Lawrence Livermore Laboratory

MECHANICAL DESIGN FOR NEUTRAL BEAM INJECTION

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Summary

At the Lawrence Livermore and Berkeley Laboratories, two major neutral beam system designs were developed, the High Voltage Test Stand (HVTS) and a conceptual system for the Two Component Tokamak-Toroidal Fusion Test Reactor (TCT-TFTR). The HVTS was designed for flexibility in performing a wide variety of tests, while the TCT-TFTR beam line was designed to satisfy particular requirements for target-plasma operation. Both designs make use of condensation cryopumping to handle very high gas loads. The HVTS design involves high-voltage isolation techniques of cryogenic and other systems. The TCT-TFTR design requires optimization of pumping and other systems. It is to be expected that experience gained from the design and operation of the HVTS systems will be of value to the final design of TCT-TFTR and to the engineering of future fusion reactors.

Introduction

Neutral beam heating and fueling is becoming increasingly important to the operation of fusion research devices. Next generation machines will require neutral injection energies of ~32 fJ, with neutral atom currents on the order of 100 umol/s. The design of facilities for testing and utilizing beams with these parameters requires provision for extremely high-speed gas pumping and high-voltage isolation of components.

At the Lawrence Livermore Laboratory, two such facilities have recently been designed. The first is the High Voltage Test Stand (HVTS). The HVTS is designed to allow testing of production of neutral hydrogen of deuterium beams with particle energies up to 32 fJ and particle currents at that energy up to 52 umol/s. This facility is currently under construction. The second project, done at the request of ERDA-DCTR and Princeton Plasma Physics Laboratory, is a conceptual design of the neutral beam injection line for the Two Component Torus-Tokamak Fusion Test Reactor (TCT-TFTR). Four beam lines inject into the torus. Each line has three neutral injectors firing beams with 28-fJ particle energy, and each delivering 135 umol/s of D0 particles. Insofar as possible, the design of this facility uses current art.

HVTS Design

Gas Handling

The HVTS is designed for flexibility, so that beam production in several modes may be tested. Accordingly, the gas handling problem has been analyzed for several configurations. The configuration exposed to the most severe gas handling problem involves the acceleration of negative ions to 32 fJ, with subsequent neutralization.

This configuration is shown schematically in Fig. 1. Low-energy positive ions are produced by the source and pass through a metal-vapor double-charge-exchange cell, where part of the beam is converted to negative ions. The beam is then magnetically separated into positive, neutral, and negative components.

Fig. 1. Schematic of HVTS in negative-ion, post-acceleration configuration.

The negative component is accelerated to 32 fJ and then enters a gas neutralizer. The neutral beam is then collected on a target. The vacuum schematic of the system is shown in Fig. 2. Gas loads are estimated for the delivery of 52 umol/s of neutrals using sodium as the double-charge-exchange medium. This gives the highest ratio of gas loads to delivered current. Design pressures (set by beam transport and voltage holding considerations) are indicated on Fig. 2. Conductances are estimated for reasonable geometries of charge exchange and neutralizer cells as well as of drift tubes and accelerators.

For the purpose of calculating required pump speeds, a three-chamber system pumping D2 gas is analyzed. Chamber 1 is a pumping volume between the source and the charge exchange cell. Chamber 2 is the bending magnet cell. Chamber 3 is a composite of the dump tanks for neutral and positive particles. Because the target tank (Chamber 4) must operate at the same pressure as the magnet chamber, it is decoupled from the system and its pumping speed requirement is calculated separately.

Solution of the pumping speed equations,

\[ S_p^1 = \frac{0_1 + C_{12}(P_2 - P_1)}{\sqrt{1 - C_{12}}}, \]

\[ S_p^2 = \frac{C_{23}(P_3 - P_2) + C_{12}(P_1 - P_2)}{\sqrt{1 - C_{12}}}, \]

\[ S_p^3 = \frac{O_3 + C_{23}(P_2 - P_3)}{\sqrt{1 - C_{23}}}, \]

\[ S_p^4 = O_4. \]
with the gas loads, design pressures, and conductances for deuterium as shown in Fig. 2 give the following D₂ speed requirements:

\[ S_1(D_2) = 396 \text{ 500 litre} \cdot \text{s}^{-1} \]
\[ S_2(D_2) = 77 \text{ 260 litre} \cdot \text{s}^{-1} \]
\[ S_3(D_2) = 58 \text{ 720 litre} \cdot \text{s}^{-1} \text{ (total)} \]
\[ S_4(D_2) = 70 \text{ 400 litre} \cdot \text{s}^{-1} \]

Analysis of pump requirements for other modes of operation show that a main pump of speed \( > 400 \text{ 000 litre} \cdot \text{s}^{-1} \), with smaller pumps of speed \( > 80 \text{ 000 litre} \cdot \text{s}^{-1} \) will produce vacua at or below required values.

