Distributed Coupling LINAC: a more efficient RF power LINAC design for EIC pre-injector

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SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Introduction
- Comparison of several e-LINAC technologies
- Benefits
- Development status of distributed coupling technology

Background

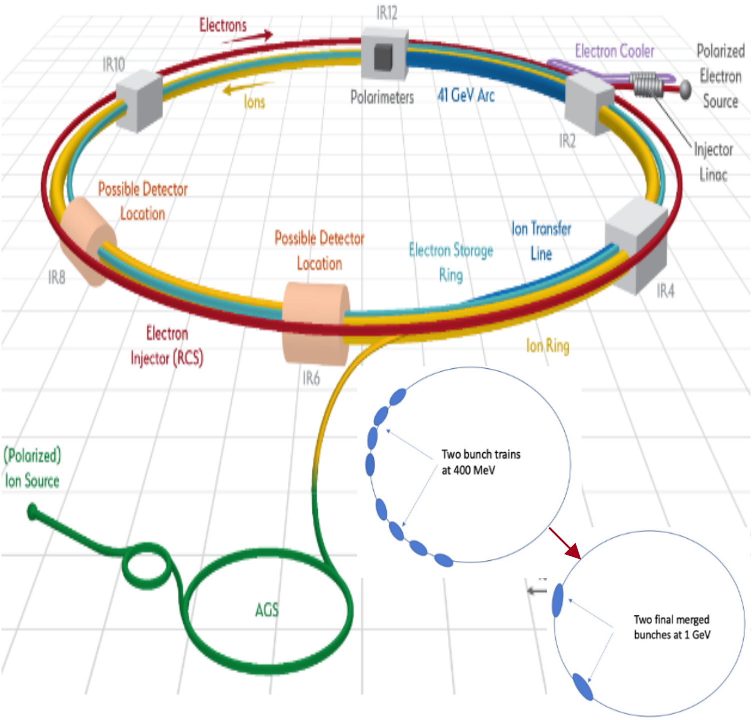
e pre-injector baseline design:

- DC polarized e-gun with SL-GaAs cathode:
  - 2 bunches every 10ms for 4 cycles to provide 4 2-bunch trains per RCS cycle
  - 7nC per bunch (Can achieve 16nC per bunch)
- e-LINAC: 4-400 MeV, 16MV/m structure gradient
  - SLC style s-band LINAC structure
  - deliver two 4 bunch trains to RCS per cycle with momentum spread ~0.25%

RCS requirements:

- Accelerate the 8 injected bunches to ~1GeV
- Inject polarized electron bunch at its full intensity (up to 28nC) into the ESR per second
- Preserve emittance and spin during the acceleration up to 18GeV

EIC schematic layout



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
- Min. (Max) Gradient 16.6 (22.2) MeV/m in structure
- Total footprint 35.6 m (11.2 MeV/m real estate gradient)

