

**BNL NEUTRAL BEAM DEVELOPMENT GROUP
PROGRESS REPORT FY 1983
and
FINAL REPORT**

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BNL Neutral Beam Development Group

Progress Report FY 1983

and

Final Report

Summary

The BNL Neutral Beam Development Group has been active in the program for the development of high energy, high power neutral beam systems since 1973. These injectors are based on the production, acceleration and neutralization of negative hydrogen or deuterium ions and are supposed to be used for plasma heating and current drive in the next generation of fusion devices. Over the span of 10 years the group has studied plasma-surface type of negative hydrogen ion sources, transport and acceleration of negative ion beams and neutralization of negative ions in gases and plasmas. As the required source parameters (current, pulse length, efficiency) were changing over this period of time, the group developed several types of sources, resulting finally in the design of a steady state device operating with an excellent gas efficiency and having the possibility of scaling-up to the size necessary for a high power neutral beam system. The funding of this program was, however, terminated in FY 83 before the neutral beam performance of the source could be shown. This report will present a summary of the BNL effort over the past ten years, with most emphasis on achievements in FY 83, including the description of the 2 A steady state H^- or D^- ion source for use in a neutral beam line and of the plasma neutralizer capable to achieve neutralization efficiencies above 80%. List of publications will include those prepared after October 1, 1983 if they describe the work done by the staff of the group in FY 1983.

Introduction

The work on negative hydrogen ion sources began at Brookhaven National Laboratory in 1972 with a proposal to replace the existing proton injection into the Alternating Gradient Synchrotron with a more efficient H^- injection, via double electron stripping in a foil. Very soon afterwards it was realized that negative hydrogen ions could find an application in neutral beam lines for fusion devices and the first proposal to develop a source delivering 0.1 to 1 A, in 10 ms pulses, was approved by the Office for Magnetic Fusion Energy. Except at the very beginning of the program, when double electron capture was considered, all BNL ion source models have been based on surface production of negative hydrogen ions using cesiated molybdenum as the converter. Although the initial tests were performed on modified models of negative hydrogen ion sources developed in the USSR, very soon the BNL Neutral Beam Development Group has become a pioneer in the field of the surface-plasma sources in this country, developing and studying many different types, introducing new features into this approach and stimulating in this way the work in other laboratories.

The first negative hydrogen ion source studied at BNL was a hollow discharge duoplasmatron. When operating with hydrogen gas only, the maximum yield of the source was 9 mA. Subsequently, the source was modified by replacing the center rod with a tube to feed cesium vapors into the discharge and the yield increased to 60 mA (a patent was awarded for this modification); corresponding H^- extracted current density was 1.27 A/cm^2 . Energy analysis of H^- ions has shown that the large increase in the H^- yield was the result of surface production.

A small magnetron source, similar to the one developed in USSR, was next to be studied. This model was very simple, but also very fragile, with a single extraction slit. Several versions were subsequently developed, much sturdier

and with more than one extraction slit, which proved to be an important improvement for the total yield and power efficiency of the source. The maximum yield was 1 A of H^- ions, in 10 ms pulses, which was the objective of the first proposal to DOE. At about the same time electrode cooling studies were initiated because it was determined that any increase in the pulse length beyond 0.1 s would require a very efficient heat removal. Experimental studies resulted eventually in the removal of 0.5 kW/cm^2 by using nucleated boiling of water.

In 1974 a modification of the magnetron geometry was considered, eliminating the return path for the $E \times B$ discharge. A source based on this approach was designed but was not fabricated due to a limited funding. Four years later results of studies of a source with similar geometry (semi-planotron) were reported in USSR.

A performance similar to that of magnetron sources was achieved also with Penning Sources. The basic design, as developed in USSR, consisted of two cathodes and the anode; at BNL it was modified to include an independently biased converter placed opposite the extraction slits for an enhanced H^- production. This was a novel feature that led to the design of other sources using an independent plasma generation and production of negative ions on a separate converter (e.g. ORNL's SITEX source). A maximum H^- current of 0.44 A was obtained from slits with a total area of 1 cm^2 , in 3 ms pulses. As it is the case with the standard magnetron, long pulse or steady state operation at an extracted current density of $0.1\text{-}0.2 \text{ A/cm}^2$ requires a very efficient heat removal from source electrodes. A larger model of a steady state Penning source with converter was designed and fabricated, incorporating nucleated boiling of water as the method for heat removal. Discharge tests of this source have shown that major modifications would be necessary in order to assure a uniform coverage of cesium on the converter; this approach has not been pursued further.

