C^3 Accelerator Developments

Ankur Dhar
LCWS 2024
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Acknowledgements

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April 12, 2022

Strategy for Understanding the Higgs Physics:
The Cool Copper Collider

JINST — Published by IOP Publishing for SISSA Medialab

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Published: *September 28, 2023*

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

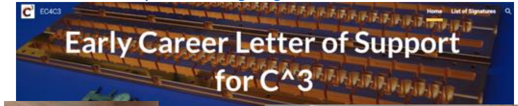
Community Events

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 Meeting at LCWS Satellite meeting July. 12th '24 @ 10:30 Science building #1, Koshiba Hall

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

Accelerator Complex

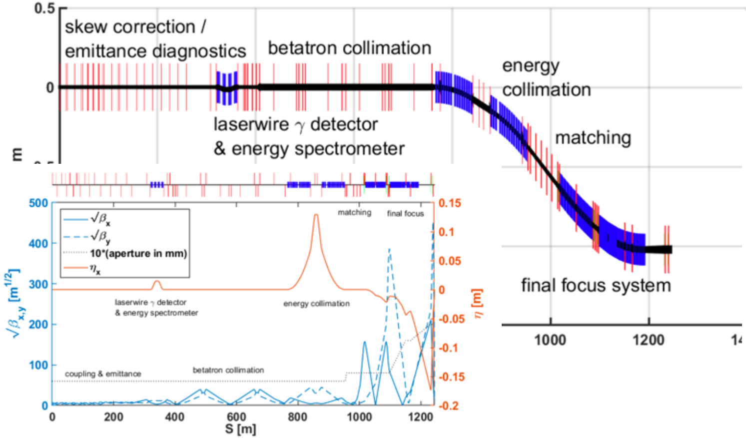
8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

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

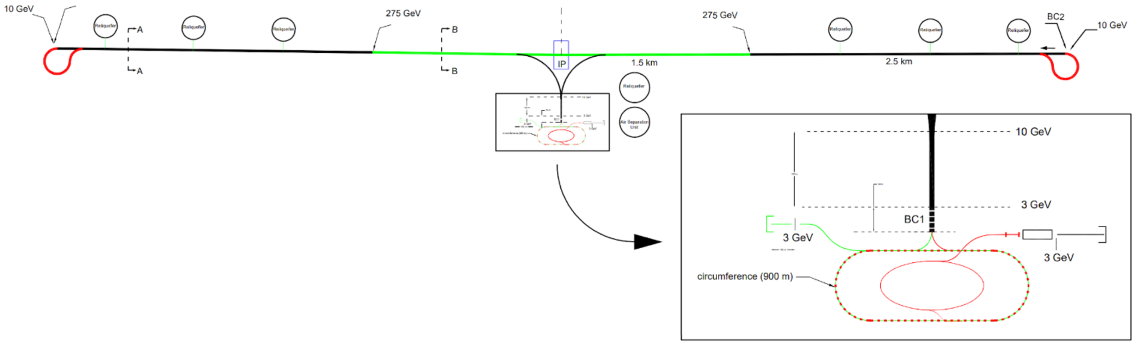
Large portions of accelerator complex are compatible between LC technologies

- 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

C³ - Investigation of Beam Delivery (Adapted from ILC/NLC)



