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CRYOPUMP OPERATIONS WITH THE TOKAMAK NEUTRAL-BEAM-INJECTOR PROTOTYPE

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INTRODUCTION

In January 1977 the Lawrence Livermore and Berkeley Laboratories (LLNL/LBL) were commissioned to develop the prototype neutral beam line for the Princeton Plasma Physics Lab (PPPL) Tokamak Fusion Test Reactor (TFTR). Construction and installation proceeded during 1978-79 at Berkeley and the cryosystem first cooldown was in July 1979.

Design has been described in earlier papers.[1-4] The present source is rated at 120 kV, 65 A and 0.5 sec pulse length with deuterium (D_2) (20 MW for 3 sources). The beam line is shown in Fig. 1. For the three ion sources the total deuterium gas flow is 100 Torr liter/sec. In the source,electrons are stripped and the D^+ is accelerated to 120 kV. The energetic beam travels through the neutralizer dense gas gradient created by excess D_2 source gas and by charge exchange becomes neutral (D^o). The magnet permits the D^o neutrals to pass and deflects the remaining D^+ ions into the ion dump. The beam then passes through the photo diode array into the calorimeter, both used for diagnostics. With the calorimeter retracted, the beam enters the duct, which models the Tokamak injector. The neutral D^o passes through the toroidal magnetic field and enters the plasma. The beam provides fuel and heating for the fusion reaction plasma. At LBL the beam terminates on a water-cooled beam dump in the target tank.

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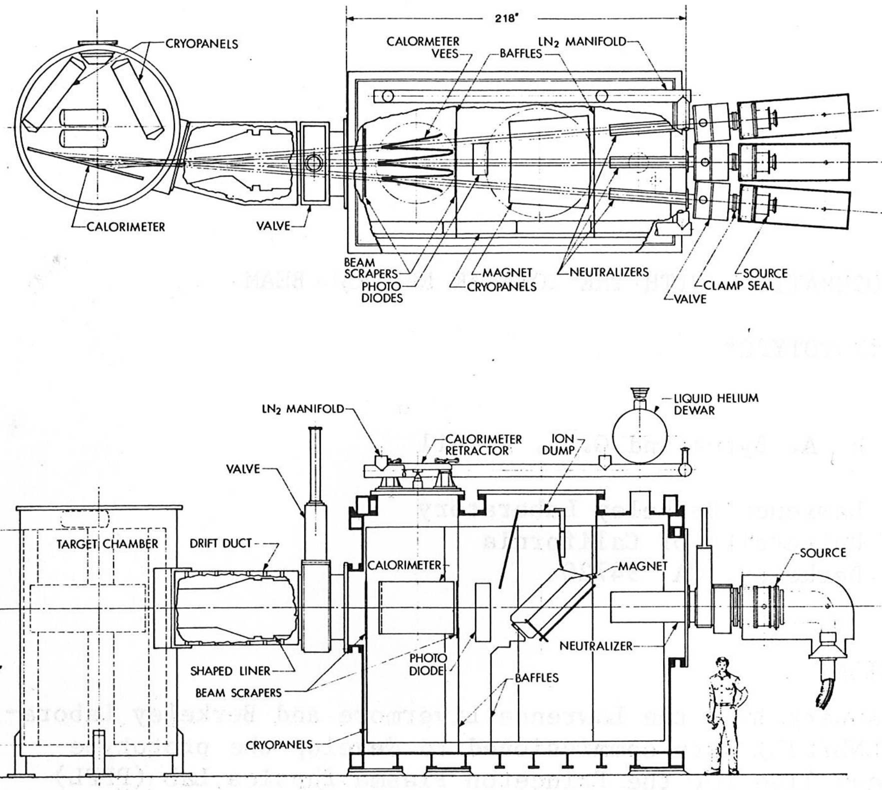

Fig. 1. Neutral beam injector with target tank.

