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NEUTRAL BEAM INJECTOR RESEARCH AND DEVELOPMENT WORK IN THE USA

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ABSTRACT

Neutral beam injection research and development at Brookhaven National Laboratory, Lawrence Berkeley and Livermore Laboratories, and Oak Ridge National Laboratory is described.

The ORNL Neutral Beam Development Program is concentrated on the development and application of tokamak neutral beam injection systems. Tokamak neutral beam development is being carried out for ORMAK, PLT, ORMAK-Upgrade, PDX and TFTR. Applications have been made to ORMAK and are being made to PLT. Basic research in support of the development program includes work in the areas of plasma sources, ion extraction and beam optics, cryopumping, beam stops and megawatt electrical power systems.

The LBL/LLL Neutral Beam Development Program can be divided into two areas: 1) Development based on positive-ion acceleration and neutralization, primarily for near-term applications on the 2X, BB, MX, and TFTR confinement experiments, and 2) a higher-efficiency-injector program based on acceleration and neutralization of negative ions, which may be required for fusion reactors and reactor-like experiments. In addition, there is related work (not described here) on negative-ion production and on direct energy recovery.

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The objective of the BNL Neutral Beam Program is to develop a 150 keV multiampere (equivalent) neutral injector with essential support systems based on long pulse, multiampere sources of negative hydrogen and deuterium ions, close coupled acceleration to the required energy and on neutralization of high energy negative ions in a gas or plasma jet. High speed cryogenic and molecular sieve pumps are being developed as part of the program.

1. INTRODUCTION

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

2. ORNL NEUTRAL BEAM WORK

2.1. ORMAK Neutral Beam Injection

More than 350 kW of neutral beam power have been injected into ORMAK, using three neutral beam systems based on 10-cm-diameter duoPIGatron ion sources.[1,2,3] This power raised the ion temperature in ORMAK to > 1.5 keV and caused the ion temperature to be higher than the electron temperature. To achieve 350 kW, it was necessary to add series floating—deck modulators[4] between the injectors and their respective high voltage supplies. It was also necessary to maximize the transmitted neutral beam power through a careful procedure of aligning the source and beam line, focusing the beam via proper grid curvature and spacing, and optimizing the source operating parameters.

Measured beam line losses were found to be consistent with those expected from inferred line densities. Thus the "choking" effect[5] was not observed over the pressure range and beam current range studied. One of the neutral injection systems is being replaced by a 15-cm duoPIGatron-based system. When this system is operational, it is expected that > 500 kW of neutral beam power will be injected.

2.2 PLT Neutral Beam Injection

1-MW neutral beam injection systems[6,7] for PLT have been designed and constructed, and testing has begun. A facility[8] for testing these and other ≤ 60-keV neutral beam systems has been built. Important features of the system are a 3.6-m beam line employing a 60-A, 40-keV ion source, 4 m^2 of cryocondensation pumping providing a conductance limited speed of 2-3 x 10^5 ℓ /sec, a magnet to deflect the unneutralized components to appropriate beam dumps, a tilted, movable, water-cooled calorimeter capable of dissipating peak beam power densities of 25 kW/cm^2, and a cryopanel providing 2 x 10^4 ℓ/sec in the drift tube for additional pumping in this critical region.

2.3 TFTR Neutral Beam Injection

A conceptual design[9,10] was done of the complete Tokamak Fusion Test Reactor (TFTR) neutral beam system, including injectors, beam lines, remote handling, power supplies, and controls. The neutral beam line features three 150-keV, 50-A multistage injectors, loosely coupled gas cells, one common magnet to deflect and dump the residual ion fractions, a 25-MW movable calorimeter, 50 m^2 of cryopumping surface, and a fast shutter.

A test facility[11] was constructed for the development of TFTR injectors and other $\leq$ 150-keV neutral beam systems. Experimental flexibility was achieved by constructing the test stand out of independent vacuum modules and by using a modular power supply capable of supplying a wide variety of voltages and currents. The fast floating-deck modulator for the facility consists of three 60-kV modulators in series.[4]

2.4 Ion Sources

A duoPIGatron ion source with a 10-cm-diameter extraction system[2,3] was developed for neutral injection in ORMAK. It produces ion currents of $\leq$ 15 A,, voltages of $\leq$ 40 kV, and pulse lengths of $\leq$ 0.75 sec. In combination, these parameters are limited to 0.2 kJ per pulse.

The duoPIGatron source was modified by adding a line cusp or magnetic multipole[12,13] arrangement in the plasma chamber to augment plasma confinement. A version of the line cusp modified duoPIGatron with a 15-cm-diameter extraction system yields 30 A at a power supply limited voltage of 27 kV.

A line cusp modified duoPIGatron with a 20-cm-diameter extraction system is used on the PLT injectors. It has been operated at 60 A, > 30 keV and > 40 msec. Design goals are 60 A, 40 keV and 300 msec.

