Conf-82/123--10

UCRL-87831
PREPRINT

MULTI-MEGAWATT NEUTRAL BEAMS FOR MFTF-B

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This paper was prepared for submittal to
7th Conference on the Application of
Accelerators in Research and Industry,
Denton, Texas, November 8-10, 1982

November 8, 1982

Lawrence
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Introduction

The Mirror Fusion Test Facility (MFTF-B) at Lawrence Livermore National Laboratory is a reactor-scale tandem-mirror experiment that will provide physics and technology bases for a D-T burning, tandem-mirror facility in the 1990's. Figure 1 is a cutaway drawing showing the major parts of the facility as it will look when completed in 1986.¹

Figure 1. The MFTF-B vacuum vessel that supports and contains the superconducting magnets. Neutral-beam injectors are attached at various locations on the vessel.

MFTF-B

The MFTF-B vacuum vessel will be 65-m long and 10-m in diameter with a volume of about 4.5×10^6 liters. The plasma confining magnets are all superconducting, will weigh a total of 1000 metric tons, and store 647 MJ when fully energized. The high-vacuum pumping will be done by cryopumping on 1000 m² of LHe cooled aluminum panels.

Neutral beams of deuterium are injected into the vessel at various places and for different purposes (Fig. 2). Plasma streaming guns located on the vessel end domes will provide a 30-cm radius, 2×10^{12} cm⁻³ density to act as a target. Ten 20-kV, 100-A sources will fire into the anchor region for 10 ms and sixteen 80-kV, 80-A, 0.5-s sources will fire into various regions to raise the plasma density to 4.8×10^{13} cm⁻³ in the solenoidal central-cell region.

Six 80-kV, 50-A sources continue for the full 30-s duration of each experimental shot. One beam is directed near the center of each minimum-B yin-yang magnet that provides the MHD stability anchor. The ions from these beams "slosh" back-and-forth in the magnetic well and create an anisotropic distribution. RF power is applied to this distribution to heat the magnetically-trapped electrons and create a "thermal barrier" that isolates the warm electrons in the potential peak region of the anchor from the cold electrons in the central cell. Another 80-keV beam is injected axially from each end of the vessel.

Figure 2. Locations of the long-pulse neutral beams on one of the MFTF-B end cells.

These two beams act to "pump" away deeply trapped ions in the barrier region by charge-exchange interactions with the 80-keV neutrals. The remaining pair of 80-kV, 30-s beams inject in the high-field axicell regions to create a local potential maximum and consequent density peak.

80 kV, 0.5 Second Sources

A prototype 80-kV, 80-A, 0.5-s source has been developed and tested at LLNL and LBL.² This source has a four grid accelerator of the slot-type (Fig. 3). Sources based on this prototype have been manufactured commercially* and two of them have undergone extensive testing.

The neutral-beam sources are made up of an arc chamber and a four-grid accelerator. A deuterium (or hydrogen) plasma is produced in the arc chamber by means of a discharge. The electron feed comes from 226 hairpin tungsten filaments lining the walls of the chamber. Typical parameters are:

$$V_{fil} = 9 - 10 \text{ V}, I_{fil} = 4600 - 5000 \text{ A},$$

$$P_{arc} = 35 - 130 \text{ kW, gas flow} = 25 \text{ T-l/sec.}$$

The arc and filament power enters via two triaxial feedthroughs in the mounting flange.

The magnetic field in the arc chamber must be kept less than 1 to 2 G in order to maintain a uniform plasma. To accomplish this in the 800-G ambient field in MFTF-B a three layer shield was

*RCA Corporation, Solid State Division, "Electro Optics and Devices," Lancaster, PA - Under DOE Contract W-7405-ENG-48, subcontract 6317709.

