# High Insulating Vacuum Pump Cart Analysis

Kelly Chicas, University of Illinois at Urbana Champaign – ASPIRE Fellow

FERMILAB-POSTER-25-0164-STUDENT

## Introduction

- The Proton Improvement Plan II (PIP-II) will be the world's most powerful high-energy neutrino beam
- For PIP-II to function properly the system must maintain superconductive and cryogenic temperatures (2K – 80K)
- To eliminate convective heat transfer, high insulating vacuum is necessary
- To reach the desirable pressure two types of pumps are used
  - Dry Scroll Roughing Pump
  - Turbomolecular Pump
- Goals
  - Create a list of possible pumps that can achieve a vacuum of $10^{-6}$ Torr
  - Reach an acceptable pump down time of ~48 hours

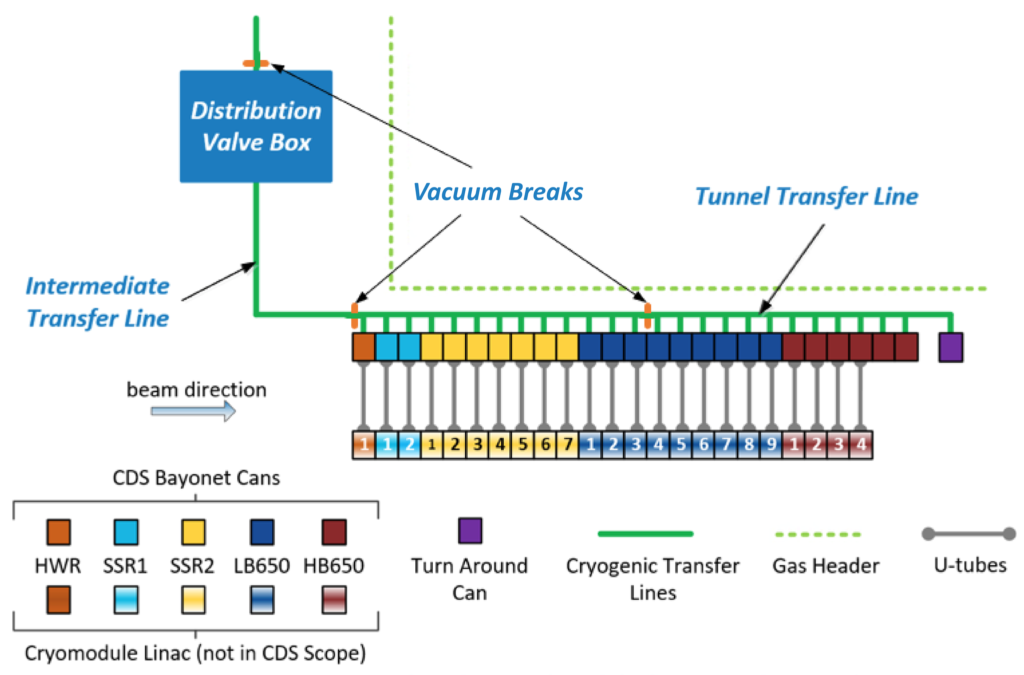


Figure 1: Tunnel Transfer Line (TTL) Single Line Diagram

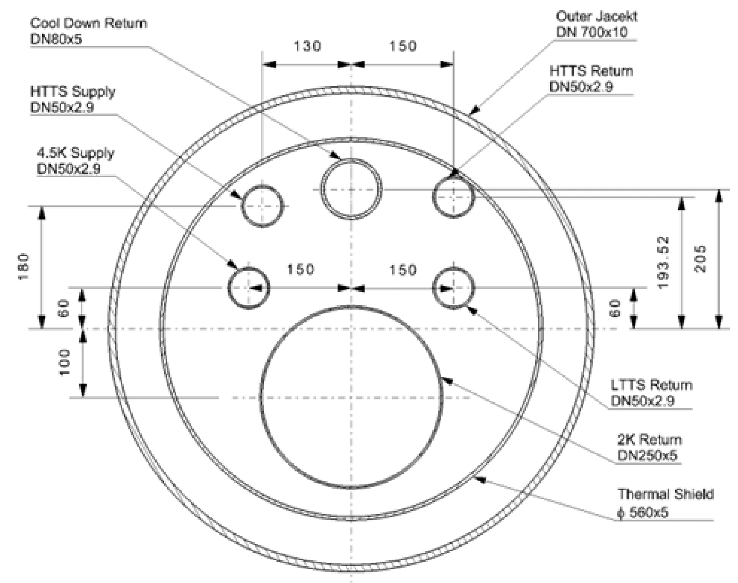

Figure 2: Mid-Section of the TTL

## Design and Methods

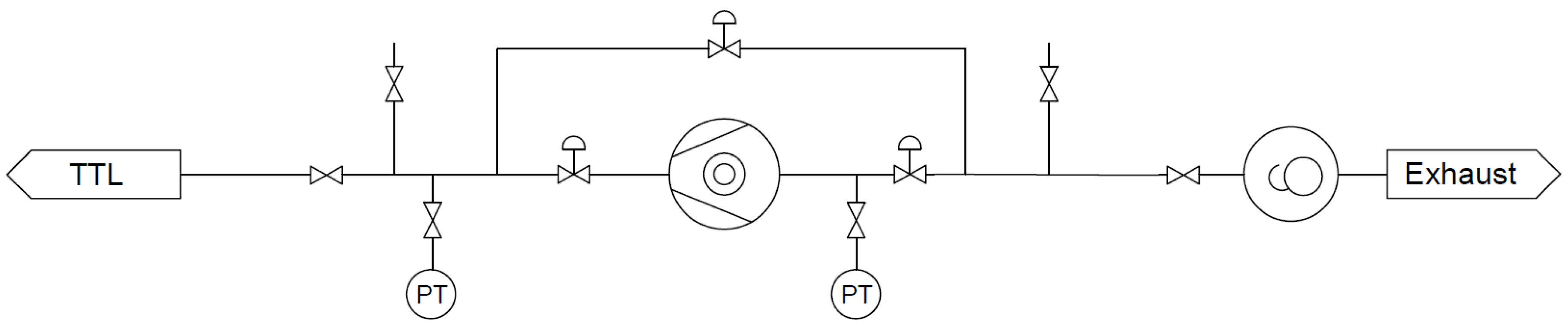


Figure 3: P&ID for the High Insulating Vacuum Cart

- The vacuum must reach $10^{-6}$ Torr in which case free-molecular flow is considered
