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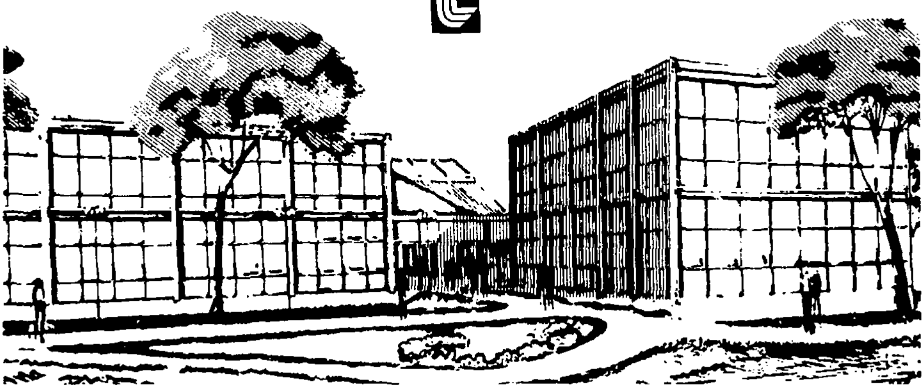

TESTING OF DEVELOPMENTAL NEUTRAL BEAM SOURCES FOR MFTF*

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Summary

The design of a four-grid, spherically-focused, 10-by-46-cm area accelerator and ion source for the Mirror Fusion Test Facility (MFTF) has been previously described.[1] This source was designed to operate at 80 kV--80 A for 0.5 s, and along with a matching, three-grid 20-kV--100-A--10-ms accelerator, has been built and tested. The 80-kV source has operated beyond design speci.ications to 90 kV--90 A for 12 ms. Pulse duration was limited by a capacitor bank accel power supply. Tests to 0.5 s on the High Voltage Test Stand (HVTS) are in progress. The major change found necessary during testing was the installation of a grounded shield to block neutralizer plasma from flowing into the region between high voltage and ground. The $D_1^+:D_2^+:D_3^+$ ratio was measured by Doppler shift spectroscopy and momentum analysis to be 0.68:0.20:0.12. Accelerator grids are built to a 7-m-radius spherical surface that aims individual beamlets at the center of curvature. The beam footprint at 7 m is $\pm 0.4°$-by-$\pm 1.4°$ at e^{-1} of peak power. Both the 20-kV and 80-kV accelerators use the same ion source. The 20-kV accelerator has been tested to 20 kV--95 A for 10 ms.

Introduction

The MFTF requires neutral beam injection to start up and sustain a mirror confined plasma of 30-cm radius. Startup is accomplished by injecting 1000 A equivalent of atoms at an average energy of 15 keV (from 20-kV sources) for a period of 10 ms into a plasma of density $n \approx 10^{12}$cm^{-3} with ion and electron energies in the 10- to 100-eV range. The startup beams raise the density to greater than 10^{13}cm^{-3} and the average ion energy to $E_i > 10$ keV. Sustaining beams then inject 750 A of atoms at an average energy exceeding 50 keV for 0.5 s to further heat the plasma and increase its density to $n \approx 10^{14}$cm^{-3} with electron energies near 1 keV.

We placed special requirements on the neutral beam sources to meet MFTF performance requirements. First, a compact cross-sectional area source module (including the magnetic shield, gimbal, and bellows) is required to allow beam modules into the area that accesses the plasma. Second, the fringe magnetic field of 400-700 G at the source position must be reduced to about 1 G to allow satisfactory ion source and neutralizer operation. Third, convenient maintenance and replacement of neutral beam sources must be possible while MFTF is under vacuum.