C³ - 8 km Footprint for 250/550 GeV

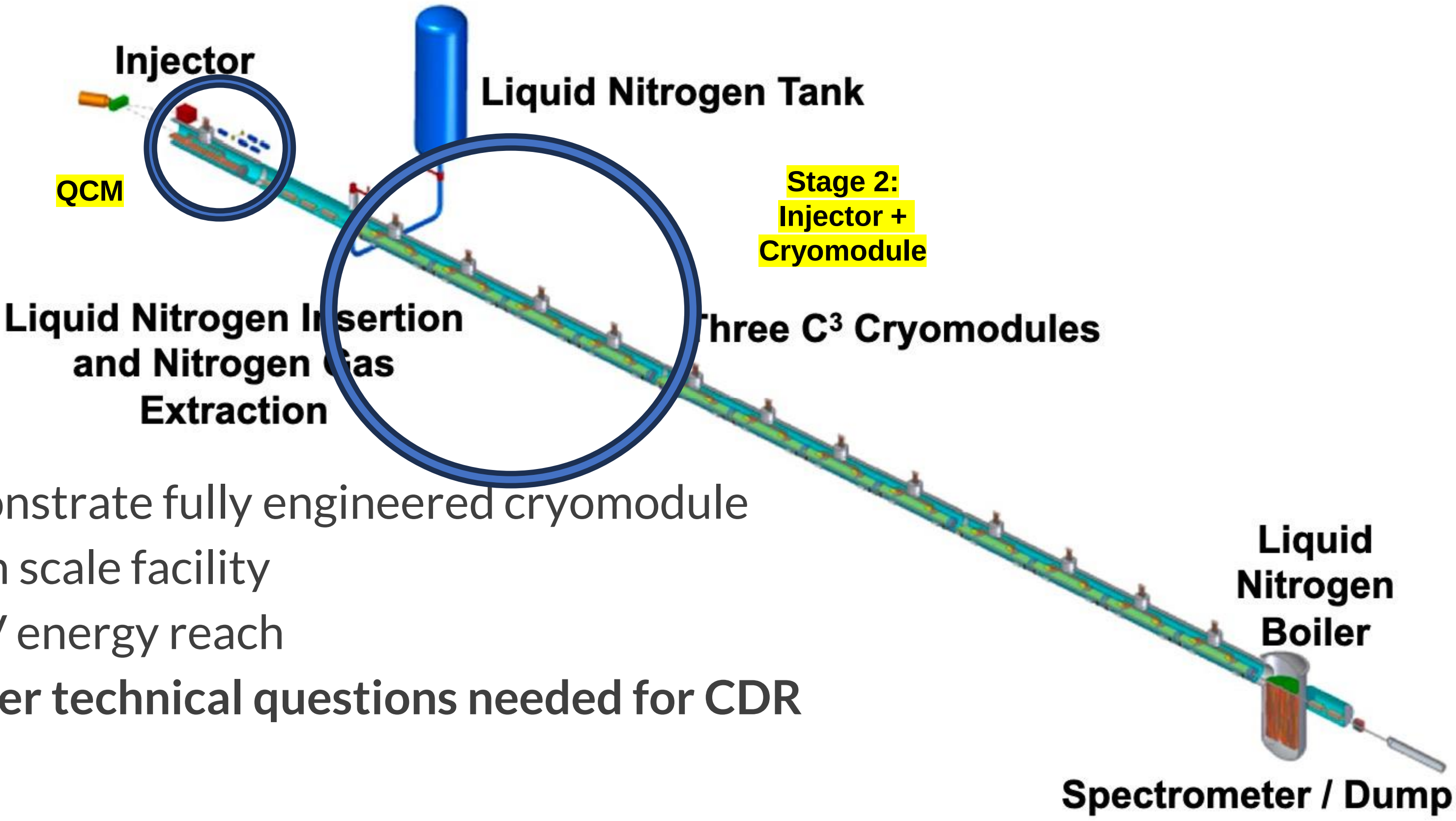


C^3 Table of Parameters

- Updated parameters (red) to be a topic of discussion during this workshop

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]	~150	~175	~110	~125

The Complete C^3 Demonstrator



Demonstrate fully engineered cryomodule

~50 m scale facility

3 GeV energy reach

Answer technical questions needed for CDR

Accelerator Design and Challenges

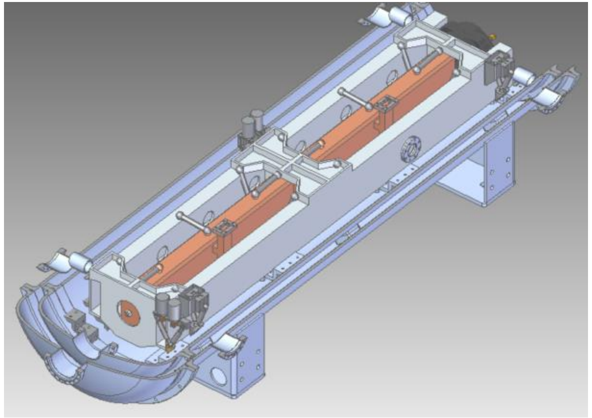
Accelerator Design

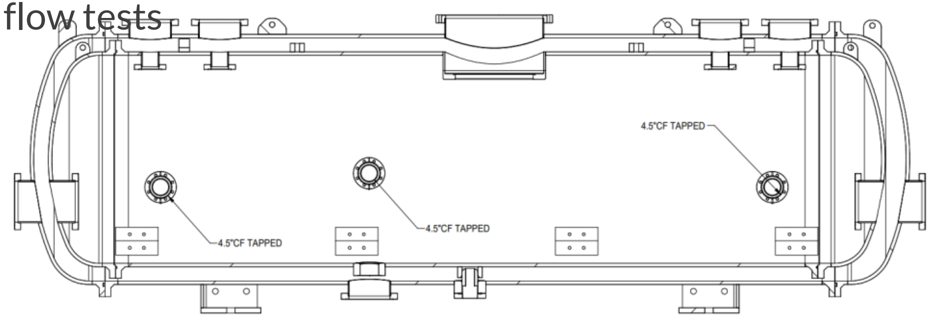
- Delivery of prototype quarter cryomodule (QCM) expected Fall 2024

Focused on challenges identified with community through Snowmass (all underway)

- Gradient – Scaling up to meter scale cryogenic tests
- Vibrations – Measurements with full thermal load
- Alignment – Working towards raft prototype
- Cryogenics – Two-phase flow simulations to full flow tests
- Damping – Materials, design and simulation
- Beam Loading and Stability
- Scalability – Cryomodules and integration

