

A NEUTRAL-BEAM SYSTEM BASED ON BNL NEGATIVE-HYDROGEN-ION SOURCES*

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Introduction

Negative ion based neutral beam systems offer an attractive option for plasma heating and current drive. Compared to positive ion based systems, their main advantage is a very high neutralization efficiency of negative ions, which is almost constant up to energies of several MeV and will be between 60% and 100% depending on the choice of the stripping method. In spite of this promising feature, until recently there was still some skepticism among potential users whether negative ion based systems could be developed on time to be useful on fusion devices under construction or even on those in the planning stage.

During the past year or so, however, substantial progress has been achieved in the development of long pulse or steady state operating negative hydrogen ion sources. Simultaneously, possible needs for negative ion based systems have been considered and tentative parameters defined. For tokamaks there are two applications, plasma heating and current drive. The former would require a beam system operating in the range of energies 200-400 keV and delivering a power of about 10 MW in pulses of less than 1 minute duration. The same system could be used for current drive experiments on TFTR; should such an experiment demonstrate an efficient current drive, the next generation of tokamaks may include this feature, although the requirements would then call for a steady state operation and probably an energy around 1 MeV. For mirror machines, neutral beam energies would again be in the range of 200-400 keV, with a beam power of 5-10 MW per unit and operating steady state. In addition, any neutral beam system should satisfy certain criteria for the size, efficiency, cost and reliability.

Among the methods for negative hydrogen ion production, the most important being surface-plasma, double electron capture and volume production, it is the surface-plasma method that has been investigated and used most and that has shown the most promise. It is based on interactions between plasma particles (neutral and charged) and a low work function surface. BNL negative ion sources have a closed $\vec{E} \times \vec{B}$ loop magnetron geometry, with the plasma produced either in the gap itself (standard magnetron) or injected almost fully ionized from a separate hollow cathode discharge (HCD). Both types of BNL sources have achieved a true steady state operation over many hours. A high extracted beam current density (0.1-0.5 A/cm²) is one of their distinguishing features. The next element of any beam line, the accelerating stage, could be designed by using one of several

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possible approaches. In the energy range up to 400 keV or so, a conventional d.c. accelerator may be the simplest and most efficient way to achieve the required parameters. For energies of about 1 MeV and above, options based on rf acceleration of bunched beams (MEQALAC, RFQ) have to be considered. Neutralization of high energy negative ions may be performed in a gas stripper (efficiency < 60%), plasma stripper (~ 80%) or by photodetachment (up to 100%).

Parameters of the conceptual design of the BNL neutral beam system, described in this paper, were determined as follows: beam energy, 200 keV; negative ion current, 10A; neutral beam power, 1 MW; pulse length, multisecond to steady state. The completed system study, supported by successful ion source operation at the required level, will serve to evaluate and compare different approaches in the design of a negative ion based system and, eventually, lead to the design and construction of an operational system.

BNL System Concept

The design of the BNL neutral beam system depends on the selected ion source concept (standard magnetron or source with HCD plasma injection). Both options are still being retained so that basic parameters of both sources can be determined and then the final choice. Both sources operate with similar power efficiencies and should eventually deliver negative ion beams with similar properties. There is, however, an order of magnitude difference in gas efficiencies in favor of the source with plasma injection. A standard magnetron has a gas efficiency of 5-6% at best; a relatively high gas flow out of the source requires that an additional beam line element be included after the source to remove the accelerating gaps from the vicinity of the source. The beam line concept, that includes a standard magnetron source, would have then a beam bending magnet serving also for differential pumping of the gas from the source, a d.c. accelerator to raise the ion energy to the final 200 keV, a plasma neutralizer, and another dipole magnet to remove the remaining charged components from the beam, followed by an energy recovery system and/or an ion dump. The other option for a negative ion source, with plasma injection from an HCD, leads to a simpler design because there is no need for a separation between the source and the accelerator. Figure 1 shows such a beam line concept; at this stage of source and system studies, it seems that this concept will be preferable.

