Cool Copper Linac in HALHF

HALHF Workshop DESY 2025

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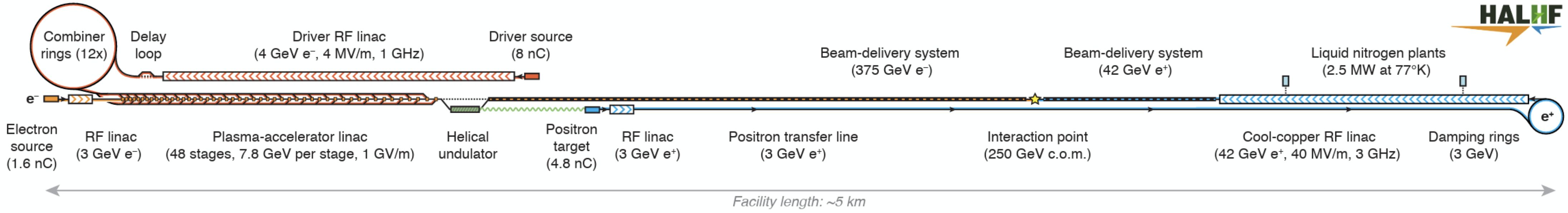
SLAC

HALHF Positron Linac

Work in progress—aim to finish before the ESPP input deadline (March 2025)



> Separate RF linacs for PWFA drivers (high I_{avg}, low E_z) and e^+ (low I_{avg}, high E_z):

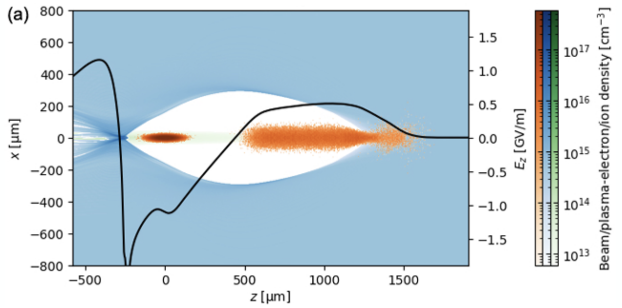
> > L-band driver linac (CLIC-like) + S-band positron linac (warm or cool copper).

> Combiner ring to decrease I_{peak} in the driver linac, and shorten the e^+ bunch train

> Lower plasma density plasma (lower E_z, better tolerances)

> Many (3x) more stages (reduces the driver energy)

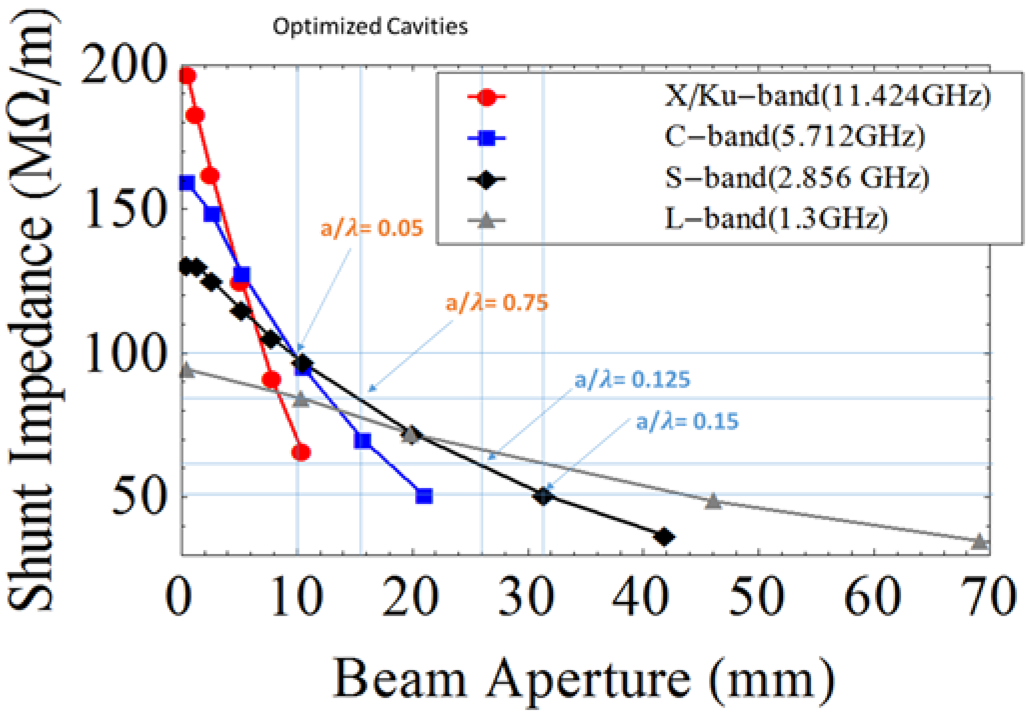
> Polarised e^- and e^+ (ILC-like helical undulator source).

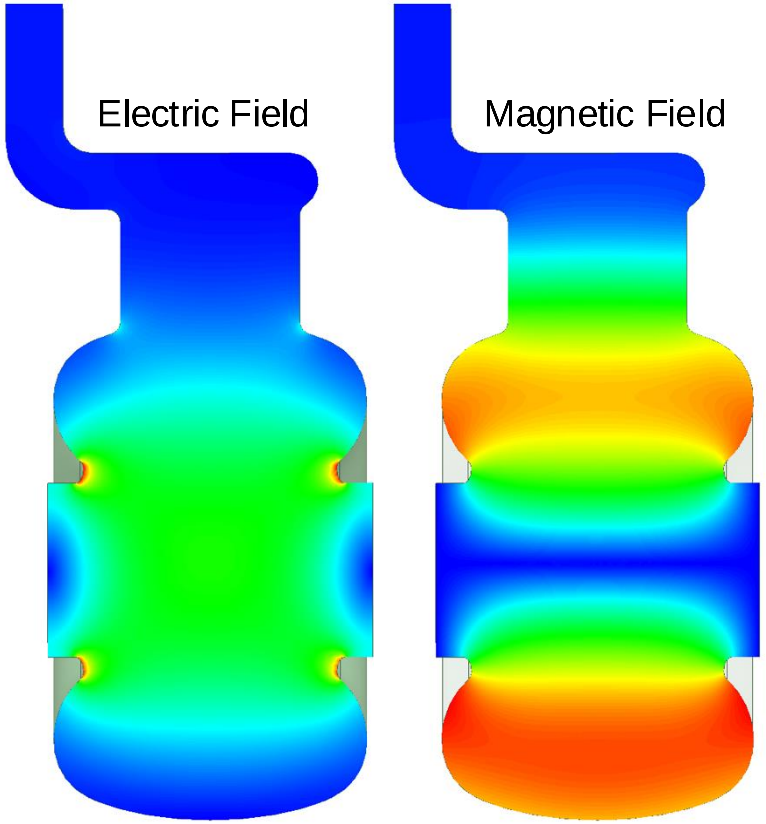


Optimizing Cavity Design Pushes for High Efficiency

Shape of cavity is optimized for efficiency (shunt impedance)

- Minimizes peak surface electric and magnetic fields $R_s = G^2/P$ [MΩ/m]
- Core technology of high gradient normal conducting accelerators





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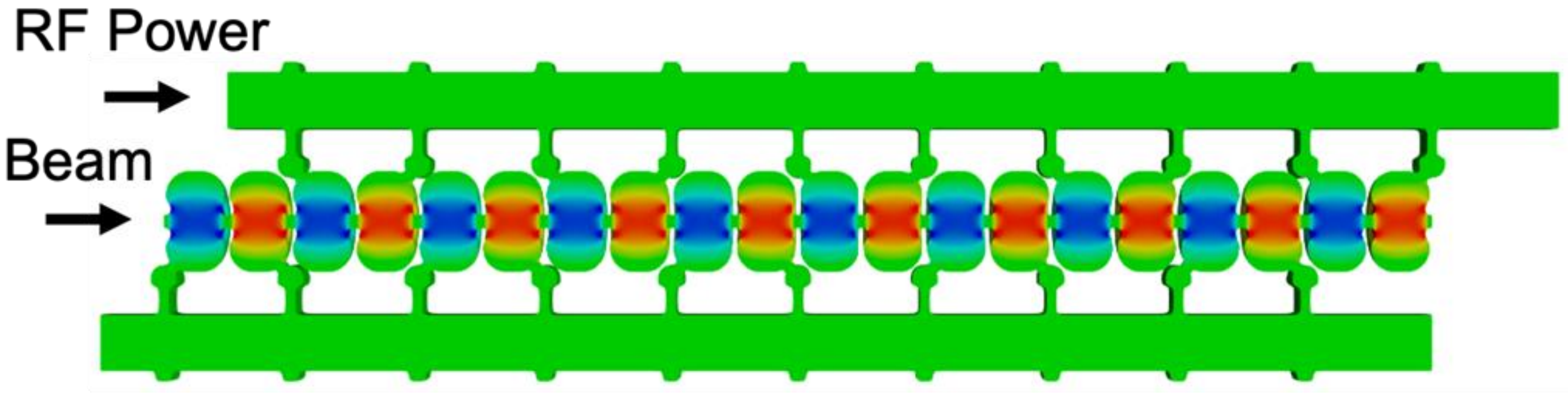
S. Tantawi, et al. *PRAB* 23.9 (2020): 092001.

Distributed RF Coupling changes Accelerator Paradigm

RF power coupled to each cavity – no on-axis coupling

- This in turn means no shape optimization is required to ensure cavity-to-cavity coupling

Full system design requires modern virtual prototyping



Electric field magnitude produced when RF manifold feeds alternating cavities equally

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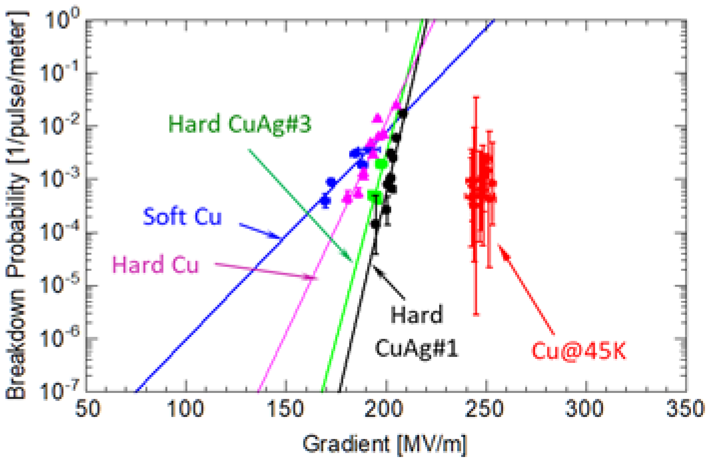
S. Tantawi, et al. *PRAB* 23.9 (2020): 092001.

