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W. B. Kunkel, B. A. Prichard, Jr.†, R. V. Pyle, and J. W. Stearns

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Abstract

The neutral-beam injection systems for the next generation of U.S. fusion experiments (TFTR, MX, Doublet III) have requirements that considerably exceed the present state of development. TFTR, for example, desires 20 MW of 120-keV deuterium atoms in pulses of 0.5-sec duration. The neutral-beam systems needed to meet these demands will be large and complex and will require much development effort.

In order to develop components for these new systems, we have constructed a new, large test facility. The vacuum system, which has a volume in excess of 170,000 liters, will handle the pulsed gas loads by volume expansion; the gas will be pumped out in the one-minute intervals between pulses. The power-supply philosophy and specifications are discussed in an accompanying paper. A mini-computer system will be used to monitor and control the power supplies and to diagnose the beam.

Of the beam-line components, we discuss a plasma source and 120-kV accelerator structure which are under construction. A new long-pulse version of our 15-cm-diam high-current plasma source has been developed. Significant improvements have been made by re-orienting the filaments, so that they produce closed magnetic field lines near the wall, and by changing the shape and position of the anode. This new geometry has allowed considerable simplification in source construction. The accelerator structure is based on a computer-optimized design with four elements. The entrance-grid element is a 60%-transparent, 10- x 10-cm array of slots designed for an extraction-current density of $\sim 0.25\ A/cm^2$.

In addition to providing long-pulse, high-voltage operating experience with a large-current system, this program will allow us to investigate the very difficult problems associated with beam dumps and beam calorimetry.

I. Introduction

The next generation of U.S. fusion experiments, which includes TFTR, MX, and Doublet III, will utilize neutral-beam injection for plasma heating. For example, the Lawrence Livermore Laboratory's proposed MX experiment will use 80-kV, 0.5-sec modules injecting a total of 750 A (equivalent) of D atoms with a mean energy of 56 keV [1]; the Tokamak Fusion Test Reactor, which is to be constructed at the Princeton Plasma Physics Laboratory, requires 20 MW of 120-keV D atoms in 0.5-sec pulses at 5-minute intervals from a total of 12 individual neutral-beam modules [2].

The components of a neutral-beam system are shown schematically in Fig. 1. The system operation is as follows: A deuterium plasma is created in the plasma generator by means of a high-current arc discharge. Ions from this plasma are accelerated in a carefully designed

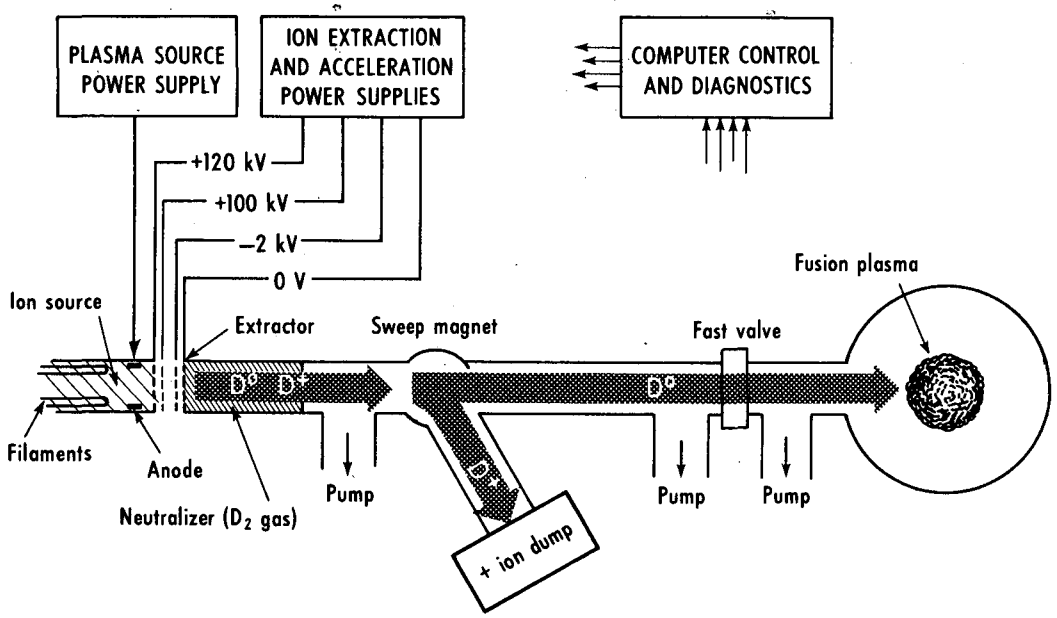

Figure 1. Schematic of a typical neutral-beam injection system.

