CMCF2 08B1-1 BEAMLINE FRONT END MECHANICAL DESIGN

CLSI Design Note 31.2.26.1 – Rev 0

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REVISION HISTORY

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A	2006-Oct-11	Original Draft	Vinay Nagarkal
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1.0 PURPOSE

This Design Note details the specifications and information used for the mechanical design of the Phase 2 CMCF2 08B1-1 Beamline Front End at the CLS.

2.0 SCOPE

This Design Note covers the specifications of all CMCF2 08B1-1 Front End mechanical components, which include the components down stream from the SR1 dipole chamber exit flange to the exit flange of the Front End inside the Primary Optical Enclosure. The mechanical design processes used are as per Beamline Front End Mechanical Design Specification, CLSI Document 5.4.1.1, Rev 0.

3.0 DEFINITIONS AND ABBREVIATIONS

FE	Front End
SR1	Storage Ring
CLM	Collimator
FM	Fixed Mask
PSH	Photon Shutter
SSH	Safety Shutter
XBPM	X-ray Beam Position Monitor
BM	Bending Magnet
OFHC	Oxygen Free High Conductivity
UHV	Ultra High Vacuum
FV	Vacuum Fast Valve
VVR	Vacuum Valve Remote
PSS	Personnel Safety System
POE	Primary Optical Enclosure
PFD	Process Flow Diagram
CCG	Cold Cathode Gauge
TCG	Thermal Capacitance Gauge
RGA	Residual Gas Analyzer
FEA	Finite Element Analysis

4.0 CMCF2 BEAMLINE FRONT END REQUIREMENTS

The specific requirements requested by the CMCF2 Beam Team [1] are as follows:

- The FE shall be at the 08B1-1 location.
- The minimum photon beam angle shall be 0.33 mrad vertical and 1 mrad horizontal.
- The FE shall have a differential pumping section outside of the SR1 wall.

5.0 FRONT END LAYOUT, FUNCTION AND OPERATION

Table 1. CLS drawings for 08B1-1 FE General Assembly and PFD’s.

Drawing Name	**CLS Number**
08B1-1 FE General Assembly Plan View	08B1-1\ME\FE\0142100
08B1-1 FE General Assembly Elevation View	08B1-1\ME\FE\0142150
08B1-1 FE PFD Optics	08B1-1\PFD\OPT\0126501
08B1-1 FE PFD Vacuum	08B1-1\PFD\VAC\0126511
08B1-1 FE PFD Cooling	08B1-1\PFD\PPG\WTR\0126521
08B1-1 FE PFD Pneumatic	08B1-1\PFD\PPG\PNU\0126531

The 08B1-1 FE component function and operation will now be detailed, see drawings listed in Table 1 for the FE layout. Starting from the SR1 08B1-1 port vacuum valve we have FM-1. FM-1 protects downstream vacuum components from miss-steered photon beam, most importantly XBPM-1. The bellows on either side of FM-1 provide alignment of the FM independent of the adjacent components.

Next is XBPM-1 which monitors vertical photon beam position. The bellows on either side of XBPM-1 allow independent movement. Section 9.0 provides further detail on XBPM-1.

Downstream of XBPM-1 is PSH-1. When PSH-1 is closed it absorbs all photon beam passing through FM-1. The closing time for PSH-1 is approximately 1 second. PSH-1 is closed when there is maintenance work being performed on the downstream Beamline (PSH-2 and SSH are also closed), or in an emergency when PSH-2 fails to close.

After PSH-1 we have VVR-1 which isolates the vacuum on either side when required. The closing time of VVR-1 is approximately 3 seconds.

The closing time of VVR-1 is too slow to prevent a vacuum leak from reaching the SR1. To provide protection for the SR1 from a vacuum leak we use FV-1 which closes in 10 milliseconds after leak detection (add another 10 milliseconds to detect the leak). The FV-1 detector is a dedicated CCG which is located approximately 3 meters downstream, outside of the SR1 wall before FM-3. The purpose of FV-1 is only to stop the shock wave created by a vacuum breach from reaching the SR1. FV-1 does not isolate vacuum.

The next component is CLM-1 which is a Bremsstrahlung collimator. CLM-1 is used to shield Bremsstrahlung originating from the SR1, confining it to the collimator through aperture, limiting exposure to the downstream Beamline. The bellows on either side of CLM-1 allow independent movement.

The next component is FM-2. FM-2 protects downstream vacuum components from miss-steered photon beam. FM-2 is mounted on the upstream end of PSH-2 with no bellows between. The surveying of these 2 components is done such that FM-2 is placed accurately.

Downstream of FM-2 is PSH-2, which is the PSH that may be controlled by the user. When the PSS does not allow photon beam into the POE this shutter is closed (along with SSH) and absorbs all photon beam passing through the components upstream of it. This FE design allows for PSH-2 to be out of theoretical position by 2-3mm. Therefore, the survey of PSH-2 is not critical and PSH-2 can be fixed solid to FM-2. The closing time for PSH-2 is approximately 1 second

When the PSS does not allow photon beam into the POE, both PSH-2 and SSH close. The purpose of SSH is to shield Gas Bremsstrahlung, allowing access to the POE. The SSH consists of 2 Gas Bremsstrahlung shutters that work in unison. Although the shutters work in unison, each shutter alone will safely shield the Gas Bremsstrahlung. The SSH is not designed to absorb photon beam, so it is not water cooled. Therefore, the control system is designed so that PSH-2 must close before SSH. If the control system fails, the SSH will absorb the photon beam temporarily, the Tungsten will out-gas and deteriorate the vacuum level. This will result in PSH-1 closing or the RF in the SR1 will trip and the beam will be lost. The SSH has a closing time of approximately 1 second. The SSH must have independent movement and has bellows on either side.

The next component is CLM-2 or also referred to as the in-wall collimator. CLM-2 is located inside the SR1 wall and is used to shield Bremsstrahlung originating from the SR1, confining it to the CLM-2 through aperture, limiting exposure to the downstream Beamline.

Downstream of CLM-2 is VVR-2 which isolates the sections of vacuum inside and outside the SR1 wall.

The next component is the last fixed mask, FM-3. FM-3 has the defining aperture requested by the Beam Team to define photon beam geometry for the Beamline.

Downstream of FM-3 is CLM-3 which is a Bremsstrahlung collimator. CLM-3 is used to shield Bremsstrahlung originating from the SR1, confining it to the collimator through aperture, limiting exposure to the downstream Beamline. The bellows on either side of CLM-3 allow independent movement (there will have to be a bellows between the FE and the Beamline, after VVR-3).

The last FE component is VVR-3 which isolates the FE vacuum from the Beamline vacuum when required.

6.0 SYNCHROTRON RAY TRACING

The method for performing Synchrotron Beam Ray Tracing is as per "Beamline Front End Mechanical Design Specification", CLSI Document 5.4.1.1 Rev 0.

Components in the FE that absorb photon beam are shown in Table 2. The vertical and horizontal ray tracings are shown in CLS drawings 08B1-1\ME\FE\0139120 and 08B1-1\ME\FE\0139130 respectively. The defining aperture on FM-3 is oversized by 0.5mm in all directions to account for possible errors in fabrication and survey. This results in the emerging photon beam angle to be 0.51 mrad and 1.10 mrad in vertical and horizontal directions respectively. However, if the beam gets misteered, the photon beam emerging from FM-3 would be 1.09 mrad and 1.48 mrad in the vertical and horizontal directions respectively.

Table 2. 08B1-1 FE Photon Beam Absorbing Components.

Component	Drawing Name	CLS Drawing Number
FM-1[*]	SXRMB Fixed Mask 1 Assembly (CMCF2)	06B1-1\ME\CLM\0127400
FM-2[*]	SXRMB Fixed Mask 2 Assembly (CMCF2)	06B1-1\ME\CLM\0127450
FM-3	CMCF2 Fixed Mask 3 Assembly	08B1-1\ME\CLM\0139370
PSH-1[±]	Large Absorber Bend Magnet Photon Shutter Ass'y Chamber Type 2	07ID-1\ME\BDP\0125550
PSH-2[±]		

7.0 BREMSSTRAHLUNG RAY TRACING

The method for performing Bremsstrahlung Ray Tracing is as per "Beamline Front End Mechanical Design Specification", CLSI Document 5.4.1.1 Rev 0.