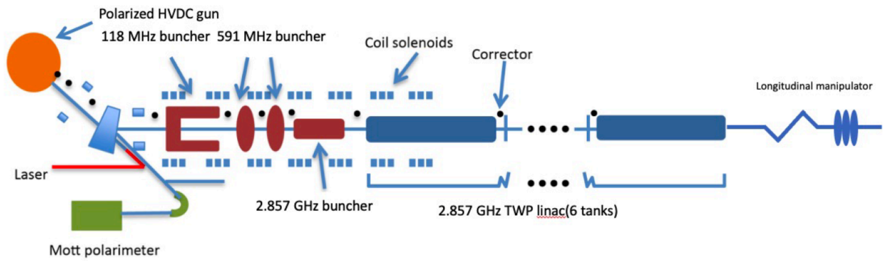


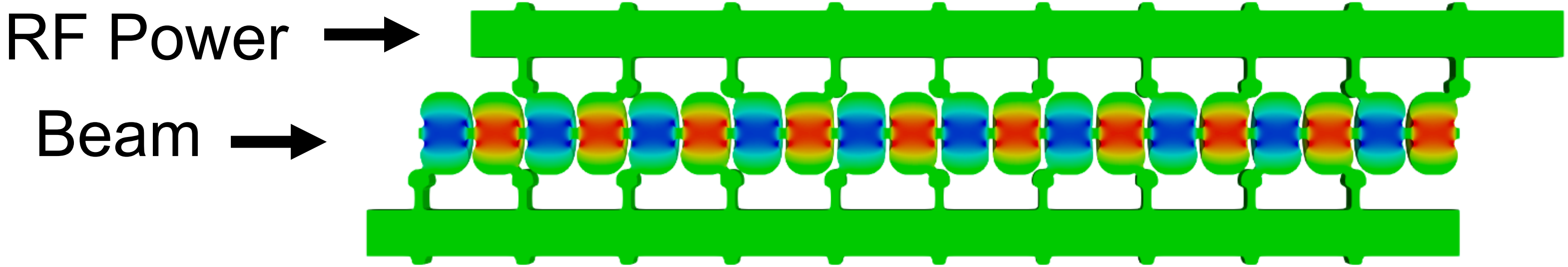
Figure 3.120: The layout of the 400 MeV beamline.

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

Breakthrough of Distributed RF Coupling Changes the Paradigm for RF Accelerator Performance

- 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

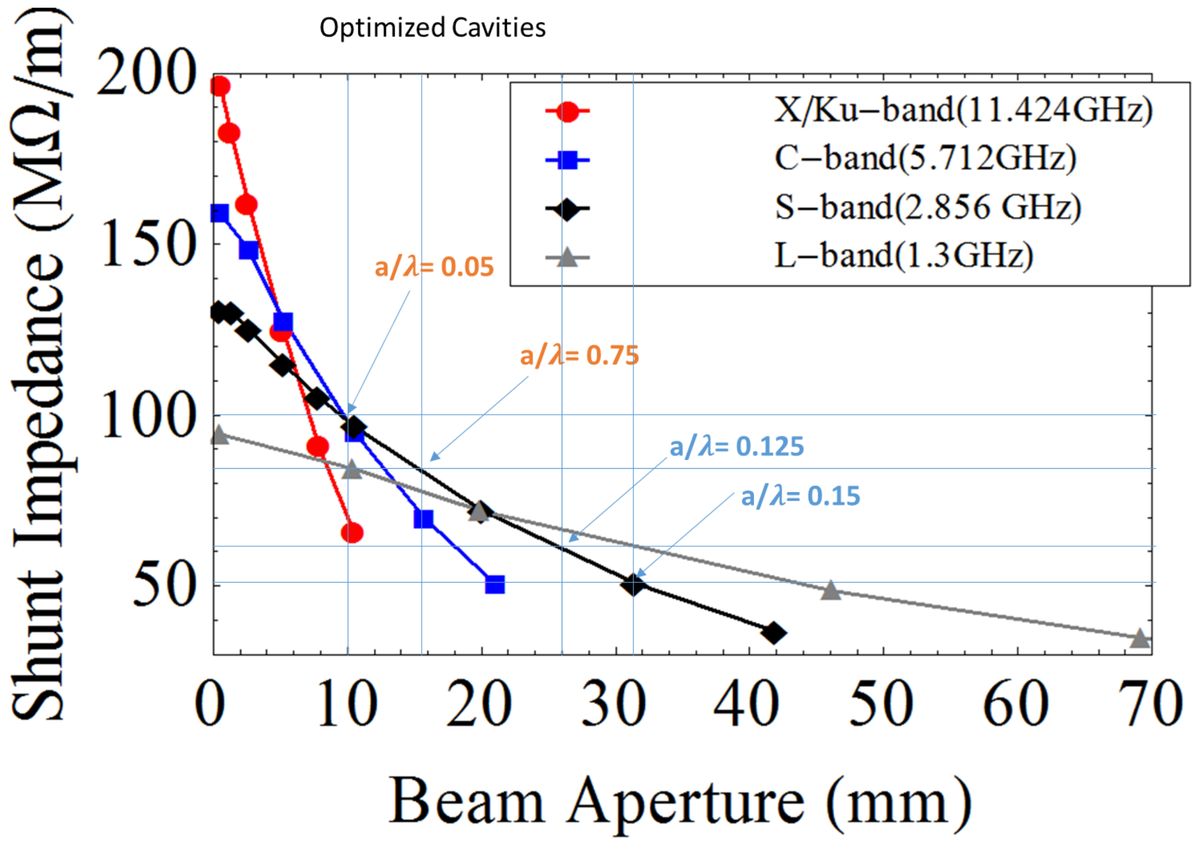
- Optimization of cell for efficiency (shunt impedance)

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

- Control peak surface electric and magnetic fields
  - Key to high gradient operation

Tantawi et al. PRAB 23.9 (2020): 092001.