- To assist in pump selection, the pump down time is calculated
- 3 Volumes are considered…
  - Distribution Valve Box (DVB) and the Intermediate Transfer Line (ITL)
  - Tunnel Transfer Line (TTL) with vacuum break at the center
- Factors
  - Volume of Vessel
  - Conductance
  - Leakage
  - O-Ring Permeation
  - Pipe Diameters
  - Steady-State Process Line Helium Leakage
  - Initial Turbomolecular Pump Down Inlet Pressure

| | |
|---|---|
| $t_p = \frac{V}{S_{eff}} \ln\left(\frac{P_1 - P_\infty}{P_2 - P_\infty}\right)$ | Pump Down Time [s] |
| $P_\infty = P_u + \frac{Q_{Total}}{S_{eff}}$ | Ultimate Pump Down Pressure [Pa] |
| $S_{eff} = \frac{C * S_s}{C + S_s}$ | Effective Pump Speed [m^3/s] |
| $C = \frac{D^3}{L}\sqrt{\frac{\pi RT}{18M}}$ | Conductance [m^3/s] : L/D > 30 |
| $C = \frac{D^2\sqrt{\frac{\pi RT}{18M}}}{\frac{L}{D} + \frac{4}{3}\left(1 - \left(\frac{D2}{D1}\right)^2\right)}$ | Conductance [m^3/s] : L/D < 30 |
| $\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$ | Conductance in Series [m^3/s] |
| $L_p = 0.7 \cdot F \cdot D \cdot P \cdot Q(1-S)^2$ | Permeation Rate [m^3/s] |