A real breakthrough in the design of H^- sources was the introduction of geometrical focusing of surface produced negative ions and widening of the electrode gap in a magnetron source. In a pulsed mode of operation (10-25 ms), with 1 A of H^- ions extracted, the gas efficiency was improved from 2% to 6% and the power efficiency from 30 mA/kW to 125 mA/kW. Based on these very promising results, a larger magnetron source was designed, fabricated and tested. Although the design value of the extracted H^- current was 1 A, not more than 120 mA was achieved with the source operating steady state and pulsing the extraction voltage. The nonuniform cesium coverage on the cathode was the main reason for the unsatisfactory performance. The electrode cooling system was upgraded to operate at 150°C, which was felt to be high enough to maintain the proper cesium vapor pressure in the discharge chamber. However, the tests with this source were also discontinued.

Even with the best results for the gas efficiency of an improved magnetron source (6%), it was felt that the gas flow would still be prohibitively high in a steady state operation. The design of a new source began with the definition of an ideal source that would avoid as much as possible the drawbacks of the existing types of sources. The indirect method of plasma generation was selected offering a much higher gas efficiency because of the possibility for differential pumping; the best candidate appeared to be a hollow cathode discharge. Many experiments were done to determine the best shape of the cathode and the best configuration of the magnetic field and eventually a uniform plasma sheet was produced parallel to the surface of the converter. The other critical element of the source is the converter, with its partial cesium monolayer. For first tests a molybdenum converter was used and cesium injected into the discharge. Up to 0.5 A of H^- ions was extracted from a steady state operating source, with extractor voltage pulsed to reduce the power load. Several success-

ful experiments were performed to improve the way cesium is supplied onto the molybdenum converter surface; studies were also done to replace the molybdenum cesium system with other materials that would have a lower work function and therefore a better H^- production efficiency and a few very promising candidates were selected for experimental tests.

Two systems for beam transfer and matching to the accelerator have been studied theoretically and experimentally: a bending magnet with weak focusing characteristics and a strong focusing transport line consisting of electrostatic quadrupoles. This work, however, has not been pursued since FY 81. Earlier in the program close coupled accelerating structures have also been studied and more than 1 A of H^- ions was accelerated to 120 keV in 3 ms pulses. However, low gas efficiency of sources existing at that time made this approach impractical. Other accelerating structures were then considered and substantial effort devoted to the construction of a high energy, long pulse test stand, but this part of the program was terminated before the beginning of experimental studies.

For neutralization of high energy negative ions a CO_2 gas jet was considered first and an experimental model developed and tested (without H^- beam). Plasma neutralizers offer a much higher neutralization efficiency and a full length model was designed and fabricated, using two hollow cathodes as sources of plasma. Preliminary tests were done with MeV beams of light negative ions (Li^- , C^- , Si^-) and higher values of the neutralization efficiency compared to gas neutralizers confirmed. Experiments have not been finished because of lack of funding.

Table I shows chronologically the progress and achievements of the BNL program.

Table I

	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
Hollow discharge duoplasmatron	20 mA 1 ms (H ₂ ,Cs)			10 mA 1 ms (H ₂ ,Cs)							
Magnetrons without focusing	7 mA 0.3 ms	100 mA (1 slit) 150 mA (2 slits)	0.6 A 10 ms	0.9 A 10 ms							
Penning sources without/with converter				0.3 A 5 ms	0.44 A 3 ms	Design Fabrication	H ₂ +Cs discharge tests steady state Penning Source				
Magnetrons with focusing (pulsed)							0.6 A 25 ms 1 A 10 ms	0.3 A 0.2 s			
Magnetron with focusing (steady state)							Design Fabrication	0.12 A steady state			
Hollow cathode plasma injection (HCD)								H ⁻ production test	Design and fabrication	Plasma studies extraction tests 0.2-0.3 A, hours 0.5 A, minutes	
Acceleration					1 A 120 keV 3 ms	Design and construction of 250 keV facility					
Neutralizers					CO ₂ jet studies					Plasma neutralizer (Li ⁻ ,C ⁻ ,Si ⁻)	

