RF Power for C^3

Emilio Nanni

2nd Workshop on Efficient RF Sources
9/23/2024

Acknowledgements

SLAC-PUB-17661
April 12, 2022

Strategy for Understanding the Higgs Physics:
The Cool Copper Collider

Jinst
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SNOWMASS'2021 ACCELERATOR FRONTIER

Status and future plans for C^3 R&D

SLAC-PUB-17629
November 1, 2021

C^3 : A "Cool" Route to the Higgs Boson and Beyond

Perspective | Open Access

Sustainability Strategy for the Cool Copper Collider

Martin Breidenbach, Brendon Bullard, Emilio Alessandro Nanni, Dimitrios Ntounis, and Caterina Vernieri
PRX Energy **2**, 047001 – Published 26 October 2023

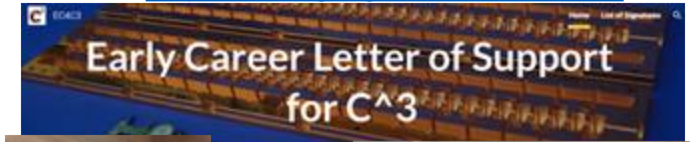
Community Events

https://web.slac.stanford.edu/c3/events

SLAC Feb. 12th-13th

https://indico.slac.stanford.edu/event/8577/

https://sites.google.com/view/ec4c3



Next C^3 Meeting at NIKHEF, Amsterdam Oct. 7-8th '24
Next Cold-Copper Meeting at Duke University, Jan. 13-14th '24

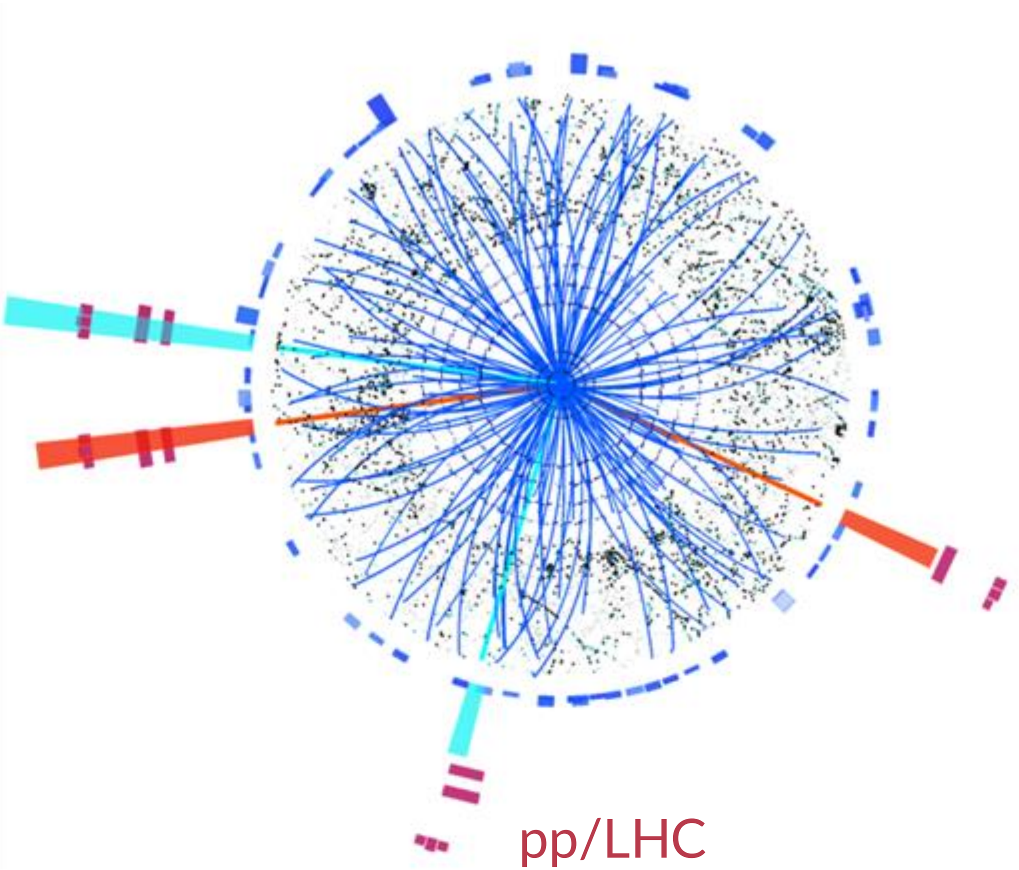
More Details Here (Follow, Endorse, Collaborate):
https://web.slac.stanford.edu/c3/

Exploring the Energy Frontier…

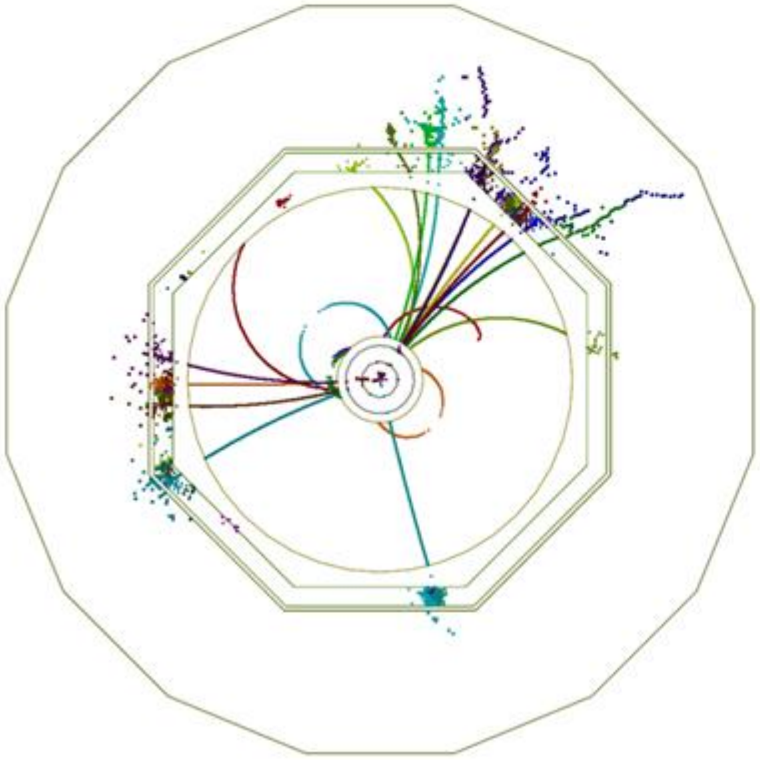
Why e^+e^-?

Initial state well defined & polarization ⟹ High-precision measurements

Higgs bosons appear in 1 in 100 events ⟹ Clean environment and trigger-less readout



pp/LHC



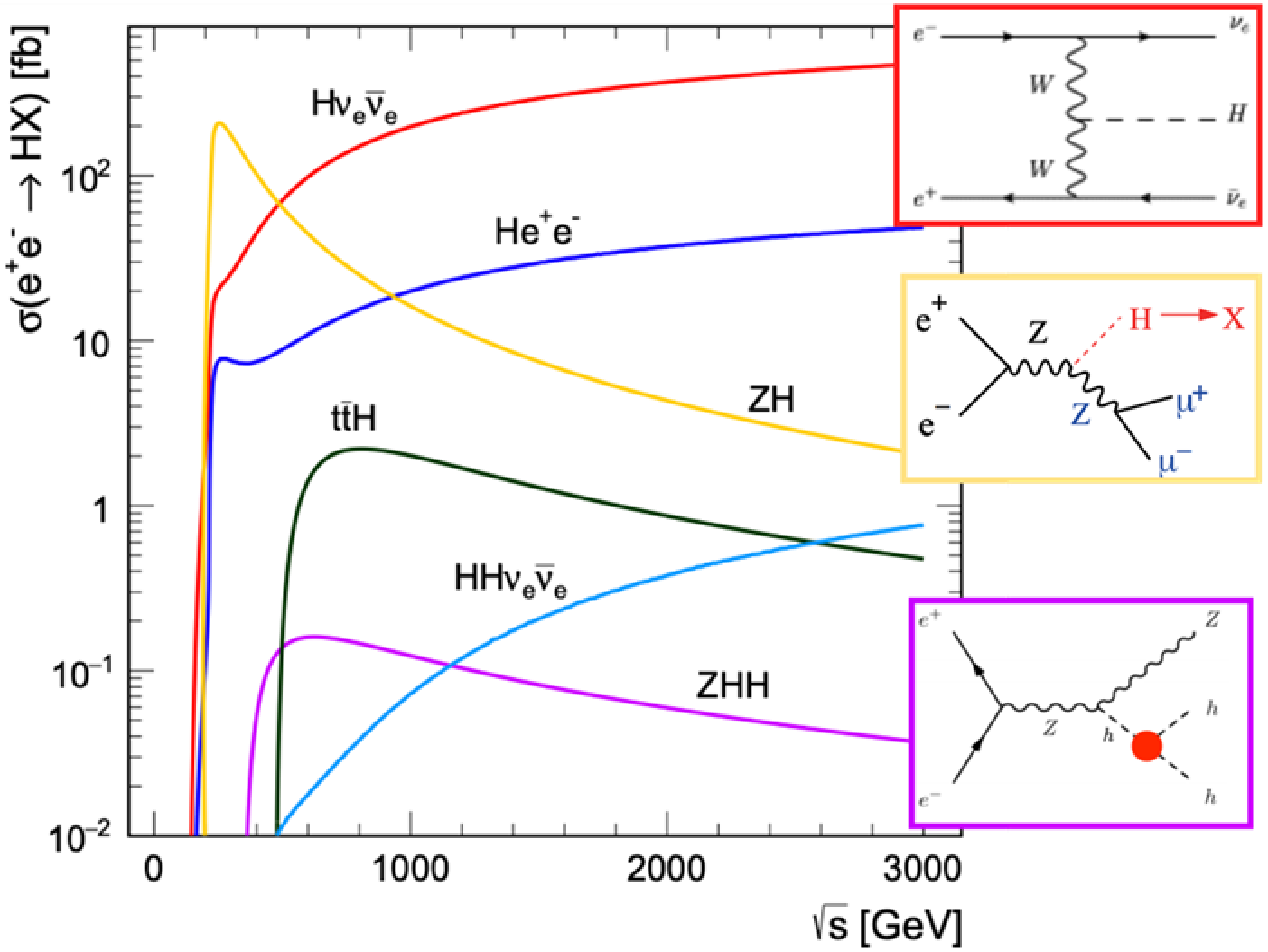
e^+e^-

Higgs Production at e^+e^-

ZH is dominant at 250 GeV

Above 500 GeV

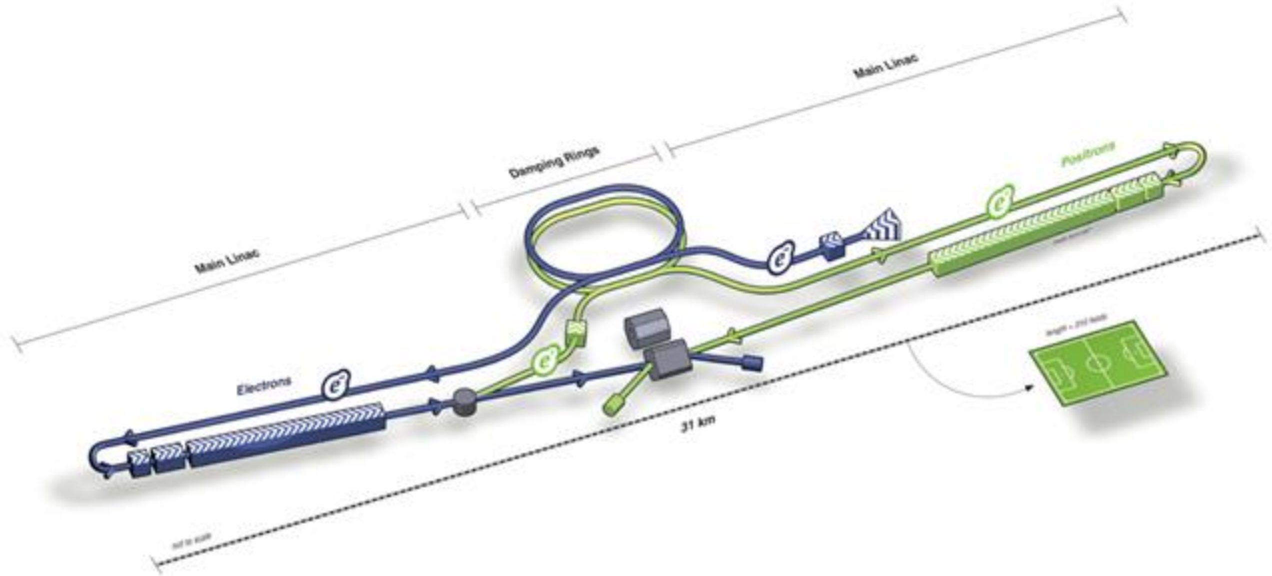
- Hvv dominates
- ttH opens up
- HH production accessible with ZHH



Linear vs. Circular

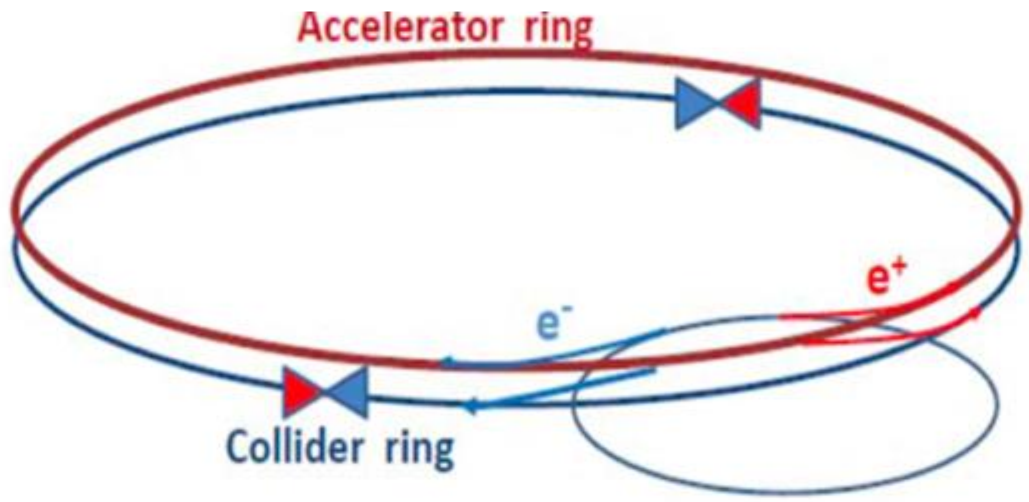
Linear e⁺e⁻ colliders: ILC, C³, CLIC

- Reach higher energies (~TeV), and can use polarized beams
- Relatively low radiation
- Collisions in bunch trains



Circular e⁺e⁻ colliders: FCC-ee, CEPC

- Highest luminosity collider at Z/WW/ZH
- limited by synchrotron radiation above 350 – 400 GeV
- Beam continues to circulate after collision

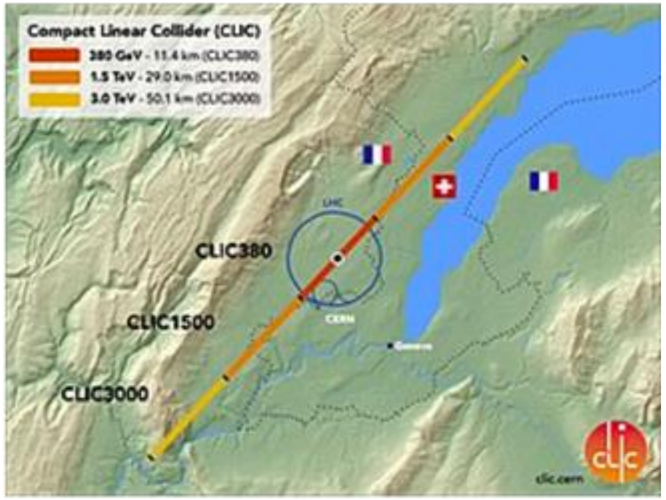


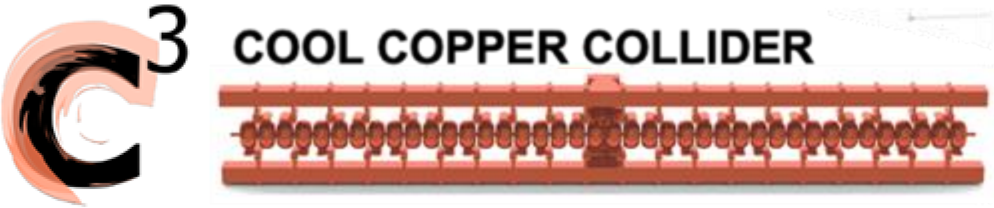
Various Proposals

ILC
250/500 GeV

CEPC
240 GeV

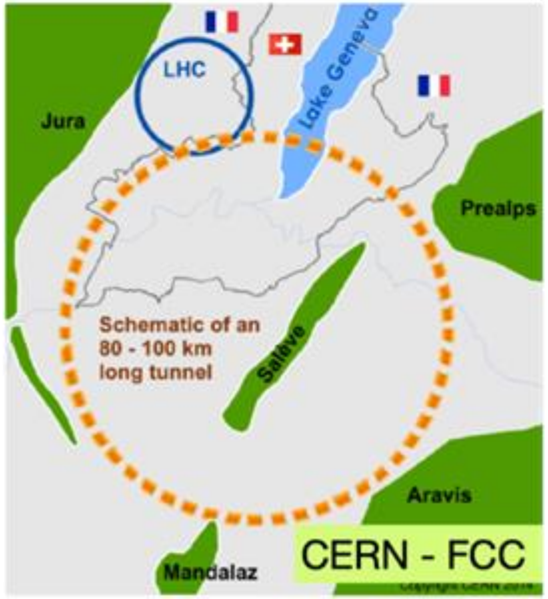
CLIC 380/1000/3000 GeV





250/550 GeV
… > TeV

FCC-ee
240/365 GeV



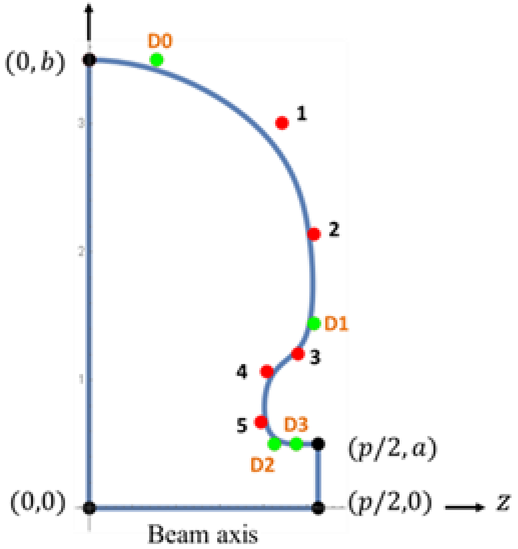
A novel route to a linear e^+e^- collider…

What Defines the Optimal Accelerator Cavity Geometry?

Performance depends on beam aperture which is driven by the bunch charge

Charge particle radiate wakefields that set the limit

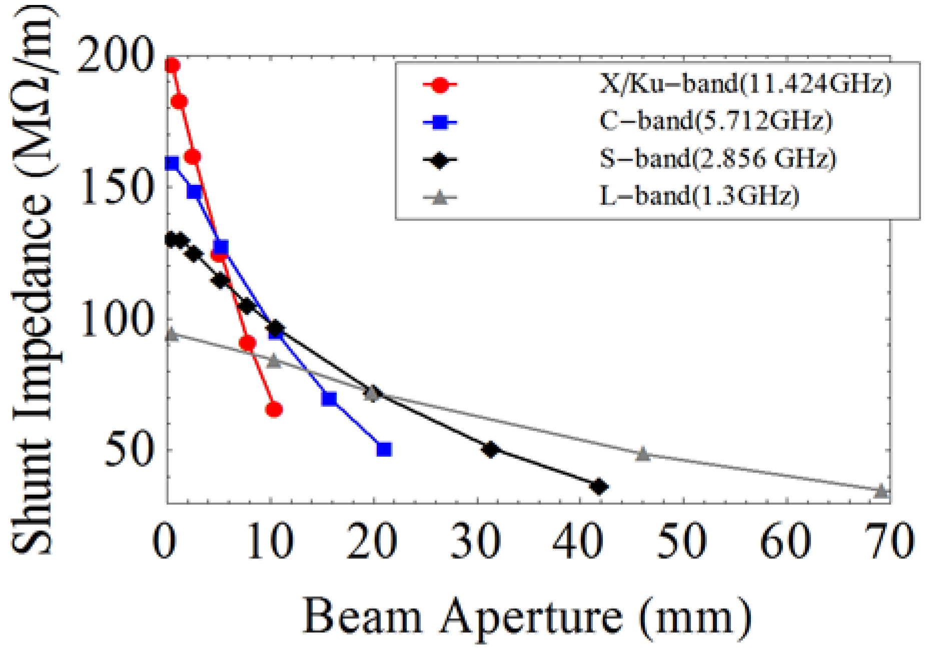
Advanced Optimization Tools



Variable control points for splines define the cavity shape.

