Distributed Coupling Linac for Efficient Acceleration of High Charge Electron Bunches

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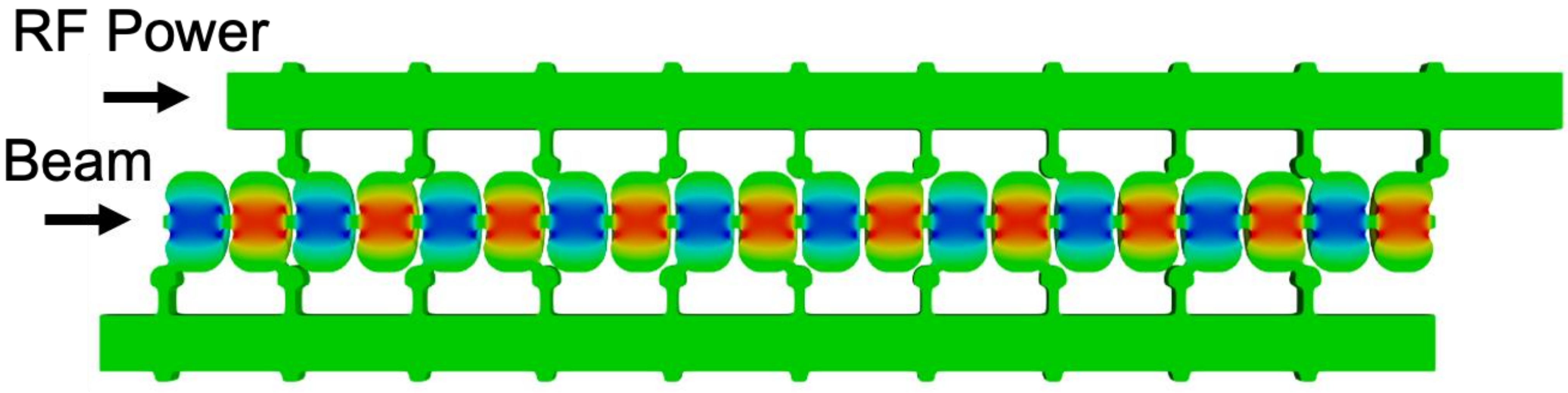
Distributed RF Coupling changes Accelerator Paradigm

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

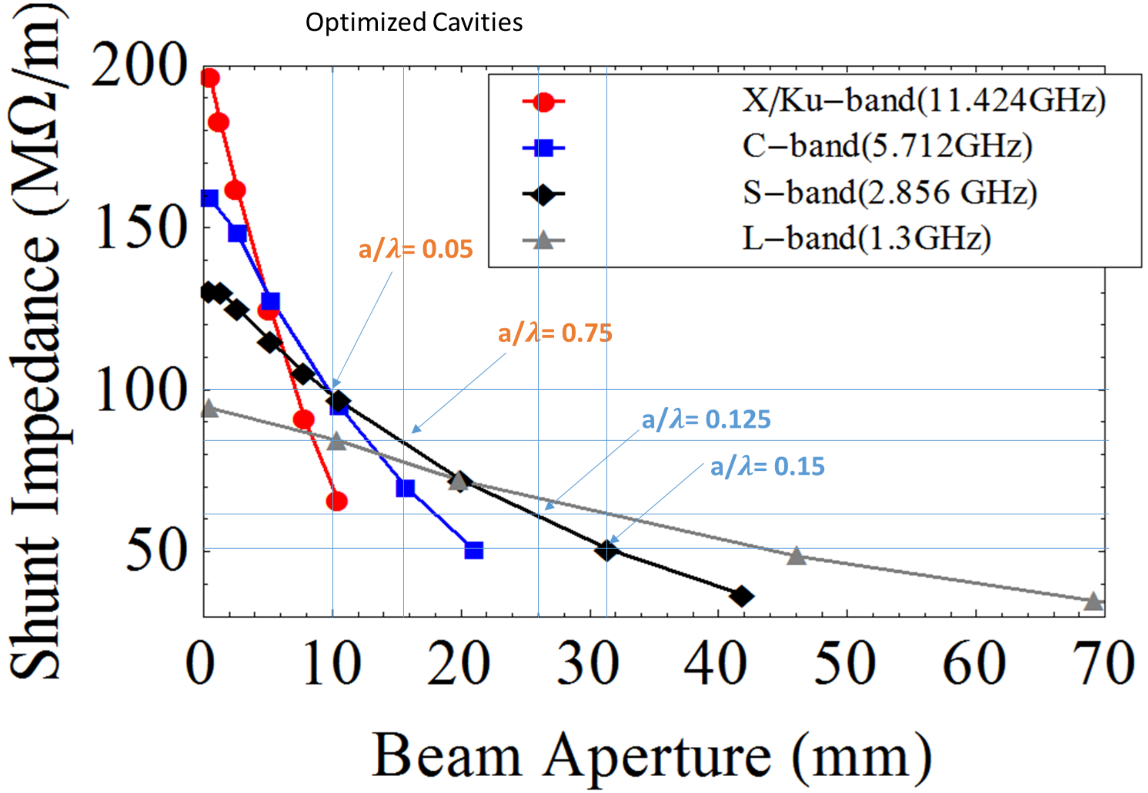
$$R_s = G^2/P \text{ [M}\Omega\text{/m]}$$

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

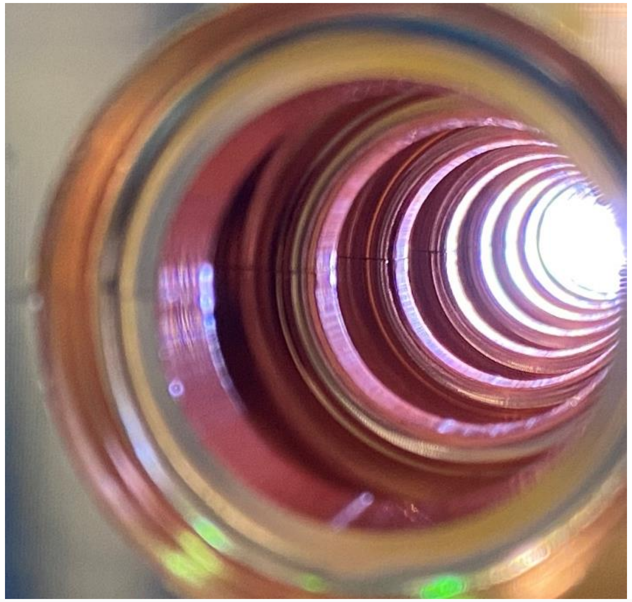
Injector Linac needs to accelerate High Charge Bunches

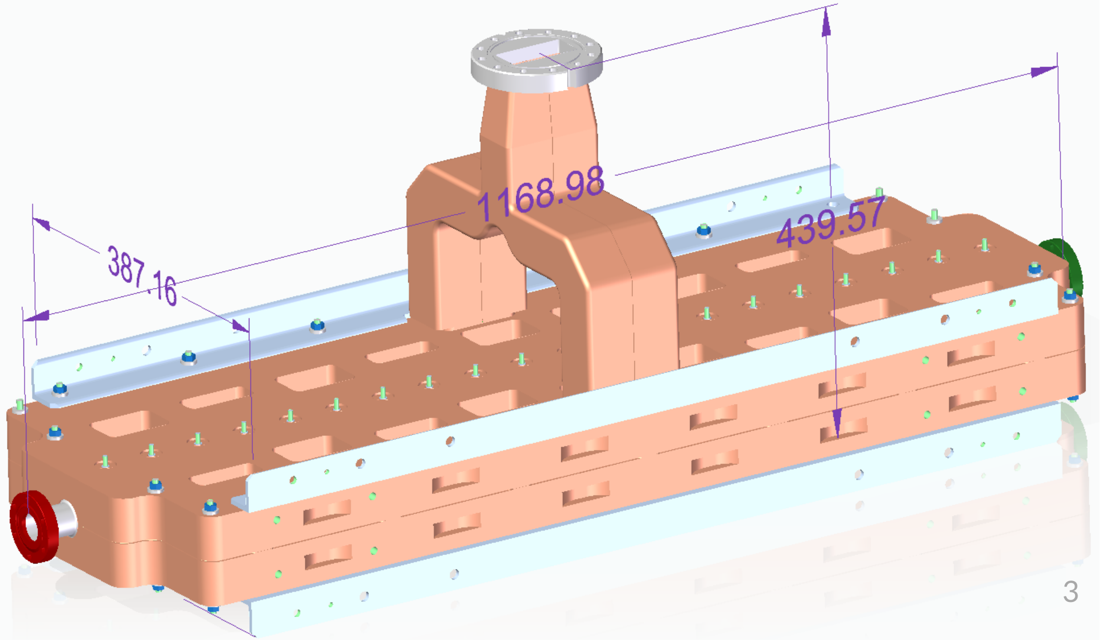
High charge bunches would require larger apertures to minimize wakefields

