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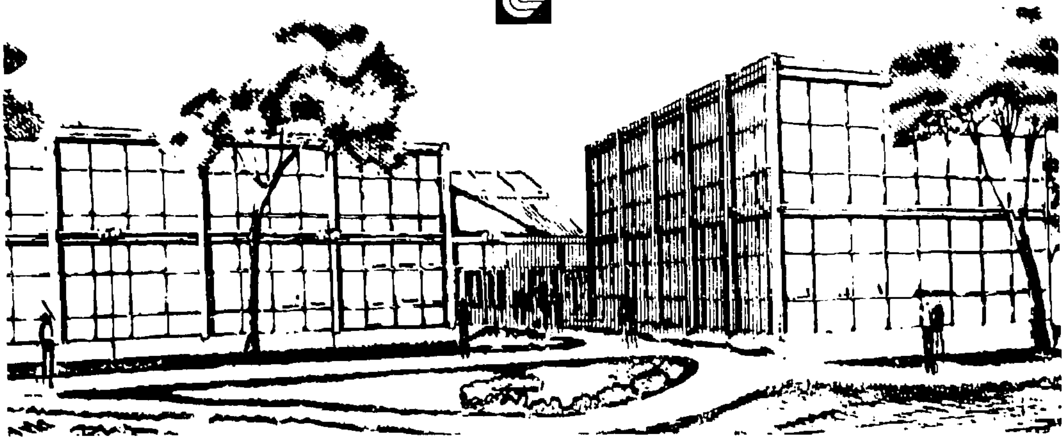

FINAL DESIGN OF THE NEUTRAL BEAM LINES FOR THE TOKAMAK FUSION TEST REACTOR*

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Summary

Final design of the neutral beam lines for TFTR has been completed. A prototype has been assembled at Lawrence Berkeley Laboratory and is undergoing testing as part of the Neutral Beam System Test Facility (NBSTF).

The final neutral beam line (NBL) configuration differs in several details from that previously reported upon;[1] certain components have been added; and testing of the cryopump system has led to some design simplification. It is these developments which are reported herein.

Final Configuration

A cutaway view of the NBL is shown in Fig. 1. The vacuum vessel itself is basically unchanged from the design previously reported upon, except that large diameter pump-out ports in the bottom have been eliminated, as conventional pump-down will be through one of the 24-inch ports at the bottom of the end walls. It is in component design that major changes have been effected.

Calorimeter and Beam Scrapers

Thermal Design. The calorimeter is designed to accept the entire output of three sources, including both ions and neutrals, so that source tuning and conditioning may be done even with the bending magnet off. It is formed of three copper vees, each vee accepting the beam from one source. Beam energy is absorbed as sensible heat in the copper. The vee angle was chosen to limit the maximum power flux normal to the copper plate surface to 2 kW . cm^{-2}. Cooling tubes brazed to the back side of the vees remove heat between shots. The outer sides of the outer vees are guarded by a thin aluminum thermal shield to provide some degree of isolation from the 80 K surfaces of the cryopumps.

Mechanical Design. Beam scrapers were incorporated into the calorimeter design. They are positioned so that the downstream scraper is nearly flush with the vessel end wall and the upstream scraper fits flush against the differential pumping baffle separating the middle and downstream chambers. In this configuration they are further apart than the diameter of the calorimeter hatch. Removal and installation of the scraper in the vacuum vessel is facilitated by the curved camming surfaces seen in Fig. 1. With the calorimeter assembly out of the machine, the scrapers hang below the vees. As the assembly is lowered into place, rollers on the bottom of the scrapers engage the camming surfaces, and the scrapers are swung out into position with the aid of a four-bar linkage.

Once the assembly is in place, movement of the calorimeter vees up and down is independent of the scrapers, which remain in position until the entire assembly is again removed. The vees are raised to permit shots into the TFTR torus by means of a lead screw assembly, and cooling and instrumentation lines are made re-entrant into the bellows seen in Fig. 1.

Photodiode Array

Provision was made in the design to accomodate an array of photodiodes used for beam diagnostics. The diodes, housed in the box seen just to the rear of the calorimeter, detect light emitted by each of the three beams on an array around their perimeters.

