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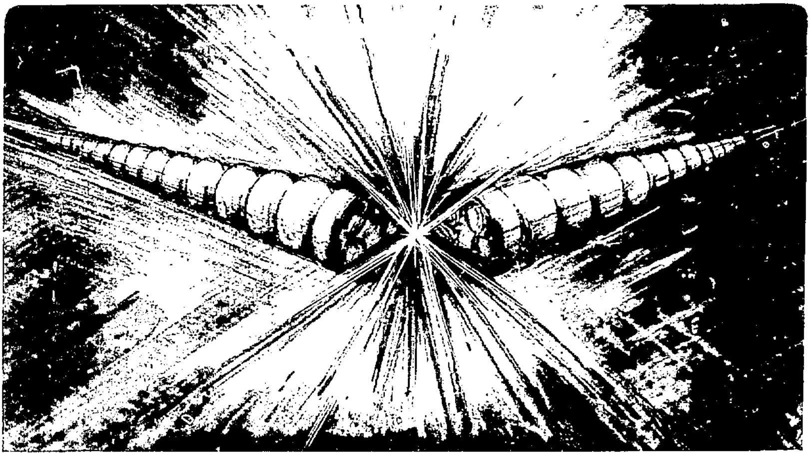

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NEUTRAL BEAM DEVELOPMENT AT LBL/LLNL*

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Abstract

In a joint program LBL and LLNL are developing and testing neutral bean injection systems based on the acceleration of positive ions, for application in the 80- to 160-keV range on MFTF-B, D III, TFTR/TFM, ETF, MNS, etc. A conceptual design of a 160 keV injection system for the German ZEPHYR project is in progress. For applications at energies above about 200 keV, positive-ion-based system efficiencies are unacceptably low for most applications, and so negative-ion-based systems are being developed also.

I. Introduction

The Lawrence Berkeley Laboratory and the Lawrence Livermore National Laboratory have a joint program to develop and test neutral beam injection systems for mirror and tokamak experiments. There are several program elements which we could categorize as research, development of hardware components and systems, prototyping, transfer of technology, and manufacturing. We also can divide the program in a different way, namely into activities based on the production, acceleration, and neutralization of either positive or negative ions. Most of our activities, and all of the near-term applications, are based on positive ion technology, including development in the 80- to 160-keV range for MFTF-B, D III, TFTR/TFM, ETF, MNS, and ZEPHYR. For applications at energies above about 200 keV, positive-ion-based system efficiencies are unacceptably low for most applications, and negative-ion-based systems are being developed. Applications of negative-ion technology are 5- to 10-years away.

The generic focus for the positive-ion development is the 150 kV, 10- to 30-second Advanced Positive Ion Source (APIS). The studies are first carried out on a fractional-area (~ 15 A) source system, and then extrapolated to full-size (about 50- to 100-A) modules. Specifications for a negative-ion system have not been fixed, but a general objective is the production of dc beams with particle energies of 200 keV and higher.

In the following sections a brief outline of the program is given, with recent references cited for details.

II. Positive-Ion Technology

A. System Elements

The main elements of a typical neutral-beam injection system are shown schematically in Figure 1.

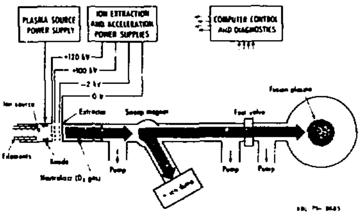

Figure 1. Schematic of a typical neutral-beam injection system.

The system operation is as follows: A deuterium plasma is created in the plasma generator by means of a high-current discharge. Ions from this plasma are accelerated in a carefully designed multi-electrode structure. The ions then pass through a neutralizer containing deuterium gas, and a fraction becomes neutralized by charge-exchange collisions. Remaining ions are removed from the beam by the sweep magnet; otherwise, the various reactor magnetic fields would bend the ions into surfaces near the entrance port, possibly releasing gas bursts or melting the surfaces. The considerable power in this ion beam must be handled by the ion-beam dump. The vacuum pumps distributed along the beam line remove most of the gas emerging from the neutralizer and the ion-beam dump and must maintain the pressure between the sweep magnet and the entrance port at a sufficiently low value that very little of the neutral beam is reionized. Well-regulated power supplies are required to assure good beam optics; to minimize accelerator damage when a spark occurs, the power supplies must also be capable of rapid turn-off with a minimum of stored energy (e.g. in cable capacitance). Optical, mechanical, and electrical sensors determine the condition and performance of the neutral-beam system and permit the control system to adjust the power-supply voltages and to shut down the system if a malfunction occurs.

