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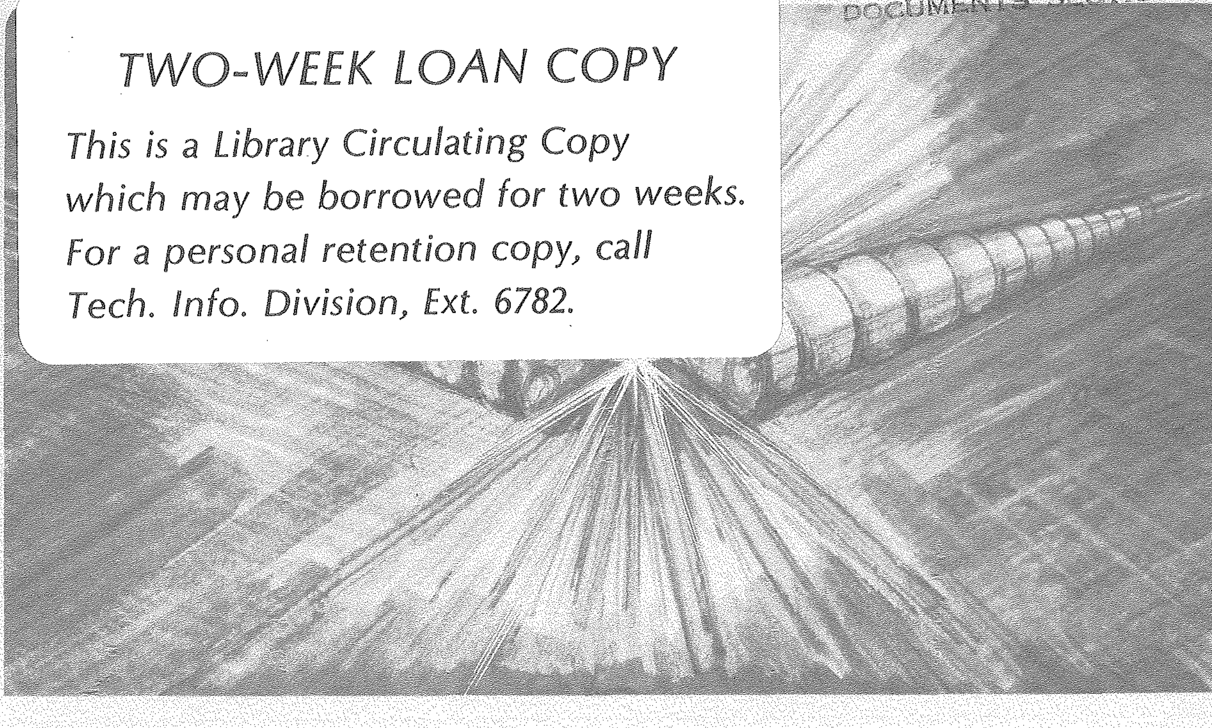

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THE MECHANICAL DESIGN AND FABRICATION OF A CONVECTIVELY COOLED ION ACCELERATOR FOR CONTINUOUSLY OPERATING NEUTRAL BEAM SYSTEMS*

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The details of a prototype 120 keV, 15 A accelerator designed for continuous operation are described. The molybdenum grids are convectively cooled by flowing water through individual grid rails and the thermal expansions are accommodated by the rail support modules. The design of these modules is such as to allow deflection and rotation at the grid rail ends, each rail being free to move independent of its neighbors. The results of structural analyses on the grids are presented along with the details of the fabrication techniques employed. A description of the cooling water system designed for this accelerator is also presented.