M. Nasr et al., IPAC'18

20% reduction in surface electric field for same shunt impedance

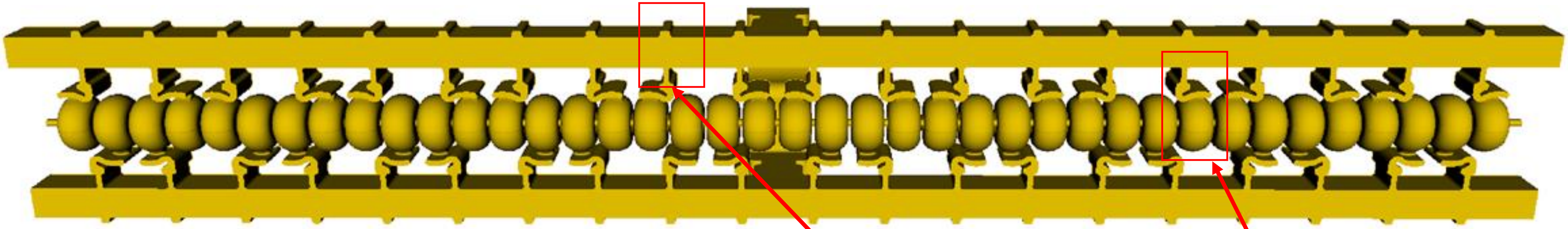


New Scaling Laws Determine the Best Performance for Accelerating Structures

Breakthrough in the Performance of RF Accelerators

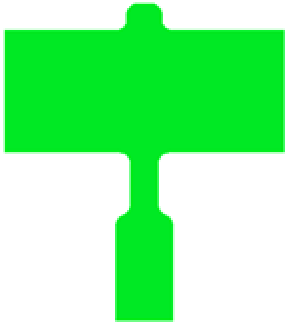
RF power coupled to each cell – no on-axis coupling

Full system design requires modern virtual prototyping



Vacuum space for rf cavities and manifold

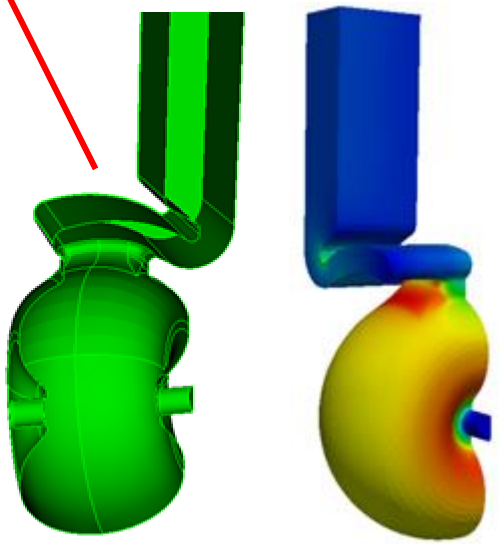
$$R_s = G^2/P \text{ [M}\Omega\text{/m]}$$



Optimization of cell for efficiency (shunt impedance)

- Control peak surface electric and magnetic fields

Key to high gradient operation



arXiv:1807.10195 (2018)
PRAB 23.9 (2020): 092001

Cryo-Copper: Enabling Efficient High-Gradient Operation

Cryogenic temperature elevates performance in gradient

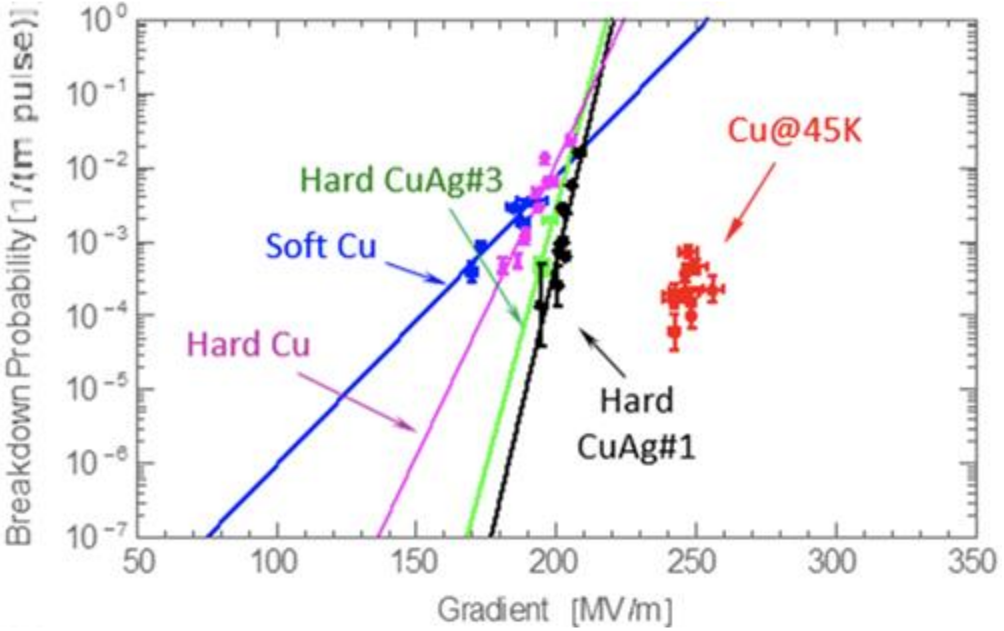
- Material strength is key factor
- Impact of high fields for a high brightness injector may eliminate need for one damping ring

Operation at 77 K with liquid nitrogen is simple and practical

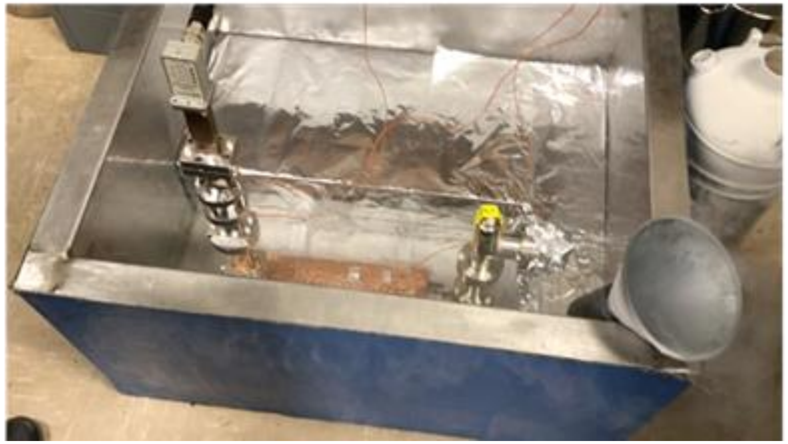
- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency

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

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



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



RF Power Requirements

70 MeV/m 250 ns Flattop (extendible to 1400 ns)

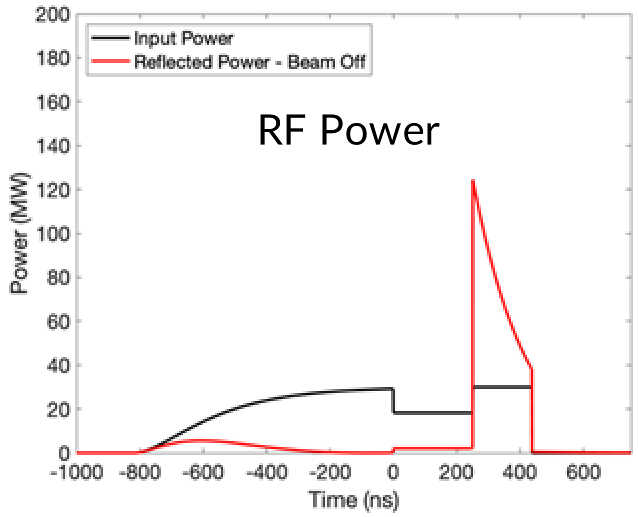
~2 microsecond rf pulse, ~30 MW/m

Conservative 2.3X enhancement from cryo

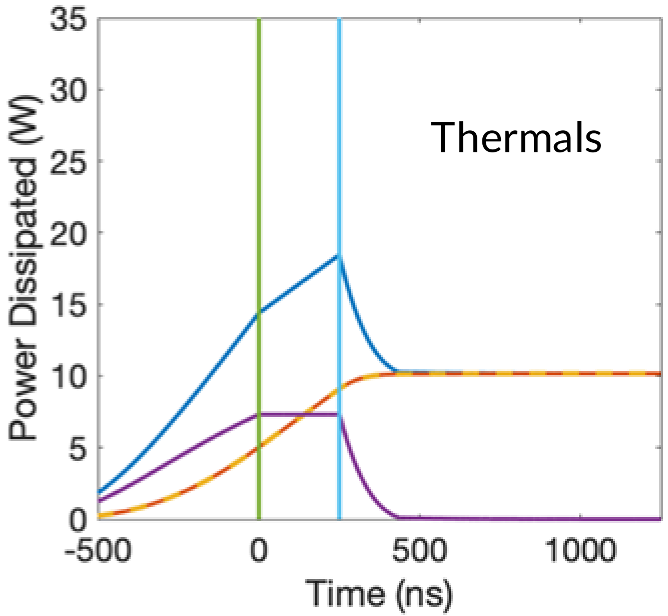
- No pulse compression

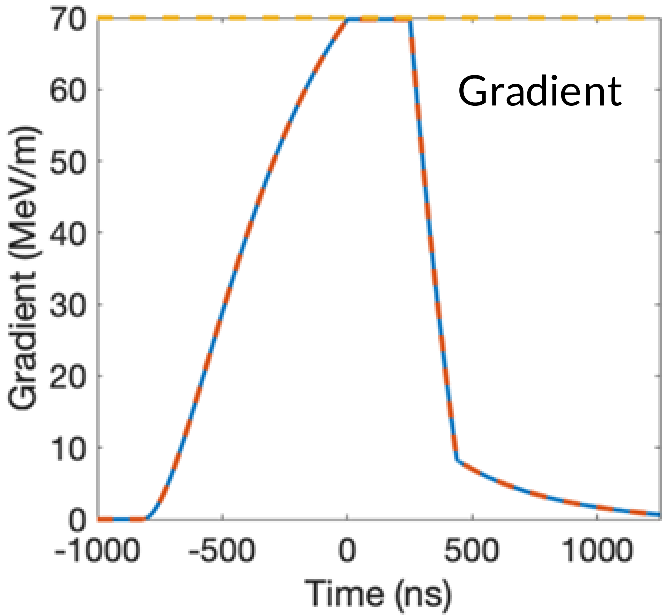
Ramp power to reduce reflected power

Flip phase at output to reduce thermals



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





Accelerator Complex

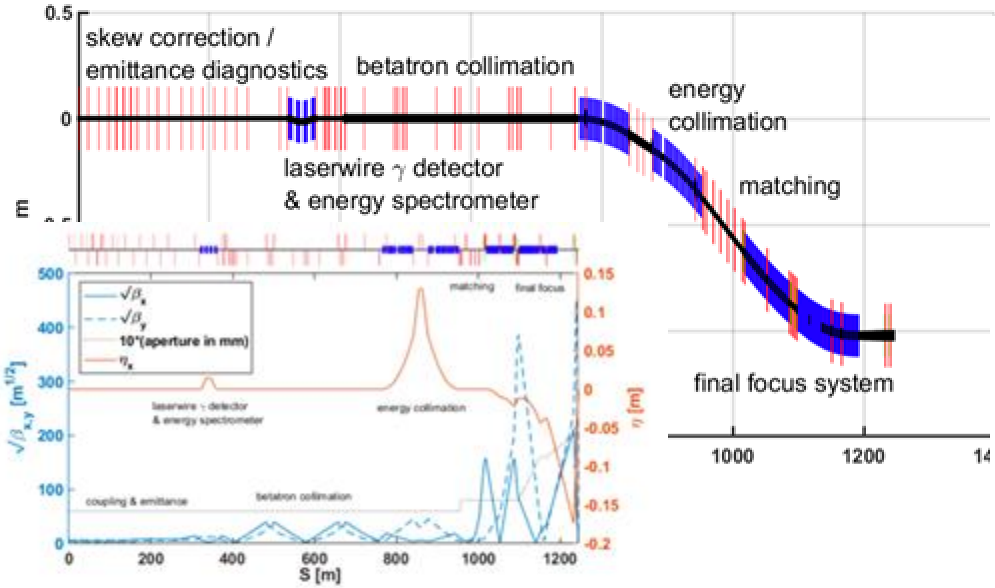
8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

- 7 km footprint at 155 MeV/m for 550 GeV CoM – present Fermilab site

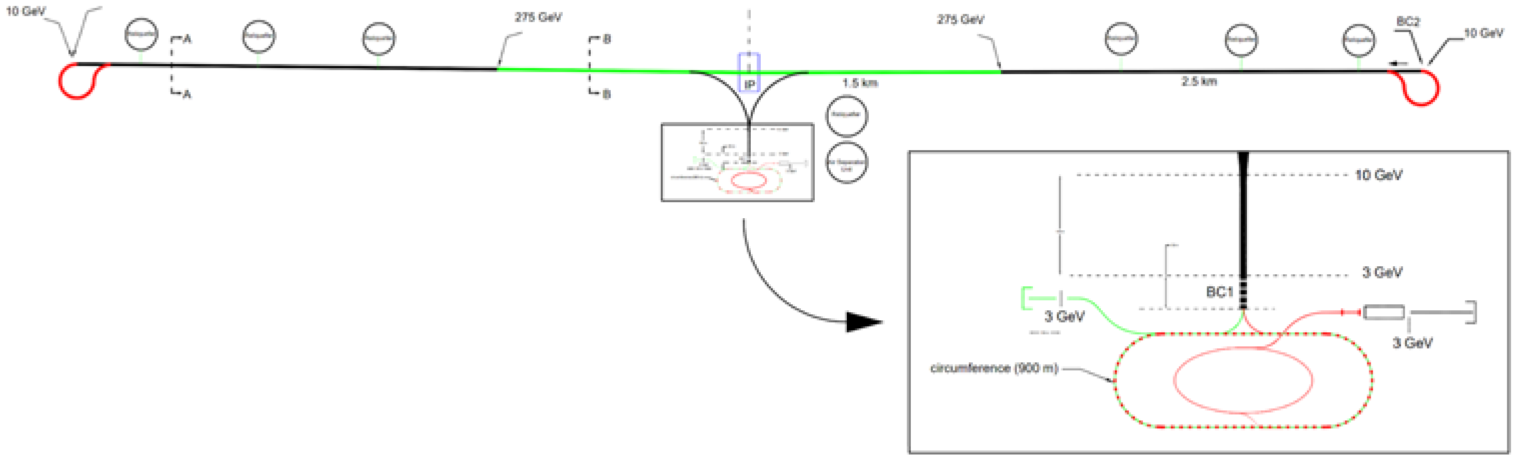
Large portions of accelerator complex are compatible between LC technologies

- Beam delivery and IP modified from ILC (1.5 km for 550 GeV CoM)
- Damping rings and injectors to be optimized with CLIC as baseline
- Costing studies use LC estimates as inputs

C^3 - Investigation of Beam Delivery (Adapted from ILC/NLC)



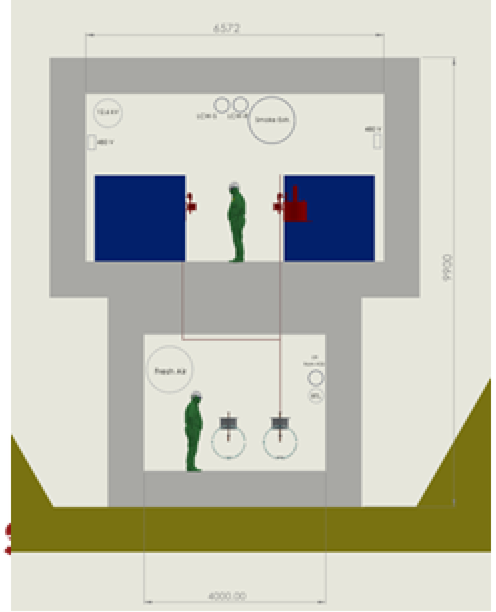
C^3 - 8 km Footprint for 250/550 GeV



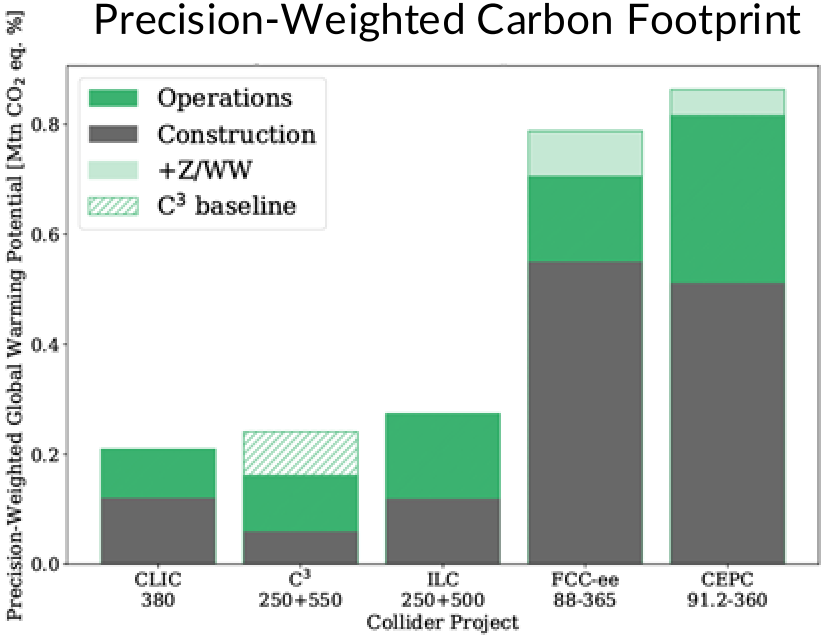
Power Consumption and Sustainability

- Compact footprint <8 km for both underground and surface sites
  - Underground – less constraints on energy upgrade
  - Surface – lower cost and faster to first physics
- Sustainability - construction + operations CO_2 emissions per % sensitivity on couplings
  - Polarization and high energy to improve sensitivity
  - Construction CO_2 emissions → minimize excavation and concrete
  - Operations → limit power, decarbonization of the grid and dedicated renewable sources

Surface-Site Mockup



Precision-Weighted Carbon Footprint



250 GeV CoM - Luminosity - $1.3x10^{34}$

Parameter	Units	Value
Reliquification Plant Cost	M$/MW	18
Single Beam Power (125 GeV 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
Cryoplant Electrical Power	MW	60
Accelerator Complex Power	MW	~50
Site Power	MW	~150

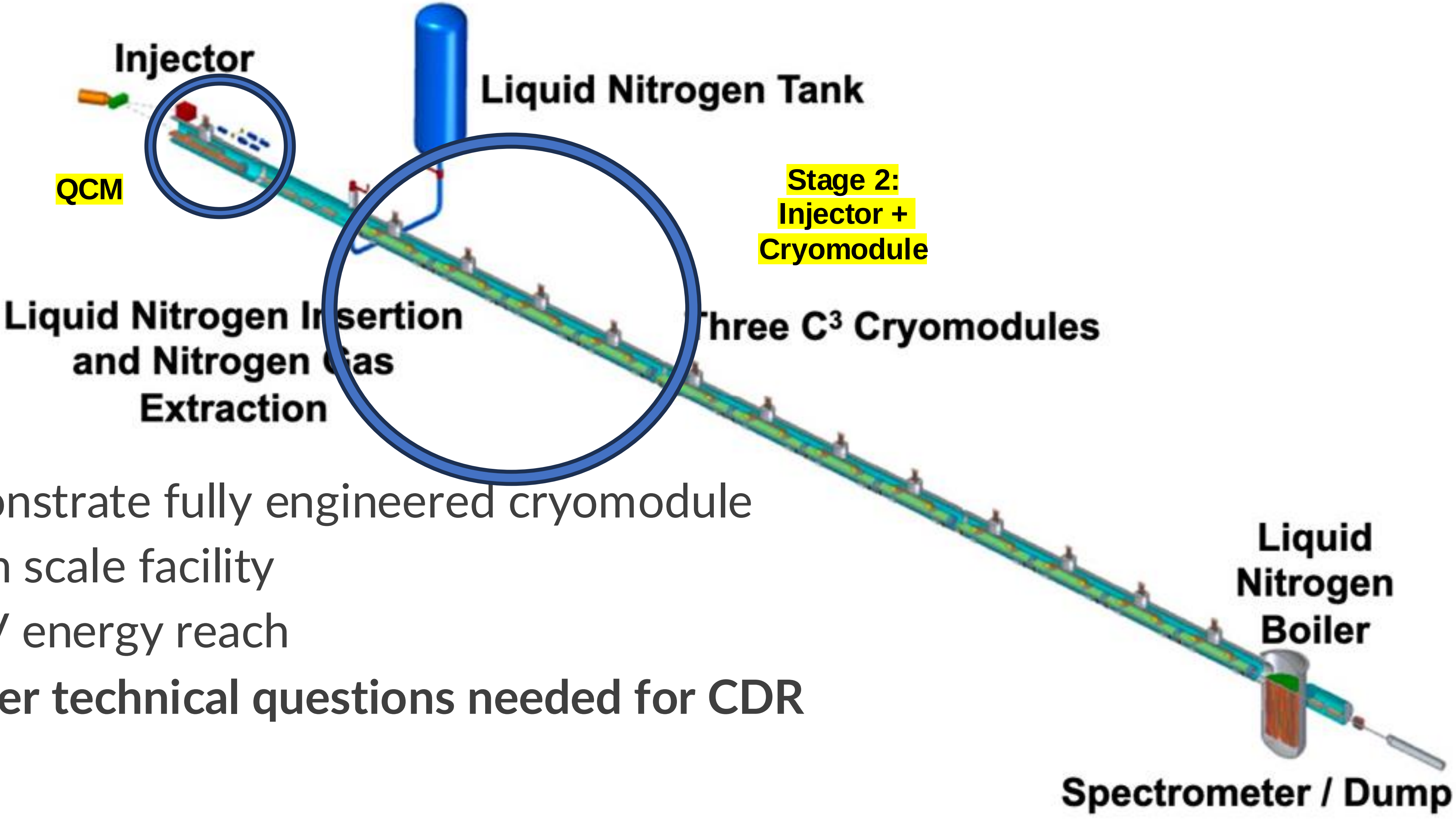
PRX Energy 2.4 (2023): 047001

Table of Parameters

- Updated parameters from LCWS 2024

Scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch Charge [nC]	1	1	1	1
Crossing Angle [rad]	0.014	0.014	0.014	0.014
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	$\sim$150	$\sim$175	$\sim$110	$\sim$125

The Complete C^3 Demonstrator



Demonstrate fully engineered cryomodule

~50 m scale facility

3 GeV energy reach

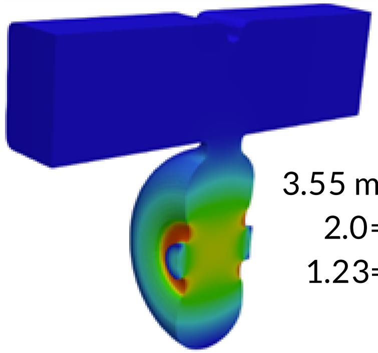
Answer technical questions needed for CDR

Ongoing R&D

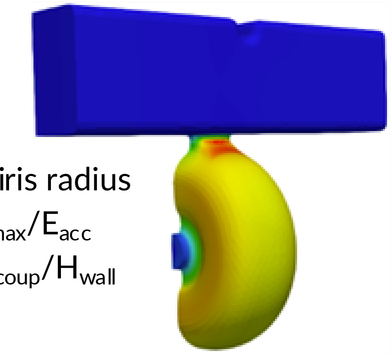
Alignment and Vibrations

System level optimization essential for achieving performance

RF Structure Optimization



3.55 mm iris radius
$2.0 = E_{max}/E_{acc}$
$1.23 = H_{coup}/H_{wall}$

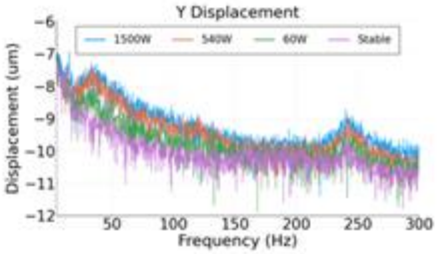


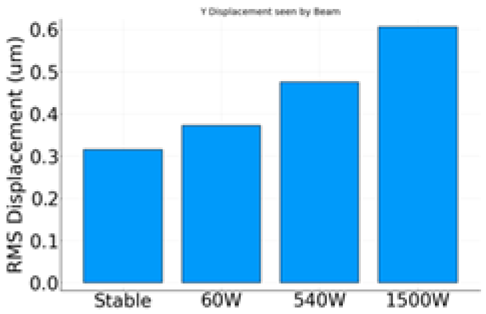
Electric Field

Magnetic Field

M. Shumail, Z. Li

Vibration Measurements and Analysis





RadiaBeam

Z. George, V. Borzenets, A. Dhar, D. Palmer

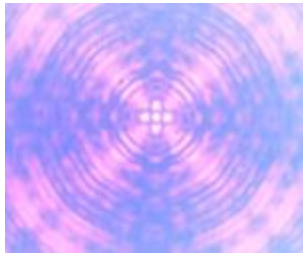
Two-Phase Fluid Simulations

FAMU-FSU College of Engineering

K. Shoele

Precision Short and Long Range Alignment

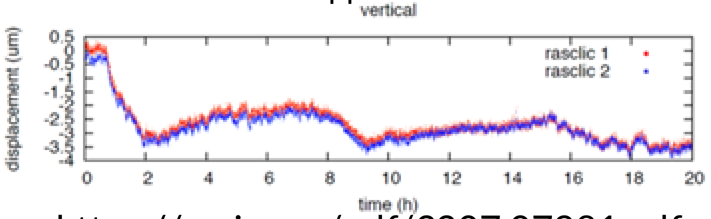
H. Van Der Graaf



Nikhef

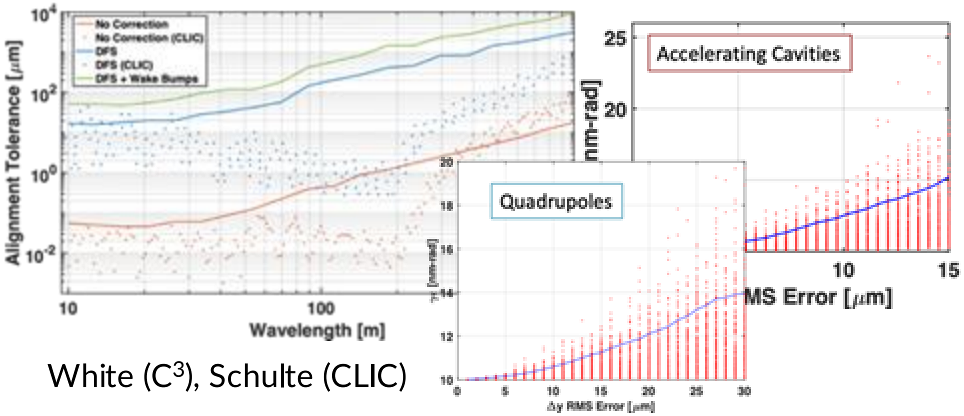
100 nm resolution

Approved effort to test cold



https://arxiv.org/pdf/2307.07981.pdf

Main Linac Beam Dynamics



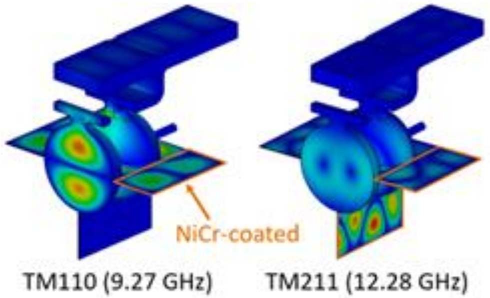
White (C^3), Schulte (CLIC)

Alignment Parameters	Units	Value
Raft Components	μm	5
Short Range (~10m)	μm	30
Long Range (>200m)	μm	1000
Structure Vert. Vibration	μm	9
Quad Vert. Vibration	nm	15
BPM Resolution	μm	0.1
BPM-Quad Alignment	μm	2