MFTF Source Design

The design of the ion source and 80-kV accelerator is shown in Fig. 1.[1] The compact cross section was achieved by a compact accelerator and ion source design by holding high voltage from the source-to-ground across a vacuum; by using the outer magnetic shield as the vacuum wall; by minimizing the thickness of the magnetic shielding[2]; and by a compact gimbal together with a rubber bellows rather than the conventional metal bellows.[3]

We designed the magnetic shield to approach, as nearly as possible, a box closed on all sides to

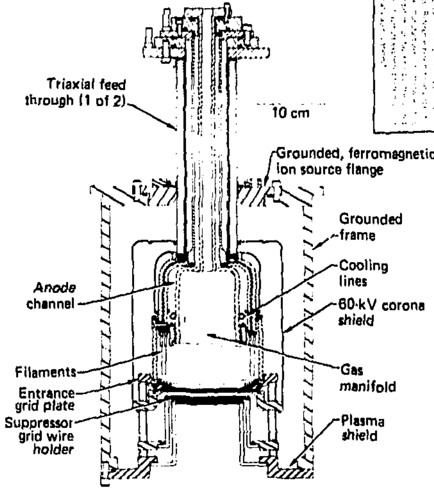

Fig. 1. The ion source and 80-kV accelerator are designed to occupy a minimum cross-sectional area and utilize vacuum insulation.

minimize magnetic flux leakage. The only penetrations are where the beam exits the neutralizer and where electrical and water cooling vacuum feedthroughs must penetrate the magnetic shield.[1] Two layers of high permeability magnetic shield further reduce the field at the ion source and neutralizer to less than 1 G. We verified this design by measurements on 1/10 scale models.[2]

An isolation valve, located inside the shield, allows changing neutral beam sources while MFTF is under vacuum[3] and eliminates the reionization loss of neutral beam that occurs in a duct not magnetic field-free. The back of the magnetic shield consists of three concentric 1010 steel flanges. The inner flange supports the ion source that can be removed by itself for refilamenting. The accelerator is cantilevered off the second flange. The third flange normally remains fixed to the magnetic shield and carries the valve actuator. It also provides cooling for the valve and neutralizer duct, feedthrough for thermocouples, a vacuum valve for pump-down and leak chasing, and electrical ground and interlock connections. The magnetic shield and gimbal usually remain in position on MFTF, while ion sources or accelerators are removed for maintenance.

80-kV Accelerator Testing

Preliminary 80-kV testing involved high-potting the accelerator and arc chamber and establishing the uniformity of the arc plasma as measured with Langmuir probes. Once these were both satisfactory, the arc chamber and accelerator were mounted together on the Lawrence Berkeley Laboratory (LBL) Test Stand IIIB.

Initial operation was poor. We achieved durations of 190 ms at 20 kV, but the duration decreased to a few milliseconds at 30 kV and did not improve with conditioning. This poor operation became understandable when we noticed that the plasma in the neutralizer was able to diffuse around the base of the accelerator and into the region separating high voltage from ground. The high voltage electrodes then sparked to ground. Similar problems were identified previously at Culham.[4] Our solution was to block the neutralizer plasma with a metal wall extending from the grounded base flange of the accelerator to the grounded vacuum wall of the magnetic shield. The accelerator was reassembled with this modification with other minor changes.

80 kV Tests

Operation begins at 30 kV to verify that the operating range of 30 to 80 kV, specified for the MFTF sustaining neutral beam power supply system,[5] is capable of conditioning a new source. The operating voltage is plotted vs the number of shots taken (Fig. 2). We achieve the design voltage of 80 kV in less than 3000 shots. The conditioning curve does not progress smoothly upwards but has dips where a new day's operation begins,an attempt is made to lengthen the duration, or problems with the source or test stand force the operation to a lower level. Extended operation at a constant voltage increases the beam current or duration or optimizes the current calorimetrically.

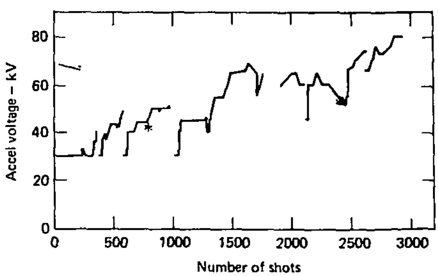

Fig. 2. Source conditioning from 30 to 80 kV is shown as a function of the accelerator voltage vs the number of shots since the accelerator was disassembled.

