C³ – Cool Copper Collider:
CLIC Discussion

7/26/2021

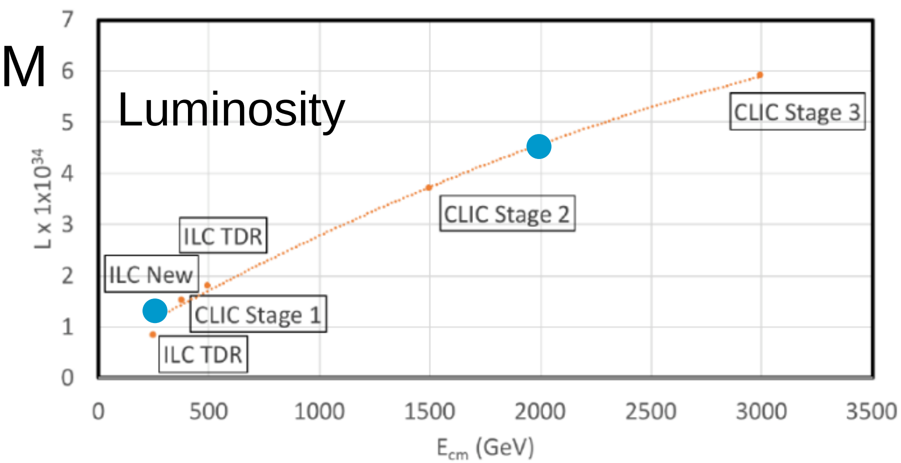
U.S. DEPARTMENT OF ENERGY
Office of Science

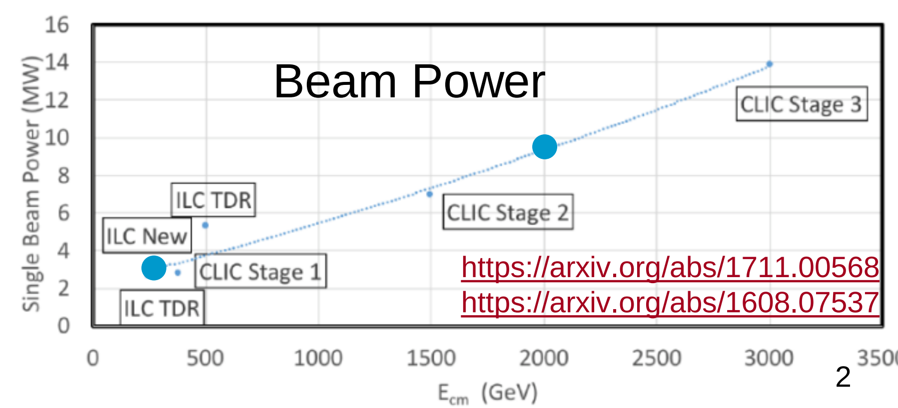
SLAC NATIONAL ACCELERATOR LABORATORY

NCRF Accelerator Concept Starting Point for a High Energy e^+e^- Linear Collider

- Using established collider designs to inform initial parameters
- Quantifying impact of wakes requires detailed studies
  - Most important terms – aperture, bunch charge (and their scaling with frequency)
- Target design at 0.25-2 TeV CoM
- 2.5-9 MW single beam power

Machine	CLIC	NLC	C^3
Freq (GHz)	12.0	11.4	5.7
a (mm)	2.75	3.9	2.6
Charge (nC)	0.6	1.4	1
Spacing	6	16	19
# of bunches	312	90	75





https://clic-meeting.web.cern.ch/clic-meeting/clictable2010.html
NLC, ZDR Tbl. 1.3,8.3

Leverage the Development of Beam Generation and Delivery Systems for C^3

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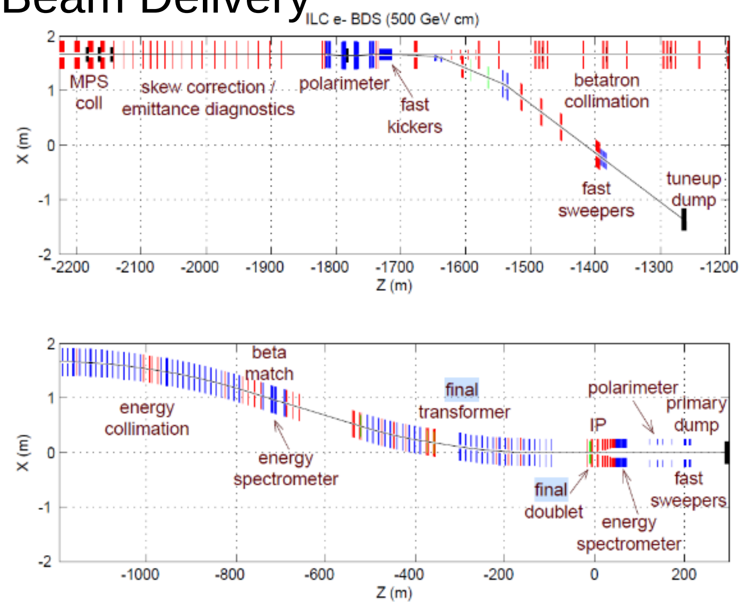
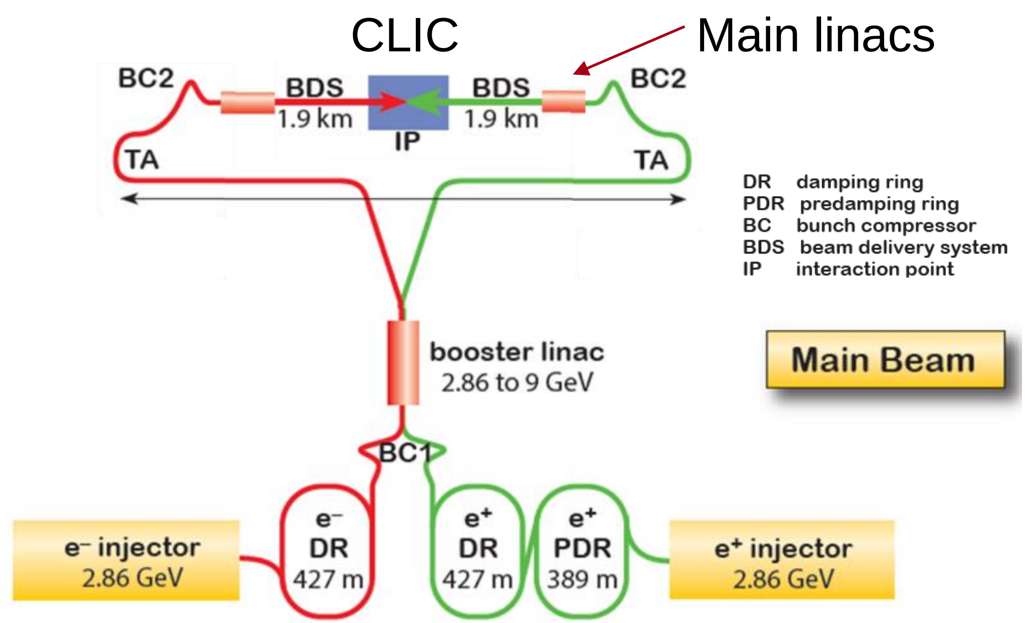
- Large portions of accelerator complex are compatible between LC technologies
  - Beam delivery and IP identical with ILC
  - Damping rings with CLIC
  - Injectors to be optimized with ILC as baseline
  - **R&D – Development of high brightness polarized e- sources**

ILC Beam Delivery



CLIC



Optimized Cavity Geometries for 2π/3-mode Standing Wave LINAC

- Small aperture for reduced phase achieves exceptional R_s
- Cryogenic operation: Increased R_s, reduced pulse heating

