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THE H^- SOURCE FOR THE HIGH INTENSITY BEAM AT TRIUMF

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Abstract.- Operational experience at TRIUMF has shown that an injected beam having a normalized emittance of 0.1 to 0.2π mm-mrad is better suited to reliable high intensity operation than the 0.32π mm-mrad specified in the original design. As a result, a study was initiated to determine the best source which would inject, within this reduced emittance, an H^- beam of 1 or 2 mA of intensity, corresponding to cyclotron extracted currents in excess of 500 μA. After comparing various sources, it was concluded that an Ehlers type PIG source is best suited for external injection into an H^- cyclotron where an intense, high brightness, reliable and full duty cycle source is important. The behaviour of the source as a function of various geometrical and arc parameters was investigated on a model test stand. Work is in progress to make the source conditions more reproducible and to increase its maintenance-free beam production time. The advantages of this source, the results of our experimental investigations and hints for a reliable behaviour will be reported.

1. Introduction.- In general a cyclotron requires a DC source which is stable, reliable, and bright. During the design of TRIUMF it was decided that The Cyclotron Corporation's version of Ehlers' [1] hot filament Penning arc source with a maximum H^- output of 2 mA in a normalized emittance of 0.32π mm-mrad was sufficient to reach the design goal of 100 μA at 500 MeV. The source was straightforward in design and of a physical size that met with TRIUMF's space restrictions. Since that time we have reached and surpassed the design goal [2] and must again consider whether or not the Ehlers source is the best source for our needs.

There are two methods for the production of beams of H^-. One of them is the direct extraction of negative ions from the plasma in an arc discharge. The other method uses charge exchange to produce H^- from a proton beam. The direct extraction method is more appropriate for cyclotrons because it has the advantages of compactness, small emittance, and low energy spread. In this group are such sources as the magnetron [3], the hollow discharge duoplasmatron [4], the Penning surface plasma source [5], and the Ehlers PIG type source [1]. The first three are usually operated with a mixture of hydrogen and cesium vapors. Negative hydrogen ions are dominantly produced on cesium-covered electrode surfaces under bombardment by particles from the discharge plasma. For this reason these three sources are classed as surface plasma sources. The Ehlers source is a volume plasma source; that is, the H^- are produced through interactions in or around the plasma column and not principally on the walls or electrodes of the source. Of these sources only the two with the Penning geometries are presently operated in a DC mode.

Table I compares some source parameters of the four source types. The most important parameters for TRIUMF are the emittance and brightness, and the table illustrates that the Ehlers source is quite competitive. The addition of cesium to the other sources reduces their arc voltage and so the power efficiency of the volume source is less than that of the surface source. Smith *et al.*[11] have designed a Penning surface plasma source with rotating electrodes to produce 100 mA of DC H^- current. At the present time, however, the simplicity and high brightness of the Ehlers source best satisfy TRIUMF's requirements.

TABLE I

	TRIUMF	LANL		BNL		Fermilab [10]
	PIG	DC mode [6]	Pulsed [7]	HDD [8]	Magnetron [9]	Magnetron
H^- current (mA)	4	2	160	60	40	50
Arc current (A)	1.6	1.0	100	150	120	150-160
Arc voltage (V)	350	45	40-120	80	160	130-135
Normalized emittance $(\text{mm-mrad})^2$	0.21πx0.045π @ 0.85 mA	0.8πx0.07π for 40% of beam	0.4πx0.3π	2.3π @ 40 mA	1.4πx0.35π	0.8πx1.5π @ 50 mA 0.2πx0.8π @ 30 mA
Normalized brightness $\frac{\text{mA}}{(\text{mm-mrad})^2}$	18	7	270 pulsed		17 pulsed	38 pulsed
Duty cycle	DC	DC	0.75% 1 msec @ 7.5 Hz	1 msec pulse	0.13% 0.25 msec @ 5 Hz	0.09% 0.06 msec @ 15 Hz

2. General description.- The source is shown in figure 1. Electrons oscillate between the filament and anticathode, ionizing the hydrogen gas that flows into the chamber. The plasma column is established in a 2.8 kG uniform magnetic field parallel to the plasma chamber. The source floats at -12 kV below the terminal voltage of -276 kV. A 40 m electrostatic injection line is used to transport the H^- ions to the cyclotron [12]. A 10" oil diffusion pump handles the high hydrogen gas load from the source maintaining the pressure in the source box to $\leq 3 \times 10^{-5}$ Torr for an H_2 flow of 20 SCCM (standard cc/min).

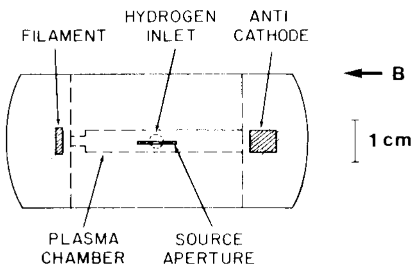

Fig. 1 : Schematic diagram of source. The diameters of the arc chamber and the collimating hole are 4.7 mm and 1.7 mm, respectively. The source aperture (9.3×0.7 mm^2) is displaced by 0.8 mm from the axis of the chamber.