Optimized Performance of Cavity Geometry

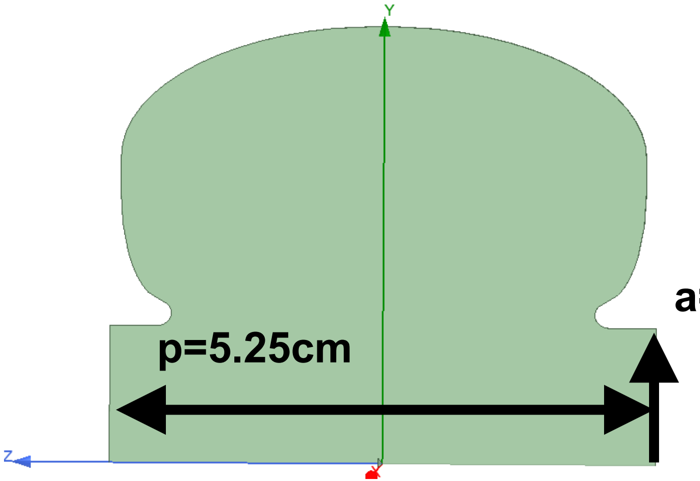


Cavity Geometry for $a/\lambda=0.125$

SLAC

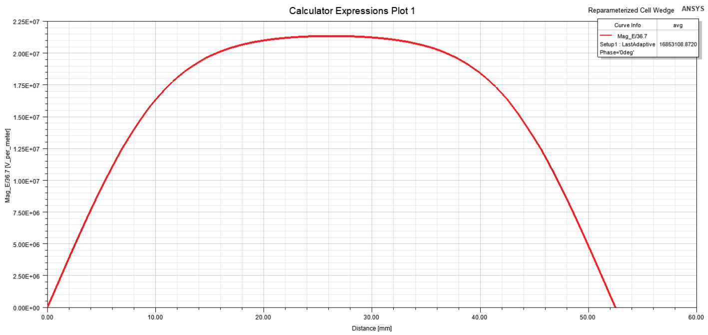
- Wakes same or slightly better than 4m PSI
- Pulsed heating < 5 deg C at 16MeV/m 4 microsec

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



a=1.31cm

A. Dahr



Comparison of Technologies for EIC pre-injector electron linac

	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 [MΩ/m] *a/λ [radius/wavelength]*	51* *0.15-0.11*	45-56⁺ *0.135-0.095*	58 *0.125*	210 *0.125*
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*

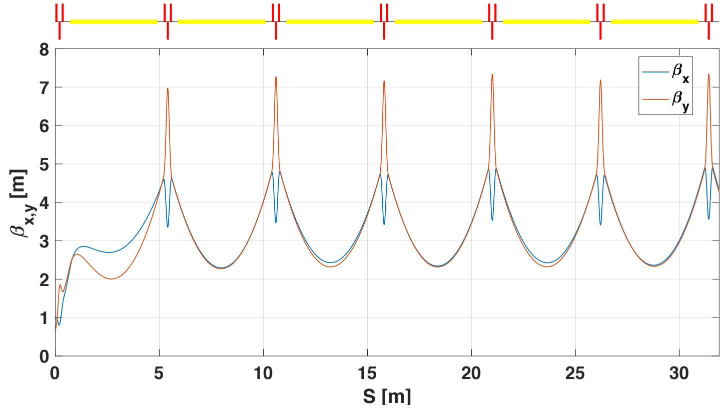
*Equivalent Rs for SW of 31 MΩ/m due to TW power to load; ⁺Equivalent Rs 41 Modeled (38 Measured) PRAB 19, 100702 (2016)

