Design and performance of an H⁻ injector cyclotron

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ABSTRACT

Two compact negative hydrogen ion cyclotrons utilising external ion sources with axial injection have been constructed for use as high energy ion sources for Tandem Van de Graaff accelerators. Approximately 2·5 mA of H^- ions (or 1·5 mA of D^- ions) are generated externally in an Ehlers[1] ion source, analysed and then axially injected into the cyclotron. The axial injection system includes two pairs of electrostatic quadrupoles and a velocity bunching system to transport the beam to an electrostatic mirror in the central region of the cyclotron.
The maximum amount of internal beam appears to be limited by space charge in the electrostatic mirror to approximately 100 μA. The peak-to-peak incoherent radial amplitude of the internal beam is about 2·5 mm. The beam is extracted by a precessional extraction system followed by a focusing magnetic channel in the cyclotron fringe field. The positive deflector electrode requires special electron dumps and shielding to prevent P.I.G. discharges. The best measured external beam has been 40 μA. The full area horizontal and vertical emittances are approximately 12 and 15 mm mrad, respectively, and a minimum energy spread of about 16 keV has been observed. The injection system, central region, and negative ion extraction system of this cyclotron are discussed in detail in this paper. Other important features of the cyclotron are discussed in a paper entitled 'Design and Performance of a Compact Multi-Particle Cyclotron' submitted to this Conference.

The first of the H^- injector cyclotrons is being used at the Triangle Universities Nuclear Laboratory[2] in Durham, North Carolina, to inject 15 MeV H^- ions into a High Voltage Engineering Corporation Model FN Tandem Van de Graaff accelerator. The external beam from the cyclotron is transported to the tandem by means of two magnetic quadrupole triplet lens systems and a small steering magnet. Internal slits in the cyclotron and a collimator in front of the tandem are used to obtain the best energy resolution of the cyclotron beam and to ensure the matching of the emittance of the cyclotron beam to the admittance of the tandem. A beam current of 1·5 μA of H^+ over an energy range of 16 to 32 MeV has been obtained at the output slits from the tandem.

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1. INTRODUCTION

Two cyclotrons have been built for use as injectors for Tandem Van de Graaff accelerators. The first has been successfully coupled to a High Voltage Engineering Corporation Model FN Tandem at Duke University and is now in operation there. The second is in operation at the Lawrence Radiation Laboratory in Livermore and is awaiting installation of the tandem accelerator. The LRL-Livermore injector cyclotron is also capable of accelerating positive ions, from an internal source, in a conventional manner.

The injector cyclotron is the standard 30-in AVF machine with the addition of an external ion source, axial injection system, and a specially designed extraction system for holding a high positive voltage. Large quantities of H^- ions have been successfully started using an internal source, but the high gas flow required resulted in unacceptable beam loss from stripping before extraction radius was reached. A beam current of 90–100 μA of H^- at 4 in dropped to $\sim$5–10 μA at extraction radius. Increasing production with increased gas flow resulted in even less beam at extraction radius. With the external source, however, the cyclotron vacuum is $< 10^{-6}$ torr and a starting current of 100 μA drops by only a few microamperes at extraction radius.

2. EXTERNAL ION SOURCE

The external ion source is of the type developed by Ken Ehlers[1] and is located in a large magnet and vacuum chamber on top of the cyclotron to provide high pumping speed. The external source and cyclotron are shown in Fig. 1.

With a 10-in oil diffusion pump and the large pumping aperture, the pressure in the vicinity of the source is $\sim 10^{-4}$ torr. This area is separated from the injector tube and cyclotron by a small aperture of 6 mm × 18 mm. Thus, the beam path length in the high pressure region is kept short, and stripping can be kept to an acceptable level. The pressure in the injection tube is maintained at $\sim 10^{-5}$ torr by a separate diffusion pump. The injection tube and cyclotron chamber are connected by a ¼ in hole, and the pressure in the cyclotron is generally 10^{-6} torr or better. Equilibrium between H^- production and stripping is reached with a hydrogen flow rate of $\sim$20 cc/min. This provides 2–2·5 mA of H^- ions at the entrance aperture to the injection tube and $\sim$1 mA through the ¼ in hole into the cyclotron chamber. The source itself, with larger slit and without regard for stripping, has produced $\sim$4 mA.

