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NEUTRAL-BEAM DEVELOPMENT PLAN

FY 1982 - 1987

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**NEUTRAL BEAM DEVELOPMENT GROUP
ACCELERATOR DEPARTMENT**

**BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.**

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Foreword

The BNL Neutral Beam Development Group has reached the stage of operating steady state negative ion plasma sources with the capability of extracting high density negative ion beams. With the need in the near future for negative ion based neutral beams in the energy range of several hundred kiloelectron-volts and at the multi-ampere level for injection into advanced mirror systems and tokamaks, the Brookhaven National Laboratory Neutral Beam Group is ready to extend in FY 82 their source program with the exploration of dc negative ion acceleration, in order to achieve by FY 87 the goal of demonstrating the operation of a 200 kV/5A neutral beam injector system. This goal is paramount to the program structure proposed by BNL and includes phased participation by industry in selected tasks.

The administration of Brookhaven National Laboratory and the BNL Neutral Beam Development Group are fully committed to the success of the program described in this document. BNL has constructed from general project funds a building dedicated to high energy neutral beam development. In addition, BNL intends to supply a 2 MW substation, which will provide adequate power for initial dc acceleration tests.

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I. Introduction

The BNL high energy neutral beam group is developing injector systems for the next generation of fusion mirror and Tokamak experiments. These injectors are based on the acceleration of negative deuterium ions, to improve neutralization efficiency which is nearly independent of energy above 75 keV/nucleon.

In 1974, Brookhaven National Laboratory took the initiative to develop direct extraction negative ion sources for fusion applications, stimulated by the early success and promising aspects of surface plasma sources for high energy accelerators.

Initially the program was aimed to reach the 1A beam current level at low energies, which was achieved in 1976 from a Mark III magnetron source for beam pulses of 10 ms. Shortly thereafter, in 1977, this short pulsed beam was accelerated to 120 kV in a close coupled, high gradient accelerating column.

Since 1977, the emphasis of the source program has shifted from high beam current to long beam pulses, improved power efficiency and improved gas efficiency. In 1979, a larger but still not cooled model of the magnetron (Mark IV) reached a pulse length of 100 ms, and the power required to produce 1A negative ions was reduced from 33 kW to 8 kW by the introduction of the asymmetric magnetron with grooved cathode. Also, the gas efficiency was thereby improved by a factor of 2 to 3. During 1980, these developments formed the basis for the design and fabrication of a steady state, water cooled magnetron source (Mark V), which is now operating, indeed, in the dc mode.

In 1980 we started to investigate a modification of the magnetron, which might have a significant impact on some of the operating characteristics of our present high current density negative ion sources, in particular, on their gas efficiency. This modification consists of the separation of the plasma production from the negative ion converter by using a hollow cathode discharge as the plasma source. This discharge has a very high ionization efficiency ($> 90\%$) and high plasma density ($n = 10^{13} - 10^{14}/\text{cm}^3$). After some successful initial tests, a steady state experimental test source was brought into operation (typically 10^{-3} Torr vs. 10^{-1} Torr) in the unmodified magnetron. It appears that magnetrons with this type of plasma injection are a viable and attractive option for multiampere neutral beam injectors.

The acceleration program has made limited progress since 1977 due to limited funding. We have studied beam transport in a 90° bending magnet, transport of the beam through small electrostatic quadrupoles, and partially constructed a 200 kV accelerator test facility. The studies have demonstrated the feasibility to transport, focus and space charge neutralize negative ion beams emerging from magnetron sources.

The present status of our steady state sources justifies and necessitates an immediate start of a vigorous acceleration and neutralization program at BNL if the goal of demonstrating 200 kV/5A injector system operation by 1987 is to be achieved. The general approach is to prove at first the operation of a 2A, 200 keV dc negative ion accelerator and neutralizer, to be followed by the construction and testing of a 1 MW (200 keV/5A) injector.

Since negative ion based neutral beam systems are expected to emerge as a generic fusion technology, it is felt to be in the interest of the national program to stimulate early industry participation in such an effort. Therefore,

initial participation by industry in design and development of a Proof-Of-Principle accelerator (P.O.P.) would be highly desirable so as to gain early experience in dealing with the complexities of large injectors for fusion reactors.

Grumman Aerospace Corporation (G.A.C.) has expressed just such an interest. Their experience and expertise in fusion energy technologies, their assistance in our program management, their close vicinity to BNL, all provide the basis for a joint effort toward the realization of a first neutral beam injector based on negative ion sources.

It is the plan of the Neutral Beam Development Group to involve G.A.C. in three areas where mutual benefits would be realized:

1. Overall program management
2. Accelerator facility integration
3. Accelerator development participation

By subsequent participation by Grumman in the development of the entire injector system, the following benefits will accrue to DOE:

- Cost/schedule optimization by industry management with substantial relevant experience
- Fostering of timely industry responsiveness to future DOE needs for generic technology
- Quick access to a broad spectrum of technical capabilities due to Grumman's physical proximity to BNL, resulting in cost savings for the program.