Introduction

Upgrades proposed for the current generation of fusion experiments such as TFTR, MFTF and Doublet III call for neutral beam injection at pulse lengths up to 30 seconds. For good ion optics it is necessary that the grids used in the accelerators of neutral beam systems be kept in alignment throughout the pulse length, in addition, the grid temperatures must be maintained within the material and thermionic emission limits. In previous designs[1] the pulse lengths have been short compared to the grid structure thermal time constants and heat-loads to the grids are at a level where it was possible to run in the heat-sink mode. In this mode the grids absorb the energy during the pulse and heat is conducted to the convectively cooled end of the grid rail between pulses. Recent operational experience has indicated that these grid designs are capable of longer pulse lengths than the original specification of 0.5 seconds.[2] It is believed however that the grid heat loads will limit pulse lengths to about 1.5 seconds for these accelerators. Several theoretical studies have been carried out to investigate the application of alternate grid designs for long pulse or continuously operating accelerators.[3,4,5,6] This paper describes the mechanical design and fabrication of a prototype 120 kV, 15A ion accelerator designed for continuous operation.

Grid Designs

Proposals for long pulse grid designs have included heat pipes, squirt tubes, once through convective cooling and solid edge cooled rails with a central separation. Grid heat loading is the dominant factor that dictates which particular design may offer a practical solution in a given system. To investigate grid heat loads on our grid designs water calorimetry was performed on an edge cooled solid grid accelerator.[7] The results of these measurements are summarized in Table 1.

GRID	1 SOURCE	2 GRAD.	3 SUPP.	4 EXIT
80 kV 0.5 sec	0.6	—	0.16	—
80 kV 1.5 sec	0.6	0.32	0.22	0.20
100 kV 0.5 sec	0.58	0.31	0.2	0.29
100 kV 1.5 sec	0.58	0.35	0.24	—

Table 1. Grid heat loads as % beam power.

To measure these heat loads it was necessary to integrate very small cooling water temperature rises over several beam pulses. The results obtained by this method are believed to be conservative as it is suspected that the cooling water was being heated by conduc-

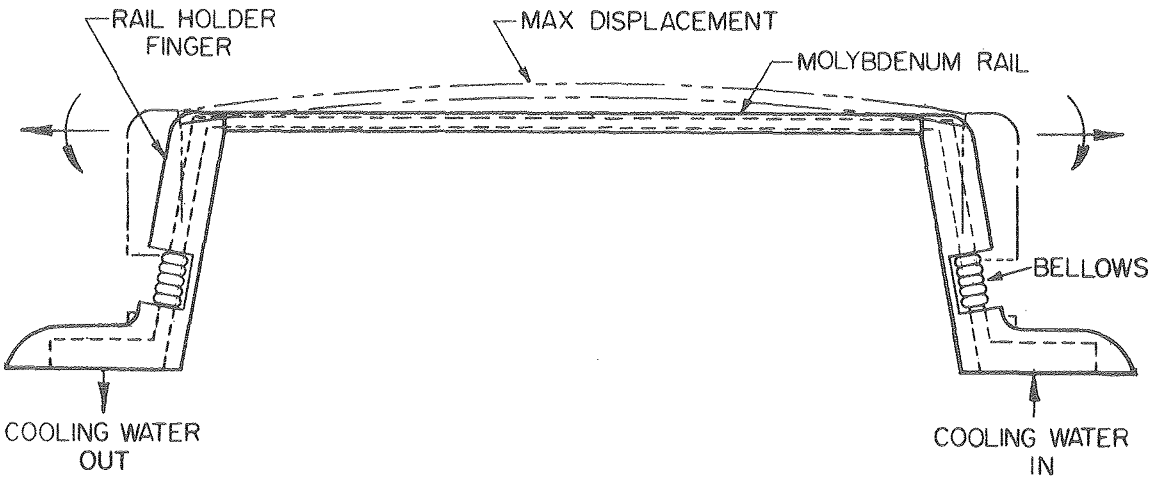

Fig. 1. Basic grid rail element.

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tion from heat shielding as well as from the grids. A once-through convective water cooling design was adopted for our grid structures based on this calorimetry data. Water was chosen over gas for the cooling fluid as this enables the grid temperatures to be limited to values where the problem of grid alignment maintenance is tractable.[4] Fig. 1 shows a basic element of our grid design, a single grid rail element. A grid module consisting of six rail elements separated by a 0.008" slot can be seen in Fig. 2. This slot allows the rail fingers and hence each grid rail to move independent of its neighbors. It is sufficiently narrow as to preclude the passage of plasma from one grid level to another. The grid rail fingers are designed with flexibility to allow both deflection and rotation at each grid rail end. The height of the rail holder fingers is minimized by relieving this member at the base and providing a bellows at this point for coolant flow. As these structures are subject to high electrical stress these bellows and all mounting bolts are protected by cover plates. In this way the contours of the assembled structure are maintained smooth. A significant improvement over previous designs has been the complete elimination of the need for thin wall molybdenum shielding.

