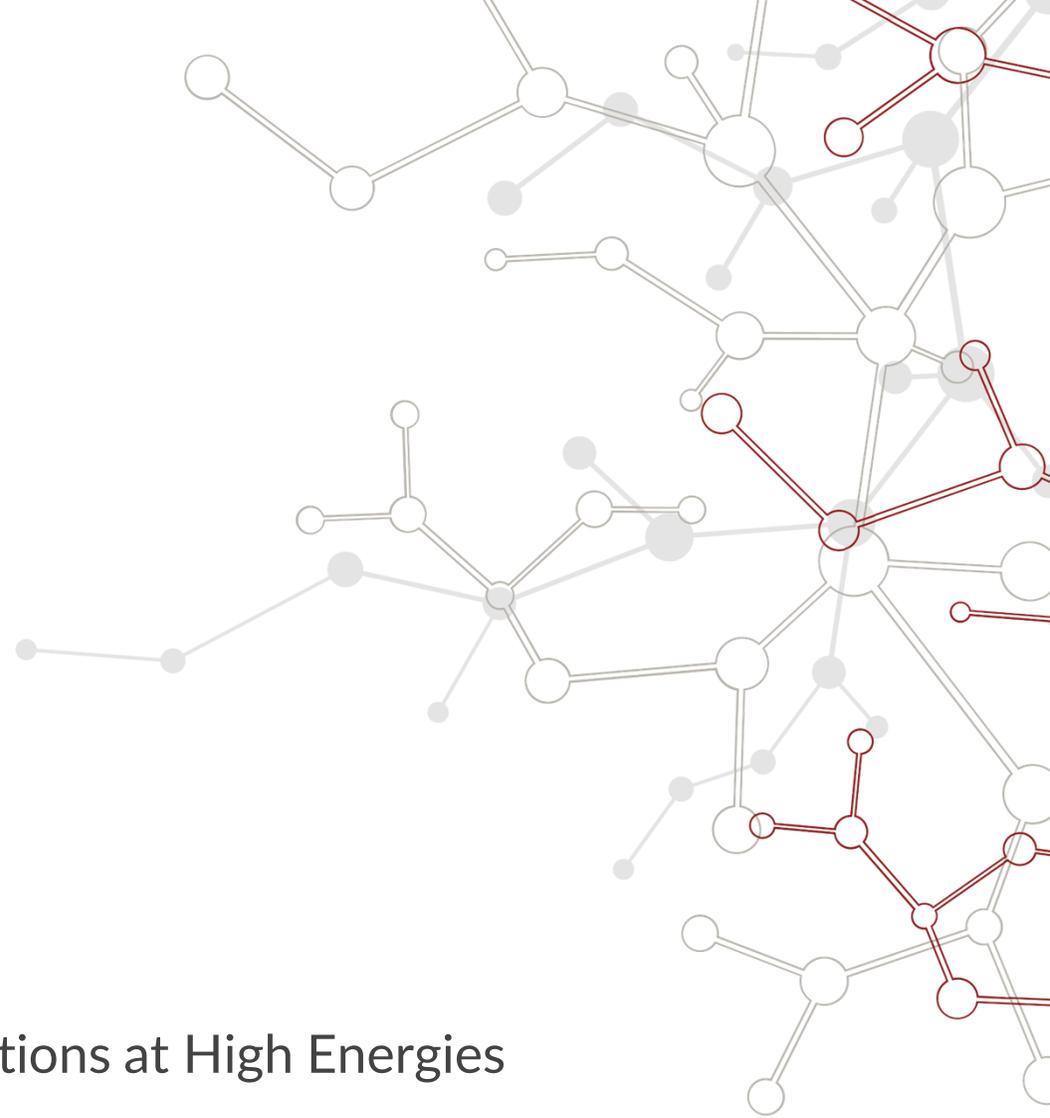


# Recent Progress on Cold Copper Technology

Ankur Dhar  
August 25<sup>th</sup>, 2025

32nd International Symposium on Lepton Photon Interactions at High Energies



# Acknowledgements

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Emilio Nanni

*FCC-ee*

Mei Bai

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Wei-Hou Tan

*Craievich Paolo*

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Glen White

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Andy Haase

*William Berg*

Matt Boyce

*ESRF*

Valery Borzenets

*Simone Liuzzo*

Dennis Palmer

*Simon White*

# Outline

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- Updates from Cold Copper
- Possible Synergies with Higgs Factories
- Next Steps with Quarter Cryo-Module
- Conclusion

# Outline

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# Accelerator Design and Challenges

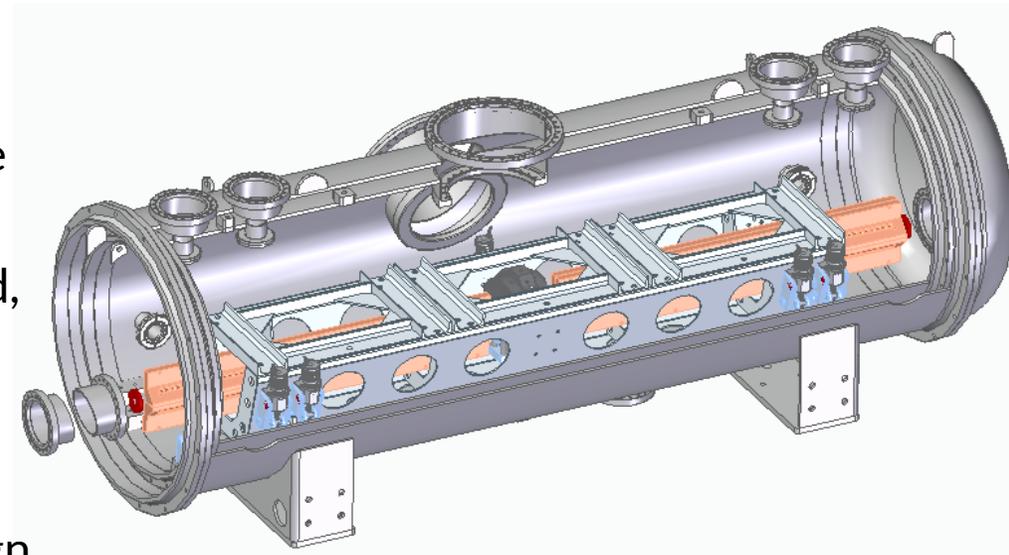
## Quarter cryomodule (QCM)

- Crucial first step towards a full demonstrator

Making good progress on challenges identified with community through Snowmass

- Gradient – Single-cell and meter scale cryogenic tests, to be repeated in **QCM**
- Vibrations – Conducted measurements with 2 kW heat load, to be repeated in **QCM**
- Alignment – Integrating Rasnik system within **QCM**
- Cryogenics – Full flow tests planned within **QCM**
- Damping – Material testing, beam simulations, and RF design are all progressing, test structure to be deployed in **QCM**
- Beam Loading and Stability - Beam test possible within **QCM**
- Scalability – Raft designs and integration to be tested in **QCM**

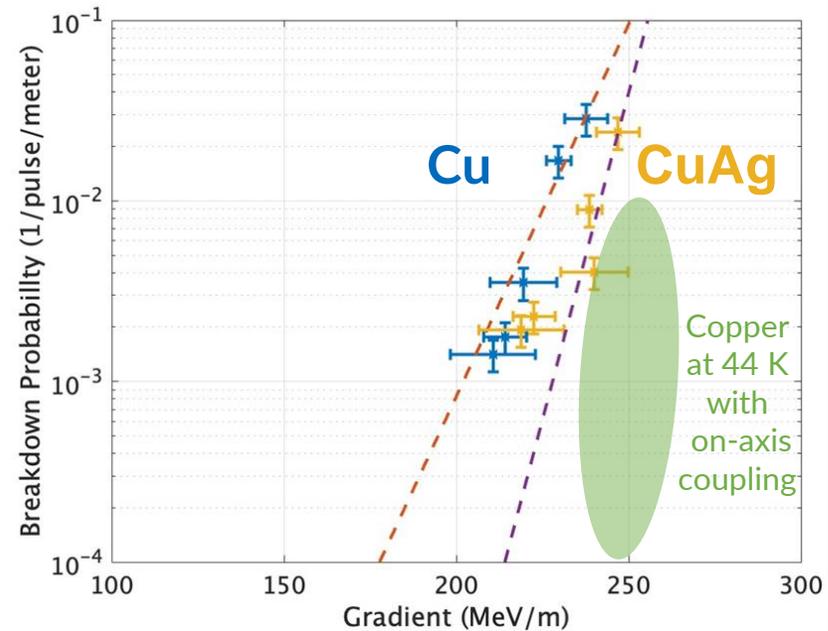
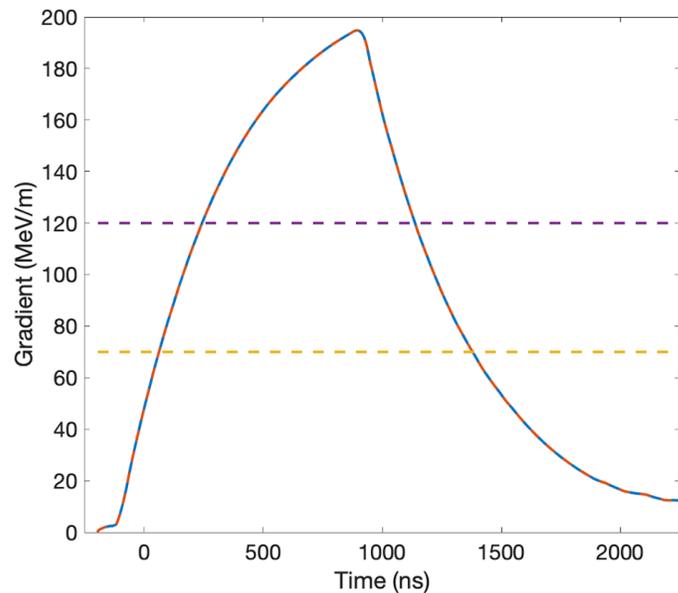
## Quarter Cryomodule (QCM)