The vertical and horizontal ray tracings are shown in CLS drawings 08B1-1\ME\FE\0139100 and 08B1-1\ME\FE\0139110 respectively. These drawings demonstrate that the required shielding is achieved when the PSS allows access to the POE, and shows the possible escaping Bremsstrahlung when the PSS does not allow access to the POE. This escaping Bremsstrahlung is the responsibility of the POE and Beamline design to shield. Table 3 lists the Bremsstrahlung shielding components.

Table 3. Bremsstrahlung shielding components.

Component	Drawing Name	CLS Drawing Number
CLM-1[*]	FE Collimator (35 x 26.5 Aperture)	06B1-1\ME\CLM\0129600
SSH[±]	Front End Safety Shutter Ass'y - Aperture 53mm	07ID-1\ME\BDP\0072400
CLM-2	08B1-1 Wall Collimator Assembly	08B1-1\ME\CLM\0143200
CLM-3	FE Collimator (18 x 14 aperture)	08B1-1\ME\CLM\0143100

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[*] FM-1, FM-2 and CLM-1 for CMCF2 (08B1-1) FE are identical to that of the SXRMB (06B1-1) FE. Therefore, the existing drawings for SXRMB FE are used for reference and procurement purposes.

[±] PSH-1, PSH-2 and SSH are identical to that used for 07ID-1 FE. Therefore the existing drawings for 07ID-1 FE are used.

8.0 FRONT END HEAT LOAD ANALYSIS

In this section the heat load on FE components due to the absorption of photon beam produced by the Bend Magnet Source will be analyzed for the 08B1-1 FE. All calculations for this section are shown in Appendix A. It will be demonstrated that the 08B1-1 FE photon beam absorbing components will safely absorb the heat load generated by the Bend Magnet Source. Table 2 gives CLS drawing numbers for 08B1-1 FE photon beam absorbing components.

Table 4 gives the 08B1-1 FE heat load information for the photon beam absorbing components. All photon beam absorbing components for this FE are made of OFHC Copper. The Total Head Load and Normal Power Density were calculated by Brian Yates using SRCalc [2]. The input variables for SRCalc are given in Appendix B. Incidence Power Density is calculated by multiplying the Normal Power Density and the Sine of the Incidence Angle. CLS Design Specification 5.4.1.1 Rev 0 requires that the Incidence Power Density be less than 15 W/mm^2 for OFHC Copper and Glidcop AL-15 and Table 4 show this to be true for all components.

Table 4. 08B1-1 Front End Heat Load.

Component		**Total Power Load** (W)	**Normal Power Density** (W/mm^2)	**Incidence Power Density** (W/mm^2)	**Incidence Angle** (deg)	**Source Distance** (mm)	**Photon Beam Size** (mrad)
FM-1	Horizontal	1,364	17.3	6.1	20.5	3922	19.54
	Vertical			0.3	1.0		2.44
FM-2	Horizontal	313	7.4	1.6	12.1	5945	4.49
	Vertical			1.7	12.9		2.44
FM-3	Horizontal	200	3.7	0.9	14.0	8466	2.40
	Vertical			0.6	8.75		1.53
PSH1	Horizontal	313	12.0	N/A	N/A	4687	4.49
	Vertical			3.5	17.0		2.44
PSH2	Horizontal	200	7.0	N/A	N/A	6120	2.86
	Vertical			2.0	17.0		1.35

The heat load absorbing capabilities and cooling requirements of the Photon Shutters PSH1 and PSH2 are detailed in CLS Document 6.8.26.1 Rev 0 [3]. This document demonstrates that the Photon Shutter with CLS part #0125550 is capable of withstanding the thermal load at both locations for the 08B1-1 FE.

The 08B1-1 FE components inside the SR1 wall will be cooled with the SR1 cooling system, which supplies dionized water at approximately 26°C ±0.1°C. The components outside the SR1 wall are cooled with the Beamline cooling system, which also supplies dionized water at approximately 26°C ±0.1°C. Table 5 gives the cooling requirements and information for the photon beam absorbing components; equations are given in Appendix A. The range of minimum to maximum flow rates listed have Reynolds numbers in the transition region between laminar and turbulent flow (2,300-10,000), producing efficient cooling. The maximum velocity specified is 2 m/s to minimize the vibration produced by the flow. The coolant temperature rises are well within acceptable limits listed in CLS documents 8.4.33.1 and 5.4.1.1 (try to keep below 10°).

Table 5. Cooling Information for 08B1-1 FE Photon Beam Absorbing Components.

	FM-1	**FM-2**	**FM-3**
Total Power (Watts)	1364	313	199
Number of Cooling Channels	1	1	1
Cooling Coils	No	No	No
Cooling Channel Diameter (mm)	9.5	9.5	9.5
Cooling Length (approx) (mm)	1,000	300	300
Minimum Requirements			
Flow Rate (L/min)	4.3	2.1	2.1
Fluid Velocity (m/s)	1.0	0.5	0.5
Reynolds Number	10,823	5,411	5,411
Heat Transfer Coefficient (W/m^2 °K)	5,552	2,759	2,759
Cooling Temperature Rise (deg)	4.7	2.2	1.4
Component Pressure Drop (Pa)	1,569	144	144
Maximum Requirements			
Flow Rate (L/min)	8.6	8.6	8.6
Fluid Velocity (m/s)	2.0	2.0	2.0
Reynolds Number	21,646	21,646	21,646
Heat Transfer Coefficient (W/m^2 °K)	10,646	10,646	10,646
Coolant Temperature Rise (deg)	2.3	0.5	0.3
Component Pressure Drop (Pa)	5,223	1,567	1,567

9.0 X-RAY BEAM POSITION MONITORS

The XBPM design that is used is from the Advanced Photon Source (APS). For Bend Magnet FE's we are only concerned with vertical photon beam position. The Bend Magnet XBPM design uses 2 Molybdenum blades (one top, one bottom) that are 0.13mm thick. In consultation with Deming Shu of the APS, it is necessary to have a minimum of 2mm vertical photon beam contact the blades for accurate position readings. CLS drawing 08B1-1\ME\FE\0139120 shows 3.23 mm photon beam contact on XBPM1. CLS drawing 08B1-1\ME\FE\0139120 also shows 0.89 mm clearance to the photon beam required for the Beamline.

Further details on the FE X-Ray Beam Position Monitors can be found in CLS document 6.4.26.1, X-Ray Beam Position Monitors, Rev 0 [4].

10.0 FRONT END VACUUM

The goal when designing a vacuum system is to maximize conductance, which results in increased effective pumping speed and therefore improved vacuum. Due to optical requirements, 08B1-1 FE has multiple low conductance apertures that make this goal difficult to achieve. The areas of low conductance are shown in Table 7. Ion Pumps are sized and placed in a "distributed pumping" method due to the multiple areas of low conductance, shown in Figure 3.

Table 7. Low conductance apertures in 08B1-1 FE.

Component	**Aperture**	**Notes**
FM-1	18 mm x 11 mm	Low Conductance
CLM-1	35 mm x 26.5 mm	Low Conductance
FM-2	17 mm x 8 mm	Low Conductance
CLM-2	30 mm x 23 mm	Low Conductance
FM-3	9.5 mm x 4.5 mm	Almost No Conductance
CLM-3	18 mm x 14 mm	Low Conductance

Vacuum calculations have been completed for the 08B1-1 FE, and the results are shown in Figures 7 through 9. The calculations are given in Appendix C. The calculations were completed for the vacuum base pressure, which is the pressure with no out gassing load due to photon beam. Figure 1 shows calculated base pressure plots for both non-saturated and saturated conditions of the ion pumps. The saturated case is modeled with Ion Pumps that are at the end of their lifetime and are "full", resulting in lower pumping speeds. The plot for the non-saturated case has the conditions of full pumping capacity and low vacuum outgassing. The plot for the saturated case has the conditions of low pumping capacity and high vacuum outgassing. The actual vacuum pressure will be somewhere between these plots. When comparing the actual measured vacuum base pressures to the calculated values for the Phase 1 FE's this method of calculation is shown to be accurate.

