C³ : An Advanced Concept for a e+e- Linear Collider

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Thanks to Many for Contributions / Discussions

August 17, 2021

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Acknowledgements

Snowmass LOI

C^3: An Advanced Concept for a High Energy e^+e^- Linear Collider

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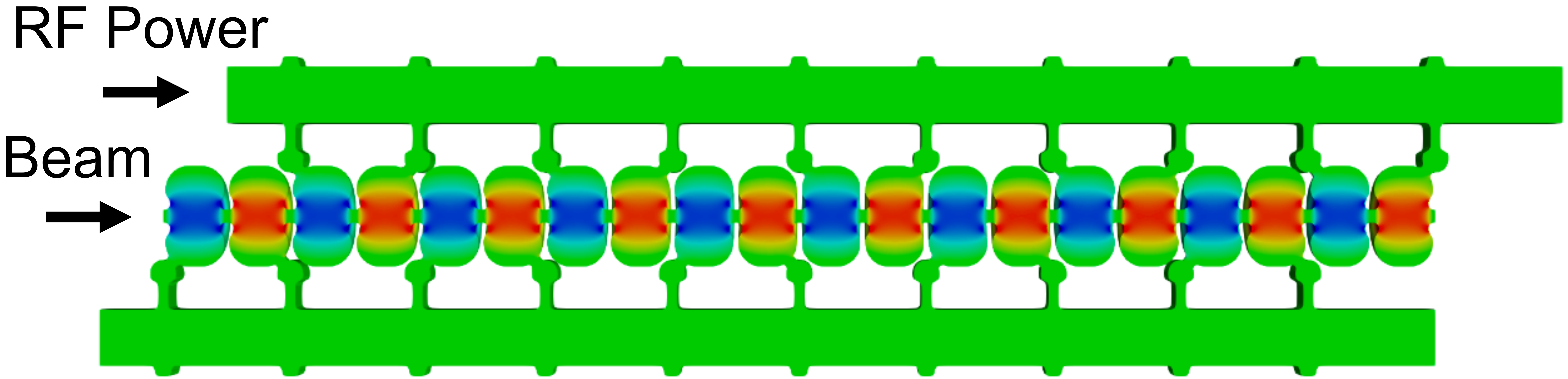
Breakthrough in the Performance of RF Accelerators

- 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

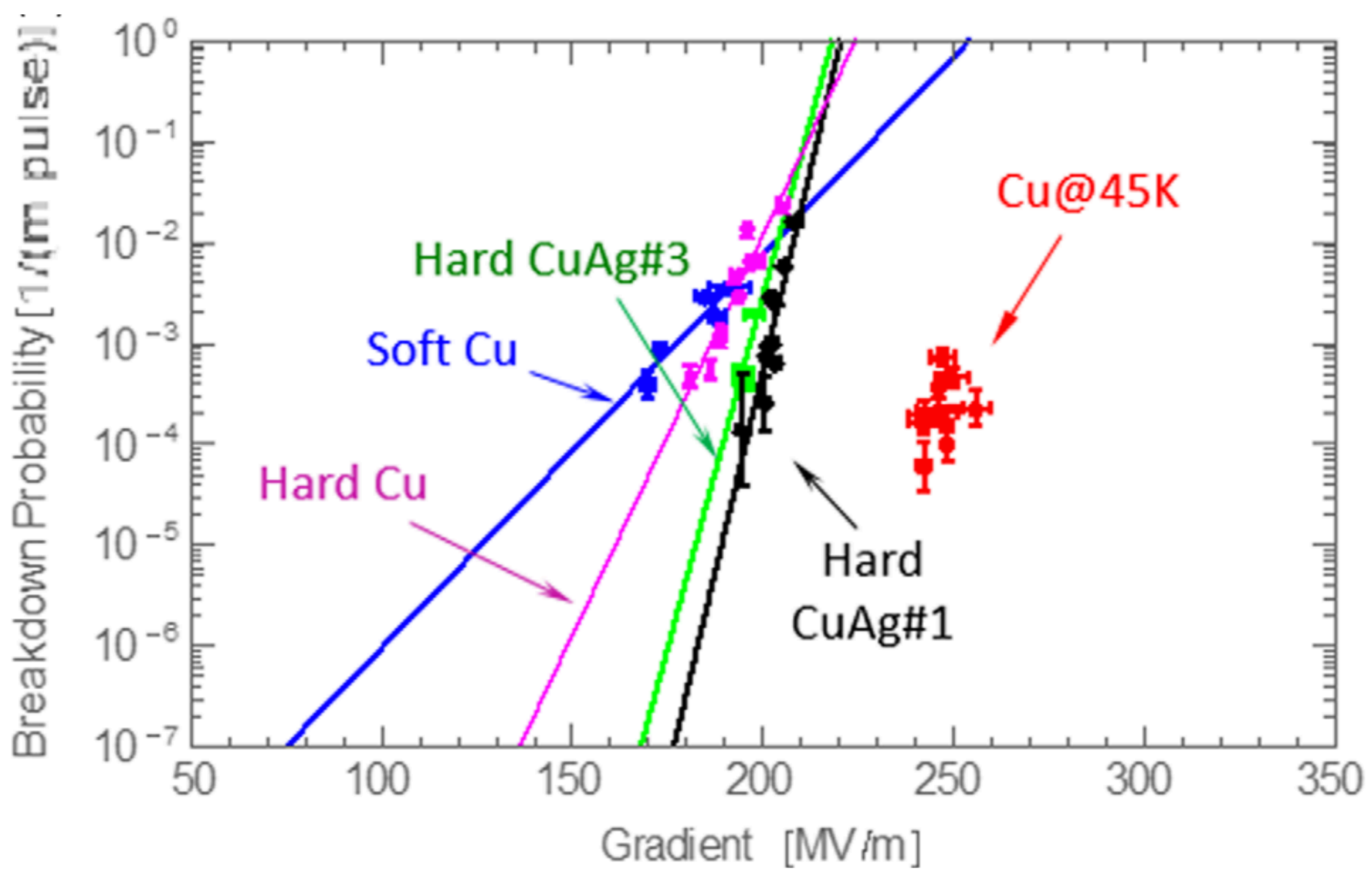
Tantawi, Sami, et al. "Design and demonstration of a distributed-coupling linear accelerator structure." *Physical Review Accelerators and Beams* 23.9 (2020): 092001.

Cryogenic Operation for High Accelerating Gradient

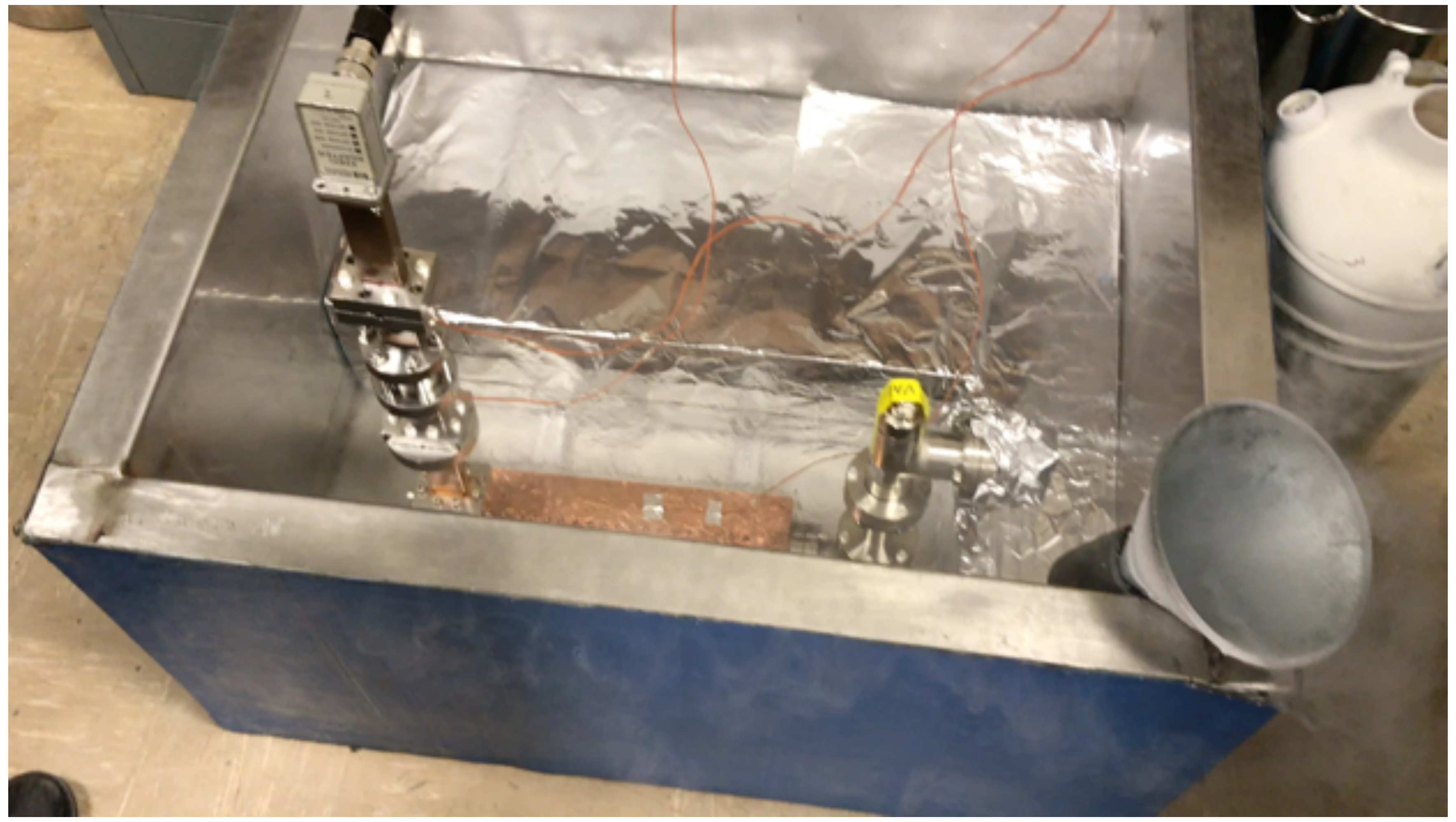
- Cryogenic temperature elevates performance in accelerating gradient
- Material strength is key factor
- Operation at 77 K with liquid nitrogen is simple and practical
- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency

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

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



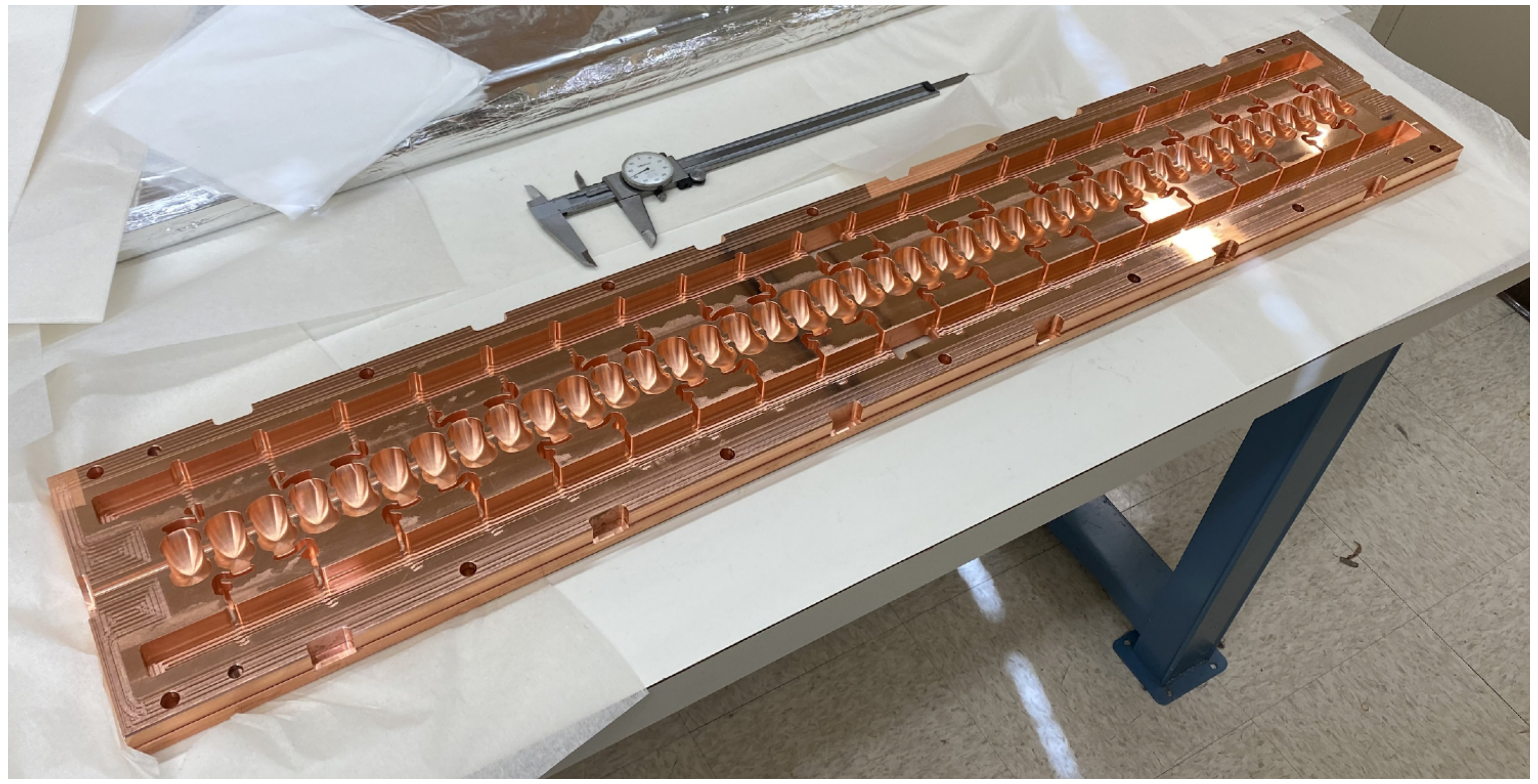
Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.



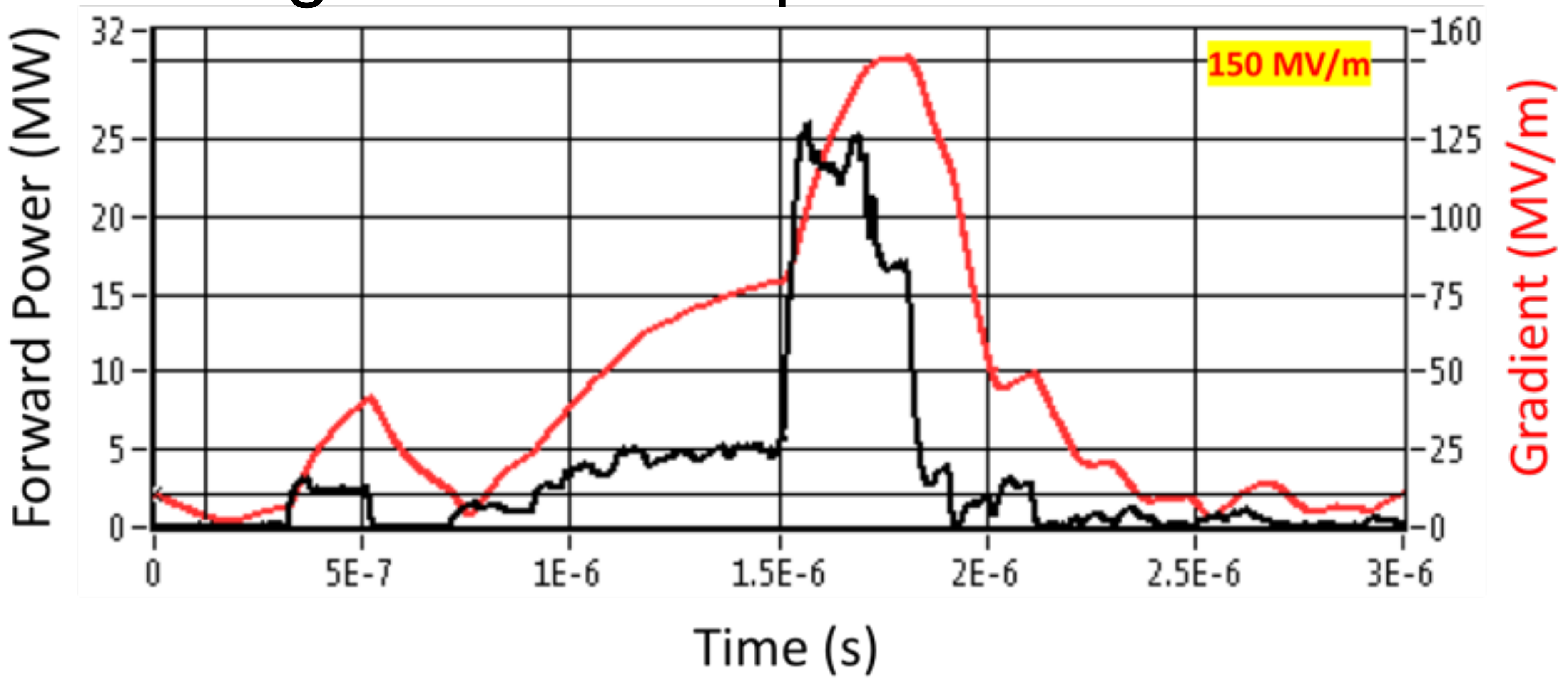
C^3 - Cool Copper Collider

- SLAC technology for normal conducting accelerator at cryogenic temperature
- Aim to achieve high gradient (110 MeV/m real footprint) on short timescale
- Potential for high brightness polarized sources to eliminate damping rings
- Scalable technology optimizing for multi-TeV operation