Ion Dump

The ion dump, located above the bending magnet, is of the same type design as the calorimeter, in that it uses the thermal inertia of copper to absorb the energy of positive ions deflected out of the beams by the magnet. The dump was designed using computer generated trajectories of the beams. Separation of the full-, half-, and third- energy ions by the magnet was found to be sufficient to enable a dump to be designed to accept them discretely. Likewise, the three beams are also well separated at the dump location. The dump consists of three sets of plates. The plate for 120 keV ions is inclined slightly from the vertical and is positioned just downstream of the magnet. The 60 keV ion dump is horizontal and located above the magnet. The 40 keV dump is vertical, located just behind the rear of the 60 keV dump. Each dump is provided with three water-cooling circuits, one for each beam

The dumps attach to and are removed with the cover of the 72 inch hatch. This opening is also used for magnet removal and installation. The 120 keV dump plate is inclined slightly rearward because it is wider at the top than at the bottom, and the inclination allows the assembly to be removed with a straight upward lift.

Space limitations and considerations such as the above for remote handleability led to a dump thermal design less conservative than that of the calorimeter. The peak power density normal to the 120 keV plate surface is 2.75 kW . cm^{-2}. At this flux, the front surface will reach the design limit temperature of 800 C in 1.0 second (well above the design requirement of 0.5 second). A design limit bulk temperature rise of 444 C limits the pulse length to 1.5 seconds. The 444 C is estimated to be a pipe fatigue life limit.

(A retrofit is being done to extend these time limits. The 120 keV plate is to be positioned vertically, thus reducing the surface power flux to 1.5 kW . cm^{-2}, which will allow 2.0 second pulses before the temperature rises to 800 C. Likewise, its thickness is being increased slightly so that the bulk temperature rise of 444 C will be reached with pulses of a like duration. The penalty paid for these changes is less convenience in remote handleability, as the assembly will have to be lifted off its seat, then shifted rearward to be removed.)

The dumps, unlike the calorimeter vees, have a rather large view factor between the heated surfaces and the cryopump panels. To cut down on the heat load to the cryopumps and to control at least direct sputtering of copper onto the panels, slatted baffles close the open sides of the dump array, the angle and pitch of the slats being chosen to minimize impedance to gas flow from the dumps to the pumps.

Magnet and Magnetic Shielding

The basic magnet design is unchanged from that previously reported upon.[1] The three gaps can be excited independently so that the three sources can be operated at different acceleration voltages and still have the ions print on the proper areas of the ion dump.

The magnet is made removeable by means of two pivoted hooked bars, one of which is visible in Fig. 1. A special handling fixture engages the hooks. As the fixture is raised, the rear hooks, which are engaged around pins in the magnet stand to provide fore-and-aft stability against seismic disturbance, disengage. Further upward motion rotates the magnet from its 45° inclination to vertical, in which position it can be raised through the 72-inch port. Upon re-insertion, the magnet is guided into position by bosses at the lower rear corners which slide down guide surfaces on the stand.

The region between the neutralizers and the magnet, and portions of the magnet itself, are shielded from the TFTR poloidal field by a shielding structure constructed of Allegheny-Ludlum 4750 electrical steel, chosen for its combination of high initial permeability with high saturation field. The portions of the shield structure which lie atop the magnet are separately removeable for magnet access. The shielding alongside of and between the beams is slatted to minimize impedance to gas flow. Perturbation of the poloidal field by all of the ferromagnetic material in as many as six NBL's is calculated to be less than the design limit of 5 gauss at a torus major radius of 350 cm.

Differential Pumping Baffles

The baffles, of sheet stainless steel construction are, for the most part, mounted to the assembly which also includes the vacuum vessel lid and the cryopanels. When this assembly is lowered into place, the baffles meet the floor of the vessel with curved edges, forming more-or-less of a seal. Partial baffles are attached to the magnet stand and the magnet, with overlaps arranged so that when everything is assembled the vessel is divided into three chambers in series, with conductance between the first and second only through the magnet gaps and conductance between the second and the third only through the beam scraper at the rear of the calorimeter. Baffling at the top and bottom of the vessel is arranged so that the volume between the cryopanels and the vessel walls is common only to the first chamber.

Source, Neutralizer and Terminal Assembly

This assembly mounts to the 90-inch port at the rear of the vessel, and consists of: three neutralizers; the 90-inch flange; three each transition spools, isolation valves, optical diagnostic spools, clamp seals, sources, source mounts, source housings, terminals, source housing mounts; a moveable assembly support; and a fixed support.

