UCRL-TR-217054

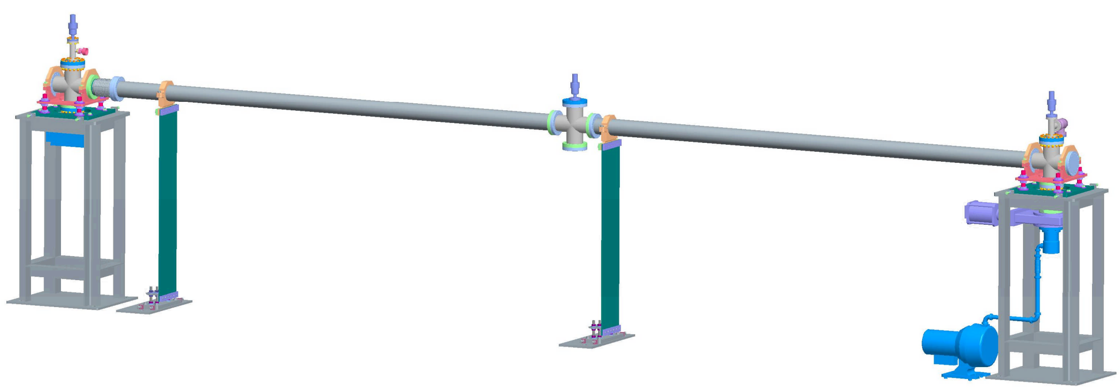
LLNL/LCLS/005-01

LCLS XTOD Tunnel Vacuum System (XVTS)

Preliminary Design Report

Richard Beale, Pat Duffy, Keith Kishiyama, Mark Mckernan,
Donn McMahon, Steve Lewis, John Trent, Louann Tung,
Stewart Shen

New Technologies Engineering Division
Lawrence Livermore National Laboratory



Submitted to: LCLS SLAC
November 9, 2005

Linac Coherent Light Source
Stanford Linear Accelerator Center
Lawrence Livermore National Laboratory

Disclaimer

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.
Work supported in part by the DOE Contract DE-AC02-76SF00515. This work was performed in support of the LCLS project at SLAC.

TABLE OF CONTENTS

1 Introduction

The vacuum system of the XVTS (X-Ray Vacuum Transport System) for the LCLS (Linac Coherent Light Source) XTOD (X-ray Transport, Optics and Diagnostics) system has been analyzed and configured by the Lawrence Livermore National Laboratory's NTED (New Technologies Engineering Division) as requested by the SLAC/LCLS program. The system layout, detailed analyses and selection of the vacuum components for the XTOD tunnel section are presented in this preliminary design report. The vacuum system was analyzed and optimized using a coupled gas load balance model of sub-volumes of the components to be evacuated. Also included are the plans for procurement, mechanical integration, and the cost estimates.

1.1 General Description

The XVTS, the tunnel segment of the XTOD section of the LCLS, is 212 meters long as measured between gate valves (Fig. 1.1). There are 3 x-ray beam transport lines with an outer diameter of 4" that serves to transport the beam from the end of the Near Experimental Hall (NEH) to the Far Experimental Hall (FEH) (Fig. 1.2). There are no other components aside from the vacuum equipment that reside in this area The vacuum requirements are to design a system that can be continuously operated for 10 years with minimal maintenance. In addition, the pressure within the line should have reasonable minimal impact on the x-ray beam loss.

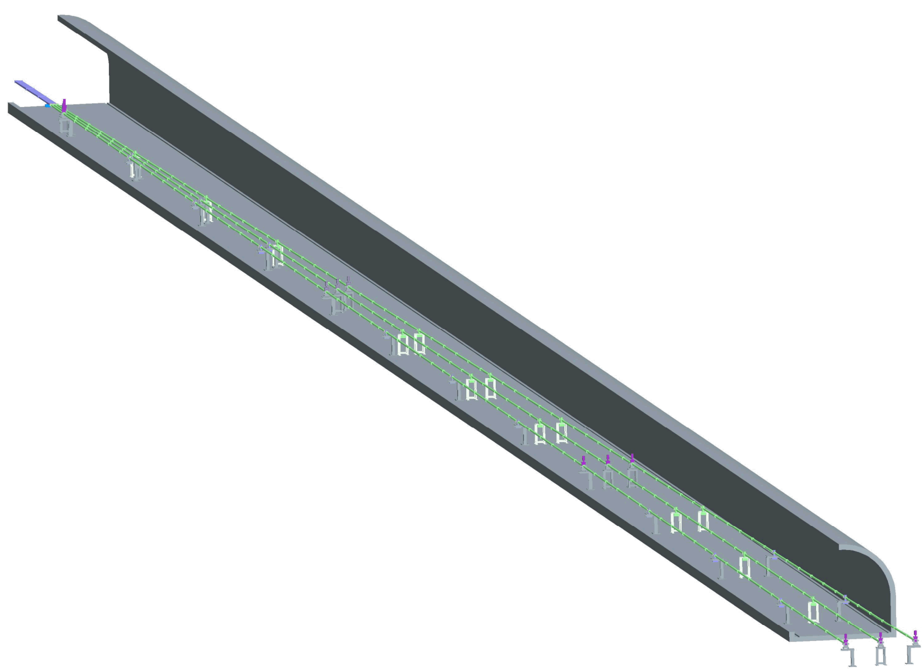


Fig. 1.1. XVTS System View-1

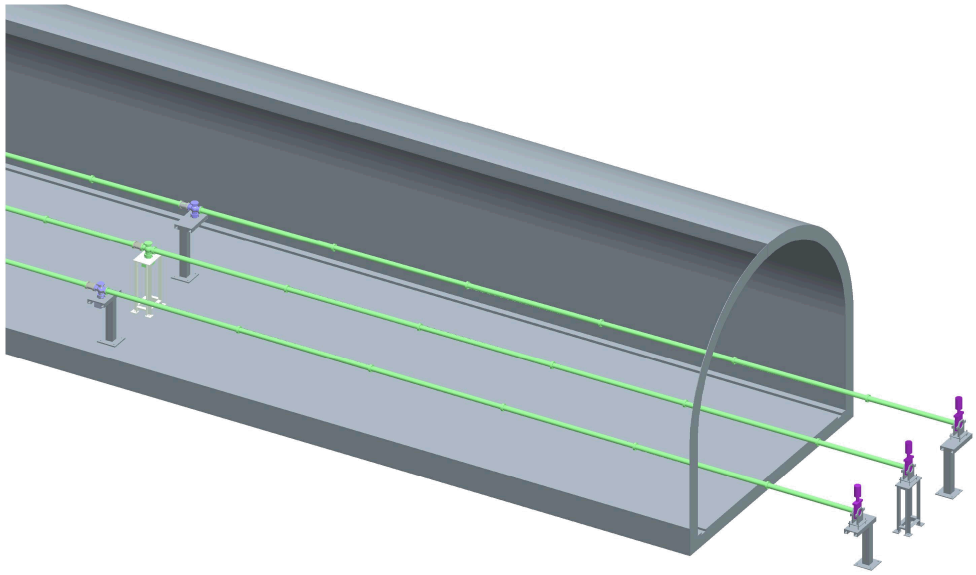


Fig. 1.2. XVTS System View 2

The preliminary design and operational goals of the XVTS system call for the following system features:

- The tunnel vacuum system will have the capability of being isolated with neighboring systems by gate valves. While the vacuum pumps may be operated in a manual mode (via their own controller), for such things as leak checking and vacuum conditioning, one local controller will supervise and operate the vacuum systems on a modular basis.
- There will be two other gate valves to separate the three 212-meter lines into 3 sections, 9 total, to facilitate repairs if necessary.
- A turbo/roughing pump combination will condition each 1/3 section and serve as transitional pumping to a suitable base pressure (10^{-6} Torr range) in order to allow for ion pump operation. Ion pumps will provide for the steady-state vacuum pumping.
- The turbo pumps will be permanently attached so that they can be used as a backup system, good for at least a year in case any of the ion pumps fails.
- A low vacuum and a high vacuum gauge will be needed on each module for system operation, vacuum monitoring and safety interlocks. Each line is equipped with an RGA head.
- Nitrogen purge lines with pressure regulators and relief valves will allow the three lines to be safely back-filled with dry nitrogen gas during maintenance periods.
- The valves, pumps and gauges are controlled by ladder logic executed on a commercial PLC such as those manufactured by Allen Bradley. A high-level EPICS control system linked to the LCLS global control software provides overall control and monitoring.

A sketch of the system model is shown in Figure 1.3 for one beam line. This shows the final selection of 6 ion pumps and 3 turbo/roughing pumps for each of the three beam lines. The XVTS system is isolated from the rest of the XTOD vacuum with gate valves. The distance between the outer gate valves is 212 meters (695.2 ft). The outer diameter of each line is 4 inches. For maintenance convenience, two interior gate valves divide the lines into thirds. The pump locations are constrained by uniform distribution and use of standardized 10-ft sections of line. Longer sections of line cannot be used because of space restrictions and geometry constraints for installation. Pumps are attached to the line with 4-way crosses. Each cross is connected to a 10-ft section by a 7-inch long bellows (see Fig. 4.2 and 4.3). Each component is joined to its neighbor by a metal seal. Each turbo pump also has a 7" long spool piece between the cross and the gate valve. Gate Valves are not required for the ion pumps.

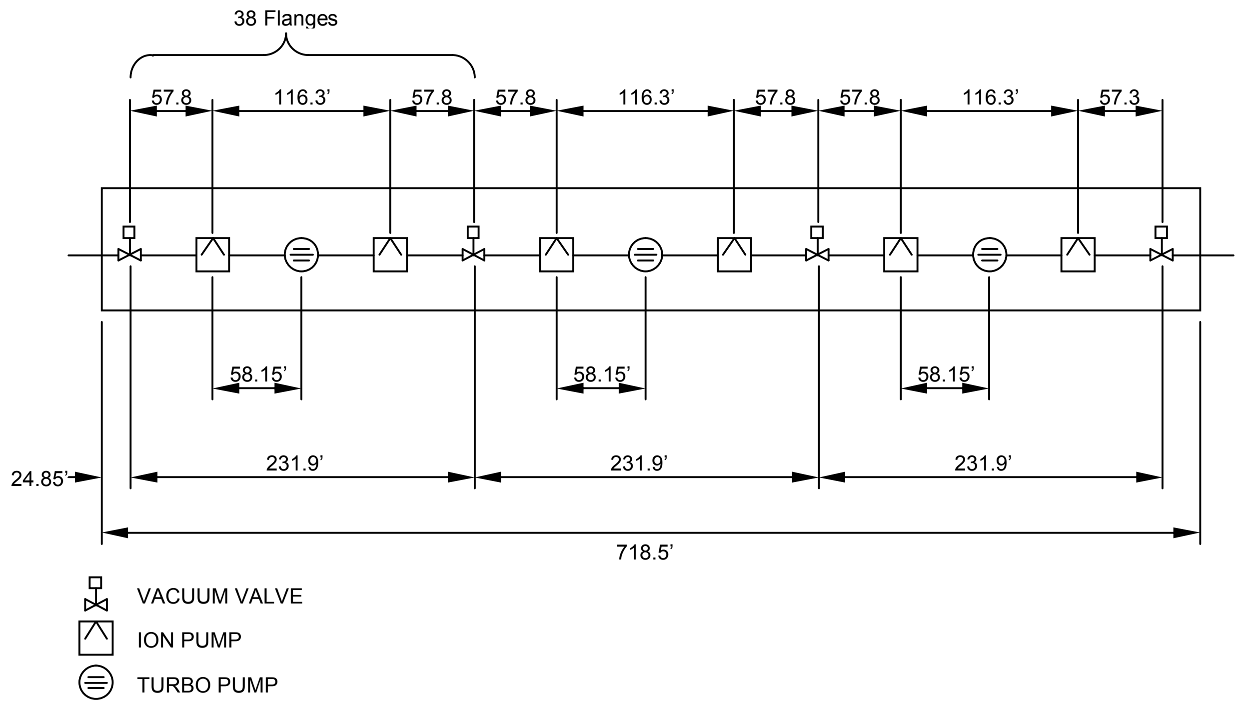


Figure 1.3. XVTS System Configuration

1.2 Deliverables

The preliminary design effort includes designing a vacuum system that meets the pumping requirements and integrates with XTOD tunnel structure. The preliminary design tasks include the following:

1. Specification of general layout of vacuum system components including the conceptual layout of vacuum lines and interfaces.
2. Engineering calculations for vacuum pump-down rates, system outgas rate and base pressures, pumping speeds, etc.
3. Selection and specification of valves, bellows, seals, and other general vacuum hardware.
4. Selection and specification of oil-free roughing pumps.
5. Selection and specification of high vacuum pumps.
6. Conceptual design of system instrumentation and controls.
7. Preliminary P&ID drawings.
8. Conceptual design of system operation and safety features.
9. Specifications and procedures for material preparation and cleaning.
10. Preliminary cost estimates for procurement.
11. Formal presentation of the preliminary design including a written report covering all of the above mentioned aspects.

1.3 General System Requirements

The requirement for the XVTS system is to provide sufficient pumping to overcome the system gas load in order to maintain a beam line pressure that results in less than 0.1% beam loss (discussed in Section 2.1.) and for long life of ion pumps. This gas load is from the surface outgassing rate of vacuum facing components and from leaks such as seals. The system must be designed for 10 years of continuous operation with minimal maintenance.

1.4 Vacuum System Design Approach and Design Layout

In developing the preliminary design for the XVTS pumping system, a conscious effort was made to build in robustness that will guarantee adequate pumping over a 10 year period of continuous operation. This was accomplished by specifying reliable components in the system to safeguard against possible failures. In addition, we installed redundancy to counteract unforeseen operating conditions or vacuum failures in the system. The design presented in this report is based on the experience with accelerator projects such as APT/RFQ, APT/LEDA/DTL-CCL, SNS/DTL-CCL, DARHT II, and SLAC B-Factory. Relevant vacuum systems of major accelerator facilities are also referenced. The major features of the design are summarized in the Table 1.1.

Issue	Design Approach	Feature Descriptions
Selection of Roughing Pumps	Dry Scroll **(Appendix B)**	Economical. Based on operation experience. Built with proper valving and operation sequence in PLC.
Roughing/Mid-High Vacuum Pumping	Turbo	Economic pumping in transition between roughing and high vacuum Ion pump backup for at least 1 yr of maintenance free operation
High-Vacuum Pumping	Ion Pump	Based on wide operation experience in accelerator applications. Selected for its reliability and ease of operation Time between maintenance of > 8 yrs
Instrumentation-Mid-vacuum	Convection Enhanced Pirani	Based on favorable operation experience.
Instrumentation-High-vacuum	Stabil-Ion or Cold-Cathode	Based on favorable operation experience.
Instrumentation-High-vacuum	RGA	Based on favorable operation experience.
Control	Allen-Bradley ControlLogix PLC	Consistent with those used elsewhere in the LCLS facility.

Table 1.1. Design Features of XVTS System

The XVTS system consists of 3 lines that are 4 inches in outer diameter and 212 meters long. The vacuum pumps and instrumentation are connected to the bottom side of the 3 lines. The vacuum pump spacing along each line is determined by detailed vacuum models (presented in Chapter 3 of this report). A permanently mounted turbo-roughing system is proposed for conditioning the lines, while ion pumps are recommended for continuous operation. Isolation valves are positioned at the ends, as well as with two in the middle of each line (as seen in Fig. 1.3) bringing a total of 12 isolation valves.

Each 70.68 meter section of each beamline is equipped with two cold cathode gauges and each beamline will have one RGA head. These instruments provide a means to monitor system pressure and gas constituents during the conditioning and operational phases. This is important for correct vacuum pump sequencing (transition from turbo pump to ion pump), monitoring vacuum system performance, and diagnosing manufacturing defects and vacuum leaks. Each isolatable section will be equipped with a valve for connecting to a source of nitrogen gas, required for venting the module during a maintenance operation.

The type and size of the pumps are chosen to provide a) a beam line pressure below the specification, with redundancy in case of ion pump failure that does not require immediate shut down of the system; b) reliable pumping during system conditioning; and c) minimal cost for the lowest reasonable pressure.

A combination of ion pumps and turbo pumps was chosen. Ion pumps are the choice to maintain the base pressure during the 10 year operation, mainly because of their high pumping speed and reliability for long-term operation. In this preliminary design, we have selected StarCell ion pump as a model, which has a lifetime of > 80,000 hrs (~ 9 yrs) at 7.5×10^{-7} T. Lower inlet pressures will further increase the lifetime that is dependent on the sputtering/erosion rate of the electrodes. Another alternative is the Gamma ion pump that has a comparable lifetime, cost, and slightly improved performance.

For our analysis, the ion pump size was chosen to meet the design specifications. In particular, once a total pumping speed for the full 212-m was chosen, then the pump size and number was varied while maintaining total pumping speed. Peak pressure plotted against pump number and compared to the design specs then determined the final pump configuration of six 75 L/s ion pumps. With this configuration, various scenarios of pump failures with turbo pump backup reveals the system robustness to meet the criteria for minimal maintenance in a 10-yr period.

The turbo pump size was optimized to reduce the pressure to within the ion pump operational range as well as to provide backup for ion pump failures. The turbo pumps can be used as backup for roughly a year. The selection of dry Scroll pump can be justified by the report in Appendix B.

The gas load in the XVTS system must be characterized during all phases of operation (i.e., start-up, conditioning, and steady-state). This is necessary to correctly choose the size, type, and number of high vacuum pumps. All vacuum system components (pumps, bellows, instrumentation, etc) must fit within the support structure. The pumps must be accessible for repair or replacement without disturbing the beam alignment. The modes of LCLS operation considered in this report are:

1. Commissioning & Preliminary Checkout (Initial Pumpdown)
2. Normal Continuous operation (10 yrs)
3. Maintenance Mode (Vacuum recovery within 1-2 shifts)

2 Performance Specifications

"Physics Requirements for the LCLS X-Ray Transport and Diagnostics" – Beam Transport Requirements states that:

"*The vacuum flight path must be sized to exclude the possibility of being struck by the x-ray beam. The average pressure throughout the system should be less than 10^{-5} Torr. In addition, the pressure at the ion pumps must be low enough to ensure long pump life (> 10 years). Vacuum components that are highly susceptible to radiation damage, such as elastomer o-rings, are discouraged. In general, SLAC standard procedures for cleaning and handling of UHV components must be followed.*"

2.1 System Requirements

The primary requirement for the XVTS vacuum system is to provide sufficient pumping to overcome the surface outgas rate of vacuum facing components and seal leaks and maintain a line pressure within the designed value.

The vacuum requirements are determined by two conditions. First, background neutral pressure should be less than 10^{-5} Torr to minimize the beam loss. Also, pump port pressure should be low enough that pump lifetime can be 10 yrs. The second requirement is actually the most stringent. Figure 2.1 below shows how the beam degrades with pressure when the beam energy is 818 eV. Higher energies (which will be more typical) degrade even less with pressure. Thus, the design pressure is chosen to be 3×10^{-6} T so that the beam loss is below 0.1% during normal operation. Should the ion pumps fail; backup turbo pumps can be turned on for up to a year to keep the pressure below 6 $\times 10^{-6}$ T until repairs can be scheduled. Detailed failure scenarios are presented later in this report.

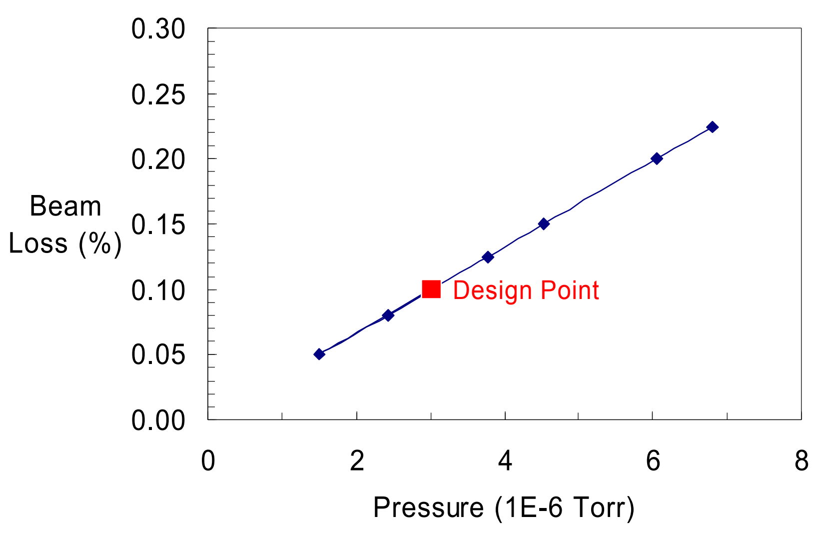


Figure 2.1. Per cent beam loss of an 818-eV x-ray beam over 370 meters

2.2 Assumptions

The operating pressures are maintained with ion pumps that are permanently attached to the three tunnel beam lines with a 4-way cross. Ion pumps are chosen because of their reliability and their ability to operate without a backing pump. The turbo pumps are permanently mounted, so that they can be turned on to not only pump down the system to the 10^{-6} Torr range but also to be used as a backup in case of multiple ion pump failures. If the turbo pumps were on moveable carts, then an additional ion pump would have to be added to plan for ion pumps failing. In addition, each time the turbo cart is used; it carries a risk of damaging the knife edge on the flanges or contaminating the system from improper procedures. Table 2.1 summarizes the pressure requirements, outgassing rate assumptions, and results of our design.

PARAMETER		REQUIREMENTS / VALUE
Pumping to overcome system outgas rate and seal leaks		1×10^{-10} T-L/sec/cm^2 at 100 hrs for stainless steel surfaces and 6×10^{-7} T-L/sec for each 6" ring
Beam line pressure Normal : all ion pumps on	Design Required	1.1×10^{-6} T, peak $< 3 \times 10^{-6}$ T , average
Beam line pressure Failure : all ion 6 pumps fail but all 3 turbos are on (good for 1 year)	Design Required	4.4×10^{-6} T, peak $< 6 \times 10^{-6}$ T, average

TABLE 2.1. XVTS System Requirements

Turbo and scroll pumps lower the pressure below 10^{-5} Torr when the ion pumps can be safely turned on. Turbo pumps are also permanently mounted and are isolated when not in use by a gate valve.

The surface outgassing rate of the stainless steel, cross, and bellows is assumed to be 1×10^{-10} T-L/s/cm^2 after 100 hrs of pumping the first time the system is pumped down. Figure 2.2 shows the history and our curve fit that is used in the time-dependent outgassing rate in our model. This curve is based on data from Roth.[†] and the APT experiment at LLNL.[††] This experiment demonstrated that after some time the outgassing rate will reduce to 1×10^{-11} T-L/s/cm^2. However this is not included in our analysis. Pressures will fall with the surface outgassing rate although half of the gas source comes from the 110 seals that each leak at a constant rate of 6×10^{-7} T-L/sec, which is very conservative to account for potential leaks. For the above pumping configuration, we also looked at how high the outgassing rate, or the total gas loads, could be and still meet the design requirements. This is discussed in Sec. 3.4.

[†] Roth, A., 1996, Vacuum Technology, (North Holland, Amsterdam) 190.
[††] APT LEDA CCDTL Phase 3A PDR Appendix 7A, LLNL/APT 99003.

