

Vacuum Analysis of MICE Cavity

Statement of Problem

The MICE cavity is surrounded by an outer volume as shown in Figure 1. The cavity and outer volume will be pumped separately. The two cavity walls at the beam center are Be windows. The concept for protecting the windows from a fault over-pressure condition is to provide a parallel bypass tube between the cavity vacuum and the outer volume vacuum. In addition, a burst disk will be provided as a redundant protection for the windows.

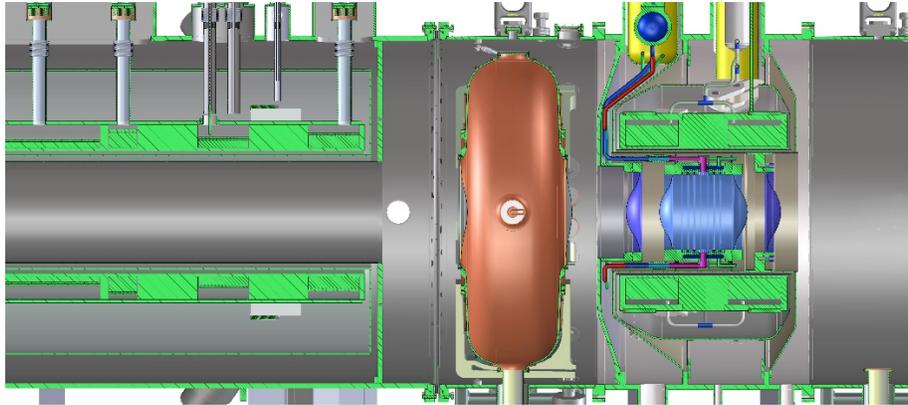


Figure 1. MICE cavity configuration.

Figure 2 shows the proposed connection between the cavity and its vacuum pump. The bypass to the outer volume would be accomplished via one of the flanged ports on the pump to cavity connector tube. The design objective for the bypass is to size it such that its conductance is appropriately small so as not to contaminate the cavity vacuum, while being large enough so that the conductance is sufficient to provide protection of the windows from a large pressure differential.

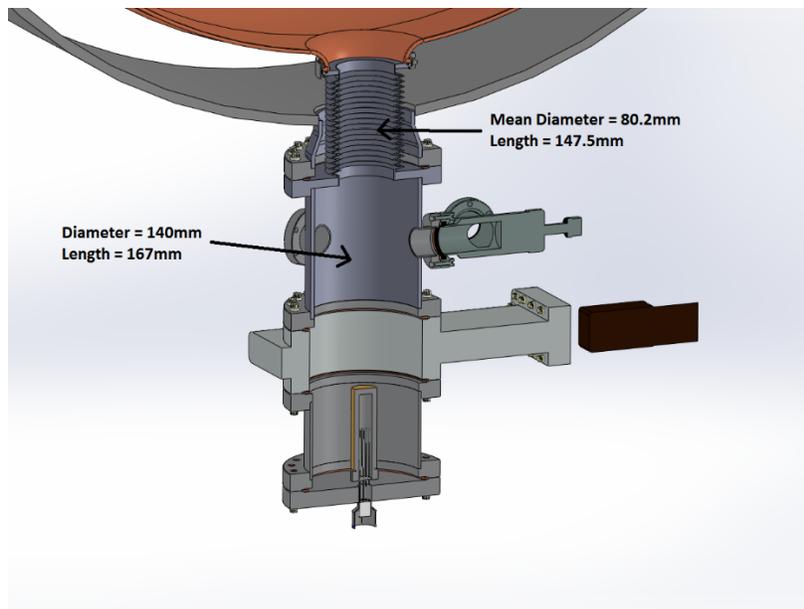


Figure 2. Connection between the cavity and pump.

Summary

This note will address the following topics:

- 1) Calculate the achievable vacuum pressure in the cavity for the current pumping design, with reasonable assumption of gas load.
- 2) Evaluate the feasibility of the bypass tube scheme for the vacuum burst protection.
- 3) Analyze the vacuum pressure in the previous MTA Single Cavity Module test in Fall 2014, including the effect of the coupler slots.

Configuration Characteristics and Assumptions

- Cavity surface area, $A_c = 3.2 \text{ m}^2$
- Use thermal desorption rate for Cu after bake-out $1.0 \times 10^{-12} \text{ T-L/s-cm}^2$ (*A. Chao, Handbook of Accelerator Physics and Engineer (3rd printing), P. 254*), $\Rightarrow Q_{th} = 3.2 \times 10^{-8} \text{ T-L/s} = 1.1 \times 10^{12} \text{ mol/s}$. After bake-out, the dominant gas should be H_2 .
- The system will be at room temperature, $T = 293^\circ\text{K}$.
- Mean molecular velocity $\hat{v} = \sqrt{\left(\frac{8kT}{\pi m}\right)} = 1800 \text{ m/s}$, where $k = 1.38 \times 10^{-23} \text{ J/}^\circ\text{K}$, $m = 3.3 \times 10^{-27} \text{ kg}$.
- H_2 pump speed, S , for Capacitor D3500 is 3.6 kL/s .
- Pressure, density in cavity: assume $p_1 = 10^{-8} \text{ T} \Rightarrow n_1 = 3.3 \times 10^{14} \text{ mol/kL}$
- Pressure, density in outer volume: assume $p_2 = 10^{-6} \text{ T} \Rightarrow n_2 = 3.3 \times 10^{16} \text{ mol/kL}$

