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A DIRECT EXTRACTION H^- ION SOURCE*

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Summary

A direct extraction H^- ion source of the Penning design described by Dudnikov[1] has been built and tested. To date a beam of 108 mA has been extracted from a 10 x 0.5 mm^2 slit and transported through a 90° bending magnet into a Faraday cup at a duty factor of ~7 Hz x 700 μs (0.5%). The duty factor limitation is imposed by operating temperature requirements so that at reduced arc current a dc beam of 4 mA has been reached.

General Description

The surface-plasma H^- ion source was first described by Belchenko, Dimov, and Dudnikov.[2] In one of several later articles Dudnikov[1] described a Penning design variation with overall properties more nearly compatible with use on an accelerator, and such a source has been built at LASL according to the design presented in that article for use as an injector to a proton linac. The magnetron and duoplasmatron H^- source developments carried out by Sluyters and Prelec[3] have also provided information helpful in our development.

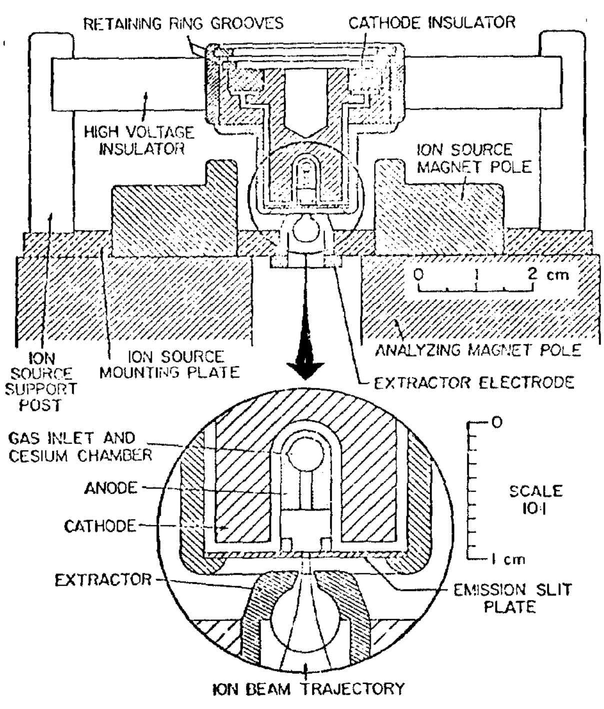

FIG. 1. CROSS SECTION THROUGH LASL VERSION OF DUDNIKOV PENNING SOURCE.

A cross section through the LASL source is shown in Fig. 1. A mixture of $Cs_2Cr_2O_7$ + Ti is packed into the anode structure to provide cesium for the discharge. A Penning discharge takes place parallel to the emission slit, from which ions are extracted and transported with an n=0.85, ρ=8 cm, θ=90° magnet of 3 cm aperture to a Faraday cup. The cathode, anode, extractor, and emission slit are of molybdenum; the housing is of stainless. Cathode and source housing temperatures are monitored with thermocouples. The test stand is pumped with a 2000 l/s diffusion pump, allowing gas flows of up to 200 atm-cm^3/min to be run continuously. Hydrogen flow into the source is controlled with a Veeco PV-10 piezoelectric valve so that gas flow may be either pulsed or continuous. A 700-V, 10-A arc supply is used to start the arc in a dc mode, and a 300-V, 200-A transistor pulser is used for pulsed operation. A regulator for the extractor power supply has not yet been put into operation, but this will be necessary to reduce beam dispersion in the 90° magnet. The ion source and its electronics are at high potential so that the extracted beam and Faraday cup are at ground potential. The emission slit dimensions are 10 mm x 0.5 mm, and all H^- ion currents have been measured at the Faraday cup.

Operation

Table I shows the present operating parameters. Best source operation occurs when the indicated cathode temperature is 500°-600°C, probably close to the true average value. With a magnetic field of 2-3 kGauss and a gas flow of 100 atm-cm^3/min a discharge can be started at 300-650 V. With a 650 V, 0.05-0.1 A arc the cathode temperature rises rapidly but the source housing takes about 1/2 hour to reach 300°C, at which time cesium is evolved from the powder stored in the anode and the arc impedance falls precipitously. A typical arc of 1.4 A, 40 V will maintain proper temperature for steady operation, and a dc beam, of 2.7 mA has been extracted at a gas flow of 21 cm^3/min. The stripping loss η of H^- from H_2 flow Q into the vacuum chamber is calculated to be

$$\eta(\%) \simeq Q(cm^3/min)/4$$

and this is confirmed by measurements in which extra H_2 gas is bled into the chamber. Brief operation up to 4 mA (2.5 A arc) was tried; however, performance was somewhat erratic, probably due to high cathode temperature (700°C) and improper cesium balance.

