Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Towards Field Emission Free Cavity Processing And String Assembly At Fermilab

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LCWS'24

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FERMILAB-SLIDES-24-0139-TD

Outline

- Introduction
- Infrastructure and Tooling Improvement
- Hardware and Component Design
- Procedure Improvement
- Summary

Introduction – Particle Sources

- Parts
  - Vacuum valves and flexible hoses
  - Fasteners
  - Flanges
  - Seals
  - Tooling
- Processes and Assembly
  - Chemistry
  - Water rinsing
  - Assembly
  - Evacuation, backfill, and purging
- Operators
- Environment

Particle Sources Mitigations

Implemented and demonstrated

- Parts
  - Vacuum valves and flexible hoses
  - Fasteners
  - Flanges
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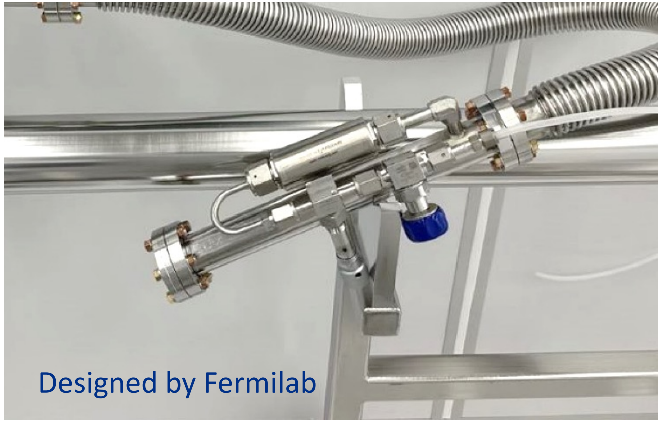
Infrastructure and Tooling Improvement – LCLS-II and HE

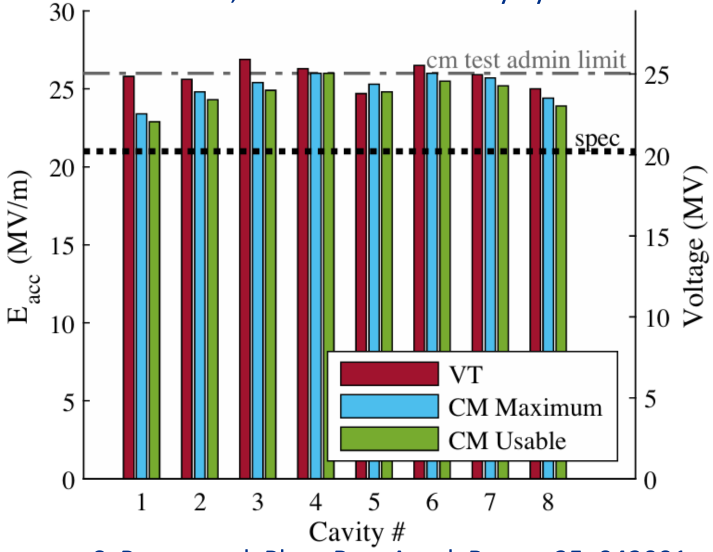


String assembly purging/backfill bypassed flexible vacuum hose

- Bypassing flexible hose proposed by Stephane Berry

- New purging design
- Skilled team
- 0.25 L/m purging and slow evacuation

LCLS-II HE vCM is completely FE-free, measured by all-around detectors, and at 100% RF duty cycle



S. Posen et al. Phys. Rev. Accel. Beams 25, 042001

Particle Sources Mitigations

Implemented and being validated

- Parts
  - Vacuum valves and flexible hoses
  - Fasteners
  - Flanges
  - Seals
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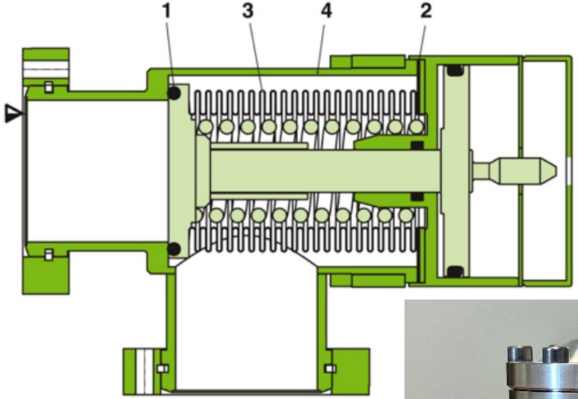
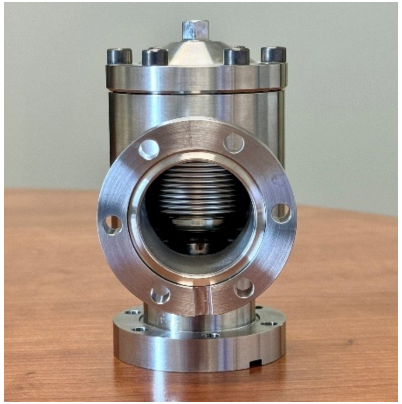
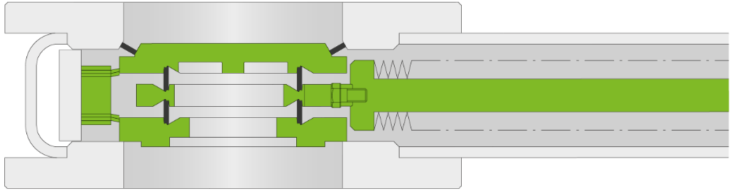
Particle Source Example – Valves



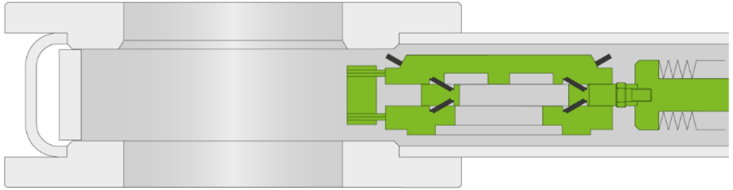
Legend

▼ - valve seat side
1 - plate seal
2 - bonnet seal
3 - bellows
4 - body

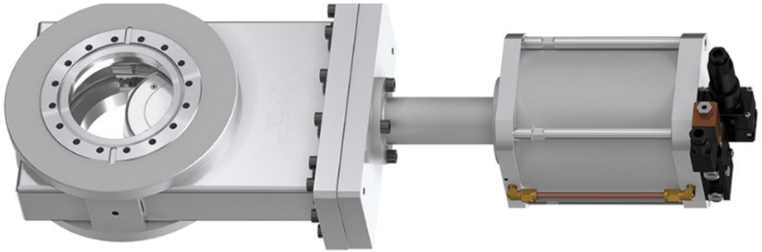




Closed



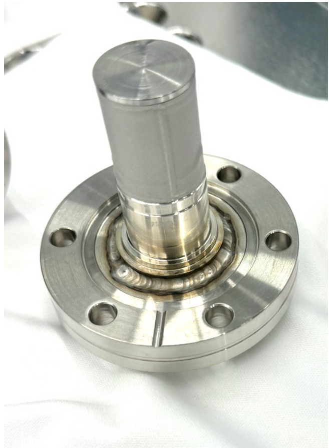
Open



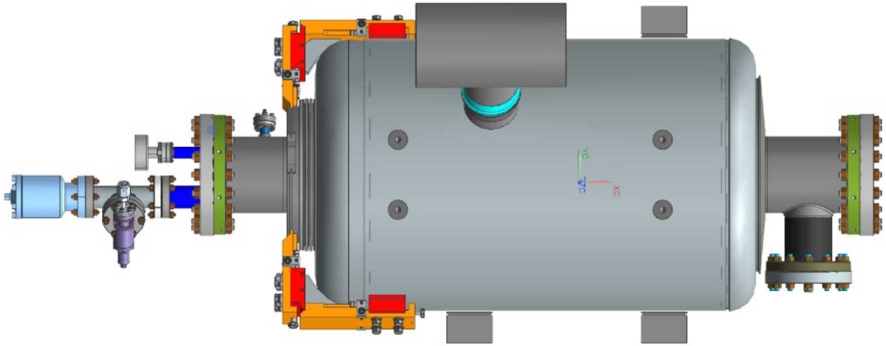
Cycling the valve generates particulates, even for the best valve on the market

Hardware and Component Design – PIP-II

- Purging through a cryogenic-compatible filter/diffuser



CEA/Saclay designed filter diffuser validated in a 9-cell cavity at CEA (Stephane Berry)



PIP-II Validation is in progress

Particle Sources Mitigations

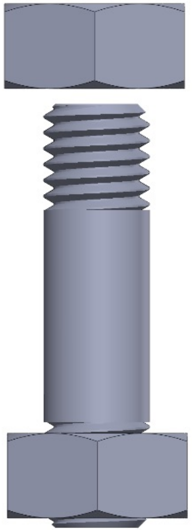
The conceptual design to be evaluated

- Parts
  - Vacuum valves and flexible hoses
  - Fasteners
  - Flanges
  - Seals
  - Tooling
- Processes and Assembly
  - Chemistry
  - Water rinsing
  - Assembly
  - Evacuation, backfill, and purging
- Operators
- Environment

