CONF-830406--28

DEVELOPMENT OF A LONG-PULSE (30-s), HIGH-ENERGY (120-keV) ION SOURCE FOR NEUTRAL-BEAM APPLICATIONS[a]

CONF-830406--28

DE83 011392

C. C. Tsai, G. C. Barber, C. W. Blue, W. K. Dagenhart, W. L. Gardner H. H. Haselton, D. J. Hoffman, E. F. Marguerat, M. M. Menon, J. A. Moeller,[b] N. S. Ponte, P. M. Ryan, D. C. Schechter, W. L. Stirling, J. H. Whealton, and R. E. Wright
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830
(615) 574-1115

ABSTRACT

Multimegawatt neutral beams of hydrogen or deuterium atoms are needed for fusion machine applications such as MFTF-B, TFTR-U, DIII-U, and FED (INTOR or ETR). For these applications, a duoPIGatron ion source is being developed to produce high-brightness deuterium beams at a beam energy of ~120 keV for pulse lengths up to 30 s. A long-pulse plasma generator with active water cooling has been operated at an arc level of 1200 A with 30-s pulse durations. The plasma density and uniformity are sufficient for supplying a 60-A beam of hydrogen ions to a 13- by 43-cm accelerator. A 13- by 25-cm tetrode accelerator has been operated to form 120-keV hydrogen ion beams. Using the two-dimensional (2-D) ion extraction code developed at Oak Ridge National Laboratory (ORNL), a 13- by 43-cm tetrode accelerator has been designed and is being fabricated. The aperture shapes of accelerator grids are optimized for 120-keV beam energy.

INTRODUCTION

Intense neutral beam injection is a proven plasma heating technique for fusion devices.[1-7] Ion sources developed for such applications are short-pulse (≤1-s) versions.[4,7,8] Long-pulse (>1-s) ion sources being developed show promise in producing multisecond beams.[9-12] For next-generation fusion devices,[13-18] such as MFTF-B, DIII-U, TFTR-U, and FED (or EPR) in the United States, high-energy (80- to 150-keV), long-pulse (up to 30-s) ion sources are needed. Additional requirements include good optics (~0.5° HWHM), high atomic yield (>90%), and low impurities ($<10^{-5}$). These sources should also be characterized by high-duty-cycle operation, high reliability, and longevity. One such source, now being developed, is the advanced positive ion system (APIS) ion source.

The ion sources[19-24] developed for ORMAK, ISX-B, PLT, and PDX are duoPIGatron ion sources scaled up from the original version developed at ORNL.[25] The development of APIS ion sources has been aggressively pursued for several years. Efforts are concentrated on technology development for the electron emitter and ion accelerator. The design philosophy, fabrication techniques, and significant achievements are published elsewhere.[8,9,26]

Based on APIS source development activities, a duoPIGatron ion source (Fig. 1) is being designed, fabricated, and developed to form 120-keV, 30-s beams. This source is similar to the 80-keV, 30-s source for the MFTF-B experiment at Lawrence Livermore National Laboratory.[27] As described below, the 30-s plasma generator and 120-keV accelerator have been successfully developed. A newly designed 120-keV accelerator will be able to form high-brightness beams, as demonstrated by the 80-keV source. Finally, the progress of this 120-keV, 30-s source development is discussed.

PLASMA GENERATOR

The plasma generator of a modified duoPIGatron ion source consists of an electron feed assembly and an arc chamber. The electron feed assembly supplies ionizing electrons to create a source plasma in the arc chamber. Longitudinal magnet columns are arranged circumferentially around the arc chamber walls to form a multiple-line cusp configuration. The multiple cusps can effectively improve confinement of fast ionizing electrons and slow plasma particles in the source plasma. Thus, a uniform plasma extending to within 5 cm of the chamber wall can readily be produced. This multicusp configuration[28] has contributed to the fast

[a]Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

[b]Grumman Aerospace Co., Bethpage, NY

NOTICE
PORTIONS OF THIS REPORT ARE ILLEGIBLE.
It has been reproduced from the best available copy to permit the broadest possible availability.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

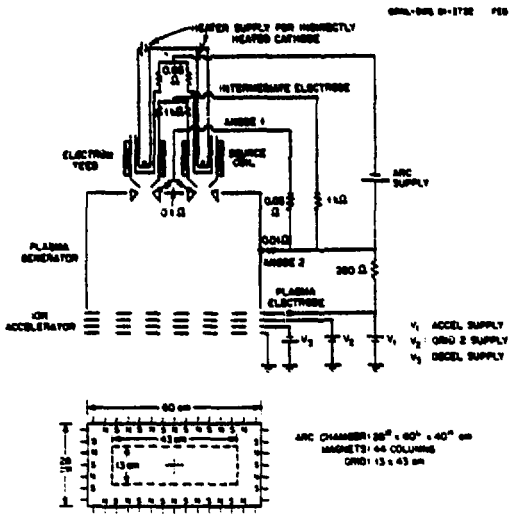

Fig. 1. Sketch of an APIS ion source including electrical connections.