Beam Dynamics and Luminosity Studies

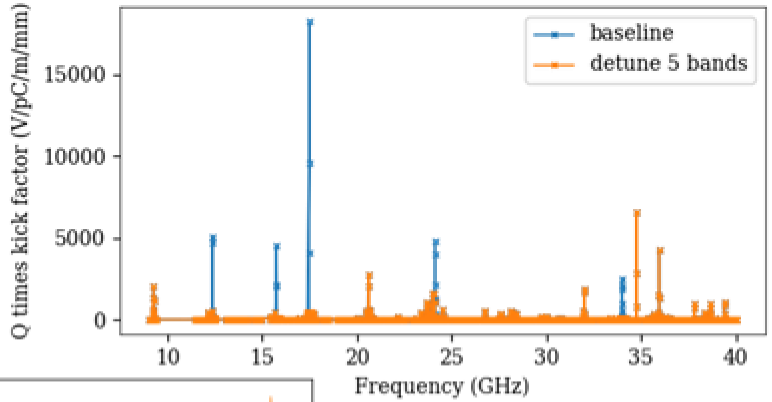
Studies ongoing towards ensuring target luminosity

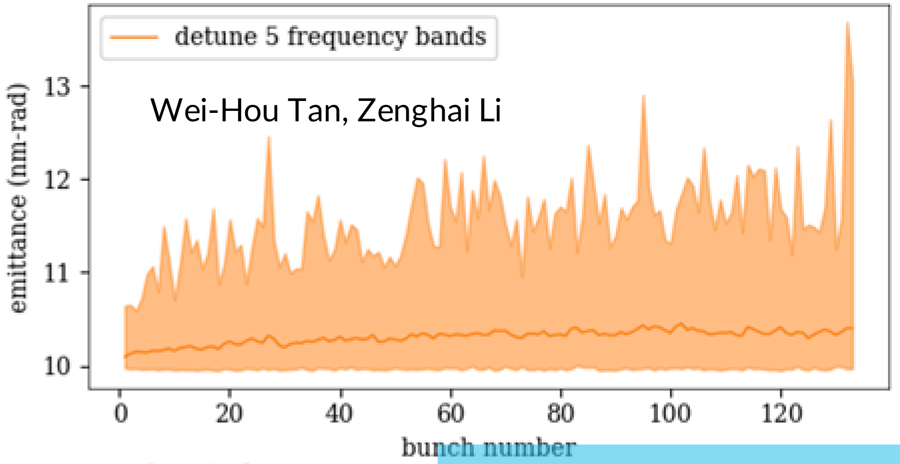
Emittance Preservation with HOM Suppression



H. Xu et al., LANL

Damped / Damped-Detuned Spectrum



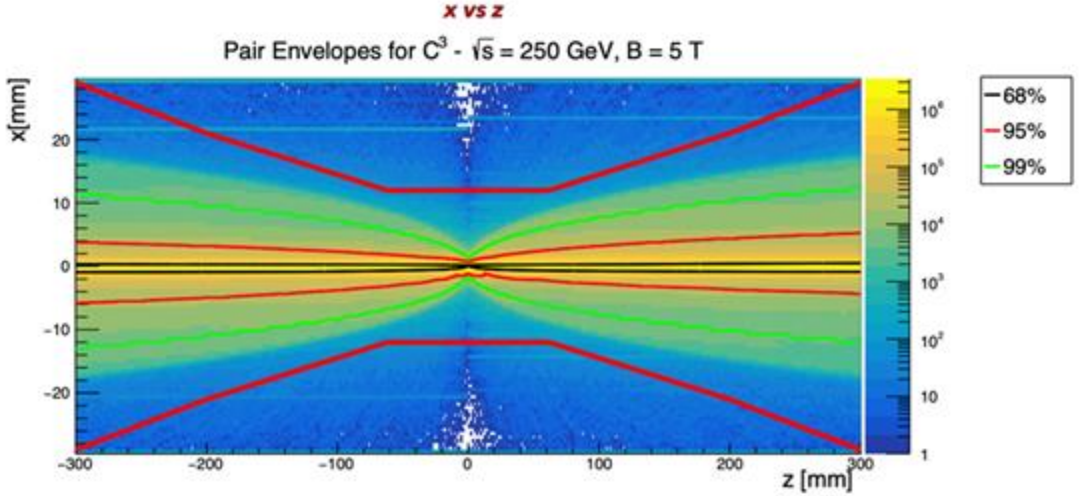


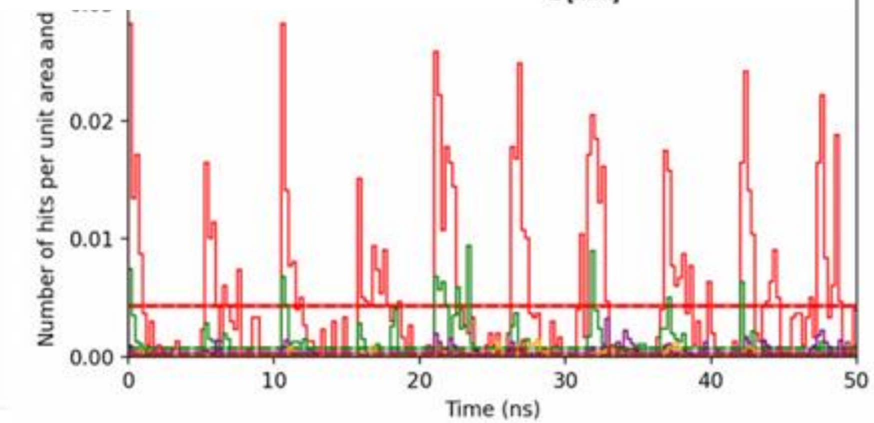
Wei-Hou Tan, Zenghai Li

Compatible with ILC-like Detector

Ntounis, Gray, Vernieri

The pair background envelopes for C³ are well contained within the beam-pipe.





See C3 talks at ECFA Workshop on e+e- Higgs/EW/Top Factories

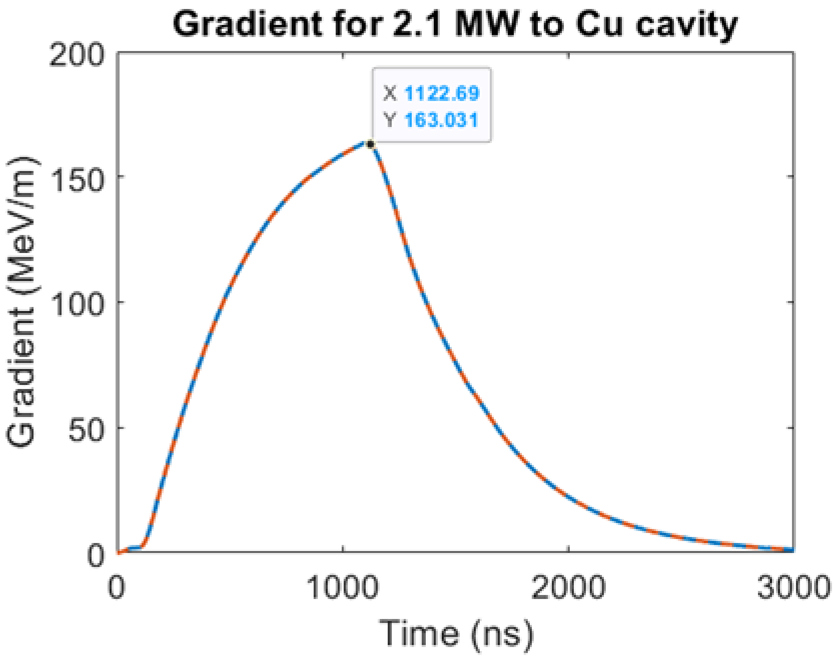
https://agenda.infn.it/event/34841/

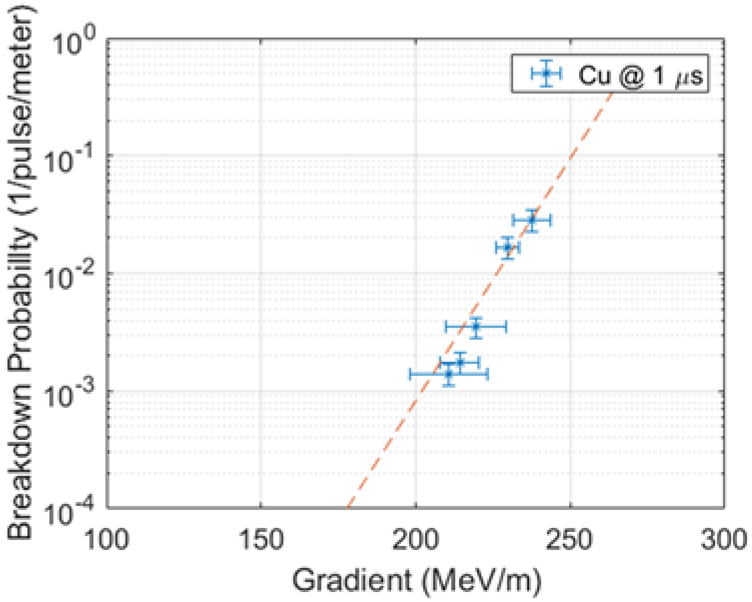
Opportunities to Collaborate: DR, Bunch Compressor, BDS, …

Single Cell Cryogenic High Gradient Tests

High power tested up to 5 MW per cavity with Cu and CuAg

- CuAg proven to give higher gradient
  - First demonstration of Cu and CuAg at C-band in cryo
    - Corresponding to fields >200 MeV/m

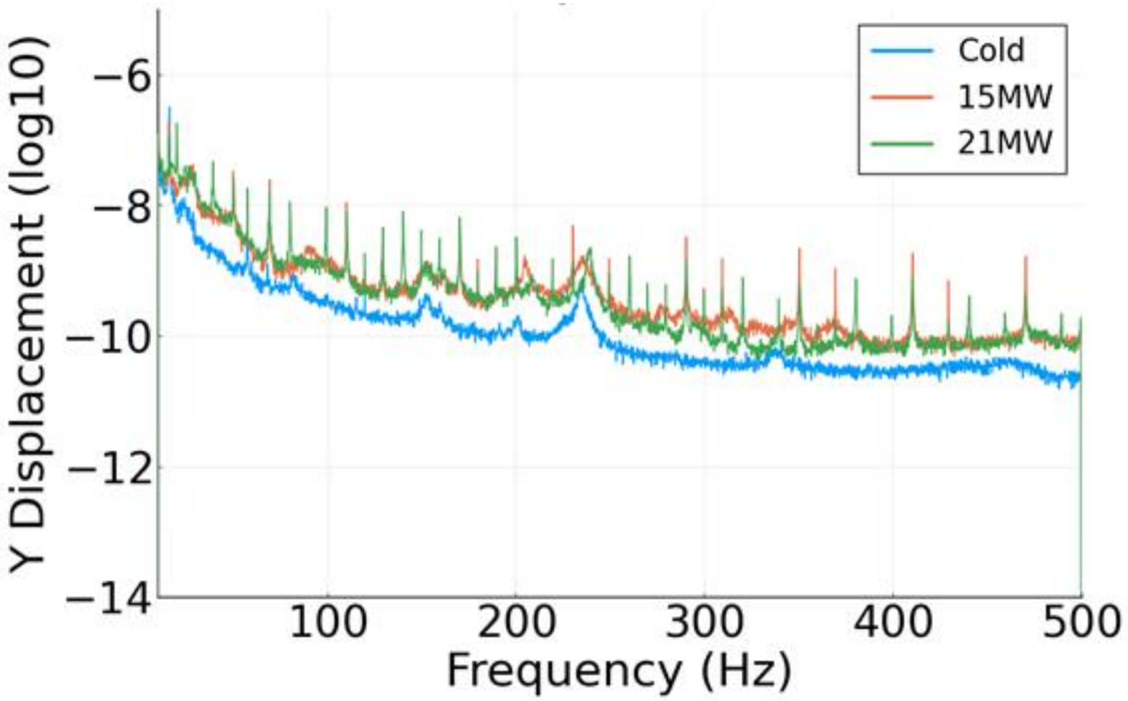


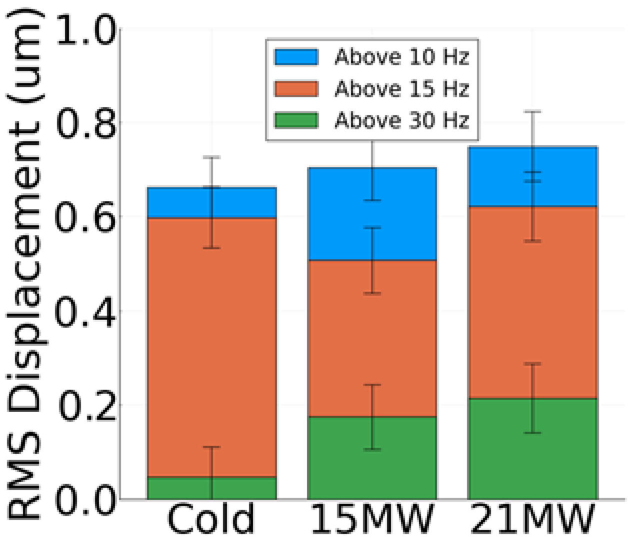


Meter-long Linac Cryogenic High Gradient Tests

Conditioned Linac at Radiabeam up to 20 MW, 60 Hz, and 1 µs

- Conditioning limited by klystron, not structure
- Accelerometer measurements at max power showed sub-micron displacements, even with mechanical propagation from outside the bunker





RF Source R&D

Special Thanks to Brandon Weatherford, Erik Jongewaard, Mohamed Othman, Ann Sy and many others…

RF Sources Requirements for C^3

50% [65%] RF Source Efficiency, 65 [80] MW peak power, 2 [1] μs, 250 [550] GeV CoM, 60 Hz

Imposes requirement that circuit efficiency be pushed to ~70% or greater

- Significant ongoing work (see next slides and this whole workshop)

Solenoidal electromagnet consumes too much power

- XL4 solenoid consumes >20 kW average power
  - Needs to go to near zero
  - Periodic permanent magnets (PPM)as an appealing option
  - Focus of Next Linear Collider (NLC) program

RF Sources Available vs. Near Term Industrial Efforts

RF sources and modulators capable of powering CCC-250 commercially available

Plan to leverage significant developments in performance (HEIKA) of high power rf sources – requires industrialization

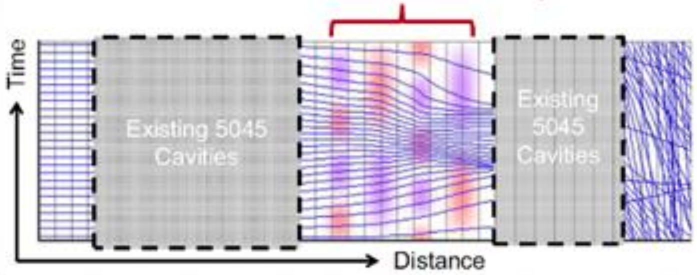
Los Alamos
NATIONAL LABORATORY
EST.1943

New 50 MW peak power C-band klystron installed in September 2019

BVEI X-band 50 MW 57% COM Prototype

SLAC BAC Prototype

S-band Retrofit +10% efficiency, 73 MW

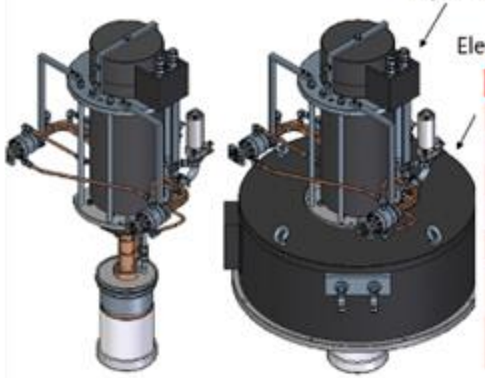


Near Term Industry

20-MW X-band Klystron

Klystron: E37116 Perveance : 1.25

Electromagnet: VT-68970



Parameter	Sim. Target	Design result
Beam voltage[kV]	265 (<290)	265
Beam current [A]	170.3 (<195)	170.3
Output power [MW]	>23	24.3
Efficiency [%]	>51	53.8
Drive power [W]	~120 (<400)	120
Max. electric field strength [kV/mm]	<64.5 (at 1.5 μs)	60.4
Stability	No reflected electrons	OK

* Actual efficiency is estimated to be 46 - 48%.

Canon

CANON ELECTRON TUBES & DEVICES CO., LTD.

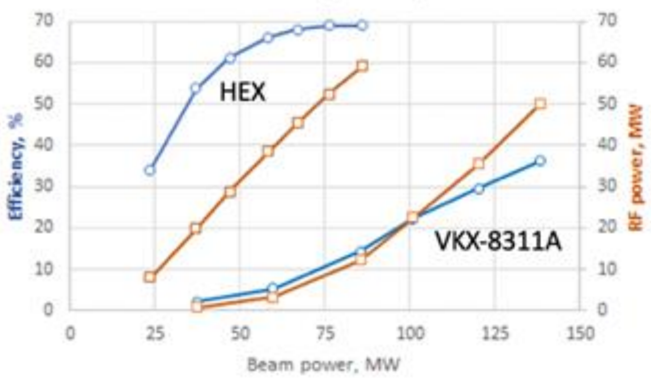
Two tubes have been built and tested up to 20MW

High Efficiency Klystrons

Please See I. Syratchev's Talk for Many Great Examples from Designs to Prototypes

Retro-fit High Efficiency 50 MW, 12 GHz klystron (CERN/CPI).

Saturated efficiency & RF power

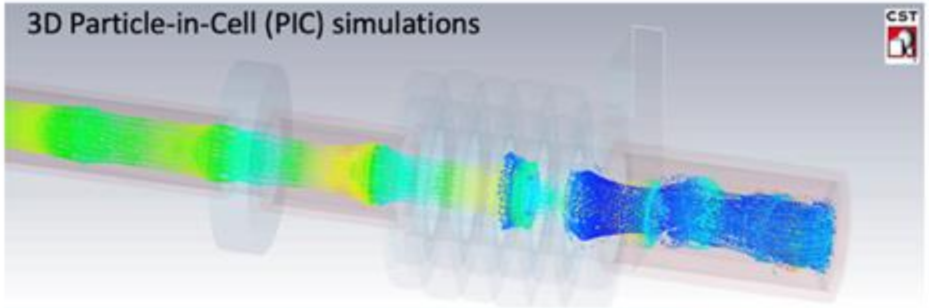


- Re-used solenoid.
- Increased life time (> factor 2)
- Reduced modulator power (~ factor 2)
- Increased power gain (10 dB)
- Reduced solenoidal field

Prototype fabrication is under negotiation within CPI/INFN/CERN collaboration.

I. Syratchev, CLIC PM #41, 13.12.2021

3D Particle-in-Cell (PIC) simulations



	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	59
Efficiency, %	36.2	69
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.37
RF circuit length, m	0.316	0.316

https://indico.cern.ch/event/1101548/contributions/4635964/attachments/2363439/4034986/CLIC_PM_13_12_2021.pdf

75XP Series Klystrons as RF sources for C^3

The SLAC 75XP is a PPM-focused, X-band klystron designed for 75 MW peak power

Motivated/funded by the Next Linear Collider (NLC) program

Years of engineering effort → attractive candidate for a potential C^3 demonstrator

Specification	Target
Beam Voltage	490 kV
Beam Current	257 A
RF Output Power	75 MW
Frequency	11.424 GHz
RF Pulses	1.5 µs @ 60 Hz
Saturated Gain	55 dB
Bandwidth	75 MHz
Efficiency	55%

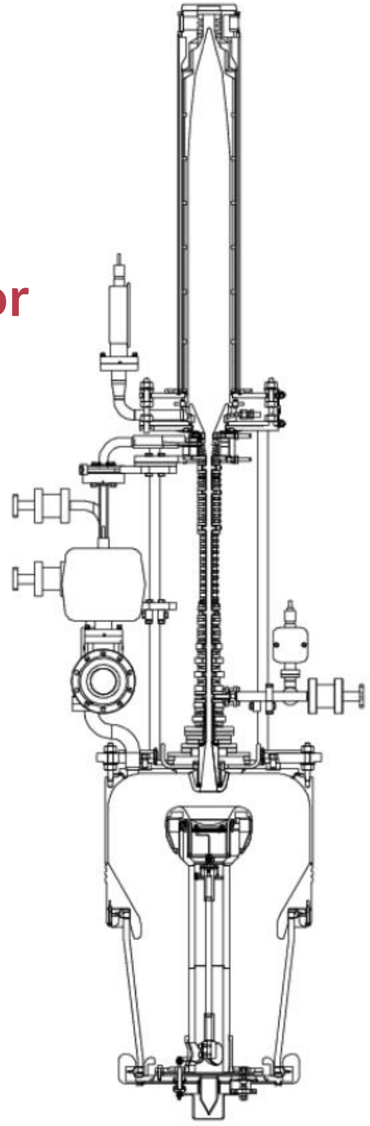
Design Features:

Large "DESY" HV gun insulator

7-cavity gain circuit

5-cell extended-interaction output

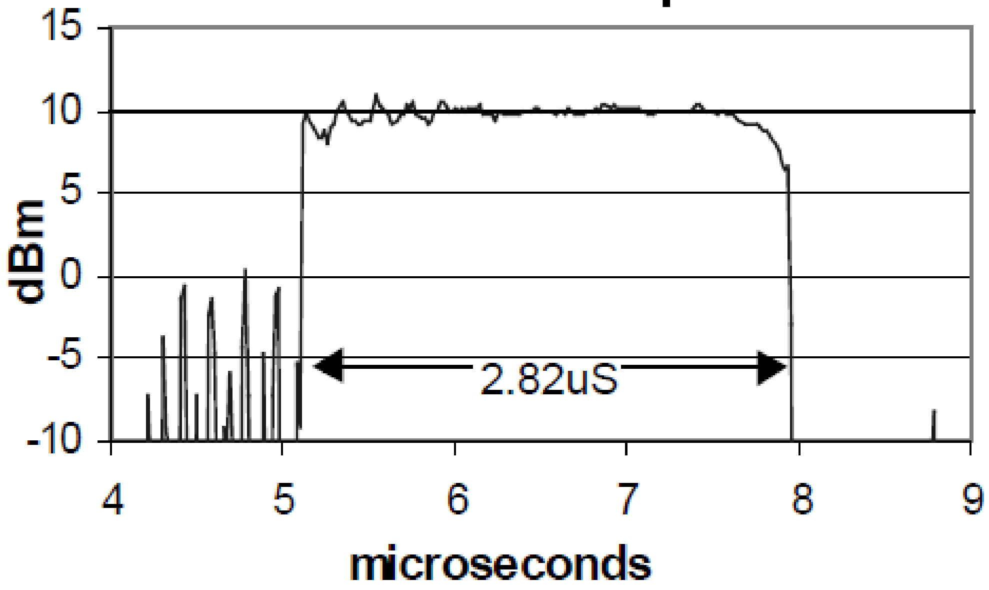
Isolated collector



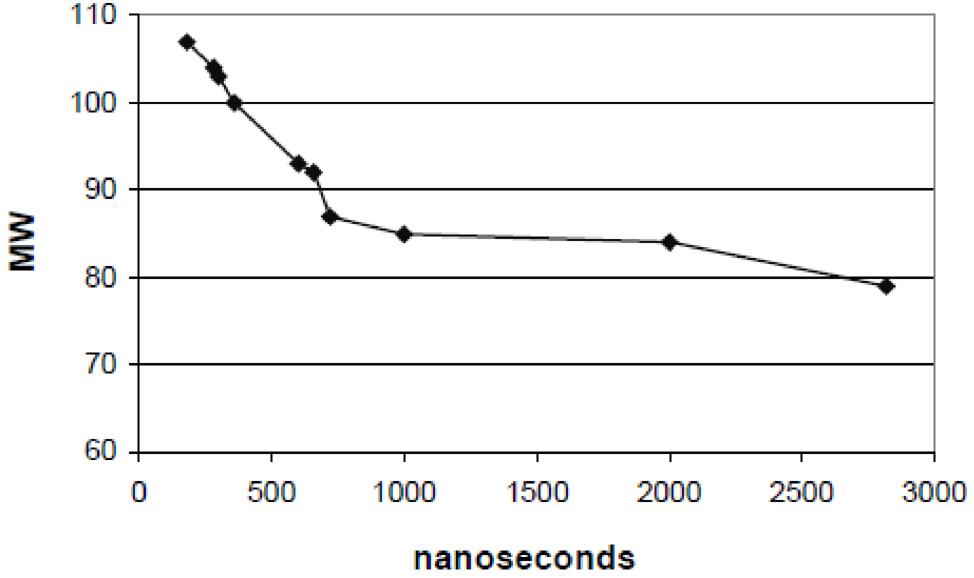
75XP1 Test Results

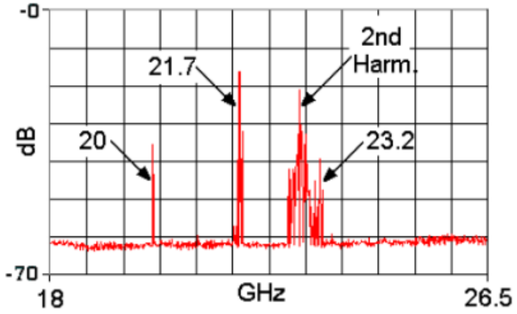
- **The original 75XP-1 was built, and eventually reached 79 MW at 2.8 μs in test**
- Power levels exceeding 100 MW were measured at shorter pulse widths

