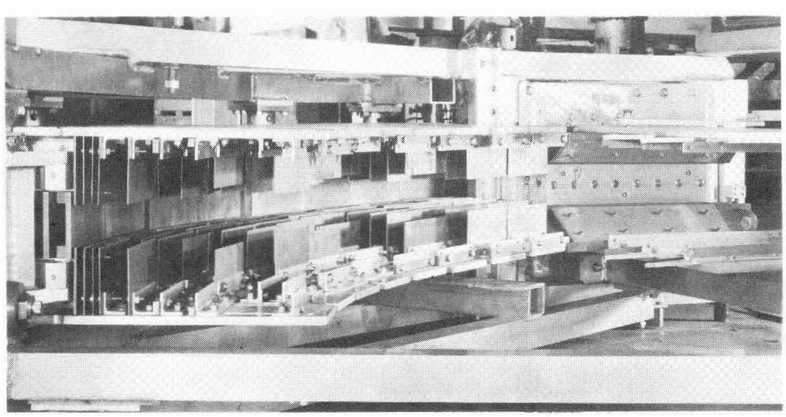


Fig. 10. General view of regenerator and extraction channel

sections are hinged so that whatever line is set each section is automatically aligned to the next.

Preliminary extraction studies have shown that, as would be expected from the poor internal beam quality, the efficiency is low. To make realistic studies it has so far been necessary to lower the bottom rf slightly to allow synchronous acceleration to 48 in. This has made necessary a corresponding reduction of top frequency, and some reduction of internal beam current. Measurements of internal intensity vs radius show that only 15% of the beam at 48 in radius reaches 49 in, whereas in the absence of channel and regenerator virtually all the beam does so. This is presumably due to vertical blow-up of particles with significant radial amplitudes. The whole of the channel entrance is illuminated by beam, but measurements with a blocking target moving across the entrance show that only beam from the inner ¼ in of the aperture is transmitted through the channel, and the total overall transmission of the channel is at best ~10%. The channel line will be re-adjusted in the near future.

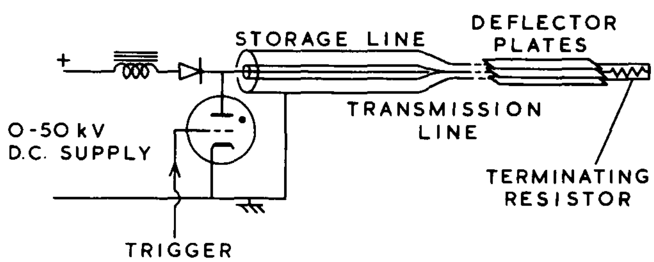


Fig. 11. Time-of-flight beam deflection circuit (schematic)

The highest intensity extracted beam outside the cyclotron tank has been achieved with the ion-source pulse timing set as described previously to produce minimum radial oscillations. Typical figures for protons are:

Optimised internal beam 1·5 μA. External beam 5 nA.

Internal beam 0·66 μA. Optimised external beam 10–15 nA.

The beam has been transported some 25 ft and a focused spot size of ~0·4 in diam. obtained using two quadrupole pairs.

6. NEUTRON TIME-OF-FLIGHT SYSTEM

The improvements made here fall under two headings:

(a) Re-design of the beam deflection system.

(b) Provision of new flight paths and experimental stations.

The new beam deflection system is illustrated schematically in Fig. 11. The circulating beam bunch is deflected vertically by the voltage and current pulse applied to a set of deflector plates which form part of a terminated 50 Ω transmission line. A 50 Ω storage line is charged to 80 kV (maximum) by a resonant charging circuit and an English Electric CX1168 double gap thyratron is used as a shorting switch to produce a 40 kV (maximum) pulse along the line to the deflector plates. The direction of current flow in the plates is opposite to

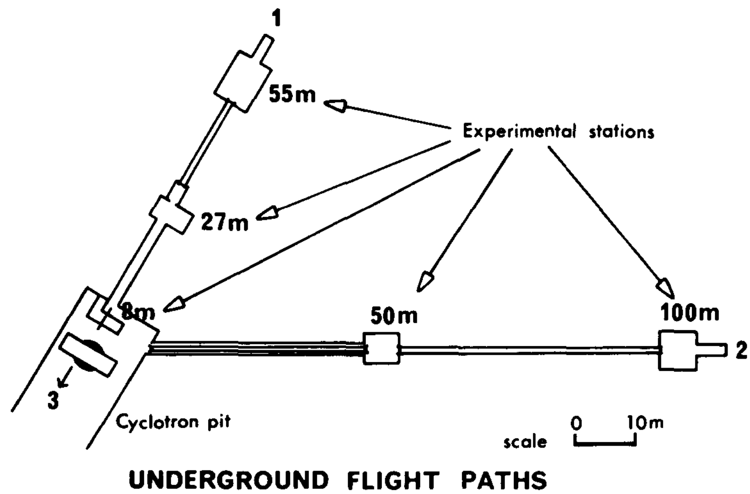


Fig. 12. Layout of neutron flight paths

that of the beam, so that the vertical deflection of the bunch is caused by the sum of the electrostatic and electromagnetic forces. The timing of the pulse relative to the azimuthal motion of the bunch is adjustable so that the whole bunch can be deflected cleanly in a single turn. The deflected particles execute the first part of an induced vertical oscillation over about one turn before striking a target placed outside the median plane. Two sets of plates are provided, for mean radii of 36·5 in (95 MeV protons) and 45 in (140 MeV protons). Both sets occupy ~60° arc, have a radial extent of 4 in and a gap of 1·2 in. The performance under normal conditions is as follows:

Pulse voltage 35 kV (700 A)
Deflection 1·2 in
Pulse risetime ~15 ns, jitter <2 ns
Pulse duration 60 ns
Maximum repetition frequency 1500 Hz.

The repetition frequency is limited by the time constants of the charging circuit and the mean current available from the power supply. In practice, the frequency is determined by the cyclotron. Slow variations in firing time of the thyratron have been found to be <5 ns and can be servo-controlled.

The main experience gained so far has been for an experiment demanding high resolution. By adjusting repetition rate and dee voltage to produce a highly constricted phase bucket a resolution of 2·5 ns *FWHM*, corresponding to an azimuthal bunch length of 18° *FWHM* has been obtained. Running in such a way as to maximise beam intensity a resolution as high as 4 ns *FWHM* is obtained, a further indication that the phase bucket is not uniformly filled under these conditions.

Two main neutron flight paths are available, as shown in Fig. 12, giving underground experimental stations at 8, 27, 50, 55, and 100 m from source. A third flight path is available on the opposite side of the cyclotron into the area normally used for charged particle work.

7. FUTURE DEVELOPMENTS

The main area in which improvement is still required is that of internal beam quality. The only known solution is to provide a dee which conforms much more closely to the standard 180° shape. This must be done without increasing the capacity, if major modifications to the whole rf system are to be avoided, in particular the rotating capacitor. Fortunately this may be possible, as the present dee aperture (average ~4½ in) and maximum radius (55 in) are needlessly large. Although a complete 180° dee may not be possible, calculations show (for example) that a dee of 10% less area which is cut-back gradually in stages from 25 in radius should induce only 0·1 in to 0·2 in radial motion, a figure at least as good as the initial quality that might be expected from the source. Such quality would hopefully give a considerably better extraction efficiency, and also provide a less diffuse neutron source for time-of-flight work.

The present cee (slow extraction electrode) requires modification to work at deuteron and $^3He^{++}$ frequencies, though if much improved beam quality is attained it will be feasible to use the magnetic bump coil system (Hogelator) described by Hogel Kim.[5]

Another region where further improvement is possible is the ion-source. In a pulsed machine, a cold cathode calutron source should have a longer life without cathode replacement than the present filament source. One has been designed but not yet built. A disadvantage of the rf puller is that ions are injected into orbits far removed from the synchronous phase so that beams with preferentially large phase oscillations are produced. A solution to this problem has been suggested by Holm,[6] in the form of a calutron source with d.c. extraction. This has some difficulties, including the necessity of holding the hood and chimney at several kV positive potential. Such a source, however, would inject particles much nearer the synchronous phase at the machine centre, and would probably enable better time resolution for neutron time-of-flight work.

Finally, further work is required on the problem of the low intensities of α-particles and $^3He^{++}$.

DISCUSSION

Speaker addressed: J. P. Scanlon (Harwell)

Question by H. Blosser (M.S.U.): How do you measure your radial oscillation amplitudes?
Answer: We measure the time distribution of beam arriving on a target at a given radius, and translate this to a radial distribution, having made some allowance for the effect of phase motion on the distribution.

Question by E. G. Michaelis (CERN): Have you investigated the effect on beam intensity or beam quality of any displacements of the ion-source?
Answer: The internal intensity is not critically dependent on the ion-source position. A source movement of ~1 cm will give ~20% change. We cannot yet say how critically the quality depends on position. However, the external beam intensity is more sensitive, and is optimised by moving the source some distance from the calculated position, in such a direction as might be expected to reduce the dee-induced radial motion.

REFERENCES

1. Scanlon, J. P., Stafford, G. H., Thresher, J. J., and Bowen, P. H., *R.S.I.* **28**, 749, (1957).
2. Watson, P. G., *Nucl. Instr. Meth.* **18**, 362, (1962).
3. de Kruif, G. T. and Verster, N. F., *Philips Technical Review* **23**, 381, (1961).
4. M.S.C. New Projects Group Programmes, CERN, (1968).
5. Hogel, Kim, *I.E.E.E. Trans. Nucl. Sci.* **NS-13**, 58, (1966).
6. M.S.C. Staff, Proposal for Improvement of 600 MeV Synchrocyclotron, private communication, 64, (1967).