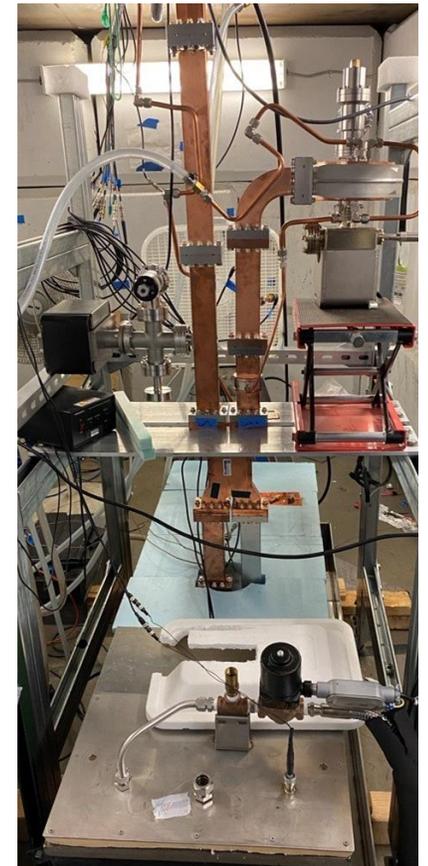
# Single Cell Cryogenic High Gradient Tests at C-Band

High power tests at LANL (room temp) and Radiabeam (cryo) with up to 5 MW per cavity

- Improved coupler design significantly reduced breakdown probability
- **C-band cavities were able to reach gradients over 250 MeV/m in cryogenic tests**
  - C-band is a sweet spot for driving high power beams with high efficiency
  - First demonstration of Cu and CuAg at C-band in cryogenic conditions



Test at Radiabeam

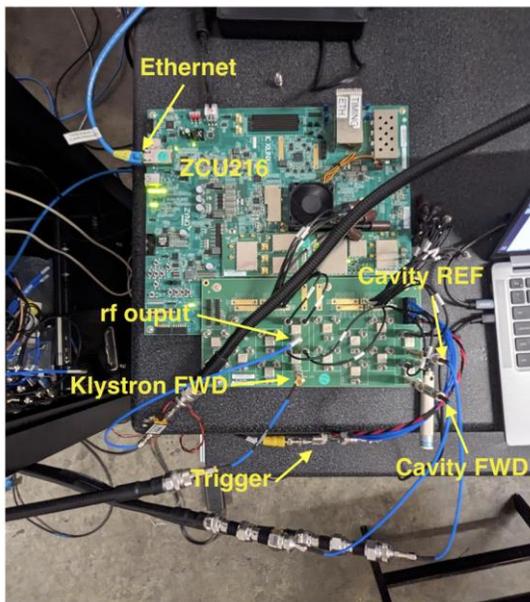


[APL 121, 254101 \(2022\)](#)  
[IPAC2024 p. MOPR29](#)

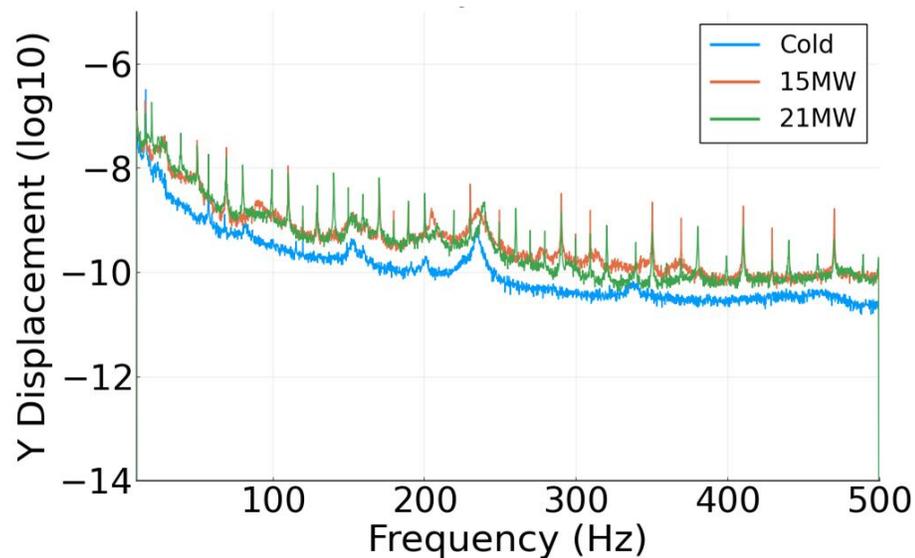
# C-Band Meter-long Linac Cryogenic High Gradient Tests

Conditioned Linac at Radiabeam up to 20 MW, 60 Hz, and 1  $\mu$ s

- Conditioning limited by klystron, not structure
- Accelerometer measurements at max power showed sub-micron displacements, even with mechanical propagation from outside the bunker

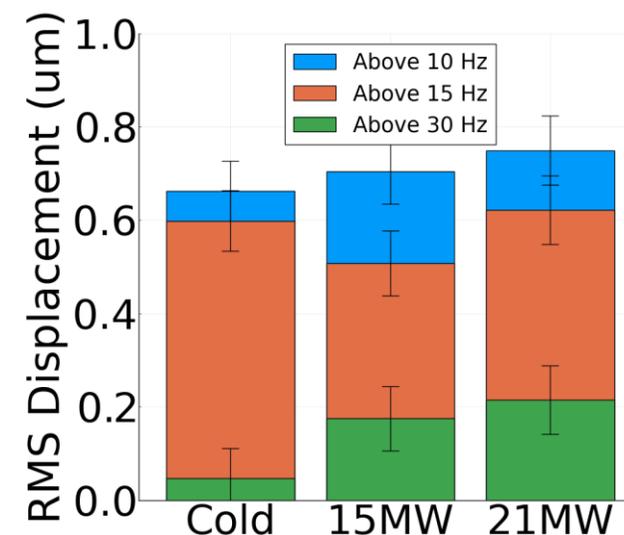


Tested Custom RFSoc LLRF



[Dhar, Ankur. No. SLAC-PUB-17776.](#)

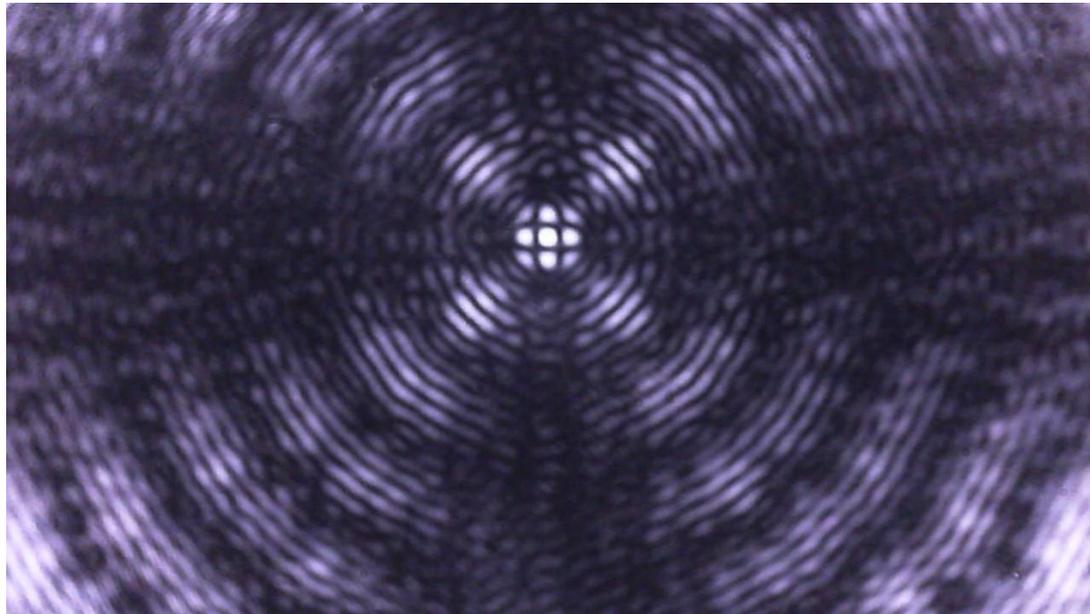
[Liu, C., et al. Rev Sci Instrum. 2025 Apr 1;96\(4\):043311.](#)



# Rasnik Alignment System Test in Liquid Nitrogen (LN2)

## Tested real-time positional measurement in liquid nitrogen

- Rasnik alignment system uses a diffraction pattern produced by a zone plate
- This pattern is imaged using a special webcam to determine deflection in XY plane
- Work is ongoing to improve quality of diffraction pattern and real-time analysis



In Air



In Liquid Nitrogen

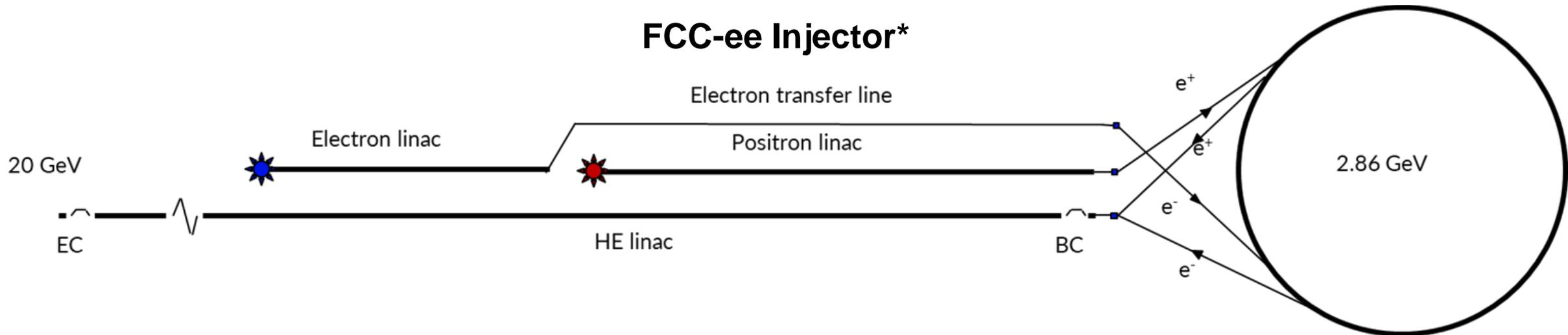
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# FCC-ee Injector Layout

- FCC-ee Injector produces both positrons and electrons
- Options considered for 6 GeV and 20 GeV
- Linac design has significant impact on beam dynamics, power consumption, footprint



