The axial injector for the Harwell variable energy cyclotron

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ABSTRACT

The design and construction of the axial injector for the Harwell Variable Energy Cyclotron is described. The injector is to replace the conventional ion source at the centre of the cyclotron for all ion beams. It is hoped that easier working with heavy ions and in particular ions of non-gaseous elements will result. The ion source is of the Penning Ionisation Gauge type and the magnetic field necessary for its operation also serves to analyse the beam into the different charge to mass ratio components. The analysed beam is injected into the centre of the cyclotron down an axial hole in the top pole of the cyclotron magnet and is focused by magnetic quadrupoles. An electrostatic mirror deflects the beam into the median plane of the cyclotron. Electrodes in the dee and dummy dee concentrate the electric field at the first rf gap to give improved acceleration without intercepting the beam.

The injector is at present being commissioned and the first preliminary results of acceleration of protons to 27 MeV and C^{2+} to 22 MeV are given.

1. INTRODUCTION

The Harwell Variable Energy Cyclotron[1] was designed with a hole through the centre of the pole to allow for axial injection if required at some future date. The axial hole was in the meantime used for insertion of the ion sources[2] into the centre of the machine.

It soon became clear on operating the cyclotron, particularly with heavy ions, that axial injection could have important advantages in replacing the conventional source for all beams and not just polarised ions (in fact there is little demand for polarised beams). To obtain reasonable currents of multiply charged heavy ions a large source slit is used, because only a small fraction of the ions are in the required charge state. However, the total current issuing from the source is quite large (up to 50 mA) and increases rf breakdown. With axial injection, the beam can be analysed, and then only small currents of the required ions enter the cyclotron. Moreover the current from the ion source can be increased by further enlarging the slit without affecting the dee.

Alternatively the source can be run under less severe conditions to increase the cathode life and yet maintain the existing current output with the enlarged slit.

The space available to the ion source in the centre of a cyclotron is usually very restricted. With external injection this limitation is removed and larger and more robust sources can be made. Also it is easier to make sources for non-gaseous materials. Non-gaseous sources tend to emit products which deposit on the surrounding surfaces. This would normally contribute to breakdown of the dee, but with an external source the amount of deposit entering the cyclotron would be much reduced.

The external source with differential pumping would result in a better vacuum pressure in the cyclotron chamber and reduce stripping losses with heavy ion beams.

In addition to these advantages for heavy ion beams the external source can be placed outside the main cyclotron vault where radiation and access would be improved, hence aiding maintenance. Furthermore polarised sources could be used should the demand arise.

Listed above are some of the advantages and reasons for building an external injector. It was decided to use axial injection rather than median plane injection[3, 4] because of the greater access and convenience within the existing cyclotron building.

2. DESCRIPTION OF THE INJECTOR

A diagram of the vertical cross-section through the injector is shown in Fig. 1. The multiply charged heavy ion source[5] is of the same design as that used conventionally in the centre of the cyclotron. It is located in the 4-in gap of a small magnet which not only provides the field for the source but analyses the beam into the various charge states. The source, shown in Fig. 2, is in two sections which are inserted through 2-in diam. holes in the poles in the magnet. To avoid the problem of discharges with a positively biased source in a magnetic field, the magnet, vacuum chamber, associated equipment and electrical supplies are all at the injection potential of 10-30 kV. This is particularly important when using sources with non-gaseous materials since deposits can build up on nearby surfaces and decrease the voltage holding.

The ions are accelerated from the source through a slit in the nose of the water-cooled copper box electrode which is at earth potential. The orbit radius of the ions is adjusted by the magnetic field to 4 in and the beam is able to leave the box electrode and pass down an iron tube into the beam measuring box. The iron tube acts as a magnetic shunt to sharpen the fall-off of the field from the magnet outside the pole tips.

Inside the beam measuring box are a pair of slit plates at the focus of the magnet. The plates are insulated for current monitoring and adjustable to vary the slit width. Behind the slits is a Faraday cup fitted with an electron suppression ring.

After the measuring box are three sets of magnetic quadrupole pairs arranged along the 2-in diam. beam pipe, and two sets of steering magnets. Current monitoring on cross wires above the cyclotron magnet can be used to centre the beam.

