RECENT DEVELOPMENT OF INTERNAL H^-/D^- SOURCE FOR COMPACT CYCLOTRONS

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ABSTRACT

Small internal H^-/D^- sources based on Ehler's PIG source[1] design have been used in recent years for a number of compact cyclotrons of various sizes needing only 50-200 μA external beams. Source performance has been optimized in terms of H^-/D^- production and survival geometry, gas efficiency, arc requirement, mechanical tolerance and thermal stability. Data were obtained with RF extraction method using the central region of several cyclotrons as test facilities. The DC equivalent output was deduced from the information of RF phase width and the vacuum characteristics. The compact source technology has been transferred to several cyclotron manufacturers and about 30 H^- or H^-/D^- cyclotrons using compact internal source are in service today worldwide.

1. INTRODUCTION

In 1965 Ehler described the performance of his H^- PIG source with a plasma expansion gap using DC extraction. Since then several H^- cyclotrons used his source for external injection, among them the TRIUMF's H^- ion source and injection system (ISIS) is the most advanced and most successful.[2] In 1976, it was discovered that the plasma expansion gap can be generated by a special rotation of a compact internal *positive* PIG source.[3] The method allows the cyclotron to be operated in proton mode or in H^- mode without changing the ion source. Likewise, a source with an anode designed for H^- production can also be used as a proton source. Variations in anode design coupled with the rotational control provide a large range of proton/H^- ratio. High current irradiation on internal targets can be done by protons or by H^-s, while the irradiation on external targets can be done by 100% extraction of H^- using charge exchange, provided that the cyclotron vacuum capability is suitable for H^- operation. Similar statements apply to d/D^- production. In short, it is possible to have a single source which can supply protons, deuterons, H^-s and D^-s with compatible intensity.

In this report we shall concentrate on the optimization of the performance of a compact internal H^-/D^- source which leads to the development of a series of compact H^-/D^- cyclotrons using this source. While the option of external H^-/D^- cusp source[4][5] provides much higher beam currents with minimal stripping loss[6][7][8] the compact internal source does find their usefulness in many medical cyclotrons needing only 50-200 μA of external beams. The following sections describe the basic test facility and parameter optimization. A summary of source performance is also presented.

2. TEST FACILITY

2.1. Source Structure and H^- Formation

The compact internal H^-/D^- source is identical to a postive cold cathode PIG source used for protons, deuterons, He^{1+} and He^{2+} productions, except that a plasma expansion gap is added between the arc column and the extraction slit. This design was suggested by Ehler to facilitate the production and survival of the H^- ions from the reaction:

$$e + H_2 \rightarrow H^+ + H^- + e.$$

The arc column is the intense electron source but no H^- survive within the column. The collisions of the low energy electrons with the molecules of H_2 gas on the surface of the arc column produce the H^-. Only those ions created behind the anode slit are available for extraction. The molecular density of the hydrogen gas and the density of low energy electrons in the gap region are two basic variables which control the H^- production. However, the production probability and the extraction capability behind the slit are related strongly as we shall see the section of parameter studies.

2.2. RF Extraction

A DC test stand was originally planned for the source development but later the central region of several cyclotrons were used. If the RF phase width can be measured using Smith-Garren method and the stripping loss can be deduced, the DC equivalent output may be inferred with reasonable confidence. In order to optimize the transmission efficiency from the first extraction to the beam current probe, sufficient electric and magnetic focusing are provided. The vertical dee alignment is also very important. A set of inner harmonic coils is used for beam centering and the adjustable source-puller gap can compensate the ion flight-time problem for the second or fourth harmonic operation.

2.3. Gas Stripping

When the internal source performance is monitored by the negative beams which have completed several tens of turns in a cyclotron central region, the knowledge of gas stripping loss becomes important. While the details of gas stripping calculation will be presented in a future publication, a very brief mentioning here should be helpful. If the relativistic and the radial dependence effects are neglected, it can be shown that the H^-/D^- beam current ratio between two radii is of a simple exponential form:

$$I(r_1)/I(r_2) = \exp(-F \cdot P_{eff} \cdot (1/\Delta E) \cdot (r_2 - r_1))$$

where F is the simplified stripping coefficient containing gas stripping cross-section and all other constants, ΔE is the energy gain per turn, P_{eff} is the effective pressure. For r in cm, ΔE in KeV and P in 10^{-6} torr, the empirical value of F for H_2 gas is 0.054. The effective pressure is given by

$$P_{eff} = P(H_2) + P(H_2O)\cdot 5 + P(O_2)\cdot 8 + P(N_2)\cdot 7 + \cdots$$

where the partial pressures are calibrated values from a gas analyser. One notes that the pressure is not a static parameter because gas composition might change between arc off and arc on; gas outgassing from the target probe and many other effects. Nonetheless this approximation is useful in obtaining the stripping loss expeditiously.