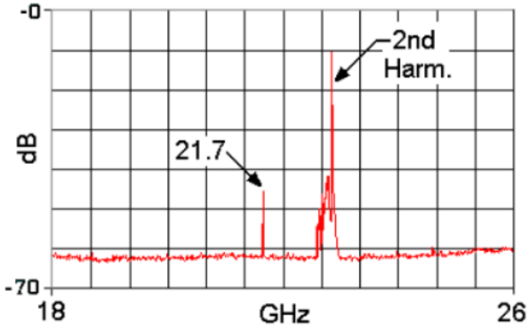
RF Pulse Envelope at 75 MW



Peak RF Power vs Pulse Width

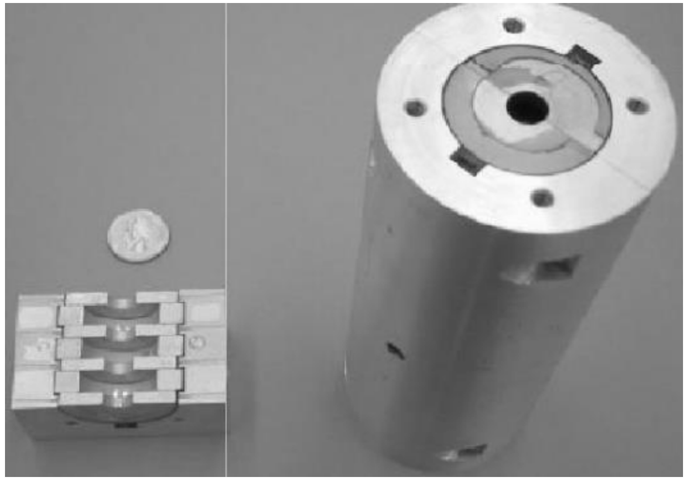






Gun and output oscillations were observed, but corrected after rework

Lessons learned from the 75XP Series

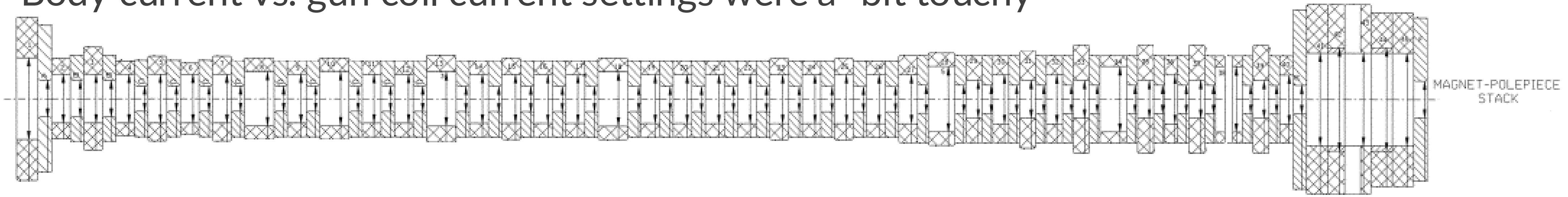


75XP series met specifications, and in some cases exceeded them (over 100 MW at < 500 ns)

Gun & output oscillations were a recurring but solvable challenge.

Key issues identified:

- 75XP1, XP Diode, and 75XP3-2 were susceptible to gun oscillations
- Magnetic circuit is quite complicated (i.e., expensive & hard to build)
- At high duty, runaway condition with NdFeB magnets overheating
- Body current vs. gun coil current settings were a "bit touchy"



The 75XP4 Redesign

The next design iteration, 75XP4, was partially complete when NLC was cancelled

The goal was to make the 75XP4 more robust against 75XP3 failure modes:

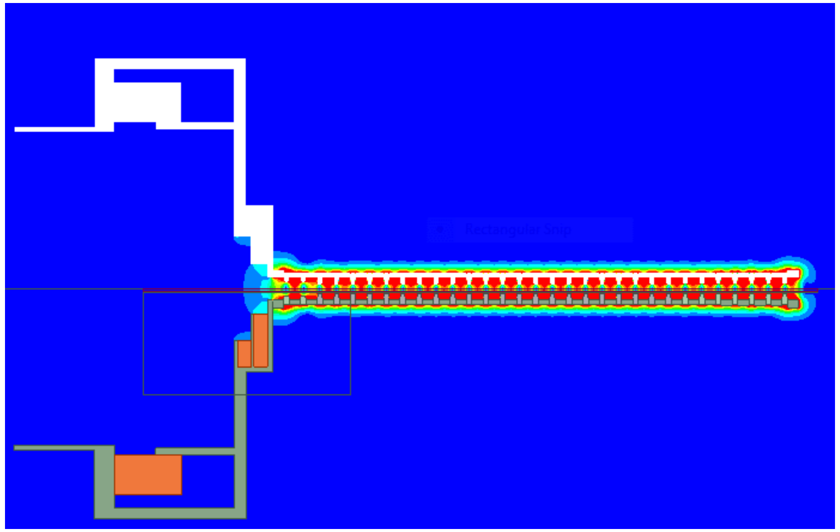
- Potential for gun and output oscillations
- Complexity of PPM stack
- Runaway conditions of overheating magnets near output
- Design sensitivity of gun coils
- High gradient RF breakdown in output

For the C^3 demonstrator source, we simulated the design that was already completed, and made further changes to address past issues.

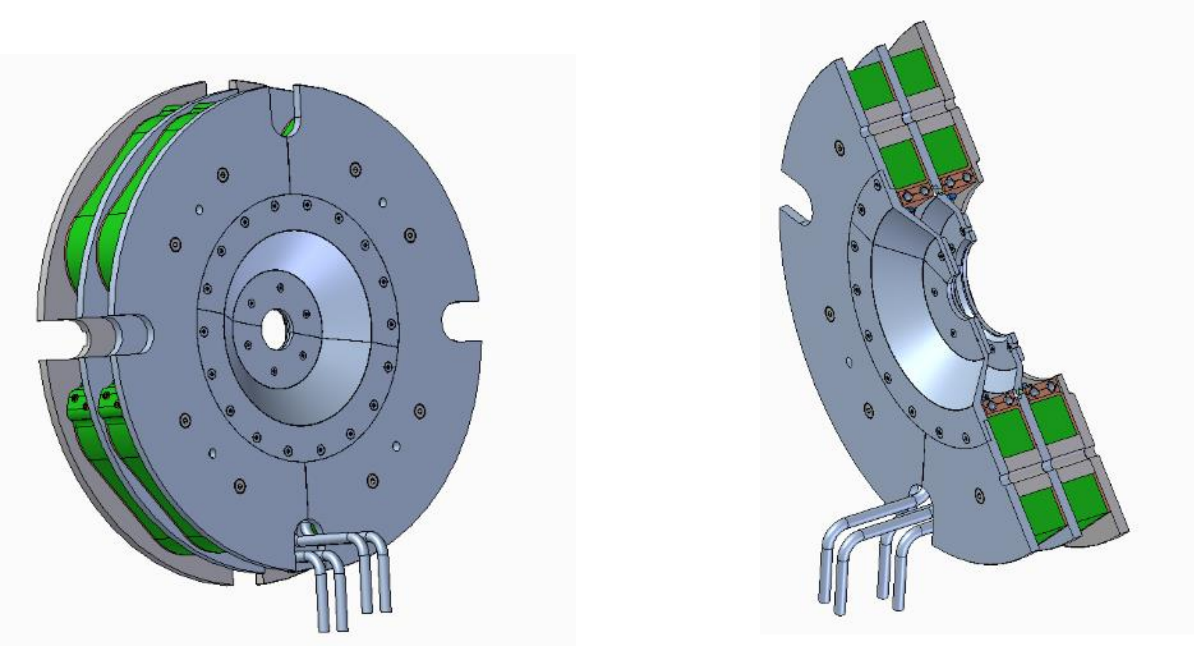
75XP4 Magnet Modifications

75XP4 magnet stack is much simpler than the previous 75XP tubes

- All NdFeB magnets replaced with SmCo – higher grades available today
- Only 3 magnet variants – reduced from ~40 unique magnets
- Nominal design will use wound-on solenoid gun coils
- New design of slide-in off-axis pot coils is being simulated now



Simplified magnet stack model in Ansys Maxwell

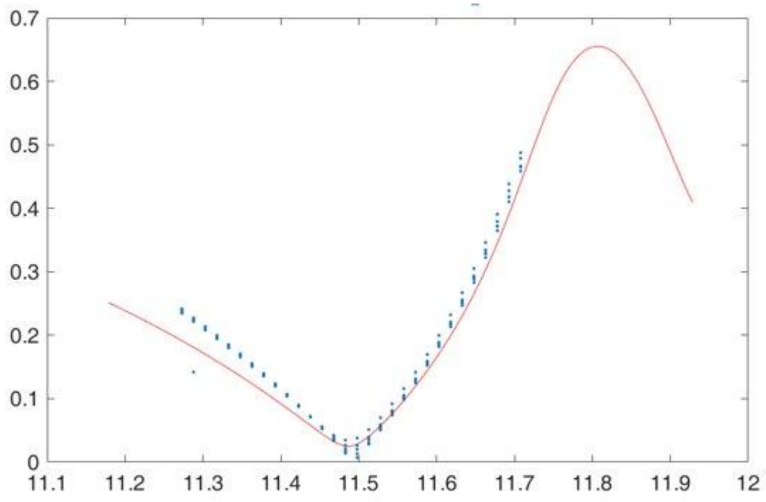


Off-axis coils for easier assembly

75XP4 Cavities & OP redesign

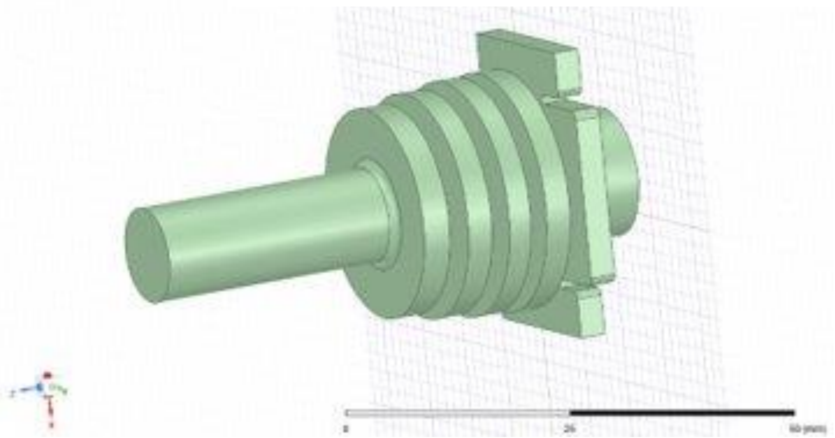
Original output cavity design (coupler cell) at risk of RF breakdown

- Output coupler cell was reoptimized to meet more modern RF breakdown criteria
- Original design: Sharp edges and small radius nose led to high surface currents
- New design: “Racetrack” coupler layout to minimize gradients and surface currents
- RF pulse heating reduced by ~3x; cell impedance unchanged from original design

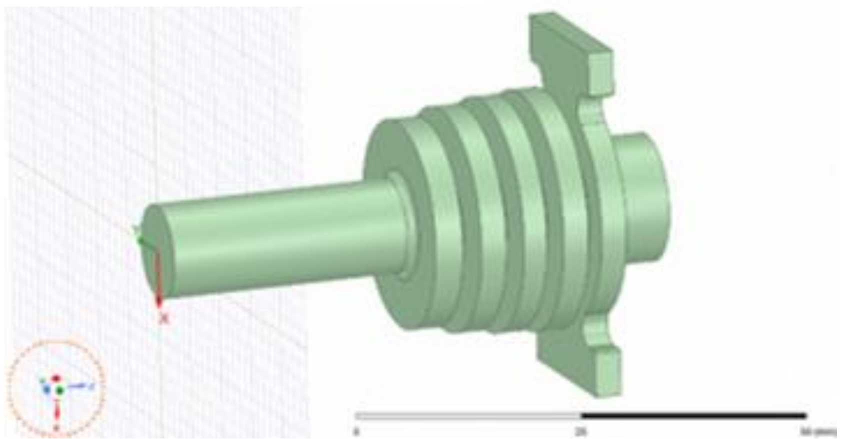


Old vs. New S_{11} vs Freq.

Output Pulse Heating Reduced from 152 K → 50 K



Original (square) output cell



New (racetrack) output cell

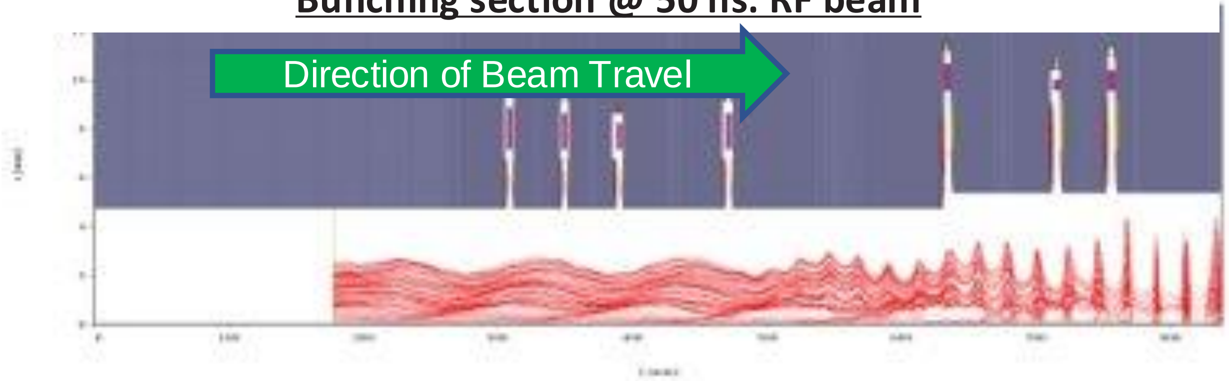
MAGIC2D PIC Simulations

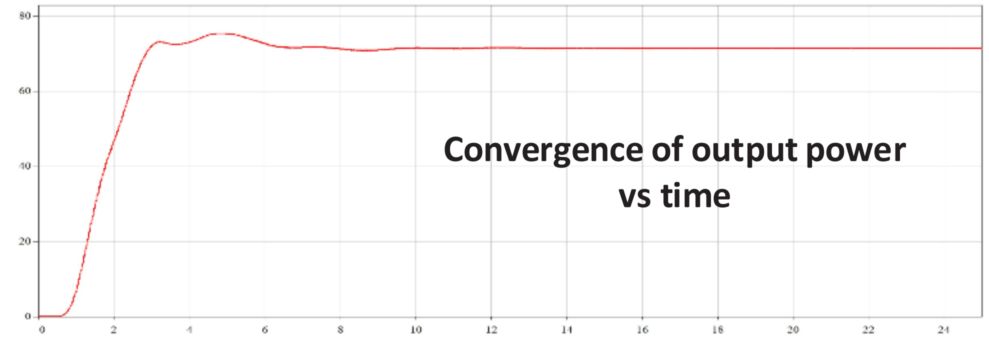
RF performance simulated in MAGIC 2D

- 72 MW achieved with 40 W drive; Gun coil & beam voltage may be adjusted in test

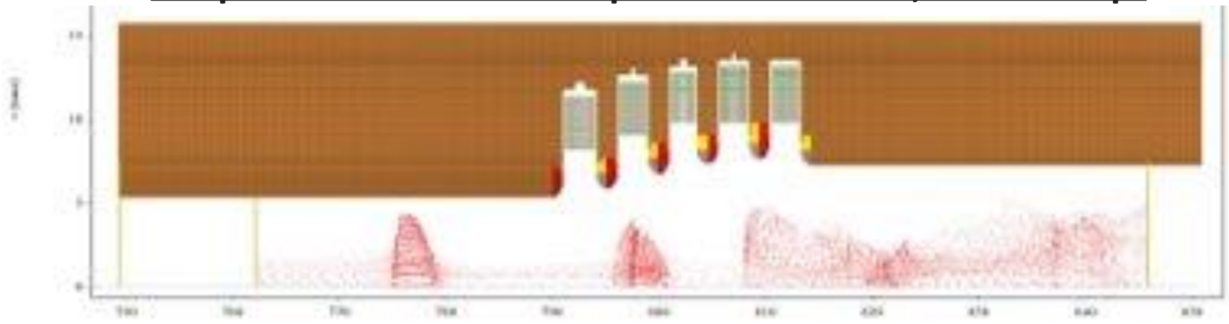
Will confirm models in CST Microwave Studio, TESLA-Z, and MAGIC 3D while build proceeds

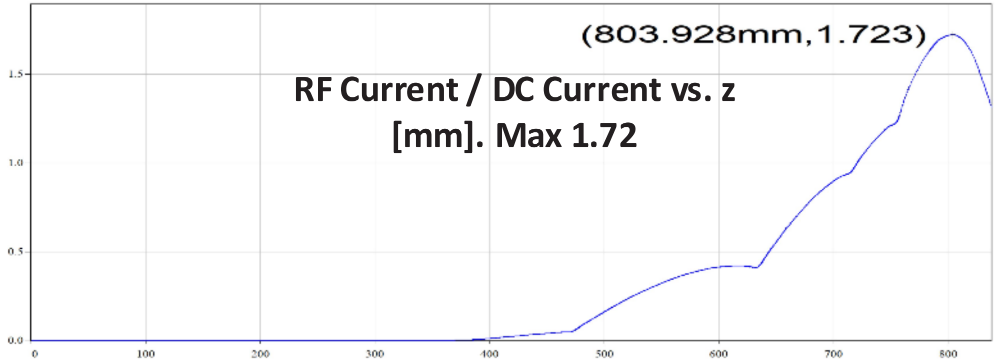
Bunching section @ 50 ns: RF beam



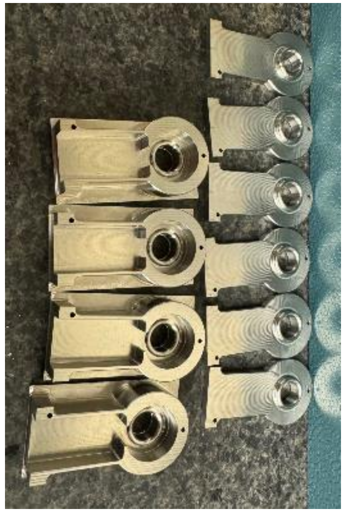


Output structure: 72 MW power extraction, no intercept





First prototype 75XP4 is under construction now



Thank you!

This work would not be possible without building on decades of past efforts from the former SLAC Klystron Department.

RF Source slide material from B. Weatherford talks at IVEC 2024 and LCWS 2024. Some material in this presentation was borrowed heavily from published SLAC-PUB articles and presentations by Daryl Sprehn, Arnie Vlieks, and Erik Jongewaard. Erik continues to be a fountain of knowledge for our department today.

Questions?

Backup

75XP3 Specifications

All specs identical to the 75XP1 **except:**

Pulse width target increased to 3.2 microseconds (for a while…)

Compact Gun Redesign for 75XP3

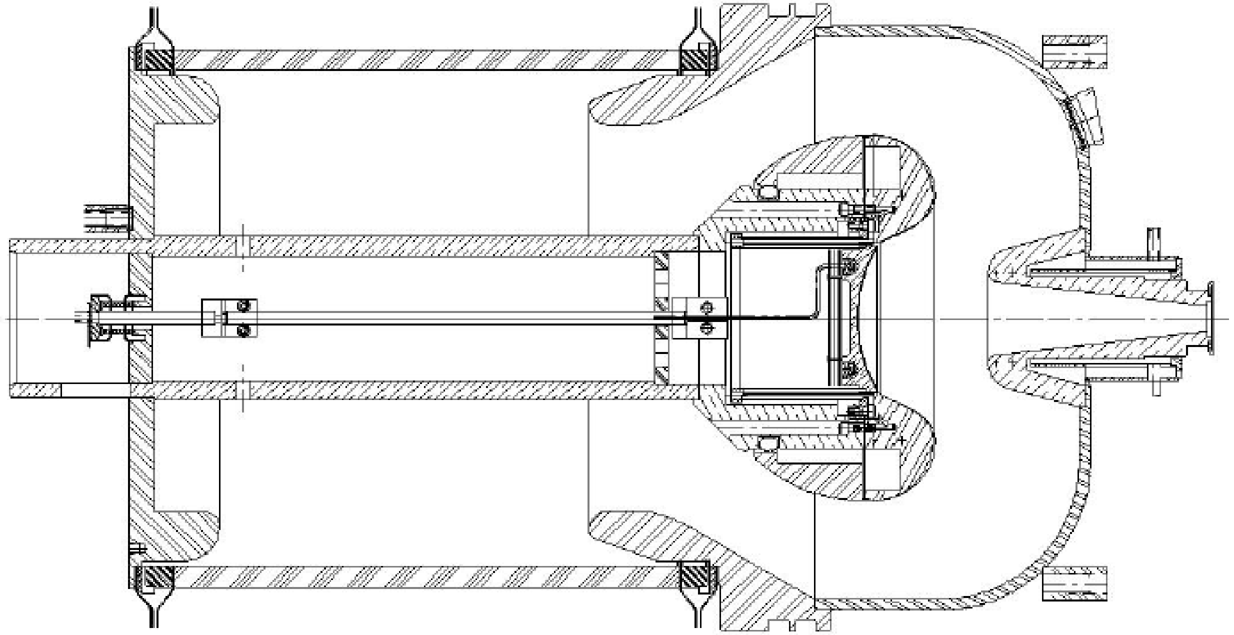


Figure 1. Electron gun outline as implemented in the XP3 klystron devices.