The beam finally enters the electrostatic mirror on the axis of the cyclotron magnet. The mirror is similar to that used by Powell[6] and is shown in Fig. 3.

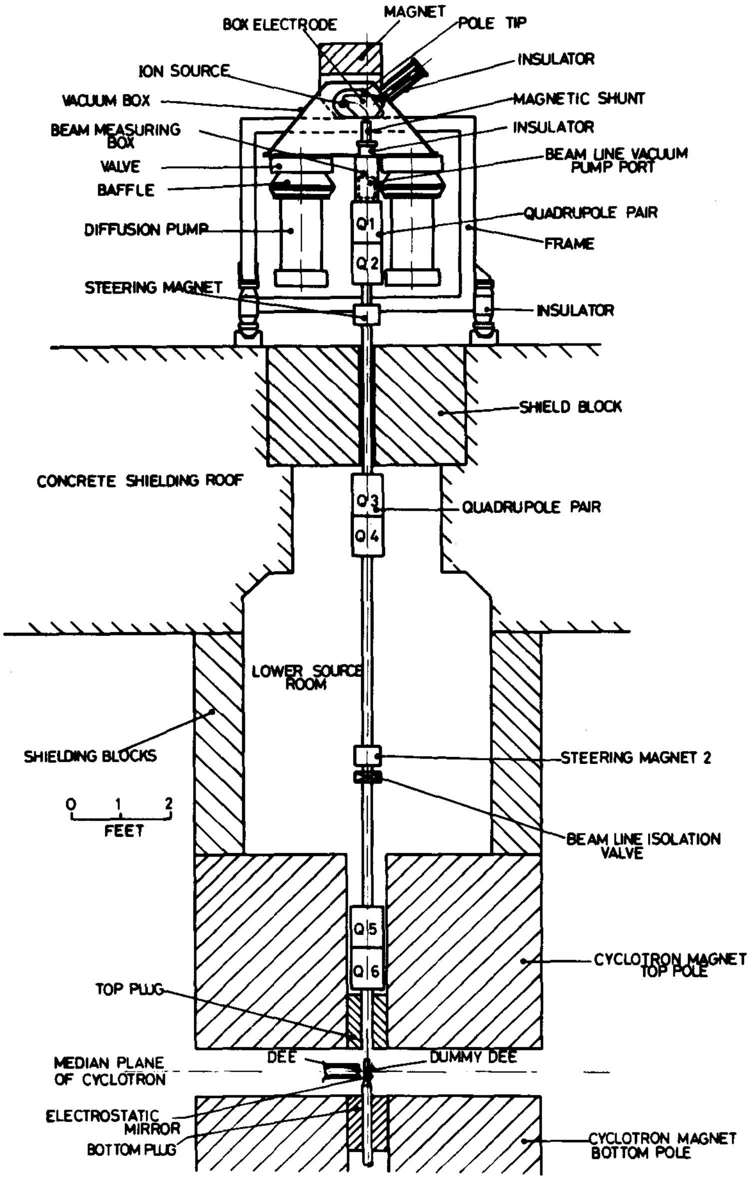

Fig. 1. Vertical cross-section through the injector

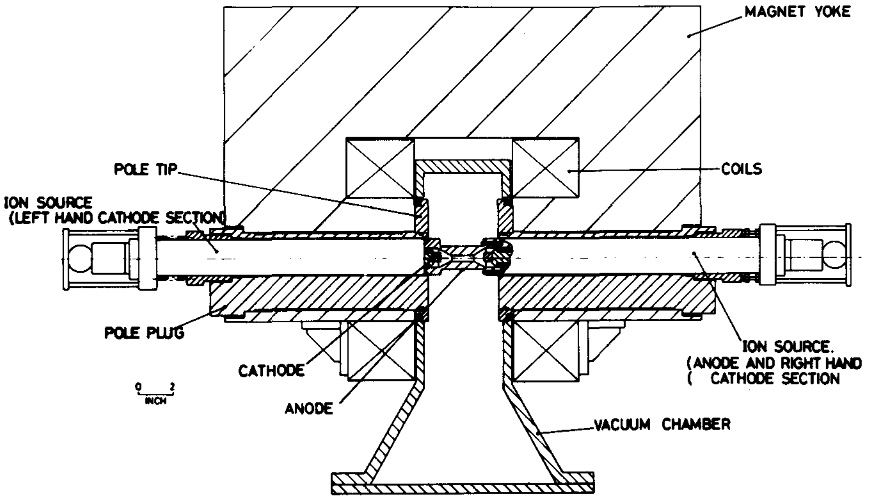

Fig. 2. Part section through the ion source and analyser magnet. Only the ion source, analyser magnet and vacuum chamber are shown, other parts of the injector being omitted for clarity. (The vertical section is in a plane perpendicular to that of Fig. 1)

The high-voltage reflector electrode is chromium-plated copper and the grid wires of tungsten are 0·0008 in diam. spaced 0·020 in apart. The reflector will withstand positive voltages up to 30 kV in a magnetic field quite readily. The insulator is made from unfired pyrophylite. Boron nitride has been used but discharges occurred on the surfaces. The mirror can be adjusted axially and rotated to obtain orbit centring in a direction perpendicular to the dee edge.

After leaving the mirror the beam enters the cyclotron towards the dummy dee, executes half a turn and then passes through the movable pusher and puller electrodes which concentrate the electric field at the first rf gap