Analysis

Achievable vacuum in the Cavity:

Conductance of pump to cavity connection, C_p : The bellows conductance, C_b will be in series with the connecting tube conductance, C_t . The two limiting cases for which conductance is easily calculated analytically are a circular aperture and a long pipe, where length, L , is large compared to radius, a . The dimensions of the connector tube correspond to neither case. The best model is to assume a series combination of an aperture and pipe. The general equation is

$$C = \left(\frac{1}{1 + \frac{3L}{8a}} \right) \pi a^2 \frac{\hat{v}}{4}$$

Using the dimension from Figure 2, $C_b = 0.94 \text{ kL/s}$, $C_t = 3.6 \text{ kL/s}$.

$$\frac{1}{C_{total}} = \frac{1}{C_b} + \frac{1}{C_t} \Rightarrow C_{total} = 0.74 \text{ kL/s}$$

Thus the net pumping speed at the cavity:

$$S_{net} = \left(\frac{1}{S_{pump}} + \frac{1}{C_{total}} \right)^{-1} = 0.62 \text{ kL/s}$$

With the estimated throughput gas load from cavity wall $Q_{th} = 3.2 \times 10^{-8} \text{ T-L/s}$, we can estimate the achievable vacuum pressure at the cavity entrance and pump entrance:

$$P_{cav} = \frac{Q_{th}}{S_{net}} = 5.2 \times 10^{-11} \text{ torr};$$

$$P_{pump} = \frac{P_{cav} \times S_{net}}{S_{pump}} = 8.9 \times 10^{-12} \text{ torr}$$

From the above calculation, we can see that the MICE cavity should be able to reach good vacuum assuming that gas loads from the annular opening and RF coupler slots are negligible, and the only gas load is due to the outgassing from the cavity inner walls.

Conductance of Bypass Tube:

Let us now consider dimensions of the bypass tube such that it does not overwhelm the gas load of the cavity. Let us assume that the bypass flow can be as high as the thermal flow.

$$Q = C_b n_2 = C_b (3.3 \times 10^{16} \text{ mol/kL}) < 1.1 \times 10^{15} \text{ mol/s} \Rightarrow C_b < 0.032 \text{ L/s}$$

If we assume the radius of the bypass tube $R_{tube} = 1.5 \text{ mm}$, the corresponding minimum bypass tube length:

$$L_{bypass} = \left[\left(\hat{v} \cdot \pi \cdot \frac{R_{tube}^2}{4C_b} \right) - 1 \right] \cdot 8 \cdot \frac{R_{tube}}{3} = 0.386 \text{ m}$$

This calculation indicates that with pressure in the vacuum vessel 10^{-6} T and gas load from bypass tube as large as the cavity inner surface outgassing, the conductance of the bypass tube is 0.032 L/s, corresponding to a tube of 3.0 mm diameter and 386 mm length.

Conductance of Coupler Slots:

Treat the slots as circular apertures. The general equation for aperture conductance is

$$C = A \frac{\hat{v}}{4}$$

The four slots have a total area of $7.2 \times 10^{-4} \text{ m}^2$. Therefore, the conductance, $C_s = 0.32 \text{ kL/s}$. The molecular flux through the aperture: $C_s (n_2 - n_1) = 1.05 \times 10^{16} \text{ mol/s}$ and the slot throughput $Q_s = 3.18 \times 10^{-4} \text{ T-L/s}$.

Conductance of Annular Bypass:

The former configuration of the pump to cavity connection with an annular bypass to the outer volume is shown in Figure 3, with the annular region blocked. The total bypass tube is composed of upper and lower part. The conductance of each part is:

Calculate old Ductwork conductance:

$$L_{\text{lowertube}} := 160\text{mm}$$

$$L_{\text{uppertube}} := 160\text{mm}$$

Old pumping ductwork geometry parameters

$$R_{\text{lowertube}} := 60\text{mm}$$

$$R_{\text{uppertube}} := 38.5\text{mm}$$

$$C_{\text{lowertube}} := \left[\frac{1}{1 + \frac{(3 \cdot L_{\text{lowertube}})}{8 \cdot R_{\text{lowertube}}}} \right] \cdot 3.14 \cdot R_{\text{lowertube}}^2 \cdot \left(\frac{v_{\text{hat}}}{4} \right) = 2.497 \times 10^3 \cdot \frac{\text{L}}{\text{s}} \quad \text{Lower tube conductance}$$

$$C_{\text{uppertube}} := \left[\frac{1}{1 + \frac{(3 \cdot L_{\text{uppertube}})}{8 \cdot R_{\text{uppertube}}}} \right] \cdot 3.14 \cdot R_{\text{uppertube}}^2 \cdot \left(\frac{v_{\text{hat}}}{4} \right) = 803.549 \cdot \frac{\text{L}}{\text{s}} \quad \text{Upper tube conductance}$$

