REVIEW OF NEGATIVE HYDROGEN ION SOURCES HIGH BRIGHTNESS/HIGH CURRENT

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Abstract

Due to the development of reliable H^- ion sources, charge-exchange injection into circular accelerators has become routine. This paper reviews recent developments in negative hydrogen ion sources. The underlying physics, operating parameters and beam characteristics of selected sources will be described and compared.

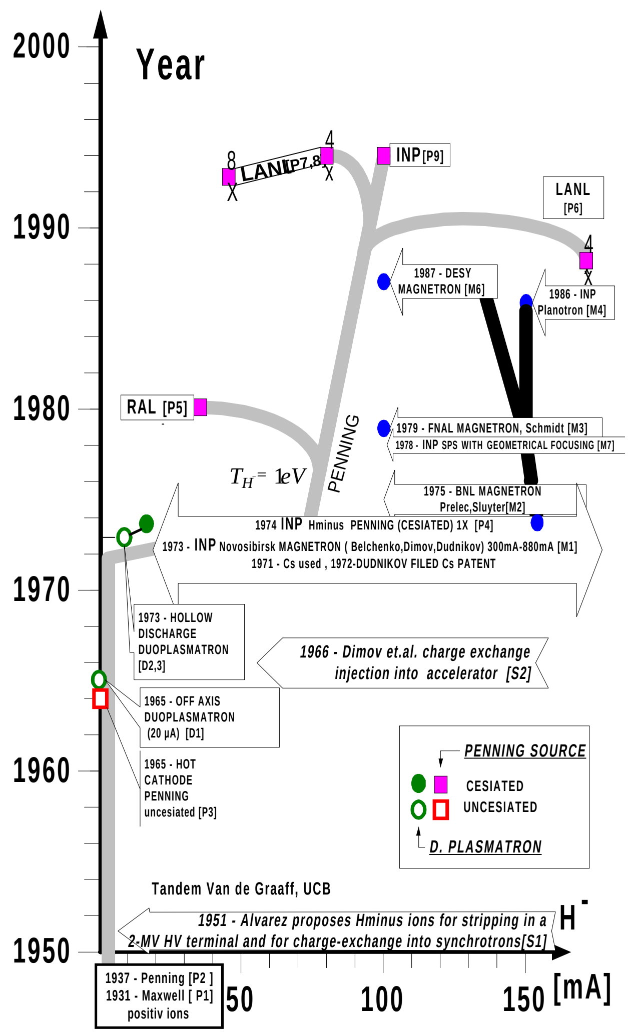

Figure 1: History of duoplasmatron and surface source development.

1 INTRODUCTION

This paper will deal primarily with H^- sources used as injectors for high energy accelerators. Usual (high) H^- currents are 10 to 100 mA dependent on the duty factor.

It has taken two decades to reach these currents since Alvarez proposed H^- ions for stripping in a high voltage terminal and for charge-exchange injection into synchrotrons (Fig.1 S1) [1].

Duoplasmatrons (D1,2,3) with their low currents are excluded as well as multi aperture sources which have high currents but low brightness .

1.1 *Definition of Brightness and Emittance*

Several definitions of brightness are in use. The following relation is adopted here :

$$B = \frac{I}{\varepsilon^N_{x,90\%} \; \varepsilon^N_{y,90\%}} \quad ,$$

where $\varepsilon^N_{x,90\%}$ is the energy normalized emittance in the (x ,x') plane for the contour containing 90% of the brightest beam and

$$\varepsilon^N = \varepsilon \, \beta \, \gamma \quad ,$$

with : $\beta = v_{BEAM}/c$ and $\gamma = 1/(1-\beta^2)^{1/2}$.

In the ideal case the contour is an ellipse and ε is the product of the semimajor and semiminor axes times π. Emittances quoted in conventions other than 90% area values can be converted using the following equations :

$\varepsilon_{90\%} = 4.6\, \varepsilon_{rms}$ and $\varepsilon_{90\%} = 1.125\, \varepsilon_{4rms}$ assuming a Gaussian distribution.