TABLE I

Operating Characteristics

H^- current (mA)	108	50	2
Arc current (A)	60	85	1
Arc voltage (V)	~80	85	45
Duty factor	7 Hz x 0.7 ms	10 Hz x 0.7 ms	dc
Average gas flow (atm-cm^3/min)	18	--	65
Gas density ($10^{15}/cm^3$)	~4	~4	~2
Normalized emittance [$(cm\text{-}mrad)^2$]	--	0.06 x 0.02	0.08 x 0.007
Extractor current (mA)	160	100-200	4
Beam energy (kV)	~18	~18	~18
Normalized brightness [$A/(cm\text{-}mrad)^2$]	--	8	0.7
Thermal efficiency (AH^-/kW_{arc})	0.023	0.007	0.044
Gas efficiency	~0.008	~0.004	0.0003

*Does not include focusing distortions

*Work performed under the auspices of the U. S. Energy Research and Development Adminstration

Since the source is cooled primarily by heat conduction down the high voltage insulators, substantial increases in the operating current could probably be achieved with simple cooling. No attempt has yet been made to do this.

Once the low impedance dc arc is struck the 300-V pulser can supply the arc power. Up to 180-A arc at about 100 V has been reached, about the current limit of the present pulser. The H^- yield has been measured under various conditions of gas flow, temperature (30°C to 800°C), and duty factor over a range of arc current from 300 μA to 180 A. Under optimum conditions

$$i_{H^-} = 0.002\ i_{arc}$$

closely describes the yield over at least the range 20-mA to 60-A arc current (Fig. 2).

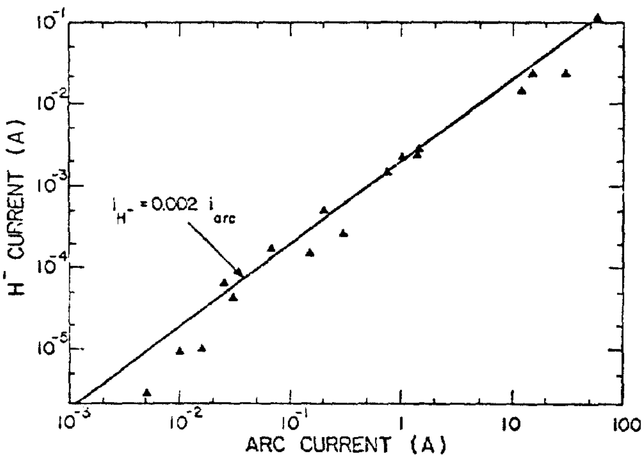

FIG. 2. H^- ION CURRENT VS ARC CURRENT

After repeated cleaning of the source to eliminate cesium only about 0.1-A arc current could be reached without excessive temperature, but the H^- yield was still about half normal. One probably cannot rule out the possibility that some cesium still remained in the surfaces; however, it is hoped to determine the optimum cesium density in the source with the use of a controlled external cesium vapor supply line, an experiment for which apparatus has been built.

Gas flow into the source is monitored and ranges from about 20-120 atm-cm^3/min in the continuous flow mode, the higher values generally being required for the highest arc current. Pressure measurements were made at room temperature and extrapolated to an estimated operating temperature of 450°C, giving a gas density of 1-4 x 10^{15}/cm^3. In the pulsed mode of the arc the gas is usually pulsed also to reduce H^- stripping losses in the ~20 cm path to the Faraday cup. Measurements of the pulsed gas flow from the Veeco PV-10 piezoelectric valve showed that a minimum risetime of 400 μs could be achieved, with a falltime of 1 ms, and that gas flow oscillated ±20% at 1 kHz, presumably due to mechanical ringing of the valve. These variations can be seen in arc current, which rises and falls in ~2 ms if a dc voltage is applied to the arc. Pulsed gas density in the arc can be inferred from the dc gas flow under comparable operating conditions.

As long as arc power remains constant, operation seems stable at various duty factors. The highest current yet reached (108 mA, an emission density of 2.2 A/cm^2) was achieved at a duty factor of 0.5% (7Hz x 700 μs), 18 keV extraction voltage (Fig. 3). This is a slightly larger current density than the calculated space charge limit, 2.1 A/cm^2, for the 2.5 mm extractor gap used.

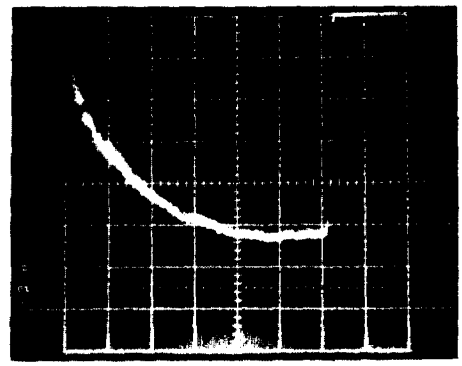

Fig. 3. H^- Current Pulse
20 mA/div., 100 μs/div.

It is interesting to note that the space-charge limited current for an H^- beam is reduced by about 20% if accompanied by an electron current ten times that of H^-, therefore the electron density at the emission surface may be relatively low.

Ion Optics and Emittance

Beam transport calculations for the 90° magnet point out an important feature of handling high current density (2 A/cm^2) low energy (20 kV) beams. Calculations of the beam profile (assuming zero emittance) in the n=0.85 magnet show that the beam will strike the magnet poles for currents in excess of 15 mA, whereas a current of 108 mA has reached the Faraday cup; moreover, photographs of the trajectory of a 50-mA beam reveal a well focused beam going into the Faraday cup.

