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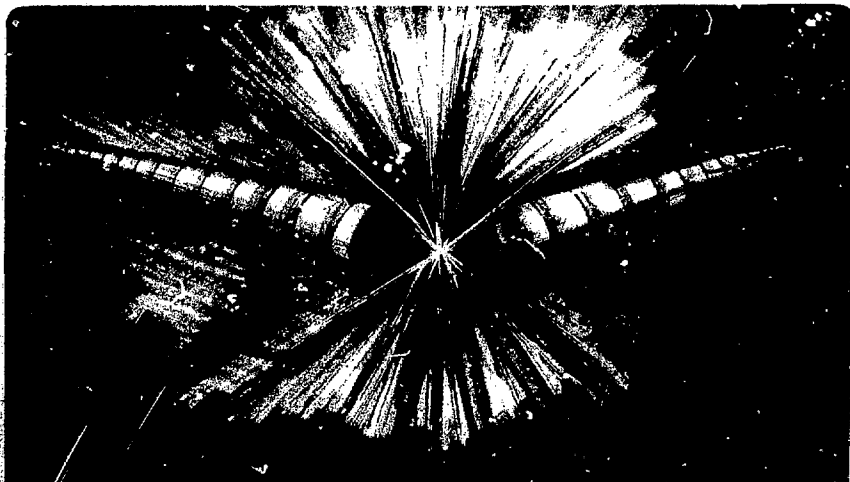
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THE PROTOTYPE NEUTRAL-BEAMLINE FOR TFTR

MASTER

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PERFORMANCE CHARACTERISTICS OF NBSTF, THE PROTOTYPE NEUTRAL-BEAMLINE FOR TFTR*

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Abstract

The Neutral Beam System Test Facility (NBSTF) at the Lawrence Berkeley Laboratory is a shielded facility for prototype development and testing of the multi-megawatt neutral-beam injection system for the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory. NBSTF includes: a power system capable of regulated, rapidly switched 120-kV, 75-A, 1.5-sec pulses every three minutes; the cryopumped TFTR prototype beamline with calorimeter, sweep magnet, ion dump, duct, and a target calorimeter; and a computer controls and diagnostic system. Beam-diagnostic systems include: temperature profiles on calorimeter, target dump, and ion dump; temperature measurements on neutralizer and beam scrapers; water-flow calorimetry; Doppler-shift spectroscopy and an electrostatic analyzer; and an array of pressure gauges to determine gas distribution. Beam operation at 120 kV, 65 A, 0.8 sec has been achieved with a molecular-ion mixture of $60\% D^+ / 30\% D_2^+ / 10\% D_3^+$. Limited operation with an improved plasma source has yielded $80\% D^+ / 15\% D_2^+ / 5\% D_3^+$ at 120 kV, 67 A, 0.5 sec. The estimated 12-keV D^+ power delivered with twelve ion sources to TFTR is 17 ± 2 MW for the standard plasma source and 22 ± 4 MW for the improved source.

Introduction

The Neutral Beam System Test Facility (NBSTF) at the Lawrence Berkeley Laboratory is the prototype of the neutral-injection beamlines for the TFTR at the Princeton Plasma Physics Laboratory. The design and fabrication of the beamline have been described previously.¹⁻³ The operational phase is almost complete, and we present here a summary of the measured performance characteristics of the beamline.

A schematic diagram of the NBSTF is shown Fig. 1. The beamline is designed with three sources and neutralizers; however, at LBL there is only one power system, and only the central beam position has been used. The magnet which is used to remove ions from the beam is the first aperture for a series of differential pumping stages. The ion dump, recently rebuilt to handle 1.5-sec beam pulses, is located in the second differential-pumping chamber. The third chamber contains a retractable calorimeter which allows beam operation and tuning when the exit valve is closed. A stainless-steel duct, with the same inner dimensions as the one to be used for TFTR, connects the beamline to the target tank, where the neutral beam is stopped. The target tank simulates the TFTR torus.

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A summary of the diagnostic instrumentation on NBSTF is given in Table I.