1.2 *Emittance Scanners and Emittance Errors*

Emittance values found in the literature may differ very much even for the same source type and current. For this paper the labs were asked for emittances and the related current, type of emittance scanner, distance from scanner to extractor and other relevant source data. Most labs now use slit-multiwire scanners [DESY, BNL, RAL] or electrostatic sweep scanners (Allison) [LANL, LBL]. These devices are able to measure rms and area emittances. The pepperpot is also still in use. It measures only area emittances. In recently published emittance collections [2] area definitions have been used.

2 SURFACE SOURCES (SPS)

After the discovery of cesiation of surfaces at INP in 1971, the attainable H^- currents increased dramatically. The magnetron was invented (see Fig.1 M1)[3] and the penning source developed to its present standard (P4) [4] in Novosibirsk at INP .

2.1 Magnetron

Magnetron technology was transferred from INP to BNL (M2) [5] and from there to FNAL (M3) [6]. There was a mutual exchange between these two labs. In 1987 magnetron plans were brought from FNAL to DESY.

Figure 2 shows the structure of a magnetron in front and side views. It consists of a central cylindrical cathode surrounded by an anode. The discharge voltage, U_D , is typically ≈150 V and the current 40 A. A magnetic field (≈0.17 T) is parallel to the cathode axis. Hydrogen gas is introduced from the top by a pulsed gas valve.

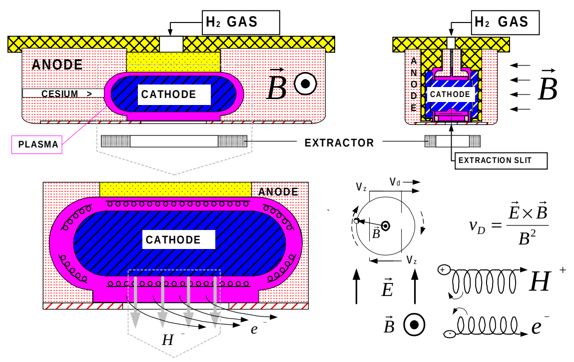

Figure 2: Magnetron source and E×B drift.

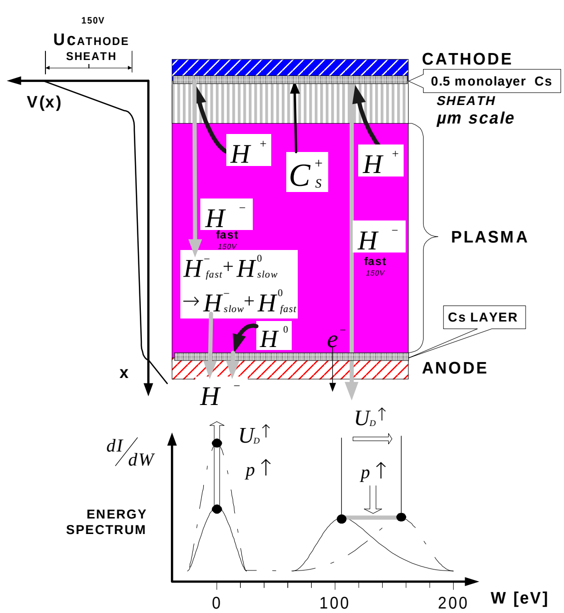

Figure 3: Production of H^- at cathode and anode of the source and their energy spectrum.

Cesium is obtained by heating metallic cesium or a mixture of cesium chromate and titanium. The mixture is available as pellets or powder.

H^- ions are extracted at 18 kV (FNAL, DESY) or 35 kV (BNL) together with electrons. Modern magnetrons have geometric focussing, developed at INP in 1978, with a groove in the cathode and slit extraction followed by a bending magnet [7]. Another possibility is to dimple the cathode and to use a hole as aperture toward the extractor electrode [8].

The electric field between anode and cathode leads to an E×B drift around the cathode, which is shown on a magnified scale Fig.2 (lower part). Positive and negative ions move in the same direction. There is no movement parallel to E as particles gain as much energy as they lose. But parallel to E×B there is a resulting difference v_d (see Fig.2). Charges are not separated due to this effect. A dense plasma is produced.