Although the vacuum calculations do not include the initial out-gassing of components due to the photon beam (usually known as photon-stimulated desorption), this is considered in the design. That is, ion pumps are typically placed close to photon beam absorbing components. The vacuum levels in the FE will be initially poor, but this is only temporary, as photon-stimulated desorption diminishes with time. Hence, this is not considered to be a major factor affecting the FE vacuum. The Ion pumps close to PSH-2 also have 1500 l/s Titanium Sublimation Pumps (TSP) that are used during this bake-out. These TSP's are not considered in the vacuum calculations.

The beam team requested a differential pumping section. A differential pumping section consists of 3 items; a low conductance point, a large Ion Pump on the downstream side and a large Ion Pump on the upstream side. The goal is to protect the SR1 in the case of a vacuum breach in the beamline, downstream of the differential pumping section. If a vacuum breach occurs in the beamline the low conductance will slow the shock wave from reaching the SR1 and the large pumps will pump down the leak until the pumps become saturated. The vacuum level on the upstream side of the low conductance will become worse; the FV CCG will detect this and close the FV. Following this the VVR's will also close. For 08B1-1 FE the low conductance point is shown as number 55 on Figure 3, which is the defining aperture of FM-3. Figure 2 is a conductance plot which shows the conductance of point 55 to be the smallest (the larger number in Figure 2 the smaller the conductance). Therefore the calculations show this differential pumping section design to be effective.

CLS Vacuum Design Specification 8.4.33.1 Rev 3 states that for UHV the performance goal is 1.33 x 10^{-8} Pa (10^{-10} Torr). Figure 1 shows that theoretically we will not reach this at every point in the FE. However, this is consistent with the Phase 1 FE's theoretical and actual vacuum levels, with values averaging 5.0 x 10^{-10} Torr. Also, CLSI document 8.8.33.4 revision 1, "CLSI Vacuum Component Fabrication Technical Specification", states that the fabrication performance requirement for UHV is below 7.5 x 10^{-10} Torr, which the theoretical design will meet. To reach 10^{-10} Torr at every point would require significantly more pumping power and locations. As an estimate, this would add about 50% extra cost to the FE pumping budget with no significant benefit. As long as the FE vacuum does not contaminate the SR1 or the Beamline the vacuum pumping design will be sufficient**.** Figure 1 shows the vacuum levels on each end of the FE to be the best, therefore there should be no affect on the SR1 or Beamline.

Typically the combination of 1 CCG, 1 TCG and 1 roughing port are placed between vacuum valves. This holds true for the 08B1-1 FE. This FE vacuum system also contains an RGA, located downstream of FM-3 (differential pumping section). An RGA monitors the gas mass spectrum. The RGA is used to monitor contamination coming from the Beamline and also to detect small vacuum leaks.

Figure 1: Plot of 08B1-1 FE Calculated Vacuum Pressure.

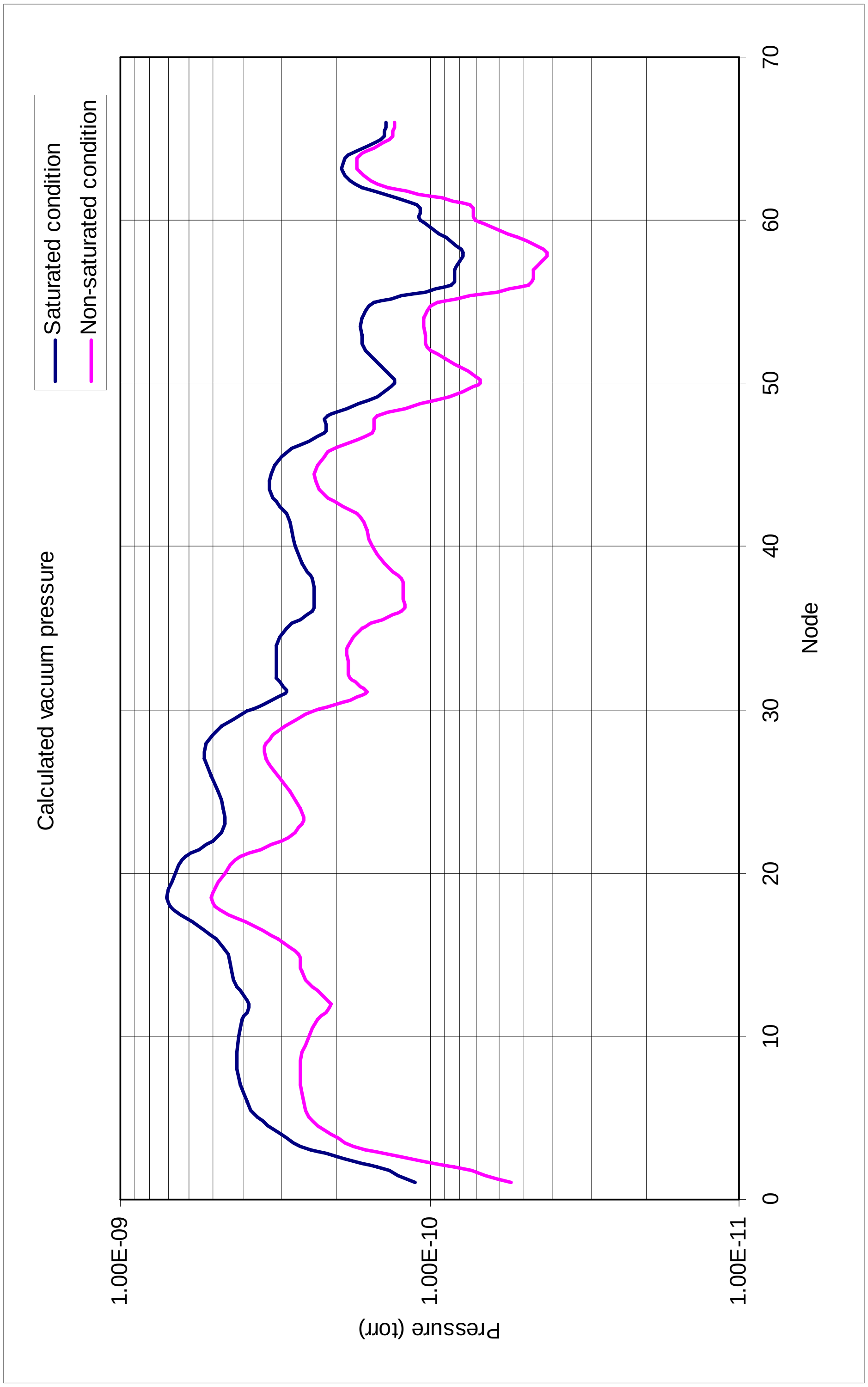
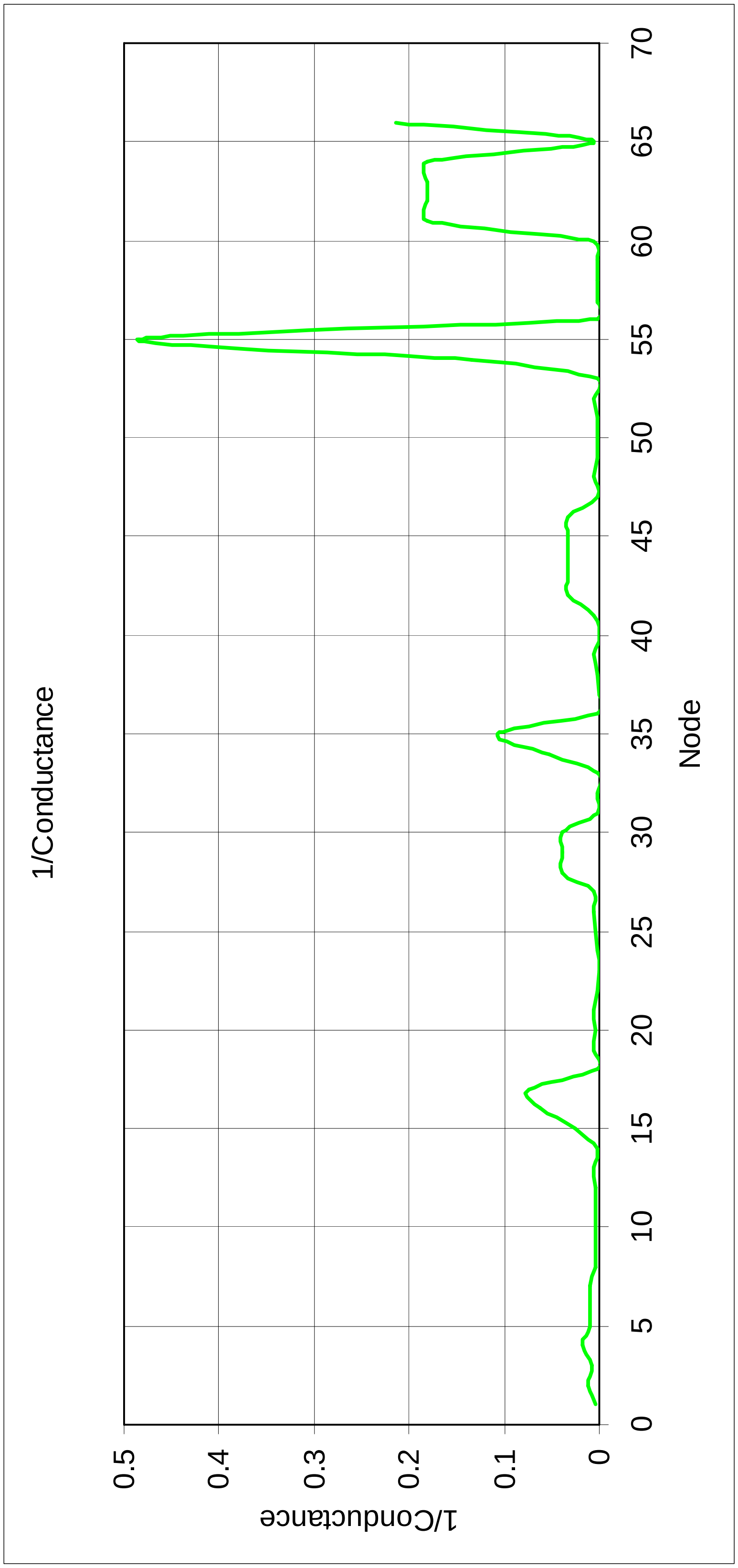


