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To: MSE Enthusiasts
Re: MSE Memo #28a: **Time Constants and Pressures in DNB Vacuum Tank**
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Figure 1 illustrates the relevant features of the DNB vacuum system. The total tank volume is 700 liters and we will assume that it is separated into roughly equal volumes V_1 and V_2 separated by a divider of area A_D. The tank system is pumped by a slow turbo pump having speed $S_T \approx 500$ Torr-liters/second and by two fast cryo pumps $S_{c1} = S_{c2} = 10^4$ T-l/s. Gas sources are provided by the neutralizer cell at pressure P_N, with aperture area A_N, and by the C-MOD torus itself at pressure P_C with aperture area A_C that is defined by the cross-section of the gate valve.

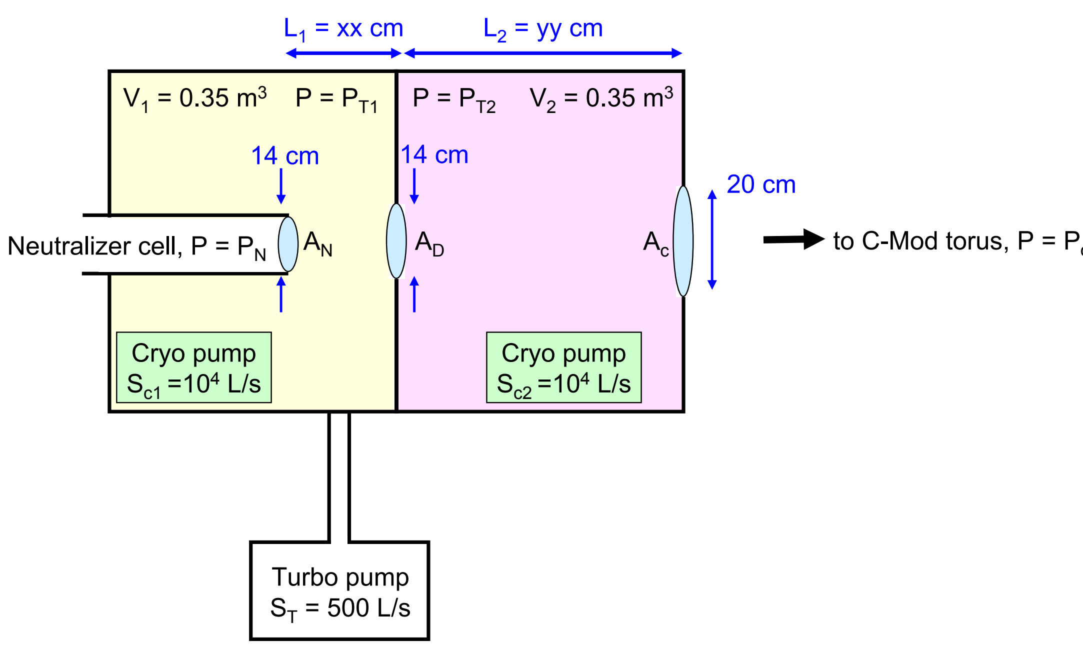

Figure 1: Model of the DNB vacuum tank

Single-tank approximation: First we will ignore the effects of the divider, and simply evaluate the two tank volumes as a single unit.

$$\frac{d}{dt}(P \cdot V_{Tank}) = \text{sources} - \text{sinks}$$

$$\frac{dP}{dt} = \frac{Q(P_N - P)A_N + Q(P_C - P)A_C - P(S_{c1} + S_{c2} + S_T)}{V_1 + V_2}. \quad (1)$$

where Q is the pumping speed of an aperture. For air at room temperature, $Q = 11.7$ Torr-liters/cm^2/sec and for hydrogen gas at room temperature, $Q = 22.2$ Torr-liters/cm^2/sec.

Note: this model assumes that the pressures in both the C-MOD torus and in the DNB neutralizer are *actively* maintained at their respective values. This is true for the torus (which has pumping, and in any event is quite large), but not for the neutralization cell - there is no pumping on the back end of the neutralizer cell.

Typical pressures: Although we do not have measurements of the pressure in the neutralizer, the gas feeds to the anode and cathode at the source are nominally chosen to provide an equilibrium cell so that we generate as fully-neutralized a beam as possible. For the neutralization cell length of 0.9 m, this corresponds to $P_N \approx 1$ millitorr. The torus pressure can range signficantly, from a small fraction of a millitorr to 1-2 millitorr. During typical beam-into-gas calibration shots, the torus pressure is nominally set at about 1.5 millitorr. Thus the normal regimes we will encounter have either $P_C << P_N$ up to $P_C \approx P_N$.