BNL Approach

Although the details of the BNL approach in the design of a high energy neutral beam system have been changing over the years, in principle the ion source would be of the plasma-surface type and the neutralization would be done in a plasma. The design of both elements is flexible and could be adapted to any of the proposed acceleration methods.

The requirements as stated most recently in the National Negative-Ion-Based Neutral Beam Development Plan call for a steady state operating source, with a linear H^- current density of 8 A/m (6 A/m for D^-), and a gas efficiency comparable to that of positive ion sources (better than 20%). Power efficiency of ion sources for use in high energy neutral beam systems is less important than some other considerations (gas efficiency, purity of the beam, long term reliability). The selected approach is based on hollow cathode plasma generation, using refractory metals as cathodes (a patent was awarded for this source); they have excellent long term properties (several weeks of continuous operation should be possible) and deliver a highly ionized plasma with a density sufficient to reach the required linear H^- or D^- current density. The other element, converter of positive ions into negative, would be a porous molybdenum plate with hot liquid cesium diffusing through it; this method has a substantial advantage compared to the deposition from the discharge, which is the method used in other sources of the plasma-surface type. Converter surface would have a curvature to focus negative ions produced on the converter into a slit after a 90° bend in the source magnetic field; the latter feature would practically eliminate the electron and heavy negative ion components in the extracted beam. The size of the source and mounting elements should match the LBL high energy electrostatic accelerator (TFF).

The performance and advantages of plasma neutralizers have been proved in small cross section, full length experiments. The BNL approach is a plasma neutralizer, where several hollow cathodes would produce the plasma with the required target cross section, thickness and ionization degree. The expected neutralization efficiency is between 80% and 85%, achieved with substantially lower power than required for laser neutralizers.

Project Goals for FY 1983

Studies of steady state negative hydrogen ion sources would continue with the objective of designing a unit delivering 2 A of beam current, at a linear current density of 8 A/m, to match the LBL accelerator. The magnetic field necessary for hollow cathode operation would be produced by one or more sets of yin-yang coils to create a thin plasma sheet in front of the curved converter. Converter would consist of a large porous molybdenum plate, with liquid cesium fed from the back. Design studies of a plasma neutralizer would continue, with the objective to determine the parameters of a unit to match the LBL accelerator.

Progress in FY 1983

Highlights

1. In January 1983 the group was informed by DOE that the program at BNL would be terminated as of September 30, 1983. This decision has affected the work in progress and future plans because the staff had to be transferred gradually to other projects in the Acceleration Department.
2. By using electrostatic probes plasma density distributions in front of the converter were studied and a geometry determined to produce a uniform plasma sheet.
3. A compound hollow cathode material was tested showing a five times lower sputtering rate than tantalum, which should extend the lifetime by a factor of 5.

4. Several ways of injecting cesium into the discharge were tried and although none was fully satisfactory, stable operation with 0.2-0.3 A of H^- ion currents was achieved over several hours.

5. Studies of available work function data have resulted in selection of several materials with values around 1 eV for further studies, in the temperature range of interest for BNL sources ($< 500^\circ C$).

6. Several contacts were made with representatives of LBL to determine requirements and design parameters of the hollow cathode discharge H^- source to be mounted on the LBL accelerator.

7. Operation of hollow cathodes with carbon compounds was achieved, with the objective of studying production of C^- ions for fusion and other applications.

8. A plasma neutralizer was designed, fabricated and preliminary neutralization studies done with MeV heavy negative ions.

9. As a tradition at BNL, the Third International Symposium on the Production and Neutralization of Negative Ions and Beams has been organized to be held in November 1984. Compared to the two previous symposia in this series, the attendance is higher by 30% and the number of presented papers higher by 50%, showing a strong and growing interest in this country and abroad.