Frequency	a/λ	Phase Adv.	Rs (MΩ/m) 300K	Rs (MΩ/m) 77K
C-band (5.712 GHz)	0.05	π	121	272
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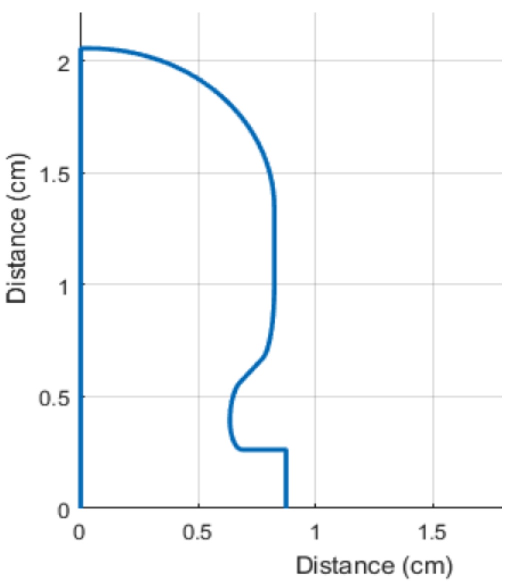
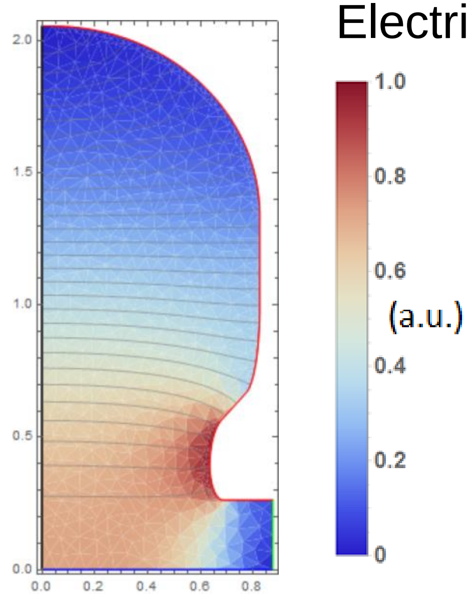
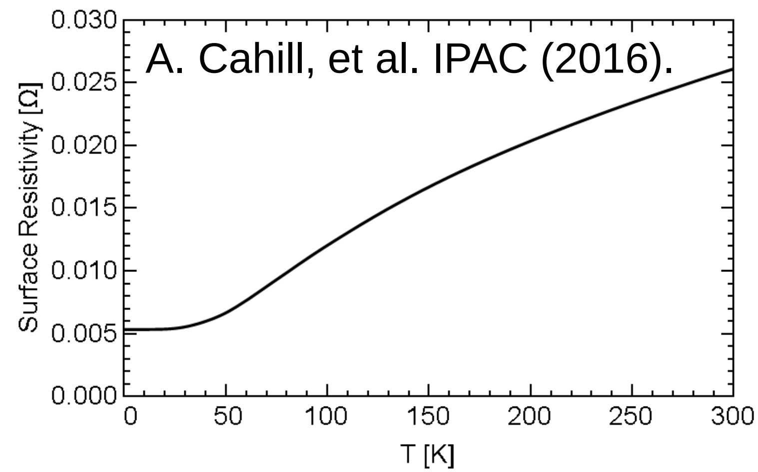


Electric Field



Surface Resistivity vs. Temp



Gaussian Detuning Provides Required 1st Band Dipole Suppression for Subsequent Bunch, Damping Also Needed

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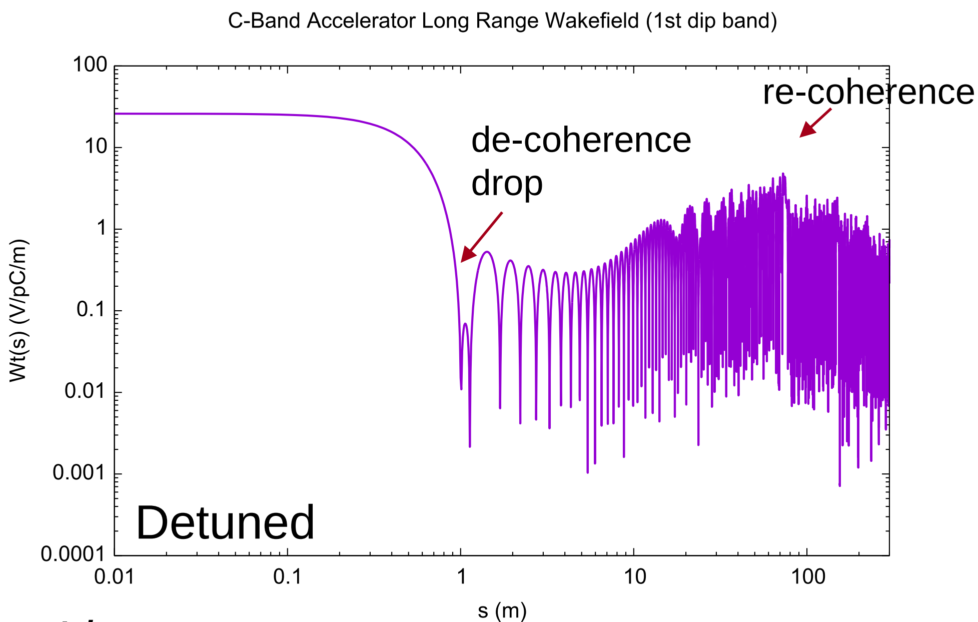
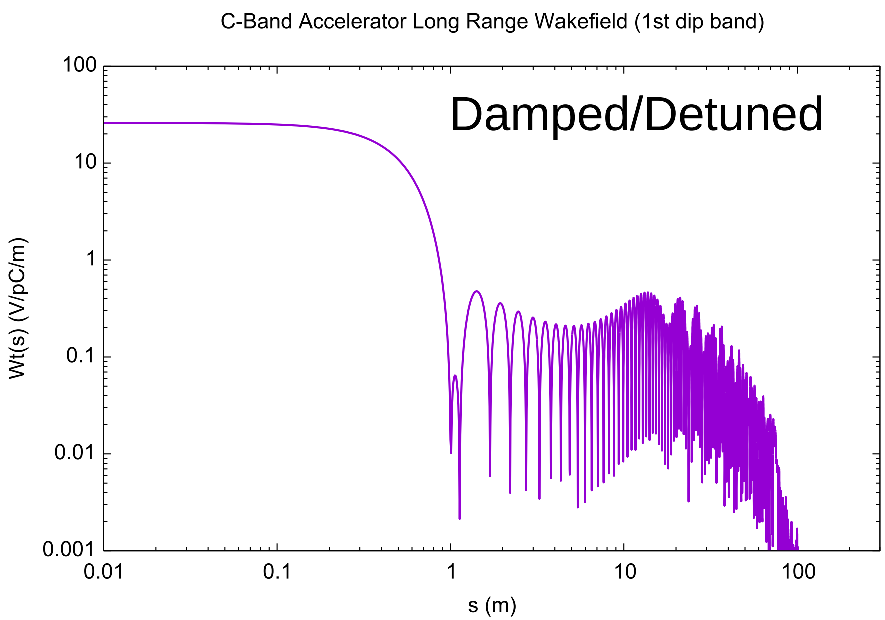
- Dipole mode wakefields immediate concern for bunch train
- 4σ Gaussian detuning of 80 cells for dipole mode (1st band) at $f_c = 9.5$ GHz, w/ $\Delta f / f_c = 5.6\%$
- First subsequent bunch s = 1m, full train ~75m in length
  - Damping needed to suppress re-coherence



Li (Only copper surface loss damping included)



(1.0e3 Q total HOM damping included)

Distributed Coupling Structures Provide Natural Path to Implement Detuning and Damping of Higher Order Modes

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- Individual cell feeds necessitate adoption of split-block assembly
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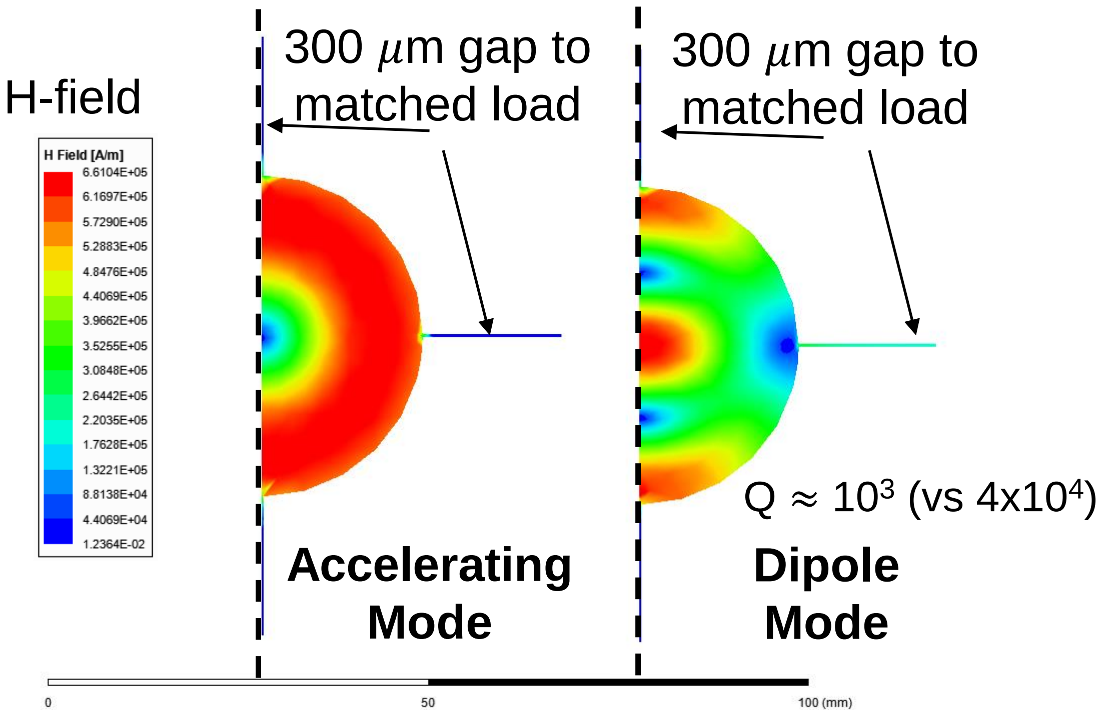
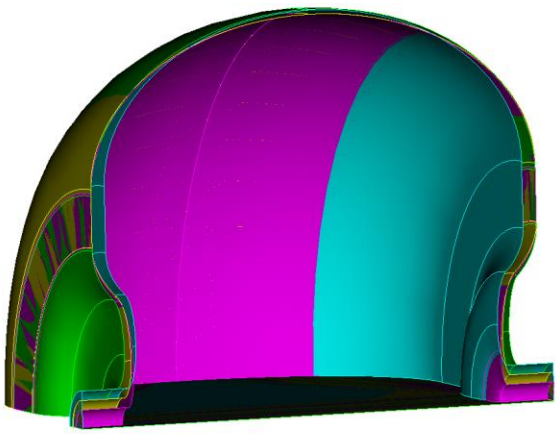
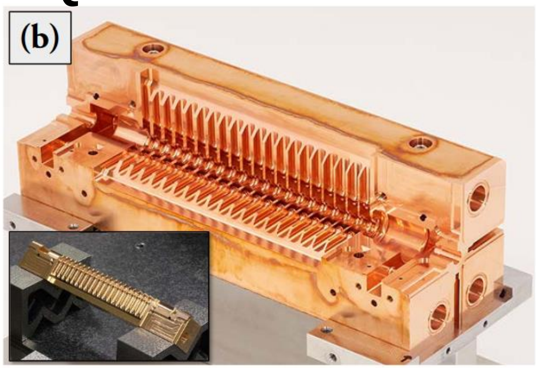
- Exploring gaps in quadrature to damp higher order mode



