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A COMPACT 80-keV NEUTRAL-BEAM MODULE*

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Summary

A compact and maintainable source of 80-keV neutral beams that focus to a high power density is required for the Mirror Fusion Test Facility (MFTF). In the new source being designed and built to meet these requirements, the cross-sectional area is reduced in two ways: by immersing the source in a vacuum where high voltage can be held over smaller distances and by redesigning grid supporting structures. Reliability is increased by reducing the electric fields everywhere else below those present between grids and by design innovations. The latter include techniques to reduce stray magnetic field and disperse gas uniformly, all metal-ceramic construction, and a 60-kV shield enclosing all 80-kV electrodes. Wherever possible, we have attempted to simplify the construction. We expect to solve problems that arise during testing either with add-on fixes or with the techniques already tested successfully on the Lawrence Berkeley Laboratory (LBL) 120-keV source. Easy maintenance is obtained by a compact isolation valve and by modular construction. Curving both the grid wires and their holders provides focusing in two planes.

Compactness

We have designed and are building an 80-keV neutral-beam module for the Mirror Fusion Test Facility (MFTF) at Lawrence Livermore Laboratory (LLL). MFTF requires 48 neutral beams: twenty-four 80-keV, 80-A, 0.5-s sustaining beams and twenty-four 20-keV, 80-A, 10-ms startup beams. Constraints must be placed on the cross-sectional area of each module in order to locate every 80-keV sustaining beam within the solid angle that can hit the plasma but miss the magnet at both the entrance and the exit. This three-dimensional problem is discussed by Horvath.[1]

An assembled module, including arc chamber, extractor, isolation value, neutralizer, and magnetic shield, is shown in Fig. 1. For compactness, we chose to immerse the arc chamber and extractor grids in a vacuum, where we can hold the voltage over shorter distances than in air. We adopted this rather than the alternative of surrounding the source with SF_6 because the latter would involve an extra set of feedthroughs: from air to SF_6 and from SF_6 to vacuum. Instead, we go directly from air to vacuum. The vacuum wall is formed by the outer, low-carbon steel, magnetic shield. Reducing the ambient field of 400 to 800 G to the desired field of $B < 1$ to 2 G in both the arc chamber and the neutralizer requires more than 2000 lb of multiple-layered magnetic shield. Assuming that the magnetic shield occupies a total thickness of 5 cm, we expect the outside dimensions of the shield to be less than 60 × 100 cm.

Maintainability

We plan to leave the magnetic shield attached to the MFTF vacuum vessel, removing only the arc chamber and grids when necessary for maintenance. A cylindrical isolation valve between the source and the neutralizer allows source maintenance while the main vessel remains under vacuum. This simplified valve, designed by Holl and Dilgard,[2] requires no housing because the magnetic shield forms the vacuum housing for the valve as well as for the source module.

We expect that refilamenting the arc chamber will be the most frequent maintenance job. For this reason, the arc chamber can be removed by itself. The extractor is mounted on a rectangular iron frame that can be removed either after the arc chamber or while still carrying the arc chamber (Figs. 1 and 2).

Arc-Chamber Design

The arc-chamber design (Fig. 2) is based on Ehler's design for the Tokamak Fusion Test Reactor (TFTR).[3] We have made the following changes:

(1) The electrical leads were reduced from 12 to 2 sets. Twelve sets of leads were originally used in the TFTR design to reduce the current in each lead and to feed the current uniformly — both uses were intended to minimize stray magnetic field. By attaching a reduced number of leads to deep, copper channels (as will be discussed further), we expect to minimize stray magnetic fields as effectively as in the TFTR design.

(2) The arc chamber leads pass through the grounded vacuum wall rather than through a high-voltage wall, within thick ceramic tubes of length chosen to allow 12 kV/cm along the surface in the vacuum and 3 kV/cm along the surface in air.

(3) A triple gas feed has been replaced by an internal manifold that feeds gas from 19 slots uniformly distributed over the anode (back plate).