Quarter Cryomodule Concept

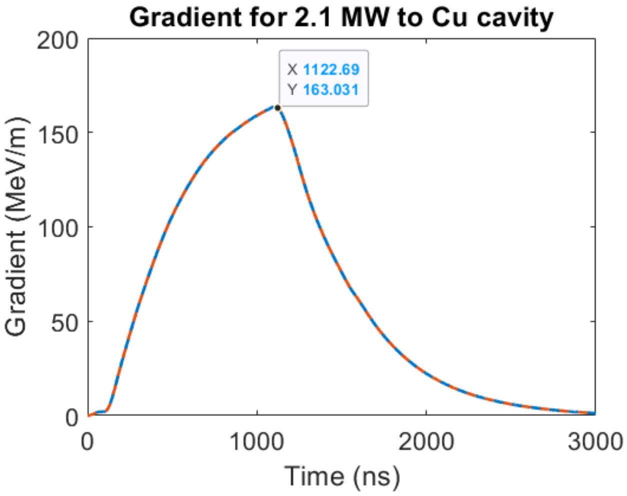


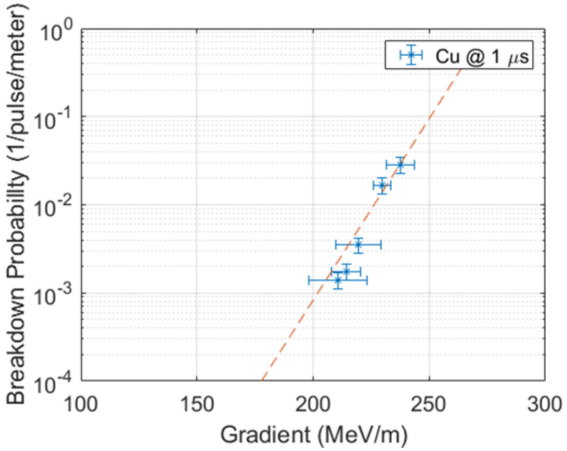


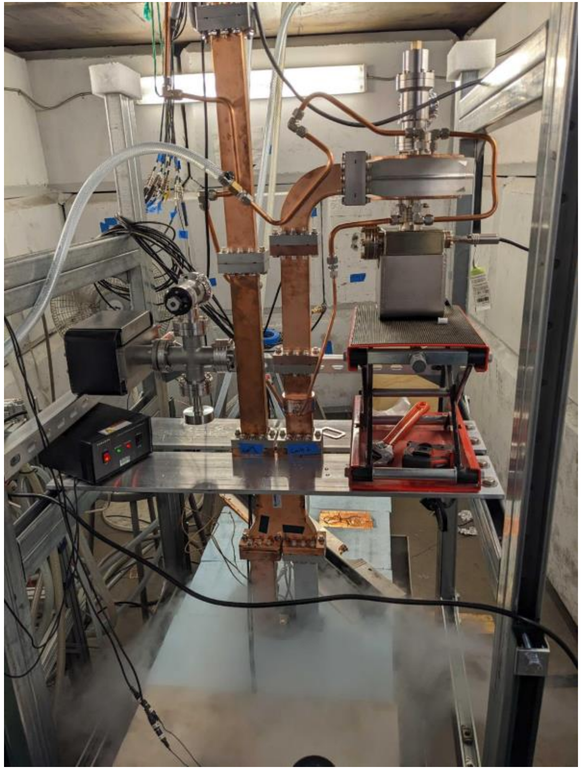
Single Cell Cryogenic High Gradient Tests

