DEVELOPMENT OF A 15 mA DC H⁻ MULTICUSP SOURCE FOR CYCLOTRON

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A 15 mA DC H^- multicusp source has been developed for TR30 cyclotrons. This source is also used for a 900kV tandem accelerator to obtain 10 mA protons at 1.8 MeV. The starting point of this development program was the 5-7 mA DC H^- cusp source developed at TRIUMF during 1987-1990 period. Major efforts included the search for the optimal filament materials, shape and location; comparison of cusp line confinement and magnetic filtering of electrons at the extraction region; optimization of extraction lenses configuration and upgrading of vacuum and power systems. The source is non-cesiated and the maximum arc power available is only 5 kW. After the H^- beams pass through an electron suppression grid and a 20 mm collimator, we obtained 15 mA with 0.65 π-mm-mrad emittance (normalized, 4 times RMS). At this output the e/H^- ratio was about 4. The best normalized emittance is 0.37 π-mm-mrad in the range 4-8 mA. Further development in the near future is planned using cesium and multiple apertures in the hope to increase the DC H^- currents to 25-30 mA while holding the normalized emittance below 0.65 π-mm-mrad.

1. - Introduction

Since 1990, the TRIUMF DC H^- cusp source has been successfully used in several compact cyclotron facilities. A maximum output of 9 mA at 7 kW arc power was obtained in May, 1990 and 7 mA was repeatable and stable enough for emittance measurement (0.34 π-mm-mrad 4 RMS normalized). However, this capability was lost after several design changes in the source-extraction system. One of the motivating reasons for further development was to recover the 7-9 mA DC capability and to document the corresponding source parameters. The benefit is that the 9 mA output plus a beam buncher in the injection line would make 1.2 mA RF H^- beams available for TR30 (30 MeV) cyclotrons. The proposed project was supported by TRIUMF and Nordion/Vancouver beginning in April, 1994. By May, 1995 the result of this development work was a 15 mA DC source with very good system reproducibility, reliability and stability. The initial source parameters and system set-up have been reported by Baartman et al. [1], Yuan et al. [2,3,4] and Jayamanna et al. [5]. Itemized and described in the next sections are the development efforts in the areas of filament configuration, vacuum consideration, cusp confinement, electron filtering and extraction geometry.

2. - Development Study

2.1 - Filament configuration

Originally the compact H^- source used a single tungsten filament bent in an arch shape as shown in the left picture of Fig.1. The sharp bend was only 2 cm from the extraction hole. Typical filament current to begin generating the arc plasma was around 180-200 amperes. The physical characteristics implied by this geometry are the following:

(a) the filament occupies the field free region of the source,
(b) the filament is emerged in the core of the plasma carrying away plasma energy,
(c) the extraction filter field is modified by the magnetic field generated by the filament current at the bend and it varies as the filament current changes,

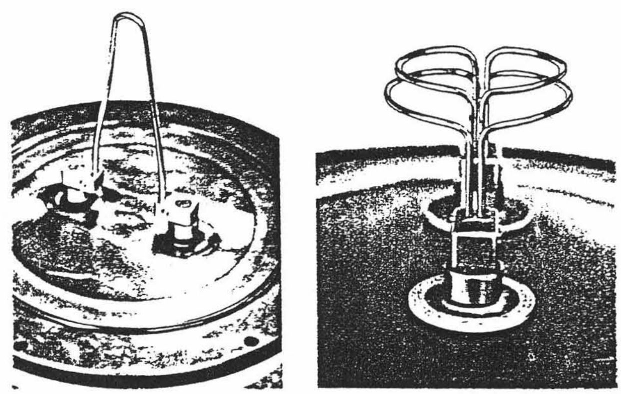

Fig. 1. Single arch shape and multiple ring shape filaments

(d) larger fraction of electrons is trapped on the surface of the filament by the high filament self field,
(e) no mechanism to stop the ExB electron drift to the filament stems.