A magnetic multipole Mackenzie plasma source, without the duoPIGatron plasma feed, having a 15-cm-diameter extraction system has been built and tested. A noise-free, uniform, $7 \times 10^{11}\text{-cm}^{-3}$ hydrogen plasma was produced in this source. The arc power efficiency is better than in the equivalent size modified duoPIGatron source.

2.5 Beam Optics

Experimental beam optics studies, correlated with numerical simulations, [14] have led to improved single-beamlet optics with both one- and two-stage extraction systems. Single-stage systems give half width at half maximum (HWHM) divergence angles of $\gtrsim 0.8^\circ$, with the optimum (smallest) divergences achieved with careful selection of extraction system dimensions and the shape of the first electrode aperture.

Two-stage extraction systems give HWHM divergence angles of $\sim 0.5^\circ$ for beam energies up to 60 keV. It is found both experimentally and with the simulations that the minimum divergence occurs when the ratio of the second (accelerating) gap voltage to the first (extraction) gap voltage is greater than $\sim$4.

2.6 H^+ Enhancement

Increasing the full energy component of the neutral beam by increasing the H^+ component in the plasma source results in better penetration of the plasma by the neutral beam. The H^+ fraction in duoPIGatron ion sources was enhanced by predissociating the hydrogen gas prior to the arc discharge and simultaneously minimizing the recombination rate on internal surfaces. The hydrogen feed was through a $\sim$ 2400-K tungsten oven, which was both a thermal dissociator and a cathode. This gave the beam a H^+ component of 75%, as opposed to a 55% H^+ component without the tungsten oven.

3. LBL/LLL NEUTRAL BEAM WORK

The LBL/LLL Neutral Beam Development Program can be divided into two areas: 1. Development based on positive-ion acceleration and neutralization, primarily for near-term applications on the 2X, BB, MX, and TFTR confinement experiments, and 2. a higher-efficiency-injector program based on acceleration and neutralization of negative ions, which may be required for fusion reactors and reactor-like experiments. In addition there is related work (not described here) on negative-ion production and on direct energy recovery.[15]

3.1 Positive-Ion-Based Development

3.1.1 TFTR Neutral Beam System Development

3.1.1.1 Conceptual Design

A conceptual design of a neutral beam system for TFTR has been carried out.[16] This system will use three rectangular sources, producing beams optimally matched to the apertures into TFTR. Pumping is by cryocondensation pumps; a sweep magnet deflects particles into "inertial" beam dumps (i.e., not dynamically cooled during the pulse). A computer system is used for beam diagnostics and control of the system. We expect to complete the engineering design by June 1977.

3.1.1.2 Test Facilities

Large test stands for TFTR and other neutral beam development projects are under construction.

We are completing a new facility[17] at LBL with power supplies capable of producing 150 kV, 20 A, 0.5 sec pulses. The gas load from the test sources is handled by a combination of expansion into an evacuated 170,000 liter volume and pumping by two 0.9-m diameter oil diffusion pumps (65,000 ℓ/sec speed) and two titanium sublimation pumps (16,000 ℓ/sec).

The high voltage power supply for this facility consists of three 50-kV, 20 A, 0.5 sec transformer-rectifier modules connected in series. Shunt regulation is used[18]; switching and fast crowbarring is done by two high-voltage silicon-controlled rectifier assemblies. A good degree of isolation between the neutral beam source and the energy stored in stray capacitance in the power supply is provided by a set of tape-wound cores surrounding the connecting electrical leads; the cores absorb most of the energy in case of a short between accelerator grids.

Early in 1977 a second, independent beam line will be added to this facility, with power supplies capable of 150 kV, 80 A, 30 msec pulses.

Construction is underway on the High Voltage Test Stand (HVTS) at LLL, which will be used for production of 200 keV efficient (D^-) beams, for testing a full-size TFTR module for 0.5 sec and MX sources for 30 sec. This facility will be capable of 200 kV, 25 A, dc, or 120 kV, 65 A, 30 sec, or 80 kV, 80 A, up to 30 sec. Cryocondensation pumping is used throughout, with a total pumping speed of 950,000 ℓ/sec for deuterium. The facility is expected to be operational in mid-1977.

3.1.1.3 Source Development

A first model of a TFTR neutral beam source has been constructed and will be the first item tested on the new LBL test facility. This source will operate with the same beam energy, current density, and accelerator grid geometry of a full-size TFTR source, but will have only 1/4 the area. The accelerator structure has four grids, of molybdenum, with provision for cooling one end of each grid rail. The shapes of the rails were computer-optimized to provide optimum ion optics with minimum interception of secondary particles.