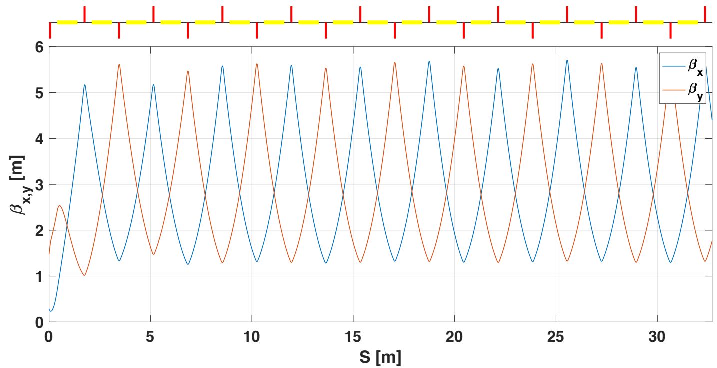
Benefits of applying SLAC D.C. technology

- Higher performance than current baseline
  - **14nC vs. 7nC**. The higher bunch intensity from LINAC can eliminate one bunch merge and reduce the longitudinal emittance growth
- Cost efficient and better operational reliability, e.g. number of klystrons
- Path for future upgrades such as higher injection energy for RCS
  - Avoid the microwave beam instability at 400MeV.
  - Requires new RCS injection scheme.

Linac Optics Configurations

E = 4 MeV E = 400 MeV



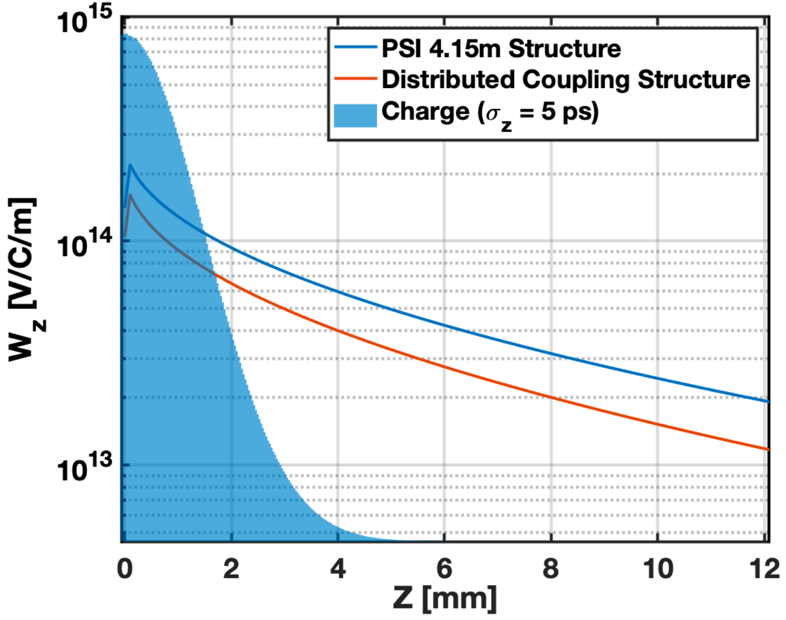


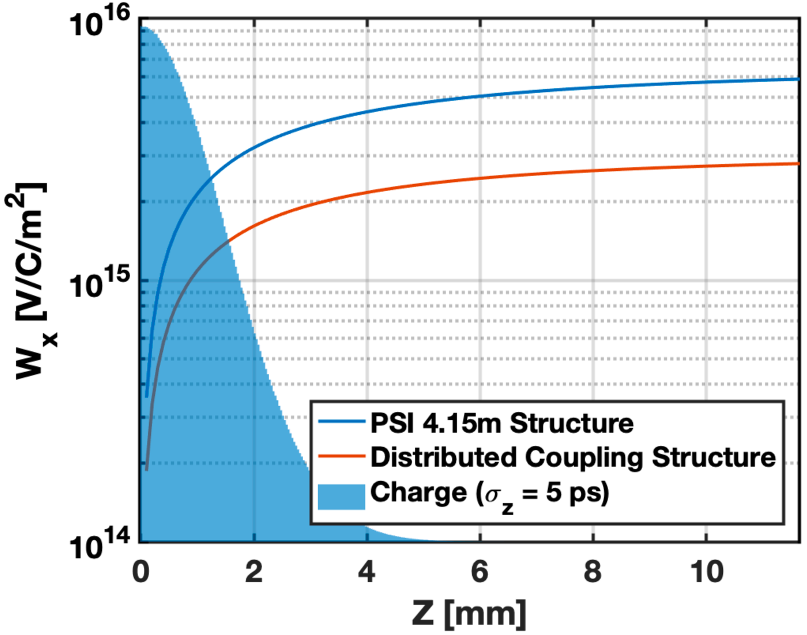
	EIC Baseline	Distributed Coupling Structure
Structure Length	4.15 m	1 m
Lattice	Triplet	FODO*
Structure aperture	1.31 cm	1.25 cm
Structure gradient	16 MV/m	21.5 MV/m
Linac Length	32 m	32 m