We optimize beam current for minimum beam divergence at a given beam energy by varying the current from shot-to-shot by means of changing the arc power. We determine the optimum beam current from plots of calorimetrically-measured beam divergence[6] vs beam current (Fig.3). Repeating this procedure at different beam energies yields the optimum perveance curve of Fig. 4. Minimum beam divergence is obtained by operating on the perveance curve. Operation up to about 15% above or below this line is possible with increased beam divergence. Operation is not possible, further off the perveance curve; increased currents to the gradient grid and to the suppressor grid indicate that beam is intercepting these grids.

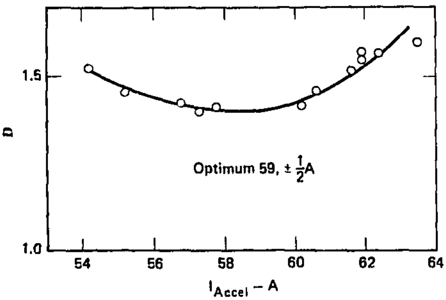

Fig. 3. The source operation is optimized by varying the beam current at a fixed energy (73 kV) to find the minimum beam divergence D, as measured calorimetrically by a thermistor array on the beam dump.

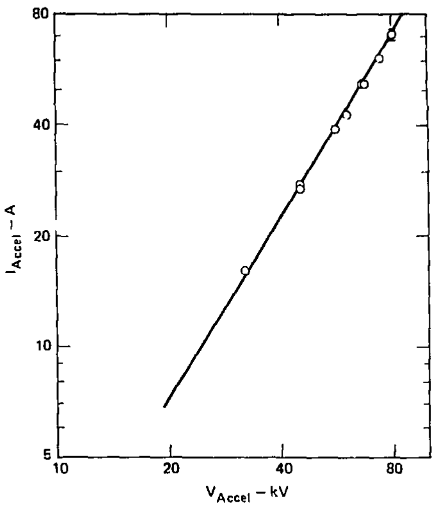

Fig. 4. The optimum beam current is plotted vs the accelerator voltage.

At 80 kV, the minimum beam divergence of 0.4° by 1.4° was achieved for 71 A. We plan to decrease the gaps between grids to raise this current to the design level of 80 A. This change will increase the electric field and the probability of voltage breakdown between grids. To evaluate the risk involved, we conditioned the source beyond 80 kV to 90 kV and 90 A (about 4 A above the optimum current of Fig. 4). The operation was satisfactory at this level; so we conclude the accelerator had adequate voltage-holding margin.

Positive ion beams include not only D_1^+ atomic ions, but also D_2^+ and D_3^+ molecular ions. In the neutralizer, dissociation and neutralization of the molecular ions yield neutral atoms at one-half and one-third the accelerator energy. We made measurements of the relative fractions of molecular ions by Doppler shift spectoscopy[6] and momentum analysis[7] (Fig. 5). We assumed a thick gas cell for evaluating the ion currents to the momentum analyzer. We checked this assumption by bleeding gas into a stripper cell preceding the analyzer. No change would indicate that our assumption was correct. The small change observed at 61 A of beam current indicates we underestimated the full energy fraction by about 4%.

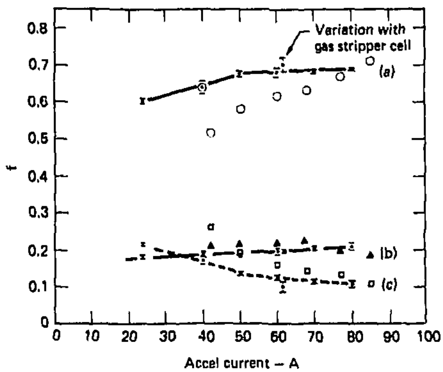

Fig. 5. The fraction of accelerated beam consisting of (a) D_1^+, (b) D_2^+, and (c) D_3^+ is shown as a function of beam current. The bar data is from the momentum analysis, and the open data points from Doppler shift spectroscopy. At 61 A, gas is injected into a stripper cell preceding the momentum analyzer. This tests whether the ion and neutral beams are in equilibrium.