First C^3 structure at SLAC



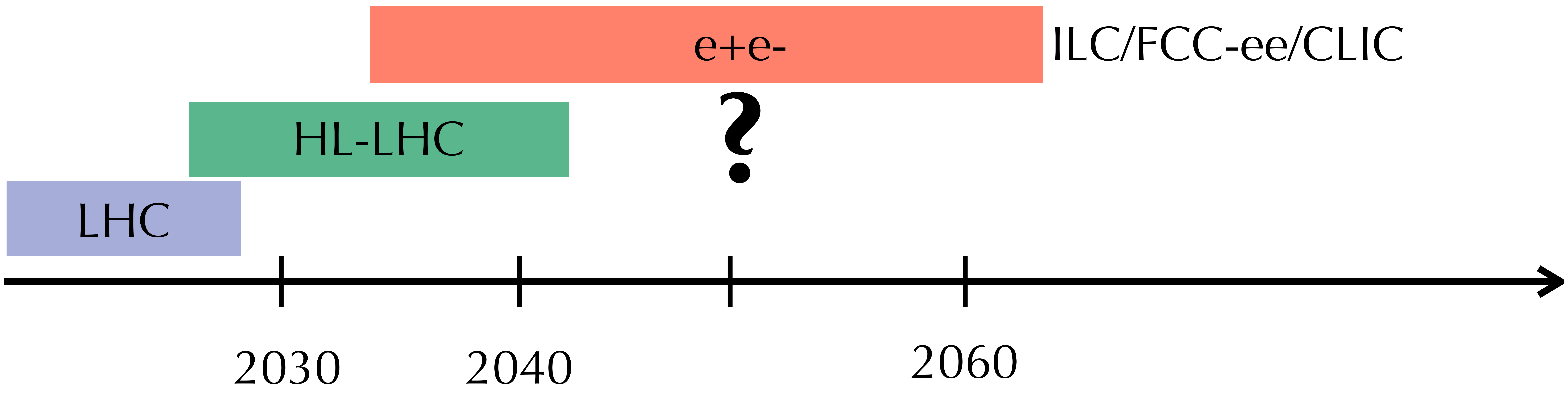
High Gradient Operation at 150 MV/m



X-band Prototype

Timeline:

- 2 years - meter scale, wakefield
- damping, cryogenics
- 4 years - modular GeV units
- Target operation in parallel w/ HL-LHC at 250 GeV CoM



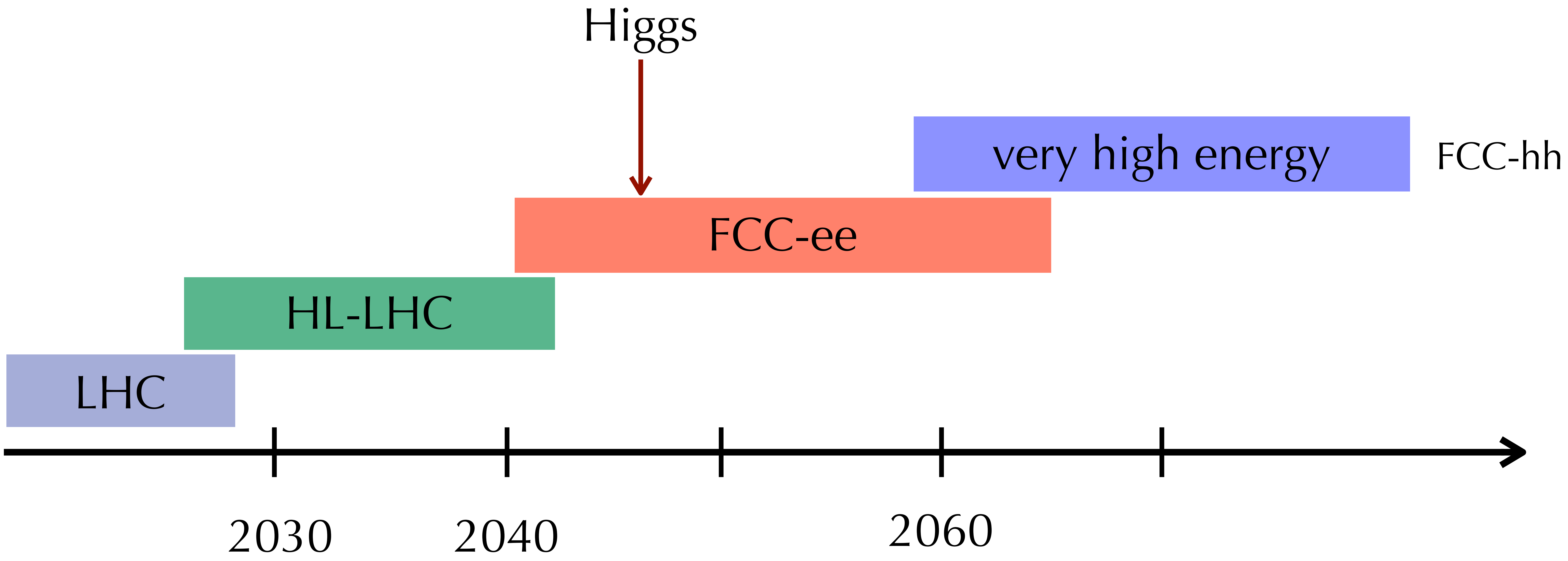
In the study of the Higgs boson properties and in the quest of new physics signs there is a complementarity between hadronic/leptonic colliders (depending on the centre-of-mass of energy) to exploit

- Direct production of new - heavy ~ O(2 TeV) - particles
- If new particles are too heavy to be produced at the HL-LHC, the resulting modifications to the Higgs couplings could be sizable enough to be detected with precision Higgs coupling measurements.

Wish list beyond HL-LHC:

1. **Establish Yukawa couplings to light flavor —> needs precision**
2. **Establish self-coupling —> needs high energy**

FCC-ee scenario:

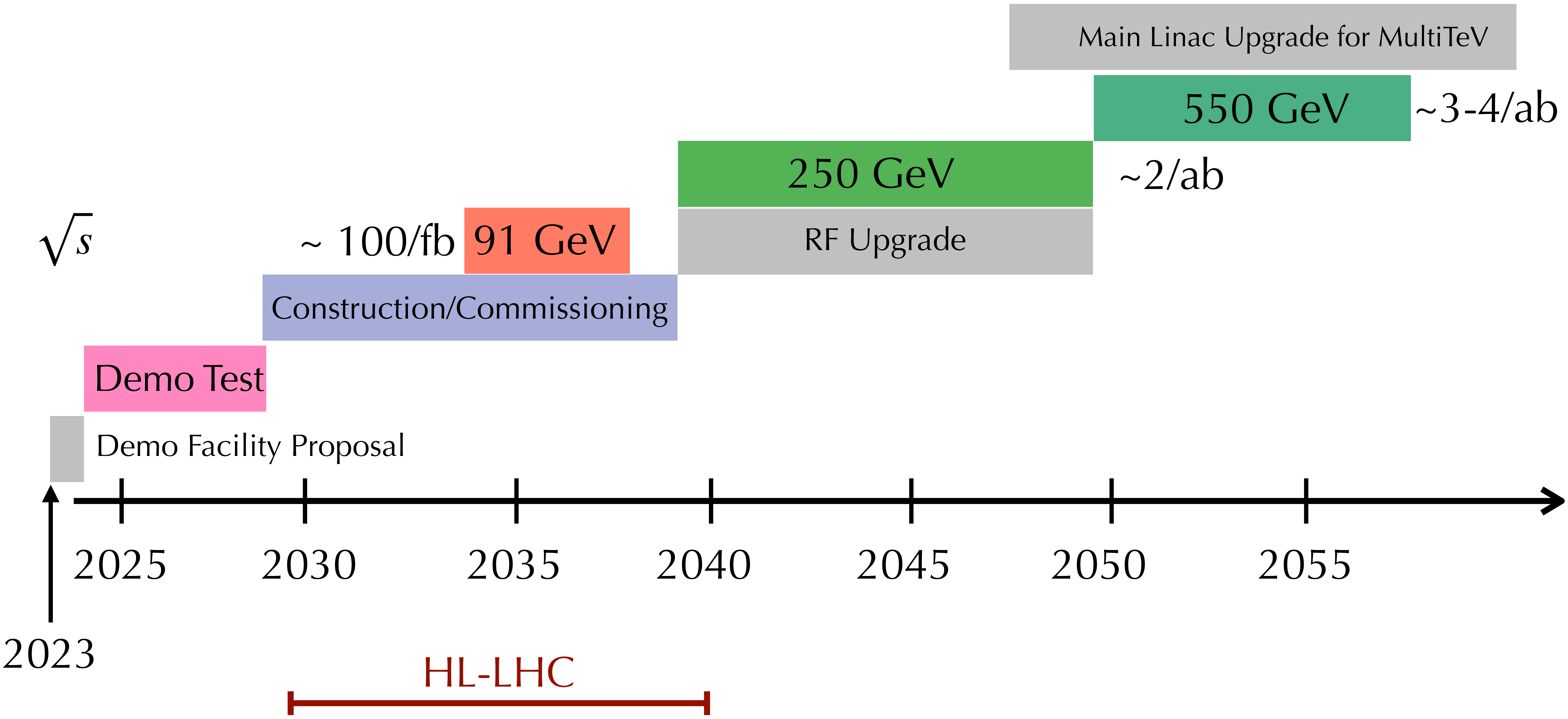


H couplings to few %

H couplings to %

H couplings to ‰
H self-coupling to %

C³ evolution: best timeline for the physics



e+e- colliders

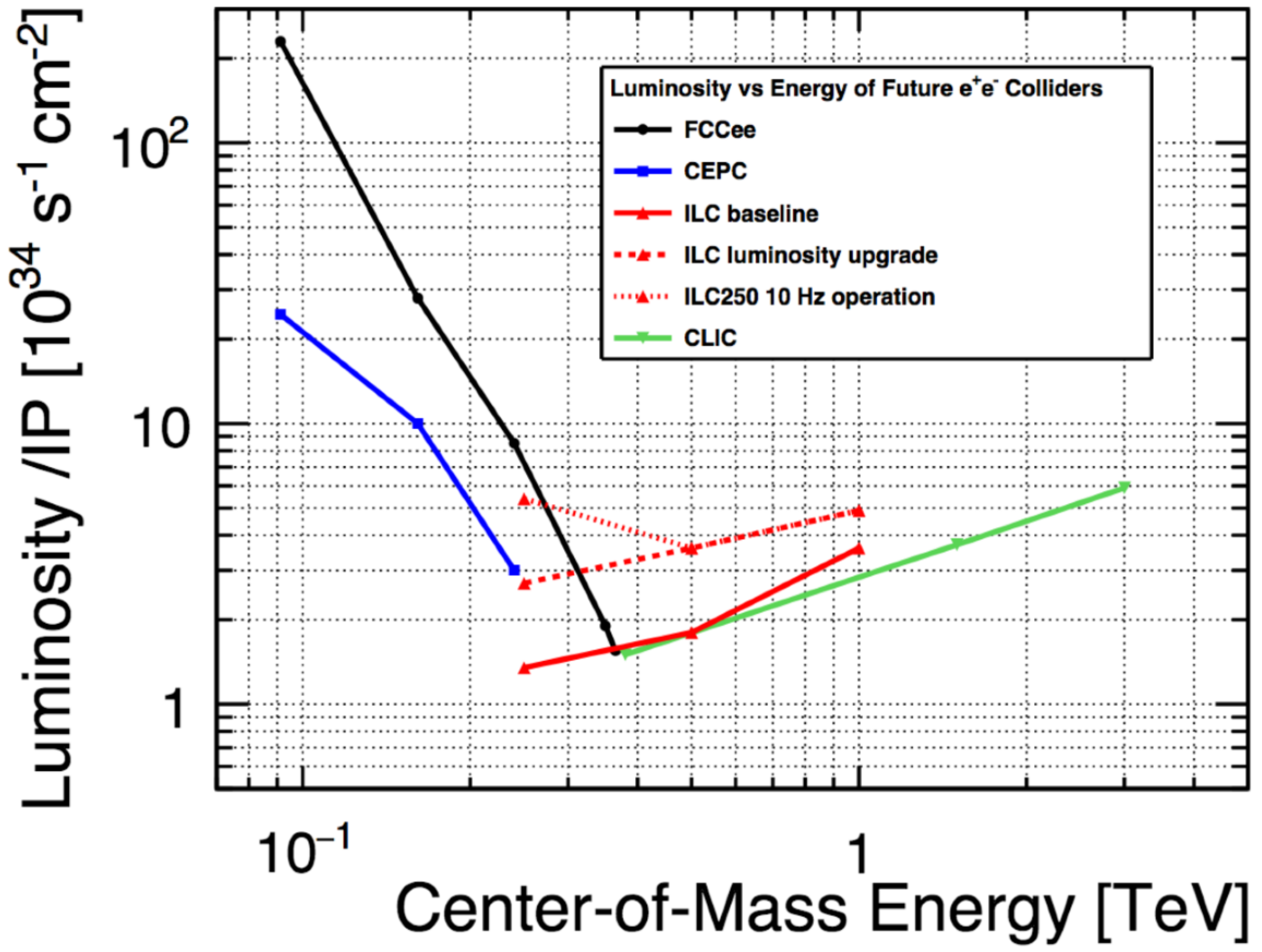
- The e+e- beams is benign environment compared to HL-LHC
  - Detectors with minimal material in the tracking volume
  - While it poses its own set of background issues that must be overcome the payout will be physics studies with unprecedented precision

- **Linear** colliders
  - Lower luminosity than circular below 300-400 GeV, but only possible way towards high-energy with leptons
  - The time structure and low radiation background provides an environment which allows us to consider **very light, low power detector structures**

- **Circular** colliders
  - highest luminosity at Z pole/WW/ZH, but strongly limited by synchrotron radiation above 350– 400 GeV
  - Tracking detectors need to achieve good resolution without power pulsing

Detectors requirements very similar between linear & circular

Collider Differences → Detector Differences



- Linear e^+e^- colliders: ILC, C^3, CLIC
  - Reach higher energies, and can use polarized beams
  - Relatively low radiation / beam induced backgrounds
  - Collisions in bunch trains
    - Power pulse - Turn off detector b/w trains
    - **Significant power saving → easier to cool detectors**

- Circular e^+e^- colliders: FCC-ee, CEPC
  - Highest luminosity collider at Z / WW / Zh, energy limited above by synchrotron radiation above
  - No power pulsing → **detectors need active cooling → more material in detector**
  - Beam continues to circulate after collision → **Limits magnetic field in detectors**

How to get C³ underway as a project?

- Timeline that is compatible and competitive on the global scale
- The accelerator is built to deliver the Higgs (250 GeV) and provide an upgrade path
  - Explore a commissioning run when the main linac 1/2 complete
    - Commission injector complex / BDS
    - Run at m_Z to commission the detector
    - Technology demo for XCC gamma-gamma collider - 30 GeV FEL
    - Deliver physics (accelerator/particle/FEL) early and often – understanding that the #1 goals is to study the Higgs
- Build a foundation for upgrades – main linac is fixed length upgrade gradient later
- Ultimately a structure operating at 120 MeV/m would be used to reach high energy -> lower energy physics targets could be reached with 70-85 MeV/m
  - Reduced peak power (less $), lower risk (power margin, gradient margin, length margin)
- Utilize commercial options at 65 MW/m to launch program
  - R&D on rf sources would have huge cost reduction impact at higher energy
  - CLIC-k study places rf source cost at 7.4 $/kW

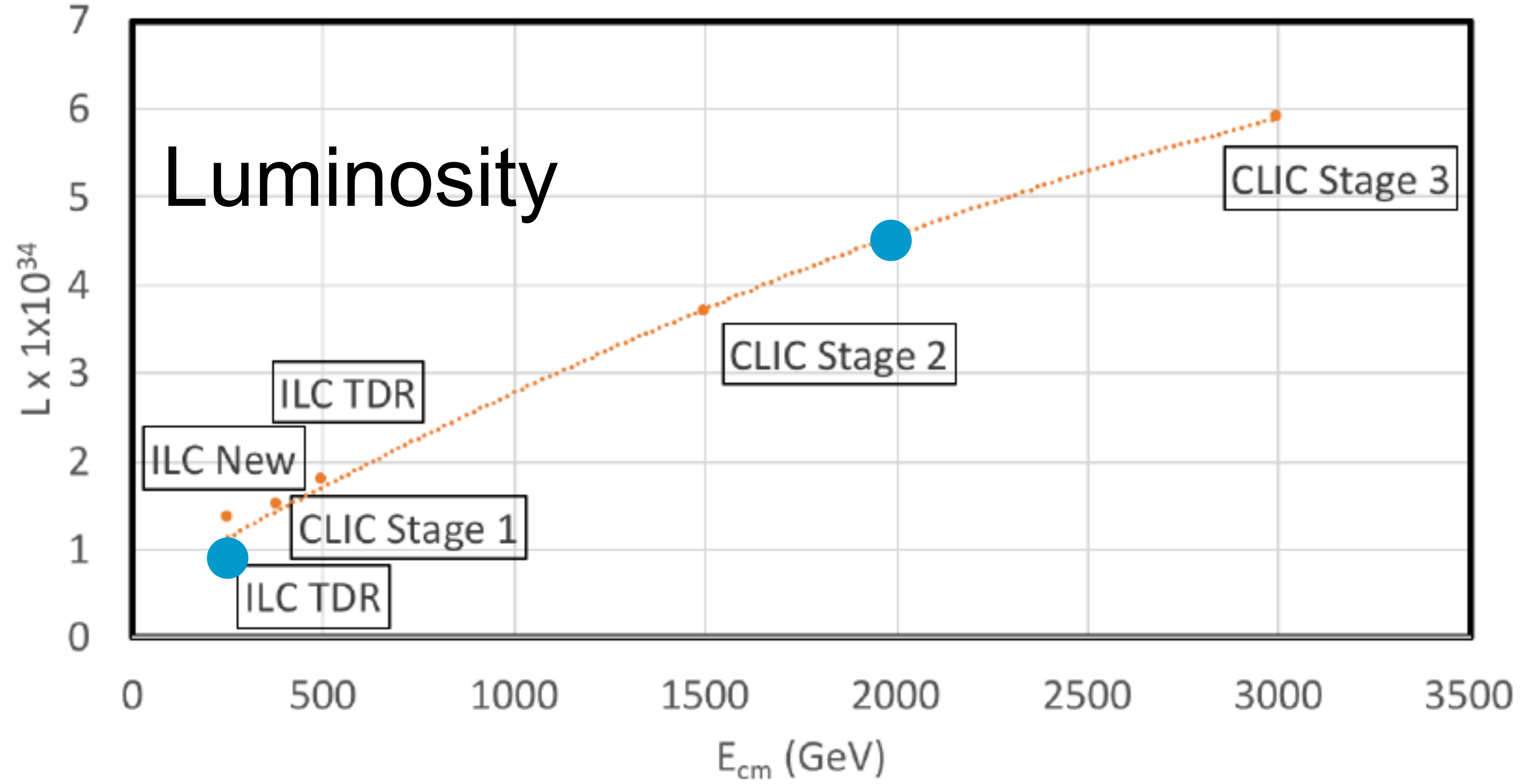
NCRF Accelerator Concept Starting Point for a High Energy e+e- Linear Collider

