AN INTENSE ION SOURCE FOR H⁻ CYCLOTRONS

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Summary

An H^- ion source, employing multicusp plasma confinement and a magnetic filter to enhance volume H^- production, has been developed for the TRIUMF cyclotron. The source was designed to operate in a dc mode, to have a long filament lifetime and to provide an intense H^- beam of low emittance. The emittance could be easily scaled, without affecting the current density, to match the acceptance of the cyclotron. The H^- beam is initially transported ~1.7 m at 25 keV with a measured 94 ± 1% space charge neutralization. A 9.4 m long beam line, containing only electrostatic optics, has been built to transport the H^- beam from a high voltage terminal into the existing cyclotron injection beam line. The source design, operating characteristics, beam quality measurements and initial operating experience with the TRIUMF cyclotron are described.

Introduction

At TRIUMF an extracted current of 140 μA at 500 MeV is routinely achieved with a current of 300 μA from the Ehlers' type PIG H^- ion source.[1] At this intensity the PIG source requires a weekly filament change. In terms of accelerator acceptance (~0.02π cm•mrad, normalized by $\beta\gamma$), the source can reliably provide up to ~800 μA (~270 μA at 500 MeV) of useful beam, but operation at this level would require source maintenance every two days. For this reason, and because 800 μA will be insufficient to reach our goal of 500 μA at 500 MeV, a program was undertaken to develop a new source which meets the TRIUMF brightness requirements.

Several laboratories are investigating the multicusp type plasma generators as volume H^- ion sources in accelerator related applications.[2-5] These sources produce a stable, quiescent and bright beam. The source dimensions easily permit the installation of multiple filaments which results in relatively long filament lifetimes. The above properties, along with the inherent simplicity of the volume source, make it a practical choice for cyclotrons with external H^- injectors. Furthermore, the output beam is axially symmetric which significantly reduces the complexity of transporting and maintaining the low emittance of an intense beam. We describe here the dc source developed and installed at TRIUMF and present some measurements of its performance.

Source Description

An outline drawing of the cusp source and the extraction system is shown in Fig. 1. The extraction system is an axially symmetric four-electrode structure designed to produce a 25 keV beam. The H^- is extracted through the 6.5 mm diameter hole by applying a positive 3 kV potential (wrt the cusp body) on the second electrode. Permanent magnets in the second electrode, arranged such that they have a $\int B\cdot d\ell$ of zero, and a peak field of 100 G serve to sweep the simultaneously extracted electrons from the beam while giving the heavier H^- ions only a small net displacement. An additional voltage increase of ~22 kV between the second and third electrodes then brings the ion energy to 25 keV. The optimum dimensions of the extraction system were calculated using the computer code AXCEL[6] for a desired beam energy of 25 keV and current density of $\lesssim$10 mA/cm^2. The long collimator of the fourth electrode serves to permit differential pumping and reduces subsequent gas stripping of the extracted beam while still allowing the source to be run at the optimum pressure. The source is a cylindrical full-line cusp source with 10 rows of 3.2 kG $SmCo_5$ magnets located axially on the outside of an all-copper water-cooled 20 cm diameter × 26 cm deep plasma chamber. This plasma chamber is divided into two regions by a strong magnetic filter which creates a magnetic field transverse to the beam axis with $\int B\cdot d\ell \approx 0.2$ kG-cm. Two filaments of tungsten wire (3 mm ϕ) are mounted on the back face extending approximatly 10 cm into the plasma chamber. The beam-forming electrode is insulated from the cusp body such that it can be biased a few volts positive wrt the anode. The value of this bias potential together with the hydrogen gas pressure inside the plasma chamber significantly influence the extracted electron current. Under certain conditions the ratio of e^- to H^- current extracted from the source could be as low as 1.

The H^- beam is transported approximately 1.7 m at 25 keV from the ion source extraction system to the entrance of the 275 kV acceleration column. A solenoid and two sets of correction dipole magnets are used to match the extraction beam optics to the acceleration column requirements.

In order to reduce gas stripping after extraction and to run the source at optimum gas pressure, the extraction system was designed to allow differential pumping. Two turbopumps are located on pumping ports in the extraction system vacuum-jacket and evacuate the region between the first and fourth electrode. The last aperture in the extraction system limits the conductance into the extracted region and allows a good vacuum (low 10^{-7} Torr) to be maintained along the beam line, while a flow of 15 cc/min of H_2 maintains a plasma chamber pressure of ~7 × 10^{-3} Torr. The beam line vacuum relies on three cryogenic pumps located on diagnostic boxes as indicated in Fig. 2.

On-line tuning of the extracted beam is accomplished with the aid of the four wire scanners shown in Fig. 2. The first wire scanner is placed in a diagnostic box immediately after the extraction system. The remaining three wire scanners are placed in diagnostic boxes downstream of a solenoid magnet.

