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DEVELOPMENT OF 120 keV NEUTRAL BEAM INJECTORS*

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Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720

Summary

Recent development efforts on 120-keV ion sources for neutral-beam systems for the fusion program have focused on producing pulse-lengths longer than the 0.5-sec originally specified for TFTR and improvement of the atomic-ion fraction of the beam. From heat-load measurements of the accelerator grids we deduce that our edge cooled grids should be capable of operation for pulse lengths of the order of 2 seconds; we have operated our 8- × 10-cm accelerator for 1.5-seconds and have fabricated a water-cooled accelerator for longer pulse operation. A multi-cusp ion source has been used to produce 65A beams with D^+ fractions of about 75%.

Introduction

The design of the neutral-beam injection system for TFTR is based on 120-kV ion-source/accelerator injector modules which produce 65-A of deuterium ions for 0.5-sec pulses at 5 minute intervals.[1] At the time of the design, no large-current 120-keV injector modules had been developed. In order to carry out the beamline design the beams from the yet-to-be-developed TFTR sources were characterized by a bi-gaussian beam uniformly distributed over a 10-cm by 40-cm area at the source with 1/e half-widths of $1^\circ \times 0.3^\circ$ and a molecular-ion composition of 70% D^+, 20% D_2^+, and 10% D_3^+. These quantities were extrapolations of our experience with 20- and 40-keV modules.

Recently, TFTR operation with ~1.5 second pulse lengths and D^+ fractions of 86% has been specified. Development of 5- to 30-second injectors for additional upgrades and/or experiments has been started.

The development of these injectors has proceeded in a two-step sequence: Design concepts are tested on relatively small sources (typically with an accelerator-grid area of 8 × 10 cm) to minimize the money and time investment in repair, modification, and power supplies. These test sources are similar to the larger prototype sources in the critical areas of grid dimensions, beam current density, and pulse length, and can be extrapolated in one dimension. Following (or more often, concurrent with) successful demonstration of performance of these test sources, full-size prototype sources are built.

These facilities pace the development program. At LBL two facilities are operational: Test Stand IIIA, which has 120-kV, 15-A, 1.5-sec capability (currently being upgraded to 150-kV, 15-A, 5-sec), and TS IIIB, which has a capacitor bank that can supply 120 kV, 70 A but only for about 15 msec. Neither of these facilities has sufficient shielding, for the d-d neutrons produced by deuterium-beam operation,[2] to permit steady deuterium operation. Two well-shielded facilities, NBSTF at LBL and HVTS at LLL are in the commissioning stage; both will have 120-kV, 65-A, 0.5-sec capability.

Several small test-sources have been operated at the 0.25-A/cm^2 current density appropriate for TFTR at 120-kV for 0.5 sec.[3] The full-size TFTR source[4-6] has been operated at 120 kV and 65 A,[7] (but the capacitor-bank power supply of TSIIIB limits full-voltage pulse lengths to about 15 msec.). Tests up to the 0.5-sec design pulse lengths are in progress on the NBSTF facility at LBL.

In this paper concentrate on recent development efforts to improve the D^+ fraction of the beam and to determine the pulse-length limitations of the edge-cooled accelerator. Other aspects of 120-keV development are described elsewhere in this conference.

TFTR Injector Module

Two modules of the type shown in Fig. 1, and described in Refs. 4-7, have been operated up to 120 kV, with either H_2 of D_2. The accelerator current vs. accelerator potential, at minimum beam divergence observed on the calorimeter is shown in Fig. 2. The

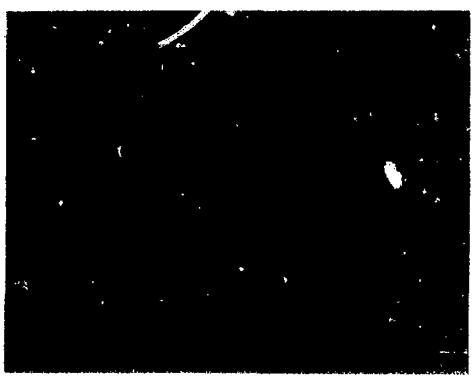

Fig. 1. Cross section of the 120-kV, 65-A, 0.5-sec TFTR injector module.

current is expected to follow the Langmuir-Child relationship for space-charge limited flow and this $V^{1.5}$ dependence is indicated by the lines in Fig. 2. With the capacitor-bank power supply we have been able to run 0.5-sec pulses at low voltages and low currents, but at 120-kV we have been limited to 13 msec.

The beam divergence, determined both from the temperature profile on the calorimeter (corrected for the finite grid area) and Doppler-shift spectroscopy,[8] can be characterized by the 1/e points of a bigaussian distribution. At 120-keV the divergence is $1.1^\circ \pm 0.1^\circ \times 0.4^\circ \pm 0.1^\circ$; the divergence is somewhat greater at lower energies.

The source module is operated with a gas flow of 10-20 T-ℓ/sec D_2 and 15-30 T-ℓ/sec H_2. The current drain on the suppressor power supply, primarily due to ions from the neutralizer striking the suppressor grid, increases with increased gas flow; it is nominally 15%

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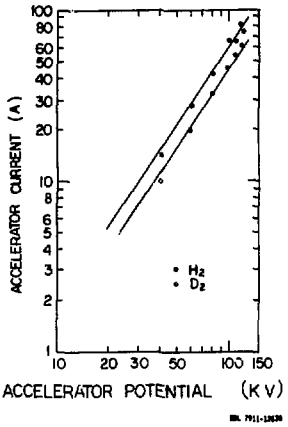

Fig. 2. Accelerator current vs. voltage for minimum angular divergence beams for the TFTR injector. Results for both hydrogen and deuterium operation are shown. The lines through the data points are proportional to $V^{1.5}$.

of the accelerator current. The net current (electrons) collected by the gradient grid, which also depends on the gas flow, is nominally 100 to 250 mA.

