Advantages of C^3 Technology for the Injector Linacs

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June 11th, 2024

Acknowledgements

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Outline

- Introduction/Motivation
- High Charge Injector Structure Prototype
- Possible Synergies with FCC-ee
- Conclusion

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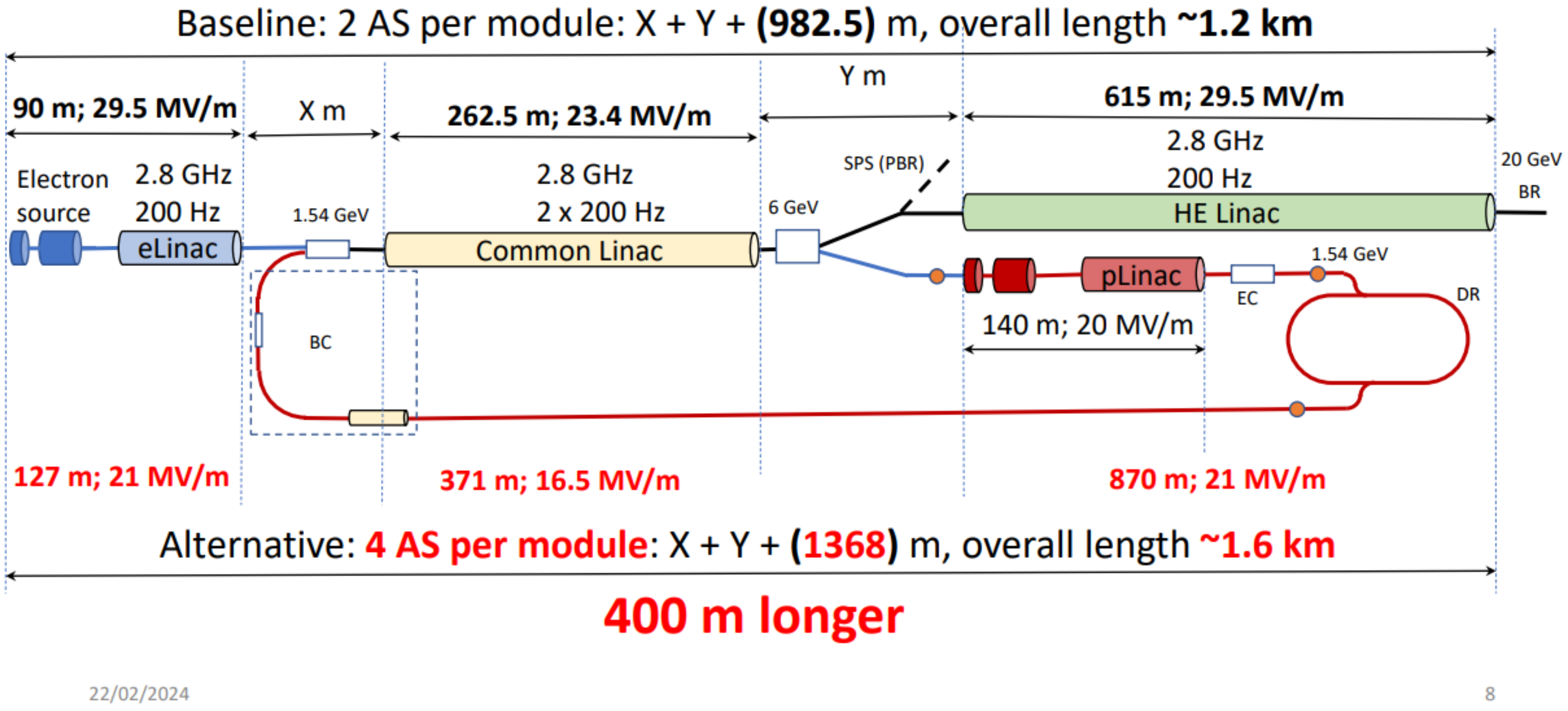
FCC-ee Injector Layout

- FCC-ee Injector produces both positrons and electrons
- Options considered for 6 GeV and 20 GeV
- Significantly different linac requirements as energy increased
- Linac design has significant impact on beam dynamics, power consumption, footprint

FCC-ee Injector*

Baseline layout with length estimates: 2 versus 4 structure per module



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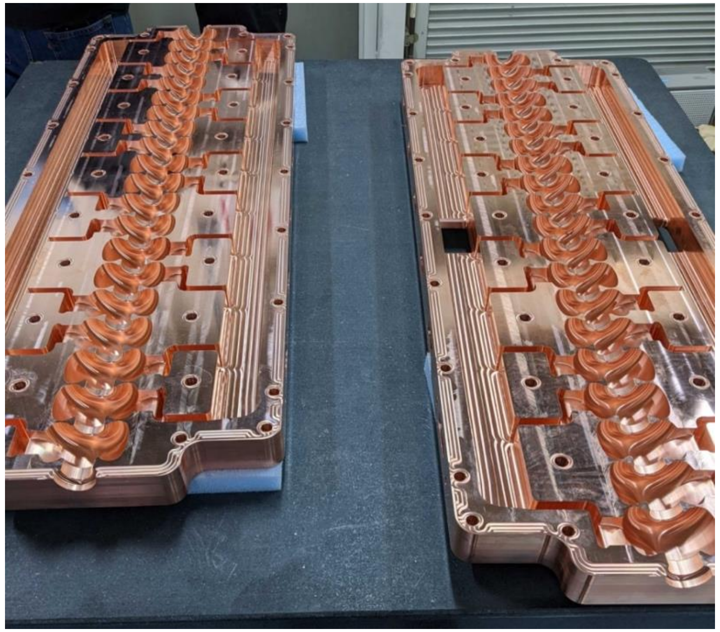
*"FCC accelerators: FCC-ee injector incl. booster (i/ii)" session for latest status/design (Tue PM)

Accelerator technical design: Synergies and innovation

Advances in development for rf accelerators…

RF Structure Design



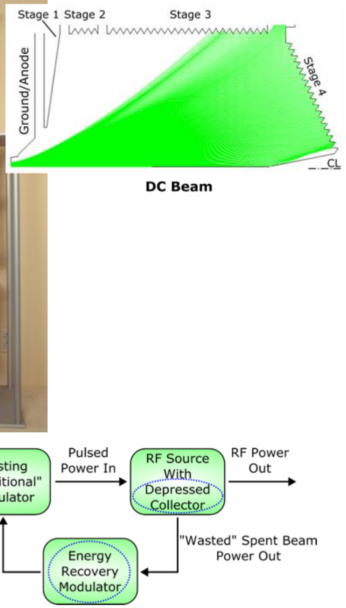
Cold Copper

RF Pulse Compression

Spherical

HTS Coated

RF Sources



Today

Could these benefit beam dynamics, power consumption, footprint?

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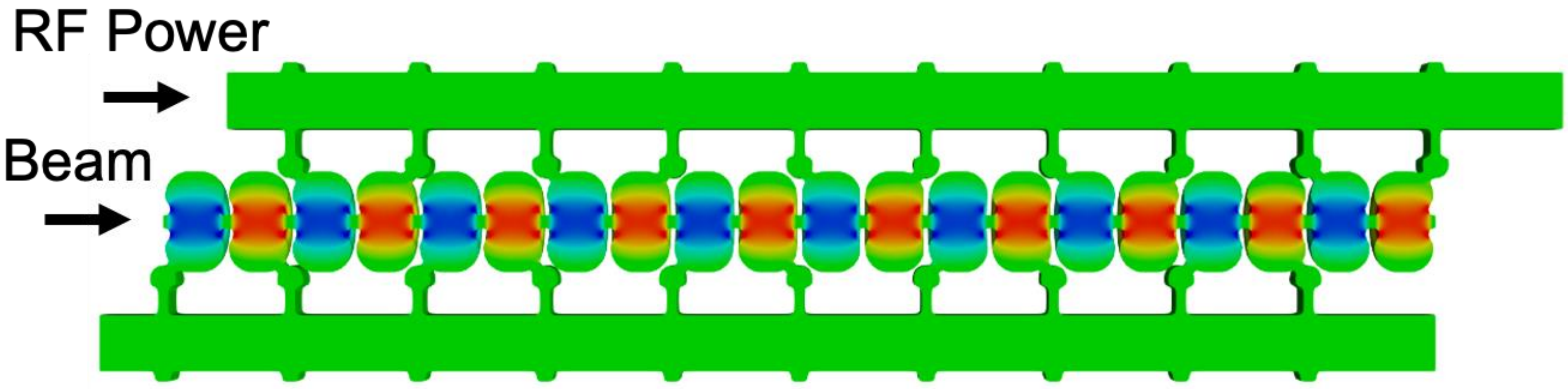
Distributed RF Coupling changes Accelerator Paradigm

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

Full system design requires modern virtual prototyping



Electric field magnitude produced when RF manifold feeds alternating cells equally

Optimization of cell for efficiency (shunt impedance)

- Control peak surface electric and magnetic fields

$$R_s = G^2/P \text{ [M}\Omega\text{/m]}$$

- Core technology of high gradient linac for Cool Copper Collider (C^3)

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

Cold Copper

Cryogenic temperature elevates performance in gradient

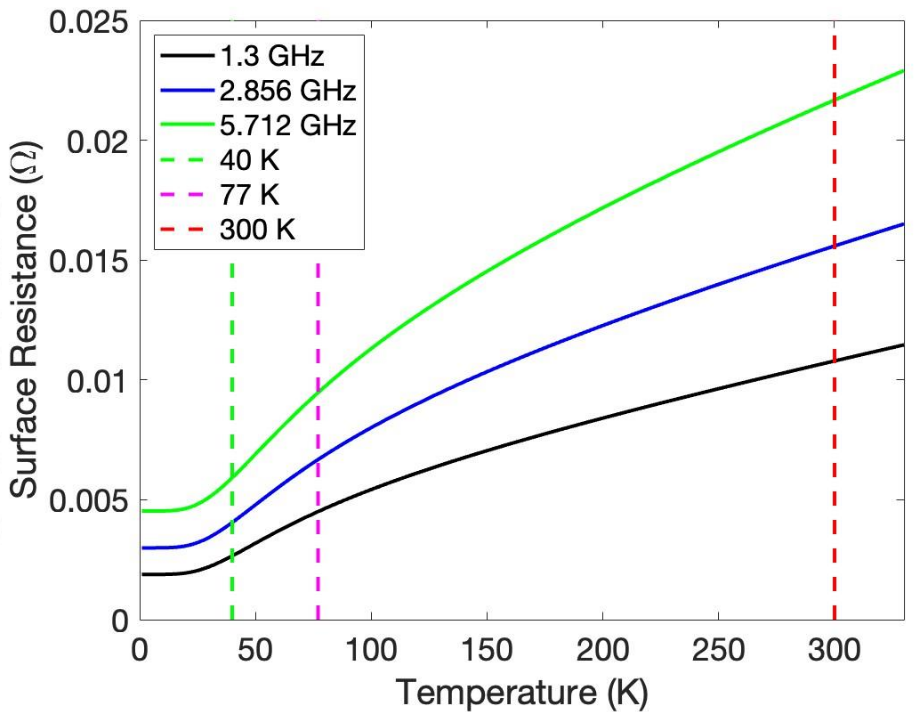
- Material strength is key factor
- Improved conductivity reduces material stress
- Increases rf efficiency