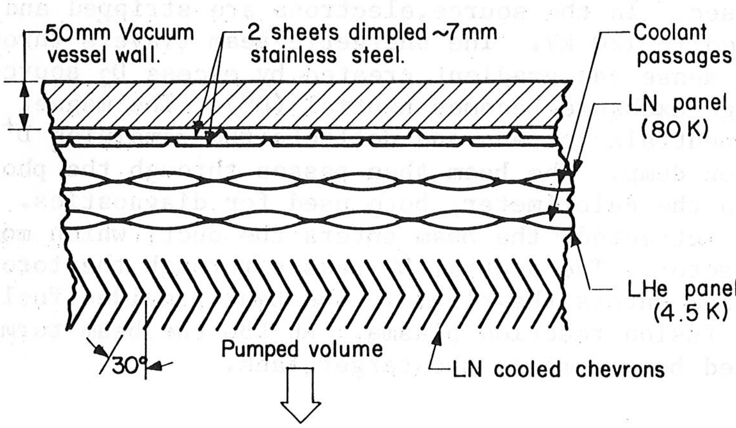

Fig. 2. Cryopanel assembly section.

CRYOSYSTEM COMPONENTS

The major cryogenic and vacuum elements are listed in Table I.

Table I. Neutral Beam Injector (NBI) Cryopump Equipment List

1. Injector Vacuum Vessel, 18 ft long x 13 ft high x 10 ft wide, Type 316 stainless steel. Gas volume (less enclosed apparatus) 50,000 liters. Vessel weight, 66,000 lb Lid weight, 38,000 lb.

2. Mechanical Vacuum Pumps.

   a) One Stokes Model 1722 two-stage consisting of a 1300-CFM rotary dry lobe high vacuum booster and a Model 412 30-CFM oil-sealed pump.

   b) One Stokes Model 412 300-CFM oil-sealed pump.

   c) One Leybold-Heraeus turbomolecular pump. 3500 liter/sec (air) backed by a Leybold 26 liter/sec rotary oil-sealed pump.

3. Eight cryopanels, each module 48 in. (1.2 m) x 144 in. (3.6 m); total active pump area 30 m^2, design pump speed on D_2 ~ 2.5 x 10^6 liter/sec at 4.5 K. Mass of one LHe quilt ~ 200 lb, volume of one LHe quilt ~ 15 liters, weight of one module ~ 1300 lb (two quilts 200 lb each plus 900 lb frame with chevrons). Mass to be cooled to LN_2 ~ 5900 Kg, includes 1070 Kg to LHe and requires minimum of 3500 ℓ LN_2; 210 ℓ LHe.[1]

Heat Load to Panels	LBL (8 meas.)	PPPL (1 and 8 meas.)[5]	LLNL Design[1]
Eight panels - LHe	30 liter/hr (21 W)	32 liter/hr (23 W)	47 W
Eight panels - LN	75 liter/hr	88 liter/hr	104 liter/hr (4700 W)

4. One 750 liter LHe dewar, with LN shield, 40 layers of superinsulation to 80 K, 10 to 4.5 K, vacuum insulated. Top and bottom co-axial bayonets.

5. One diverter valve contained within the 750-liter dewar.

6. One LN dewar, 20 cm diam. tube, 1. m long (~380 liters), vacuum insulated.

7. One Sullair oil lubricated helical screw compressor, displacement, 880 CFM, delivery 700 CFM (55 g/s), 18 atm discharge, 3600 RPM, 300 kW, 2 pole induction motor.

8. One coldbox CCI (Cryogenic Consultants, Inc.) 400 W at 4.5 K with one dry (20 K) expander engine and one wet (6 K) engine. 250 W with only the dry engine.

9. External LHe distribution system,[8] 72 m of separate supply and return 2.5 cm diam. vacuum insulated transfer line with 40 layers of superinsulation (18 W), 20 bayonet connections (25 W) and 4 broken stem valves (3 W) for flow control to the NBI and target tank. A 9 kW heater tied to GHe storage provides for warm-up/cooldown transients.