The Ehlers source operates in a magnetic field of 2–3 kG and at a potential of 12–14 kV. Spectrometer type focusing is obtained in one plane by a 105° bend in the magnetic field, and electrostatic focusing is provided in the other plane by the grounded extractor electrode. The beam is extracted from the magnet after the 105° bend by a magnetic channel.

3. AXIAL INJECTION SYSTEM

The axial injection system consists of a velocity buncher, four electrostatic quadrupoles and an electrostatic mirror in the cyclotron central region.
The quadrupoles and velocity buncher fit into a 3-in diam. hole in the cyclotron magnet yoke and have an aperture of 1 in. The quadrupoles focus the beam

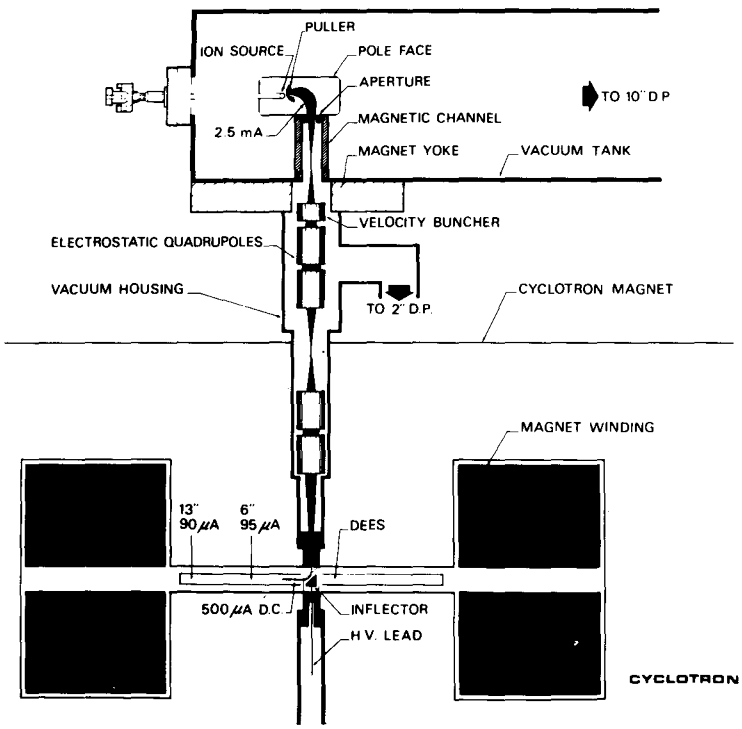

Fig. 1. External source and injection system

through a ¼ in hole into the centre of the cyclotron. Here the strong magnetic field focuses the beam to a very small spot, about 1 mm in diam., in the electrostatic mirror. Space charge density in this small spot appears to limit the maximum current that can be delivered to the cyclotron for acceleration. Fig. 2 shows the current started in the cyclotron and the current inflected to the dees as a function of current started from the ion source.

This figure indicates that the buncher has a much larger effect on the beam intensity at low source currents than at high currents. Such an effect could be explained by space charge blow-up in the small beam diameter at the inflector.

The electrostatic mirror consists of a grounded wire mesh spaced 0·090 in away from a high voltage electrode in an arrangement similar to that reported by Powell and Reece.[3] In this geometry, and at the optimum injection voltage, the plane of the mirror is set at an angle of 42·5° to the incoming beam. This angle is a function of the injection voltage and mirror electrode voltage. Varying either of these voltages varies the time spent in the mirror gap and, thus, the exit angle as well as the height.

The wire mesh has 35 wires/in made of 0·004 in molybdenum. A simple calculation shows that at 45° to the beam, the mesh has a transmission of about 66%. With no coherence between exit and entrance beam, the overall transmission of the mirror would be $(0{\cdot}66)^2$ or ~44%. However, adjustment of mirror voltage and slight rotation of the mesh showed very strong correlation between entrance and exit, and transmission of nearly 66% could be achieved.