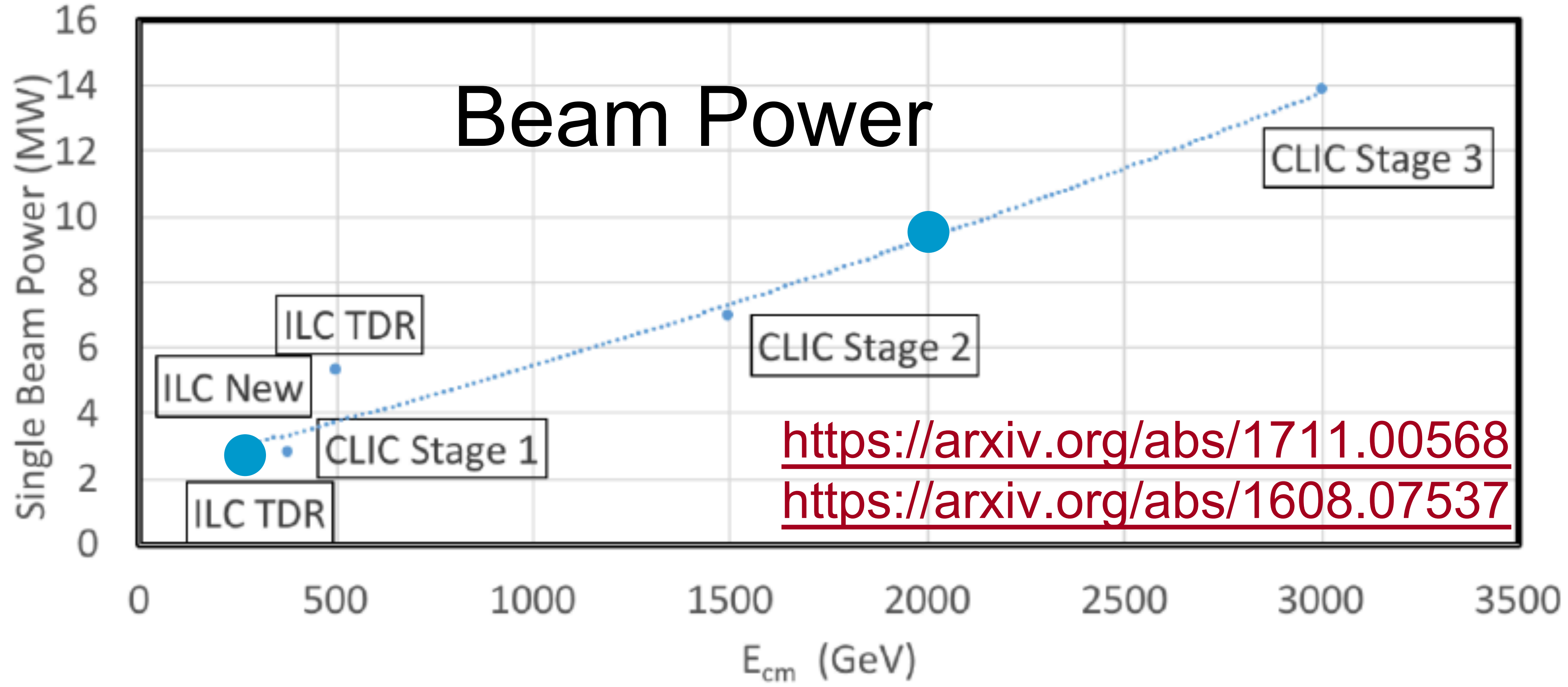
- Using established collider designs to inform initial parameters
- Quantifying impact of wakes requires detailed studies
- Most important terms – aperture, bunch charge (and their scaling with frequency)
- Target design at 2 TeV CoM with 9 MW single beam power (~2 MW at 250 GeV CoM)

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

2 TeV CoM





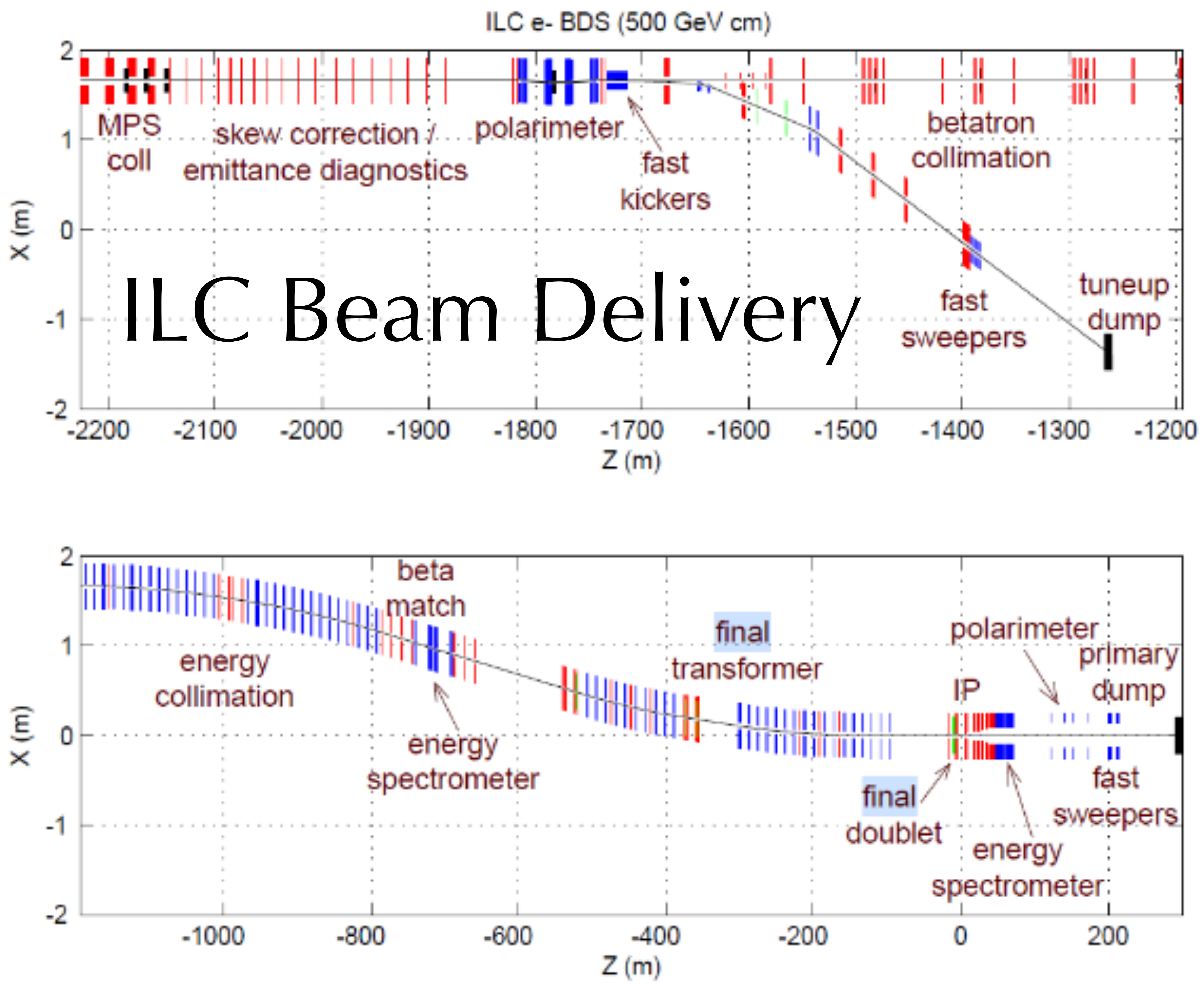
https://arxiv.org/abs/1711.00568
https://arxiv.org/abs/1608.07537

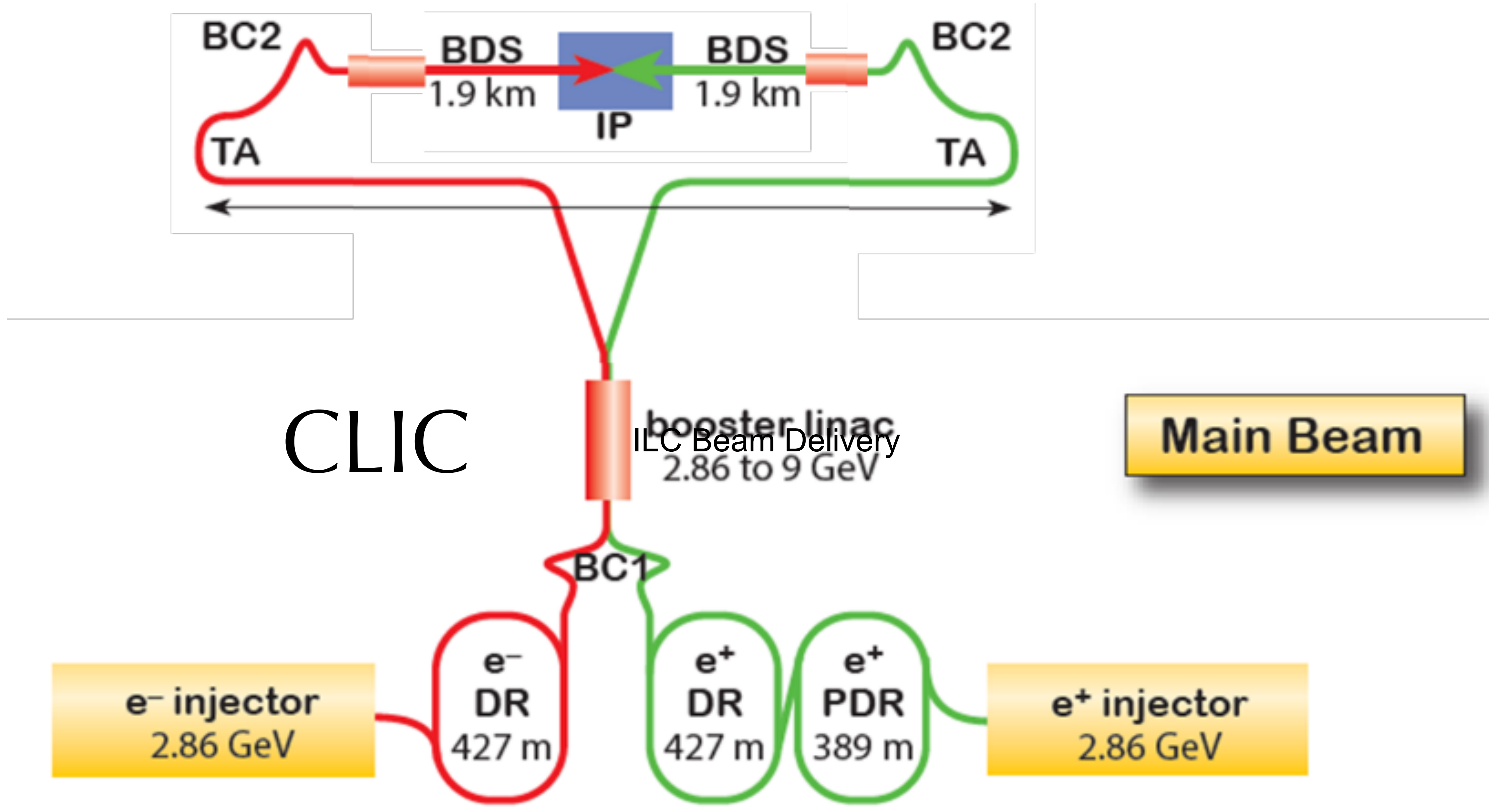
Leverage the Development of Beam Generation and Delivery Systems for C3

- 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 CLIC as baseline
- R&D – Development of high brightness polarized e- sources

Growing an International Collaboration for C3:

- International community can make deep technical contributions to C3
  - CERN/CLIC - damping rings, alignment
  - Japan - rf systems
  - …..