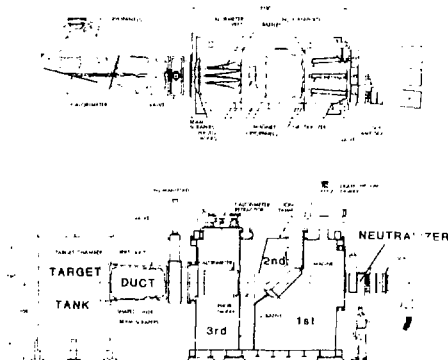


Figure 1: TFTR Neutral Beam Injector

Plasma Sources

Two different plasma sources have been used as ion generators for the accelerator. Most of the operation has been with the LBL field-free source,⁴ which contains 206 hairpin filaments, 9.5-cm long and 0.5-mm in diameter. The filaments, operated at about 4800A and 10V, are run in the space charge limited mode. Arc parameters to achieve a deuterium current density of 270 mA/cm^2 are 45V and 1800A. When mated to an accelerator the gas flow for these conditions is 22 T-l/sec. Eight Langmuir probes, distributed around the periphery of the $10 \text{ cm} \times 40 \text{ cm}$ grid area, are used to monitor the plasma uniformity; peak-to-peak variations among the saturated ion currents of the eight probes are typically less than $\pm 6\%$. The average filament life for 0.5-sec full-power operation is 9000 pulses.

A new "hybrid" plasma source has recently been used to achieve a higher fraction of atomic ions. This consists of a field-free source coupled to a 23-cm-deep magnetic-bucket expansion chamber.⁵ This expansion chamber, electrically isolated from the field-free source and the accelerator by anodized aluminum plates, is the primary anode for the discharge. The filaments are operated in the emission-limited mode. To prevent a change in emission current when the arc is turned on, the filament power is reduced to compensate for the extra current in the filaments and maintain a constant emission current. With the control of the emission

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current, this arc can be operated at various impedances - ion densities of 270 mA/cm² have been obtained in the range from 85V, 1400A to 130V, 800A. Peak-to-peak variations on the probe array have been as low as +/- 2%. Although we do not have sufficient operating experience to determine an average filament life, we expect longer life because the filament temperatures are reduced in the emission-limited mode. Results quoted in this paper for this source are based on only a few weeks of operating experience and should be considered preliminary.

Both plasma sources produce quiescent plasmas; the only time variations observed are a few percent of 720 Hz ripple from the power supplies. Both plasma sources have been operated at full power for 1.5-sec pulses.

Accelerators

Four accelerators - two built at LBL and one each built by McDonnell Douglas and Hughes Research Laboratories - have been used to produce 120-kV, 0.5-sec deuterium beams. All are slot-type, four-grid accelerators with a 10-cm x 40-cm flat grid area and a transparency of 60%.^{6,7} We experienced some accelerator failures (secondary electrons melted parts of the gradient grid, leaks developed in cooling lines, etc.) as we were determining the operating parameters for the system, but all have now been repaired or modified and are operational. For deuterium, the current for which minimum beam divergence is attained (optimum permeance) is 65A (1.56 micropervees). We have only limited data on the time required to condition a new accelerator; from our experience we estimate that three to five thousand beam pulses (starting at 40 kV and gradually increasing the accelerator potential and current) are required to condition a new accelerator to the 120-kV, 65-A, 0.5-sec level.

One of the accelerators has been operated for pulse lengths longer than 0.5 sec. Up to 90 kV there was no difficulty in achieving 1.5-sec pulses; at higher power levels, the pulse lengths were limited by multiple sparking: 1.4 sec at 100 kV, 1.25 sec at 110 kV, and 0.9 sec at 120 kV. From measured heat loads we estimate that the edge-cooled grids have sufficient heat capacity for 1.5-sec pulses at 120 kV. We do not know whether the observed pulse-length limits were caused by local hot spots on the grids or by outgassing in the plasma source caused by backstreaming electrons. Since long-pulse operation has been attempted only with one accelerator we do not know whether the pulse-length limits are inherent to this design or whether they are characteristic of this particular accelerator.

The divergence of the beam is determined from temperature distribution on the flat-plate beam dump in the target tank, 11 m from the accelerator. Divergences perpendicular and parallel to the slots are obtained from a least-squares fit of the temperatures from an array of thermocouples imbedded in the dump to a bi-Gaussian distribution (bi-Gaussian point sources uniformly distributed over the 10-cm x 40-cm grid array); the fit to the data is excellent. For a well-tuned beam at 120 kV, the perpendicular divergence (1/e angle) is $0.92^\circ \pm 0.05^\circ$ and the parallel divergence is $0.42^\circ \pm 0.05^\circ$. The uncertainties indicate day-to-day variations; repeatability on successive beam pulses is +/- 0.020°. We note that the temperature distribution on the V-shaped, retractable calorimeter 6 m from the accelerator is more highly peaked in the center than a bi-Gaussian function. We do not know

whether this is an artifact of the instrumentation or whether the beam has this shape near the accelerator.