A 15-cm-diameter ("10-Ampere") source has been modified to demonstrate the long-pulse ($\gtrsim$ 1/2 sec) capability required by TFTR and other experiments now being planned. This source has 56 tungsten filaments, operated with dc heater current, and oriented so as to provide a ring-shaped region of magnetic field (about 45 gauss) between the plasma volume and the outer wall. Langmuir probe measurements indicate that the deuterium ion current density in the central 8 cm diameter region is uniform to $\pm$ 1% in space and time for 1 sec pulses at $j_+ = 0.25$ A/cm^2 and to $\pm$ 4% for 0.5 sec pulses at $j_+ = 0.5$ A/cm^2. No filament lifetime tests have been performed, but the source has produced in excess of 4000 0.5-sec-long pulses at 0.35 A/cm^2,

This source was coupled to a standard "10-A" accelerating structure with uncooled Mo and W rails, and successfully produced 1.0-sec, 7.5 A deuterium beam pulses at 15 keV ($j_+ = 0.25$ A/cm^2), and 0.75-sec, 15 A pulses at 20 keV ($j_+ = 0.5$ A/cm^2).

Eventual improvements in gas efficiency, control of ion species, ion temperature, and electrical efficiency require a better understanding of the physics of the plasma source. A combined experimental and theoretical advanced development program is underway to achieve this understanding.

3.1.2 MX and BB Neutral-Beam-System Development

Development of 80 keV injectors for the large MX mirror experiment, and 50 keV injectors for the Baseball mirror experiment is in progress; the design of these injectors is based on modification and extensions of the TFTR design.

3.2 Efficient Neutral Beam Production by Negative Ions

Our primary approach is to produce a beam of 1 keV D^+ ions, convert a fraction of them to negatives in a Cs charge-exchange cell, and accelerate the resulting D^- beam first to 100 keV, then at a later date, to 200 keV. A modified LBL "10-A" source is used to produce 10 A of 1 keV deuterium ions in a 10 msec pulse. In the present experiment about 1 A of the beam passes through the narrow apertures of the Cs cell. At least 18% of these 1 keV ions are converted to D^- ions in a Cs cell; these will be accelerated to 100 keV in an accelerator nearing completion. Long pulses at much higher currents will be accelerated to 200 keV after completion of the High Voltage Test Stand.

The transport of a dense, low-energy negative ion beam has been achieved experimentally and also studied computationally; measured profiles (through the beam) of $V_{floating}$, n_i, and n_e show good agreement with those from a computer model. The electron density can be kept low; even some focusing of the beam by plasma potentials should be possible. There are also additional small experiments and theoretical studies of D^- production techniques.

4. BNL NEUTRAL BEAM DEVELOPMENT

The objective of the BNL Neutral Beam Program is to develop a 150 keV multiampere (equivalent) neutral injector with essential support systems based on long pulse, multiampere sources of negative hydrogen and deuterium ions, close coupled acceleration to the required energy and on neutralization of high energy negative ions in a gas or plasma jet. High speed cryogenic and molecular sieve pumps are being developed as part of the program.

4.1 Negative Ion Sources

Three types of negative ion sources are being investigated: magnetron, Penning and hollow discharge duoplasmatron (HDD). Their common features are a cold cathode operation mode and the addition of cesium vapors. A magnetron source with a cathode area of 13.5 cm^2 was designed and tested.[19] Using six extraction slits with a total extraction area of 1.3 cm^2, H^- currents of up to 0.9 A were obtained in pulses of 10 ms duration and at a pulse rate of 0.1 Hz. The extraction voltage was up to 18 kV and the gas flow about 3-4 torr ℓ/cm^{2}s. It was possible to extend the pulse length to 20 ms, but due to the arc power supply limitations the H^- yield was only 0.6 A. A small Penning source with a cathode area of 2 cm^2 was tested, yielding H^- currents above 100 mA from a three slit aperture with an area of 0.3 cm^2. Pulse length was 20 ms and the pulse rate 0.1 s. Compared to the magnetron source, a Penning source has a lower arc power efficiency, but its gas efficiency is appreciably better. A larger model, for H^- currents up to 1 A, is under construction. Finally, H^- currents up to 60 mA were obtained from a HDD source,[20] with a current density above 1 A/cm^2 at the extraction aperture. Studies of the cathode temperature control for magnetron and Penning sources are underway, with the goal to design a source capable of operating with pulses of 0.1 to 1 s duration.

4.2 150 kV Test Facility

The accelerating system (150 kV) has been designed by computing particle trajectories in a single slit geometry. At an initial current density of 0.5 A/cm^2 calculations predict a quasi-parallel beam. The 150 kV test facility has been constructed and initial tests with high energy H^- beam have begun. As a part of the focusing system an air core quadrupole was constructed producing a uniform gradient of 0.05 T/cm within a 7 x 7 cm^2 aperture.

4.3 Cryopumping

A 100,000 ℓ/s cryopump was put into operation. Its design was based on small model measurements of properties of frozen hydrogen and deuterium layers. Pumping speed measurements showed values of 120,000 ℓ/s for hydrogen and 100,000 ℓ/s for deuterium, dropping by about 20% with a 0.2 mm thick frozen gas layer.

Slides

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