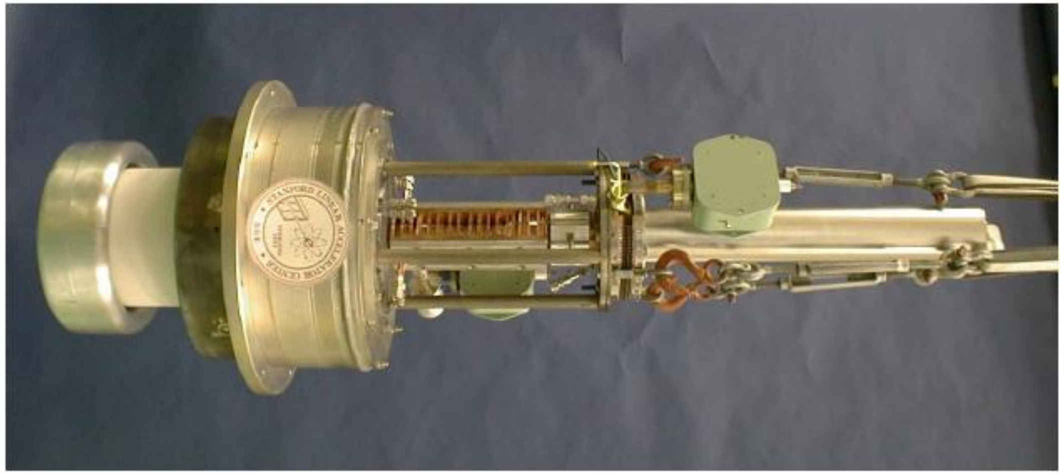
75XP3 Diode

Gun/PPM/Collector Diode was built to validate new components for the 75XP3:

- New beam tunnel size and focusing magnets
- New compact gun and collector designs
- Addition of gun coil assembly

Gun oscillation at 3.17 GHz corrected w/ loss collar

After loss collar added, 99.9% transmission, ran to full beam spec at 490kV / 3 μs / 120 Hz



SLAC

Summary of 75XP3 Serial Numbers

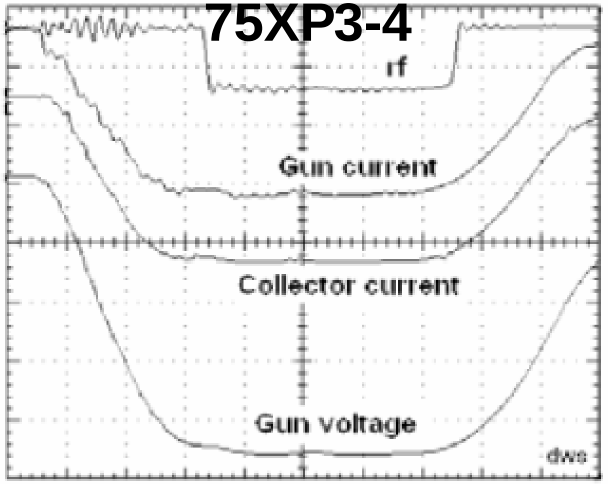
75XP3-1 (first serial number):
- First tube with clamped-on magnets
- **Result: OP Oscillation @ 11.7 GHz**
  - Arose due to a fabrication error. It is suppressed when output chain is assembled correctly

75XP3-2:
- Also used clamped-on magnets
- **Result: Died from gun arc at 3.2 microsecond pulse width**
  - Smaller gun size had reduced safety factor; also, 3.2 µs was 2x original design target
  - Also observed a gun oscillation

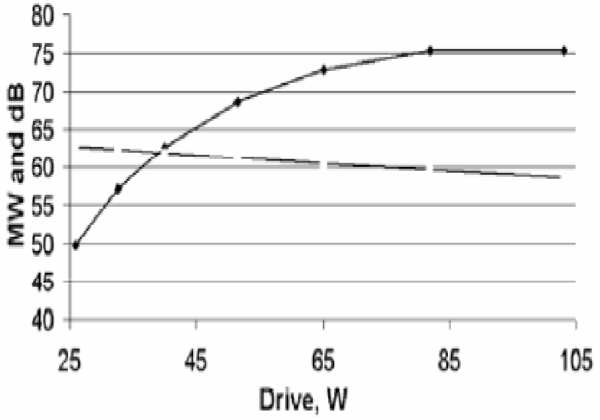
75XP3-3: Added gun loss ceramic
- **Result: Met specification**
  - 75 MW @ 120 Hz / 1.6 µs
  - NLC spec at this point was reduced back to 1.6 µs
  - Some beam intercept
  - No temperature monitoring due to clamp-on magnet stack

75XP3-4: Integral Pole Pieces
- **Result: Met specification again**
  - 75 MW @ 120 Hz / 1.6 µs
  - Beam loss was 1.3%
  - Needed slight voltage increase to meet power

RF, current, and voltage waveforms for 75XP3-4

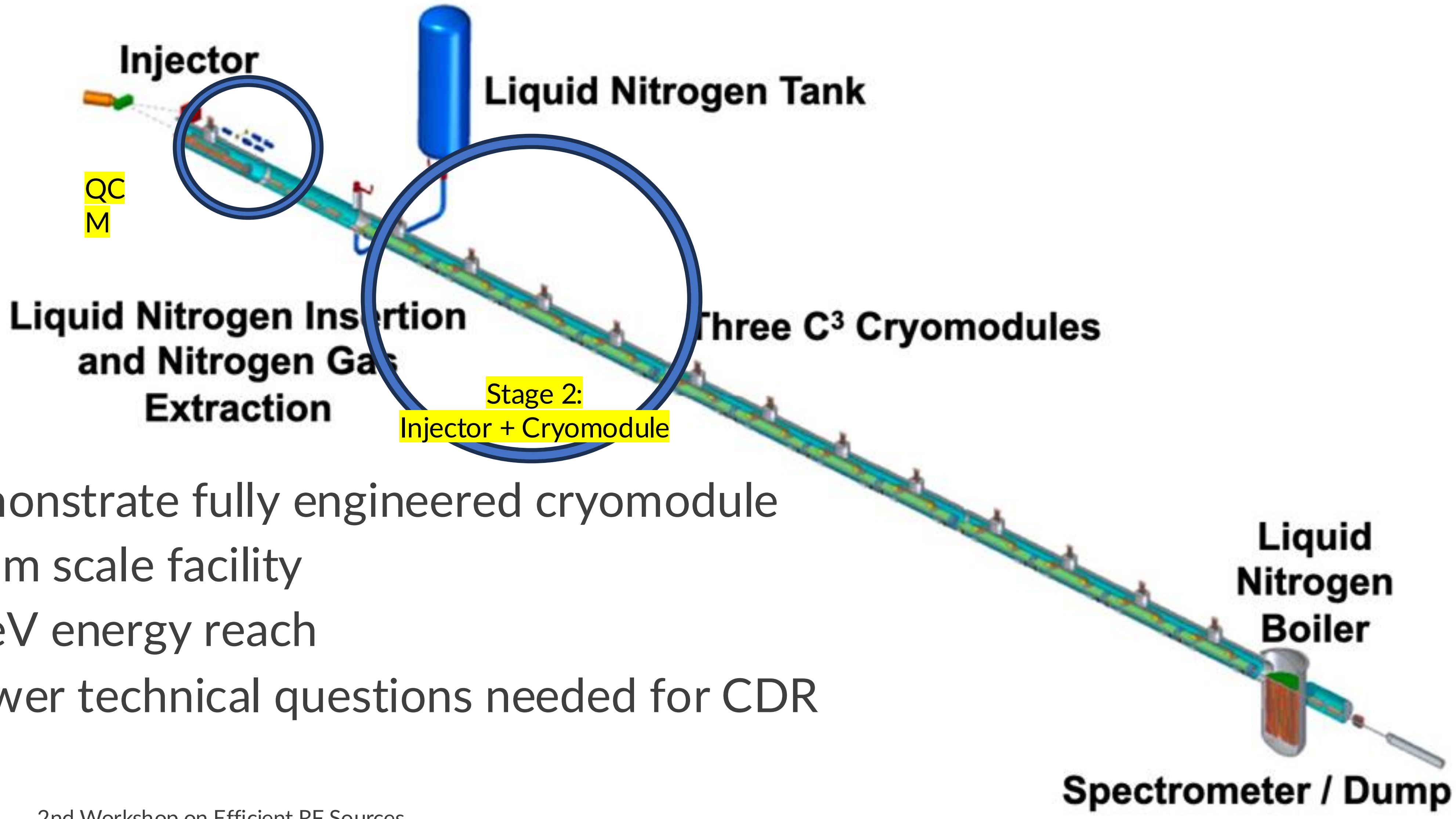


Power & gain vs. drive



Outlook

The Complete C^3 Demonstrator



Demonstrate fully engineered cryomodule

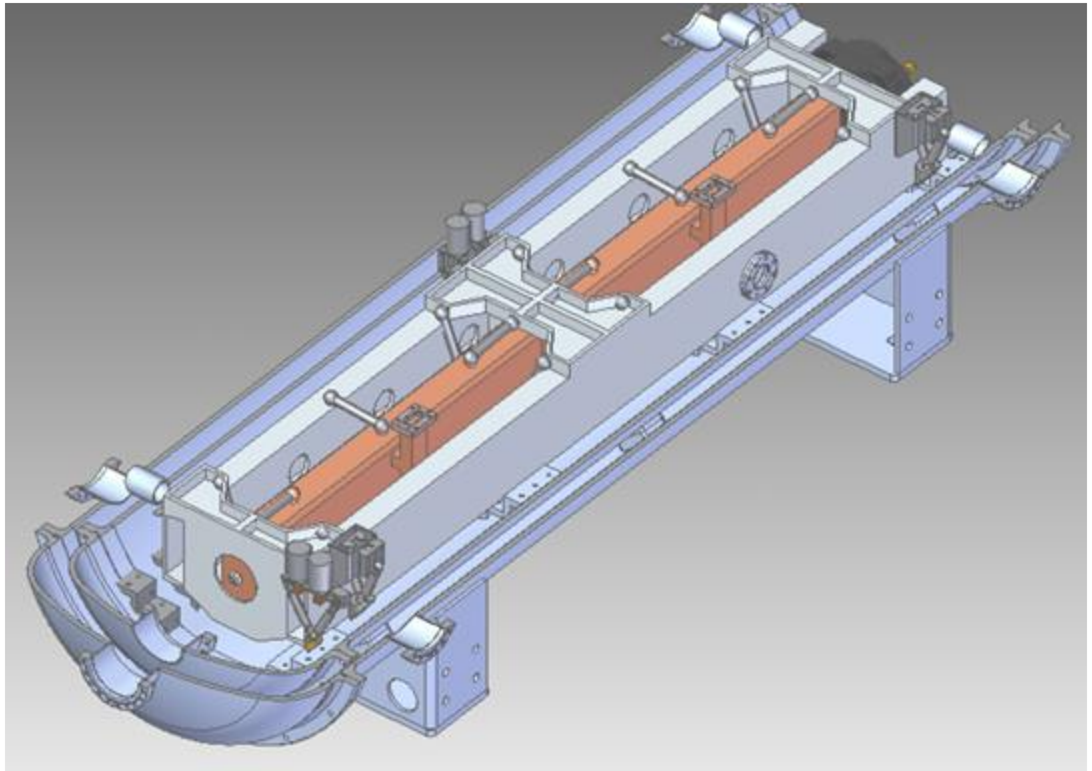
~50 m scale facility

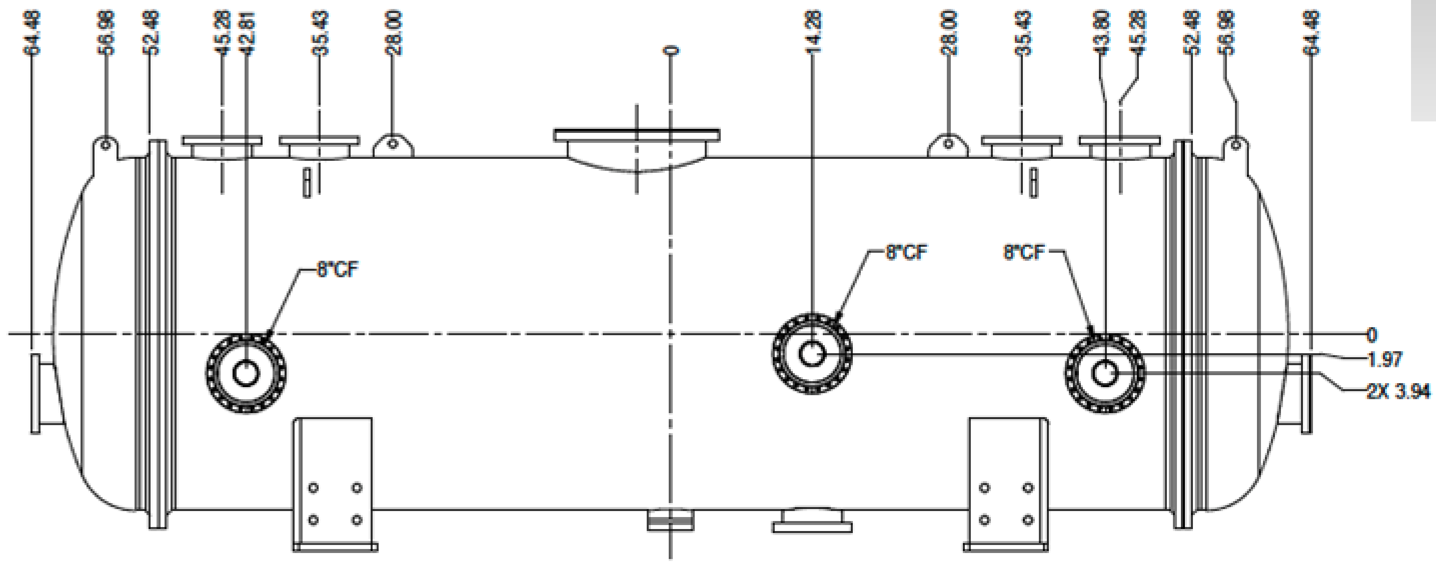
3 GeV energy reach

Answer technical questions needed for CDR

Quarter Cryomodule (QCM)

- Vacuum insulation, raft length up to 2.5 m
- Expected delivery Fall 2024
- Outfit for alignment and vibration testing
- Follow-on experiments with structures at high gradient and beam acceleration





Synergies with Future Colliders

RF Accelerator Technology Essential for All Near-Term Collider Concepts

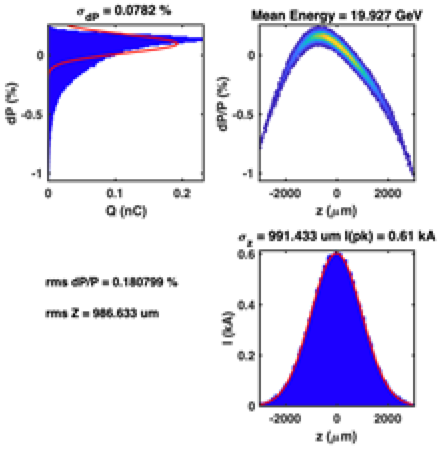
C^3 Demo is positioned to contribute synergistically or directly to all near-term collider concepts

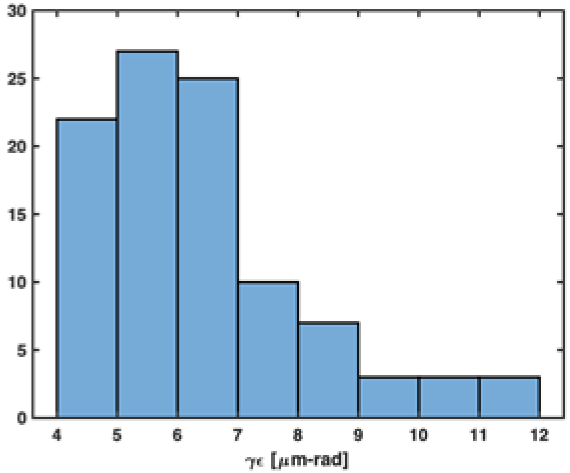
- CLIC - components, damping, fabrication techniques
- ILC - options for electron driven positron source based C^3 technology
- Muon Collider - high gradient cryogenic copper cavities in cooling channel, alternative linac for acceleration after cooling
- AAC - C^3 Demo utilized for staging, C^3 facility multi-TeV energy upgrade reutilizing tunnel, $\gamma\gamma$ colliders
- FCC-ee - common electron and positron injector linac from 6 to 20 GeV
  - reduce length 3.5X OR reduce rf power 3.5X

Wide Aperture S-band Injector Linac
$a/\lambda = 0.125$

- Planned test at Argonne
- Tracking with Lucretia includes longitudinal and transverse wakes, chromatic effects etc
- Error study is 100 seeds, 100 μm element offsets, 300 μrad element rolls (rms)
  - No corrections applied

90% seeds < 8 um-rad with lattice errors





Vibrant International Community for Future Colliders is Essential

Conclusion

C^3 can provide a rapid route to precision Higgs physics with a compact 8 km footprint

- Higgs physics run by 2040

C^3 time structure is compatible with SiD-like detector overall design and ongoing optimizations.

C^3 can be quickly be upgraded to 550 GeV

C^3 can be extended to a 3 TeV e+e- collider

With new ideas, the C^3 lab can provide physics at 10 TeV and beyond

May be possible to do physics at an intermediate stage in the construction at 91 GeV

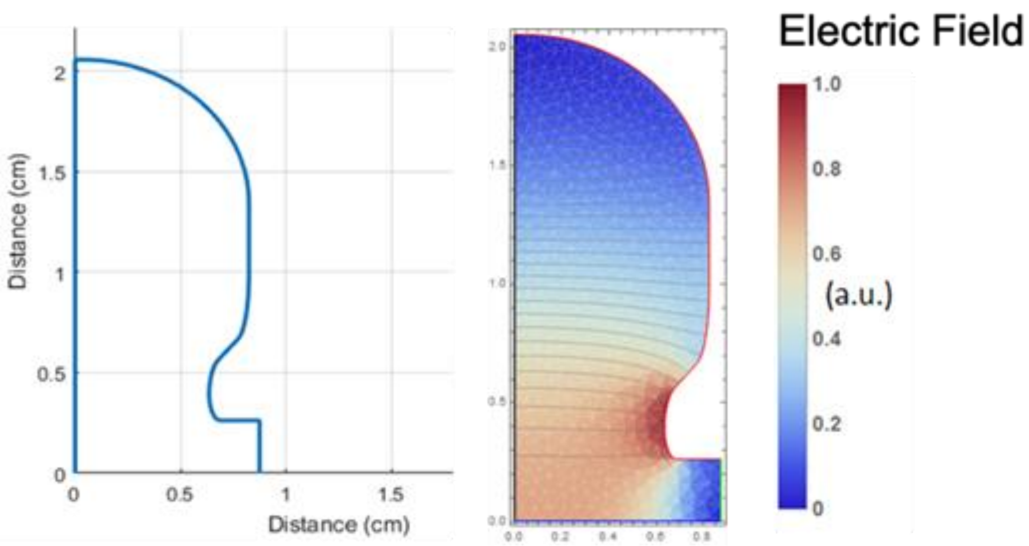
- We do not consider this a part of our baseline, but we mention the possibility in case there is community interest for a Giga-Z (2 yrs) program

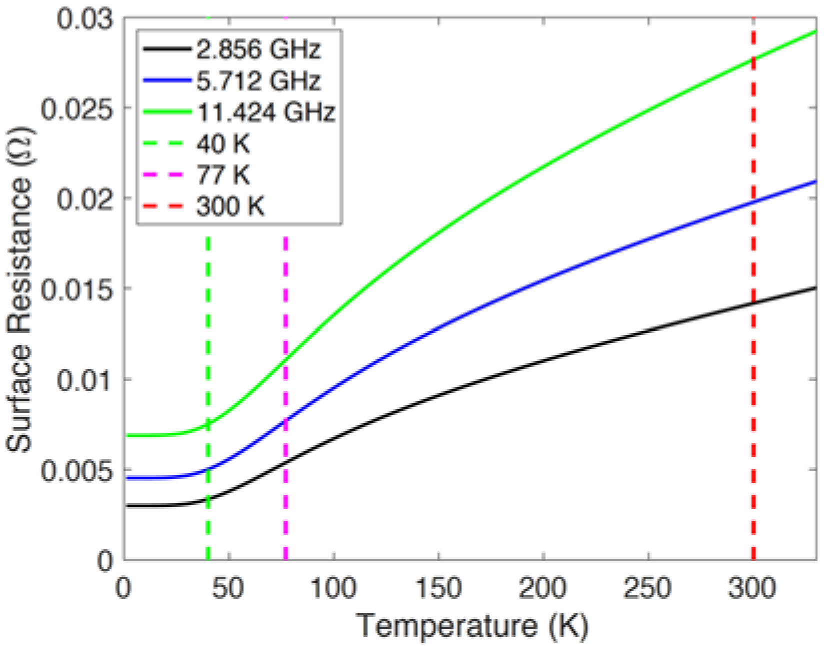
More Details Here (Follow, Endorse, Collaborate):
https://indico.slac.stanford.edu/event/7155/

Optimized Cavity Geometries for Standing Wave Linac

Small aperture for reduced phase achieves exceptional Rs
Cryogenic operation: Increased Rs, 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
C-band (5.712 GHz)	0.05	2π/3	133	300
X-band (11.424 GHz)	0.1	π	133	300

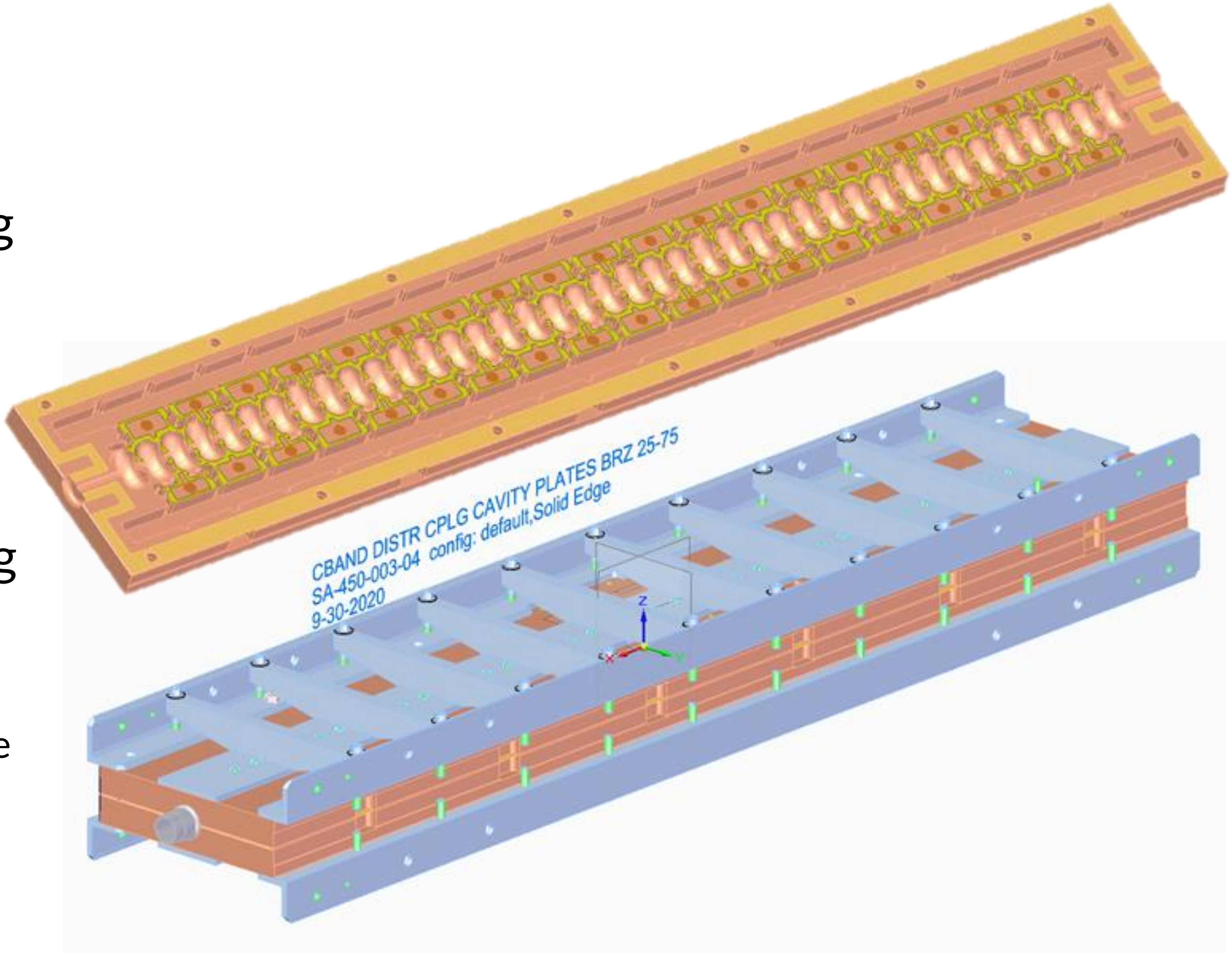




Main Linac Structure Update

Next iteration of main linac module is undergoing design

- Main goals are to address poor surface bonding along the irises and post-machining warping
- This is being addressed through the addition of an additional strongback along the center of the structure
  - Braze alloy will also be applied inside the structure close to the irises, with copper spacer to ensure braze material flow