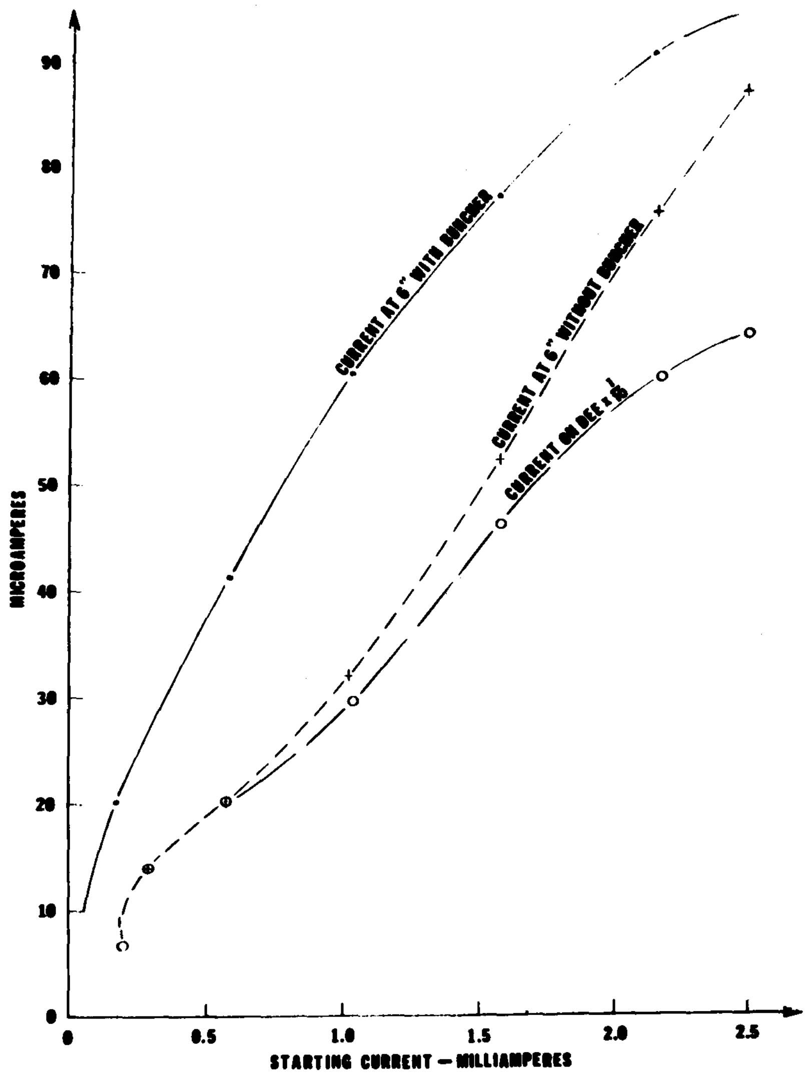

Fig. 2. Cyclotron current as a function of current at entrance to injection tube, showing effect of buncher

After the injection system was in operation and all of the steering and focusing parameters were optimised, some parts of the horizontal wires of the mesh were carefully removed where the beam was being intercepted. Further improvement in transmission was obtained with time as the small intense beam eroded away more of the remaining grid wires. Fig. 3 shows one of the wire grids after several hours of operation.

Several types of inflectors were considered, such as the type described by Belmont and Pabot.[4] However, with our modest dee voltage, 30–35 kV and 16·4 kG central field, a more compact geometry seemed necessary. To obtain orbit centring and maximum inflector clearance, a geometry of the type reported by Powell[5] was used. Orbit centring requires that the beam enter the central region off-centre and for a two-dee machine, the optimum injection voltage can be shown to be one-third of the dee voltage. For our case, an injection voltage of 12–14 kV is used, and the beam passes through a ¼ in diam. hole in the cyclotron pole tip, ¼ in off-centre. A similar ¼ in hole in the opposite pole tip is used for the high voltage feed-through and support for the high voltage mirror electrode and provides horizontal symmetry in the magnetic field. This configuration is shown in Fig. 4. The azimuthal asymmetry is uncompensated and can apparently be tolerated.