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



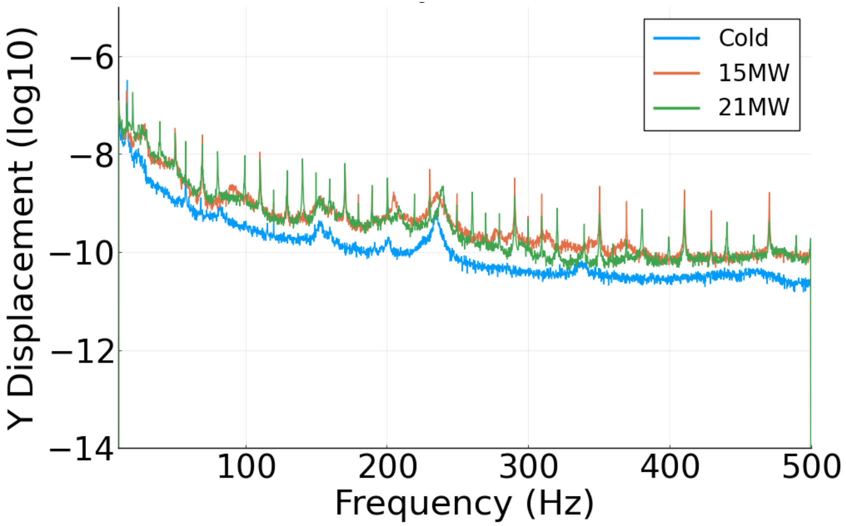


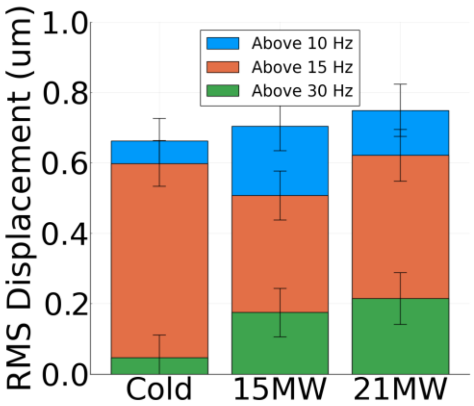


Meter-long Linac Cryogenic High Gradient Tests

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



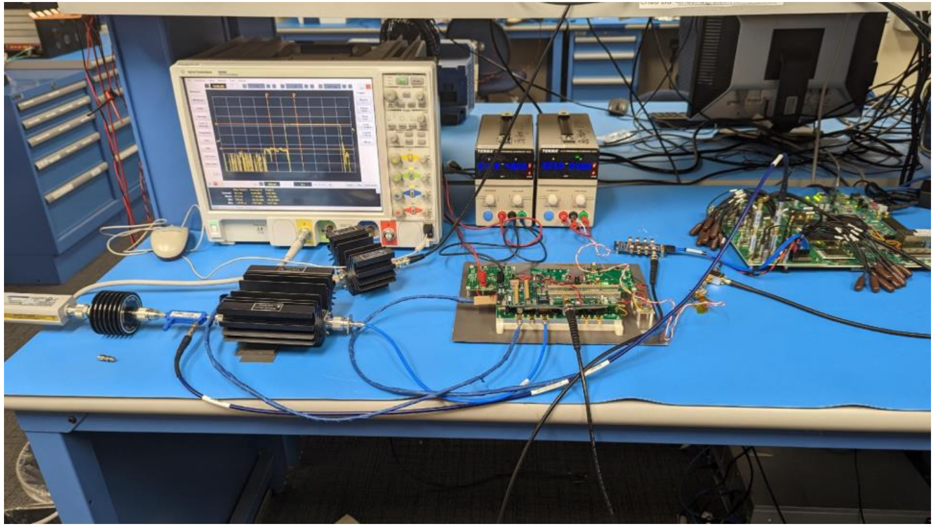


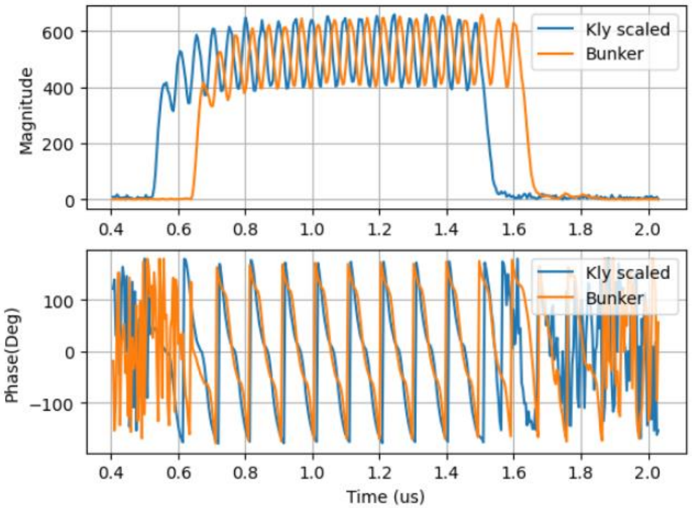
SLAC D. Palmer - NCRF Session: Wednesday 9:40

LLRF Control with RF System on Chip (RFSoC)

Devices can directly sample up to 6 GHz for LLRF feedback

- Direct sampling for S-band and C-band and partial with X-band
- Demonstrated precise control of C-band klystron during high power tests at Radiabeam



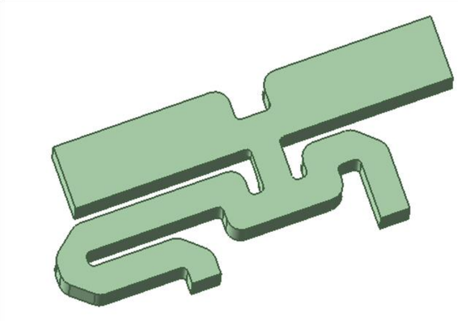


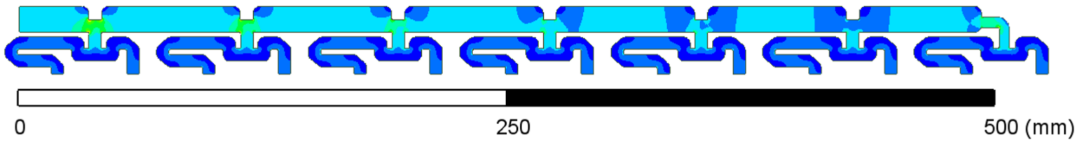
Wakefield Resilient Meter-long Linac Structure

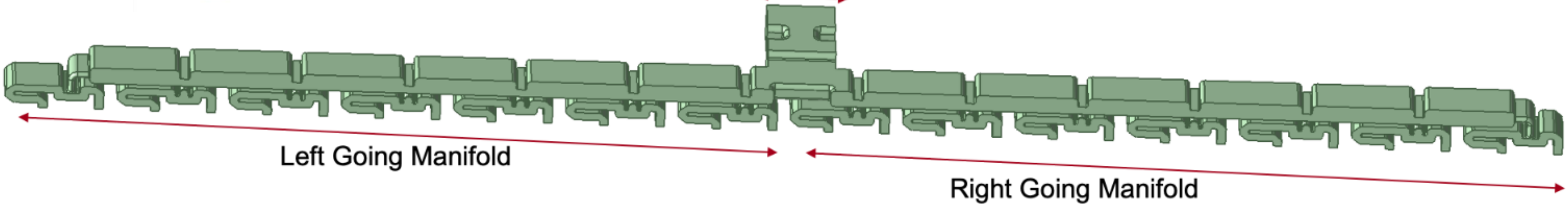
Increased beam aperture with no decrease in shunt impedance for reduced phase advance

Reduced phase advance structure has larger aperture but needs new manifold

Two fold symmetry possible by bifurcating feed

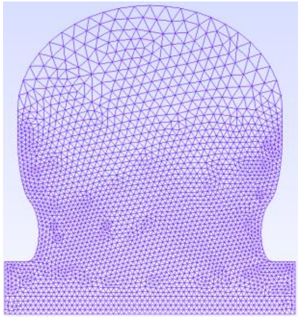




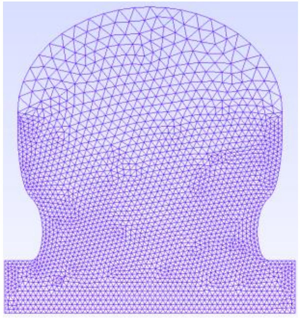


HOM Damping and Detuning

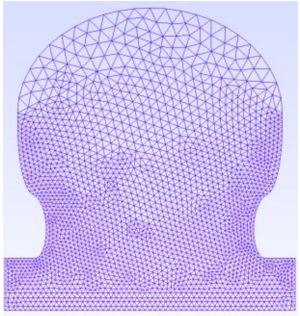
Detuning through nose cone profiles, damping through lossy thin slits