Hollow Cathode Discharge Experiments

Plasmas for several cathode geometries and magnetic field configurations were studied by using five electrostatic probes for plasma density measurements in all three directions. Figure 1 shows a distribution in a plane parallel to the converter, with the horizontal axis corresponding to the slit direction. Two very broad peaks can be distinguished, approximately in line with the two hollow cathodes. The asymmetry is probably due to the secondary ionization of background gas by electrons drifting around the converter. The region of

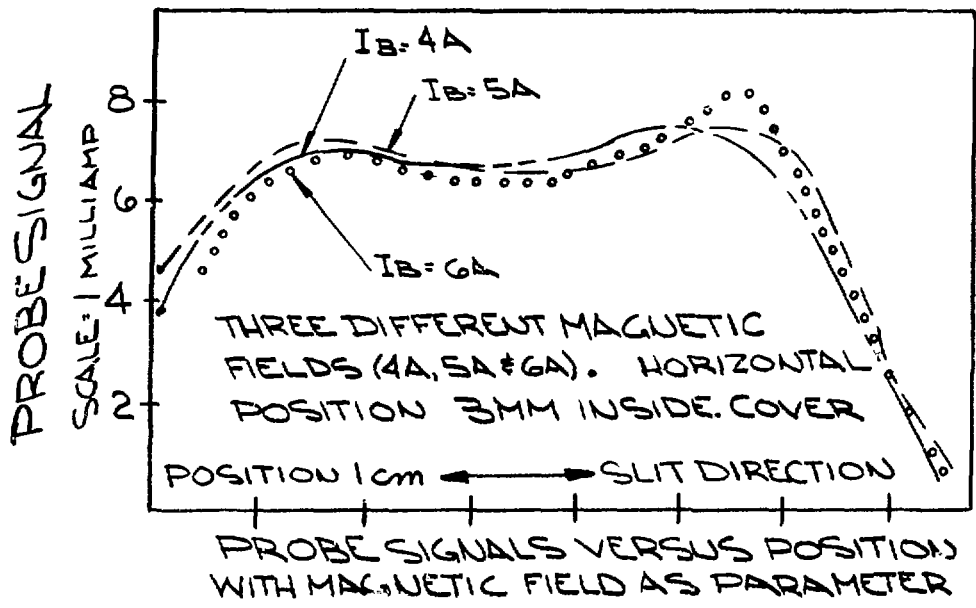


Figure 1. Plasma density distribution in the HCD source.

uniform plasma density ($\pm 10\%$) covers a converter area of 5 cm x 5 cm, which is the design parameter of the source. Figure 2 shows the chart of the hollow cathode currents recorded over $2\frac{1}{2}$ days of continuous running; the longest run was about $3\frac{1}{2}$ days (most of the time without supervision) and was terminated by factors not related to the cathode itself. Figure 3 shows the extracted H^- current over a period of more than 1 hour. In this test the plasma generator and converter (elements for surface production of negative ions) were running steady state, while the electrostatic field outside the source was pulsed because there was no cooling of the extractor electrode. The chart shows a stable production and extraction of H^- ions with a total current of 0.2 A, corresponding to a current density of 40 mA/cm^2 . Runs of similar stability were

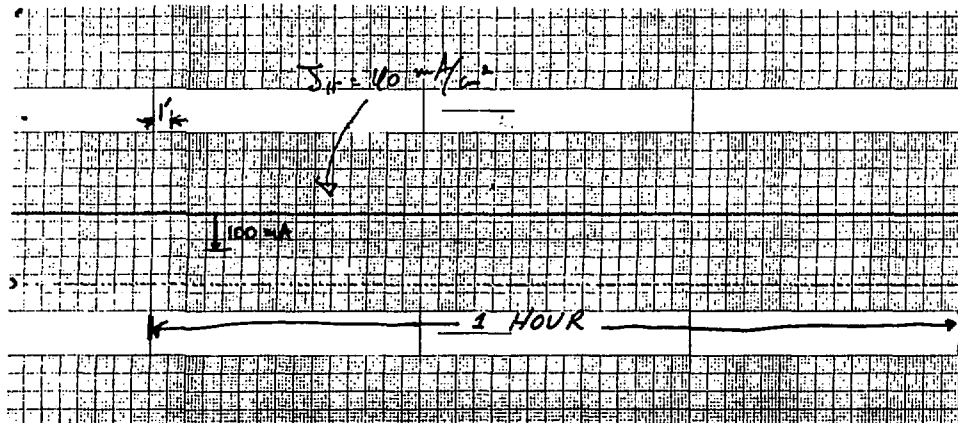


Figure 3. Chart recording of the extracted H^- current from the HCD source.