Fig. 2. Typical waveforms of 120-V, 1200-A, 35-s arcs.

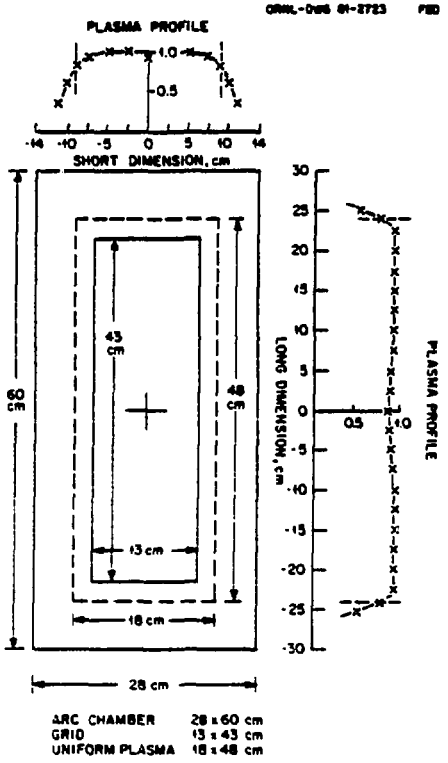

Fig. 3. Typical density profiles of the source plasma.

progress in ion source technology in the last decade.

To match the rectangular accelerators of APIS ion sources, the development of a rectangular plasma generator has been pursued at ORNL since 1979.[29] A long-pulse plasma generator using a double electron feed configuration has been operated at an arc level of 1200 A for pulse lengths of ~30 s (see Fig. 2).[30,31] As shown in Fig. 1, the electron feed assembly is mounted at the back of a 28- by 60-cm arc chamber. The typical spatial uniformity of the plasma so created is shown in Fig. 3. Such a plasma is sufficient for forming 60-A hydrogen ion beams when a 13- by 43-cm accelerator with 48% grid transparency is used. Based on this plasma generator, a long-pulse ion source is being designed, fabricated, and developed for MFTF-B applications.[27] For long-pulse (>30-s), high-duty-factor (>10%) operations, active water cooling has been provided for the close-fitting, thin-walled electrodes enclosing the intense arcs. Using the electroforming technique to prepare the water cooling channels in these thin-walled electrodes is a novel application.

The electron feed assembly is made up of an electron emitter, an intermediate electrode, and anode 1 (Fig. 4). This assembly is similar to that used in PLT/ISX-B injectors.[20] The electron emitter is an indirectly heated lanthanum-molybdenum (LM) cathode,[32] which uses La_2O_3-doped molybdenum emitter surfaces and is heated indirectly by a graphite heater.[30] Working at 1700°C, it needs a heating power of 3.9 kW. Such a cathode, with a 100-cm² emitter area on the inside of a paraboloid, is capable of 1000-A emission current. Normally, the electron emission of the cathode is independent of time for a constant cathode temperature, anode potential, and gas pressure. For 30-s pulsed intense arc discharges, the cathode

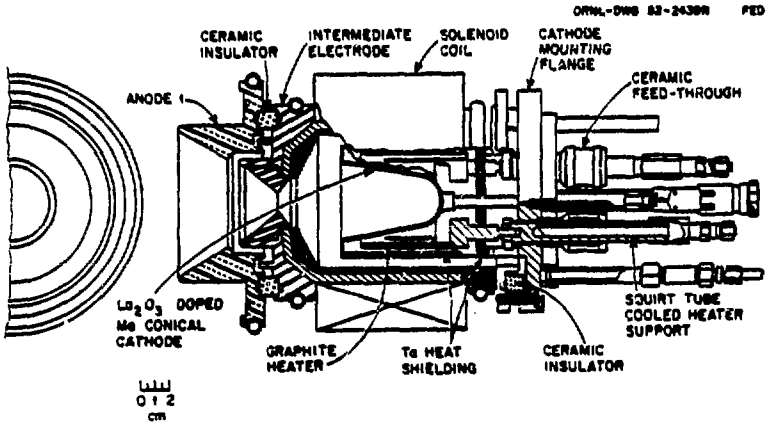

Fig. 4. Electron feed assembly.

temperature increases ~100°C as a result of additional arc heating. To maintain constant plasma density during the arc pulse, regulation of cathode temperature is needed.