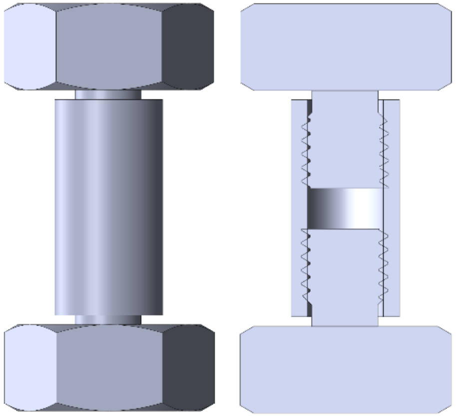
Hardware and Component Design – Low particulate hardware

The conceptual design will be evaluated

Standard design



Design #1



Design #2

Particle Sources Mitigations

Implemented and validated

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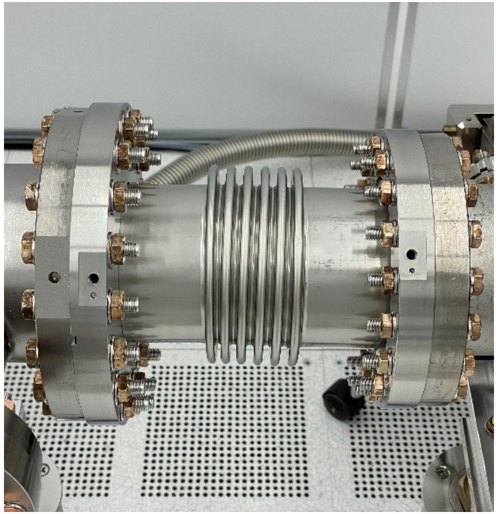
- Environment

Hardware and Component Design – Low particulate flanges

- Inter-cavity bellows

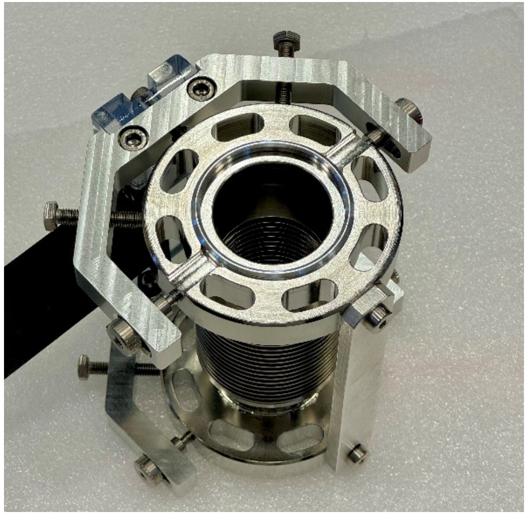


Standard Bellows

One side flange is fixed, and one side flange is rotatable.

LCLS-II HE bellows

Use the stud slots instead of through holes
It still has a rotatable flange on one side



PIP-II bellows

Use the slotted bolt holes instead of rotatable flanges - Mattia Parise and the PIP-II team

Particle Sources Mitigations

Implemented and is being validated

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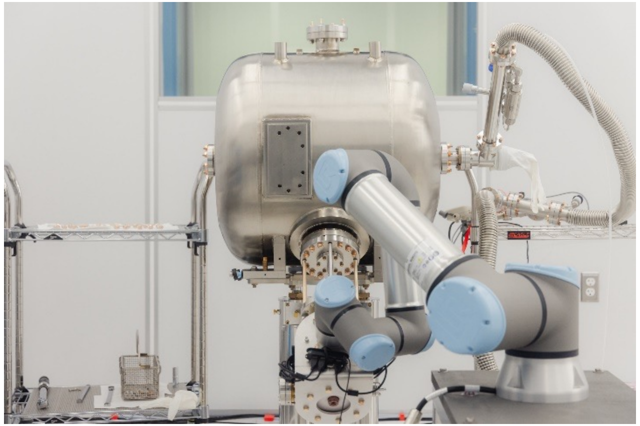
Infrastructure and Tooling Improvement – PIP-II

Robotic-assisted clean assembly

- Replaced complex support tooling
- Improved assembly ergonomic
- Reduced potential cavity contamination risk
- Potential for improved efficiency



Pre-alignment of the power coupler flange

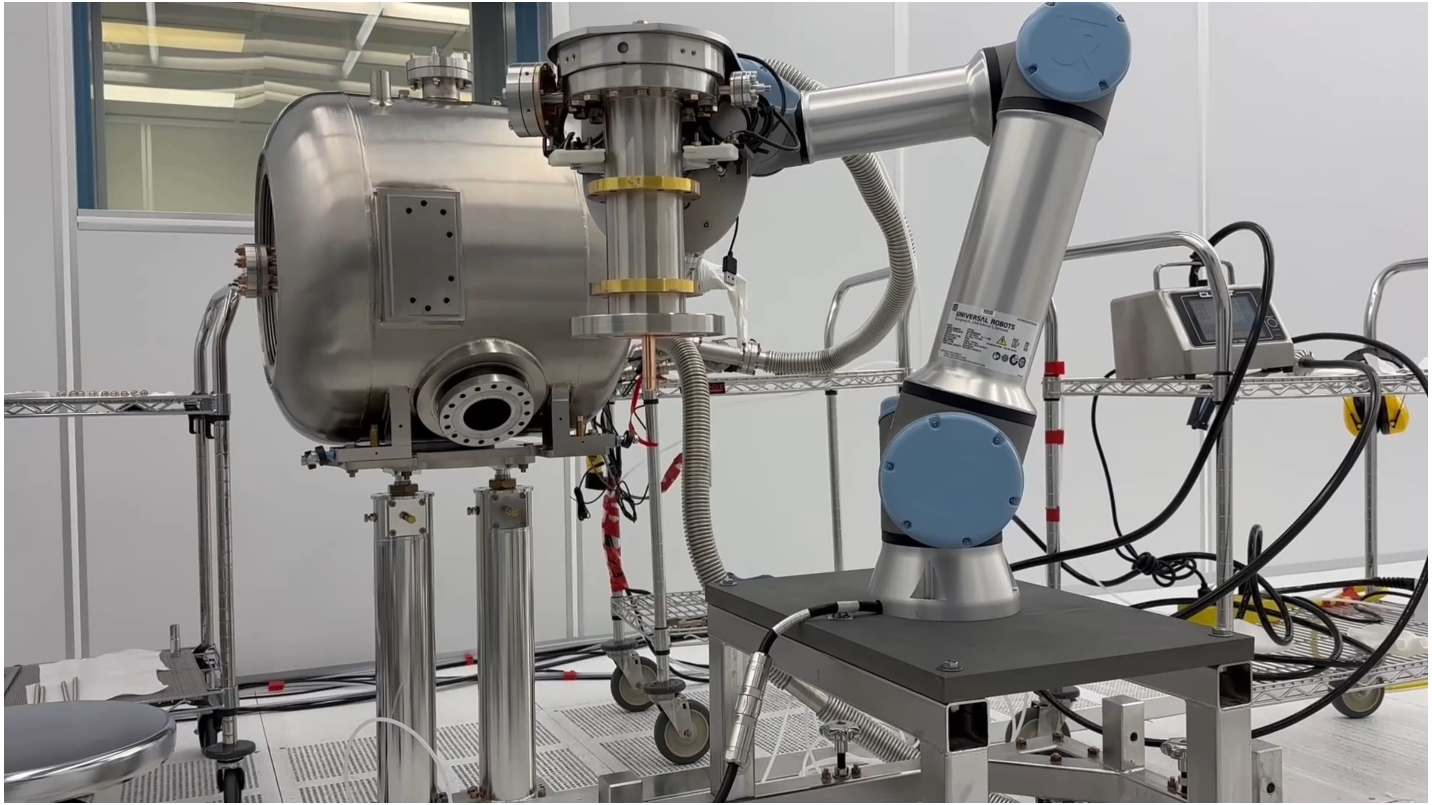
Fastener insertion after coupler inserted