molybdenum converter was fabricated and installed in the source but due to a crack it could not be tested. Further tests were not performed, but should results similar to small scale structures be obtained, the yield of negative ions in the existing source would increase to 1 A. This expectation agrees very well with the LBL multicusp source results, where the same primary converter current of about 10 A yielded more than 1 A of H^- ions. It is to be noted that 0.3 A already achieved corresponds to a linear current density of 6 A/m, while 1 A of total current corresponds to 20 A/m which is more than required.

Plasma Neutralizer Experiments

Requirements for the plasma in a neutralizer are somewhat different from those in a negative ion source: in the former a certain density should be maintained in a cross section equal to or larger than the beam size with as lit-

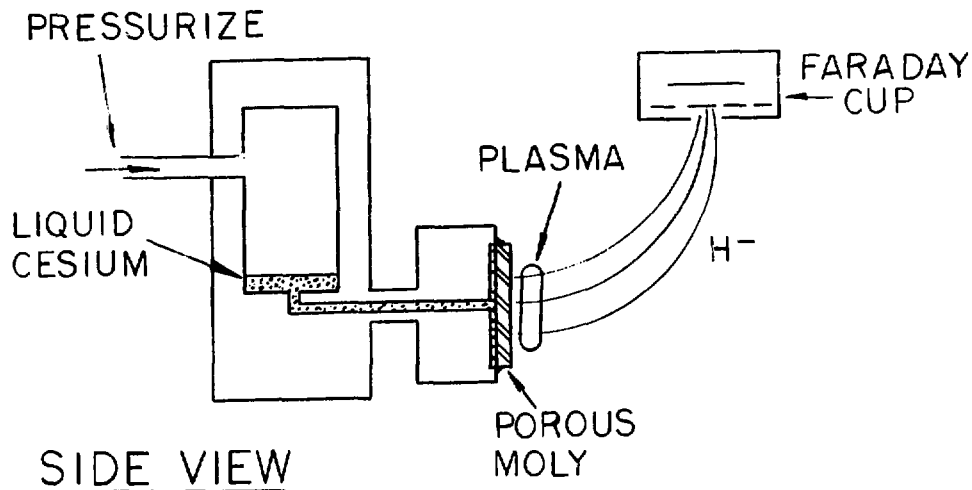


Figure 4. Experiment to compare the H^- yield for different methods of cesium supply.

the loss as possible, while in the latter a thin plasma sheet is desirable with a constant current flowing to the converter (ions) and the anode (electrons). For neutralization efficiency studies, using Tandem Van de Graaff beams, a circular plasma cross section was the most favorable and a 1 m long neutralizer was designed and fabricated (Fig. 5). A steady state plasma is generated by two cylindrical tantalum hollow cathodes and confined by a solenoid field of 200 G. By using differential pumping the background pressure was maintained below 10^{-4} torr, which with achieved values of plasma density would correspond to an ionization degree of about 50%. Theoretical studies have shown that further improvements in the ionization degree would contribute little to the neutralization