Motivation for Developing Cold Copper RF Accelerators

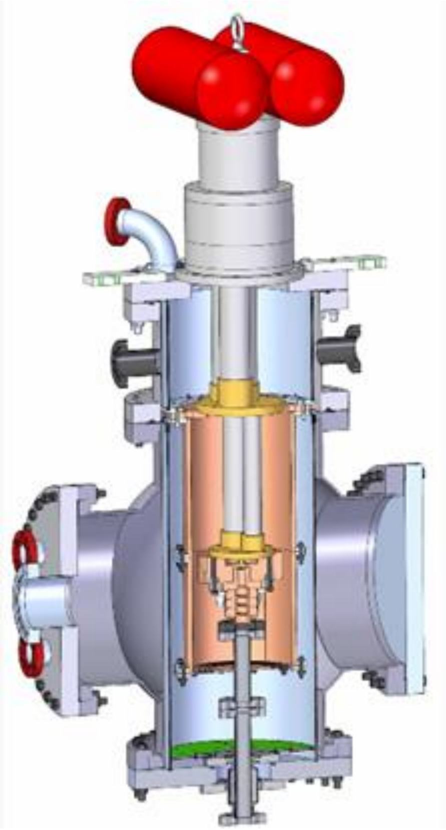
Cold-copper established as a pathway for achieving high gradients in single cavities (2015)

Distributed-coupling established a novel topology for achieving higher efficiency (2018)

Cold-copper program has focused on understanding fundamental limits



[High Gradient Workshop (2015)](#) [PRAB 21, 102002 (2018)](#)



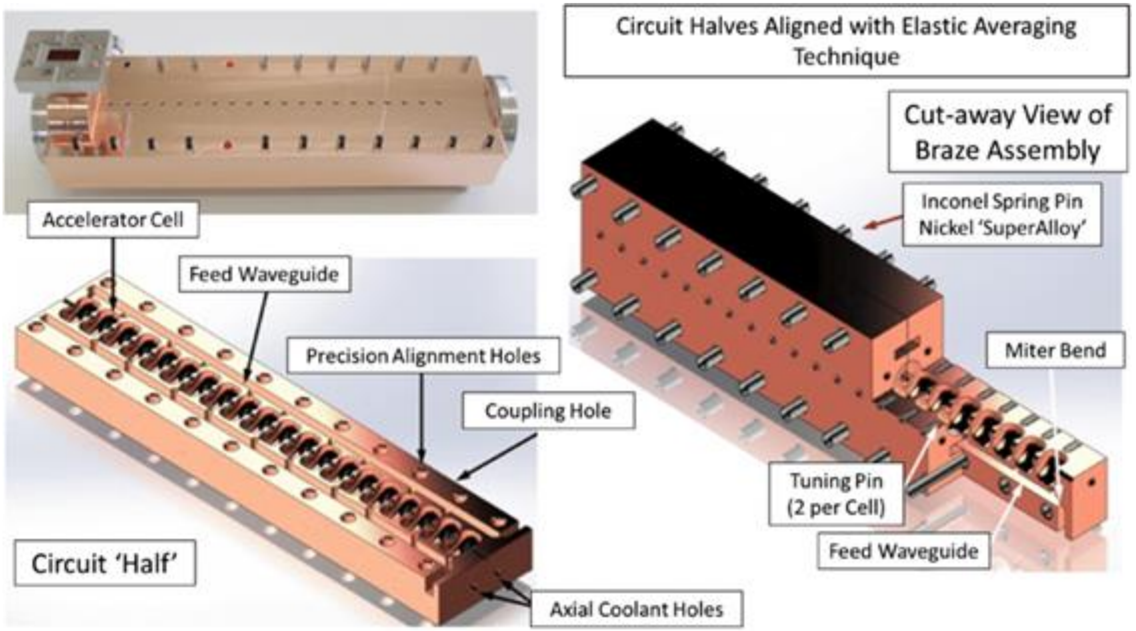
- What gradients can we achieve?
- How efficient can we make these structures?
- How do we achieve and maintain precision alignment?
- Can we preserve beam quality with damping and detuning?
- Can we operate at higher beam powers?
- Is this concept scalable?

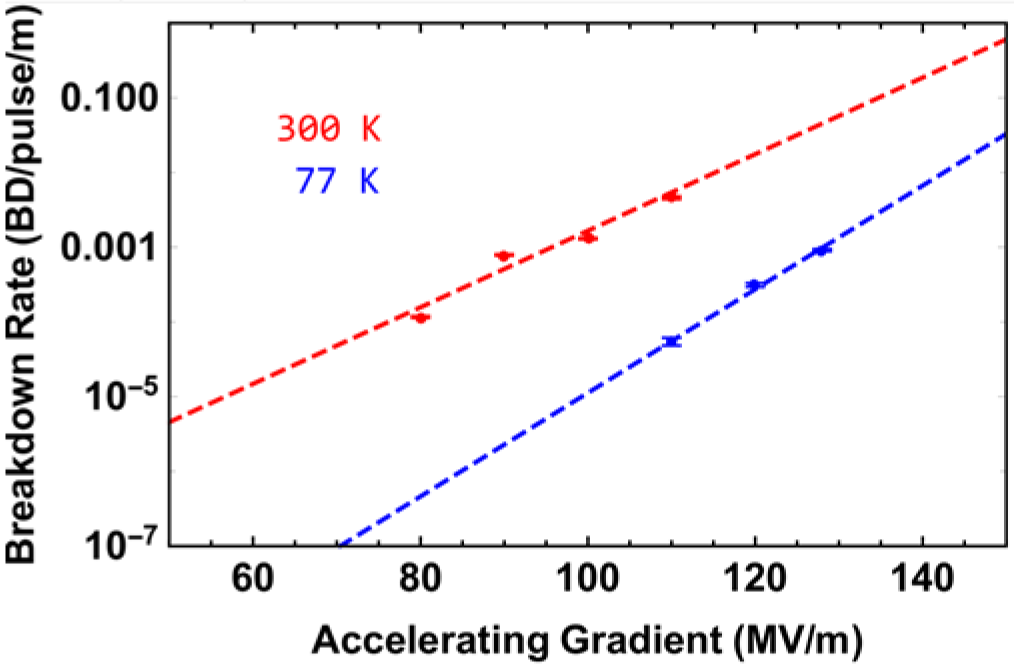
First Demonstration of Cold Copper Accelerating Structure

140 MeV/m measured with beam tests at NLCTA

Breakdown rate (BDR) reduction by 50x from room temperature operation

Breakdown limits primarily driven by high H-field regions within cell coupler





[PRAB 23, 092001 (2020)](#)

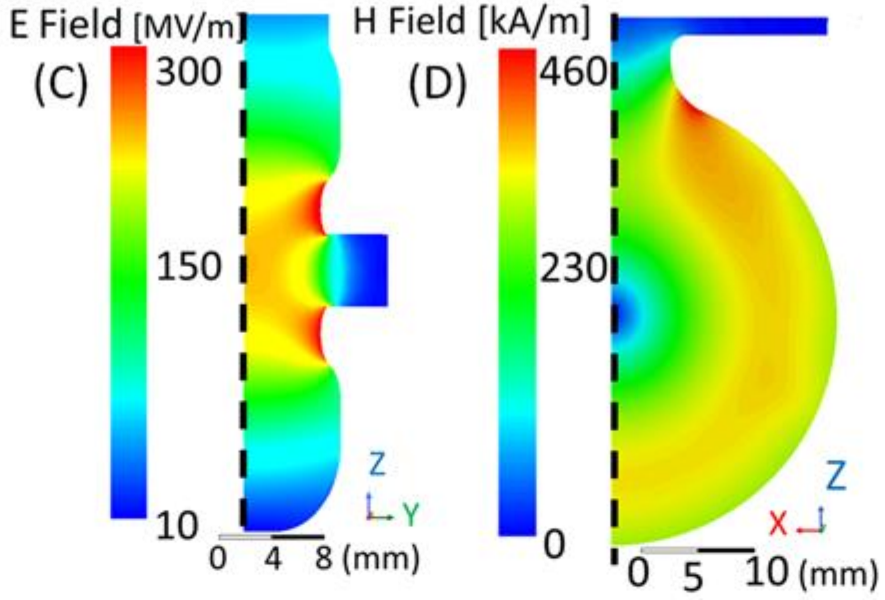
[PRAB 24, 093201 (2021)](#)

Cold copper can dramatically reduce breakdown rates at high gradient

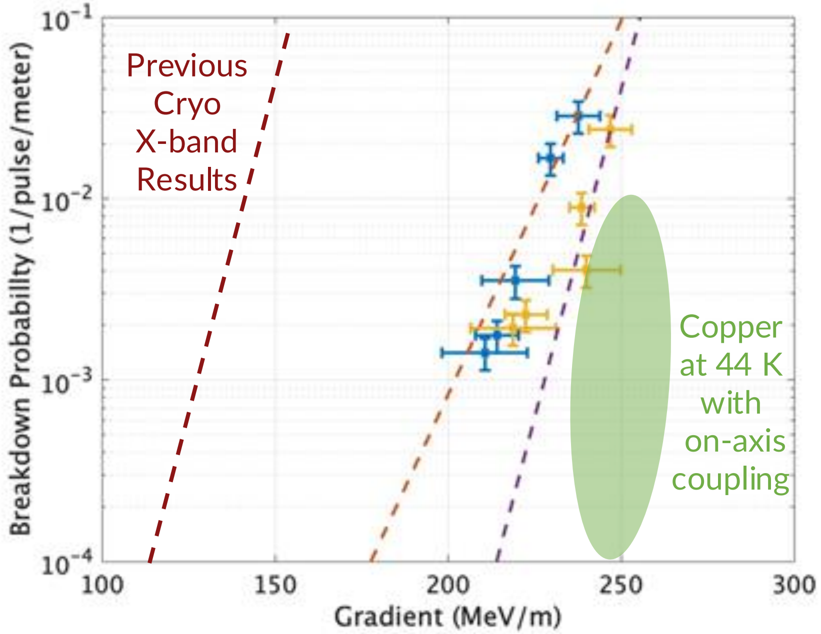
Single Cell High Gradient Tests with Cu and CuAg Cavities

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
- **All tests are done off-site due to lack of on-site high power C-band sources**

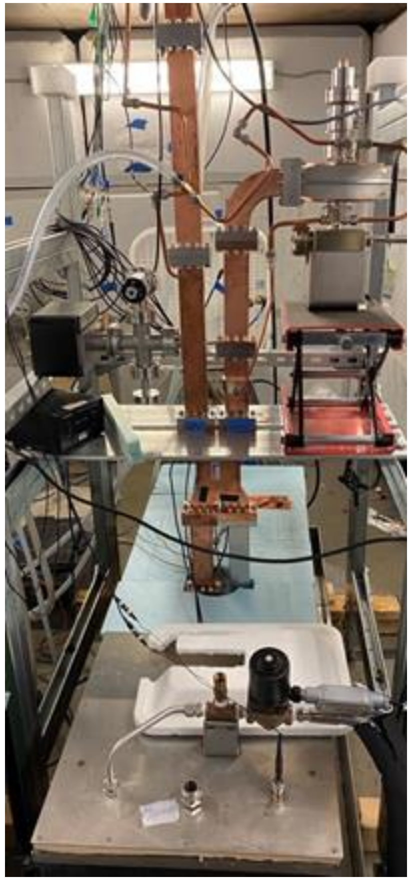


[APL 121, 254101 (2022)](#)
[IPAC2024 p. MOPR29](#)