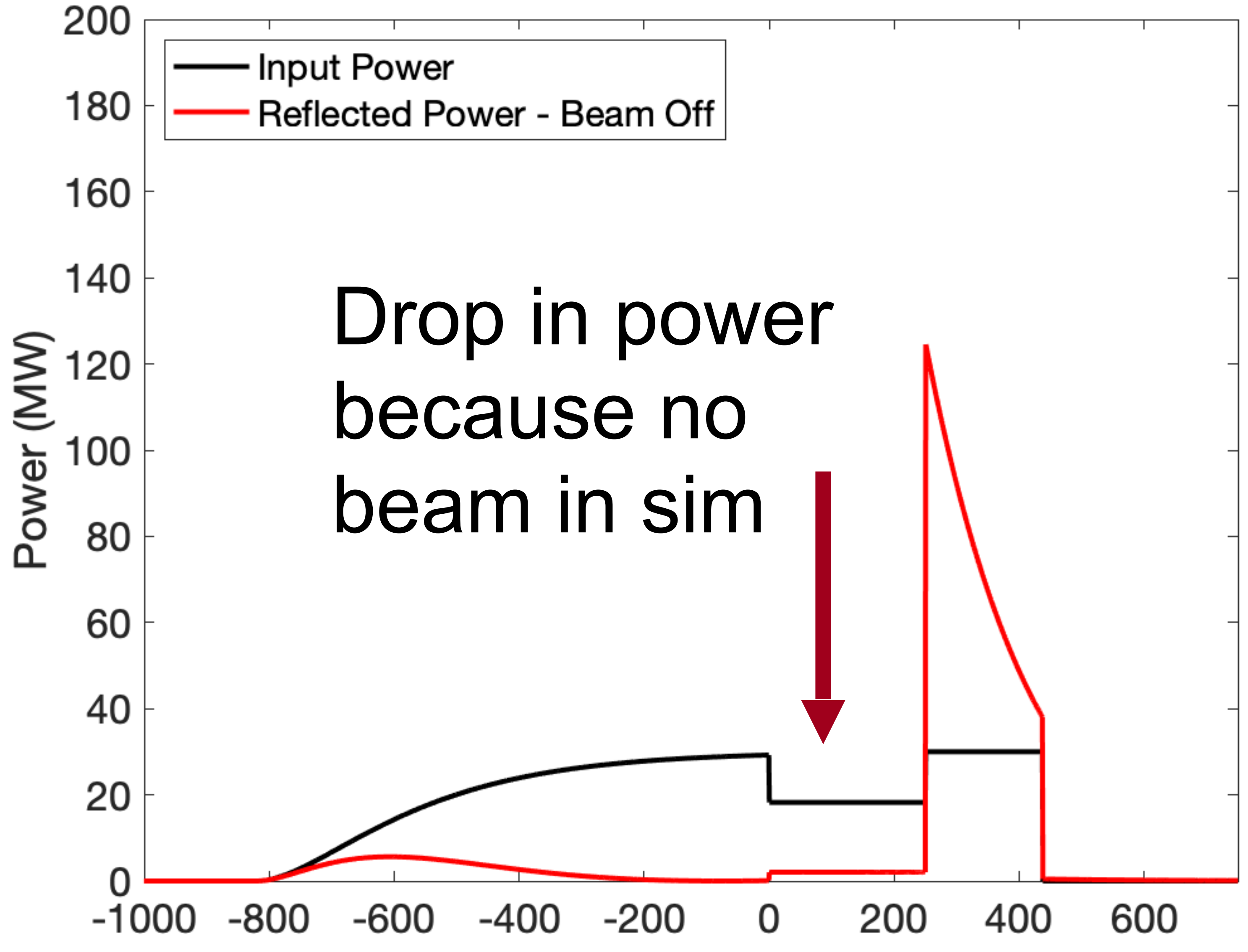


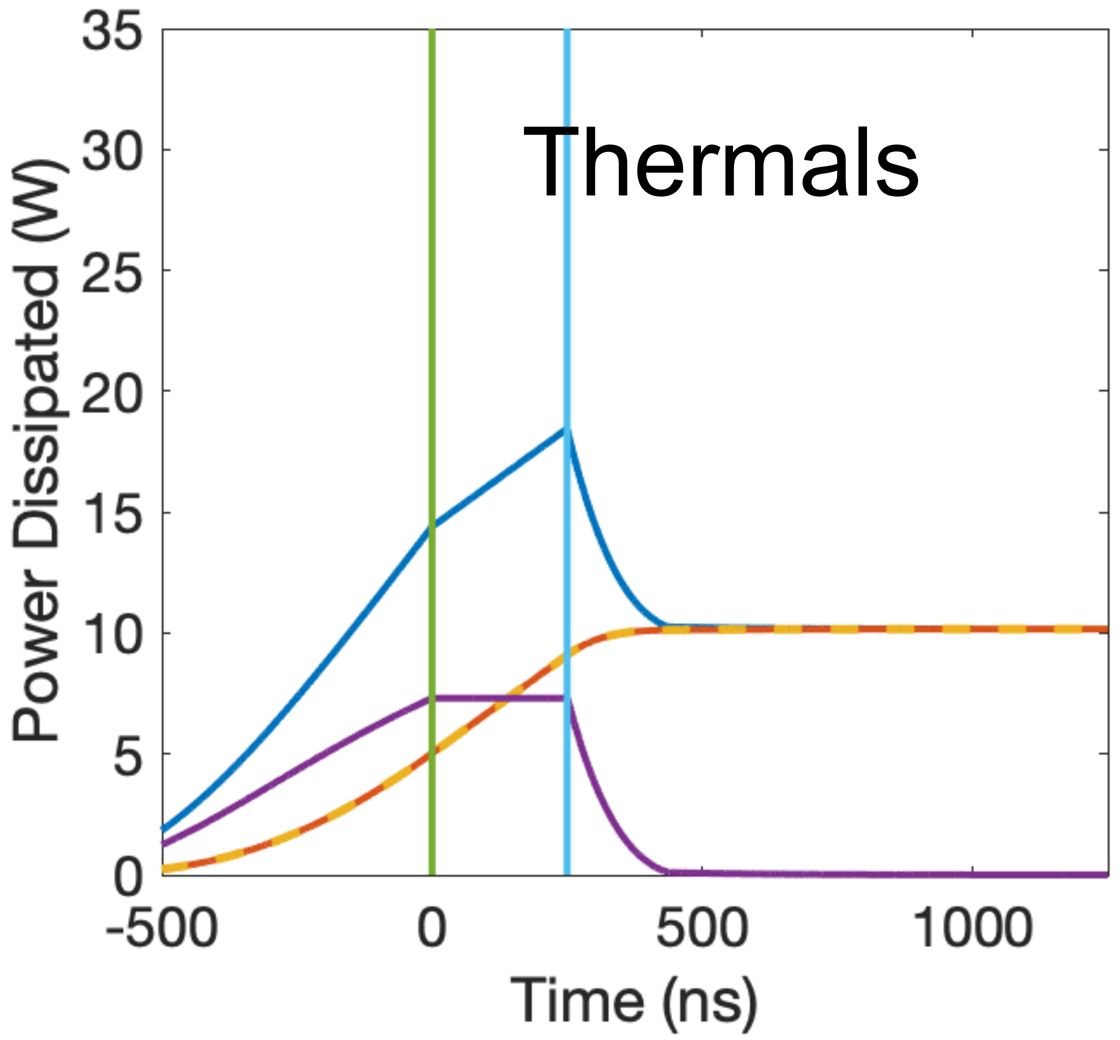


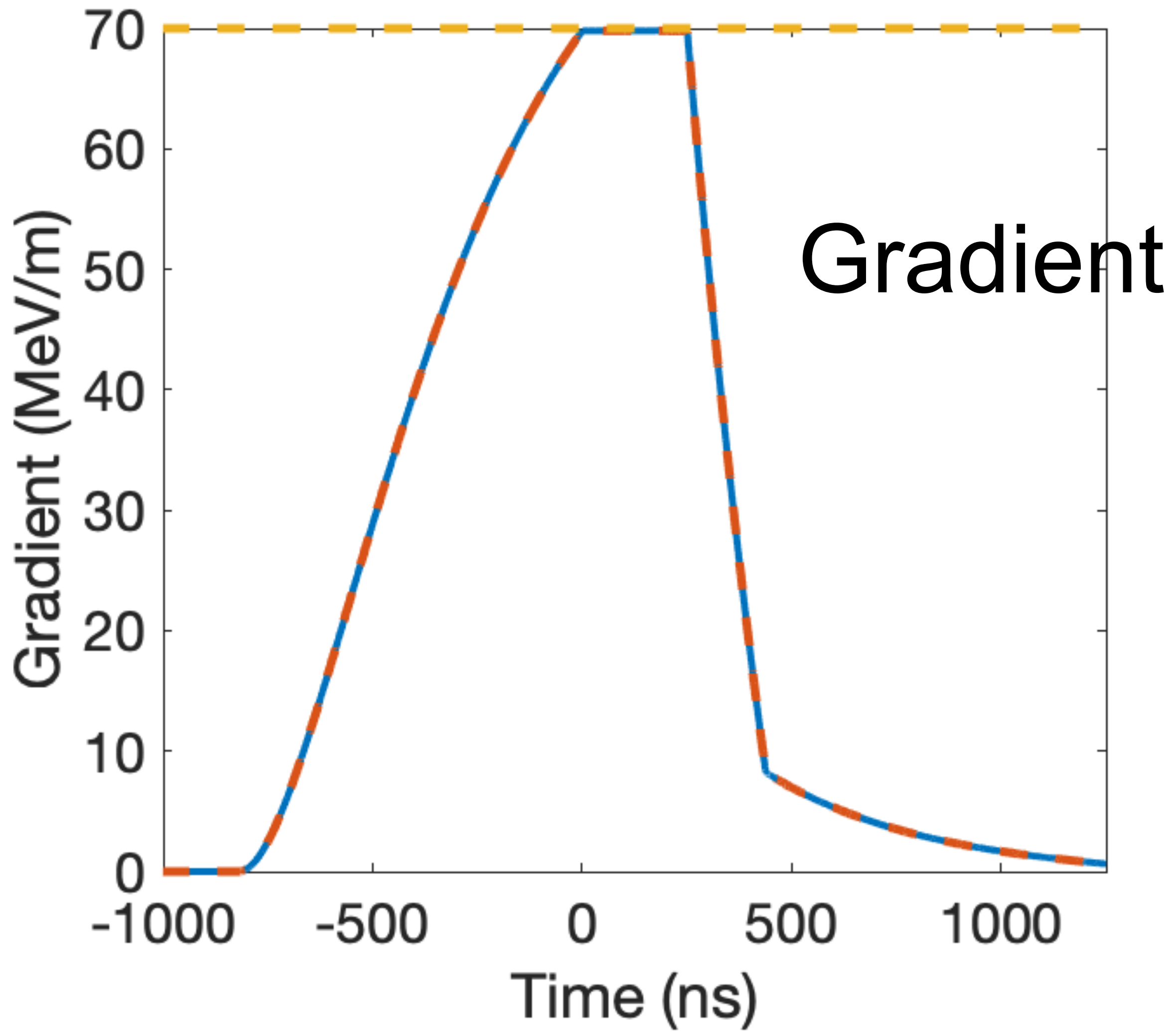
RF Power Requirements

- 70 MeV/m 250 ns Flattop (extendible to 700 ns)
- ~1 microsecond rf pulse, ~30 MW/m
  - Conservative 2.3X enhancement from cryo
- No pulse compression
- Ramp power to reduce reflected power
- Flip phase at output to reduce thermals

- One 65 MW klystron every two meters -> Matches CLIC-k rf module power



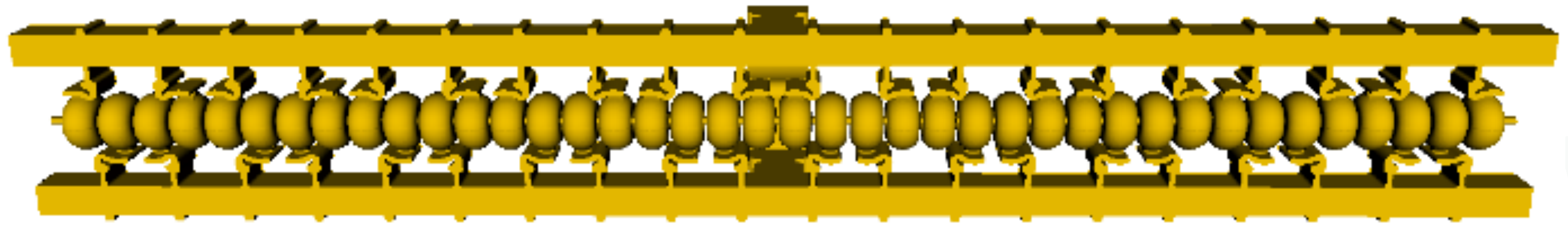


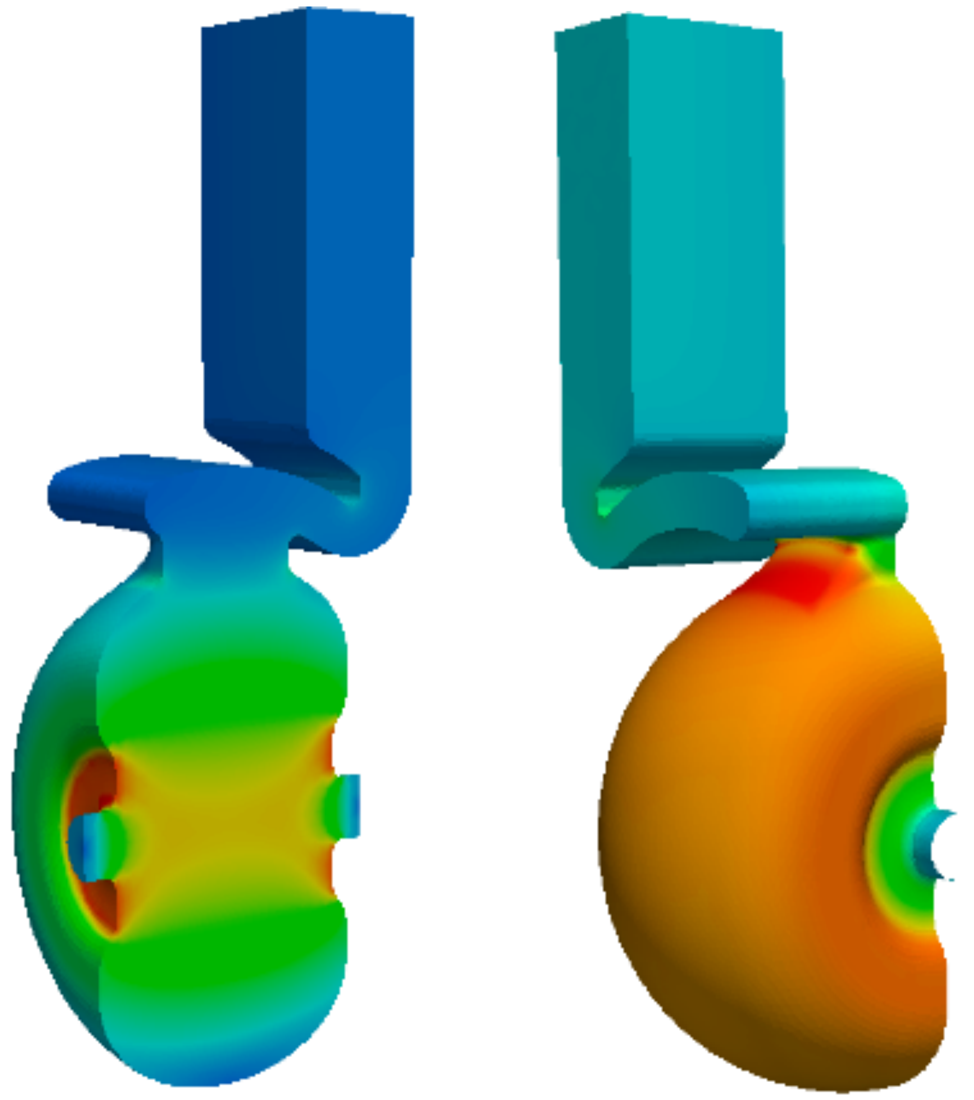


Development of C³ Accelerating Structure

- Envision meter-scale accelerating structures, technology demonstration underway
- Implement most high-gradient advances

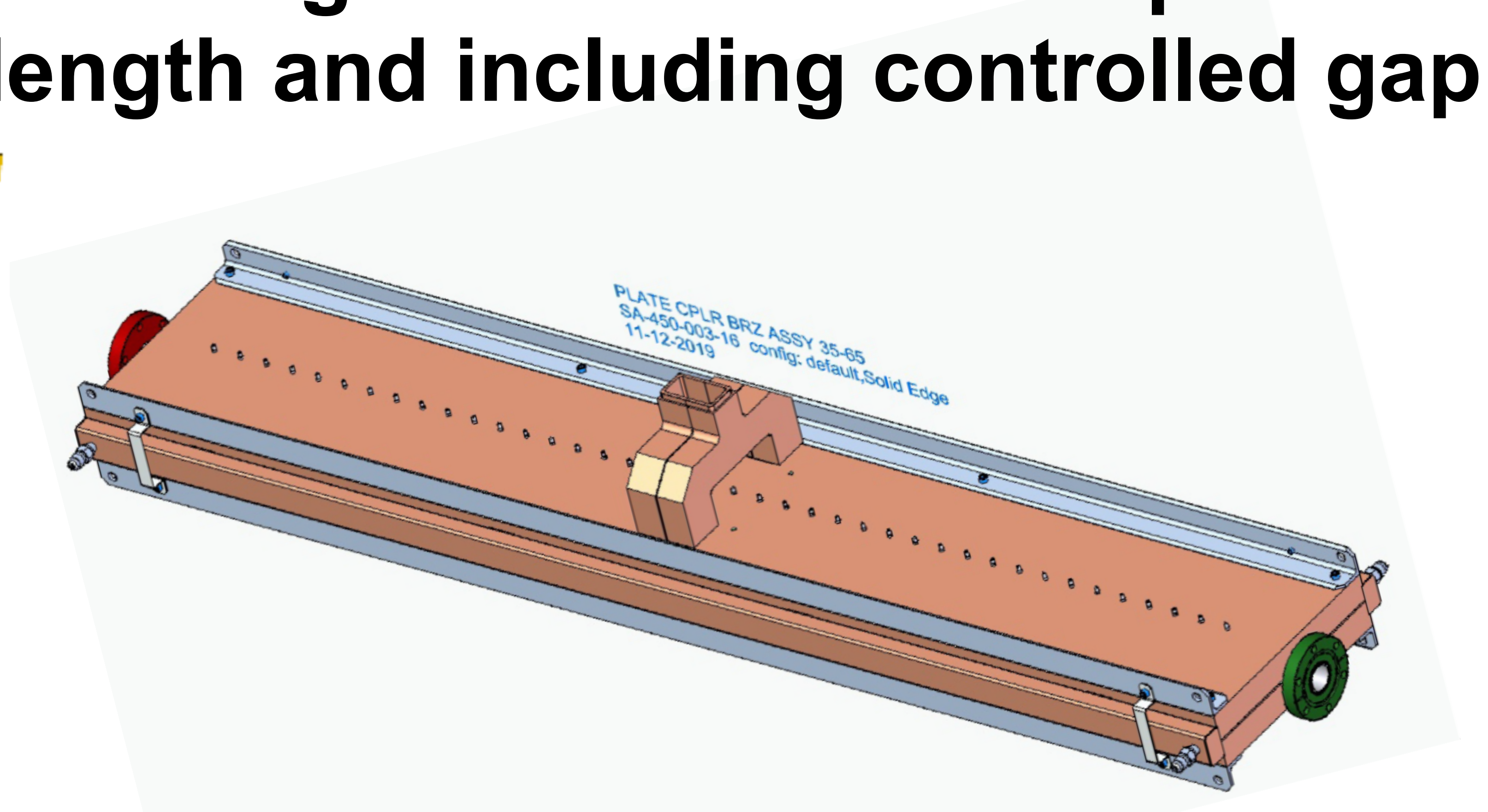
One meter (40-cell) C-band design with reduce peak E and H-field