The effectiveness of a water-cooled design was demonstrated by reliable operation of a few 30-s arc pulses at 75% duty factor. After 70 h of 30-s, 30%-duty-cycle arc operations (2500 arc pulses), the electron feed assembly still behaves normally. In addition to its longevity, this assembly is very reliable and stable, as demonstrated by the fact that no arc breakdowns were detected during the test operation. Moreover, the arc characteristics (monitored by arc voltage and current, plasma density, electrode power loadings, and cathode temperature) are repeatable for every pulse. Thus, we are confident that a reliable, efficient, and durable long-pulse plasma generator has been successfully developed.

ION ACCELERATOR

In forming high-energy (>80-keV), 30-s beams, the main concerns of the accelerator development are the optical quality of the beam, the stability of grids, and the high-voltage holdoff capability. For a conditioned multiaperture ion accelerator, the voltage holdoff capability of 80 kV/cm is often achieved for a short gap below 1 cm. For long-pulse accelerator development, rectangular grids with improved cooling efficiency and reduced beam loadings were designed for achieving thermal stability.[33] This design effort was carried out after an initial thermal and stress analysis for 30-cm-diam grids for PDX injectors.[34,35] Normally, the optical quality of the beam is determined by the primary optics, the steering and geometric focusing of each beamlet, and the extracted current density. Through the ion source development for various neutral beam applications, the optical quality of beams has been studied extensively and improved substantially, via both experimental and computational efforts.

The primary beamlet optics depends on the aperture geometry, which can be optimized using the ORNL 2-D ion extraction code.[26,36] The optics improvement has been proven by the increase in beam transmission efficiency of a triode accelerator[37] and the decrease in beam divergence of a tetrode accelerator.[38] Employing notched apertures on the beam-forming grid (plasma grid, or grid 1), a long-pulse ion accelerator with a rectangular extraction geometry of 10 × 25 cm in a scaled APIS ion source[12] has been designed, fabricated, and operated. High-energy beams up to 120 keV have been successfully formed, and beam optics properties have been characterized.

For forming 120-keV beams, the first and second gaps of the tetrode accelerator (Fig. 5) were set at 8 and 10 mm, respectively. The

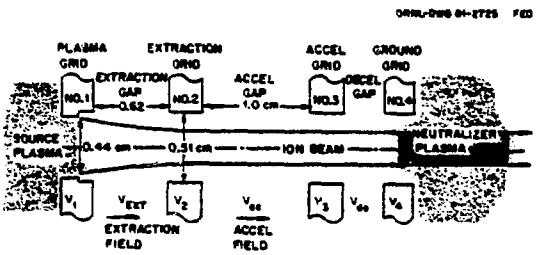

Fig. 5. Schematic aperture dimensions of a tetrode accelerator of a scaled APIS ion source.

maximum voltage holdoff of the second gap is 84 kV. The high-energy beam formed is 122 keV/16 A/0.1 s. The beam optics has been studied by beam power flow measurement, perveance scan, and beam profile scan for 60-keV, 80-keV, and 100-keV beams. The optics of beams at a constant field ratio [the electric field in gap 2 (accel gap) to that in gap 1 (extraction gap)] is independent of beam energy. For instance, at a field ratio of 2, the minimal power loadings to grids 1, 2, 3, and 4 are respectively 0.6%, 0.6%, 0.1%, and 0.2% of beam power for high-energy beams. But the power loading to the back plate of the arc chamber, due to backstreaming electrons created in the accelerator column, is below 2% of beam power and increases with the beam energy. Figure 6 shows these power loadings as functions of beam perveance. With such low power loadings, the rectangular grids of the accelerator can be cooled to achieve thermal stability with active water cooling. In fact, power loadings on grids were measured to be a linear function of beam pulse length, when long-pulse ion beams were formed with energy in excess of 100 keV and pulse length of many seconds.[12]