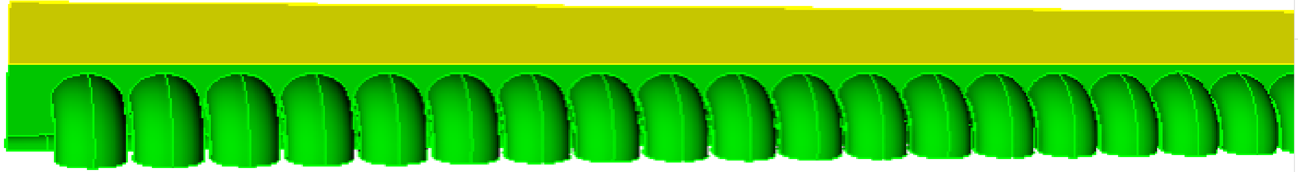
Frontend cell:
Gap1
R=113.67 MΩ/m

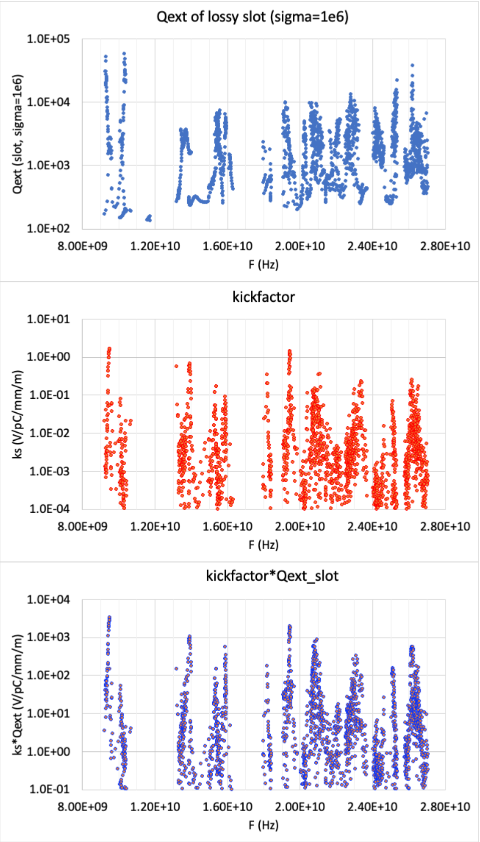


Middle cell:
Gap1-0.5mm
R=114.32 MΩ/m



Backend cell:
Gap1-1mm
R=114.38 MΩ/m

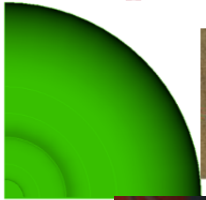


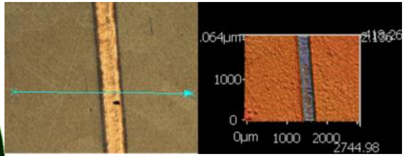


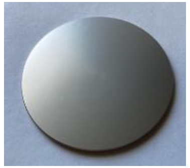
NiChrome High Power Testing

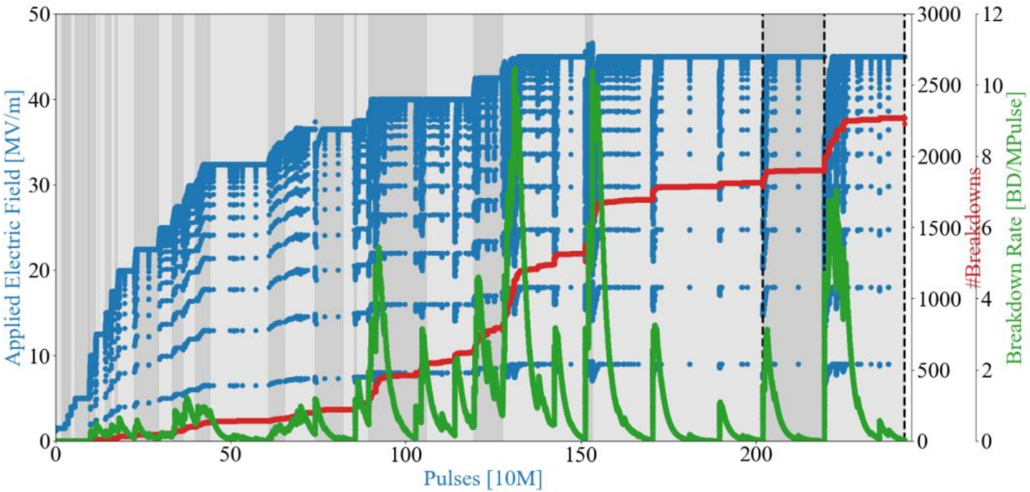
Field emission study using electrodes and breakdown light detection