Cryopanels and Heat Loads

Eight modular cryopanels line both sides of the injector vessel, four panels to a side. In addition, two cryopanel modules are installed in the target tank. Panel construction (Figure 2) consists of two stainless-steel quilts and a copper chevron assembly. The quilts are fabricated with spot welds, sealed by edge welding and hydroformed at 400 psi. For heat load reduction, the chevrons are painted black and the vacuum tank wall is shielded with two dimpled stainless steel sheets. The cryopanel heat loads as measured at LBL are 30.3 liters/hr (21 W) LHe by a 5-hour level decay in the LHe dewar. LN losses were measured by level decay at 75 liters/hr. These values correlate well with independent measurements by Garzotto[5] at PPPL of boil off gas for a single panel, 4.5 liters/hr LHe and 11 liters/hr LN, and 32 liters/hr LHe for eight panels and the LHe dewar. Considering 60 m^2 of 4.5 K surface looking at 80 K, the 22 W/60 m^2 or 0.36 W/m^2 indicates a good value for emissivity ($\varepsilon < 0.2$).

Diverter Valve[6,7]

The diverter valve is a single package removable from the dewar as a unit. The valve has all-metal seats with varied spring loads and requires careful seat lapping, alignment and flow/leak calibration prior to installation. It can be remotely operated by electric motors from the control room console, combines four valve functions, and includes a phase separator for return flow from the panels. The diverter valve has three operating modes: 1) cool-down from 300 K where cold helium gas flow is forced through the cryopanel bottom, 2) circulation, where phase separation occurs in the 750-liter dewar and the cryopanels are gravity fed, and 3) regeneration where the panels are emptied of LHe, warmed by gas conduction in the vessel, then the frozen deuterium is sublimed and pumped out, and LHe is transferred back to the panels for rapid cooldown. Figure 3 shows schematically the diverter valve located in the LHe dewar.

Regeneration

For safety reasons it is necessary to de-rime or regenerate the panels. The administrative limit for frozen H_2 or D_2 has been set at 12 Torr (at 300 K in the 50,000-liter volume this is 600,000 Torr liter).[4] For regeneration valve sealing is critical, to prevent leakage and provide pressure to transfer LHe from the panels into the dewar. Heat must be added to the panels to boil enough LHe to make the transfer and empty the panels, raise the temperature, and sublime the frozen D_2. The first "REGEN" test with frozen H_2 required 15 minutes after valve closing to initiate the cycle, the next test on D_2 required almost an hour. Since then we have done many "REGEN" tests with H_2, D_2 and He for initiation of panel de-rime.[6]

The preferred technique (Figure 4) for handling the administrative limit is to admit 12 Torr liters of GHe to the vacuum. Response is within 10 minutes, temperature goes to 66 K, pressure

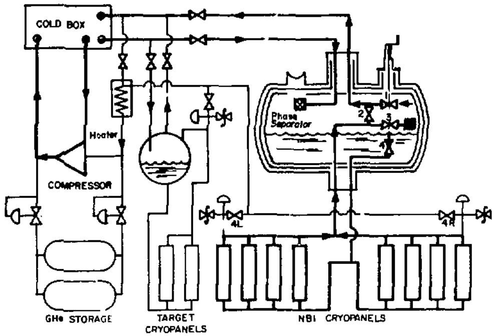

Fig. 3. Helium system schematic. For cooldown V-1 is closed, V-2 is open, V-3 acts as 4 psi relief. For circulate V-1 is open, V-2 as 4 psi relief, V-3 is open. For regenerate V-1 is open, V-2 as a 10 psi relief, V-3 closed, and V-4 closed acts as a 5 psi relief.