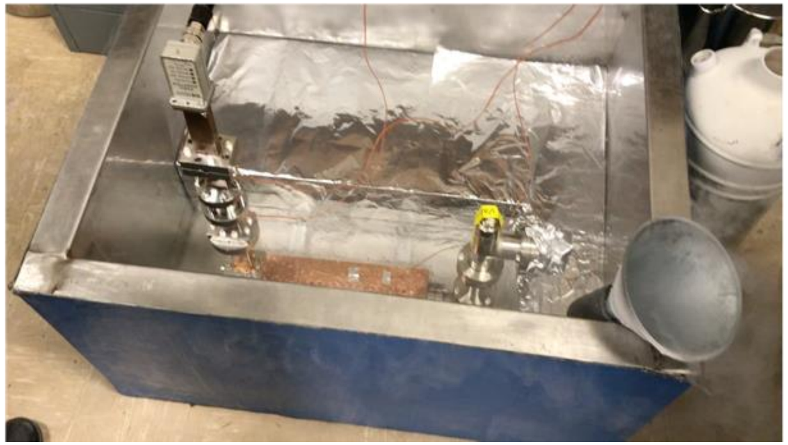
Operation at 77 K with liquid nitrogen is simple and practical

- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency*

$$\eta_{cp} = LN\ Cryoplant$$
$$\eta_{cs} = Cryogenic\ Structure$$
$$\eta_k = RF\ Source$$

$$\frac{\eta_{cs}}{\eta_k}\eta_{cp} \approx \frac{2.5}{0.5}[0.15] \approx 0.75$$





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*Assumes long pulse regime, no rf compression

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EIC Pre-Injector Baseline

- Min Six (Max 8) 3 meter long* 2.856 GHz SLAC-style traveling wave accelerating structures
- Initial Energy 4 MeV
- Energy Gain total 400 MeV
- 7 or 14 nC bunches
- Min. (Max) Gradient 16.6 (22.2) MeV/m in structure
- Total footprint 35.6 m (11.2 MeV/m real estate gradient)

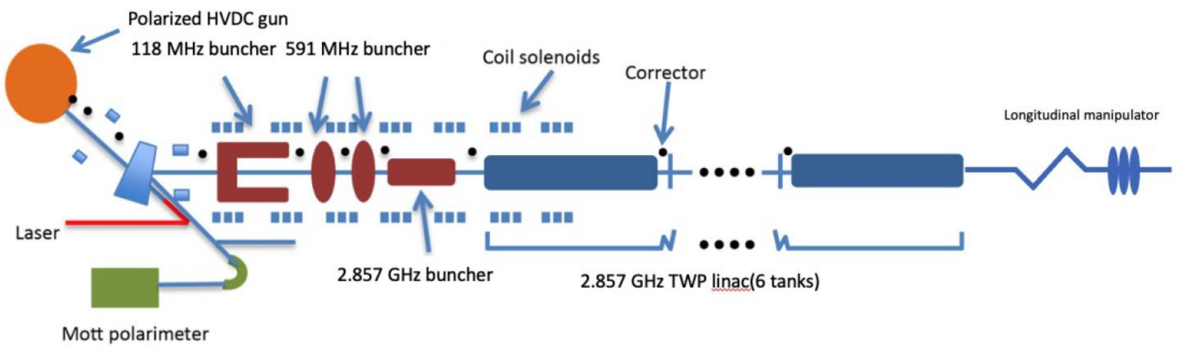

Figure 3.120: The layout of the 400 MeV beamline.

Table 3.49: EIC pre-injector beam requirements.

Parameter	Value
Charge [nC]	7
Frequency [Hz]	1
Energy [MeV]	400
Normalized emittance [mm-mrad]	< 40
Bunch length [ps]	40
dp/p	0.25
polarization [%]	85

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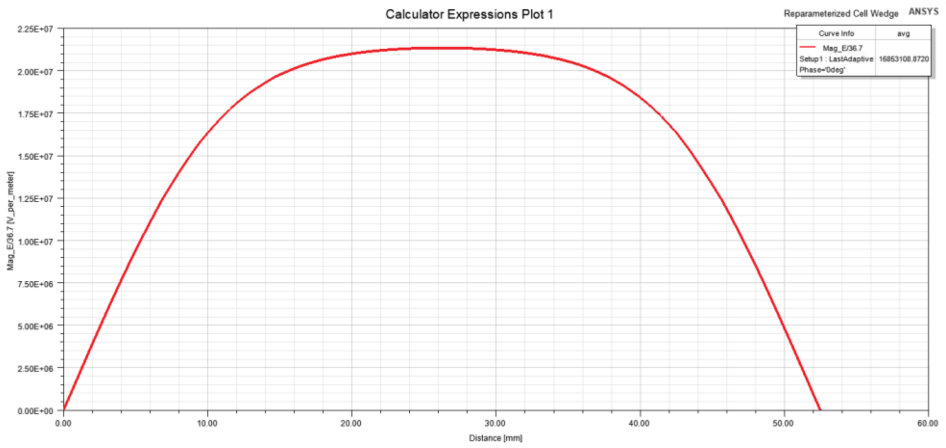
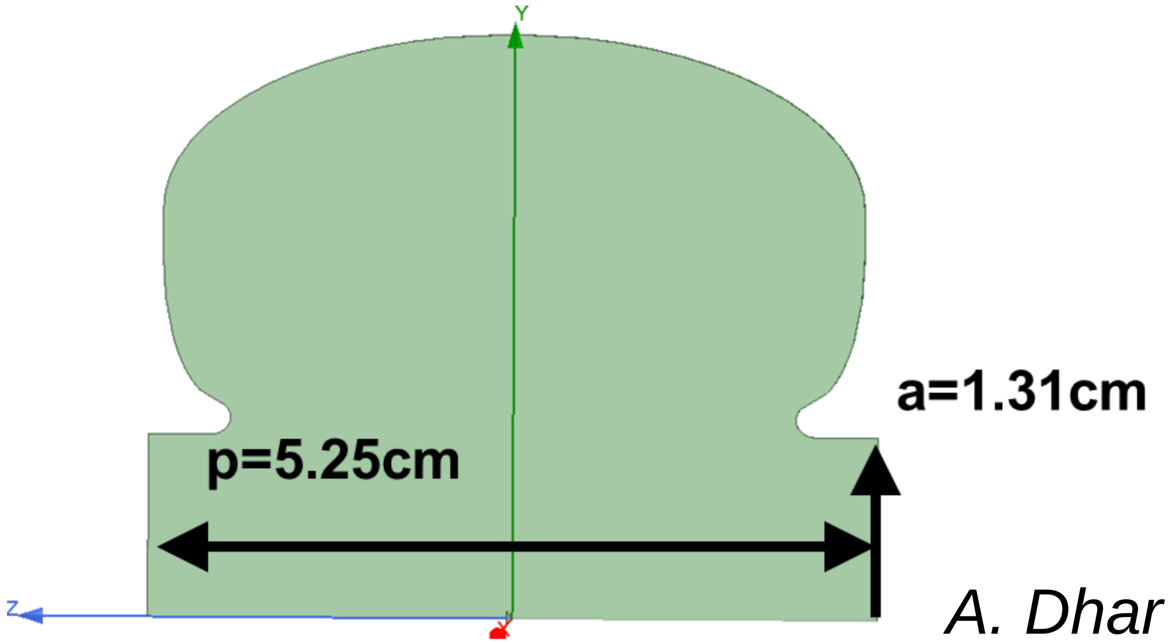
*Post-CDR also evaluation 4.15 m PSI TW linac

Cavity Geometry for a/λ=0.125

- Wakes same or slightly better than 4m PSI
- Pulsed heating < 5 deg C at 16MeV/m 4 microsec
- Compare with reentrant cavity
- Expected increase in shunt impedance X2.5-2.9 at 77 K*





A. Dhar

π-mode
Shunt impedance: 60 MΩ/m (300 K)
E_{max}/E_a = 3.4
Power Dissipated @ 16MeV/m = 221 kW
H_{max} @ 16MeV/m = 3.27e4 A/m

*10.18429/JACoW-IPAC2024-MOPR29

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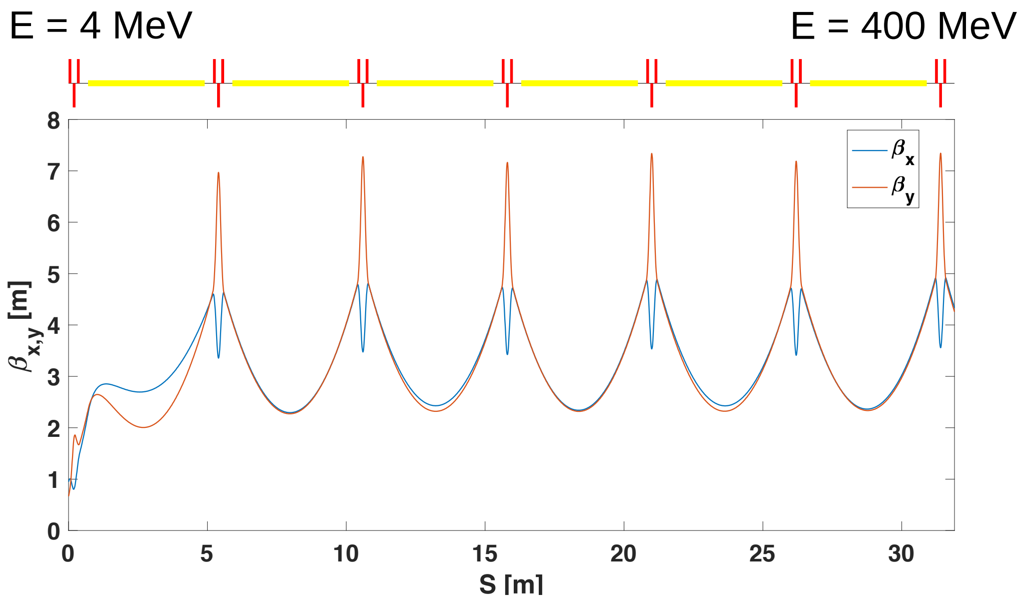
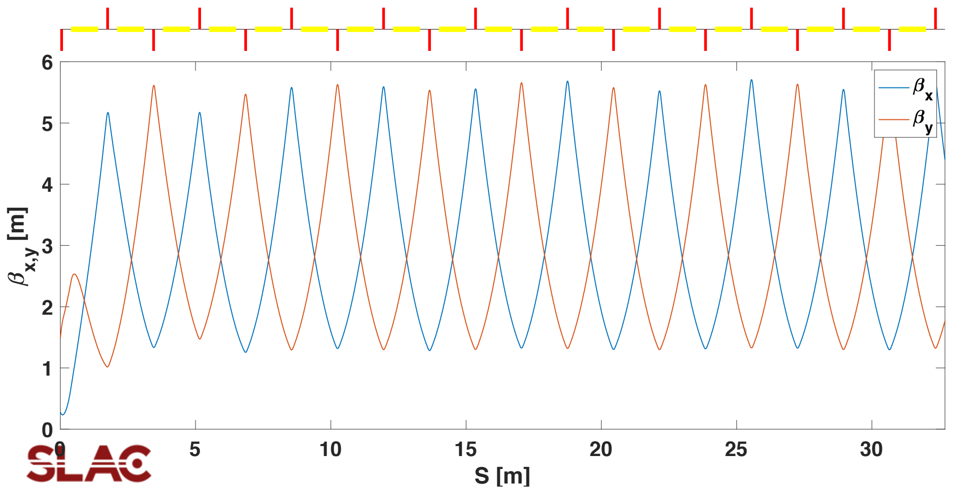
Linac Optics Configurations