If one looks with a bigger magnification at the space between anode and cathode (Fig. 3) one notices a transition zone, the so-called sheath, between the plasma and the cathode. Here the potential drops to cathode level. There is only a small potential difference across the plasma. H^+ ions generated in the plasma are accelerated through the sheath. They produce H^- ions at the cathode surface, which is covered in the ideal case with approximately half a mono layer of Cs in order to minimize the surface work function. These H^- particles are then accelerated to U_D passing through the sheath. Some move through the plasma and are extracted. They form a maximum in the energy spectrum (Fig.3 lower part). Others hit slow H^0 particles and exchange speed and charge; this is resonant charge exchange. In this way slow H^- ions are produced. Slow H^- can also be produced by H^0 hitting the cesiated anode surface.

Due to these mechanisms a low and a high energy peak appear in the energy spectrum. To increase the fraction of low temperature ions one can increase the source pressure and discharge voltage U_D, as indicated in the plot. In addition, the position of the high energy peak can be changed by varying U_D and the amplitude lowered by increasing the pressure.

2.2 Semiplanotron

The semiplanotron (see Fig. 4) is an optimized magnetron, with geometric focussing and without a discharge at the back of the cathode. These modifications make it more efficient. Operational experience is, however, limited. Source lifetime may be limited by the accumulation of sputtered particles from the cathode as a result of their drift path being blocked. This might result in a short circuit, consistent with DESY experience.

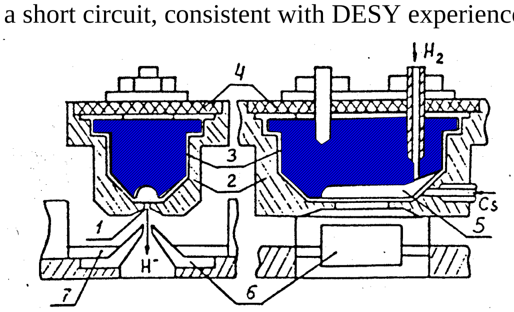

Figure 4: The semiplanotron source. 1. emission slit, 2. anode, 3. cathode, 4. insulator, 5. groove, 6. extractor, 7. steel inserts.

2.3 *Penning*

In order to avoid the high energy peak of the magnetron spectrum the cathode surface should not face the ion extraction aperture. This is how the penning source is constructed (see Fig. 5).

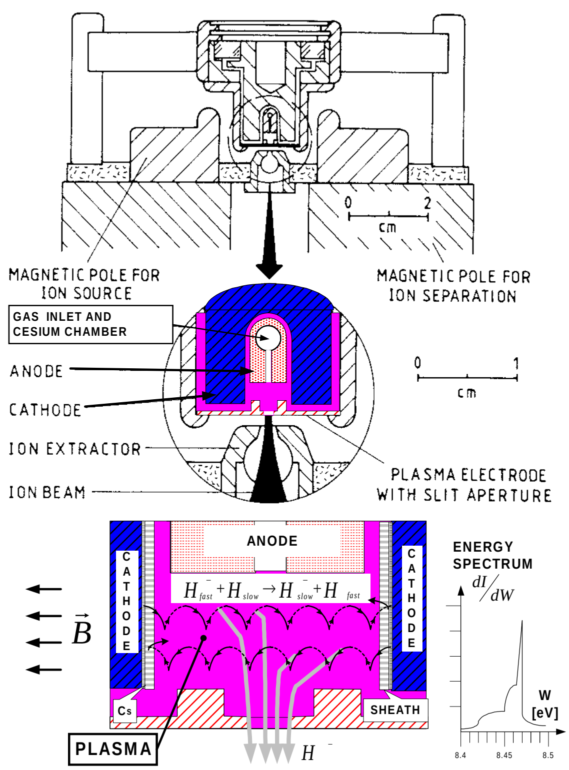

Figure 5: Penning source schematic and its energy spectrum.