These data are similar to those previously measured[8] on the LBL 120-kV--65-A source designed for the TFTR. This is reasonable since the MFTF ion source discharge chamber[1] was designed to be similar to that of the LBL ion source.[9] We calculate the average neutral atom energy to be 53 kV for an 80-kV accelerator energy using the data in Fig. 5 along with neutralization efficiencies.[10]

The beam duration on the LBL Test Stand IIIB was limited by a capacitor bank to 12 ms at 80 kV. However, we were able to operate the ion source for 0.5-s durations on IIIB and successfully accelerate beam at the pulse end. This operation tests all problems that might occur with 0.5-s beam pulses, except for beam heating of grid wires, which is being tested on the HVTS as it is brought into operation. The HVTS has been able to operate the MFTF 80-kV source for full 0.5-s pulses at levels up to 40 kV. No indication of source grid heating problems has been observed.

20-kV Accelerator Design and Testing

We designed a new 20-kV, three-grid accelerator to take advantage of the larger 10-by-46-cm uniform plasma produced by the MFTF ion source, rather than using the 2XIIB 7-by-35-cm aperture accelerator. We thus expect to increase the accelerated current from the 75-A level of 2XIIB sources to about 100 A, while decreasing the current density from 0.5 to 0.4A/cm^2 and using larger, more rugged grid wires. The increased current per accelerator allows decreasing the number of startup beams on MFTF from 24 to 20 for a substantial saving on power supply costs. The reduced current density is expected to produce faster conditioning, proving more reliable operation at design level.

The support structure of the 20-kV accelerator is similar to that developed for TMX 40-kV accelerators.[11] Like the MFTF 80-kV and the TMX 40-kV accelerators, it aims the multiple beamlets at the center of curvature of a spherical grid,[12] rather than use electrostatic steering as on the 20-kV sources designed for 2XIIB.[13]

The 20-kV and 80-kV accelerators use the same design ion source, magnetic shield, isolation valve, neutralizer, and gimbals to minimize design, fabrication, and spare parts costs. The 20-kV accelerator has operated to 20 kV--95 A for 10-ms duration pulses using the MFTF arc chamber. The accelerator conditioned easily with only two problems: the current at 20 kV optimized at 87 A rather than the 100 A expected, and the gas risetime is about 20 ms, which injects excessive gas for a beam that has a duration of only 10 ms. Installation of a new, lower impedance gas diffuser is expected to shorten the gas rise time.

The low current could be due to a wide gap between grids, a nonuniform arc, or leaks of water or air resulting in the acceleration of heavier ions. Measurements of the grid gap eliminated the first possibility, and careful leak chasing found no leaks larger than 1 x 10^{-10} Torr ℓ/s, making the third explanation unlikely. Langmuir probe scans of the ion saturation current show an asymmetrical profile that is peaked at one end. This is corrected and expected to bring the beam current to about 100 A for minimum beam divergence at 20 kV.

Conclusion

Matched 20- and 80-kV neutral beam sources use as many identical components as possible and satisfy the MFTF requirements on available space, magnetic shielding, and maintainability. Both sources have successfully completed most of their tests. Tests underway are 0.5-s operation of the 80-kV source and full 100 A, rather than 85- to 95-A operation of the 20-kV source.

Acknowledgment

This development required the contributions of many people. F. Coensgen and K. Thomassen encouraged and supported this work. Major contributions to the design of these sources were made by K. Berkner, T. Duffy, K. Ehlers, J. Fink, B. Arfin, D. Baird, D. Garner, and C. Hansen.

