Fermilab

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Cavity Preparation and Assembly:
Challenges and Future R&D Directions

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Genfa Wu
GARD RF Roadmap Update - SRF

U.S. DEPARTMENT of ENERGY
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Agenda

Current State-of-the-Art and Challenges

- ✓ Cavity statistics
- ✓ Cryomodule statistics
- ✓ Linac cavity experiences
- ✓ LCLS-II and PIP-II approaches

Improvement Opportunities and Future R&D

- ✓ Knowledge gaps
- ✓ Tailored mitigation strategies
- ✓ Comprehensive studies for particle dynamics
- ✓ Systematic design optimizations

This presentation is not meant to be all things considered.

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01

Current State-of-the-Art and Challenges

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Cavity statistics

LCLS-II [1] / XFEL [2]

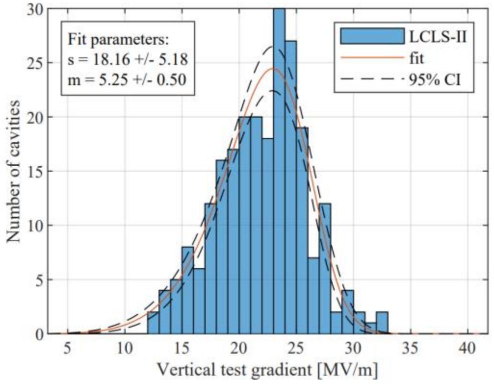

Figure 1: Distribution of peak gradients achieved by LCLS-II cavities in vertical test after administrative limit was removed. Also shown is the model with fitted parameters and 95% confidence interval.

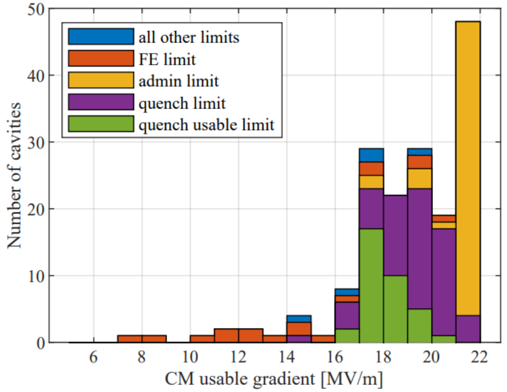

Figure 2: Stacked histogram of the distribution of limits to the usable accelerating gradient of LCLS-II cavities installed in cryomodules.

LCLS-II and HE cavity VT acceptance requires FE-free

XFEL Cavity acceptance*

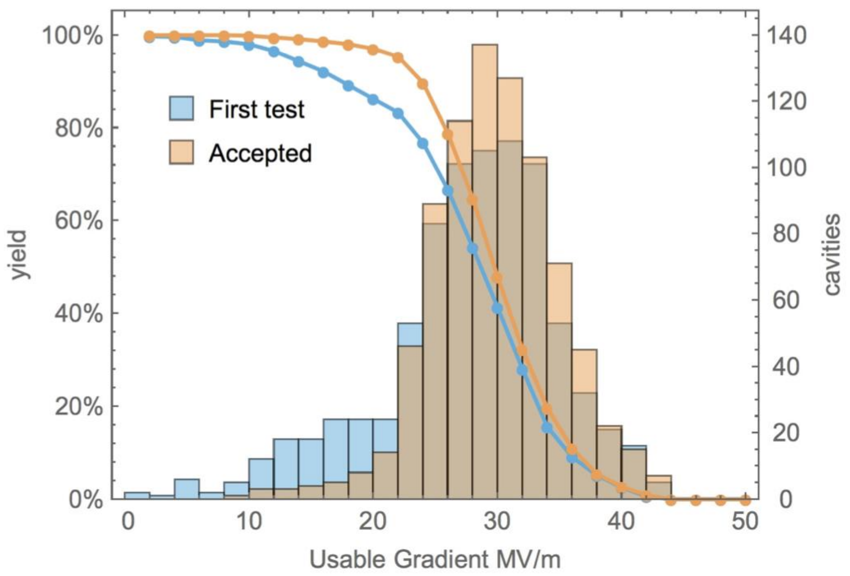

Figure 9: Comparison of the first ("as received") and final accepted usable gradient distributions.