A strong magnetic field parallel to the electric field of the sheath guides electrons and ions on cyclotron spirals from cathode to cathode. Fast H^- ions are generated at the cathodes as in the magnetron. They are slowed down due to the charge exchange reaction as they migrate to the plasma aperture. There is only one low energy peak and the H^- temperature has been measured to be less than 1eV [9].

2.4 *Multicusp Surface-plasma (converter) Source*

Fig. 6 shows a multicusp surface-plasma source. A discharge is produced with filaments. The plasma is confined by a multicusp field. A converter biased at ≈300 V is located in the middle of the source. Secondary emission of negative ions takes place. The H^- ions are produced by H^+, H_2^+ and H_3^+ bombarding the converter. Cesium is injected into the source to increase the H^- yield. Self extraction of H^- takes place with focussing provided by the curvature of the converter. A magnetic filter is used to repel electrons.

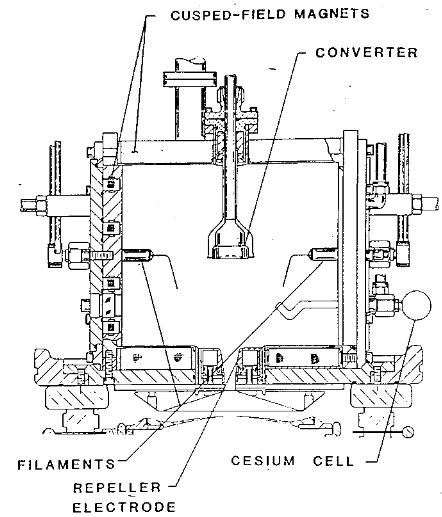

Figure 6: LANL surface production multicusp.

3 VOLUME SOURCES

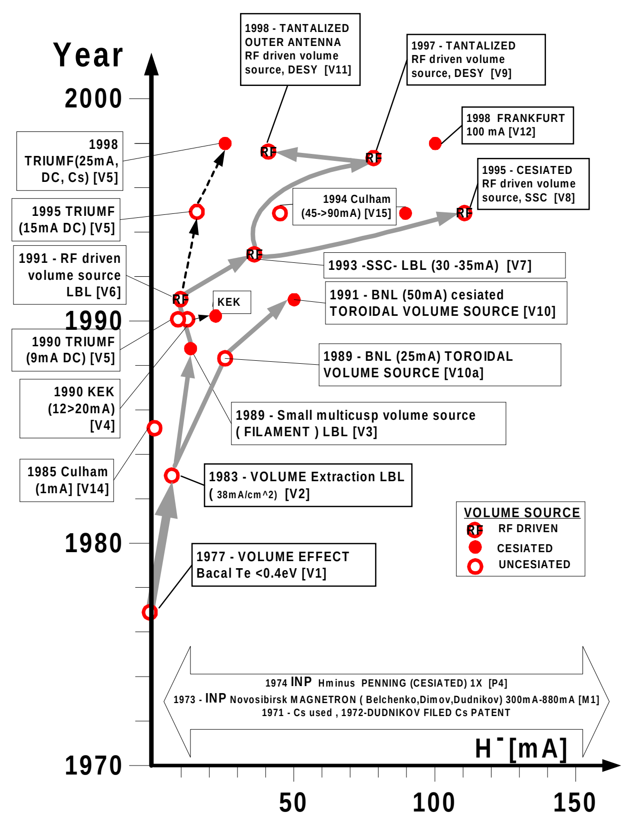

Figure 7: History of volume source development.

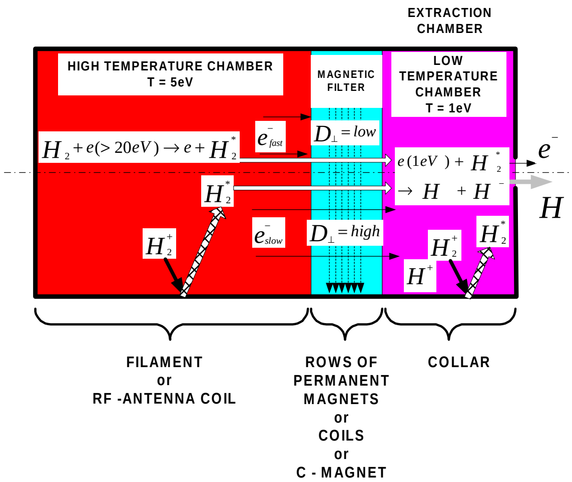

Figure 8: Tandem source for volume production.

