Sixth Symposium on Engineering Problems of Fusion Research
November 18-21, 1975 San Diego, Calif.

BNL 20656
Conf-751125--87

AN INTENSE NEGATIVE HYDROGEN ION SOURCE FOR NEUTRAL INJECTION INTO TOKAMAKS*

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Summary

Development of high current sources of negative ions at Brookhaven National Laboratory is a part of the program to produce intense high energy beams of neutral atoms to be injected into Tokamaks. In this scheme negative ions are extracted from a plasma source, accelerated to the required energy and then neutralized by stripping in a gas, metal vapor or plasma jet. One of the most promising direct extraction sources is the magnetron source, operating in the mixed hydrogen-cesium mode. In the present source cathode current densities are up to 20 A/cm^2 at arc voltages between 100 V and 150 V. In order to utilize the discharge more efficiently multislit extraction geometry was adopted. Highest currents were obtained by using six slits, with a total extraction area of 1.35 cm^2. At an extraction voltage of 18 kV negative hydrogen ion currents close to 1 A were obtained, which corresponds to current densities of about 0.7 A/cm^2 at the extraction aperture. Pulse length was 10-20 ms and the repetition rate 0.1 Hz. The total extracted current was usually 2-3 times the H^- current.

Introduction

Three approaches are being pursued presently with the goal to produce intense high energy beams of neutral particles for injection into fusion devices. The approach chosen at BNL (Fig. 1, top) is based on direct extraction negative ion sources.[1] Negative ions are created on the cesium covered cathode surface under bombardment by fast positive and neutral particles diffusing out of a discharge in mutually perpendicular electric and magnetic fields. After extraction, ions are accelerated, using a close coupled geometry, to the required energy, focused and then neutralized by stripping in a diffuse medium (gas or metal vapors, plasma jet). The advantage of this scheme lies in its basic simplicity together with a high neutralization efficiency of 60-90%, which does not decrease with energy.[2] However, there are several problems to be solved before a 10 A, > 100 ms source unit will be developed, among them an efficient cathode temperature control and the improvement of a relatively high gas load.

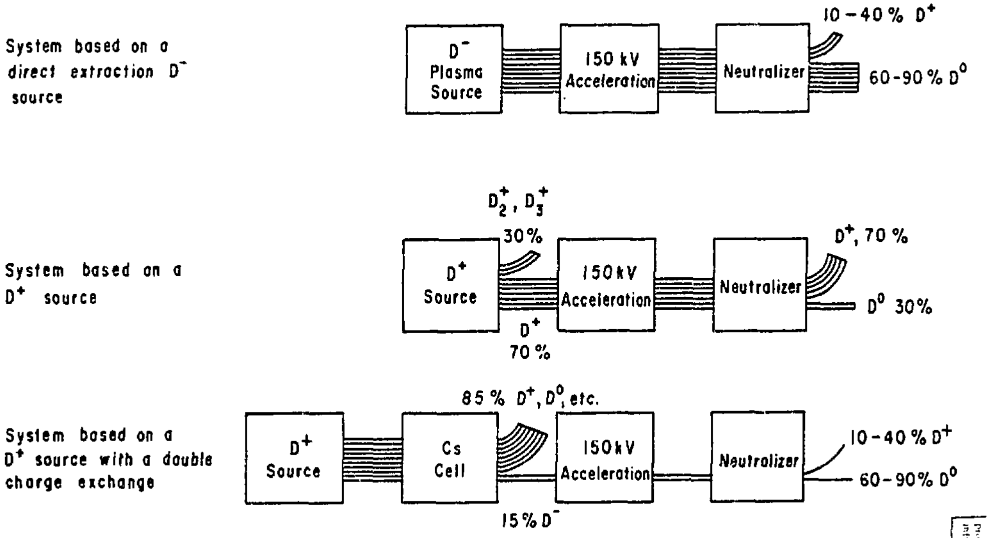

Fig. 1 Comparison of Systems for the Production of High Energy Neutral Beams

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

The other two schemes are based on positive ion sources. The more straightforward approach of these two is to accelerate positive ions to the required energy and then to neutralize them. The simplicity of this scheme is its main attractiveness, but already at energies of 100 keV or so the neutralization efficiency is lower than for negative ions and falls off sharply with energy. Recirculation schemes have been proposed in order to decrease the power loss, but at high beam currents the design of such a device is not trivial. The other approach uses a double charge exchange process at very low particle energies (≈ 1 keV); this would be performed in a cesium vapor curtain with an efficiency of at most 20% and possibly as low as 10%. Problems of handling high current low energy beams and of creating a sharply defined cesium curtain represent main disadvantages of this scheme, while a high neutralization efficiency is its advantage.