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 paper we discuss some phases of the Lawrence Berkeley Laboratory's program for the development of such neutral-beam systems. As examples of the development of individual components, we discuss in detail some recent modifications of the plasma generator (along with results obtained with a small test version) and the design of a 120-kV accelerator grid system. These features have been incorporated into a 15-A, 120-kV, 0.5-sec module which will be operated on a new test facility; both are in the final stages of construction and will be described.

II. Plasma Generator

The plasma generator, or ion source, has to provide a hydrogen or deuterium ion-current density of 0.25 to 0.5 A/cm^2, with combined spatial and temporal variations less than ± 5% over a large area (e.g. approximately 400 cm^2 for the TFTR design). It is very desirable for the source to generate a high percentage of atomic ions and to operate with a high gas effi-

ciency. Our plasma generator [3] is a high-current low-voltage discharge with no externally applied magnetic fields. The advantages of this type of discharge are that it produces a dense and uniform plasma that is reproducible from pulse to pulse and free from noise. The geometry is very compact, an important consideration when a number of sources are stacked to inject into a common entrance port.

In a high-current discharge the cathode is the most important design consideration; in our sources this consists of an array of hot tungsten filaments around the periphery. In 1973 we constructed a source with 56 ac-heated filaments that was operated for pulse lengths up to 10 seconds [3]. Despite special winding of these filaments there remained a ± 8% 120 Hz modulation of the plasma density, an effect caused by the alternating magnetic field of the combined heater and emission currents that exist near the surface of the filaments. To eliminate this plasma-density variation we returned to dc-heated filaments. We also made an attempt to utilize the unavoidable magnetic field of the filaments by orienting the hairpin-shaped filaments such that all the negative-potential legs were located on the inner radius and the positive-potential legs on the outer radius of the filament circle. With this arrangement we generate a surface magnetic field similar to that used in the SURMAC experiments [4]. Although only ∿45 gauss, the ring magnetic field between the two legs of the 0.5-mm-diam tungsten filaments is sufficient to reflect energetic electrons which normally would be lost to the walls. The plasma is thus partially contained on the inside of the filament ring where the magnetic field is very weak. Figure 2 is a photograph of a 15-cm-diam test source modified for this new filament arrangement.

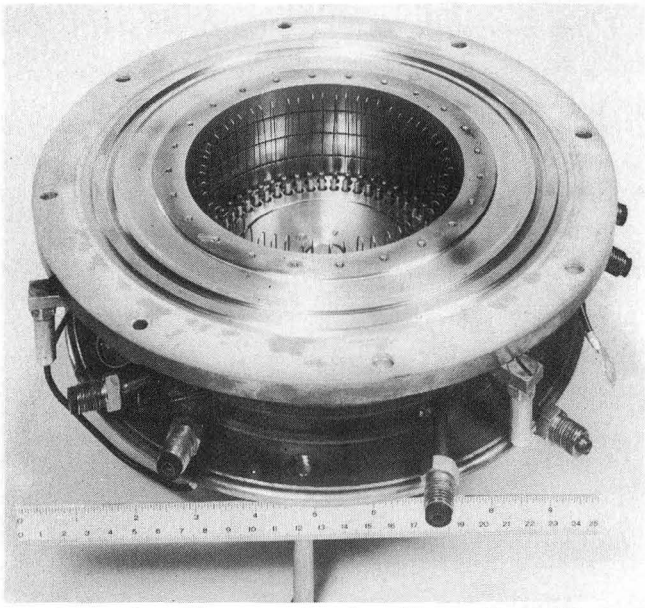

Figure 2. Photograph of a 15-cm-diam, 56-filament plasma generator.