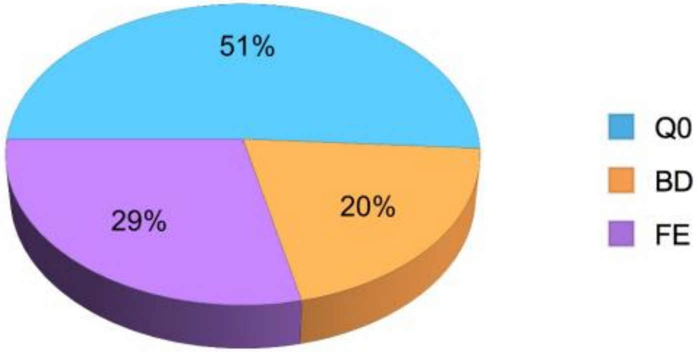

Figure 4: Breakdown of limiting factor (quench "BD", Q_0 "Q0" or field emission "FE") for the "as received" usable gradient.

[1] J.T. Maniscalco, et al., Proc. of 20th Int. Conf. on RF Superconductivity SRF2021, East Lansing, MI, USA, **HPCAV009**.
[2] N. Walker et. al., Proceedings of LINAC2016, East Lansing, MI, USA, **WE1A04**

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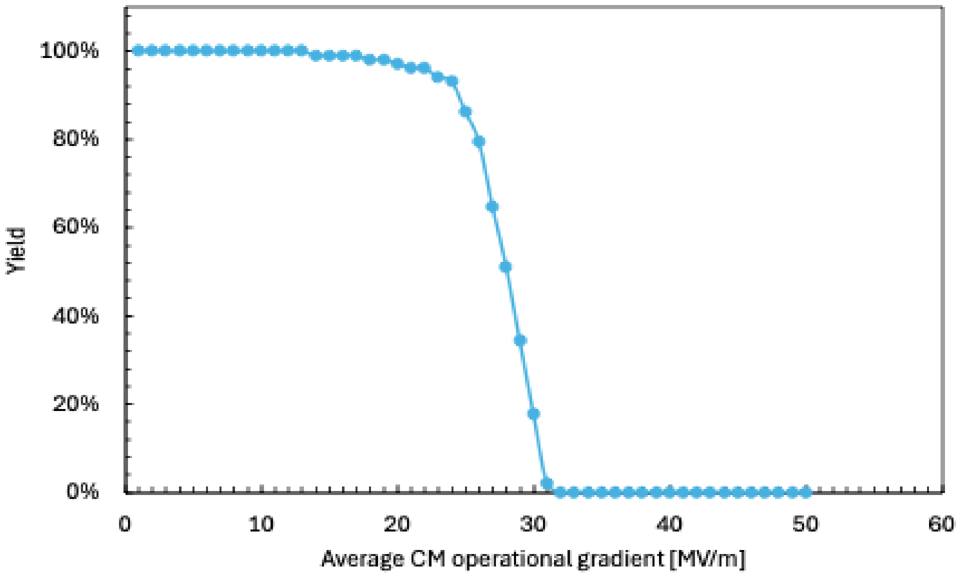
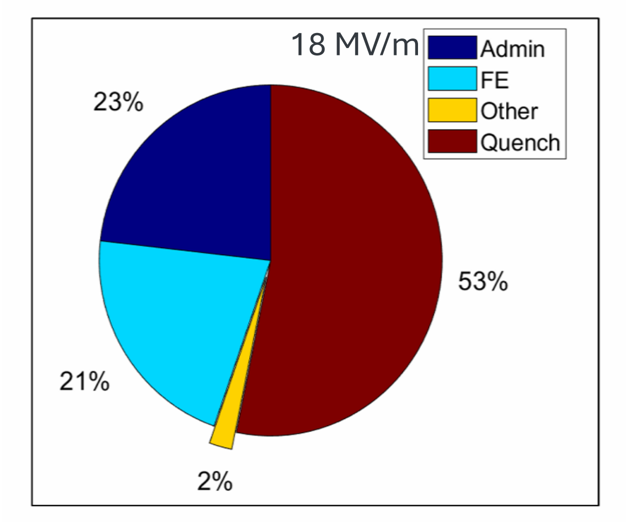
Cryomodule statistics