Neutralizers. The neutralizers consist of rectangular, water-cooled copper ducts surrounded by magnetic shielding. They are sized to give 75% of infinite line density beam neutralization at one-third of the nominal source gas flow.

Transition Spools. The transition spools, of mild steel construction for magnetic shielding, are made with the flanges on the two outer spools angled so as to provide initial beam aiming.

Diagnostic Spools. The diagnostic spools, between the valves and the clamp seals are fitted with front-surface mirrors angled so as to accept light radiated from the beams along a path lying in the vertical center plane but inclined so that the frequency is doppler shifted down, then combine that light with light radiated along a horizontal path through the beam's center, inclined so that the frequency is doppler shifted up. The combined beam is sent up through a window to a spectrometer. The angles are chosen so that six peaks are observed, three for each energy (120, 60 and 40 keV) as observed looking vertically through the beam and three observed looking horizontally. Relative intensities provide an indication of species mix; broadening of the peaks indicates the source angular divergence.

Source Housings. Each source housing consists of a pressure vessel of mild steel, designed for one atm. gage of SF_6 pressure, with a high permeability liner. The pressure vessel is split on a diagonal joint for good source access. The liner is designed with all joints vertical, i.e. more-or-less aligned with the poloidal field, to minimize in-leakage of field.

Terminals. The terminals are provided to make connections both at the rear of the source and to cabling from the source power supplies at the bottom rear of the source housings with a cabling harness (indicated by dashed outline in Fig. 1) which flexes to allow source aiming. The terminals are designed so that a push-on, pull-off motion will make and break over 80 separate filament, arc, and suppressor connections as well as diagnostic lead connections.

Source Mounts. The source mounts are two-axis gimbals with motor drive to give vertical and horizontal aiming.

Support Structure. A fixed support, welded to the vessel, carries all the weight of the assembly. A moveable support, to which all other components are mounted, has linear roller bearings on its bottom, which ride on round ways on the fixed support. This permits the final mating of the 90-inch flange to the vessel to be made with a straight in push. Similarly, for disassembly, the moveable support is first rolled back a few inches to part the sealing surfaces with no scrubbing. Then the entire assembly is lifted by crane to clear the linear bearings, whereupon the neutralizers can be backed out for final clearance. A similar arrangement is provided for each of the three source housing assemblies, which demount by means of the clamp seals.

Cryogenic System

The final design of the cryosystem was substantially as previously described.[2] Some differences of detail did occur, as results of either fabrication experience or tests that were performed on system components prior to the completion of system assembly. These differences and tests will be described. The completed cryosystem was first tested in June 1979 and the results are given elsewhere in these proceedings.[3]

Cryopanels. The original design called for the modular cryopump chevron assemblies to be oven-brazed, and indeed one such unit (out of the ten ordered) was successfully made. Ultrasonic examination of a test sample revealed more than adequate bond area and the one completed unit, although not ultrasonically examined, appeared generally to have good braze quality. However, a less expensive fabrication procedure was developed for the remaining units. The chevrons were individually TIG-brazed to the LN_2 cooling tubes using Everdur 1010, a copper-silicon alloy. A total of roughly 1,700 such brazes were required per module. The work was done at the LBL shops; the staff made a heroic effort in completing these assemblies. The final assemblies for the operational TFTR beamlines are now being fabricated at LBL using the same method.

The oven-brazed assembly was put to use as a test pump for improving and simplifying liquid nitrogen circulation within the assembly. Initial problems with LN_2 circulation were primarily due to much larger heat loads on the LN_2 circuit than anticipated. The tests were performed in the Baseball II vacuum vessel, which had previously been used for oil-impregnating high voltage assemblies. After the problem was clearly identified (equivalent wall emissivity 0.7), insulation was installed to bring the heat load into the design range (about a factor of 3 lower). At this level LN_2 circulation was good; by substituting a fixed orifice for a valve in the feed system the potential reliability problems with the valve were eliminated. Further tests were performed to optimize the orifice size.

<u>LN_2 Manifold</u>. In view of the circulation tests performed, the individual solenoid valves at each module were replaced with fixed orifices. This system worked quite well when tested. No other changes were made.