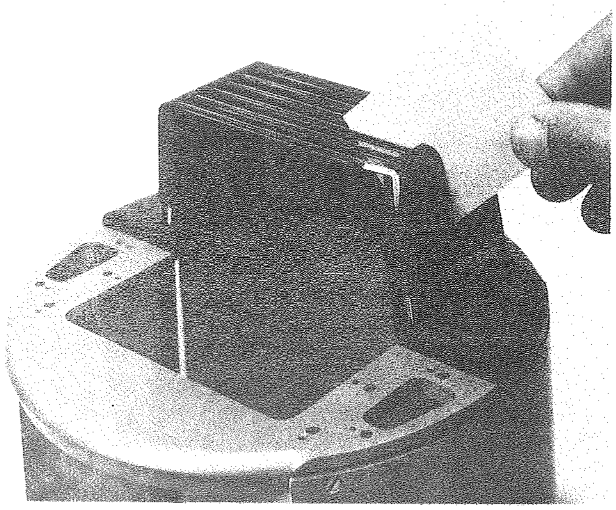


Fig. 2. Grid rail module.

Structural Analysis

As the grid rails thermally expand during the beam pulse the rail ends will be subject to displacement and rotation at both ends as indicated by the arrows in Fig. 1. This motion is accomplished by a bowing of the grid rail. The mid-point displacement is kept below the rail location tolerance by careful design of the rail holders. The finite element code SAP4 was used to perform a complete structural analysis on all the accelerator grid assemblies. The mid-span rail deflections, rail end moments, and rail assembly natural frequencies are presented in Table 2.