One option to solve these multiple problems is to use at least two filaments *far away* from the extraction region and to avoid the hot core of the plasma. The two filaments are made into a two-half circle ring shape. Four filaments identical in length would make two two-half circle rings as shown in the right picture of Fig.1. The center line magnetic field generated by these two or four filaments is cancelled out, and the surface magnetic field in the vertical stem segments will not maintain cylindrical symmetry and thus cut off the ExB drift. In addition, tantalum wire is used instead of tungsten for the reasons of ease of shaping, lower emission temperature and higher secondary emission coefficient.

The initial result of this change is shown in Fig. 2. The H^- beam currents improved immediately from 6 mA at 40 A arc (at 120V) using the single arch shape tungsten filament, to 10 mA using the tantalum two-half circle ring. A tungsten ring identical to a tantalum one was also tested. The improvement over the arch shape is still substantial, but the arc current stopped at 30 A

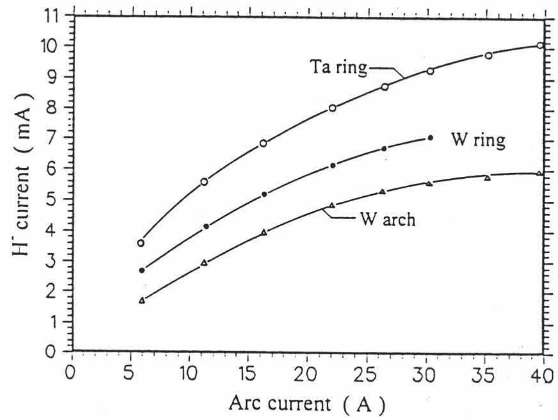

Fig. 2. Comparison of H⁻ currents as a function of arc currents between W and Ta, ring shape and arch shape

due to electron emission limitation. The extracted electron currents were reduced almost by half by using ring shape geometry and Ta wire. A similar phenomenon was observed by the Brookhaven group [6]. The 4-filament option was used for 500 hours continual operation but an 8% reduction of H⁻ was observed as more mass is present to drain away the plasma energy. However, electrons are emitted from a larger surface at lower temperture, the emittance of the ion beam at the same current output improves about 10% resulting in more transmitted beam through the injection line.

2.2 - Vacuum Consideration

For high current CW mode operation, the source needs higher gas flow and thus higher pressure in the extraction region, resulting in larger stripping loss. In our measurement the source pressure in the 10-30 mT range is independent of pumping speed. Hence a higher pumping will not decrease the H⁻ ion density [7] inside the source, but will decrease the stripping loss and allow even higher operating pressure than needed in order to reduce the e/H⁻ ratio. Improving the gas conductance in the extraction canal and upgrading the turbo pump capacity to 900 l/s give almost 30% more H⁻ current as compared to the original 250 l/s pumping speed and a restrictive extraction channel.

2.3 - Cusp Confinement

An extensive comparison study of H⁻ currents extracted at a fixed arc power as a function of cusp field strength and number of cusp lines has been carried out. Our finding is that 10 cusp lines using 20 rows of 7.2 kG Sm_2Co_{17} bars gives the best result for H⁻ currents, e/H⁻ ratio and emittance for a 10 cm diameter plasma chamber. The improvement on H⁻ current over the earlier structure is not very large, about 15% at lower arc power and only 5% at high power (5 kW). Nonetheless, the e/H⁻ ratio is reduced and the emittance is improved permitting a more stable high power operation and better beam transmission to the cyclotron. There seems to be a strong coupling between the filter field and cusp field which influences the source performance.