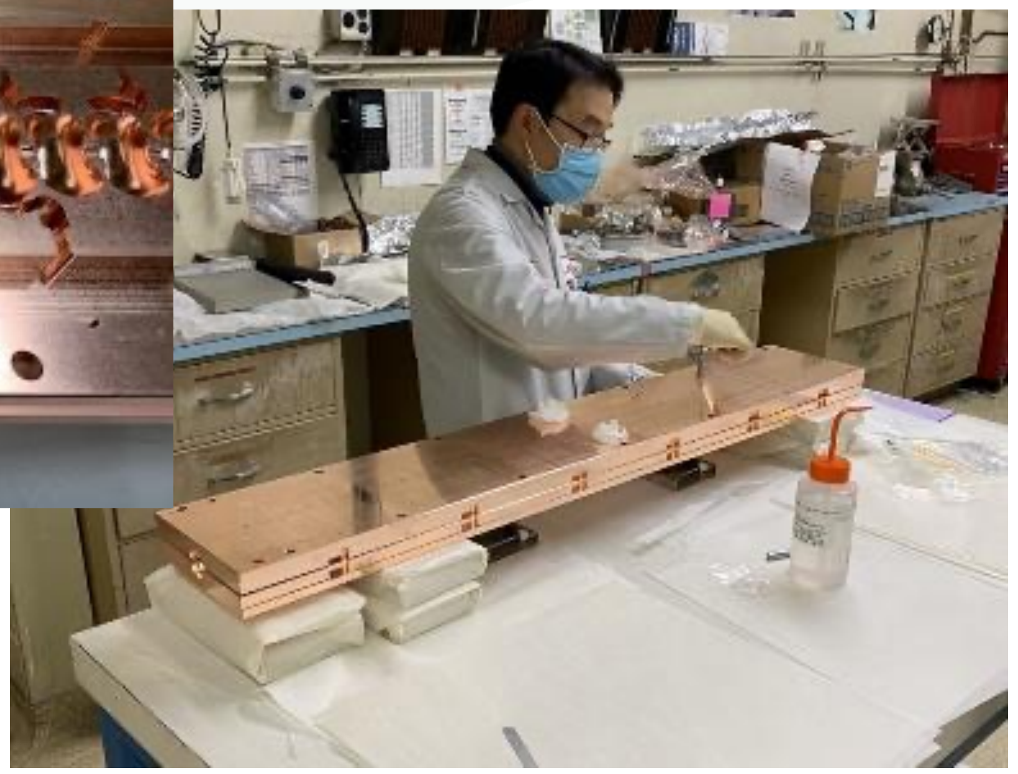




Z. Li, S. Tantawi

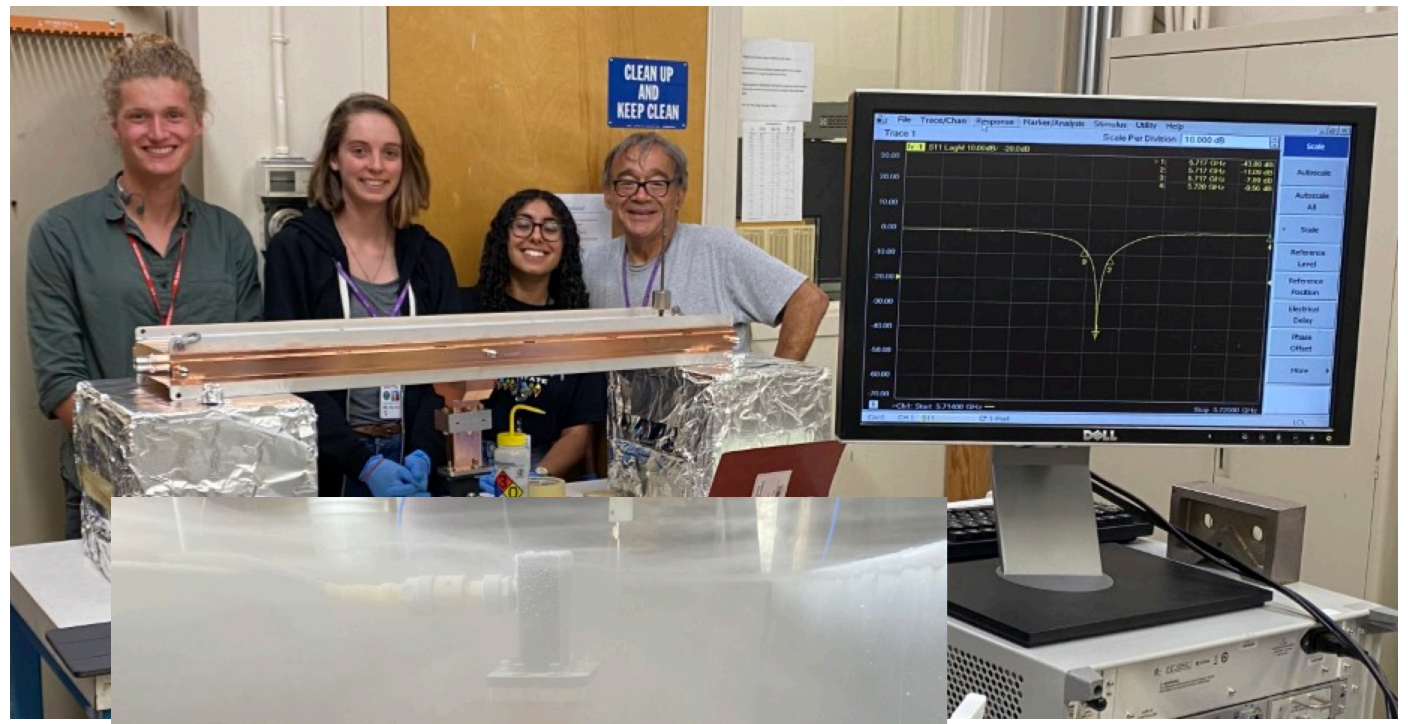
Scaling fabrication techniques in length and including controlled gap





August, 17 2021

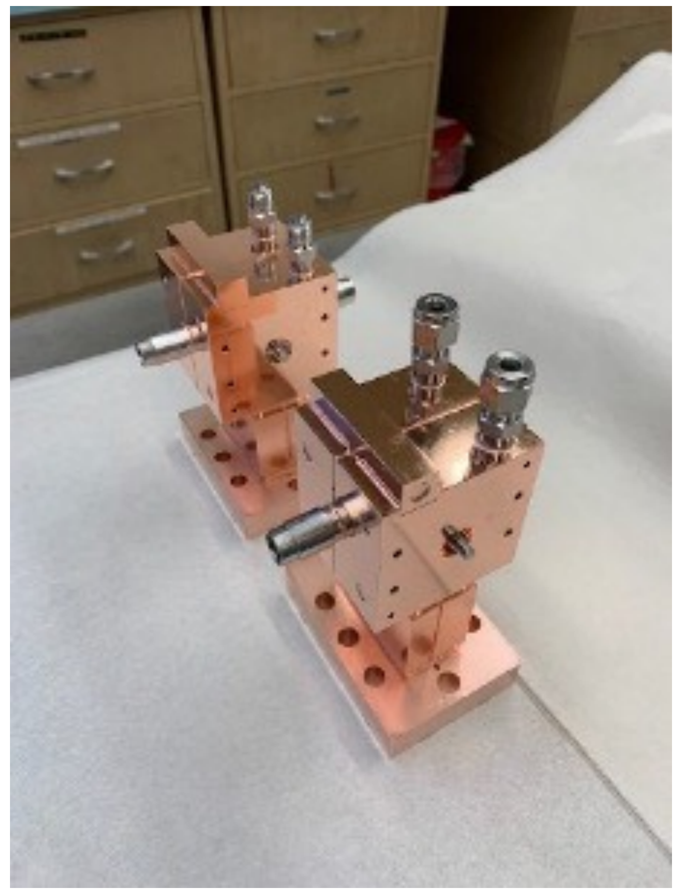
Tuned, vacuum tight, performance at 77K confirmed

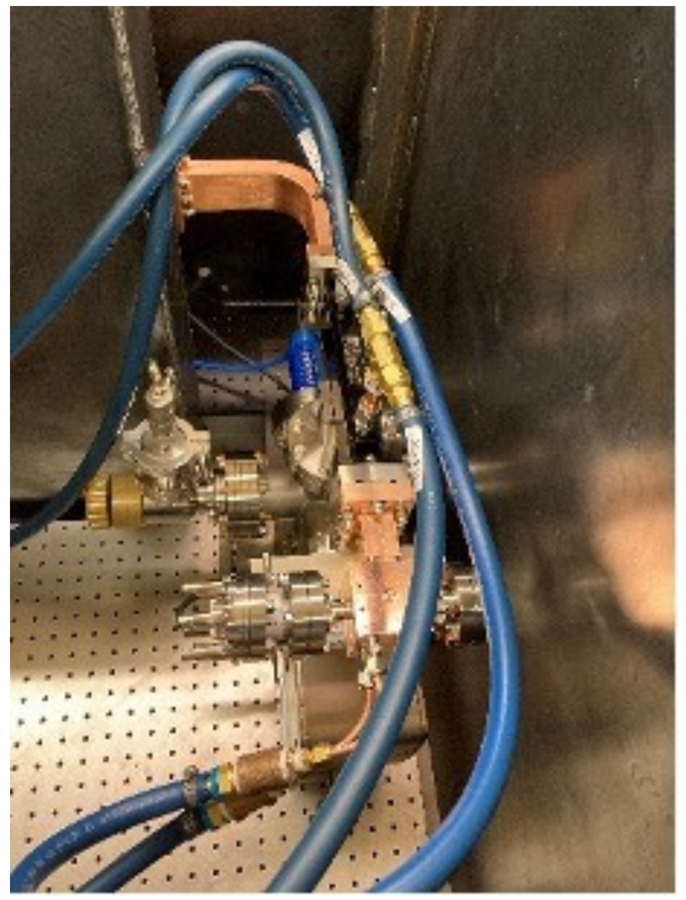


Performance of Single-Cavity Structure Prototypes

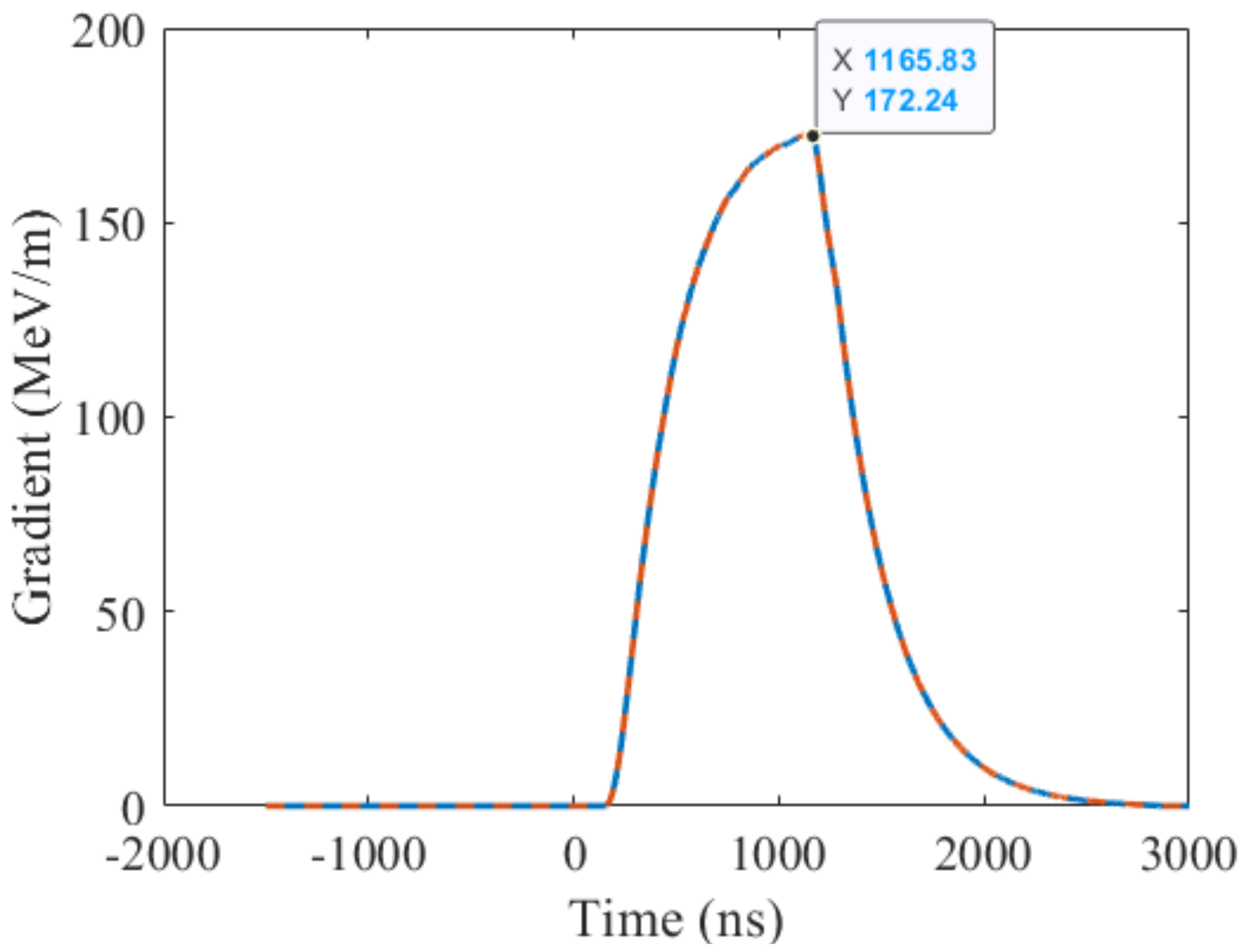
- First high gradient test at C-band
- Side coupled, split-cell reduced peak field, reduced phase adv.
- Exceed ultimate C3 field strengths
- High power in up to 1 microsecond - break down rate statistics collected and being prepared for release