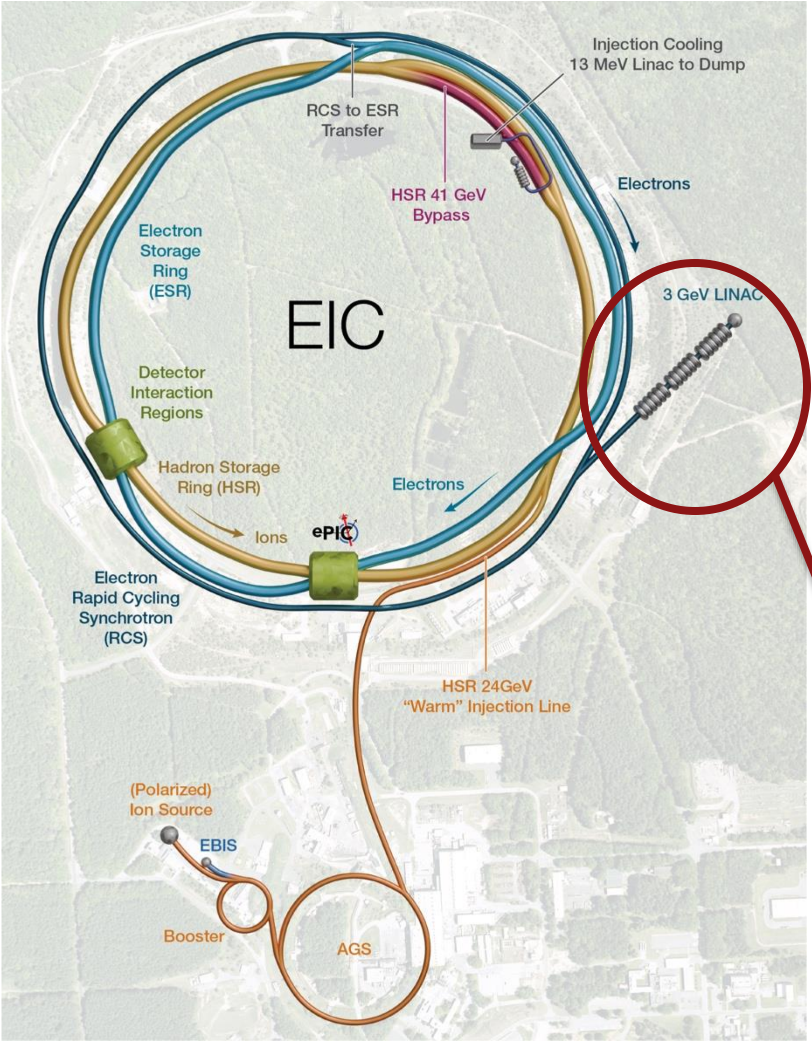


Improved RF design further enhances the achievable gradient

Test at Radiabeam



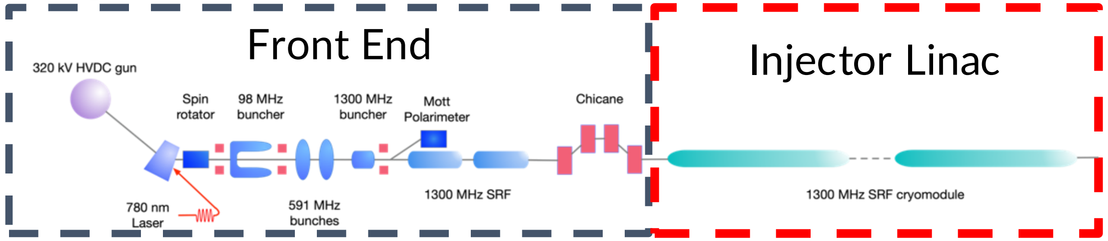
Need for Injector Linacs for Future Colliders



All future colliders will need injector linacs to boost electron bunches up to relativistic speeds.

The Electron-Ion Collider (EIC) underway at Brookhaven will answer questions regarding Nuclear Physics by colliding electrons with heavy ions.

- As such the needs for generating large relativistic electron / positron bunches is comparable to the needs of ILC, C^3 and FCC
- Due to the higher maturity of the facility design, we looked at their Conceptual Design Report (CDR) as a benchmark.