Our plan is presented in detail in the following chapters.

II. Status of BNL Negative Hydrogen Ion Source Development

BNL negative hydrogen ion sources belong to the group of devices in which negative ions are produced by interaction between particles originating in a plasma and a low work function surface placed in the plasma. The energy spectrum of negative ions reaching the field of the extraction electrode is wide and reflects different mechanisms of production, including the charge exchange process between fast primary negative ions and slow atoms in the plasma volume.

Until late 1979, BNL sources were of the standard design, without electrode cooling. A relatively low power efficiency (about 30 kW/A) and the desire for an H^- current density of 0.5 A/cm^2 in the source extraction slits limited the pulse length to several tens of milliseconds, with intervals of the order of 10s between pulses to cool the source by conduction and radiation. H^- currents of up to 1 A were obtained in 10 ms pulses; the cathode current density was 20 A/cm^2 . A common drawback of all source models of this type has been a poor gas efficiency, not exceeding 2-3%. Still, at that time this was the state-of-the-art in the source design, and cooling methods using nucleated boiling techniques were contemplated for models operating with long pulses ($> 0.5\text{s}$) or steady state.

In late 1979 there was a breakthrough in the design of magnetron sources. First, geometrical focusing of negative ions formed on the cathode was tried on a small magnetron source and a substantial improvement in the performance observed due to a much wider cathode collecting area for the same slit width.

The second change in the design was the widening of the back side of the race-track discharge gap; these two new features resulted in an improvement in the power and gas efficiencies by about a factor of 3 (to less than 10 kW/A and up to 6 percent, respectively) and in the reduction of the required cathode current density (and, therefore, in the cathode power density) by an order of magnitude. As a consequence, electrode cooling requirements for a long pulse or steady state operating source could be relaxed and simple water flow cooling should suffice. Even BNL magnetron sources without cooling, modified in this way, have reached a pulse length of 0.1s, at a current density of 0.5 A/cm² (Table II-1). Another interesting and important fact was also observed: at cathode current densities of 1-2 A/cm², which are sufficient for H⁻ current densities of 0.5 to 1 A/cm², there was no isotope effect.

Table II-1

Performance of BNL Magnetron Sources

	<u>Mk III</u>	<u>Mk IV</u>	<u>Mk V</u>	
			<u>Design</u>	<u>Preliminary</u>
	(1978)	(1979)	(1980)	Tests
				(1981)
H ⁻ Current (A)	0.6	0.5	1	---
V _{extr} (kV)	15	10	> 10	15
H ⁻ Current Density (A/cm ²)	2.2	0.5	0.5	---
Pulse Length (s)	0.01	0.1	D.C.	D.C., 150 hrs. total
Cathode Surface Area (cm ²)	12.5	38	60	60
Cathode Current Density (A/cm ²)	3.6	2.1	1	0.5 achieved
Cathode Power Density (kW/cm ²)	0.45	0.25	0.1-0.2	0.1 achieved
Power Efficiency (kW/A)	9	28	10	---
Gas Efficiency (%)	6	---	6	---
Pumping Factor	15.7	---	15.7	---

These encouraging results from tests of sources without cooling have warranted the design of a large magnetron with a cathode surface area of 60 cm^2 , incorporating the cooling of all electrodes and capable of nominally delivering 1 A of negative ion current in a steady state mode of operation. Fig. II-1 shows the cross section of this source (Mk V); cooling channels are visible in the cathode, anode and the extraction grid. In the first fabricated model, tested during the past year, the grid was not cooled, so the extraction voltage had to be pulsed, while the discharge ran steady state. Due to power supply limitations, the source was tested only up to 75 percent of the designed input power (7 kW instead of 9 kW); it operated for a total of 120 hours steady state, both in hydrogen and hydrogen-cesium modes (see Table II-1). During this test period only minor changes had to be made in the source geometry to improve the uniformity of the discharge and reliability of operation. Several ways of supplying cesium have been tried, and while it was possible to establish and maintain a cesium mode discharge for many hours, they are still not yet ideal. The fact that all the walls have to be cooled is a new complication compared to pulsed sources, usually operating at temperatures of several hundred degrees C. In a cooled source, cesium has the tendency to condense in the coldest place, where it may cause a short circuit. On the other hand, loss of cesium from the source should be substantially reduced if all the walls are kept cool. Preliminary extraction tests done at reduced power levels have yielded an H^- current of more than 20 mA. These tests have clearly demonstrated the feasibility of the extraction of high density steady state H^- beams from BNL magnetrons.