LANL Test of single cell SLAC C-band structure

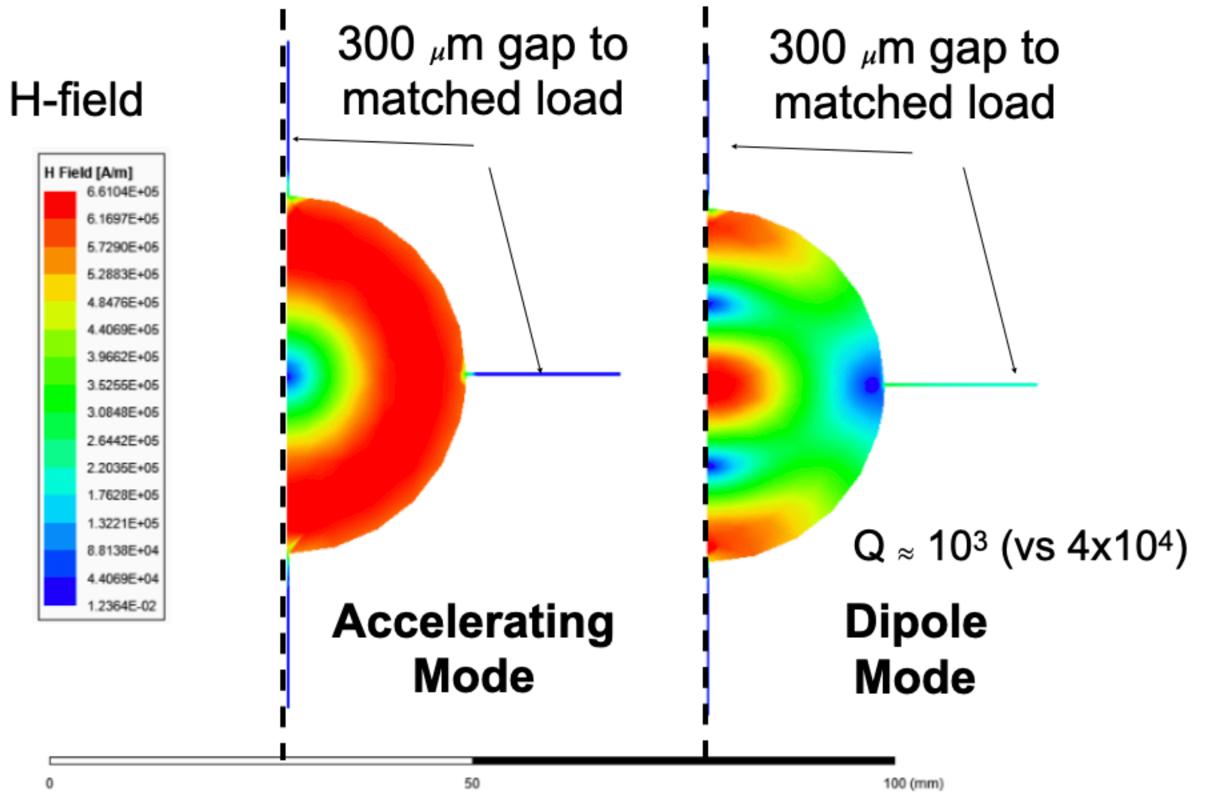


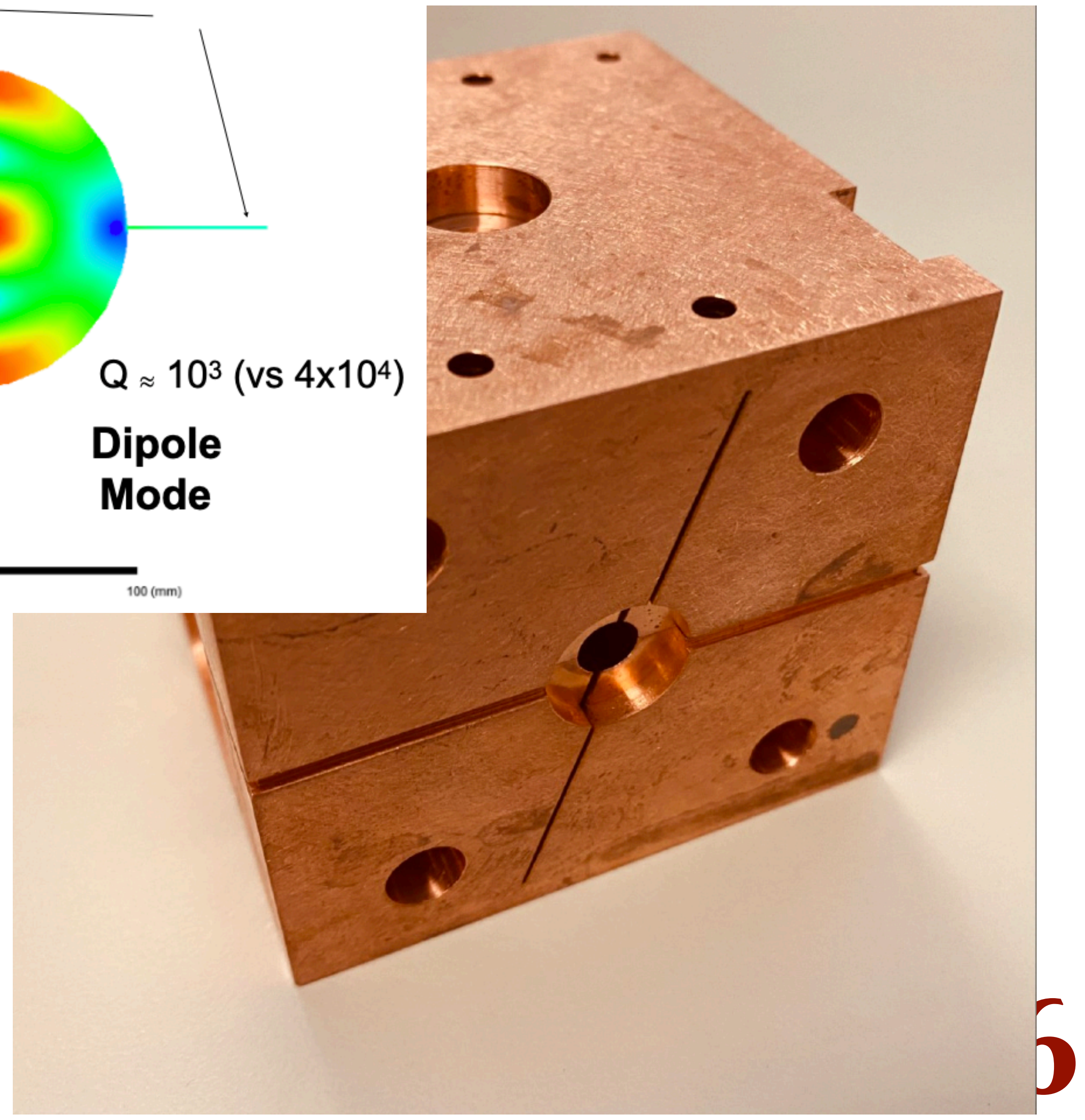


Structure Exceeds 120 MeV/m for 500 ns @ Room Temp BDR Data Collected



Slot Damping Prototype Working on NiCr Coating

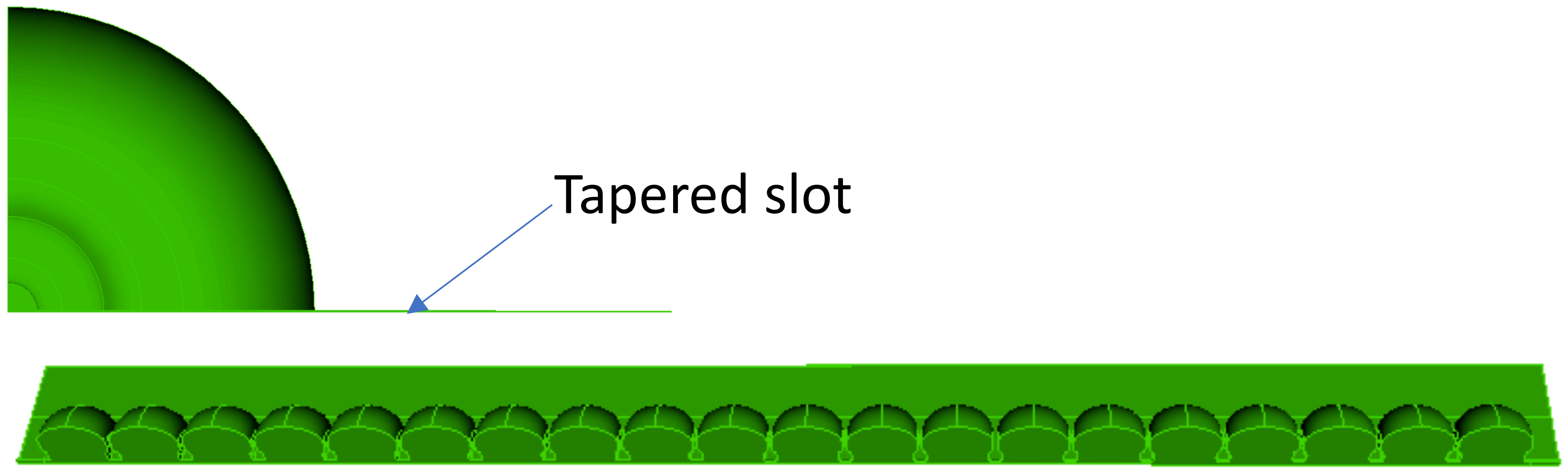


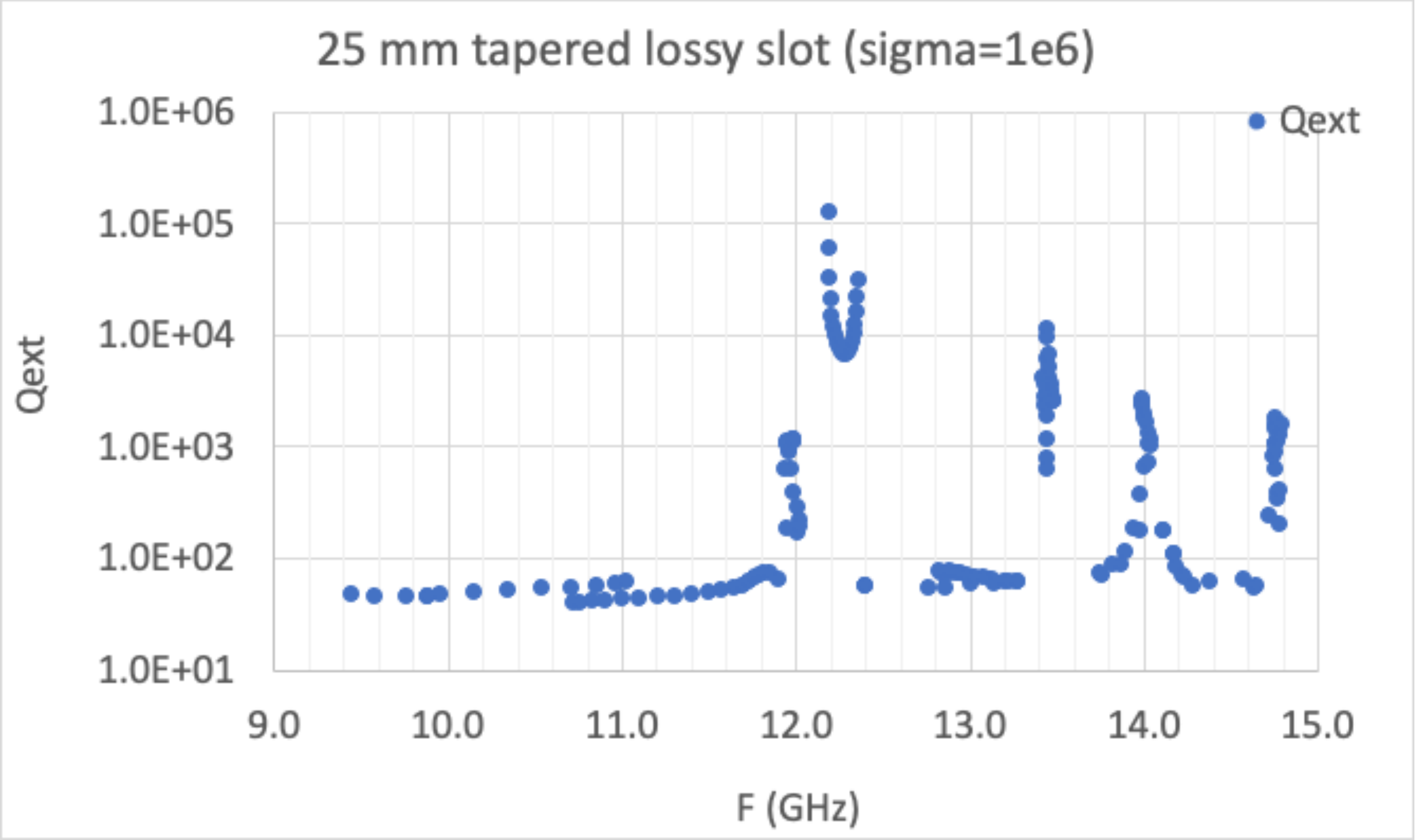


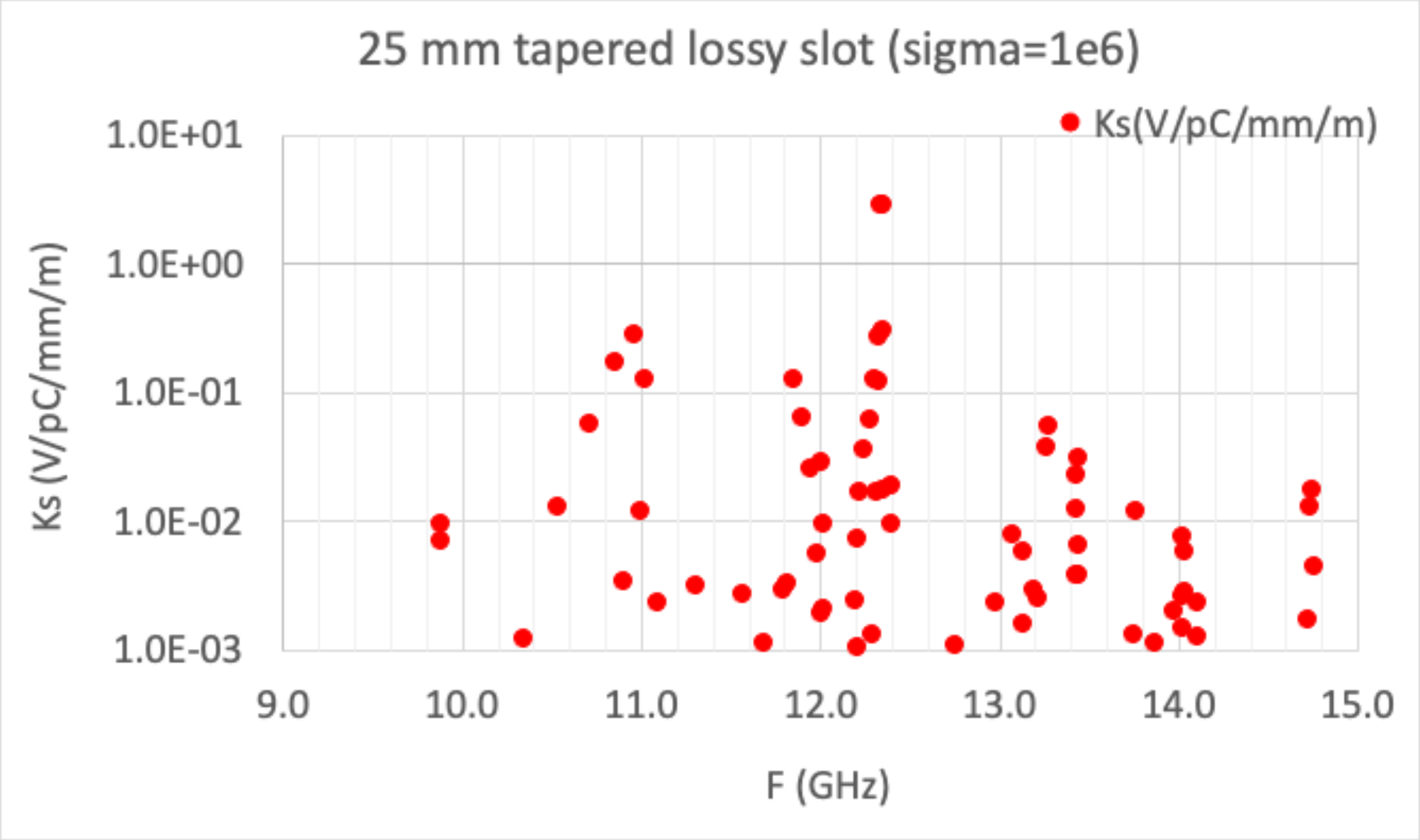
Very promising for polarized cryo-gun (Rosenzweig, et al. NIM 909 (2018): 224-228)

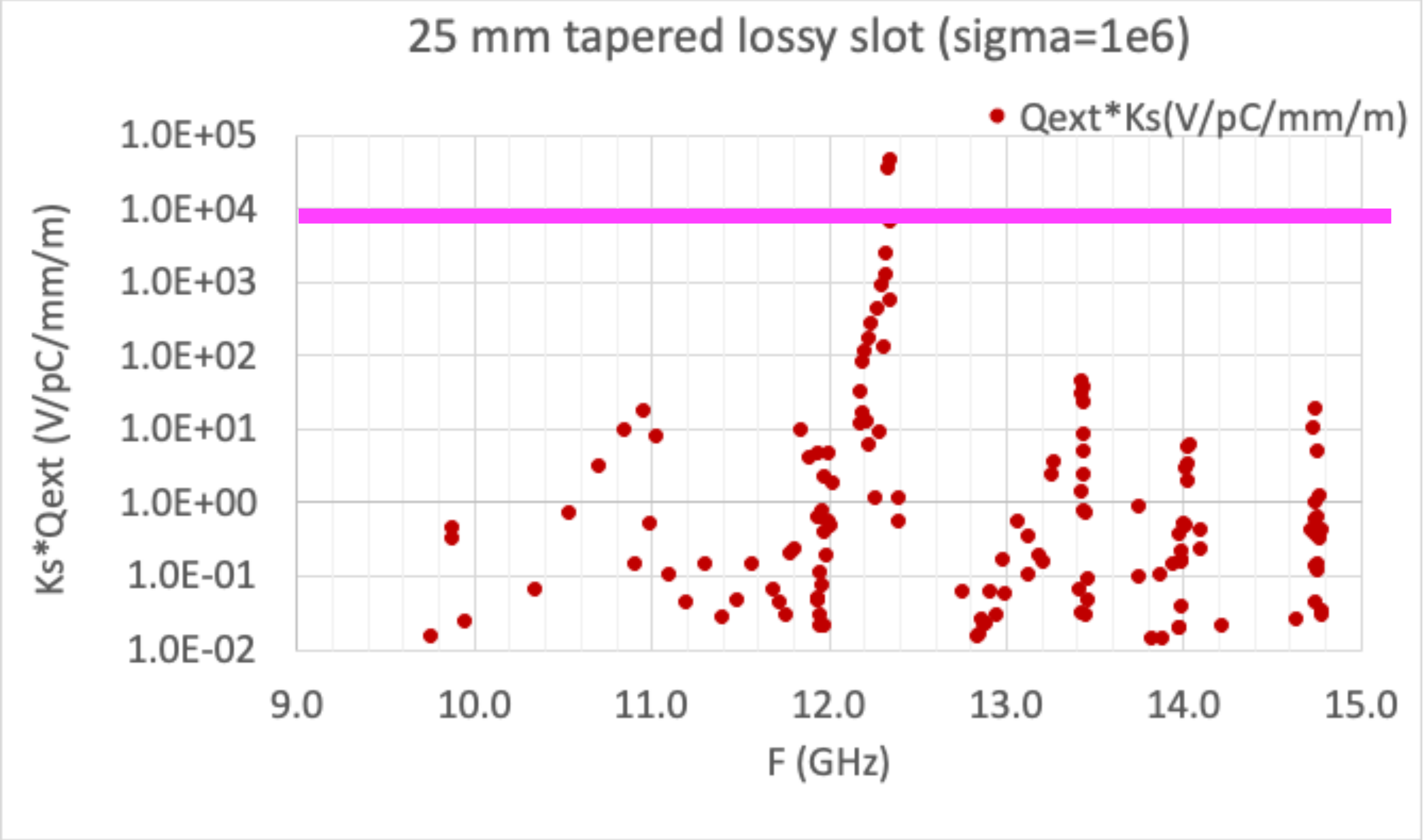
HOM Damping with Tapered Lossy Slot - Preliminary - Z. Li

- Slot surface conductivity: 1e6
- Tapered slot height: from 300 micron to 100 micron