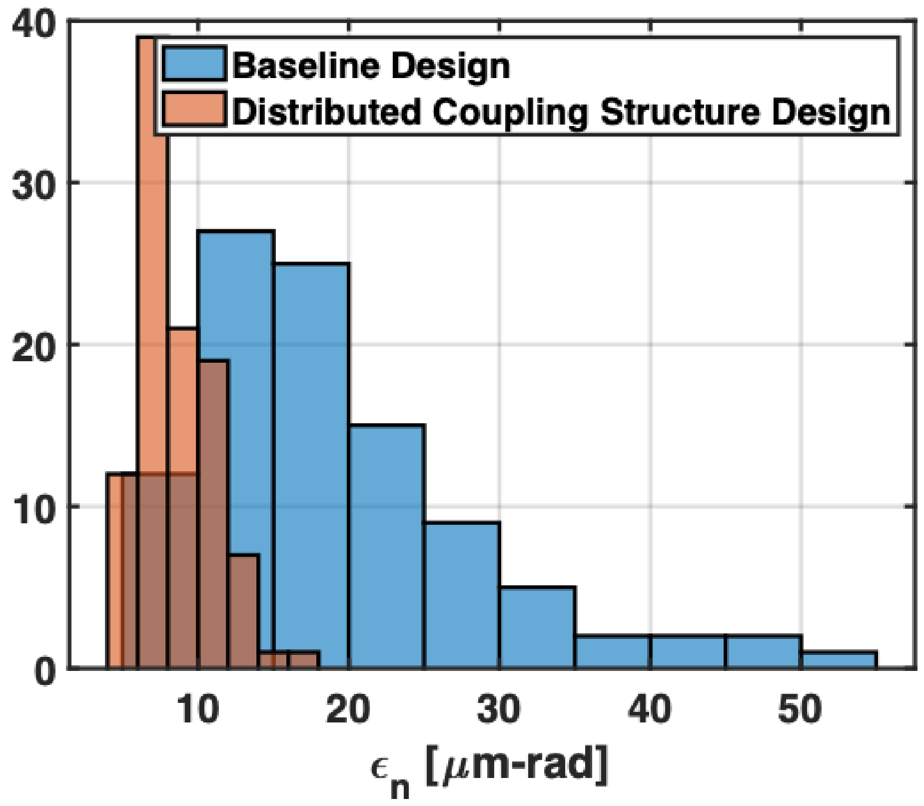


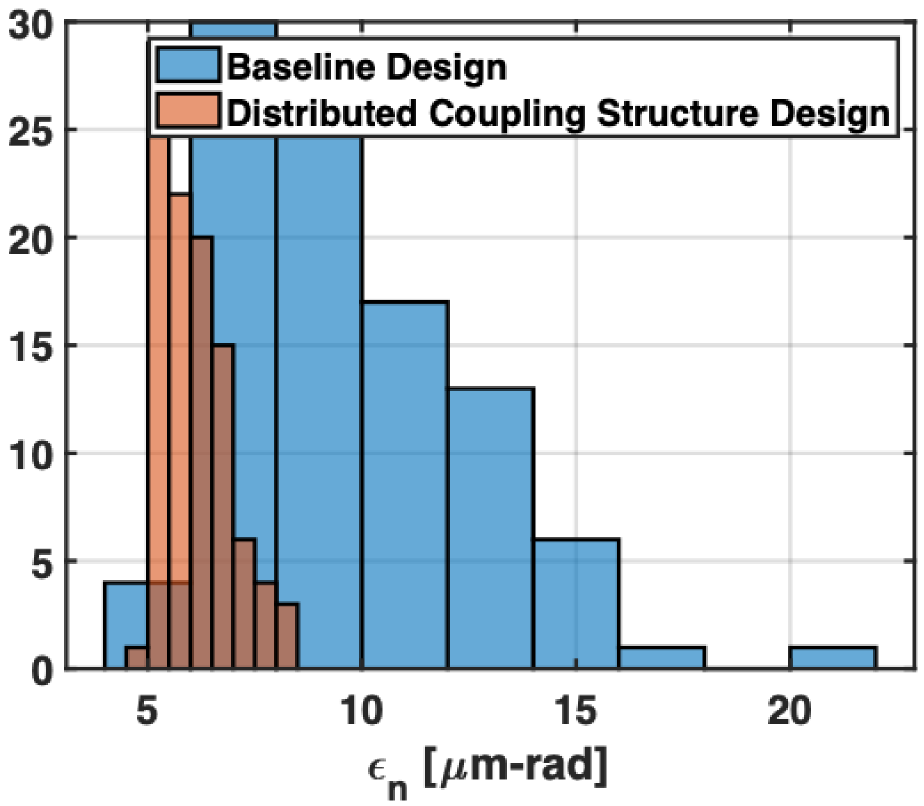


	EIC Baseline	Distributed Coupling Structure
Structure Length	4.15 m	1 m
Lattice	Triplet	FODO*
Structure aperture	1.31 cm	1.25 cm
Structure gradient	16 MV/m	21.5 MV/m
Linac Length	32 m	32 m

*Structure is versatile – FODO or Triplet configuration possible

Particle Tracking, Q=14nC + Beamline Element Offsets





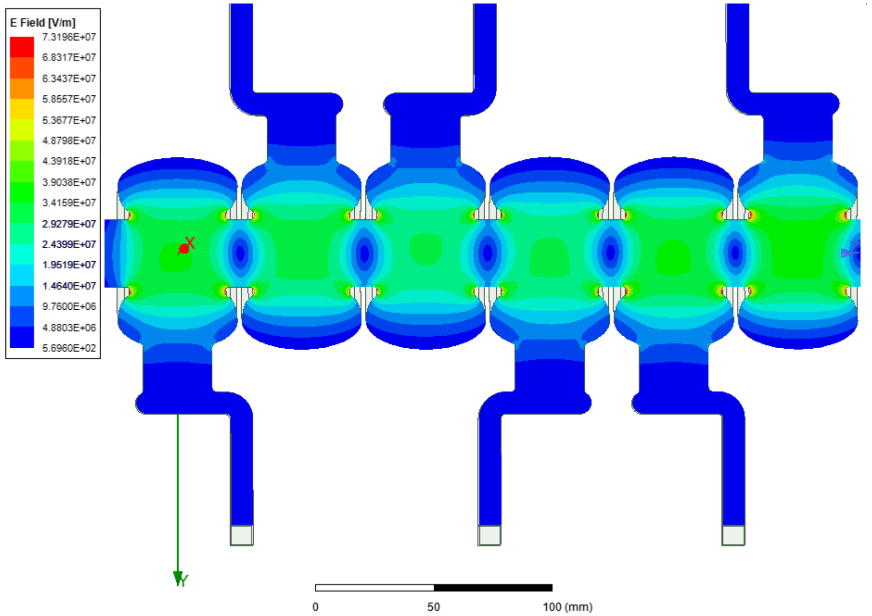
- 100 μm, 300 μrad structure & quad offsets/roll (left)
- 50 μm, 150 μrad structure & quad offsets/roll (right)
- 100 random offset seeds tracked (no steering corrections applied)

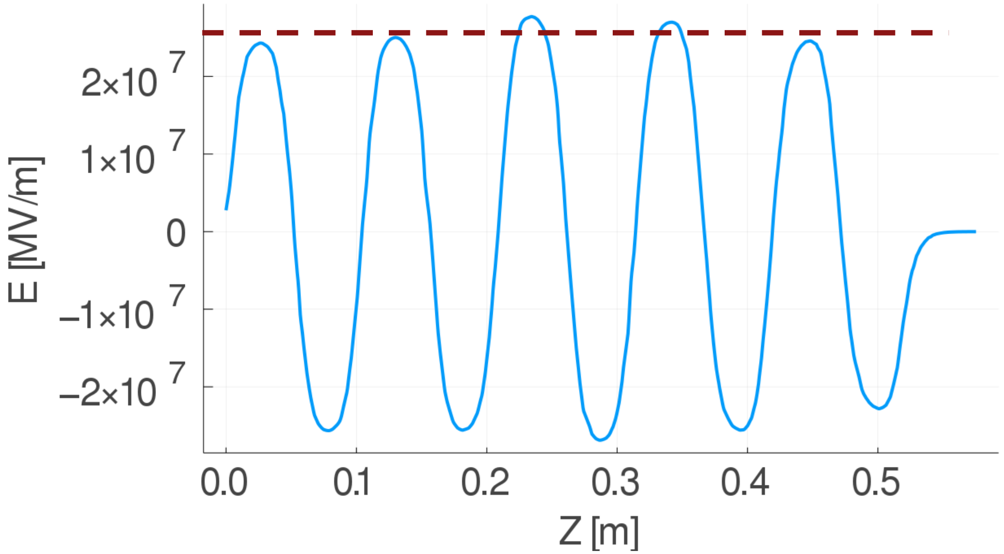
Characterizing a Large Aperture Distributed Coupled Linac

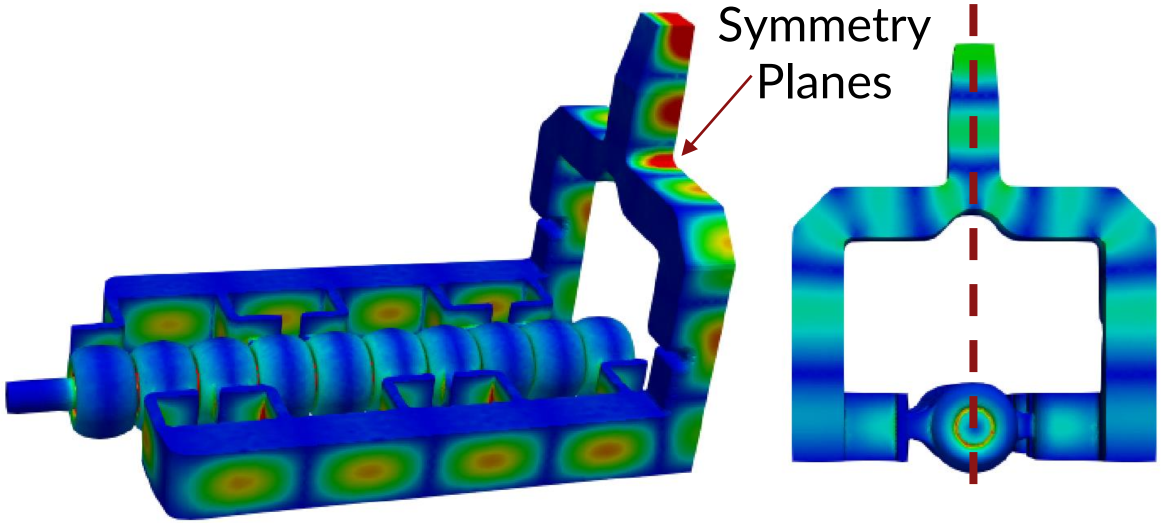
Large apertures introduce coupling between cavities