Figure 2: Plot of 08B1-1 FE Calculated Conductance, units of sec/liter.



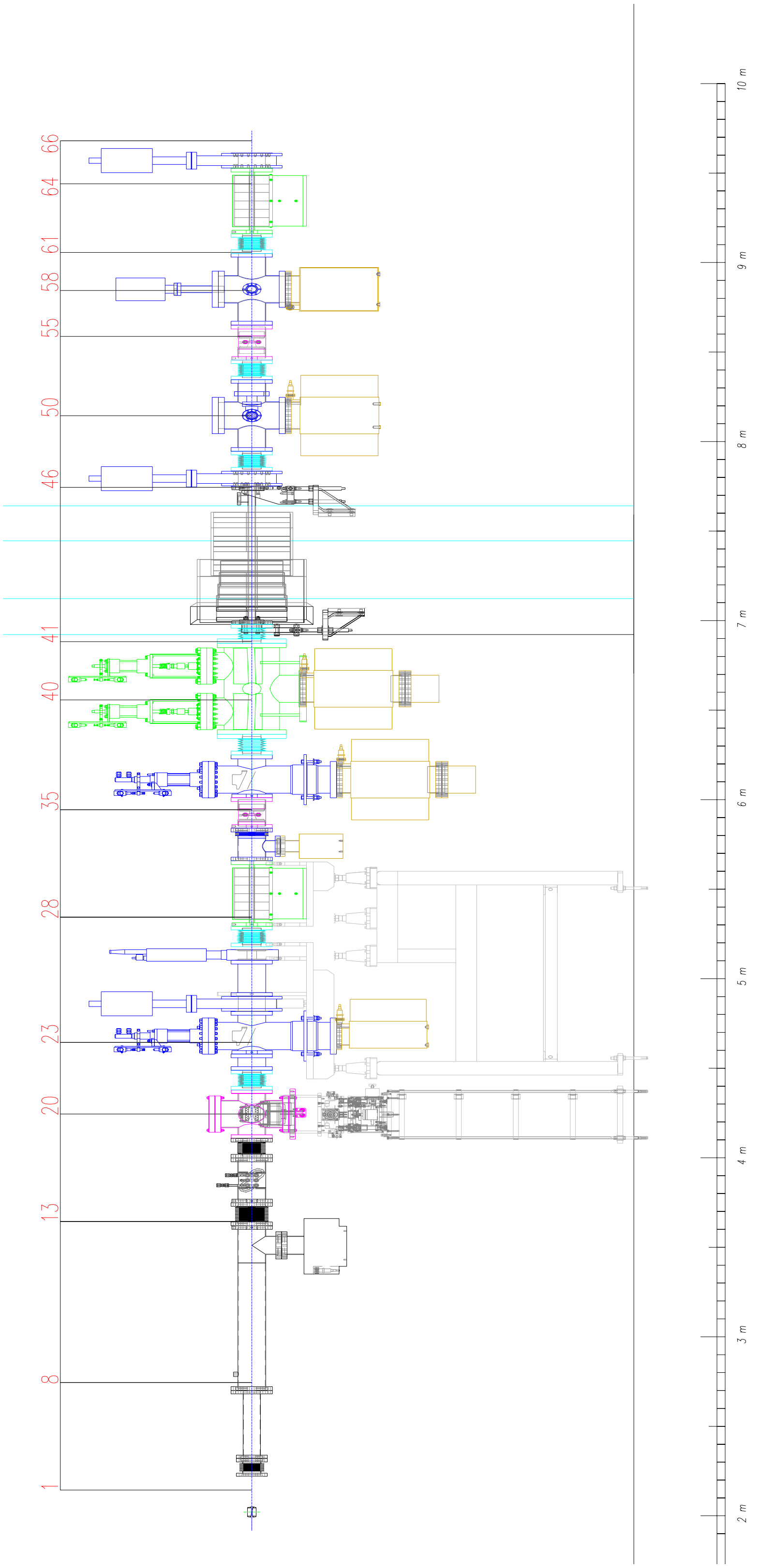


Figure 3: 08B1-1 FE General Layout showing vacuum calculation points.

11.0 APPLICABLE CODES, STANDARDS AND PROCEDURES

Beamline Front End Mechanical Design Specification, CLSI Document 5.4.1.1, Revision 0.

CLSI Vacuum Design Specification, CLSI Document 8.4.33.1, Revision 3.

Beamline Front-End Control and Instrumentation Manual, CLSI Document 7.9.26.1, Revision 0.

Vacuum Equipment Technical Specification, CLSI Document 8.8.33.1, Revision 1.

12.0 REFERENCES

[1] CMCF 08B1 - High Throughput Macromolecular Crystallography Beamline at the CLS – Conceptual Design Report, CLS Document 31.2.1.1, Revision 0.

[2] SRCalc, R. Reininger (2001) – Scientific Answers and Solutions (http://sas-rr.com/).

[3] Bend Magnet Photon Shutter Analysis, CLS Document 6.8.26.1, Revision 0.

[4] X-Ray Beam Position Monitors, CLS document 6.4.26.1, Revision 0.

APPENDIX A

For cooling photon beam absorbing components, it is desirable to have the coolant flow in the turbulent region. The Reynolds Number, Re, is defined as:

$$\mathrm{Re} = \frac{\rho \cdot V \cdot D}{\mu} \qquad (1)$$

where:

ρ = fluid density, 971 Kg/m^3 for water at 26°C,

V = fluid velocity (m/s),

D = cooling channel diameter (m),

μ = fluid Dynamic Viscosity, 8.55 x 10^{-4} N s / m^2 for water at 26°C.

Turbulent flow is defined as 2300 < Re < 5e6.