The beam divergence can also be determined from the Doppler broadening of light emitted by the atoms in the beam.⁸ The full-energy atoms, produced by charge exchange of D⁺ ions have the least divergence, whereas the fractional energy atoms, produced by dissociation of molecular ions, have larger divergences. The RMS width of the third-energy atoms is typically twice that of the full-energy atoms, and that of the half-energy atoms falls between these two. The Doppler-broadened spectral lines are not Gaussian, hence the divergences obtained spectroscopically cannot be compared directly with the 1/e divergences from the beam dump; we have, however, compared the sum of the RMS angles for each of the three energy components, weighted by the fraction of the beam in that component, with the RMS angles at the dump. The weighted Doppler angles tends to exceed the angles determined from the thermal pattern by 10 to 20%.

Beam Composition

The mixture of atomic and molecular ions (D⁰/D⁺/D₂⁺) in the ion beam leaving the accelerator is deduced from the relative intensity of the light emitted by the full, half, and third-energy atoms in the beam (Doppler-shift spectroscopy).⁸ The beam produced by the field-free plasma source contains a mixture that is about 60% D⁰/30% D₂⁺/10% D⁺ at a current density of 270 mA/cm². Slight variations in composition can be obtained by varying the gas flow, but the atomic component is usually in the range 60-65%. Preliminary results with the hybrid source indicate a significant increase in the atomic-ion component, 80% D⁰/15% D₂⁺/5% D⁺ at 270 mA/cm².

We also observe light emitted by atoms with one-tenth energy, which we attribute to atoms produced by the dissociation of D₂⁰. For the first few beam shots of the day the intensity of the tenth-energy light may be as high as 10% of the total Doppler-shifted emission; this quickly drops to 4%, and, after several dozen pulses reduces to less than 1%. We are unable to quantify the D₂⁰ fraction in the beam because of a dearth of relevant cross sections. We estimate that in the steady-state we may have one or two percent of D₂⁰.

An electrostatic analyzer has been mounted on the exit of the target tank to analyze a small portion of the neutral beam. This has proved to be an extremely difficult measurement because of the high power densities in the beam, and we have no results to report at this time.

Power Inventory

The beamline is instrumented with ten water-flow calorimetry modules to measure the power deposited in various parts of the beamline.⁹ Unfortunately, some of the beamline components have such long thermal diffusion times that they are not amenable to this measuring technique: The plasma source (we estimate 3% of the electrical power is in backstreaming electrons); the accelerator grids (1-2%); the first 125 cm of the neutralizer (5-8%); the one-third-energy ion dump (2%); the negative ion dump (1%); and the duct (from a comparison of the power measured with the calorimeter at the entrance to the duct with the power measured on the target-chamber dump, we estimate that 0.5 - 2% of the power is deposited on the duct).

We directly measure 80 - 85% of the beam power on components which have sufficiently short time constants to permit water-flow calorimetry: About 6% of the power is deposited in the second 125 cm of the neutralizer; 3 - 4% on the magnet aperture; 1-2% on the calorimeter aperture; and about 0.5% on the exit aperture. In the target tank we measure 70-75% of the total electrical power when the magnet is off (ions plus neutrals). The neutral power on the target plate at 120 kV is 40 +/- 4%, or 3.1 +/- 0.3 MW at 120 kV, 65A.

Pressure Distributions

Pressure distributions in the TFTR beamline have been measured with and without beam.^{10,11} We have found that the temperature of the gas in the beamline is about 100 K, streaming from the neutralizer is consistent with a cos θ distribution, and that beam-induced gas desorption from the beam dumps increases rapidly with pulse duration. Reionization losses between the magnet and the exit of the duct have not been measured directly; from the pressure measurements we estimate 6 - 9 % reionization losses.