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

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







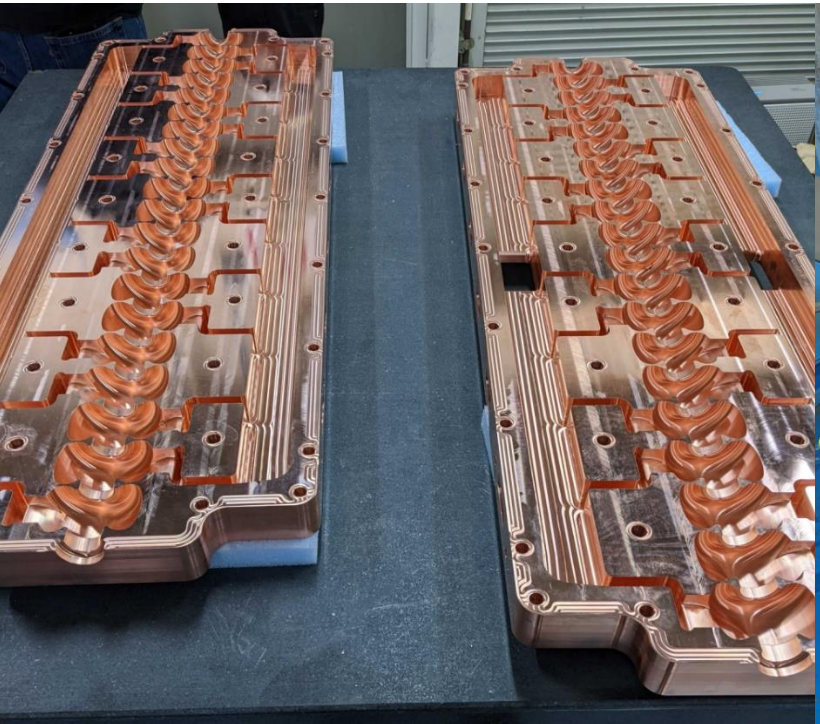
Z. Li, et al. AIP Conference Proceedings ,Vol. 1507, No. 1 p. 837-842

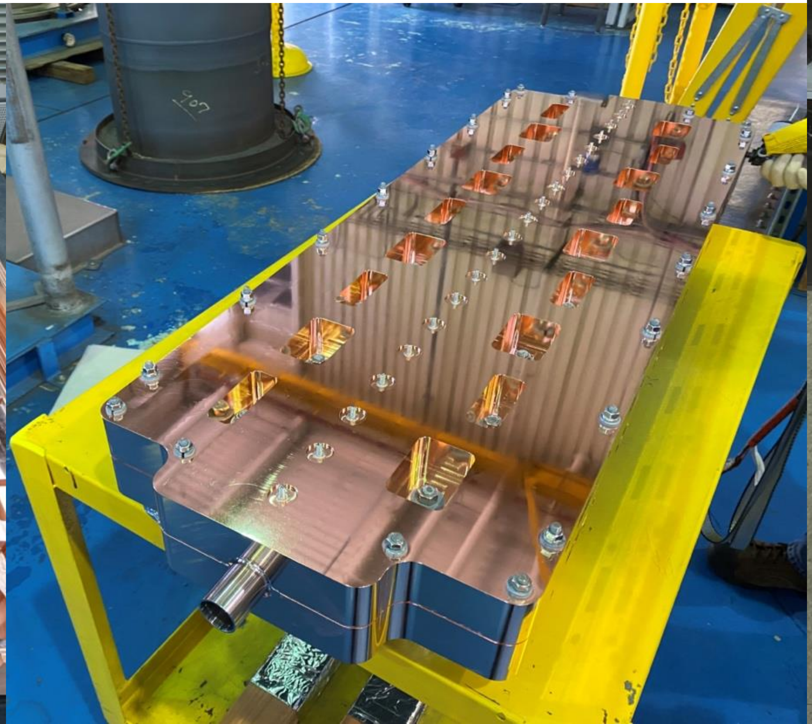
Assembly of Injector Linac

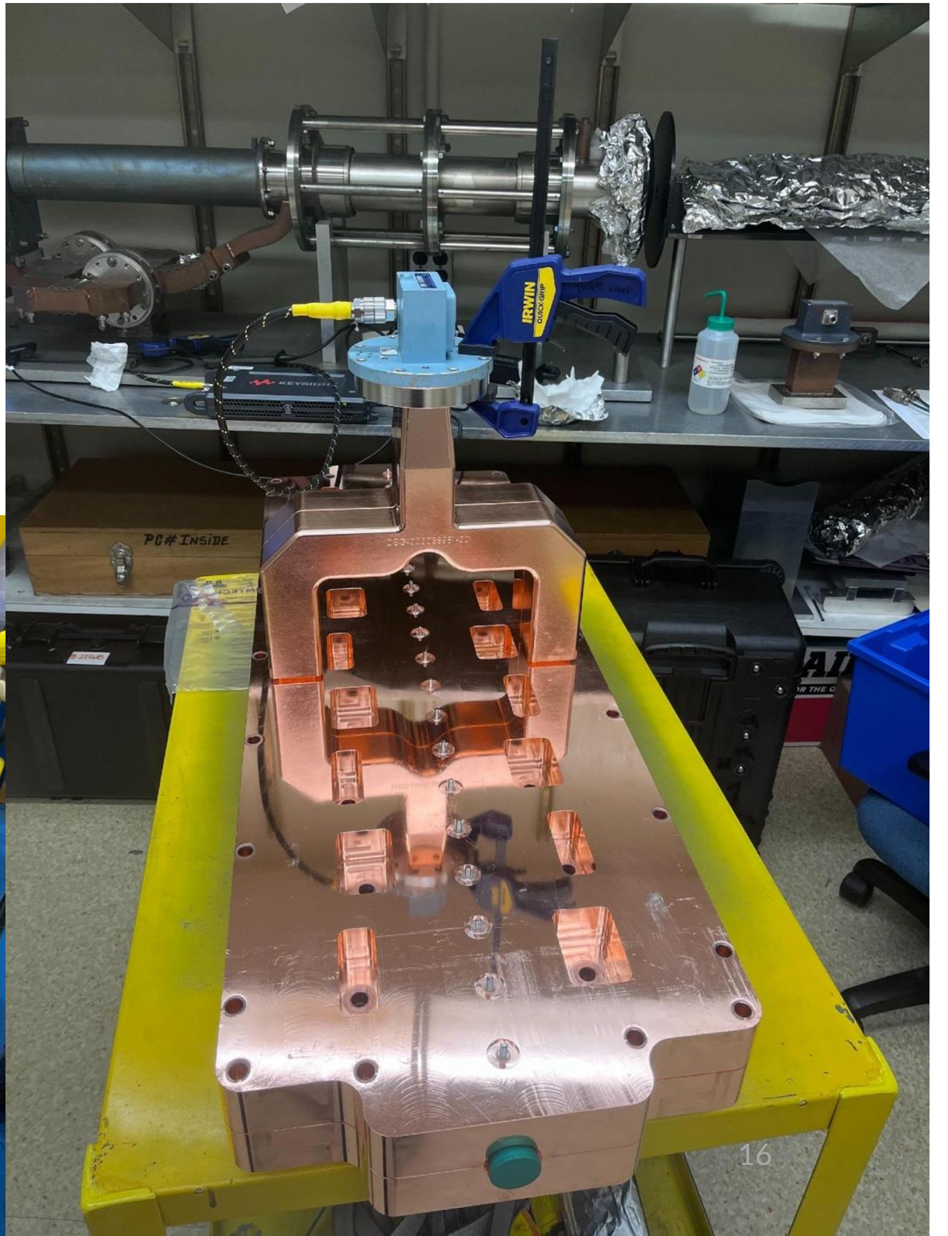
Linac formed from two slabs, which are brazed

Y-Coupler is brazed on afterwards to provide even power splitting between each side