The required high speeds make diffusion pumps, or any conductance-limited pumps, impractical, especially for the first chamber where it is desirable to keep the beam transport length short. Instead, it was decided to use condensation cryopumping, with the pumping surfaces separated from the pumped volumes only by chevron baffles for radiation shielding.

To maintain flexibility, it was further decided to provide one large pump of \( > 400 \text{ 000 litre} \cdot \text{s}^{-1} \) speed and several smaller cryopump modules of \( > 80 \text{ 000 litre} \cdot \text{s}^{-1} \) speed. Details of the design and testing of these modules are reported elsewhere in these proceedings. Basically, the modules are short cylinders with cryopump surfaces covering their inner peripheral area (see Fig. 3). The modules may be used as extensions of cylindrical dump, target, or magnet tanks, or may be used, with reducing heads, to provide differential pumping along beam lines.

The basic arrangement of chevrons, condensing surfaces, and shields is shown in Fig. 4. The speed of such an array is given by:

\[ S(\text{litre} \cdot \text{s}^{-1}) = 11.6 \sqrt{\frac{29}{M} A (\text{cm}^2)} G, \]

where

- \( A \) = projected baffle area,
- \( C \) = overall capture probability,
- \( M \) = molecular weight of pumped gas.

For solid panels,

\[ G = (t^{-1} + c^{-1} - 1)^{-1}, \]

where

- \( t \) = chevron transmissivity (taken as 0.3),
- \( c \) = sticking probability for condensation on the panels.

At 4.3 K, reevaporation is negligible above \( \approx 7 \text{ mPa} \) for D₂ and above \( \approx 130 \text{ uPa} \) for H₂.

For the sake of conservatism in initial design, \( c \) was taken to be 0.25 for D₂, or just half the value reported by Chubb et al., for D₂ condensing on hare
metal at temperatures between 2.1 and 3.7 K. Accordingly, a test module was constructed with a 16 000 cm$^2$. Early tests show that the module pumps D$_2$ at 150 000 litres$^{-1}$ and H$_2$ at $\approx$ 310 000 litres$^{-1}$, indicating that c is sufficiently near unity so that $G = 0.3$. High values of c ($\approx 0.85$) were, in fact, reported by Chubb et al. for condensation onto solid H$_2$ and D$_2$ and, at a pressure of 1.3 mPa our deposition rate is $\approx 2.9 \times 10^{15}$ molecules/s/cm$^2$, so that we are nearly always pumping onto previously condensed layers.

To preserve the modularity concept, an overall size change will be made in the modules. The favorably high pump speed to area ratio enables us to provide 500 000 litre$^{-1}$ D$_2$ speed in the main pump with a smaller overall size than originally planned. This main pump incorporates built-in valves to allow for isolation under vacuum without warm-up for changing sources or servicing other parts of the beam line.

Refrigeration loads for the helium-cooled pumps will be handled by a liquefier capable of providing 80 W of refrigeration at 4.6 K and 30 W at a reduced pressure of -80 kPa, corresponding to a liquid temperature of 4.6 K with a supercharger maintaining net positive suction head to the compressors. The lower temperature capability is to permit pumping of H$_2$ at pressures below its vapor pressure at 4.2 K.

High Voltage Isolation

Flexibility of operation requires that all HVTS components be capable of floating at up to 200 kV with respect to each other and the surroundings. For example, if the neutral beam is to be delivered at ground potential, then in the configuration of Fig. 1 all components upstream of the accelerator are at -200 kV. The cryopumps are designed with sufficiently large integral dewars for cryogen storage for several days' operation, obviating the need for liquid transfer across the potential gradient. The boil-off helium mist, however, be recovered, preferably cold, during operation.

Designs for electrically and thermally insulated helium return lines are currently being evaluated, and a final choice of design will depend upon testing results. Typically, the lines incorporate vacuum-insulated glass or ceramic sections, with high resistance leakage current paths along the length for potential gradient control.

All major components are supported on high-voltage insulators. Each cryopump is supplied with a mercury diffusion pump for initial pump-down. The diffusion pumps are at ground potential and are connected to the cryopumps with $\approx$ 1.5-m long glass pipes, valved at both ends. During operation, the valve at the cryopump end is closed and the resulting hard vacuum in the pipe withstands the voltage. Roughing line connections for pump-down from atmospheric pressure and for removal of accumulated H$_2$, or D$_2$ during defrost cycles are also made to the glass pipes.

TCT-TFTTR Beam Line Design

General

The design philosophy for these beam lines differs significantly from that for the NHTS. Whereas a prime requisite for the NHTS is flexibility, as exemplified by the modular pumping concept, the ICF-TFTTR beam line is designed for the task of delivering beams of specified energy and current into a particular target. Optimization, particularly of pumping arrangements, is necessary. Additionally, all design features must be compatible with remote handling techniques. The following is a brief summary of some of the design features. Detailed information may be found in the conceptual design document.

