Operation of the polarised ion source and axial injection system for the 88-in cyclotron*

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Presented by D. J. Clark

ABSTRACT

A polarised-ion source for protons and deuterons is now in operation at the Berkeley 88-in Cyclotron. The source is of the atomic beam type, using rf transitions and a strong field ioniser. It is mounted vertically above the cyclotron roof shielding. A new axial injection transport system, whose optical elements are electrostatic quadrupole triplets, brings the beam 4·5 m down to the cyclotron median plane. A duoplasmatron source can inject unpolarised protons through a 90° bending magnet. A gridded electrostatic mirror inflects the beam into the dummy dee. Electrodes inserted into the dummy dee and dee give narrow accelerating gaps to allow the beam to clear the mirror. They are designed to unplug under vacuum for easy conversion between axial injection and internal source operation. Maximum beam currents at present are up to 3 μA of polarised protons at the source, 0·05 μA accelerated in the cyclotron, and 0·02 μA external beam with a polarisation of 70%.

1. INTRODUCTION

The first objective of the external injection system for the 88-in Cyclotron is to provide high intensity beams of polarised protons and deuterons from the cyclotron. The previous polarised proton beam, produced by α-p scattering, had an intensity of 0·02 nA. Using a polarised source one can obtain at least 20 nA external beam with much better beam quality and energy resolution.

Another requirement for the system is that it should be capable of pulsing unpolarised beams on a ns to μs time scale. For this type of operation, high peak

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intensity beams are required, and space charge forces become important. Later, heavy ions will be injected.

The requirement for the transport line to the median plane is that it should provide flexible matching between the emittances of various ion sources and the acceptance phase space of the cyclotron. It should transmit both low and high intensity beams with good efficiency, and provide fast monitoring of beam intensity and size along the line.

The inflection and centre acceleration electrodes should transport the beam with high efficiency and low distortion into a centred cyclotron orbit. The conversion from internal to external source should be as fast as possible, because of the heavy demands on cyclotron time.

The following sections describe the new system which has been designed and installed since the original axial injection test of 1966.[1]

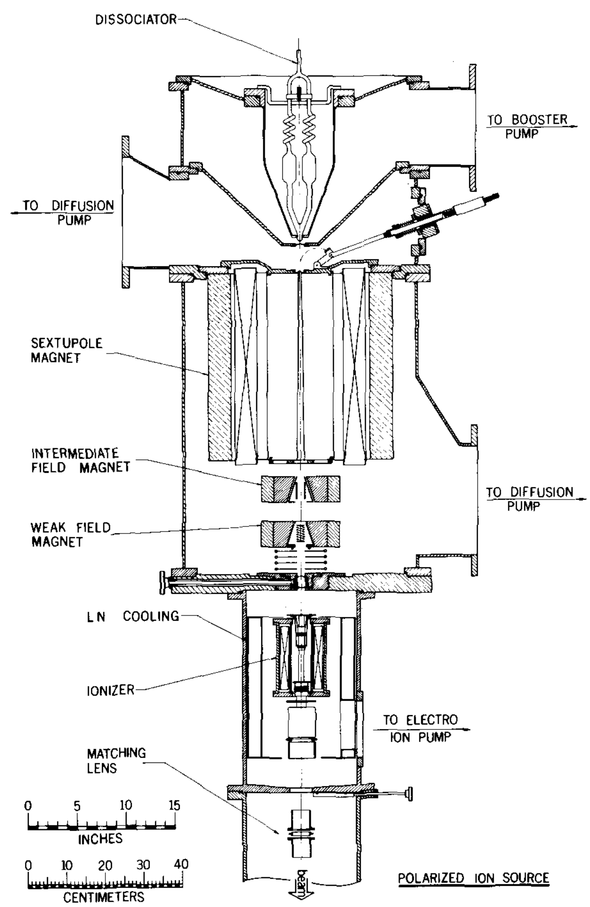

Fig. 1. Polarised-ion source schematic cross-section, showing principal components and vacuum pump ports

2. THE POLARISED-ION SOURCE

A polarised-ion source, shown in Fig. 1, was constructed to provide d.c. beams for injection.[2] To allow for future development it is designed for easy replacement of components and has a large pumping capacity to handle high gas loads. It is located in a low radiation area above the cyclotron shielding roof for convenient maintenance and development. Its axis is vertical, to match the injection line without spin rotation. A brief description of the source follows.