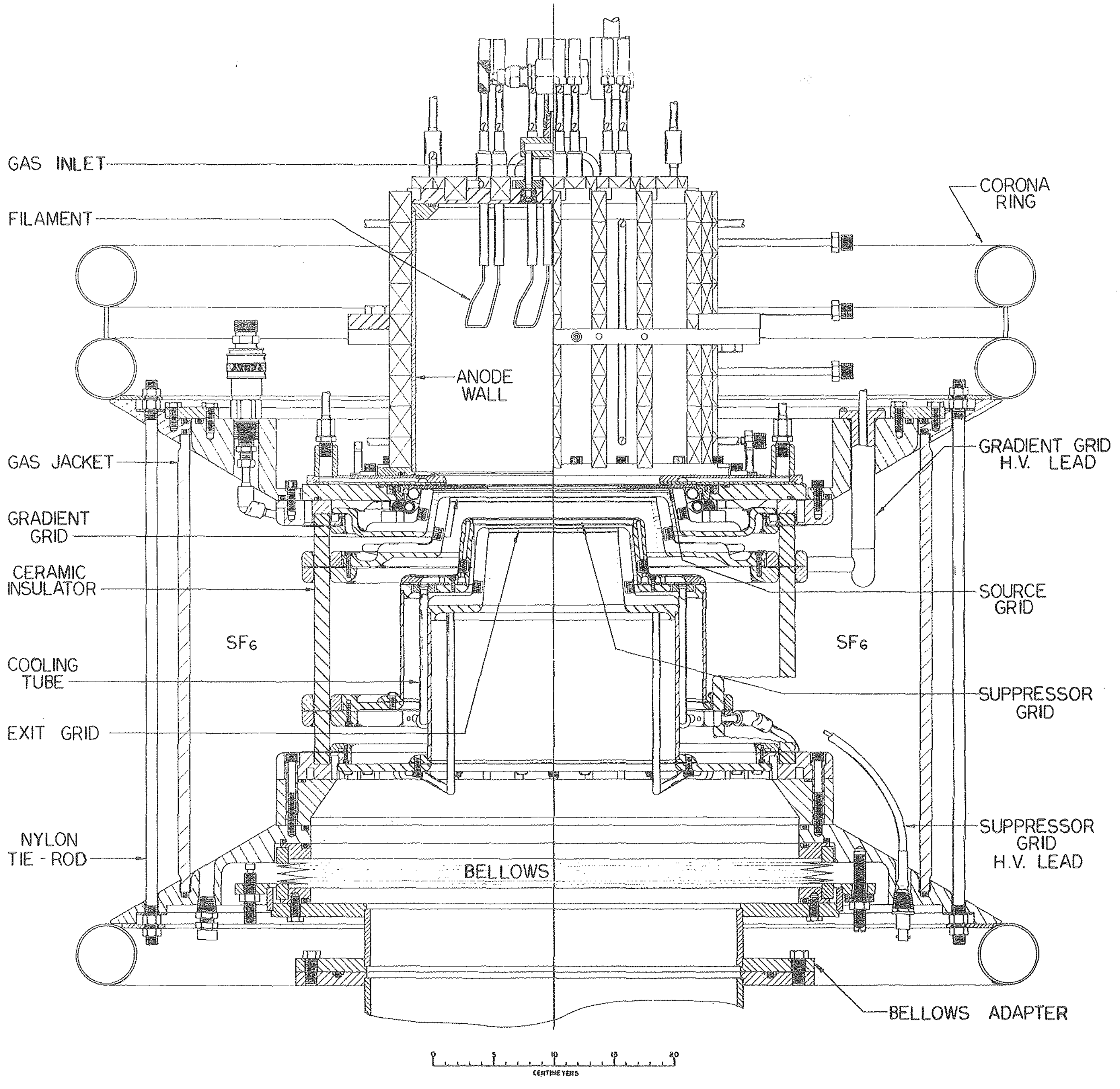
The numbers presented in table 2 result from an assumed rail temperature of 150°C over a central 10 cm span. Under operating conditions the maximum rail temperature is expected to be somewhat less, around 100°C.

Critical Heat Flux Measurements

Critical heat flux measurements were carried out on a gradient grid rail module. The rail was resistively heated over a 10 cm central span and the pressure drop over the module was measured as the power was increased for fixed supply pressure and flow rate. Supply pressures from 200 psi down to 50 psi and flowrates from 0.3 gal/min to 0.12 gal/min were tested. Each combination was tested to dissipation of 3.1 kW, the limit of the power supply. This power supply limitation did not allow us to reach critical heat flux conditions except for a supply pressure of 50 psi and a flow rate of 0.12 gal/min. At these conditions burnout occurred at dissipation of 2.5 kW. This corresponds to a critical heat-flux of 10^6 Btu/ft^{2}hr °F which is a factor of 2 below the lowest predicted critical heat flux using published correlations.[8] This discrepancy is believed to be a combination of two effects. Firstly, in small tubes the hydraulic diameter becomes comparable to the vapor bubble dimensions resulting in the presence of a large non-equilibrium vapor volume, this is not the case in large tubes for which the published correlations were made. Secondly, our test set up used flexible supply piping to the test module. This upstream compressible volume has been found to dramatically reduce burnout heat fluxes, this is in opposition to the small diameter effect and has been documented to be the dominant variable.[9] The necessity for high voltage standoff and accelerator aiming suggest that rigid

GRID	RAIL CENTER DEFLECTION IN	RAIL END AXIAL FORCE LB	RAIL END MOMENT in. lb	RAIL ROTATION rad.	FUNDAMENTAL FREQUENCY hz.
1 Source	-0.66×10^{-3}	1.34	0.03	0.00161	190
2 Gradient	2.24×10^{-3}	1.02	0.13	0.00127	309
3 Suppressor	1.55×10^{-3}	0.81	0.09	0.00109	302
4 EXIT	0.89×10^{-3}	0.62	0.13	0.00076	257

Table 2. Results of grid structural analysis.