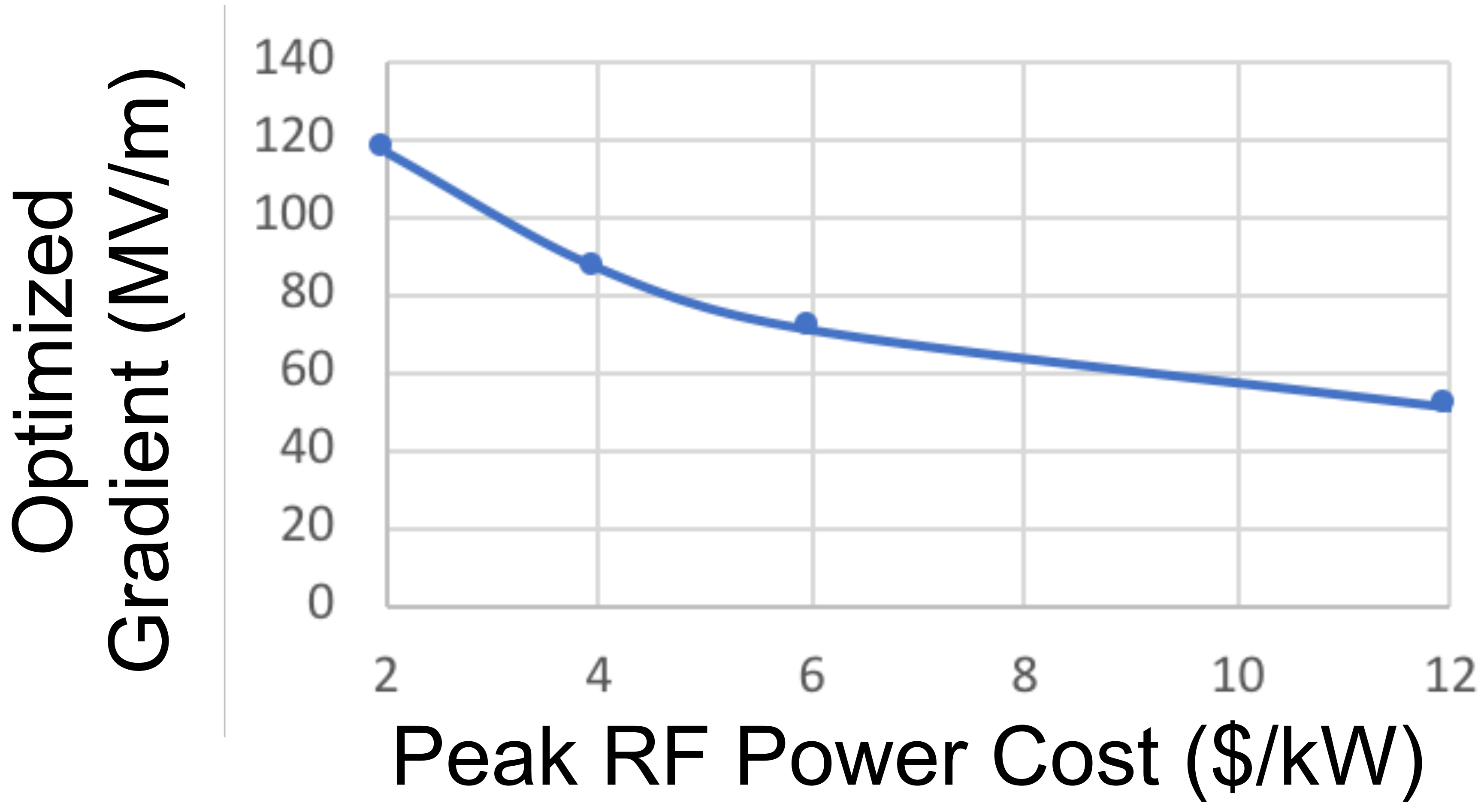


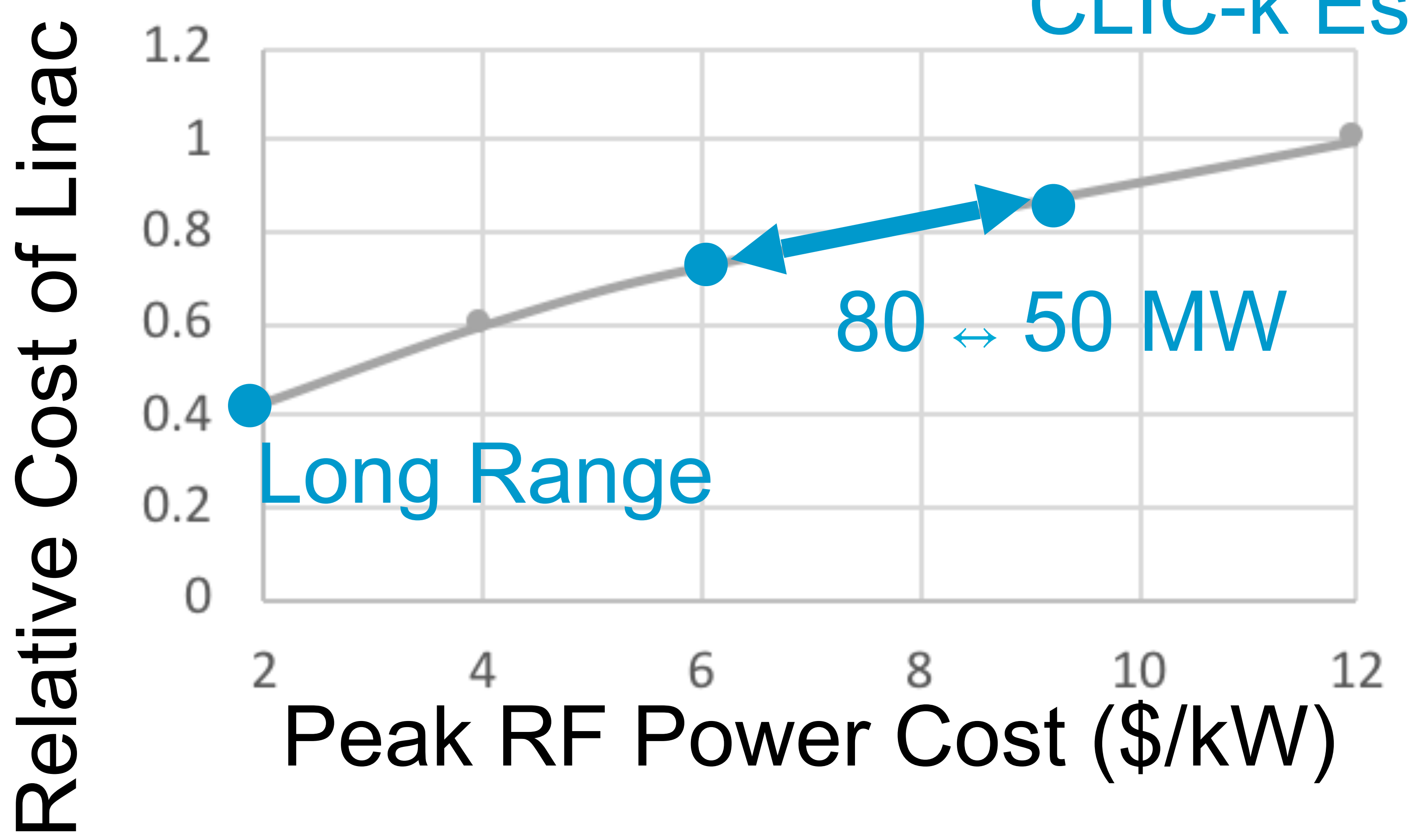
Need to extend to 40 GHz / Optimize coupling / Modes below 10^4 V/pC/mm/m

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

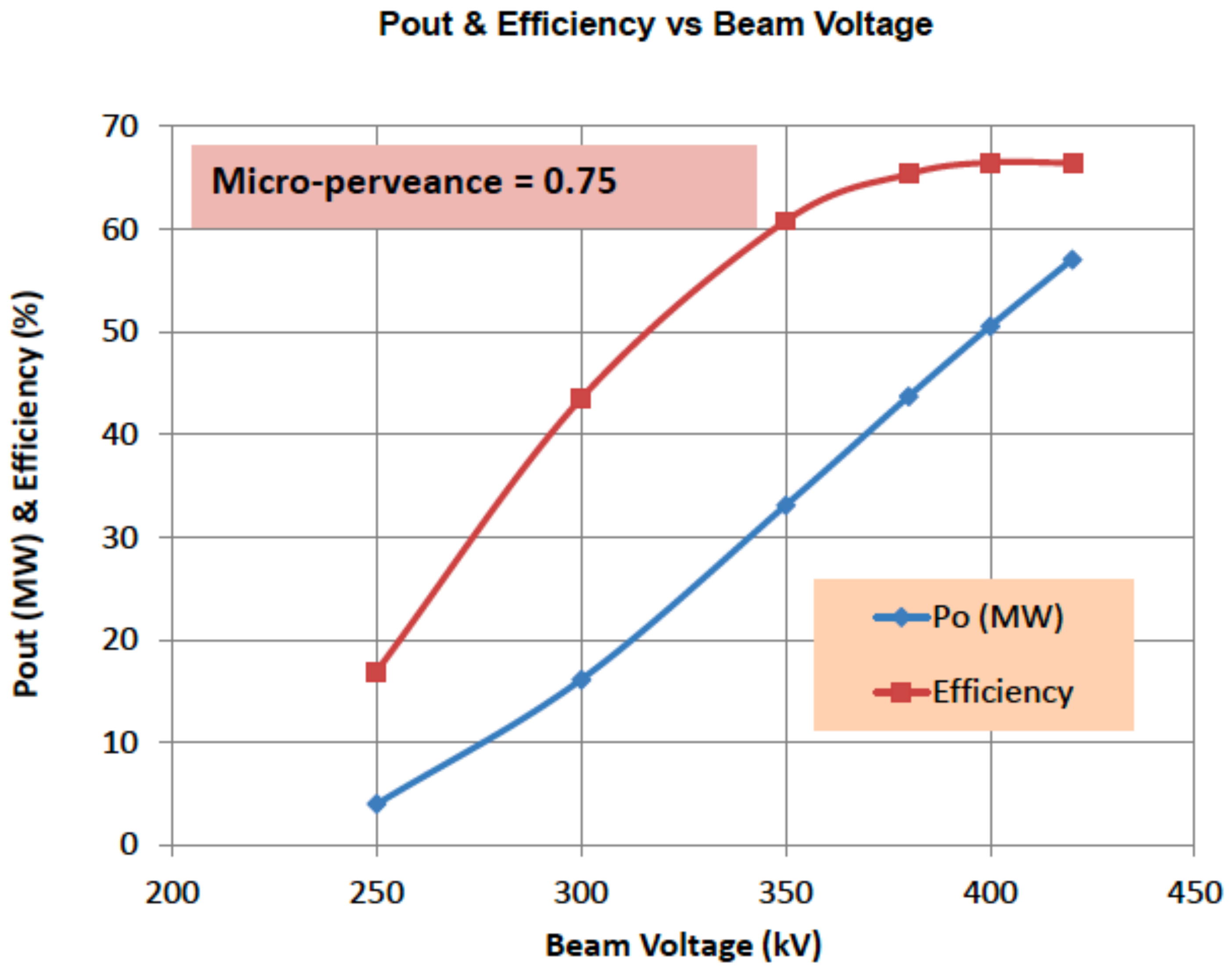
- Optimizing the cost of NCRF technology a fundamental requirement for its implementation for future facilities
- RF source cost is the key driver for gradient and cost – need to focus R&D on reducing source cost

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





Near Term Industry

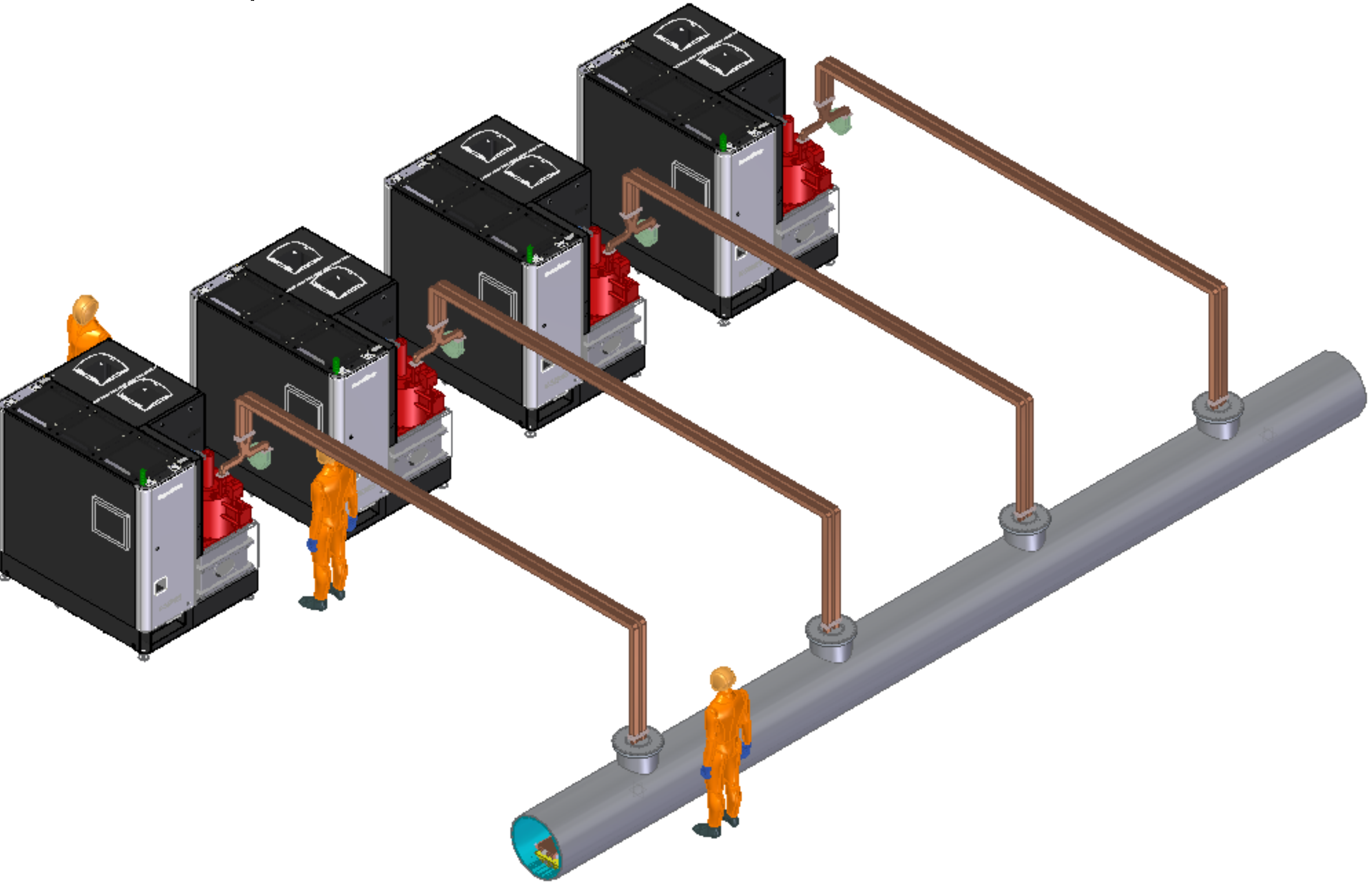


Understand the Impact on Advanced Collider Concept Enabled by the Goals Defined in the DOE GARD RF Decadal Roadmap

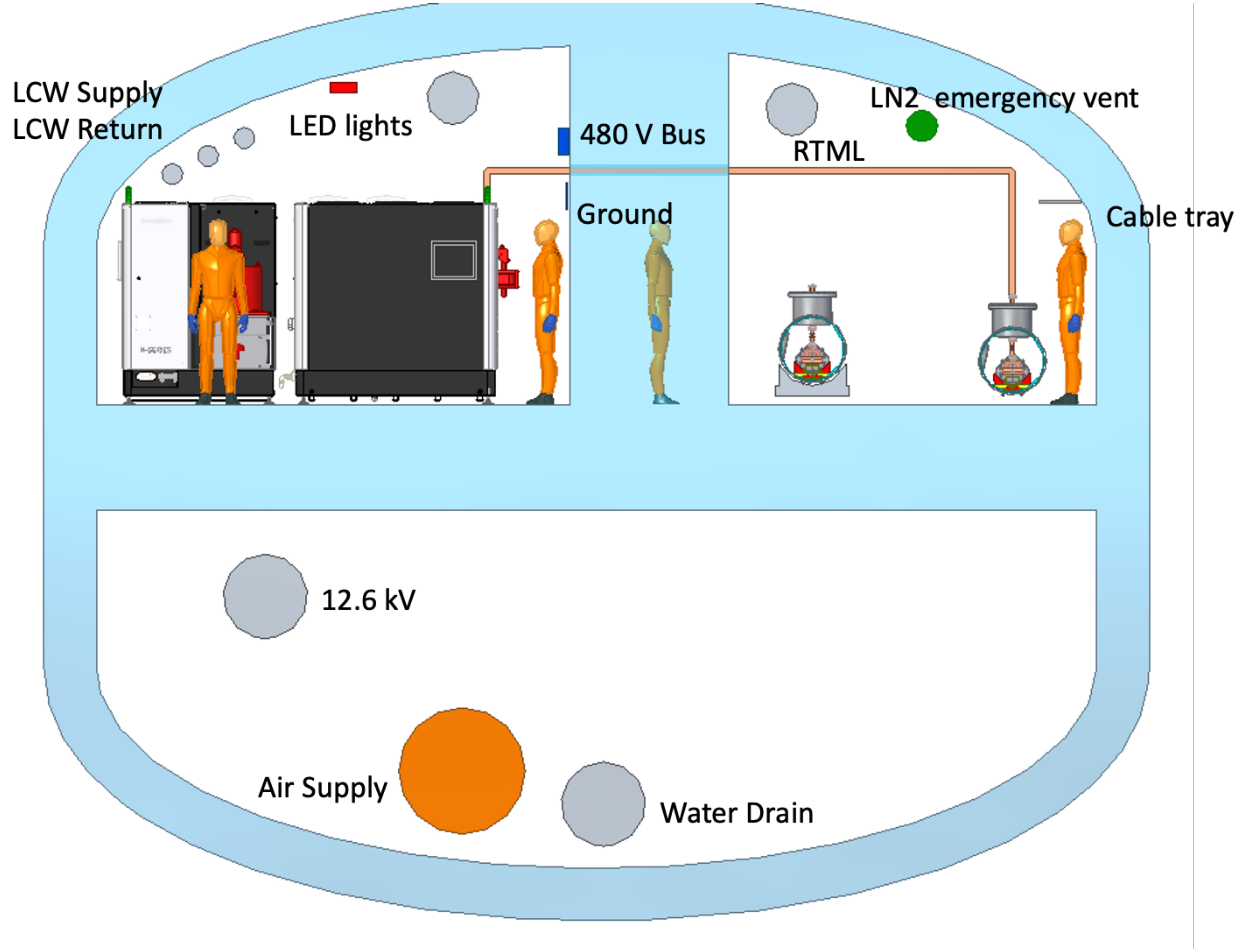
https://science.energy.gov/~/media/hep/pdf/Reports/DOE_HEP_GARD_RF_Research_Roadmap_Report.pdf

Tunnel Layout for 250 GeV CoM

- Cryomodule unit - 9 m (630 MeV)