Design of Detuned Cavities



Quadrant Structure

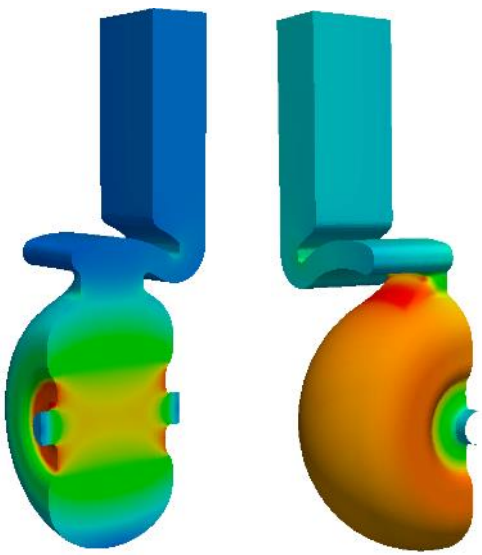


Abe et al., PASJ, 2017, WEP039

Development of C³ Technology is Ongoing

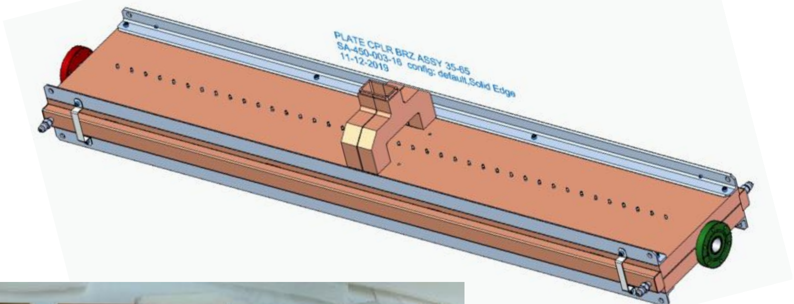
- Key focus - C³ is a practical technology
- Exploring 250 GeV to 2 TeV COM

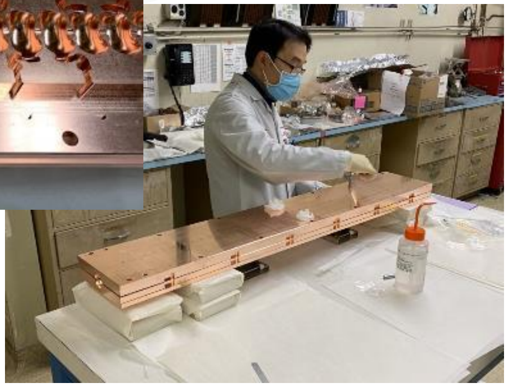
One meter (40-cell) C-band design with reduce peak E and H-field



S. Tantawi, and Z. Li

Scaling fabrication techniques in length and including controlled gap





C3 Prototype Structure Built and Tuned

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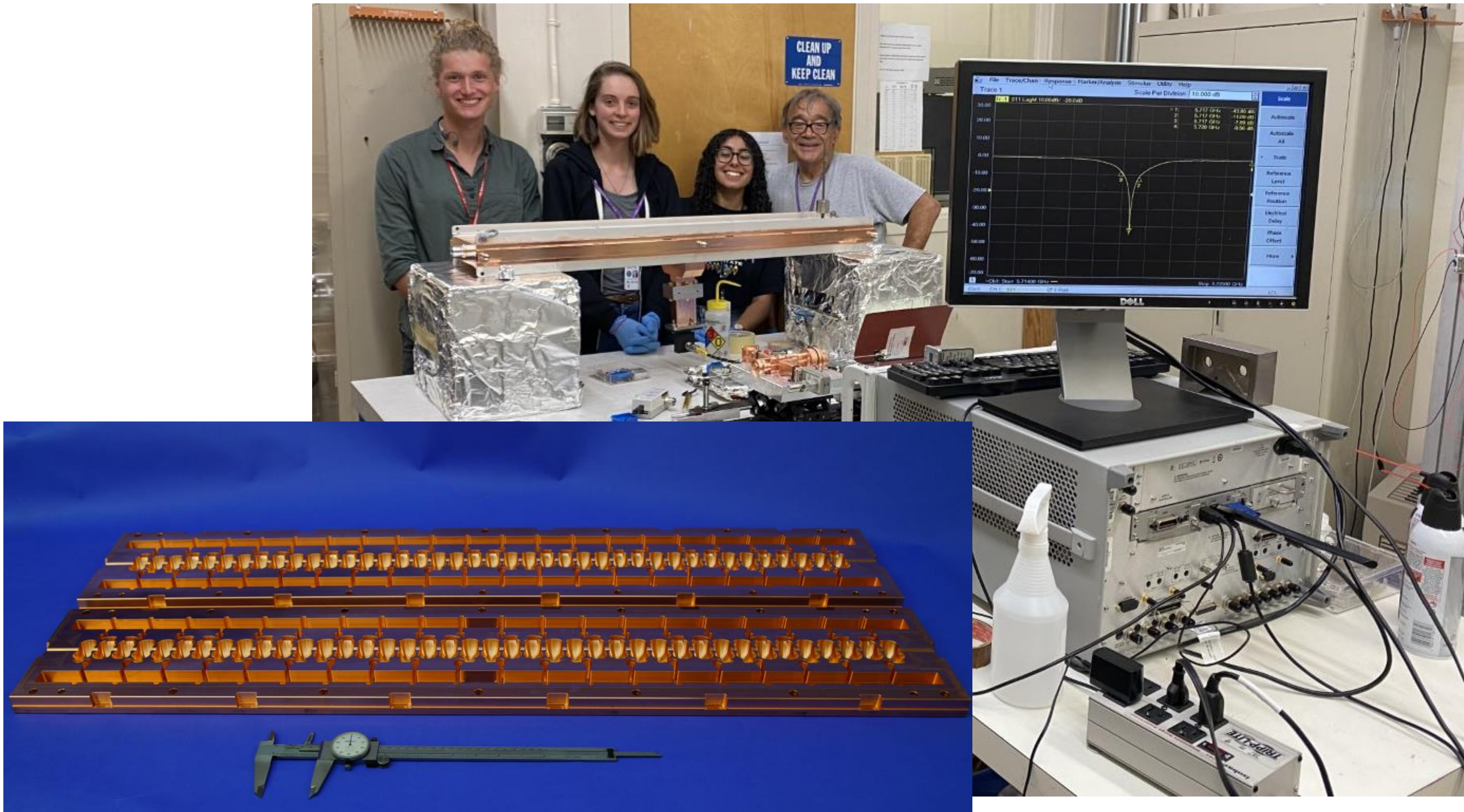
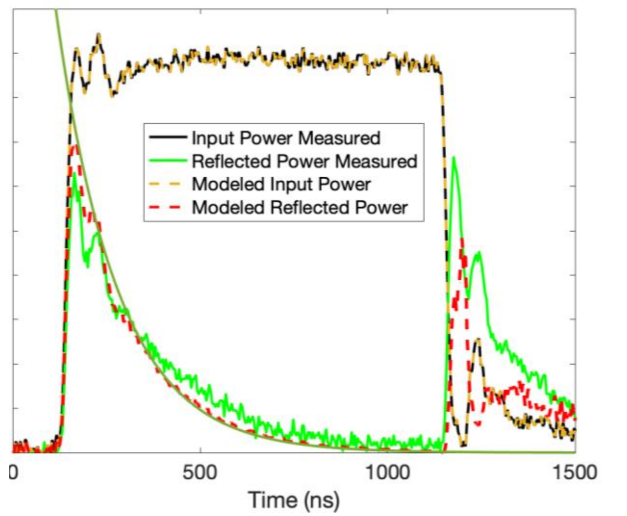