Next the Nusselt Number, Nu, is calculated as follows:

$$Nu = \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)} \qquad (2)$$

where:

Pr = Prandtl Number, 5.83 for water at 26°C,

f = Friction Factor,

$$f = (0.79 \ln \mathrm{Re} - 1.64)^2 \qquad (3)$$

With this the Heat Transfer Coefficient, h, is calculated:

$$h = \frac{k \cdot Nu}{D} \qquad (4)$$

The change in channel coolant temperature, dT, is defined as:

$$dT = \frac{P_w}{V \cdot A \cdot n \cdot \rho \cdot C_p} \qquad (5)$$

where:

Pw = Power to absorb (Watts),

A = coolant channel area (m^2),

n = number of coolant channels in parallel,

Cp = Specific Heat, 4179 J / Kg °K for water at 26°C.

The Pressure drop over the component, ΔP, is calculated:

$$\Delta P = \rho \cdot g\left(z + f \cdot \frac{L}{D} \cdot \frac{v^2}{2 \cdot g}\right) \qquad (6)$$

Where:

g = acceleration due to gravity (m/s^2),

L = cooling length (m),

z = change in elevation (m).

References

Fundamentals of Heat and Mass Transfer, Third Edition, Incropera and DeWitt.

APPENDIX B

CLS Storage Ring Parameters for Dipole Bend Magnet 1:

Electron Energy:	2.9 GeV
Electron Current:	500 mA
Bending Magnet Radius:	7.1428 m
Relative RMS Energy Spread:	0.00111
Horizontal Emmitance:	17.9 nm radians
Horizontal Beta:	1.06 m
Horizontal Alpha:	0.952 radians
Horizontal Dispersion:	0.062 m
Horizontal Dispersion Derivative:	0.023 radians
Vertical Emmitance:	0.0179 nm radians (0.1% coupling)
Vertical Beta:	25.57 m
Vertical Alpha:	-4.8 radians
Vertical Dispersion:	0 m
Vertical Dispersion Derivative:	0 radians

CLS Storage Ring Parameters for Dipole Bend Magnet 2:

Electron Energy:	2.9 GeV
Electron Current:	500 mA
Bending Magnet Radius:	7.1428 m
Relative RMS Energy Spread:	0.00111
Horizontal Emmitance:	17.9 nm radians
Horizontal Beta:	0.745 m
Horizontal Alpha:	0.503 radians
Horizontal Dispersion:	0.127 m
Horizontal Dispersion Derivative:	-0.152
Vertical Emmitance:	0.0179 nm radians (0.1% coupling)
Vertical Beta:	26.92 m
Vertical Alpha:	-3.11 radians
Vertical Dispersion:	0 m
Vertical Dispersion Derivative:	0 radians

APPENDIX C

CMCF2 Front End 08B1-1. Rev.1 (saturated pumps)

Abstract:

The CMCF2 Front End is represented as a number of separate spools with individual properties: conductance, desorbtion and pumping speed (if applicable). The pressure distribution along the front end vacuum tract is obtained by solving matrix equations and is as shown in the graph following the calculations.

Data:

$q_s := 3.0 \cdot 10^{-12}$ (Torr liter/sec cm^2) - average outgassing rate for the stainless steel, baked at 300°C, see [1] page 42.

$q_c := 1.0 \cdot 10^{-11}$ (Torr liter/sec cm^2) - avarege outgassing rate for OFHC copper, baked at 300°C see [1] page 42.

$S_{D20} := 26.0$ (liter/sec)- Pumping Speed of Vaclon Plus 55 **Diode**, **unsaturated.** Taken from [2] graph p.116 under pressure ~10^{-10} mbar (~$7.5x10^{-11}$ Torr)

$S_{D20s} := 16.0$ (liter/sec)Pumping Speed of Vaclon Plus 55 **Diode**, **saturated.** Taken from [2] graph p.116 under pressure ~10^{-10} mbar (~$7.5x10^{-11}$ Torr)

$S_{D55} := 65.0$ (liter/sec)- Pumping Speed of Vaclon Plus 55 **Diode**, **unsaturated.** Taken from [2] graph p.116 under pressure ~10^{-10} mbar (~$7.5x10^{-11}$ Torr)

$S_{D55s} := 37$ (liter/sec) - Pumping Speed of Vaclon Plus 55 **Diode**, **saturated.** Taken from [2] graph p.116 under pressure ~10^{-10} mbar (~$7.5x10^{-11}$ Torr)

$S_{D75} := 88$ (liter/sec) - Pumping Speed of Vaclon Plus 75 **Diode**, **unsaturated.** Taken from [2] graph p.114 under pressure ~10^{-10} mbar (~$7.5x10^{-11}$ Torr)

$S_{D75s} := 44$ (liter/sec) - Pumping Speed of Vaclon Plus 75 **Diode**, **saturated.** Taken from [2] graph p.114 under pressure ~10^{-10} mbar (~$7.5x10^{-11}$ Torr)

$S_{D150} := 160$ (liter/sec)- Pumping Speed of Vaclon Plus 150 **Diode**, **unsaturated.** Taken from [2] graph p.112 under pressure ~10^{-10} mbar (~$7.5x10^{-11}$ Torr)

$S_{D150s} := 80$ (liter/sec) - Pumping Speed of Vaclon Plus 150 **Diode**, **saturated.** Taken from [2] graph p.112 under pressure ~10^{-10} mbar (~$7.5\text{x}10^{-11}$ Torr)

$S_{D300} := 320$ (liter/sec)- Pumping Speed of Vaclon Plus 300 **Diode, unsaturated.** Taken from [2] graph p.110 under pressure ~10^{-10} mbar (~$7.5\text{x}10^{-11}$ Torr).

$S_{D300s} := 170$ (liter/sec)Pumping Speed of Vaclon Plus 300 **Diode, saturated.** Taken from [2] graph p.110 under pressure ~10^{-10} mbar (~$7.5\text{x}10^{-11}$ Torr).

$S_{SC300} := 144$ (liter/sec)Pumping Speed of Vaclon Plus 300 **StarCell**, **unsaturated.** Taken from [2] graph p.106 under pressure ~10^{-10} mbar (~$7.5\text{x}10^{-11}$ Torr) as ~60% from Nom. pump speed 240 (l/s)

$S_{SC300s} := 72$ (liter/sec)- Pumping Speed of Vaclon Plus 300 **StarCell**, **saturated.** Taken from [2] graph p.106 under pressure ~10^{-10} mbar (~$7.5\text{x}10^{-11}$ Torr) as ~30% from Nom. pump speed 240 (l/s)

Calculations:

The following equation form the base of the matrix equation, see [3], [4] and [5] p.18

$$Q_i + C_{i-1}\cdot\left(P_{i-1} - P_i\right) + C_i\cdot\left(P_{i+1} - P_i\right) = P_i\cdot S_i$$

(for the static regime,after pressure decay)

where $Q_i = q\cdot F_i$ (Torr liter/sec) is the total gas load in element i with the surface area F_i (cm^2),

S_i (liter/sec) is pumping speed,

P_i (Torr) is the pressure of element i.

$C_i = 11.6A_i\cdot\alpha$ (liter/sec) is conductance between element i and element i+1 where A_i is area of the aperture (cm^2) and α transmission coefficient.

Clausing transmission coefficient α for the **circular cross section** is given by Santeler equation as a function from diameter D (cm) and length L (cm), see [6]:

$$\alpha_1(D,L) := \left[1 + \frac{3}{4}\cdot\frac{L\cdot\left(1 + \dfrac{1}{3 + \dfrac{6}{7}\cdot\dfrac{L}{D}}\right)}{D}\right]^{-1}$$

Clausing transmission coefficient α for the **rectangular cross section** is given as a function from the cross-sectional dimensions H and W (cm) with $W \geq H$ and length L (cm)

$$\alpha_2(H,W,L) := \left[1 + \frac{3\cdot L\cdot(H+W)}{8\cdot H\cdot W}\right]^{-1}$$

Define the typical elements of the vacuum scheme:

$ID_{6.0} := 14.6$ (cm) - Internal Diameter of 6" tube (if 8"CF)

$ID_{4.0} := 9.7$ (cm) - Internal Diameter of 4" tube (if 6"CF)

$ID_{2.5} := 6.0$ (cm) - Internal Diameter of 2.5" tube (if 4.5"CF)

$ID_{1.5} := 3.48$ (cm) - Internal Diameter of 1.5" tube (if 2.75"CF)

Typical Round Spool.