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



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





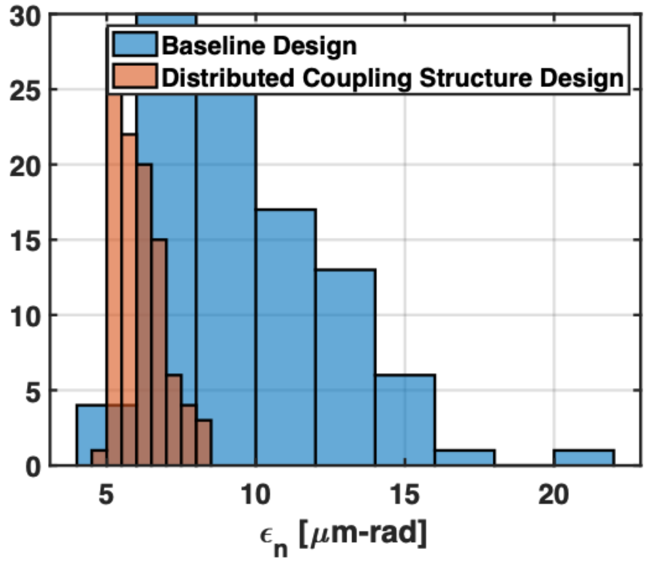
Distributed Coupling as applied to Injector Linac Design

Design balances shunt impedance with aperture size

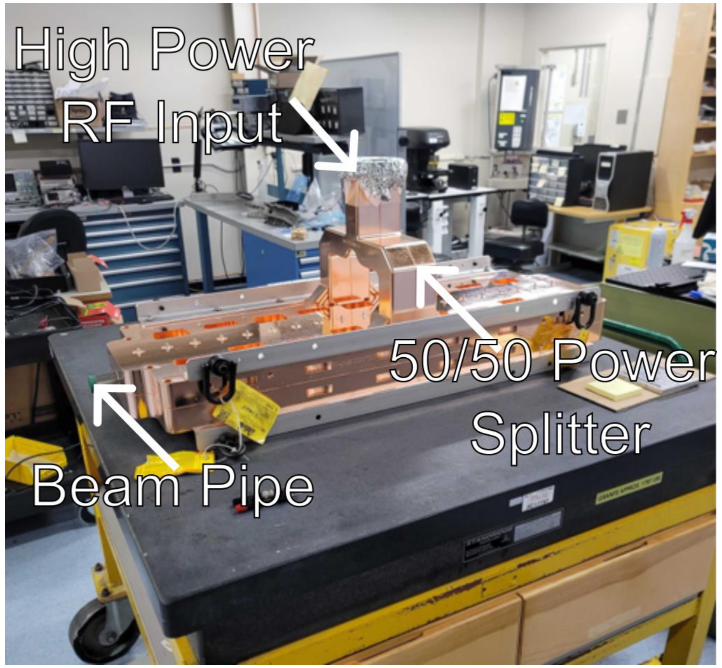
- S-band cavities designed with aperture ratio a/λ=0.135

Better output emittance compared to baseline traveling wave structures with 14 nC bunches

- Emittance calculated for a/λ=0.125 cavities
- Baseline design informed by EIC 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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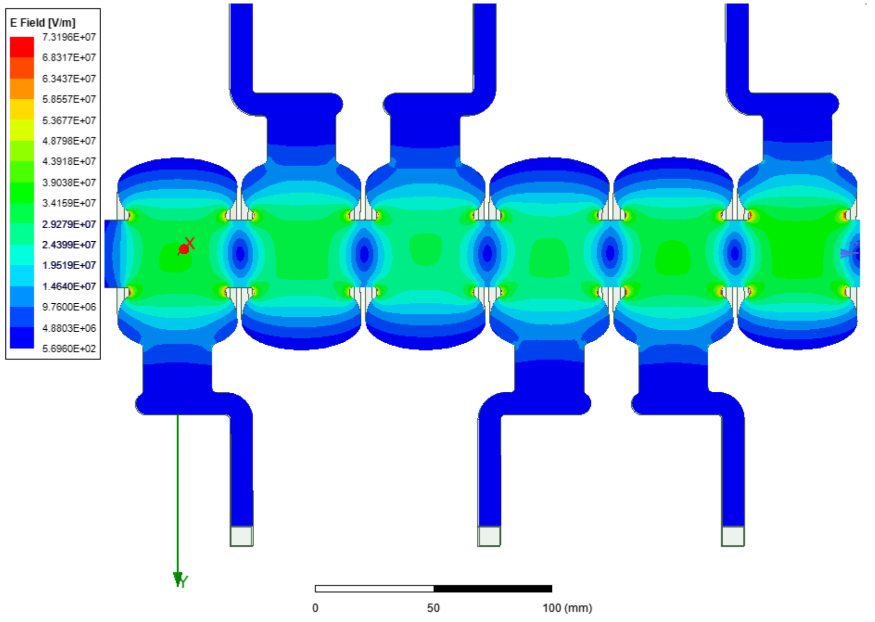
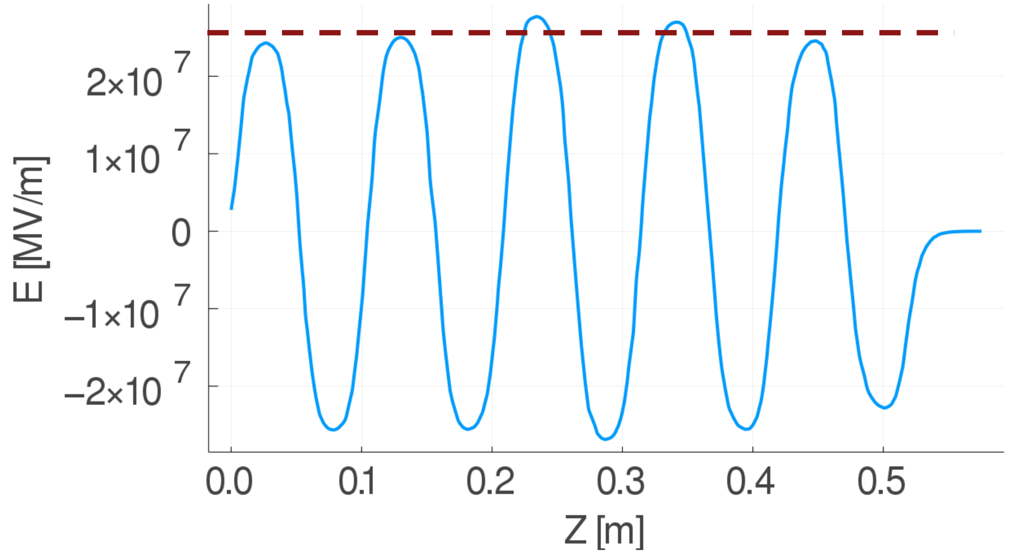
Characterizing a Large Aperture Distributed Coupled Linac