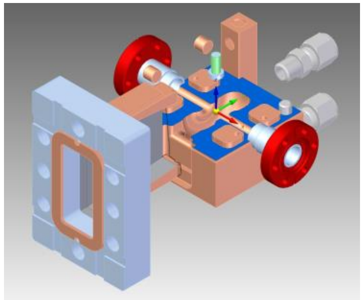
High Gradient Test with Single-Cell C-band

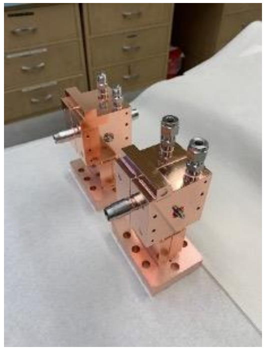
- Reduced phase advance structure in test at LANL for high power
- Also tested at low power and cryogenic temperature
  - Cool down improved Q by >2.3X; also observed at X-band

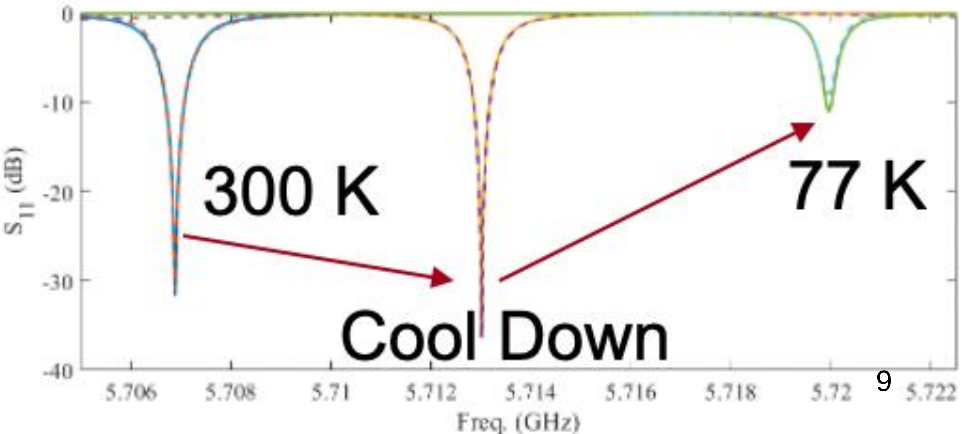
LANL High Power Tests Ongoing
Eagerly Await Benchmarked Results!



C-band Cavity (@LANL/@SLAC cold)

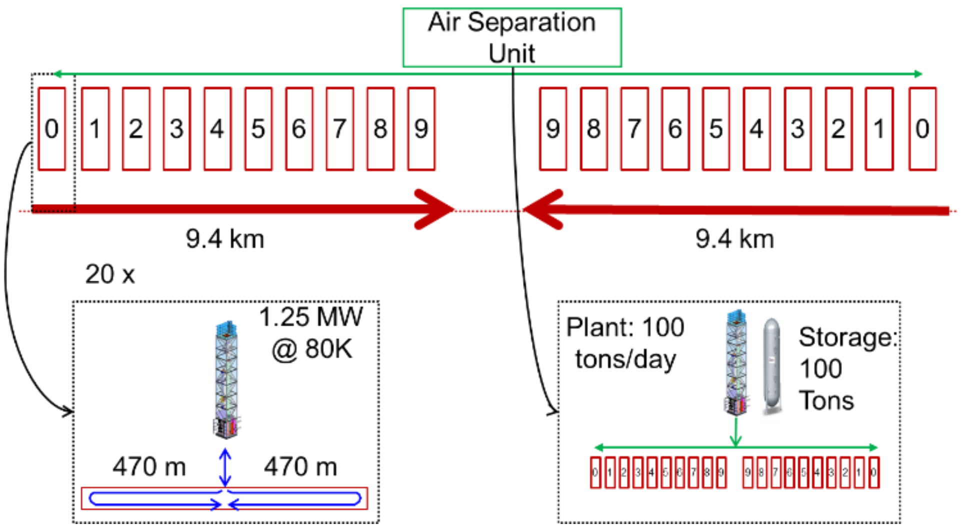


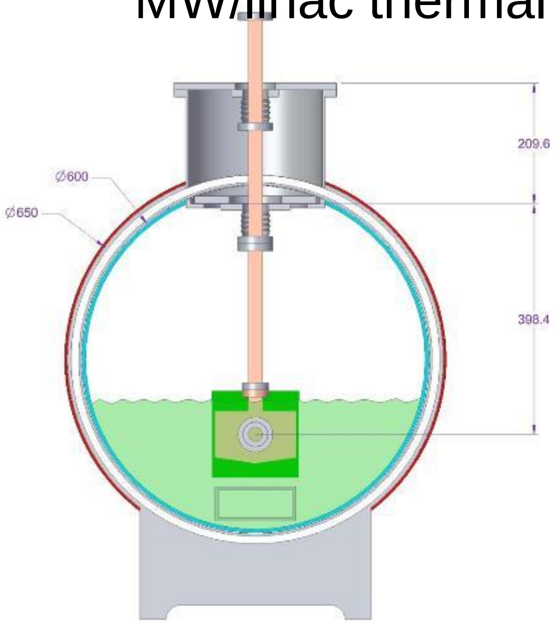




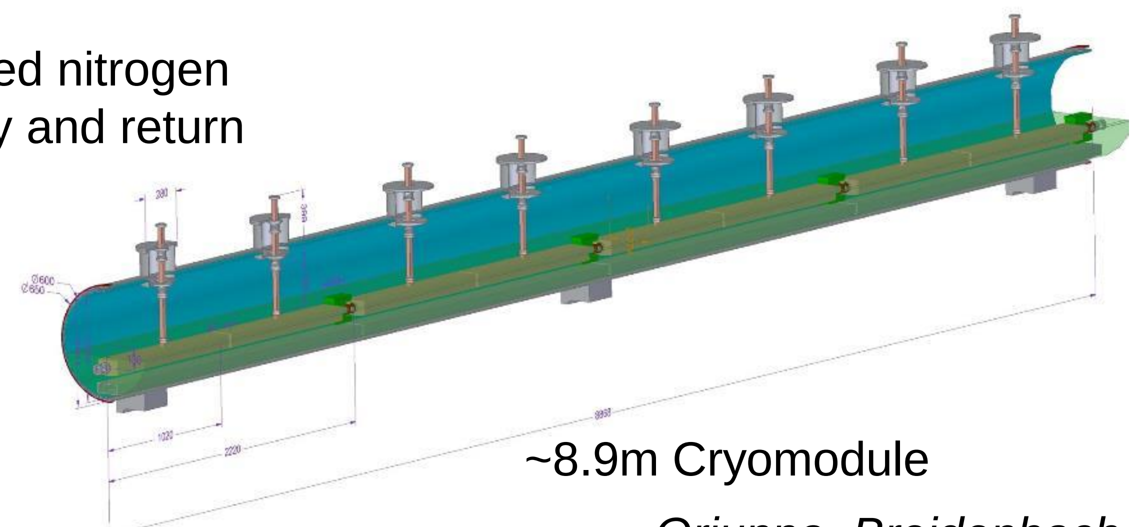
C³'s Scalable Design

- Preliminary ΔE = 1 GeV Cryomodule Design for High Average Power Implementation with ~90% Fill Factor
- Cryomodule design developed for cryoplant layout to cool 24 MW/linac thermal load at 77K





Shared nitrogen supply and return



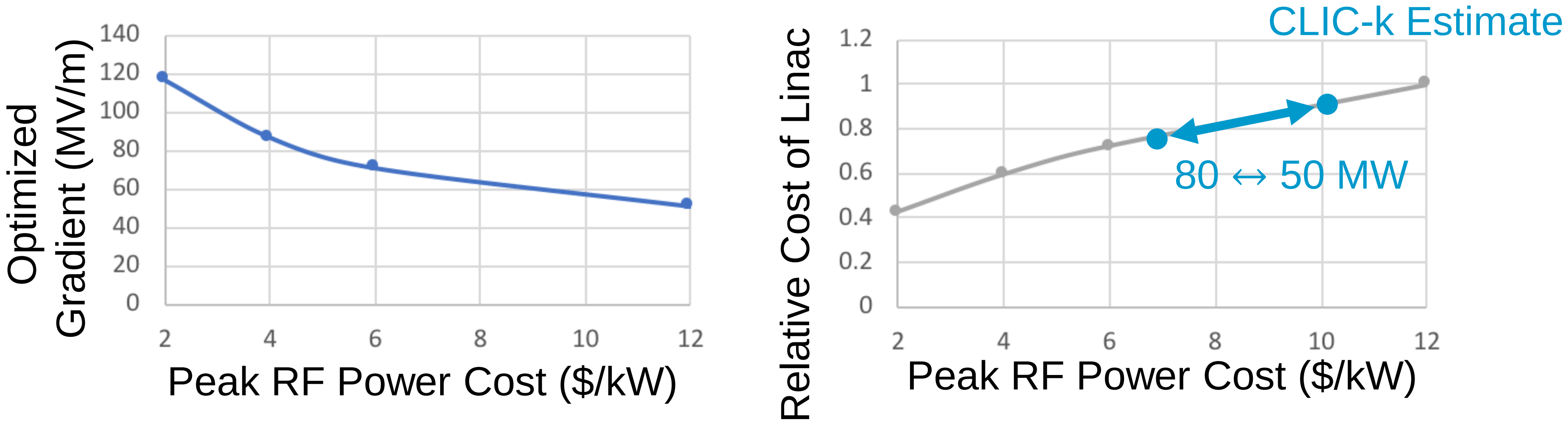
~8.9m Cryomodule

Oriunno, Breidenbach

RF Source R&D Remains a Major Focus Over the Timescale of the Next P5

- Optimizing the cost of NCRF technology a fundamental requirement for its implementation for future facilities
- RF source cost is the key driver for gradient and cost – need to focus R&D on reducing source cost

