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HIGH CURRENT NEGATIVE ION BEAMS

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Summary and Introduction

Two years ago during the 1975 Particle Accelerator Conference in Washington, we reported the development of an intense negative ion magnetron source, capable of extracting short pulsed negative ion beams of several hundred mA. For most particle accelerators these pulsed beams are more than adequate, but for efficient neutral injector systems in future fusion reactors multi-ampere dc negative ion beams are required.

In the past two years significant progress was made in the development of three direct extraction negative ion sources. The first source, the hollow discharge duoplasmatron (HDD) was extensively studied and optimized up to currents of 60 mA. With the second source, the magnetron, a beam current of almost one ampere has been obtained for more than ten milli-seconds beam pulses. Several prototype Penning sources were constructed with yields similar as the magnetrons and with the expected advantage of higher gas efficien-

In order to improve our knowledge of the origin of negative ion production, a program has started to measure the pertinent plasma parameters of the above mentioned sources by spectroscopic means and electrostatic probes.

A first attempt was made to integrate a magnetron source in a 150 kV accelerator structure; so far, beams of 200 mA were accelerated up to 120 kV for several millisecond beam pulses.

Hollow Discharge Duoplasmatron

A parametric study was made of the pulsed hollow discharge duoplasmatron as a negative hydrogen ion source in the pure hydrogen mode and in the mixed hydrogen-cesium mode.1 Figure 1 shows the cross section of the HDD source. The center tube that creates the hollow discharge is protected from the discharge by an insulating sleeve with the exception of the tip, which is removable. This tip has a small cavity that is filled with a mixture of cesium bichromate and titanium powder. The diffusion rate of cesium into the arc chamber was regulated by a heating wire in the center tube. When the source is operating in the hydrogen mode, an oxide-coated thermionic cathode serves as the electron emitter; in the hydrogen-cesium mode best results were obtained with a non-heated, oxide-coated cathode.

In the hydrogen mode a maximum H beam of 11 mA was obtained from an anode aperture of 2.45 mm diameter with a normalized emittance of 0.1 cm-mrad. In the mixed hydrogen-cesium mode an H beam of 60 mA was achieved from the same aperture; a 40 mA beam in the same mode had a normalized emittance of 0.237 cm-mrad. Other relevant source parameters are summarized in Table I. Energy spectra of H ions in the hydrogen mode reveal that negative ions are generated mainly by volume processes, while in the hydrogen-cesium mode the negative ions are mainly produced by a surface process with the tip of the center tube as the apparent H emitting surface.2

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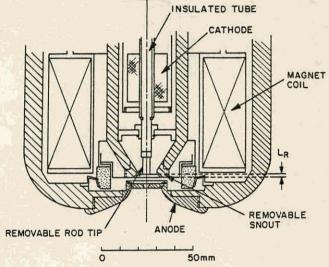
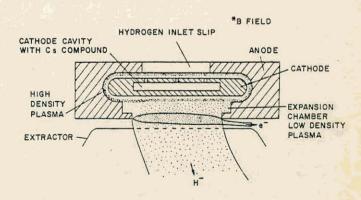


Fig. 1 Cross section of the HDD source.

The HDD source with its rotational symmetric beam and small emittance value appears to be a realistic choice for a negative hydrogen accelerator. The removal of the extracted electron beam current at extraction voltage can be achieved by a small permanent magnet without seriously affecting the primary H beam. The extraction of large electron beam currents does not, however, stimulate the development of HDD sources into multi-ampere units.

Magnetron

The basic design and operation of the magnetron as an intense negative ion source has been extensively described elsewhere³. See Fig. 2. Hydrogen gas passes through a slit in the anode into an annular race track region. During the discharge this region fills with a dense plasma. The molybdenum cathode has a small cavity containing cesium bichromate and titanium. At a high enough temperature of the cathode, cesium enters the discharge region through small holes in the cathode, and the discharge changes into the hydrogen-cesium



Schematic view of the magnetron.