It is not clear yet which among these three approaches will ultimately be the most practical for the development of high energy neutral beams in single units with equivalent currents of the order of 10 A, with a pulse duration of 100 ms or longer, operating reliably with good power and gas efficiencies.

Magnetron Source

Several types of negative ion sources exist today, but the magnetron is presently the most intense and the most efficient among them. The discharge chamber of a magnetron has a ribbon shaped race track geometry (Fig. 2 and 3), with mutually perpendicular electric and magnetic fields (0.15-0.2 T). The distance between the cathode and the anode now used is 1 mm, but narrower gaps will be tried as well. The discharge is established in hydrogen gas fed via a pulsed valve, with a small addition of cesium vapors. A cavity in the cathode is filled with a 3:1 mixture of titanium powder and cesium bichromate; when heated to a temperature of 500°C cesium is released and diffuses through several capillary holes into the discharge chamber. The diffusion rate and, therefore, the density of cesium vapors is controlled by the pulse rate and pulse length of the arc. Independent methods of the diffusion rate control are under study. The gas pressure in the discharge chamber is of the order of 100μ, the density of cesium vapors in our source has not been determined but it should be of the order of 10^{13} cm^{-3}.[3] The arc power is supplied by a pulse forming network; units with pulse lengths of 10, 20 and 25 ms have been built. In the mode of operation yielding highest negative ion currents the voltage accross the discharge is between 100 and 150 V. Negative ions are created on the cesium covered cathode surface under bombardment by positive and neutral particles diffusing out of the plasma. There are several theories trying to explain these processes, but the basic requirement is the existence of a very thin layer of cesium on the surface. During the arc pulse the cathode temperature rises approximately with the square root of the time.