Assembly and brazing was done in house at SLAC





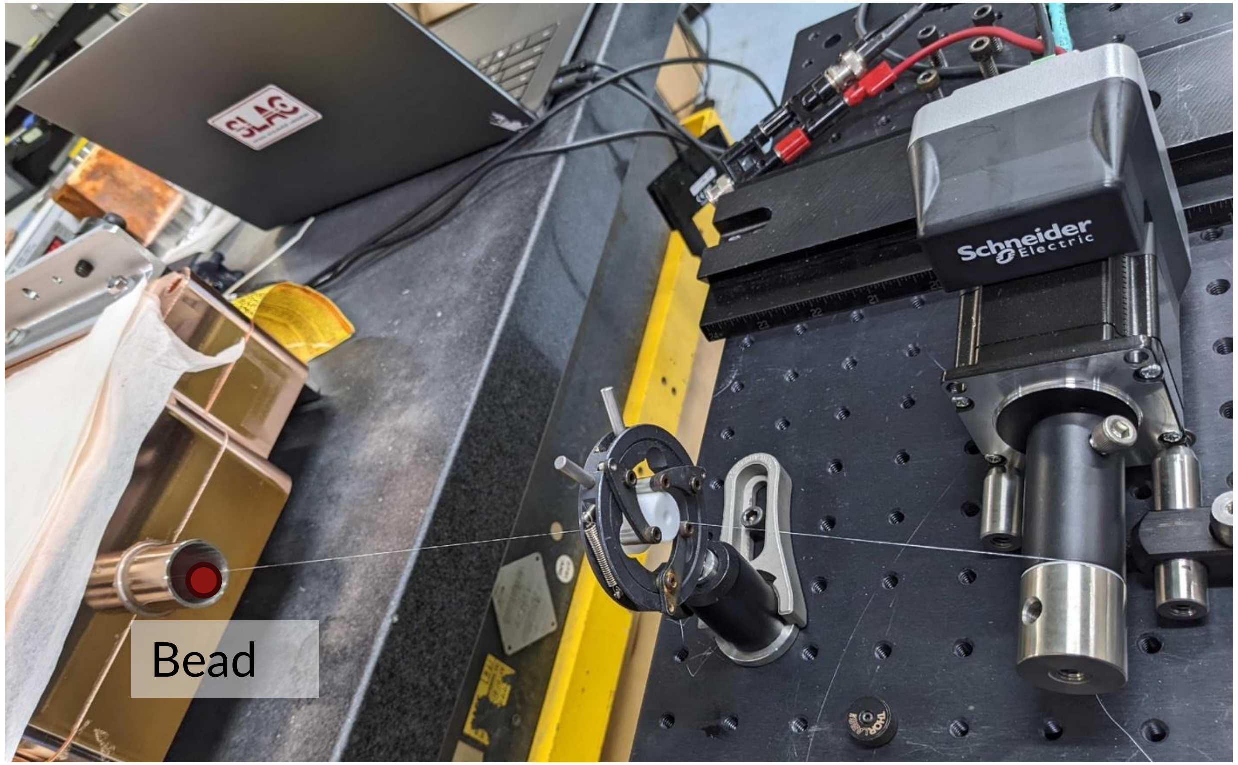


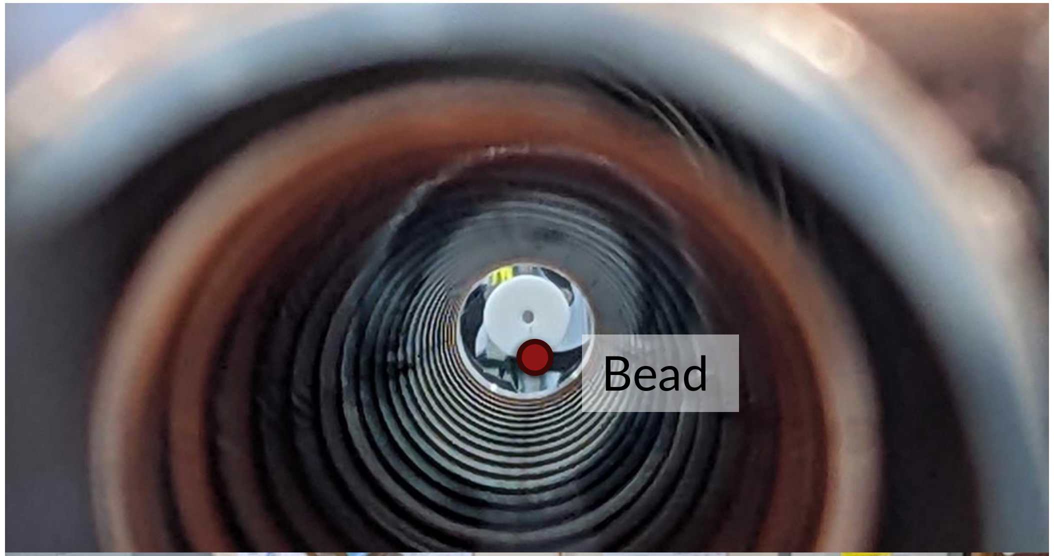
Bead Pull Characterization

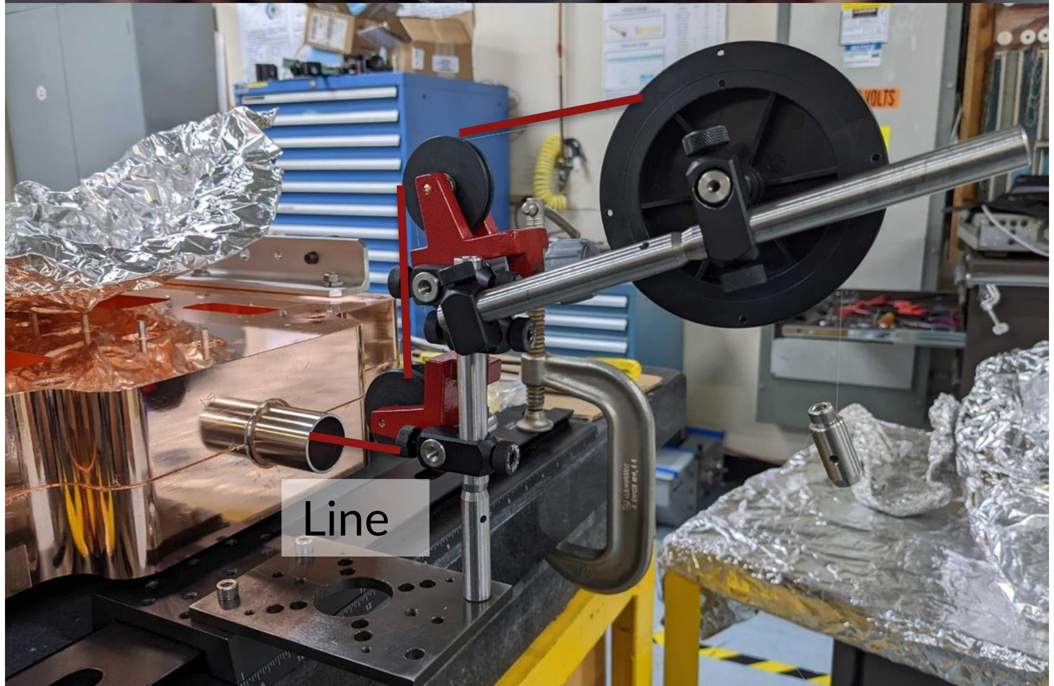
Measuring field flatness within structure requires running a dielectric bead along line

Tension is maintained via pulleys

Alignment is handled with optical stages





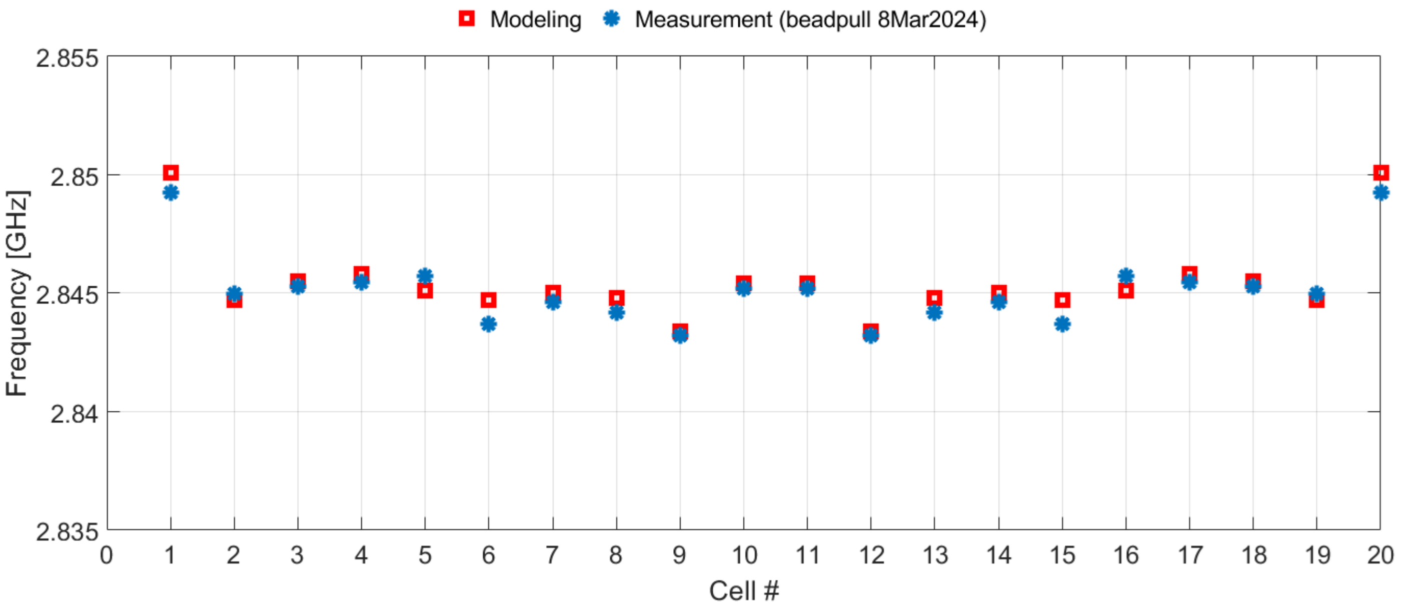


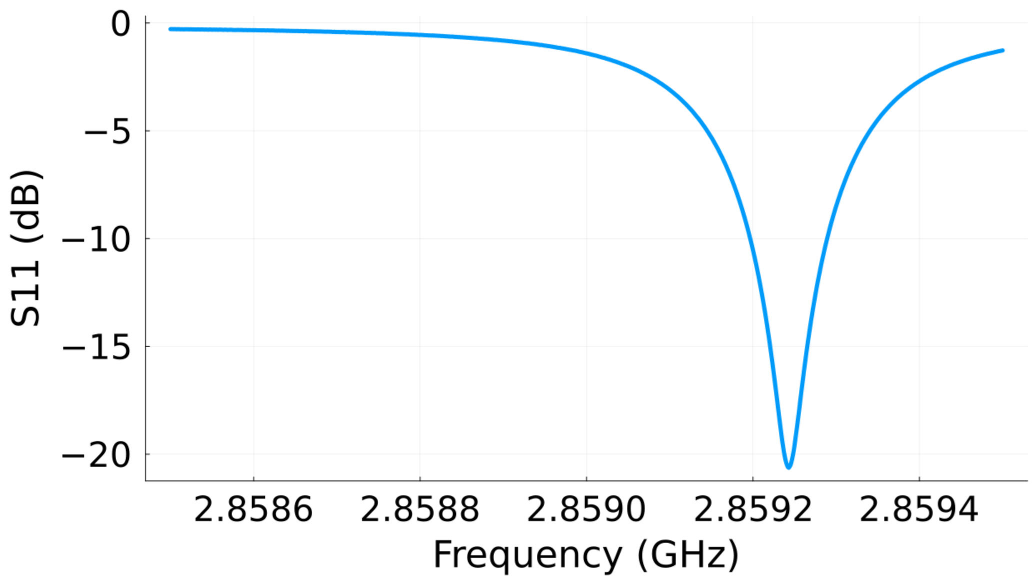
Cold Test and Tuning Results

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

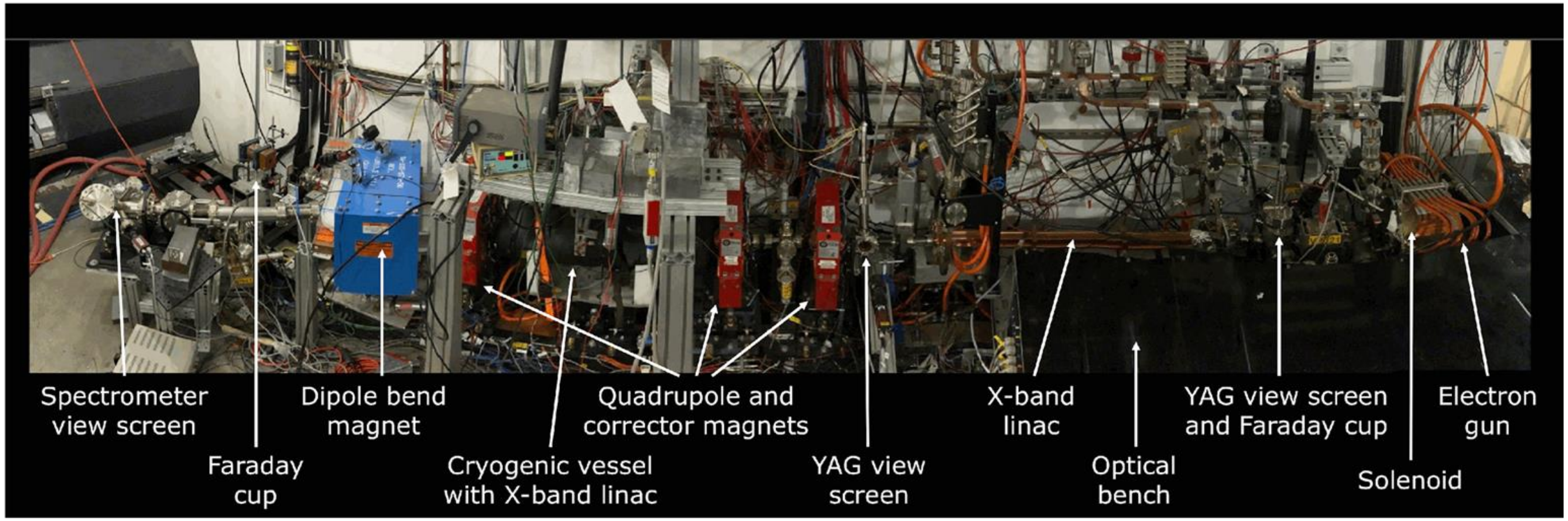




Future Test Plans

Various proposals to testing the structure are in preparation:

- High power test measuring breakdown rate with 35 MW klystron at Station S-band at NLCTA
- ASSET-style wakefield measurement without high power at FACET-II
  - Also potentially at XTA within NLCTA
- Full power + beam tests at CLEAR and/or APS
- Open to further suggestions for test sites



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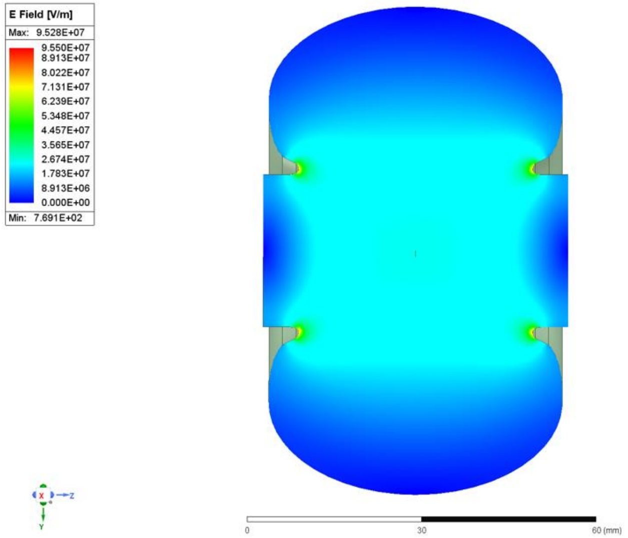
FCC-ee High Energy Linac

- Injector linac operates with closely spaced bunches – up to 5.5 nC
- Initial study with a/wl = 0.125 (conservative, average for HE linac concept is 0.12)
- Gradient 22.5 MeV/m
- **Baseline: 6 MW/m, 3 microsecond**

Linac Properties	
Charge (nC)	0-5.5 nC
Number Bunches	1-4
Bunch Spacing	25 ns spacing
Initial Energy	6 GeV
Final Energy	20 GeV



Shunt impedance 300 K (77 K): 58.5 MΩ/m (146-158 MΩ/m)
a/wl = 0.125
Emax/Ea = 4.35
Sc max = 242mW/um^2
Period: 53.5 mm
Aperture: 13.4 mm
Nose Cone Gap: 41.1 mm
Height: 42.9 mm
R/Q: 3.04
Q: 19250 (300 K)
Power Dissipated @ 21.9MeV/m = 440 kW

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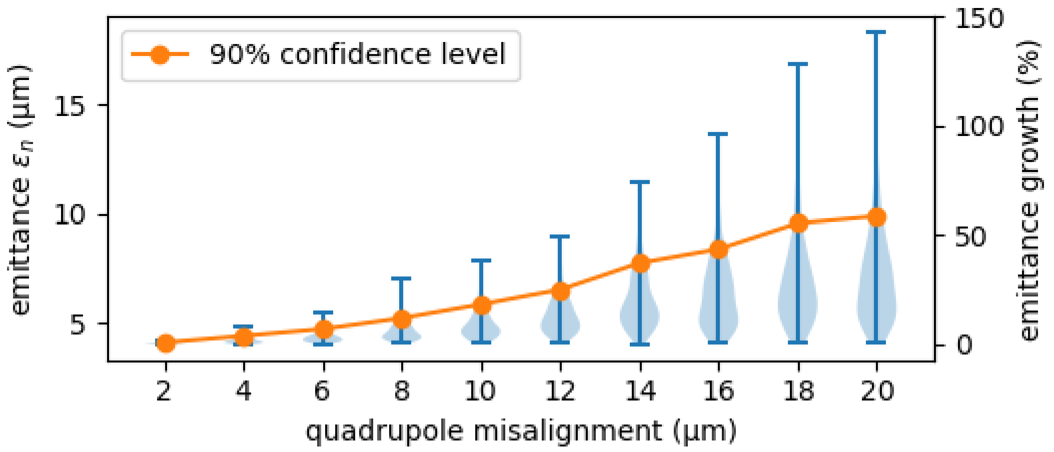
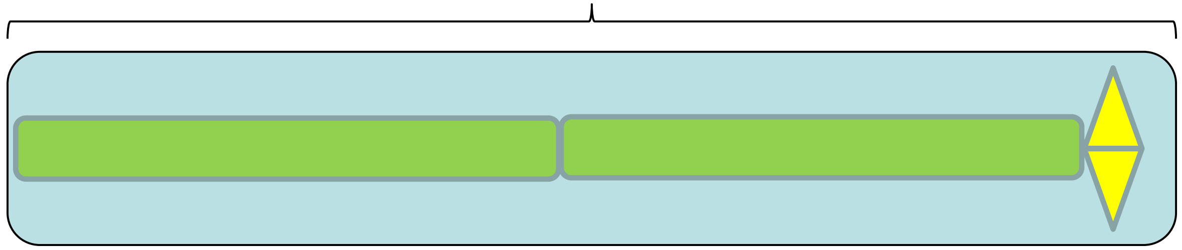
FCC-ee Injector linac simulation

- 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



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

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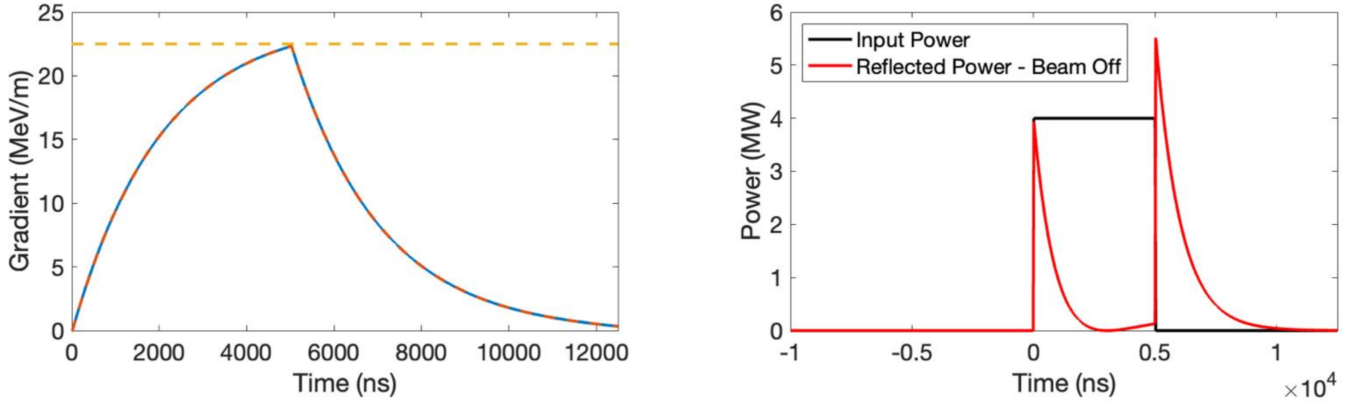
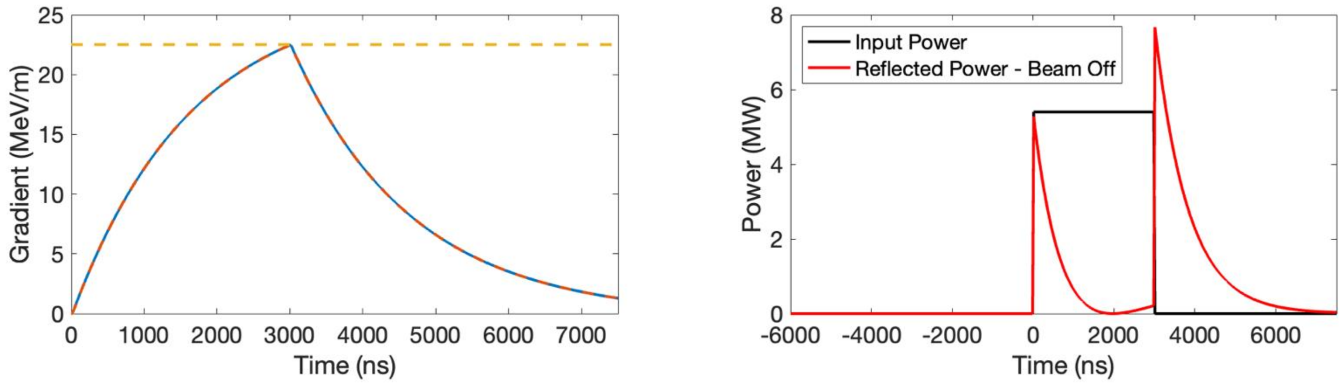
RF Power for Cold Copper Structures

- Cold-copper distributed coupling structure has high shunt impedance with long fill fill time
- Reduces peak power requirement, ideal for long bunch trains (C3) or large bunch spacing (EIC)
- However, rapid fill time ideal for few closely spaced bunches

5 microsecond, 4 MW/m



3 microsecond, 5.4 MW/m



Simple rf network, no pulse compression

Reduced Fill Time of Structures Improves Overall Efficiency

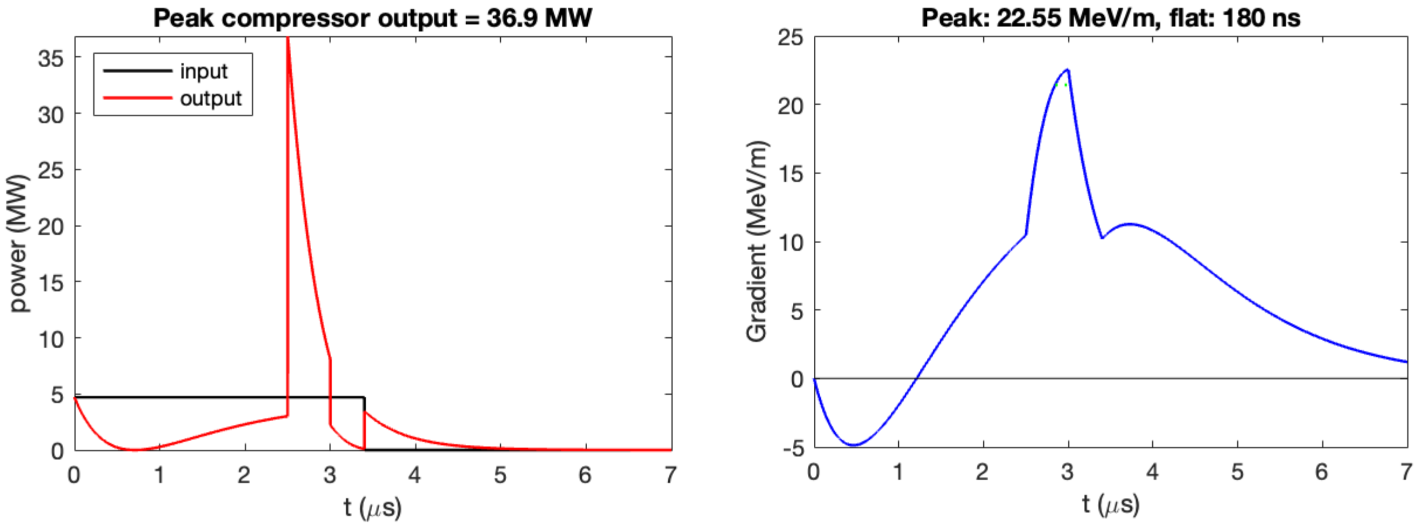
- RF Pulse Compression – Increase peak power and severely overcouple structure
- Possible Investigations:

Traveling Wave Manifold

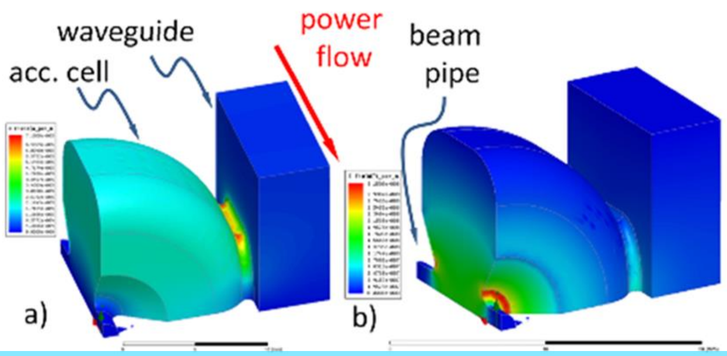
Fast or Cascaded Filling

Reduce Qo for cavity – reduced phase advance structure

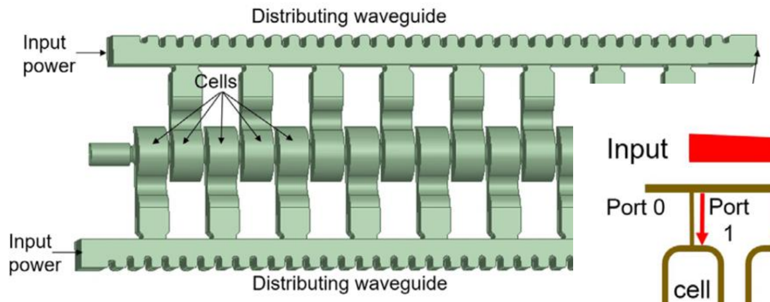
RF Pulse Compression
4.7 MW/m, 3.2 J (vs 7 J) Deposited Energy



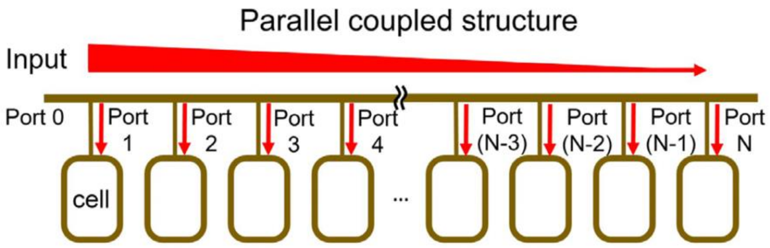
TW Manifold



Fast / Cascaded Filling



PRAB 24, 112002 (2021)



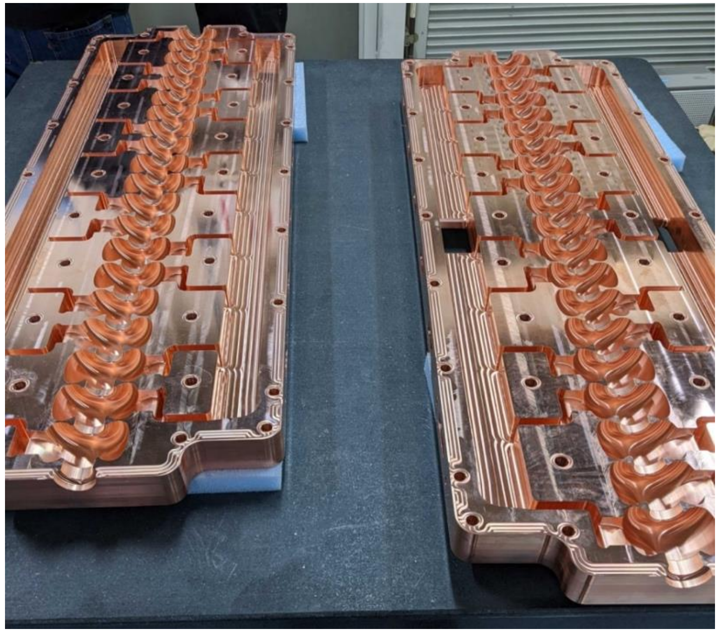
doi:10.18429/JACoW-LINAC2022-THPOJO16

Need to explore reduced fill time under the beam dynamics constraints of HE lianc

Conclusion

Advances in development for rf accelerators...

RF Structure Design



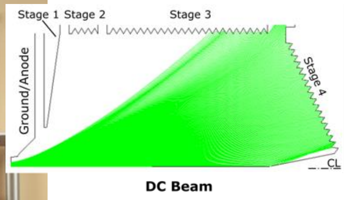
Cold Copper

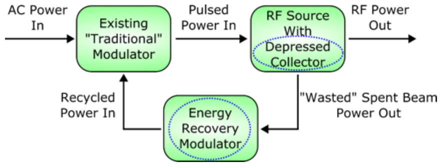
RF Pulse Compression

Spherical

HTS Coated

RF Sources





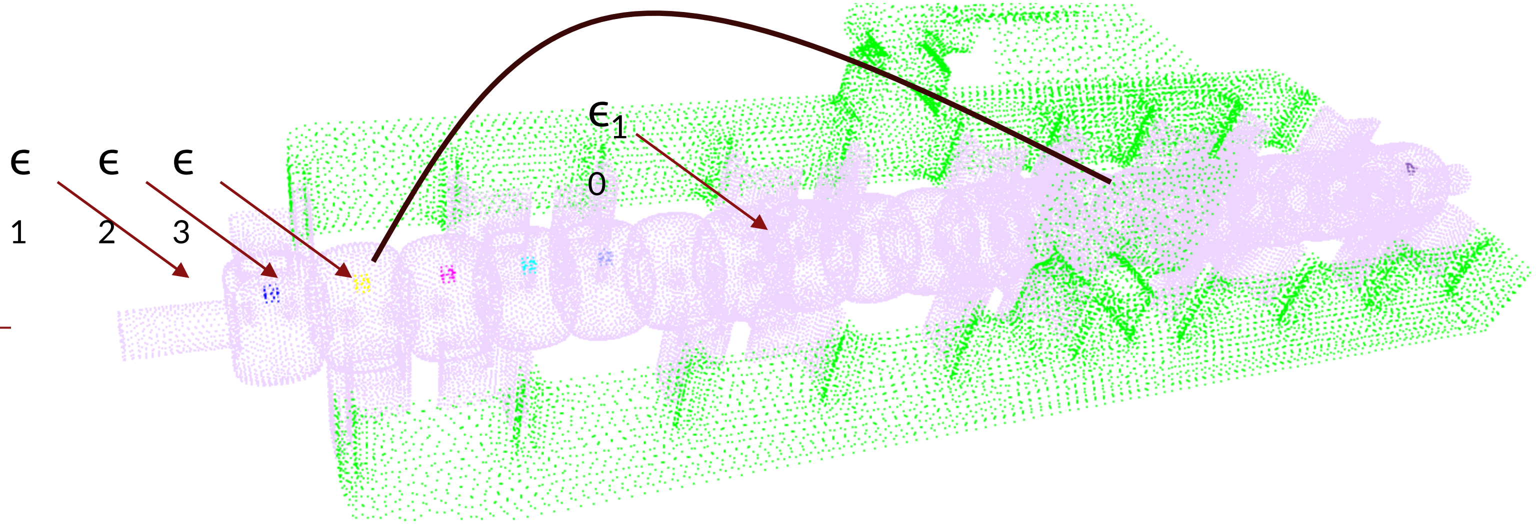
Eager to Understand Requirements and Concepts Better + Hopefully Contribute

Questions?

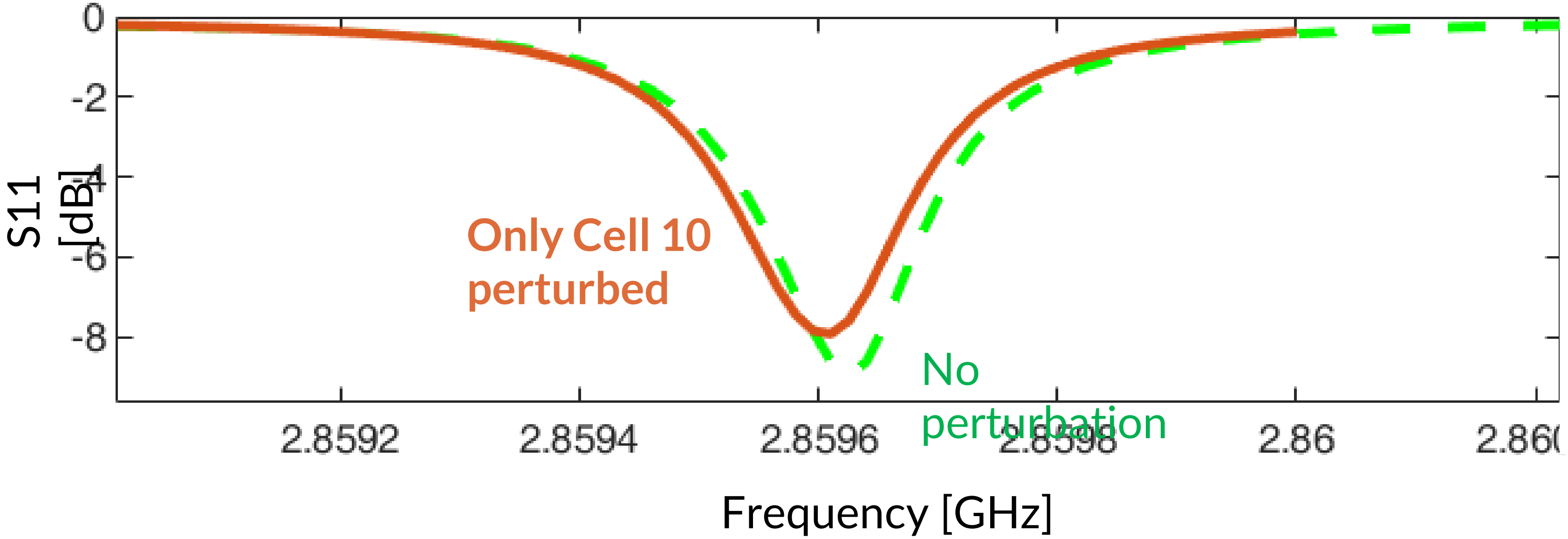
Virtual RF Tuning with ACE3P

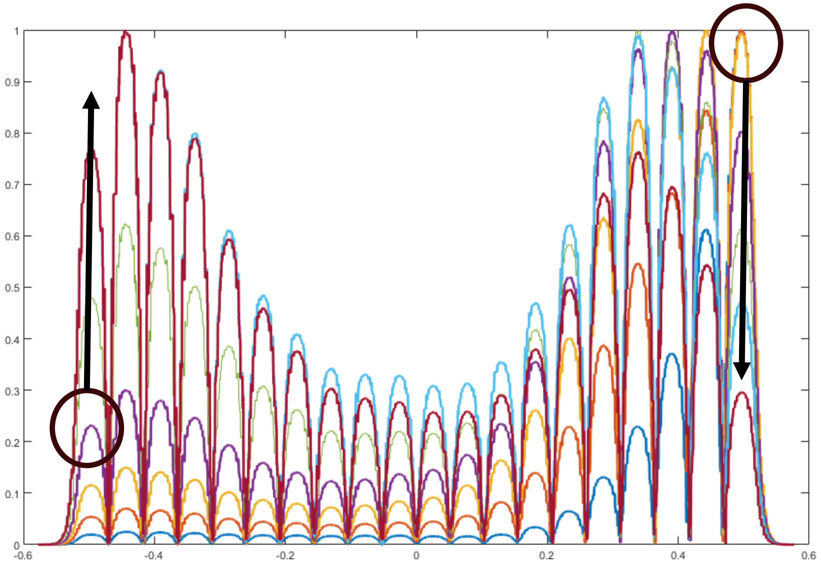
Each cavity has a dielectric bead with a relative permittivity to induce tuning