Gradient/Cost Scaling vs RF Source Cost for 2 TeV CoM



Understand the Impact on Advanced Collider Concept Enabled by the Goals Defined in the DOE GARD RF Decadal Roadmap

https://science.energy.gov/~/media/hep/pdf/Reports/DOE_HEP_GARD_RF_Research_Roadmap_Report.pdf

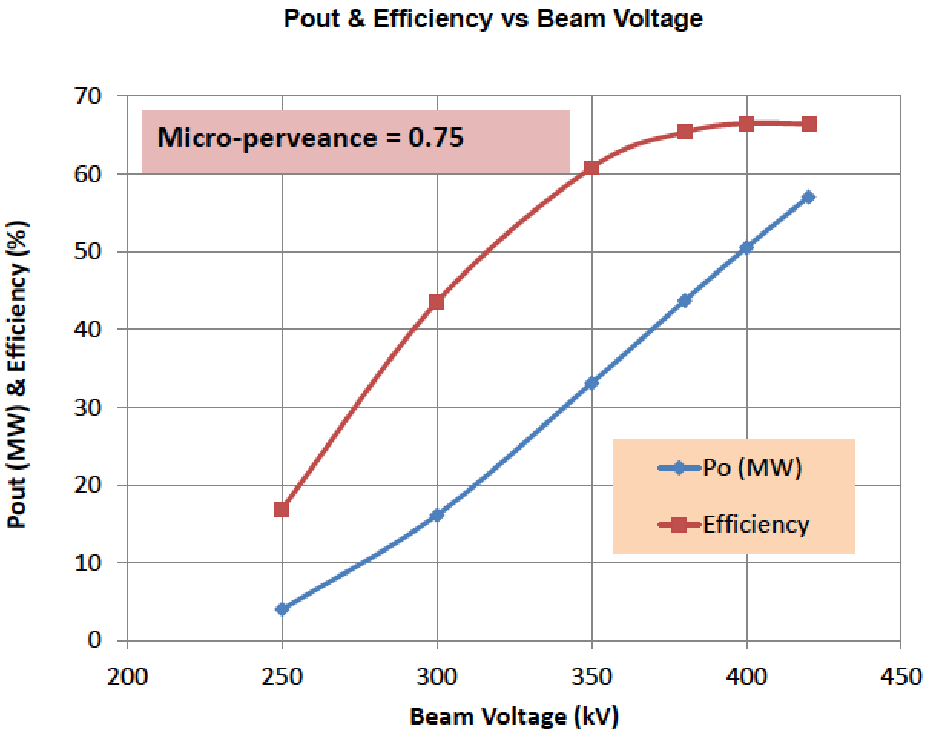
CERN/HEIKA Collaboration

Timeline to demos?

Interest in extending work to C-band?

PM design?

Details of costing for rf source?



CPI/CERN Collaboration on 50 MW X-band – CLIC Meeting 2019

RF Power Requirements – Lower Gradient Starting Point?

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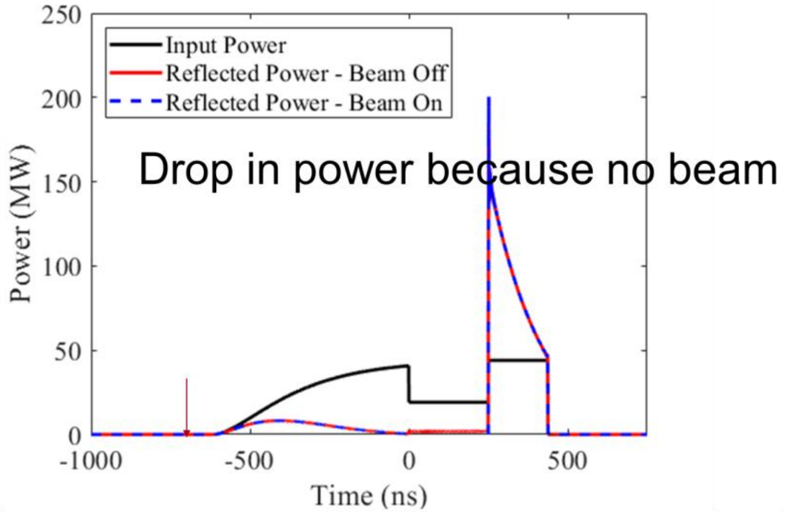
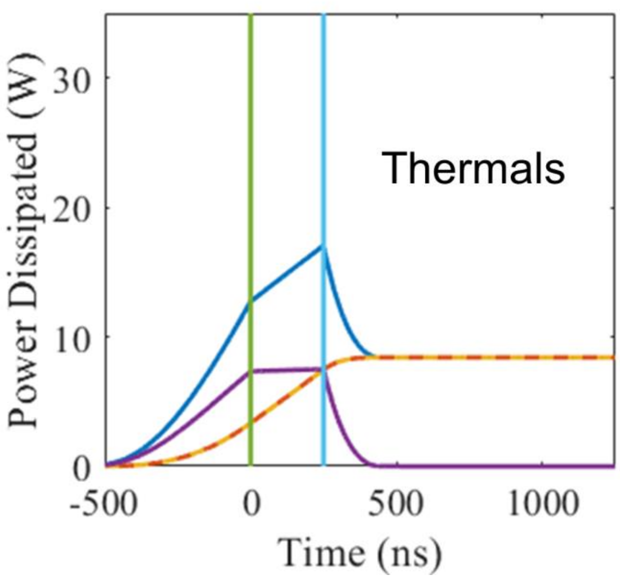
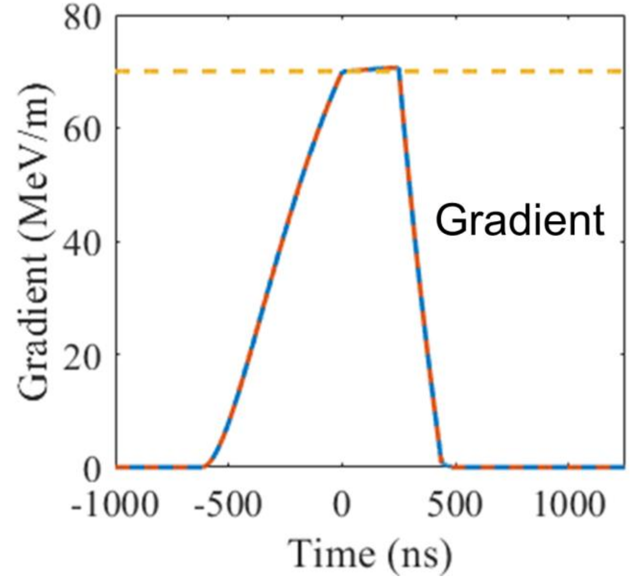
- 70 MeV/m 250 ns Flattop (extendible to 500 ns)
- ~1 microsecond rf pulse, ~44 MW/m (with beam loading)
  - Conservative 2.3X enhancement from cryo
- No pulse compression
- Ramp power to reduce reflected power
- Flip phase at output to reduce thermals
- Operation at full gradient 117 MeV/m requires 80 MW/m (45 MW/m to gradient, 35 MW/m to beam)







Summary of Parameters for 1 GeV Cryomodule Based on C-Band 5.712 GHz, a/λ=0.05, 2π/3 Structure

SLAC

Key Assumption: 120 Hz

Temperature (K)	77
Cryomodule Length (m)	9
50 MW Klystrons	8
Gradient (MeV/m)	117
Pulse Length (μs)	0.25-0.5
Cryogenic Load @ 77K (kW/m)	<2
Electrical Load Cryo-Cooler (kW/m)	<20

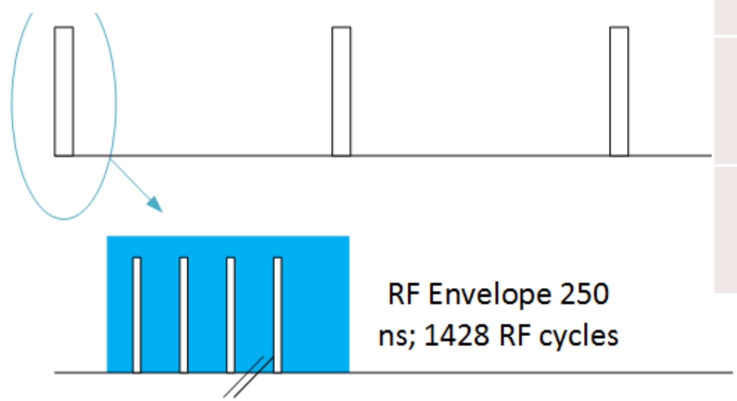
Single Bunch

Parameter (500 GeV CoM)	Units	Value
Reliquification Plant Cost	M$/MW	18
Single Beam Power	MW	4
Total Beam Power	MW	8
Total RF Power	MW	15
Heat Load at Cryogenic Temperature	MW	5.4
Electrical Power for RF	MW	22.8
Electrical Power for Cryo-Cooler	MW	51.6