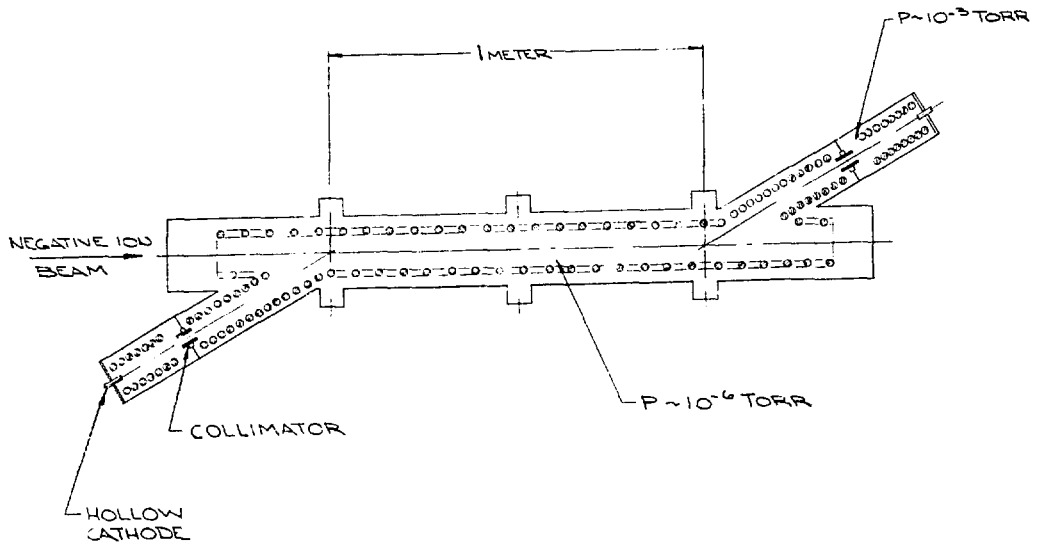


Figure 5. Plasma neutralizer for light negative ions.

efficiency. The target thickness of the neutralizer was sufficient to approach the optimum neutralization of H^- beams of several hundred keV energy (> 80%). The neutralizer was tested with 3 MeV Si^- , C^- and Li^- beams and in spite of an imperfect alignment substantially higher neutralization efficiencies were achieved than with gas neutralizers, which is in agreement with published results for H^- neutralization studies.

Plans for FY 1984 and Beyond

Work on parts of the program may continue should funding become available from other sources than the Office for Magnetic Fusion Energy. In particular, the following areas would merit further studies:

1. development of low work function converter surfaces that would be uniform and stable over the same period of time as already achieved with hollow cathodes for plasma generation (days instead of hours); porous molybdenum and

tungsten with liquid cesium feed would be used in the first phase of experiments;

2. development of more efficient converter surfaces that would require a lower primary ion current and, therefore, less power for the discharge; for some complex surfaces work function values around 1 eV have been reported and converters using such complex surfaces would be built and tested;

3. development of an H^- or D^- ion source for continuous operation (a week or longer) requiring very few adjustments over this period of time, with improved power and gas efficiencies;

4. development of light negative ion sources (Li^- , C^- , O^- , Si^-) based on surface conversion, for fusion or other applications; and

5. modification of the existing plasma neutralizer for accurate measurements of neutralization efficiencies as function of ion energy and target thickness and of relevant cross section values.

Final Comments

Over the past ten years the BNL Neutral Beam Development Group has always been in the forefront of the program for the development of negative ion based neutral beam systems, a program with requirements surpassing in many aspects those for existing positive ion based systems and calling very often for an advance in the state-of-the-art. In the design of negative ion sources several different types have been developed and studied, in accordance with the requirements changing over this period of time, and resulting finally in the proof-of-principle of a novel approach, hollow cathode discharge source. Acceleration part of the program was terminated after the pulsed operation had been achieved and neutralizer studies were supported only partially. In our opinion, the negative ion development program as a whole and the BNL program in particular have suffered from the lack of support and guidelines from the users community, which

was reflected in frequent changes in the objectives, and from serious underfunding, which was reflected in year-to-year uncertainties about the funding level and in painful decisions about eliminations of parts of the program. Another consequence of inadequate funding was the tendency of participants in the program to work for the best showing at so called "shoot-outs," which very often resulted in unfulfilled promises and in less than optimum use of limited funds. For the BNL group, the termination of the program has come at a stage in the source development when the principle has been proved and all the elements tested for the design of a very efficient and reliable steady state operating source. It is regrettable that this program was not allowed to continue until the final performance of the hollow cathode discharge source as well as of a plasma neutralizer could be shown in a neutral beam line.

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Ady Hershcovitch
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September 27, 1983

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K. Prelec
November 7, 1983