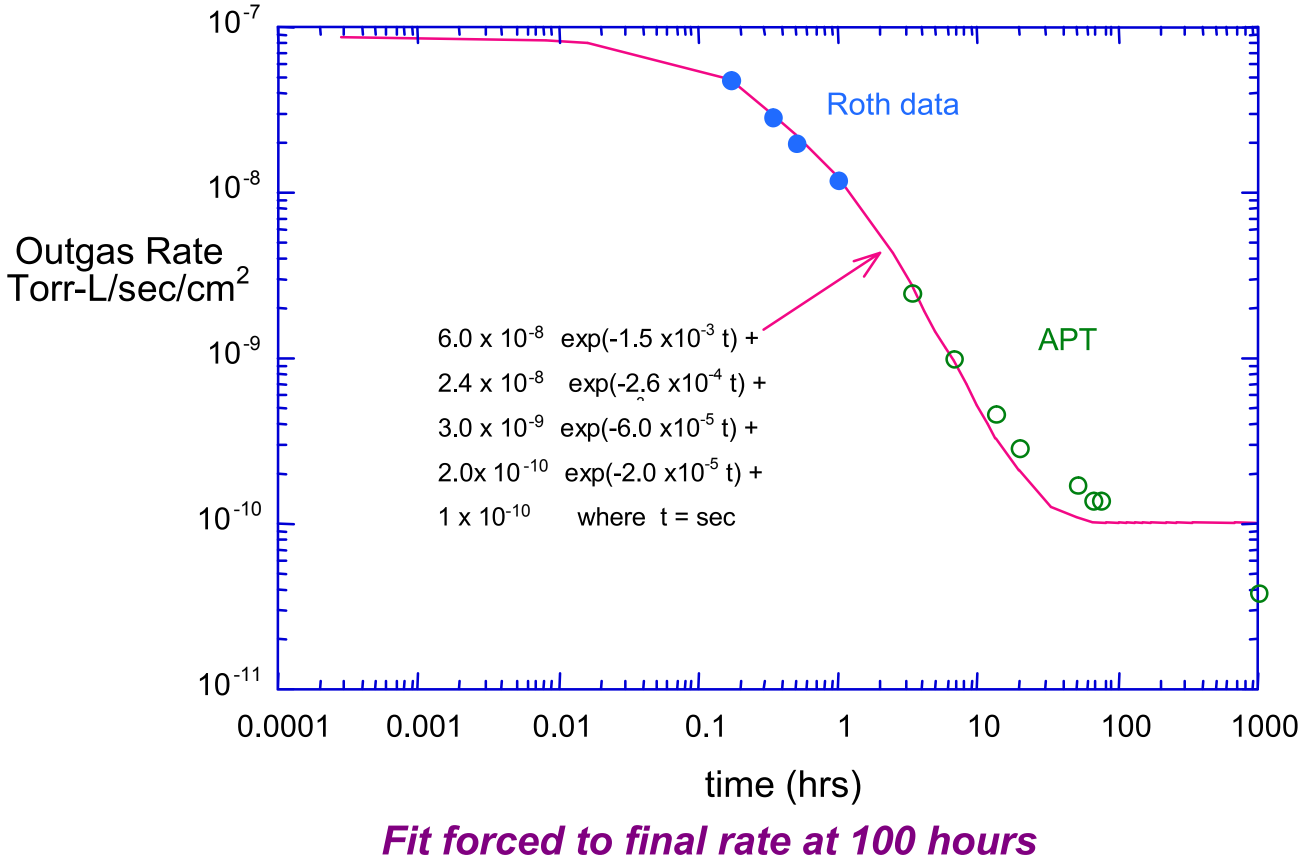


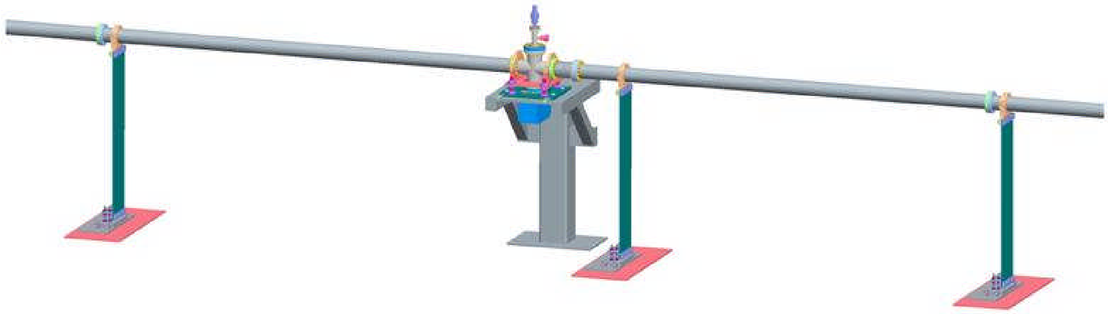
Figure 2.2. Outgassing Rate History for polished Stainless Steel.

2.3 Optimized Vacuum System Description

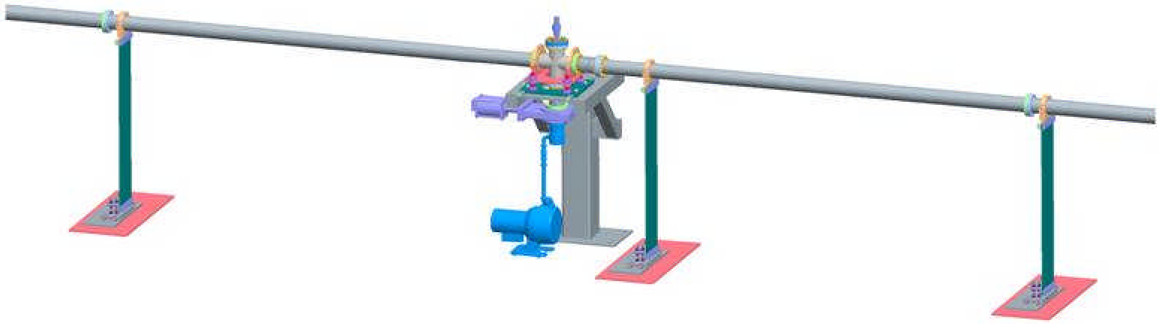
A description of components to be evacuated along with our optimized pumping system is provided in Table 2.2. Figure 2.3 shows a 3D drawing of the XVTS pumping configuration for both ion pumps and turbo-scroll pumps.

XVTS BEAM LINES
3 beam lines
Lines composed of 10 ft sections of stainless steel tube joined with 6” diameter metal seal flanges
For each beam line: 212 meters, 4” OD x 0.083” wall tube
For each beam line: 3 turbo pumps backed with 3 dry scroll pumps and 6 ion pumps connected with one bellows and 4-way cross
PUMPING SYSTEM SPECIFICATIONS PER BEAM LINE
Three DS 300 dry scroll roughing pumps (5 L/s nominal)
Three V70 turbo pumps (70 L/s nominal)
Six VacIon Plus 75 StarCell pumps (75 L/s nominal)
4-inch gate valve for each turbo and ion pump
One bellows and 4-way cross for each turbo and ion pump
6” diameter metal seal flanges (Conflat Type) between components
DETAILED SYSTEM PARAMETERS PER BEAM LINE
Total stainless steel surface area = 663,764 cm^2
Total volume = 1612 L
Total surface outgas rate= 6.67 $x10^{-5}$ T-L/sec at 100 hrs
Total leak rate = 6.66 $x10^{-5}$ T-L/sec at 100 hrs
Total gas loads = 1.33 $x10^{-4}$ T-L/sec at 100 hrs based on a rate of 6 x 10^{-7} Torr-L/sec for 110 4” seals
Peak pressure after conditioning with 6 ion pumps (normal mode) = 1.1 x 10^{-6} Torr
Peak pressure after conditioning if all 6 ion pumps fail and 3 turbos are running (failure mode) = 4.4 x 10^{-6} Torr

TABLE 2.3. Optimized vacuum system for three 212-m tunnel beam lines.



Ion Pump Cross



Turbo+ Scroll Pump Cross

FIG. 2.3. Pumping Configuration (Ion and Turbo+Scroll)

3 Vacuum System Design and Analysis

3.1 General Description

3.1.1 Numerical Vacuum Model

Our numerical model of the vacuum system analyzes the gas load balance for the XTOD tunnel beam lines. One beam line is modeled and the length is assumed to be 212 meters as determined by the convenient location of gate valves. The beam tube is composed of 10-ft long sections. Restrictions in the tunnel determined this section length for assembly.

To solve the gas load matrix for each pumping system, the beam tube needs to be subdivided into discrete sections or subvolumes. These subvolumes are connected to each other through effective conductances. We have benchmarked our simple model with the theory of a single pump that evacuates a long beam tube. This theory predicts that

$$p(x) = q\,B\,(L/S + x/C - x^2 / (2CL))$$

where q = outgas rate (T-L/sec/cm^2), B = perimeter (cm),

L = length (cm) between the pump and tube end,

S = pump speed (L/sec), and

C = conductance for a long tube (L/sec) =

$$12.1\, D^3/L\, [15\, L/D + 12(L/D)^2]/[20+38\, L/D + 12(L/D)^2].^{\dagger}$$

Subvolume conductances are chosen so that the sum of the inverse of the conductances equals the inverse of the conductance of the total tube length between pumps. Smaller subvolumes more closely agree with theory but cause the computer run time to be too long. We used a conductance length that was about 10 X the line diameter. The whole model took about 30 seconds to run on a 1.6 GHz PC. When a subvolume length equal to the diameter was chosen then the run time was 7 hours and the maximum pressure was only 2% less. Thus our rough model adds a few percent of conservatism to the answer and system optimization studies can be conducted within convenient run times.

Pressure history is studied by solving the coupled gas load equations between all the sub-volumes. A summary of the features in the code is presented in Table 3.1. Details of these features are discussed in the following subsections.

† Roth, A., 1996, Vacuum Technology, (North Holland, Amsterdam) Eq. 3.109.

FEATURES OF NUMERICAL MODEL
Solves entire pumpdown curve for any location using time-dependent outgassing rates
Separate time-dependent outgas rates for pre- and post-conditioning
Pressure-dependent pumping speeds for all three pump types
Automatic distribution of pumps for parametric studies
Automatic selection of appropriate gate valve sizes with each pump size
Inclusion of O-ring permeability rates independent of time, and other potential leaks
Pressure solved for 217 sub-volumes for 4 phases: roughing, turbo pumping, normal operation with ion pumps, failure mode during the transients when ion pumps fail and the turbo pumps come on
Written with Mathematica† and runs in 36 seconds on a 1.6 GHz PC

Table 3.1 Features of Numerical Model

The gas load equations, shown below, are solved simultaneously for all sub-volumes for each time during pumpdown:

$V_i \, dp_i/dt = \Sigma Q_{i\,in} - \Sigma Q_{i\,out}$

where i is the index for the i-th volume,

V is the volume (L);

dp_i/dt is the rate of change in pressure (Torr/sec);

$\Sigma Q_{i\,in}$ is the sum of surface outgassing or leakage into V_i (Torr-L/sec);

(surface outgassing is a function of time; O-ring leakage is constant)

and $\Sigma Q_{i\,out}$ is sum of the gas throughput from V_i into V_j,

where $Q_{i\,out} = C_{i\rightarrow j} (p_i - p_j)$

and $C_{i\rightarrow j}$ is the conductance (L/sec);

and/or $\Sigma Q_{i\,out}$ is sum of the gas throughput out of V_I,

where $Q_{i\,out} = S\, p_i$,

where S, the effective pump speed (L/sec), is

$S = S_p(p_i)\, C_p / (S_p(p_i) + C_p,$

where C_p is the conductance between V_i and the pump

and $S_p(p_i)$ is the pressure dependent pump speed.

† Mathematica 4.0 by Wolfram.

3.1.2 Outgassing Rate Assumptions

As discussed earlier, all vacuum-facing surfaces are composed of electro polished stainless steel. The numerical fit for the outgassing rate history is a combination of three parts and is shown in Fig. 2.2. The early outgassing rate (first hour) is taken from Roth.† The history from 2 to 80 hours is taken from measurements made from the LANL-APT experiment.†† For our model, the final outgassing rate is assumed to be 1 x 10^{-10} Torr-L/sec/cm^2. For reasonable pump down times as a design goal, the final rate is assumed to occur at 100 hours. Note in Fig. 3, the APT data shows that an even lower outgassing rate will be achieved beyond 100 hours. This curve fit represents the outgassing rate history for the first time that the system is pumped down. After the first time and if the system is purged with dry nitrogen, then the outgassing rate will be closer to 10^{-10} Torr-L/sec/cm^2 in the early time. This value or even less will be likely achieved in a few hours provided that good vacuum practices are followed.

3.1.3 Pump Models

For each pump, the dependence of pump speed on local pressure S_p (p_i) was scanned from the manufacturer's catalog and fit to a numerical formula. Figures 3.1, 3.2 and 3.3 show the pump characteristics for the roughing, turbo, and ion pumps, respectively.

The roughing pumps are permanently mounted and pumped through the turbo pumps. The roughing phase is from 760 Torr to 0.01 Torr. Roughing pumps are represented with a Varian 300 DS (dry scroll) pump with a nominal pump speed of 5 L/sec. The 600 DS could also be used for a slightly greater cost that would reduce the roughing phase by half from roughly 1 hour to 30 min. The gas load balance is solved with an initial pressure at 760 Torr. The roughing time is chosen so that the final beam tube pressure is 0.01 Torr. Next the final pressures for the 217 sub-volumes are saved to provide the initial conditions for the turbo-pumping phase.

† Roth, A., 1996, Vacuum Technology, (North Holland, Amsterdam) 190.
†† APT LEDA CCDTL Phase 3A PDR Appendix 7A, LLNL/APT 99003.

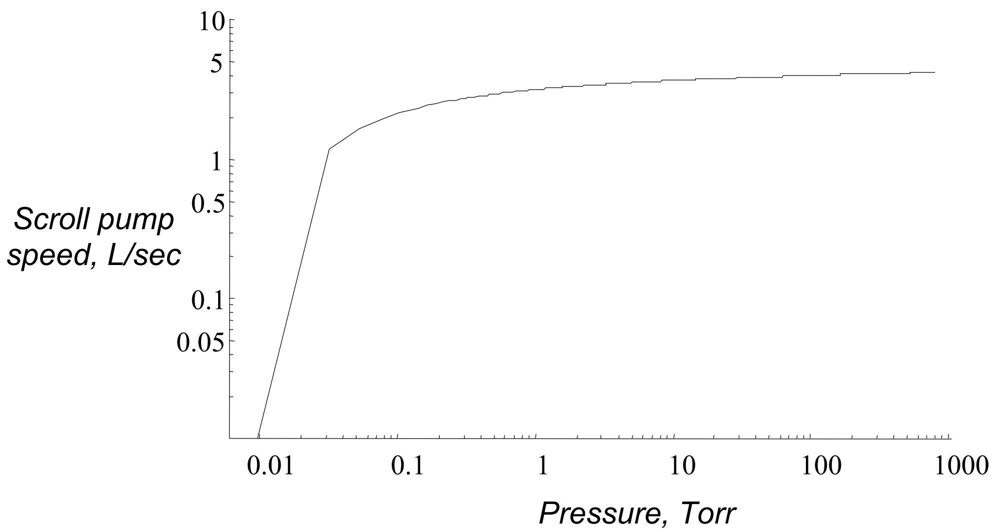


Figure 3.1. DEPENDENCE OF PUMP SPEED ON LOCAL PRESSURE FOR A 300 DS DRY SCROLL PUMP FROM VARIAN. $S = 10^{(0.72-0.49/(\mathrm{Log}\,P)+2.26))}$

The function of the turbo pumps is to pump the system down into the high vacuum range to where the ion pumps can be turned on (this will typically be below 10^{-5} Torr) and to provide temporary (less than 1 year) back-up pumping in case an ion pump fails during normal operation. Turbo pumps are represented with a Varian 70 L/sec turbo molecular pump. Note in Fig. 3.2 that the actual speed is 60 L/sec.

For steady state operation, a Varian VacIon 75 StarCell Ion pump is used. Figure 3.3 shows the pressure profile with six 75 l/s StarCell ion pumps. For typical pressures in front of the pump, the actual pump speed is 60 L/sec.

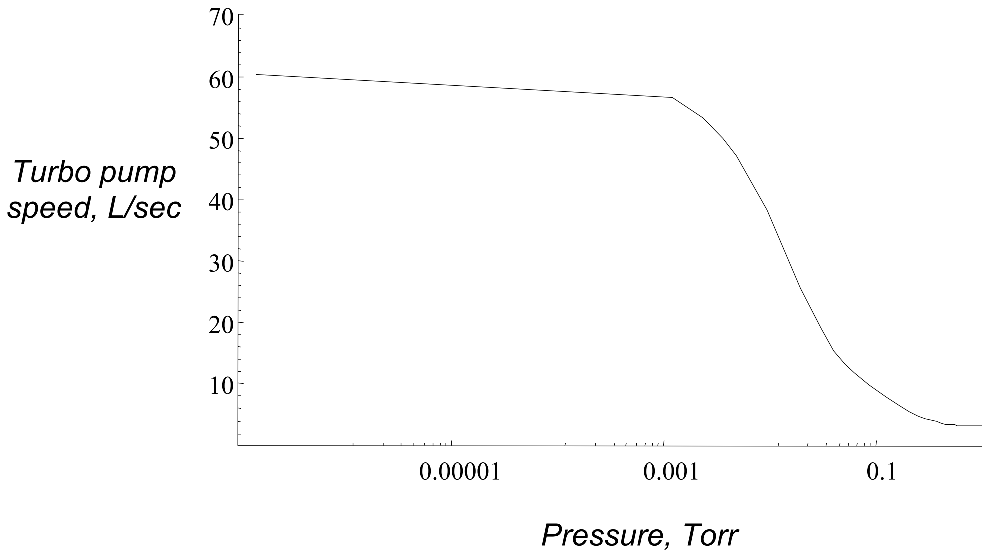


Figure 3.2. Dependence of pump speed on local pressure for a 70 L/sec turbo molecular pump from Varian. ***S = 13.5 Exp (-8.51 P) + 43.5 Exp (-70.4 P) + 3.24***

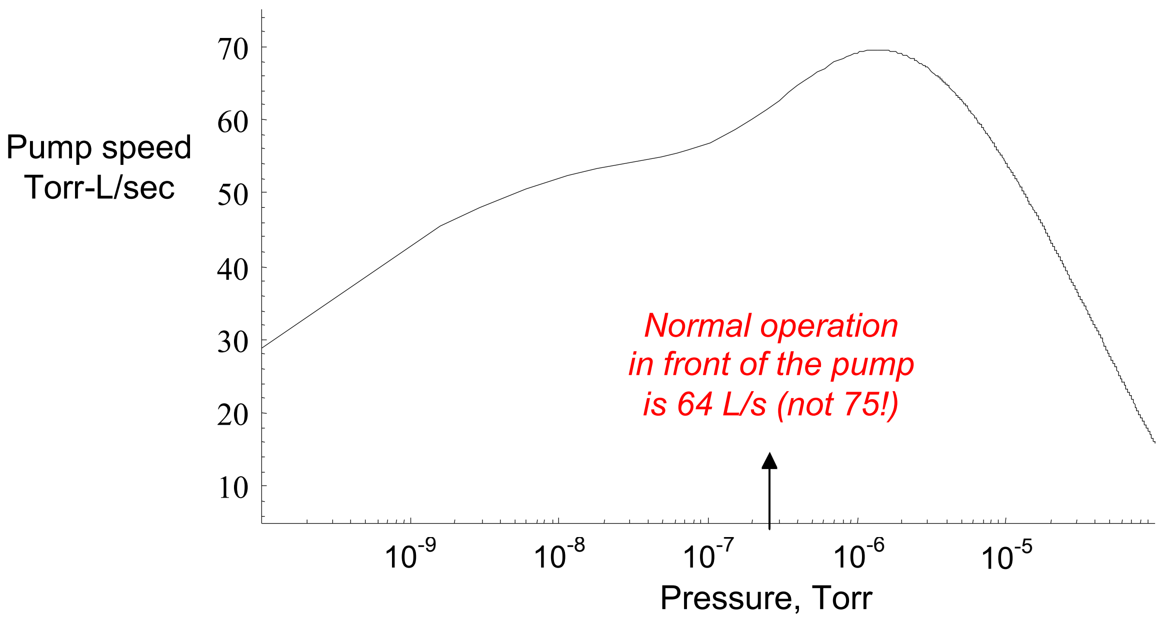


Figure 3.3. Dependence of pump speed on local pressure for a VacIon 75 StarCell ion pump from Varian.

Another ion pump under consideration is the Gamma 100 l/sec ion pump. With the diode pump configuration, the nominal pumping speed is 80 l/sec. The general characteristic of a Gamma ion pump is shown in Fig. 3.4. To model this pump, for the pressure range under consideration, then a constant value of 76 l/sec would be used. Since this is roughly 25% greater than the StarCell ion pump, then pressures would be less. Thus the StarCell model provides a more conservative answer in our analysis.

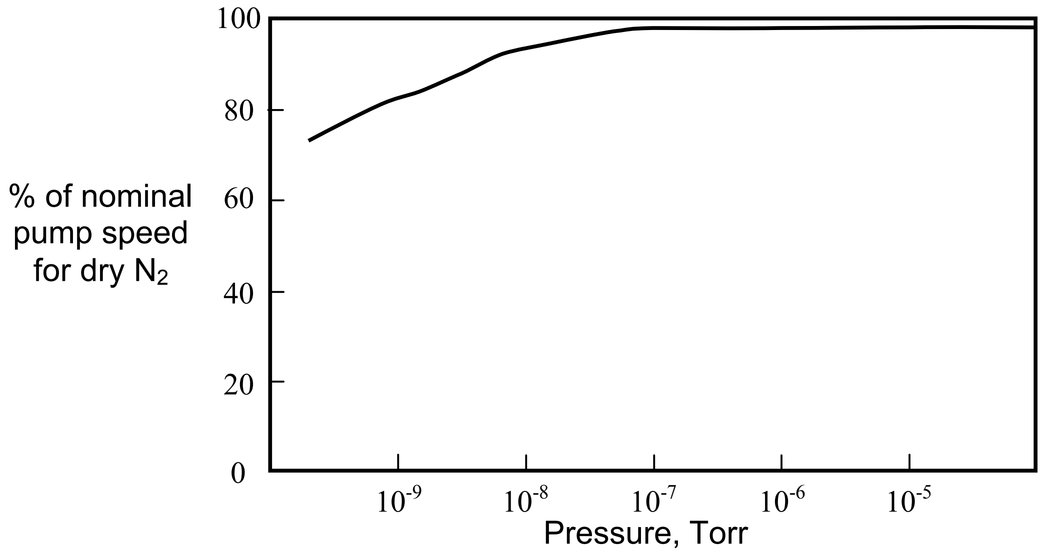


Figure 3.4. DEPENDENCE OF PUMP SPEED ON LOCAL PRESSURE FOR A GAMMA 100 L/S S NOBLE DIODE ION PUMP

Figure 3.5 shows the pumpdown history at the location of maximum pressure using the outgassing history in Fig. 2.2. Since this represents the first time the system is pumped down, subsequent pumpdowns will occur much faster. This time will depend on how the system is handled during maintenance. For example, a dry nitrogen purge should provide the least amount of gas adsorbed into the vacuum-facing surfaces. To remove the effect of a changing outgassing rate and to look at the shortest possible pumpdown time, we also ran the case of a constant outgassing history of 10^{-10} Torr-l/s/cm^2. As shown in Fig. 3.6, the pumpdown time is 1.5 hours. One hour of this is just roughing with the 300 DS pump. We could have chosen a 600 DS with a nominal pumping speed of 10 L/sec and this would have roughed the system down in a half-hour. LLNL will build a prototype of a section of the XVTS and outgassing rates will be measured for the first and subsequent pumpdowns and the changing outgassing rate will be quantified (see Section 7.3).

