

SEVENTH INTERNATIONAL CONFERENCE ON PLASMA PHYSICS
AND CONTROLLED NUCLEAR FUSION RESEARCH

23 - 30 August 1978
Innsbruck, Austria

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NEUTRAL BEAM INJECTOR RESEARCH AND DEVELOPMENT WORK IN THE USA*

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* Work done under the auspices of the United States Department of Energy.

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ABSTRACT

We describe neutral beam injector research and development at the Brookhaven National Laboratory, Lawrence Berkeley and Lawrence Livermore Laboratories, and Oak Ridge National Laboratory.

All neutral beam systems for present and near-term applications are based on the acceleration and neutralization of positive ions. The research and development is carried out at LBL/LLL and ORNL. Present emphasis at LBL/LLL is on 80 to 120 kV systems for the mirror program and for the TFTR and D III tokamaks. Present emphasis at ORNL is on 40 to 80 kV systems for the PLT, ISX, and PDX, and 80 to 200 kV systems for LPTT and TNS tokamaks.

Injectors for the future experiments and reactors may operate at energies of 200 keV or higher, especially for mirror machine applications, where positive-ion-based efficiencies will be very low, assuming no energy recovery. Research on negative-ion-based systems with potentially high efficiencies is carried out at BNL and at LBL/LLL and ORNL. The first demonstration of a high-power neutral beam based on negative ions is planned for 1980.

1. INTRODUCTION

The US neutral beam injector research and development work is carried out primarily at Department of Energy (DOE) Laboratories: The Brookhaven National Laboratory (BNL), The Lawrence Berkeley and Livermore Laboratories (LBL/LLL), and The Oak Ridge National Laboratory (ORNL).

High-power neutral beam systems based on positive-ion acceleration and neutralization have produced effective heating in recent confinement experiments [1, 2, 3]. For near-term applications, multi-megawatt neutral beam systems with particle energies up to 120 keV are in the testing phase. Systems using negative ions, for increased efficiency at high energies, are in the research phase, but are receiving increasing emphasis for applications in the mid-1980's. The development of suitable test facilities has been the pacing item in our program; four test stands with multi-megawatt capabilities at voltages above 100 kV are in operation or nearing completion.

2. NEUTRAL BEAM INJECTORS BASED ON POSITIVE IONS

2.1 LBL/LLL Neutral Beam Work

The Lawrence Laboratories Neutral-Beam Development Group's positive-ion-based work [4] proceeds along two lines: The first is required for the near-term applications: The presently identified applications, 2XIIIB, TMX, MFTF, TFTR, and D III, require injection at energies up to 120 keV, ion currents per module up to 80 A, and pulse lengths to 0.5 sec. We have achieved 120 kV, 0.5 sec operation of a fractional-area (14 A) TFTR prototype source, and have tested a full-size TFTR source to 120 kV and 65 A for 20 ms. Half-second testing of the full-size TFTR source will begin in August 1978, when the High Voltage Test Stand (HVTS) is fully operational (section 4.4).

A first model of a fractional area, MFTF/DIII 80 kV source has been operated with 80 kV, 14 A, 0.5-sec pulses. No basic problems with the source designs have shown up; full-scale module tests will start soon. (The overall design and construction of the full-scale MFTF source has been carried out by MFTF personnel.)

The second part of our program is devoted to development for longer-term applications. The next few years will be devoted to increasing efficiency (ion species, gas, electrical), pulse length, energy (to 150 kV), and reliability. All of these items require major advances over present technology.

As part of this program we are developing a new generation of plasma sources with improved ion and electron confinement by cusp magnetic fields at the walls. These sources should have improved electrical efficiency and should produce ion beams with an enhanced atomic ion fraction. We are also developing the technology necessary for direct recovery of the energy of that portion of the beam which remains un-neutralized. The experiments to date, carried out with a 1 kW, 15 keV steady-state beam, gave 70% recovery efficiency. Electrostatic as well as magnetic fields were used for electron suppression. Recovery of a single species 10 keV H^+ beam using magnetic electron suppression gave over 85% recovery efficiency. Scaled up experiments on a 50 kW, 105 keV beam is underway with recovery efficiency over 20% initially, but decaying during the 500 msec pulse. The collector self-biased to a voltage over 75 kV. In the area of long-pulse operation, we are developing cathodes with d.c. capability, and have undertaken a computational analysis of secondary particle trajectories in the accelerator structure, which, together with experimental measurements, should permit us to identify and reduce the dominant heating mechanisms.

We are developing, through industrial vendors, techniques for manufacturing sources that are to be entirely hard sealed. Recently, a method for brazing rectangular ceramic insulators to metal electrodes has been developed at LBL for use on the ion accelerators for TFTR. [5]

New approaches to the design of electronics [6] and computerized controls [7] are included in the program.