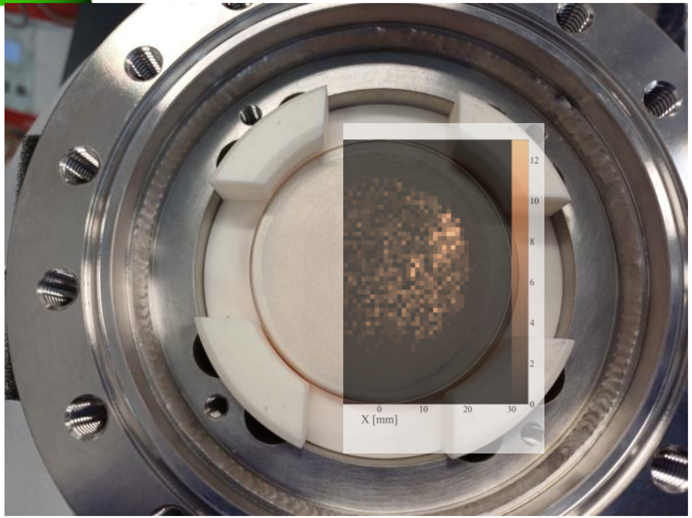
- NiChrome a promising material for damping slits
- Tested up to 47.5 MV/m, 1 kHz, and 1 microsecond
- TWT tests for high power RF tests to begin soon
- Very promising high power performance so far









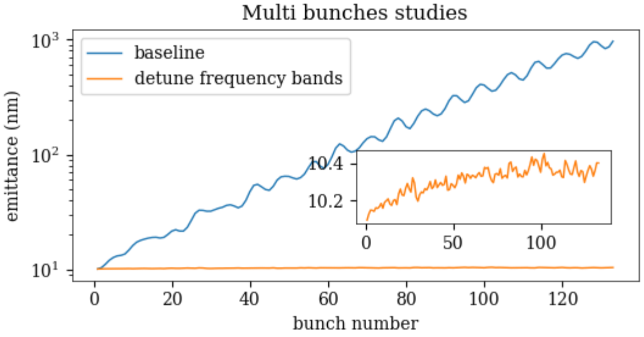


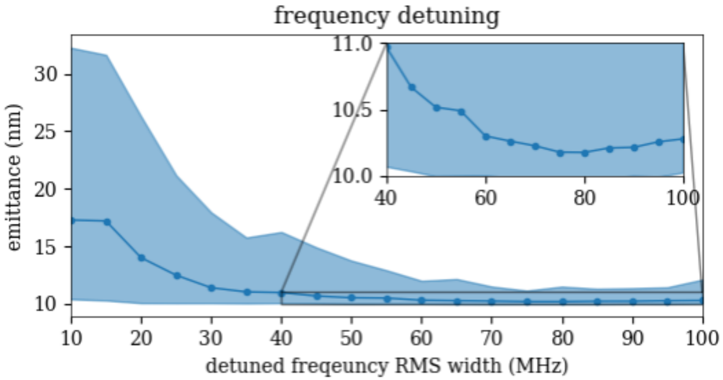
V. Bjelland, W. Wuensch

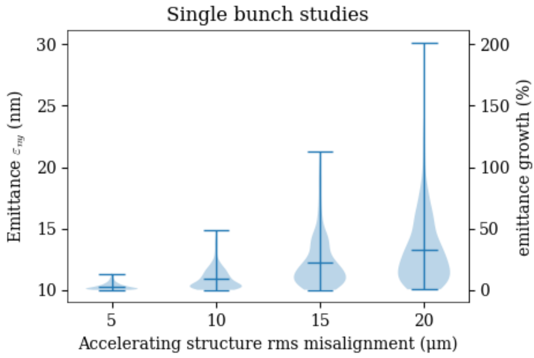
Main Linac Beam Dynamics Studies

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





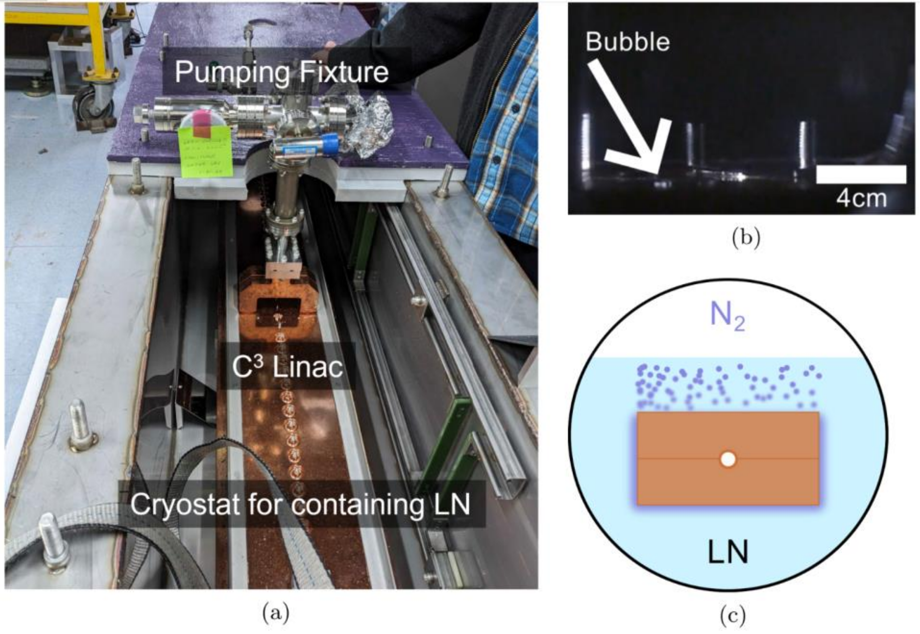


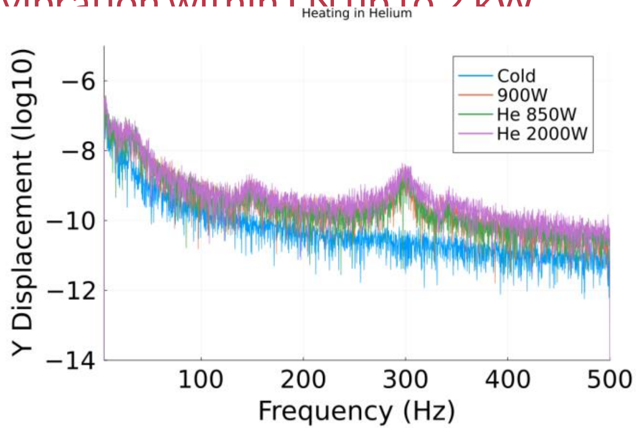
SLAC W.H. Tan - Beam Dynamics Session: Wednesday 09:00