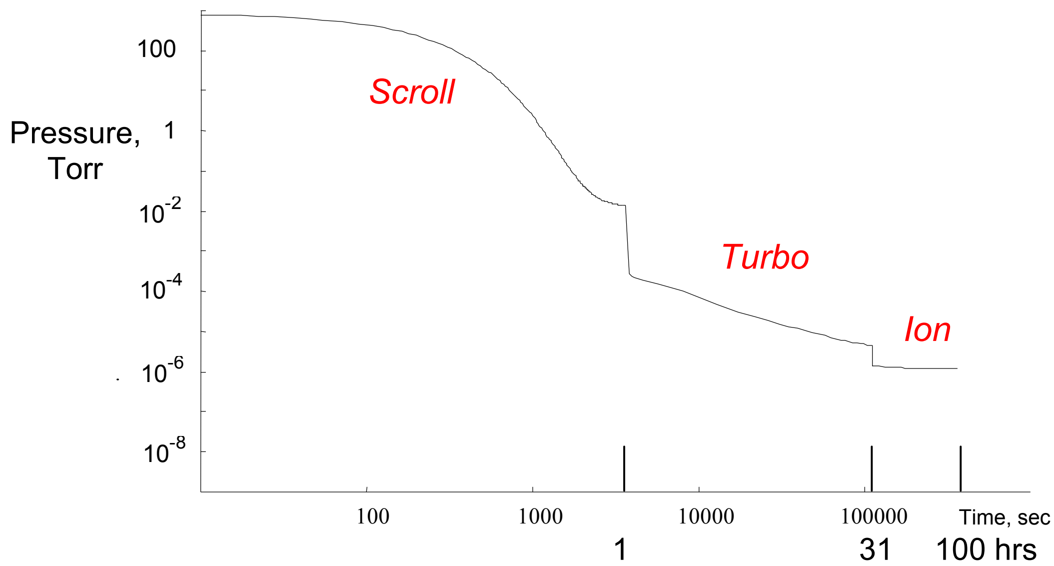


Figure 3.5. PUMPDOWN HISTORY AT LOCATION OF MAXIMUM PRESSURE

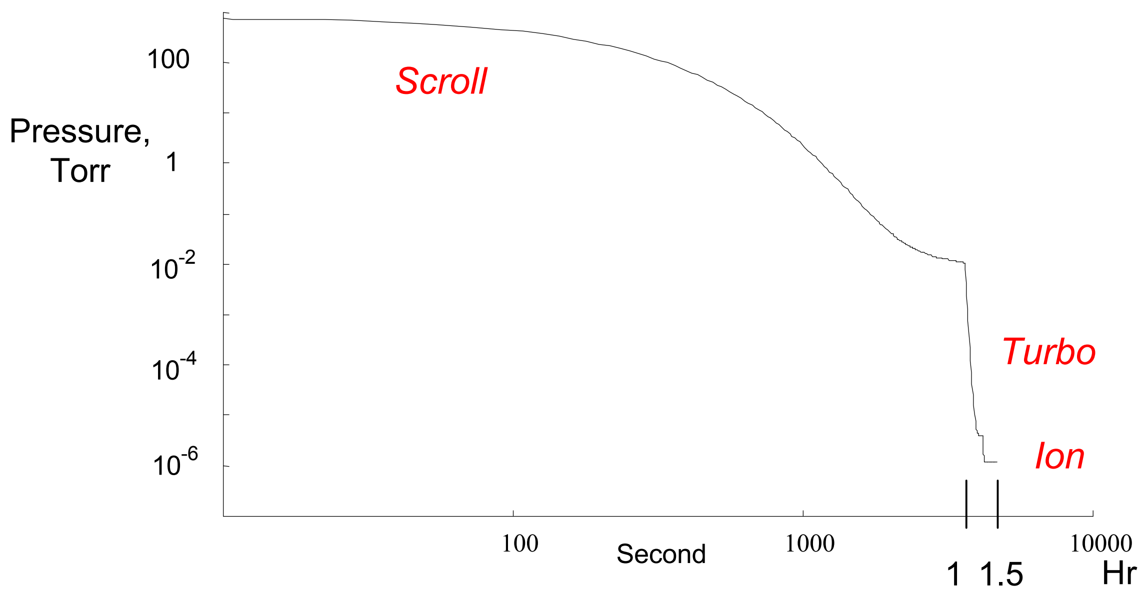


Figure 3.6. Pumpdown history at location of maximum pressure for a constant outgassing rate of 10^{-10} Torr-L/sec/cm^2.

For the initial pumpdown phase, the turbo pumps are on for 30 hours which is the time needed for the pressure to reach below 10^{-5} Torr. This long time occurs because the outgassing rate is not constant until the total pumping time exceeds 100 hours. This final maximum pressure of 4.5×10^{-6} Torr is about 90% of what could be achieved if the turbos were on for 100 hours. Figure 3.7 shows the pressure profile with the three 70 l/s turbo pumps at 31 hours. For all the plots shown in this report, the analysis was conducted using 217 subvolumes. This was the value that generated a cell length that is equal to 10 X the inner diameter. The pressure dips indicate the 3 pump locations between the parabolic pressure profiles.

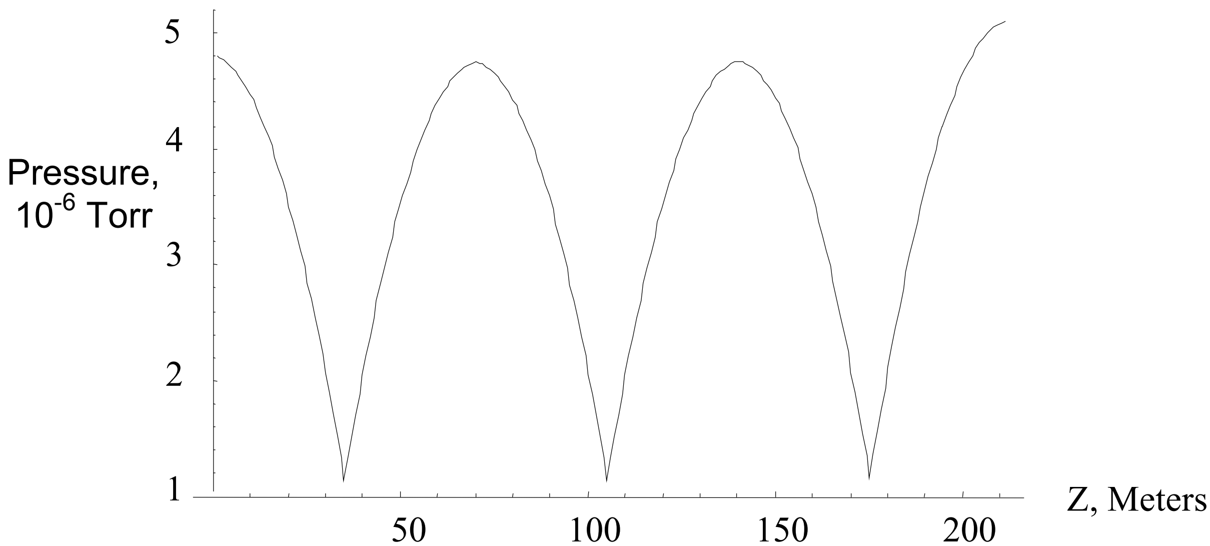


Figure 3.7. **PRESSURE PROFILE USING THREE 70 L/S TURBO PUMPS AT 31 HOURS.**

The model assumes that the system is closed at the ends at the gate valves. During normal operation, these valves will be open and an outside pump will reduce the pressure at the beginning and end of the 212-m that we model. Consequently when maximum and minimum values are reported, the end values are excluded. The maximum pressure shown is 4.8×10^{-6} Torr which is well within the safe pressure to start an ion pump. The minimum pressure is 1.1×10^{-6} Torr. At this value the turbo pump speed is actually 60 L/s (not the nominal 70 L/s). Also each turbo pump is attached to the tube with a 4” cross, 7” long spool piece, adapter, and gate valve. The net conductance of this assembly is 110 L/s. Thus the net pumping speed is only 39 L/s per pump.

For steady state operation, a Varian VacIon 75 StarCell Ion pump is used. Figure 3.8 shows the pressure profile with six 75 L/s StarCell ion pumps. For typical pressures in front of the pump, the actual pump speed is 64 L/sec.

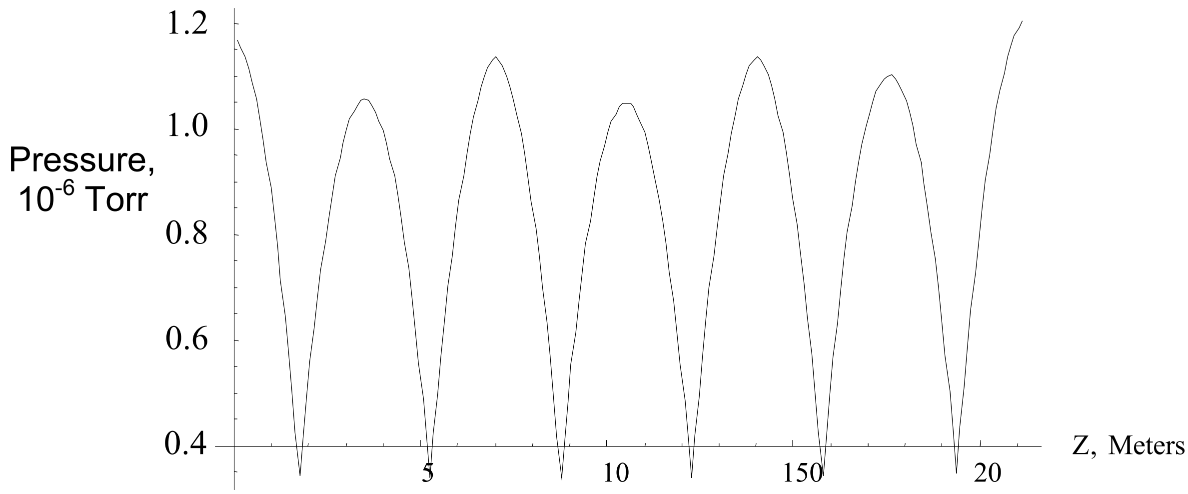
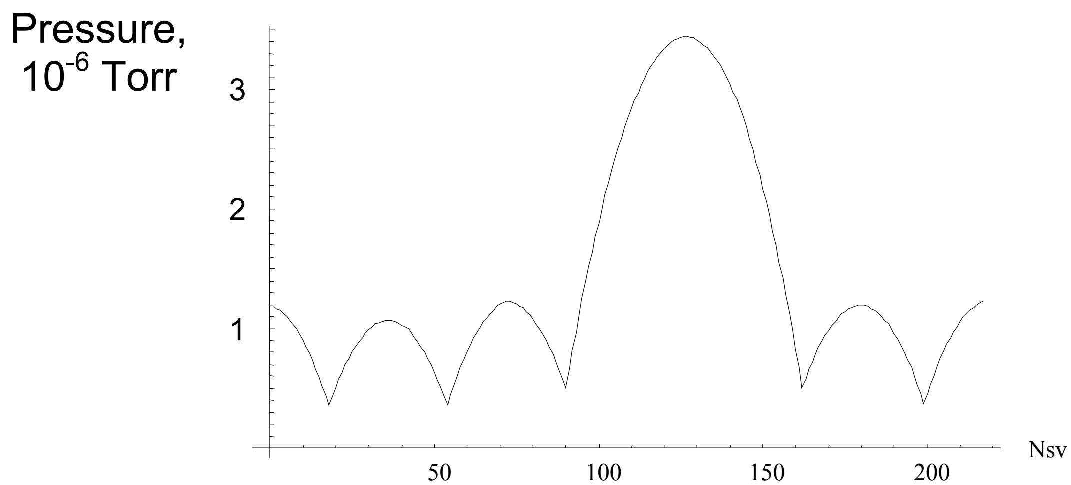


Figure 3.8. PRESSURE PROFILE USING SIX 75 L/S STARCELL ION PUMPS AT 100 HOURS.

3.2 Failure Analysis

We also studied the system response when one or more ion pumps failed and the turbo pumps were used as a backup. Figures 3.9A and 3.9B shows the pressure profile when the 4th ion pump fails without a turbo backup and the time response of the pressure in front of that failed pump. Pressure at the 4th pump increases from 3.6 x 10^{-7} to 3.4 x 10^{-6} Torr within 2 minutes but is still within the maximum design value of 6 x 10^{-6} Torr. Even when two non-adjacent pumps fail, as shown in Fig. 3.10, the pressure is still within the maximum design value. However for the failure of two (or more) adjacent pumps, the pressure is outside of the maximum value and the turbo pumps are needed for backup to stay below 6 x 10^{-6} Torr. Figure 3.11A shows the pressure profile with two adjacent failed pumps (only 4 working), then in Fig. 3.11B shows the profile with the middle turbo pump on. Figure 3.11C shows the system response is about two minutes to equilibrate after the ion pumps fail and after the turbo pump comes on.

The full range of ion pump failures with turbo backup was modeled. Results are listed in Table 3.1 and plotted in Fig. 3.12. In the worst case of 4 ion pumps failing and no backup, the pump throat pressure is 1 x 10^{-6} Torr which is safe for the pumps but would shorten pump life if operated there for years. However with turbo pump backup, even with four ion pumps failed, the throat pressures are safely within the 10^{-7} Torr range and can be operated here for the several year. As seen in Fig. 3.12, for even 4 ion pumps failing, the turbo pump lowers the maximum pressures to within the maximum design limit of 6 x 10^{-6} Torr.



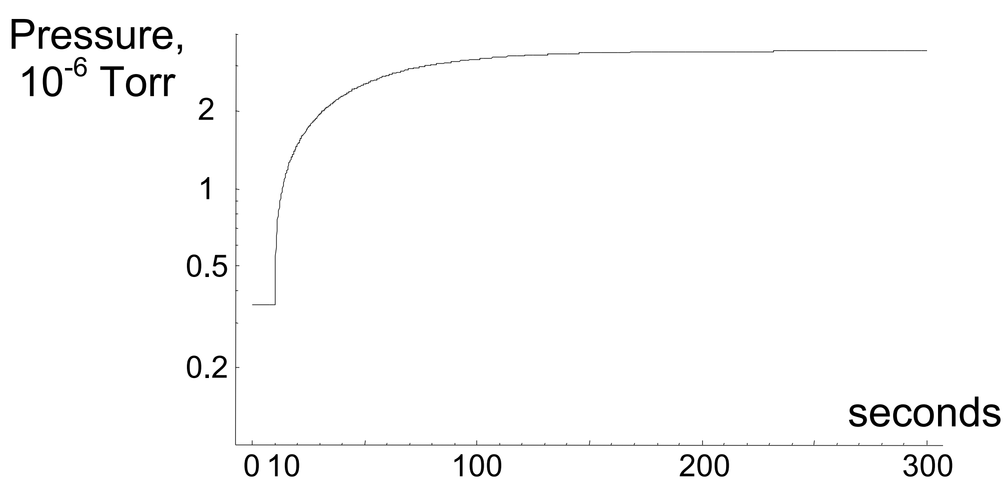


Figure 3.9. **A) PRESSURE PROFILE WITH FIVE 75 L/S STARCELL ION PUMPS 20 MINUTES AFTER 4TH PUMP FAILS AND**

B) PRESSURE RESPONSE AT THE FAILED PUMP

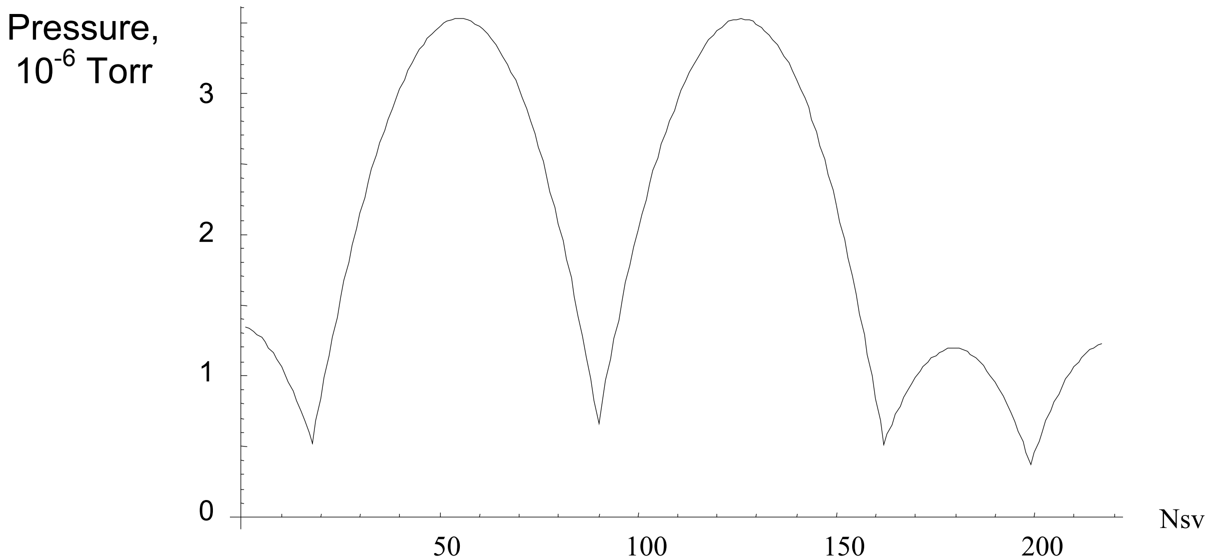


Figure 3.10. PRESSURE PROFILE AFTER TWO NON-ADJACENT (2^{ND} AND 4^{TH}) PUMPS FAIL.

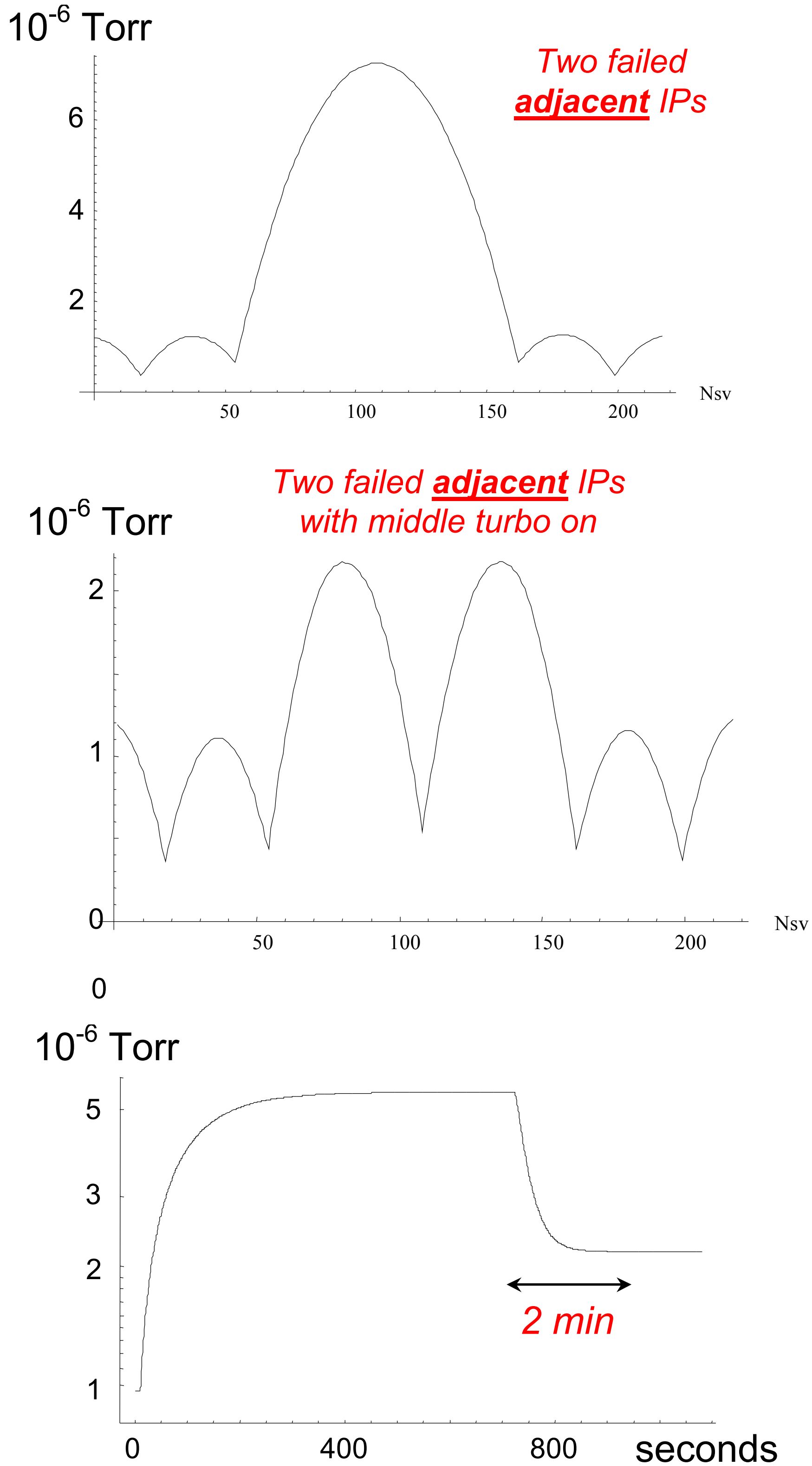


Figure 3.11. A) Pressure profile after two adjacent (3rd and 4th) pumps fail.
B) Pressure profile with 3rd and 4th ion pump off but 2nd turbo pump is on.
C) Pressure history at maximum pressure during transients

NUMBER OF 75 L/S ION PUMPS	NEAREST TURBO ON	MAX PRESSURE (TORR)	MIN PRESSURE (TORR)
6	-	1.2×10^{-6}	3.5×10^{-7}
5 (4th failed)	-	3.4×10^{-6}	3.6×10^{-7}
5 (4th failed)	2nd on	2.1×10^{-6}	2.8×10^{-7}
5 (4th failed)	2nd and 3rd on	2.0×10^{-6}	2.1×10^{-7}
5 (4th failed)	1st, 2nd, 3rd on	2.0×10^{-6}	2.0×10^{-7}
4 (2nd and 4th failed)	-	3.5×10^{-6}	3.7×10^{-7}
4 (2nd and 4th failed)	2nd on	3.4×10^{-6}	3.7×10^{-7}
4 (2nd and 4th failed)	1st and 2nd on	2.1×10^{-6}	2.8×10^{-7}
4 (2nd and 4th failed)	1st, 2nd, 3rd on	2.0×10^{-6}	2.1×10^{-7}
4 (3rd and 4th failed)	-	7.2×10^{-6}	3.7×10^{-7}
4 (3rd and 4th failed)	2nd on	2.2×10^{-6}	3.6×10^{-7}
4 (3rd and 4th failed)	2nd and 3rd on	2.2×10^{-6}	2.0×10^{-7}
4 (3rd and 4th failed)	1st, 2nd, 3rd on	2.1×10^{-6}	2.0×10^{-7}
3 (2nd, 4th, 5th failed)	-	7.6×10^{-6}	5.2×10^{-6}
3 (2nd, 4th, 5th failed)	2nd on	5.3×10^{-6}	4.5×10^{-7}
3 (2nd, 4th, 5th failed)	2nd and 3rd on	3.5×10^{-6}	3.0×10^{-7}
3 (2nd, 4th, 5th failed)	1st, 2nd, 3rd on	3.5×10^{-6}	2.8×10^{-7}
3 (3rd, 4th, 5th failed)	-	1.3×10^{-5}	3.8×10^{-7}
3 (3rd, 4th, 5th failed)	2nd on	5.4×10^{-6}	3.6×10^{-7}
3 (3rd, 4th, 5th failed)	2nd and 3rd on	3.6×10^{-6}	3.0×10^{-7}
3 (3rd, 4th, 5th failed)	1st, 2nd, 3rd on	3.6×10^{-6}	2.0×10^{-7}
2 (2nd, 3rd, 4th, 5th failed)	-	2.0×10^{-5}	1.0×10^{-6}
2 (2nd, 3rd, 4th, 5th failed)	2nd on	5.5×10^{-6}	6.0×10^{-7}
2 (2nd, 3rd, 4th, 5th failed)	1st and 2nd on	5.3×10^{-6}	3.0×10^{-7}
2 (2nd, 3rd, 4th, 5th failed)	1st, 2nd, 3rd on	3.6×10^{-6}	2.9×10^{-7}