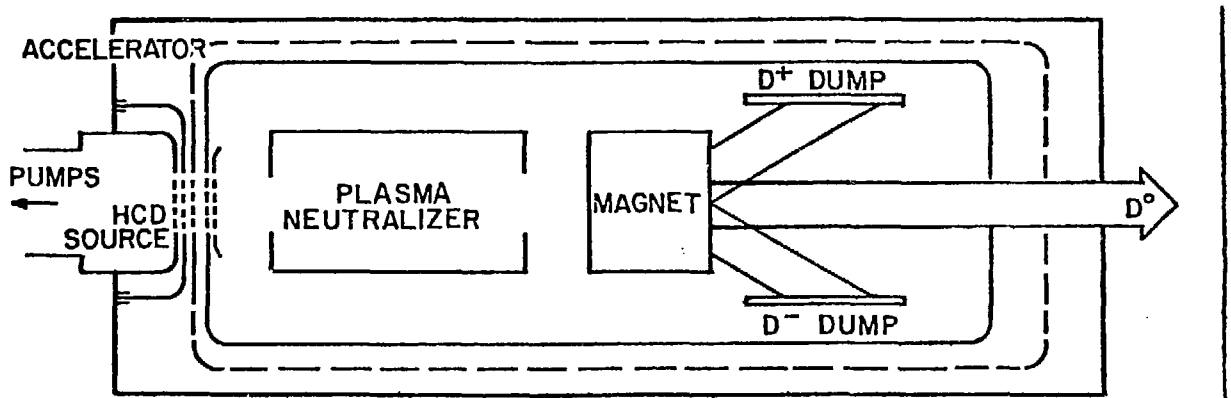


Figure 1 - BNL Beam Line Concept

Ion Source

Interactions between particles diffusing out of a plasma and an adjacent, low work function surface are the mechanism common to many negative ion sources.

Several approaches in the source design have been investigated at BNL and efforts are presently concentrated on the magnetron geometry, without and with plasma injection. Based on the performance of smaller models, without cooling and operating with short pulses (10 ms), a larger water cooled magnetron¹ of the standard design was fabricated and tested.² In such a source, the cathode serves a dual purpose: to maintain the discharge and as a converter surface for production of negative ions. In the steady state operation, the maximum input power was 7.5 kW (80% of the design value; limited by the power supply), with the longest run lasting about 77 hours. The production mechanism of H⁻ ions requires that the molybdenum cathode be covered with less than a monolayer of cesium in order to create a low work function surface. While this is easy to achieve in small, pulsed sources where electrode temperatures reach several hundred degrees C, in a water cooled source the surface temperature of electrodes is low and injected cesium tends to condense at the coolest spot. With only a part of the cathode covered with cesium, an H⁻ beam of 0.12A (0.06A/cm²) was extracted, with the source operating steady state and the extractor voltage pulsed. The cooling system is presently being modified to operate with water temperatures up to 200°C, which should be sufficient to establish a uniform cesium vapor density throughout the source volume.

In the second ion source approach, the basic magnetron geometry of the converter has been preserved, but the plasma is produced independently in one or more hollow cathodes. Position of the converter and its bias can be varied to optimize the production of negative ions.

Figure 2 shows a sketch of the source. Hydrogen gas is fed through the cathodes and is highly ionized when leaving the cathodes. The electron component of the current is confined by the magnetic field, while positive ions serve to neutralize the space charge. Part of the gas flow may be supplied through the anode in order to increase the plasma density. In an earlier feasibility test³ up to 100 A of steady state arc current has been obtained from a 3 mm diameter tantalum tube, at a background pressure of 10⁻³ Torr. Central plasma density was 10¹⁴ cm⁻³ and 1 A/cm² of positive ion current was collected on a negatively biased converter. The negative ion yield from the converter was estimated to be 0.3A/cm². The source

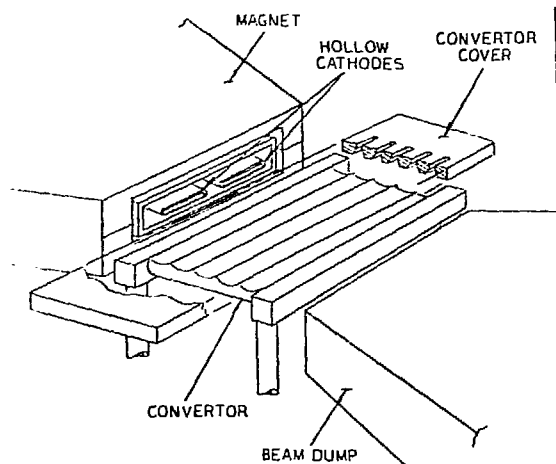


Figure 2 - HCD Source

shown in Figure 2 has been extensively studied, including the measurement of converter current characteristics. The two cathodes have inside dimensions of 15 mm x 0.75 mm and they have run at 75 A each. The operation is very stable and the arc current would change less than 10% over several days of continuous running. The source could not be tested with all parameters at full power simultaneously because of power supply limitations, but even at a reduced arc current of 50 A, the positive ion current reaching the converter was more than 8 A or about 0.3 A/cm². It has been shown that in a wide range of arc currents the converter current is proportional to the arc current;⁴ with a total arc current of about 150 A, the converter current density should approach 1 A/cm² which is more than sufficient for an extracted H⁻ current density of 0.5 A/cm² if geometrical focusing is used. Studies of H⁻ production and extraction have also begun, with the source (arc, converter) operating steady state and extraction voltage pulsed. With cesium injected from one edge of the converter and only a partial surface coverage, the extracted beam was about 0.5 A. Based on these preliminary results, it is expected that the yield at full power will reach 1 A of H⁻, with a gas efficiency between 30% and 50%.