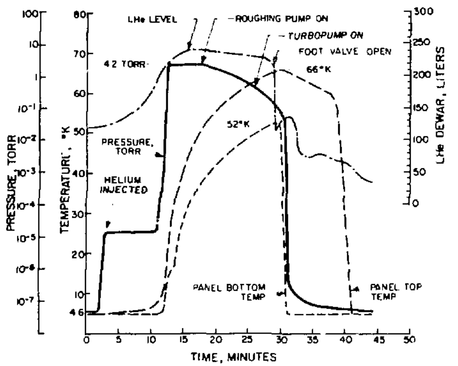

Fig. 4. Cryopanel regeneration with diverter valve. 12 Torr-liters GHe injected to remove 13 Torr @ 273 K frozen D_2.

goes to 4 Torr, pumps are valved in, foot valve V-4 is opened and pressure drops to 10^{-7} Torr, all within 35 minutes. The pressure rise to 4 Torr shows the gas is very cold, ~100 K, which is also significant for line density. About 90% of the frozen D_2 is removed by the mechanical pumps before the foot-valve, V-4 is opened.

Vacuum Pumping System

Design values for the 30 m^2 of cryopanel were 2.5×10^6 liter/sec pump speed using a specific speed of 8.3 liter/sec cm^2 for deuterium.[1] For a gas load of 100 Torr liter/sec average pressure would be 4×10^{-5} Torr. To minimize pressure at the delivery to the Tokamak, the beam line vessel is divided into three differentially pumped sections. The baffles, shown in Figure 1 block each section except for beam passage apertures at the magnet and the end section. Line density of gas along the beam path to minimize beam loss is of more importance than pumping speed per se. Thus, location of the baffles is critical and can be optimized.

During gas loading of the cryopanels for the de-riming tests, hydrogen gas pulses up to 40 Torr liter/sec for periods up to 100 sec were injected. Pressures at the exit end remained constant at 2×10^{-5} Torr. Similar pulses for D_2 of 300 Torr liters gave 2×10^{-6} Torr (from 1.5×10^{-7} Torr) at the exit end, with a rise to 5×10^{-5} Torr and return to 2×10^{-7} Torr at the neutralizer. These values seem consistent with H_2/D_2 vapor pressures, and show the cryosystem meets acceptable criteria for beamline pressure gradient. A more detailed report of beam line performance will be published later by J. Feist, Max Planck Institute, Garching.

REFRIGERATOR AND OPERATIONS

Initial refrigerator capacity selection was based on 1) an estimated 100 W for the NBI plus external distribution system, 2) simultaneous test operation of the General Atomic Doublet III injector, and 3) cryopanel loads for a target tank on the end of the NBI. The first specification called for 400 W or 80 liter/hr, but this was lowered to 300 W (80 liter/hr) to permit all bidders to quote. Four firms quoted in 1977 and Cryogenic Consultants, Inc. of Allentown, Pa. was low at $300,000. The package included a cold box, an 80 K adsorber, two expander engines and an oil lubed screw compressor with oil clean-up and controls.

Both LBL and PPPL[5] measured the heat load at 22 W for eight cyropanels and the LHe dewar. External heat loads were calculated[8] at 46 W, and the target tank cryopanel heat load is estimated at 8 W when on-line. Total heat load is then estimated at 68-76 W. The refrigerator, with 47 g/s mass flow at 18 atm, has delivered 85 liter/hr while holding the 68 W static heat load. On this basis, performance should be in excess of 475 W or 95 liter/hr and easily meets the original specification of 400 W or 80 liter/hr.

The refrigerator is run at maximum capacity for cooldown, LHe filling of eight panels with total volume of 120 liters plus 200 liters in the dewar matches the gas storage capacity and requires about 4 hours. Then the refrigerator is backed down to a flow of 21 g/s at 11 atm and the compressor draws about 150 kW. The helium system as of July, 1981 has about 2700 clock hours and only requires occasional operator time. The simplified control system[9] using a standard industrial controller (Barber Colman) and a suction pressure transducer (Gulton Corp.) permits long periods of unattended night and week-end operation.

The excess refrigerator capacity has been a real boon, providing rapid cooldown and liquefaction, great operating time economy, and enhanced system reliability due to a wide margin for error. The screw compressor with its slide valve and pressure controls together with the cold box reciprocating expanders permit an infinite number of pressure and mass flow combinations, minimizing power draw for various operating modes.

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