Trains repeat at 120 Hz

Pulse Format

130 1 nC bunches spaced by
11 RF periods



Summary of Parameters for 250 GeV Conceptual Design Based on C-Band 5.712 GHz, a/λ=0.05, 2π/3 Structure

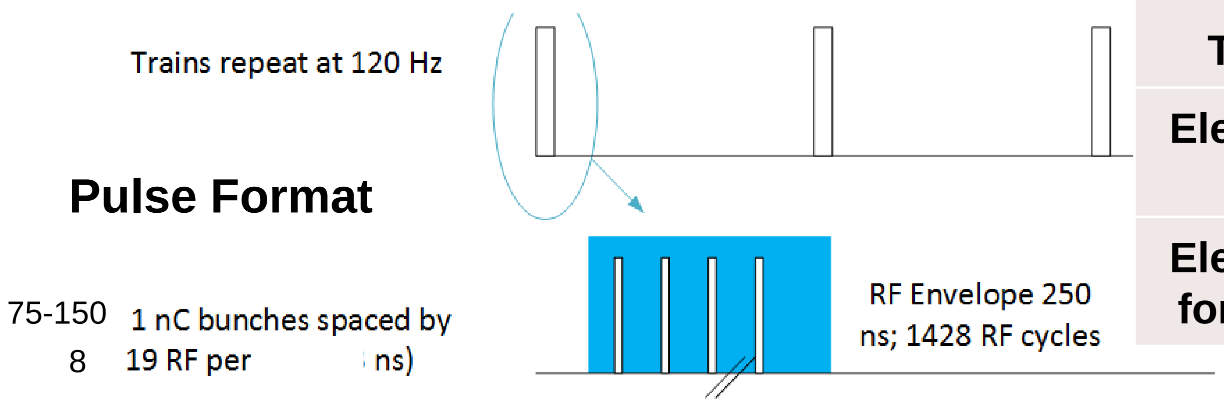
SLAC

Key Assumption: RF source - $2/peak-kW

Temperature (K)	77
Beam Loading (%)	65
Gradient (MeV/m)	117
Pulse Length (μs)	0.25-0.5
Cryogenic Load @ 77K (MW)	2.7
Electrical Load (MW)	37

Parameter (250 GeV CoM)	Units	Value
Reliquification Plant Cost	M$/MW	18
Single Beam Power (1 TeV linac)	MW	2.5
Total Beam Power	MW	5
Total RF Power	MW	7.6
Heat Load at Cryogenic Temperature	MW	2.7
Electrical Power for RF	MW	11.4
Electrical Power for Cryo-Cooler	MW	25.6

Pulse Format



Summary of Parameters for 2 TeV Conceptual Design Based on C-Band 5.712 GHz, a/λ=0.05, 2π/3 Structure

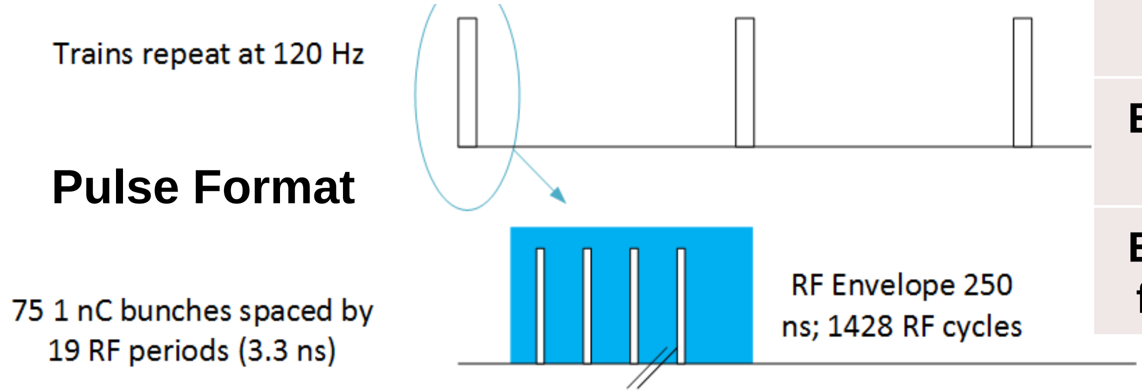
SLAC

Key Assumption: RF source - $2/peak-kW

Temperature (K)	77
Beam Loading (%)	42.5
Gradient (MeV/m)	117
Pulse Length (μs)	0.25
Cryogenic Load @ 77K (MW)	22
Electrical Load (MW)	170

Need Pulse Compressor

Pulse Format



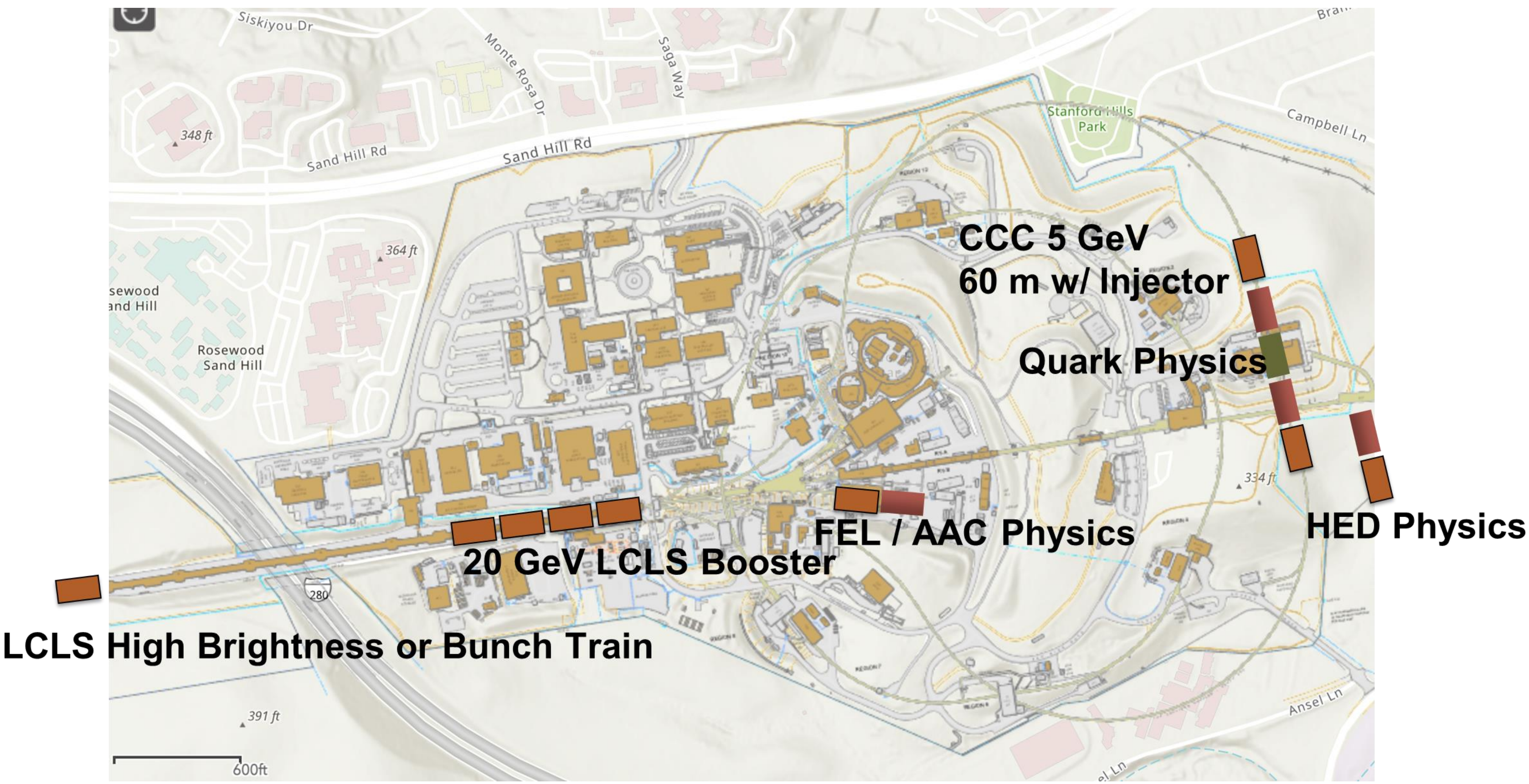
Parameter (2 TeV CoM)	Units	Value
Reliquification Plant Cost	M$/MW	18
Single Beam Power (1 TeV linac)	MW	9
Total Beam Power	MW	18
Total RF Power	MW	40
Heat Load at Cryogenic Temperature	MW	22
Electrical Power for RF	MW	60
Electrical Power for Cryo-Cooler	MW	110

