

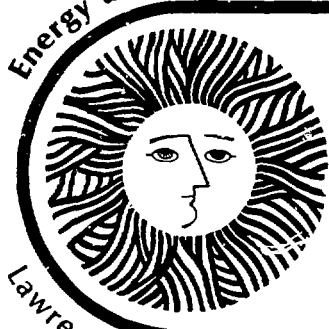
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The Design and Fabrication of an Ion
Accelerator for TFTR-Type Neutral
Beam Systems

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THE DESIGN AND FABRICATION OF AN ION ACCELERATOR FOR TFTR-TYPE NEUTRAL BEAM SYSTEMS*

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The design of the prototype 120-keV, 65-A, 0.5-sec ion accelerator for TFTR-type beam systems is described. Details of the manufacture of the constituent parts are given along with descriptions of the major components of the accelerator. Included are the molybdenum grid structures, molybdenum shields, stainless steel hats and the epoxy insulator. Specific manufacturing problems are discussed along with the results of tests to determine the voltage holding capabilities of the assembly.

Introduction

The next generation of U.S. fusion experiments which include TFTR, MFTF and Doublet III will utilize neutral beam injection for plasma heating. TFTR, for example, desires 20 MW of 120 keV deuterium atoms in pulses of 0.5-sec duration at 5 minute intervals from a total of twelve individual neutral beam sources.

This paper describes the mechanical design and fabrication of the prototype 120-keV, 65-A, 0.5-sec ion accelerator currently being tested on the test facility at the Lawrence Berkeley Laboratory. This accelerator has been developed from the earlier 120-keV, 15-A, 0.5-sec models as described elsewhere.

Mechanical Design

A schematic of the 120-keV, 65-A, 0.5-sec-pulsed ion source and accelerator is shown in Fig. 1. This module comprises an ion source chamber, accelerator electrode structure, SF₆ enclosure, bellows, and an adapter box to mate up to the test stand beam line. Whereas in earlier designs the accelerator grids were mounted on a separate "plug in" structure which fitted to an outer cylindrical insulator, this design utilizes a rectangular insulator both as a vacuum wall and as the basic support member for the grids. The insulator is rectangular to facilitate close packing of the source modules on the fusion experiment.

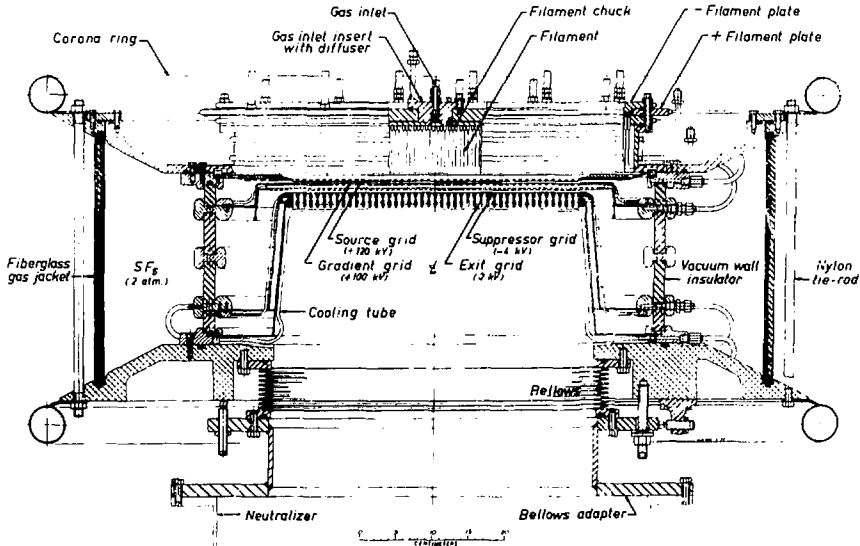


Figure 1. LBL "65-A" Neutral-Beam Source Module (65 A, 120 keV, 0.5 sec).

*Work done under the auspices of the United States Department of Energy.

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This insulator provides water cooling to the grids directly through the voltage divider rings, thus eliminating the hollow tubular insulators of the previous 15-A design. Because of the flexibility of the thinly sectioned sheet metal used to join these hollow insulators to the grid structure, difficulty was experienced in maintaining tolerances on the grid wire alignments. We also had several localized failures in the insulators themselves; thus the more rigid reliable present design was preferred. An additional advantage of the design is the easy access for probes to measure the ion density close to the first grid of the accelerator. To keep this insulator acceptably short this section of the module is contained within a filament-wound fiberglass jacket pressurized to 2 atm (absolute) with SF_6 . Pressure sensors insure the presence of the gas during operation, and standard safety features prevent overpressurization. A rectangular bellows gives flexibility to the mounting of the module and allows the accelerated beam to be steered to the calorimeter at the extreme end of the beamline. Figure 2 shows the accelerator and plasma source mounted on the test facility beamline. In this photograph the SF_6 jacket has been removed.