High intensity operation at TRIUMF requires ~300 µA of current from the source within a normalized emittance of 0.1-0.2π mm-mrad. Nominal source parameters which produce this current are V_{arc} = 350 V, I_{arc} = 250 mA and H_2 flow = 14 SCCM. Under these conditions filaments composed of tantalum with 2.5% tungsten have a lifetime of ~200 h. Pure tantalum filaments have a better emission but last only ~20 h at this intensity and are difficult to machine. Filaments with 10% tungsten have a much longer lifetime but require higher filament currents because of the need for higher temperature operation. The anticathode is pure tungsten and lasts ~800 h. Experience has shown that anticathodes composed completely or partially of tantalum have a tendency to crack.

A major factor in achieving TRIUMF's present stable source operation was the incorporation in 1974 of a servo-loop which varies the filament current such that the arc current remains constant to within 0.1%. This makes the beam relatively insensitive to filament erosion. Also, as a result of this "loop" control, one can vary the arc current without affecting the arc voltage. Consequently it is a trivial matter to continuously change the source current between 10 µA and 500 µA.

3. The test source.- A strong interest in high intensity operation at TRIUMF [13] has placed demands on improving the emittance and current output of the source and the transmission of the injection system. To this end, tests are continuing on a model source terminal. The test terminal includes an optics box with defining slits S1 (5 mm H × 12 mm V) and S2 (11 mm H × 4 mm V or 11 mm H × 2.5 mm V) set 340 mm apart and a Faraday cup for current measurement (see figure 2).

Special anode blocks were constructed to allow quick changes to parameters such as the size and position of the source aperture and the dimensions of the arc chamber. Movable tantalum jaws were used to form the source aperture. The H^- current through the emittance limiting slits S1 and S2 was optimized by using an anode block having an aperture of 9.3×0.7 mm^2. The results of measurements to determine the effect of the aperture thickness are shown in figure 3. The optimum thickness was found to be ~0.4 mm. Apertures

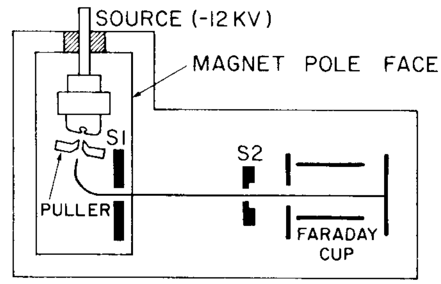

Fig. 2 : A schematic drawing of the test ion source.

thinner than the optimum produce high total currents but much of this is lost on S1 and S2. Apertures thicker than the optimum produce beams which have good transmission through S1 and S2 yet have a low total current. Measurements are in progress to determine the emittance variation due to the change in aperture thickness.

The position of the aperture with respect to the plasma chamber was also varied. In scanning the aperture perpendicular to the arc column in the plane of figure 1 it was found that the optimum H^- beam occurred with the aperture slightly (~0.8 mm) off centre. However, even with the aperture at one edge of the arc chamber the Faraday cup current was only reduced by 20% from the optimum.

A collimating hole near the filament centres the arc with respect to the discharge column. The size of this collimating hole was also varied. It was found that with the diameter reduced from 2.5 mm to 1.7 mm the arc was more stable with reduced plasma oscillations and the current through S1 and S2 increased by ~20%. Copper and Elkonite alloy were used for the anode blocks.

With the optimum source configuration gas flow, arc current and arc voltage were varied to generate figures 4(a) and 4(b). Although total H^- current increases with increasing gas flow and arc current [1], the figures show that the beam through the slits reaches a maximum at a certain arc current. It is felt that the current through the slits is limited by an emittance growth at the source. Also at large hydrogen flow rates gas-stripping of the H^- beam becomes important. It is our experience that gas-stripping becomes a factor at pressures larger than 5×10^{-5} Torr. Figure 4(a) shows that, as the density of neutral molecules increases, the arc current needed to maintain

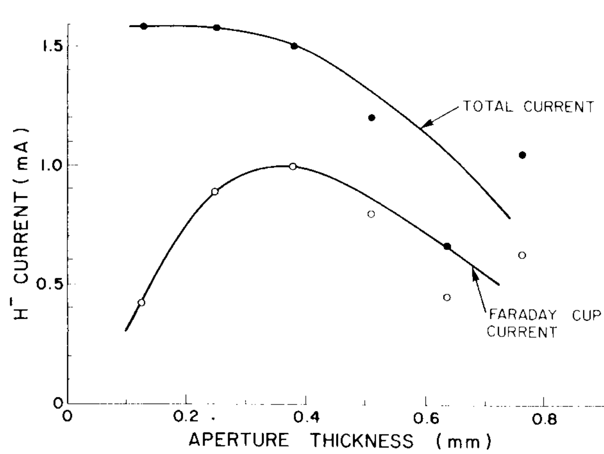

Fig. 3 : Measured H^- current as a function of aperture thickness.