Thus the conductance of the bypass is:

$$C_{\text{totalold}} := \frac{1}{\left[\left(\frac{1}{C_{\text{lowertube}}} \right) + \left(\frac{1}{C_{\text{uppertube}}} \right) \right]} = 607.89 \cdot \frac{\text{L}}{\text{s}} \quad \text{Total conductance to the cavity}$$

Thus the net pumping speed at the cavity is:

$$S_{\text{netold}} := \frac{1}{\left[\left(\frac{1}{S_{\text{pump}}} \right) + \left(\frac{1}{C_{\text{totalold}}} \right) \right]} = 520.072 \cdot \frac{\text{L}}{\text{s}} \quad \text{Net pumping speed at the cavity}$$

The gas load now includes both the cavity inner surface outgassing and the coupler slots:

$$Q_{\text{totalold}} := Q_{\text{slots}} + Q_{\text{th}} = 3.181 \times 10^{-4} \text{ torr} \cdot \frac{\text{L}}{\text{s}} \quad \text{Total throughput gas load}$$

Thus the pressure in the cavity is:

$$P_{\text{cavityold}} := \frac{Q_{\text{totalold}}}{S_{\text{netold}}} = 6.116 \times 10^{-7} \text{ torr}$$

Pressure at the cavity

This calculated pressure is consistent with what was measured at MTA ($\sim 10^{-6}$ torr). From this calculation, we can see that the gas load from the coupler slots is much larger than the outgassing from the cavity surface. It deteriorates the vacuum inside the cavity significantly and prevents the cavity from being pumped to its desired pressure. They will be sealed in the future coupler design for a better vacuum performance.

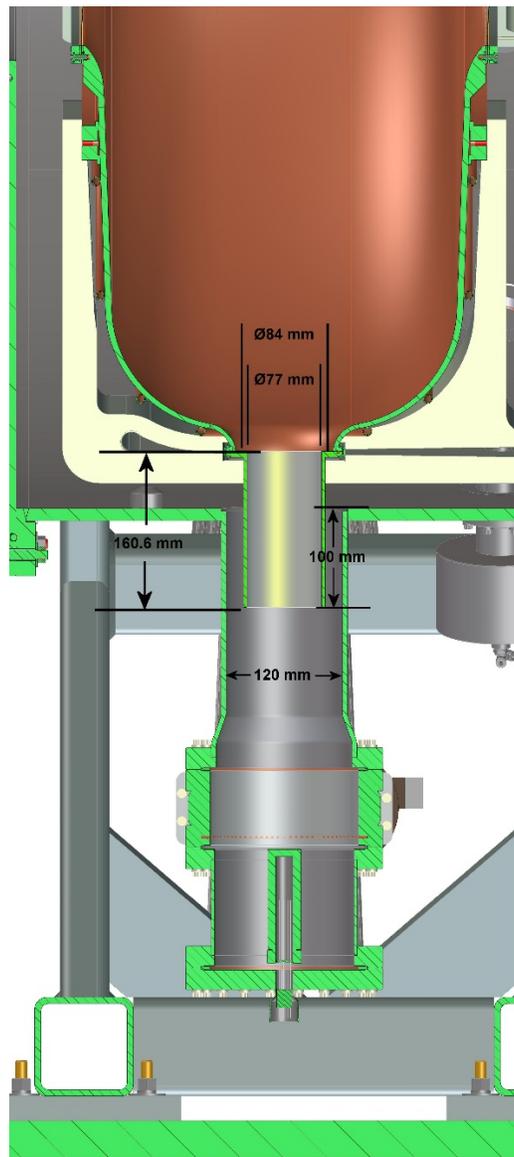


Figure 3. Annular bypass configuration.

Conclusions and Recommendations

- 1) The vacuum pressure calculation shows the MICE cavity should be able to reach good vacuum with current pumping system design, considering mainly the outgassing from the cavity body inner surface.
- 2) For the proposed bypass tube between cavity and vacuum vessel as a safety precaution of pressure burst, we have estimated the upper limit conductance of this bypass tube and its corresponding geometry parameters. The calculation shows such a scheme is feasible. Besides the bypass tube, use of an appropriately sized burst disk will also provide protection of the Be windows. While breaking a burst disk will be inconvenient, this is there to protect what should be a rare fault. Thought should be given to incorporating a scheme that minimizes the possibility of human error resulting in an over-pressure condition. For example, a common pneumatic solenoid could be used to open valves to the two volumes simultaneously.
- 3) The analysis on the previous MTA Single Cavity Module shows the coupler slots are the dominant gas load for the cavity vacuum and deteriorate the cavity vacuum significantly. They must be capped in order to reach the desired cavity vacuum.