Figure 2. Test Facility Beam Line

trajectories of the accelerated ions. The cross-hatched regions represent the half sections of the grid rails which, starting at the plasma source end and moving in the direction of the accelerated beam, are called the source, gradient, suppressor, and exit grids respectively. The shape of the source-grid rail is determined by the physics of the extraction process, the angle of the rail side being such that space-charge blow up of the beam is prevented. The gradient- and suppressor-grid rail shapes are chosen in an attempt to minimize heating of the rails by energy deposition from secondary particles created in the beam or emanating from surfaces.

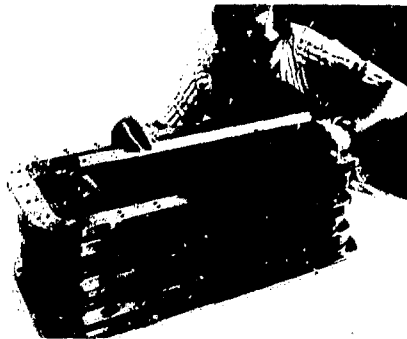


Figure 3. Accelerator Assembly.

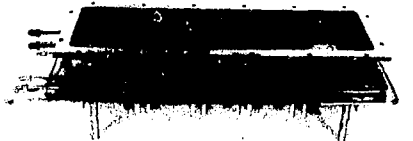


Figure 4. Ion Source Chamber.

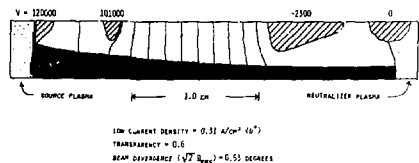


Figure 5. Calculated beam trajectories and equipotentials for a 120-kV accelerator.

The insulator with the accelerator grids in position is shown in Fig. 3; the plasma generating chamber, or ion source bolts to this assembly and the grids accelerate ions from a 10- x 40-cm area. This ion source has been described elsewhere.⁶ In brief, the source is a high-current, low-voltage discharge with no external magnetic fields. The cathode consists of 204 0.050-cm-diam tungsten filaments; the isolated sections of the back plate of the chamber, through which the gas is introduced, form the anode. This source chamber (see Fig. 4) provides a hydrogen or deuterium ion-current density of 0.25 A/cm² to 0.5 sec. The ions are accelerated in the multiple slot grid array, the molybdenum rails being designed for minimum beam divergence with the aid of the WOLF code.⁴ A half section of a grid set is shown in Fig. 5. The darkened region shows the

The sensitivity of the beam divergence to the rail-to-rail and the grid-to-grid alignments was investigated using the WOLF code and it was found that variations on the order of 0.002 in. could give a 30% increase in beam divergence over the theoretical. The most critical grid was found to be the gradient grid; the exit grid was found to influence the beam divergence least.

Figure 6 shows the gradient assembly with the grid rails and holders mounted on the gradient-grid hat. Each rail is braced at one end into a slot provided in the rail holder; the other end slides freely in the opposite holder thus allowing thermal expansion. The rails are cooled by radiation and by conduction through the brazed end to the rail holder. The rail holder has a copper cooling tube brazed along its length. This design is typical of each grid assembly.

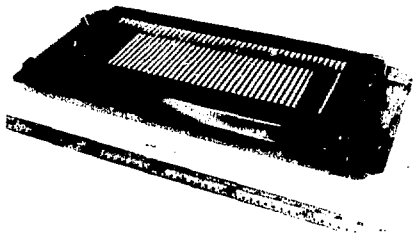


Figure 6. Gradient Grid Assembly.

Fabrication

Molybdenum Parts

The grid rails, grid-rail holders and sheet-metal shields are manufactured from molybdenum. Molybdenum was chosen for these components because of its low coefficient of thermal expansion, high melting point, high thermal conductivity, and good voltage-holding properties. Arc-cast material is preferred; where sintered molybdenum is used, however, final assembly is preceded by a bake-out at 1100°C in a dry hydrogen atmosphere for ten minutes. For all fabrication procedures care was taken to avoid the use of coolants or lubricants containing sulphur.

Grid rails. The source- and gradient-grid rails are cold rolled from molybdenum rod via impressions ground or machined into hardened mill rolls. Feedstock dimensions, structure, and work-thermal history are critical to achieve final size in flow-free rails. Good surface finishes are produced by this method with no particular effort. The formed wire is straightened by creeping at elevated temperature in vacuum; the fine worked structure is preserved by keeping the temperature below the recrystallization level.

After cutting to the desired length the rails are checked for straightness by observing the single slit diffraction pattern produced by a ruby laser. One edge of the slit is formed by a straight-edge and the other by the rail under test. With this method, it is possible to see deviations from straightness of less than 0.001 in. over the full length.

The larger suppressor- and exit-grid rails are machined with contour cutters, from rod and bar stock. Because of their larger cross-section the manufacture of these rails is not amenable to the cold rolling technique. Locked-in stresses resulting from the machining operations necessitate stress-relief annealing of the rails in a straightening fixture. Recently success has been achieved in drawing the teardrop-shaped suppressor rails; this method gives more uniformity between rails and an improvement in straightness. Drawn rails were found to contain internal cracks which can probably be eliminated by increasing the number of reduction stages.