Beam Line Geometry and Operation

The beam line is shown in Fig. 5. The three sources are situated so as to fire through the injection "window" defined vertically by the equilibrium field (EF) coils and horizontally by the toroidal field (TF) coils of the torus. The horizontal window location, the allowable spread at the plasma target, and the estimated source hardware size combine to set the overall beam line length. The entire beam line pivots horizontally through $\approx$ 8° about a flex joint to allow for target impact at torus major radii from 2.2 to 2.7 m.

All acceleration of the ions to $\approx$ 20 MeV is done in the sources. Neutralization is by charge exchange with gas drifting from the sources themselves. The gas is maintained at sufficiently high density by the gas tubes, or neutralizer ducts, shown extending $\approx$ 2 m from the source exit faces. The gas is then pumped by cryopanels in the first chamber.

The mixed beam, consisting mainly of neutral and positive particles, then passes between the poles of a sweeping magnet. The interpolar spaces also serve as a limiting gas flow impedance for differential pumping. The neutrals pass straight through the second chamber, which is maintained by cryopumping at sufficiently low pressure for acceptable reionization loss rates. The positive ions are swept downward through slots forming a gas-flow impedance between the second chamber and a third cryopumped chamber in which they are collected and neutralized on a target, or ion trap.

The neutral beam then passes through a test gate valve. The purpose of this valve is not to keep D$_2$ gas from flowing into the torus after the beam pulse, but rather to minimize backflow of T$_1$ gas from the torus. (The pressure in the second chamber is sufficiently low, because of beam transport requirements, so that D$_2$ flow into the torus is well below specified values.) A hard-sealed valve of 1-m aperture (development of which will require extension of current art) is provided for isolation of the beam line from the torus for servicing.

A beam-stop calorimeter is provided in the second chamber. The calorimeter is normally swung up out of the beam path and lowered for aiming as well as warm-up source shots independent of torus operation. Mounted on the same frame as the calorimeter is an ion trap for the small negative ion current swept upward by the magnet.

Optimization of Cryopumping

The vacuum schematic of the beam line is shown in Fig. 6. The gas load from the neutralizer ducts is Q$_1$. The loads of neutralized gas developing from the negative and positive ion targets are Q$_2$ and Q$_3$. The inter-chamber conductances are C$_{12}$ and C$_{23}$; the conductance into the torus is C$_{20}$. The value of P$_2$ is fixed by beam transport considerations to be 0.513 mPa.
A first attempt at optimization was made with no regard for apportionment of pump speeds among the chambers. Thus the flow balance equations,

\[ (S_1 + C_{12})P_1 - C_{12}P_2 = Q_1, \]
\[ -C_{12}P_1 + (S_2 + C_{12} + C_{20} + C_{23}) P_2 - C_{23}P_3 = Q_2, \]
\[ -C_{23}P_2 + (S_3 + C_{23}) P_3 = Q_3, \]

in the five unknowns, \( S_1, S_2, S_3, P_1, \) and \( P_3, \) were solved for the absolute minimum total pumping speed by requiring that:

\[ \frac{2}{P_1} (S_1 + S_2 + S_3) + \frac{3}{P_2} (S_2 - S_3) = 0, \]

\[ \frac{3}{P_3} (S_1 + S_2 + S_3) + \frac{2}{P_3} (S_2 - S_3) = 0. \]

The solution for \( P_1 \) and \( P_3 \) is:

\[ P_1 = 6.86 \text{ mPa}, \]
\[ P_3 = 1.29 \text{ mPa}, \]

with required pump speeds:

\[ S_1 = 1.706 \times 10^6 \text{ litre\(s^{-1}\)}, \]
\[ S_2 = S_3 = 7.930 \times 10^5 \text{ litre\(s^{-1}\)}. \]
where

\[ \Delta T = \sqrt{2 \frac{q''(t/K)}{k \rho c}} \]

and it is found that even tungsten begins to melt after only 43 ms. To allow for the maximum specified pulse length of 500 ms, the calorimeter plates are inclined to the beams to reduce the surface flux by a factor of 10.

Then, in 500 ms the surface of a molybdenum plate will rise in temperature to only half the melting point. To further reduce the surface flux density, the calorimeter faces are serrated with a 60° saw-tooth pattern running lengthwise. The positive ion target is of similar design.

The calorimeter and the ion targets are cooled between shots by low conductivity water, with ~110 litre per beam line per three beam shot required with an average 50 K water temperature rise.

Conclusion

The HVTS design incorporates techniques, such as high mass flow cryopumping, that will be required in next-generation fusion research machines as exemplified by TCT-TFTP. Techniques developed in the design and operation of large systems such as these will be of value to the continuing engineering effort required for the eventual production of fusion power.

References