2.2 ORNL Neutral Beam Work

The ORNL Plasma Technology Section participates in a variety of fusion plasma heating activities. Neutral beam injection systems have been designed for use on several state of the art tokamaks (PLT, [8] ISX, [9] PDX, LPT and TNS). The development and qualification of four PLT injection systems was recently completed with operating parameters of 0.75 MW (1 MW) neutral beam power per injector utilizing hydrogen (deuterium) extraction. Initial operation of two (four systems are installed on PLT) of these systems at about 1 MW neutral power produced record tokamak ion temperatures of about 2.3 keV.

ISX and PDX ion sources have been operated at plasma parameters consistent with 100 A extraction. A complete 100 A source is being assembled. The PLT injection system has been upgraded in pumping and will transport

50-60 keV neutral beams for pulses of 0.5 sec (0.1 sec) for PDX (ISX). The PDX system is in fabrication and assembly. LPT and TNS are in the conceptual phase and half-scale ion sources are under test in the 100 kV range, which will soon be extended to 150 keV.

An intense research and development program with modified three-grid duoPIGatron source [10] provided a dense (400 mA/cm^2), uniform ($\pm 5\%$), and quiescent ($\pm 10\%$) plasma from which 70 amperes of positive ions have been extracted at 40 kV. The source has also been operated using deuterium under similar conditions. Permanent magnets have been placed around the 2nd anode region to produce a cusp field which confines the plasma in a highly uniform manner. The source operation is characterized by moderate filament and arc power requirements, high gas efficiency (50%) and a high degree of reliability. The arc efficiency has been measured to be about 1 kW for every ampere of extracted beam. Although the source has generally been operated for pulse durations of 100 ms at 10% duty cycle, it has near dc capabilities, and 40 A pulses of 500 ms duration have been extracted. A smaller source has been operated for 10 s at 200 mA/cm^2 .

An outstanding feature of the ORNL source is its ability to provide very high atomic yields, 85%. The high energy atomic fraction plays an important part in beam penetration and power deposition in a tokamak plasma. Control of the ion species will provide means of controlling the beam penetration to match the varying tokamak plasma density.

Initial experiments in energy recovery employing crossed magnetic field blocking of the electrons from the gas charge exchange cell have proved successful. The un-neutralized component is collected at ground potential. Energy recovery has been measured to be (40 + 20)%. A 200 keV, 100 A positive ion source with c.w. capability and energy recovery is in the design stage. The entire 200 keV beam line is being redesigned to insure a high efficiency system. Such a positive ion system with direct recovery efficiency of $\sim 80\%$ might well satisfy the injector requirements for heating future reactor size tokamaks.

Future research and development plans also include simplifying and increasing the reliability of 40 to 80 keV injector systems.

Computer simulations [11] are available and are found to be an extremely valuable aid in every phase of this program, both in predicting and verifying systems performance.

3. NEUTRAL BEAM INJECTORS BASED ON NEGATIVE IONS

3.1 BNL Negative Ion Activities

The objective of the BNL program is to develop multiampere (equivalent) high-energy injection systems based on direct extraction from negative ion plasma sources. Two types of direct extraction negative ion plasma sources have been extensively investigated, namely the magnetron source and Penning type source. Several improvements were implemented on these sources, which are basically of the cold cathode type operating in a mixture of deuterium gas and cesium vapor. These improvements (independent cesium vapor control,

constant gas flow during the beam pulse, cooling of the cathode) together with extensive probe and spectroscopic studies of the plasma parameters (such as plasma and gas densities as well as atom energy distributions) enabled us to improve our fundamental knowledge of the negative ion creation and to construct a multiampere negative ion plasma source for extracted beam currents between 1-2 A in beam pulses up to 50 ms. [12]

Negative ion acceleration and beam transport are being studied on a 150 kV test stand. Two accelerator systems have been investigated, the close coupled geometry in which 1 A beams have been accelerated across a 2 cm accelerating gap and a system with the accelerator separated from the source and extractor by a bending magnet. Beam transport studies include the effects of space charge neutralization and beam focussing by means of a quadrupole doublet.

Neutralization of negative ion beams will initially take place with gas jets, being the simplest neutralizer to realize with relatively high (up to 60%) neutralization efficiency. A CO₂ effusive gas jet was constructed and its gas-dynamical properties analyzed.

3.2 LLL/LBL Negative Ion Activities

The LLL/LBL negative ion development effort is oriented toward longer-term applications requiring efficient neutral beam systems at energies well above 120 keV. Most of these systems probably will require the production and acceleration of large currents of negative ions. Two of our goals are the demonstration of a 200 kV, 5 A (D⁰), long pulse system by 1980, and a 400 kV, 20 A (D⁰), dc system by 1983.