# Cold Copper as applied to FCC HE-Linac Design

FCC needs a High Energy Linac to boost to 20 GeV

Initial study with  $a/\lambda = 0.125$

- Aperture: 13.4 mm

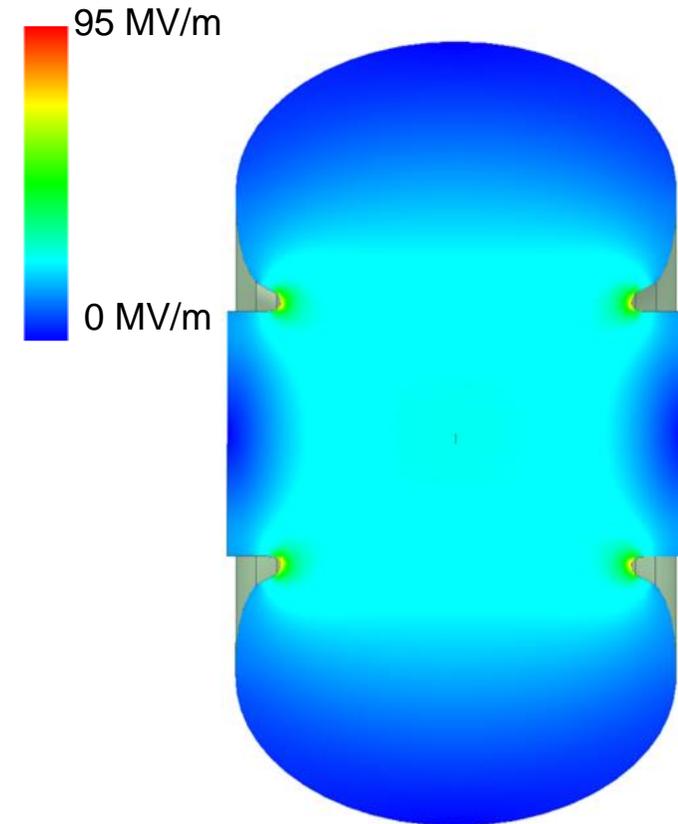
Shunt impedance at 300 K: 58.5 M $\Omega$ /m

- At 77 K: 146-158 M $\Omega$ /m

Expected performance for 22.5 MeV/m :

- Efficiency: 3.5 MW/m
- Fill time: 3 microseconds

Pulse compressed version could use over-coupled manifold for faster fill time and higher efficiency



# Linac Performance: Warm versus Cold

As compared to existing designs, the power consumption per unit length is dramatically lower

Cryogenic operation and/or pulse compression can improve this even further

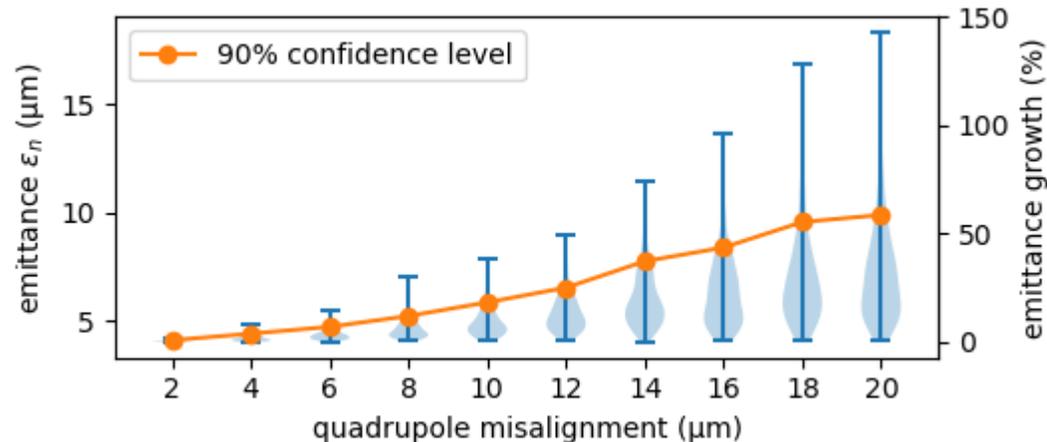
	SLAC Linac 3 m structure	PSI Linac 4 m structure	Distributed Coupling 1 m structure	Cryo-Distributed Coupling [77 K] 1 m structure
Shunt Impedance [M/m] $a/ [radius/wavelength]$	56* 0.125-0.092	45-56+ 0.135-0.095	58 0.135	150 0.135
Power / Length @ 22.5 MeV/m [MW/m]	16.4	12.2	8.7	3.5
Achievable Gradient [MeV/m] Constant BDR Scaled from Pulsed Heating	50	60	74	118

\*Equivalent Rs for SW of 37 MΩ/m due to TW power to load;

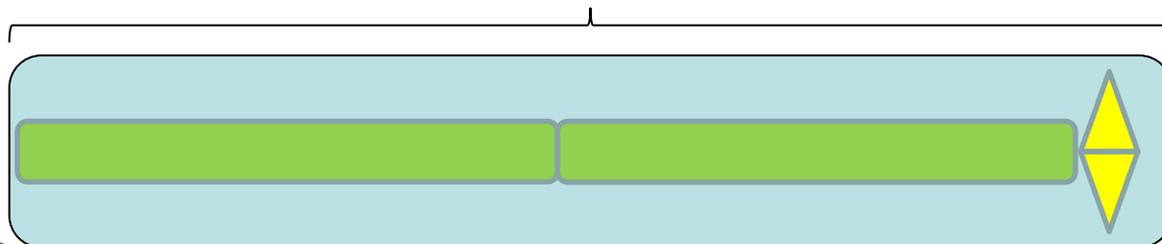
+Equivalent Rs 41 MΩ/m Modeled (38 Measured) PRAB 19, 100702 (2016)

# FCC-ee HE-Linac simulation

- 2X 1-meter S-band structure
- Simulation with rms quad misalignment, 300 random samples
- No BBA, vibrations measured at <1 micron



2X 1-m S-band structure + 0.15-m quad



## FCC HE-Linac Properties

Freq	2.8 GHz
charge (nC)	5 nC
initial energy	6 GeV
final energy	20 GeV
initial emittance	4 mm-mrad
target final emittance	10 mm-mrad
initial energy spread	0.1%
final energy spread	0.14%
initial beam size	0.2 mm
bunch length	1 mm

# RF Sources for FCC HE-Linac

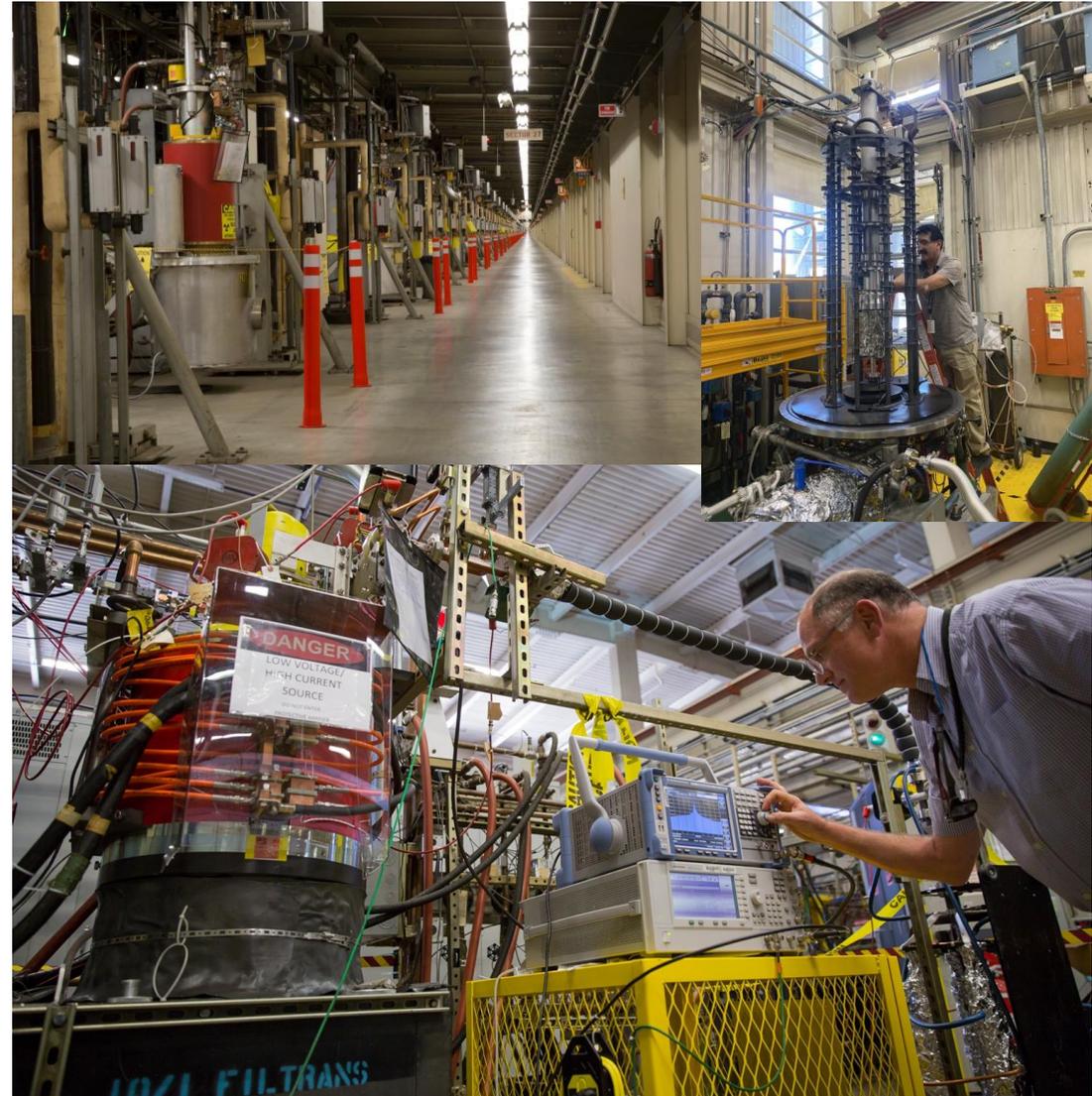
SLAC maintains active klystron development and manufacturing to power future colliders

In FY24 we delivered 4 new 5045 S-band klystrons

- Also refurbished another 7 for LCLS and FACET
- Working to increase output in FY25, including XL4 X-band klystrons

Solenoidal electromagnet consumes too much power

- XL4 solenoid consumes >20 kW average power
  - Needs to go to near zero
  - Periodic permanent magnets (PPM) are an appealing option
  - Focus of Next Linear Collider (NLC) program
  - Production resumed on X-band PPM klystrons
  - Technology can be scaled to other



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# QCM Currently at SLAC

Undergoing inspection, to be followed by assembling and mounting.