2.4 - Electron Filtering

It is generally believed that H⁻ ions are formed in the extraction region very near the plasma exit aperture after most of the fast electrons are filtered. Several filter options are employed by different source groups. At TRIUMF both the water cooled dipole columns and the virtual filter method have been used. We found that the dipole columns absorb a large percentage of plasma energy for a low power source (<5kW) while a simple virtual filter is either too thick that the slow electrons are also filtered [5] or too weak that it does not filter the fast electrons completely when the arc power is high. It is important that the filter should be thin and having the right strength. For this reason a more elaborate arrangement of virtual magnet bars was made and it is shown in Fig.3.

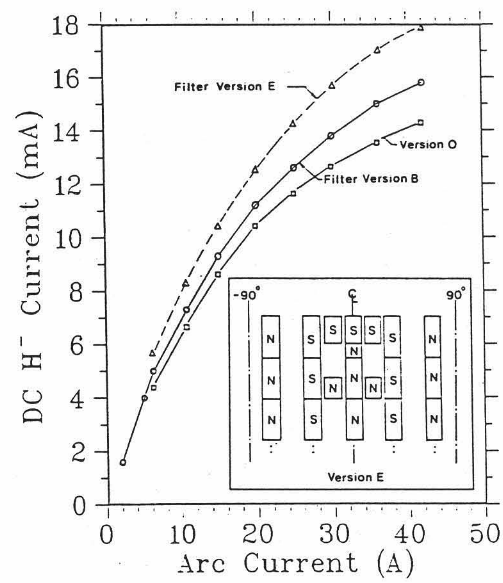

Fig. 3. Comparison of H⁻ currents as a function of arc currents between different magnetic filter versions.

Originally, the top bar (2.5 cm) of the center line "N" polarity column (15 cm) was replaced by a "S" bar, and vise versa for the diamatrically opposite "S" column (version O). Later, this top "S" bar was replaced by a "S-N" combination and two equal size but shorter "S" bars on each side (version B). In order to make the filter even thinner, a pair of anti-dipole (small "N" bars) were added in the indicated location (version E).. If one traces the "S" bars along , a cusp line is closed and the discharge will be well defined. A very clean cusp line burn trace follows this bar line very precisely. The surface of the plasma electrode becomes very clean and the strange discharge patterns previously seen from version O have completely disappeared.

The H⁻ current achievable from these three versions is also shown in Fig. 3. It is clear that the version E performs best.. Aside from the 18 mA peak current obtainable from the version E, the electron current is much lower and the emittance does not proportionally increase as rapidly as beam current increases.

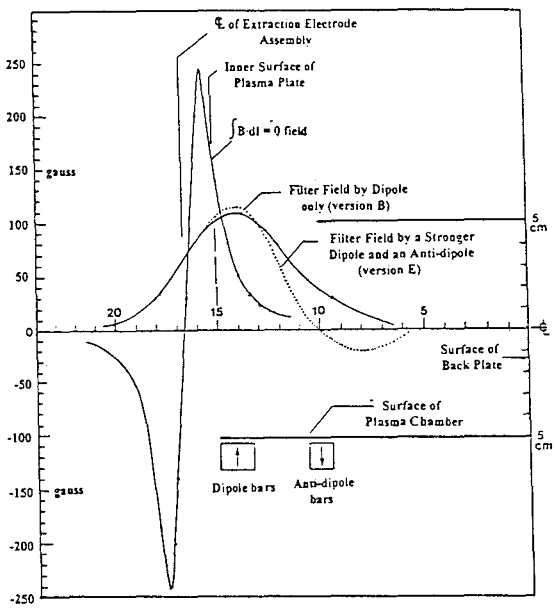

Fig. 4. Dipole filter field profile along the source line

The dipole filter field along the center line of the source for versions B and E are shown in Fig. 4. The B dl = 0 field for the extraction lenses will superimpose to this dipole field so that the resultant field is about 250 gauss at the extraction aperture and 70 gauss at 3 cm before extraction.