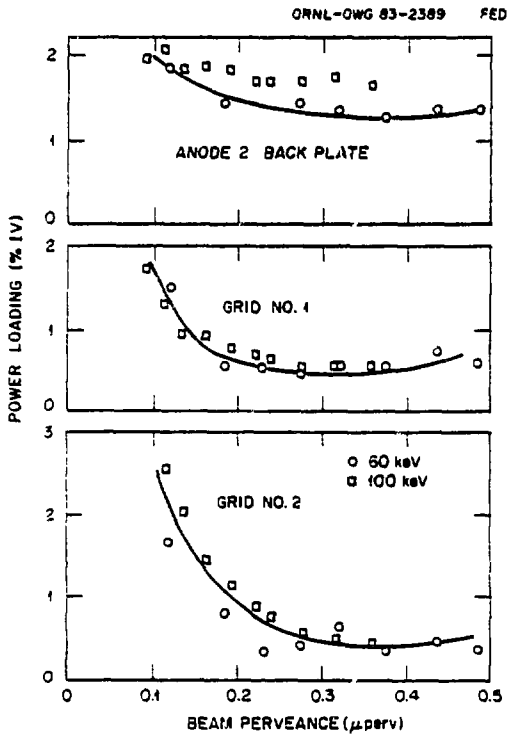

Fig. 6. Power deposition to several components for 60-keV (circles) and 100-keV (squares) beams.

For a tetrode accelerator, beam optics and extracted current density are sensitive functions of the field ratio, as shown in Fig. 7. Thus, at a constant beam energy, the beam power deposited on a target plasma with a constant acceptance angle can be adjusted for a wide range by simply changing the field ratio.

For MFTF-B applications, long-pulse (30-s) deuterium beams with very stringent optics (±0.5°) requirements are needed. The aperture shapes of the grids were designed using the 2-D ion extraction code.[35,39] As shown in Fig. 8, the primary optics of beamlets so formed will have a divergence angle of 0.25° rms at a current density (D^+) of 0.15 A/cm^2 and a field ratio of 2. With such large-diameter (0.8- to 1-cm) apertures and serpentine cooling channel arrangements, the active extraction area of the 13- by 43-cm rectangular grids is about 250 cm^2 (i.e., a 43% geometry transparency). The cooling efficiency has been improved substantially by using serpentine cooling passages along the short dimension and between adjacent rows of apertures.

At present, the preprototype MFTF-B source is being actively and aggressively developed. Short-pulse beams of 80 keV and 50 A have been formed and characterized. The pulse length has been extended to 3 s. The

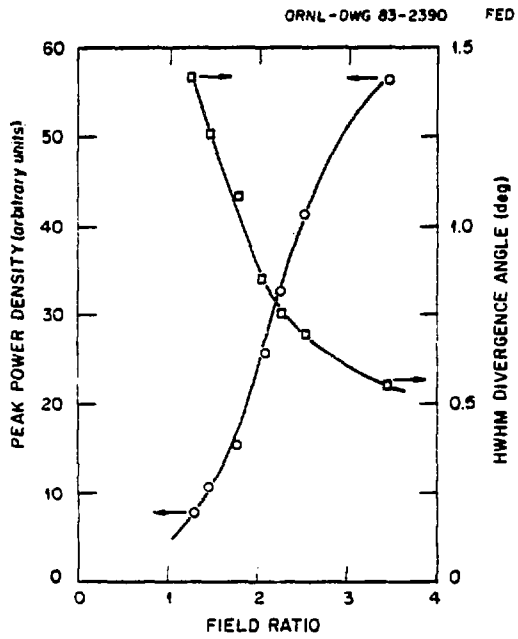

Fig. 7. Peak power density and divergence angle varied with the field ratio for 90-keV, 9-A beams.

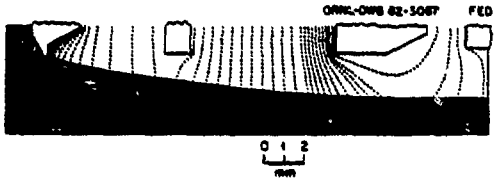

Fig. 8. Aperture shapes, including ion trajectories, of an 80-keV tetrode accelerator.

analysis based on beam profile scans gives an effective divergence angle of 0.47° HWHM at a field ratio of 1.8. A typical beam profile is shown in Fig. 9. This is consistent with that measured by an energy analyzer. The divergence of $H^+(E)$, $H^+(E/2)$, and $H^+(E/3)$ in the total beam is 0.38°, 0.5°, and 0.56° HWHM, respectively. The discrepancy between the computed beamlet divergence angle and the measured total beam divergence angle is consistent with the facts that the beamlets are not purely Gaussian and the beamlet steering and geometric focusing are not perfect. The heat loading to source components due to the beam at a field ratio of 2 was also carefully measured. The typical values of power loadings to grids 1, 2, 3, and 4 are 0.6%, 0.1%, 0.1%, and 0.8%, respectively. The maximum power density to the grids is below 125 W/cm^2, assuming 1% power loading of 4-MW beam power. This accelerator should be capable of forming 30-s beams of 80 keV and 50 A (H^+).