Even with those improvements in the design of standard magnetron sources (where a discharge is established by applying a voltage between the cathode and the anode) the gas efficiency is still low due to the low ionization degree of

Fig. II-1 Cross section of the Mk V Magnetron

Fig. II-2 Sketch of the HCD experiment

the gas in the discharge. An experiment has been performed to test the feasibility of plasma injection into a negative ion source. A hollow cathode discharge was used as a plasma source, delivering a cylindrical plasma column along the magnetic field lines, with central plasma densities of up to 10^{14} cm^{-3} . The background pressure (10^{-4} to 10^{-5} Torr) was substantially lower than in our standard ion sources, indicating a high ionization degree. When a negatively biased flat converter electrode was inserted into the plasma column, a current density of about 1 A/cm^2 was measured. Coating of the converter surface with cesium resulted in an increase of the converter current density to 2.7 A/cm^2 , while at the same time a negative current was detected flowing into a properly placed collector electrode, resulting from at least 0.3 A/cm^2 of negative ions leaving the cesiated converter surface. A larger experiment was then designed to test not only the production, but the extraction of negative ions as well from a structure with magnetron geometry. Two flat hollow cathodes supply a plasma current of 100 A, in the shape of a sheet with a cross section of about $1 \times 5 \text{ cm}$, while a biased converter electrode with an area of $5 \times 5 \text{ cm}$ and a race-track shape can draw up to 25 A of primary ion current (Fig. II-2). All the critical electrodes are water cooled, allowing a steady state operation. As it was the case with the Mk V magnetron source, the extractor grid is not cooled and will operate in the pulsed mode. First tests of cathode ignition have shown that it is possible to operate two flat cathodes in parallel, at pressures of the order of 10^{-4} Torr.

Operating parameters of a structure with plasma injection from hollow cathodes makes the design of a single large source, operating steady state and with a gas efficiency improved by an order of magnitude (up to 50 percent), feasible. However, a comparison of all beam parameters will be necessary before making the choice between a standard magnetron and a magnetron with plasma injection.

III. Source Development Program

The objective of the source development program is to take 1 A H⁻ ion sources from initial tests of the steady state mode of operation, performed in FY 81, to the fabrication of 10 A units and their tests in a neutral beam system (Table III-1). The 10 A unit could be a single source or a stack of several identical smaller sources. As an intermediate step toward the final, 10 A unit, a single 2.5 A model will be designed and tested in the 200 kV Proof-Of-Principle neutral beam system.

Although initial tests of standard magnetrons, as well as of magnetrons with plasma injection, have shown that it is feasible to design a steady state H⁻ source based on either concept, studies of the existing devices (Mk V, injection of α plasma from hollow cathodes) will continue during FY 82. Evaluation studies will include:

- A. Operation of both structures at full power, which has not previously been possible because of power supply limitations.
- B. Selection of methods of cesium vapor injection and density control (direct injection, porous wall transpiration, modifications in the electrode design to prevent condensation, possible recirculation). Related to this is the development of low work function surfaces, that do not require a continuous feed of cesium vapors (in cooperation with BNL Chemistry Department).
- C. Measurements of extracted beam properties (current density, emittance).
- D. Optimization of the extraction grid shape (pulsed mode of grid operation).
- E. Operation of the grid in the steady state, requiring the fabrication of water cooled structures.

Table III-1

10 A Source Development Program

TASKS	FISCAL YEAR				
	1982	1983	1984	1985	1986
Evaluation of 1A Sources	xxxxxxxx				
Design and Fabrication of 2.5 A Source		xxxxxxxxxxx			
Tests of 2.5 A Source		xxxxxxxxxxx			
Design and Fabrication of 10 A Source			xxxxxxxxxxx		
Tests of 10 A Source				xxxxxxx	

It is expected that by April 1, 1982 enough information will be available to begin the design of peripheral parts of the 2.5 A source (mounting structures, magnet, cooling system, targets) common to either of the two possible concepts. Toward the end of FY 82, the concept of the 2.5 A source will be selected, design finished, and early in FY 83 this source fabricated so that studies may begin in the second half of the fiscal year. It is also anticipated that in the first half of FY 83 a 1 A steady state source will be fabricated, similar to one of the existing designs, but incorporating possible changes and improvements. This source will serve for initial tests of the 200 kV, Proof-Of-Principle accelerator. As a low priority part of the program,

depending on available funding and manpower, studies of the other concept at the 2.5A level may also continue.

Design of the 10 A source unit will begin early in FY 84. The decision on whether to proceed with a single source option or with the stack of several smaller sources will depend on the performance of the 2.5 A unit as well as on considerations for a good match to the accelerator structure. Fabrication of the 10 A unit should be finished by the end of FY 84 and tests of the source itself done in the first half of FY 85. Beyond that time, sources will be tested as part of the whole neutral beam system.

While source units with H⁻ beams up to 2.5 A can be operated on the existing source test facility (with minor modifications only), the 10 A source unit will require a new extractor power supply (25 kV, 15 A, steady state), a cooling capacity of 500 kW, a vacuum enclosure to be attached to the existing vacuum box, and a pumping system with a higher pumping speed.