SSR2 cavity test validated

5-cell LB650 cavity validation test planned

C. Narug, TTC’2023, Fermilab

Infrastructure and Tooling Improvement – PIP-II



C. Narug, TTC'2023, Fermilab

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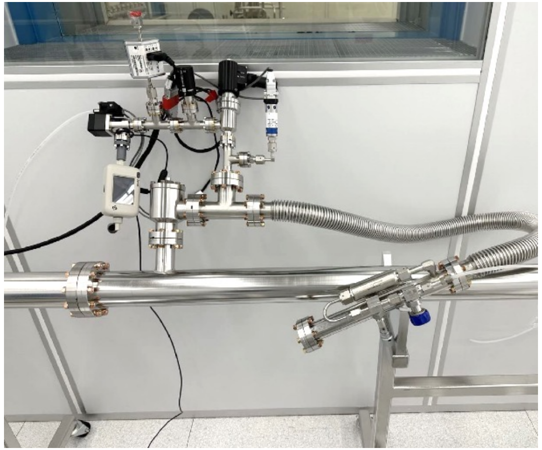
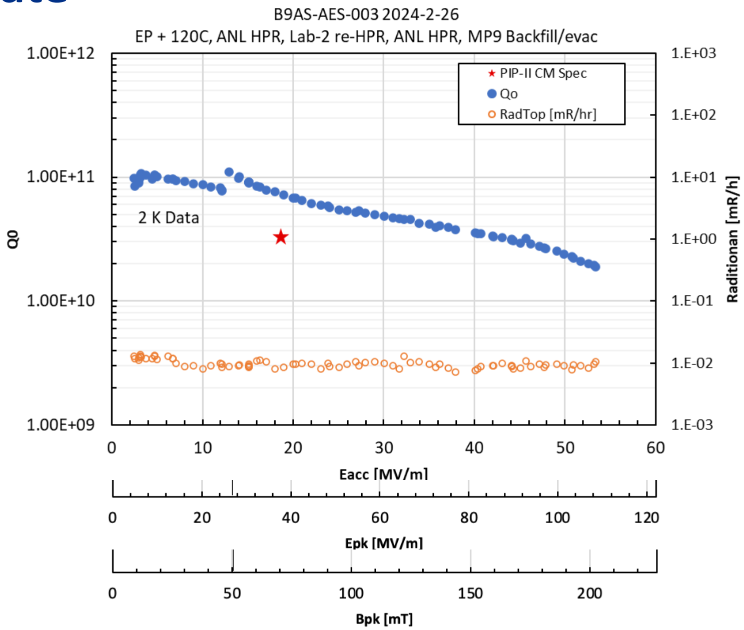
Procedure Improvement – PIP-II

- String assembly purging/backfill bypassed flexible vacuum hose
- **Backfill through RAV at a slow rate**
- **Evacuation through RAV at a slower rate**

Slow backfill and evacuation validated





1 L/m backfill and 0.3 L/m evacuation

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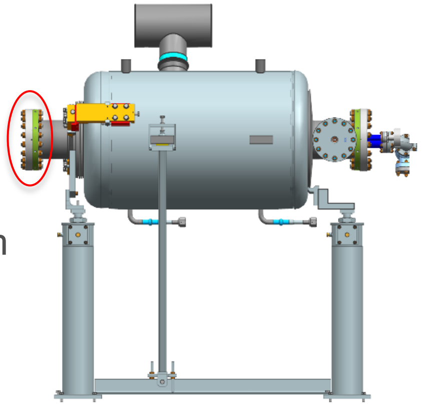
Purging Test – Flange replacement

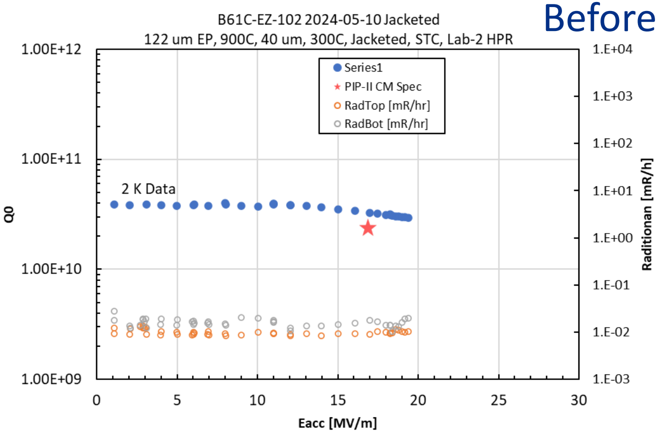
- Replaced cavity blank-off flanges with 1 L/m purging through RAV.
- Rotate and vertical test

  FE turn-on possible causes

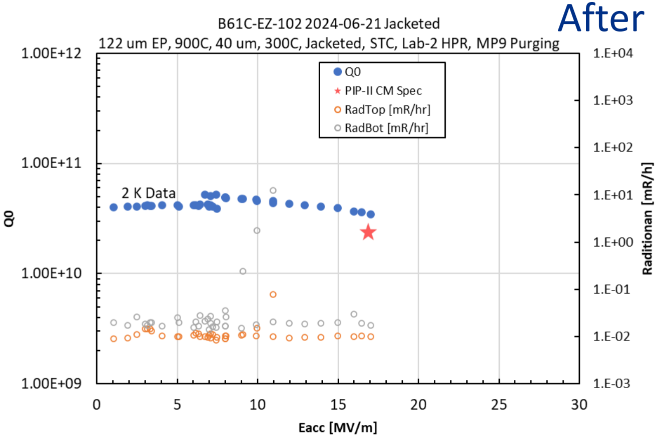
  - RAV purging moved the particulates into the cavity
  - Purging was not sufficient in preventing particles from migrating into the beam pipe from the left port.
  - Particulates at the left flange area fell into the cavity (likely event)



Before purging

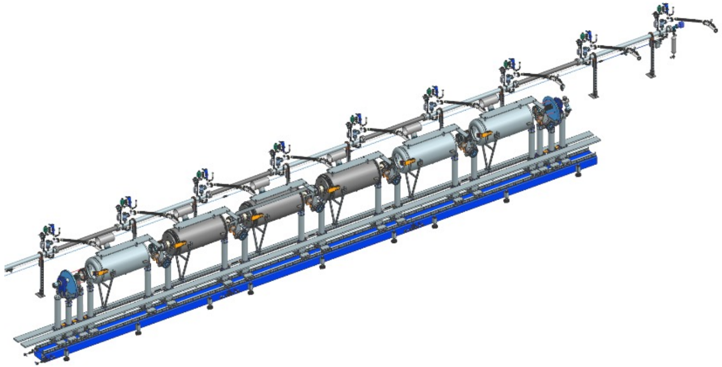


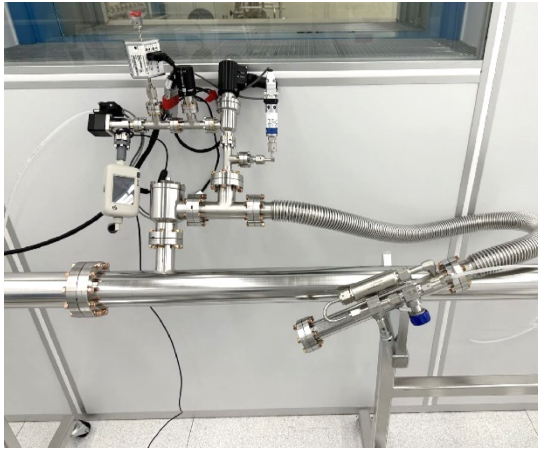
After purging



Flange connection has potential particulates

Infrastructure and Tooling Improvement – PIP-II





- String assembly purging/backfill bypassed flexible vacuum hose
- **Adjustable lower overpressure**

A precise pressure measurement, controllable overpressure, and fast detection of pressure drops were implemented for the new system.

A three-cavity HB650 half-string assembly has a volume of 0.29 m^3.
A 50 mbar overpressure could result in an effective 86 L/m flow rate through the half string.

Lower over pressure implemented and is being validated

Procedure Improvement – Slow purging and evacuation

Aperture	ID [mm]	MFC (LCLS-II) [L/m]	Double flow rate to HB650 [L/m]	HB650 Adopted [L/m]
1.3 GHz	78	0.25	0.5	
HB650 B92	118	0.38	0.76	0.85
HB650 B90	100	0.32	0.64	0.64
HB650 beampipe	61.4	0.2	0.39	0.32

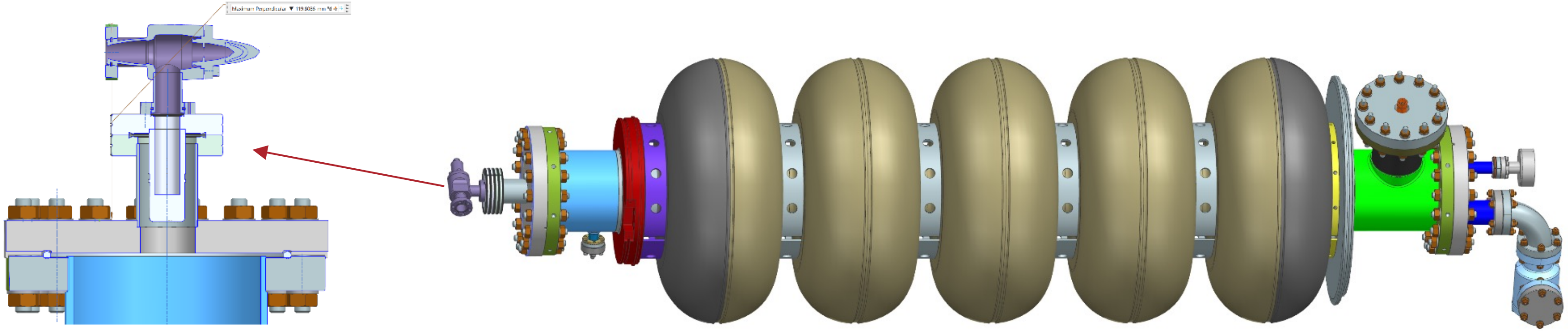
- The LCLS-II scaled flow rate was below the minimum 0.32 L/m of the temporary MFC unit.
- To avoid the uncertainty of the counter flow at the non-symmetric aperture connections,
  - Lowered the two beampipe rate to the MFC minimum, 0.32 L/m. Our hypothesis was the flow to the end sub-assembly is safer than the potential flow to the cavity.
  - Increased the B92 flow to 0.85 during the two B92 cavities to bellows joints.
- Flow rate was adjusted for each connection according to the table
- Purging system should have a range of 0.25 – 3 L/m. (Fermilab R&D purging system had 0.32 – 12 L/m.)