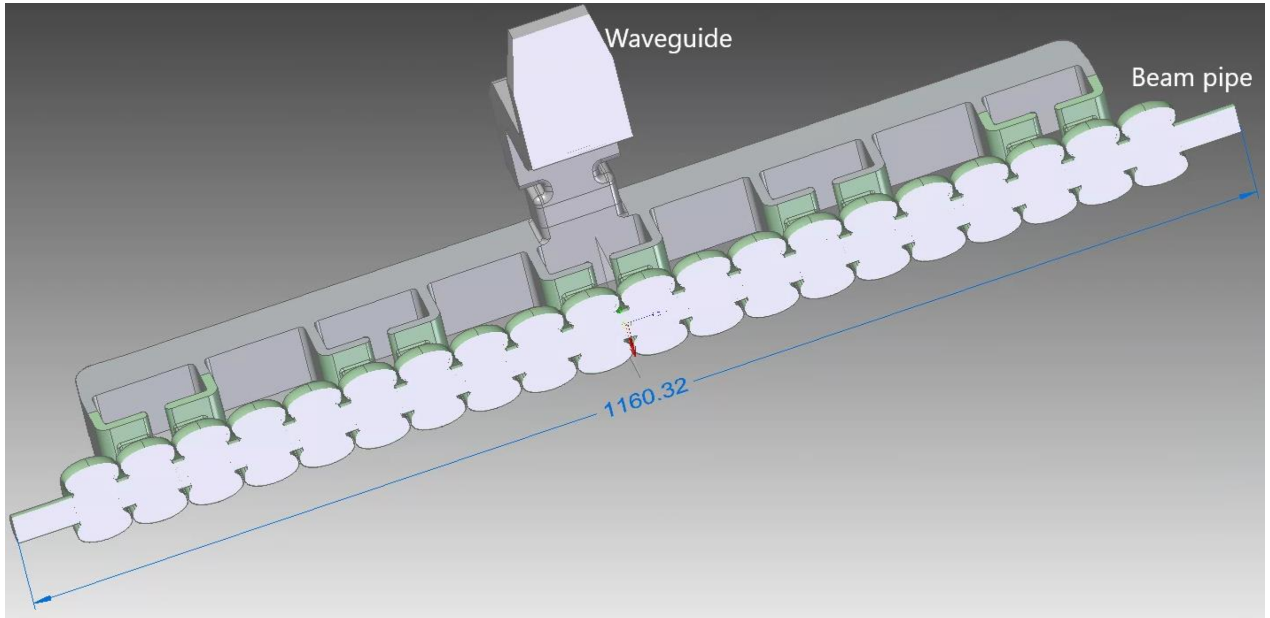


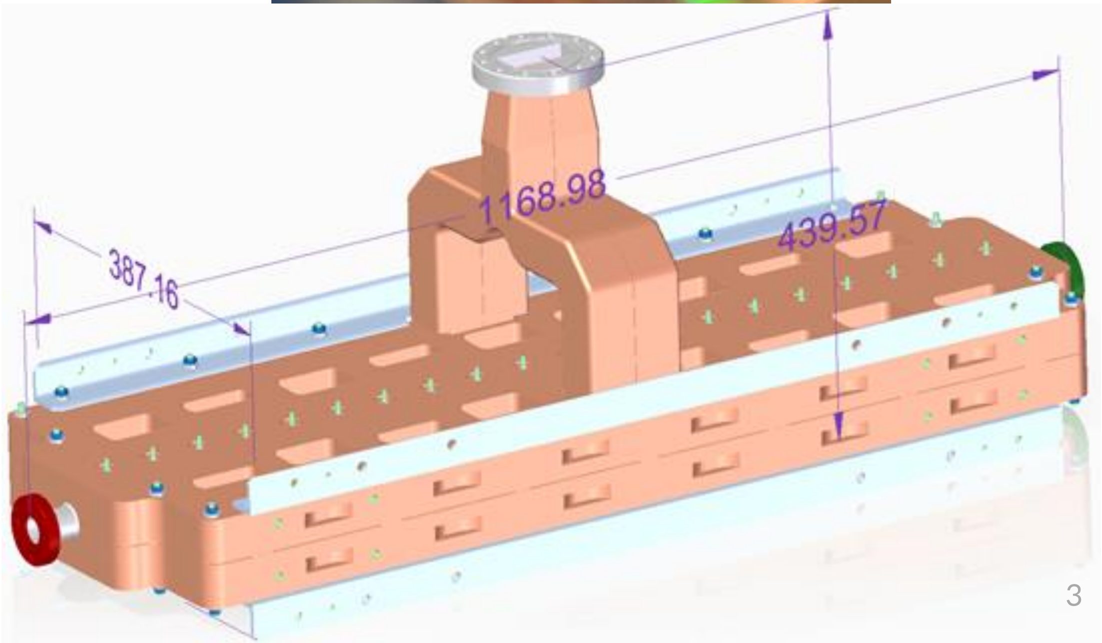
V. Ranjbar. EIC CD-3B Director's Review

Injector Linacs needs 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



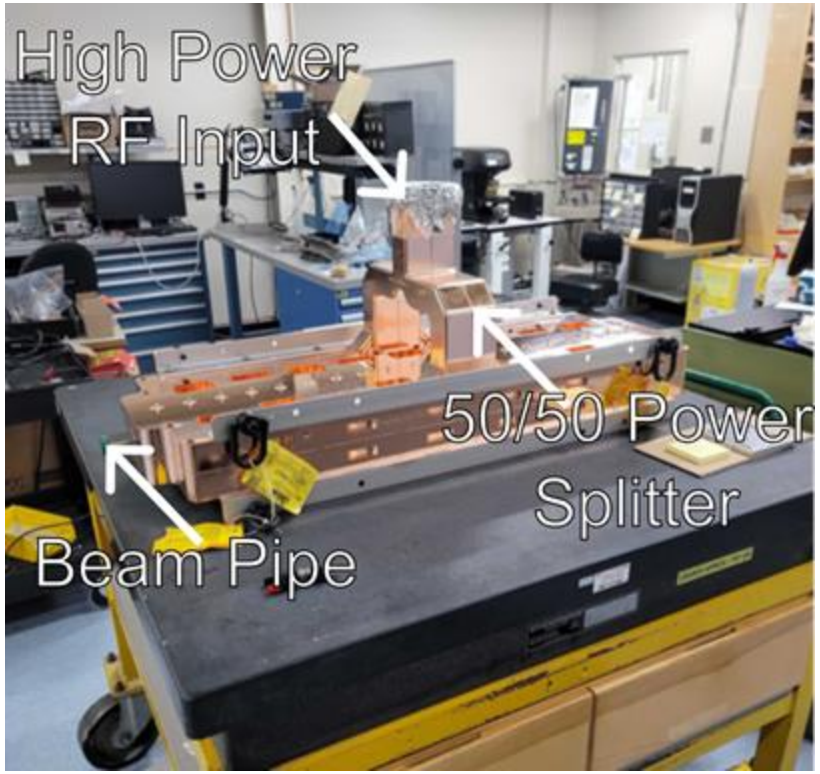


Distributed Coupling as applied to Injector Linac Design

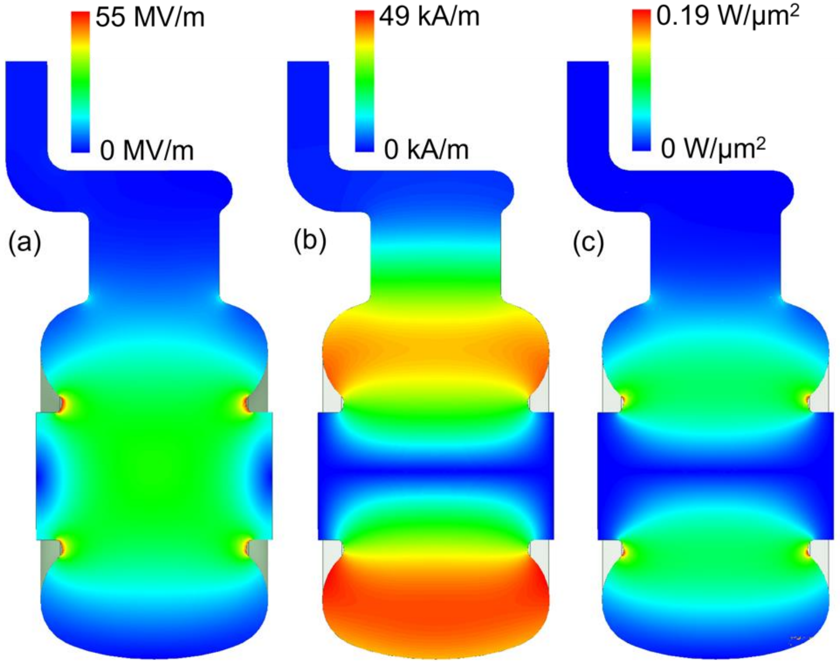
Design balances shunt impedance with aperture size

- S-band cavities designed with aperture ratio a/λ=0.135

Baseline design informed by EIC CDR specs



Linac Properties			
Freq (GHz)	2.856	E_{max}/E_{acc}	2.63
a (mm)	14.12	E_{acc}/Z_0H_{max}	0.995
a/λ	0.135	R_s (MΩ/m)	58
P_{diss} (MW)	5	E_{acc} (MV/m)	18



A. Dhar, et al. *JACoW* , Vol. IPAC2024 p. TUPR14.

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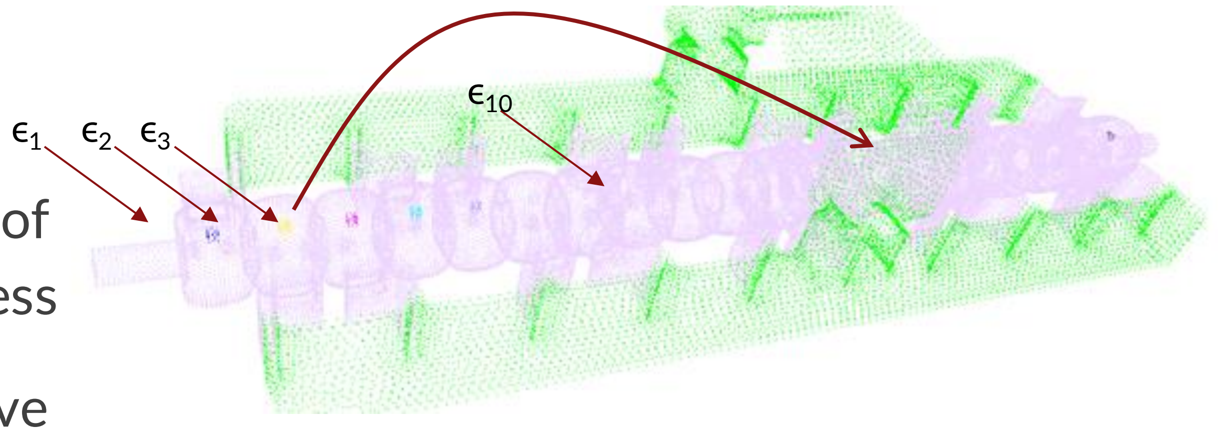
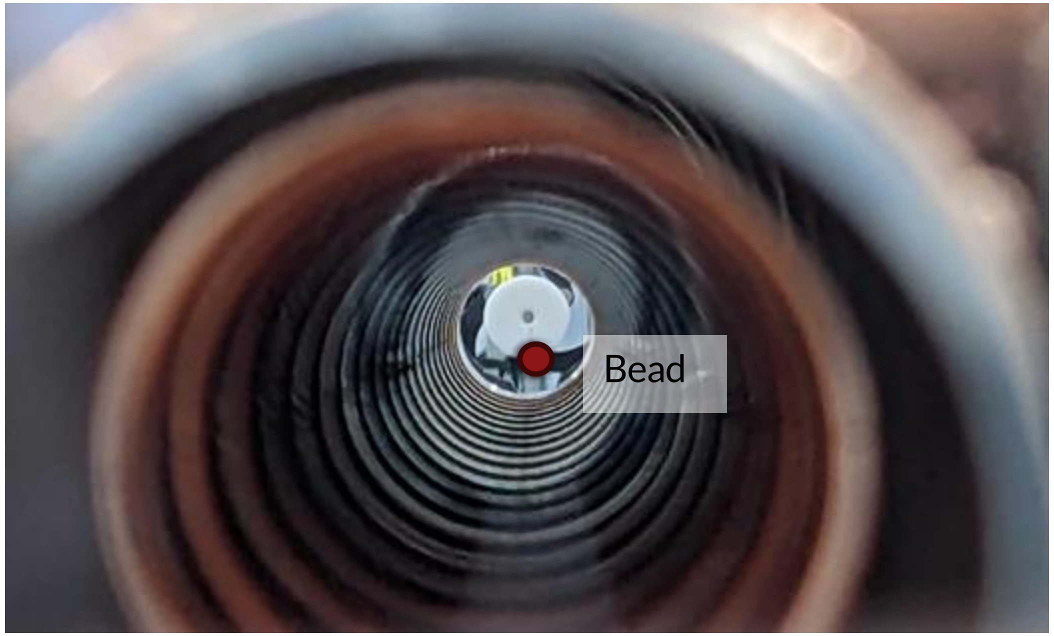
Characterizing a Large Aperture Distributed Coupled Linac

Large apertures introduce coupling between cavities

This cross coupling means individual adjustment of cavity frequency is required to ensure field flatness

- These adjustments were verified with extensive simulation with ACE3P
- Bead pulls were conducted to measure field flatness as tuning was conducted



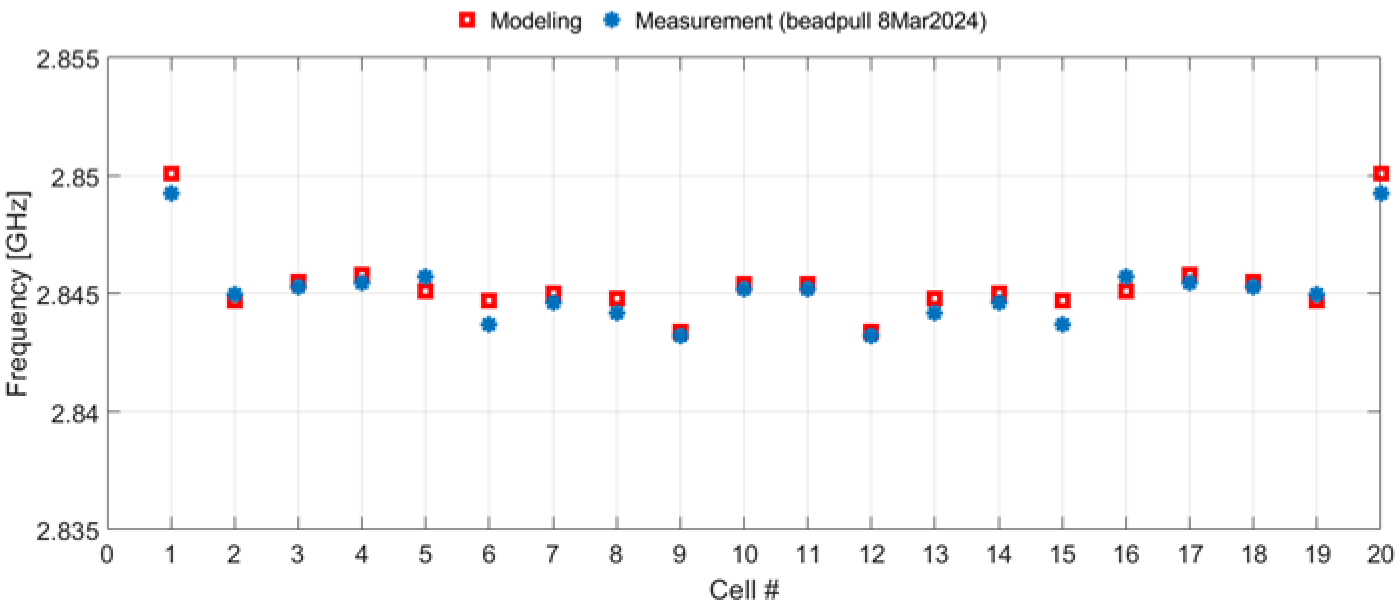


Cold Test and Tuning Results

The distribution of frequencies for each cavity was chosen through iterative measurements and simulations

Relative distribution ensured all cavities couple strongly to the pi mode of the structure

Global tuning with water blocks can be used to shift pi mode frequency during operation