The atomic beam of hydrogen or deuterium is produced in an rf dissociator powered by a self-excited oscillator. After collimation by 3 apertures the beam passes through a 50 cm long sextupole magnet. Next it passes through the rf transition sections. For protons a weak field transition gives 1·0 theoretical vector polarisation when the atomic beam is ionised in a strong magnetic field. For deuterons a weak field transition produces 0·67 theoretical vector polarisation, and intermediate field rf transitions give tensor polarisations of ±1·0. Ionisation of the separated atomic beam takes place in a strong field ioniser built by ANAC Company[3] and purchased as a system from ORTEC Corporation. Reversal of vector polarisation of protons or deuterons is done by reversing the ioniser magnetic field. A high capacity pumping system is used.

3. THE AXIAL INJECTION TRANSPORT LINE

The beam transport line,[4] shown in Fig. 2, brings beams from the ion sources 4·5 m down to the cyclotron. It is composed of three sets of electric quadrupole triplet lenses. It accepts beams from either the polarised-ion source directly above on-axis, or from the duoplasmatron test source[5] through the 90° bending magnet.

The optics of the line[6] was designed to transport beams of up to 800 mm mrad emittance at energies of 5–20 kV, and to allow flexible matching between the external beams and the cyclotron phase-space acceptance. Calculations on high current beams including space charge forces show[7] that this line will transmit 600–800 μA of protons if the beam has a suitable emittance shape.

Beam monitoring along the line is done by biased Faraday cups and phosphor plates mounted on air cylinders, and motor-driven X–Y scanning wires with oscilloscope readout. Several X–Y steering plates are mounted between quadrupoles. One set will later be used for fast beam pulsing. A sine-wave buncher is placed between the second and third triplets. It is a drift tube with a drift length of 3/2 of a cyclotron period. It is located near the cyclotron end of the line to minimise debunching from polarised-ion source energy spread. We use the sine-wave rather than the previously proposed sawtooth wave shape[8] because of its ease of construction, and because its performance would closely approach the sawtooth type after adding a higher harmonic drift tube.

The beam enters the cyclotron through a half-solenoid 'hole lens', the region where the cyclotron magnetic field increases from near zero to its median plane value of 5–17 kG. Calculations of phase space beam trajectories[9] show that several modes of operation are possible, depending on injection energy, and cyclotron magnetic field. In the 'λ mode' the hole lens can transform the phase space from a waist outside the lens to a similar waist in the median plane. In the '3/2 λ mode' the lens transforms a large cross-section beam to a small cross-section beam.

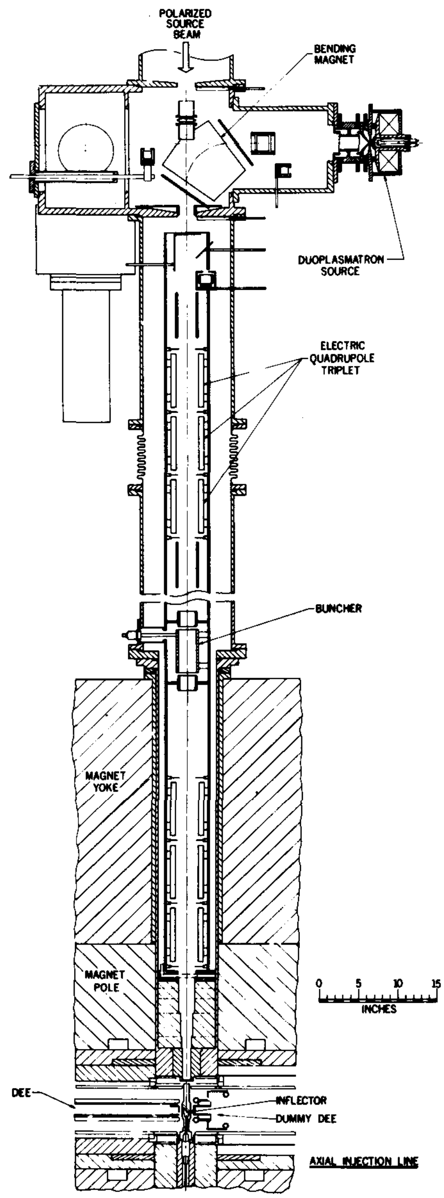

Fig. 2. Axial injection transport line schematic cross-section, showing components. Note that one quadrupole triplet lens has been omitted