*Structure is versatile – FODO or Triplet configuration possible

Wakefields

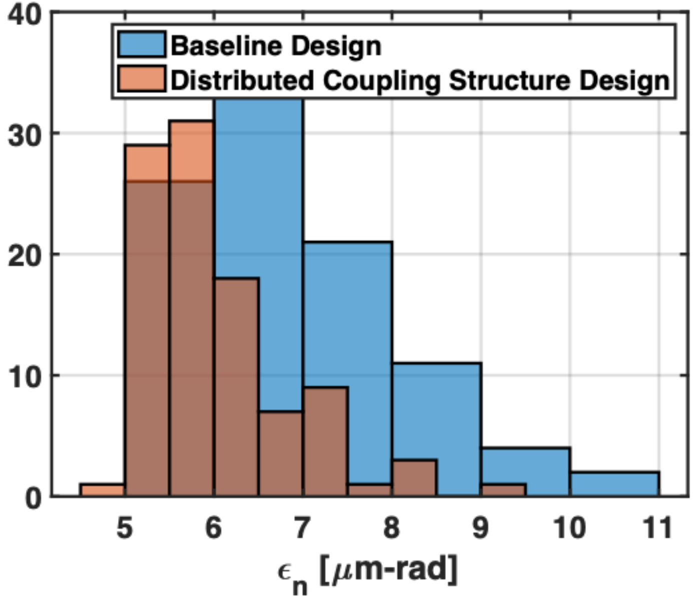
- Longitudinal and transverse wakes used for tracking through accelerating structures*