Each bead can be turned ON or OFF in simulation



$\epsilon_{i=1,2,..20,i\neq 10} = 1,\ \epsilon_{10} = 3.5 \rightarrow$ Overall pi mode shift of -15 kHz

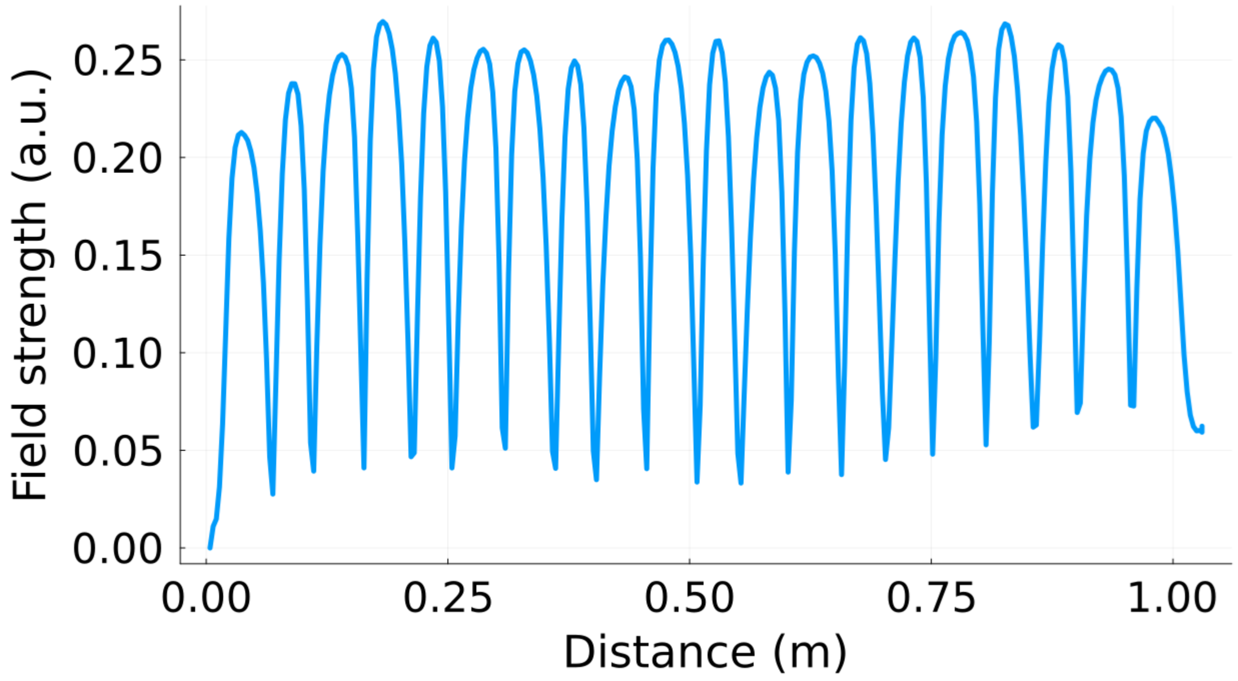


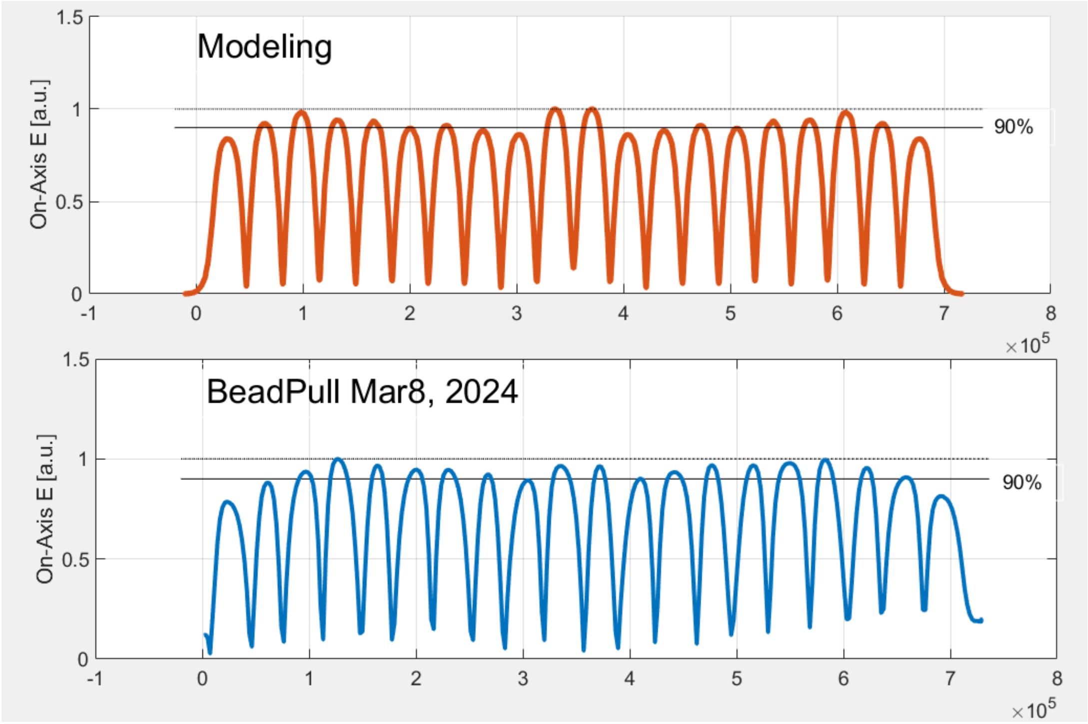


Cold Test and Tuning Results

Final tuning shows all cavities coupling to the pi mode strongly

End cavities are roughly 80% of maximum field strength





Tuning Distributed Coupling S-Band LINAC

- First, calculate derivatives of pi mode frequency of each cell versus perturbation ε_i

$$f_m = \frac{\partial f_m}{\partial \varepsilon_m}, m = 1,2,\dots,20$$

- Gradient perturbation in each cell

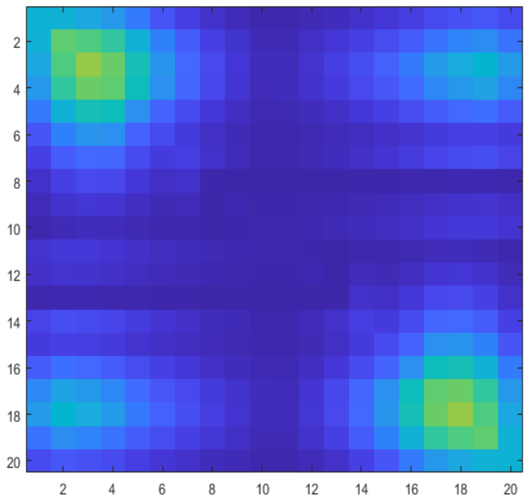
$$E'_{mn} = \frac{\partial E_m}{\partial \varepsilon_n} \times \left(\frac{\partial f_n}{\partial \varepsilon_n}\right)^{-1} = \frac{\partial E_m}{\partial f_n}, m,n = 1,2,\dots,20$$

- In general good agreement, some discrepancies due to accuracy of frequency measurement s (100 kHz)

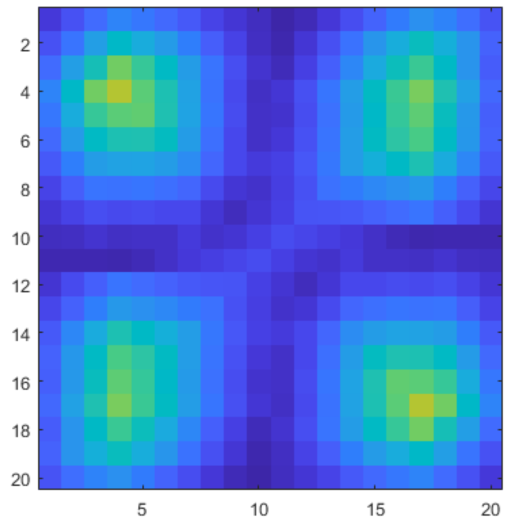
- Cavities in the middle are less sensitive to tuning, need collective tuning

$\left|\frac{\partial E_{mi}}{\partial f_{mi}}\right|$ unit is MV/m / GHz with 1 W input power

Modeling



Measurement



$\arg\left(\frac{\partial E_{mi}}{\partial f_{mi}}\right)$ unit is degree

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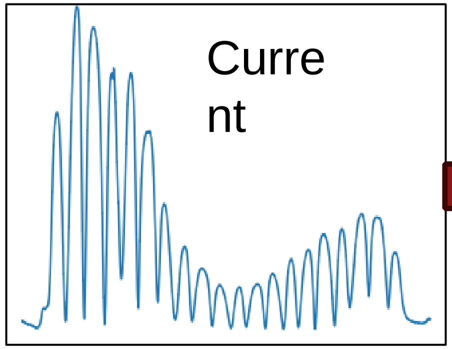
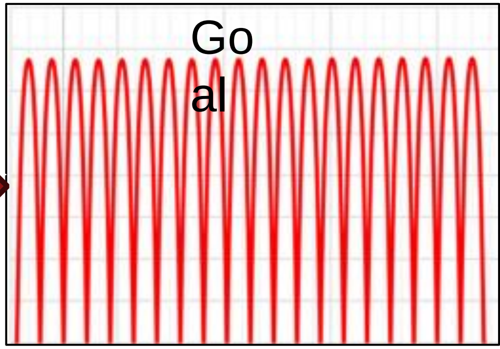
Target Optimal Frequencies Based on Perturbative Method

- The resulting field in the cell j after iteration i $E_{m,i} = E_{m,i-1} + df_{m,i-1}\frac{\partial E_{m,i-1}}{\partial f_{m,i-1}} + \dots$

- Target normalized fields are given by the following

$$E_{im} = 1e^{jm\pi}$$





- Target frequencies are given by $f_{m,i} = f_{m,i-1} - df_{m,i}$

$$f_{m,i} = f_{m,i-1} - \left(\frac{\partial E_{m,i-1}}{\partial f_{m,i-1}}\right)^{-1} \left(1e^{jm\pi} - E_{m,i-1}\right)$$

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