Grid-rail holders. The grid-rail holders are matched machined in pairs to guarantee a good alignment on assembly. Numerically-controlled tape mills are used for this operation. It was found that delamination of the parts was eliminated by an anneal at 1100°C for ten minutes. An examination of the microstructure revealed that this treatment removed the anisotropic character of the rolled material by a partial recrystallization. Excessive grain growth did not occur and the resulting room temperature brittleness of the material did not cause any problems. This process also reduced the Vickers hardness of the molybdenum from 236 to 196. The material was found easier to machine and tool wear was reduced.

Shields. Molybdenum shields are used to cover sharp edges and thus reduce the electrical stresses. The shields are fabricated from 0.010- and 0.015-in. thick molybdenum sheet by standard techniques at elevated temperatures. For some of the more complex shapes a welded design is used. These sheets are welded in an argon atmosphere, in carbon jigs relieved in the weld area to minimize carbon contamination of the weld joint. A strip of the stock sheet is used as the filler material. After welding, the shields are stress relieved in vacuum.

Hat Structures

With the exception of the source grid which is mounted on a flat molybdenum plate, each grid assembly is mounted on a stainless steel "hat" structure. These structures are manufactured by standard techniques and electropolished prior to assembly in the accelerator. Any variations in the mounted surfaces for the rail holders can be accommodated using the push-pull screws used to tie down the rail holders.

Insulator

The large rectangular insulator can be seen in Fig. 3. As ceramic material was not available for the insulating sections, these parts were cast in Epon 828; the voltage divider rings of the insulator were milled on a numerically controlled machine out of stainless steel. The rings and insulator sections were then glued together using an epoxy adhesive. A clear adhesive was chosen to enable any voids in the joint to be easily detected. Prior to gluing, the surfaces were sand blasted and cleaned.

To eliminate the possibility of adhesive flowing down the sides to the insulator, a two-step gluing procedure was adopted. Sample glue tests indicate bond strengths over 4000 lb/sq in. tensile and 2000 lb/sq in. shear were obtained. As an added insurance, the glue joints are reinforced with stainless-steel shear pins; these pins also serve to accurately align the insulator stack. The use of these shear pins necessitates the provision of bleed holes in the epoxy insulator to allow trapped air to escape during the mating of the parts.

Cooling Tubes and Fittings

Our original design called for molybdenum cooling tubes, however, great difficulty was experienced in their manufacture as these tubes could develop cracks. Currently, the tubes are made from copper in the shielded

area along the rail holders, and stainless steel elsewhere. A brazed copper sleeve provides the junction between the two materials. All water fittings are manufactured from stainless steel; the vacuum joints were achieved by sandwiching a soft copper washer between two knife edges.

Assembly

For each grid, the rail holders, rails, cooling tubes and water fittings are hydrogen brazed in a single operation on precision fixtures. This operation is described in detail elsewhere.⁵ The grids are then mounted on the hac structures and aligned one to another using an optical co-ordinate measuring engine. At all times, the parts are handled using surgical-type disposable plastic gloves, to minimize surface contamination.

Voltage Holding

The accelerator structure was evacuated and enclosed in a clear plastic envelope containing SF₆. High voltage was then incrementally applied to the grids, and the resulting sparking and leakage currents were observed. A voltage of 115 kV was held between the suppressor and the gradient grids with a leakage current of 0.57 mA. Further increase caused excessive sparking followed by loud noises; thereafter, the voltage-holding capability was severely reduced. Disassembly of the accelerator revealed that the bottom shield on the gradient grid was bent downwards towards the suppressor grid shield which was severely marked in the middle. The latter shield had been pulled up by the electrostatic forces, and it was found that the screws for this shield had not been fully tightened.

Future Development and Discussion

TFR and those experiments that produce neutron environments require the use of hard seals and ceramic insulating materials in the design of the neutral-beam modules. To meet these requirements an intensive effort is currently underway to develop suitable ceramic-to-metal seals and techniques that will permit the successful brazing of the large rectangular insulators. Provisions for remote handling are also under consideration.

The large numbers of neutral-beam sources that future fusion experiments require will place an increased emphasis on the reliability of these units. Operating experience has underlined that small displacements of the shielding can result in a runaway situation with damage to the grid structures. Thus methods of shield attachment, and stability under thermal and electrostatic loading, demand careful attention. Reductions in the number of mechanical seals and brazed joints are desirable goals.

In the future, pulse lengths of the neutral beam sources are to be extended to 30 nsec. Such pulses can be considered an steady state operation and it is anticipated that severe cooling problems will be faced. At this time the thermal loading on the grids is not known, and a developmental accelerator is currently under construction that will enable experiments aimed at obtaining this information to be performed.

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