The purging rate needs to balance between preventing particles from migrating into the cavity through openings and migrating from joint area to cavity cells.

Procedure Improvement – Install filter diffuser before test preparation

- Use top mounted filter diffuser to purge during the cavity HPR and drying during test preparation

The conceptual design to be evaluated



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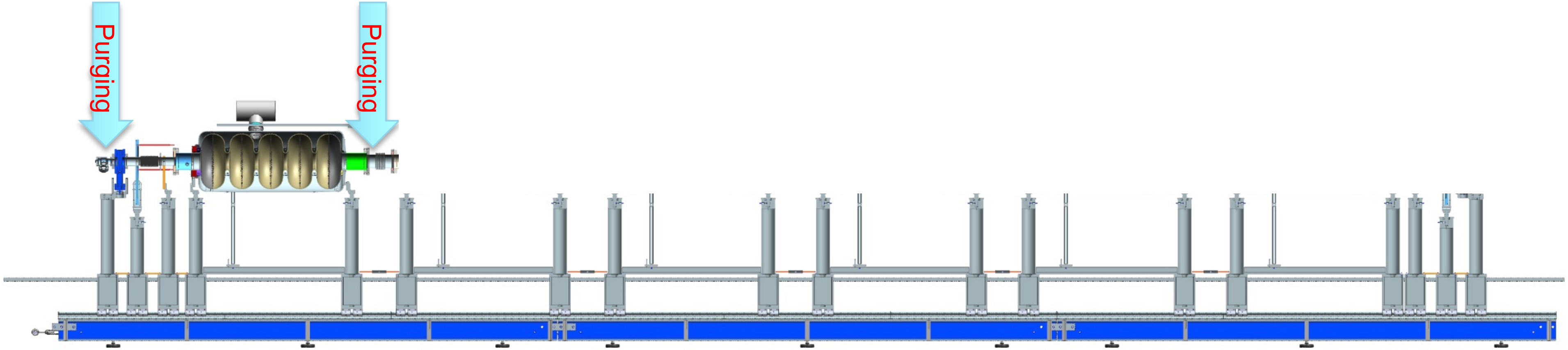
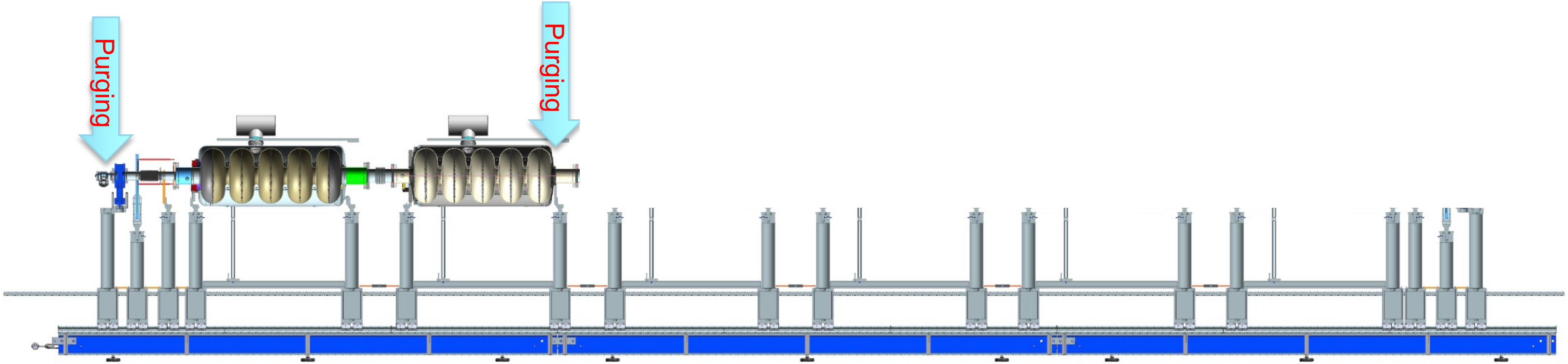
Procedure Improvement – Local purging instead of purging through string end



- Current purging design in a string assembly

Procedure Improvement – Local purging instead of purging through string end



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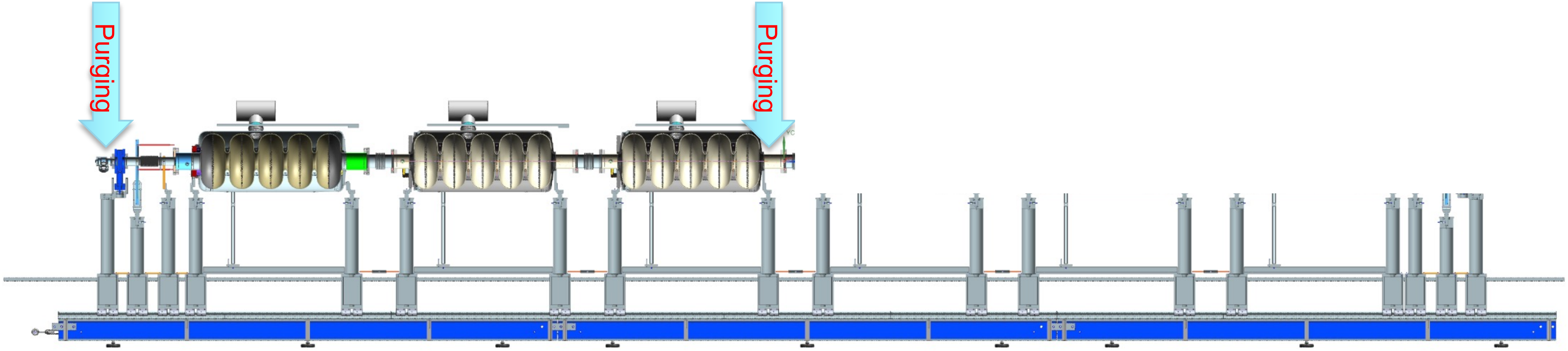