$$RoundSpool(ID,L,q,S) := \begin{pmatrix} q\pi\cdot ID\cdot L \\ 11.6\cdot\frac{\pi\cdot ID^2}{4}\cdot\alpha_1(ID,L) \\ S \end{pmatrix}$$

- is the gas load Q_i

- is conductance C_i from element i to element i+1

- is pumping speed S_i inside the element i

Cross Spool (8"x 6" for BPM, has additional outgassing from the top and bottom 8" flanges).

$$CrossSpool(ID,L,S) := \begin{bmatrix} q_s\cdot\pi\cdot\left(ID\cdot L + 2\cdot\frac{ID_{6.0}^{\,2}}{4} + ID_{6.0}\cdot 18.0\right) \\ 11.6\cdot\frac{\pi\cdot ID^2}{4}\cdot\alpha_1(ID,L) \\ S \end{bmatrix}$$

- is the gas load Q_i

- is conductance C_i from element i to element i+1

- is pumping speed S_i inside the element i

Typical Square Spool.

$$SquareSpool(H,W,L,q,S) := \begin{bmatrix} q\cdot 2(H\cdot L + W\cdot L) \\ 11.6\,H\cdot W\cdot\alpha_2(H,W,L) \\ S \end{bmatrix}$$

- is the gas load Q_i

- is the conductance C_i from element i to element i+1

- is pumping speed S_i inside the element i

Box Spool, has additional outgassing from the front and back walls (use when proportion between inlet/outlet aperture and front/back wall above 50%)

$$\mathrm{BoxSpool}(H,W,L,q,S) := \begin{bmatrix} q\cdot 2(H\cdot L + H\cdot W + W\cdot L) \\ 11.6\,H\cdot W\cdot \alpha_2(H,W,L) \\ S \end{bmatrix}$$

- is the gas load Q_i

- is the conductance C_i from element i to element i+1

- is pumping speed S_i inside the element i

Bellow 275-175, P/N 275-175-4-EE-4.5" CFF NR, R has 4 segments with 10 convolution each. Bellow are certified to have a leak rate of less than 2×10^{-9} (Std. cc/Sec) ~ $Q_{leak} := 1.52\times 10^{-9}$ (Torr liter/sec).

$ID_{275\_175} := 4.4$ (cm) [1.75 in] - Internal Diameter of bellow

$OD_{275\_175} := 6.9$ (cm) [2.75 in] - Outside Diameter of bellow

$$S_{275\_175} := \pi\cdot\left(\frac{OD_{275\_175}^{\;2}}{4} - \frac{ID_{275\_175}^{\;2}}{4}\right)\cdot 4\cdot 1$$

Inside surface area would be:

$S_{275\_175} = 908.483$ (cm^2)

$$\mathrm{Bellow275175}(L) := \begin{pmatrix} q_s\cdot S_{275\_175} + 1.52\times 10^{-9} \\ 11.6\dfrac{\pi ID_{275\_175}^{\;2}}{4}\cdot\alpha_1\left(ID_{275\_175}, L\right) \\ 0 \end{pmatrix}$$

- is the total gas load Q_i (outgassing and leak)

- is the conductance C_i from element i to element i+1

Bellow 399-269, P/N 399-269-4-EE-6" CFF NR, R has 4 segments with 10 convolution each. Bellow are certified to have a leak rate of less than 2×10^{-9} (Std. cc/Sec) ~ $Q_{leak} := 1.52\times 10^{-9}$ (Torr liter/sec).

$ID_{399\_269} := 6.8$ (cm) [2.69 in] - Internal Diameter of bellow

$OD_{399\_269} := 10.1$ (cm) [3.99 in] - Outside Diameter of bellow

$$S_{bellow} := \pi\cdot\left(\frac{OD_{399\_269}^{\;2}}{4} - \frac{ID_{399\_269}^{\;2}}{4}\right)\cdot 4\cdot 1$$

Inside surface area would be:

$S_{bellow} = 1.765\times 10^{3}$ (cm^2)

$$\text{Bellow399269}(L) := \begin{pmatrix} q_s \cdot S_{bellow} + 1.52 \times 10^{-9} \\ 11.6 \dfrac{\pi ID_{399\_269}^{2}}{4} \cdot \alpha_1\left(ID_{399\_269}, L\right) \\ 0 \end{pmatrix}$$

- is the total gas load Q_i (outgassing and leak)
- is the conductance C_i from element i to element i+1
- is pumping speed (zero for the bellows)

Define the geometry of elements.

$$\begin{pmatrix} Q_1 \\ C_1 \\ S_1 \end{pmatrix} := \text{SquareSpool}\left(3.2, 40.0, 40.0, q_s, S_{D300s}\right)$$

- SR vac. chamber

$$\begin{pmatrix} Q_2 \\ C_2 \\ S_2 \end{pmatrix} := \text{SquareSpool}\left(2.4, 6.0, 4.1, q_s, 0\right)$$

- Neck

$$\begin{pmatrix} Q_3 \\ C_3 \\ S_3 \end{pmatrix} := \text{RoundSpool}\left(ID_{2.5}, 9.2, q_s, 0\right)$$

- VAT 10

$$\begin{pmatrix} Q_4 \\ C_4 \\ S_4 \end{pmatrix} := \text{Bellow275175}(10.0)$$

- Bellow, welded

$$\begin{pmatrix} Q_5 \\ C_5 \\ S_5 \end{pmatrix} := \text{RoundSpool}\left(ID_{2.5}, 12.7, q_s, 0\right)$$

- 1/3 of Spool

$$\begin{pmatrix} Q_6 \\ C_6 \\ S_6 \end{pmatrix} := \text{RoundSpool}\left(ID_{2.5}, 12.7, q_s, 0\right)$$

- 1/3 of Spool

$$\begin{pmatrix} Q_7 \\ C_7 \\ S_7 \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{2.5}, 12.7, q_s, 0\right)$$

1/3 of Spool

$$\begin{pmatrix} Q_8 \\ C_8 \\ S_8 \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 18.4, q_s, 0\right)$$

- 1/5 of Spool

$$\begin{pmatrix} Q_9 \\ C_9 \\ S_9 \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 18.4, q_s, 0\right)$$

1/5 of Spool

$$\begin{pmatrix} Q_{10} \\ C_{10} \\ S_{10} \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 18.4, q_s, 0\right)$$

1/5 of Spool

$$\begin{pmatrix} Q_{11} \\ C_{11} \\ S_{11} \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 18.4, q_s, 0\right)$$

1/5 of Spool

$$\begin{pmatrix} Q_{12} \\ C_{12} \\ S_{12} \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 18.4, q_s, S_{D75s}\right)$$

1/5 of Spool

$$\begin{pmatrix} Q_{13} \\ C_{13} \\ S_{13} \end{pmatrix} := \mathrm{Bellow399269}(12.8)$$

Bellow, welded -

$$\begin{pmatrix} Q_{14} \\ C_{14} \\ S_{14} \end{pmatrix} := \mathrm{RoundSpool}\left(9.1, 8.0, q_s, 0\right)$$

- FM1, Pre volume

$$\begin{pmatrix} Q_{15} \\ C_{15} \\ S_{15} \end{pmatrix} := \mathrm{SquareSpool}\left(1.325, 6.45, 4.2, q_c, 0\right)$$

- FM1, taper, input

$$\begin{pmatrix} Q_{16} \\ C_{16} \\ S_{16} \end{pmatrix} := \mathrm{SquareSpool}\left(1.175, 3.35, 4.2, q_c, 0\right)$$

- FM1, taper, mid

$$\begin{pmatrix} Q_{17} \\ C_{17} \\ S_{17} \end{pmatrix} := \mathrm{SquareSpool}\left(1.1, 1.8, 1.3, q_c, 0\right)$$

- FM1, output

$$\begin{pmatrix} Q_{18} \\ C_{18} \\ S_{18} \end{pmatrix} := \mathrm{RoundSpool}\left(9.1, 7.5, q_s, 0\right)$$

- FM1, Post volume

$$\begin{pmatrix} Q_{19} \\ C_{19} \\ S_{19} \end{pmatrix} := \mathrm{Bellow399269}(11.0)$$

- Bellow, welded

$$\begin{pmatrix} Q_{20} \\ C_{20} \\ S_{20} \end{pmatrix} := \mathrm{CrossSpool}\left(ID_{4.0}, 27.0, 0\right)$$