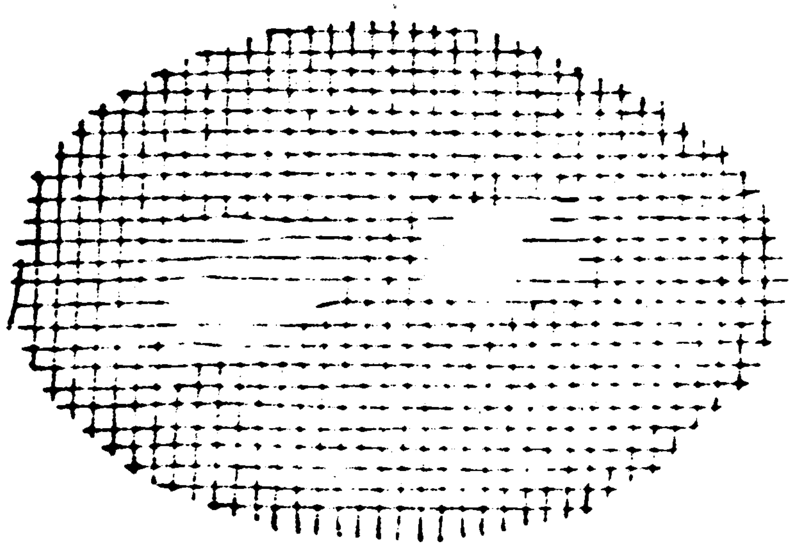

Fig. 3. Inflector grid

4. ACCELERATION AND EXTRACTION

The central region geometry is also shown in Fig. 4. The beam passes behind a shield in each dee to assure full energy gain and prevent distortion by transverse electric fields. Vertical grid wires are used at the entrance to each dee to provide vertical focusing on the first two gap crossings. A description of the cyclotron is given elsewhere[6] and only a summary of some of its specifications will be given here (Table 1).

The precessional extraction system is also discussed elsewhere,[6] but for negative ions, the electrode must run at a positive 60 kV. This requires special care to avoid excessive current drain by $\bar{E} \times \bar{B}$ and P.I.G. discharges in the magnetic field. The support insulator must also be protected from heavy bombardment by electrons precessing along the high voltage elements. The general approach is to create an electric field component parallel to the magnetic field at various places so that the precessing electrons are dumped

Table 1. 15 MeV CYCLOTRON

Pole diam.	32·0 in
Outside hill diam.	30·0 in
Valley gap	4·0 in
Hill gap (minimum)	2·0 in
Dee voltage	30–40 kV
Dee angle	120°
Frequency	25 MHz

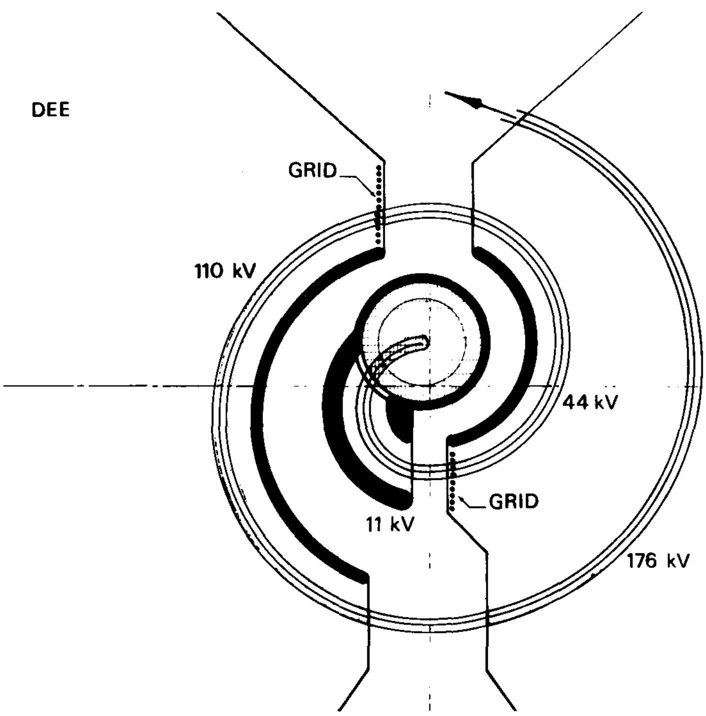

Fig. 4. Inflector and central region

before they travel far enough to build up a large discharge. Care must be taken to avoid any geometry that produces an electric potential well where P.I.G. discharges can build up. The general arrangement of the extractor is shown in Fig. 5.