SLAC

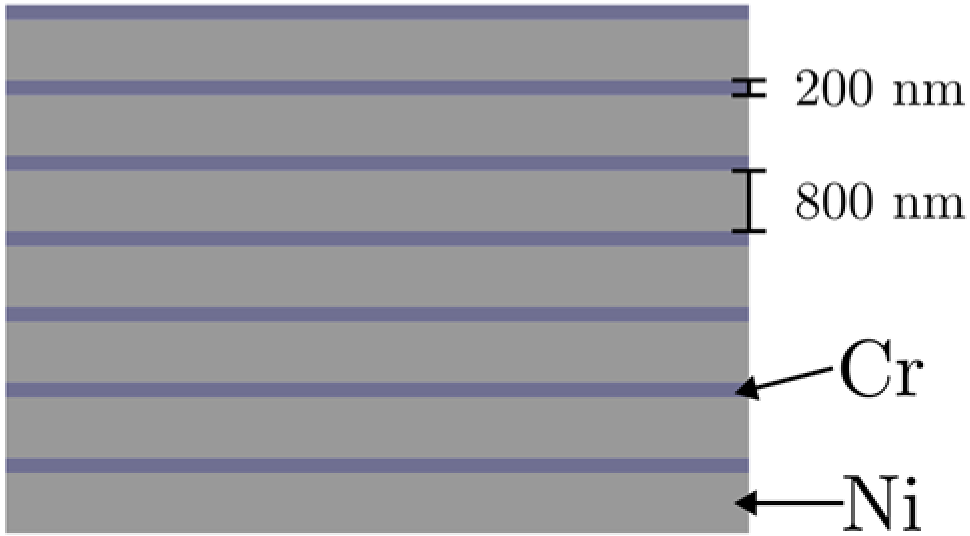
NiCr Deposition Method

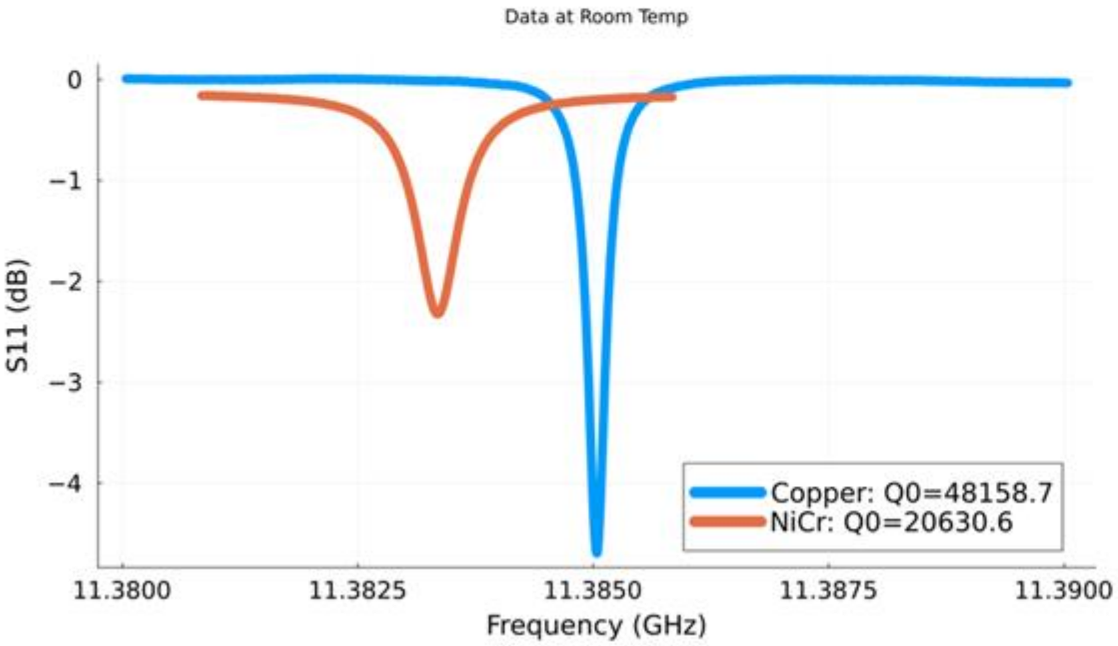
NiCr is typically sputtered for thin film applications

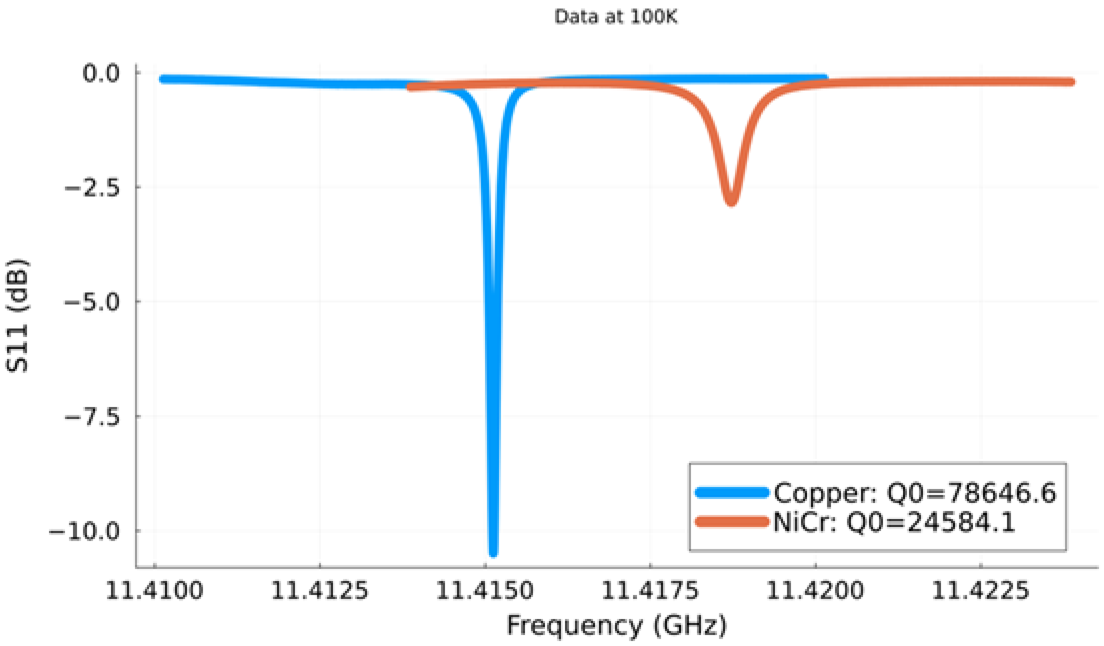
- This is not viable for coating large damping slits

Potential solution is to electroplate layers of Ni and Cr and then use a hydrogen furnace to form NiCr

- The RF loss of this fired sample was verified through S11 measurements of a resonant cavity



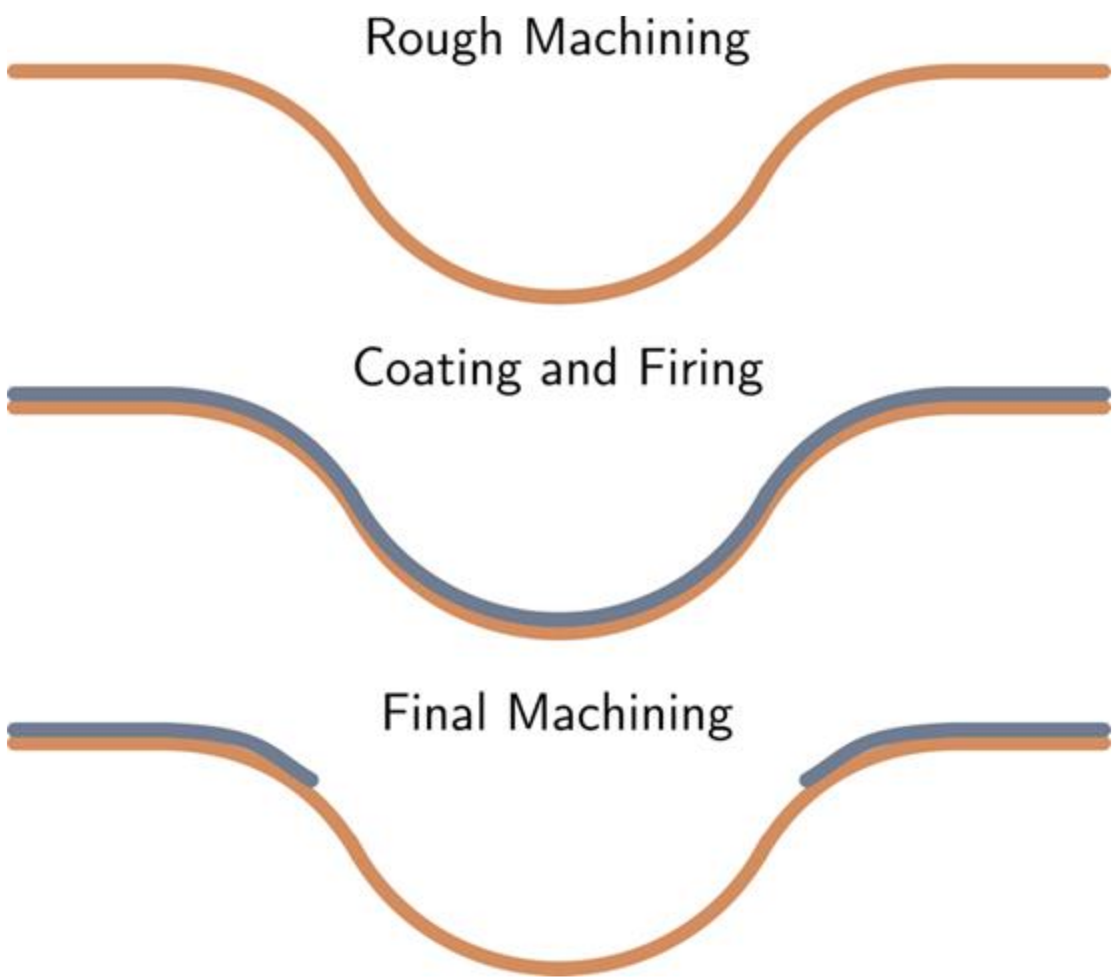




NiCr Application to Main Linac

This electroplating method provides a scalable solution for depositing NiCr on damping slits

- Linac cavities would be rough machined along with slits, waveguides, etc
- Electroplating would cover entire linac
- Final machining removes NiCr layer from unwanted areas, leaving coated slits



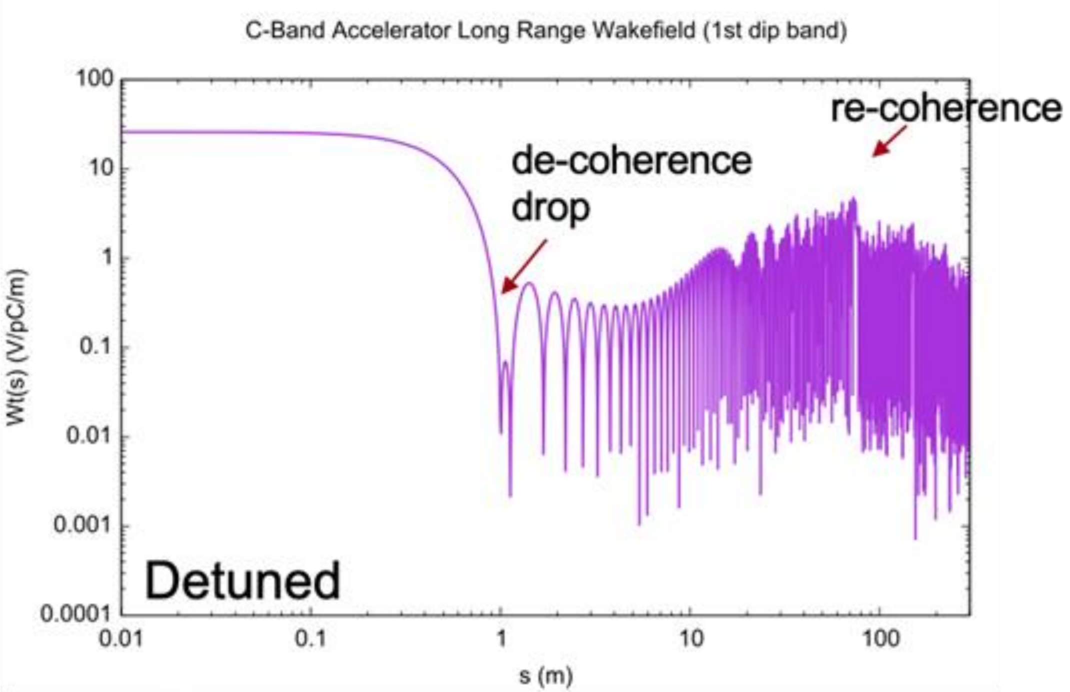
Gaussian Detuning Provides Required 1st Band Dipole Suppression for Subsequent Bunch, Damping Also Needed

Dipole mode wakefields immediate concern for bunch train

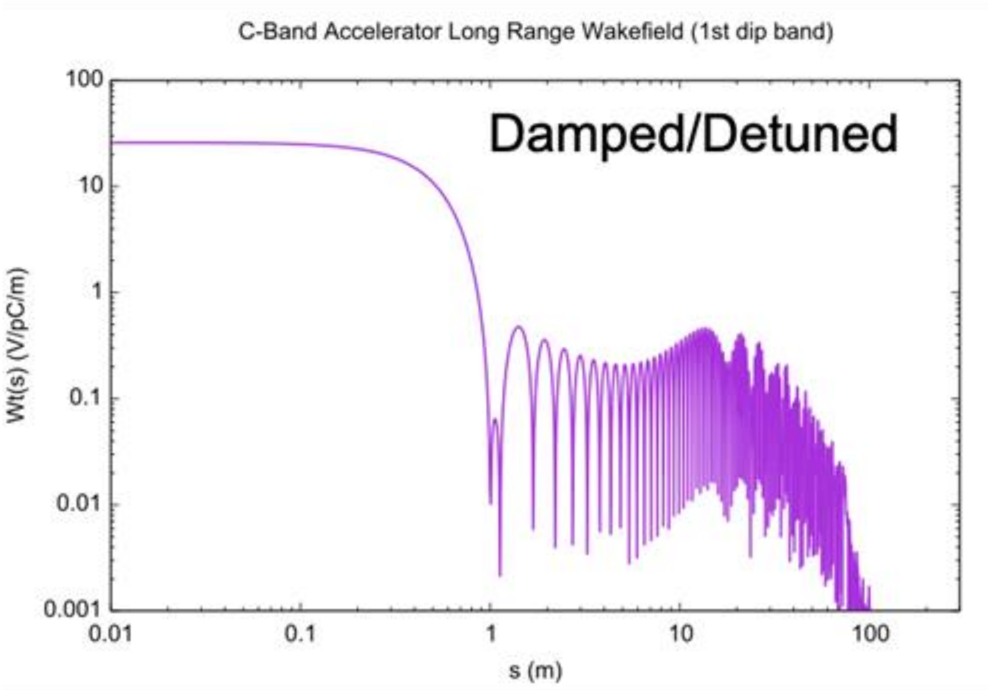
4σ Gaussian detuning of 80 cells for dipole mode (1st band) at f_c=9.5 GHz, w/ $\Delta f/f_c$=5.6%

First subsequent bunch s = 1m, full train ~75 m in length

- Damping needed to suppress re-coherence



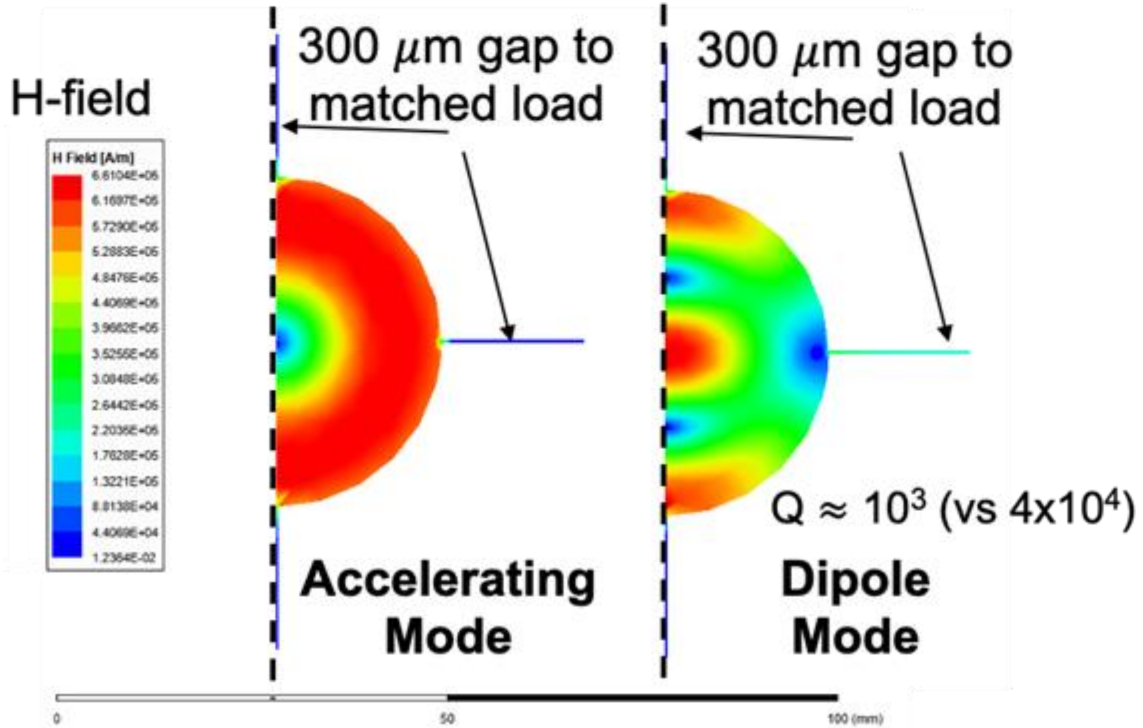
(Only copper surface loss damping included)



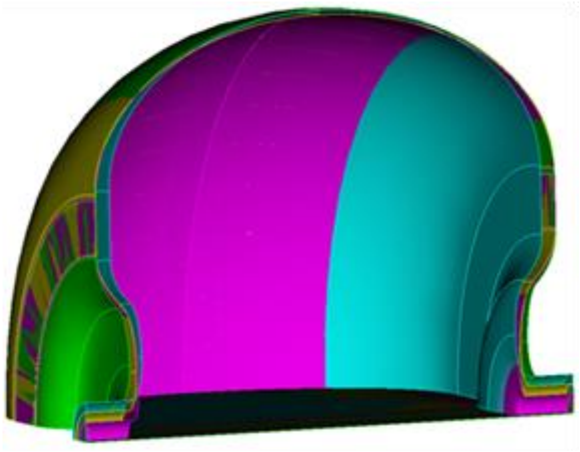
(1.0e3 Q total HOM damping included)

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

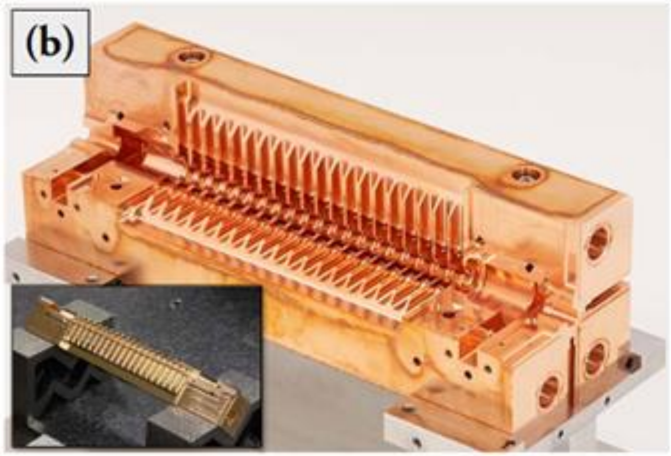
Individual cell feeds necessitate adoption of split-block assembly
Perturbation due to joint does not couple to accelerating mode
Exploring gaps in quadrature to damp higher order mode



Detuned Cavity Designs



Quadrant Structure



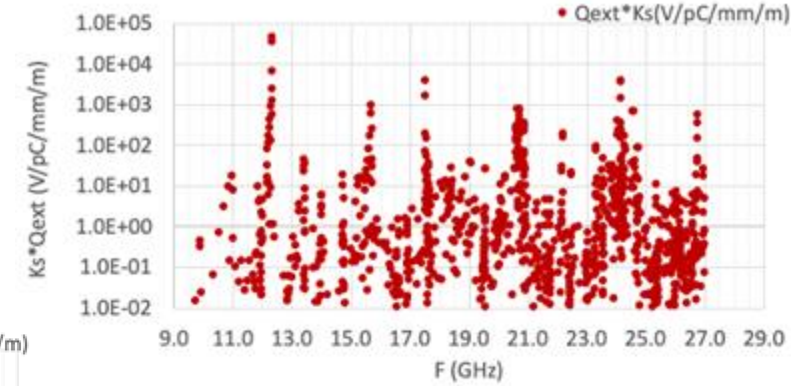
Abe et al., PASJ, 2017, WEP039

Implementation of Slot Damping

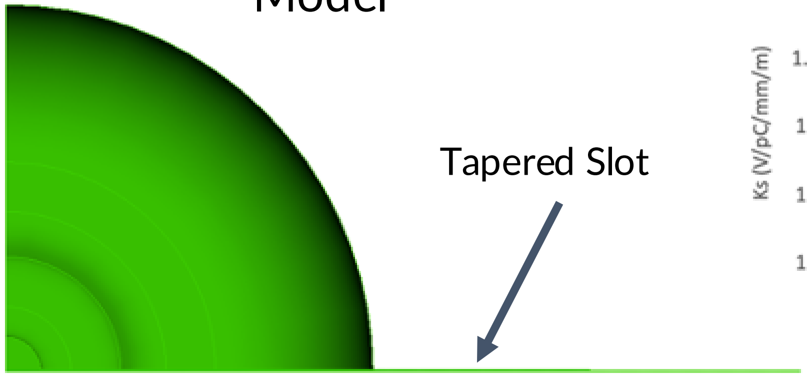
Need to extend to 40 GHz / Optimize coupling / Modes below 10^4 V/pC/mm/m