XFEL/LCLS-II/HE

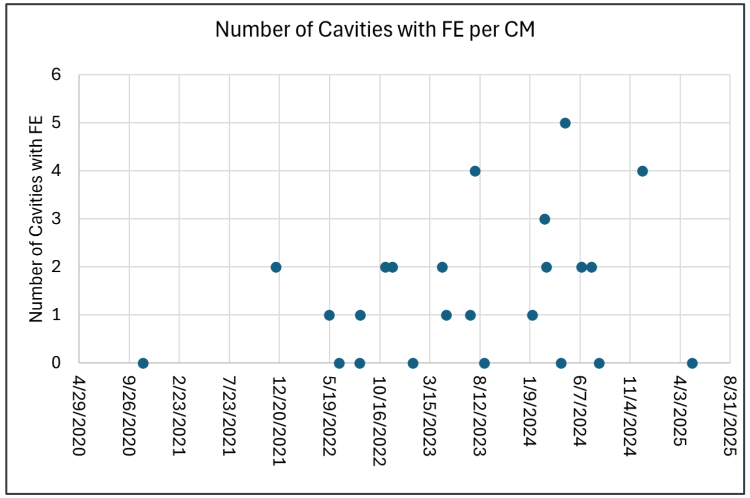
LCLS-II and HE cavity acceptance requires FE-free



XFEL Cryomodule performance [1]



LCLS-II Cavity performance limitations [2]



LCLS-II-HE: number of cavities with FE [3]

[1] N. Walker et. al., Proceedings of LINAC2016, East Lansing, MI, USA, WE1A04
[2] D. Gonnella, Proceedings of SRF’23, Grand Rapids, MI, USA, MOIAA04
[3] M. Checchin, Private communication

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Linac Cavity Statistics

XFEL[1] and LCLS-II[2]

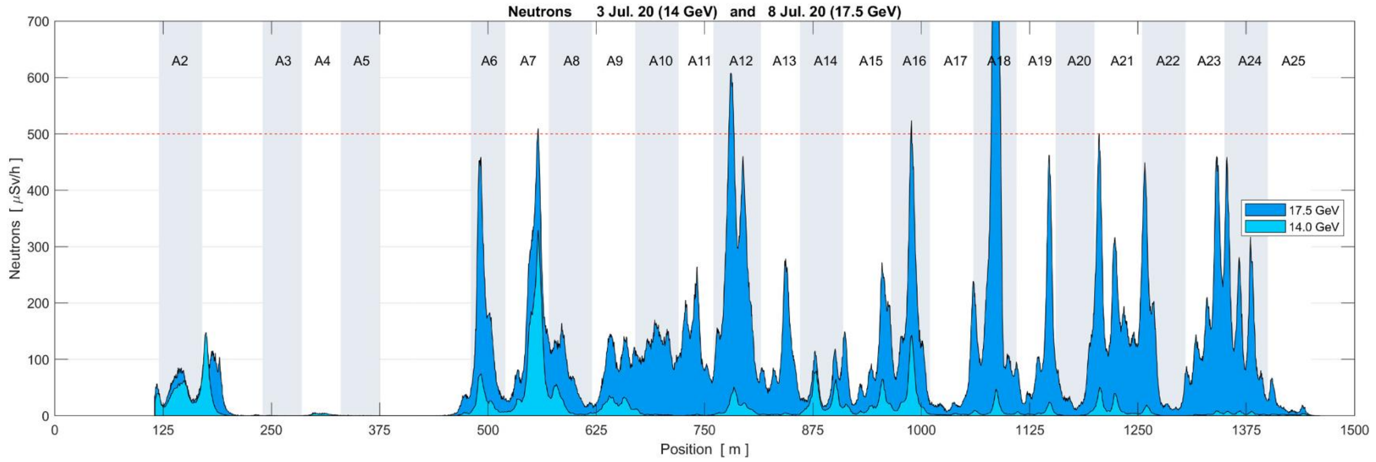
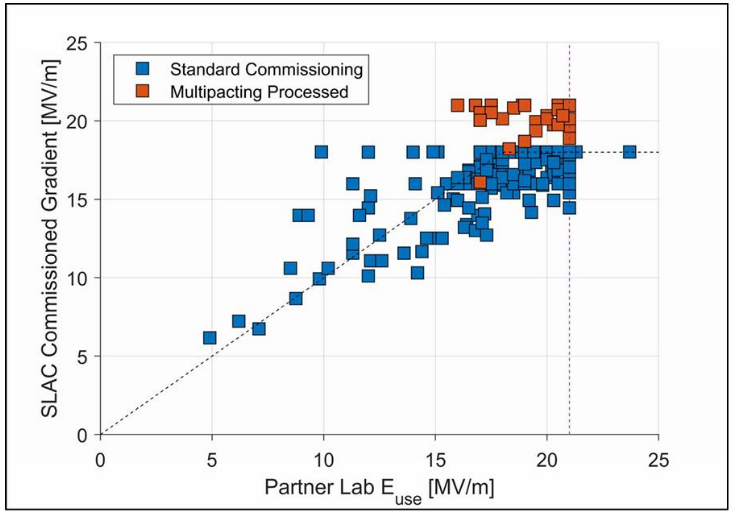
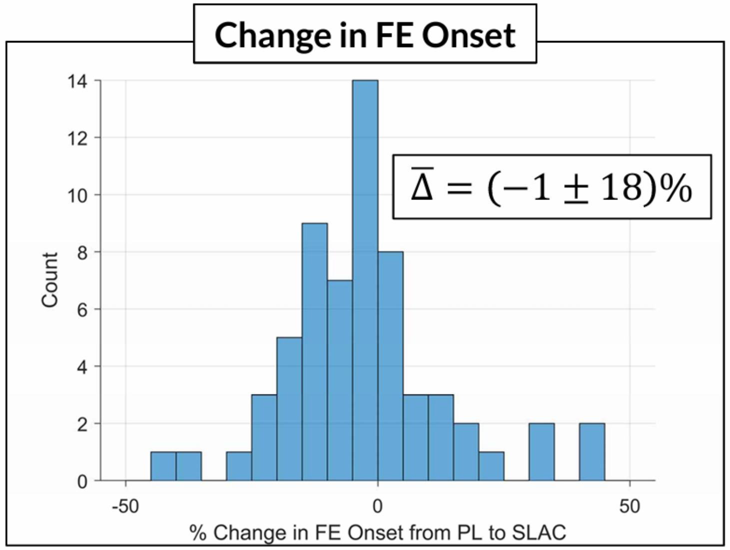