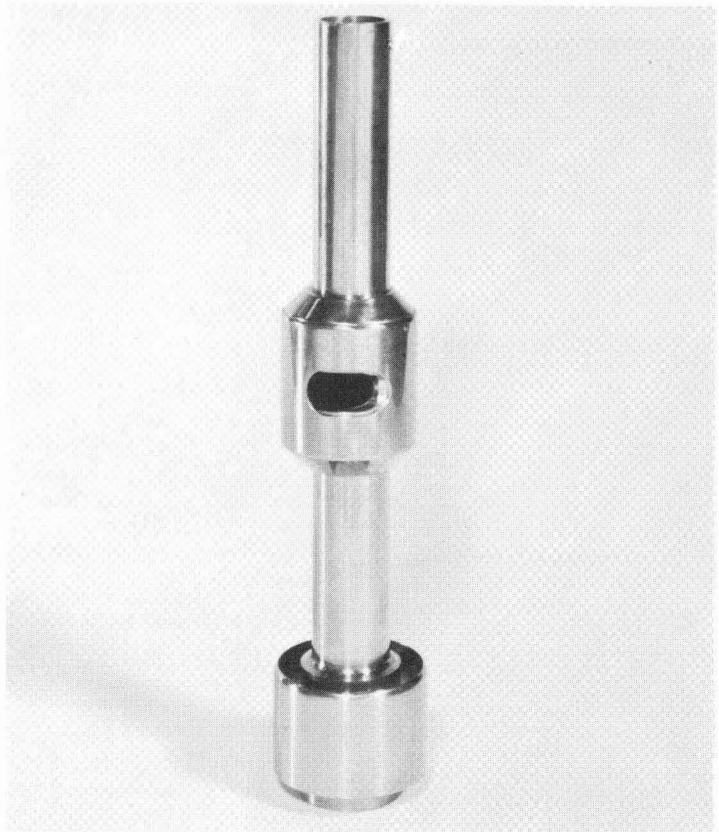

Fig. 3. Inflector housing. Exit slot at centre brings beam into dummy dee. Material is inconel

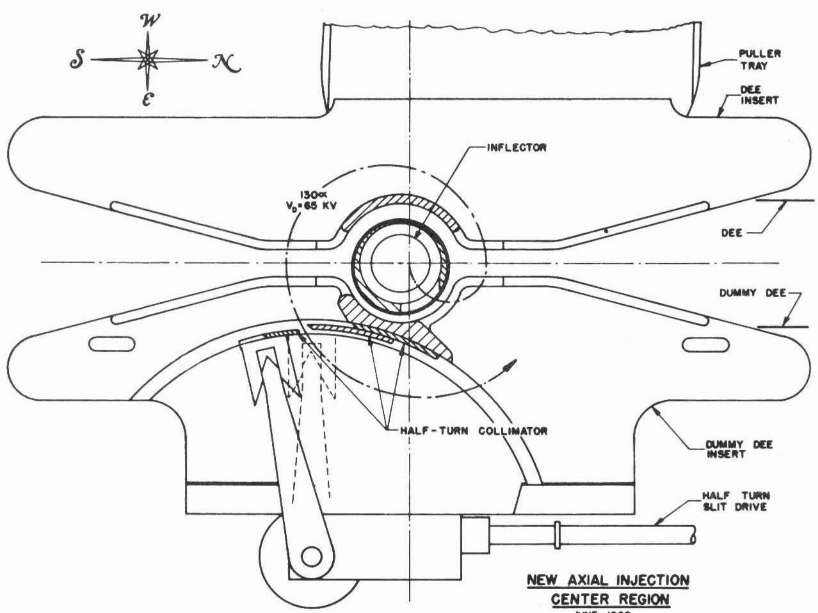

Fig. 4. Axial injection centre region plan view, showing smallest beam trajectory for maximum energy α-particles. 'Plug-in' dee and dummy dee inserts are shown