and ensure that the particles have a good acceleration. Fig. 4 shows the geometry in the centre of the cyclotron. The shield attached to the dee is necessary to screen the particles on the second half revolution from the field between the dee and the mirror head.

Two 3000 l/s diffusion pumps are hung below the vacuum chamber of the magnet and ion source and a small 600 l/s pump is attached to the top of the beam line at the measuring box. Pressures up to 4×10^{-6} mm Hg are obtained in the main vacuum chamber with the source gas on. The pressure in the beam line is 1×10^{-6} mm Hg.

3. DESIGN OF THE CENTRE REGION OF THE CYCLOTRON

To examine the particle motion and optimise the centre region geometry in the cyclotron, experiments with a simulated axial injection system were carried out in the Model Cyclotron.[7] A source at a positive bias potential of up to 10 kV was placed on the axis of the cyclotron. A small earthed 'puller' electrode was placed immediately in front of the source slit which faced into the dummy dee.

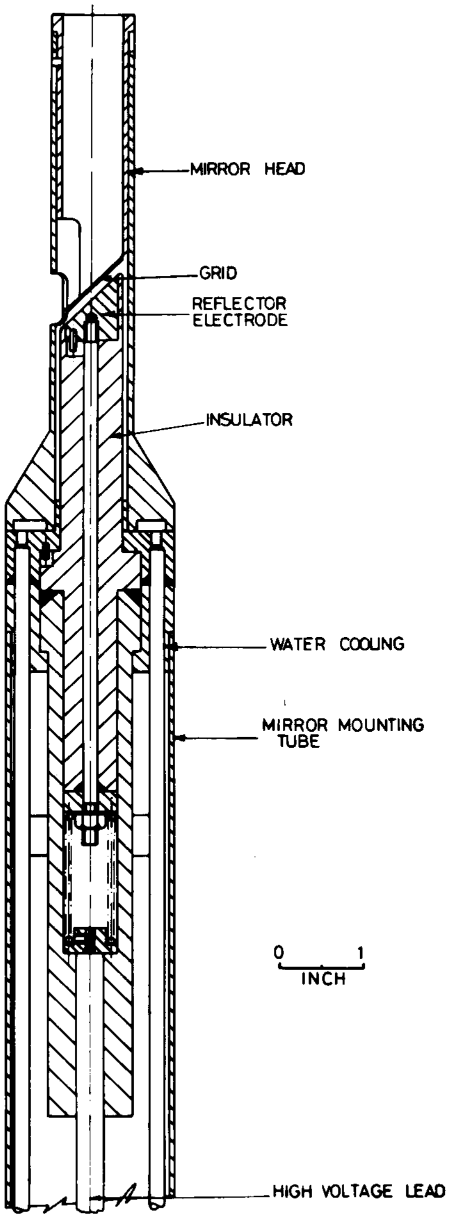

Fig. 3. Section through the head of the electrostatic mirror

A beam of ions thus emanated from the source as if from the mirror of an axial injection system.