Figure 5: Neutron map of the accelerator at 14.0 and 17.5 GeV. The administrative limit is 500 μSv/h. A12 was operated above its maximum allowed gradient (radiation limited). A18 had a newly detected field emitter. After investigation, the emitting cavity was detuned, returning the overall neutron radiation of the station below the administrative limit.

LCLS-II





No statistical degradation due to installation. Operational experience is still pending.

[1] J. Branlard et al., "Four Years of Successful Operation of the European XFEL", Proceedings of 20th Int. Conf. on RF Superconductivity, SRF2021, East Lansing, MI, USA, MOOFAV06
[2] D. Gonnella, Proceedings of SRF'23, Grand Rapids, MI, USA, MOIAA04

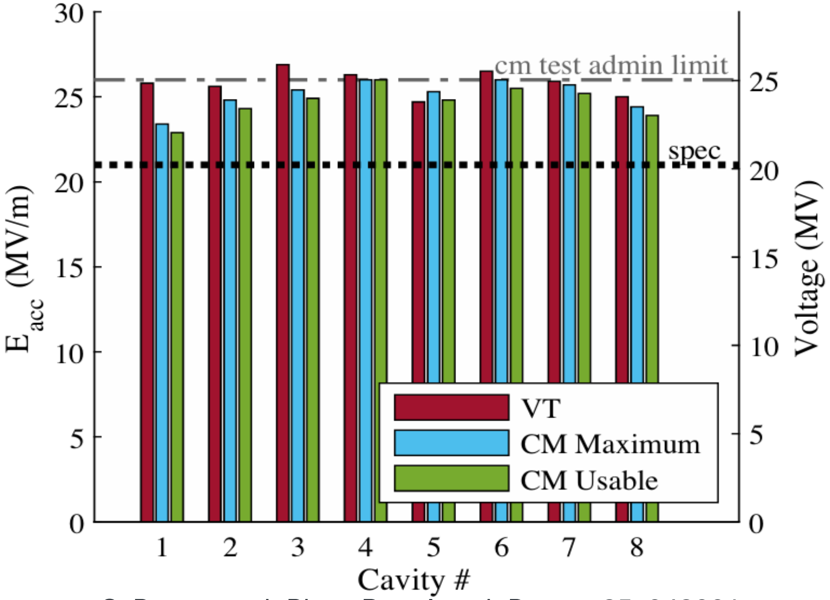
LCLS-II and HE Improvement