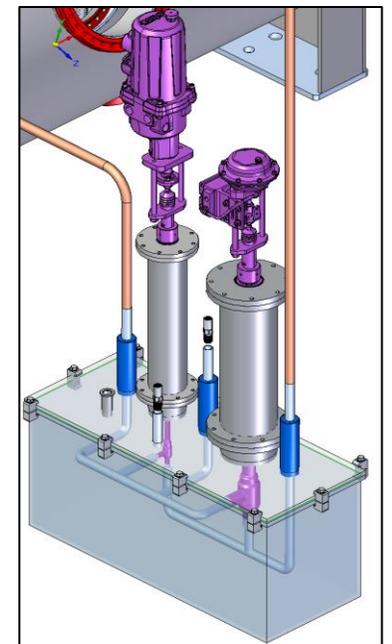
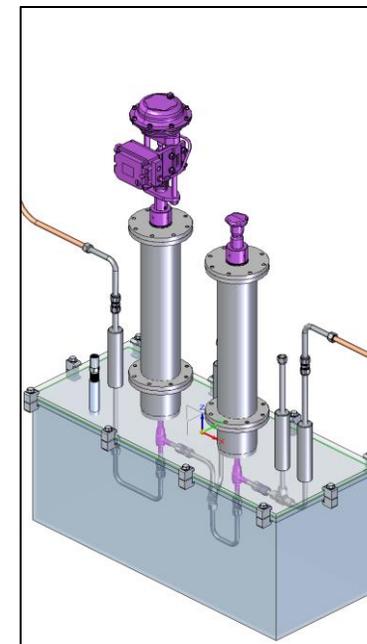
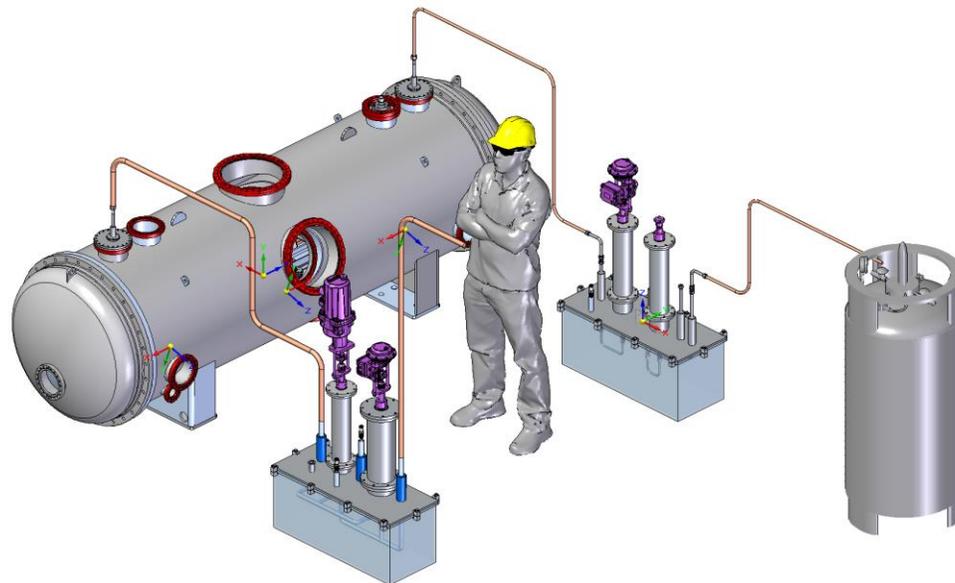
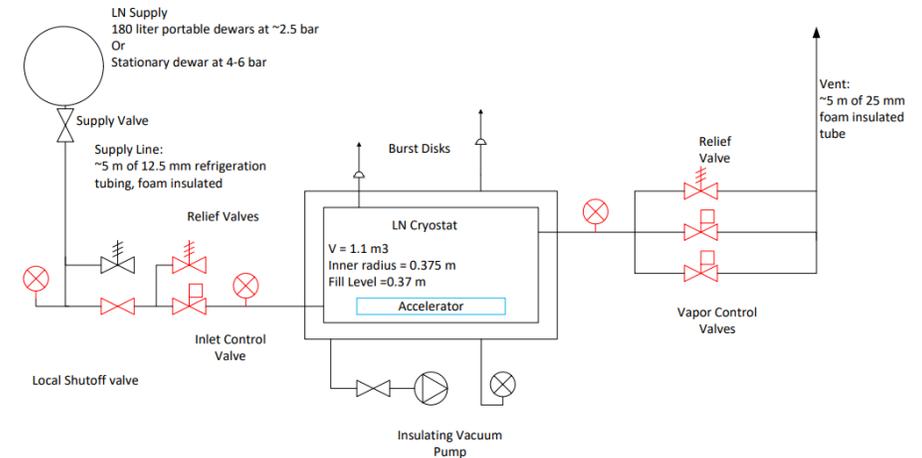
# QCM with Cold Boxes for Cryogenic Testing

The LN2 plumbing includes cold boxes for supply and venting, implementing cryogenic valves (both manual and actuated) to meter the amount of LN2 in the QCM.

It includes pressure relief valves and burst disks as appropriate in the LN2 lines, vacuum cold boxes, and the QCM.

It is shown with placeholder copper lines to illustrate the paths, but it will utilize vacuum jacketed transfer lines.

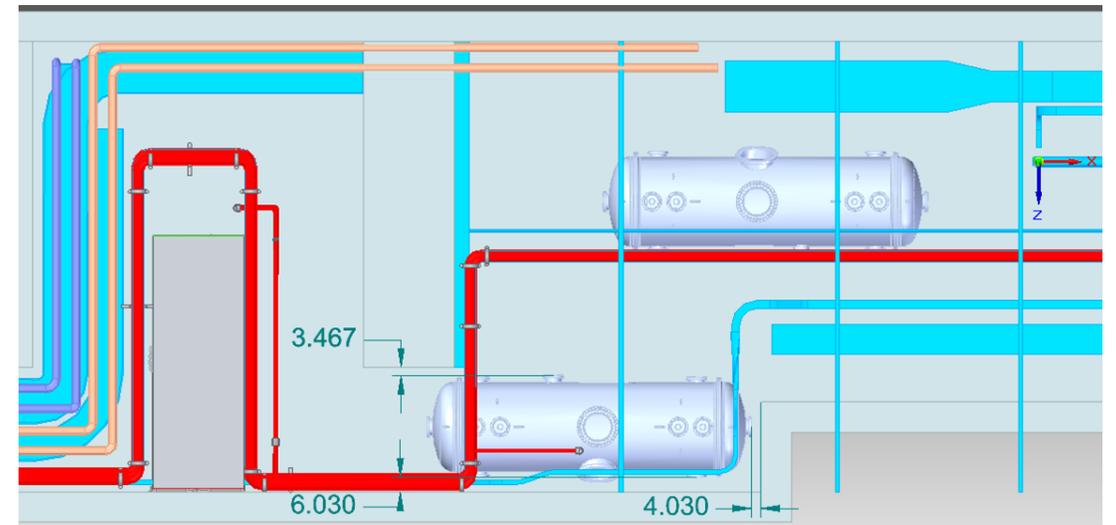
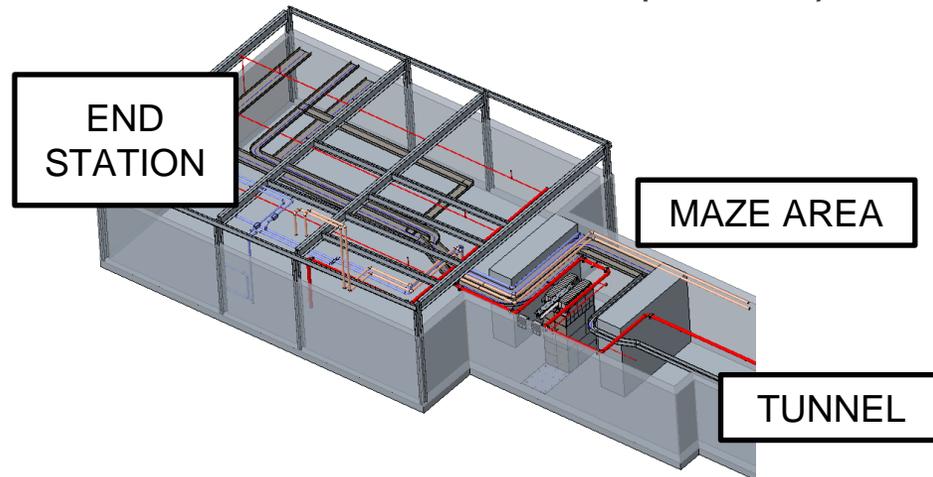
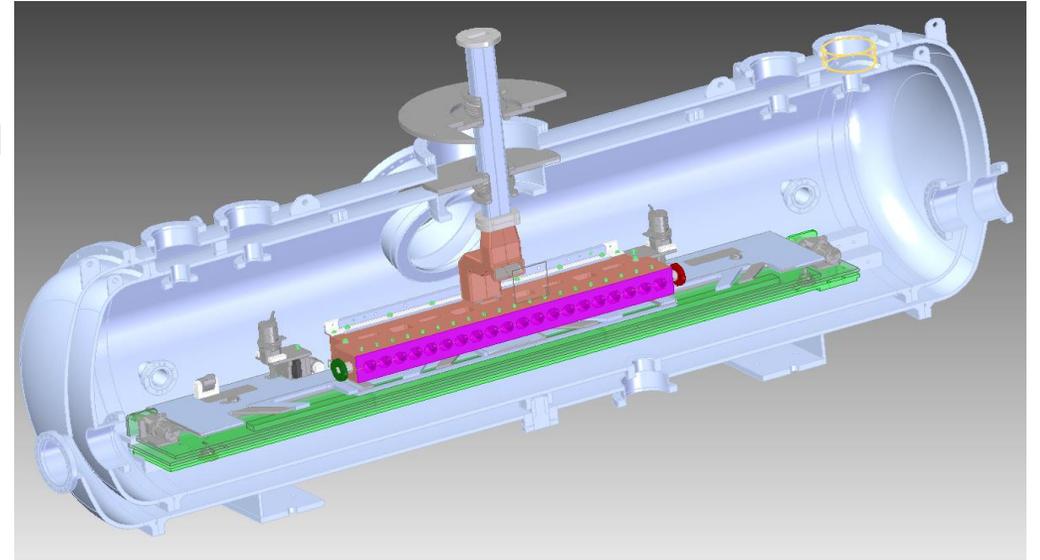
The design is in the detailing phase.