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

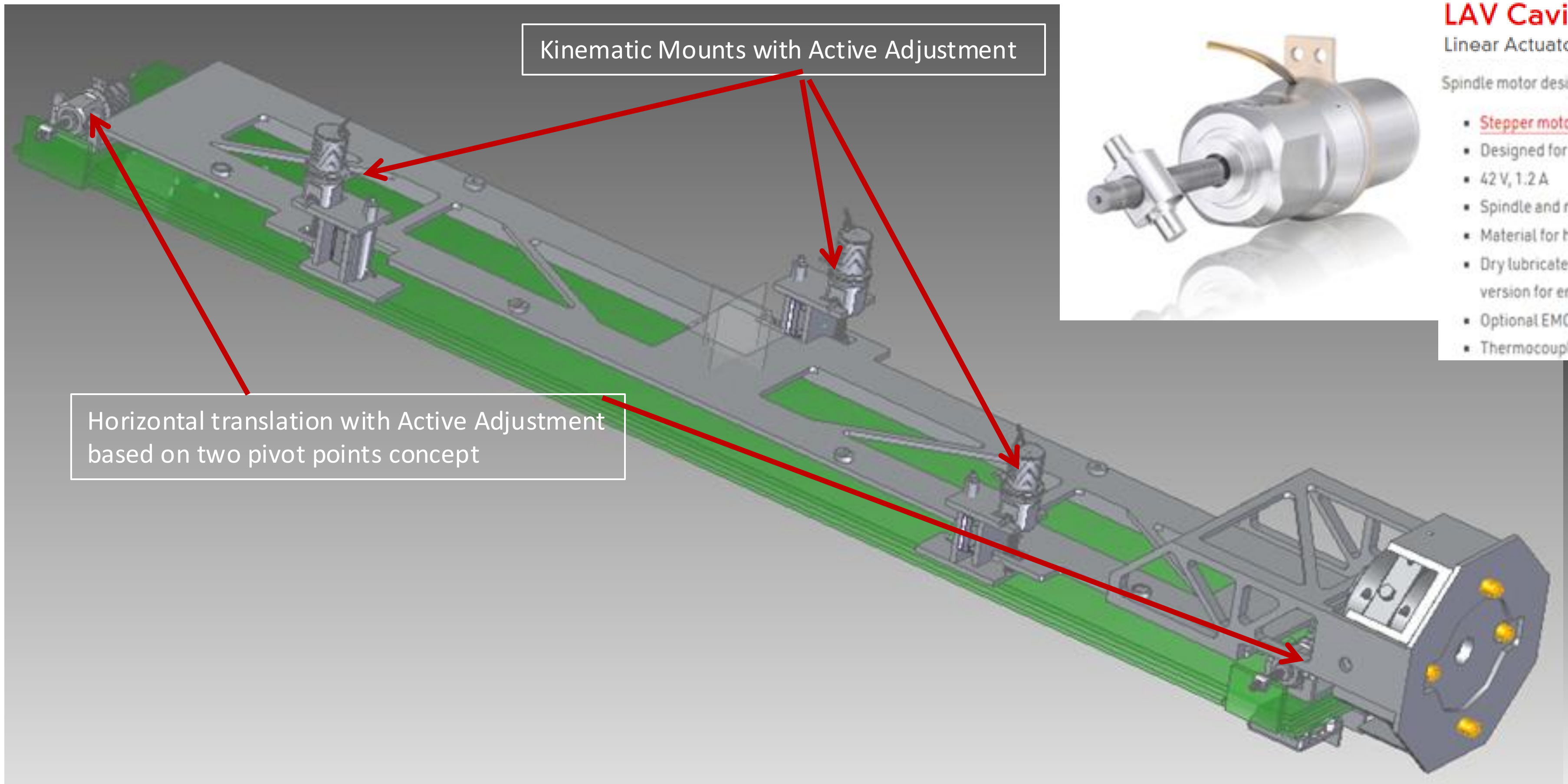
	SLAC Linac 3 m structure	PSI Linac 4 m structure	Distributed Coupling 1 m structure	Cryo-Distributed Coupling [77 K] 1 m structure
Shunt Impedance [M/m] *a/ [radius/wavelength]*	56* *0.125-0.092*	45-56+ *0.135-0.095*	58 *0.135*	145 *0.135*
Power / Length @ 40 MeV/m [MW/m]	43	39	28	11
Achievable Gradient [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)

Adjustable Raft for Linac Handling

Steel raft is mounted on kinematic movers to allow for six-axis adjustments

Movers used stepper motors for slow, large adjustments, and piezos for smaller, faster ones

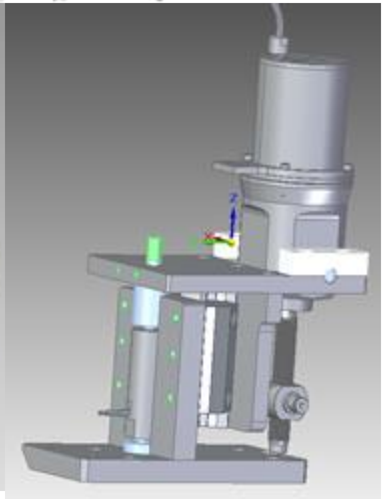


LAV Cavity Tuner

Linear Actuator Design e.g. for Particle Accelerator Cavity Adjustments

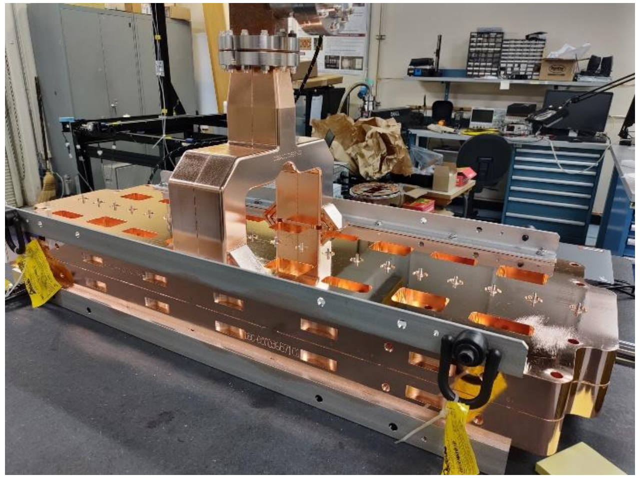
Spindle motor design for particle accelerator applications based on the VSS standard:

- Stepper motor with 200 steps/rev (1.8°), with integrated gear 50:1 (10:000 steps/revolution)
- Designed for 1300N axial force
- 42 V, 1.2 A
- Spindle and nut system, non magnetic
- Material for housing, flanges and internal parts stainless steel or titanium
- Dry lubricated suitable for usage under vacuum at -270 °C up to +40 °C (also as grease lubricated version for environments > -35 °C)
- Optional EMC cable shielding
- Thermocouple K-type in winding



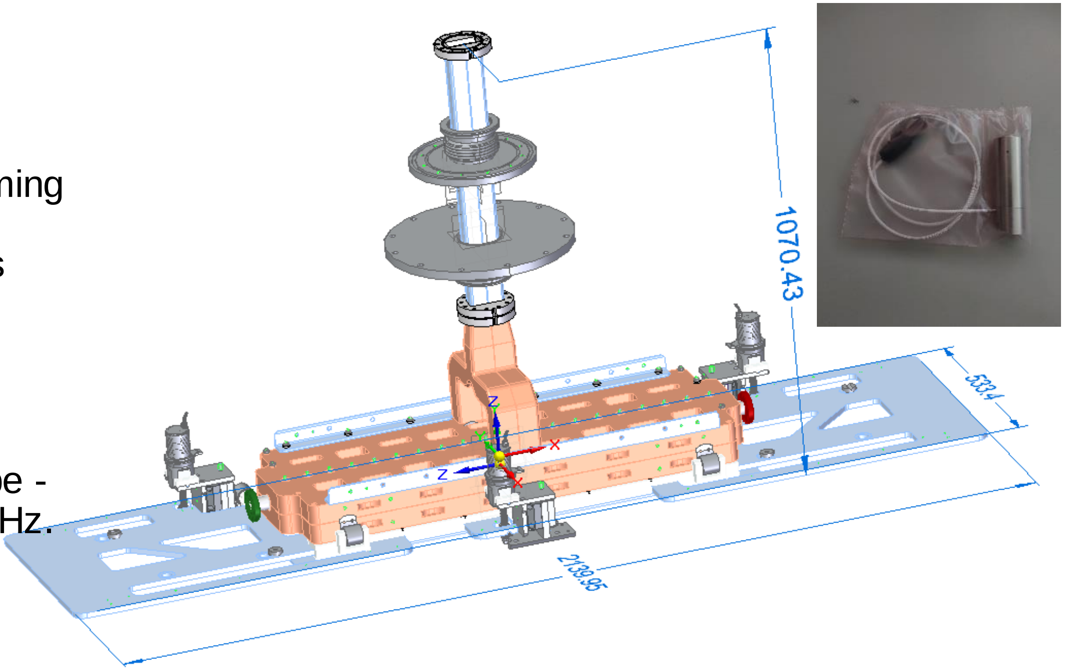
RAFT PLATE CONCEPT

S-BAND LINAC

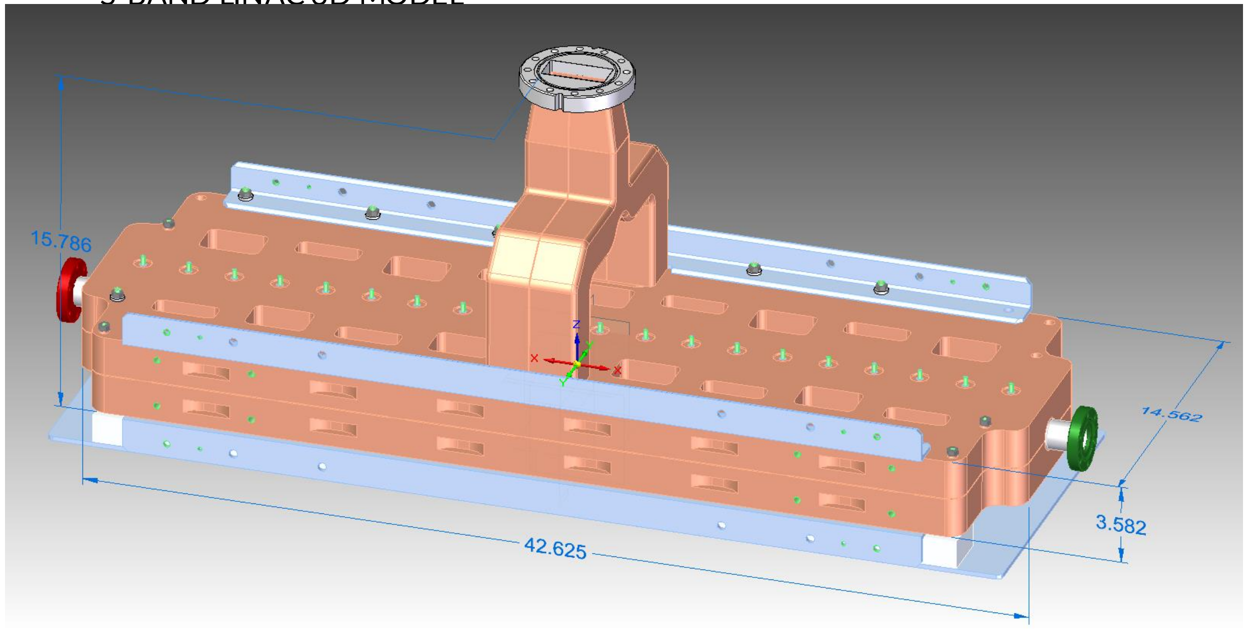


Kinematic mount of S-BAND LINAC LINAC on the raft.

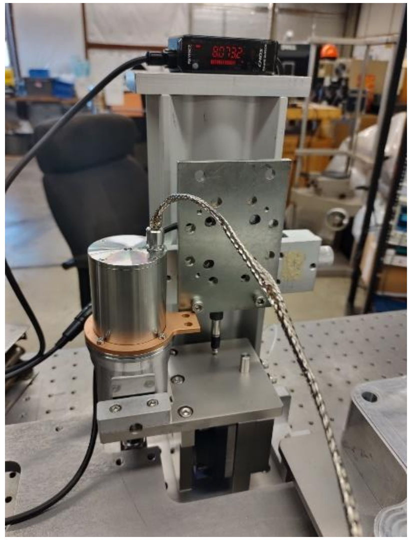
- Phytron LAV actuator and PI PIEZO are forming active alignment post. Structural stability is provided by short Thomson 500 series cross roller slide.
- Phytron LAV accuracy ~100nm, backlash ~1.5µm.
- Actual PIEZO range of motion expected to be -20µm - +20µm @80K with the speed of >1kHz.