3. PARAMETER STUDIES

3.1. Plasma Expansion Gap

In order to investigate how critical an effect on H^- production and survival in the plasma expansion gap, a mechanism to rotate the source anode orientation is installed, as shown in Fig. 1. The axial angle of the anode with respect to the main magnetic field is adjustable for $\pm 5°$. When the angle is deviated from 0°, the arc column moves away from the extraction slit and the gap width is varied.

The effect of the gap width is illustrated in Fig. 2. On the left is the source with a positive beam anode (gap=0 at 0°). At 0°, the H^- beam is about 0 but gradually climbs to a maximum at about $\pm 2.5°$. Larger gap results in lesser beam current.

We used this $\pm 2.5°$ to measure the optimal gap, which turned out to be about 1 mm. Then we fabricated a negative beam anode which provided a 1 mm gap at 0°. As we can see, interesting results appear. The peak currents for both H^-/D^- occur at 0° and falls off at either directions of rotation. The D^- beam is less sensitive to the rotation and the nature of the higher peak at 4.5° is not quite understood. In the event that the initial source installation does not get the gap at its optimal value, this rotational drive can be used to make corrections.

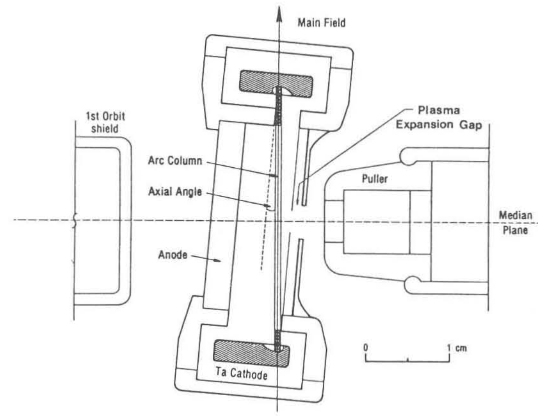

Fig. 1. A rotation mechanism to adjust the value of the expansion gap.

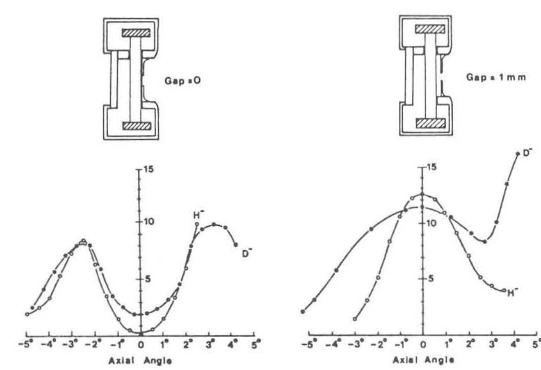

Fig. 2. H^-/D^- output measured as a function of axial angle

3.2. Chimney Slit Opening

One of the more complex source parameters is the Slit Opening, which faces the extractor. For a higher H^-/D^- current, one would like to have a wider opening for a larger ion emission area and a deeper electric field penetration. As the first result, the extracted electron current increases as well in a much higher electron to negative ion ratio because the molecular density behind the slit decreases. The arc column would have to be placed further from the slit in order to make this ratio manageable, i.e., without overloading the extraction circuit. If not so, the extractor would have to be moved away from the slit to avoid the excess of electrons, or the space charge loading effectively decreases the electric field between the source and the puller. Thus, the gain of the total H^-/D^- emission area is somewhat cancelled by the drop of electric field.