It was found that beam could be accelerated without grid wires in the dee and dummy dee, but better beam current and quality were obtained by concentrating the electric field at the first rf acceleration. This was achieved by a puller in the dee and a similar electrode, called a pusher, in the dummy dee. These electrodes do not intercept any beam.

It was also found that the electric field between the dee and the ion source affected the first orbit and moved the orbit centre ½ inch towards the dee. A shield was therefore placed in the dee between the orbits and the ion source.

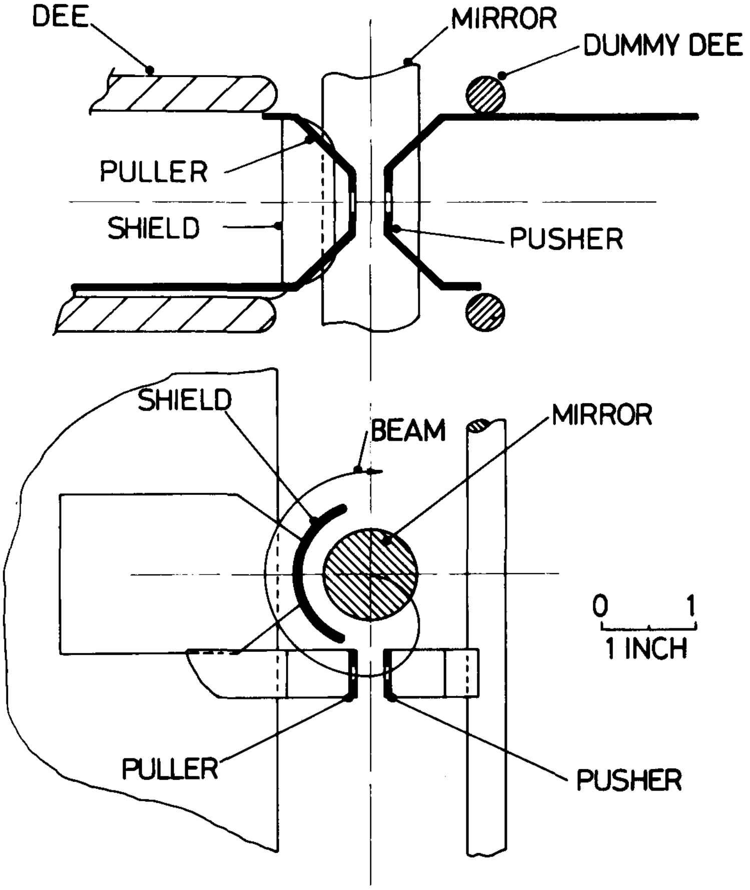

Fig. 4. Centre region geometry of the cyclotron. Vertical and median plane sections

Measurements of the internal beam quality in the cyclotron showed that the incoherent oscillation amplitude was less than 0·1 inch despite the large phase acceptance range of 90°–double the range found with the conventional source arrangement.

To produce a centred beam in the cyclotron the ratio of injection voltage to dee voltage should be ~ 0·2. However, if the gap factors are not equal on successive half-turns this figure will change. By concentrating the electric field with the pusher and puller the injection voltage ratio was increased to nearly 0·3. This is an advantage since high injection voltages reduce space charge effects in the focusing of the beam in the injector.

Computer calculations were also carried out on the particle motion in the median plane of the cyclotron to confirm the measurements on the model cyclotron and to estimate the injection voltage required for beams accelerated on harmonics. On fifth and higher harmonics the centring depended quite critically on the electric field configuration. Injection voltages of up to twice the value required for fundamental mode were necessary to obtain centred beams.

Because of the finite injection velocity into the rf accelerating structure of the cyclotron the accelerations at the centre are improved. A wider phase acceptance and better gap factors are achieved. These factors are very important for harmonic operation. It is not possible to compare the efficiency of harmonic operation on the model cyclotron with fundamental operation, because of the fixed rf on the dee. However, greater currents were accelerated on third harmonic with the biased source then with the conventional system and acceleration of small beams was achieved up to the eleventh harmonic.