It seems clear that positive ion neutralization of the H^- beam has been closely achieved, with a chamber pressure of 10^{-5}-10^{-4} mm Hg, not surprising considering that a 110-mA, 20-keV beam would have a potential drop of 1.6 keV across it in the absence of neutralization. Any attempt to use electrostatic focusing would cause these positive ions to be swept out of the beam, thus magnetic focusing is seen to be distinctly advantageous where space charge is important.

If zero current is assumed, it can be shown that the maximum emittance that a beam can have, based on its trajectory in the magnet is:

$$\varepsilon \leq \beta\gamma r_i r_f / \rho a$$

where

ε = normalized emittance ($\beta\gamma$ area/π)

r_i = initial radius at entrance to magnet

r_f = final radius at exit of magnet

ρ = ion radius of curvature in magnet

$$a_x = \frac{\sin \frac{\pi}{2} \sqrt{1-n}}{\sqrt{1-n}}$$

$$a_y = \frac{\sin \frac{\pi}{2} \sqrt{n}}{\sqrt{n}}$$

and the equality holds only for optimized initial convergence. When our conditions

(y_i=0.025 cm, x_i=0.5 cm, n=0.85, ρ=8 cm,

$y_f \leq 1.5$ cm, $x_f \leq 1.5$ cm, $\beta\gamma$=0.0062 are applied

$$\varepsilon_x \leq 0.4 \text{ cm-mrad}$$

$$\varepsilon_y \leq 0.03 \text{ cm-mrad}$$

Some preliminary emittance measurements have been made by the pepper-pot method, wherein small holes in the Faraday cup allow beamlets to pass through and drift to a glass plate, where scintillation gives the beamlet diameters and hence their angular divergence.

The normalized emittance of a 1-mA beam is thus estimated to be 0.02 x (<0.004)(cm-mrad)^2, and that for a 50-mA beam is 0.06 x 0.02 (cm-mrad)^2. These cannot be regarded as ultimate values for several reasons.

First, the quoted values do not include the distortion produced by magnetic and electrostatic focusing aberrations, and this is substantial although presumably reducible to a low value with proper design. Second, the normalized emittance can be written as

$$\varepsilon = r_i \sqrt{\frac{2\ T\perp}{mc^2}}$$

where T⊥ is the random transverse energy (or ion temperature) and r_i is the radius at the plasma surface, thus for ε_x=0.06 cm-mrad and r_i=0.5 cm

T⊥≤7 eV, a reasonable value for ion temperature; however, the value calculated using ε_y and r_y is T⊥ = 300 eV, unlikely since the arc voltage is only ~100 volts.

The arc and the extracted ion currents are generally noisy, but sometimes relatively quiet currents are produced, resulting in an increase in H^- current by as much as 100%. No emittance measurement has been made with a quiet arc, but there is reason to believe that the emittance will be low since very noisy arcs have produced beam of very bad emittance. (See also Ref. 1.)

The normalized brightness is given by

$$B = \frac{2I}{\pi^2 \varepsilon_x \varepsilon_y}$$

$$= \frac{J}{\pi} \frac{mc^2}{T\perp}$$

if it is assumed that the effective value of T⊥ is the same in x and y. Therefore if distortion in the beam phase space produced by extraction and focusing can be made sufficiently low, high current density at extraction will lead to a beam of high brightness. Since high current density in an accelerating column is difficult to handle, the extracted beam must be refocused magnetically for reduced density. If an effective ion temperature of 10 eV could be reached for a 2 A/cm^2 beam then the brightness would be 60 A/(cmmrad)^2, unusually good.

Future Work

The results obtained so far are preliminary and leave many questions unanswered. A separately controlled cesium injector will be used to explore the effect of cesium density. It is hoped that this will lead to quieter arcs. The space-charge limit of the source can be increased by a factor of 6 by reducing the extractor gap to 1 mm. An ion energy analyzer has been built with the hope of understanding H^- production and ion temperature in the plasma, and an electronic emittance scanner is nearing completion. To achieve ultimate brightness it will be necessary to design a low aberration magnet for the arc and focusing regions. Ultimately an extention of the duty factor will be necessary. Cooling can help, and Thomas D. Hayward of Los Alamos has suggested a rotating cathode version. With a 10-cm wheel diameter and a rotational speed of of 1800 rpm the duty factor could be extended 31.4 times for the same average power density into the arc electrodes. Design of this source is being studied.

References

[1]V.G. Dudnikov, "Surface-Plasma Source of Penning Geometry," IV USSR National Conference on Particle Accelerators, 1974.

[2]Iu.I. Belchenko, G.I. Dimov, V.G. Dudnikov, Novosibirsk Preprint IIF 6672, Novosibirsk, 1972. LASL-TR-73-1.

[3]For example, K. Prelec and Th. Sluyters, "An Intense Negative Hydrogen Ion Source for Neutral Injection into Tokamaks," Sixth Symposium on Engineering Problems of Fusion Research, Nov., 1975, San Diego.