In addition, the gas pressure inside the discharge volume drops accordingly, resulting in a decrease of negative ion production. One can step up the gas flow to compensate this drop, but the extra gas increase the vacuum chamber pressure which in turn decreases the final beam by the extra stripping loss. If one chooses to elongate the vertical slit length to increase the emission area the constraints are mainly the allowable vertical beam size developed later in the acceleration process and the maximum stripping loss permitted.

For a cyclotron system having 10^4 l/s effective pumping speed, 30% stripping loss at extraction, the slit size optimized is about 0.6 mm × 4 mm while the plasma expansion gap is set at 0.6 mm.

3.3. Geometry Optimization

After the critical plasma expansion gap has been established, we also searched for the optimum relationship between the inner anode wall and the arc column. Fig. 3 shows some of the representative geometry tested. The diameter of the inner anode wall is fixed at 6.3 mm, while the diameter of the arc column varies from 3 mm to 5 mm. In all cases from [A] to [G], the H^-/D^- output is best with gap dimensions about equal to the slit width. For an arc column length (cathode to cathode) of 30 mm and a permissible gas flow up to 7 sccm, the H^-/D^- output is best with an arc column diameter of 4.25±0.25 mm.

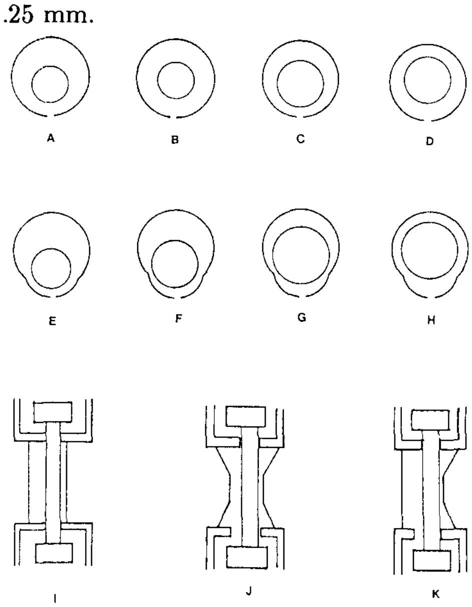

Fig. 3. Examples of arc column geometry optimization

For the cases of E, F, G, J, and K, the anode inner structure is less straightforward. Such design favors the electron flow near the extraction slit thus improving the arc current efficiency. We found that the combination of F and J is the best, while K is used if the fabrication of J is not feasible. Cases B, D, and H were expected to give less output but were explored as well for the purpose of completeness.

3.4. Gas Passage

There has been suggestion that gas efficiency can be improved if the H_2/D_2 gas is sent directly into the chimney near the extraction slit. An alternative passage, where the gas is passed through the larger opening of the bottom cathode chamber, is also used (as shown in J or K). We compared these two methods by providing two gas lines with valves controllable externally. One can choose either gas line or an adjustable combination of these two gas passages. However, for a given gas flow, we did not detect any differences in H^- output. On the other hand, when the opening of the lower cathode chamber is closed down to the same size as that of the upper chamber, all gas molecules must pass through the hot plasma if this route is taken. The H^- beam output drops about 15% to 20%. The vacuum gauge also reads lower when the arc is turned on and set at higher arc currents.

When gas molecules flow out of the internal source slit, they immediately become destructive. Thus gas utilization must be optimized and any leakage other than slit opening *must be* sealed off.

4. SOURCE PERFORMANCE

4.1. Gas Flow and Arc Current

With the parameters optimized as described in the previous sections, the H^- ions achievable measured at r=15 cm (~ 3.0 MeV) with a 32 kV RF dee voltage and a 0.6 mm × 4 mm slit opening is plotted as a function of gas flow and arc current. This is shown in Fig. 4. The plot is organized either by fixing the arc current while adjusting the gas flow or vice versa. It is interesting to point out that with the angular position set at the easiest arc generating orientation (about 0°), the beam current is continuously adjustable from picoamp range to several hundred microamps by a current regulated power supply.

Please note the H^- beam rises rapidly as the arc current increases at the low end and gradually saturates at high arc currents in all cases except for the very high gas flow. Also note that at arc currents below 0.5 A, the H^- goes through a maximum, then decreases as the gas flow increases. As an example, if one wants only 30 μA of H^-, one could use only 1.5 sccm gas flow with 0.2 A arc rather than 7 sccm at 0.2 A. Likewise for a 160 μA H^-, one could choose 4 sccm instead of 7 sccm. For a 300 μA demand, one has to use 6-7 sccm at 1.5 A or higher.