Transport and Acceleration

Several years ago a pulsed 1 A beam from the standard magnetron source was accelerated to 130 kV in a single gap, close coupled geometry.⁵ Great difficulties were encountered in maintaining high voltage gradients in the presence of the gas streaming out of the source. This experiment has shown that, if the source has a low gas efficiency, it is necessary to separate the source from the accelerator. Experiments subsequently were done⁶ on the beam transport through a 90°, $n=1$ bending magnet, and it was possible to transfer through the magnet a 0.5 A pulsed beam with only 20% loss; the initial divergence of the 15 keV beam parallel to the slits remained 4° at the exit, while in the other direction it was reduced from 13° to 4°. The reduction in the divergence was accompanied by a substantial reduction in beam current density (from 0.5 A/cm² to 0.012 A/cm²).

If a steady state standard magnetron is the source of choice, the beam line will incorporate a bending magnet between the source and accelerator. Figure 3 shows such a system;⁷ it has been designed for a total transported current of 2 A. The $n=0.5$ bending magnet deflects the beam by 63.5° and transforms a rectangular beam cross section into a circular one, with a diameter of about 8 cm. The design value of the beam current density at the entrance and through the accelerator is 40 mA/cm². A three-gap structure has been chosen, with the last, decelerating gap to serve to prevent backstreaming of positive ions. If a reduction in the beam angle after acceleration proves to be necessary, a magnetic quadrupole focusing system could be placed downstream, before the neutralizer. To obtain the 10 A beam current, five such 2 A units will have to be stacked.

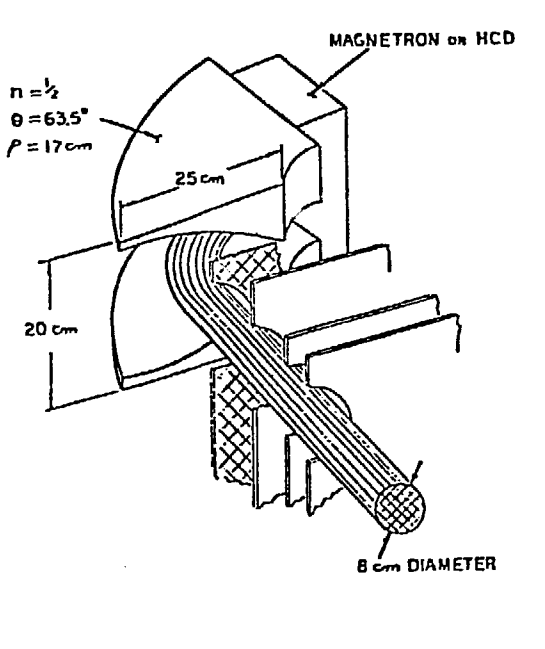


Fig. 3 - Detail of the Beam Line With a Bending Magnet

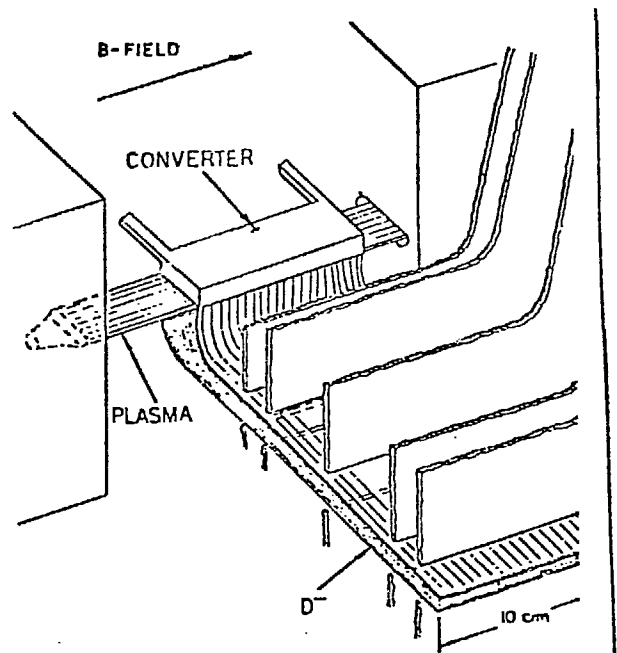


Fig. 4 - Detail of the Beam Line With an HCD Source and Close Coupled Acceleration.