10 X 10 CM LONG PULSE ACCELERATOR

XBL 7910-12420A

Fig. 3

cooling water supply piping is not a practical possibility at this time. The resulting uncertainty in critical heat flux would thus indicate that grid designs relying on sub-cooled or bulk boiling for cooling may have poor reliability. The cooling water supply pressure and flow rates to our grids have thus been specified to result in operation at a point where the difference in grid wall temperature to bulk water temperature are below the level where boiling incipience will occur. Cooling is this regime is also expected to result in more stable operation as should some grid rails receive more heat than others the cooling water flow will increase to compensate. This effect will result from the reduced fluid viscosity at the grid wall.

Accelerator Manufacture

Grid Structures

For rapid repair in the event of a failure, and potential cost savings, it was decided to make the grid structures modular in design. A single such module is shown in Fig. 2. The grid rails are manufactured by drawing molybdenum tubing to the desired section and the rail holders are machined 304 stainless steel. To achieve a structurally sound and vacuum tight joint between the rails and holders, a recess is machined in the holder fingers by spark erosion. The module is a brazed assembly, the brazing being completed in two stages on a precision fixture. The stainless steel bellows are first brazed in the rail holder fingers using the nickel gold eutectic braze filler. In a second operation, at a lower temperature, the grid rails are brazed to the rail holders with a paladium-copper-silver alloy. Both operations are carried out in a dry hydrogen atmosphere and at a temperature at least 20 degrees C above the alloy liquidus. With thorough prebrazing inspection and careful cleaning, vacuum tight joints were consistently achieved. All components of the grid assemblies are hydraulically pressurized and vacuum checked prior to assembly. The grid modules are also vacuum checked after each brazing operation. Each rail holder has a flow distribution cavity which is sealed by a welded-in cover plate. It was discovered that several of these welds were cracked after the brazing operation, repairs were affected by sealing with braze filler. The precise reason for this cracking has not been established, but possibilities include stress risers from incomplete penetration, hydrogen effects in the material of the heat affected zone and carbide precipitation at the grain boundaries. The material specification for these components has now been changed to call for low carbon stainless steel.

As the grid rails of each module are in parallel, it was possible that uneven flow distribution would be a problem. To check out the flow in each rail, a clear plastic model of the flow distribution cavities and rails was made. With the design water flow passing through the model, a small quantity of nitrogen was indroduced to the flow stream and a photograph taken. Comparison of the bubble streaks in each rail indicated the desired uniform distribution of flow was present.

Subsequent to the brazing operations, several of the grid rails were found to have developed cracks. No attempt was made to seal these cracks, instead, these rails were machined out of the modules and replacement rails brazed in their place. The successful development of this process has given us confidence that should grid structures be damaged in operation, we will be able to replace damaged rails quickly and simply. In order to inspect the as-brazed grid modules for plugged up coolant channels, hot dry nitrogen was flowed through each module. The surfaces of the grids were then scanned with an infrared sensor to identify if any rails were being starved of gas. This test was made more sensitive by simultaneously blowing air over the grid rails.

Figure 3 shows the grid modules assembled in the ceramic insulator. The alignment of these grids is carried out in a co-ordinate measuring machine and is facilitated by push-pull screws in each of the rail holders. The magnetic bucket plasma source is shown mounted to the accelerator which is itself housed in an insulating sulphur hexafluoride chamber.

As the cooling water to the accelerator will be pressurized, all the bellows used in the cooling tubes are restrained by covers. These covers additionally serve to protect the bellows and give smooth contours to minimize voltage gradients.