Table 1: General Equations for the Pump Down

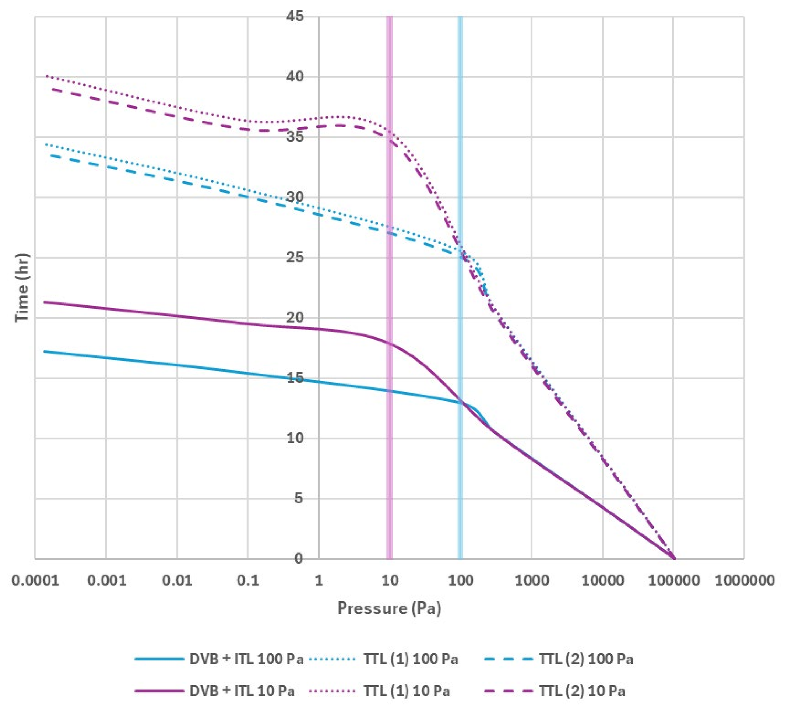

Figure 4: Turbomolecular Pump Down Comparison at Inlet Pressure of 10 Pa & 100 Pa

| Input Data Name | DVB + ITL | TTL (1) | TTL (2) |
|---|---|---|---|
| Inner Diameter [m] | 1.6 | 0.691 | 0.691 |
| Outer diameter [m] | 1.7 | 0.711 | 0.711 |
| Length [m] | 71 | 104 | 106 |
| Vacuum Volume [m^3] | 23.2 | 45.7 | 44.7 |
| Vacuum Volume [l] | 23200 | 45667 | 44702 |