Proposed Next Steps for C^3

- Goals:
  - Develop and verify performance of GeV cryomodules
  - Develop and integrate advanced RF sources
  - Beam line elements – beam monitoring and precision transport
- Option: Upgrade ESB to house and develop C^3 technology
  - Applications to motivate this? UCXFEL is the prefect scale to develop the technology
  - Added benefit with cryo-gun development
- Mid-term R&D: Sources, damping, cryogenic quads, fabrication…

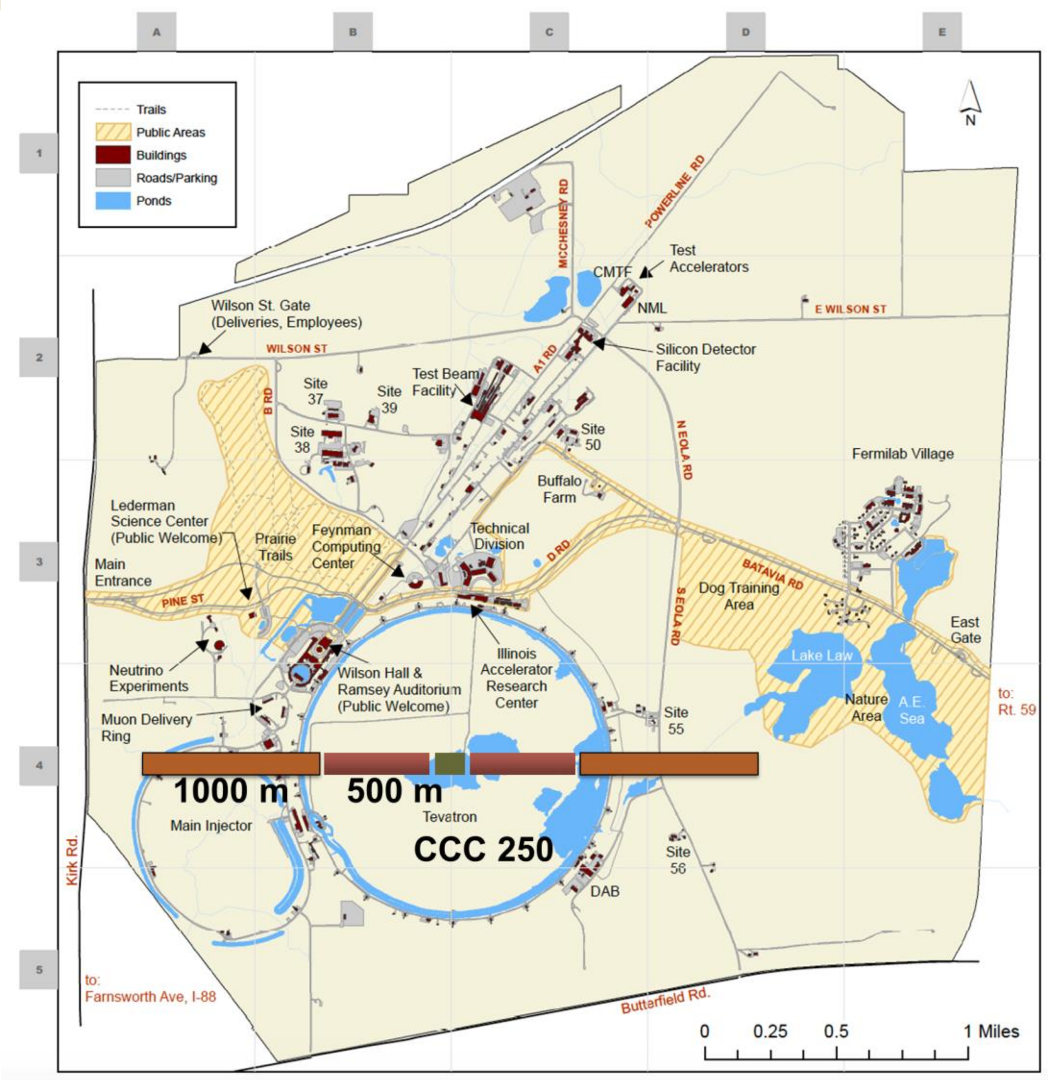
CCC to Scale

String test fits on the scale of existing research infrastructure



CCC to Scale

250 GeV main linac at Fermilab



Questions?

NCRF Accelerator System Cost Model for Innovative Standing-Wave Accelerator Topologies

- Total accelerator system cost (C) can be expressed as:
  - **$C \approx xE/G + yE(I + G/R_s)$ + aux systems cost (e.g. injector)**

    Length (xE/G) — ***Beam Power*** (yEI) — ***Power Dissipated Structure*** (yEG/R_s)

  - Where
    - E – beam energy (eV)
    - x – accelerator cost/length ($/m) (tunnel cost + structure cost)
    - G – accelerating gradient (V/m)
    - y – RF system cost/peak power ($/kW (include power supply, RF source,...)
    - R_s – shunt impedance (Ω)
    - I – beam current (A)
  - Cost Optimized Gradient
    - $G=(R_s\ x/y)^{0.5}$

**Will hold these* <u>*assumptions*</u> *chosen to evaluate relationship between parameters constant unless specified*

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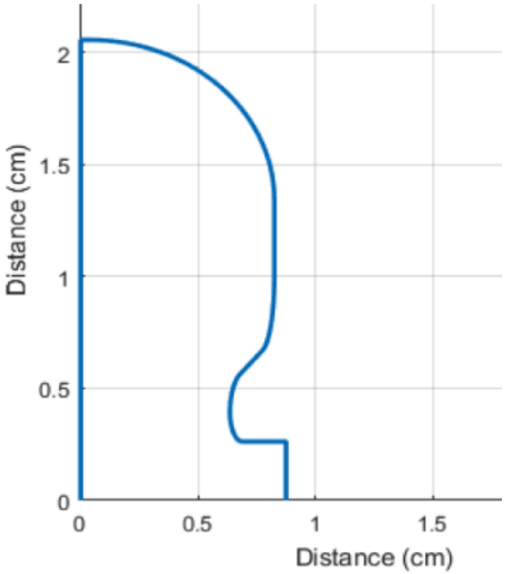
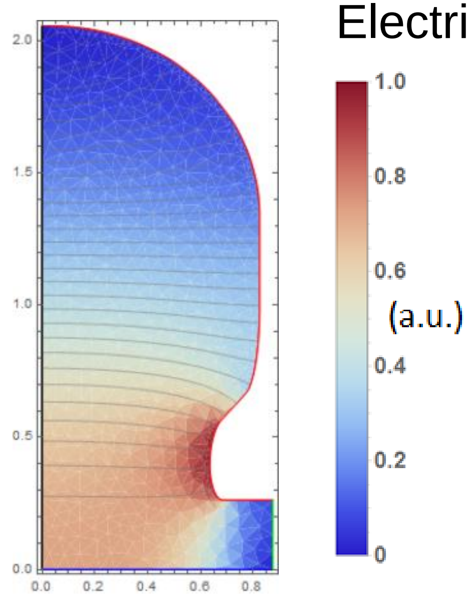


Electric Field



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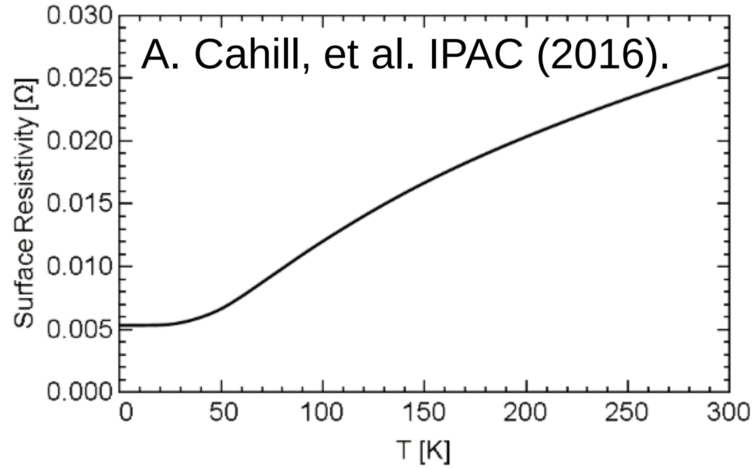

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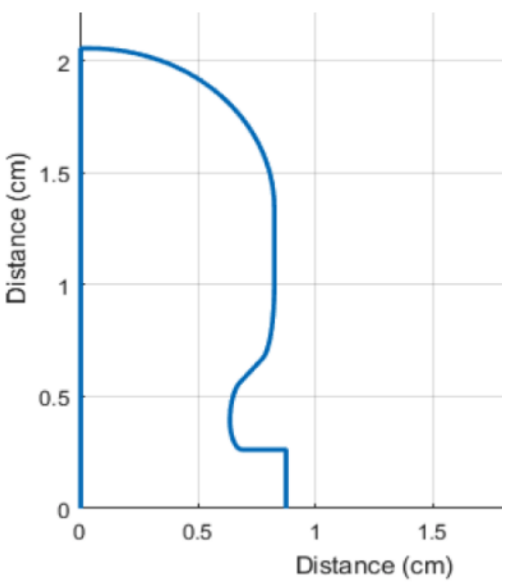