In 1977 M. Bacal [10] discovered volume production for H$^-$ generation. This started the development of a new type of sources (Fig. 7). The volume source consists of two chambers, which are connected by a magnetic filter (Fig. 8). In the high temperature chamber energetic electrons hit H_2 , which become vibrationally excited. Excited molecule are also produced at the chamber walls out of H_2^+ and H^+ . Electrons from the high temperature chamber move by diffusion through a perpendicular magnetic field into a second chamber. Whereas high energy electrons are effectively blocked, slow electrons collect in the second chamber. In this low energy chamber, low temperature 1eV electrons attach to the H_2^* producing H$^-$ ions.

Multi-cusp magnets are used to confine the plasma.

3.1 Filament Volume Source

The first volume sources were uncesiated and had filaments. Currents of up to 20 mA DC [11] were reached with small sources and 45 mA [12] (Fig. 6 V15) with larger ones. Cesiated currents of 25 mA DC [13] and 90-100 mA at 6% duty factor [12,14] V12 have been achieved. The lifetime of these sources is limited by that of the filament.

3.2 RF Volume Source

The filament was first replaced by an rf antenna coil in 1991 [15]. Fig. 9 shows the DESY RF volume source; it is similar to the sources of LBL and SSC. The antenna heats the high temperature chamber and the filter is constructed with two rows of permanent magnets. The low temperature chamber is located inside a collar.

The antennas are coated to reduce plasma modulation by the rf voltage and sputtering. With uncesiated rf volume sources 35 mA were reached. At DESY the collar was biased and tantalum coated, and currents of 80 mA were achieved uncesiated.

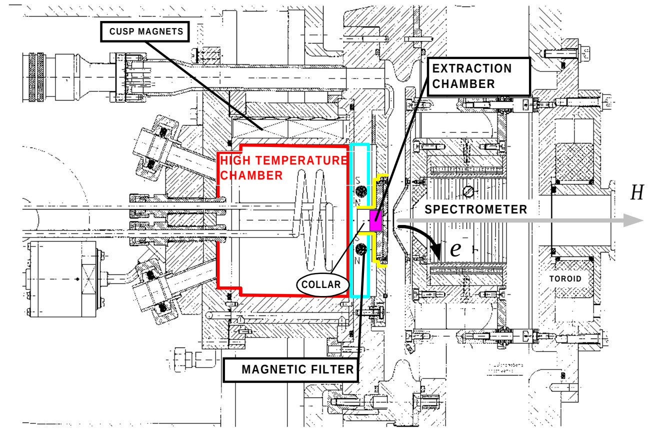

Figure 9: RF driven volume source.

The antennas used by LBL, SSC and DESY were all coated by the same manufacturer. An analysis of the coating found a high percentage of K and Na (Table 1). Different contents of potassium might have contributed to reported differences in source performance.

Table 1: Results of Analyses of the Antenna Coating

ELEMENT	PERCENTAGE
Si	46.9 %
Ti	29.6 %
K	15.2 %
Al	5.7 %
Na	2.6 %

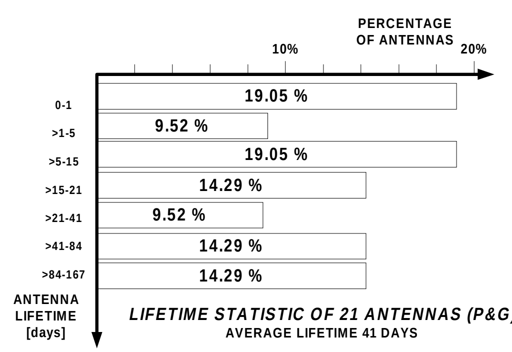

Figure 10: Lifetime statistic of the coated antennae.