IV. Status of Beam Transport and Acceleration

The acceleration in 1977 of a pulsed negative ion beam in a close coupled, high gradient electrostatic accelerator demonstrated the desirability of separating the high pressure magnetron source from the accelerator by a bending magnet, in order to operate with lower pressures in the accelerator region. In addition, the magnet can improve the match of the source emittance to the accelerator acceptance, it eliminates impurity ions and electrons which may be coming from the source, and protects the source from backstreaming particles. Subsequently, beam properties (emittances) from the magnetron were studied at energies around 15 keV, both before and after a focussing 90° bending magnet with a radius of 20 cm. Before the magnet, the divergence of a 0.5A beam ($0.5\text{A}/\text{cm}^2$ density in the emission slits) is approximately 4° parallel to, and 13° perpendicular to, the emission slits. After the magnet, the angles were approximately 4° in both directions, and the current density was about 12 mA/cm².

On the basis of these results, and beam trajectory calculations, the parameters of a 2A, 200 keV, dc electrostatic accelerator have been determined, which will serve as the Proof-Of-Principle accelerator (P.O.P.) for the 10A, 200 kV injector. The beam optical requirements are fairly stringent since neutral beams must be transported over several meters. Final angles of approximately 1° are generally mentioned. In addition, very little stray beam can be tolerated because of the large amount of beam power involved. The accelerator optics is very sensitive to the current density in the aperture because one must balance the focussing forces and the space charge blow up of the

beam in order to minimize the beam divergence. For acceleration in slot apertures, it is therefore essential to obtain a uniform current density along the aperture. In addition, the ratio of aperture length to width should be large (> 10) in order to minimize the end effects. Calculations have shown it to be difficult to meet both these requirements for a slot aperture after transporting the beam around a bending magnet. A better and more practical solution is to match the beam to a circular accelerator aperture at the exit of the magnet. We have started with a design to transport and accelerate the beam from the Mk V magnetron (1-2A, DC) which is shown in Figure IV- 1. The average current density in the 8 cm diameter aperture is $20-40 \text{ mA/cm}^2$. It should be noted that there is the possibility with this circular beam to put a magnetic quadrupole or solenoid lens after the accelerator if a reduction in the final beam angle is required.

If we use the modified magnetron (HCD source) we should easily be able to fill the round aperture to its current density limit after transport through the same bending magnet used for the regular magnetron. However, the lower operating pressure in the HCD source also allows us to again apply close coupled acceleration. In order to retain the advantages of the bending magnet, the "beam" from the converter could be transported 90° inside the HCD source before extraction. This is shown in Figure IV-2. The advantages are:

- a built-in mass analyzer
- backstreaming ions from the accelerator will not hit the converter
- the plasma is moved away from the anode emission slit
- negative ions are focussed naturally at 90° , so there is no need for grooves or curvature in the converter

Fig. IV-1 200 kV - 2A d.c. accelerator with bending magnet

Fig. IV-2 200 kV - 2A close-coupled accelerator with HCD source

For the Proof-Of-Principle accelerator, a 2A beam will be accelerated in a 1 cm x 10 cm slot aperture (density 200 mA/cm²). Calculations and experiments on the TFTR source indicate that these acceleration parameters should be attainable. If not, however, we have considerable flexibility with the HCD with respect to both the aperture dimensions and operating current densities. The scaling of this configuration to 10A and beyond will be more compact than the magnetron, as will be discussed in the neutral beam system in Chapter VII.

V. Accelerator Development Program Plan

The achievement of steady state operation of BNL surface plasma sources justifies an immediate start of the accelerator phase of the neutral injector program in FY 82. Acceleration of intense d.c. beams to energies beyond 120 keV is practically non-existent, except for the rotating target neutron source (RTNS) at LLNL, which operates at an energy of 400 keV and 150 mA positive deuteron beam current. Problems associated with the production of a continuous high current negative ion beam should not be underestimated, in particular high voltage breakdown of the accelerating tube induced by breakdown across the acceleration gaps due to field emission or particle collisions with rest gas molecules, or x-ray induced photo-ionization charges on the surface of insulators, etc.

The accelerator development is a two-phase program. The first phase consists of the design, fabrication and test of a 200 kV, 2A, Proof-Of-Principle accelerator to be completed in FY 84. This accelerator module will prove that:

- the beam from the source matches properly into the accelerator and
- the beam is accelerated and focused within 1° on the target, located at the position of the neutralizer.

The second stage of the program is the construction of the 10A accelerator, which consists in principle of five identical accelerator modules. The 10A acceleration tests will be completed by FY 86.

In addition to the construction of these accelerators, the accelerator test facility will be upgraded, also in two phases. The first phase requires the

completion of an existing test stand in order to start the study of the 200 kV-2A ion acceleration in FY 83. For testing the 200 keV, 10A ion beams, we can use in principle the same test facility by applying an energy recovery scheme. However, for testing the 1 MW neutral injector by FY 86, a new 200 kV-10A test facility seems to be a more practical solution than upgrading the 200 kV - 2A facility. The construction of this test facility should start in FY 84.

The two-phase accelerator program is summarized in the tables below.