2.5 - Extraction Geometry

Fig. 5 shows schematically the extraction system used by our source. The energy voltage V_E is fixed by the cyclotron requirement while the extraction voltage V_{ext} is determined by V_E, g_1, beam optics requirement and arc characteristics such as arc power, plasma potential, filter configuration, etc.. The 7 geometric parameters, apertures and gaps, were systematically optimized to obtain optimal H^- currents, lowest e/H^- ratio and best emittance. It should be pointed out that many factors affect the e/H^- ratio and emittance and we shall discuss these in more detail in the next section.

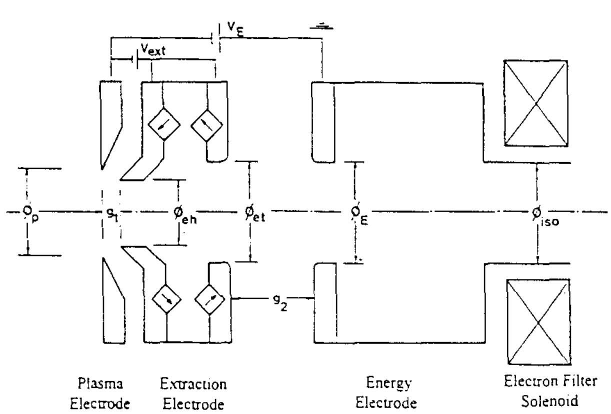

Fig. 5. Schematic of extraction geometry

For a 17.5 mA DC H^- extraction at V_E = 28 kV, The parameter set is: V_{ext} = 3.8 kV, g_1 = 2.5mm, g_2 = 10mm, ϕ_p = 13.0mm ϕ_{eh} = 9.5mm, $\phi_{et} = \phi_E = \phi_{iso}$ = 14.0mm.

3. - Results of Development

The results of our development at the present stage are summarized in Fig. 6. Up to 17 mA was extracted for emittance measurement. The beam was tuned and optimized through a 20 mm collimator 40 cm away from the extraction. An Allison style emittance probe was then inserted and scanned across the beam. Scanner control and emittance analysis were by CAMAC and VAX system. In most cases, the normalized emittance ε_n were equal to 4RMS emittance. The normalized brightness was calculated using the expression $B_n = 2If^2/\varepsilon_n^2$. The beam fraction f^2 is defined as the square of the fraction of beam inside the one-dimensional emittance contour.

Some Authors quote RMS emittance, therefore their values are four times smaller than those we quote here by definition. Furthermore, the factor of π is always explicitly expressed including for the brightness calculation. So comparison of emittance merit with different sources from different laboratories would be difficult.

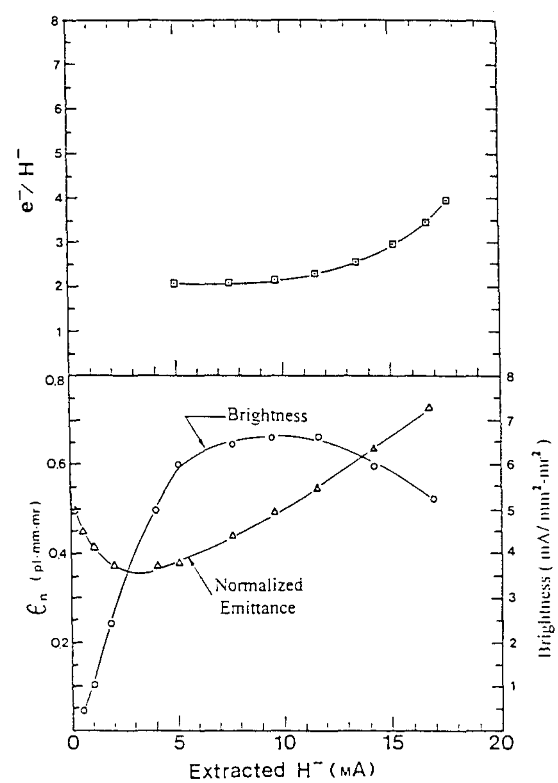

Fig. 6. Performance of the 15 mA DC H^- source in terms of e/H^- ratio, emittance and brightness.