The behavior of these gas flow and arc current interdependence can be understood if one realizes that the production and the neutralization of H^- ions takes place simultaneously in the same environment by different reaction mechanisms. Take the case of 0.2 A arc, for example. The maximum H^- production is reached at 3 sccm. Beyond that, the electrons having suitable energy for production are exhausted and the high gas pressure inside the source decreases the survival of the H^- already produced. The increase of stripping loss before reaching 15 cm also contributes to the trend of decrease, but only about a 10% drop from 3 sccm to 7 sccm. For each gas flow, the saturation at higher arc current might be due to the insufficient supply of gas molecules, the increased percentage of neutral gas being positively ionized, the over supply of electrons with destructive energy and greater H^- neutralization rate in the vicinity of a hotter plasma.

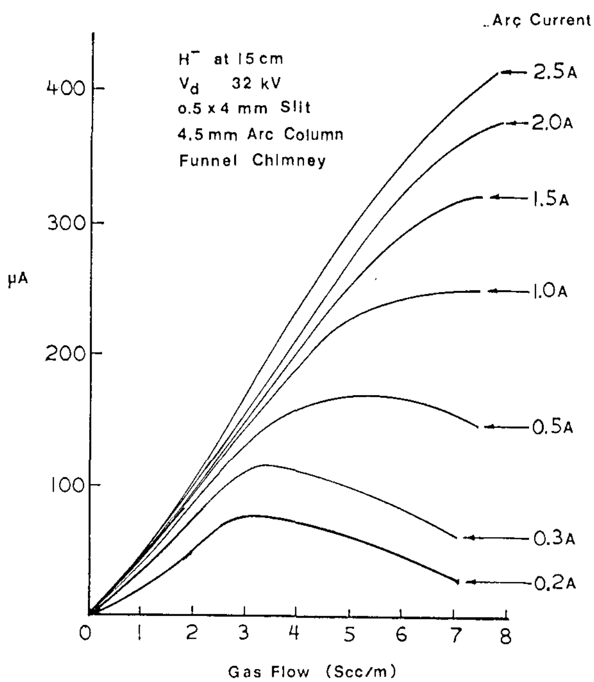

Fig. 4. H^- output as functions of gas flow and arc current.

The H^- beam dependence on gas flow and arc current is also tune dependent. The plot obtained in Fig. 4 is the result of a high arc current tune. The ion source is fed with high gas flow first and set at 1.5 A arc. The H^- beam is optimized with adjustments of ion source positions. At this tune mode the source slit to puller gap is larger ($\sim$3.0 mm) than that from a lower current tune mode (H^- beam is optimized with lower gas flow at 0.3 A arc). The high current tune mode already includes the space charge effect. The low current tune mode would suffer the space charge effect when the arc current is ramped up. The high or low current tune also affects the gas pressure behind the slit because of the restriction of gas passage between the source and puller.

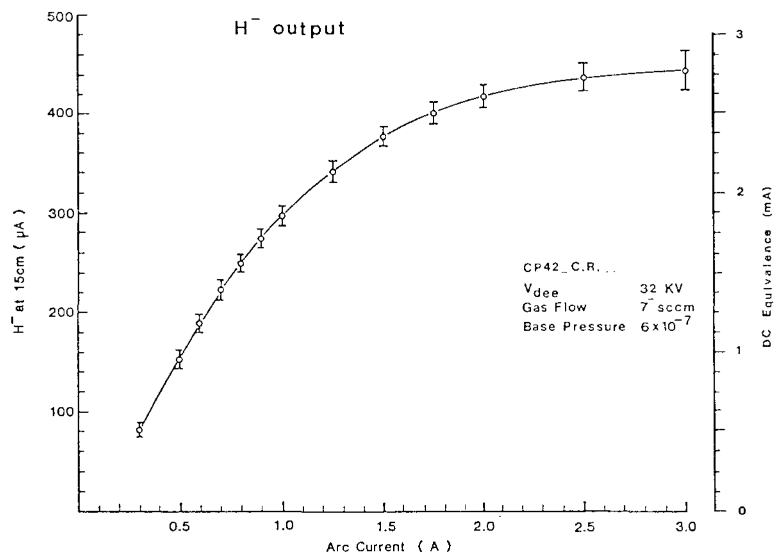

Fig. 5. H^- output as a function of arc current. The beam is adjustable from a fraction of a μA to a few hundred μA.