<u>Liquid Helium Dewar</u>. The liquid helium dewar was constructed substantially as described.[2] The inner dewar was supported by the vendor's proprietary design rather than the tension struts of the original design. The valve assembly was modified to incorporate the additional function of blocking the cryopanel exhaust to provide self-syphoning return of LHe to the dewar for regeneration; because the seats are metal-to-metal, careful hand fitting was required. Final system test showed that LHe circulation worked well, even though the dewar was nearly empty.

<u>Up-to-Air Accident Simulation</u>. A simulation of the worst-case up-to-air accident defined by PPPL was performed in November of 1978. A schematic of the test system in this configuration is given in Fig. 2. One cryopump module was installed in the 25 m^3 Baseball II vacuum vessel, and steady state circulation of both LN_2 and LHe was established. Fast response pressure transducers were teed to the LHe feed line; a rupture disc set at 75 psid was installed on the exhaust side, venting to air. The exhaust circulation side was through a quite restrictive line(60 cm of 0.6 cm ID tube). (The fact that good circulation of LHe was obtained nevertheless, as shown by temperature stability at 4.3 K at the top of the panel, gave good confidence that no LHe circulation problems would be encountered in the complete system.) A 7.2 cm restrictor plate, outside of which an aluminum foil seal was installed, was used as a fast-opening air valve. We had no means to measure or infer the LHe circulation quality prior to starting the test.

All exhaust valves shown were closed, the dewar vented and the solenoid valve closed. It was not possible to close the foot valve shown. The strip chart recorder was started, and the test performed.

A facsimile of the response produced when the aluminum foil vacuum seal was ruptured is given in Fig. 3, together with the calculated response.

Several points should be noted:

1. The peak rate of pressure increase, at 80 ms into the accident, corresponds, to within 10%, to a 7 W/cm^2 heat load.
2. The opening of the burst disc is delayed from 18 ms calculated, to 110 ms observed. This is probably due to the effective pumping of the large chamber volume, as well as thermal diffusivity effects, neither of which were included in the calculation.
3. The periodicity of the pressure fluctuations corresponds closely to the transit time of a sound wave, at the speed of sound for those conditions, from the sonic flow region to the transducer.
4. Since the calculation was performed for 0% gas fraction at 3.8 K, as opposed to an unknown gas fraction at 4.3 K, the agreement may be somewhat fortuitous.

Conclusion

The objective of this design has been to achieve, with a minimum of compromises, the requirements for performance and remote handleability originally set forth by PPPL. The extent to which the objective has been met will, of course, be measured by the testing now underway at LBL.

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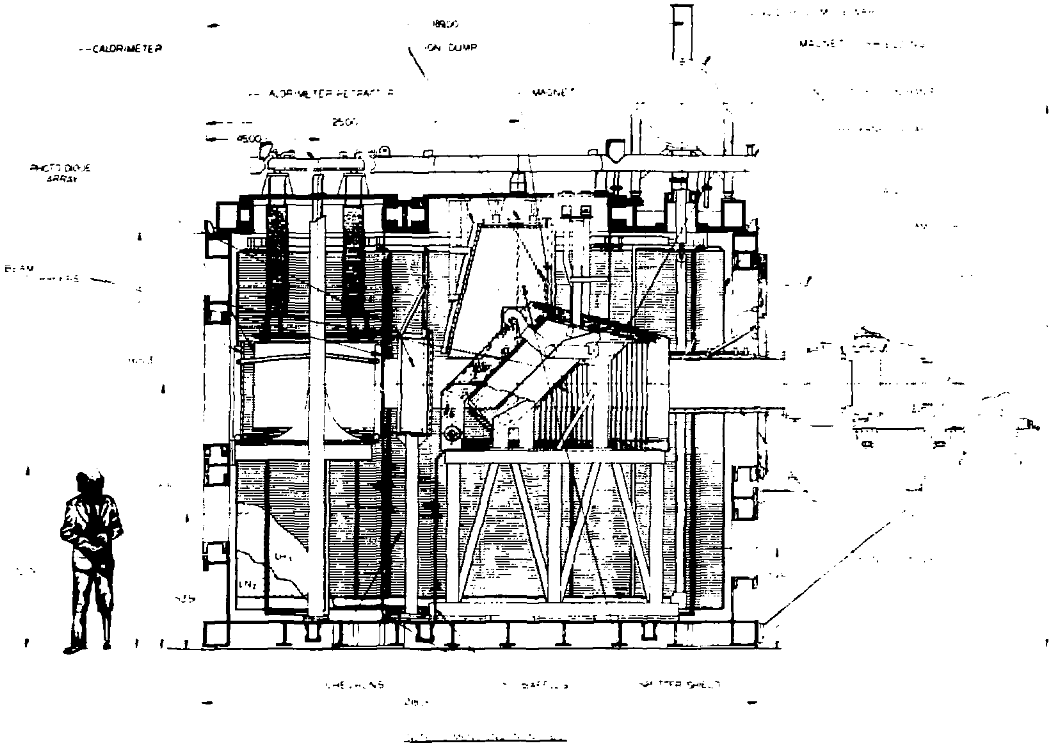