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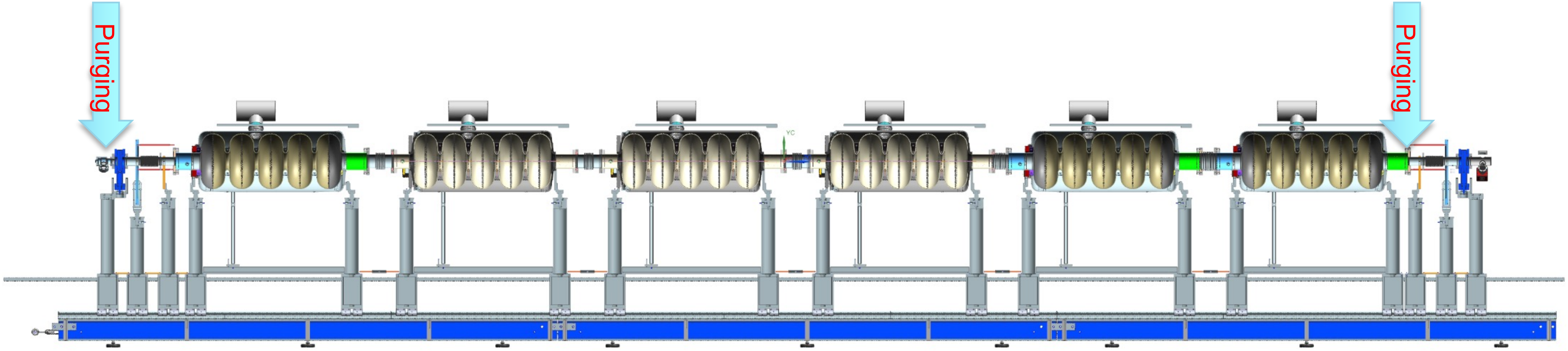
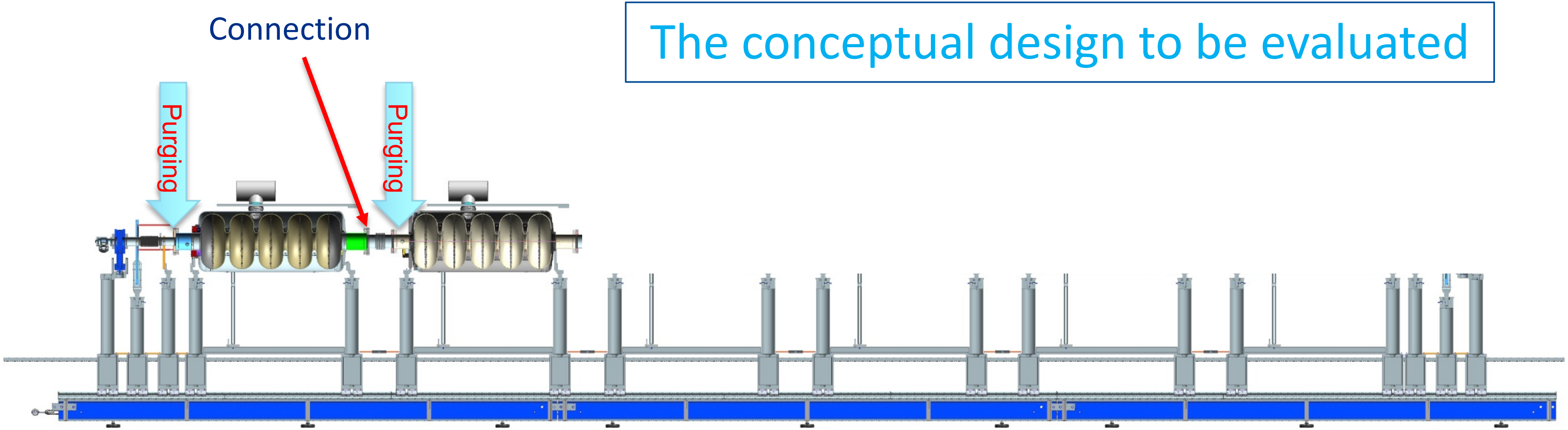


- Current purging design in a string assembly

Procedure Improvement – Local purging instead of purging through string end

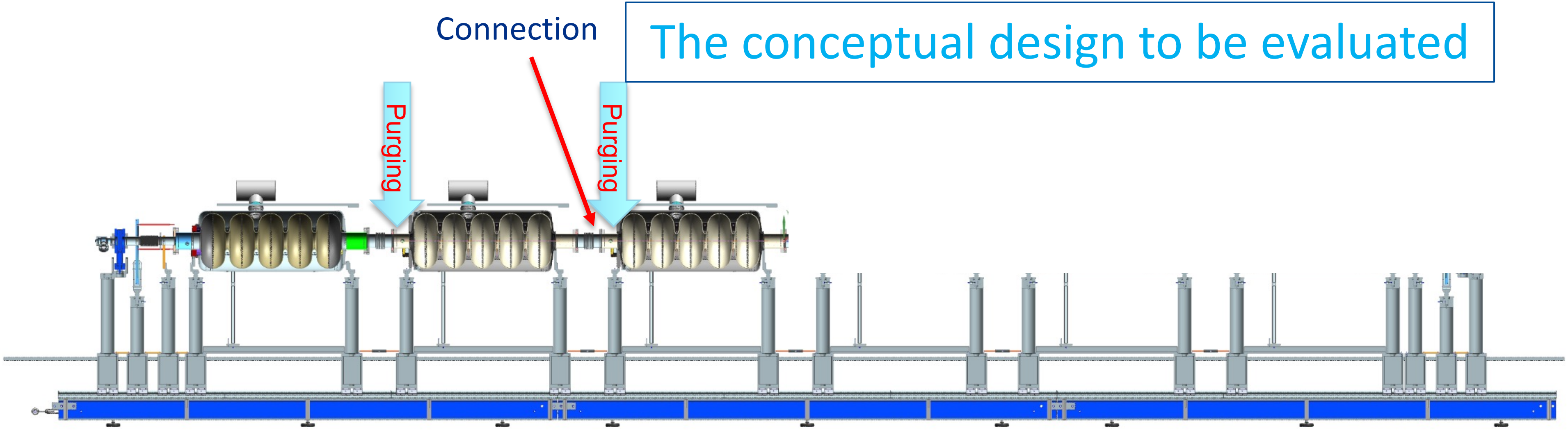
The conceptual design to be evaluated



- Adding a dedicated purging port near the field probe
- Or use the field probe port to purge

Procedure Improvement – Local purging instead of purging through string end

The conceptual design to be evaluated



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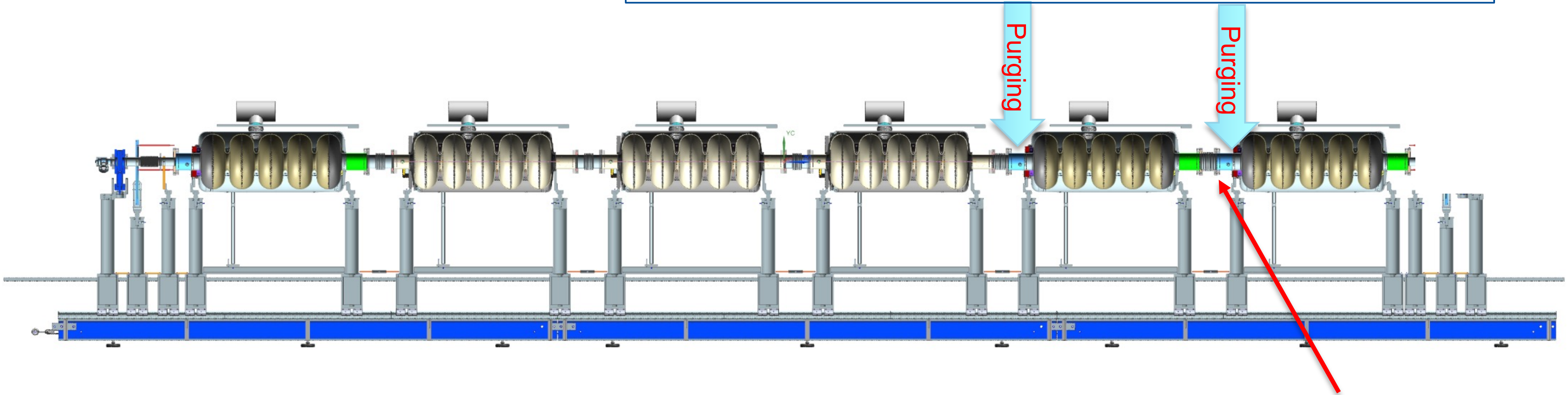

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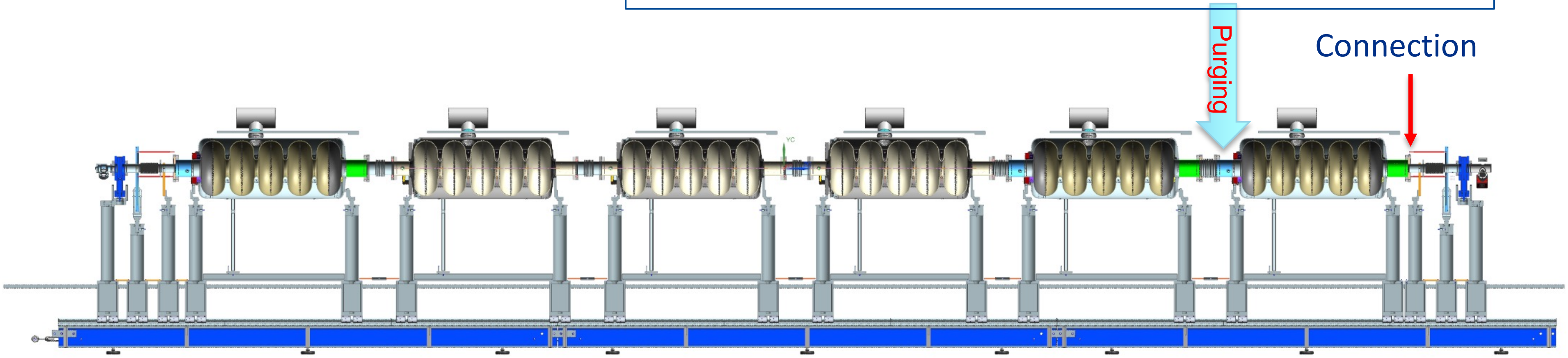

Three options

1. Keep the filters in the cryomodule
2. Replace the filter with blank-off flanges
3. Using the field probe port filters and replace the filters with field probes after completion