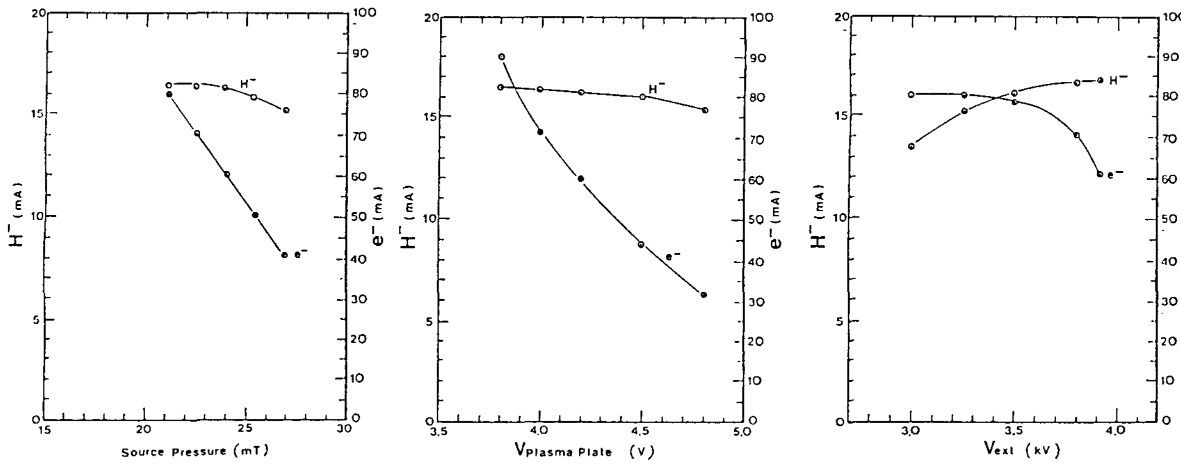

Fig. 7. Extracted delectron and H- current as function of source pressure, plasma voltage and extraction voltage.

For a lower e/H⁻ ratio, we have examined the effects of filament material and shape, confinement and filtering, surface condition and contamination, source pressure and pumping speed, plasma and extraction voltage tuning, as well as from the matching of beam quality with beam quantity. Fig. 7 shows the change of H⁻ and e⁻ currents as a function of source pressure, plasma plate voltage and extraction voltage at 16 mA H⁻ current level. As can be seen from these plots, the e⁻ current can be brought down substantially by using higher gas flow and higher plasma voltage while only a small fraction of H⁻ beam is lost. This was possible because the vacuum system has enough capacity to handle higher gas flow and the extraction system has been optimized.

4. - Summary and Discussion

As shown in Fig.3 and Fig.6, we have obtained more than 15 mA DC H⁻ current at 5 kW of arc power with e/H⁻ ratio less than 5. Moreover, this performance is reproducible. The high beam current can be realized immediately after the source is turned on and no fall-off is observed for several hours of operation. The new source is now being used for 1.2 mA beams at 30 MeV for the TRIUMF-operated TR30 cyclotron. It will also be used to provide 12 mA DC beam at 1.8 MeV for a Tandem accelerator. Out of the five major areas we have studied, The tantalum ring filament and the filter version E are most intriguing as they offer rich physics information. The vacuum upgrade reduced stripping in the extraction region. The cusp confinement and extraction studies did not produce a large increase in H⁻ current but did improve the e/H⁻ ratio and emittance giving much better beam transmission and a more stable system.

Encouraged by these results, we plan in the near future to upgrade the source performance further aiming at 25-30 mA DC while maintaining the normalized emittance under 0.65 π-mm-mrad. Cesium [8,9] and multiple aperture techniques will be tried. Supplemental studies such as IGUNe simulation, plasma parameter measurement, LaB_6 filament operation, higher arc power and injection energy as well as D⁻ beam capability will be pursued.

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