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18900
ION DUMP
CALORIMETER RETRACTOR
MAGNET
2500
4500
PHOTO DIODE ARRAY
BEAM
MAGNET
LH2
LN2
CHEVRONS
BAFFLES
SPATTER SHIELD

Fig. 1

SYSTEM FOR UP-TO-AIR TEST

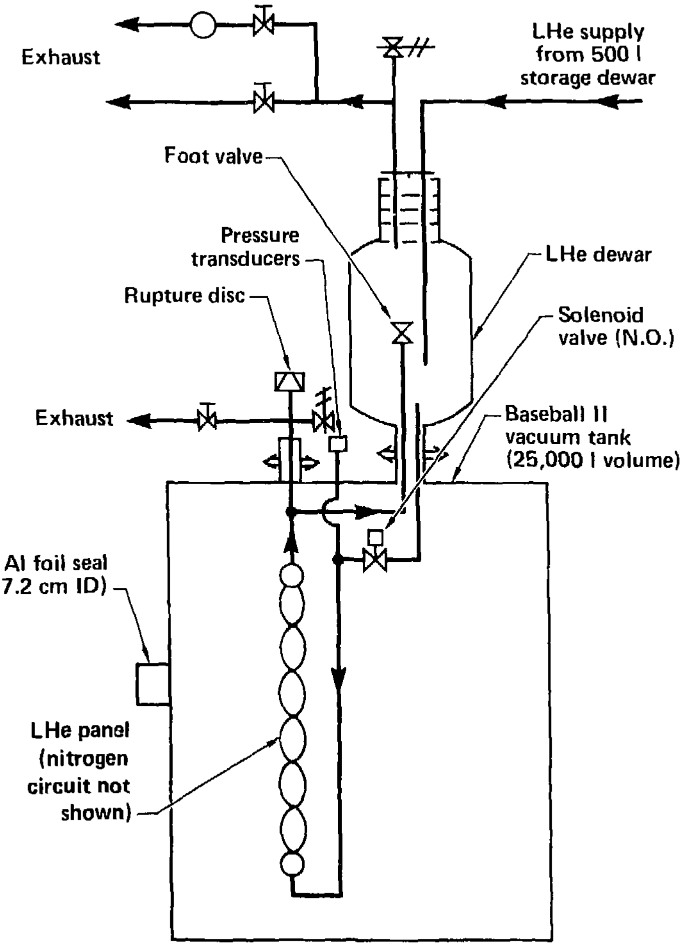

Fig. 2

RESULT OF UP-TO-AIR TEST

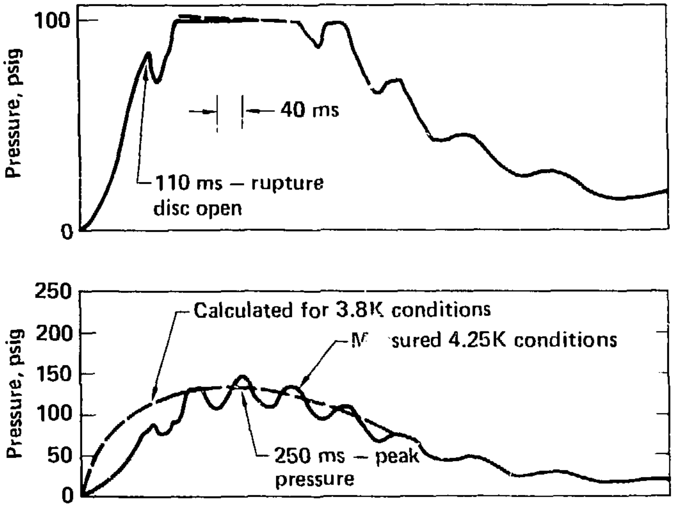

Fig. 3