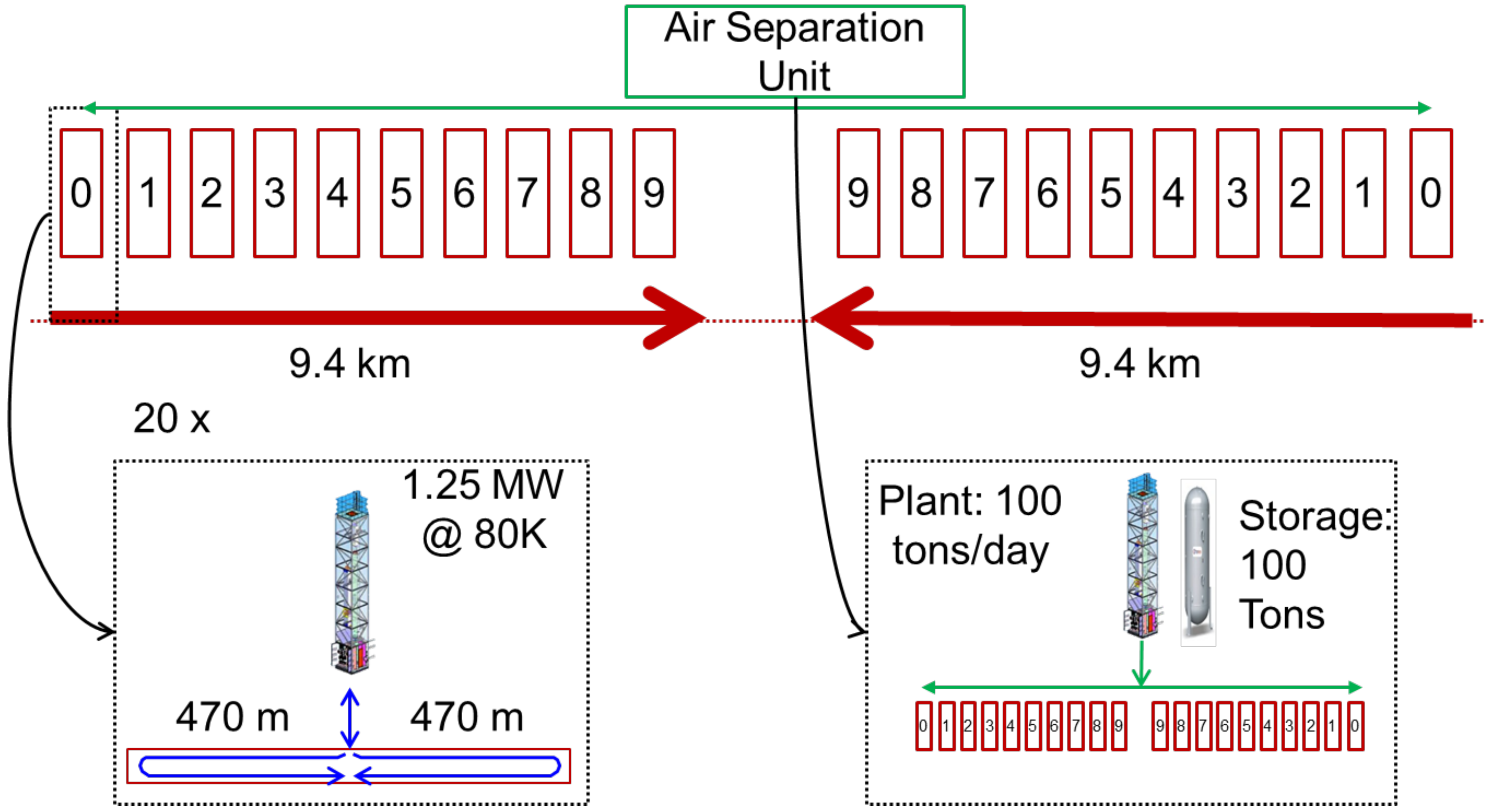


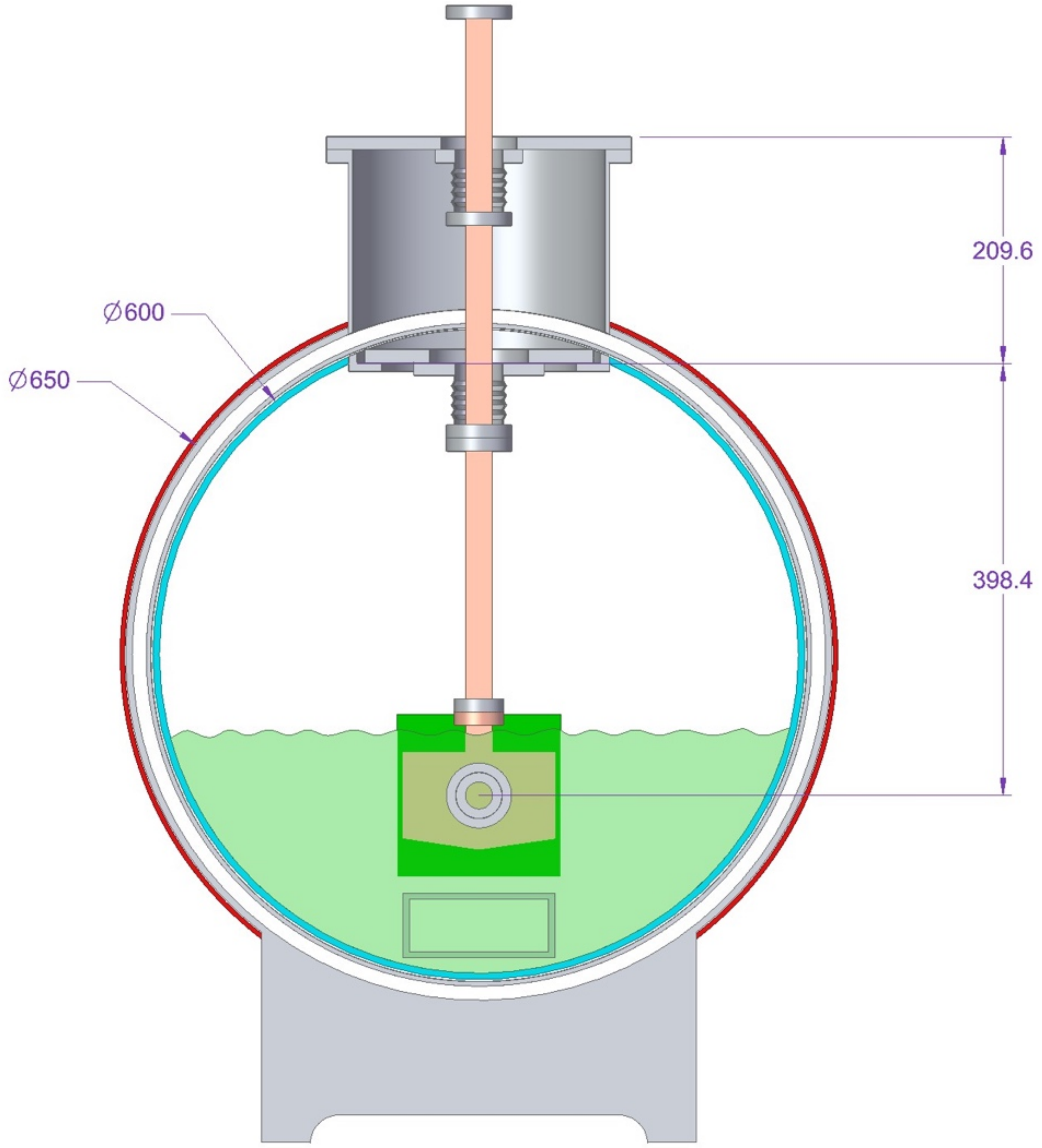
Usable Tunnel Width - 9.5 m (Same as ILC)



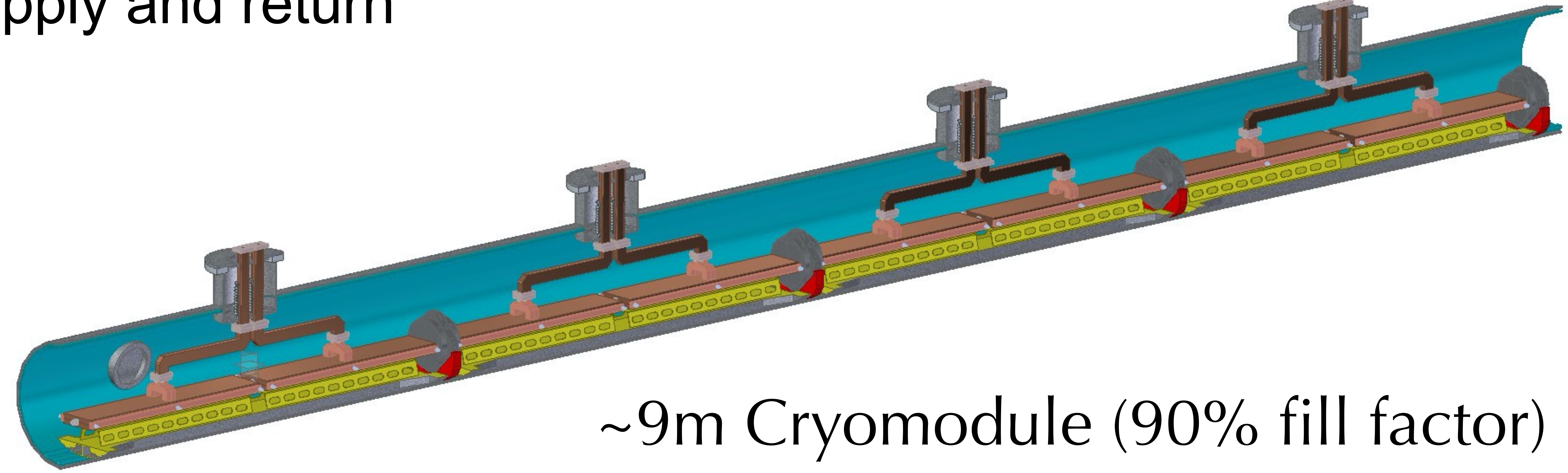
Cryomodule Design Scalable from 250 GeV to multi-TeV

- X-band structure test demonstrated full average power over short length (0.25 m)
- Cryomodule design developed for cryoplant layout to cool 1.2 MW/km thermal load at 77K





Shared nitrogen supply and return



~9m Cryomodule (90% fill factor)

Summary of Parameters for 250 GeV Conceptual Design

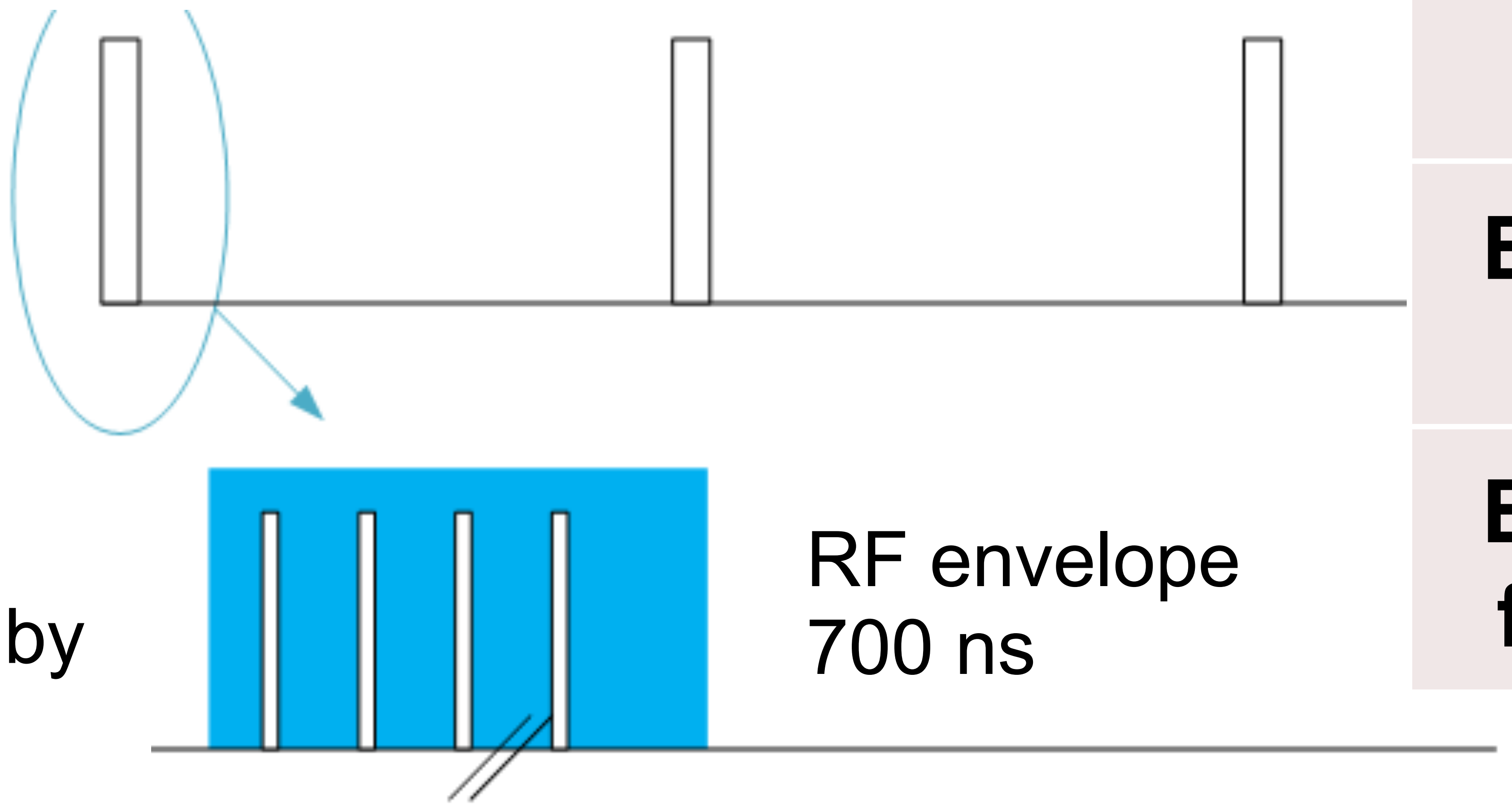
Luminosity - 1x10^34

Temperature (K)	77
Beam Loading (%)	45
Gradient (MeV/m)	70
Flat Top Pulse Length (μs)	0.7
Cryogenic Load @ 77K (MW)	9
Electrical Load (MW)	100

Parameter (250 GeV CoM)	Units	Value
Reliquification Plant Cost	M$/MW	18
Single Beam Power (1 TeV linac)	MW	2
Total Beam Power	MW	4
Total RF Power	MW	18
Heat Load at Cryogenic Temperature	MW	9
Electrical Power for RF	MW	40
Electrical Power for Cryo-Cooler	MW	60

Trains repeat at 120 Hz

Pulse Format



133 1 nC bunches spaced by
30 RF periods (5.25 ns)

Costing Studies for C^3 ($=CHF=ILCU)

- Ongoing development of a cost model for C3 -> following other LC formats
  - Capital Costs - M&S/Construction - External vendors $
  - FTE - Lab Labor
- Using CLIC-k vs ILC Inputs for C^3 250 CoM 60 MeV/m gradient - cost difference for M&S vs. Construction was **1.3% (ILC Inputs Cheaper)**
  - Main difference - ILC itemizes conventional facilities - CLIC-k lumps them together
- Use a hybrid-model built from ILC, CLIC-k and vendor estimates
    - Use itemized ILC conventional facilities for scaling of cost per meter for the main linac
- C^3 costs are ~35% sources, ~35% main linac, ~15% IP, ~15% supporting infrastructure
  - **Unique position for LC - cost not dominated by the main linac - improvements to the full complex can have a significant effect**
- Working estimate for Capital Costs 3.5-4B$ (10% RF margin, 10 GeV energy margin, 250 GeV CoM)
- Labor - CLIC-k and ILC quote similar #s 1.8-1.9FTE/M$
  - Need to assess the validity of this for C^3
- **Reached the limit of cost scaling - need to evaluate C^3 specific subsystems of accelerator complex**

Construction Timeline

Total Yrs	Yrs	Physics	Klystrons/yr	Energy Increase	Cyromodules/yr	Energy Increase	Energy Reach CoM	EQ Funding Klystron/CM (M$/yr)		Start
6	6		200	150	50	150	150	150		2029
7	1	Comission	200	25	50	25	175	150		2035
9	2	Z-cal / FEL	200	50	50	50	225	150		2036
10	1	Comission	200	25	50	25	250	150		2038
18	8	e+e- 250 CoM	320	260			510	160		2039

This profile would result in a 10% surplus

Demonstrator R&D Plan

- Facilities that are auxiliary to the main linac at an advanced TRL level
- Minimum requirement for Demo Facility:
  - Demonstrate operation of fully engineered and operational cryomodule
    - Possible option to iterate (replace cryo-module)
  - Demonstrate operation during cryogenic flow equivalent to main linac at full liquid/gas flow rate
  - Operation with a multi-bunch photo injector - high charges bunches to induce wakes, tunable delay witness bunch to measure wakes
  - Demonstrate full operational gradient 120 MeV/m in single bunch mode (1GeV)
  - **Fully damped-detuned accelerating structure**
  - Work with industry to develop C-band source unit (3 vendors for klystron / 3 vendors for modulator and integration)
- **$100 M / 5 yr Demo Facility that we can propose for Snowmass/P5**
- **Continues with CCC R&D (rf sources, pulse compressors), XCC R&D and other relevant R&D (FEL, Cryo-gun, etc.) including possible energy upgrade for Demo Facility**

CCC to (Not Quite) Scale

250 GeV CoM - Main Linac 4 km
3 km for BDS ?!