5. PERFORMANCE

The performance of our injector cyclotron is summarised in Table 2. The group at Duke University is presently experimenting with internal slits to try to improve energy resolution. The best reported has been ~16 keV *FWHM*. Normally, the resolution is <50 keV without the aid of internal slits

Table 2. PERFORMANCE OF INJECTOR CYCLOTRON

Source current	2–3 mA
D.C. H^- beam inflected to dees	600–800 μA
Maximum current accelerated	120 μA
Maximum current extracted	40 μA
Energy	15 MeV
Energy spread *(FWHM)* (routine)	<50 keV
Best measured (internal slits)	16 keV
Pulse length (normal)	3 ns
Minimum observed (reduced current)	2 ns
Output of tandem	
Energy (variable)	16–32 MeV
Current–H^+ (not maximum)	1·5 μA

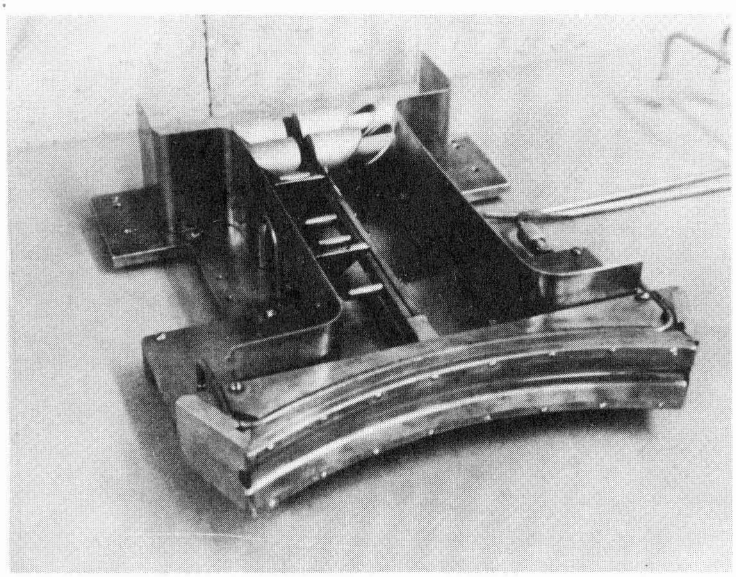

Fig. 5. H^- *extractor*

The cyclotron has not yet been used at full intensity as an injector. The combination of cyclotron and tandem have operated over an energy range of 15–32 MeV and with maximum beam current of 1·5 μA on target, which has been sufficient for their work thus far. They have measured emittances as low as 12 × 15 mm mrad, and all of the beam passes through the tandem.

Pulse length at the output of the cyclotron has been measured using a fast Faraday cup and sampling scope. At reduced ion source current, a pulse length of ~2 ns *FWHM* was obtained.

DISCUSSION

Speaker addressed: G. O. Hendry (Cyclotron Corporation)

Question by R. W. Müller (AEG): You have a constant geometry on the first revolution. Is the geometry also fixed with internal ion source operation, for all types of ions?
Answer: With internal ion source operation, H^+ and D^+ beams have the same orbit geometry; for $^3He^{++}$ and $^4He^{++}$ it is changed. Since this is a H^- and D^- external injection system, the problem of altering the orbit geometry does not arise.

Question by N. Hazewindus (Philips): You showed in your slide the effect of a buncher at different current levels. Does the source have the same emittance at these different currents?
Answer: We have only measured the emittance of the source at 2 mA output. At this current the emittance was between 150 and 200 mm mrad in both planes referred to 11 keV beam energy.

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