NiCr coated damping slots in development

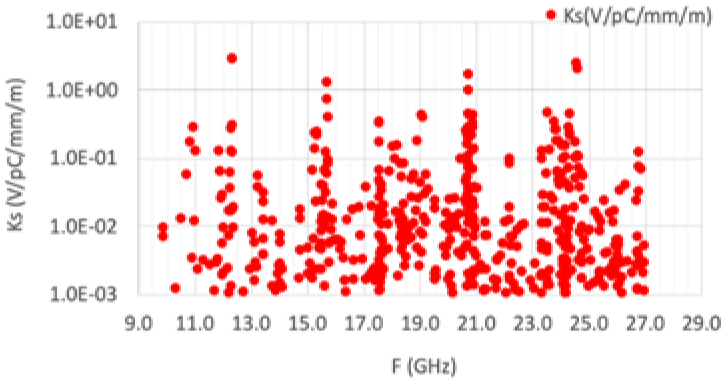
Kick Factor * Q

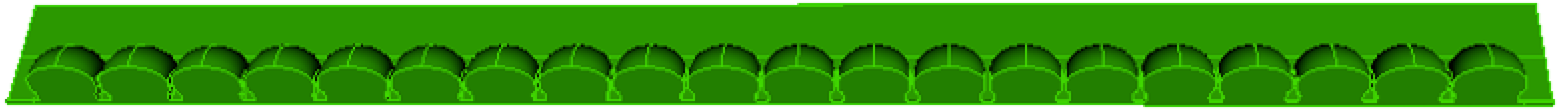


Vacuum Space Model

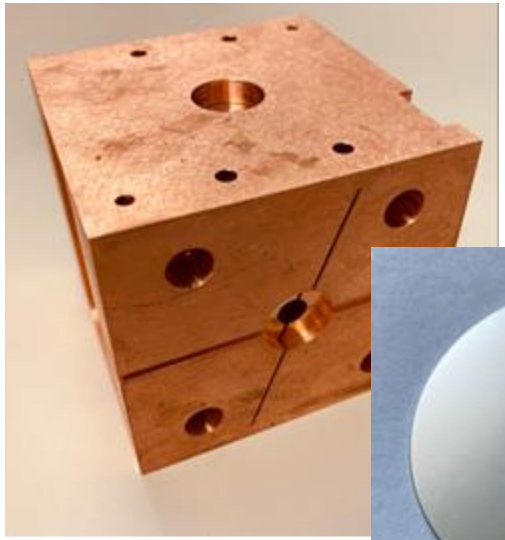


Kick Factor

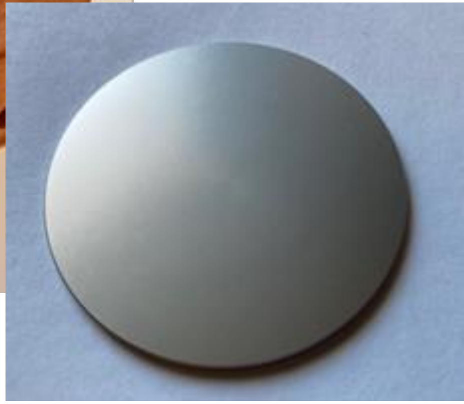




Damping Slot Prototype

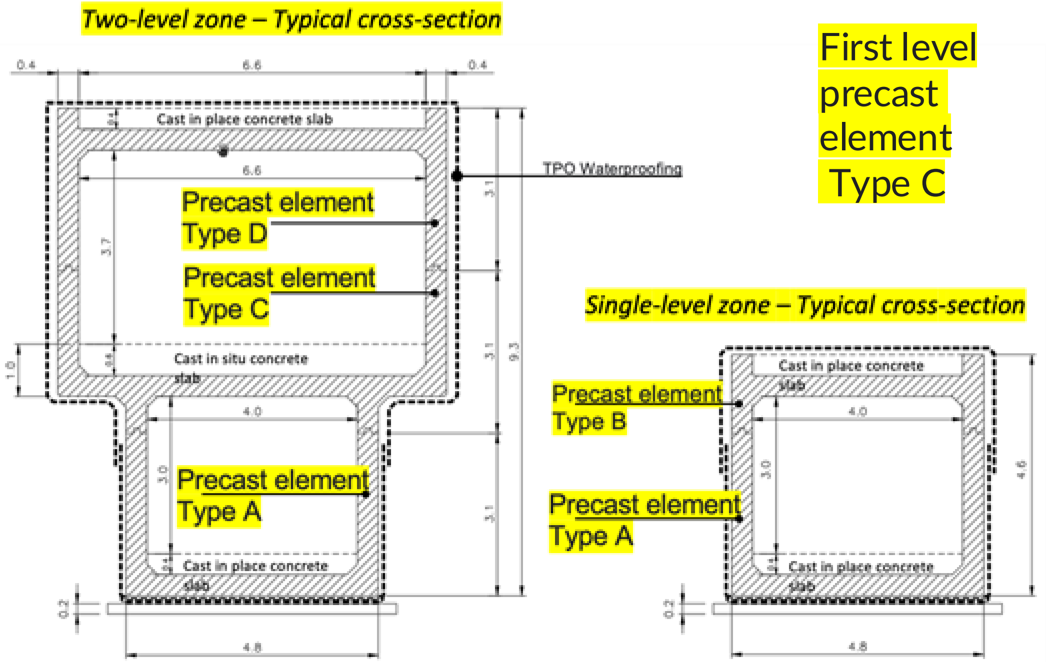


NiChrome

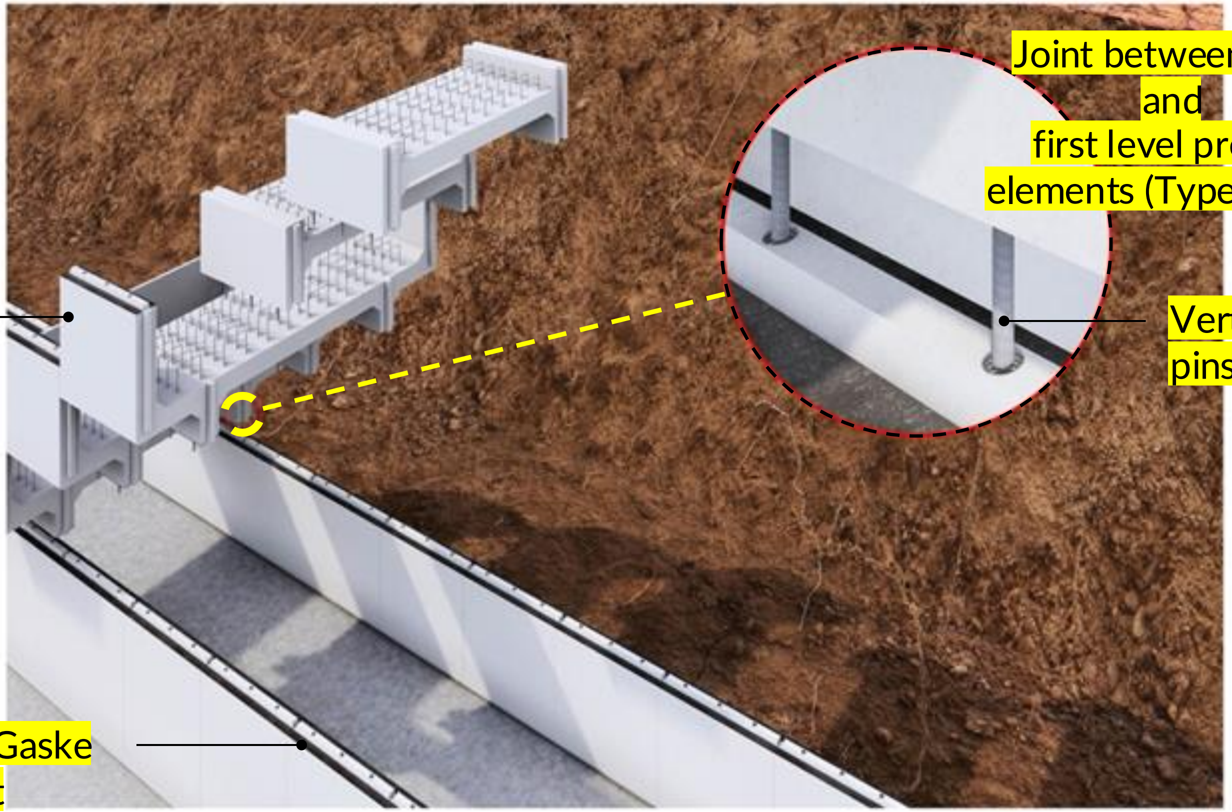


Rapid Construction with a Surface Site

- “Cut and cover” construction
- Precast concrete housing elements made on site
- Limited waster material – reuse material to cover tunnel
- Requires low density site e.g. Hanford



First level precast elements installation

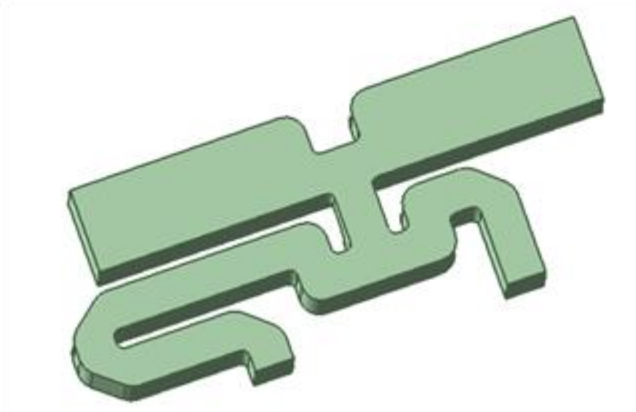


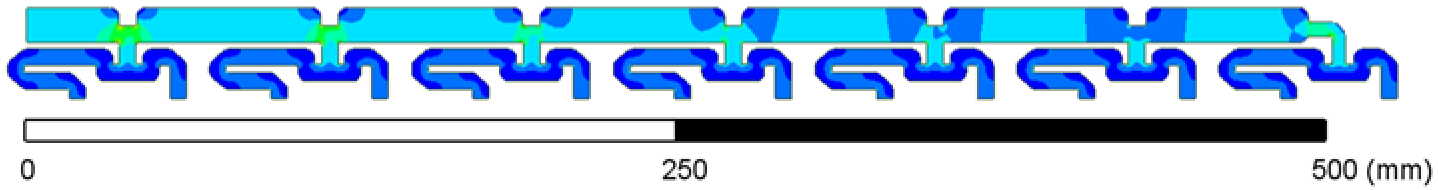
Wakefield Resilient Meter-long Linac Structure

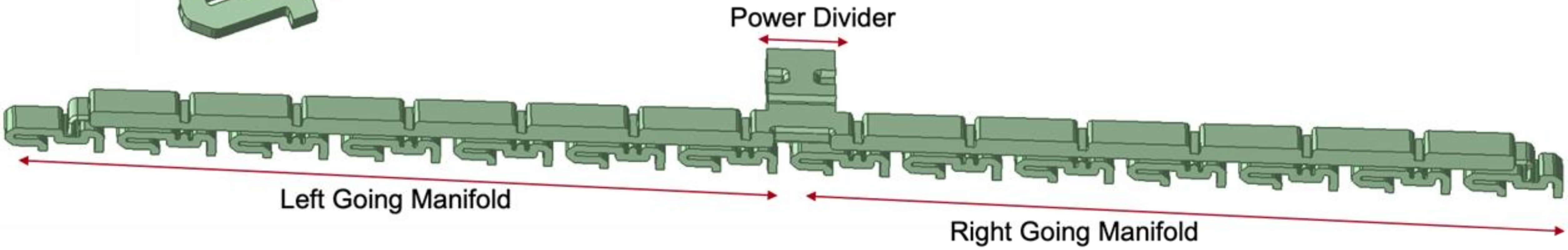
Increased beam aperture with no decrease in shunt impedance for reduced phase advance

Reduced phase advance structure has larger aperture but needs new manifold

Two fold symmetry possible by bifurcating feed



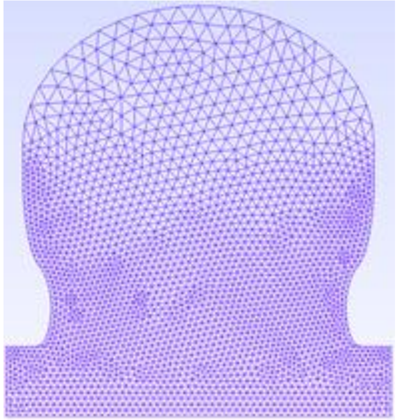




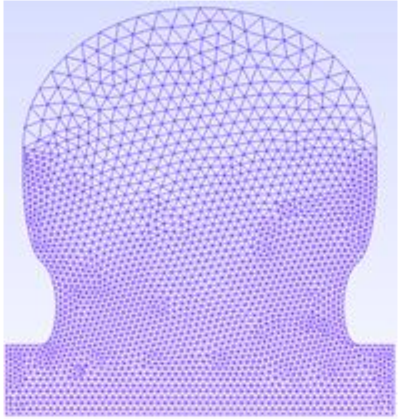
SLAC M. Shumail - NCRF Session: Wednesday 11:20

HOM Damping and Detuning

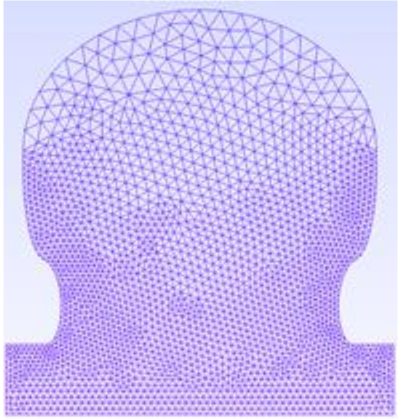
Detuning through nose cone profiles, damping through lossy thin slits



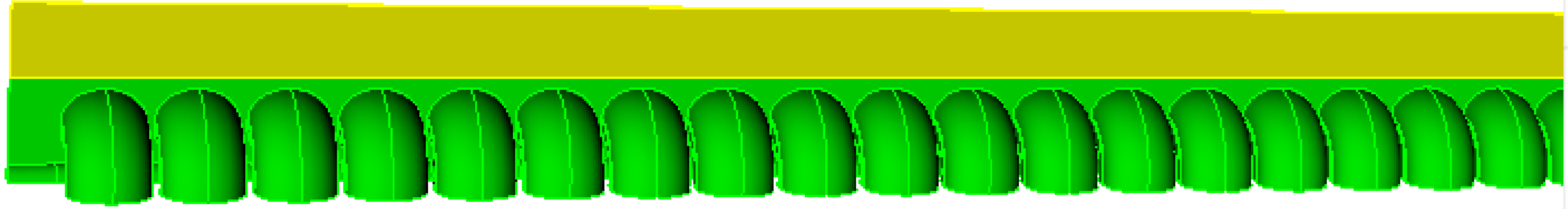
Frontend cell:
Gap1
R=113.67 MΩ/m

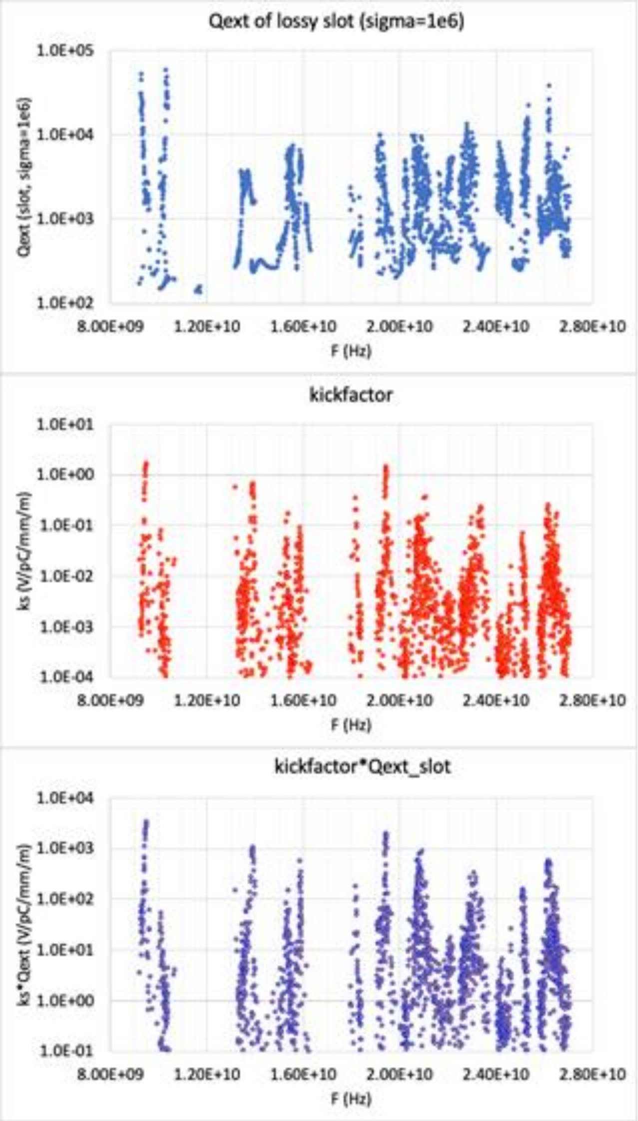


Middle cell:
Gap1-0.5mm
R=114.32 MΩ/m



Backend cell:
Gap1-1mm
R=114.38 MΩ/m

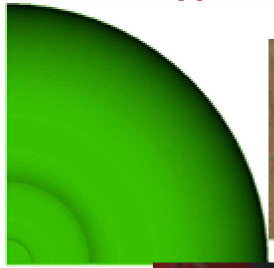


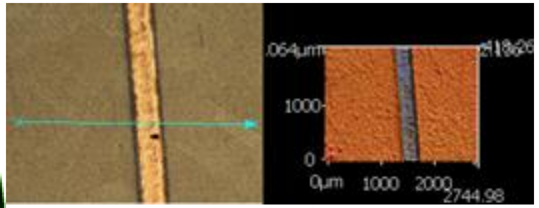


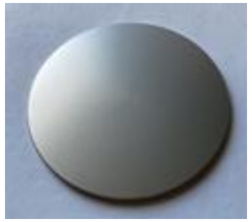
NiChrome High Power Testing

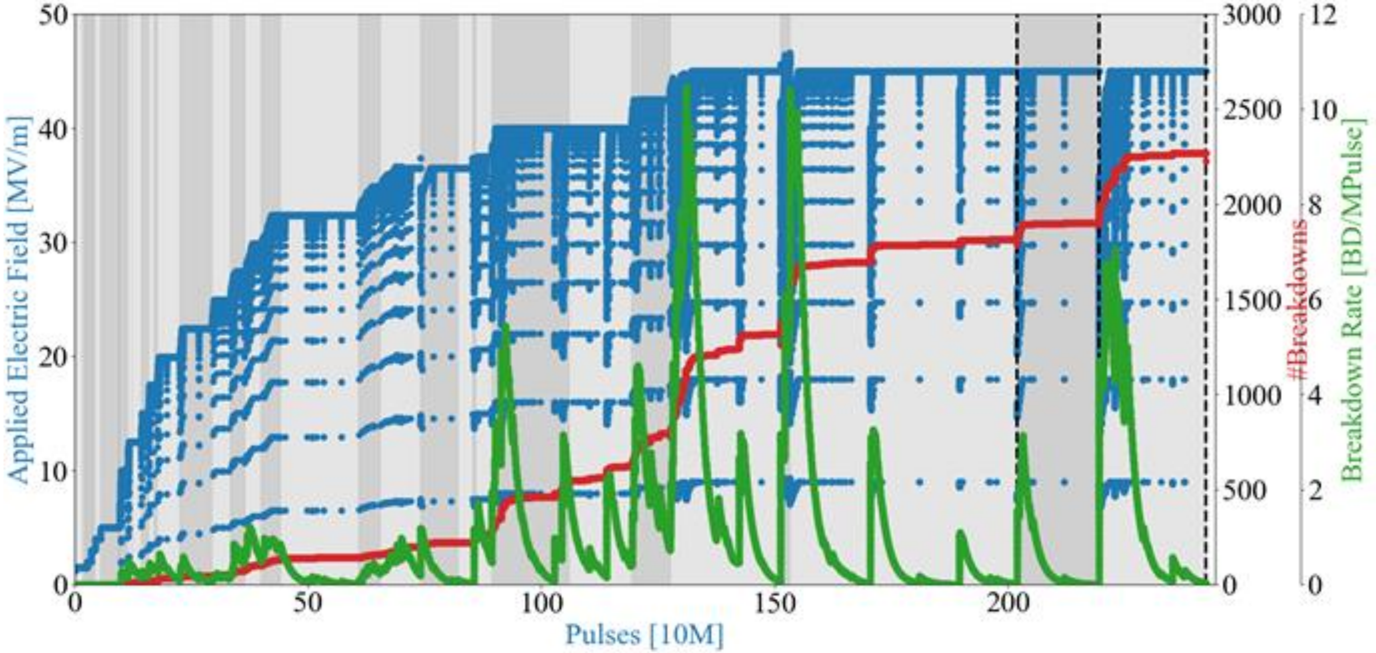
Field emission study using electrodes and breakdown light detection

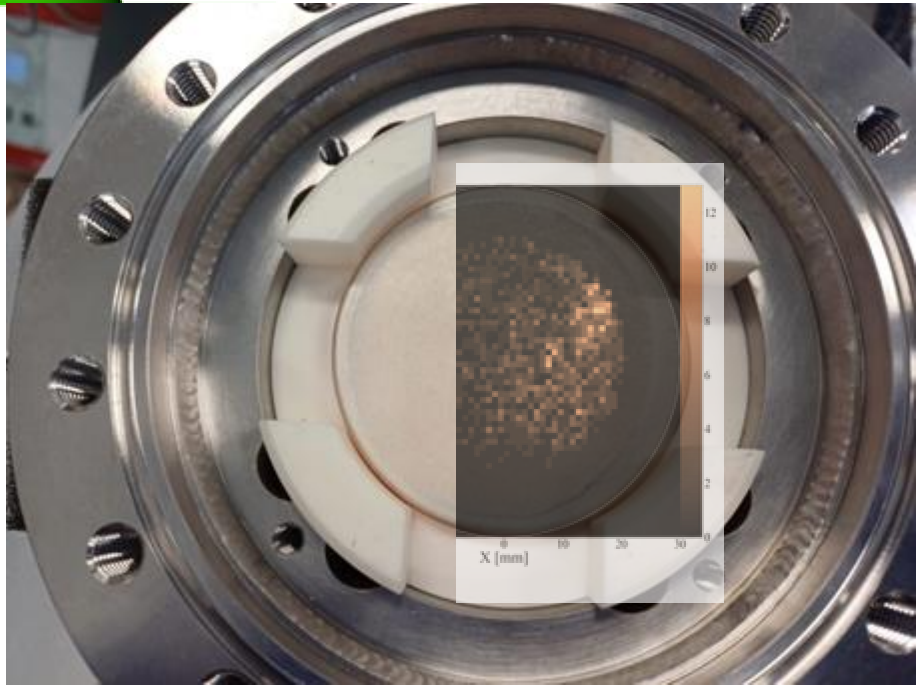
- NiChrome a promising material for damping slits
- Tested up to 47.5 MV/m, 1 kHz, and 1 microsecond
- TWT tests for high power RF tests to begin soon
- Very promising high power performance so far









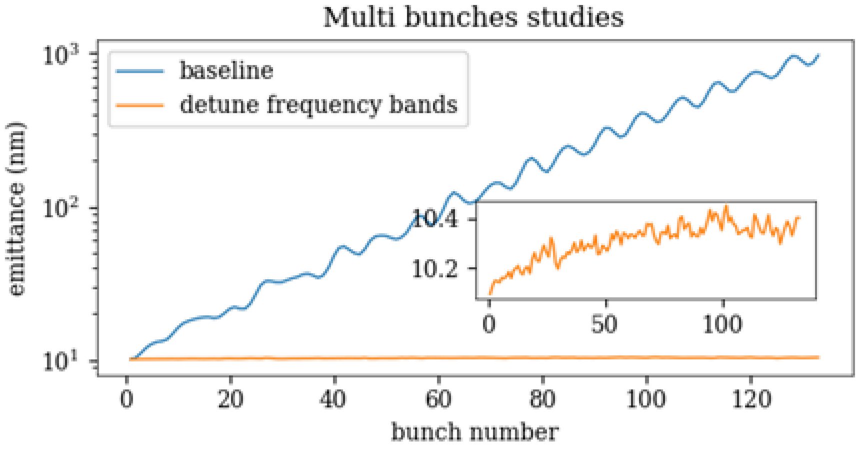


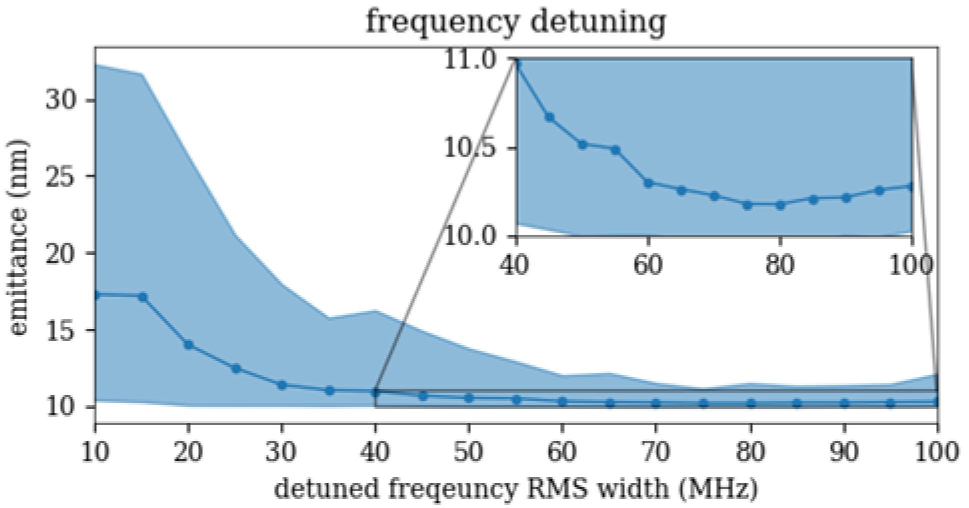
SLAC V. Bjelland, W. Wuensch

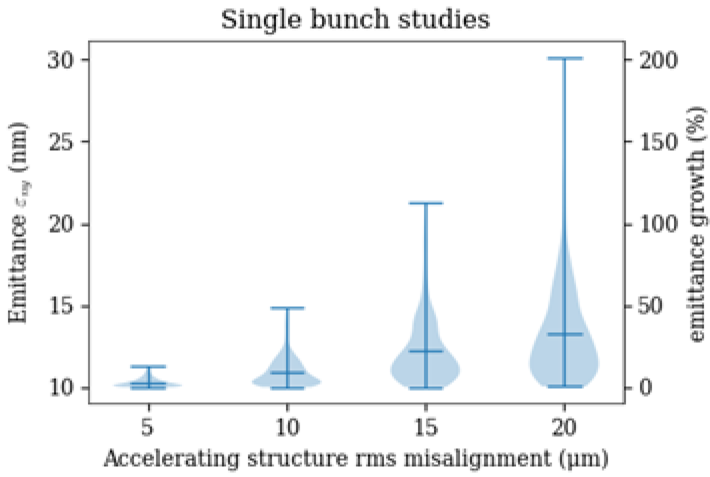
Main Linac Beam Dynamics Studies

Studies needed to guide accelerator design and alignment tolerances with novel structures

- Test Case: C^3 is a cryogenic-cooled e^+e^- collider concept with a distributed coupling accelerator structure
- Multi-bunch simulation studies were conducted to identify long-range HOMs that deteriorate beam's quality
- Single bunch studies also used for studying alignment tolerances