Table V-1
2A P.O.P. Accelerator Program

TASKS	FISCAL YEAR				
	1982	1983	1984	1985	1986
1. Design	xxxxxxx				
2. Fabrication (includes diagnostics)		xxxx			
3. Ion Beam Tests		xxxxxxxxxxxxx			
4. Neutral Beam Tests				xxxxxxx	
200 kV/2A Facility Upgrade	xxxxxxxxxxxxx				

Table V-2
10A Prototype Accelerator Program

TASKS	FISCAL YEAR					
	1982	1983	1984	1985	1986	1987
1. Design			xxxxxxx			
2. Fabrication				xxxxxxx		
3. Ion Beam Tests				xxxxxxxxx		
4. Neutral Beam Tests					xxxxxxxxx	
200 kV/10A Facility			xxxxxxxxxxxxx			

VI. Neutralizer Concepts

As a consequence of the weak electron affinity (0.75 eV) of D^- ions, efficient neutralization of negative ion beams is possible. In the energy range of interest to fusion devices, there are two basic types of neutralization mechanisms: collisions with particles or molecules and photodetachment. Consequently, three types of neutralizers are being considered: gas (or metal vapor) neutralizers, plasma neutralizers, and laser neutralizers.

Theoretically, the most attractive system is the laser neutralizer.¹ It is the cleanest system and the theoretical limit for neutralization efficiency by photodetachment is 100 percent. However, this method needs further development work. A proposal to do this work has been submitted by M.W. McGeoch from Avco Everett Research Laboratory in parallel to our work. Thus, should this system prove feasible, the laser neutralizer will be integrated into our system.

The efficiency of plasma neutralizers can exceed 80 percent, while gas neutralizers are limited to about 60 percent.

Our plan is to concentrate on the development of a plasma neutralizer, while keeping the deuterium gas cell neutralizer proposed by Fink and Prelec¹ as an alternative option. Conceptually, our plasma neutralizer relies mostly on the stripping of an electron from the D^- by electron impact. The neutralization efficiency can exceed 80 percent.

Preliminary considerations reveal that in order to obtain the highest steady state plasma density (implying the shortest possible neutralizer) one needs a magnetized plasma. A device which can produce an appropriate plasma

is the Hollow Cathode Discharge (HCD). The magnetic field must be oriented in the direction of the propagation of the beam, since even a perpendicular field of approximately 200 Gauss would produce an angular spread in the neutral beam of 5° for a neutralizer which is only 30 cm. long.

In view of these considerations, the following neutralizer concept emerges: the plasma in the neutralizer will have a cross-section to match the beam. This plasma will be fed along magnetic field lines from HCD's which are located at the entrance of the beam. Figure VI-1 is a schematic representation of the systems (depending whether the negative ion source is a magnetron (1a) or an HCD (1b)). The other dimension (1) would be determined by the maximum achievable beam current density and plasma density. Using data from K.H. Berkner, et. al.,¹ the target thickness needed for maximum neutralization efficiency of D⁻ in a deuterium plasma is $12 \times 10^{14}/\text{cm}^2$. For this thickness, the neutralization efficiency is about 84 percent.

To determine the feasibility of this approach, experiments must be done with injection of an HCD plasma into a configuration which simulates the neutralizer. The plasma density must be measured. However, from previous knowledge of HCD plasmas, upper and lower limits on the plasma density can be estimated at 10^{14}cm^{-3} and 10^{13}cm^{-3} respectively. These values imply that the length of the neutralizer will be between 120 cm and 12 cm. The number of cathodes to be used will be determined from the experiments.

¹All references are taken from Proceedings of the Second International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, October 1980, edited by Th. Sluyters (Brookhaven National Laboratory, BNL Report 51304).

Fig. VI-1a Plasma neutralizer for a magnetron based system

Fig. VI-1b Plasma neutralizer for a system utilizing HCD sources

VII. Neutralization Program Plan

The objective of the first phase of this program is to fabricate and install a neutralizer for the 2 A - 200 KeV P.O.P. accelerator. The time schedule is such that testing should commence by FY 85. Our approach is to aim for the most efficient and clean system, while maintaining an alternative option which is less efficient.

During the last three quarters of FY 1982, a study will be conducted to determine which neutralizer will be built. This study consists of an experiment designed to determine the feasibility of the HCD plasma approach, and simultaneously, a mostly paper study of metal vapor neutralizers. At the end of FY 1982, a choice will be made among the HCD plasma neutralizer, metal vapor, or gas neutralizer.

The neutralizer will be designed during the first half of FY 1983. Fabrication and installation will be done from April 1983 through April 1984. During the last half of FY 1984, the neutralizer will be tested with a low energy beam.

All indications are that a 10 Amp neutralizer will be a scaled up version of the 2 Amp neutralizer, i.e., the same neutralizer but with a cross-section five times larger. The design of the 10 Amp neutralizer will be done during the last half of FY 1985; its construction from April 1985 to April 1986; and, testing will be done during the last half of FY 1986.