Insulators

Accelerator Insulator

This insulator forms the vacuum wall and is the primary structural element on which the grids are assembled. The insulator is circular in section and is a brazement of 94% alumina ceramic and titanium. The manufacturing techniques used for this insulator resulted from a brazing development program described in detail elsewhere.[10] The circular 0.6 inch thick ceramic is brazed directly to 0.035 inch thick titanium in a one-step vacuum braze operation using a titanium-copper silver braze alloy. The cooling water to the grids passes through Tantalum tubes brazed directly through the ceramic wall. Tantalum was chosen to result in a compression joint after brazing. As the braze alloy does not wet tantalum as readily as titanium, it was arranged during brazing to be able to view this section of the braze joint. Subsequent to brazing in vacuum at 945°C, it was discovered that some fittings that were welded to the tantalum tubes had brazed to the titanium rings despite the use of the boron nitride stopoff to prevent this. This problem caused a buildup of axial stress in the tubes during cool down resulting in vacuum leaks at the braze joints of several of the tubes. In prior braze tests, we had no problem in achieving vacuum tight joints with this design. The eight large titanium to ceramic braze joints were all found to be vacuum tight on inspection. In the final stage of insulator assembly, the thin titanium rings at the ends are spot and fusion welded to the large titanium end flanges, thus completing the insulator unit.

Ion Source to Accelerator Insulator

The multi-cusp ion source is electrically isolated from the accelerator by an insulator.[11] Recent test-stand experience has indicated that the use of anodized aluminum for insulating material is satisfactory in this application. Our specification calls for 0.002" to 0.003" thick natural anodizing followed by lapping operation to achieve reliable vacuum seals. The use of anodized aluminum allows us to simply manufacture insulators of complex geometry. As the insulator is heated by plasma and the filaments of the ion source, active cooling is necessary for long pulse operation. This is achieved by providing a machined water channel sealed by a welded-in cover plate. During operation the insulator surfaces get covered with deposited tungsten from the filaments. To break up the resulting conductive layer area into smaller units, and to preserve the electrical insulation, the design incorporates regions which are shadowed from the filaments, in this way they maintain their insulating properties.

Cooling Water Supply System

A self-contained cooling water system was designed for continuous operation and built to provide controlled flow and back pressure to each accelerator grid module. A simplified schematic of our system is shown in Fig. 4. A triplex water pump is used with an accumulator to smooth out the flow fluctuations. Each grid module has separate flow control and metering and the cooling water temperature rise over the grids is recorded. Minimum grid water pressure is assured by the use of a back pressure regulator. Heat from the grids is rejected to the cooling water of the heat exchanger and the water resistance is maintained at 1 MΩ-cm minimum by the demineralizer. The reservoir is pressurized by nitrogen gas to help reduce algae growth and to minimize dissolved gases in the water. Interlocks to the beam are provided on the flow and pressure of each accelerator cooling circuit and a high temperature alarm will sound if the cooling water supply temperature rises.

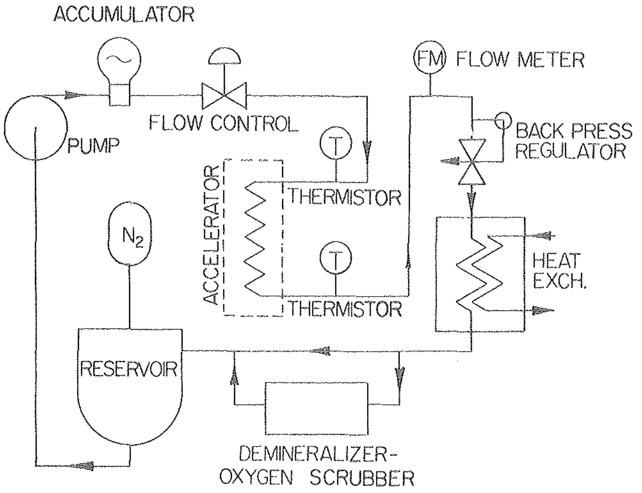


Fig. 4. Cooling water system schematic.

Discussion

To date, no operating experience has been gained on this accelerator and such questions as to the reliability of the design remain unanswered. The accelerator represents a marked increase in complexity over previous designs and the potential for damage is great. Increased quality control over all stages of manufacturing are required. Our original worries as to the difficulty in repairing such structures are now reduced as we have found repairs to be no more difficult to perform than our previous accelerators. Gross nonuniform heat distributions on the grids could obviate the conservatism in our design. Whereas qualitative evidence for such nonuniformity has shown up in operation, no quantitative information is available to the designer.

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