DEVELOPMENT OF A 120-keV, 30-s SOURCE

A 120-keV, 30-s ion source can be developed simply by regapping the tetrode accelerator of the preprototype MFTF-B source. Based on the

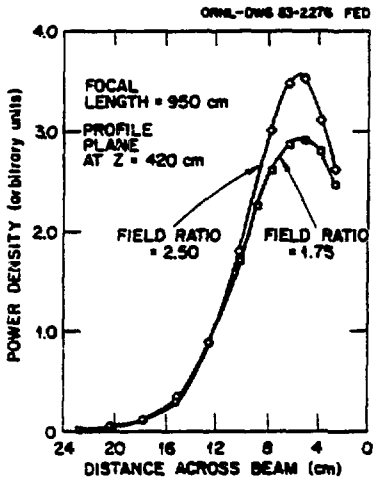

Fig. 9. Typical power profile of a total beam formed by the 80-keV accelerator of Fig. 8.

results of the scaled APIS ion source, the first and second gaps can be set at 8 and 10 mm, respectively. In fact, if the grids are made of molybdenum instead of OFHC copper, shorter gaps may be set. Usually, molybdenum is superior in voltage holding, secondary emission, particle sputtering, and mechanical strength at elevated temperatures. Its disadvantages include lower thermal conductivity, higher cost, and difficulty in fabrication.

A new tetrode accelerator with four molybdenum grids has been designed to improve cooling efficiency and mechanical strength and is being fabricated. If 3% of the 7.2-MW beam power (120 kV and 60 A) is deposited, each grid has been designed to handle 10-s beams.[33] The cooling efficiency is improved by incorporating integral cooling, with cooling passages along the short dimension of the grid and around each aperture. The thermal stability is improved by allowing grid edges to expand and rotate. The stress and deflection of grids are minimized by using NASTRAN plate models.[33] Relative axial deflection of the gaps is estimated to be within 0.38 mm, and transverse deflection is estimated to be within 0.13 mm, for 3% beam power loading. In fact, the grid loading of APIS ion sources is always below 1% of beam power. Hence, the molybdenum grids should be able to deliver high-energy ion beams of 120 keV, 60 A, and 10 s, as designed. If the thermal time constant is only 2 to 3 s, the grids should be able to produce 30-s beams.

Molybdenum grids are being fabricated by the United Technologies Research Center. The coolant passages are machined into the grid plates by chemical machining; then the two plates are brazed together. Two grids have been successfully completed. Like the copper grids for the MFTF-B source, the molybdenum grids use serpentine cooling passages and large shaped apertures (8 to 10 mm in diameter). The overall grid transparency of the rectangular extraction area (13 × 43 cm) is 48% (or a 268-cm^2 active extraction area). For cost-effectiveness, these grids are being made with no focusing curvatures.

The aperture shapes in these grids are optimized for 120-keV beam energy with the 2-D ion extraction code.[36,39] Using unfocused grids with the advanced aperture design, the beam transmission through an existing beam line will be increased substantially and the peak power density will be several times smaller than that with focused grids.

REFERENCES

1. L. A. BERRY et al., in *Plasma Physics and Controlled Nuclear Fusion Research. Proceedings of the 6th International Conference, Berchtesgaden, 1976*, Vol. I, International Atomic Energy Agency, Vienna, 1977, p. 49.

2. H. P. EUBANK et al., *Phys. Rev. Lett.*, *43*, 270 (1979).

3. M. MURAKAMI et al., in *Plasma Physics and Controlled Nuclear Fusion Research. Proceedings of the 8th International Conference, Brussels, 1982*, Vol. I, International Atomic Energy Agency, Vienna, 1981, p. 377.