Particle Sources Mitigations

- Parts
  - Validating – Vacuum valves by-passing
  - Validated – flexible hoses by-passing
  - Conceptual – Fasteners cleaner design
  - Validating – Flanges clean design
  - Seals
  - Validated – Tooling Robotic
- Processes and Assembly
  - Chemistry
  - Water rinsing
  - Validating – Assembly Robotic
  - Validated, validating and Conceptual – Evacuation, backfill, and purging Optimization
- Validated – Operators Robotic

Summary

- Fermilab has assembled thousands of vertical tested cavities and ~38 CM.
  - The particulate control remains a challenge from time to time.
    - Many lessons learned and improved over the years.
- Fermilab has developed and implemented a mature design of the vacuum operations of SRF cavities and strings.
- Future improvements were identified and planned to be validated and implemented

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Acknowledgement

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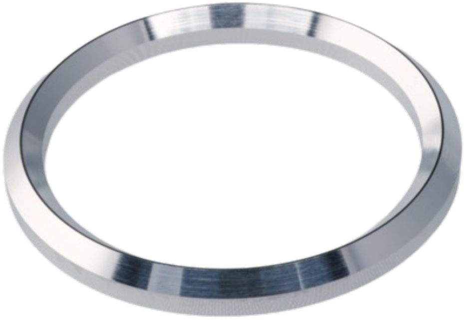
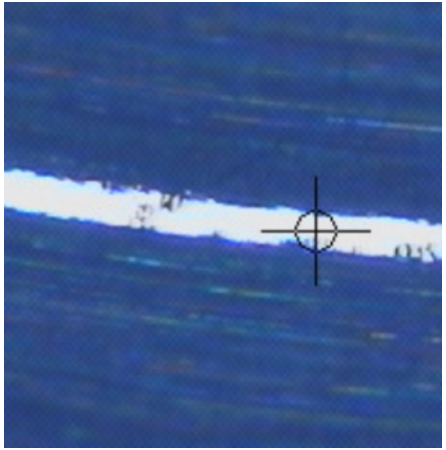
- Support comes from projects like the LCLS-II, PIP-II, and GARD.

Backup

Particle Source Example – Fasteners and Seals





Fastener torquing and seal crush/cutting generate particulates

Particle Source Example – Tooling

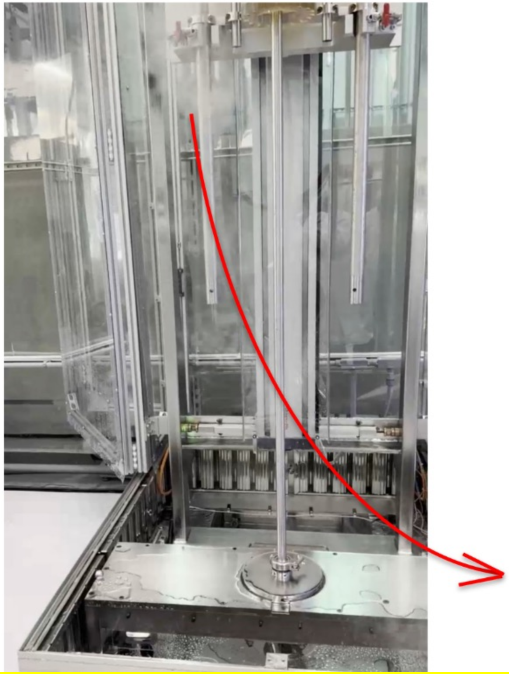
Tooling movement generates particulates

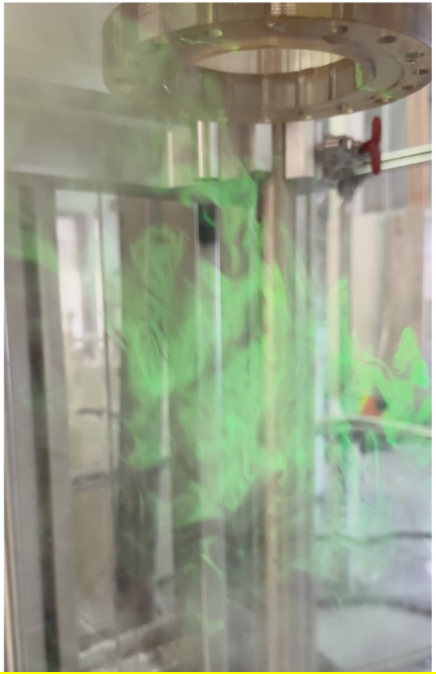
Particle Source Example – Processing and Assembly

- Chemical residuals
- High-pressure water rinsing
- Assembly
- Evacuation, Backfill, and Purging
  - Flexible vacuum hose a challenge to clean
  - Vacuum pumps

Particle movement can be hard to mitigate

Particle Source Example – Operator and Environment





Operator in an unfavorable airflow exacerbates the particle moving into the cavity

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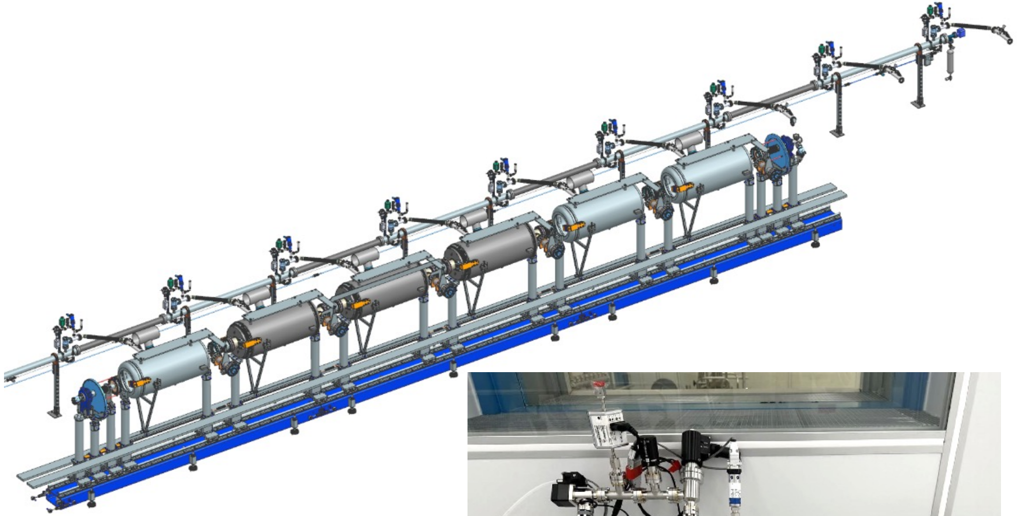
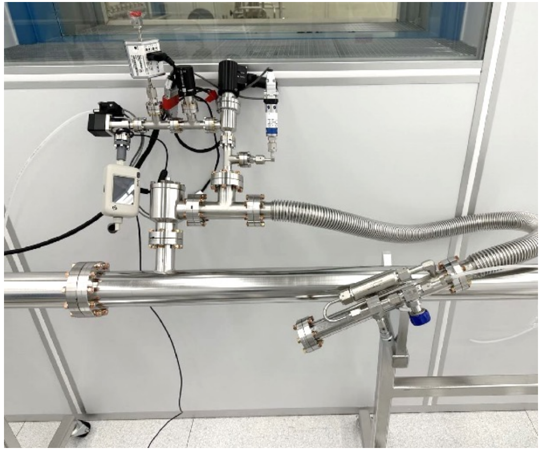
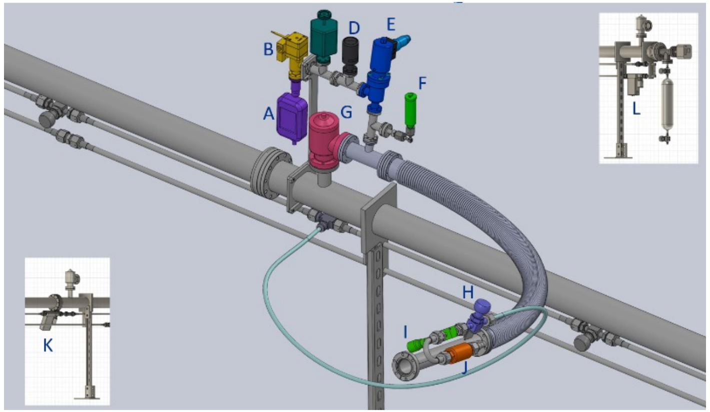
Special purging configuration at Fermilab







A	Flow meter – Vent
B	Electric RAV for opening vent
C	Differential pressure transducer
D	1 psi blow-off safety valve
E	Manual RAV to isolate vent purge system
F	Absolute pressure sensor – UHV rated
G	RAV vacuum system isolation
H	¼ turn valve
I	Manual flow control needle valve
J	Filter
K	Upstream MFC with shut off
L	Downstream MFC with shut off

