C3 Status and Plans

Ankur Dhar, Emilio Nanni
CLIC Mini-Week
12/12/2023

Acknowledgements

SLAC-PUB-17661
April 12, 2022

Strategy for Understanding the Higgs Physics:
The Cool Copper Collider

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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

Fermilab, SLAC, LANL &
Snowmass Session in Seattle

Cornell Aug. 31st-Sept. 1st

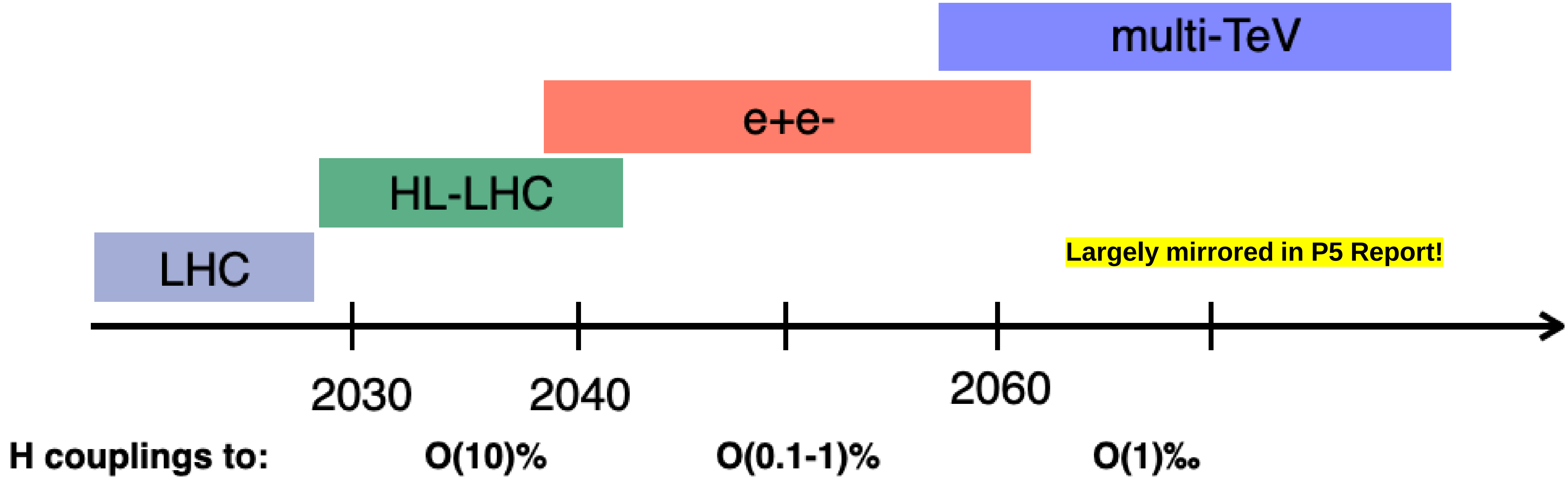
https://indico.classe.cornell.edu/event/2283/overview

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

Next Workshop In Feb. 12/13th '24 @ SLAC

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

What's Next for the Energy Frontier?



Physics goals beyond HL-LHC:

1. Establish Yukawa couplings to light flavor ⟹ precision & lumi
2. Search for invisible/exotic decays and new Higgs ⟹ precision & lumi
3. Establish self-coupling ⟹ > 500 GeV e+e- operations

[The Energy Frontier 2021 Snowmass Report]

C^3 Relevant Text and Recommendations in P5 Report (1)