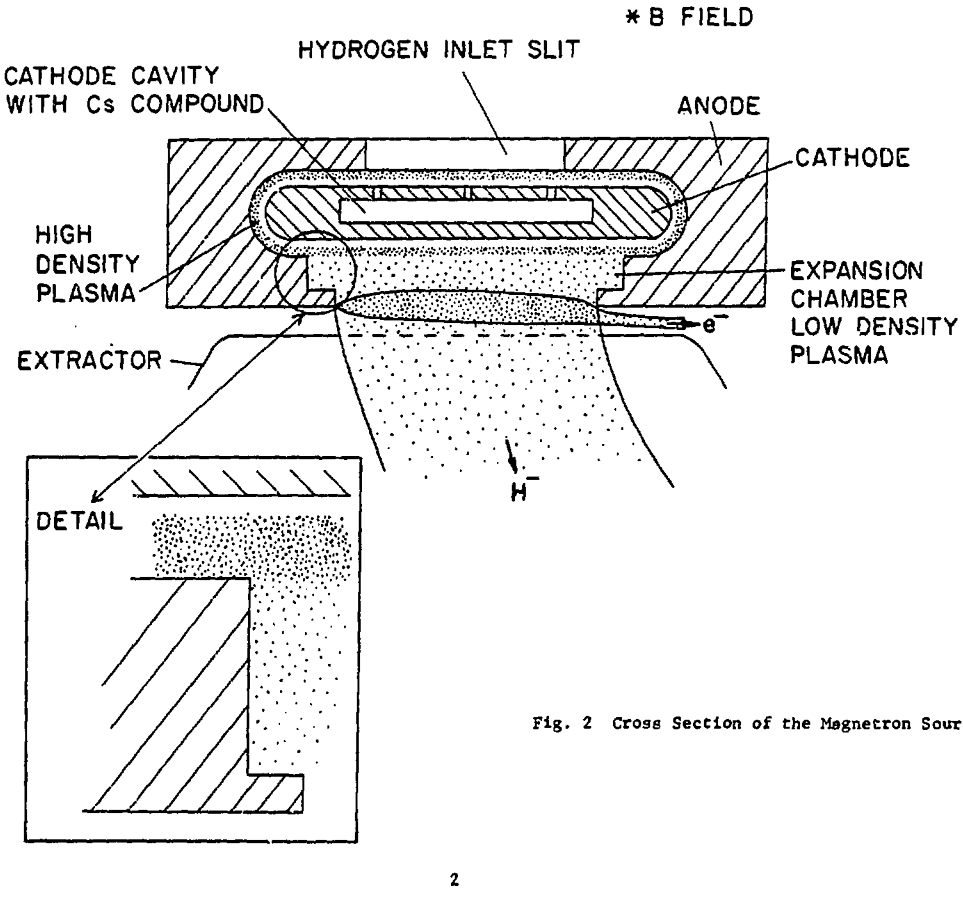

Fig. 2 Cross Section of the Magnetron Source

For a certain pulse length this determines the limit to the cathode current (or power) density[4] because otherwise the cesium layer would evaporate from the surface. It has been observed that the negative ion current density is in a wide range proportional to the cathode current density, so that the thermal load of the cathode will ultimately be the determining factor for the H^- yield. In the large BNL source, but without any cooling, this effect would limit the arc current to about 260 A (20 A/cm^2) for a 20 ms pulse, and to about 400 A (30 A/cm^2) for a 10 ms pulse. An efficient cooling of the cathode is required if either longer pulses or higher arc current densities or both are desired. Negative ions emitted from the cathode are accelerated by the cathode potential fall, pass through the dense plasma region and enter the anode expansion chamber opposite the extraction slits. Most of these primary, fast negative ions exchange charge with the background neutral atoms. Then, as thermalized ions, they diffuse due to the weak electric field toward the extraction slits, cut in the anode cover. The extraction voltage is applied to the extractor blades or wires mounted 2-2.5 mm from the source. The expansion chamber serves also to decrease the electron diffusion rate from the dense plasma, lowering in this way the electron component of the extractor current to a value comparable to the negative ion component.

The negative ion current was measured by a beam transformer, and the current density distributions in two directions by scanning the beam with two perpendicular slit Faraday cups.

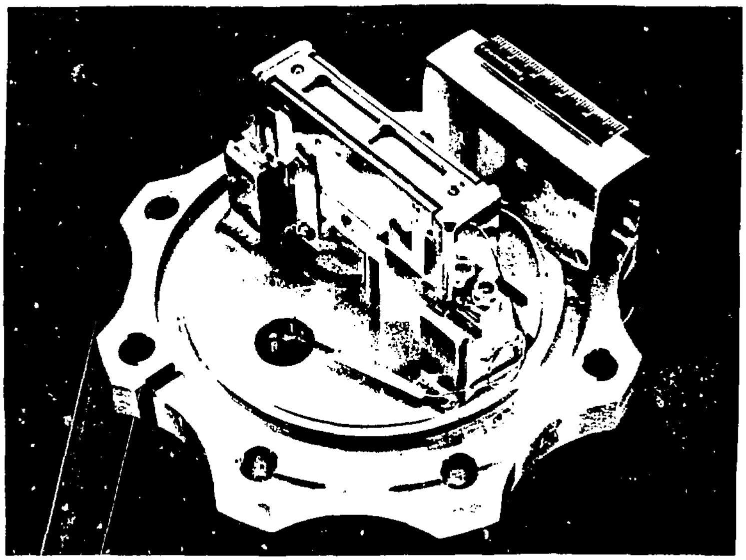

Fig. 3 Magnetron Source

Results

Two pulse forming networks have been used in present experiments with the magnetron source: 2.5 Ω,700 V, 20 ms and 1.25 Ω, 700 V, 10 ms. The higher impedance delay line was the limiting factor when the source was operated with 20 ms pulses; the maximum achievable arc current was 200 A, dropping to 160 A at the end of the pulse (Fig. 4, top trace). Arc currents up to 300 A at the beginning of the pulse have been obtained when the shorter delay line was used. With the new 0.4 Ω, 25 ms delay line it should be possible to reach arc currents up to 500 A.

A series of measurements was performed in order to determine the capabilities of this source. Usually the extracted H^- current and the total load of the H.V. power supply were measured as function of the extraction voltage, with the arc current as the parameter. The influence of the magnetic field and of the gas pressure was not studied in detail; both parameters were kept in the vicinity of the optimum, which generally was close to the lower limit of the stable operating range. Only the results obtained with six slit extraction aperture will be reported here. Extraction voltage was varied up to 18 kV; at higher values sparks often appeared between the extractor and the source cover. In addition to these parameters the cathode stem and anode block temperatures were monitored. It was found that the cathode stem temperature should be between 350° and 400°C for the best density of cesium vapors in the source, yielding highest H^- currents. The average temperature of the center cathode piece was probably ≈ 50°C higher.

The extracted negative ion current is an increasing function of the extraction voltage, the increase being caused by smaller space charge effects and by smaller losses in collisions of H^- ions with the molecules of the neutral gas streaming out of the source. Redistribution of the beam between the extractor and the downstream target may also have an effect on this behavior.