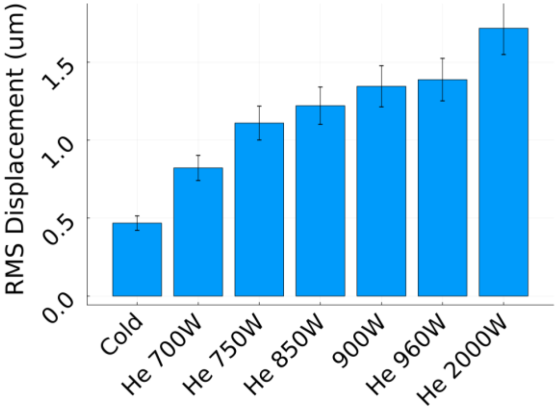
Vibration Characterization

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 OCM to test displacements induced on quads



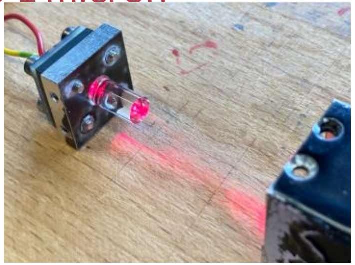


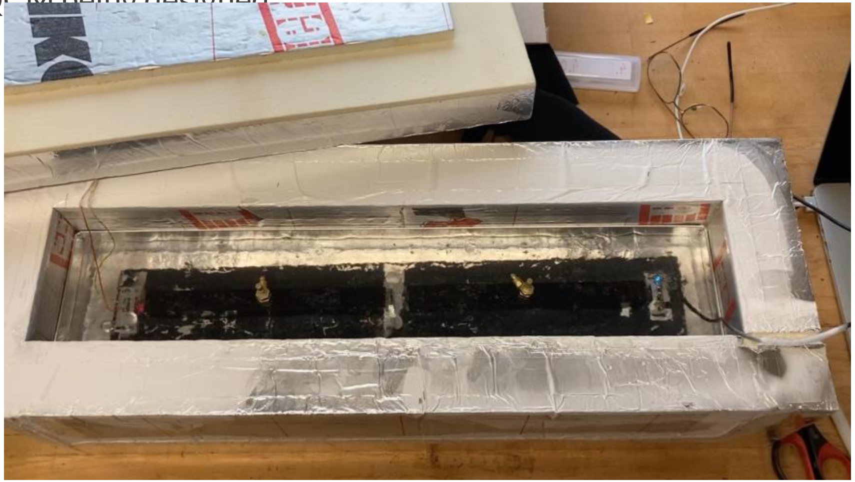


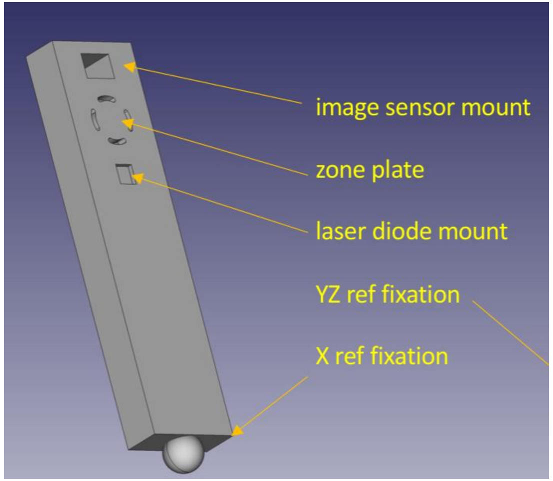
Precision Alignment with Rasnik System

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





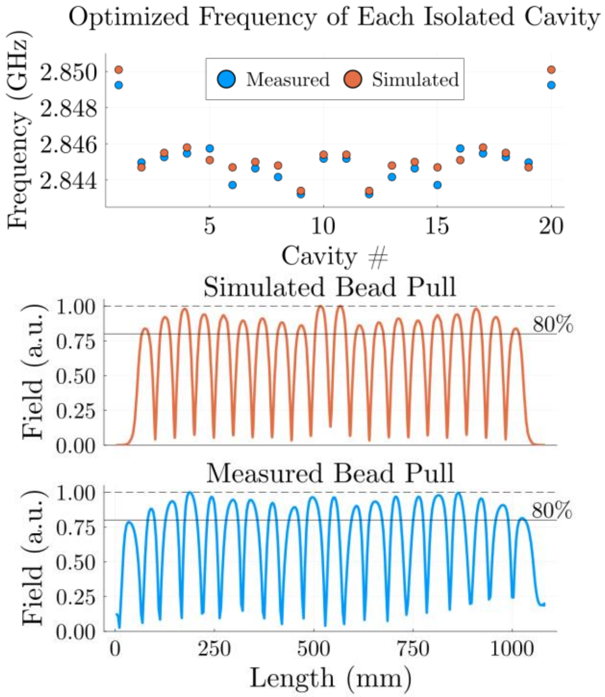


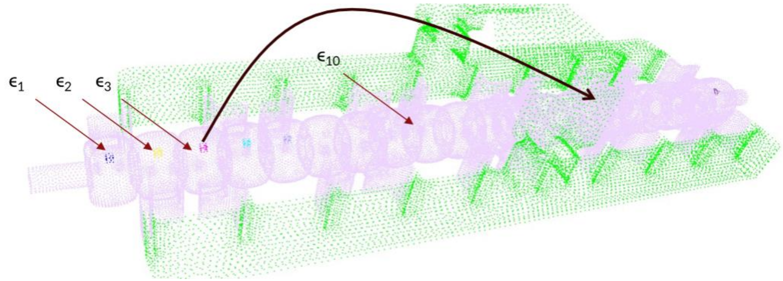
H. Van Der Graaf - Applications Session: Wednesday 14:30

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





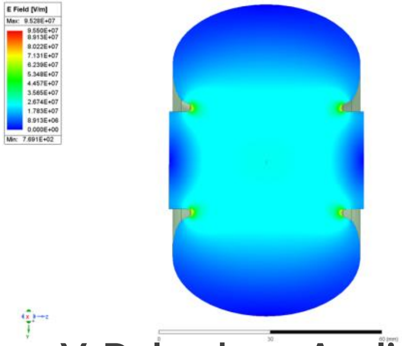
A. Dhar - NCRF Session: Wednesday 16:00

Synergies with Future Circular Collider

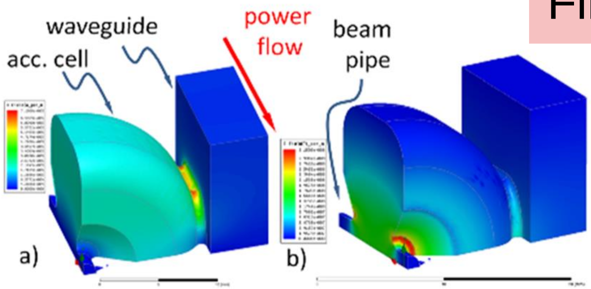
C³ RF Accelerator Technology could Improve Efficiency of HE-Linac

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

Linac Properties	
Charge (nC)	0-5.5 nC
Number Bunches	1-4
Bunch Spacing	25 ns spacing
Initial Energy	6 GeV