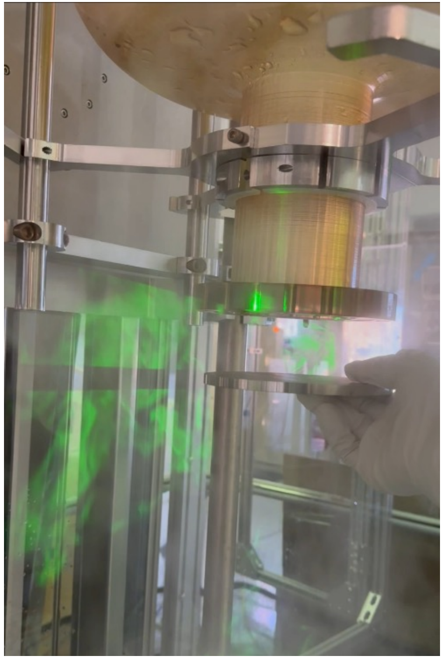
Large-size cavity overpressure optimization

- A standard 50 millibar overpressure would cause high-speed flow when released during cavity flange removal. The mass flow increases when cavity volume increases. 650 MHz and spoke cavities have a substantial risk of uncontrolled pressure change
- 1.3 GHz string assembly has the potential risk of pressure surge for the last several connections.
- Avoid the potential pressure wave that could have moved the particulates in the string assembly

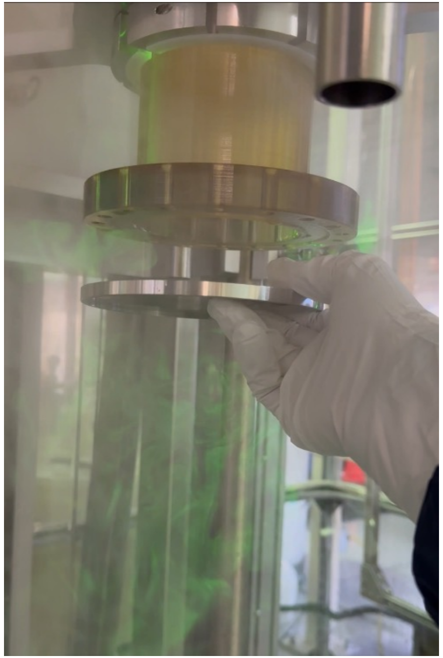
- A much lower overpressure, such as 5 mbar instead of 50 mbar, would reduce this risk significantly. A precise pressure measurement, controllable overpressure, and fast detection of pressure drops are required for a new system

The purging rate

- 0.25 – 1 L/m std.
- Purging rate needs to balance between preventing particles from migrating into the cavity through openings and migrating from joint area to cavity cells.

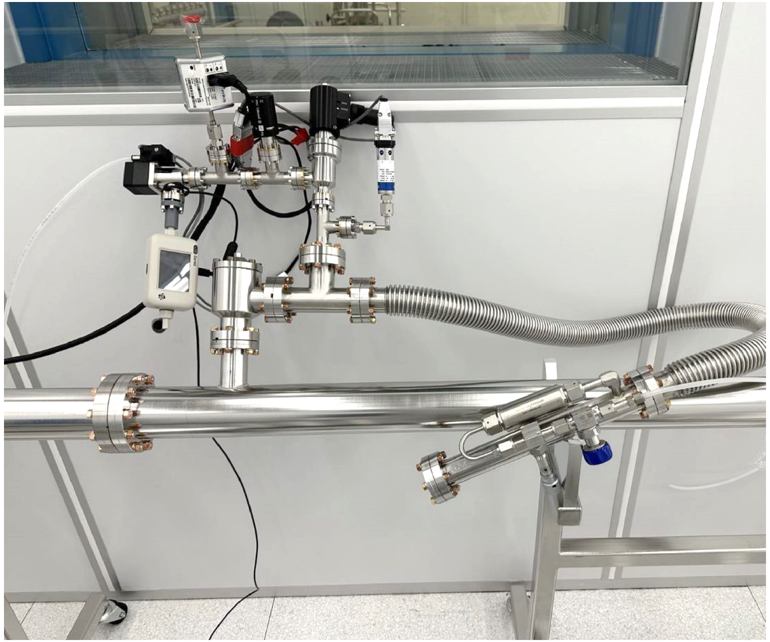


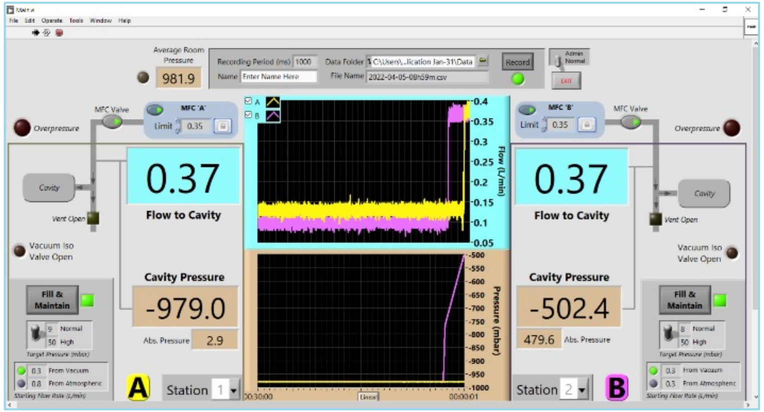
cavity top port covered



cavity top port open

Special purging configuration at Fermilab





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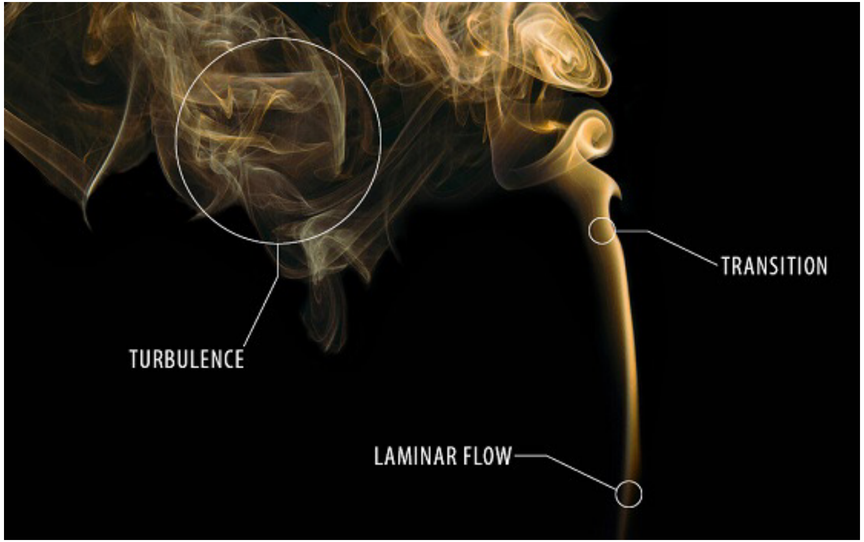
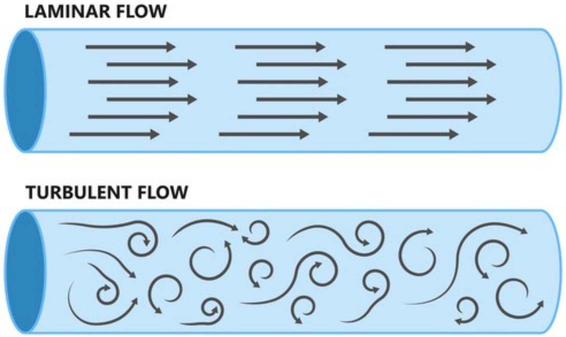
Laminar and turbulent flow