The HCD source operates at pressures around 10^{-3} Torr and the gas flow should be reduced correspondingly. Close coupled accelerating structures become attractive again because the pressure even in the vicinity of the source should be less than 10^{-4} Torr. A modification of the basic design has been proposed,⁷ made possible by the fact that magnetic field and converter voltage can be independently adjusted. In this design, a flat converter would be used and negative ions transported over a 90° arc inside the source. This scheme has several advantages: the beam is focused into the extraction slit, impurity ions are removed from the beam, and the electron component of the beam is substantially

reduced because the slit is in the region of a low plasma density. Figure 4 shows a 2 A, 200 kV accelerator; a similar, three-gap structure has again been chosen. The sketch shows the source with the cover removed so that the orientation of the converter is visible. A 10 A beam current would require stacking of five such units.

A possible modification of an electrostatic accelerator would start with a large number of beamlets, transported first through separate channels consisting of electrostatic quadrupoles. This transport line would match the beamlets to an accelerating structure, where low gradient d.c. accelerating gaps would alternate with electrostatic quadrupoles. A 10 A system may consist of 200 beamlets (and separate channels), each with a current of 50 mA.

Any of the systems just described could be extended to provide even higher beam energies. However, electrostatic systems become impractical if beam energies around 1 MeV or higher are desired. MEQALAC and RFQ systems would have to be considered in this case.

Neutralizer

While photodetachment offers the neutralization efficiency approaching 100%, it is also true that it would require most development time. A simple deuterium cell has been proposed,⁸ with a total length of about 1.5 m, where most of the gas would be pumped away on cryopanel mounted inside the cell itself. A stripping efficiency of about 60% should be achievable.

High current tantalum hollow cathode discharges, developed as plasma generators for negative ion sources, may serve as plasma sources for neutralizers. It has been shown^{9,10} that the neutralization efficiency of a deuterium plasma may be higher than 80%, with a target thickness of about 10^{15}cm^{-2} . A concept has, therefore, been developed at BNL⁷ to utilize high density steady state HCD plasmas for this purpose. The concept is shown in Figure 5 and it consists of a longitudinal solenoidal field of the length determined by the required target thickness and the achievable plasma density. Plasma would be fed from a number of hollow cathodes along magnetic field lines. By differential pumping, the background pressure could be reduced below 10^{-4} Torr, so that there should be no excessive gas flow into the rest of the system. First experiments have been performed with a double cathode feeding the plasma from both ends into a solenoid and have shown that this is indeed possible. Plasma densities of between 10^{13} to 10^{14}cm^{-3} have been achieved with this type of cathodes,^{3,4} which leads to a neutralizer less than 1 m long. Although a deuterium plasma may be preferable, similar efficiencies can be achieved with other gases or vapors (argon, cesium), but with a lower gas flow and a reduced power requirement.

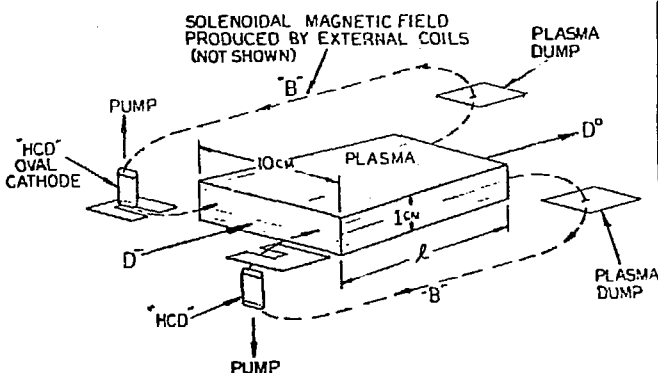


Figure 5 - BNL Concept of a plasma Neutralizer

System Parameters

Tentative parameters have been determined for a 10 A, 200 keV D- beam line.⁷ The option based on HCD sources has been selected, with five 2 A units stacked to deliver the required current. Table I summarizes the neutral beam

line parameters. HCD and converter parameters have been scaled up from measurements on the smaller models. If the final beam angle after acceleration is $\pm 1^\circ$, then the beam size at the injection port would be about 20 cm x 30 cm.

Table I
Tentative Parameters for a 10 A, 200 keV $D^- \rightarrow D^0$ Beam Line

<u>HCD Sources</u>	
Arc current (total), voltage	1000A, 50V
Converter current (total), voltage	100A, 100V
Pressure	10^{-3} Torr
Gas flow through the extractor	1 Torr ℓ/s
<u>Accelerator</u>	
Apertures	Five, 1 cm x 10 cm ea.
Current density	0.2 A/cm ²
Voltage gradient	< 60 kV/cm
<u>HCD Neutralizer</u>	
Neutralization efficiency	> 80%
Arc current (total), voltage	1000A, 30-50V
Plasma density	4×10^{13} cm ⁻³
Length	30 cm
<u>Overall Beam Line</u>	
Size	4m x 1.5m x 1.5m
Power density	> 0.1 MW/m ³
Beam power	1.2-1.5 MW
Neutral flux density	12 mA eq./cm ²

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