The mixture of D^+, D_2^+, and D_3^+ that is accelerated is determined by momentum analysis of ions surviving passage through the neutralizer[9] and by analysis of the relative intensity of the Doppler shifted light emitted by the full, half, and third energy atoms in the beam.[8] The measured beam composition, as a function of accelerator current (arc power), for the conventional 12-cm-deep plasma source of Fig. 1 are shown by the dashed lines in Fig. 3. A 23-cm-deep multi-cusp plasma source[10,11] improved the D^+ fraction of the accelerated ions from about 65% to about 75% (solid line in Fig. 3) at the 65-A level. (In an attempt to raise the D^+ fraction even higher, a second 23-cm

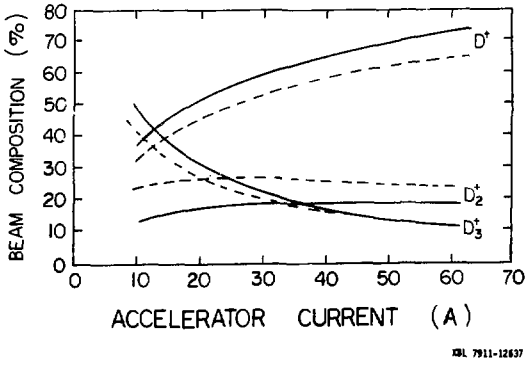

Fig. 3. Molecular ion composition of the beam vs. accelerator current: ---, conventional plasma source (Fig. 1) at 24-T-ℓ/sec; ——, multi-cusp source, 17-T-ℓ/sec.

multi-cusp wall section[11] will be added to form a 46-cm deep plasma chamber.) The variation of beam composition with gas flow is shown in Fig. 4 for 80-kV operation with the 23-cm multi-cusp source.

8- × 10-cm Test Source

The accelerator grids for the TFTR source are solid molybdenum rods which are end-cooled;[5] heat transfer by conduction to the ends is slow, and several minutes are required for the grids to cool. Thus, the heat load and the heat capacity of the grids determine the grid temperature at the end of a beam pulse. To measure the heat load to the grids we fabricated a test source, Figs. 5 and 6, on which the cooling water

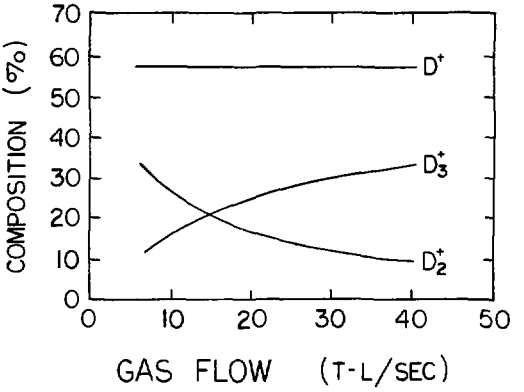

Fig. 4. Molecular ion composition of an 80-kV deuterium beam vs. gas flow for the multi-cusp ion source.

Fig. 5. Schematic of the 8- × 10-cm test source used for grid calorimetry.

Fig. 6. Photograph of the 8- × 10-cm test source.

for each set of grids is on a separate circuit. Each cooling circuit is equipped with a flowmeter and thermistors to measure the water temperature of the inlet and exhaust lines; the average heat load to each grid could thus be determined by water-flow calorimetry.

For a 9-A, 110-kV deuterium beam (1 MW) we measure heat loads of about 5, 2, 2, and 2 kW for the source, gradient, suppressor, and exit grids. About one-half of the heat load on the source grid is from the plasma source. The heat load on the source grid increases as the source is detuned from minimum beam divergence by increasing or decreasing the accelerator voltage for a fixed arc power; the gradient and suppressor grids are relatively insensitive to beam tuning; and the heat load to the exit grid decreases monotonically as the accelerator voltage is increased from below optimum divergence to above optimum divergence.

For these heat loads, the heat capacity of the grids is such that we should be able to operate with beam pulses of the order of 2 seconds and still maintain the source grid (the hottest) below about 2000°C. To date we have operated this source for 1.5-sec pulses. At 110 kV and 9-A we were able to operate steadily at the 4-min repetition-rate limit of the power supply. At 120 kV and 10-A we could operate only about six consecutive 1.5-sec pulses at 4-minute intervals; after that the grids would not hold voltage. However, we could operate 120-kV, 10-A, 1.5-sec pulses repetively at 10-minute intervals, or 1-sec pulses at 3-min intervals. We do not know whether this was caused by overheating of some of the uncooled grid masks, or local hot spots on either the gradient or suppressor grids, or perhaps something else. The various grid currents showed no time variation during these 1.5-sec pulses.

We have built a new test accelerator with hollow, water-cooled grid rails for operation beyond 1.5 seconds.[12] The TSIIIA power supply is being modified for 5-sec capability, and we expect to start tests on this system in December.

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