TA BLE 3.1 MAXIMUM AND MINIMUM PRESSURES WITH VARIOUS ION PUMP FAILURES AND TURBO PUMP BACKUP

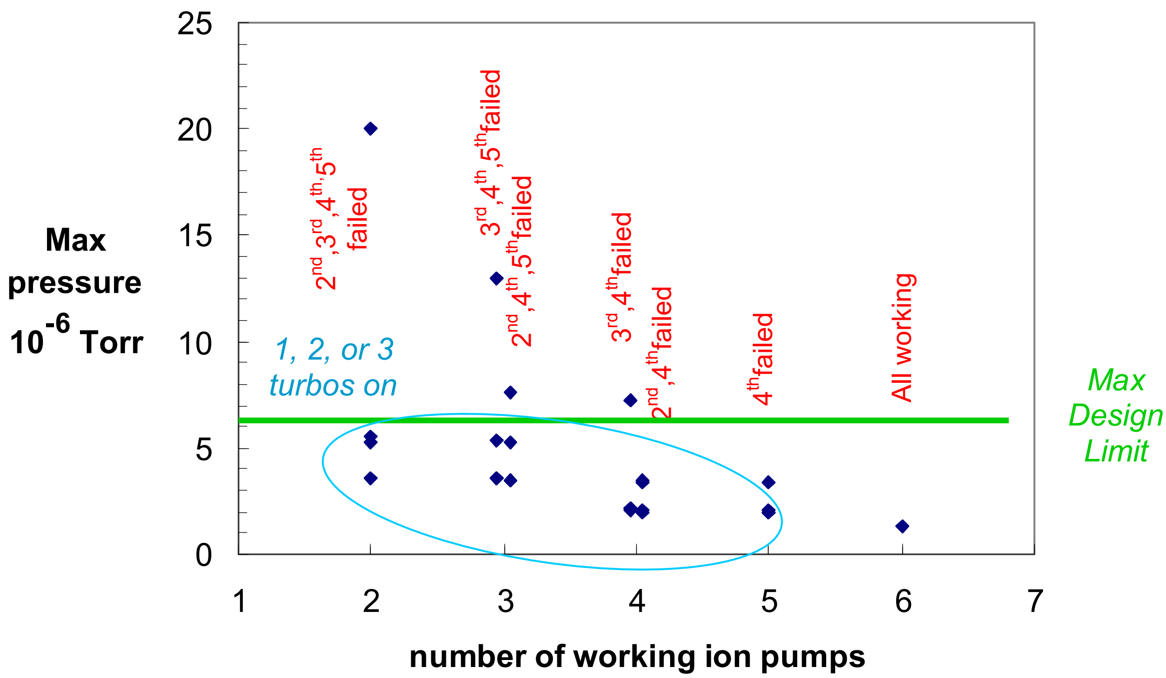


FIGURE 3.12. MAXIMUM PRESSURE (PLOTTED FROM TABLE 5) FOR VARIOUS FAILURE SCENARIOS.

3.3 Optimization of Numbers of Ion Pumps

Once it was established that six 75 L/s ion pumps could satisfy the requirements, we tested whether or not this was the optimum number of pumps. The model was run with a variable number of ion pumps but with a pump size that kept a constant nominal pumping speed of 450 L/s. Figure 3.13 shows these results for the case of normal operation and for one ion pump failing with no turbo pump backup. For normal operation, even four ion pumps met the design limit of 3 x 10^{-6} Torr. (Note that these 4 ion pumps would each have a nominal speed of 112 L/s). However when one pump fails then the maximum pressure is right at the maximum design limit of 6 x 10^{-6} Torr. So the next number up that still satisfies minimal costs would be 5 pumps at 90 L/s. (In addition we can only chose the nearest pumps sizes available from the vendors.) For ion pump costs, the larger the pump speed, the less the cost per unit L/s. However for the mechanical design, the entire 212 meters needs to be divided into at least 3 sections that can be isolated. Consequently 6 ion pumps with two per section was a reasonable value to choose. In addition, as seen in the Fig. 3.13, the smaller pumps contribute little to decreasing the pressure while adding to the total costs.

3.4 System robustness to higher outgassing rates

The typical outgassing rate of a clean system as discussed earlier is at least 1 x 10^{-10} Torr-L/s/cm^2. If additional leaks develop or the surface is not properly vented with dry nitrogen, then the total system gas load could be higher than the value included in our model. To quantify the system robustness, we also studied how large an outgassing rate that our design could tolerate. Figures 3.14 and 3.15 show the results of maximum and minimum pressure for an outgassing rate that varies from our design value of 1 x 10^{-10} Torr-L/s/cm^2 to 10 times that rate. Note that the gasket leak rate is a fixed value that is at half the total rate at the design value. At 1 x 10^{-9} Torr-L/s/cm^2, the gasket leak rate is insignificant. For the peak pressures, the surface can outgas at a rate that is 3 times higher than designed and still fall within the design limit of 3 x 10^{-6} Torr.

For the case of one ion pump failure with one turbo backup, the system can tolerate a rate that is 4 times higher. In summary, our chosen configuration of six-75 L/s ion pumps meets the specifications for normal and maximum design operation with comfortable operating margin.

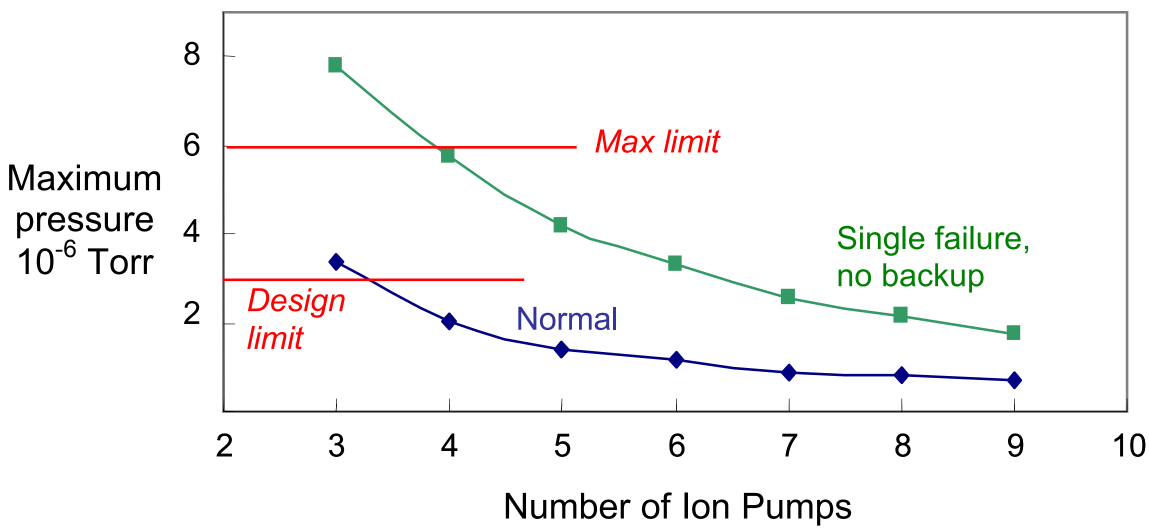


FIGURE 3.13. PEAK PRESSURE VERSUS NUMBER OF ION PUMPS FOR A CONSTANT NOMINAL PUMPING SPEED OF 450 L/S FOR TWO CASES: NORMAL OPERATION AND ONE ION PUMP FAILURE WITH NO BACKUP.

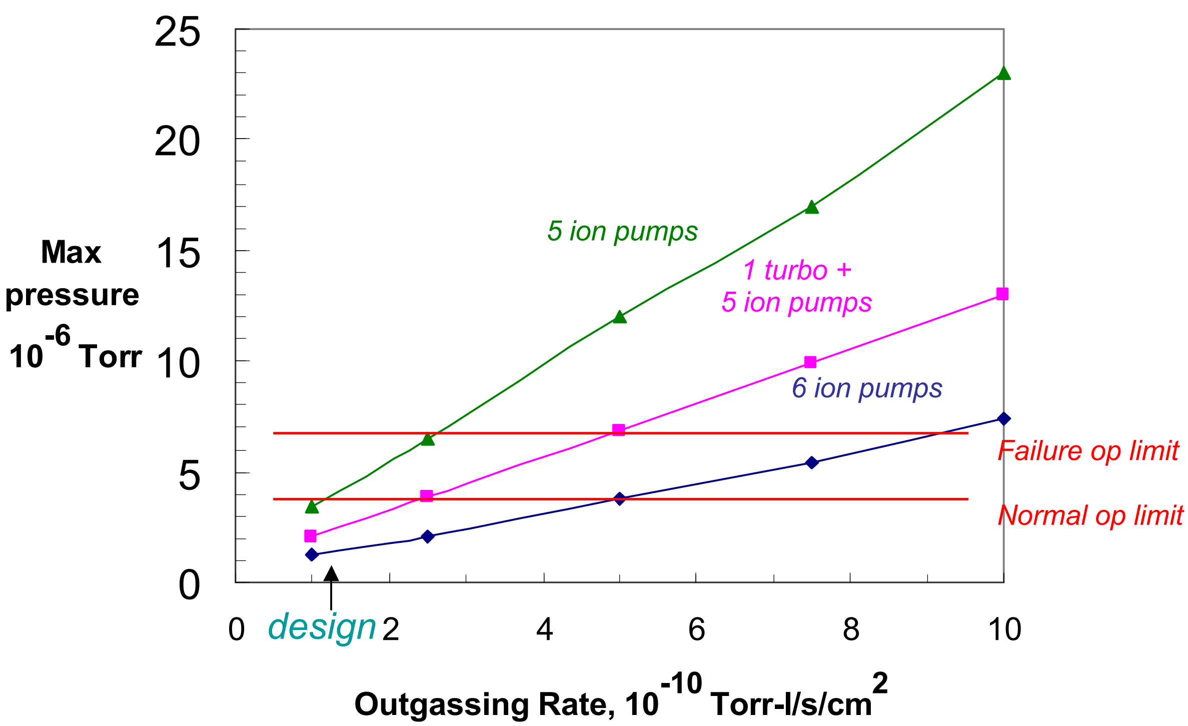


FIGURE 3.14. PEAK PRESSURE VERSUS OUTGASSING RATE FOR NORMAL OPERATION, ONE ION PUMP FAILING, AND ONE FAILING WITH TURBO BACKUP.

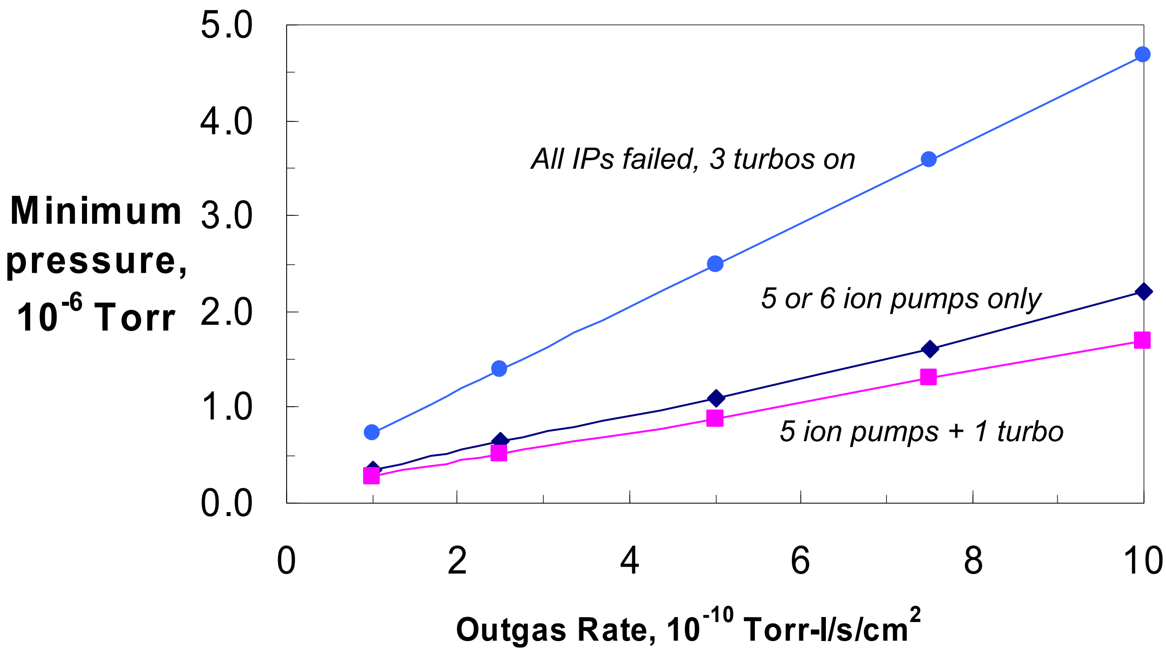


FIGURE 3.15. MINIMUM PRESSURE (PUMP THROAT) VERSUS OUTGASSING RATE FOR NORMAL OPERATION UP TO ALL ION PUMPS FAILING WITH ALL TURBO BACKUP

4 Mechanical Design

4.1 Introduction

This section reviews the mechanical design of the x-ray tunnel vacuum system of the Linac Coherent Light Source (LCLS) project. The x-ray tunnel extends over 200 meters from the Near Experimental Hall (NEH) to the Far Experimental Hall (FEH) at the Stanford Linear Accelerator Center (SLAC).

Preliminary evaluation of the mechanical strength and deflection under seismic loading has been completed. The seismic loads are per the SLAC document, “Specification for Seismic Design of Buildings, Structures, Equipment, and Systems at the Stanford Linear Accelerator Center” dated December 4, 2000.

4.2 General Description

The x-ray tunnel will contain three evacuated beamlines to transport the x-ray laser from the NEH to the FEH. The two beamlines diverge from a common beamline to deliver the beam to three end stations for experiments in the FEH. The beamlines are structurally broken into sections approximately 60 feet long that are mechanically isolated by bellows. The 60-foot spacing corresponds to the optimal layout given from vacuum calculations (Chapter 3). Each section is supported by a pump stand and a series of flex supports, each spaced about 10 feet apart. The design of the conventional facility limits the beam tube length to 10 feet... Tube with 4-in diameter is selected because it provides better conductance, beam clearance and less deflection, as compared to 2-in beam tube. Each pump stand is capable of supporting an ion pump or turbo pump and a UHV gate valve as well as the seismic loading in the beamline direction of 60 feet of 4” vacuum tube. A typical layout of a section of beamline is shown below (Fig. 4.1).

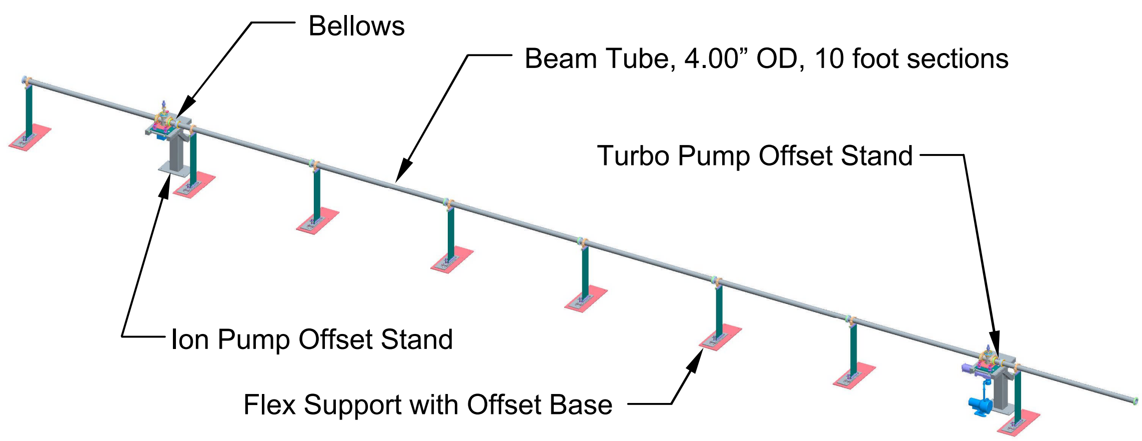


Figure 4.1 Typical 60 Foot Section of South Beamline

The south beamline center is currently spaced 12 inches from the tunnel wall with a 6 inch trough 6” from the wall, so there is little room for the structure to support and anchor the beamline. An offset stand has been designed in order to allow for this configuration. The offset stand is shown in Figure 4.2 with an ion pump. There are two other configurations that use an identical stand to support a turbo pump with a gate valve and one with a gate valve alone.

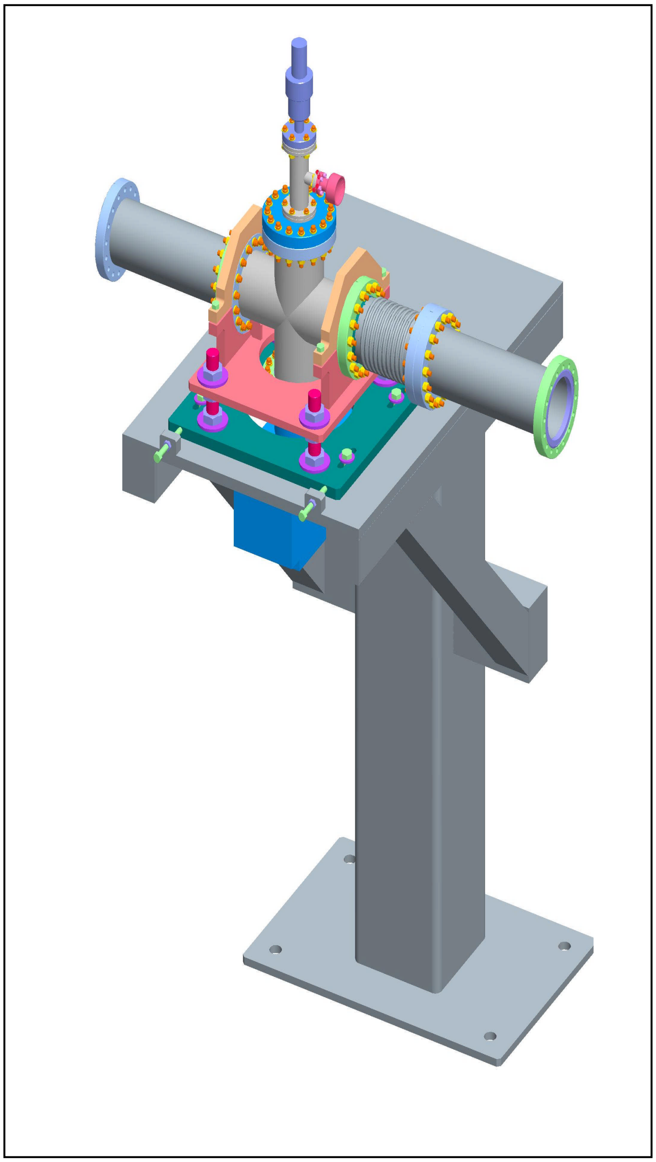


Figure 4.2 Offset Pump Stand

The central and north beamlines are away from the wall for most of their lengths and allow a simpler stand design to be used. The in-line stand design is shown on in Figure 4.3. It also can support a turbo pump or gate valve.

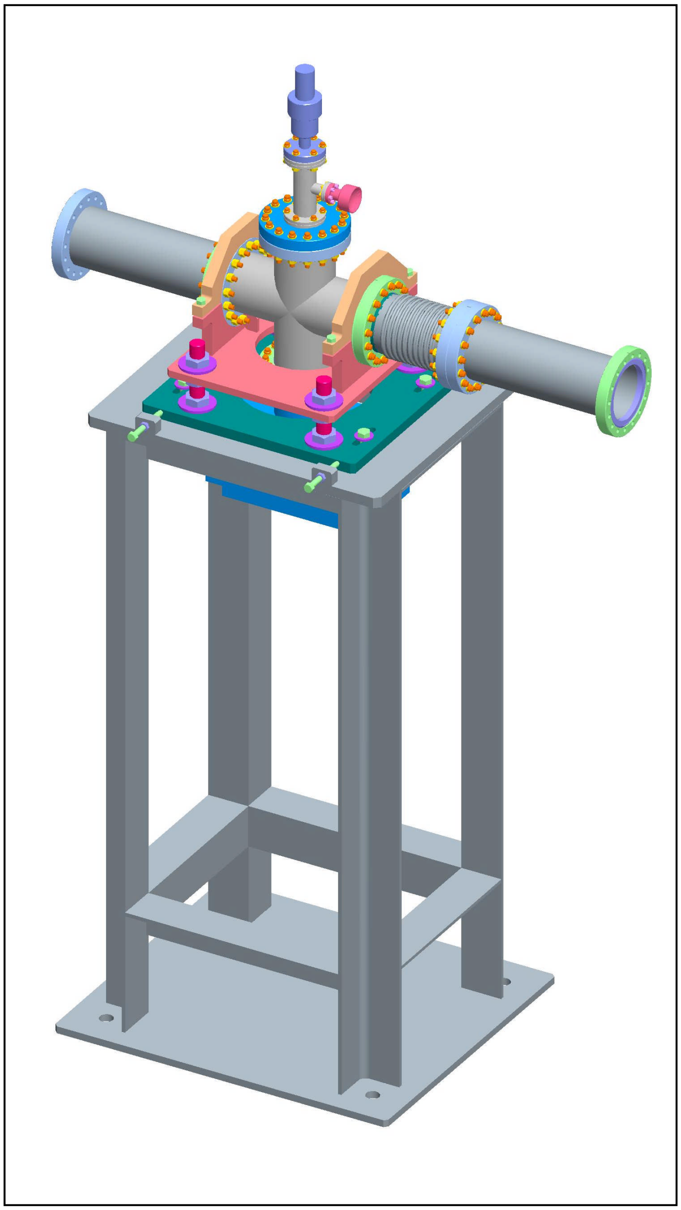


Figure 4.3. In-Line Pump Stand

The stands have adjustments in five degrees of freedom, with no horizontal adjustment in the beamline direction. None is required for the beamline direction as the bellows will allow for installation tolerances. The formed bellows range of motion is from 6.2 to 7.4 inches in length and allow for ¼” of offset. The stands will have defined lift points for ease of installation.

4.3 Seismic Analyses – Structural

Preliminary evaluation of the mechanical strength and deflection under seismic loading has been completed.

The main analysis tools used were the SAP 2000 version 9.1.7 program and the HILTI PROFIS anchoring analysis program version 1.5. SAP 2000 is a highly capable structural analysis program. It gives the fundamental modes of the structure, deflections under load, and analyzes the structure, both aluminum and steel, per the appropriate design codes, Aluminum Association Allowable Stress Design (AA ASD) and American Institute of Steel Construction's Load Resistance Factor Design (AISC LRFD), and gives the reactions at the structure's restraints.