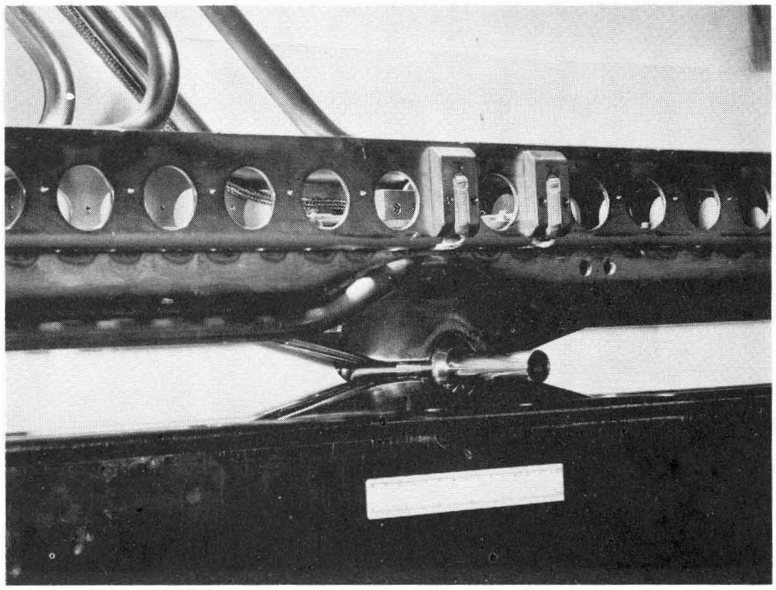

Fig. 5. Photo of axial injection centre region when set up prior to installation, showing dummy dee with insert, inflector, and dee with insert

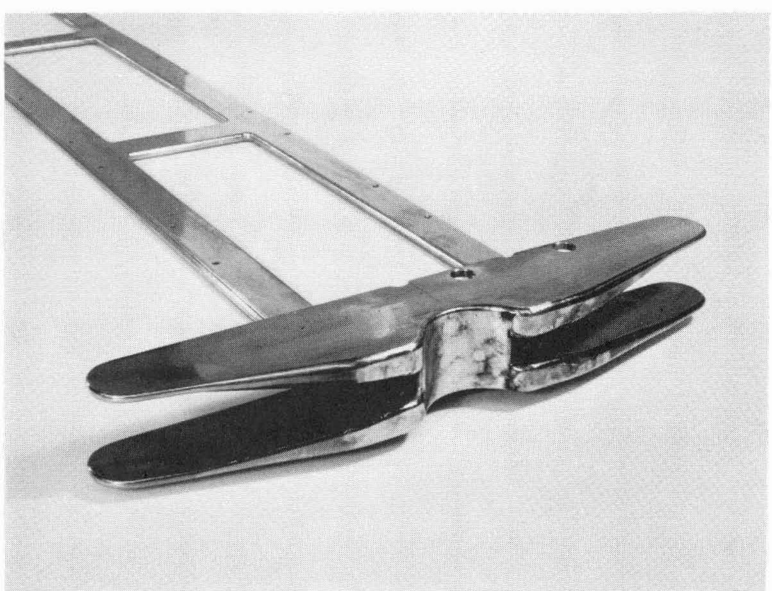

Fig. 6. Dee insert for axial injection mounted on its tray. Material is inconel

4. CYCLOTRON CENTRAL REGION

When the beam reaches the median plane of the cyclotron, it must be bent through 90° into the horizontal plane and enter the dee accelerating gaps in such a way as to be centred radially on the cyclotron centre. Simple calculations show[10] that if the beam is injected on the magnet axis and inflected toward the dummy dee, the ratio of injection voltage, V_i, to dee voltage, V_D, should be 0·2 for a single dee cyclotron with narrow accelerating gaps. This is a convenient ratio, since our highest dee voltage of 65 kV would mean 13 kV injection energy. On axis injection is also convenient because it avoids the problem of shimming the magnet leakage flux which would deflect the beam in off-axis injection.