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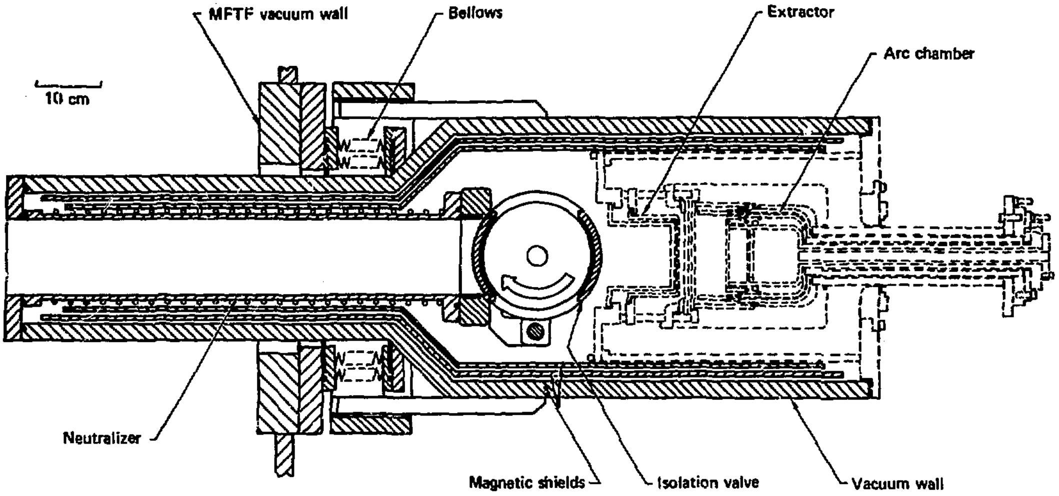

Fig. 1. The outer magnetic shield forms the vacuum wall around the arc chamber, extractor, and cylindrical isolation valve. The arc chamber is mounted off the grounded back plate by two triaxial feedthroughs. The extractor is supported by a grounded frame from an annular backplate. The isolation valve is mounted on the neutralizer tube, which is cantilevered from the exit end.

(4) An all metal-ceramic design has replaced the Kapton* insulators separating electrodes. We expect the arc chamber to withstand at least a mild bake, which may provide more rapid conditioning and decrease the impurity content of the beams.

(5) Eliminating the filament cover plate allows the number of filaments to be increased by 10% to 226.

(6) A disadvantage to this construction is that cooling lines along with multiple demountable joints are now inside rather than outside of the vacuum. This requires careful design and assembly to avoid leaks. The joints will be sealed with deformable metal gaskets, similar to the LBL design.

(7) Because the arc-chamber extractor is no longer gas tight, the surrounding pressure could be as high as the arc-chamber pressure ($\sim 10^{-2}$ Torr).

Techniques for avoiding long-path breakdown will be discussed under that heading. Design innovations (1) and (3) will be discussed in more detail below.

Minimizing Magnetic Fields

Magnetic fields greater than a few gauss affect arc-chamber operation by perturbing the flow of electrons and to a lesser degree of ions. Reducing magnetic fields to about 1 G requires reducing the field created by arc-chamber leads carrying thousands of amperes as well as shielding against the ambient 400- to 800-G MFTF fringing magnetic field.

The stray magnetic field from a current lead can be treated as a dipole for the worst case since higher-order multipole fields will fall off more rapidly with distance. The field scales with the current per lead I, the area where the lead attaches A, and the distance to the discharge chamber R as $B \propto IA/R^3$. Reducing the number of leads by a factor of 6 increased I by 6. However, changing the lead geometry from parallel to triaxial reduced the effective perturbation area to the region of the triaxial-to-parallel channel transition. At worst, the area stayed approximately constant. Therefore, we increased R by $6^{1/3} \approx 1.8$ by replacing parallel plates with deep channels. The deep, nested channels allow the current to distribute uniformly to filaments and to the anode, and the return current path stays close to and parallel to the input current. This minimizes the magnetic field from asymmetric and skewed current paths.

A second source of stray magnetic field is from insufficient shielding of the MFTF fringe field (~800 G near the sources). The shape of the magnetic shield for this 80-keV neutral-beam module is similar to that designed for the Tandem Mirror Experiment (TMX).[4] It consists of multiple, nested rectangular tubes, tightly fitted over the neutralizer and then flared to enclose the valve, extractor, and arc chamber. The outer shield, which also forms the vacuum wall, is low-carbon steel. The inner layers are high-permeability alloys. Magnetic fields leak through removable joints. Therefore, as in the TMX design, each tube in the shield is of one-piece construction with no removable joints from the end of the neutralizer to the back of the arc chamber.