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mode. A six-slit magnetron, with a 5 cm long cathode, vields H currents of 0.9 A in pulses of 10 ms and 0.6 A in pulses of 20 ms. In the latter case the current was limited by the power supply. The gas flow was found to be 3.3 torr l/s cm2, which corresponds to a gas efficiency of 0.2 As/torr &. Other pertinent parameters of this source are summarized in Table I.

Experimental results with existing sources, as well as our studies of scaling problems of magnetron sources, have shown that multi-ampere and/or longer pulse length can only be achieved by cooling of the cathode. The product of the extracted current and the pulse length is roughly a constant. The next generation of sources will therefore include cathode cooling.

Very little is known about the details of how the plasma surface sources precisely work, although the analysis of the energy spectra suggests that a surface effect at the cathode is the primary production mechanism. While Kishinevskii⁵ concentrates its theory on the probability of escape of H ions, produced on a metal surface, through the image field between the surface and negative ion, Hiskes et al. developed the theory on the formation of H ions by the surface interaction of a hydrogen atom and an adsorbed Cs atom, via the intermediary of the CsH and CsH molecular configurations. In order to determine the rate of H production on the cathode surface one has to know the parameters of the partially ionized medium, that contains a high density of neutral hydrogen atoms, cesium atoms and ions, hydrogen molecules and ions, as a function of energy. Preliminary estimates, based on spectroscopic measurements, show that for a Maxmellian distribution of velocities and for a neutral hydrogen temperature of 0.37 eV, atoms of energy between 1.5 eV and 2.5 eV will be reaching the cathode at a flux density equal to the proton flux. The gas pressure inside the standard magnetron source of 1 ampere measured with a transducer is 0.4 torr for an arc current of 150 A.

The adaption of a short-pulsed magnetron source to a particle accelerator has been initiated at Fermi National Accelerator Laboratory.8

Penning Source

It is expected that Penning-type negative-ion sources, operating in the hydrogen-cesium mode, will have yields comparable to magnetron sources, but with a gas efficiency better by up to a factor of three. This is the reason that Penning sources are being investigated at BNL for possible applications in neutral beam injectors.

Recently a new Penning source with a special emitter electrode was constructed at BNL and extensively studied.9 Figure 3 shows its cross section. It is

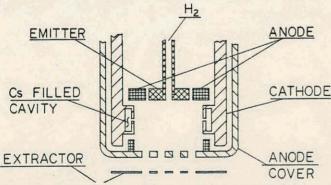


Fig. 3 Schematic view of the Penning source with "emitter".

similar in design to our magnetron source, except that I-7 the race track part of the cathode has been removed in order to create a Penning geometry. Both cathodes are hollow and these cavities are filled with the usual titanium-cesium bichromate mixture. Opposite the extraction slits a flat electrode or "emitter" was placed with the idea to enhance the production and diffusion of H ions.

Results obtained with this small model (cathode area is 2 cm2) are encouraging. Negative beam currents exceeding 0.32 A in pulses of 4 ms have been recorded with a rather uniform current density of 0.58/cm2, from five extraction slits, although there is a tendency of higher current density from the outer slits nearest the two cathodes. The effect of the grounding, floating or biassing the "emitter" on the H production is not very conclusive and difficult to explain (a 10% enhancement of the yield was observed with a positive bias). Other parameters of this source, including some results with deuterium gas, are summarized in Table I.

The normalized emittance of this Penning in the plane perpendicular to the slits is 0.65 m cm-mrad for a 120 mA beam (1.15 π cm-mrad for 0.24 A). Low current Penning sources are therefore quite useful for particle accelerator applications. LASL actually started to investigate the adaption of a negative ion Penning source to a pre-accelerator.10

Acceleration of Intense Negative Hydrogen Beam

Acceleration of several hundred milliamperes pulsed beams up to several hundreds of kilovolts is a well established technique in modern proton injectors. The expectation is that the negative ion plasma sources mentioned above can be adapted to these machines without serious problems, provided their pulse length and current densities do not exceed today's operating proton levels. High voltage acceleration of dc beams for beam currents beyond several tens of milliamperes has not been established yet, because of severe voltage breakdowns inside the tube for not well-understood reasons.