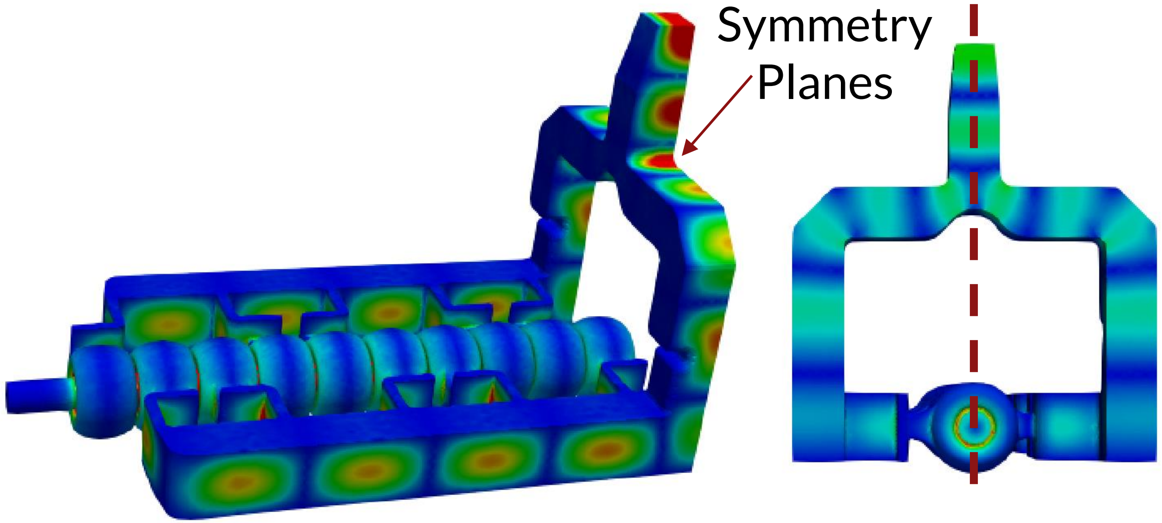
Large apertures introduce coupling between cavities

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

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







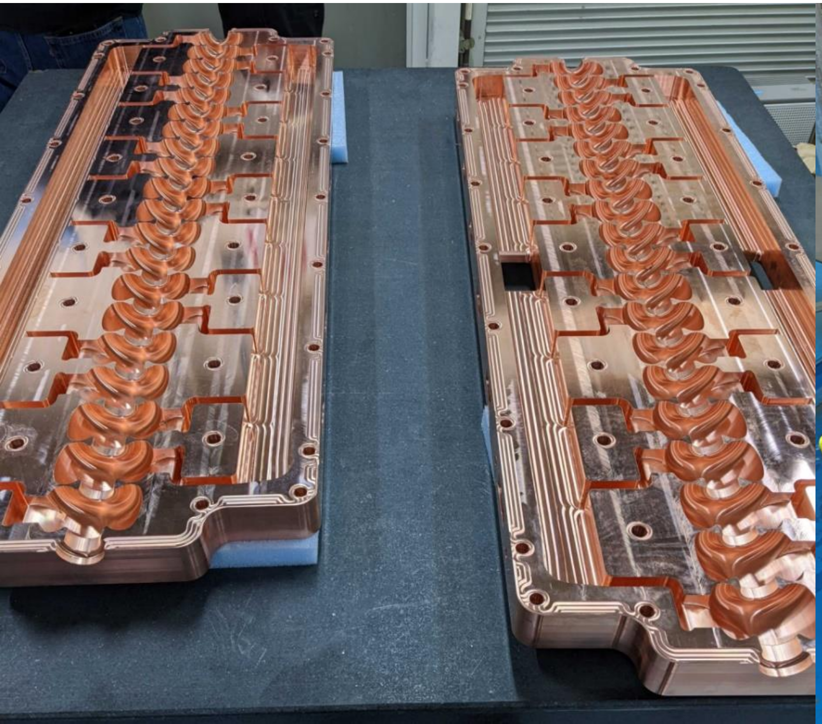
Z. Li, et al. AIP Conference Proceedings ,Vol. 1507, No. 1 p. 837-842

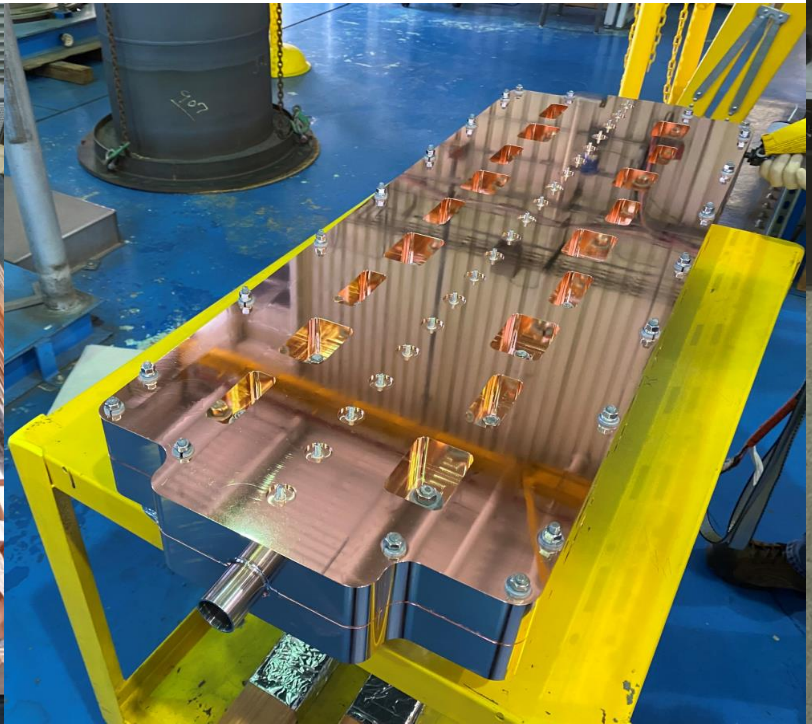
Assembly of Injector Linac

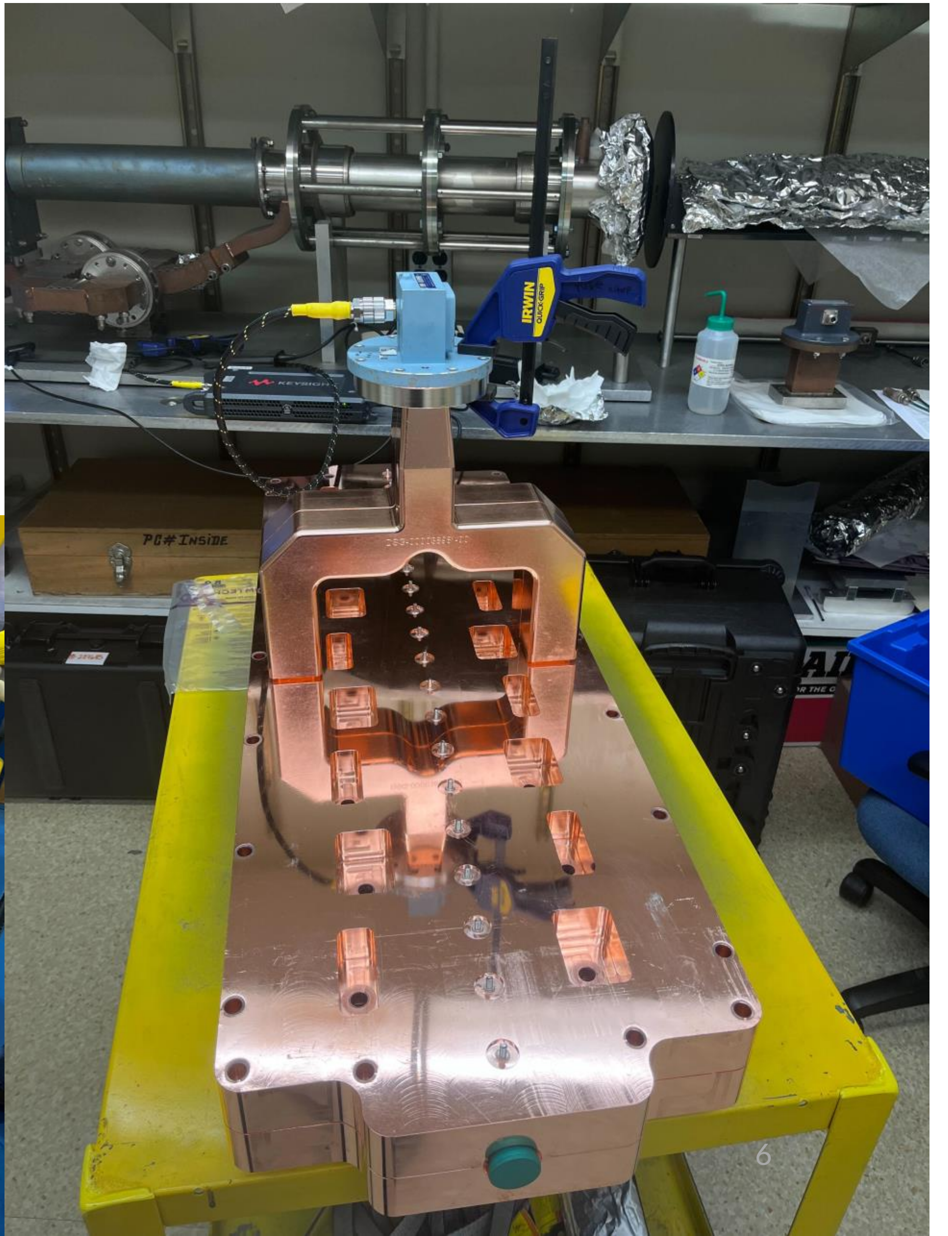
Linac formed from two slabs, which are brazed