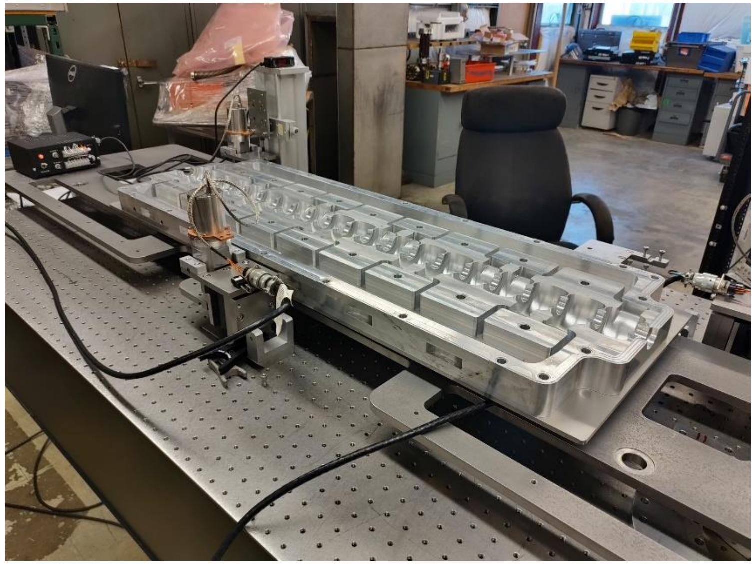


S-BAND LINAC 3D MODEL



S-BAND LINAC MOUNTED ON THE RAFT

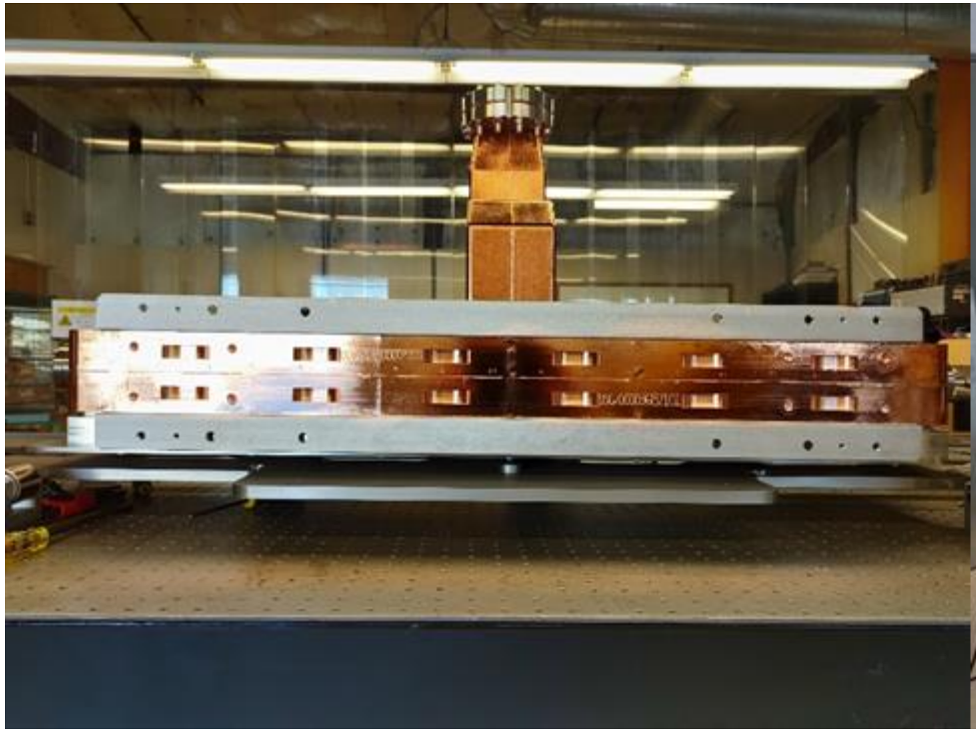


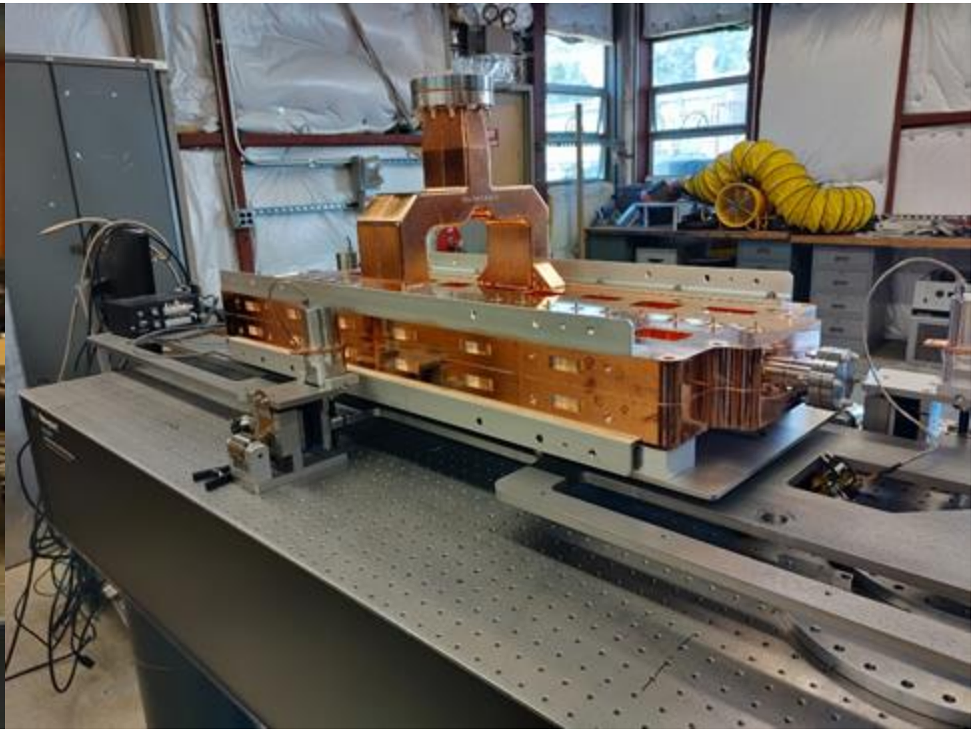


Raft Mounted Structure

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.

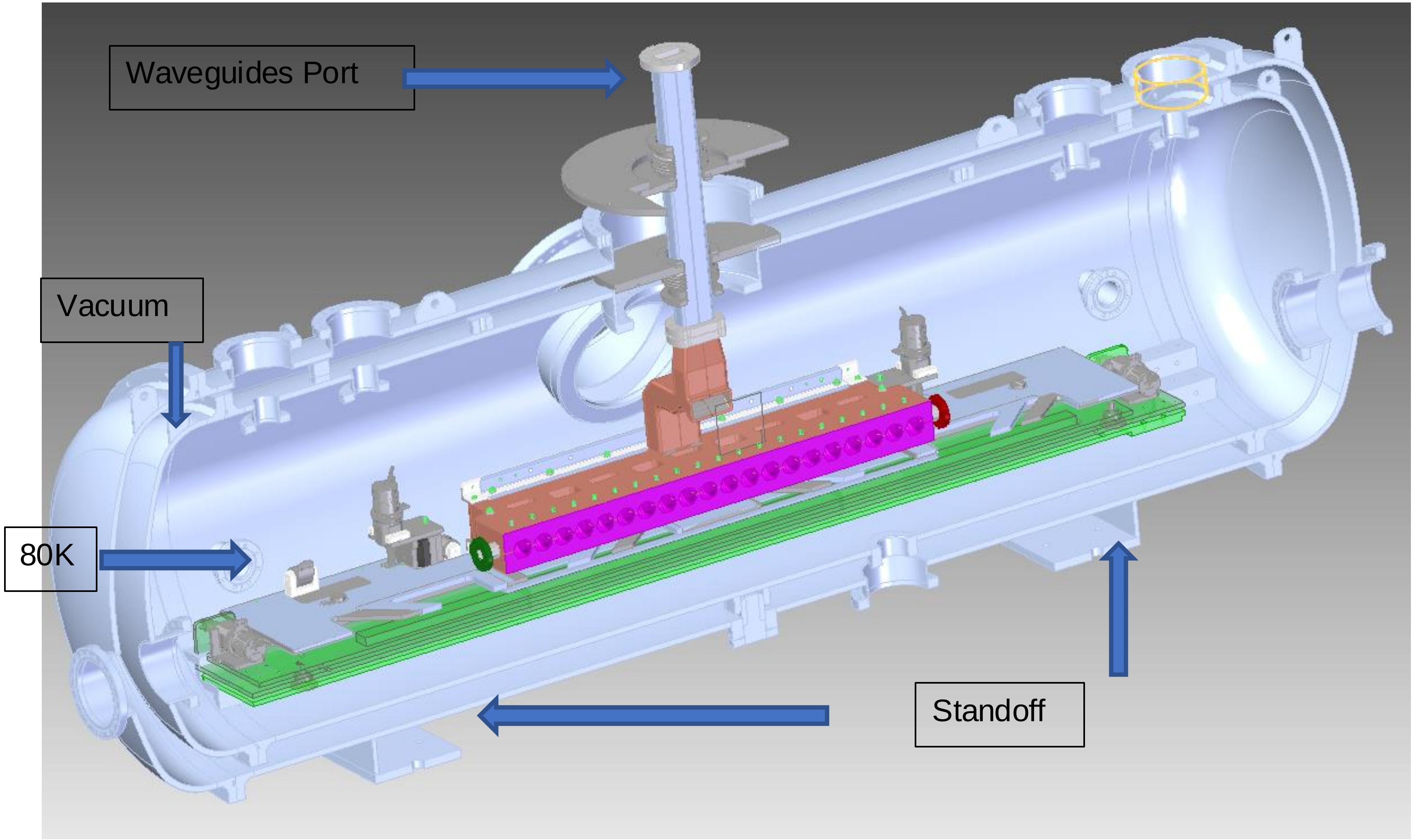
Polytech PI PIEZO was tested with accuracy of 100nm. Visual inspection shows operation at least at 100Hz.