In order to learn about these problems we started with the construction of a rudimentary 150 kV, 1 A accelerator, based upon the principles and experience with close-coupled acceleration. In such a scheme acceleration takes place immediately after extraction without prefocusing. If successful, such a system would be the simplest to construct.

An analysis of the beam performance in a single accelerating gap taking into account space charge shows that in principle it is possible to accelerate dense (up to 1 A/cm2) negative ion beams provided gradients of 60-70 kV/cm can be achieved across those gaps. 11

Figure 4 is a cross section of the experimental set-up. The accelerator consists of a \$\phi\$ 62 cm ceramic tube, a re-entrant structure, a multi-slit magnetron source, a multi-slit extractor and a multi-rod accelerator. Materials of the electrodes are either titanium or molybdenum. This unit is bolted onto a 1 m in diameter and 2 m long vacuum chamber, pumped either by two 5000 l/s oil diffusion pumps or by a 100,000 l/ s cryopump. Diagnostic equipment is mounted on movable platforms.

We operated the accelerator with a single slit magnetron in the configuration shown in Fig. 5. With a current density of 0.33 A/cm2 at the single emission slit beam currents in excess of 200 mA were accelerated to 120 kV across a 2 cm accelerating gap for 5 ms pulses, pulse length was limited by the source power supply. The column breakdown rate is five out of hundred pulses. The beam divergence perpendicular to the slits is about 6° , while the divergence in the direction of the slits is smaller than 0.5° . These results are very preliminary and we can expect significant improvements with more adequate shielding, improved electrode configurations and alignment, improved cleaning procedures, etc.

Initially the transport of the one ampere negative ion beam will take place by two pulsed quadrupoles, located as close as possible to the last electrode.

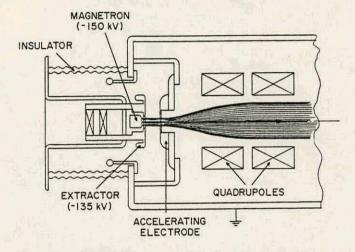


Fig. 4 Experimental set-up of a 150 kV negative ion accelerator.

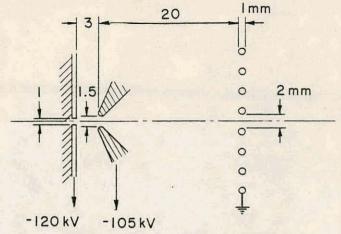


Fig. 5 Configuration of a single slit accelerator.

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TABLE I

	HDD	MAGNETRON	PENNING	
			Н2	D ₂
Extracted H Current	0.06 A	0.9(0.6) A	0.32 A	0.14 A
Energy	40 kV	20 kV	14 kV	14 kV
Total Current	1.2 A	~ 2 A	0.55 A	0.4 A
Pulse Length	1 ms	10(20) ms	4 ms	4 ms
Emittance (area χ βγ)	0.23mcm·mrad(40mA)		1.15mcm·mrad(0.24A)	
H Current Density	1.2 A/cm ²	0.7(0.47) A/cm ²	0.58 A/cm ²	0.25 A/cm ²
Arc Current	150 A	260(180) A	80 A	40 A
Arc Voltage	80 V	150 V	220 V	420 A
Cathode Area		13.5 cm ²	2 cm ²	2 cm ²
Cathode Current Density		20(14) A/cm ²	40 A/cm ²	20 A/cm ²
Arc Power Efficiency		0.03(0.02) A/kW	0.018 A/kW	0.008 A/kW
Gas Flow Rate		3.3 torre/s cm ²		
Gas Efficiency		0.2(0.13)As/torra		