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

Assembly and brazing was done in house at SLAC





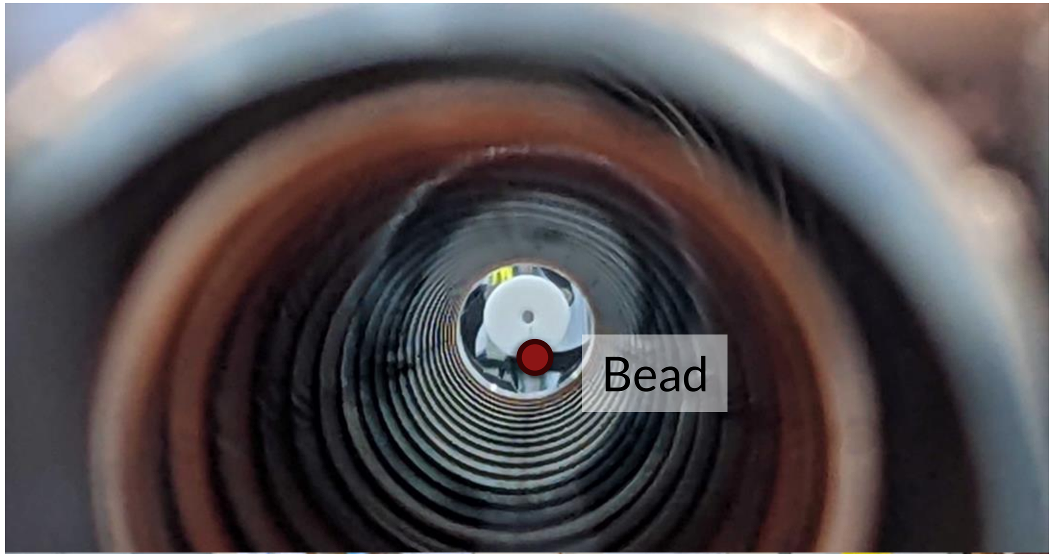


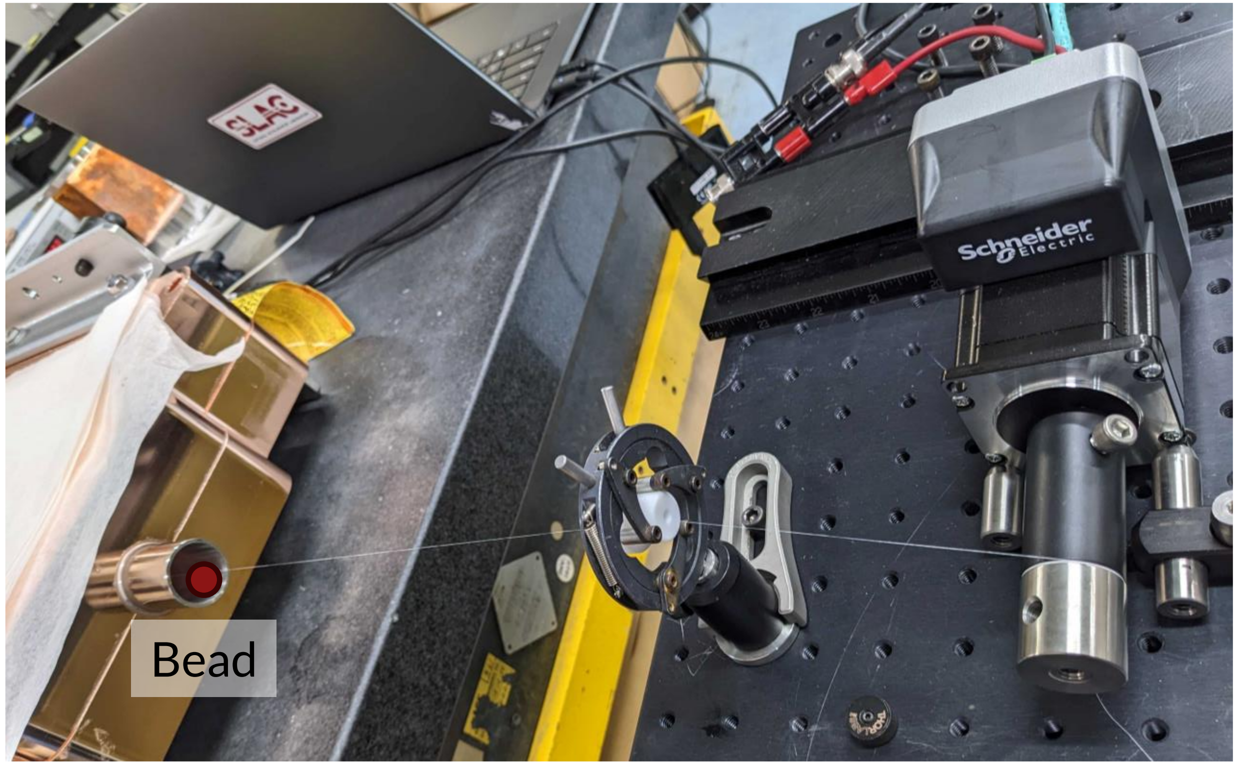
Bead Pull Characterization

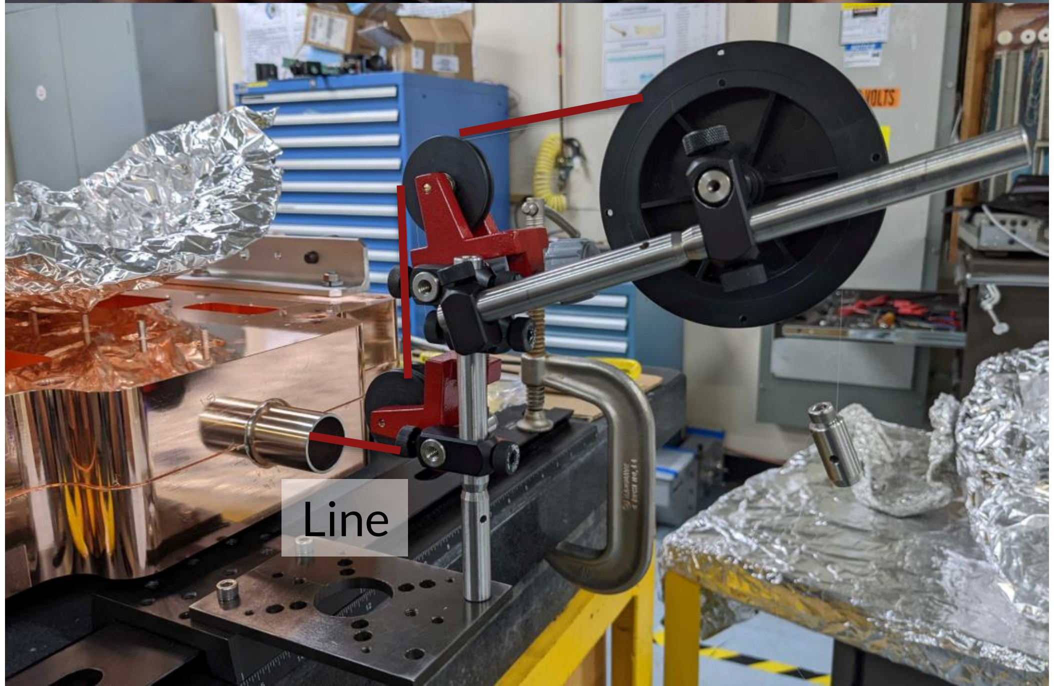
Measuring field flatness within structure requires running a dielectric bead along line