The seismic loads are per the SLAC document, "Specification for Seismic Design of Buildings, Structures, Equipment, and Systems at the Stanford Linear Accelerator Center" dated December 4, 2000. The SLAC document yields a load of 1.5g's in the horizontal plane and 1.15g's vertically for a structure with 2% damping with a natural frequency of 20 Hz. Structures with 2% damping are typically welded, while structures with 5% damping are usually bolted. The seismic response curve is about 25% higher for 2% damping. The use of 2% damping is therefore conservative in this case, but not overly so. The first natural frequency being around 20 Hz was confirmed by SAP 2000.

The structure was modeled with various beam elements to closely approximate the real life structure of a 60 foot section of beamline. The beam line can be broken in sections at each bellows, which mechanically isolates the sections from each other.

The sections of beamline are replicable 60 foot sections only differing with the particular items on the pump stand or the type of pump stand, which is offset or not. One end of each section has a pump stand with flex supports spaced 10 feet apart, one for each 10 foot section of beam tube. The flex supports allow motion in the beamline direction, but constrain vertical and lateral motions. The layout of the SAP model for the offset stand can be seen in Figures 4.5 and 4.6.

To create the worst case load the pump stand is loaded with an ion pump and a gate valve as these are the two heaviest items to load the stand. The pump stand also takes the entire load from the beamline tubing in the beamline direction in the case of a seismic event, so the horizontal load is placed in the beamline direction. The base of the pump stand and all the flex supports are fixed to the ground in the model in all degrees of freedom. These settings are applied to both the offset and inline pump stand section models.

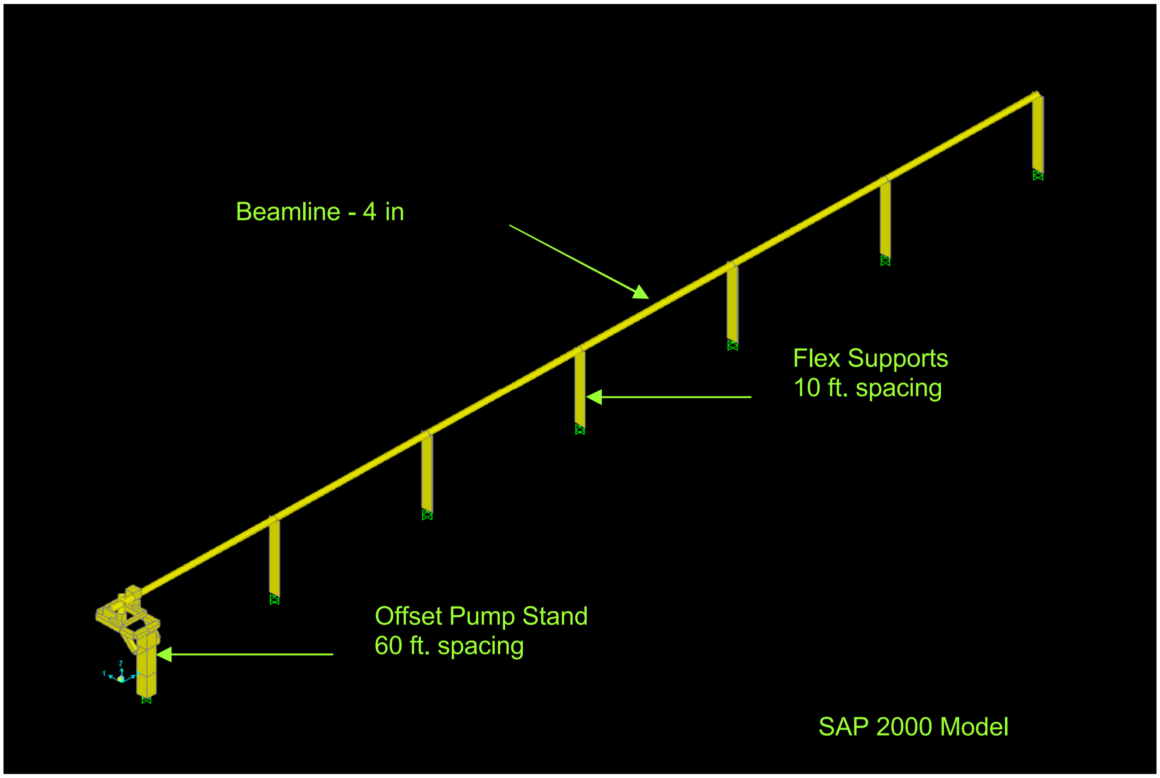


Figure 4.4. Typical Section of Beamline with Offset Stand

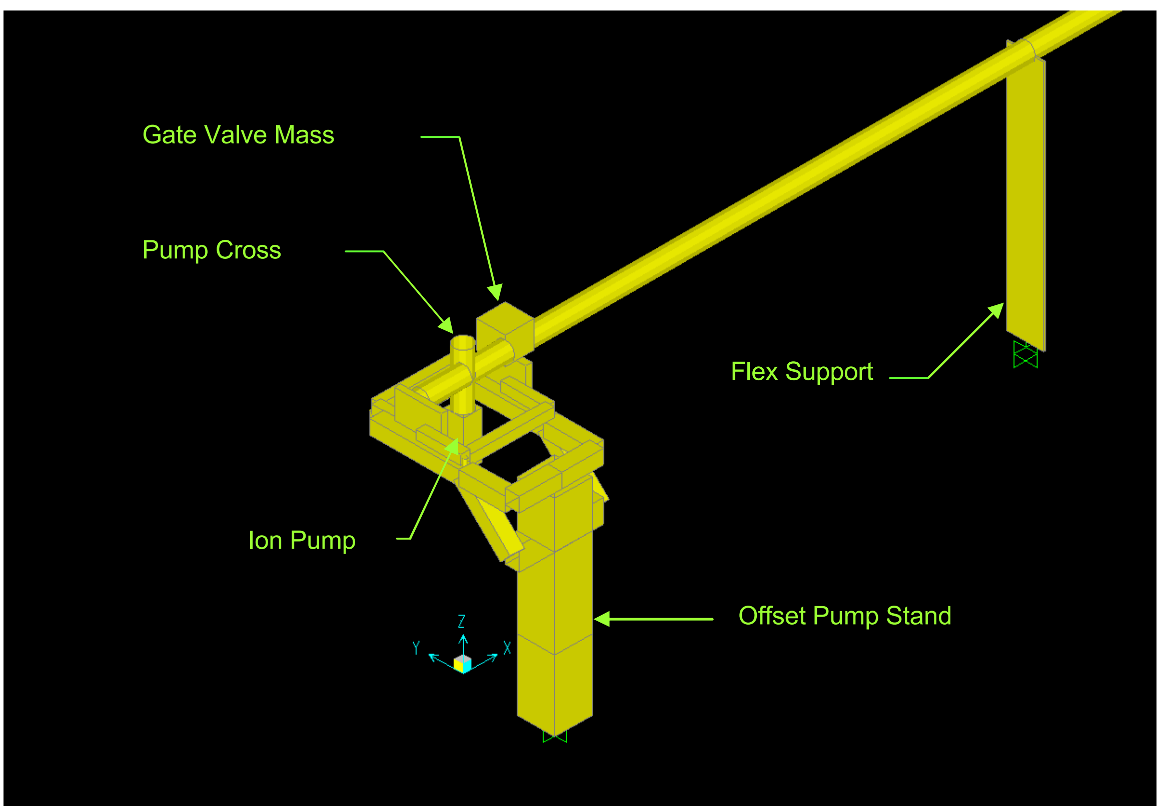


Figure 4.5 Close-up of Offset Stand in SAP 2000 model

A summary of the results of the analyses using SAP 2000 for an offset stand section can be seen in Figure 4.6.

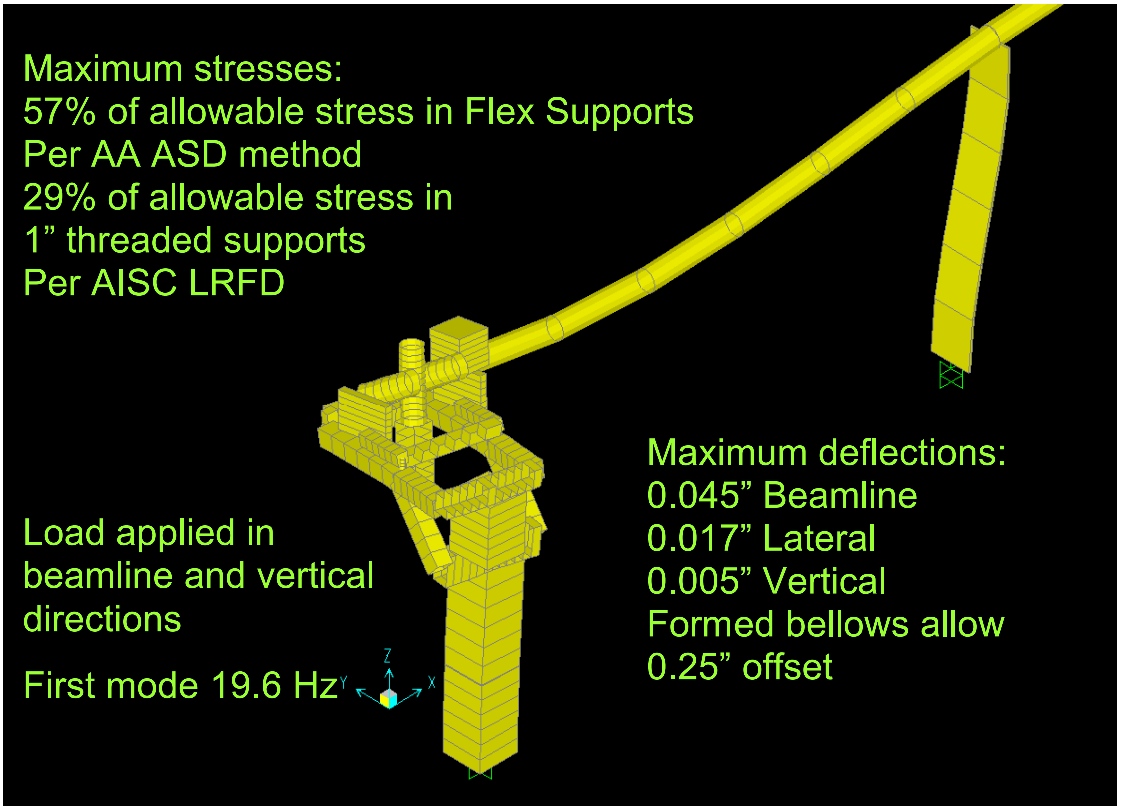


Figure 4.6 Summary of Off-set Stand results using SAP 2000 model

A summary of the results of the analyses using SAP 2000 for an inline stand section can be seen in Figure 4.7. As the figures show, the inline stand has less deflection and similar stress levels.

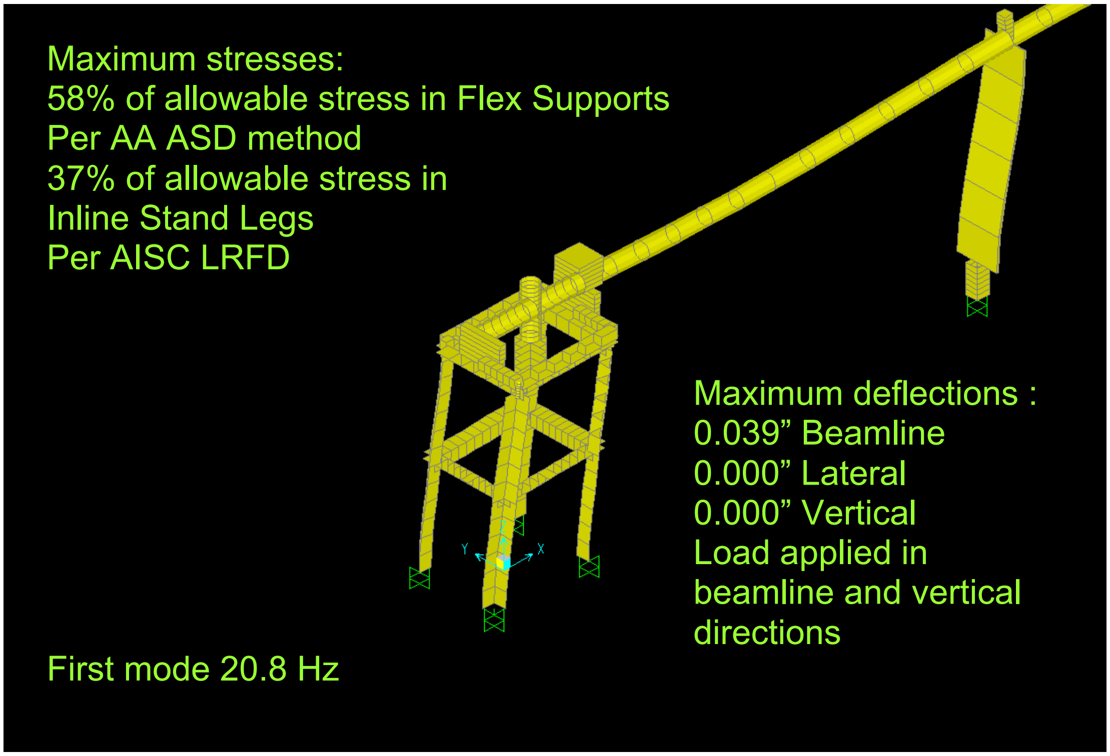


Figure 4.7 Summary of Inline Stand results using SAP 2000 model

The load that tests the maximum strength of the flex plates is a horizontal load lateral to the beamline. This lateral load was applied and the flex plates were well within their allowable stress range. All steel components exceeded the requirements of the AISC LRFD. All aluminum components, which are the flex plates, passed the AA ASD code.

All steel components exceeded the requirements of the AISC LRFD. All aluminum components, which are the flex plates, passed the AA ASD code.

4.4 Seismic Analyses - Anchoring

The anchoring calculations were accomplished using the HILTI PROFIS anchoring program.

The inputs to the anchoring analyses for the offset stand are:

- Reactions at base of stand from FEA
- 2" gap from base to floor – grouted
- Anchor pattern: 12"x 20"
- Base plate size and thickness: 24"x 14"x 0.75"
- Loads are short term – seismic
- Base clamped on all thread – nuts both sides

The HILTI anchoring program stated that ¾" HILTI Kwik Bolt 3 anchors meet the ICC uninspected anchoring criteria, and will therefore function for our design of the offset stand anchoring.

The loads for the in-line stand are lower, while the anchoring pattern is larger, so the same anchors will meet the standard and will be used.

The inputs to the anchoring analyses for the flex support are:

Reactions at base of flex support from FEA

2" gap from base to floor – grouted

Anchor pattern: 3 inline, spaced 9.875"

Base plate size and thickness: 9"x 23.25"x 0.5"

Loads are short term – seismic

Base clamped on all thread – nuts both sides

The HILTI anchoring program stated that 3/8" HILTI Kwik Bolt 3 anchors meet the ICC uninspected anchoring criteria, and will therefore function for our design of the flex support anchoring.

The actual layout of the anchoring for the flex support has the center anchor offset 4 inches in the beamline direction, but this only makes the pattern stronger, so the anchor design is slightly conservative.

4.5 Static Analyses – beam tube clamping by Flexible Support

The beam tube is clamped to the flex support. The force on the beam tube from properly torquing the clamping bolts is large. There is one clamping bolt on each side of the tube. They are both ¼", grade 5 fasteners. Proper torquing of the fasteners gives a force of 1800 lbs. from each. This induces stress in the wall of the beam tube.

An FEA model was created using Pro/E and Mechanica to find the length of clamp that would sufficiently distribute the stress from the clamping bolts. The result is that it takes a 2 inch long clamp to properly distribute the stress. The FEA model results are shown in Figure 4.8.

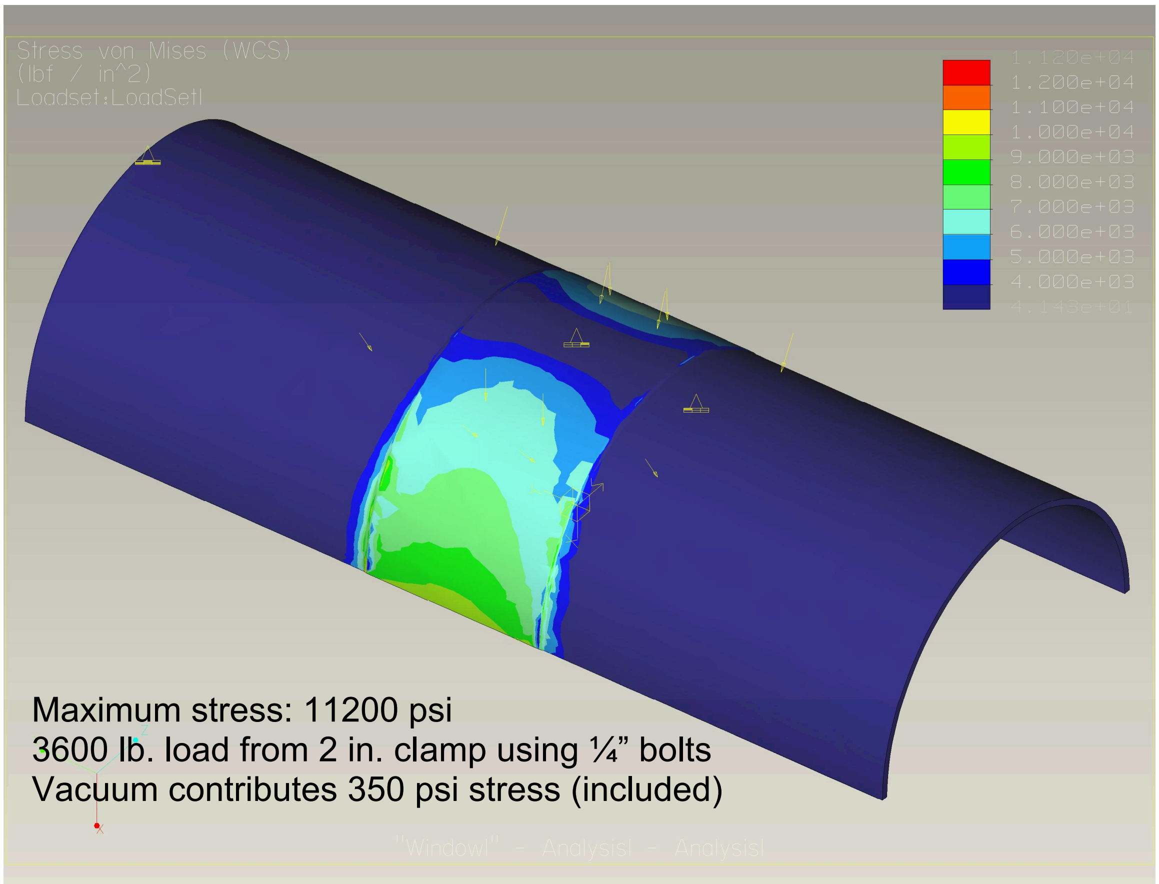


Figure 4.8 Summary of beam tube clamping results using Mechanica model

5 Instrumentation and Control

5.1 Introduction

The design of the instrumentation and control system for the LCLS XTOD Tunnel Vacuum System (XVTS) will be based on the design of the SNS DTL/CCL vacuum system. The control system's basic design is to have a Programmable Logic Controller (PLC) controlling the vacuum pumps and gate valves. The PLC will be connected to a network which will have EPICS I/O Controllers (IOCs) that will provide the data to a user interface in a client server model. The PLC will monitor the status of the vacuum pumps and vacuum setpoints from the vacuum gauge controllers and use interlocks generated from the PLC's logic to ensure proper operation of the vacuum system. In the event of a vacuum system malfunction, interlocks will be available to the Machine Protection System to safely shutdown the system.

The XVTS vacuum system will be in full compliance with LCLS standards for hardware, software and safety.

The design of the XVTS uses ion pumps connected to a pump cross, which in turn is connected directly in the beam line. A scroll pump and a turbomolecular pump also be mounted on pump crosses in the beam line and will be used to pump down the system from atmosphere to a pressure where the ion pumps can be started without overheating the pump or causing internal electrical discharges. There are 3 sections per beam line and there are 3 beam lines in the transport tunnel. A preliminary P&ID for a typical beam line of the XVTS is shown in Fig. 5.1.

During a power failure, the vacuum system will shut down. When power is restored, the PLC will reboot, but will not restart the vacuum system. The state of the vacuum system will have to be determined by an operator who will then use the EPICS control system to co command the PLC to restart the vacuum pumps and open gate valves. If a reasonable vacuum condition still existed after a power failure, the ion pumps could be restarted immediately and high vacuum could be re-established very quickly.

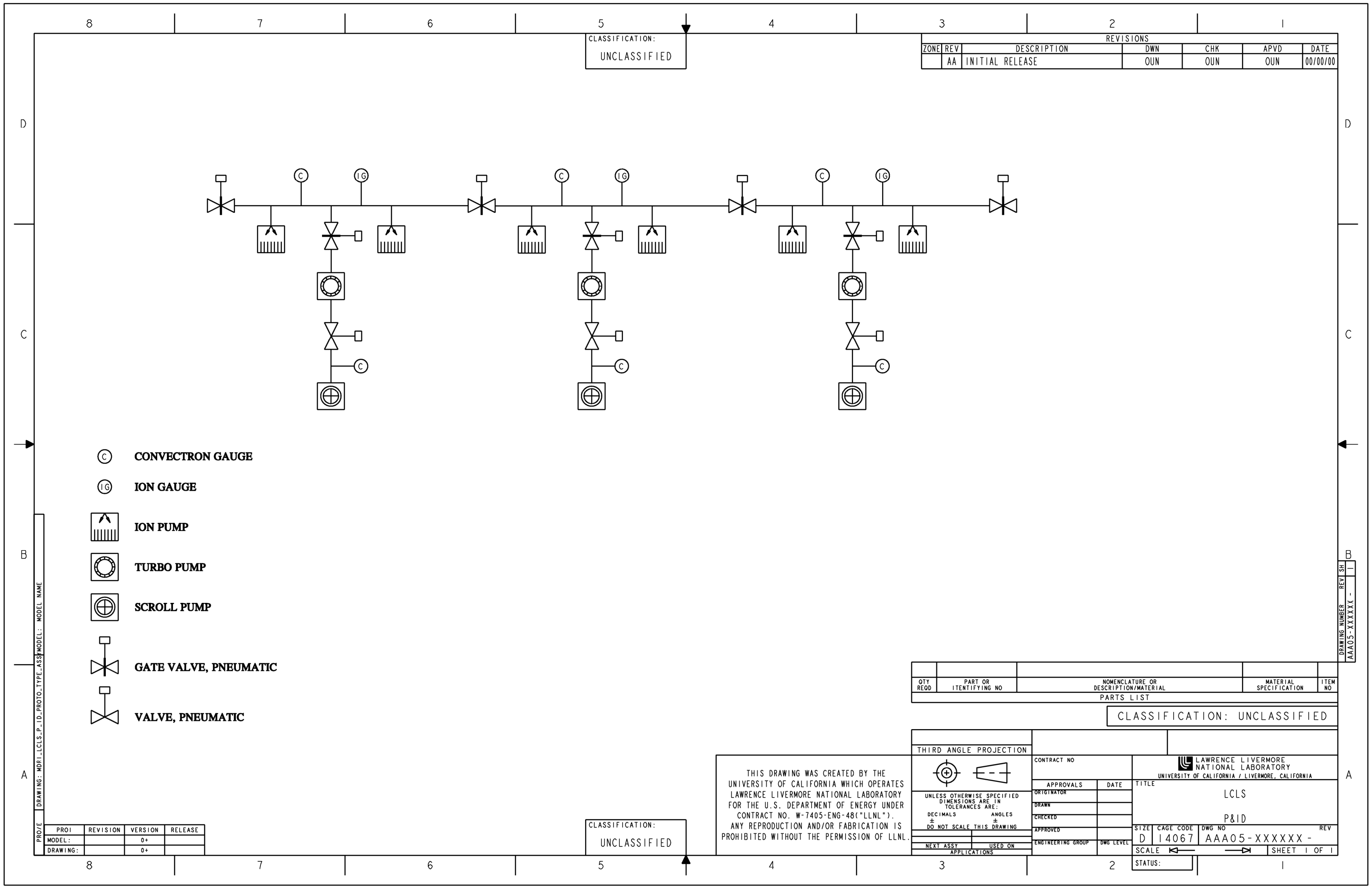


Figure 5.1. Preliminary P&ID for one beam line in the LCLS XTOD Tunnel

5.2 Vacuum Controls

The control system for the XVTS will consist of a Programmable Logic Controller (PLC) that will be connected via a network to the global control system, EPICS. The PLC will execute its ladder logic software in a continuous loop, evaluating the status of the vacuum system. Based on the ladder logic and the status of the vacuum system, the PLC can automatically close a valve or shutdown a pump. The PLC can not automatically open a valve or start a pump, such an operation must be done by an operator using EPICS. Interlock logic within the PLC will prevent the operator from selecting an improper valve or pump operation.