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

String assembly purging/backfill bypassed flexible vacuum hose

- Bypassing the flexible hose proposed by Stephane Berry

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



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

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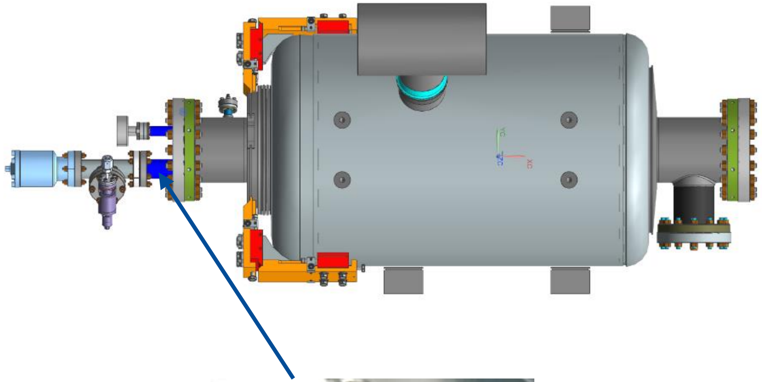
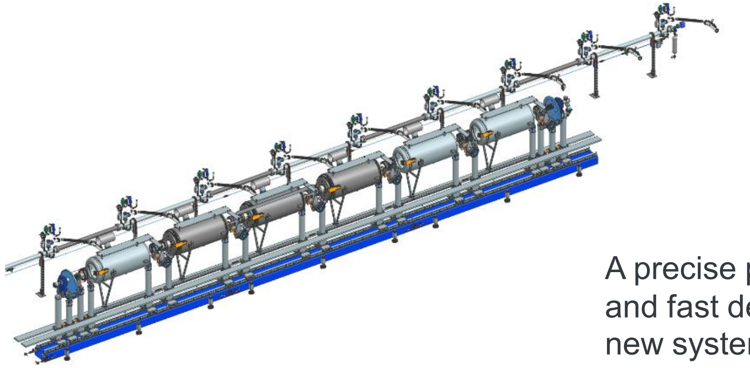
Infrastructure and Tooling Improvement

PIP-II Improvement

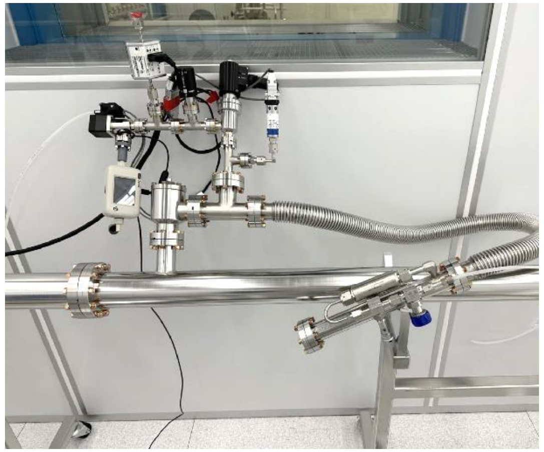


CEA/Saclay designed filter diffuser (Stephane Berry)
Validated



- 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 overpressure was implemented and is being validated

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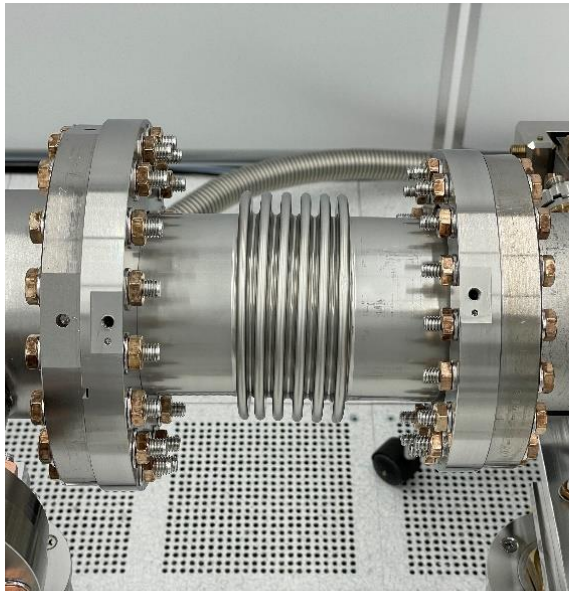
Hardware and Component Design