Tension is maintained via pulleys

Alignment is handled with optical stages



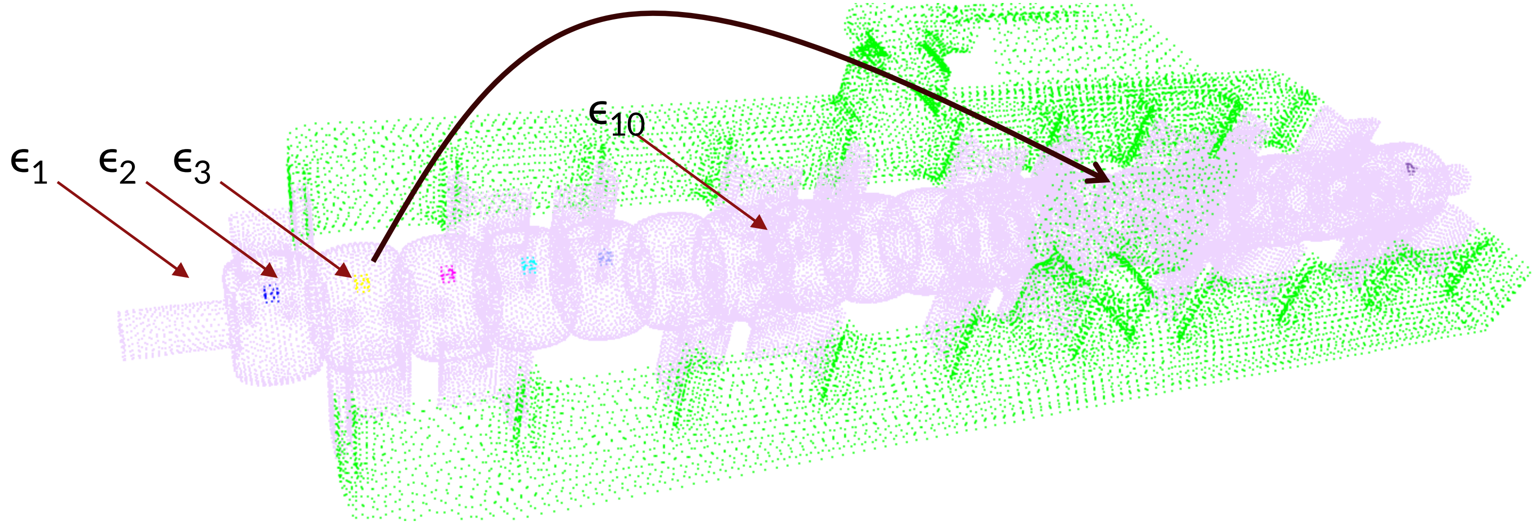




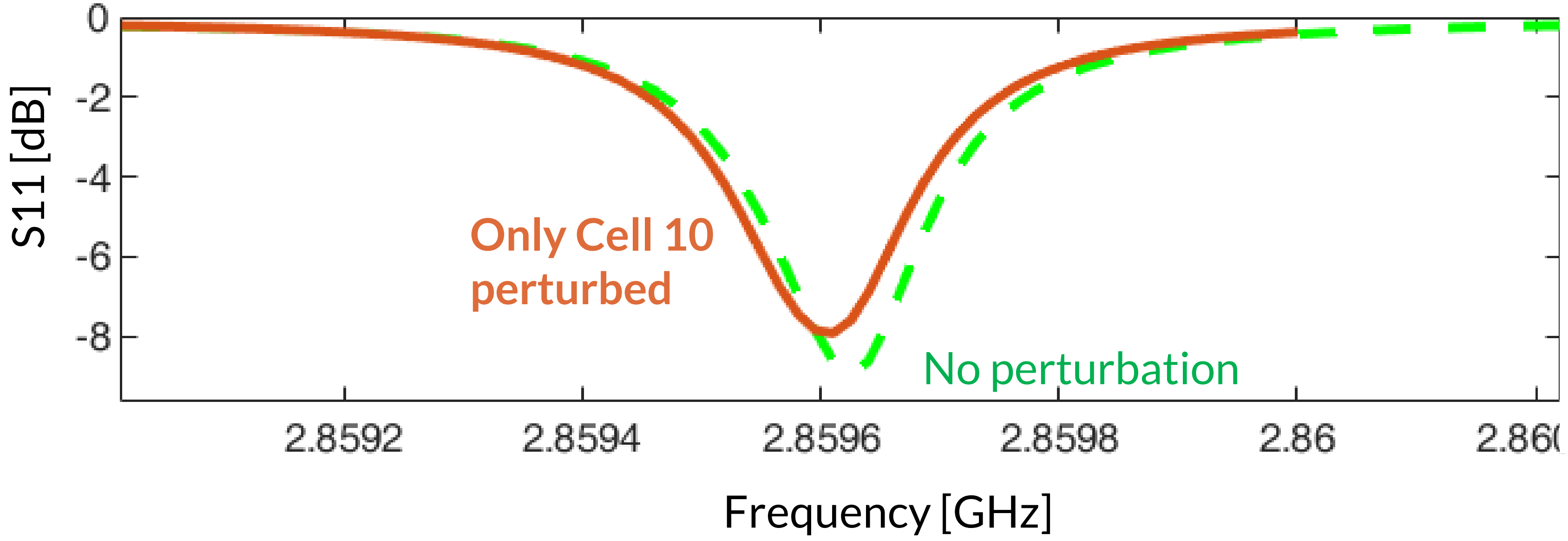
Virtual RF Tuning with ACE3P

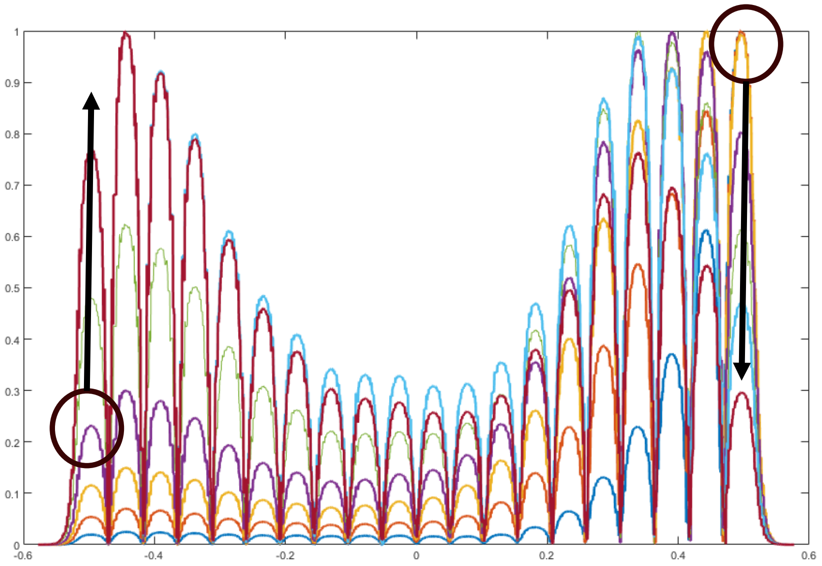
Each cavity has a dielectric bead with a relative permittivity to induce tuning