The beam emittance is determined by a method, developed at LAMPF,[7] which employs electrostatic

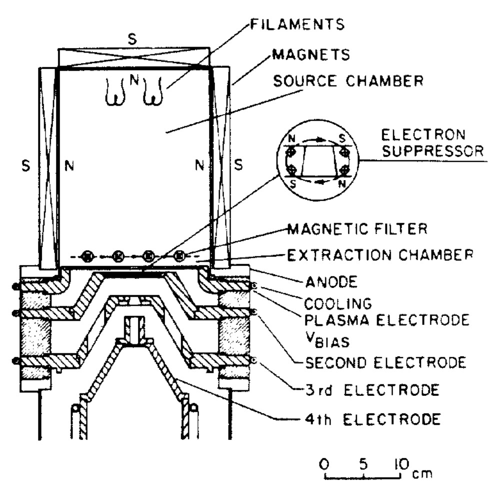

Fig. 1. A cross-sectional schematic of the TRIUMF H^- cusp ion source and the extraction system.

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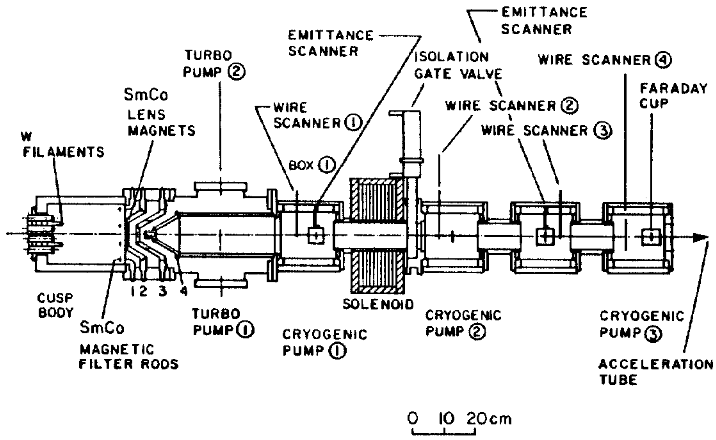

Fig. 2. A schematic diagram showing the relative locations of the cusp source and H^- beam diagnostics.

deflecting plates located between two slits. A linear feed screw allows the precise positioning of the slit detector in the beam. A portion of the beam passes through a narrow slit (0.06 mm) into a region where two parallel plates (2.8 mm gap by 38 mm long) impose a variable transverse electric field. The beam, which passes through the second slit (0.06 mm), is detected by a Faraday cup. The plate voltage can be stepped uniformly from -500 to +500 and the cup current digitized for each voltage. The detector position is moved and a set of curves generated whose width is proportional to the angular spread of the beam at each position. A computer is then used to contour plot the beam emittance figure. A second scanner is being used to measure emittance changes along the beam line due to effects such as space charge and lens aberrations.

Beam Characteristics

Figure 3 shows the extracted H^- current and its normalized emittance at the 90% level as a function of the discharge current for a constant arc voltage. The H^- current initially increases linearly with arc current. At higher arc powers the H^- current exhibits a tendency to saturate. Higher arc voltages appear to delay the onset of this saturation.

The beam emittance appears fairly independent of the discharge current (over a range of 10-40 A) when the beam energy is used as an optimizing parameter [see dash line in Fig. 3(b)]. The rapid emittance increase observed at high arc currents (above 40 A) is due to non-linear space charge effects in the first gap of extraction system and due to lens aberrations. These non-linear effects can be observed by comparing measured emittances for a H^- current of 0.8 mA to that for a current of 3.2 mA. The normalized emittances at the 90% for the two currents are in the ratio 1:3.6 whereas at the 20% level the ratio is 1:2.7. The maximum extracted current and rapid emittance growth at these currents is in agreement with Keller[8] who claims a practical application of Childs' law for ion sources with an aspect ratio equal to 1 yields

$$I(\mathrm{mA}) = 0.7 \times V^{3/2}\ (\mathrm{kV})$$

which for the operating conditions of our source implies $I \lesssim 3.6$ mA.