Low particulate flanges



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

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Infrastructure and Tooling Improvement

PIP-II Improvement

Robotic-assisted clean assembly
- Reduced potential cavity contamination risk
- Improved assembly ergonomics
- Improved efficiency

Pre-alignment of the power coupler flange C. Narug, TTC'2023, Fermilab

Cobot-assisted coupler assembly at CEA J. Drant and S. Berry, PIP-II Communication

Cobot-assisted cavity assembly for vertical test

- SSR2 cavity coupler assembly validated
- 5-cell LB650 coupler assembly validated
- 5-cell LB650 cavity VT cleanroom assembly validation in progress

02

Improvement Opportunities and Future R&D

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A Big Knowledge Gap

Anecdotal

We believe

Statistics

Empirical

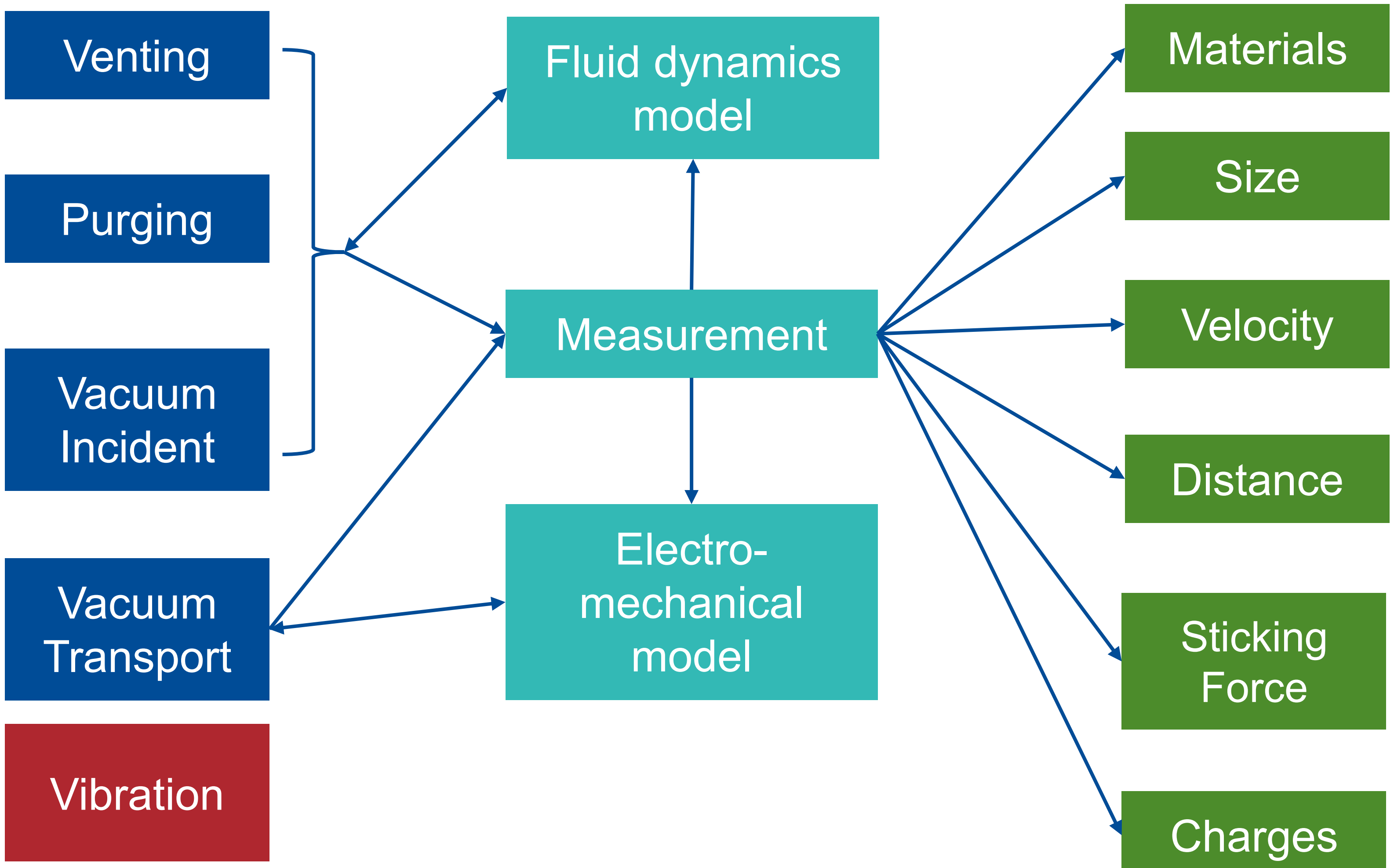
Hypothesis

Very likely

Best practice

We are not sure

Comprehensive studies for particle dynamics



Improve our understanding from empirical to experimental

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Tailored mitigation strategies

The first few steps

	• Parts
Validating	– Vacuum valves
Validated	– flexible hoses
Conceptual	– Fasteners
Validating	– Flanges
	– Seals
Validated	– Tooling
	• Processes and Assembly
	– Chemistry
	– Water rinsing
Validating	– Assembly
Validated, validating and Conceptual	– Evacuation, backfill, and purging
Validated	• Operators

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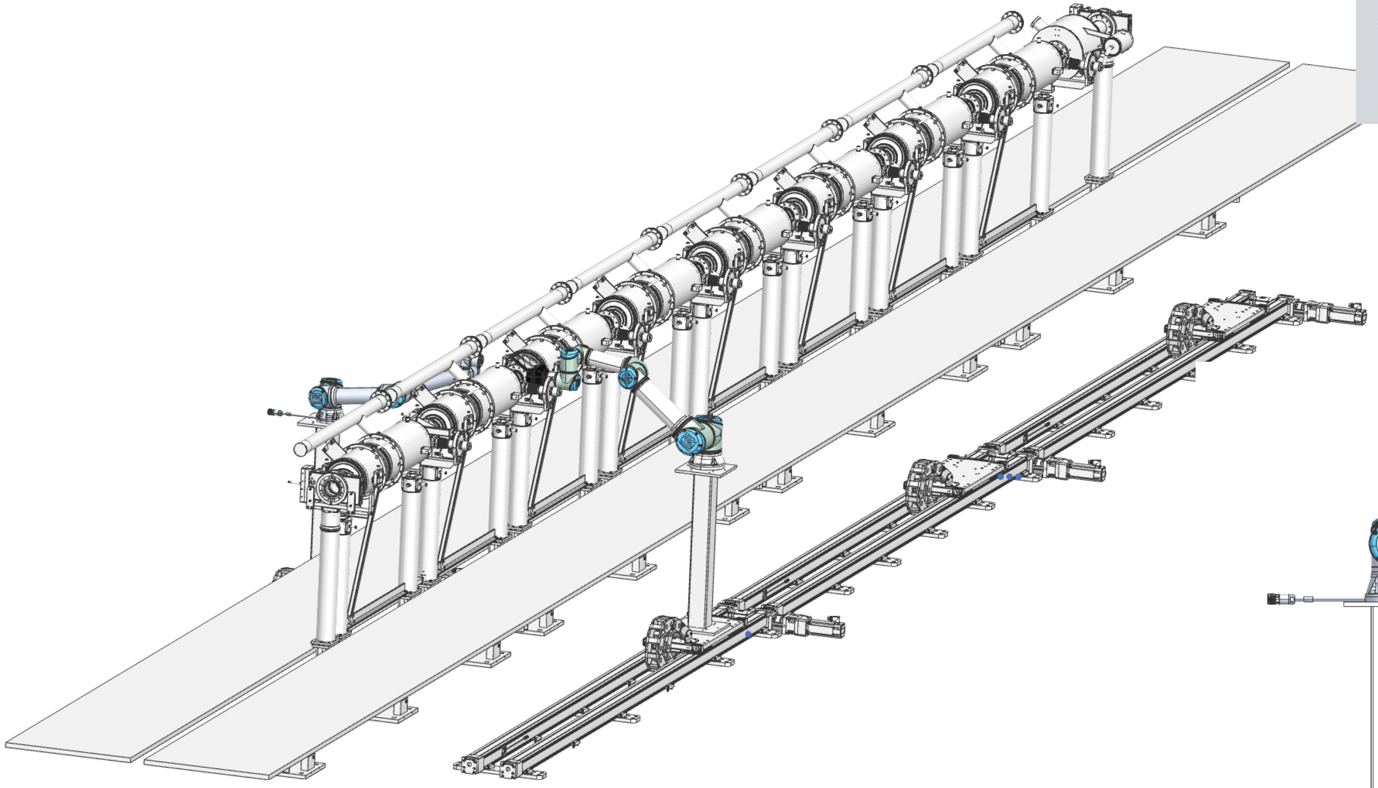
Infrastructure and Tooling Improvement