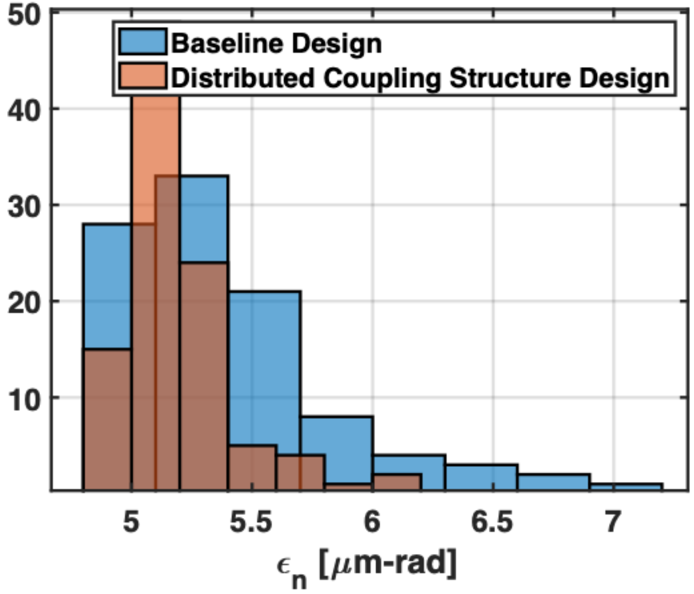




*SLAC SLC 3 meter structure wakes in between DC and PSI

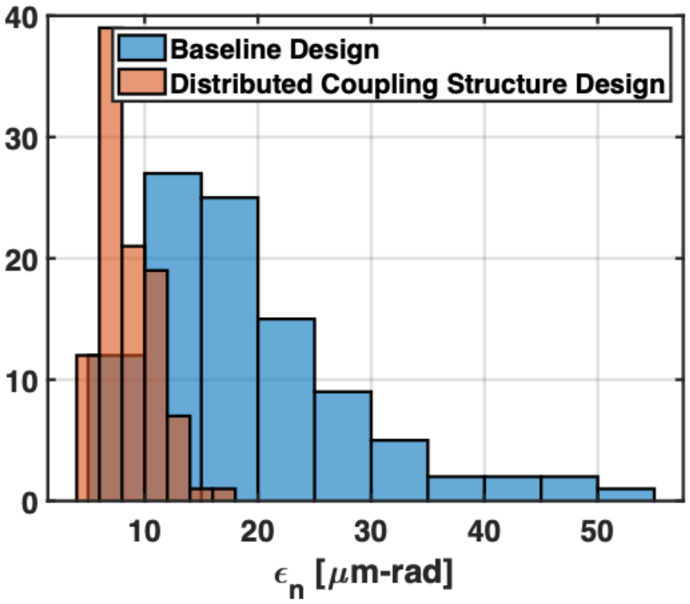
Particle Tracking, Q=7nC + Beamline Element Offsets

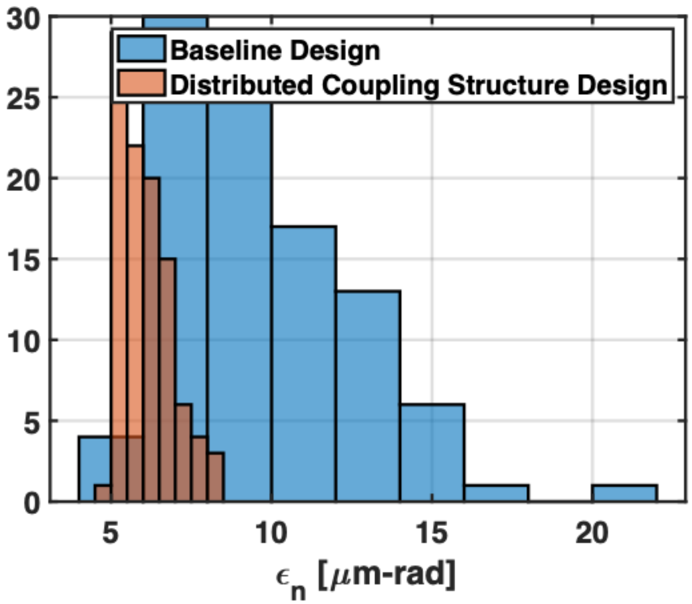




- 100 µm, 300 µrad structure & quad offsets/roll (left)
- 50 µm, 150 µrad structure & quad offsets/roll (right)
- 100 random offset seeds tracked (no steering corrections applied)

Particle Tracking, Q=14nC + Beamline Element Offsets



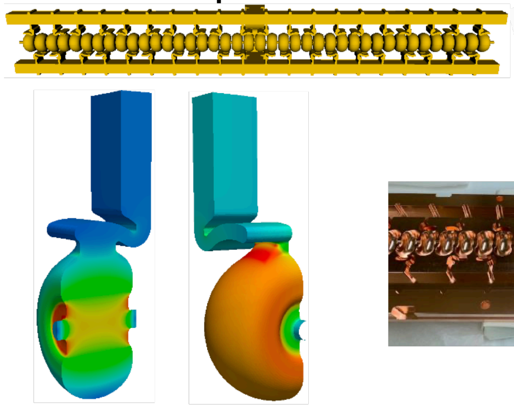


- 100 µm, 300 µrad structure & quad offsets/roll (left)
- 50 µm, 150 µrad structure & quad offsets/roll (right)
- 100 random offset seeds tracked (no steering corrections applied)

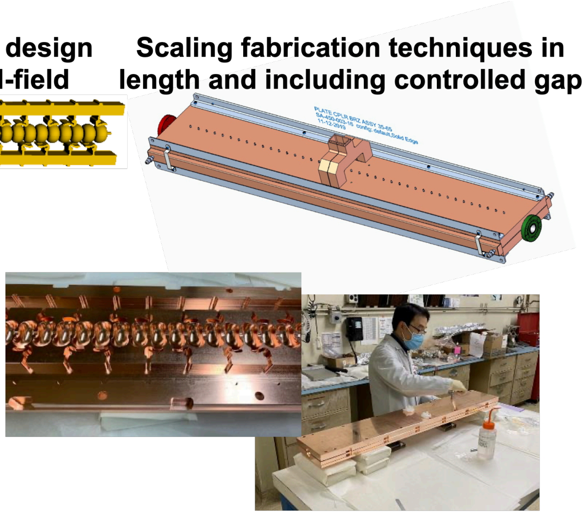
Distributed Coupling and Cold Copper Achievements