For arc currents below 200 A a saturation starts to appear at voltages above 15 kV, for higher arc currents no saturation was observed up to 18 kV. There is a rough proportionality between this optimum H⁻ current density and the arc current density

$$J_{H^-} \approx 0.03 J_{arc} \qquad (1)$$

The overall conversion efficiency of positive particles bombarding the surface of the cathode is therefore much lower than one could expect from the measurement of the secondary emission factor on cesium covered surfaces.[5] Following reasons can be mentioned for this difference: conditions of the cathode surface not at the optimum, losses of H⁻ ions in the plasma, losses of H⁻ ions in the neutral gas during and after the extraction. Figure 4 shows the extracted H⁻ current (center trace) and the total current load of the H.V. power supply (lower trace). Performance summary of the source is given in Table I; all parameters refer to a pulse length of 10 ms, but similar behavior can be expected with longer pulses.

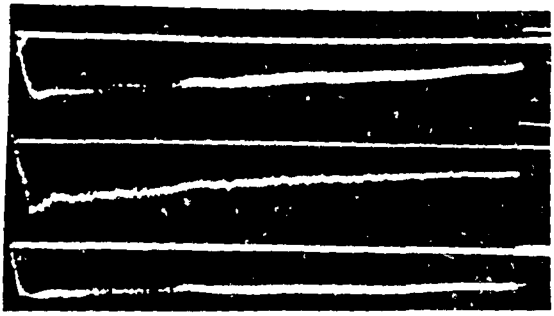

Fig. 4. Top trace: arc current, 200 A/division; center trace: extracted H⁻ current, 540 mA/division; bottom trace: total H.V. power supply load, 2 A/division; pulse length 20 ms.

Table I

Performance Summary of the BNL
High Intensity H⁻ Magnetron

Extracted H⁻ current	0.9 A
Pulse length	10-20 ms
Extracted H⁻ current density	0.7 A/cm²
Arc current	260 A
Cathode area	13.5 cm²
Cathode current density	20 A/cm²
Arc power efficiency	0.03 A/kW
Gas flow rate	3.3 torr ℓ/s cm²
Gas efficiency	5 torr ℓ/As

Density distributions have been measured with slit targets situated about 5 cm downstream from the extractor (Fig. 5 and Fig. 6). The divergence of the beam is very pronounced in both directions. This is due to space charge forces in the beam (H⁻ current densities at the extraction aperture up to 0.7 A/cm² at a relatively low voltage of 15-18 kV) and to the divergent lens effect of the extractor. However, measurements of beam emittances are planned for the near future and the results will show if it is possible to focus the beam into the required aperture. Preliminary results of the computer trajectory tracing indicate that by using a close coupled geometry for the acceleration of the beam it should be possible to obtain a high energy beam with a low divergency.

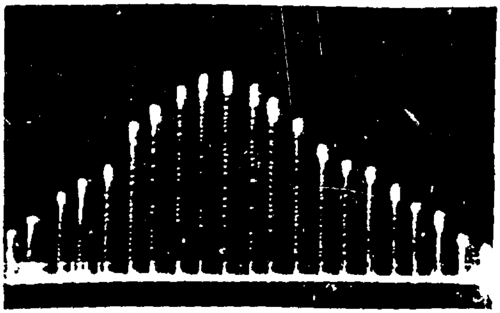

Fig. 5. H⁻ beam density distribution in the direction of the extraction slits, 4 cm downstream from the source; horizontal scale: 1 cm/division.

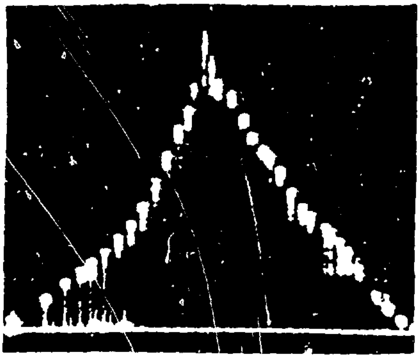

Fig. 6. H⁻ beam density distribution in the direction perpendicular to the extraction slits, 4 cm downstream from the source; horizontal scale: 1 cm/division.

Conclusions

Experiments with the present magnetron source have shown that it is possible to develop a source yielding negative hydrogen ion currents of the order of 1A, with pulse lengths of up to 20 ms. The gas flow, although appreciably higher than in positive ion sources, is still manageable. If an order of magnitude higher currents and longer pulses are required, simple scaling up of the present source would lead to very large units with a low gas efficiency. Improvements are possible, but the cathode surface temperature will have to be kept within the same limits as in the smaller 1 A source by an efficient cooling and the gas flow will have to be decreased by optimizing the design. The parameters of such a 10 A, 100 ms source should probably be as follows:

a. extracted current density at the extraction aperture 1 A/cm^2;
b. gas flow of 10-20 torr ℓ/s;
c. cathode current densities 20-30 A/cm^2;
d. close coupled acceleration of the beam to the required energy.

Acknowledgements

The work described in this paper was made possible by an excellent support and efforts of all members of the BNL Neutral Beam Development Group.

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