Earl Holland, J. Jessup, B. Bauhofer, and G. Young fabricated the precision parts. J. Pastrone, R. Gressman, and A. Gjerko assembled the sources. Both groups deserve commendation, not only for the initial source construction, but for their quick response in repairing or modifying the source as required during testing.

We appreciate the support of R. Pyle and K. Berkner during tests at LBL on Test Stand III B. D. Massoletti, D. Robinson, M. Gart, and D. Williams capably operated the test stand. H. Owren and K. Milnes kept the test stand operating reliably. H. Hughes and his crew installed the source on the test stand and provided quick fixes to problems.

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References

1. A. W. Molvik, E. D. Baird, K. H. Berkner, W. S. Cooper, T. J. Duffy, K. W. Ehlers, J. Fink, D. Garner, and C. Wilder. "A Compact 80-keV Neutral Beam Module," Proc. 7th Symp. Engineering Problems of Fusion Research, Knoxville, TN, 1977 (IEEE, 1978), p. 295.

2. J. Shearer, et al, "Magnetic Shielding of Neutral Beam Sources in the Mirror Fusion Test Facility," UCRL-52824, 1979.

3. P. M. Holl, "Design and Development of Neutral Beam Module Components," Proc. 8th Symp. Engineering Problems of Fusion Research, San Francisco, CA, 1979, (03-03).

4. E. Thompson, private communication.

5. R. D. Eckhard, H. W. Van Ness, and H. Stern, "The Sustaining Neutral Beam Power Supply System for the Mirror Fusion Test Reactor," Proc. 8th Symp. Engineering Problems of Fusion Research, San Francisco, CA, 1979, (06-04).

6. C. F. Burrell, W. S. Cooper, W. F. Steele, and R. R. Smith, "Calorimetric and Optical Beam Diagnostics on the LBL 120-keV Neutral Beam Test Facility," Proc. 7th Symp. Engineering Problems of Fusion Research, Knoxville, TN, 1977 (IEEE, 1978), p. 374.

7. K. H. Berkner, R. V. Pyle, and J. W. Stearns, "Intense Mixed Energy Hydrogen Beams for CTR Injection," Nuclear Fusion 15, 249 (1975).

8. K. W. Berkner, W. S. Cooper, K. W. Ehlers, H. M. Owren, J. A. Paterson, R. V. Pyle, "Development of 120-keV Neutral Beam Injectors," Proc. 8th Symp. Engineering Problems of Fusion Research, San Francisco, CA, 1979, (03-07).

9. K. W. Ehlers, "Rectangularly Shaped Large Area Plasma Source," Proc. 7th Symp. Engineering Problems of Fusion Research, Knoxville, TN, 1977, (IEEE, 1978), p. 291.

10. C. F. Barnett, J. A. Ray, E. Ricci, M. I. Wilker, E. W. McDaniel, E. W. Thomas, and H. B. Gilbody, "Atomic Data for Controlled Fusion Research," Report ORNL-5206, 1977.

11. T. J. Duffy, A. W. Molvik, E. D. Baird, D. L. Correll, R. H. Munger, K. Gillespie, E. D. Holland, and G. T. Santamaria, "Engineering Design of a 40-keV Neutral Beam Source," 8th Symp. Engineering Problems of Fusion Research, San Francisco, CA, 1979, (03-08).

12. H. H. Haselton, D. E. Schechter, G. Schilling, L. D. Stewart, and W. L. Stirling, "Extraction Systems for Neutral Beam Heating of PLT and Doublet III Tokamaks," Proc. of 6th Symp. of Engineering Problems of Fusion Research, (Nov. 18-21, 1975), p. 169.

13. K. H. Berkner, W. R. Baker, W. S. Cooper, K. W. Ehlers, W. B. Kunkel, R. V. Pyle, and J. W. Stearns, "Performance of LBL 20-kV, 10-A and 50-A Neutral Beam Injectors," Proc. 2nd Symp. Ion Sources and Formation of Ion Beams, Berkeley, CA, (1974), Paper VI-12.