In this discussion of the status of the program, the elements of the injection system will be described in turn. Background material is given in Reference 1.

1. Plasma Source

The plasma sources from which ions are extracted in all of our applications to date are of the "field-free" type[2], in which the plasma is produced by a high-current arc from many small filaments. These plasma sources have given fairly satisfactory operation for pulse lengths up to 1.5 seconds, and give an atomic-ion (D^+) fraction in the accelerated beam of about 65%. We are presently testing a larger-volume "magnetic bucket" plasma source,[3,4] in which the walls are lined with permanent magnets in a cusp arrangement, and there are fewer, but larger-diameter filaments. This source has been tested for several seconds without ion acceleration, and appears suitable for 30-second operation. No facility is available for determining long-pulse properties of an accelerated beam, but short-pulse (20 msecond) testing at 100 kV indicates that the atomic-ion (D^+) fraction will be 75% to 80% at the arc power appropriate for 120 kV.

When operated under proper conditions, including electronic control of the heating current, plasma sources with filaments of the present "bucket" kind are expected to go 10^5- to 10^6 seconds before requiring replacement. Longer-lived and more rugged cathodes, perhaps hollow cathodes, are desirable and under investigation.

2. Accelerator

A four-grid 10 cm x 40 cm accelerator electrode array is used. A cross section of one half of a single slot is shown in Fig. 2.

Ions are accelerated and electrostatically focused in the first two gaps; the third gap has a weak decelerating field to suppress downstream electrons. The transparency of the array is 60%; the scale size was set by the desire to limit the maximum potential gradient to about 100 kV/cm. The ion-current density would be

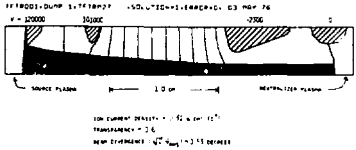

Figure 2. Calculated beam trajectories and equipotentials for a 120-kV accelerator.

0.31 A/cm^2 for a pure D^+ beam, and is about 0.25A/cm^2 for a beam with a realistic mixture of D^+, D_2^+, and D_3^+ ions.

During a pulse these electrodes are heated by the impingement of secondary particles produced by the beam. Uncooled electrodes of the kind shown in Fig. 2 have sufficient thermal capacity to permit operation for about 1-1/2 seconds - enough for present-generation experiments.

A prototype fractional-area (~ 10A) 120 keV accelerator designed for continuous operation is being tested.[5,6] The molybdenum grids are convectively cooled by flowing water through individual grid rails and the thermal expansions are accommodated by the rail support modules. The design of these modules is such as to allow deflection and rotation at the grid rail ends, each rail being free to move independent of its neighbors. The accelerator module has been operated for 5 second pulses at 100 kV. The heat loads to the individual electrodes are monitored and found to be roughly 1/2 % of the total beam power for each of the electrodes, under optimum tuning conditions. If the plasma density is not appropriate to the accelerating voltage, the heat loads are considerably larger. A larger unit, capable of 65 A operation at 120 kV is under construction. As there is at present no facility capable of testing such a unit at full voltage and pulse length, the initial testing probably will be at 80 kV.

For some applications bakeable, neutron-resistant ceramic insulators with metal seals have been specified for the modules. The design and manufacture of large ceramic insulator assemblies have proven to be quite difficult. In reference 7 the development of two candidate materials, machinable glass ceramic and alumina, is described along with the ceramic-to-metal brazing techniques developed for each material. The microstructures of the brazed joints are examined and the results of microprobe studies presented. It has been found that the surfaces produced by different machining methods have a significant effect on the strength of brazed joints to the machinable glass ceramic. Lapped surfaces have given bond strengths up to three times those produced with other surfaces. Successful full-size brazes have been realized between alumina and titanium and between machinable glass and titanium. Vacuum tight joints between machinable glass and titanium have not been reliably achieved.