The PLC can be operated in a stand-alone mode by using a PC running the PLC software development environment to open a valve or start a pump. This mode will only be used for initial testing and commissioning and only by personnel experienced with the PLC software development environment and vacuum systems. This mode may also be used after commissioning in the event EPICS is not running and only when an urgent vacuum system problem must be diagnosed.

LCLS has decided to standardize on the Allen-Bradley ControlLogix family of PLCs and associated hardware and software. This will utilize the experience and software that SNS has developed with the ControlLogix PLCs in the EPICS environment. Allen-Bradley provides a large software development environment (i.e. RSLogix, RSNetWorx, RSLinx) that runs under Windows and is used to configure and program the ControlLogix PLC. A block diagram of the XVTS is shown in Figure 5.2.

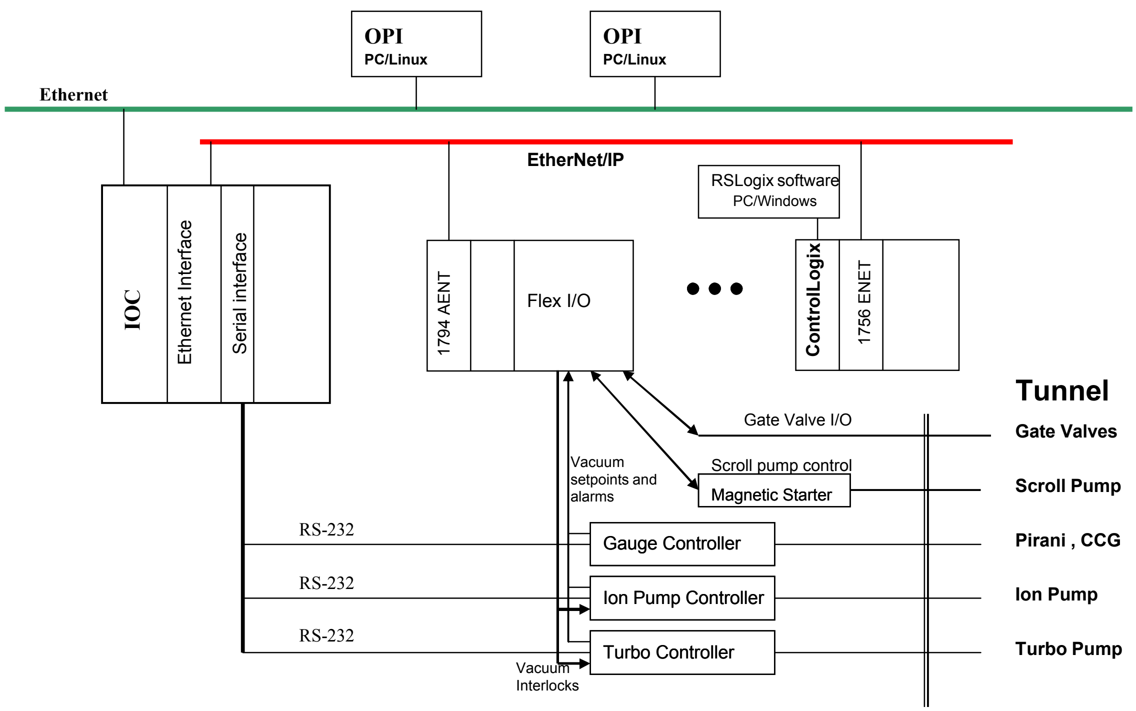


Figure 5.2. Block diagram of the vacuum control system

The XVTS will use the Allen-Bradley modular distributed I/O system known as Flex I/O. Flex I/O consists of a family of I/O modules with each module having its own terminal strip and communications backplane. The I/O modules can be mounted on DIN rails in a local rack or cabinet.

A network module using the Ethernet Industrial Protocol (EtherNet/IP) is then added to the DIN rail and connected to the I/O modules' communication backplane, allowing the I/O modules to communicate their data to the PLC via EtherNet/IP. Flex I/O requires only local wiring to the devices, eliminating long and complex wiring runs back to the PLC.

There will be two types of external vacuum interlocks. General-purpose interlocks will be provided by the PLC via a Flex I/O digital output module and will be used for such things as beam permit and interlocks for isolation gate valves between sections controlled by a different PLC. Software interlocks will be generated by the PLC and are essentially the same as general purpose interlocks and will be mostly used to display the status of the system.

There may also be special interlocks that use the fast analog output from a gauge controller. MKS gauge controllers can provide the analog signal of the gauge directly from their electrometers. The average delay of the signal is approximately 15 milliseconds. The analog signal can be sent to a fast analog to digital converter on the IOC. Once in the IOC, the threshold for this fast interlock is programmable from EPICs. The interlock is then available for the fast protect system for such things as the fast acting valves and beam dumps.

5.3 Instrumentation

Although vacuum pressure can be derived from ion pump current, there is a need to measure vacuum pressure before the ion pumps are started. An ion pump requires a moderately high vacuum condition to be established by the turbo pump before it can be started. The better the vacuum, the longer the life of the ion pump. Another reason for using an ion gauge rather than relying solely on an ion pump's current to determine the vacuum pressure is that any leakage current in the pump, cable or connector will cause the ion pump controller to give a false pressure reading.

To provide the most robust control system, an independent ion gauge is required to determine if the turbo has pumped out the XVTS to a sufficient vacuum condition for the ion pumps to be started. The ion gauge will also provide pressure readings and might be able to help diagnose problems if the ion pump controller is giving false readings. The preliminary design calls for three ion gauges per section, for a total of nine ion gauges per beamline.

The ion gauge that has been selected is a MKS Type 422 inverted magnetron cold cathode gauge. The Type 422 is identical to the standard Type 421 cold cathode gauge except that is uses LEMO type connectors which are bakeable to 250 C and are radiation resistant.

At least one convection enhanced pirani gauge will be used on each section of the beamline. A convection enhanced pirani is used to measure pressure from atmosphere down to the milliTorr range. The convection enhanced pirani gauge will be useful to monitor the vacuum system during pumpdown from atmosphere. The convection enhanced pirani gauge was selected because it is more accurate at the higher pressures than a thermocouple gauge or a basic pirani gauge since it has a temperature compensated heat sensor and can measure convection current. The gauge that has been selected is the MKS Type 317.

A residual gas analyzer (RGA) will be available to measure the partial pressure of gas species in the vacuum system. This is an important diagnostic tool for high vacuum systems and the preliminary design calls for one RGA in each of the beamlines. A quadrupole type RGA with an electron multiplier from Leybold-Inficon has been selected. Leybold-Inficon supplies stand-alone software to operate the RGA from a PC running Windows. A set of LabView drivers also exists for this RGA that enables the user to write custom applications.

5.4 Software

One of the primary goals of the vacuum control system software will be full compatibility with the global control system EPICS. The Allen-Bradley ControlLogix PLC has been selected for the vacuum control system. The use of the ControlLogix PLCs will capitalize on the software that was developed for EPICS at SNS. A typical EPICS Control System block diagram is illustrated in Fig. 5.3.

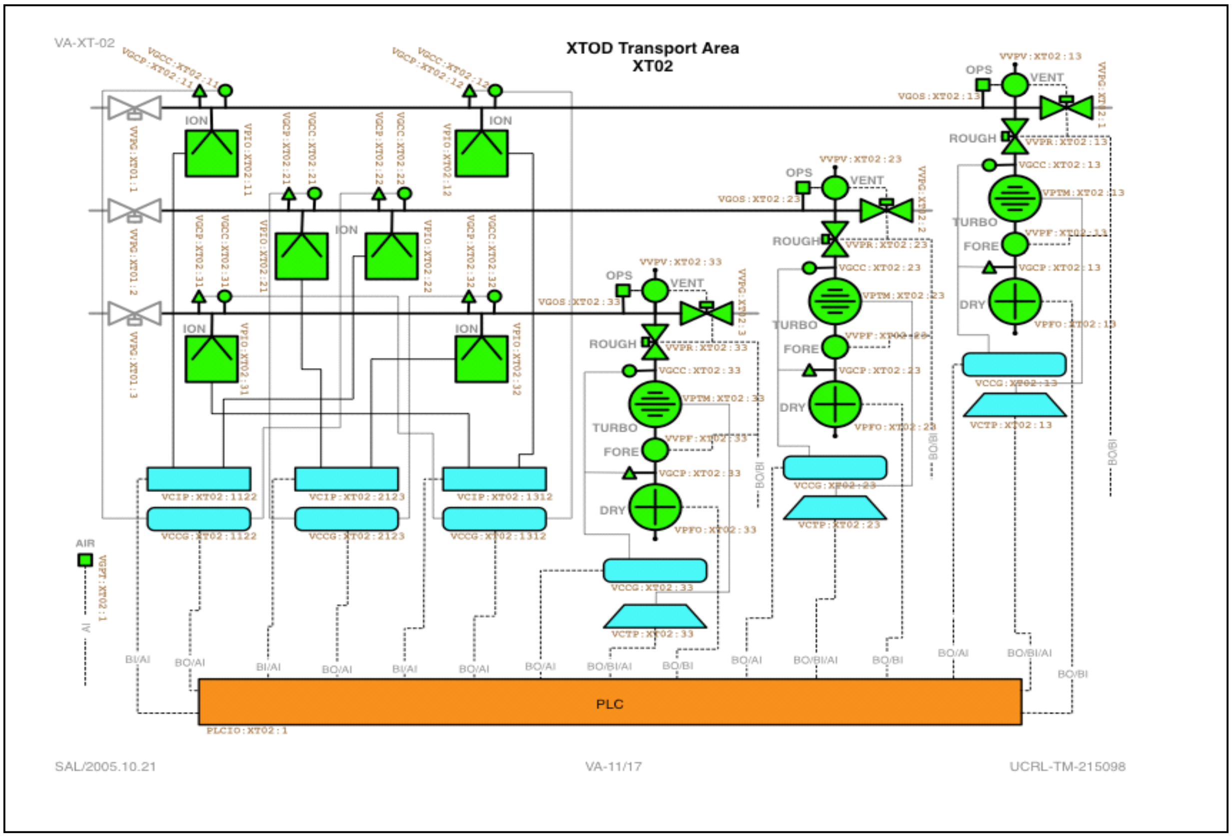


Figure 5.3. EPICS System Block Diagram for XVTS

The vacuum control system will use ladder logic in the PLCs. Ladder logic describes the sequence of switch closures, interlocks and process control setpoints that have to be executed in order to energize a valve or start a vacuum pump. The start up and operation of any vacuum system will in general have the same basic sequence of switch closures, interlocks and setpoints and therefore the ladder logic can become part of a toolkit of software that can be re-used.

The ladder logic is solved in a specific sequential order and coils from one function are used as interlocks in the next function. The ladder logic structure is in essence, a flow chart. For example, to open the a foreline valve to a turbo pump, the scroll pump backing the turbo must have been started in the previous function and must be currently running. If the scroll pump were to experience a thermal overload and shut down the foreline valve be forced to close too.

For example, there will be five basic steps that must be executed in the proper order to bring the vacuum system up to high vacuum. They are:

1. Start the scroll pump
2. Open the foreline valve to the turbo
3. If conditions permit, open the gate valve to the beamline and start roughing down the beamline
4. If conditions permit, start the turbo
5. Once the turbo is up to speed, and the beamline is at sufficient vacuum, start the ion pumps

These basic steps are examples from operational ladder logic software on the SNS vacuum system and with modifications can be used to operate the LCLS XVTS vacuum system.

5.5 Failure Mode Analysis

An analysis of possible failure modes in the vacuum system are show in the tables 5.1 and 5.2. Table 5.1 shows various failure modes, an empirical (i.e. low, med, high) probability of each failure, common symptoms of each failure and how the vacuum control system would react for the protection of the vacuum system. Table 5.2 is a very similar table but its focus is on vacuum system failure modes and the risk to personnel safety.

Note that only a single point of failure is considered in this analysis. An analysis using multiple simultaneous failures is generally only used for critical life support systems and does not apply here. Also, note that a statistical analysis of failure modes was not performed in the preliminary design. A statistical analysis will only be performed in the final design if all other subsystems completed a statistical analysis and then integrated into an overall analysis on the complete system.

Table 5.1 Failure Analysis and Control System Response for Machine Protection

System	Failure or Condition	Probability	Symptom	PLC Response/Interlock
Scroll and Turbo Pumps	Scroll pump head failure	Low/med - failures are usually due to lack of periodic maintenance (every 10,000 hours)	Low base pressure Low pump speed	Vacuum gauge monitoring foreline pressure PLC interlock will shutdown scroll pump PLC interlock will shutdown turbo PLC interlock will close turbo gate valve PLC sends scroll pump fault message to EPICS
	Scroll pump motor failure	Low - motor bearing or winding failure uncommon	High motor current or windings open or short	Motor control circuit (or circuit breaker) will shutdown the scroll pump and send fault signal to PLC PLC interlock will shutdown turbo PLC interlock will close turbo gate valve PLC sends scroll pump fault message to EPICS
	Scroll pump gas load too high	Low/med - vacuum system leak or contamination	High motor current	System will not pump down, PLC will timeout, stop pump, send timeout message to EPICS Scroll pump will overheat, motor control circuit will shutdown the scroll pump and send fault signal to PLC PLC interlock will shutdown turbo PLC interlock will close turbo gate valve to protect scroll pump PLC sends scroll pump fault message to EPICS
	Turbo pump bearing failure	Low - modern ceramic bearings are very reliable	High motor temp High motor current	Turbo controller will provide safe shutdown and send fault signal to PLC PLC interlock will close turbo gate valve PLC sends turbo fault message to EPICS
	Turbo rotor crash	Low - Unless turbo ingests foreign object or is subject to multiple atmospheric vents while operating at full speed	Sudden drop in RPMs	Turbo controller will shutdown pump and send fault signal to PLC PLC interlock will close turbo gate valve PLC sends turbo fault message to EPICS
	Turbo gas load too high	Low/med – vacuum system leak or contamination	High motor current High motor temp Low RPMs	Turbo controller will provide safe shutdown and send fault signal to PLC PLC interlock will close turbo gate valve to protect turbo PLC sends turbo fault message to EPICS

System	Failure or Condition	Probability	Symptom	PLC Response/Interlock
Ion Pump	Insulator high leakage current or shorted by sputtered titanium	Low - insulator is shielded	High pump current	Ion pump controller will shut down pump and indicate a fault. PLC sends ion pump fault message to global control. Single ion pump failure does not cause immediate shutdown in beam. Ion gauges monitor pressure. If pressure rises too high, PLC interlock will send pressure fault message to EPICS.
	Anode to cathode short	Low -large amounts of conductive/ magnetic particles would be needed to cause short	High pump current or short circuit	Same as above
	High voltage feed through Failure	Low/med - usually results from physical damage	No pump current	Same as above
	High voltage cable failure open circuit	Low/med - usually results from physical damage	No pump current	Same as above
	High voltage cable failure short circuit	Low/med - usually results from physical damage	High pump current	Same as above
	Pressure too high	Med – Turbo has not pumped out beam line to a sufficient vacuum	Pressure too high to start ion pumps	Ion gauges monitor pressure. If pressure is too high, PLC interlock will prevent ion pumps from being turned on. Beam permit interlock from PLC will not be set.
	Pressure initially good, then rises above set point	Low/Med - high gas load created by beam or mechanical failure (a leak is created), ion pumps cannot overcome	Pressure too high	Ion gauges monitor pressure. If pressure climbs too high, PLC interlock will shutdown ion pumps. PLC interlock will send pressure fault message to EPICS.
	Ion pump end-of-life	Low - over 60,000 hours of operation - cathode sputtered through	Low base pressure Pump instability	Ion gauges monitor pressure. If pressure climbs too high or pressure burst, PLC interlock will shutdown ion pumps. PLC interlock will send pressure fault message to global control.

System | Failure or Condition | Probability | Symptom | PLC Response/Interlock

Isolation Valves	Opening Isolation Valve between sections	Normal operation	Cannot open Section Isolation Valves due to large difference in pressure between tanks or modules	Vacuum gauges monitoring the pressure in an upstream section indicates low vacuum. PLC interlock to downstream section will not allow downstream interlock to open valve.
	Isolation valve between sections is open, then a large pressure difference develops	Low/med - higher pressure or a burst of gas could develop in a section due to pump failure, physical damage	Isolation Valve closes	Vacuum gauges detect a rise in pressure to an unacceptable level in a section. PLC will close its Isolation Valve and send low vacuum interlock to interlock controlling downstream tank or module. Downstream logic will close its valve and send valve closed message to EPICS.

Table 5.2 Failure Analysis and Control System Response for Personnel Protection

System	Symptom	Failure or Condition	Risk to Personnel	Response/Control
Scroll Pump	High motor current	Very high gas loads for extended periods	Motor temp could become hot enough to melt conductor insulation and cause electrical fire	Properly sized and installed UL listed thermal overloads in accordance with the NEC will trip magnetic starter circuit off. PLC will indicate pump has stopped via auxiliary contact on magnetic starter.
	High motor current	Locked rotor due to bearing failure or pump head failure	Motor temp could become hot enough to melt conductor insulation and cause electrical fire	Properly sized and installed UL listed thermal overloads in accordance with the NEC will trip magnetic starter circuit off. PLC will indicate pump has stopped via auxiliary contact on magnetic starter.
	Motor short circuit	Short circuit due to wire or motor damage or improper wiring	Electric shock	Proper grounding. Properly sized circuit breaker will trip. Installation and inspection by qualified personnel. Lock out Tag out procedure must be followed if diagnosing wiring problem.
	Motor open circuit	Open circuit due to wire or motor damage or improper wiring	Electric shock	Installation and inspection by qualified personnel. Lock out Tag out procedure must be followed if diagnosing wiring problem.
	Oxygen deficient atmosphere	Pumping very large quantities of nitrogen or argon	Suffocation	**A concern for confined space such as LCLS tunnel environment. Pump exhaust should be properly vented. Oxygen monitoring is required.**

System	Symptom	Failure or Condition	Risk to Personnel	Response/Control
Turbo Pump	High pump current	Very high gas loads	Pump temp could become hot enough to melt conductor insulation and cause electrical fire	Pump controller will shut down pump and indicate a fault. Also, ion gauge setpoint would be used as an interlock in the PLC and disable pump operation if pressure is too high. PLC sends pump fault or overpressure message to global control.
	High pump temperature	Very high gas load for extended periods or bearing failure	Pump temp could become hot enough to melt conductor insulation and cause electrical fire	Pump controller will shut down pump and indicate a fault. Also, ion gauge setpoint would be used as an interlock in the PLC and disable pump operation if pressure is too high. PLC sends pump fault or overpressure message to global control.
	Pump short circuit	Short circuit due to cable or motor damage	Electric shock	Pump controller will shut down voltage and indicate a fault. PLC sends pump fault message.
	Pump open circuit	Open circuit due to wire or motor damage	Electric shock	Pump controller will shut down voltage and indicate a fault. PLC sends pump fault message.
	Pump controller fault	Internal circuit failure or damage	Electric shock	Proper fusing and grounding. GFI if necessary.
	Pump connector damage	Connector physically damaged	Electric shock	Visually inspect connector for signs of damage before connecting cable. If damage is suspected, hi-pot by qualified personnel following procedures consistent with tunnel environment.

System	Symptom	Failure or Condition	Risk to Personnel	Response/Control
Ion Pump	High pump current	High gas load	Pump temp could become hot enough to cause burns or ignite flammable materials	Ion pump controller will shut down pump and indicate a fault. Also, ion gauge setpoint would be used as an interlock in the PLC and disable ion pump controller output. PLC sends ion pump fault or overpressure message to EPICS.
	High pump current with controller in start mode	High gas load	Pump temp could become hot enough to cause burns or ignite flammable materials	Ion pump controller will timeout if current stays high. Controller will attempt to re-start three times and then shut down pump and indicate a fault. If a turbo pump is permanently mounted in section, PLC interlocks will prevent ion pump enable at high pressure
	High voltage present on cable after being removed from pump	High voltage connector	Electric shock	Administrative controls – never assume cable is safe, always verify that no voltage is present. Lock out Tag out procedure for ion pump controller
	High voltage cable damaged	High voltage cable failure open circuit	Electric shock	Cable may be damaged, never assume cable is safe, always verify
	High voltage cable damaged	High voltage cable failure short circuit	Electric shock	Ion pump controller will shutdown voltage due to overcurrent, unless shorted to ungrounded surface. Proper cable tray, conduit and rack design will insure there are no ungrounded surfaces. If damage is suspected, hi-pot by qualified personnel following procedures consistent with tunnel environment.
	High voltage connector damage	Connector physically damaged	Electric shock	Visually inspect connector for signs of damage before connecting cable. If damage is suspected, hi-pot by qualified personnel following procedures consistent with tunnel environment.
	Ion pump controller fault	Internal circuit failure	Electric shock	Proper fusing and grounding. GFI if necessary.

System	Symptom	Failure or Condition	Risk to Personnel	Response/Control
Ion Gauge	High voltage present on cable after being removed from gauge	Connector is not interlocked	Electric shock	Administrative controls – never assume cable is safe, always verify that no voltage is present. Lock out Tag out procedure
	High voltage cable damaged	High voltage cable failure open circuit	Electric shock	Administrative controls – never assume cable is safe, always verify that no voltage is present. Hi-pot cable if necessary. Lock out Tag out procedure
	High voltage cable damaged	High voltage cable failure short circuit	Electric shock	Gauge controller will shutdown voltage due to overcurrent, unless shorted to ungrounded surface. Proper cable tray, conduit and rack design will insure there are no ungrounded surfaces. Hi-pot cable if damage is suspected
	Gauge controller fault	Internal circuit failure	Electric shock	Proper fusing and grounding. GFI if necessary
	High voltage connector damage	Connector physically damaged	Electric shock	Visually inspect connector for signs of damage before connecting cable. If damage is suspected, hi-pot by qualified personnel following procedures consistent with tunnel environment.