The neutralizer program is summarized in the following table.

Table VII-1
Neutralizer Development Schedule

TASK	FISCAL YEAR				
	1982	1983	1984	1985	1986
Develop Neutralizer Concept	XXXXXX				
Design/Fab./Test Neutralizer		XXXXXXXXXXXXXXXXXX			
Test With 2A P.O.P. Accelerator				XXXXXXX	
Design/Fab. 10A Neutralizer				XXXXXXXXXX	
Test With 10A Prototype Accelerator					XXXX

VIII. Neutral Beam Systems

While a great deal will undoubtedly be learned from the operation of the 2A P.O.P. accelerator, it is possible at this time to give some details of the next step, namely, the construction of a 1 MW (200 kV - 5 A) neutral beam injector.

A 10A beam line based on the close coupled acceleration of the HCD beam is a direct scaling of the 2A P.O.P. beam. As shown in Figure VIII-1, the unit has 5 of the 1 x 10 cm, 2A beams, with 4 cm distance between them. This provides sufficient space in the source, and room for electrode cooling, while still giving an overall density of approximately 40 mA/cm². Figure VIII-2 shows the overall neutral beam system with the source at ground potential to simplify electrical connections and pumping at the source and to allow for beam deceleration tests. Figure VIII-3 shows the system with the source at high voltage potential, which is standard for today's neutral beam systems.

The overall size of the beam line is primarily determined by the neutralizer, the ion deflector and the dumps. Our estimate of the outer dimensions of the beam line, as well as parameters, are given in Table VIII-1. We have chosen to show the beam line parameters using a plasma neutralizer. If one were to use instead a gas neutralizer, the overall beam line would remain essentially the same. Because of the reduced neutralization efficiency, the final neutral power (and density) is reduced, while the power to the beam dumps is approximately doubled (but still relatively easy to handle). The gas neutralizer is longer (approximately 1.5 m), but the gas load is about the same as for the plasma neutralizer.

Fig. VIII-1 Accelerator configuration for the 10A module

Fig. VIII-2 Neutral beam line with the source on ground potential

Fig. VIII-3 Neutral beam line with the source at 200 kV

Table VIII-1
Tentative Parameters for a 1.6 MW D^o Beam Line
(10A, 200 keV D-)

HCD SOURCE

Cathode Current, Voltage	500A, 50V
Converter Current, Voltage	100A, 100V
Pressure	10^{-3} - 10^{-4} Torr
Source Pumping	$\leq 200,000$ l/sec
Gas Flow From Source	≤ 1 T-l/sec

ACCELERATOR

Apertures	5 x (1 cm x 10 cm)
Current Density in Aperture	$0.2\text{A}/\text{cm}^2$
Voltage Gradient	≤ 60 kV/cm
Length	~ 5 cm

HCD PLASMA NEUTRALIZER

Neutralization Efficiency	80%
Cathode Current, Voltage	1000A, 50V
Plasma Density	$4 \times 10^{13}/\text{cm}^3$
Length	30 cm
Gas Load	40 T-l/sec

ION DEFLECTION MAGNET

Field	1 kG
Length	50 cm
Gap	25 cm

ION BEAM DUMPS

Size	20 cm x 60 cm
Power Density	170 Watts/ cm^2
Power Per Dump	200 kW

OVERALL BEAM LINE

Approximate Size	4 m x 1.5 m x 1.5 m
Overall Power Efficiency	50 - 60%
Final Neutral Current Density*	8 mA/ cm^2
Final Neutral Power Density*	1.6 kW/ cm^2

*5 meters from the accelerator, assuming $\theta = \pm 1^\circ$, and no aiming of beams.

If the magnetron or HCD is used with a bending magnet before acceleration, the 2A units (Fig. IV-1) are sufficiently small to be stacked and aimed to a common point at the reactor port. In this case, the final neutral beam density is about 16 mA/cm^2 , assuming a 1° beam divergence and 5 m beam transportation. Because of the larger initial beam size with this configuration, the details of the neutralizer, ion deflector and beam dumps are different from the HCD beam line, but the overall beam line parameters remain essentially the same.

There are several prospects for reaching higher beam energies. Energies around 400 keV are talked about for heating in mirror devices, and 1 MeV for current drive in tokamaks. Electrostatic acceleration, similar to that used at 200 keV (but with reduced current densities to maintain a reasonable voltage gradient) should continue to be a viable approach at 400 keV. An alternative, if one can solve the problem of capturing the extracted beam in small electrostatic quadrupole arrays, is to use rf acceleration in a MEQALAC, or to use low gradient dc acceleration in a periodic structure consisting of electrostatic quadrupoles between multiple accelerating gaps (Fig. VIII-4).