# High Power Test Plans

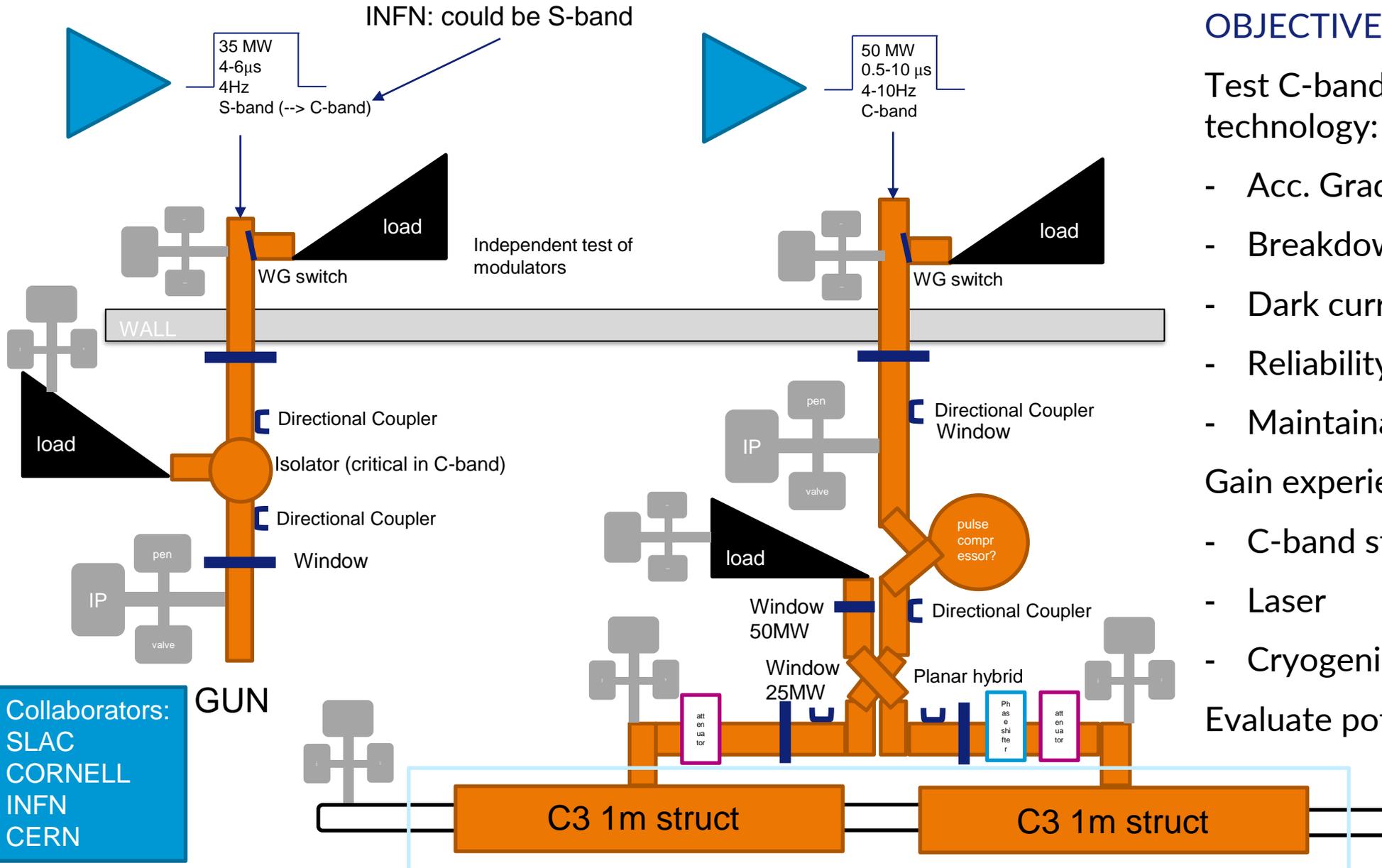
Preparations are underway for high power tests of an S-band cold copper structure at Argonne National Laboratory (ANL), Advanced Photon Source (APS) using the Linac High-Power RF Test stand and the Linac Extension Area (LEA). Tests are expected to start this fall.

- High power test measuring breakdown rate with 30 MW klystron
- Second phase with two structures and 60 MW klystron
- One structure will be housed within quarter cryo-module



Plan to maneuver QCM through the maze

# COOL COPPER OPERATION LINAC DEMONSTRATOR (COLD) AT ESRF



Collaborators:  
SLAC  
CORNELL  
INFN  
CERN

## OBJECTIVES:

Test C-band 77K high gradient technology:

- Acc. Gradient
- Breakdowns
- Dark currents
- Reliability
- Maintainability

Gain experience:

- C-band structures / modulators
- Laser
- Cryogenics

Evaluate potential to extend to 6GeV

## Phase 1

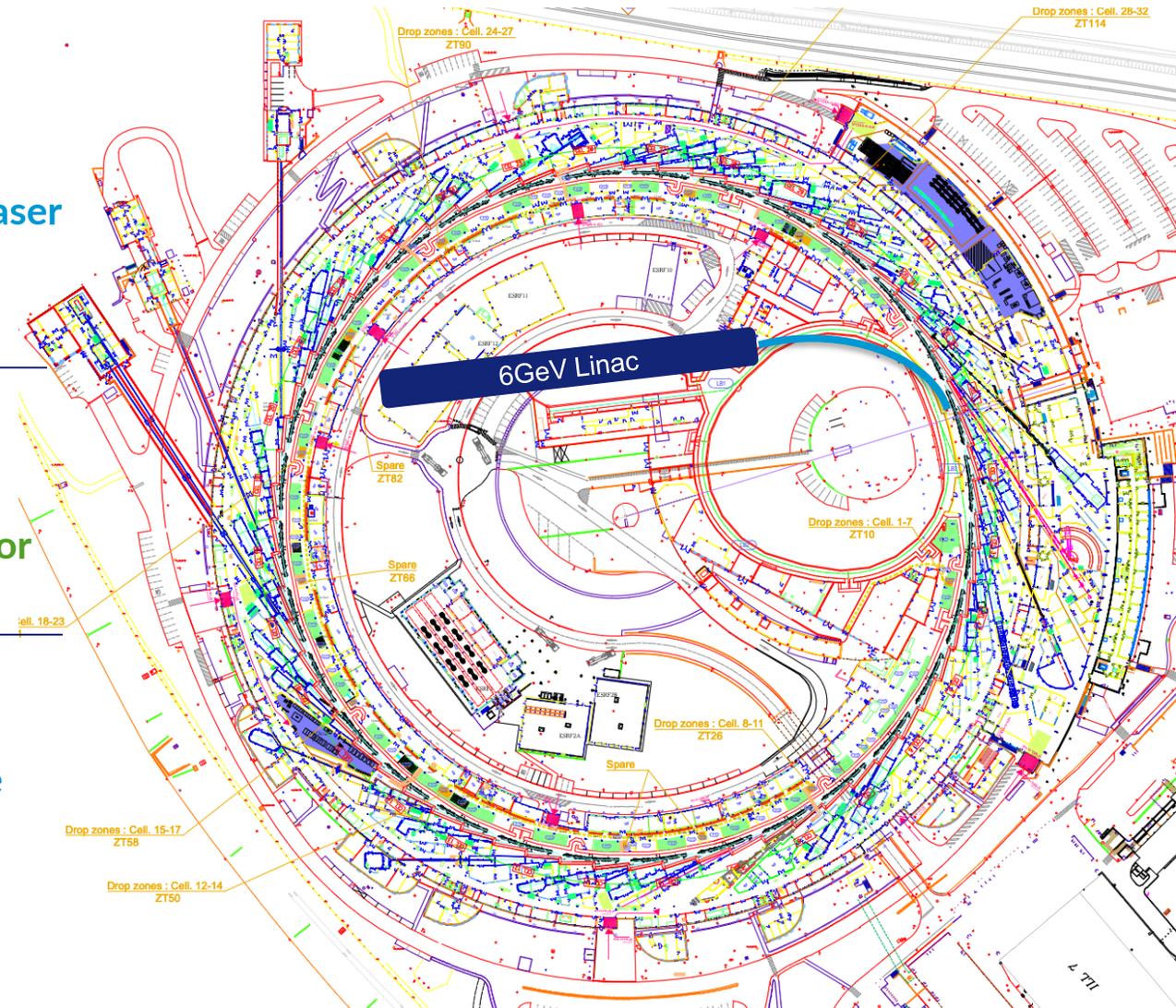
- 2025 S-band RF-unit for photo-gun (usable for present linac)
- 2026 2x C-band RF-unit for Cryomodules diagnostics for Linac refurbishment
- 2027 RF test of 77K C-band acc.struc. +dark currents +laser
- 2028 photogun, diagnostics
- 2029 beam measurements

## Phase 2

- 2030 + 2xC-band accelerating structures for: pulse compression, phasing studies, EU cryomodule development and/or: install undulators
- 2031 COLD as ~300-350MeV alternate operation injector for ESRF. (Two injector linacs will be operational)

## Beyond

- 2032: new 12x100 m tunnel construction
- 2033: install and commission 6GeV Linac
- 2034: decommission booster, installation of transfer line 6GeV linac to SR (~2 months dark time)



[S. Liuzzo, et al., Proc. IPAC'25, TUPM107](#)

# Conclusion

## RF Accelerator Technology Essential for All Near-Term Collider Concepts

Cold Copper is positioned to contribute synergistically or directly to all near-term collider concepts

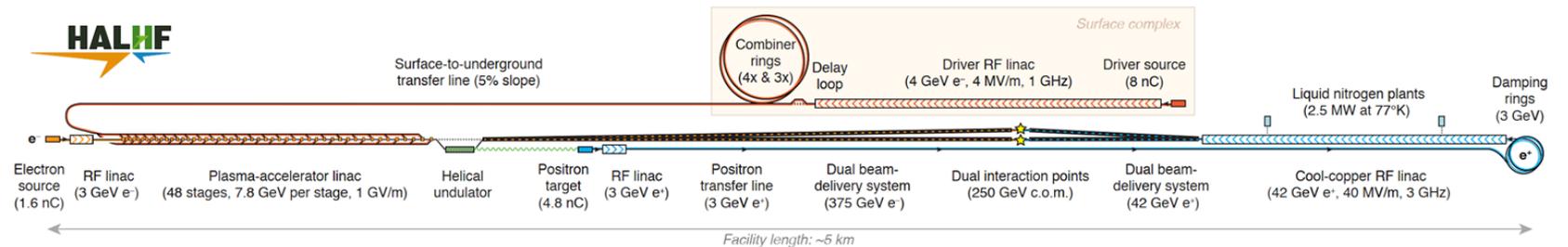
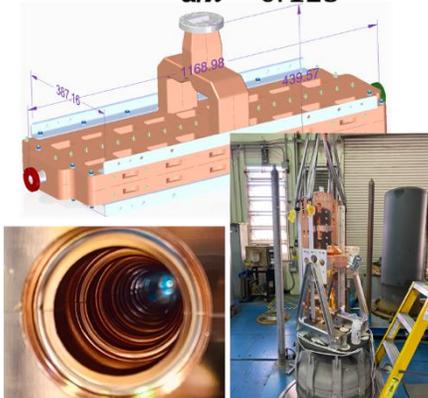
- FCC-ee - common electron and positron injector linac from 6 to 20 GeV
  - reduce length OR reduce RF power from existing design
- ILC - options for electron driven positron source based Cold Copper technology
- Linear Collider Facility at CERN - High energy upgrade for up to 2 TeV (<https://arxiv.org/pdf/2503.24049>)
- HALHF – Positron linac for asymmetric particle collisions (<https://arxiv.org/pdf/2503.19880>)
- Muon Collider - high gradient cryogenic copper cavities in cooling channel, alternative linac for acceleration after cooling