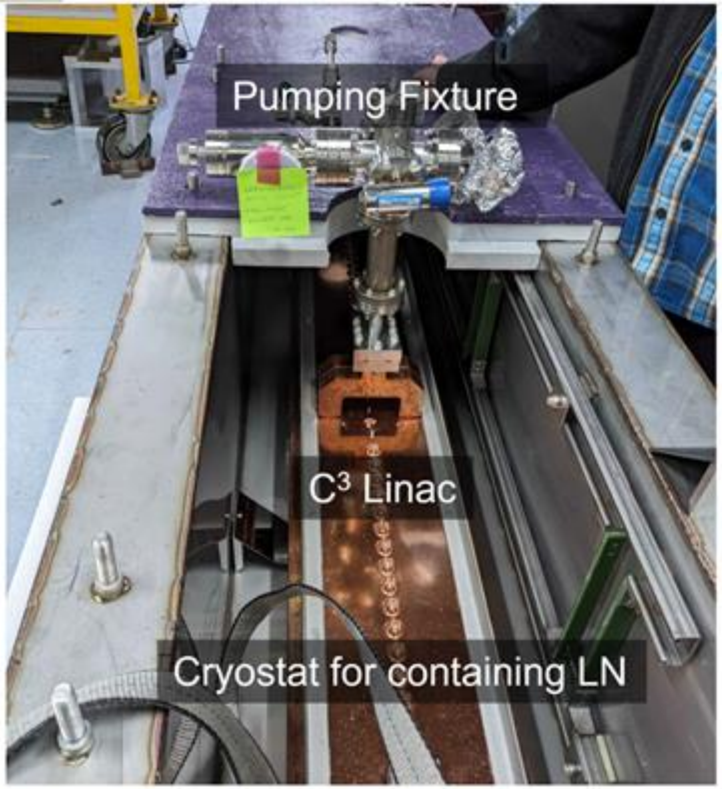


W.H. Tan - Beam Dynamics Session: Wednesday 09:00

Vibration Characterization

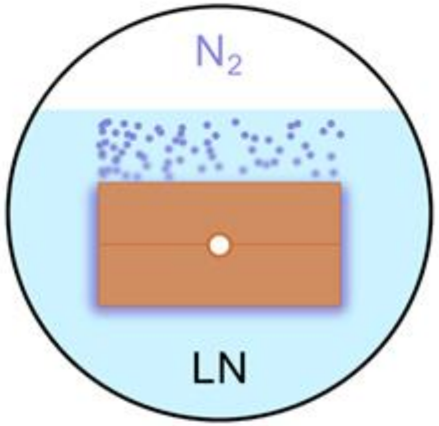
Prototype C3 Linac with a resistive heater was used to test vibration within LN up to 2 kW

- Displacement induced by heating LN remained below tolerances
- Next tests within QCM to test displacements induced on quads

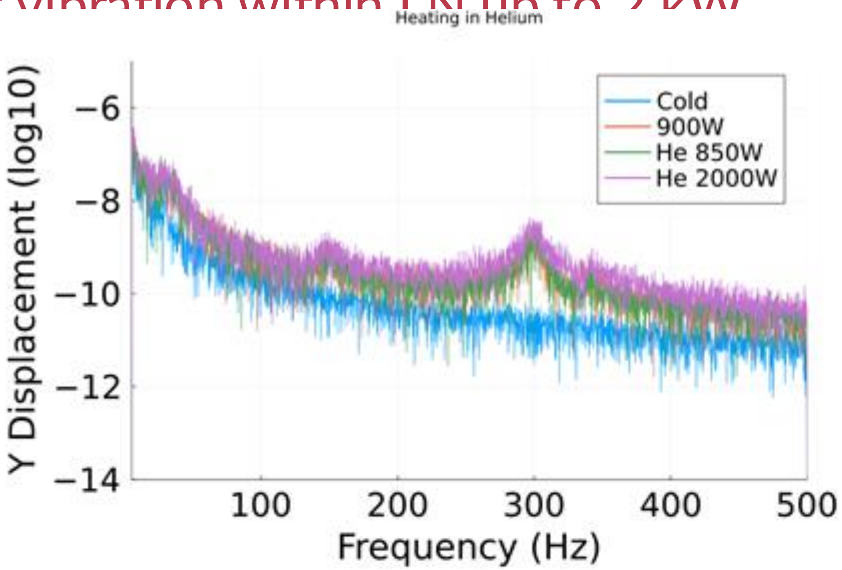


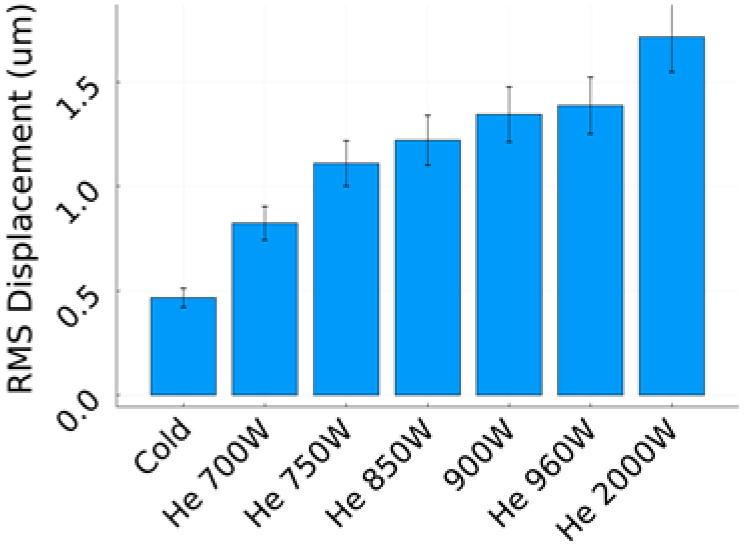
(a)

(b)



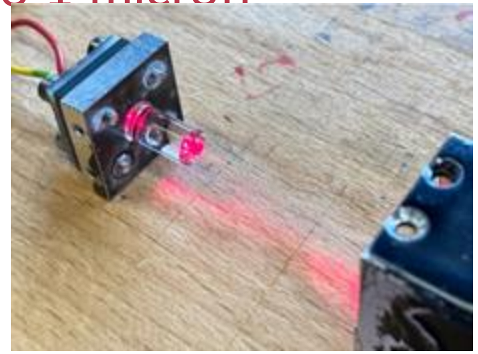
(c)



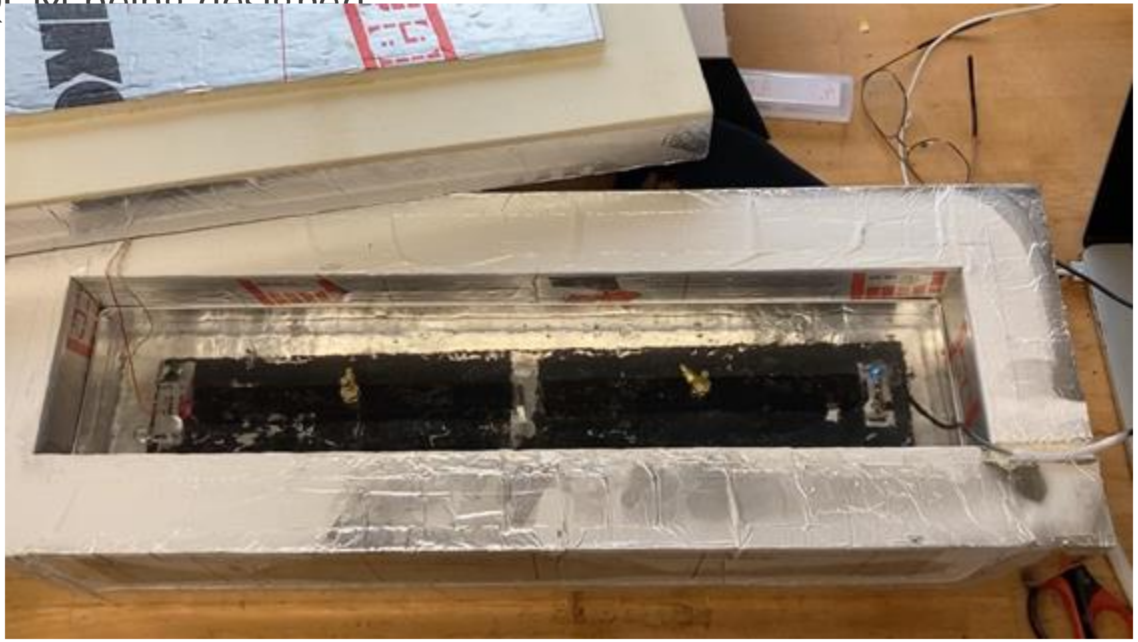


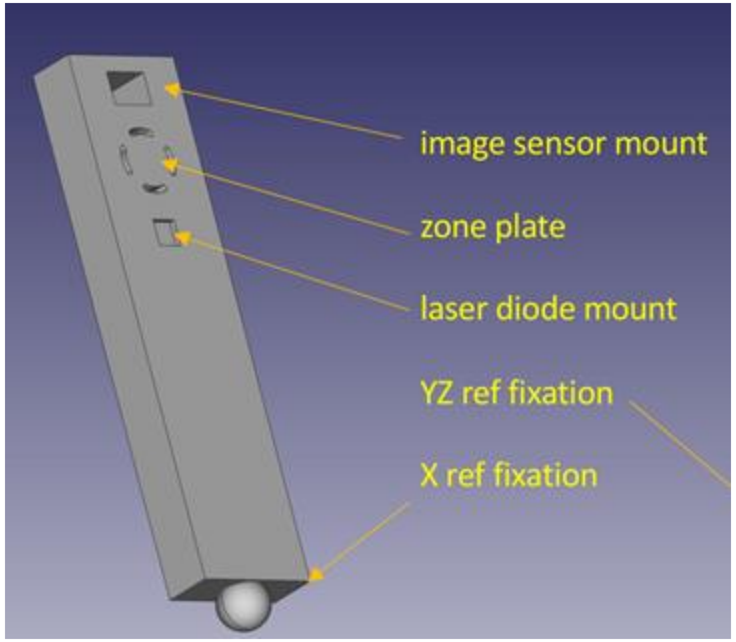
Precision Alignment with Rasnik System

Uses Fresnel mask within liquid nitrogen for alignment down to 1 micron



- Response time limited by refresh rate, currently using repurposed webcam sensors
- Future purpose-built ASIC should be capable of 300 Hz, enabling real time measurements of vibrations
- Mounting system for “Stick” assembly to mount within QCM being designed.



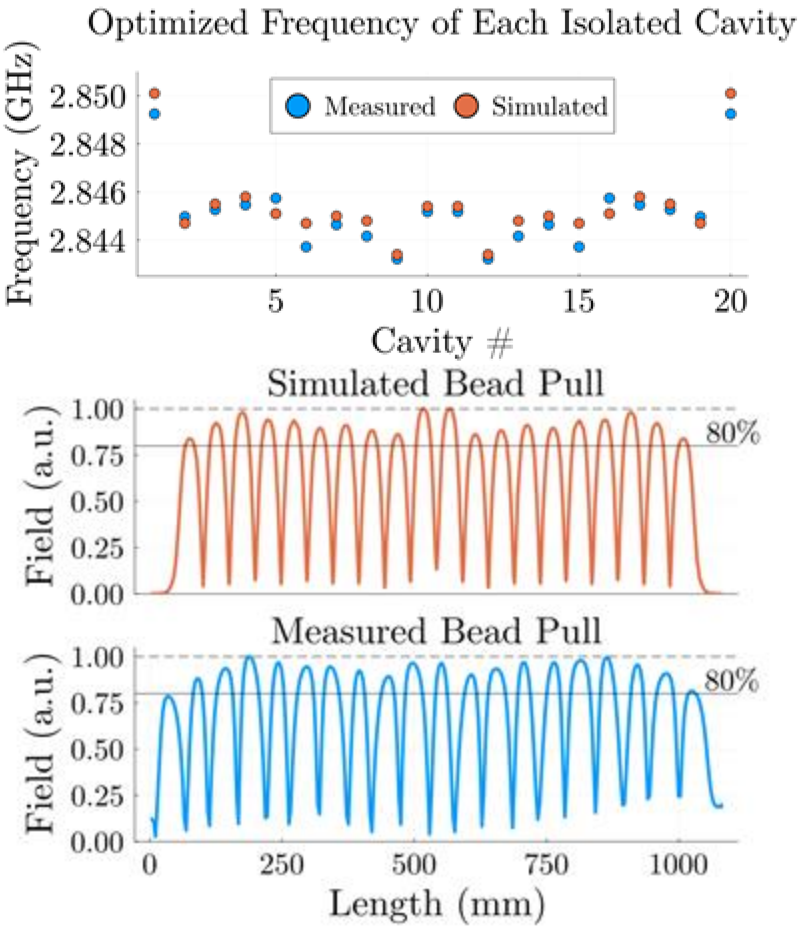


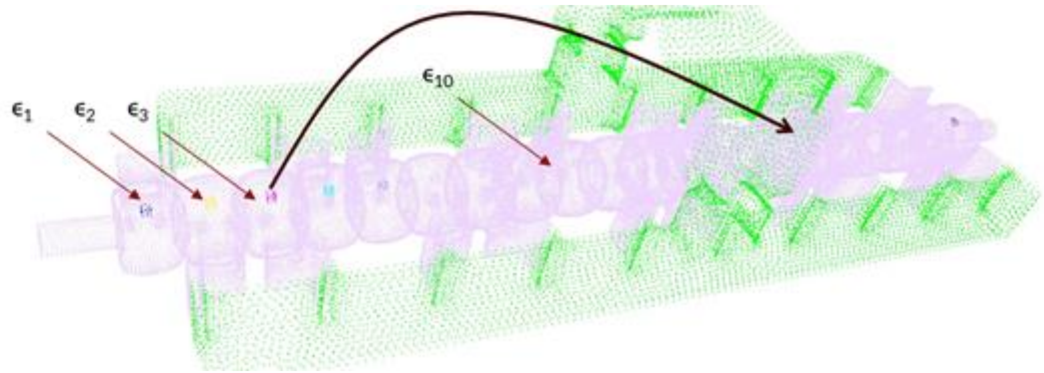
H. Van Der Graaf - Applications Session: Wednesday 14:30

Injector Linac Characterization and Tuning

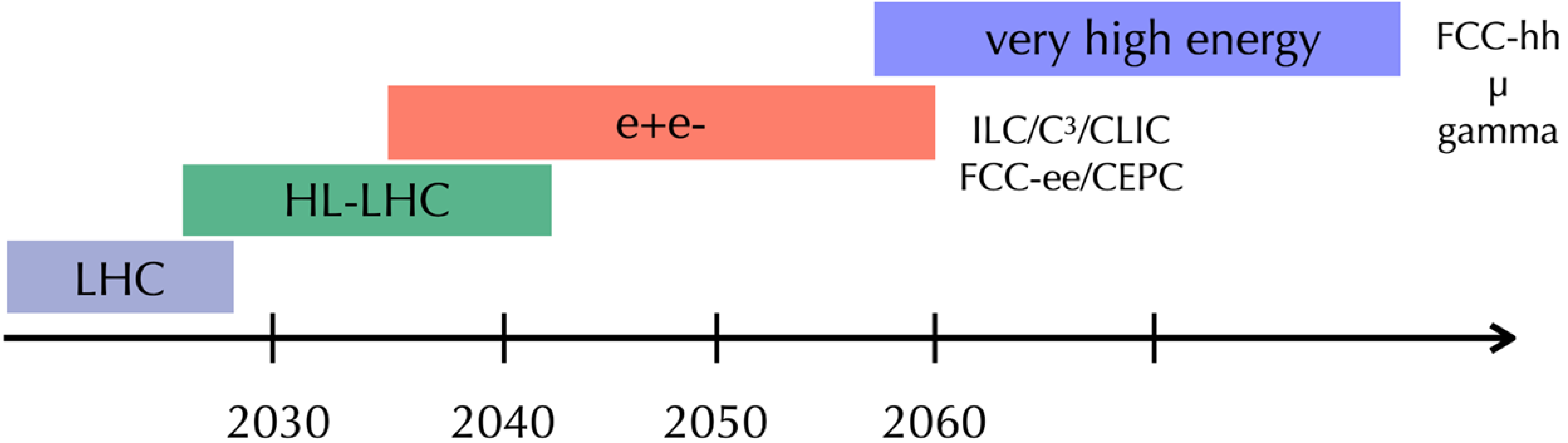
S-Band Linac Development for Efficient Acceleration of High Charge Bunches

- S-Band structure assembly and tuning is complete
  - Tuning procedure utilized iterative measurements with bead pulls and simulation in ACE3P
  - Current design would maintain low emittance for up to 14 nC bunches while accelerating them at 18 MV/m
    - Power draw would only be 5 MW for a meter-long 20 cavity linac
  - Operating cold would allow for even higher gradients
    - Second structure would be tuned with cryogenic tests in mind





What's Next for the Energy Frontier?



Wish list beyond HL-LHC:

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

For the next e^+e^- Linear Collider

1. 5X the Beam Energy
2. 1000X the Luminosity (Effectively Beam Power Density)

Cool Copper Collider

C^3 is based on a new rf technology

- Dramatically improving efficiency and breakdown rate

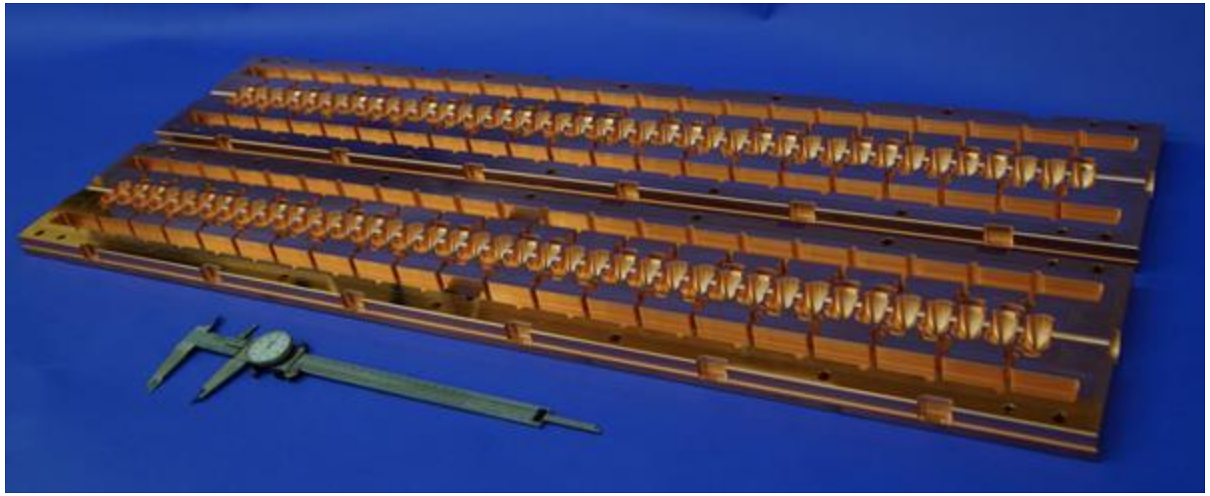
Distributed power to each cavity from a common RF manifold

Operation at cryogenic temperatures (LN_2 ~80 K)

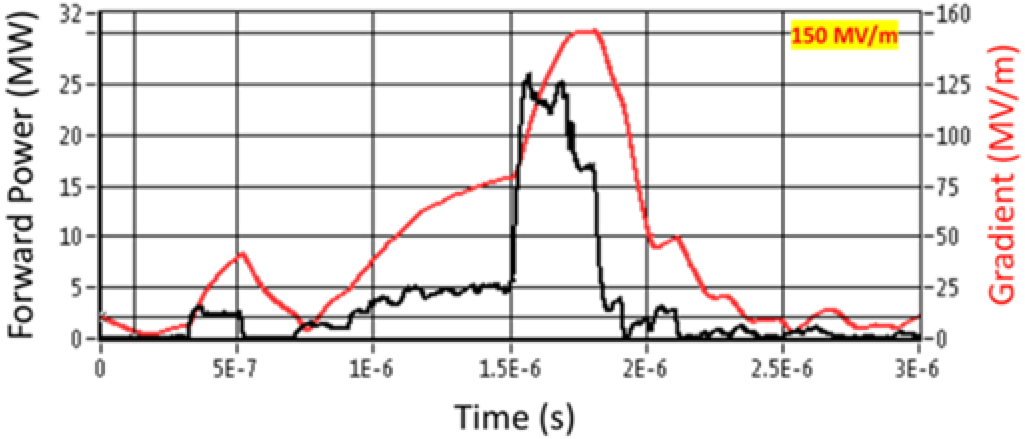
Robust operations at high gradient: 120 MeV/m

Scalable to multi-TeV operation

C^3 Prototype One Meter Structure



High Gradient Operation at 150 MV/m



Cryogenic Operation at X-band

High power Test at Radiabeam

Requirements for a High Energy e^+e^- Linear Collider

Using established collider designs to inform initial parameters

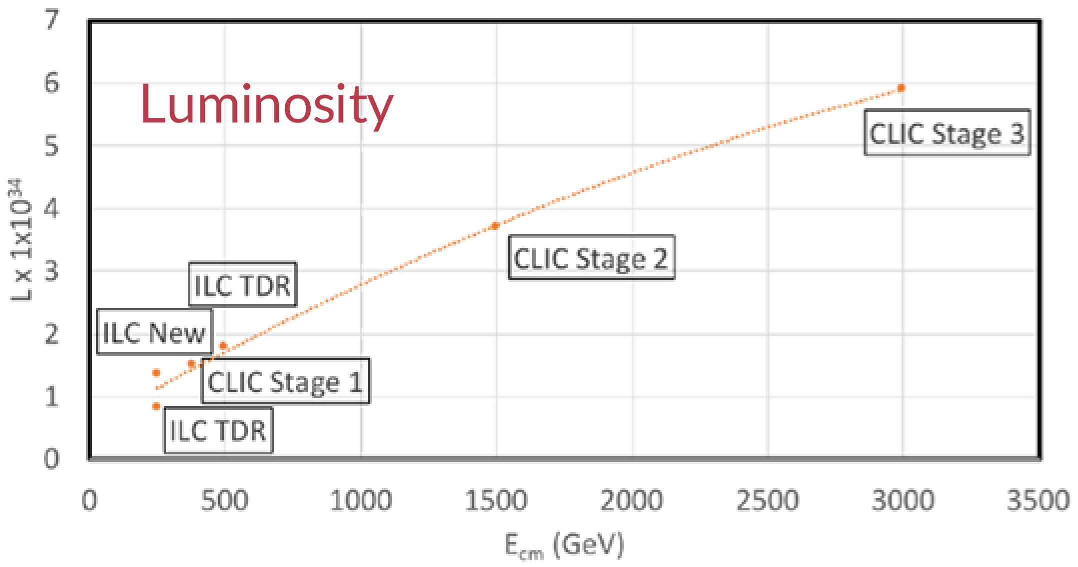
Quantifying impact of wakes requires detailed studies

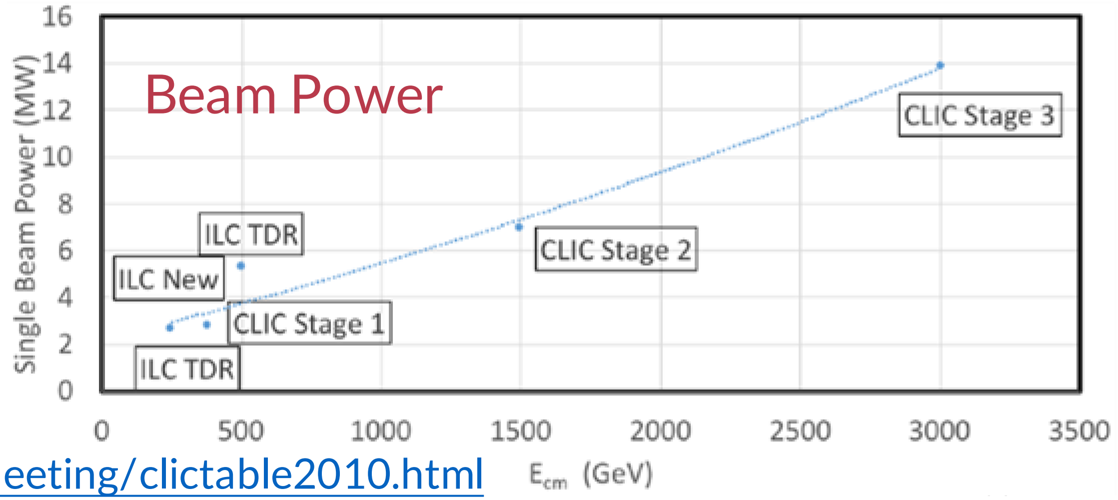
- Most important terms – aperture, bunch charge (and their scaling with frequency)

Target initial stage design at 250 GeV CoM

- 2 MW single beam power

Machine	CLIC	NLC	C³
Freq (GHz)	12.0	11.4	5.7
a (mm)	2.75	3.9	2.6
Charge (nC)	0.6	1.4	1
Spacing (λ)	6	16	30/20
# of bunches	312	90	266/150





https://clic-meeting.web.cern.ch/clic-meeting/clictable2010.html

NLC, ZDR Tbl. 1.3,8.3