DESY has the longest experience in running this type of volume source with the P&G antenna. The performance of the antennae is first limited by spots in the coating. If it survives this period then cracks due to sputtering of the coating material become the lifetime limitation. The average lifetime of only 41 days is higher than that of a filament. However ≈50% of all antennae fail during the first 15 days. This unpredictability is a serious problem for reliability.

In addition it was found that sputtered glass from the coating insulates the chamber walls. After such an event it is necessary to do a careful time consuming cleaning of the whole source. Based on this experience a new rf coupling was developed, which couples through a ceramic of Al_2O_3. This type of ceramic has a sputter rate seven times lower than that of glass and three times lower than Ti.

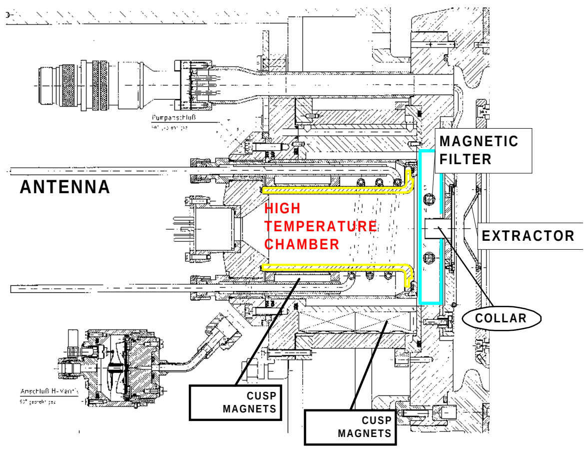

Figure 11: The DESY volume source with an rf coil shielded by Al_2O_3 ceramic.

A source of this type, Fig. 11, was run for 2800 h at 40 mA with a duty factor of 0.05 % and a pulse length of 100 µsec. No degradation in performance was observed.

4 SUMMARY

Table 2: Collection of Source Data

tested uninter-rupted run [h]	SOURC TYP	DUTY FACTOR [%]	$\varepsilon_{n,90\%}$ [π mm mrad	REF.	BRIGHTNESS [mA/m² mrad²]	Cs CONS [mg/day	CURRENT I/mA
7224 4320	MAGNETRO 16 years a.	0.05 0.48	.98 1.2	[16] [17]	6.4 4.9	2.8	60 (->120 75
	PLANOTRO	0.25	0.14	[19]	500	24	100
960	PENNIN 15 years. exp	2.5 2.5	0.3 ->0.1	[18] [19]	670	24	35 (->170 80
500	VOLUM FILAMEN 9 years a.	100	0.75	[20]	3.6	NO	20
	FILAMEN	100 6	0.52(0.6 ≈0.23	[21] [22]		5 29	20 100
72-984	RF Antenna Plasm	0.1	0.5	[23]	12	NO but K	30 (->80
	RF Antenna Plasm	0.1	0.5	[24]	28	Cs	91 (->120
2800	RF out of	0.05	0.75	[25]	7.2	NO	40

For high energy accelerators it is important to have a reliable source. Magnetrons have been used for the longest time in accelerators and have tested runs of 7000 h. They have, however a poor brightness. Penning sources provide the highest brightness but run for only about 900 h.

The best tested volume source is a DC 6 - 20 mA source, which runs (limited by the filament) for 500 h.

A new rf volume source with an rf coil shielded by ceramic exhibited no degradation in performance after a run of 2800 h.

According to recent results [11, 14] the future prospects of filament volume sources as high duty factor accelerator sources are very good.

Since the antenna problem was solved [27] rf sources are expected to replace magnetrons. They have a higher brightness, higher reliability and are easier to maintain.

5 ACKNOWLEDGEMENTS

The author is grateful for the contribution of the following colleagues at DESY :

N.Holtkamp, I.Hansen, H.Sahling and R.Subke. I wish to thank the technical groups at DESY for their support, and M. Lomperski of DESY for helpful suggestions to the wording of the report. The support of the source groups of BINP, BNL, FNAL, LANL, LBL, RAL and TRIUMF is gratefully acknowledged.

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