At steady state,

$$P = \frac{Q(P_N A_N + P_C A_C)}{S_{c1} + S_{c2} + S_T + Q(A_C + A_N)} \qquad \text{(steady-state).} \tag{2}$$

Note that this reduces to the expected result in the limit of no pumping on the vacuum tank - the tank's pressure is just the area-weighted mean of the two sources:

$$P = \frac{P_N A_N + P_C A_C}{A_C + A_N} \qquad \text{(steady-state, no pumping).} \tag{3}$$

We can also evaluate the early pressure rate-of-rise, when $P << (P_N, P_C)$. For simplicity we will evaluate situations in which there is just one source of gas, either from the neutralizer or from the C-MOD torus. In each case, we can define a time constant, which is the characteristic time that the tank pressure rises to its new equilibrium value after the source pressure (P_N or P_C) is rapidly increased to some steady-state value.

$$\begin{aligned} \tau_N &\equiv \frac{P_N}{\dot{P}} = \frac{V_1 + V_2}{Q A_N} \\ &= 0.20 \quad \text{sec} \\ \tau_C &\equiv \frac{P_C}{\dot{P}} = \frac{V_1 + V_2}{Q A_C} \\ &= 0.10 \quad \text{sec} \end{aligned} \tag{4}$$

Typically, the anode gas source is started 40 ms before the start of the actual DNB pulse, and this gas source continues for the duration of the pulse. The cathode gas source is a short 8 ms blip that occurs 20 ms before the start of the DNB pulse, and we will ignore it. There is therefore 90 ms for gas to accumulate in the tank by the end of a 50 ms beam pulse, which is roughly half the time constant τ_N of the vacuum tank / neutralizer system. *So by the end of a beam pulse, the vacuum tank will not reach its steady-state pressure with respect to the neutralizer pressure, but it will get part-way, roughly 1/2, of the way there.*

By contrast, the time constant for equilibration with the torus, $\tau_C = 0.1$ sec, is short compared to the duration of the C-MOD plasma. *So the vacuum tank will be in equilibrium with the torus pressure.*

Steady-State Pressures: The DNB vacuum system has $A_C = 2A_N$ so we can re-write the equation for the steady-state tank pressure, Eq. 2 in a more convenient form:

$$P = \frac{P_N + 2P_C}{3 + \frac{S}{QA_N}} \tag{5}$$

$$\begin{aligned} &= \frac{P_N + 2P_C}{8.8} \qquad \text{(all pumps operating)} \\ &= \frac{P_N + 2P_C}{3.2} \qquad \text{(turbo pump only)} \end{aligned} \tag{6}$$

Some special cases:

- If the torus pressure is low, i.e. $P_C << P_N$, then the equilibrium pressure in the vacuum tank is 1/3 the pressure in the neutralizer even if there is no active pumping by either a turbo pump or by cyro pumps, because the torus itself acts as a sink for gas. With the cryo pumps operating, the tank pressure is reduced by a factor of 8.8 relative to the pressure in the neutralization cell.
- If $P_C = P_N$, then the the equilibrium pressure in the tank is $P = 0.34P_N$ if all pumps are operating, and $P = 0.93P_N$ if only the turbo pump is operating.
- If the torus pressure is high, $P_C >> P_N$, then our model breaks down because the neutralizer pressure cannot be maintained at its nominal value P_N but instead will rise to the pressure in the vacuum tank because there is no active pumping on the neutralizer. In this case, the tank pressure rises to

  $$\frac{P}{P_C} = \frac{A_C Q}{A_C Q + S_{c1} + S_{c2} + S_T} \tag{7}$$

  which yields $P = 0.25P_C$ if all pumps are operating, and to $P = 0.93P_C$ if just the turbo pump is operating. *So in this limit, operating the cyro pumps reduces the pressure in the vacuum tank by a factor of four compared to the torus pressure.*

So over all conditions, the cryo pumps are capable of maintaining a tank pressure at least a factor of 3-4 less than the pressure of the dominant gas source to the system.

Two-volume tank: With respect to ionization losses and beam scattering issues, the pressure of the downstream volume (labelled '2' in Fig. 1) is more important, because it is considerably longer, i.e. $L_2 >> L_1$. We need to consider the particle balance in each volume separately:

$$\begin{aligned} S_{c1}P_1 &= Q\left[A_N(P_N - P_1) + A_D(P_2 - P_1)\right] \\ S_{c2}P_2 &= Q\left[A_D(P_1 - P_2) + A_C(P_C - P_2)\right] \end{aligned} \tag{8}$$

We will make the assumption that $P_N >> P_1$ and $P_N >> P_2$. The result is

$$\begin{aligned} P_1 &\approx \frac{QA_N P_N}{S_{c1} + QA_D} \\ P_2 &\approx \frac{Q(A_C P_C + A_D P_1)}{S_{2c} + Q(A_D + A_C)}. \end{aligned} \tag{9}$$

For the numbers appropriate to the C-MOD DNB,

$$\begin{aligned} P_1 &\approx 0.20 P_N \\ P_2 &\approx 0.07 P_N + 0.34 P_C. \end{aligned} \tag{10}$$

Thus, the divider is quite effective at reducing the pressure in the second tank relative to the pressure in the neutralization cell (factor 14), but it is less effective in reducing it with respect to the pressure in the torus (factor 3). In fact, when the gas load from the torus is dominant, the pressure P_2 is slightly *greater* if a divider is imposed (thereby creating two individual tank volumes) than if it is absent. It is easy to understand why: in the limit $P_1 << P_2$, the divider aperture effectively acts like a cryo pump on the second tank volume, having a speed $S = QA_D = 3,500$ Tl/s. Thus if a divider is inserted into the system, its pumping speed on the second tank volume is effectively reduced from $10,000$ to $3,500$ Tl/s