To inflect the axial beam into the median plane, we use an electrostatic mirror orientated at 45° to the median plane, which is shown in Fig. 3. As a grid we use a tungsten mesh woven with 0·025 mm wire and 0·25 mm space, with an overall transparency of 60% for the two 45° traversals. The grid-electrode spacing is 5 mm. The inflector is mounted on a probe which is inserted through a hole in the lower pole, in place of the normal ion source.

To design the centre region, orbit calculations in the median plane have been done with the Michigan State Pinwheel computer code on the first few particle revolutions. The first electric fields used were measured in the University of Maryland electrolytic tank facility.[11] The electrodes modeled those used in the 1966 axial injection test.[1] The results showed that there were electric field distortions from vertical baffles close to the beam. A new geometry was designed to reduce these distortions. The gaps are 180° apart to minimise sensitivity. Narrow electrode gaps of 1 cm were used to give the beam enough acceleration to clear the inflector housing. For Pinwheel calculations the electric fields in the median plane were approximated by uniform fields perpendicular to the dee gap, using gaps somewhat larger than the electrode spacings. The calculations for this case showed the ratio of $V_i/V_D = 0{\cdot}18$, very close to the 0·2 of the simple calculation.

The resulting geometry is shown in plan view in Fig. 4, along with the calculated orbit for the highest energy α-particle beam. A baffle across the median plane in the dee shields the beam from the dee-mirror electric field. A 'half-turn collimator' is provided in the dummy dee to select phase on the first turn, but is normally retracted for polarised-ion injection, because maximum transmission is desired. A photo of the centre region is shown in Fig. 5.

This axial injection geometry is not compatible with the normal internal ion source, since the source would have to come through the dummy dee. So a 'plug-in' concept was adopted, in which the central parts of the dee and dummy dee out to a 14 cm radius, the 'inserts', are removable at vacuum through the dee stem. The dee insert is mounted on a tray in the dee, similar to that holding the normal puller, as shown in Fig. 6. The dummy dee insert is held by ball detents in the main section of the dummy dee, which is bolted to the poles. It can be removed by a tool tray through the dee stem. The material of the inserts and dummy dee is inconel, which is a high temperature nickel alloy with good high voltage characteristics.

At the same time that a new axial injection centre region was designed, a centre region for the internal source had to be provided. The plug-in facility allows a wide choice of centre geometry. We decided to try a narrow gap design here also, as shown in Fig. 7. The structure is again based on 180° symmetry. The design provides a source-puller set-back as in the original design to give electric focusing, and a 'half-turn' collimator to clip the phase to 6° as required for some experiments. One interesting feature is a sliding edge on the dummy

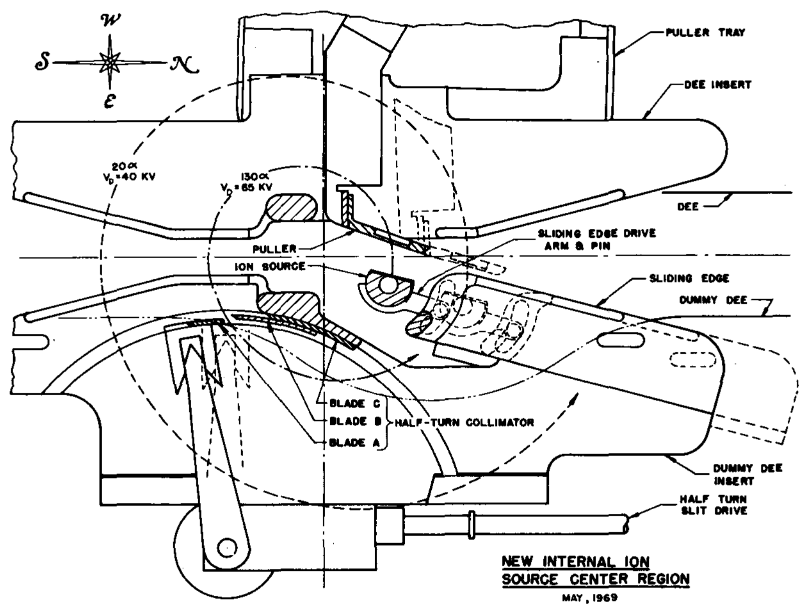

Fig. 7. New internal ion source centre region plan view, showing beam trajectories for lowest and highest energy beams. Note sliding edge on dummy dee insert, moved by pin on anode

dee insert, moved by a pin on the ion source, to maintain 180° symmetry for various ion source and puller positions.