Regeneration of the Cryopanel

The cryopanel must be defrosted periodically to remove the condensed deuterium gas, to prevent the accumulation of sufficient deuterium to form an explosive mixture in an up-to-air accident or (for TFTR) to limit the tritium inventory in the system. A spring-loaded ball valve in the liquid helium dewar allows recovery of liquid helium for rapid regeneration.^{1,12} The ball valve is closed, as is the liquid helium exhaust valve; the panels are heated by introducing a few Torr-liters of helium gas into the system; the liquid helium is forced past the spring-loaded ball valve into the storage dewar; the deuterium gas is removed by turbomolecular pumps; and the panels are again filled with liquid helium. The entire sequence takes about an hour. Most of this time is used in removing the deuterium with the turbomolecular pump.

Autoconditioning

For 12-source operation on TFTR it is imperative to have computer control for the ion sources. A computer control system has been developed and successfully demonstrated for autoconditioning of the sources. For the demonstration, a source was operated strictly under computer control from 80 to 120 kV. The criterion for increasing or decreasing the accelerator voltage was the fraction of beam time with respect to beam-request time. False interrupts (with a timer) could be introduced to simulate a deterioration in accelerator condition; these were recognized and the voltage was decreased (along the permeance curve) to allow grid conditioning. This accelerator was already conditioned from previous operation, so the test was not as severe as with an unconditioned accelerator, but the computer model for decision making is the same in either case.

Summary

The beamline performance characteristics are summarized in Table II. In the column labeled "Design" we have listed the performance goals from the 1975 conceptual design for the NBST project.¹⁵ Under "Achieved" we show the results obtained with the field-free plasma source and preliminary results obtained from limited operation with the hybrid source. We have estimated the power

in the 120 kV D⁰ component from the molecular species mix determined by Doppler-shift spectroscopy, calculated neutralization efficiencies for a thick-target neutralizer, and the total neutral-beam power measured on the target dump with water-flow calorimetry. To estimate the 12-source performance on TFTR we have included a possible 6% beam loss due to re-ionization.

As can be seen from Table II, the measured performance characteristics of the TFTR beamline meet the design specifications of 1975.

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Table I: NBSIF Diagnostics

1. Plasma Density Profile (8 Probes)			
2. Thermocouple Temperatures	Tables	Isotherms	Bi-Gaussian Fit
(A) Ion Dump	X		
(B) Beamline Calorimeter	X	X	X
(C) Target Dump	X	X	X
(D) Apertures	X		
(E) Duct	X		
3. Doppler-Shift Spectroscopy for Divergence and Molecular-ion Species			
4. Water-flow calorimetry			
(A) Neutralizer (last 125 cm)			
(B) Magnet aperture			
(C) Ion Dump			
(D) Calorimeter Aperture			
(E) Beamline Calorimeter			
(F) Target Dump			
5. Summary Display of Performance Data			
6. Shot-to-Shot Correlation			
(A) Source Tuning $\theta_L, \theta_{II}, I_{GG}, P_{dump}, I/V^{3/2}$			
(B) Neutral Beam Source Characteristics			
(a) Filament: V vs I			
(b) Arc: V vs I			
(c) Acc1: V vs I			
(d) Arc - Acc1: I_{Acc1} vs P_{Arc}			

Table II: TFTR Beamline Performance Characteristics for Deuterium Operation

	1975 Design	Achieved	
		Field-Free Source	Hybrid Source*
Source Parameters			
Volts	120 kV	120 kV	120 kV
Amps	65 A	65 A	67 A
Pulse Length	0.5 sec	0.9 sec	0.5 sec
Gas Flow	30 T-l/sec	22 T-l/sec	22 T-l/sec
Divergence ($\pm$ l/e)			
Perpendicular to slots	1°	$0.92^\circ \pm 0.05^\circ$	$0.95^\circ \pm 0.05^\circ$
Parallel to slot	0.3°	$0.42^\circ \pm 0.05^\circ$	$0.35^\circ \pm 0.05^\circ$
$\%D_1^+/ \%D_2^+ / \%D_3^+$	70/20/10	60/30/10	80/15/5
Power Through Duct Per Source			
All neutrals	2.1 MW	3.1 $\pm$ 0.3 MW	2.4 $\pm$ 0.3 MW
120 keV D^0	1.6 MW	1.5 $\pm$ 0.2 MW	1.9 $\pm$ 0.4 MW
Expected 12-Source Performance			
On TFTR All Neutrals	25 MW	35 $\pm$ 3 MW	27 $\pm$ 3 MW
120 keV D^0	18.7 MW	17 $\pm$ 2 MW	22 $\pm$ 4 MW

*Based on limited operation; not yet optimized