When this source was initially operated, the conventional anode (the top wall-ring in Fig. 2) was used and an extremely unstable discharge resulted, possibly because the magnetic field from the filaments was preventing electrons from reaching the ring anode. We therefore chose the back plate (which formerly was electrically isolated and through which the gas is introduced) as the anode, since the magnetic fields from the filaments are weak in this region. With this anode position the discharge operates in the quiescent and reproducible manner that has been characteristic of these sources.

The floating potentials of the various segments of the source body were found to be very close to filament potential. Thus these elements could be, and now are, electrically connected to the negative leg of the arc power supply. This simplifies the source construction, in that the revised source structure consists of a cathode ring (at the same potential as the walls) and an anode, which is the end plate.

A saturated ion-current-density profile for this test source, obtained with Langmuir probes near the plane of the accelerator grid, is shown in Fig. 3. Within a diameter of 8 cm

the current-density is uniform within ± 1%. (The position of the filaments is indicated for comparison.) Time-variations are also less than ± 1%, as can be seen from the oscilloscope traces of the arc-current, arc-voltage, and saturated ion-current of two probes located 3 cm either side of center. (The 60 Hz variation on all waveforms comes from the arc power supply and is also present when a resistive load is used.) In addition to providing noise-free, uniform ion-current densities of 0.25 to 0.5 A/cm^2, filament damage due to electrical breakdowns is minimized by this new discharge version. Although no detailed filament lifetime tests have yet been performed, we note that this source has produced in excess of 4000 0.5-sec-long pulses at 0.35 A/cm^2.

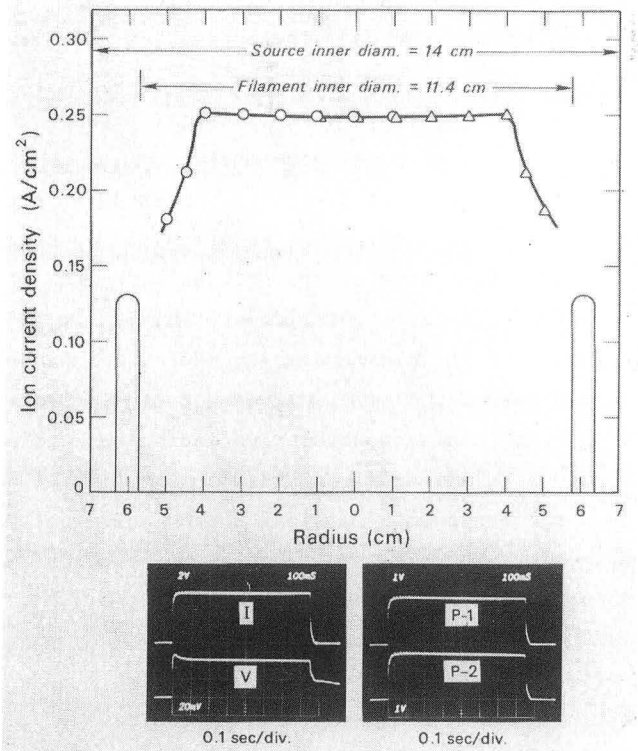

Figure 3. Ion-current-density profile for the plasma generator shown in Fig. 2. Also shown are oscilloscope traces of arc current (475 A), arc voltage (40 V), and saturated-ion current drawn by two probes, 3 cm on either side of the axis.

This plasma source has been used in conjunction with one of our 20-kV extractors [5]. Measured long-pulse performance characteristics are shown in Table I for two accelerating voltages. The quoted upper limits to the angular divergences are greater than those previously reported [5] for short-pulse operation, because of calorimeter limitations for the higher energy deposition.