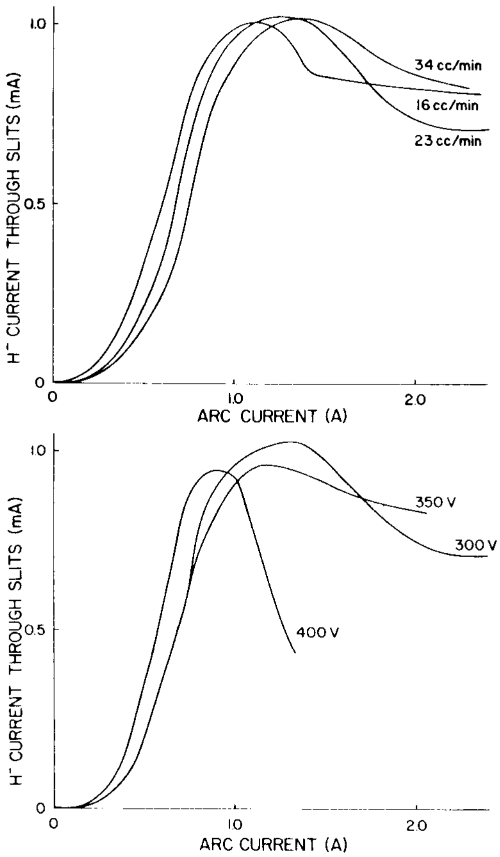

Fig. 4 : (a) Slit selected H^- current as a function of the current for various H_2 gas flows. (b) Slit selected H^- current as a function of arc current for various arc voltages.

the ideal H^- production must also increase. Likewise figure 4(b) shows that as the arc voltage is decreased, the arc current must increase to yield the optimum H^- production.

With the present source configuration and with the acceptance restrictions of S1 and S2, there is little to be gained by using arc currents significantly larger than 1.0 A. With the arc parameters V_{arc} = 300 V, I_{arc} = 1.0 A, and H_2 flow = 23 SCCM, a scanning wire was used to measure the beam emittance immediately downstream of S2. The results are shown in figure 5. The emittance areas (90% of beam) were 0.21π mm-mrad horizontally and 0.07π mm-mrad vertically. At 1 mA, this implies a brightness of

$$B = \frac{2I}{\varepsilon_x \varepsilon_y} = 0.014 \frac{A}{(\text{mm-mrad})^2} .$$

In another mode of operation at TRIUMF, the vertical size of S2 is decreased to 2.5 mm to improve the beam emittance. When this is done, one loses only the lower left-hand "finger" of the vertical emittance figure (figure 5). As a result, the emittance becomes 0.045π mm-mrad vertically while the current drops only slightly to 850 μA. Hence the brightness improves to 0.018 A/(mm-mrad)^2.

Also drawn on the emittance figures are the acceptances of the slit system S1 and S2. It is interesting to note that the emittance figures fit almost exactly inside these acceptances despite the fact that

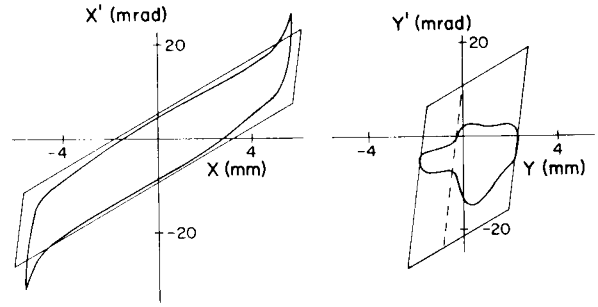

Fig. 5 : The measured emittance of the 1 mA slit selected H^- beam. Also shown is the estimated acceptance of the slit system. The dashed line shows the reduced acceptance when the S2 width is reduced from 4 to 2.5 mm.

the acceptances were calculated assuming no space charge. A beam transport computer program which includes Kapchinsky-Vladimirsky equations was used to show that, with no space-charge neutralization, S1 would have to be 16 H × 21 V mm^2 in order to give the measured emittance figures at S2. However, S1 is actually 6 times smaller. This suggests that the H^- beam is largely space charge neutralized.

One of the problems of the original ion source was a high rate of sparking between the -12 kV anode block and the surrounding electrodes. In order to disperse the electrons draining from the source extraction region and hence eliminate local hot spots created by these electrons, the external surface of the anode block was reshaped and a smooth copper shroud was placed around it. These measures substantially reduce the sparking rate.

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