BPM cross -

$$\begin{pmatrix} Q_{21} \\ C_{21} \\ S_{21} \end{pmatrix} := \mathrm{Bellow399269}(11.0)$$

- Bellow, welded

$$\begin{pmatrix} Q_{22} \\ C_{22} \\ S_{22} \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 9.0, q_s, 0\right)$$

- Spool

Photon Shutter, chamber 6" tube 46.8 cm long, represented by square spool 6" (15.2 cm) width and 6" (15.2 cm) length (without neck).The hight 32.1 cm is taken from the condition to have the same volume.

$$\begin{pmatrix} Q_{23} \\ C_{23} \\ S_{23} \end{pmatrix} := \mathrm{SquareSpool}\left(32.1, 15.2, 15.2, q_s, \frac{S_{D150s}}{1 + \dfrac{S_{D150s}}{11.6 \cdot \dfrac{\pi \cdot {ID_{6.0}}^2}{4} \cdot \alpha_1\left(ID_{6.0}, 25.9\right)}}\right)$$

$$\begin{pmatrix} Q_{24} \\ C_{24} \\ S_{24} \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 14.9, q_s, 0\right)$$

- VAT 48 and Neck of Photon Shutter together

$$\begin{pmatrix} Q_{25} \\ C_{25} \\ S_{25} \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 21.9, q_s, 0\right)$$

- Spool

$$\begin{pmatrix} Q_{26} \\ C_{26} \\ S_{26} \end{pmatrix} := \mathrm{SquareSpool}\left(3.5, 8.0, 4.6, q_s, 0\right)$$

- Fast valve

$$\begin{pmatrix} Q_{27} \\ C_{27} \\ S_{27} \end{pmatrix} := \mathrm{Bellow399269}(13.0)$$

- Bellow, welded

$$\begin{pmatrix} Q_{28} \\ C_{28} \\ S_{28} \end{pmatrix} := \mathrm{SquareSpool}\left(2.6, 3.5, 12.2, q_s, 0\right)$$

- 1/3 of Collimator

$$\begin{pmatrix} Q_{29} \\ C_{29} \\ S_{29} \end{pmatrix} := \mathrm{SquareSpool}\left(2.6, 3.5, 12.2, q_s, 0\right)$$

- 1/3 of Collimator

$$\begin{pmatrix} Q_{30} \\ C_{30} \\ S_{30} \end{pmatrix} := \mathrm{SquareSpool}\left(2.6, 3.5, 12.2, q_s, 0\right)$$

- 1/3 of Collimator

$$\begin{pmatrix} Q_{31} \\ C_{31} \\ S_{31} \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 14.1, q_s, S_{D55s}\right)$$

- Spool

$$\begin{pmatrix} Q_{32} \\ C_{32} \\ S_{32} \end{pmatrix} := \mathrm{Bellow399269}(1.4)$$

- Bellow, welded

$$\begin{pmatrix} Q_{33} \\ C_{33} \\ S_{33} \end{pmatrix} := \mathrm{RoundSpool}\left(9.1, 5.6, q_s, 0\right)$$

- FM2, Pre volume

$$\begin{pmatrix} Q_{34} \\ C_{34} \\ S_{34} \end{pmatrix} := \mathrm{SquareSpool}\left(1.6, 2.45, 3.5, q_c, 0\right)$$

- FM2, taper, input

$$\begin{pmatrix} Q_{35} \\ C_{35} \\ S_{35} \end{pmatrix} := \mathrm{SquareSpool}\left(0.8, 1.7, 1.0, q_c, 0\right)$$

- FM2, taper, output

$$\begin{pmatrix} Q_{36} \\ C_{36} \\ S_{36} \end{pmatrix} := \mathrm{RoundSpool}\left(9.1, 7.5, q_s, 0\right)$$

- FM2, Post volume

Photon Shutter, chamber 6" tube 46.8 cm long, represented by square spool 6" (15.2 cm) width and 6" (15.2 cm) length (without neck).The hight 32.1 cm is taken from the condition to have the same volume.

$$\begin{pmatrix} Q_{37} \\ C_{37} \\ S_{37} \end{pmatrix} := \text{SquareSpool}\left(32.1, 15.2, 15.2, q_s, \frac{S_{SC300s}}{1 + \dfrac{S_{SC300s}}{11.6 \cdot \dfrac{\pi \cdot {ID_{6.0}}^2}{4} \cdot \alpha_1\left(ID_{6.0}, 25.9\right)}} \right)$$

$$\begin{pmatrix} Q_{38} \\ C_{38} \\ S_{38} \end{pmatrix} := \text{RoundSpool}\left(ID_{4.0}, 6.6, q_s, 0\right)$$

- Neck of the Photon Shutter

$$\begin{pmatrix} Q_{39} \\ C_{39} \\ S_{39} \end{pmatrix} := \text{Bellow399269}(11.5)$$

- Bellow, welded

Safety Shutter, chamber 8" tube 50.8 cm long, represented by square spool 17.7 cm width and 17.7 cm hight.Square size is taken from the condition to have the same volume.

$$\begin{pmatrix} Q_{40} \\ C_{40} \\ S_{40} \end{pmatrix} := \text{BoxSpool}\left(17.7, 17.7, 50.8, q_s, \frac{S_{SC300s}}{1 + \dfrac{S_{SC300s}}{11.6 \cdot \dfrac{\pi \cdot {ID_{6.0}}^2}{4} \cdot \alpha_1\left(ID_{6.0}, 9.6\right)}} \right)$$

$$\begin{pmatrix} Q_{41} \\ C_{41} \\ S_{41} \end{pmatrix} := \text{Bellow399269}(12.1)$$

- Bellow, welded

$$\begin{pmatrix} Q_{42} \\ C_{42} \\ S_{42} \end{pmatrix} := \text{SquareSpool}\left(2.3, 5.3, 15.4, q_s, 0\right)$$

- 1/5 of the Wall Collimator

$$\begin{pmatrix} Q_{43} \\ C_{43} \\ S_{43} \end{pmatrix} := \text{SquareSpool}\left(2.3, 5.3, 15.4, q_s, 0\right)$$

- 1/5 of the Wall Collimator

$$\begin{pmatrix} Q_{44} \\ C_{44} \\ S_{44} \end{pmatrix} := \mathrm{SquareSpool}\left(2.3, 5.3, 15.4, q_s, 0\right)$$

1/5 of the Wall Collimator

$$\begin{pmatrix} Q_{45} \\ C_{45} \\ S_{45} \end{pmatrix} := \mathrm{SquareSpool}\left(2.3, 5.3, 15.4, q_s, 0\right)$$

1/5 of the Wall Collimator -

$$\begin{pmatrix} Q_{46} \\ C_{46} \\ S_{46} \end{pmatrix} := \mathrm{SquareSpool}\left(2.3, 5.3, 15.4, q_s, 0\right)$$

1/5 of the Wall Collimator -

$$\begin{pmatrix} Q_{47} \\ C_{47} \\ S_{47} \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 8.5, q_s, 0\right)$$

VAT 48 (6"CFF) -

$$\begin{pmatrix} Q_{48} \\ C_{48} \\ S_{48} \end{pmatrix} := \mathrm{Bellow399269}(11.0)$$

- Bellow, welded

$$\begin{pmatrix} Q_{49} \\ C_{49} \\ S_{49} \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 12.7, q_s, 0\right)$$

- 1/3 of Cross

Vertical part of the cross, chamber 6" tube and 24.5 cm long represented by square spool 6" width and 6" length.The hight 19.2 cm is taken from the condition to have the same volume.

$$\begin{pmatrix} Q_{50} \\ C_{50} \\ S_{50} \end{pmatrix} := \mathrm{SquareSpool}\left(10.0, 15.2, 19.2, q_s, S_{D300s}\right)$$

- 1/3 of Cross

$$\begin{pmatrix} Q_{51} \\ C_{51} \\ S_{51} \end{pmatrix} := \mathrm{RoundSpool}\left(ID_{4.0}, 12.7, q_s, 0\right)$$