Table I. Typical Operation of a Long-Pulse, 20-kV, Neutral-Beam Source for Two Accelerating Voltages

Ion-Current Density	0.25 A/cm^2	0.5 A/cm^2
Ion-Current Density Variation	± 1%	± 1%
Pulse Length	1.0 sec	0.5 sec
Gas Flow (D_2)	4 T-ℓ/sec	4 T-ℓ/sec
Beam Energy	15 keV	20 keV
Power Supply Drain	7.5 A	15 A
Beam Divergence ∥ to Slots ($\pm\frac{1}{e}$)	$\lesssim 0.6°$	$\lesssim 0.6°$
Beam Divergence ⊥ to Slots ($\pm\frac{1}{e}$)	$\lesssim 2.6°$	$\lesssim 2.6°$
Ion Species	67% D^+, 29% D_2^+, 4% D_3^+	72% D^+, 25% D_2^+, 3% D_3^+

III. Accelerator

A cross section of a single slot of the ion accelerator is shown in Fig. 4. The design is a conventional "accel-decel" system, with the addition of a fourth, or "gradient", grid which provides the capability of electrostatic focusing, and which we hope will reduce the problem of electrical breakdown. The transparency is 60%; the scale size was set by the desire to limit the potential gradient in the second gap to about 100 kV/cm, and resulted in

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a required ion-current density of 0.31 A/cm^2 for a pure D^+ beam, or about 0.25 A/cm^2 for a beam with a realistic ionic composition. This design has been optimized, using the WOLF code [6], by varying the shape of the first, or "beam-forming" electrode, and the potential of the second electrode. The shapes of all electrodes except the first were chosen to minimize energy deposition in the structure by secondary particles created in the beam or from surfaces. We anticipate a maximum heat rise of 500°C in any electrode during the 0.5-sec pulse.

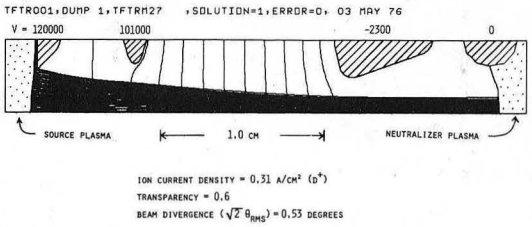

Figure 4. Calculated beam trajectories and equipotentials for a 120-kV accelerator.

IV. 15-A, 120-kV, 0.5-sec Module

A 15-A, 120-kV, 0.5-sec module, incorporating the plasma generator and grid designs described in this paper, is shown in Fig. 5. The accelerator consists of an outer, vacuum-wall insulator that is sectioned to distribute the potential gradients; to keep these insulators reasonably short, the outside of this insulator is pressurized with two atmospheres (absolute) of SF_6. The plasma generator and grid assembly are mounted on an inner plug-in structure. The tubular insulators to which grid assemblies are mounted also carry cooling water to the plates that support the final three grids; cooling for the first (beam-forming) grid is obtained from the plasma-source body. The 10-cm-long grid rails, arranged in a 10-cm-wide array, are end cooled. The solid molybdenum rails are brazed to a fixed support on one end, forming a comb-shaped structure, and allowed to expand in the long direction to prevent buckling when heated. The heat is conducted away in the 1-minute interval between pulses.

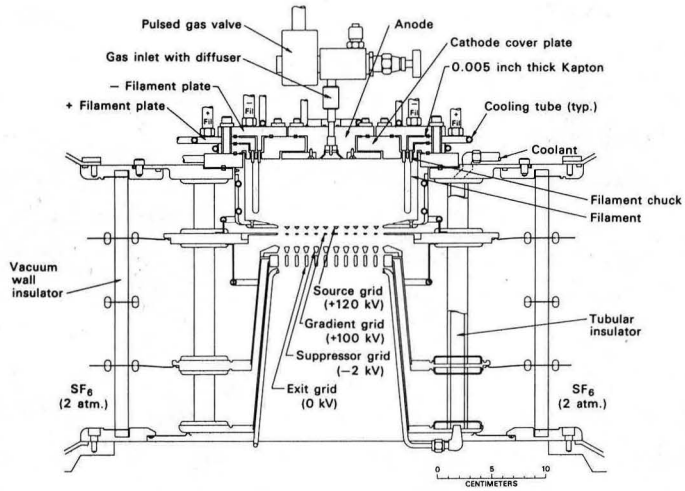

Figure 5. Cross-section of the 120-kV, 15-A, 0.5-sec module.