The normalized beam brightness as a function of H^- current density for various beam fractions is shown in Fig. 4. The brightness here is defined as $B_n = 2If^2/\varepsilon_n^2$, where I is the total beam current as measured on the Faraday cup of Fig. 2 and f is the appropriate emittance fraction. The normalized brightness increases slightly with current density (up to ~6 mA/cm²). Above

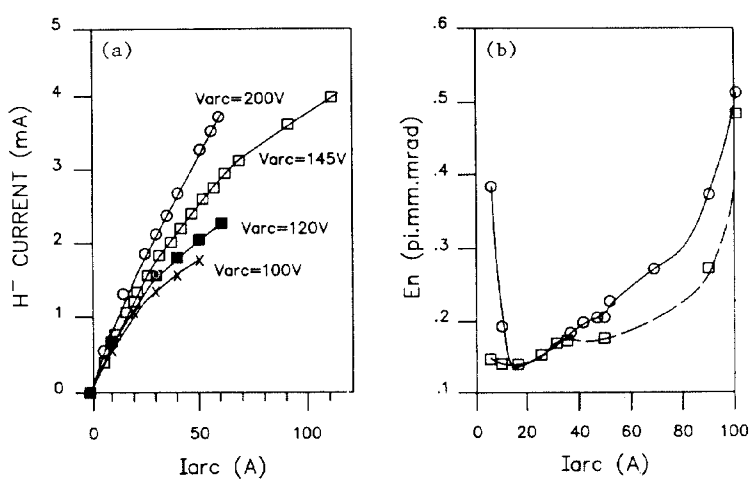

Fig. 3. (a) H^- current as a function of the arc discharge current for various discharge voltages (6.5 mm ϕ extraction hole). (b) Normalized emittance (90% contour level) vs arc current for 145 V. Solid line has a 25 keV fixed beam energy. For the dashed line the beam energy is an optimized variable. (Note offset zero).

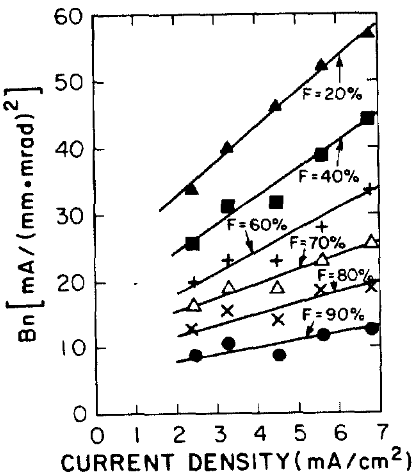

Fig. 4. The normalized beam brightness as a function of H^- current density at various (labeled) emittance contour levels.

10 mA/cm^2 the apparent brightness falls because the extraction geometry is not optimized for such high current densities. The maximum measured normalized brightness for a 81% beam fraction (a 90% emittance contour) was 14 mA/(mm·mrad)^2 at a current density of 5.6 mA/cm^2. For these data ε_n = 0.147π mm·mrad. The equivalent value in terms of the normalized rms emittance is 0.038π mm·mrad. Brightness is sometimes defined in terms of rms emittance without consideration of beam fraction and for this case the value is 250 mA/(mm·mrad)^2. The measured emittance implies a ~0.5 eV ion temperature.

The change in beam size and beam divergence during a drift of ~53 cm has been examined, using the two emittance scanners in adjoining diagnostic boxes, for various H^- currents and several different vacuum conditions. The emittance measurements allow us to determine the beam growth as a function of the beam fraction and then to compare the observed changes with theoretical predictions which include the effect of space charge. Furthermore, assuming that the observed difference between measurement and calculation is the result of space charge neutralization, we deduce that at a nitrogen partial pressure of 1×10^{-4} Torr the H^- beam is 99.7 ± 1.0% neutralized and at a pressure of 7×10^{-7} Torr the H^- beam is 94.0±1.0% neutralized. The results appear to be independent of H^- current in the range 1 to 3 mA.

Simple models predict that neutralization should saturate at a level given by one minus the ratio of the ion thermal energy to the potential well depth for the unneutralized beam. From this we derive a neutralization of at least 99%. However, at the lower pressures, the time for neutralization to build up becomes comparable with the time it takes the neutralizing ion to drift out of the field free region; neutralization can therefore not build up to the 99% level.

Present Status

The cusp source is located in a 275 kV high voltage terminal. A 9.4 m beam line has been built to transport the 300 keV H^- beam into the existing injection line. This new section of the beam line is basically a quadrupole FODO periodic section run at a 90° phase advance per cell. As in the injection line all quadrupoles are electrostatic.

The source has demonstrated advantages over the existing PIG source. A cw proton current of 150 μA was extracted from the cyclotron with less beam spill inside the cyclotron than is normal with the PIG source at these currents. In a 10% pulsed mode a ~31 μA average (~310 μA peak) extracted current was achieved for the first time at TRIUMF. The average extracted current is at present limited by the performance of the old section of the injection line and the 500 MeV targets.

Toroids in the injection line, used as nonintercepting current monitors, confirm the quiescent nature of the source plasma. In particular, in the frequency range up to 1 MHz, no beam oscillations greater than ~1% are apparent. With the PIG source the beam oscillates in intensity by typically 10% with a frequency of around 200 kHz.

The filament lifetime, as extrapolated from present data, is expected to be approximately one month of continuous running for an ion source H^- current of 1 mA. This lifetime is, at least, an order of magnitude better than that of the PIG source.

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