An attractive approach for MeV energies is radio frequency quadrupole acceleration (RFQ). The 200 keV beam from either the close coupled acceleration or the bending magnet/acceleration arrangement could be injected into such an RFQ. During the December 1980 workshop "Formation and Acceleration of High Energy Neutral Beams for Magnetic Fusion", parameters were given for such a device which took a 2A, 200 keV, dc D⁻ beam and accelerated it to 1 MeV in a single, 16 cm diameter aperture. The total RFQ length was 3.4 meters. Figure VIII-5 shows a possible 2A, 1 MeV beam line. In addition, a four-channel RFQ was shown, which might then give a 8 MW D⁻ beam.

Fig. VIII-4 200 kV - 10A d.c. accelerator

Fig. VIII-5 2A - 1 MeV neutral beam injector

IX. Test Facilities

Two test facilities are required to support the R&D program as discussed above: one facility for the development of multiampere (10A) dc ion sources and the other one to be used for the 200 kV acceleration and neutralization of those beams. Present facilities require modifications to test the higher powered beams.

Negative Ion Source Test Stand

The parameters of the source test facility currently in operation are summarized in Table IX-1. It has the capacity to study at least 1 A dc ion sources with extracted energies up to 25 keV.

Table IX-1
D.C. Source Test Facility
(Main Components)

Parameters	Present FY 81	New Requirements FY 83/84
Pumping Capacity	80.000 l/s (at 10^{-4} Torr)	Plus 20.000 l/s (at 10^{-3} Torr)
Cooling Capacity	40 kW	500 kW
Main Arc P.S.	200 V - 200 A	200 V - 200 A
Extractor p.s.	25 kV - 3 A	25 kV - 15 A
Vacuum Chamber (V)	4' x 4' x 8'	4' x 4' x 8' (plus attachment)

In order to study the 2.5 A and 10 A steady state sources, some facility upgrading is required in the power, vacuum and cooling capacity of this test rig. These modifications, to be implemented during FY 83-84, are listed in Table IX-1 above.

200 kV Accelerator Test Facility

In 1979 a High Energy Neutral Beam Test Facility building was constructed and equipped with a 14' long cylindrical vacuum chamber, 7' in diameter. This vacuum vessel is now connected with one 80.000 l/s and one 20.000 l/s oil diffusion pump. In addition, two power supplies are available: a 25 kV - 3 A dc extractor power supply and a 100 kV - 25 mA dc accelerator supply (see Table IX-2). It is the intention of the Grumman Aerospace Corporation to bring this 200 kV - 2 A facility into operation as part of a collaborative effort to demonstrate the feasibility of a 1 MW negative ion based neutral beam injector (see Chapter XI).

Table IX-2
2A - 200 kV Accelerator Test Facility

Parameters	Present	FY 82/83 Requirements
Pumping Capacity	100.000 l/s	100.000 l/s
Cooling Capacity	---	1000 kW
Main Arc P.S.	200 V - 200 A	200 V - 200 A
Extractor P.S.	30 kV - 3 A	30 kV - 3 A
Second Grid P.S.	100 kV - 25 mA	100 kV - 25 mA
Main Accelerator P.S.	---	200 kV - 2 A d.c.
Vacuum Chamber	14' - 7'	14' - 7'

In order to test acceleration of 10 A- 200 kV beams, one can use (in principle) the 2 A - 200 kV facility by using an energy recovery scheme with the source on ground level. However, for testing a 1 MW neutral beam, an extension of the existing building is required. This upgrade should start in FY 84. A detailed cost evaluation of this approach is shown in Chapter XII.

X. Program Milestones and Time Schedules of Component Development

The schedule for the BNL neutral beam development program is shown in Table X-1 and Table X-2. Both tables are essentially the same. The first table summarizes the time schedule and critical milestones of the three main components: the dc source, the dc accelerator and the neutralizer. The second table shows the development and critical milestones in terms of the two development phases, the first is the 2 A - 200 kV acceleration and neutralization phase and the second one is the 10 A - 200 kV acceleration and neutralization phase.

The program milestones show that the Proof-Of-Principle demonstration of the 200 kW (200 kV - 1 A) neutral injector will be completed in FY 85 and that the 1 MW (200 kV - 5 A) neutral injector will be completed in early 1987.

Table X-1 Negative Ion Neutral Beam Program

XI. Organization and Grumman Participation

The BNL Neutral Beam Development Group and Grumman have, as a team, the objective to develop a 10 A, D⁻ source, to accelerate this beam current to the 200 kV level, to develop an efficient neutralizer, and to incorporate these elements into a 1 MW neutral beam system. Each member of the group has his primary responsibility for a part of the program, but there is a close co-operation between group members working on different parts of the program as well as sharing of responsibilities in the development of the neutral beam system.