### Linear Collider Vision

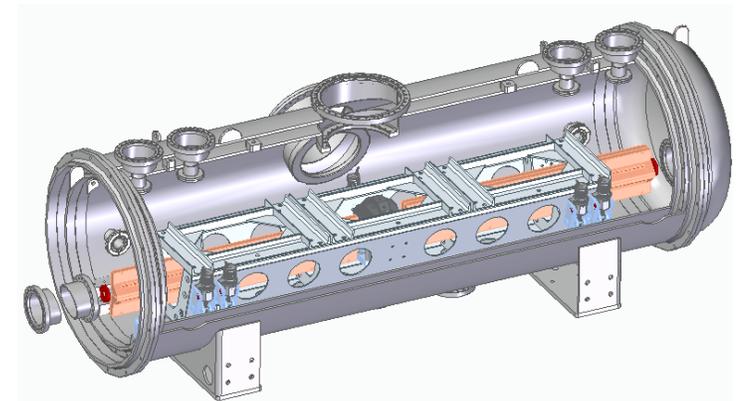


### Wide Aperture S-band Injector Linac

$$a/\lambda = 0.125$$



- Planned S-band tests at Argonne
- High power tests to include cryogenic high power tests with newly arrived QCM
- QCM studies will form the basis of a platform for maturing cold copper technology
- Installation at ESRF for full QCM demonstration



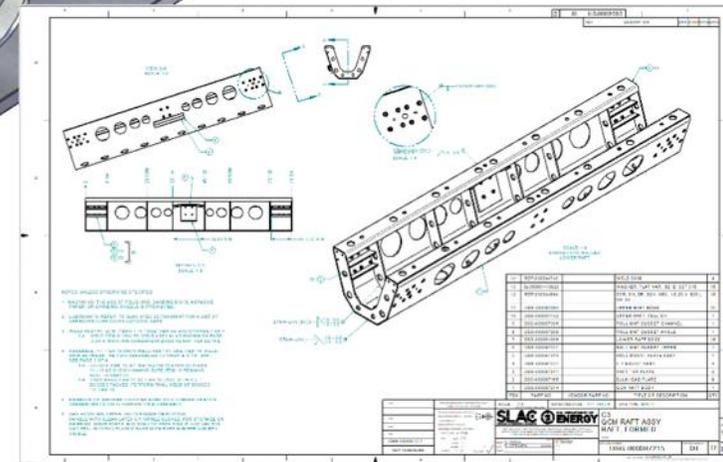
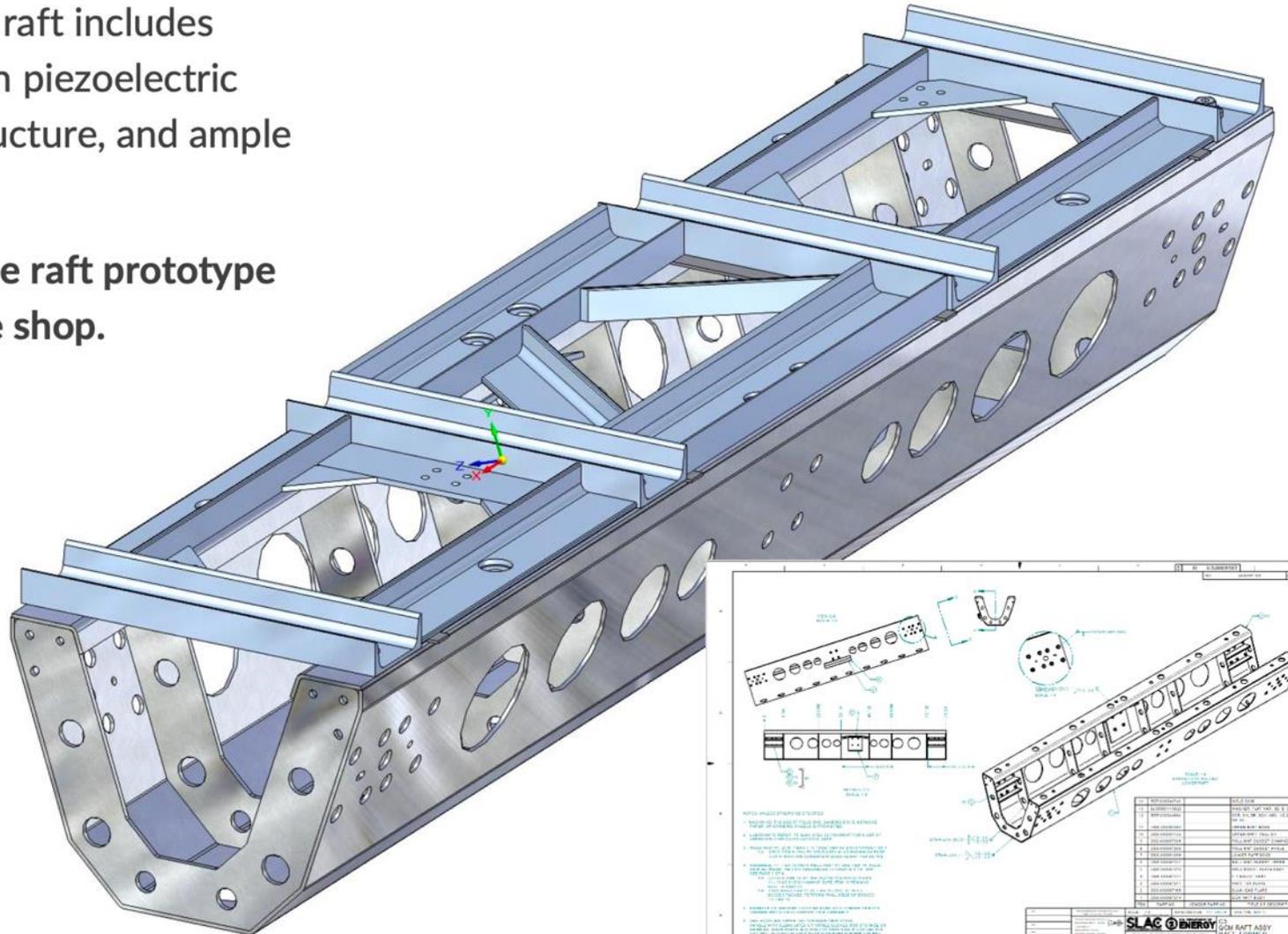
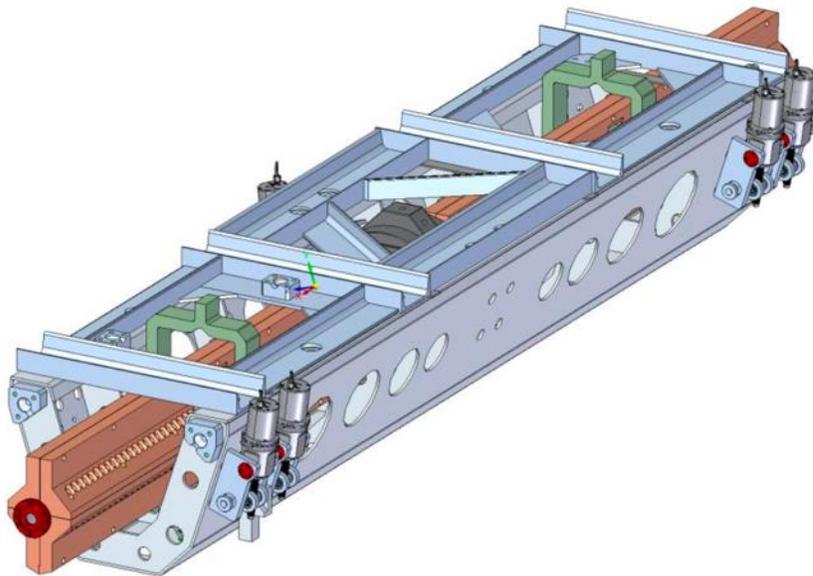
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# Questions?

# QCM with Raft

The raft is designed to support the accelerator structure during assembly and permanently once installed. The raft includes mounting points for alignment adjustment with piezoelectric motors, compliant mounting points for the structure, and ample flow channels for LN2.

The design and drawings are complete, and the raft prototype has been placed on order with a local machine shop.