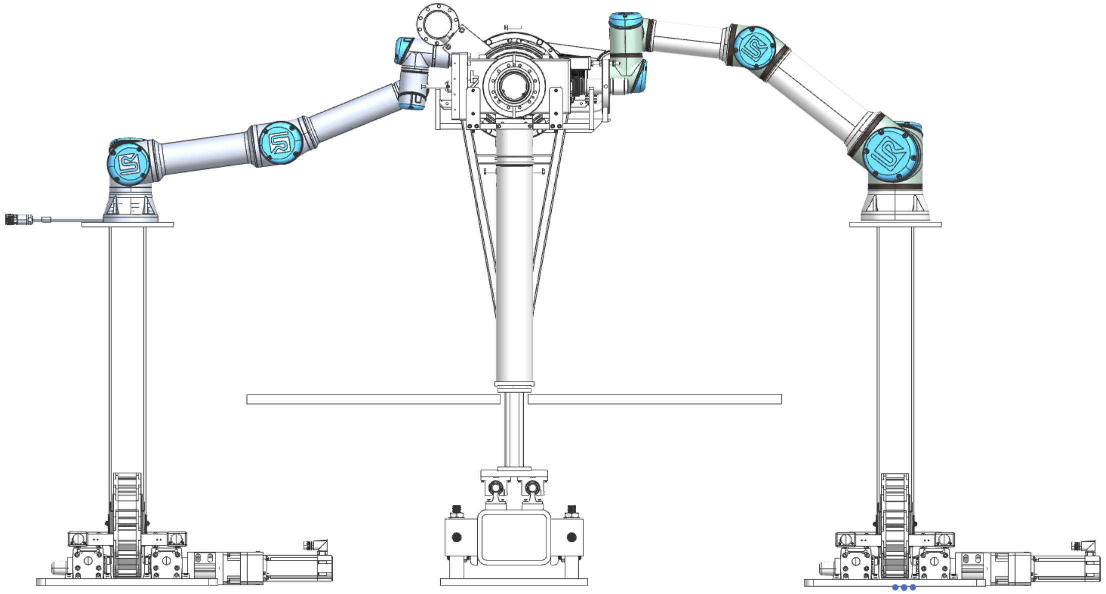
Advance the AI-powered robotic assembly

- 7th-axis (rail) for robotic arm
- End effector development
- AI development for the Robotic operating system integration

Collaboration with JLab, KEK, and CEA



Robotic-assisted clean assembly



Systematic design optimization for clean assembly

Needs a paradigm shift thinking for the AI Robotic future for cryomodule gradients >40 MV/m

- Vacuum interface
  - Can we invent low-particulate vacuum seals?
  - Can we engineer low-particulate fasteners?
  - Can we engineer low-particulate flanges?
- Cavities
  - Are there improvement opportunities for cavity design?
  - Can we reconsider the current cavity-to-cryomodule workflow?
- Tooling
  - Are robotic hands (end effectors) clean room compatible?

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Conclusion – an Advocacy for Particulates free future with AI/Robotic SRF

- Clean assembly has a knowledge gap (**R**&D)
- Cavity string design is “mature”, also “stale” (R&**D**)

If sufficiently supported, the future could be very “clean and FE-free”.

- In 5 years, a robotic assembly with many improvements to the current cryomodule design
- In 10-15 years, a new type of cryomodule design that is robotically compatible and achieves high yield, high performance

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