4. M. M. MENON, *Proc. IEEE*, *69*, 1012 (1981).

5. J. SHEFFIELD, *Proc. IEEE*, *69*, 885 (1981).

6. T. C. SIMONEN, *Proc. IEEE*, *69*, 935 (1981).

7. W. B. KUNKEL, LBL-10447, Lawrance Berkeley Laboratory (1980).

8. *Proceedings of the 3rd IAEA Neutral Beam Workshop, October 19-23, 1981, Gatlinburg, Tennessee*, CONF-8110118, International Atomic Energy Agency, Vianna, 1981.

9. H. H. HASELTON and R. B. PYLE, in *Transactions of the Fourth Topical Meeting of the American Nuclear Society, King of Prussia, Pennsylvania, 1980*, Vol. 1, p. 81.

10. K. H. BERKNER et al., *Bull. Am. Phys. Soc.*, *25*, 982 (1980).

11. Y. OKUMURA et al., *Rev. Sci. Instrum.*, *51*, 728 (1980).

12. C. C. TSAI et al., *Rev. Sci. Instrum.*, *53*, 417 (1982).

13. M. M. MENON, in these Transactions.

14. W. LINDQUIST, private communication.

15. G. D. PORTER, *Bull. Am. Phys. Soc.*, *27*, 969 (1982).

16. H. P. EUBANK, Princeton Plasma Physics Laboratory, private communication.

17. W. A. HOULBERG et al., in *Proceedings of the 9th Symposium on Engineering Problems of Fusion Research*, IEEE, New York, 1981, p. 68.

18. D. H. METZLER and L. D. STEWART, in *Proceedings of the 9th Symposium on Engineering Problems of Fusion Research*, IEEE, New York, 1981, p. 748.

19. R. C. DAVIS et al., *Rev. Sci. Instrum.*, *46*, 576 (1975).

20. C. C. TSAI et al., in *Proceedings of the 7th Symposium on Engineering Problems of Fusion Research*, IEEE, New York, 1977, p. 278.

21. W. L. STIRLING et al., *Rev. Sci. Instrum.*, *50*, 576 (1979).

22. M. M. MENON et al., *J. Appl. Phys.*, *50*, 2484 (1979).

23. J. KIM et al., *J. Appl. Phys.*, *51*, 1984 (1980).

24. W. L. GARDNER et al., *Rev. Sci. Instrum.*, *53*, 424 (1982).

25. O. B. MORGAN, in *Proceedings of the 2nd Symposium on Ion Sources and Formation of Ion Beams*, LBL-3399, Lawrance Berkeley Laboratory, 1974, papar VI-1.

26. J. H. WHEALTON et al., in *Transactions of the 4th Topical Meeting of the American Nuclear Society, King of Prussia, Pennsylvania, 1980*, Vol. 1, p. 91.

27. M. M. MENON et al., in *Proceedings of the 12th Symposium on Fusion Technology, 1982*, p. 1375.

28. W. L. STIRLING et al., *Rev Sci. Instrum.*, *48*, 533 (1977).

29. C. C. TSAI et al., in *Proceedings of the 8th Symposium on Engineering Problems of Fusion Research*, IEEE, New York, 1979, p. 665.

30. D. E. SCHECHTER and C. C. TSAI, in *Proceedings of the 9th Symposium on Engineering Problems of Fusion Research*, IEEE, New York, 1981, p. 1515.

31. C. C. TSAI et al., in *Proceedings of the 3rd IAEA Neutral Beam Workshop, October 19-28, 1981, Gatlinburg, Tennessee*, CONF-8110118, International Atomic Energy Agency, Vienna, 1981, p. 149.

32. C. BUXBAUM, Brown Boveri Rev. 1-79, p. 43; C. BUXBAUM et al., U.S. Patent 4010081, 1977.

33. D. A. BOWERS et al., MDC E-2204, McDonnell Douglas Astronautics Company (1980).

34. D. A. EVERITT et al., in *Proceedings of the 8th Symposium on Engineering Problems of Fusion Research*, IEEE, New York, 1979, p. 1051.

35. J. A. MAYHALL et al., in *Proceedings of the 8th Symposium on Engineering Problems of Fusion Research*, IEEE, New York, 1979, p. 1070.

36. J. H. WHEALTON et al., *J. Comput. Phys.*, *27*, 32 (1978).

37. W. L. GARDNER et al., *Rev. Sci. Instrum.*, *52*, 1625 (1981).

38. C. N. MEIXNER et al., *J. Appl. Phys.*, *52*, 1167 (1981).

39. J. H. WHEALTON, *J. Appl. Phys.*, *53*, 2811 (1982). (1982).