- 1/3 of Cross

$$\begin{pmatrix} Q_{52} \\ C_{52} \\ S_{52} \end{pmatrix} := \mathrm{Bellow399269}(11.0)$$

$$\begin{pmatrix} Q_{53} \\ C_{53} \\ S_{53} \end{pmatrix} := \mathrm{RoundSpool}(9.7, 7.1, q_s, 0)$$

- FM3, Pre volume

$$\begin{pmatrix} Q_{54} \\ C_{54} \\ S_{54} \end{pmatrix} := \mathrm{SquareSpool}(1.02, 1.87, 3.5, q_c, 0)$$

- FM3, taper, input

$$\begin{pmatrix} Q_{55} \\ C_{55} \\ S_{55} \end{pmatrix} := \mathrm{SquareSpool}(0.43, 0.94, 1.0, q_c, 0)$$

- FM3, aperture

$$\begin{pmatrix} Q_{56} \\ C_{56} \\ S_{56} \end{pmatrix} := \mathrm{RoundSpool}(9.7, 7.1, q_s, 0)$$

- FM3, past volume

$$\begin{pmatrix} Q_{57} \\ C_{57} \\ S_{57} \end{pmatrix} := \mathrm{RoundSpool}(ID_{4.0}, 12.7, q_s, 0)$$

- 1/3 of Cross

Vertical part of the cross, chamber 6" tube and 24.5 cm long represented by square spool 6" width and 6" length.The hight 19.2 cm is taken from the condition to have the same volume.

$$\begin{pmatrix} Q_{58} \\ C_{58} \\ S_{58} \end{pmatrix} := \mathrm{SquareSpool}(10.0, 15.2, 19.2, q_s, S_{D300s})$$

- 1/3 of Cross

$$\begin{pmatrix} Q_{59} \\ C_{59} \\ S_{59} \end{pmatrix} := \mathrm{RoundSpool}(ID_{4.0}, 12.7, q_s, 0)$$

- 1/3 of Cross

$$\begin{pmatrix} Q_{60} \\ C_{60} \\ S_{60} \end{pmatrix} := \text{Bellow399269}(13.0)$$

- Bellow, welded

$$\begin{pmatrix} Q_{61} \\ C_{61} \\ S_{61} \end{pmatrix} := \text{SquareSpool}\left(1.4, 1.8, 9.05, q_s, 0\right)$$

- 1/4 of Collimator

$$\begin{pmatrix} Q_{62} \\ C_{62} \\ S_{62} \end{pmatrix} := \text{SquareSpool}\left(1.4, 1.8, 9.05, q_s, 0\right)$$

- 1/4 of Collimator

$$\begin{pmatrix} Q_{63} \\ C_{63} \\ S_{63} \end{pmatrix} := \text{SquareSpool}\left(1.4, 1.8, 9.05, q_s, 0\right)$$

- 1/4 of Collimator

$$\begin{pmatrix} Q_{64} \\ C_{64} \\ S_{64} \end{pmatrix} := \text{SquareSpool}\left(1.4, 1.8, 9.05, q_s, 0\right)$$

- 1/4 of Collimator

$$\begin{pmatrix} Q_{65} \\ C_{65} \\ S_{65} \end{pmatrix} := \text{RoundSpool}\left(ID_{2.5}, 7.5, q_s, 0\right)$$

- VAT 48 (4.5"CFF)

$$\begin{pmatrix} Q_{66} \\ C_{66} \\ S_{66} \end{pmatrix} := \text{RoundSpool}\left(1.0, 1.0, q_s, 0\right)$$

- End

Define the number of vacuum elements as Nodes

$\text{Nnodes} := 66 \qquad i := 1..\,\text{Nnodes} \qquad j := 1..\,\text{Nnodes}$

$$M_{i,j} := \left|\begin{array}{l} -C_i \ \text{ if } \ i = j-1 \wedge j > 1 \\ -C_{i-1} \ \text{ if } \ i = j+1 \\ S_i + C_{i-1} + C_i \ \text{ if } \ i = j \wedge i > 1 \\ S_1 + C_1 \ \text{ if } \ j = i \wedge j = 1 \\ 0 \ \text{ otherwise} \end{array}\right. \qquad P := M^{-1} \cdot Q$$

Pressure: $P := M^{-1} \cdot Q$

Calculated vacuum pressure and conductance values are tabulated below:

Nodes	Calculated vacuum pressure (Torr)		Conductance (liter / sec)
	Pressure (saturated)	Pressure (non-saturated)	
1	1.11678E-10	5.45773E-11	0.004083041
2	1.46863E-10	8.35535E-11	0.011355813
3	2.42372E-10	1.61796E-10	0.007367948
4	3.00508E-10	2.08729E-10	0.016781073
5	3.61674E-10	2.44378E-10	0.008894529
6	3.87707E-10	2.56886E-10	0.008894529
7	4.07351E-10	2.63006E-10	0.008894529
8	4.20608E-10	2.62738E-10	0.003184984
9	4.19997E-10	2.57285E-10	0.003184984
10	4.14029E-10	2.46474E-10	0.003184984
11	4.02704E-10	2.30305E-10	0.003184984
12	3.8602E-10	2.08779E-10	0.003184984
13	4.18076E-10	2.40411E-10	0.006378111
14	4.38809E-10	2.60297E-10	0.002432234
15	4.45047E-10	2.66211E-10	0.024540561
16	4.91955E-10	3.09858E-10	0.061553745
17	5.86217E-10	3.95938E-10	0.074626226
18	6.9487E-10	4.94673E-10	0.002365834
19	6.96793E-10	4.96281E-10	0.005843889
20	6.61723E-10	4.60434E-10	0.004054093
21	6.13273E-10	4.11445E-10	0.005843889
22	5.03613E-10	3.01009E-10	0.002192241
23	4.60672E-10	2.57776E-10	0.000274312
24	4.63238E-10	2.60486E-10	0.002821861

25	4.85797E-10	2.84512E-10	0.003542162
26	5.07021E-10	3.0758E-10	0.005260105
27	5.3687E-10	3.40166E-10	0.006437052
28	5.29536E-10	3.36181E-10	0.038525561
29	4.6844E-10	2.95128E-10	0.038525561
30	3.90141E-10	2.36873E-10	0.038525561
31	2.9464E-10	1.61416E-10	0.002737891
32	3.14172E-10	1.8125E-10	0.002828569
33	3.15076E-10	1.82468E-10	0.002110649
34	3.14738E-10	1.82363E-10	0.051812693
35	2.91733E-10	1.65091E-10	0.107082799
36	2.38835E-10	1.24039E-10	0.002365834
37	2.36145E-10	1.21611E-10	0.000274312
38	2.389E-10	1.24167E-10	0.001928011
39	2.571E-10	1.4097E-10	0.005992989
40	2.72839E-10	1.52364E-10	0.000867474
41	2.80196E-10	1.60001E-10	0.006171179
42	2.90481E-10	1.72282E-10	0.032534385
43	3.21854E-10	2.14182E-10	0.032534385
44	3.30381E-10	2.33235E-10	0.032534385
45	3.16061E-10	2.29441E-10	0.032534385
46	2.78894E-10	2.02801E-10	0.032534385
47	2.1888E-10	1.53313E-10	0.002137639
48	2.13275E-10	1.484E-10	0.005843889
49	1.58134E-10	9.51499E-11	0.00258997
50	1.30689E-10	6.85427E-11	0.001244149
51	1.41535E-10	7.94383E-11	0.00258997
52	1.61106E-10	9.91128E-11	0.005843889
53	1.65444E-10	1.03685E-10	0.00198352
54	1.65629E-10	1.0395E-10	0.135074481
55	1.50909E-10	9.46398E-11	0.484360165
56	8.48538E-11	4.79835E-11	0.00198352
57	8.32958E-11	4.6505E-11	0.00258997
58	7.82544E-11	4.15673E-11	0.001244149
59	8.87721E-11	5.21327E-11	0.00258997
60	1.0766E-10	7.11198E-11	0.006437052
61	1.10741E-10	7.44481E-11	0.181633956
62	1.6613E-10	1.36801E-10	0.181633956
63	1.89958E-10	1.67594E-10	0.181633956
64	1.82226E-10	1.66825E-10	0.181633956
65	1.42933E-10	1.34496E-10	0.006609391
66	1.387E-10	1.30517E-10	0.213426169

References:

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