Final Energy	20 GeV



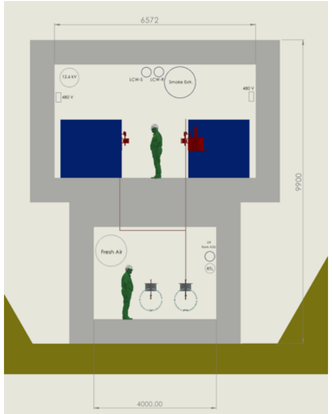
TW Manifold



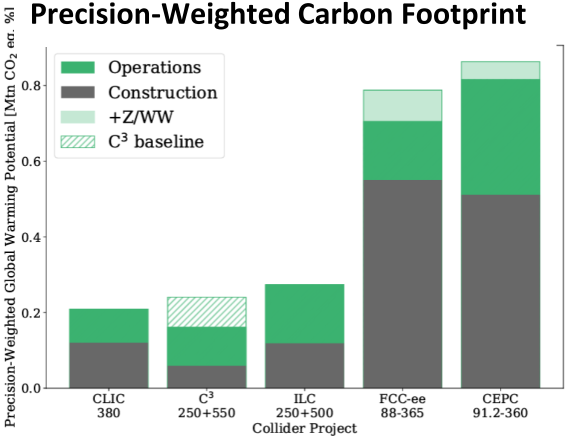
Sustainability Studies

- 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 - 1.3×10^{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

B. Bullard - Sustainability Session: Tuesday 16:15

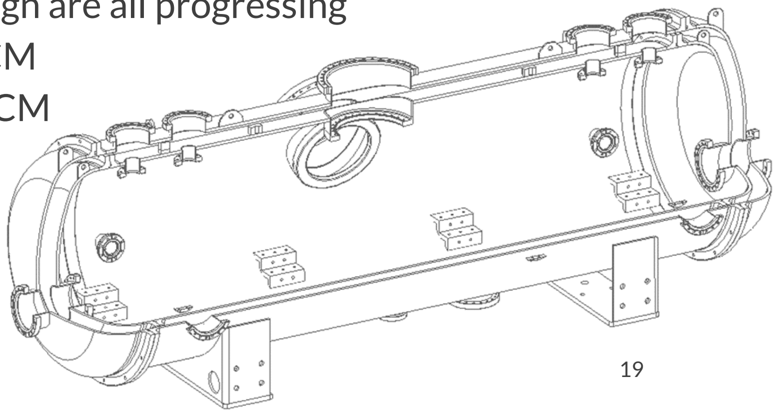
Accelerator Design and Challenges

Quarter cryomodule to arrive this fall

- Crucial first step towards a full demonstrator

Making good progress on challenges identified with community through Snowmass

- Gradient – Started meter scale cryogenic tests up to 20 MW
- Vibrations – Conducted measurements with 2 kW heat load
- Alignment – Integrating Rasnik system within QCM
- Cryogenics – Full flow tests planned within QCM
- Damping – Material testing, beam simulations, and RF design are all progressing
- Beam Loading and Stability - Beam test possible within QCM
- Scalability – Raft designs and integration to be tested in QCM



Questions?