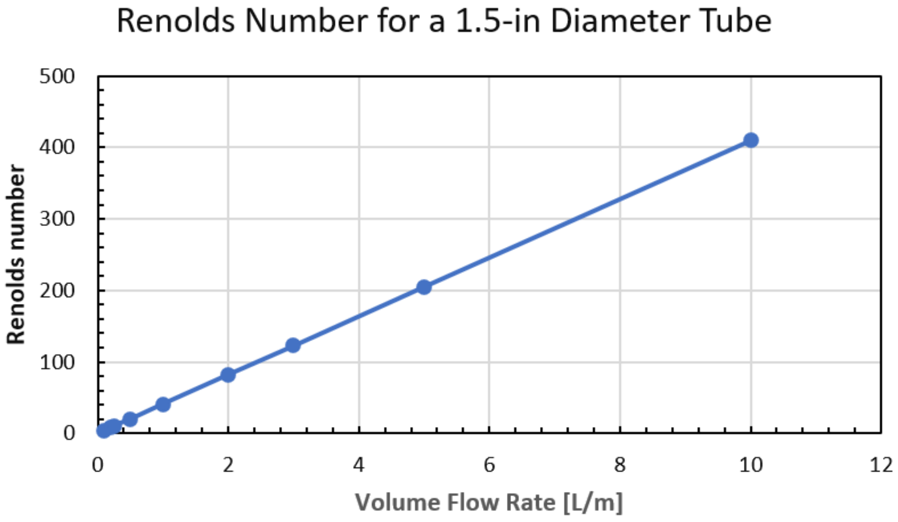


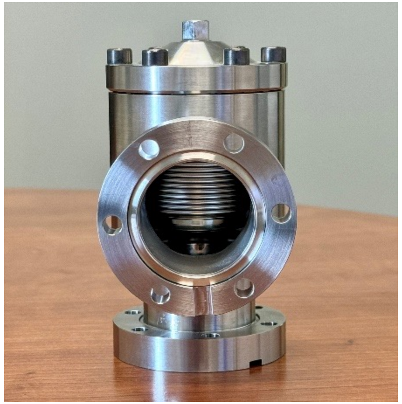
$$\text{Reynolds number (Re)} = \frac{\text{Density} \times \text{Velocity} \times \text{Characteristic linear dimension}}{\text{Dynamic viscosity}}$$

https://www.bronkhorst.com/

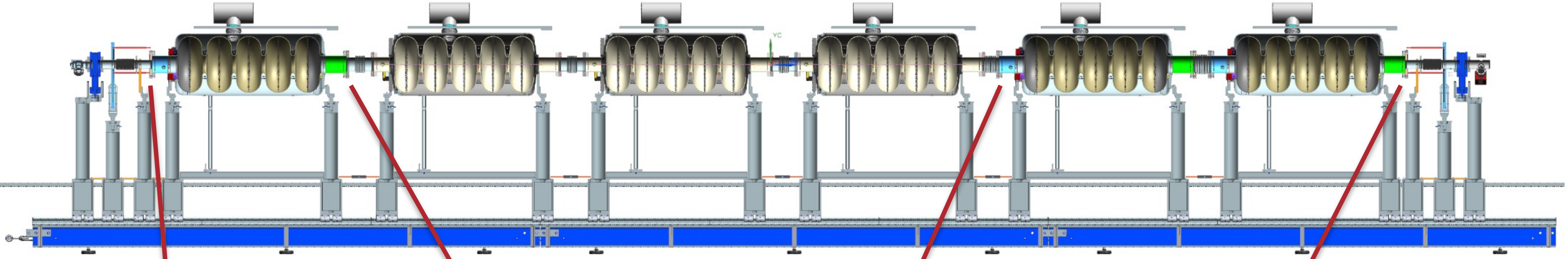
Slow evacuation

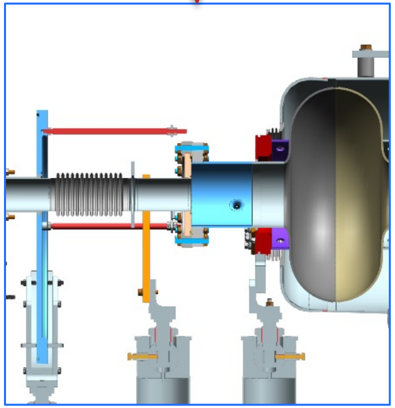
- Much lower flow rate for a laminar flow
- 0.25 L/m std.

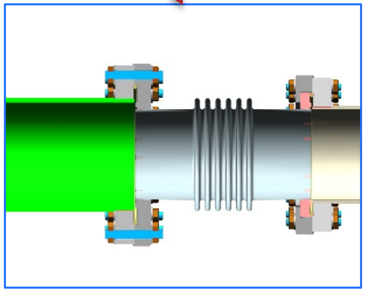


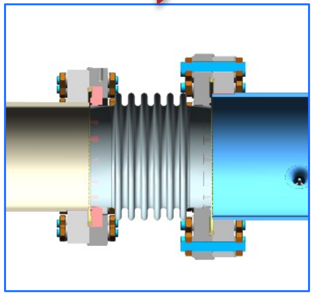


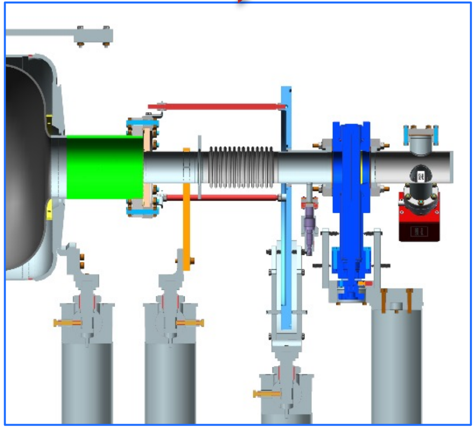
PHB650 String assembly – four connections have non-symmetric purging



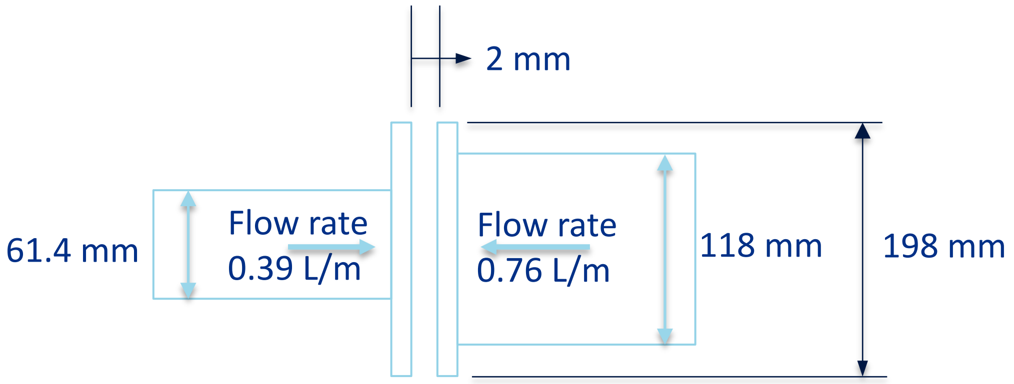








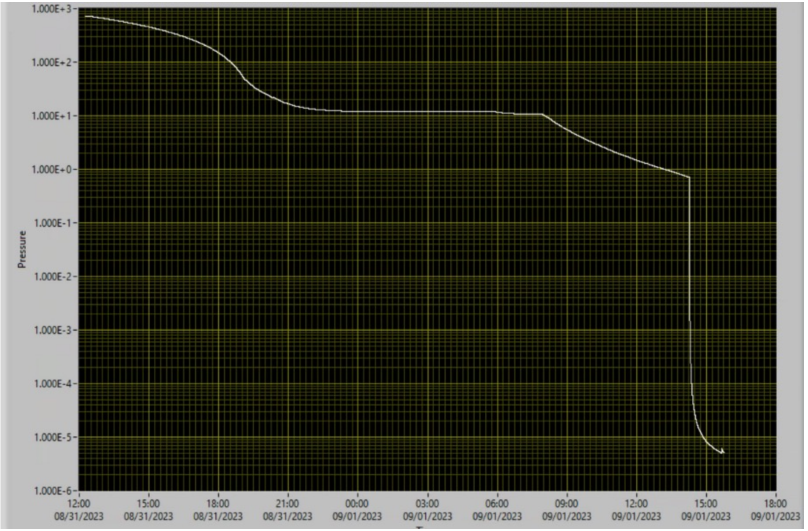
Flow dynamics at the non-symmetric connections
Work in progress

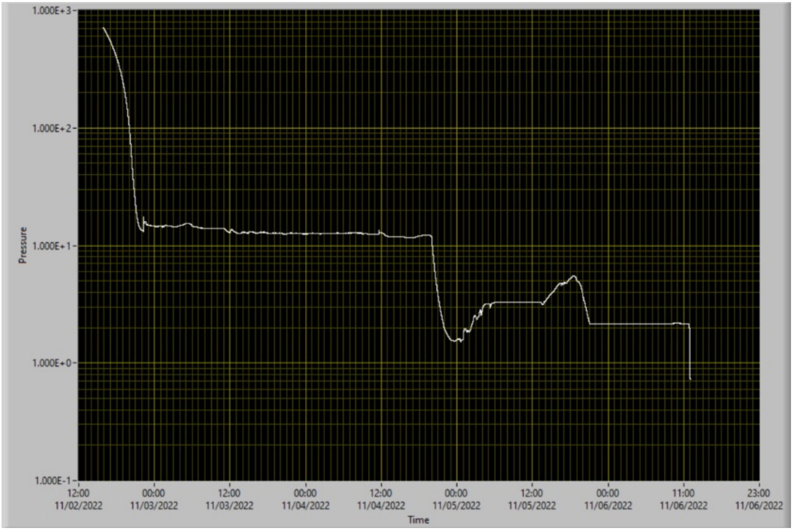


Need to know the local turbulence

Need to know if there is flow going inside of either beam pipe

Particle source – Processing and Assembly: Vacuum pump





Particle movement can be hard to mitigate