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



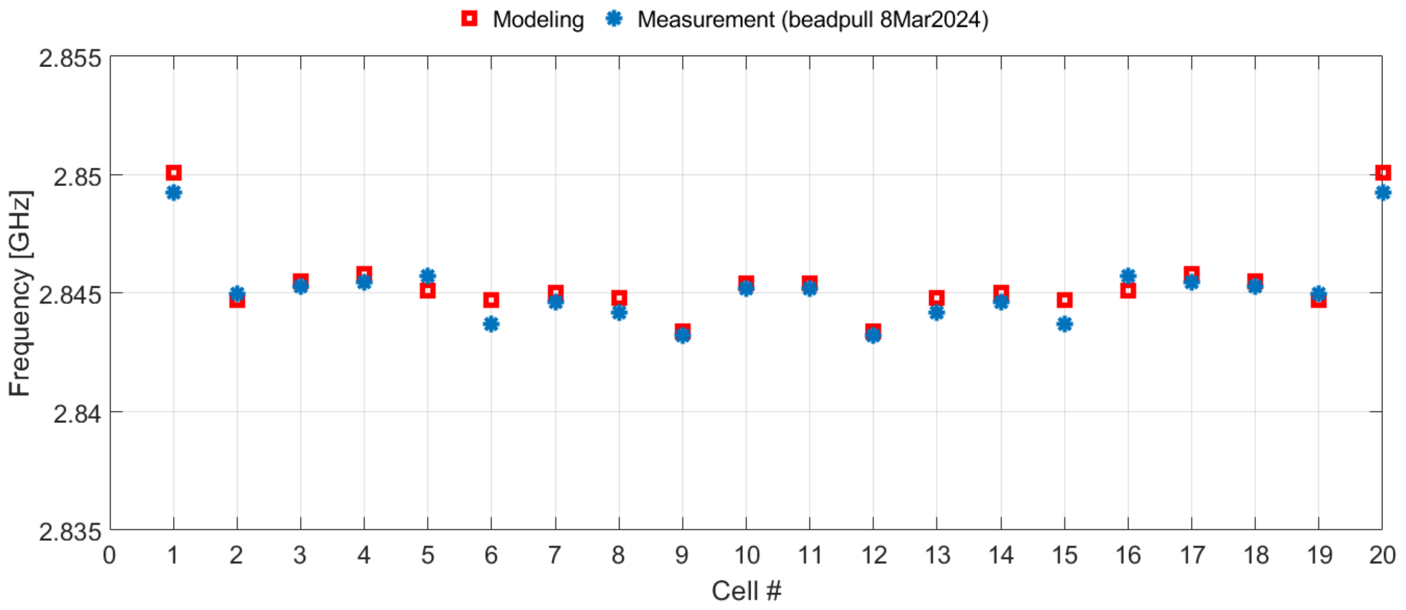


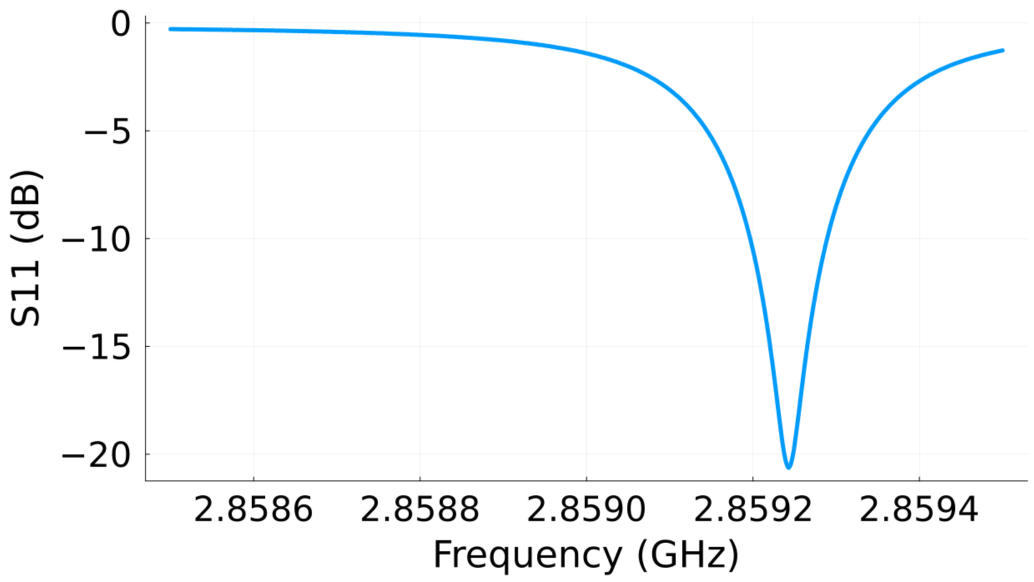
Cold Test and Tuning Results

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

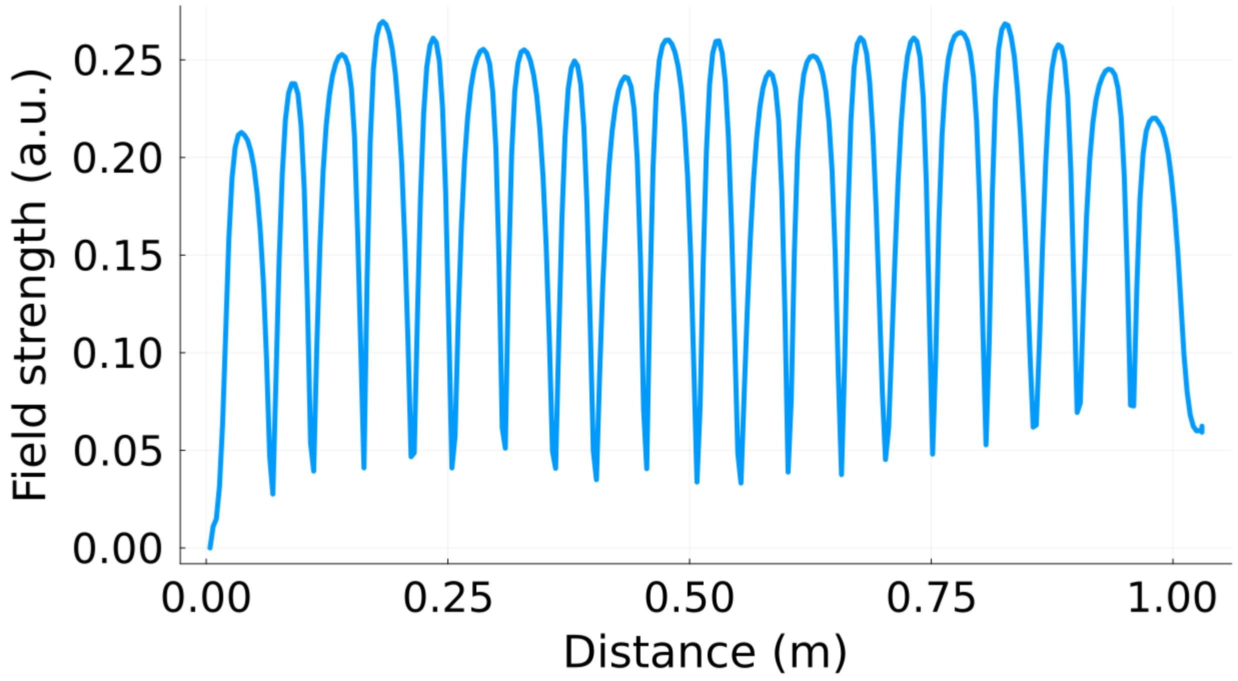


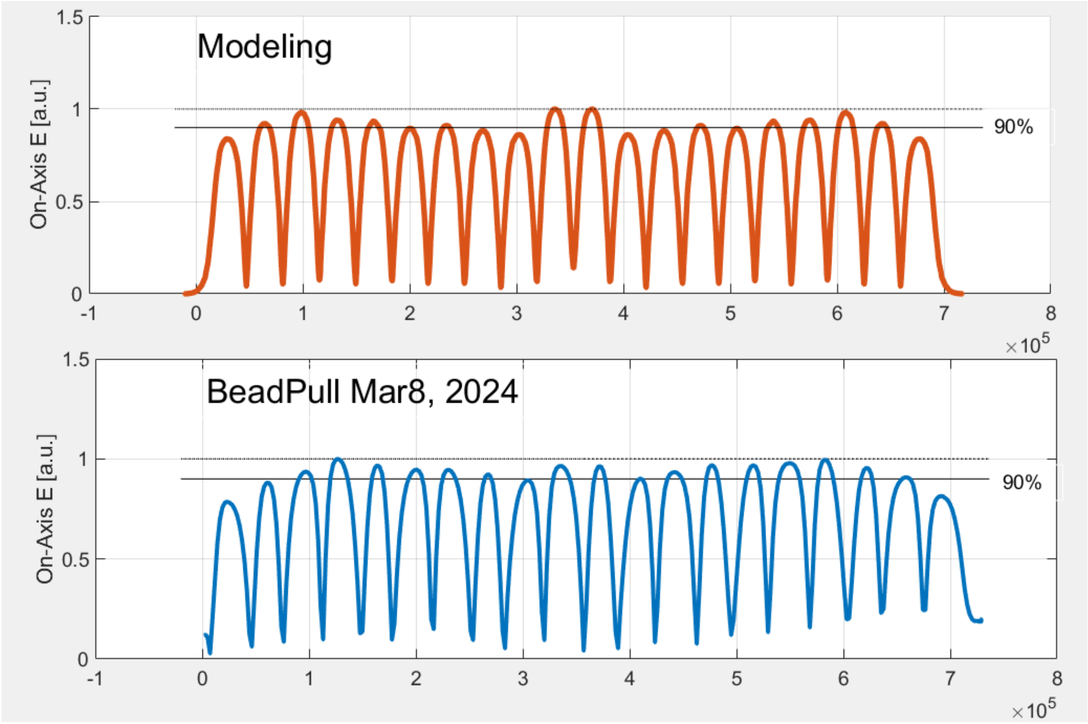


Cold Test and Tuning Results

Final tuning shows all cavities coupling to the pi mode strongly

End cavities are roughly 80% of maximum field strength





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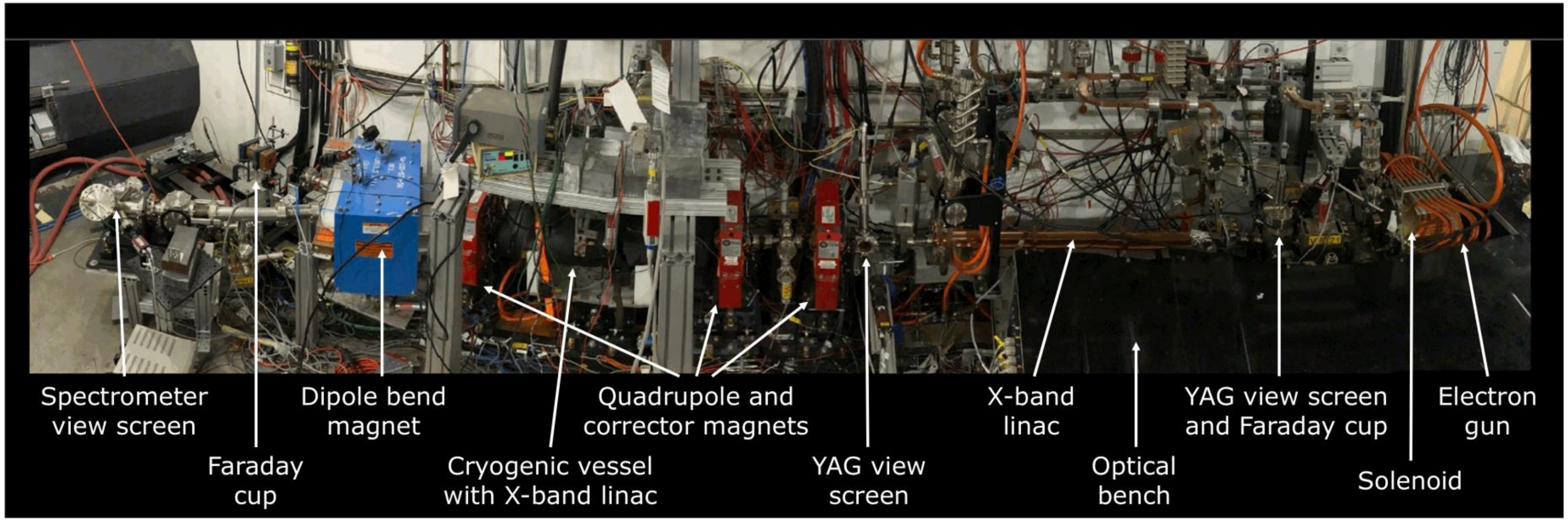
Future Test Plans