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

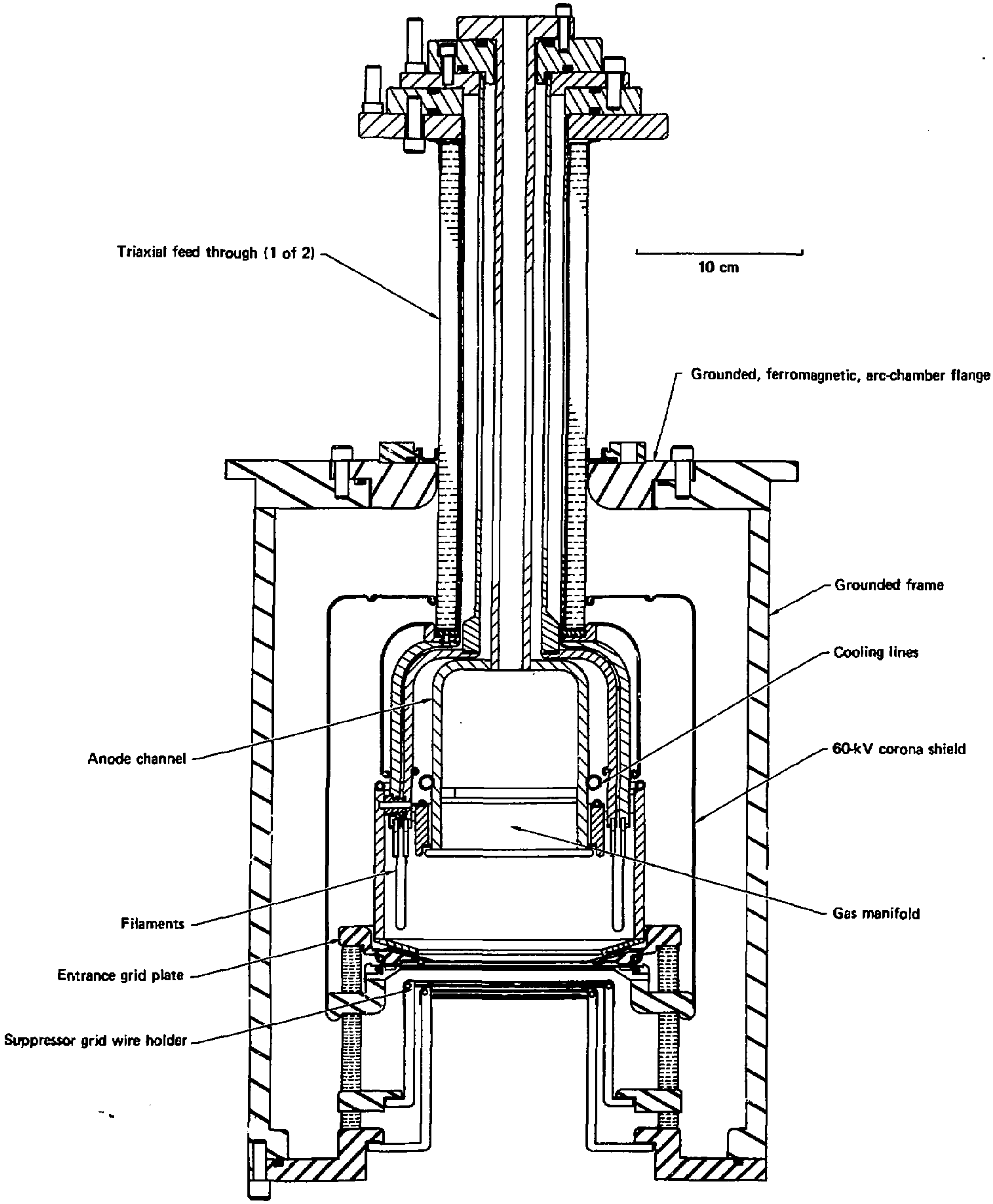

Fig. 2. The arc chamber and extractor are designed to occupy a minimum cross-sectional area.

The effectiveness of this shield is greatly improved by removable steel caps at each end. An annular cap tightly fits around the beam emerging from the neutralizer, and the steel vacuum flange at the back is punctured only by necessary feedthroughs.

Uniform Gas Injection

The deep channels provide room for an internal gas manifold to feed gas from 19 slots that are spread over the back plate. The more uniform gas distribution should produce a more uniform ion density and improved operation. The cross section of the manifold was chosen to be large enough to maintain its pressure uniform to within 15% with viscous flow, but small enough that the pressure rises within 5 ms to the equilibrium value of ~0.1 Torr. The fast rise time provides the option of using the same arc chamber on 10-ms-duration startup beams.

To disperse the gas uniformly, the distance between slots should be less than the depth of the discharge region. The 19 slots are separated by the 2.5-cm-wide molybdenum bars that form the anode. We calculate that 0.086-cm-wide slots will produce a transition flow rate of 30 Torr·l/s. A flow rate of this order is required to produce the 10^{-2} Torr necessary for arc-chamber operation.

Extractor Design

Ion Optics and Geometric Focusing

The grid wire design (Fig. 3), developed by Cooper, is basically a two-third scaling of his 120-keV structure for the TFTR.[5] The expected current density is increased from 0.25 A/cm^2 to 0.3 A/cm^2 over a 60% transparent area of 10 × 45 cm. The 80-keV power-supply drain is 80 A. The shape of the gradient grid is changed from oval to circular to stiffen the grid against electrostatic forces. A redesigned holder allows the exit grid to be circular rather than the deep rectangular bar used with the 120-keV source.