Operational experience with the inserts show that they can be changed in about 2 h. There have been occasional problems with engaging the ion source pin in the sliding edge upon source insertion. There has been slight insert melting near the puller, and on the first half turn on the dee insert during a bad vertical misalignment of source and puller. Maximum beam currents are as large as before: hundreds of μA of protons, He^3, and α-particles accelerate well, and intensity is normally limited by septum power dissipation. Careful transit surveys of the source and puller heights have shown that the source rises gradually 1 mm when the main magnet current increases, and the dee and puller drop gradually 0·25 mm as the rf power increases. These surveys are used to get a vertical alignment of 0·25 mm between source and puller, since larger misalignments are observed to cause large vertical beam oscillations, and heating of the top or bottom of the inserts.

5. OPERATION OF POLARISED SOURCE AND AXIAL INJECTION SYSTEM

The first test of the entire system of polarised-ion source, axial injection system, and cyclotron acceleration was in April 1969. In that test the source gave 700 nA of polarised protons, and there was an extracted beam of 1·5 nA of 20 MeV protons. The polarisation was measured as 80% in Cave 4. Since then some improvements have been made. The atomic beam collimator apertures have been optimised. The ioniser alignment has been improved, and a quartz dissociator tube has been installed, to replace the pyrex tube. The best results of system operation to August 1969 are given in Table 1. The polarisation was measured in Cave 5 by scattering from carbon at 16·7 MeV.

Table 1. SYSTEM TESTS WITH 22 MeV PROTONS

	Ion source	
	Polarised	*Duoplasmatron*
Injection energy	12 keV	10 keV
Source current, FC_0	1·4 μA	40 μA
Accelerated current	50 nA	3·6 μA
External current	20 nA	1·8 μA
Transmission: Source-ext. beam	1·5%	4·5%
Polarisation	70%	0
Buncher used?	No	No

6. ACKNOWLEDGEMENTS

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DISCUSSION

Speaker addressed: D. J. Clark (LRL)

Question by W. B. Powell (Birmingham University): There seem to be no pullers or pushers at the centre. Is your initial electric field defined in any way?
Answer: The combination of small vertical apertures in the dee and dummy dee, and narrow dee-dummy dee gaps give small enough effective initial gaps to give good acceleration on the first turn.

Comment by J. R. J. Bennett (Rutherford Laboratory): We have experimented on our small model cyclotron on electrodes which are similar to those described for the 88 in cyclotron, and found that the accelerated beam quality and current

were not as good as with the system using the puller and pusher geometry used on the Harwell V.E.C.
Answer: I suppose it affects the gap factor.

Question by Bennett: Do you restrict the dee aperture on both sides of the source
Answer: Yes.

Further comments by Bennett: We wanted to have good acceleration at the first rf crossing, which would then enable us to increase the injection voltage whilst maintaining a centred beam in the cyclotron.

Question by H. Willax (Zurich): What is a typical value of your beam phase width?
Answer: 60–90°.

Question by E. G. Michaelis (CERN): What insulating material did you use for the inflector support?
Answer: Alumina.

Question by F. A. Ripouteau (Grenoble): What was the atomic beam intensity at the ioniser level for the 2 μA polarised proton beam current you quoted?
Answer: 10^{16} to 10^{17} atoms per cm^2/s, but we have not made extensive measurements on that point.

Question by P. A. Roche (Saclay): Have you made any measurements of the emittance of the polarised beam after the ioniser?
Answer: Measurements were made by Glavish (ref. 3) on this ioniser. Most of the beam is inside 600 mm mrad at 10 kV energy.

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