3. Neutralizer

Our beam neutralizers are channels with restricted pumping speed, fed by excess gas passing from the ion source through the accelerator structure, in which some of the positive ions capture electrons from the gas. For future applications it is possible that we must pump out the excess gas from the ion source before it reaches the accelerator structure, for example by conducting the plasma through magnetic-multipole guide structure[8] with radial pumping. In this case gas, not necessarily hydrogen, will have to be supplied for neutralization.

There is a possibility that at high energies, > 80 keV for example, there can be an interaction between the charged component of the beam and the plasma produced in the neutralizer by the beam. This possibility is being studied theoretically and experimentally.

4. Bending Magnet

A bending magnet is used to separate the charged component from the neutral component. To date the magnet design has been fairly straightforward, but very careful attention to the design is required in the future for high-energy, high-power, longer-pulse operation, because the power density on calorimeters and beam stops is uncomfortably high, and poor optics of the deflected ion beam could be disastrous. The beam-dump problem will be eased when direct-energy-recovery techniques are developed.

5. Direct-Recovery

Following the neutralizer, it is possible, in principle, to decelerate the remaining charged beam and collect it at low energy. We have performed some experiments[9] which showed promise, but have no experimental program at this time, and are following with interest the work at ORNL reported elsewhere in this paper.

6. Calorimeter and Ion Beam Dump

At present, beams are stopped on thick copper plates instrumented with arrays of thermocouples. The beam divergence is determined by on-line computation from the heat profiles.[10] Actively-cooled calorimeters and beam stops are required for the HVTS upgrade and the NBETF (see next section).

Test Facilities

The availability of high-voltage, high-power, long-pulse test facilities continues to pace the development program. At LBL three facilities are operational: Test Stand III A has 150 kV, 15 A, 5-second capability, and will be upgraded for 30-second operation during the coming year. TS IIIB has a capacitor-bank high-voltage supply configured for 120 kV, 70 A, 20 millisecond operation. The Neutral Beam System Test Facility (NBSTF) is devoted completely, through September 1981, to work for the PPPL TFTR/TFM Program. It presently has 120 kV, 65 A, 0.5 second capability, and is being upgraded to operate for 1.5 seconds. Following the work for PPPL the NBSTF will be converted to a facility that can test the next generation of positive ion sources. It will be called the Neutral Beam Engineering Test Facility (NBETF) and will be capable of operation at 170 kV, 65A, 30 seconds with a 10% duty factor. The NBETF is scheduled to be operational in April 1983. At LLNL the High Voltage Test Stand (HVTS) is operational for 80 kV, 80A, 0.5 second development work, and will be upgraded for 30 second operation in about 1-1/2 years.

Most confinement experiments will use deuterium neutral beams, and most of our development tasks involve deuterium operation. The instantaneous neutron production rates from d-d interactions in the neutralizers and in the calorimeter and beam stops are high.[11] TS IIIA and TS IIIB are not shielded, and must operate at very low duty factors when deuterons are used. The NBSTF and HVTS are adequately shielded for deuterium operation.

Electronic development is vitally important to the successful operation of these test facilities. We are aiming at components and techniques to make the operation of neutral beam systems more reliable and to reduce the construction costs.[12] For example, we have developed reliable high-voltage, high current solid-state switches, and a feed-back controlled arc power modulator. The arc modulator has been successfully used to vary the beam current as $V^{3/2}$ when V was changing with time, permitting operation with good beam optics even with no regulation of the high voltage. This is a promising approach for reducing the costs of neutral injection systems.

III. Negative-Ion Technology

Next we describe the status of the LBL/LLNL negative-ion-based neutral beam development program, which has as its objective the development of megawatt d.c. injection systems. Until last year we concentrated on a system in which the negative ions were produced by double charge-exchange in sodium vapor. At present, the emphasis is on a "self-extraction" source in which the negative ions are produced on a biased surface imbedded in a plasma.

In a short-pulse experiment using double charge-exchange a beam of approximately 10 keV D^+ ions was converted to 2A of D^- ions in a supersonic sodium vapor jet, demonstrating one way to produce a useful negative ion source.[13] A d.c. surface-production "self extraction" source[14] is operating with ~ 1/2A of "self extracted" 200 eV negative ions. Negative ion "research" should develop into negative ion "technology" within a few years.

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