6 Environmental, Safety, and Health

6.1 Design Details

XVTS components will be designed at LLNL based on calculations and operation of prototype beam sections. During this process, the vacuum system design will be continually evaluated for safety in every phase of LCLS work, including design, transportation, installation, testing, operation, and maintenance. The following is a brief description of design safety considerations in the LLNL Integration Worksheet LCLS X-Ray Tunnel Vacuum Transport System:

1. Seismic stability of the vacuum system will be documented in a formal, peer-reviewed engineering document, and designed based on Specification for Seismic Design of Buildings, Structures, Equipment and Systems at the Stanford Linear Accelerator Center. SLAC-1-720-0A24E-002.
2. Electrical system components will be NRTL listed or equivalent, as determined by the LLNL AHJ testing and certification program, and will meet the requirements of the SLAC EEIP program. Procedures will be written to establish safe methods for de-energizing, installing, testing, and maintaining (including effective lock-out tag-out capability) ion pumps and their power supplies and cabling.
3. Construction, Lifting and Industrial Hazards: A as part of the design process, LLNL will consider how components can be delivered and installed into LCLS.
4. The potential for creating oxygen deficient atmospheres will be considered
5. Fire Hazard: Equipment will be designed to limit the amount of combustibles in the underground areas, and to avoid interference with the tunnel fire suppression system. Cables and other potentially combustible materials will meet LCLS fire prevention requirements.
6. As a backup to proper design and operating procedures, gas and vacuum system components will be protected from overpressure by relief valves.
7. The planned arrangement of equipment will take into consideration the need for emergency egress, and the need to access critical equipment or operating stations (crash buttons etc.).
8. The effects of radiation on personnel and equipment will be evaluated for normal, emergency, and maintenance operations.
9. LLNL will anticipate quantities of hazardous materials and pollutants that will be part of, or used by, LCLS components. This will allow implementation of industrial hygiene controls and proper documentation of environmental regulatory compliance.

6.2 ES&H Policy

All work will be done in accordance with LLNL ES&H policies. These policies are addressed in the LLNL "Health and Safety Manual" and the "Environmental Protection Handbook". Furthermore, LLNL ES&H policies implement U.S. Department of Energy orders to comply with all local, state, and federal regulations. These policies are carried out in accordance with LLNL's Integrated Safety Management program using and Integrated

Worksheet. Furthermore, all work performed by LLNL employees at SLAC will be in accordance with SLAC safety rules, and all LLNL safety documentation for LCLS will be written with the goal of meeting SLAC documentation requirements.

LLNL IWS #12920 "LCLS X-Ray Tunnel Vacuum Transport System" follows the five steps of the LLNL Integrated Safety Management Program:

1. Define the scope of work: LLNL LCLS management has written a detailed description of the design, fabrication, installation, operation, maintenance, and servicing of the X-Ray Vacuum Transport System (XVTS). The scope of work additionally identifies the individuals assigned to the activity, where each task will be performed, the source of funding, the authorization chain, and required reviewers.
2. Analyze the Hazards: The IWS Responsible Individual (RI), the workers listed on the IWS roster, and the LLNL ES&H Team reviews the proposed work to identify potential safety, regulatory, and environmental hazards. Each hazard is separately described in the IWS
3. Develop/Implement Controls: The RI, workers, and ES&H disciplines (industrial safety engineer, a fire protection engineer, health physicist, industrial hygienist) work together to determine and document how each of the hazards identified in step 2 can be mitigated. For the XVTS, this includes the standards that must be complied with to ensure adequate seismic design, electrical codes and LCLS wiring standards, procedures for installing and testing ion pumps, calculations to determine if inert gas use could cause an asphyxiation hazard, etc.
4. Perform the Work: Once each ES&H discipline, the ES&H team leader, the RI and the authorizing individual signify their approval (by changing their light on the IWS from red to green) that all hazards have been identified and addressed, work is allowed to proceed under the conditions of the IWS.
5. Feedback and improve: The process of designing, fabricating, transporting, installing, testing, operating, and maintaining LCLS vacuum system components will change significantly over the next four years. Initially the IWS will call for generalized controls such as procedures that will have to be written, or hazards that will have to be analyzed before certain actions can be performed. As new information becomes available, or when changes are made to the design or procedures, the IWS is updated by the RI, causing an automatic e-mail message to be sent to all LLNL LCLS workers and managers, describing the details of the change. It is expected that the IWS will change daily during some periods, and weekly in others. Major changes that affect safety will be reviewed by the ES&H Team and LLNL LCLS management (major changed to an IWS cause the reviewer's electronic lights to change from green to yellow, signifying that they must re-review the hazards and controls). Minor changes such as clarification, changes to the personnel roster, and other details that do not have a significant safety impact can be performed by the RI made additional review. This allows the RI to continually adjust the IWS to incorporate the best available information.

6.3 Design Details & Potential Hazards

During certain maintenance operations, some or all of the sections of the XVTS vacuum system may be purged with a positive pressure of dry N_2 gas to prevent contamination from the atmosphere from reaching the interior surfaces of the vacuum system. LLNL is responsible for the pressure safety of the XVTS system. Each section will have a valve to vent the system to atmosphere pressure. It is recommended that clean, dry nitrogen be used to vent the system and to continuously purge the system while it is open so that the interior surfaces of the vacuum remain as clean and moisture free as possible. A low pressure regulator is required to prevent overpressurization of the system. Burst discs of the proper relief pressure will be installed on all sections in the event of overpressurization. Since nitrogen displaces oxygen, the facility will have to determine if a confined space exists and provide the appropriate controls for such a hazard. Other than the pressure safety of the vacuum vessels, the operation of a vacuum system poses few hazards. The obvious hazards are generally associated with the operation of the vacuum pumps and electromechanical equipment such as valves.

The ion pumps selected for the XVTS vacuum system requires up to 7000 VDC. The ion pump controller that has been selected for the XVTS vacuum system is the Gamma Digitel Multiple Pump Controller (MPC). The ion pump controller can provide up to 100 mA in a short circuit, but the ion pumps are generally operated in the micro-amp range. The high voltage connector on the back of the MPC is a Kings 10kV SHV.

The connector on the ion pump will either be a Varian StarCell type connector or a Gamma Safe Conn type connector. The type of connector is to be selected by the LCLS.

The ion pump controller will be mounted in an equipment rack that has a lockable rear panel to prevent unauthorized or accidental removal of the high voltage cable from the rear panel connector on the ion pump controller. High voltage safety will require proper administrative control of these keys.

The turbomolecular pump controller outputs a 56 VAC, 3 phase, 700 Hz signal to the pump. The turbomolecular pump controller can detect an open circuit and will not output a voltage under such a condition. There is also over current protection that will also shut down the output voltage if the operating current of the pump is abnormally high or in the event of a short circuit.

The scroll pump operates on 120 VAC, single phase, 60 Hz and will be controlled by a Nationally Recognized Testing Laboratory approved motor control circuit with thermal overload protection.

The vacuum valves will be electropneumatic and require compressed air up to 125 psi. The 125 psi compressed air system will comply with Chapter 32 of the LLNL "Health and Safety Manual", "Pressure Safety", which is in accordance with all applicable ASME and DOT codes and regulations. Failure in the compressed air lines are usually the result of a damaged hose or improperly installed pneumatic fitting. Hoses and fittings of the proper rating should be inspected after installation and also periodically afterwards. The solenoids on the electropneumatic valves will be 24 VDC, which is classified as low voltage.

The vacuum valves will be normally closed valves, so that in the event of a power failure, the valves will close and isolate the vacuum if the compressed air system has an adequate reservoir.

7 Procurement / Fabrication Plan

7.1 Hardware Costs/Procurement Plan

All components recommended in this preliminary design are standard catalog items that do not require any development. Cost estimates were made for purchasing all hardware required for the complete vacuum system. Also not included are the spare parts. Suggested vendors are for reference only. Similar components by other manufacturers will be considered in the final design. The summary is listed in Table 7.1.Estimated procurement costs (Bill of Materials) for the XVTS vacuum system is listed in Table 7.2, 7.3 and 7.4.

System	Estimated Procurement Costs (k$)
Vacuum Component	440
Transport Hardware	200
Stand	577
Total	**1217**

Table 7.1. XVTS Hardware Cost Estimate

In the Final Design phase, procurement documents including the detailed performance specification for all components will be prepared. These items will be sent out for bid to DOE/LLNL specified vendors and purchased by the LLNL procurement department. They will be subject to Final/Approved Detail Drawings and LLNL Mechanical Engineering Department Specifications. Established LLNL ISM and Quality Assurance Procedures will be followed. All selected materials will meet ASTM specifications and/or LLNL approval.

System Description	Unit Costs	Quantity	Costs
Flexible Support	$1,898	216	$409,968
In-Line Stand	$3,753	24	$90,072
Off-set Stand	$4,685	15	$70,275
Misc.			$6,567
Total			**$576,882**

Table 7.2. XVTS Stand System – Cost Estimates

7.2 Fabrication and Testing Plan

Fabrication, preliminary assembly and testing of the vacuum pumping components are planned to take place at the LLNL Vacuum Sciences and Engineering Lab (Fig. 7.1 and 7.2). The facility provides ample room for complete module system assembly and testing. There is a wide variety of hardware and software in the LLNL Vacuum Sciences and Engineering Lab that will be available for recording experimental data. All technical staff will receive required vacuum technical training as specified by all LLNL LCLS IWS's.

LCLS XVTS Procurement Cost Estimate-Vacuum Components					
Gamma Ion Pumps, VAT series 48 in beam line, VAT series 10 above turbos					
(Note: the cost of spares is not included in this cost estimate.)					
Vendor	**Description**	**Part number**	**Unit cost**	**Quantity**	**Cost**
Gamma	Ion pump, 100 L/S w/ TiTan elements (80 L/S)	100L-30-6S-SC-110-N	$3,028.00	18	$54,504.00
Gamma	Cable, 10 kV, Safeconn connector, 30 m	380053	$535.00	18	$9,630.00
Gamma	Digitel MPC ion pump power supply	MPC-2-110-232-HVE-N	$3,400.00	9	$30,600.00
		100-POS-7KV-K1			
Varian	TriScroll 300 single phase motor, US cord	PTS03001UNIV	$5,600.00	9	$50,400.00
Varian	Vacuum pump isolation valve	VPI251205060	$645.00	9	$5,805.00
Varian	Turbo V70LP Pump 4.5" CFF	9699366	$4,155.00	9	$37,395.00
Varian	Turbo V70LP Controller, 120vac	9699505	$1,759.00	9	$15,831.00
Varian	Vent Valve, for standard rack controller	9699843	$665.00	9	$5,985.00
Varian	Air cooling kit (V70LP)	9699310	$245.00	9	$2,205.00
Varian	Inlet screen DN63	9699300	$65.00	9	$585.00
MKS	Series 937 Vacuum gauge controller	937A-120V-60-TR-CC-CC-CT	$1,688.00	18	$30,384.00
MKS	RS-232 Plug in controller board	100009183	$235.00	18	$4,230.00
MKS	Type 422 cold cathode sensor	104220006	$625.00	27	$16,875.00
MKS	Cold cathode cable, 100 ft	100006174	$280.00	27	$7,560.00
MKS	Convection Pirani Sensor, 2.75" CFF	103170024SH	$195.00	18	$3,510.00
MKS	Convection Pirani Sensor cable, 50 ft	103170008SH	$100.00	18	$1,800.00
VAT	Series 10 viton seal gate valve, 24vdc, 4.5" CFF	10836-UE44	$2,030.00	9	$18,270.00
VAT	Series 48 all metal gate valve, 24vdc, 6" CFF	48240-CE74 (Metric Threads)	$9,840.00	12	$118,080.00
Leybold Inficon	Transpector 2 RGA, C100M	TSP2-0211100000	$7,905.00	3	$23,715.00
Total					**$437,364.00**

Fig. 7.3. Bill of Materials for XVTS Vacuum Components

Description	Vendor	Part Number	Cost Per Unit	Units Required	Total Cost
Beam Tube, 4" OD X .083 W X 120" LG, 6" CF Flange	Nor-Cal Products	2N-400-120	$610.00	72	$43,920.00
Beam Tube, 4" OD X .083 W X 7" LG, 6" CF Flange	Nor-Cal Products	2N-400-7	$225.00	7	$1,575.00
6" CF Flange OFHC Copper Gasket (10/pkg)	Nor-Cal Products	G-600	$3.50	117	$409.50
4.5" CF Flange OFHC Copper Gasket (10/pkg)	Nor-Cal Products	G450	$2.50	3	$7.50
2.75" CF Flange OFHC Copper Gasket (10/pkg)	Nor-Cal Products	G-275	$1.70	21	$35.70
1.33" CF Flange OFHC Copper Gasket (10/pkg)	Nor-Cal Products	G-133	$1.30	3	$3.90
6" CF Flange Bolt Set (25/pkg)	Nor-Cal Products	B-600-12-SP	$50.00	75	$3,750.00
4.5" CF Flange Bolt Set Tapped (25/pkg)	Nor-Cal Products	B-450T-12-SP	$36.00	1	$36.00
2.75" CF Flange Bolt Set Tapped (25/pkg)	Nor-Cal Products	B-275T-12-SP	$23.00	3	$69.00
2.75" CF Flange Bolt Set (25/pkg)	Nor-Cal Products	B-275-12-SP	$31.00	4	$124.00
1.33" CF Flange Bolt Set (25/pkg)	Nor-Cal Products	B-133-SP	$11.00	1	$11.00
6" CF 4-Way Cross	Nor-Cal Products	4C-400V	$540.00	9	$4,860.00
6" X 4.5" CF Zero Length Flange	Nor-Cal Products	600-450-150Z	$130.00	6	$780.00
6" X 2.75" CF Zero Length Flange	Nor-Cal Products	600-275-150Z	$100.00	9	$900.00
6" CF Flange Flexible Coupling	Nor-Cal Products	2FC-400-4	$450.00	13	$5,850.00
All-Metal Angle Valve Series 54, DN40 with position indicator	VAT	54032-GE02	$510.00	3	$1,530.00
2.75" CF Tee	Nor-Cal Products	3T-150	$83.00	3	$249.00
2.75" X 1.33" CF Reducer Tee	Nor-Cal Products	3TR-150-075	$78.00	3	$234.00
2.75" CF Flange Blank	Nor-Cal Products	275-000N	$14.00	3	$42.00
25 to 16 NW Reducer Nipple	Nor-Cal Products	2NRNW-25-16	$35.00	3	$105.00
16 NW 90 degree Radius Elbow	Nor-Cal Products	2E-NW-16B	$38.00	3	$114.00
25 NW 90 degree Radius Elbow	Nor-Cal Products	2E-NW-25B	$43.00	6	$258.00
25 NW Flex Coupling	Nor-Cal Products	2FC-NW-25-3	$70.00	3	$210.00
25 NW X 9" Long Nipple	Nor-Cal Products	2N-NW-25-9	$48.00	3	$144.00
25 NW X 11" Long Nipple	Nor-Cal Products	2N-NW-25-11	$60.00	3	$180.00
16 NW Center Ring with Viton O-Ring	Nor-Cal Products	NW-16-OR-V	$2.50	6	$15.00
25 NW Center Ring with Viton O-Ring	Nor-Cal Products	NW-25-OR-V	$2.50	24	$60.00
16 NW Clamp	Nor-Cal Products	NW-16-SSC-L	$10.00	6	$60.00
25 NW Clamp	Nor-Cal Products	NW-25-SSC-L	$12.00	24	$288.00
Burst Disk, 1.33" Del Seal Flange	MDC	420030	$210.00	3	$630.00
Estimated Total Cost per Beam Line					**$66,450.60**
Estimated Total Cost for 3 Beam Lines					**$199,351.80**

Fig. 7.4. Bill of Materials for XVTS Beam Transport

Fabrication of all vacuum components must comply with the specifications listed below and their front pages are attached in Appendix A.

1. MEL95-001818-00, “Fabrication and Handling of Components for Ultra-High Vacuum Environment”, Mechanical Engineering Department, LLNL, University of California.
2. ENC-93-910-REV 01, “Cleaning Stainless Steel Alloy Components”, Mechanical Engineering Department, LLNL, University of California.
3. ENC-93-912-REV 01, “Cleaning Copper and Copper Alloy Components”, Mechanical Engineering Department, LLNL, University of California.
4. MEL95-001817-00, "Welding of Stainless Steel components of Ultra-High Vacuum Environment", Mechanical Engineering Department, LLNL, University of California.

Preserving the cleanliness of the components during installation is essential in order to meet the required pressures in a timely manner. It is recommended that the LCLS facility develop a written installation procedure for all vacuum systems for training technical staff.

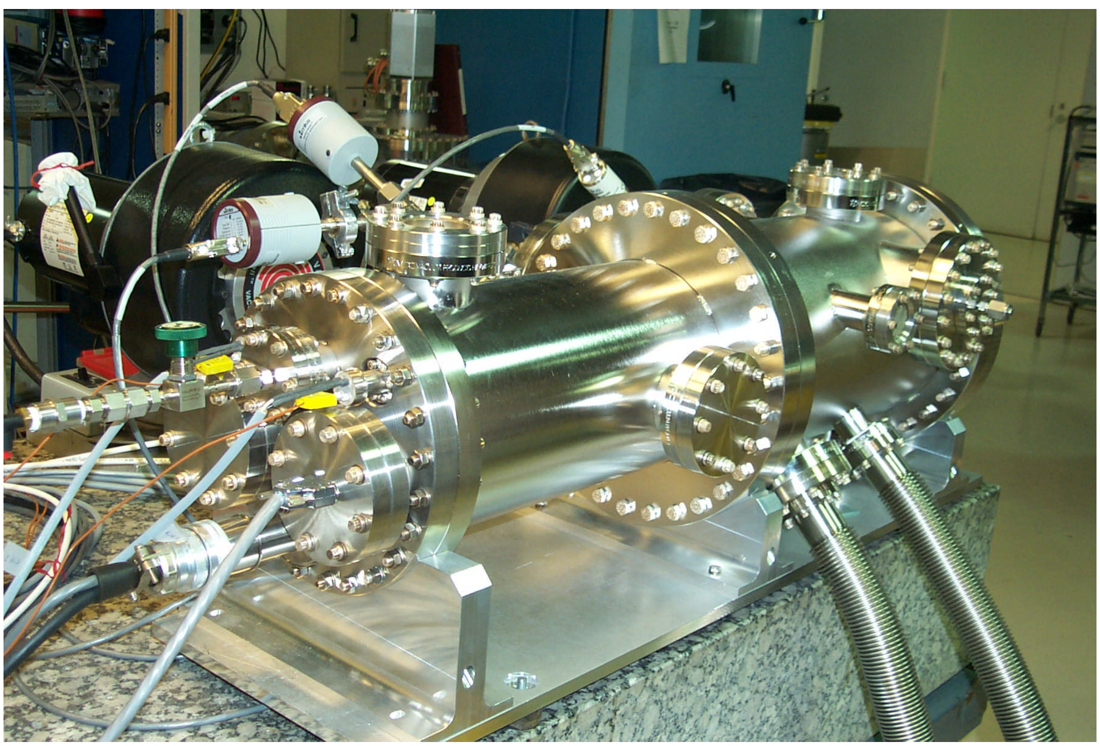


Figure 7.1. LLNL Vacuum Sciences and Engineering Lab View-1

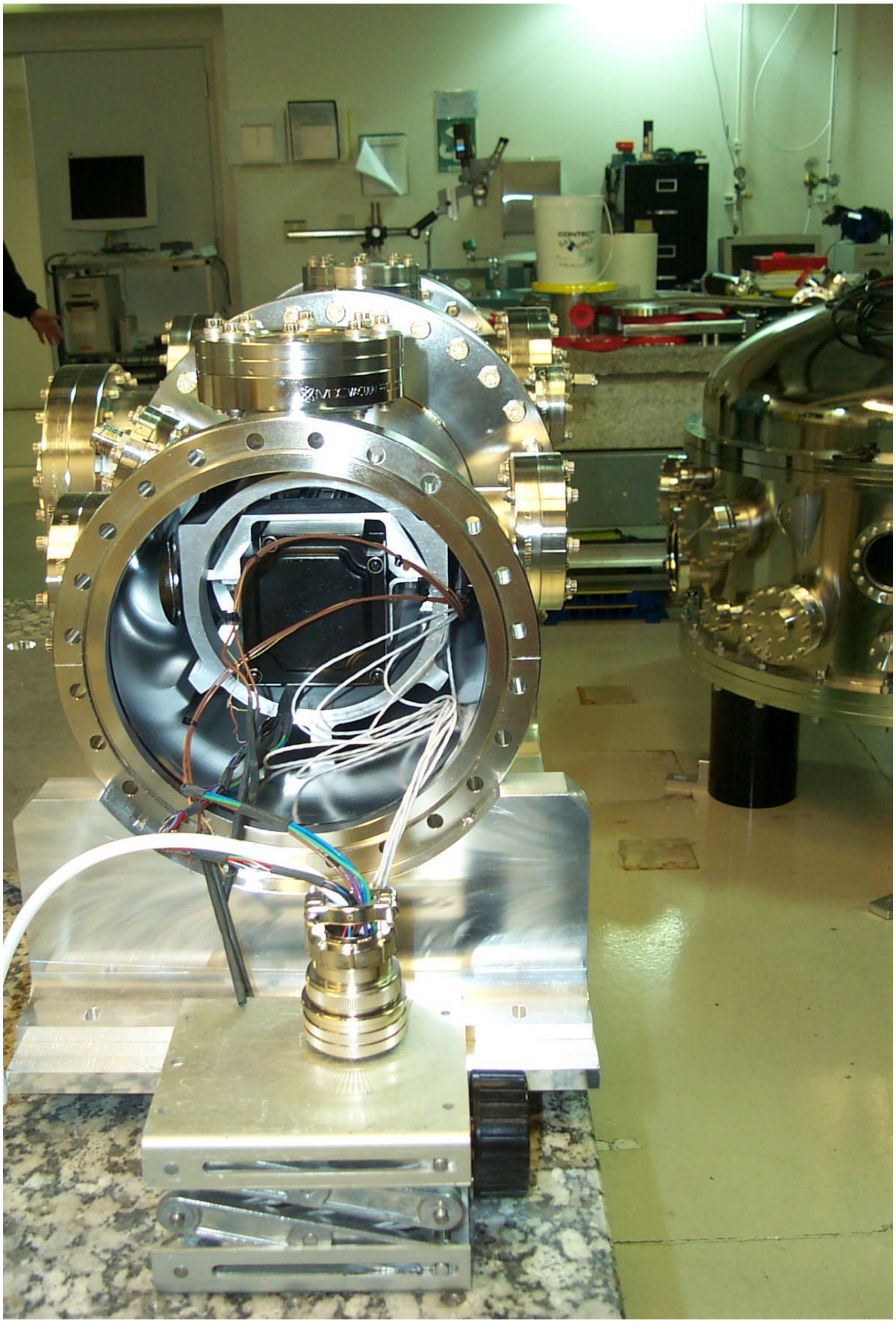


Figure 7.2. LLNL Vacuum Sciences and Engineering Lab View-2

7.3 Prototype Plan

The final design of the XVTS will be prepared based on the operation of a prototype beam sections at LLNL. One subassembly that contains pumping sections and structures (Fig. 7.3) will be fabricated and tested. The PLC and EPICS control software will also be developed and simulated. When completed, assemblies and parts will be shipped from LLNL to SLAC. Most parts of the system such as the pipes and stand components may be used in the actual XVTS.