The neutralizer to which this structure is attached is constructed of iron to shield the beam from stray magnetic fields. It has an internal cross-section of 15 cm x 30 cm and is two meters long. D_2 gas emerging from the plasma generator through the grids will produce a line density of $\sim 10^{16}$ molecules/cm^2 ($\sim$0.5 Pa-m) in this section.

This module is in the final stages of construction and testing should begin in June 1976.

V. Test Facility

To operate this module a new test facility, to be operational in June 1976 (Fig. 6), is under construction. In this paper we limit our discussion to the vacuum system. The 20-A, 150-kV, 0.5-sec power supply is described in an accompanying paper by Baker and Hopkins [7]; the philosophy of the MODCOMP IV computer monitor/control system and the calorimeter design can be found in [2].

Since gas to the system is pulsed on for only 0.5 sec at intervals of 1 minute or more, it is convenient to use a large-volume vacuum chamber to handle the peak gas load by volume

expansion. The test facility [8] has a total volume of 172,000 liters, and the vessel pressure does not exceed about 2.5×10^{-5} Torr (3.3×10^{-3} Pa) at the end of a 0.5-sec pulse. Sufficient pumping is supplied to return the system to its base pressure in the interval between shots. Rapid pumpdown of the system is provided by two well-baffled 0.9-m-diam diffusion pumps. The pumping fluid is Santovac 5, a polyphenyl ether which has a very low vapor pressure of 5×10^{-10} Torr (6.7×10^{-8} Pa) at room temperature, is resistant to oxidation, and does not break down to form insulating layers on surfaces struck by the beam. The measured pumping speed of the two baffled pumps (for D_2) is 65,000 ℓ/sec.

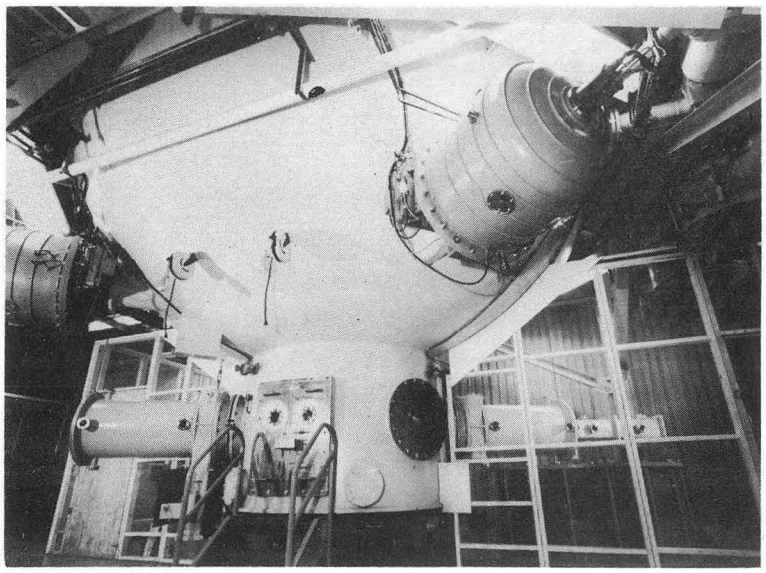

Figure 6. Photograph of the test facility.

To minimize oil contamination during routine source operation the system also incorporates two 8000 ℓ/sec (D_2) titanium sublimation pumps. A 75-kW array of lamps suspended at the center of the sphere allows a mild bakeout of the chamber. This array can maintain the walls 50°C above ambient and is effective in shortening the pump-down time. The base pressure of the system is $\sim 5 \times 10^{-5}$ Pa.

The vacuum system is interlocked to protect against operator error and loss of power or cooling water. Controls for the vacuum system, as well as controls for all beamline components and power supplies, are located in an adjacent control room.

Two separate beam lines are attached to the vacuum system. One will be used for testing the previously-described 120-kV, 15-A, 0.5-sec modules. In the Spring of 1977, testing of 50-120 kV, 65-80 A, 25-100 msec modules will start on the second beam line.

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†Permanent address, Princeton Plasma Physics Laboratory.

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