4. DESIGN OF THE BEAM FOCUSING

As the particles from the injector pass through the hole in the pole of the cyclotron magnet into the magnetic field in the gap they experience strong forces which set the particles into a rotary motion in the plane perpendicular to the magnetic field. This motion affects the initial centre spread of the beam in the cyclotron as well as introducing a vertical angular spread. Analytical calculations were made assuming the field rose from zero in the pole to the maximum value at the pole tip in a single step. The particle motion through the mirror was then calculated. The calculations were backed up by computer studies using the actual measured field shapes. From these studies it was possible to find the conditions for the beam entering this region which minimised the centre spread in the cyclotron.

Using the measured emittances of several beams from the ion source, the quadrupole focusing was designed to accept and transmit the beam with a minimum loss and finally focus it near the pole tip of the cyclotron to minimise the centre spread introduced by the cyclotron magnetic field. By using magnetic quadrupoles the entire path of the ion beam from initial acceleration at the ion source, to the mirror is electrically field-free. Separate experiments had shown that in such a region space charge neutralisation of the beam could be expected. In this way large beam currents (10 mA of protons) should be transportable over the 20 ft from the ion source to the mirror with only three quadrupole pairs.

Calculations were also carried out on the effects of the mirror grid wires. The electric equipotentials between the positive reflecting electrode and the grid are not perfectly planar but distorted as the field penetrates through the grid spaces. This introduces an angular spread to the beam emerging from the mirror. The magnitude of the effects was studied using the calculations of Banford.[8] At present a commercially available tungsten mesh is being used but a closer spacing of finer wires would be more desirable.

5. PERFORMANCE

The injector has just been installed and commissioning is in progress. In the short time so far available over 20 μA of protons have been accelerated to 27 MeV and over 20 μA of C^{2+} to 22 MeV (third harmonic). With the mirror voltage off, injected beam currents of 60 μA of protons and 240 μA of C^{2+} ions were measured on the mirror reflector electrode. (Since there is no secondary electron suppression, these currents may be larger than the true values.) The injection voltage was 16 kV. Reasonably well centred beams were obtained at dee voltages of 55 kV and 65 kV for the proton and C^{2+} beams respectively. The stripping loss of the carbon beam was significantly reduced with axial injection since the cyclotron vacuum pressure (1×10^{-6} mm Hg) was not increased by the ion source gas. Almost half the beam at 6 in radius reached 30 in. Hence about one-sixth of the injected beam was accepted by the cyclotron. This figure is half that for the proton beam and is probably due to the third harmonic operation.

ACKNOWLEDGEMENTS

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DISCUSSION

Speaker addressed: J. R. J. Bennett (Rutherford Laboratory)

Question by D. J. Clark (L.R.L.): We know from presently operating external injection systems that the beam quality and transmission can be very good at low beam intensities. Do you feel that for the case of high beam currents up to 100-200 μA of protons or other light ions that the beam quality using an external source can be as good as with an internal source, considering space charge effects?
Answer: Yes, I think it could possibly be better.

REFERENCES

1. Lawson, J. D., Rutherford Laboratory Report NIRL/R/85.
2. Bennett, J. R. J., Rutherford Laboratory Memo. NIRL/M/80.
3. Beurtey, R. and Thirion, J., *Nucl. Instr. Meth.* **33**, 338, (1965).
4. Gladishev, V. A., Katsaurov, L. N., Kuznetsov, A. N., Martinova, L. P., and Moroz, E. M., *Atomnaya Energiya* **18**, 213, (1965).
5. Bennett, J. R. J., Proceedings of this Conference, p. 499.
6. Powell, W. B. and Reece, B. L., *Nucl. Instr. Meth.* **32**, 325, (1965).
7. Chen, C. E. and Rogers, P. S., Rutherford Laboratory Report RHEL/R 116.
8. Banford, A. P., Rutherford Laboratory Internal Report, P.L.A. Acc. Phys. 29.