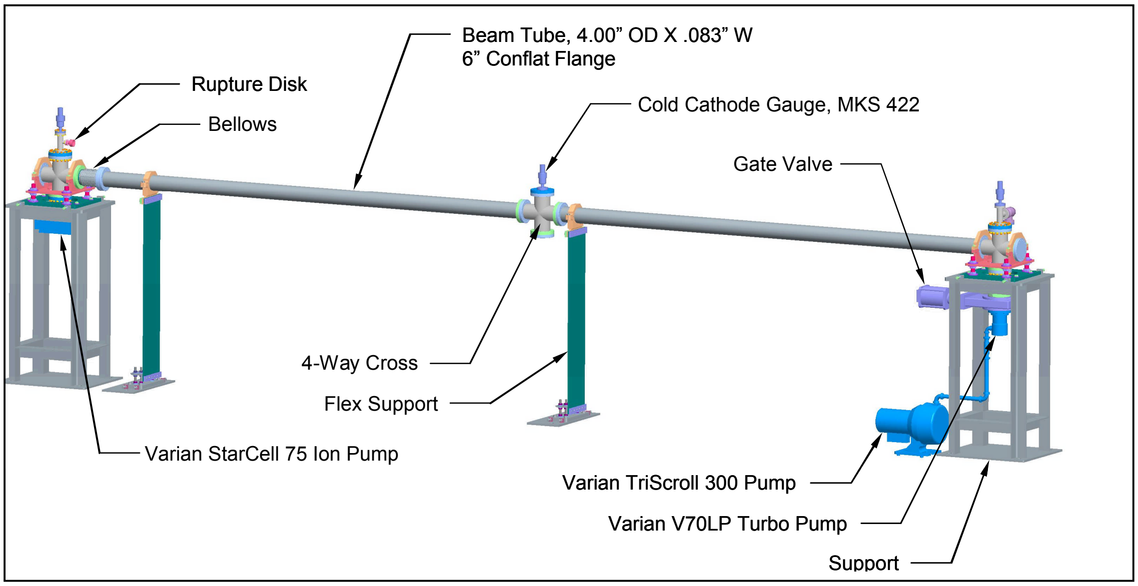


Figure 7.3 XVTS Pump Cross Prototype Configuration

8 Final Design and Project Schedule

The overall schedule for completing the final design, procurement, assembly, testing, and the installation of the XVTS vacuum system is presented in Fig. 8.1 and 8.2. Current schedule meets the following major project milestone:

1. Final Design Review and Package (4/06)
2. Complete Procurement (2/07)
3. Start of Site Installation (10/07)
4. System Commissioning (4/08)

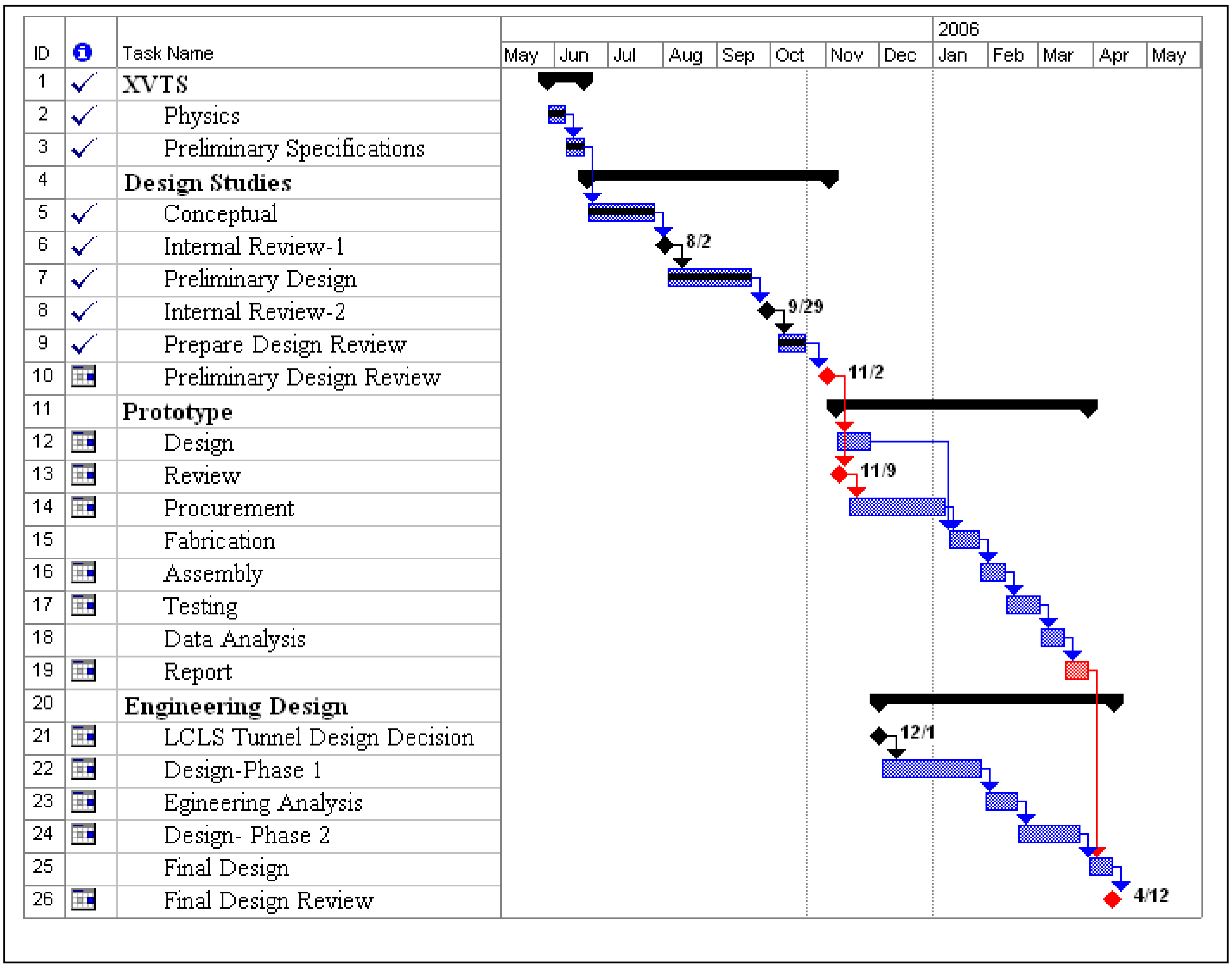


Figure 8.1. Short-Term Schedule (Final Design)

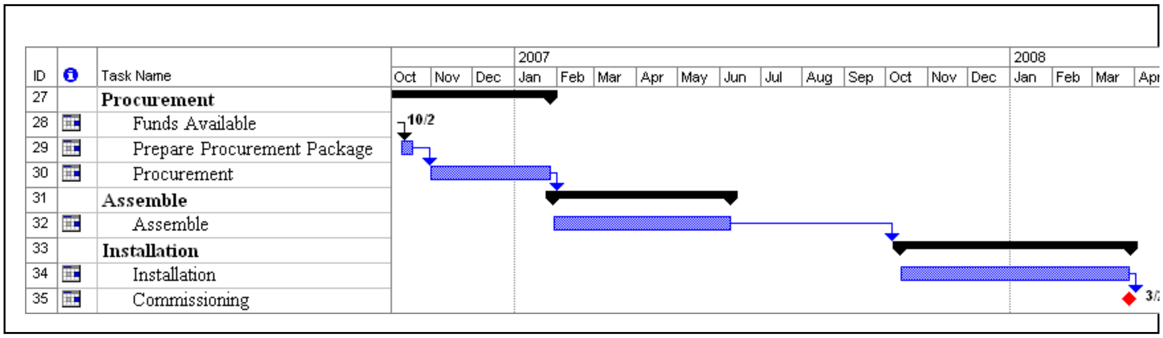


Figure 8.2. Final Phase Project Schedule

9 Summary

The preliminary design of the vacuum pumping system for XVTS is completed. The major subjects presented in this report are:

1. Design of the complete vacuum system.
2. System analysis results.
3. ES&H issues and plan.
4. Project cost estimates and schedule.

All deliverables planned in the preliminary design phase for XVTS vacuum pumping system is presented herein. It is shown that the designed system:

1. Is consistent with the interface requirements of the XVTS system.
2. Is a robust and redundant system capable of providing the required vacuum level for XVTS operation with comfortable margin.
3. Is compliant with ES&H requirements.
4. Can be procured and fabricated with standard catalog items at reasonable costs, and meeting the LCLS schedule.

The conclusion is also presented with respect to the System Requirements in Table 9.1.

ISSUE	PRELIMINARY DESIGN
Operating Pressure	***Sufficiently provided for beam transport***
Mechanical Interface	*Meets the requirements for all operating conditions*
Installation and Operation Plan	*Sufficiently provided*
Control System Interface	*Fully compatible with LCLS EPICS system*
System Costs	*Reasonable procurement costs.* *No component needs development.*
Schedule	*Meeting LCLS project needs*
Safety/Codes	*In full compliance with all ES&H regulations*

TABLE 9.1. XVTS Vacuum Pumping Preliminary Design - Summary.

We are ready to proceed with the Final Design phase of the project.

Appendix A - Ultra-High Vacuum Component Handling Procedures

AAN95-106130-00

MEL95-001817-00

SPECIFICATIONS

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE NATIONAL LABORATORY

MECHANICAL ENGINEERING DEPARTMENT, LIVERMORE

TITLE	WRITTEN BY / DATE
Welding of Stainless Steel Components for Ultra-High Vacuum Environment	Michael R. McDaniel 9/1/95
	APPROVED-SPEC. & STDS.: N/A 12/95
	APPROVED-DIVISION HEAD: Dean P Arthur 9/1/95

1. SCOPE

1.1 Purpose This specification defines the procedures for controlling the quality of material to be used and the welds to be made on stainless steel components subject to Ultra-High Vacuum (UHV) environment for Lawrence Livermore National Laboratory (LLNL). Extreme care is required in the design fabrication and assembly of said components. This specification is applicable to the welding of austenitic, chromium-nickel steels (ASTM 300 series) using gas metal arc welding (GMAW) and/or gas tungsten arc welding (GTAW) processes. This is a general specification and not all sections necessarily apply to all drawings which refer to this specification. Refer to section 5.0 for required documentation for LLNL information and approval.

2. REFERENCE DOCUMENTS

The following documents form a part of this specification to the extent specified herein. Unless otherwise indicated, the issue used shall be the one in effect on the date of request for quotation. Any conflicts between this specification and the referenced documents shall be brought to the attention of LLNL in writing for resolution before any action is taken by the seller.

		CLASSIFICATION
REV. A BY	DATE	

AAN 93-104962-0A

SPECIFICATION **ENC-93-912-REV 01**

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE NATIONAL LABORATORY

MECHANICAL ENGINEERING DEPARTMENT, LIVERMORE

TITLE	WRITTEN BY	DATE
Cleaning Copper and Copper alloys	C.P. Steffani	9-1-1993
	CHECKED BY J. W. Dini	9-1-1993
	APPROVED BY J.C. Whitehead	9-1-1993

SEQUENCE

1. Remove all tape, inks, and other residue using Acetone and a clean cotton rag or paper wiper. Other solvents may be used as long as they are permitted for use in the shop and the requester is aware of the change.

2. Pressure wash using RELEASE D'GREASE @ 10 vol. % and 3-5 KSI setting.
*** FOR FRAGILE PARTS IMMERSE IN ACETONE OR BRULIN 815GD. For components having tubes, blind holes, and passageways cleaning/rinsing agents will be fed into these areas at low pressure.**

3. Spray water rinse.

4. Immerse in ENTHONE NS-35 non-silicated cleaner (30 gm/L @ 65 C) for a minimum of 10 minutes.

5. Spray water rinse until all traces of cleaner are removed. If water breaks are present repeat step 4.

6. Descale in 50 % vol. HCL.

7. Spray water rinse.

8. Acid dip in ENTHONE ACTANE 97 (10 gm/L "A", 12 gm/L "B" @ 25 C) until surface is clean and bright.

SPECIFICATION

ENC-93-910-REV 01

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE NATIONAL LABORATORY

MECHANICAL ENGINEERING DEPARTMENT, LIVERMORE

TITLE		DATE
Cleaning Stainless Steel Alloy Components	WRITTEN BY C.P. Steffani	9-1-1993
	CHECKED BY J. W. Dini	9-1-1993
	APPROVED BY J.C. Whitehead	9-1-1993

SEQUENCE

1. Remove all tape, inks, and other residue using Acetone and a clean cotton rag or paper wiper. Other solvents may be used as long as they are permitted for use in the shop and the requester is aware of the change.

2. Pressure wash* using RELEASE D'GREASE @ 10 vol. % and 3-5 KSI setting.
*** FOR FRAGILE PARTS IMMERSE IN ACETONE OR BRULIN 815GD. For components having tubes, blind holes, and passageways cleaning/rinsing agents will be fed into these areas at low pressure.**

3. Immerse in ENTHONE NS-35 non-silicated cleaner (30 gm/L @ 65 C) for a minimum of 10 minutes.

4. Spray water rinse until all traces of cleaner are removed. If water breaks are present repeat step 2.

5. Acid pickle (50 % vol. HNO_3 = 5 % vol. HF @ 25C) for:
   A. 10 minutes or until all mill scale is removed.
   B. 30 seconds to remove all traces of alkaline film.

6. Spray water rinse. All but welds and blind holes should be given special attention to remove all traces of trapped chemicals. The air water aspirator can be used to help rinse these hard places. Ultrasonic rinsing in DI water can also remove trapped material.

7. Cold water rinse. ($2x10^6$ ohm resistivity). Resistivity is monitored and maintained by automatic additions of fresh DI water.

AAN95-106131-00

MEL95-001818-00

SPECIFICATIONS

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE NATIONAL LABORATORY

TITLE	WRITTEN BY	DATE
Fabrication and Handling of Components for Ultra-High Vacuum Environment	Michael R. McDaniel	9/1/95
	APPROVED-SPEC. & STDS. N/A	12/95
	APPROVED-DIVISION HEAD [signature]	9/1/95

1. SCOPE

1.1 Purpose This specification defines the procedures for controlling the cleaning and handling of material and components subject to Ultra-High Vacuum (UHV) environment for Lawrence Livermore National Laboratory (LLNL). Extreme care is required in obtaining clean components that will not produce contamination at the end use machine. This specification will cover machining and cleaning techniques required before, during and after fabrication of said components. This is a general specification and not all sections necessarily apply to all drawings which refer to this specification. Refer to section 5.0 for required documentation for LLNL information and approval.

2. REFERENCE DOCUMENTS

The following documents form a part of this specification to the extent specified herein. Unless otherwise indicated, the issue used shall be the one in effect on the date of request for quotation. Any conflicts between this specification and the referenced documents shall be brought to the attention of LLNL in writing for resolution before any action is taken by the seller.

		CLASSIFICATION
REV. A BY	DATE	

Appendix B- Technical Note: Scroll Pump vs. Dry Piston Pump Operation

Applied Research Engineering Division
Accelerator Technologies Engineering Group

LLNL-ATEG-00-205
January 24, 2000

Technical Note: Scroll Pump vs. Dry Piston Pump Operation

Keith Kishiyama, Electrical Engineer, ATEG/LLNL

1.0 Pump specifications

The Varian Dry Scroll pump utilizes an orbiting scroll moving within a stationary scroll, forming crescent shaped pockets that progressively decrease in volume towards the center of the scrolls. As the volume decreases, gases are compressed and moved from inlet to exhaust. The seals on the vane tips of the orbiting scroll are PTFE-based and are oil-free. The scroll pump provides a very high pumping speed and a very good ultimate base pressure at reasonable cost. There are two models, one is rated at 20.5 cfm and the smaller one is rated at 10.6 cfm.

The VRC Dry Piston pump available through Kurt Lesker Co. operates with a high compression reciprocating piston that is also PTFE based with precision machined cylinder walls. There are two sizes in the standard models and two sizes in the soft start model. The standard models are rated at 28 cfm and 14 cfm. The soft start models offer programmable motor speed control. One feature of the soft start reduces the pumping speed in half when lower steady state gas loads are reached, thus extending the maintenance free period. The two soft start models are rated 10 cfm/5 cfm and 20 cfm/10 cfm.

A comparison of specifications from the vendor catalogs shows that in general, the scroll pump can reach a lower ultimate base pressure, but the single speed (standard) dry piston pump has greater pump speed. The soft start dry piston models operating at their normal speed have about the same pump speed as the scroll pumps. The catalog prices show that the standard model 28 cfm dry piston costs 179% more than the 20.5 cfm scroll pump. The cost of a 20 cfm soft start dry piston is 193% more than the 20.5 cfm scroll pump. The standard 14 cfm dry piston costs 197% more than the 10.6 cfm scroll pump. The 10 cfm soft start dry piston costs 212% more than the10.6 cfm scroll pump.

One clarification of terminology must be made here; the statistics shown in both catalogs are not Mean Time Between Failure (MTBF). A more appropriate term should be Mean Time Between Maintenance (MTBM). The recommended maintenance schedule for the scroll pump is every 6,000 hours for a minor maintenance and 12,000 hours for a major maintenance. In general, LLNL has been performing only the major maintenance with very good reliability and performance from the pumps.

The standard speed dry piston states a maintenance free period of 10,000 hours. The soft start feature can extended the maintenance free period to between 25,000 to 30,000 hours depending on the vacuum system gas loads.

2.0 Pump operation

To obtain a "clean" vacuum system, it is absolutely essential that the pumps, valves and interlocks are correctly designed and operational procedures strictly followed. This discussion will focus on the apparent contamination of the forelines from backstreaming of condensed vapors and/or particulates from scroll pumps.

LLNL does not currently have any VRC dry piston pumps in operation and cannot comment directly on backstreaming from these pumps. However, it can be stated that any of these pumps if operated improperly, will backstream and that the VRC is not immune from this problem.

Since both these pumps are oil-free pumps, they do not have any fluids to flush out condensed vapors or accumulated particulates. Particulates will be generated as part of the normal operation of both pumps as the sealing surfaces move against each other. When backing a turbo at high vacuum, some natural flushing will occur in these pumps due to the throughput of gases pumped by the turbo. The amount of flushing obviously depends on the gas load that the turbo is pumping against.

VRC recommends a periodic purge of the dry piston pump to help flush out the condensed vapors and particulates. Older Varian scroll pumps were manufactured by Iwata Inc. and Varian also recommends a periodic purge for these pumps. Newer Varian Tri-scroll pumps have a gas ballast system near the center of the scrolls to automatically bleed air into the pump to help flush out the pump.

The particulates generated by the wear of the sealing surfaces in a scroll pump are not a problem under normal vacuum operations. The particulates generally do not migrate upstream against the decreasing volumes of the orbiting scroll. In the newer TriScroll pumps, the gas ballast system further reduces the probability of particulate migration by helping to flush particulates out of the pump and into the exhaust vent. In addition, the newer TriScroll pumps have a port available for a nitrogen purge in critical applications. In the older scroll pumps without the gas ballast or external periodic purge, the particulates will tend to accumulate in the pump near the exhaust port, but still can not backstream under normal vacuum operations as stated before. However, this accumulation could present a problem under abnormal vacuum conditions in a vacuum system without proper interlocks.

If the scroll pump is shut down by a power outage for example, but still remains open to the foreline, the vacuum in the foreline will cause backstreaming of the particulates into the foreline. Varian addresses this in a Product Information Bulletin #914S, "Isolation and Venting of TriScroll Pumps". Varian recommends an automatic isolation and venting valve (P/N VP25-120-50-60 for NW25) that isolates the scroll pump from the foreline during a loss of power and then vents the foreline at the inlet of the pump to prevent backstreaming.

3.0 LEDA Vacuum Systems Experience

There are four scroll pumps on the LEDA RFQ vacuum system. Two older model scroll pumps are used to regenerate the cryopumps and pump down the RFQ from atmosphere. Both operations are short term, high gas load operations and because of this high gas load, do not require a periodic purge and have never shown any contamination of the forelines.

The other two scroll pumps are the newer TriScroll pumps and back a total of six turbo pumps used for the regeneration of the NEGs on the RF windows. The turbos also operate full time to help pump the non-getterable gases in the RF window vacuum. The RF window vacuum system on the LEDA RFQ has been operational for over a year and there is no evidence of backstreaming of condensed vapors or particulates in the forelines of the RF window vacuum system.

The contamination in the LEDA power coupler test bed could have occurred during a period when the interlocks were disabled. It was observed that the interlocks were disabled on the power coupler test bed during one of the visits to LANL. Upon further investigation, it was found that one of the turbos had shut down due to an over temperature alarm. (It was later determined the turbo shutdown was due to a faulty bearing causing it to overheat.). It is unknown how long the interlocks had been disabled or how long the turbo had been shutdown. Also, during this time period the LEDA power coupler test bed had borrowed an older 610DS scroll pump since its TriScroll had been damaged due to a mis-wired electrical connection.

Since the interlocks were disabled, the gate valve that isolates the turbo from high vacuum did not close. Also, the foreline valve did not close and the still running scroll pump was then looking at high vacuum through the static turbo. This condition could have caused backstreaming of particulates and condensed vapors into the foreline. The worst case now would be to shutdown the vacuum system from this state, which would cause the high vacuum region to be vented to atmosphere through the stopped scroll pump. With the interlocks disabled, this condition could have occurred. This would most certainly guarantee backstreaming of particulates from the scroll pump.

4.0 Conclusion and recommendation

Both pumps if used properly in a properly designed vacuum system will provide for a "clean" vacuum system. In general, the roughing system should be designed with a foreline valve as close as practical to the pump to minimize the volume that will be vented when the pump is shut down. Proper interlocks are essential for the operation of a "clean" vacuum system. Interlocks should only be disabled by knowledgeable personnel who will be absolutely sure of the results. Any of these pumps (even the newer TriScroll) will backstream particulates and condensed vapors into the foreline if operated incorrectly.

The Mean Time Between Maintenance for the standard dry piston is roughly the same as the scroll pump. The additional cost of the soft start dry piston will extend the Mean Time Between Maintenance by a factor of 2.5 to 3.

The main factor in recommending a pump is to consider the requirements of vacuum system. For the SNS XVTS, the scroll pumps will be used on carts to back turbos that will be used for the initial pumpdown of the linac and RF conditioning. Long term operation of the turbo cart will only be necessary in the very unusual failure mode where two ion pumps on a manifold are not operational since the XVTS has redundant pumping for ion pumps. Therefore the Mean Time Between Maintenance is not the critical determining factor in which pump to recommend for the XVTS.

The APT ED&D cryomodule vacuum system will utilize scroll pumps on turbo carts that will pump down the insulating vacuum. Once the insulating vacuum system is pumped down, then the cryomodule will be chilled down. When the cryomodule is cold, the turbo cart will remove since the system will cryopump itself. Because the scroll pump is not used for long term operation on the insulating vacuum the Mean Time Between Maintenance is not the critical determining factor.

The APT ED&D cryomodule power coupler vacuum system will also use scroll pumps to back turbos. This design does call for continuous long term operation of the scroll pump. However, to realize a reduced maintenance schedule over the scroll pump, a soft start dry piston pump would have to be specified. The initial purchase cost of the soft start dry piston pump is about twice the cost of a scroll pump, but does provide a Mean Time Between Maintenance that could be 2 to 2.5 times the scroll pump.

However, the cost of major maintenance for the scroll pump is approximately $1,400 for the larger scroll pump. The major maintenance kit is essentially a complete rebuilt pump head. There are five bolts that connect the head to the motor and it takes a technician 10 minutes to replace the head. Therefore, the scroll pump must be operated over several maintenance periods before the soft start dry piston pump becomes cost effective. Since maintenance periods are well over a year, it will take many years for the soft start dry piston pump to become cost effective. The APT ED&D cryomodule program will be completed long before that, so it is doubtful whether the higher initial purchase cost of the soft start dry piston pump can be recovered during the life of the program.

Because the cost the scroll pumps are significantly less for comparable pump speed and ultimate base pressure, scroll pumps are still the recommended pump.