QCM Demo Unit with S-BAND LINAC

Quarter Cryo-Module with Rafts Assembly



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

Currently Open Questions

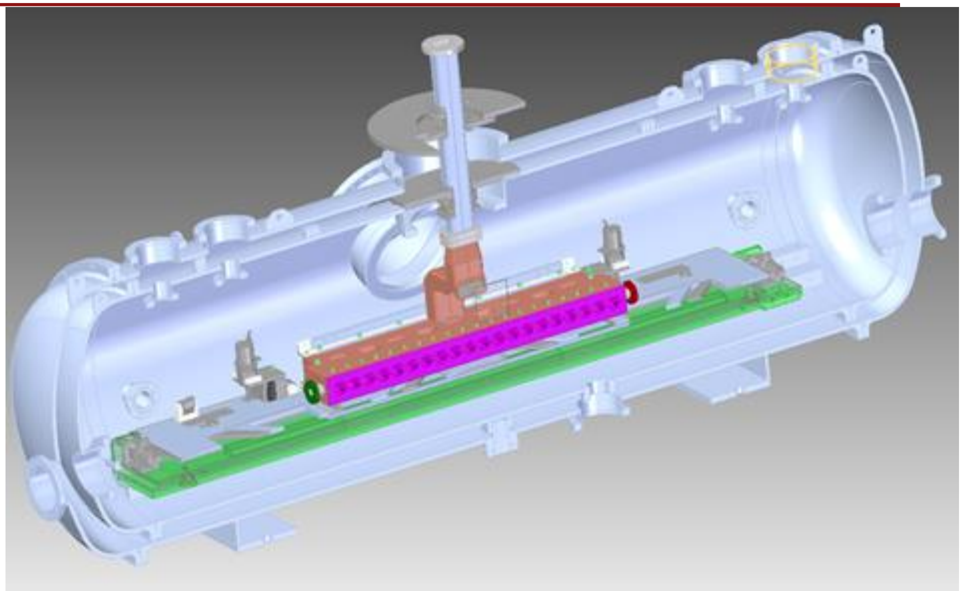
- Nitrogen flow distribution
- Waveguides inside the cryostat, including thermal break and phase shifter
- Concept of vacuum interconnections
- Vibration compensations and dampers if needed

Quarter Cryomodule (QCM) Production

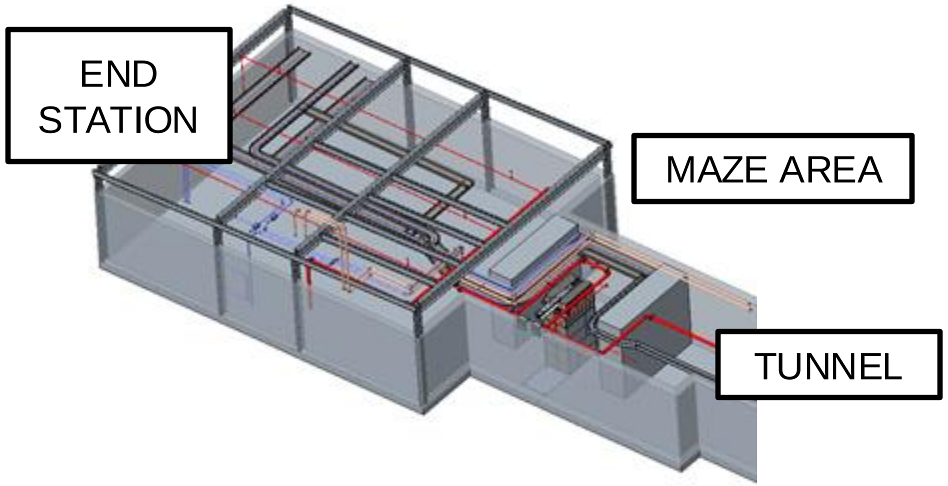
High Power Test Plans

Preparations are underway to test this structure at high power at Argonne National Laboratory (ANL), Advanced Photon Source (APS) using the Linac High-Power RF Test stand and the Linac Extension Area (LEA).

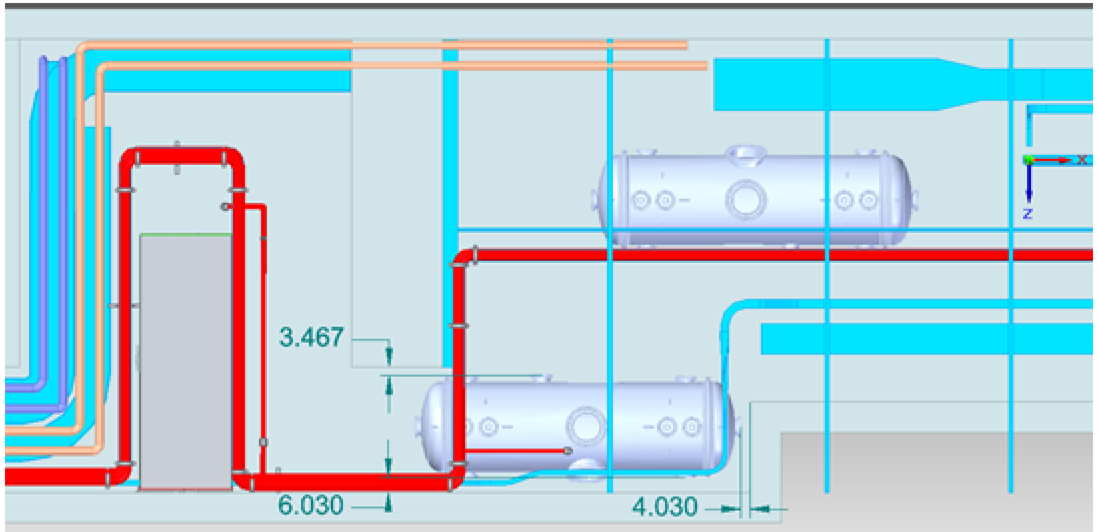
- High power test measuring breakdown rate with 30 MW klystron
- Full power + beam tests
- Second phase with two structures and 60 MW klystron
- Eventually repeat full test within quarter cryo-module



Single S-band structure within Quarter Cryo-module



Linac Extension Area at Argonne

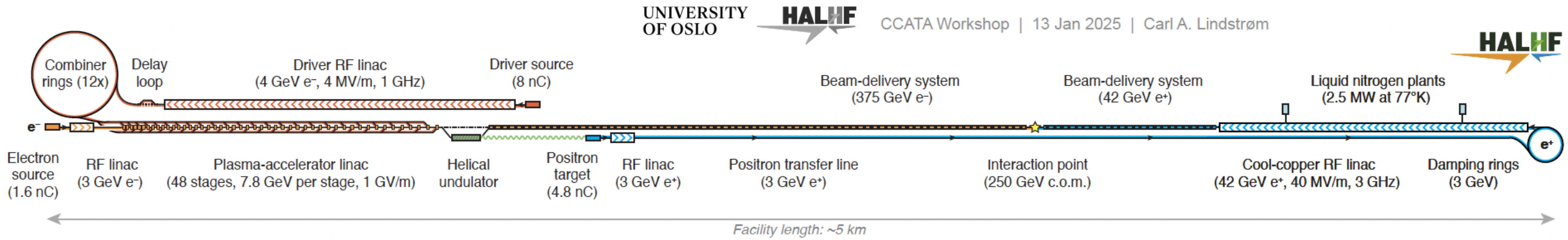


Plan to maneuver QCM through the maze

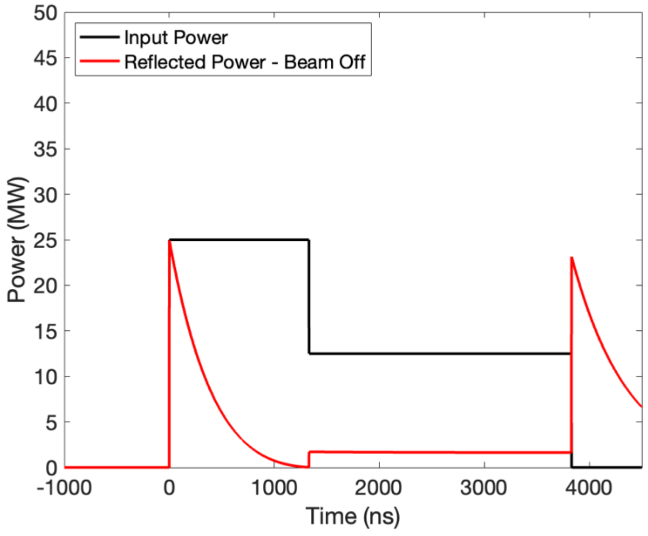
SLAC

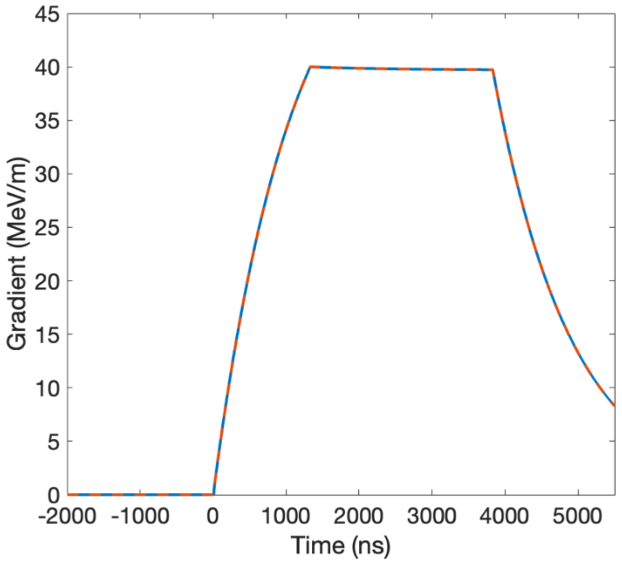
HALHF Positron Linac

> Need to accelerate 160 e^+ bunches of ~4.8 nC in a 2.5 μs train (16 ns spacing) at 100 Hz