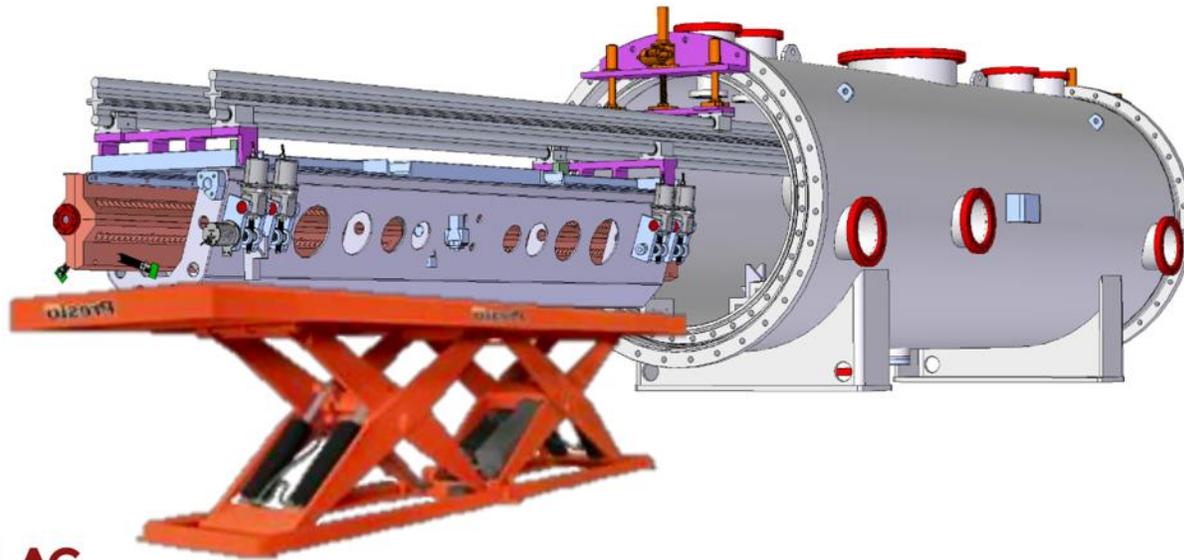
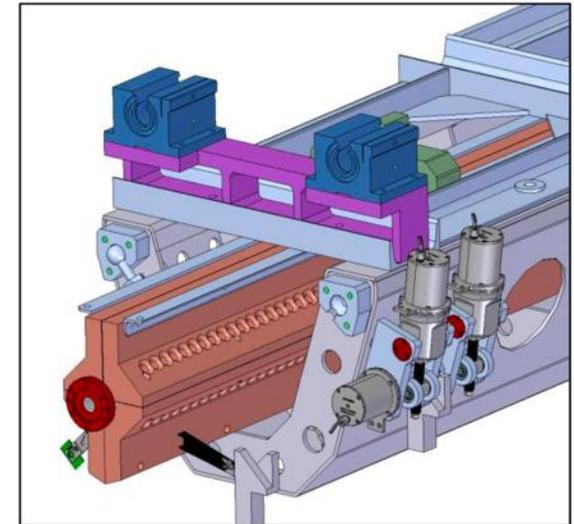
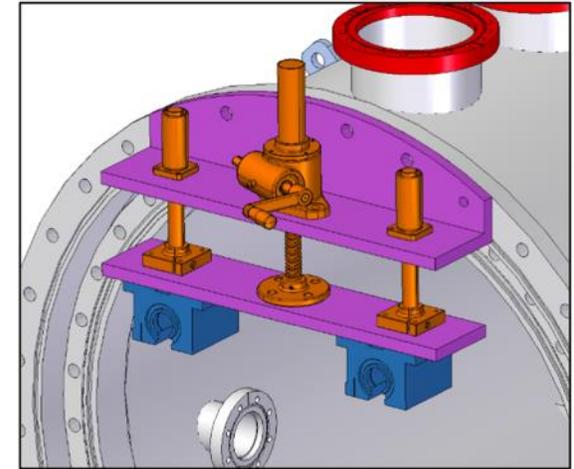


# Raft Loading Setup

The loading setup enables horizontal installation of the raft and structure with vertical adjustment to clear mounting hardware.

Loading is done with adjustable height bearings which can be manually adjusted or controlled with stepper motors. All fixtures and bearings are removed once installed.

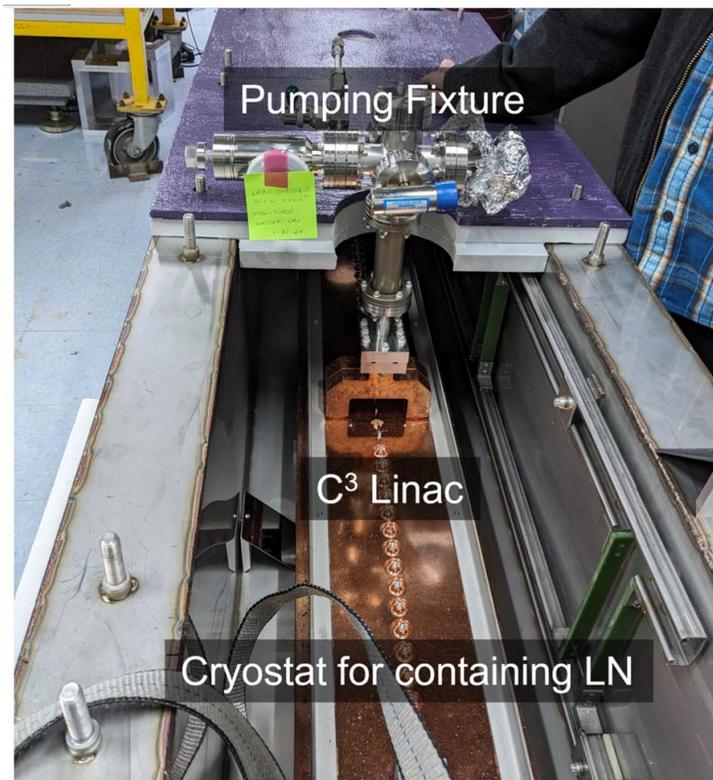
The design is still in the conceptual design phase.



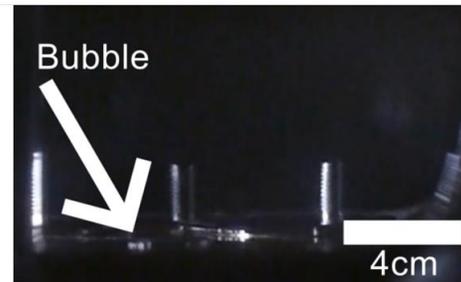
# Vibration Characterization

Prototype C3 Linac with a resistive heater was used to test vibration within LN up to 2 kW

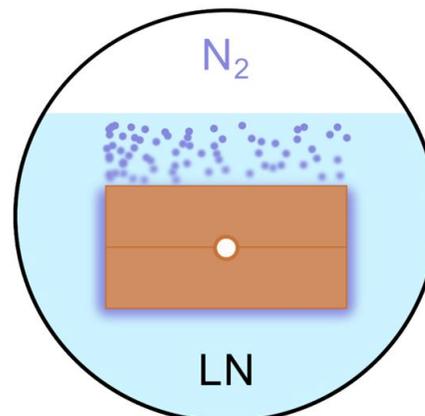
- Displacement induced by heating LN remained below tolerances
- Next tests within QCM to test displacements induced on quads



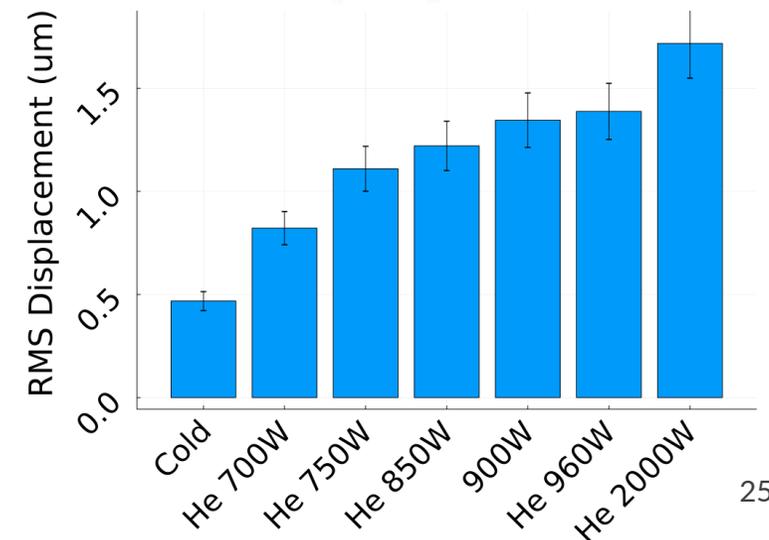
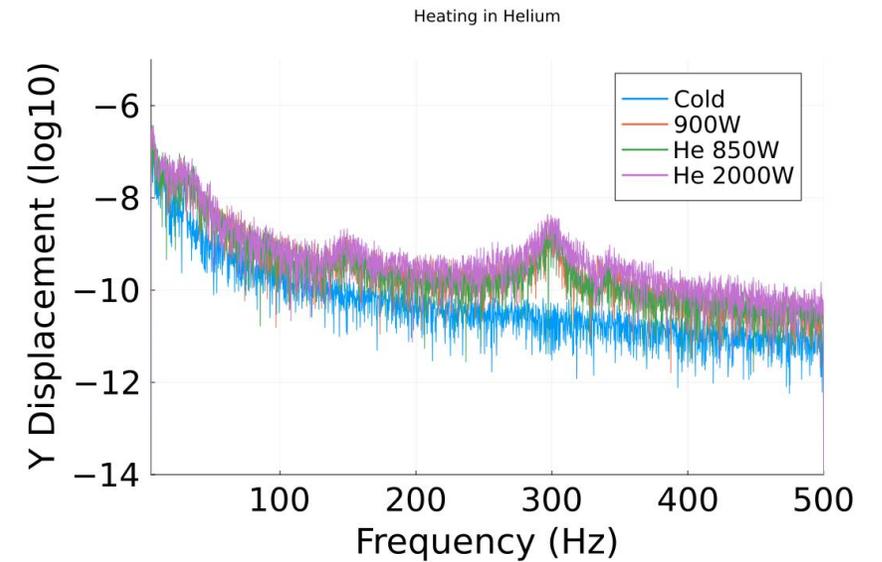
(a)



(b)



(c)