To deliver the maximum neutral power density to the plasma for possible field-reversal experiments, we focus the beam in two planes — the first by curving the wires (except for the exit grid wires, which are straight) and the second by curving the wire holders. The focal lengths are both equal to 7 m, the distance to the plasma.

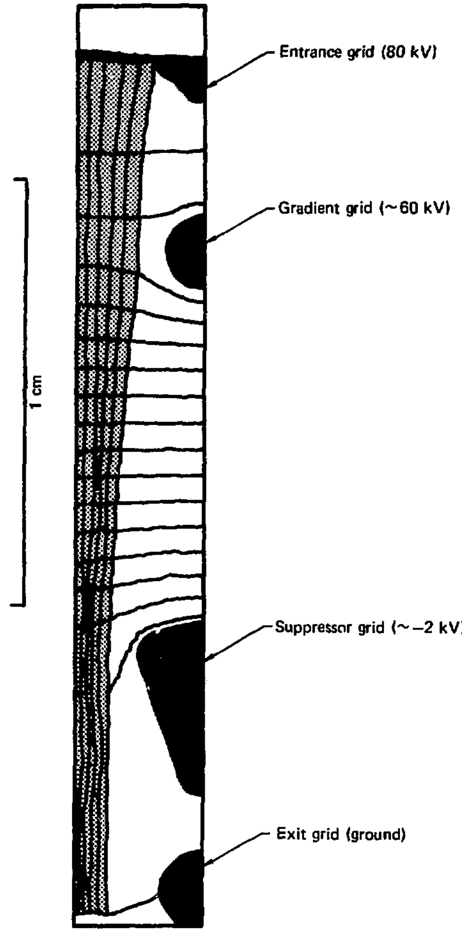

Fig. 3. The LBL-designed 80-keV grid design, based on a 2/3 scaling of the 120-keV grids.

Wire Holders

The wires are held in grooves that allow them to slide at both ends as they thermally expand. Bumpers at each end prevent wires from falling out of their grooves. Masks cover any sharp points at the ends of wires and holder grooves to reduce voltage breakdown. These masks are formed from 0.025-cm-thick molybdenum sheet. The entrance and gradient grids are elastically curved by the holders.[6] Grids assembled using this technique have been tested to 0.5-s duration, 20 keV, at LBL.[5] The teardrop-shaped suppressor grid is precurved, then held in a groove by spring tension of the mask. The circular exit grid is straight and held by the same technique as the suppressor grid. These grid-assembly techniques should be simpler than the brazed, 120-keV construction.

Our design does not maximize cooling of the grid wires, but does emphasize maintaining the locations of the wires as they heat. To prevent expansion of the slots between wires in one grid, the wire holders are water-cooled. As long as the wires remain fixed and do not thermionically emit electrons, higher temperatures should be beneficial because they keep surfaces cleaner.

The design of insulators and grid hats is aimed at making a brazable and bakable structure, although the first model will probably be fastened together with epoxy. The spacing and radii of grid hats are chosen to reduce the average electric field to ≤40 kV/cm compared with 80 kV/cm between grids.

Long-Path Breakdown

The arc-chamber pressure of P ~ 10^{-2} Torr of D_2 is expected to fill most of the high electric field regions. Breakdown at 80 kV is expected for Pd > 0.2

Torr·cm in hydrogen,[7] where d is the breakdown distance between electrodes. In deuterium, we gain the square root of the mass ratio,[8] so that breakdown occurs for Pd > 0.3 Torr·cm. To prevent breakdown, we reduce the breakdown distance along electric field lines by means of nested 60-keV and 80-keV shields, which divide the distance in half and which tend to keep electric fields normal to surfaces rather than skewed. This results in path lengths of $d \leq 5$ cm normal to surfaces. By closing the outer magnetic shield at the rear, except for feedthrough penetrations, we minimize the magnetic field strength and reduce the possibility that a long path along magnetic field lines will connect two electrodes. We thus achieve a safety factor of as much as 6 against long-path breakdown. If necessary, the arc chamber, the extractor, and the isolation valve can be sealed to confine the gas.

Conclusion

An 80-keV neutral-beam module has been designed that consists of the following elements:

(1) A vacuum-insulated arc chamber and extractor with a compact cross section.

(2) A compact isolation valve.

(3) A neutralizer.

(4) An efficient magnetic shield enclosing (1) through (3) that has no joints except for a front annular flange and a back plate, both of which improve the shielding efficiency over an open tube. The outside cross section of the shield is less than 60 × 100 cm.

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