Figure 3. Cross-section of the 80-kV, 0.5-s prototype neutral-beam source. Only slight changes have been made for the commercial sources.

developed. This was made up of two inner layers of 0.25-cm nickel-iron alloy surrounded by 5.4 cm of mild steel. A 1/10th scale model of this shield was built and tested,³ and the full scale shield has also been tested under actual operating conditions and found to reduce the internal field to less than 1 G.⁴

Accelerator

The 0.50-source accelerator is of the 4-grid multiple-slot type. Each grid wire is curved with a 700-cm radius and the set of grid wires is held in a plate with a 700-cm radius in the orthogonal direction. The sources are therefore focussed at 700 cm that is the nominal distance to the plasma. The grid wire shapes and spacings for the production sources are shown in Fig. 4. The design optimization for minimum beam divergence is based on calculations by Cooper⁵ using the WOLF code. The individual grid wires (the entrance and suppressor grids are molybdenum, the gradient and exit grids are tungsten) are conduction cooled through the ends that are in spring contact with water cooled copper. The entrance grid is the most sensitive to thermal damage due to its small cross section. Tests on the prototype source indicated a peak temperature rise of 366°C for the entrance grid at the design operating point.⁶

Two production sources and the prototype have been extensively tested.^{2,7} The prototype grid-gap spacing was 0.093 in., 0.284 in., and 0.061 in. that resulted in lower than desired currents. The gaps were recalculated to 0.070 in., 0.277 in., and 0.060 in. for the production sources which resulted in operation at the design level current. Figure 5 shows the divergence data taken to optimize the operating parameters. These data are obtained by operating at a given constant accelerator voltage

Figure 4. Cross section of the MFTF-B 80-kV, 0.5-s source accelerator grid wires. (Dimensions are in inches).

while varying the power to the arc chamber. This changes the current density and the shape of the plasma sheath edge in the vicinity of the extraction electrode. The divergence of each beamlet is sensitive to this shape and is evidenced by a change in the power deposition profile on the beam dump at the end of the beam line. The total beam divergence is deduced from this profile. The divergence shown is in the direction perpendicular to the grid slots; the divergence parallel to the slots remains constant

Figure 5. Beam divergence measured calorimetrically on a beam dump versus accelerator current, the minimum of each curve defines the optimum operating conditions.

as the current is varied. The dramatic improvement in divergence for the two commercial sources is thought to be due to more accurate machining and measuring during assembly, and to the fact that the prototype gaps were not exactly uniform across the source. The accel current values at the minimum divergences in Fig. 5 define the perveance curves, relating accelerator power supply drain current to accelerator power supply voltage, as shown in Fig. 6. The data for the prototype source were taken prior to the re-gapping. The two commercial sources operate identically within experimental accuracy.

Figure 6. Pervance curve showing optimum beam current versus accelerator voltage. The data points for the prototype source are taken prior to re-gapping.

80-kV, 30-s Sources

The 30-s duration neutral beams present a great challenge to the state-of-the-art technology. Many parts of the sources that can be inertially cooled for pulses up to ~ 1 s must now be continuously cooled with water. The most difficult task, and one which has been successfully addressed, is to actively cool the accelerator grids.

The source development groups at ORNL and LBL have modified their advanced positive ion sources to build prototypes applicable to the MFTF-B program. These sources will be tested to full operating parameters at LBL in the spring of 1983. The plasma sources are somewhat different, but the most striking differences in the two labs' approaches is in the accelerator design. The LBL design is made up of multiple rectangular slots (Fig. 7), while the ORNL model has multiple circular apertures (Fig. 8). These designs are extrapolations of several years of building high power neutral beam systems by these laboratories for the national fusion research effort.

Figure 7. LBL prototype gradient grid segment for the long-pulse accelerator. Four identical units make up the complete gradient grid. The individual grid wires are shaped hollow tubes of molybdenum. Note the bellows and cover at the end to accommodate thermal expansion. (Photo courtesy of Lawrence Berkeley Laboratory).

Figure 8. ORNL prototype gradient grid for the long-pulse accelerator. There are serpentine cooling channels running vertically between the beamlet apertures to water manifolds. The machined channels have been electroformed over prior to final machining. (Photo courtesy of Oak Ridge National Laboratory).

The LBL long pulse prototype source has been operated up to 80 kV for as long as 2 s. The pulse duration was limited by the beam dump that is currently being replaced as part of the long-pulse upgrade of the Neutral Beam Engineering Test Facility at LBL. The beam divergences were 0.9×0.24 degrees at a deuterium-beam current of 38 A. This source is designed with a lower perveance than the 0.5-s sources, in order to insure its long-pulse operation.

Conclusion

Multi-megawatt neutral-beam sources have successfully made the transition from prototype to commercial production, with some operational improvements due to the commercialization. Long pulse source operation results will be available soon.

Acknowledgements

The author wishes to acknowledge the cooperation

of the Neutral Beam Development Groups at LBL and ORNL in supplying data and photographs of their sources.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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