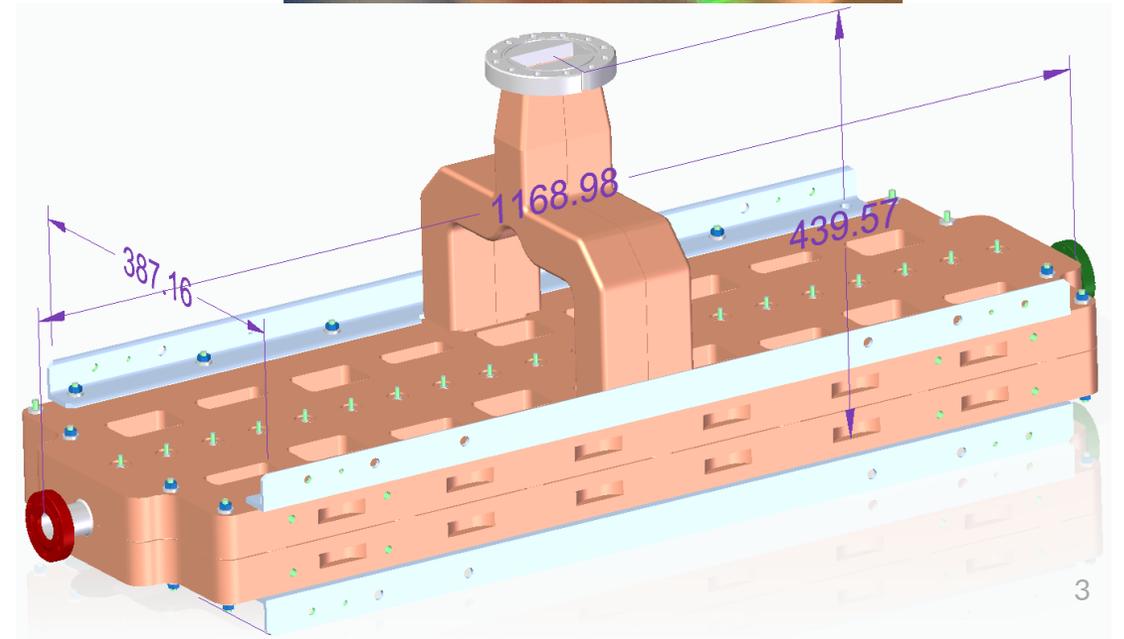
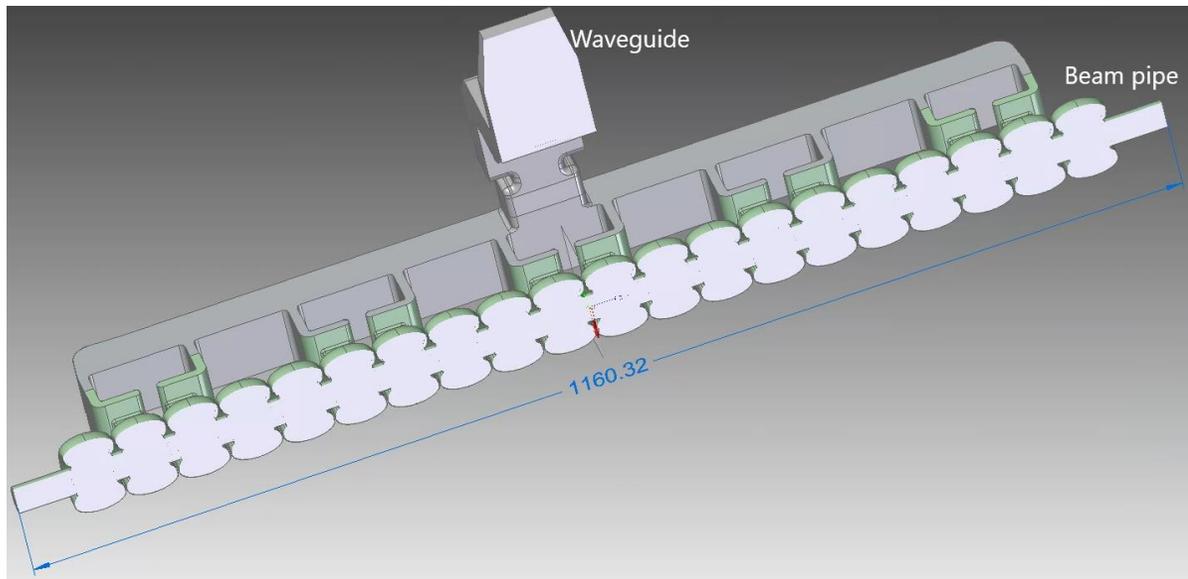


# Injector Linacs needed to accelerate High Charge Bunches

High charge bunches would require larger apertures to minimize wakefields which can disrupt the beam

S-band provides significant larger aperture compared to C-band for a given shunt impedance

Impact of high fields for a high brightness injector may eliminate need for one damping ring



# Distributed Coupling as applied to Injector Linac Design

Design balances shunt impedance with aperture size

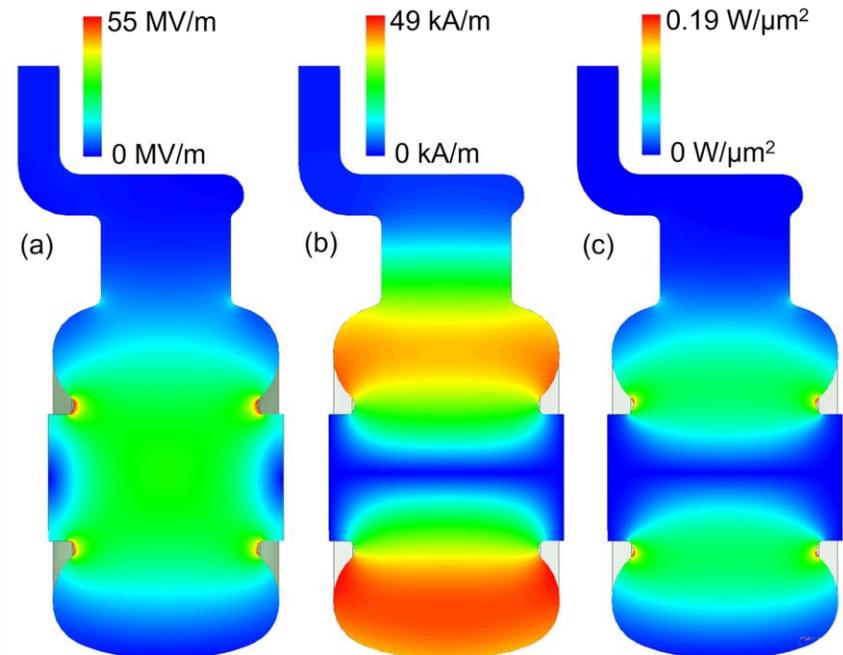
- S-band cavities designed with aperture ratio  $a/\lambda=0.135$

Baseline design informed by EIC CDR specs



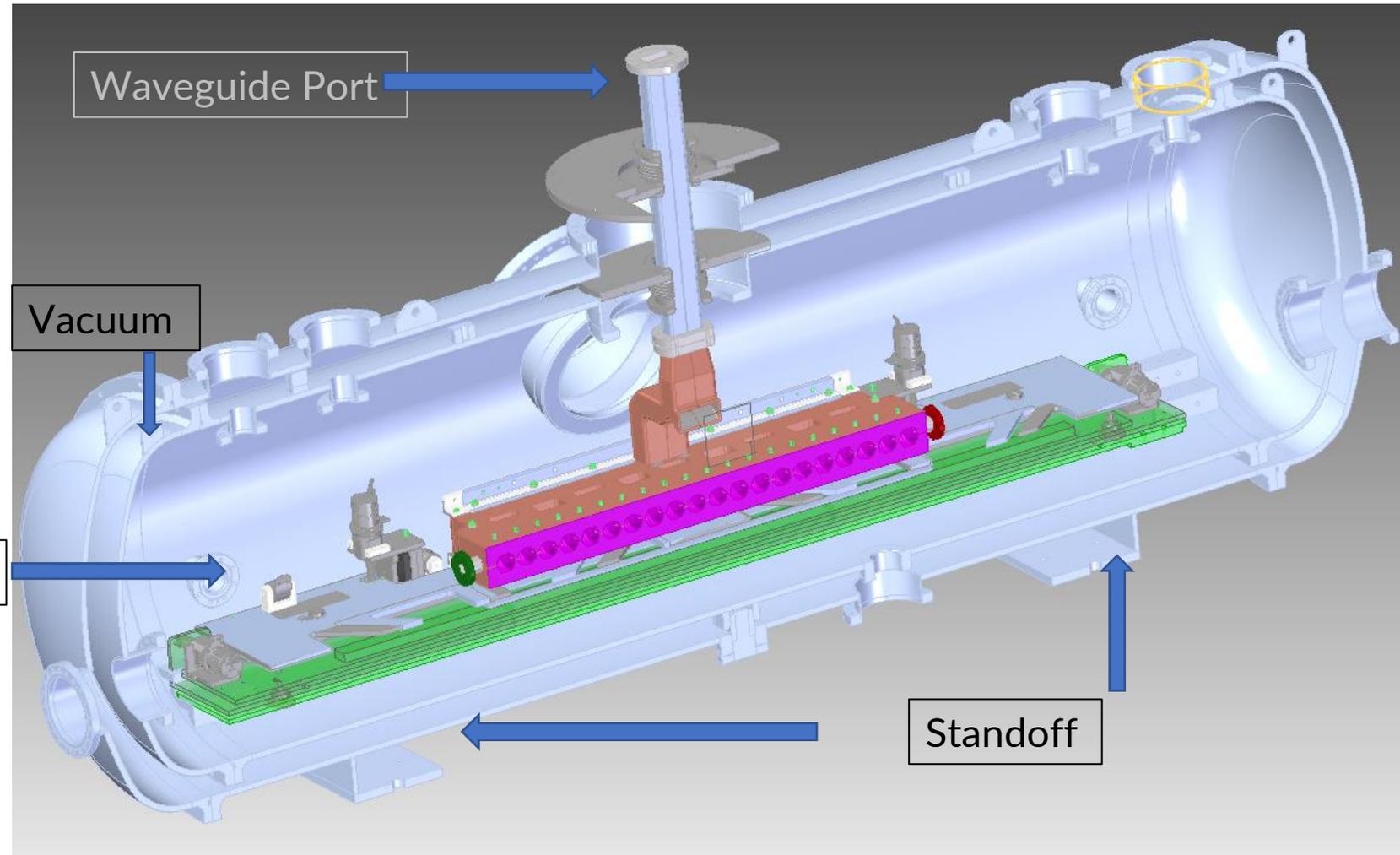
## Linac Properties

Freq (GHz)	2.856	$E_{\max}/E_{\text{acc}}$	2.63
a (mm)	14.12	$E_{\text{acc}}/Z_0 H_{\max}$	0.995
a/ $\lambda$	0.135	$R_s$ (M $\Omega$ /m)	58
$P_{\text{diss}}$ (MW)	5	$E_{\text{acc}}$ (MV/m)	18



# S-Band Linac in Quarter CryoModule (QCM)

QCM with Raft Assembly for cryogenic high power testing



CRYO MODULE SIZES ARE:  
Length - 2600mm+side flanges.  
Outside DIA - 900mm  
Inside DIA - 750mm

## Planned Studies

- Nitrogen flow distribution
- Waveguide installation inside the cryostat, including thermal break and phase shifter
- Concept of vacuum interconnections
- Vibration compensations and dampers if needed
- Alignment during cooldown
- RF testing at low and high power
- Update: QCM has arrived at dock in Oakland, delivery to SLAC next week

# Raft Mounted Structure

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Kinematic mounts were tested on full range of motion with S-band LINAC mounted on the raft plate (weight load is more than 600 lb.). Steppers motors used for large motion.

Polytech PI PIEZO was tested with accuracy of 100nm. Visual inspection shows operation at least at 100Hz.