- Many distributed coupling structures designed and built
- One structure tested with beam both cold and warm*

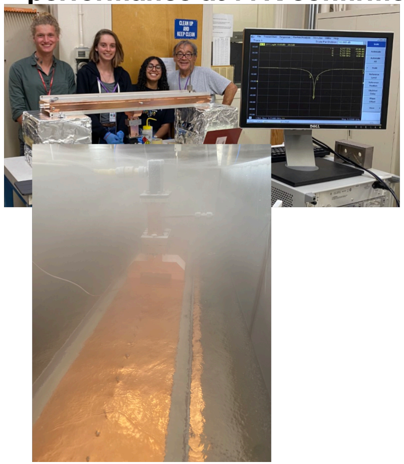
One meter (40-cell) C-band design with reduce peak E and H-field



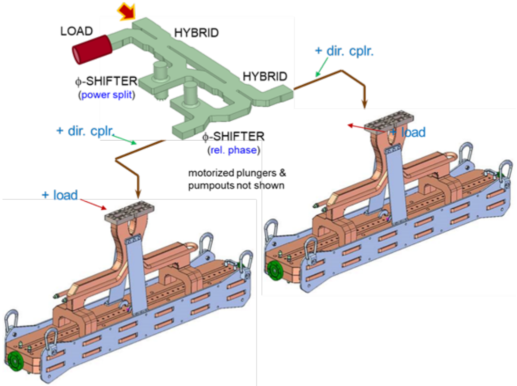
Scaling fabrication techniques in length and including controlled gap



Tuned, vacuum tight, performance at 77K confirmed

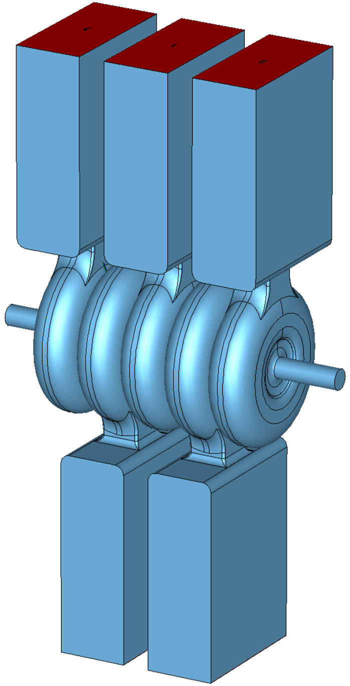


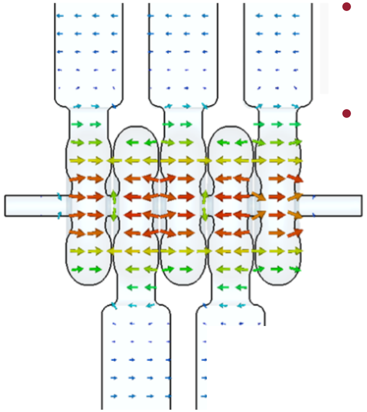
RF Distribution to Avoid Reflection to RF Source



*Nasr et al. https://link.aps.org/doi/10.1103/PhysRevAccelBeams.24.093201

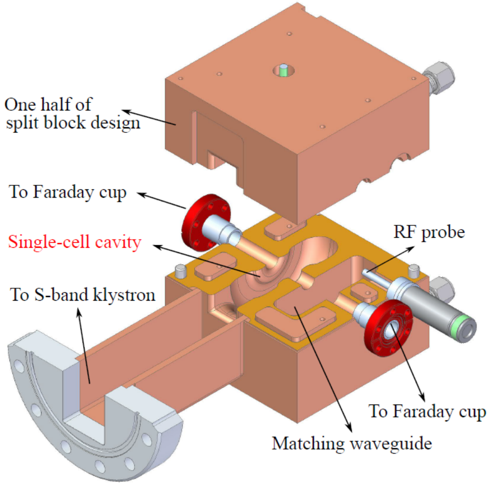
Extending Distributed Coupling to S-band