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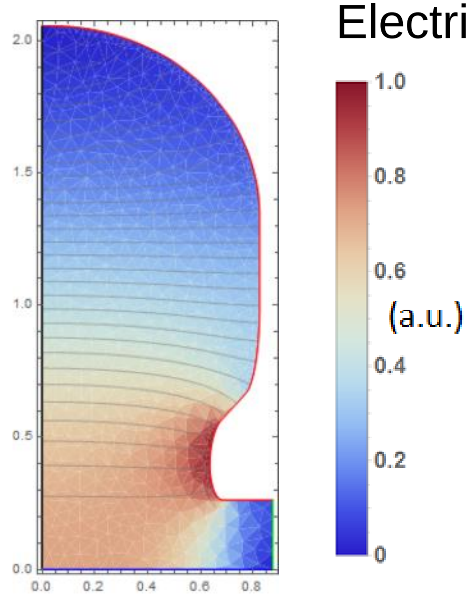

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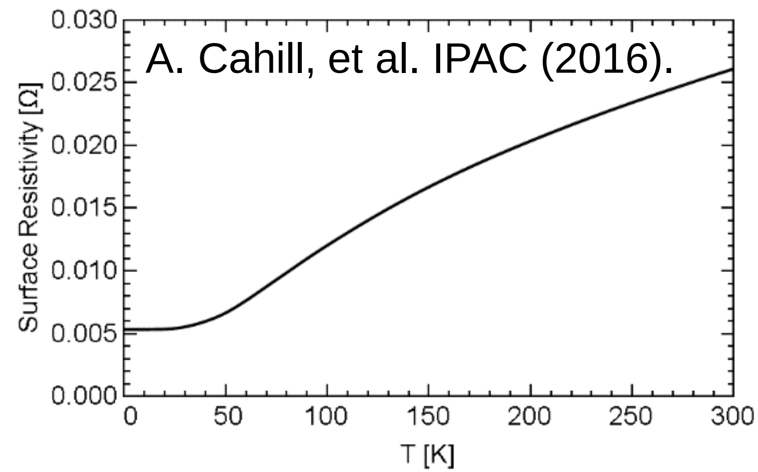

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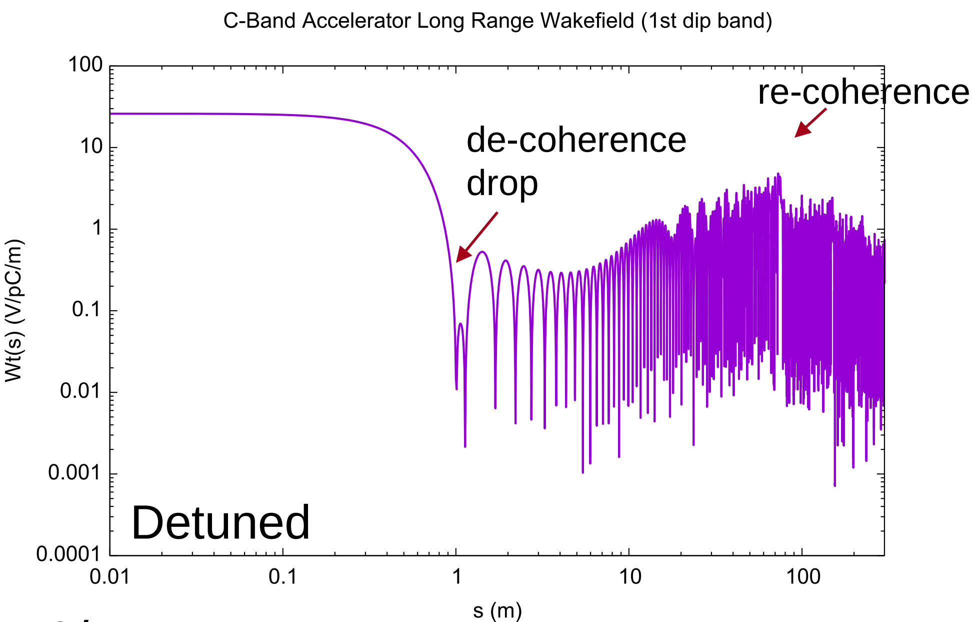

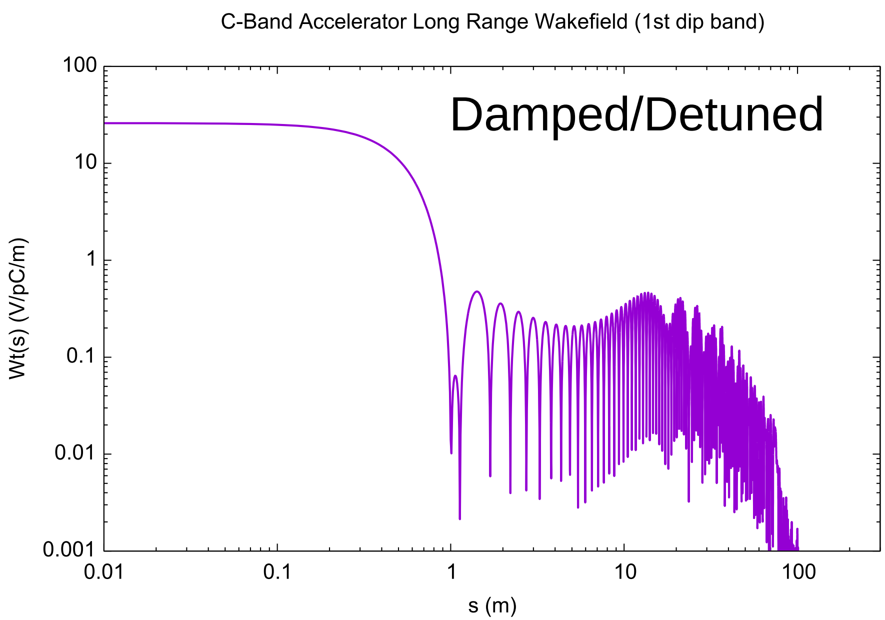

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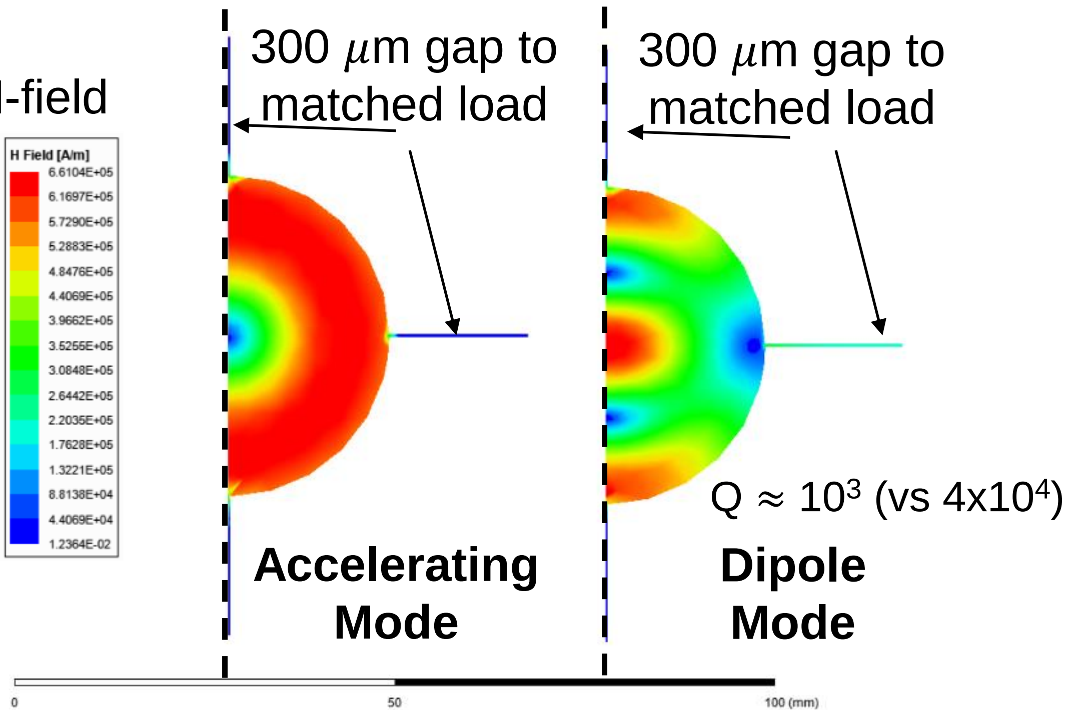
H-field

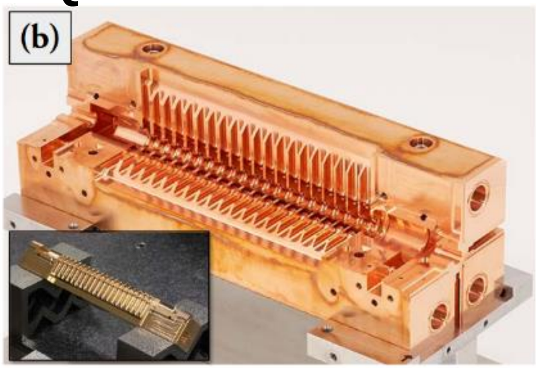


Accelerating Mode

Dipole Mode

Design of Detuned Cavities

Quadrant Structure



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