The BNL scientific and professional staff members are:

J. Alessi	(beam transport, acceleration)
A. Hershcovitch	(ion sources, neutralizers)
V. Kovarik	(neutral beam electrical and electronic systems)
R. Larson	(ion source electrical and electronic systems)
R. McKenzie-Wilson	(ion source mechanical engineering, BNL budget manager)
K. Prelec	(principal investigator, ion sources)
Th. Sluyters	(principal investigator, beam transport and acceleration)

Grumman will make available a program manager with substantial relevant experience. This individual will report to the principal investigator who has overall program responsibility (K. Prelec and Th. Sluyters alternate in this

role). The program manager, initially serving part time, will establish and monitor budgets for individual tasks, develop program schedules, apply a suitable performance measurement system as the program's scope expands, prepare monthly reports, handle purchase orders, monitor subcontractor/vendor schedules and budget performance as well as recommend corrective actions.

Supervised by the BNL project engineer, Grumman will be assigned the responsibility to integrate all accelerator facility activities. Initially, specific tasks for the 200 kV, 2A power supplies include preparation of specifications, issuing of invitations to quote, evaluation of vendor proposals, monitoring of design and construction, review/approval of acceptance test procedures as well as monitoring of acceptance tests, preparation of interface documents for installation drawing preparation by BNL, and to provide technical supervision during installation and checkout phases. Tasks for the existing 100 kV power supplies include preparation of drawings/specifications for modification of existing equipment including arc protection and digital interfacing with the computerized control system, purchasing and/or manufacturing of modification hardware as well as providing technical supervision for the modification itself. Another integration task is to assure accelerator design compatibility with facility requirements.

The BNL project engineer will be supported by a senior design engineer from Grumman who will direct the mechanical design of the accelerator based on BNL specifications, and utilizing BNL personnel as well as drawing on Grumman's technical capabilities as required. For example, design of the source bending magnet poles will be based on a geometry determined by BNL employing a ray optics code. For the grid design, a code will be employed by BNL to optimize grid geometry, and to provide inputs for the analysis of grid heating. To determine and find solutions for high voltage problems, Grumman's capabilities

are available, and will be drawn upon besides BNL's extensive experience.

Table XI-1 illustrates the functional relationship of key program participants.

Should DOE elect to restrict the proposed program in FY 82 to source development, activities would be carried out by BNL's current staff as shown in Table XI-2.

Table XI -1 System Development Organization

Table XI -2 Source Development Organization

XII. Funding Tables

Budget requirements for the source, accelerator and neutralizer development program, are given in Table XII-1 for the period 1982 to 1987. These funding levels cover the 2 A - 200 keV Proof-Of-Principle acceleration and neutralization tests as well as the construction of the 10 A - 200 keV prototype accelerator and the prototype 5 A - 200 keV neutral injector.

Table XII-1

Budgets
(in thousands of 1982 dollars)

	Fiscal Year					
	1982	1983	1984	1985	1986	1987
<u>Source Development</u>						
Operational	940	905	870	855	620	560
Equipment (test fac., etc.)	100	450	525	250	100	0
<u>Accelerator Develop.</u>						
Operational	325	690	730	620	620	640
Equipment (excl. 10A-200kV test facility)	210	225	100	100	100	100
<u>Neutralizer Develop.</u>						
Operational	80	230	270	385	130	130
Equipment			150	200	200	
	1,655	2,500	2,645	2,410	1,770	1,410
Contingency 15%	250	375	400	360	265	210
TOTALS	1,905	2,875	3,045	2,770	2,035	1,620

In order to test the neutralization of the 10 A negative ion beam, an extension to the existing building is required with additional test equipment. These extra costs are summarized separately in Table XII-2. The 2 MW power station and power distribution will be supplied by BNL.

Table XII-2
Modifications of 10A Neutral Beam Test Facility
(in thousands of 1982 dollars)

Building Additions	400
Power Substation	250
Power Distribution	100
H ₂ Cooling	Use Existing
Source Power Supplies	250
Neutralizer Power Supplies	250
Accelerator Power Supplies	400
Cryosystems (refr. & distr.)	250
Vacuum Systems	300
NBL Vacuum Box(es)	100
Diagnostics	200
Instrumentation & Controls	250
X-ray Shielding (local)	-
	<hr/> 2,750
Contingency 15%	<hr/> 400
TOTAL	<hr/> 3,150

XIII. Concluding Remarks

In the past year, it has been demonstrated that negative ion sources will not limit the feasibility of high energy neutral beam injectors. Both BNL sources are operating reliably in the d.c. mode. Although there may be a preference for the modified HCD magnetron (higher gas efficiency), the final selection between the two BNL sources will be made when beam qualities for both sources are completely analyzed. With the beam quality of the pulsed regular magnetron already measured, we can start immediately with the design and fabrication of the 200 kV accelerator and finish the construction of the accelerator test facility in order to be able to start high voltage tests in 1983.

The main difference between the BNL negative ion source and other sources is the high averaged ion density. Practical negative ion densities after acceleration may vary from 25 to 100 mA/cm², so that for instance, a 10A beam covers an area not more than 20 x 20 cm².

Acceleration and neutralization of an intense steady state negative ion beam has still to be realized. Only an immediate addressing of these tasks can make demonstration of a 1 MW neutral beam injector system by 1987 possible.

Acknowledgements

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