The production of negative hydrogen ions by double charge exchange in cesium or other vapors offers the possibility of being scalable to arbitrarily large currents and long pulse lengths. We start with a 1 keV D⁺ beam, of which somewhat more than 1 A passes through a cesium charge-exchange cell. The measured conversion efficiency is about 20%, in reasonable agreement with the value of 24% obtained in an atomic collision experiment. The plasma produced in the charge exchange cell is greatly reduced by flow transverse to the propagating (1 keV) beam, so the random electron current is less than the beam current. A 100 mA negative deuterium beam produced in this way has been accelerated to 60 keV. The accelerator was designed to yield good beam optics over a wide range of currents; in the present case $\pm 2.5^\circ$ divergence was obtained.

The production of beams by this method requires the propagation of low energy positive and negative ions distances of order of a meter in a low gas pressure environment. Analysis of the background plasma indicates that for such a case, space charge effects tend to expand positive ion beams significantly. This is reflected by difficulties in obtaining high quality, 1 keV D⁺ beams. The analysis also shows that negative ion beams should be weakly confined by the forces, and the low energy negative ion beam is observed to propagate with low divergence. Analysis of angular scattering in the charge-exchange process shows that the effect is small at 1 keV, but may become important at low beam energies.

Alternative techniques for producing negative ions are being studied, including surface and volume production in plasmas confined by magnetic-multipole fields.

3.3 ORNL Negative Ion Activities

The ORNL negative ion program is directed toward small scale experiments to develop negative ion plasma generators. Simultaneously, we are making a complete neutral beam line study for both positive and negative ion based systems in order to evaluate the relative merits of each and thereby determine a realistic efficiency for each system as a function of beam energy.

Two experiments, both employing direct negative ion extraction, are under study. The first utilizes the duoPIGatron ion source with a system of cesiated chevrons or vanes, on which the positive ions in the plasma generator impinge, placed directly above the extraction grids. Both electric and magnetic fields are used to reduce the flow of electrons to the grids. One ampere of unanalyzed beam has been extracted from this source. The second experiment utilizes a Calutron ion source employing a hot filament Penning discharge. Positive ions from the discharge are accelerated into a cesiated molybdenum surface which has independent temperature control. The arc discharge voltage, the energy of the positive ions striking the molybdenum surface and the cesium oven temperature are all independently controlled, which permits determination of optimum source performance. Preliminary results from the source have been achieved in both a pulsed mode, about 100 msec, and a c.w. mode, about 20 sec. About 60 ma/cm² of H⁻ have been observed in pulsed mode. For the c.w. mode, limitations in the arc power supply required lower discharge power and consequently lower output current, about 30 ma/cm². The gas efficiency in the c.w. mode was measured to be 4%.

Future plans are to extend either or both of these sources to 1 A H⁻ output and design a 10 A version for extraction at 50 keV. At this time, a complete beam system will be developed based on criteria determined from the system studies now under way. Beam systems of 100's keV are also being contemplated. However, the extracted beam density will be limited to approximately 100 ma/cm².

4. TEST FACILITIES

4.1 General

A large part of our effort in recent years has been the development of suitable test facilities. In the process of designing and constructing them it has been necessary to develop new concepts and components for the high power electronic circuits, and new diagnostic techniques. Two neutral beam facilities (HVTS at LLL, NBSTF at LBL) will have sufficient neutron shielding to permit extensive operation with deuterium.

4.2 BNL Facilities

A 1 ampere, 150 kV, 0.01 second, cryopumped facility is operating, and a 10 A, 250 kV, 0.1 sec, test stand is under construction.

4.3 LBL Facilities

Two beam lines with 120 kV electronics, one capable of operating at 15 A, 0.5 s, the other at 65 A, 30 ms, are in operation. Electrical, thermal, and optical diagnostics with on-line data analysis are used. Computer control of power supplies for semi-automatic source conditioning is installed. The Neutral Beam System Test Facility (NBSTF) for testing TFTR components and systems 120 keV, 65 A, 0.5 sec will start operation early in 1979. It will be converted to a general Research and Development Facility about three years later.

4.4 LLL Facilities

A 100 kV, 1 A, 10 ms test stand is operational, and the High-Voltage Test Stand (HVTS) with 200 kV, 20 A, DC, or 120 kV, 65 A, 30 s, or 80 kV, 80 A, 30 s capability is nearly operational.

4.5 ORNL Facilities

The Medium Energy Test Facility has been used to test PLT beam line systems and is currently in use for R & D on sources and system tests for ISX and PDX beam lines. It is a cryopumped system with electrical, thermal and optical diagnostics. A 60 kV, 60 A, 2 sec (10% duty cycle) power supply is presently in use. Modifications are under way to upgrade to 80 kV, 100 A, 20 s. It will be further modified to 120 kV, 100 A 30 s capability in about 1 year. A PDP-11/40 is used for computer monitoring of the entire beam line on a shot basis. A study is under way to extend this to a computer controlled system.

A second test facility in operation is the High Energy Test Facility. This is a 7 M long diffusion pumped system with a 168 kV, 50 A, 20 sec (10% duty cycle) power supply. Design modifications are under way to convert to cryopumping and increase the beam energy capability to 200 keV. This facility has identical diagnostic and computer capability as the Medium Energy Test Facility.

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