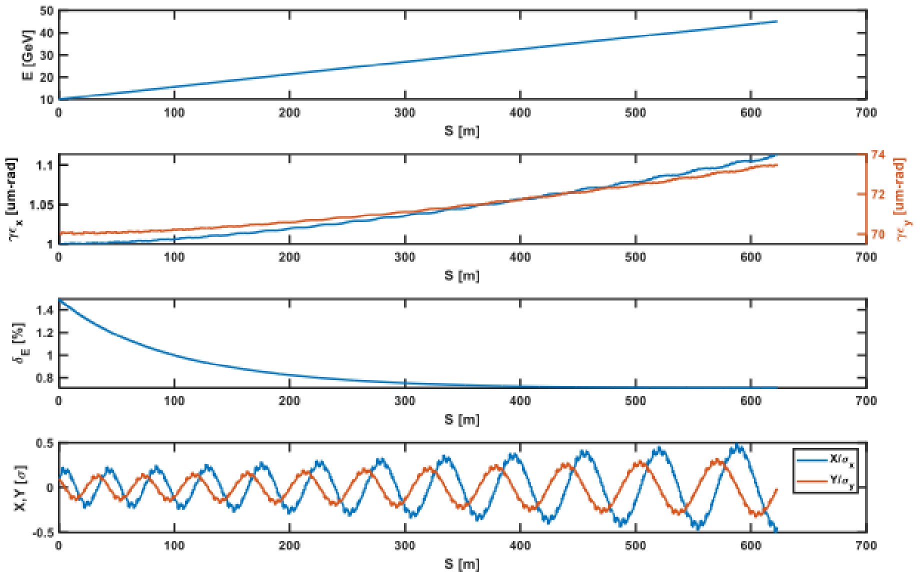


- Simple RF Power: 25 MW/m no rf compressors, no circulator





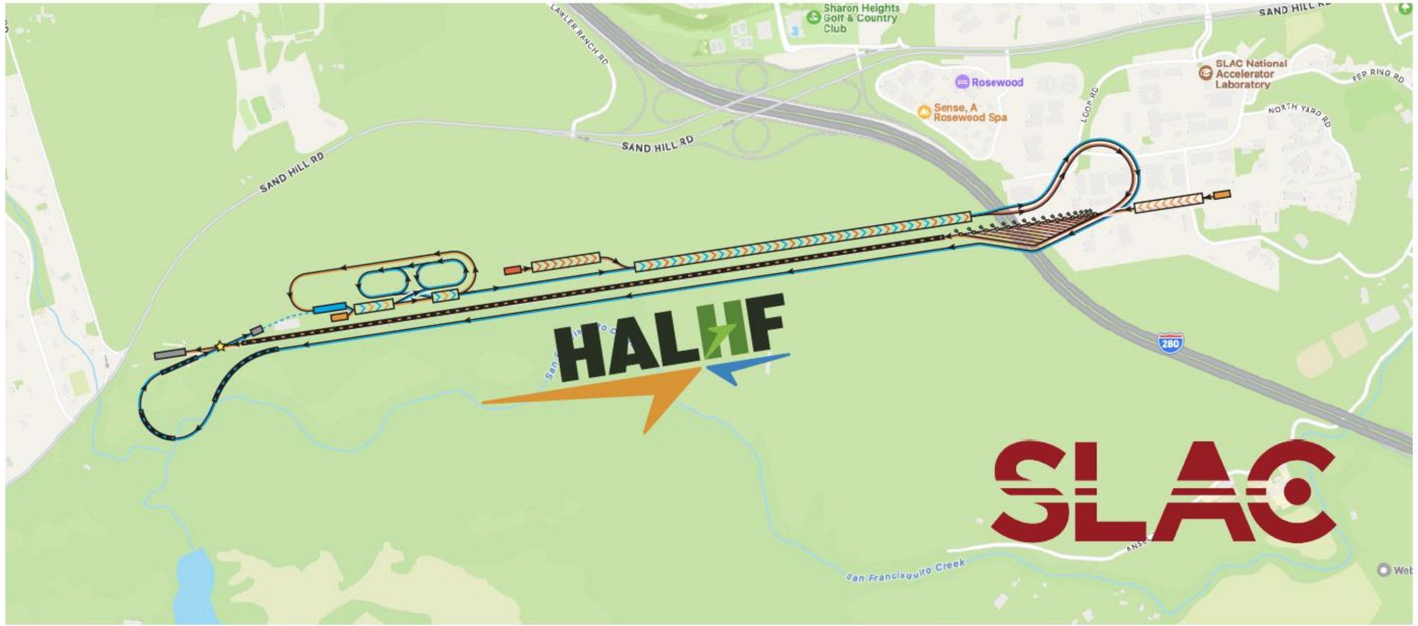
Future Work: Linac Sims at Proper Gradient/Emittance



HALHF @ SLAC?

A collider on a "national" scale

Plasma acceleration for electrons + RF acceleration for positrons



> Overall footprint: 3–5 km (TBD): Fits in most major particle-physics laboratories

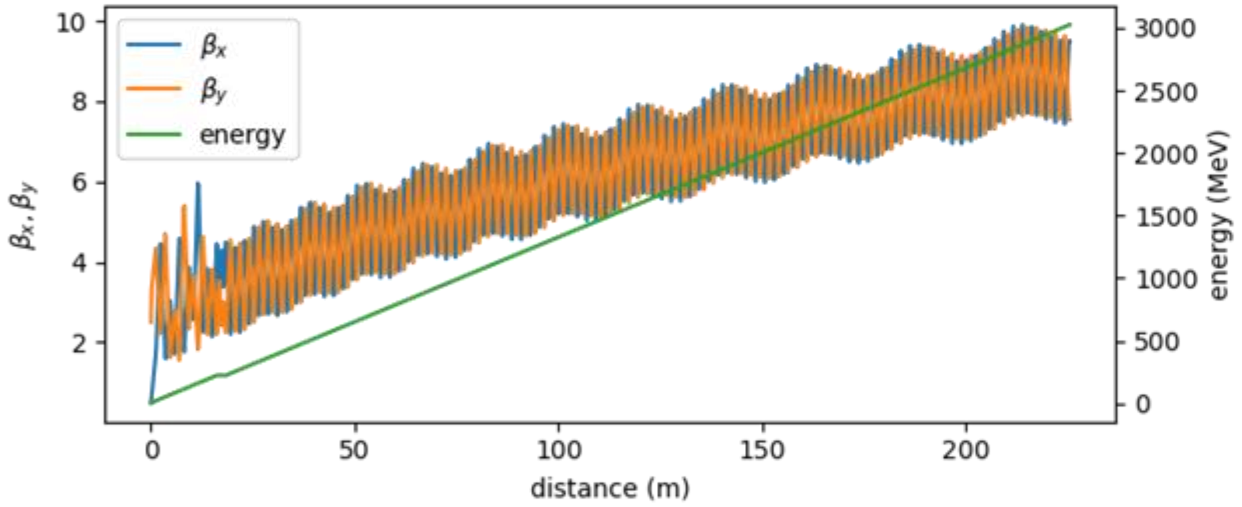
> Construction cost estimate around \$2–4B (TBD) — national, not international scale.

Questions?

Synergies with Electron-Ion Collider

EIC needs an injector linac to boost their 7 nC electron bunches up to 1-3 GeV

- Beam dynamics simulations were considered with the S-band structure operating at 16 MV/m
- The first 18-meter section is used to match the beam from the upstream, and accelerate the beam to ~200 MeV
- From there alternating quadrupole magnets and linac structures up to 3 GeV



Parameter	Initial value	Target value
Beam energy	4 MeV	3 GeV
Emittance x, y	60 µm	
Energy spread	1% (assumption)	0.3%
Bunch length	1 mm	N/A
Charge	11 nC	11 nC
Field gradient	16 MV/m	N/A
RF frequency	2.856 GHz, S-band	N/A
Quad length	15 cm	N/A
RF structure length	1 m	

SLAC

Synergies with Future Circular Collider

FCC needs a High Energy Linac to boost to 20 GeV

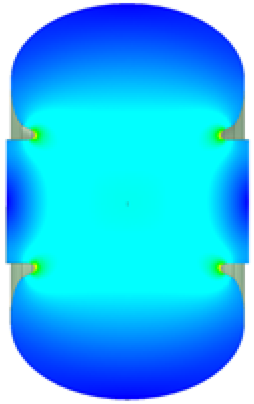
- Initial study with a/λ = 0.125
- Shunt impedance at 300 K: 58.5 MΩ/m
- At 77 K: 146-158 MΩ/m
- Expected performance for 22.5 MeV/m
- Efficiency: 6 MW/m, 3 microsecond fill time

Beam dynamics studies show emittance growth is within spec for <10 μm shifts

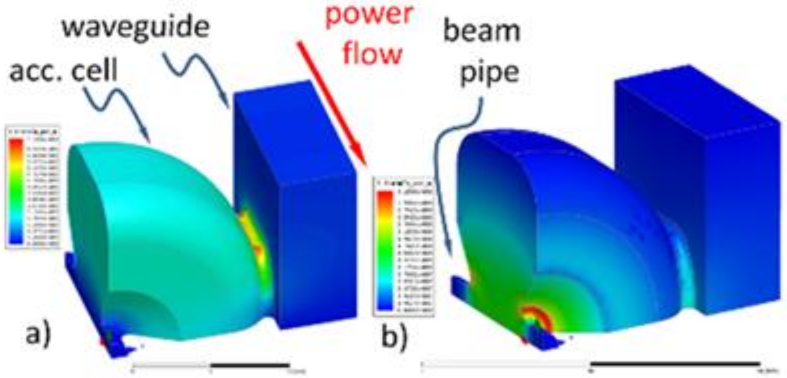
Pulse compressed version could use traveling wave manifold for faster fill time and even higher efficiency

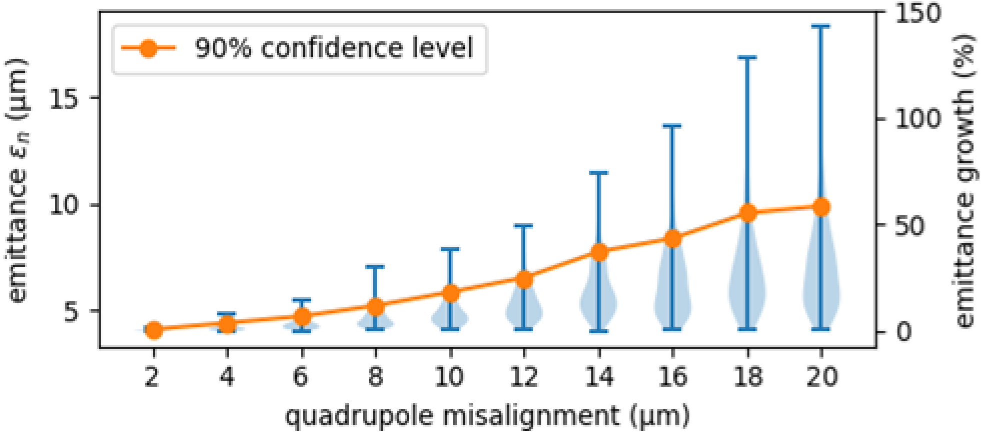
FCC HE-Linac Properties	
Freq	2.8 GHz
charge (nC)	5 nC
initial energy	6 GeV
final energy	20 GeV
initial emittance	4 mm-mrad
target final emittance	10 mm-mrad
initial energy spread	0.1%
final energy spread	0.14%

Single Cavity



TW Manifold





R&D Reports on S-band Structure

Fabrication Process Linac 2022

https://epaper.kek.jp/linac2022/papers/thpojo14.pdf

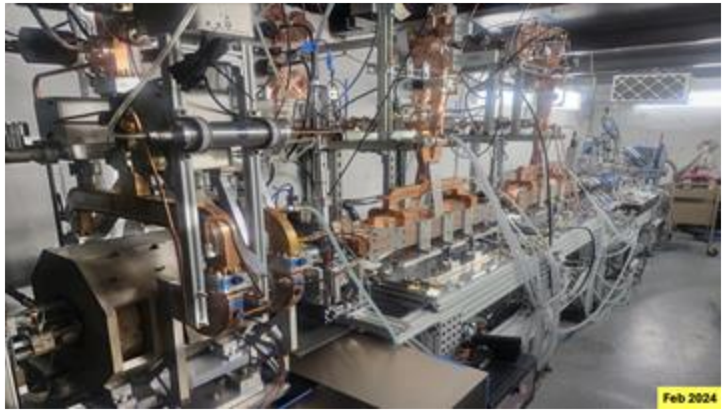
Tuning IPAC 2024

https://accelconf.web.cern.ch/ipac2024/pdf/TUPR14.pdf

Talk on Tuning IPAC 2024

https://agenda.linearcollider.org/event/10134/contributions/54536/

Radiabeam (Distributed Coupling)
Designed and Built at SLAC



ASU CXLS (Distributed Coupling)
Designed at SLAC