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

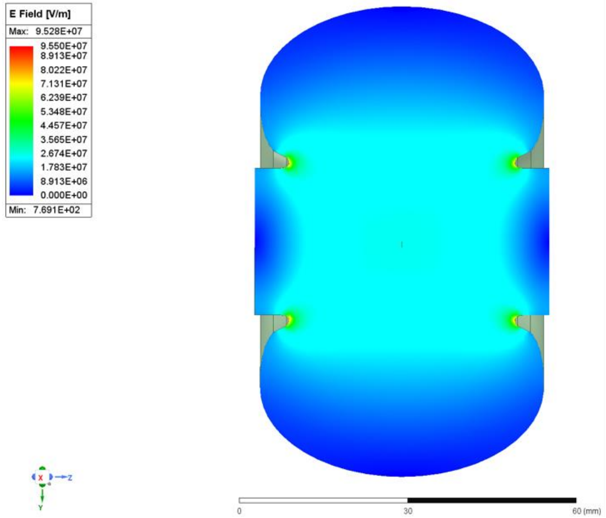


Synergies with Future Circular Collider

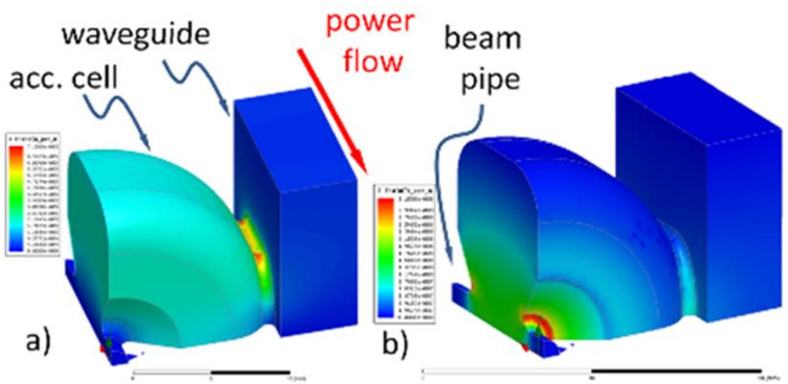
Distributed Coupling Technology could Improve Efficiency of HE-Linac

- Initial study with a/wl = 0.125 (conservative, average for HE linac concept is 0.12)
- Shunt impedance at 300 K: 58.5 MΩ/m
  - At 77 K: 146-158 MΩ/m
- Gradient: 22.5 MeV/m
- Baseline design: 6 MW/m, 3 microsecond
- Pulse compressed version could use traveling wave manifold for fast fill time

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



TW Manifold



Questions?