Table 2: DVB, ITL, and the TTL Geometry

## Results

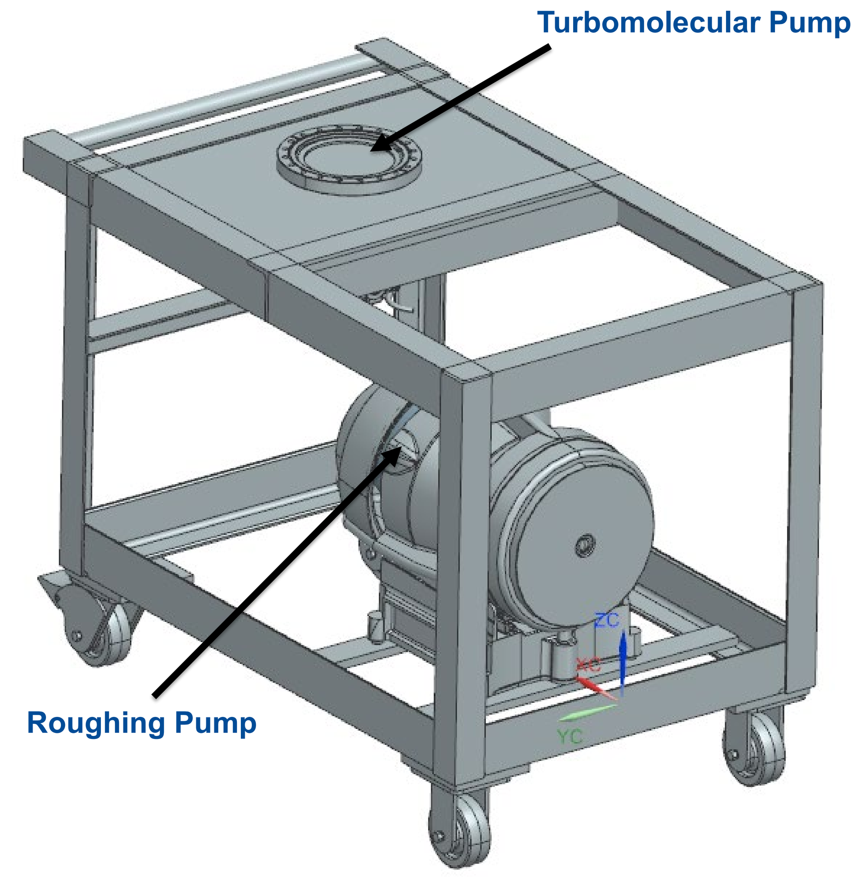


Figure 5: 3D Model High Insulating Vacuum Pump Cart

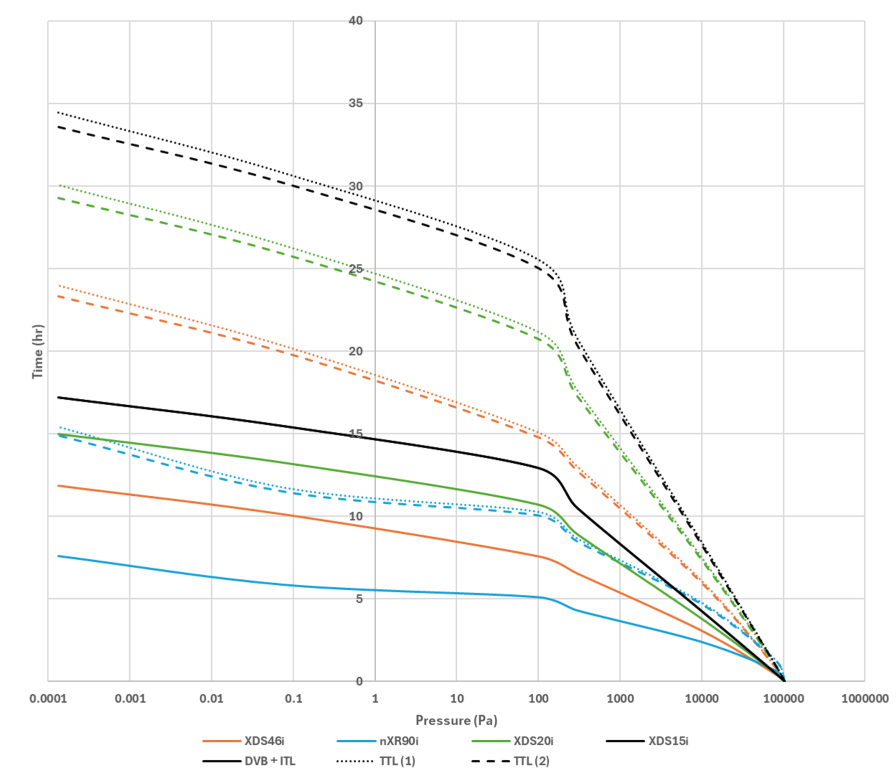

Figure 6: Pump Down Time Comparison

- Conductance was calculated for different design aspects such as…
  - 3" Pipe connecting the module and the pumps
  - 6" Flange at the inlet of the turbomolecular pump
  - 28" Diameter of the TTL
  - Thermal Shields and Supports
- Calculated total leakage for ~1080 welds at a specified leak tightness of 1.3E-10 Pa*m^3/sec, concluding the turbomolecular pumps studied are acceptable
- The pump down time was compared with various pumps and considered in Table 3 and Figure 6
- Total pump down time for starting case for mXDS15i and nEXT400
  - DVB + ITL: 17.21 hours
  - TTL (1): 34.43 hours
  - TTL (2): 33.56 hours

| Roughing Pump | Turbomolecular Pump | Total Cost ($) | DVB + ITL Time (hr) | TTL (1) Time (hr) | TTL (2) Time (hr) |
|---|---|---|---|---|---|
| mXDS15i | nEXT400 | $31,610 | 17.208 | 34.433 | 33.564 |
| mXDS20i | nEXT400 | $33,269 | 14.977 | 30.073 | 29.296 |
| nXR40i | nEXT400 | $40,835 | 9.465 | 19.032 | 18.464 |
| XDS46i | nEXT400 | $39,018 | 11.851 | 23.987 | 23.340 |
| nXR60i | nEXT400 | $41,817 | 7.876 | 15.931 | 15.429 |
| nXR90i | nEXT400 | $45,322 | 7.608 | 15.408 | 14.917 |

Table 3: Cost and Pump Down Time Comparison

## Conclusion

- Calculated the pump down time for a multitude of different pumps
- Created combinations of the roughing and turbomolecular pumps that can sustain the leakage rate, and pump down to $10^{-6}$ Torr at a reasonable time
- Created a preliminary 3D model of the High Insulating Vacuum Pump Cart
- This analysis assisted engineers in understanding and specifying the best pumps to use in high vacuum
- Future Work
  - Create drawings for the High Insulating Vacuum Pump Cart
  - Conduct a stress and deflection analysis on the High Insulating Vacuum Pump Cart during lifting

## Acknowledgements

This manuscript has been authored by FermiForward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Thank you to my mentors Vrushank Patel and Bill Soyars for their guidance and patience throughout the summer. Thank you to Jeremiah Holzbauer for this wonderful opportunity.

## References


O'Hanlon, J. (1989). *A User's Guide to Vacuum Technology*, John Wiley & Sons.

Lafferty, J. (1998). *Foundations of Vacuum Science and Technology*, John Wiley & Sons.

Atrey M. (2014). *Cryogenic Engineering*, National Programme on Technology Enhanced Learning.

O-Ring Division. (2007). *Parking O-Ring Handbook*, Parker Hannifin Corporation.