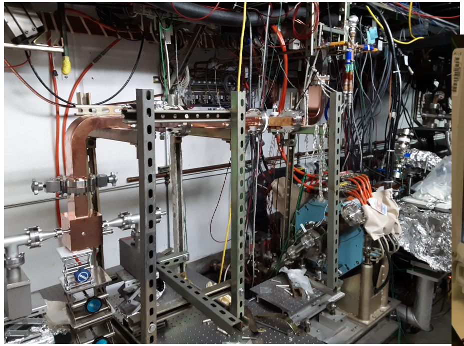


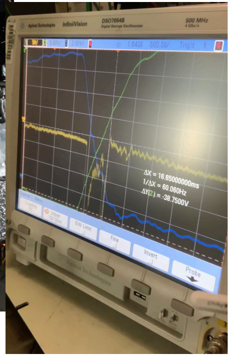
- S-band distributed coupling structure under development for proton radiation therapy
- Single cell room temp test reached 50 MeV/m (one day) – stopped as it was beyond program goal – setup ready to push higher

	Design	Cold Test
f (GHz)	2.856	2.853 Cu-Ag, 2.854 Cu
Q0	11936	12014 Cu-Ag, 12197 Cu
Coupling β	1.0021	1.04 (both)



Injector Station Operational w/ Structure



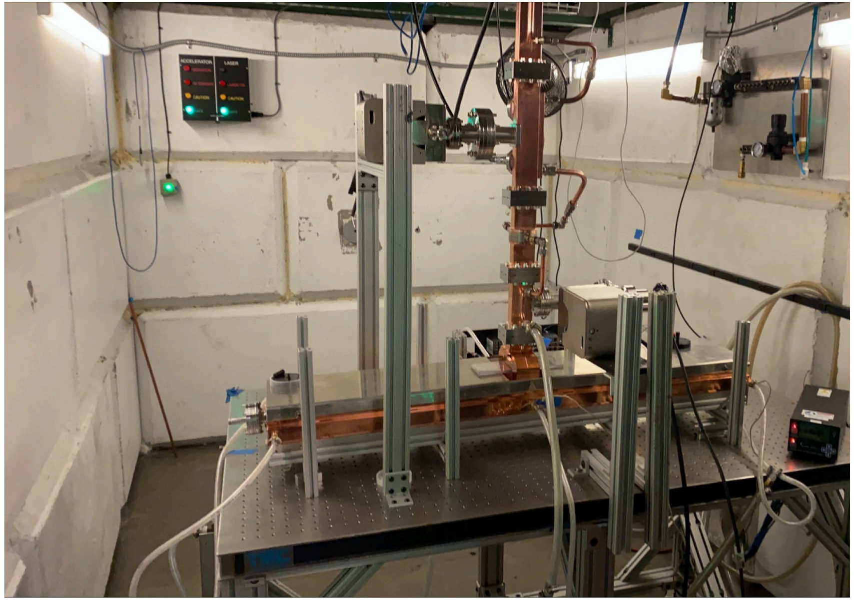


Dark Current Signal

Lu, Xueying, et al., *Review of Scientific Instruments* 92.2 (2021): 024705.

High Power Testing of Meter-Scale Structure

- One meter C-band distributed coupling linac in test at Radiabeam
- Operating at 30 MeV/m in less than 2 weeks
- Will soon max out available rf power



Conclusion

- Novel distributed coupling linac could reduce rf power requirements and/or increase gradient of EIC pre-injector
  - Possible cost savings – fewer rf soures, simpler rf dist., weaker alignment tolerane
  - Path to energy upgrade
- Path to high bunch charge operation – 7 vs. 14 nC
- Linac structure compatible with present rf source selection – high power S-band klystron
- Next steps
  - Detailed beam dynamics and optimization to determine aperture
  - Preliminary longitudinal emittance calcs. comparable to CDR
  - Possible test of S-band meter structure meeting operational requirements

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