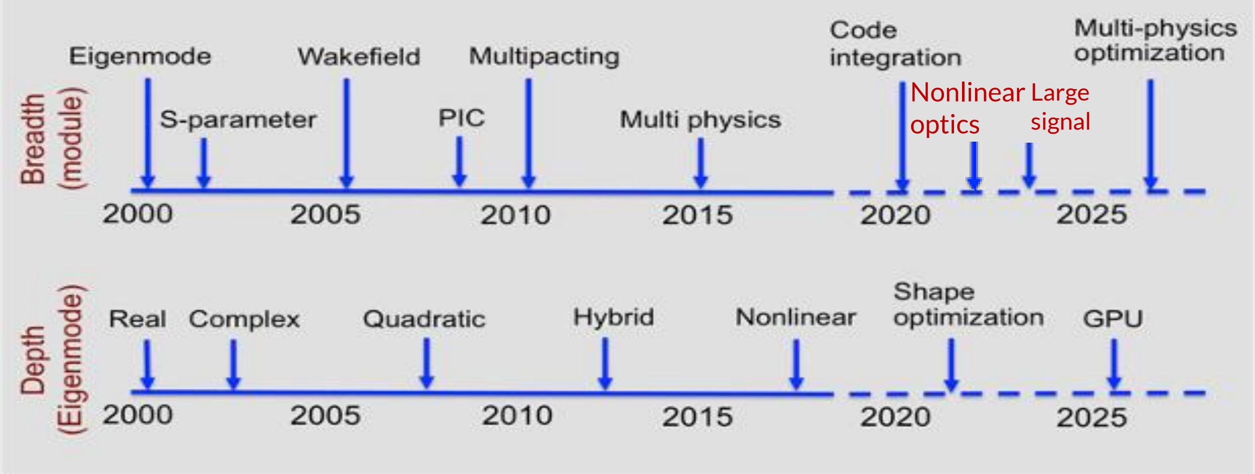
Multi-Physics Modeling Capabilities of RF Accelerators

- **ACE3P** is a parallel multi-physics code suite including electromagnetic (EM), thermal and mechanical simulations for virtual prototyping of accelerator and RF components
  - Based on *curved high-order finite elements* for high-fidelity modeling
  - Implemented on *massively parallel computers* for increased problem size and speed
  - C++ & MPI based

- **Capabilities to match CCC R&D needs (add more…)**

ACE3P (Advanced Computational Electromagnetics 3P)

Frequency Domain:	Omega3P	– Eigensolver (damping)
	S3P	– S-Parameter
Time Domain:	T3P	– Wakefields and Transients
Particle Tracking:	Track3P	– Multipacting and Dark Current
EM Particle-in-cell:	Pic3P	– RF guns & space charge effects
Multi-physics:	TEM3P	– EM, Thermal/Mechanical analysis
Static Particle-in-cell:	Gun3P	– DC guns & space charge effects
Optimization:	Opt3P	– Cavity shape optimization



- ***"ACE3P is the advanced EM code available to the community and the result of thousands of person-hours over the past several decades. Maintaining broad access to this code while providing continual improvements will be a challenge."***

Tuning Distributed Coupling S-Band LINAC

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

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

- Gradient perturbation in each cell

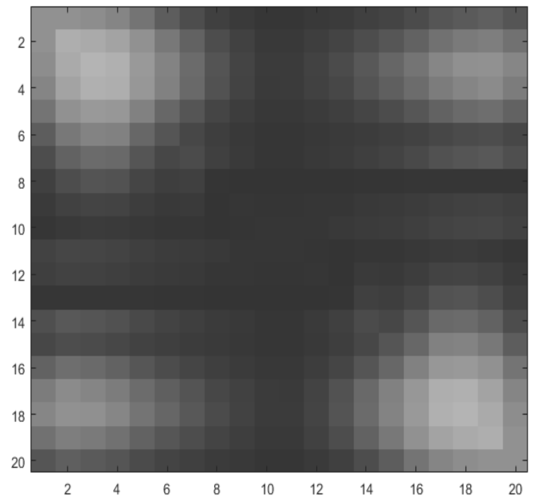
$$E'_{mn} = \frac{\partial E_m}{\partial \varepsilon_n} \times \left(\frac{\partial f_n}{\partial \varepsilon_n}\right)^{-1} = \frac{\partial E_m}{\partial f_n}, m, n = 1,2,\ldots,20$$

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

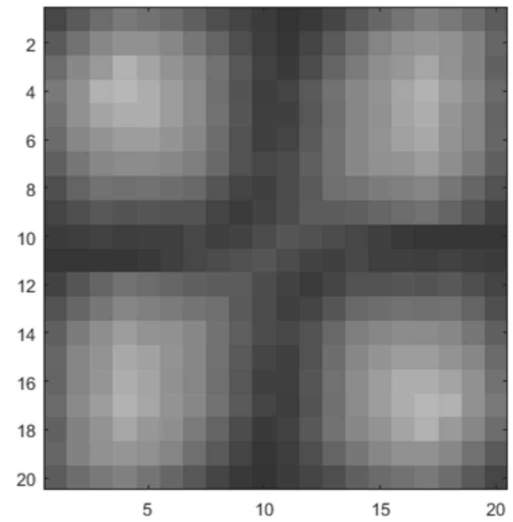
- Cavities in the middle are less sensitive to tuning, need collective tuning

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

Modeling



Measurement



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

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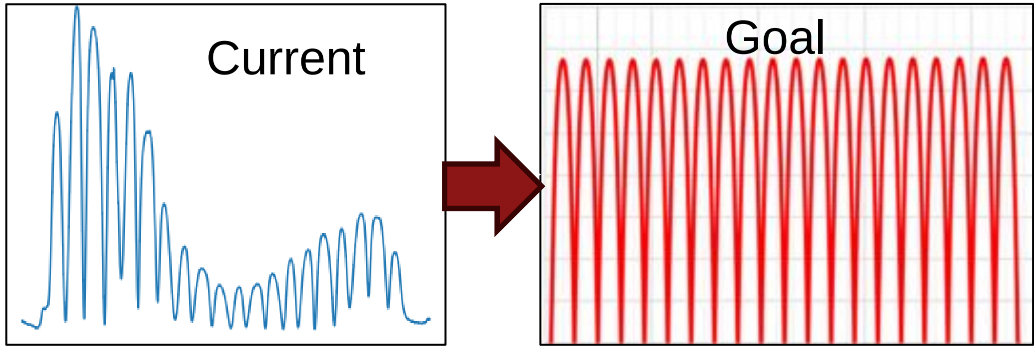
Target Optimal Frequencies Based on Perturbative Method

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



- 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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Comparison of Technologies for pre-injector e^- linacs

	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]*	51* *0.15-0.11*	45-56 *0.135-0.095*	58 *0.135*	145 *0.135*
Power / Length @ 16 MeV/m [MW/m] / Power for 400 MeV [MW] in 25 m *Min. 65 MW 5045 Klystron*	8.3 / 210 *4 klystrons*	6.2 / 156 *3 klystrons*	4.4 / 110 *2 klystrons*	1.8 / 44 *1 klystron*
Achievable Gradient [MeV/m] Constant BDR Scaled from Pulsed Heating	50	60	74	118
Power for 400 MeV in 8 m [MW] Corresponds to 50 MeV/m *Min. 65 MW 5045 Klystron*	645 *10 klystrons*	488 *8 klystrons*	344 *6 klystrons*	138 *3 klystrons*

F. Willeke, “Electron ion collider conceptual design report 2021,” English, Tech. Rep., 2021, doi:10.2172/1765663

T. Schietinger, et al., *PRAB* 19.10 (2016):100702

M. Nasr, et al., *PRAB* 24.9 (2021):093201