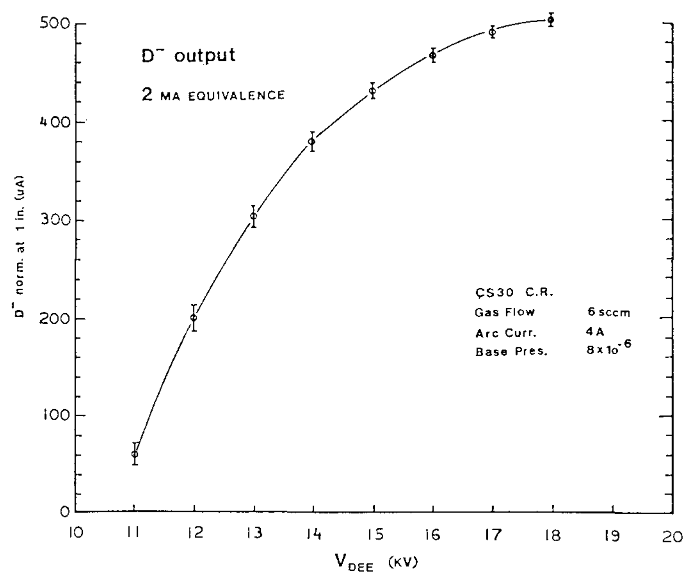

Fig. 6. D^- output as a function of dee voltage or RF phase width. Note that the result was obtained with a discrete current P.S.

4.2. DC Equivalent H^-/D^- Output

Figure 5 shows another H^- output curve as a function of arc current with a fixed gas flow of 7 sccm. The beam available at the cyclotron center is traced back to be $\sim$ 500 μA. The RF phase width is calculated to be $\sim$ 64°. Since the negative ions extractable are emission limited at rather low voltage, the ion density per unit phase is considered constant. The DC equivalent output is then inferred to be 2.8 mA, the current density is 144 mA/cm^2.

Figure 6 shows the D^- output traced back to the cyclotron center as a function of dee voltage. The DC equivalent is already fixed but the beam available is RF phase width dependent. The inferred DC D^- output is about 2 mA.

4.3. Source Reproducibility

The source head assembly tolerance has been within 0.1 mm in critical area. Gas leakage in the head was to be checked by means of pressure bubbling in an alcolhol bath. The cooling path should take into account of differential thermal expansion such that the source dimension and position will remain constant and independent of arc power and RF power used. The cathode stems must be cooled to maintain accurate arc column and expansion gap relationship. Using a precision central region position calibration fixture and four dimensional ion source position drives, the beam current output reproducibility has been excellent. For a properly assembled source we have not yet encountered the situation of beam fall-off phenomenon, short term or long term at high or low beam currents.

5. SOURCE TECHNOLOGY TRANSFER

Several commercial cyclotron producers have adapted the internal source technology just described through the authors of this report.

- CP-42 series cyclotrons: uses H^- only. The routine extractable external proton beam has been in excess of 200 μA at 30 MeV. 300 μA at 30 MeV on external target has also been achieved.[9)]

- An 11 MeV H^- cyclotron: uses a miniture source with 4 dimensional position controls. Peak proton beam on target is 100 μA. An axial source geometry has also been developed for a four sector version.

- A 10 MeV H^-/5 MeV D^- cyclotron: adopts a 2-source central region which accepts H^- source on one side of the dee center linkage and the D^- source on the other. Initial orbits must clear both sources and the central region. The sources are not movable and the pumping speed is limited thus the source performance has been compromized.[10)]

- An 18 MeV H^-/9MeV D^- cyclotron: an extension of the 10/5 cyclotron, but two dimensional source drives are added.

- A 16.5 MeV H^-/8.5 MeV D^- cyclotron: also 2-source central region. The source structure has been simplified to eliminate cathode stems. The source output from a test stand is strong and the RF extraction output is more than adequate for 50 μA on target.[11)]

6. REFERENCES

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