- **Section 6.4:**
  - "There are exciting opportunities in the development of (i) new high average power, efficient drivers (RF, lasers, and electron beams), (ii) accelerating structures that can sustain high average power and gradient (metallic, plasma and dielectric)" …"
  - "Normal conducting radio frequency (RF), superconducting RF, superconducting magnets, targets, and advanced acceleration concepts are essential to develop the next generation of accelerators for particle physics. The normal conducting RF program should incorporate innovative concepts such as cryogenic cool copper and distributed coupling."
  - **Area Recommendation 8: Increase annual funding to the General Accelerator R&D program by $10M per year in 2023 dollars to ensure US leadership in key areas.**
  - "Technical and scientific plans should be developed for test facility projects that could be launched within the next 5–10 years. These could include the second stage cool copper test, which could develop high gradient normal conducting RF technology."
  - **Area Recommendation 9: Support generic accelerator R&D with the construction of small scale test facilities. Initiate construction of larger test facilities based on project review, and informed by the collider R&D program.**

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C^3 Relevant Text and Recommendations in P5 Report (2)

- **Section 6.5:**
  - "End-to-end designs are needed well before a decision can be made on a project in order to understand potential performance parameters and costs. These will guide research priorities and technology development as well as demonstrator facilities. Such early designs will also play a critical role in creating and sustaining the expertise to design such machines. Progress on these end-to-end designs should be evaluated (Recommendation 6)."
  - "R&D efforts in the next five years will inform test facilities as discussed in Section 6.4 for the mid-to-late decade time period and collider design results will set the stage for initiating a demonstrator facility (Recommendation 6), that would feed into future decisions on a potential collider project."
  - **Area Recommendation 10: To enable targeted R&D before specific collider projects are established in the US, an investment in collider detector R&D funding at the level of $20M per year and collider accelerator R&D at the level of $35M per year in 2023 dollars is warranted.**
- **Section 6.9:**
  - "Accelerator technologies play a key role in sustainability."
  - "Accelerator structure improvements can also play an important role, including higher quality factor, and concepts like cool copper."
  - **Area Recommendation 20: HEPAP, potentially in collaboration with international partners, should conduct a dedicated study aiming at developing a sustainability strategy for particle physics.**

C^3 Initial Reaction to P5 Report (Emilio's Opinion)

- P5 creates room for a future Higgs Factory!
- We are in! Report highlighted value that cold copper technology can bring to HEP
- We will start with targeted push under GARD with the goal of building test capabilities
- Need to understand timeline for "second stage" tests (injector + one cryomodule)
  - "Small" scale project ($<50M) vs. mid/large scale which require "panel" review (Recommendation 6)
- Future Collider Initiative relies on our connection multiple collider concepts – a highlight in presentation to P5 (next slide)
- Eager to find areas to collaborate with CLIC (Sustainability? Collider design studies?)

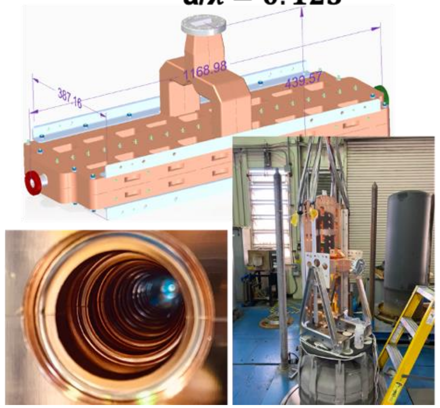
Synergies with Future Colliders

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

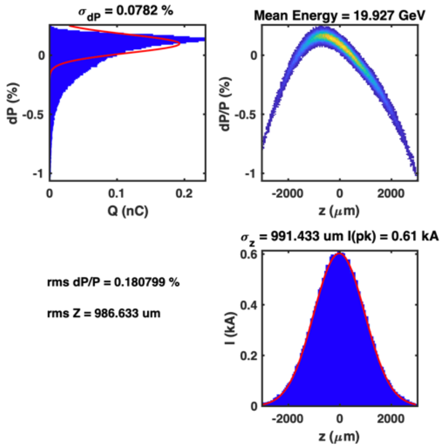
- CLIC - components, damping, fabrication techniques
- ILC - options for electron driven positron source based C^3 technology
- Muon Collider - high gradient cryogenic copper cavities in cooling channel, alternative linac for acceleration after cooling
- AAC - C^3 Demo utilized for staging, C^3 facility 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 <u>OR</u> reduce rf power 3.5X**

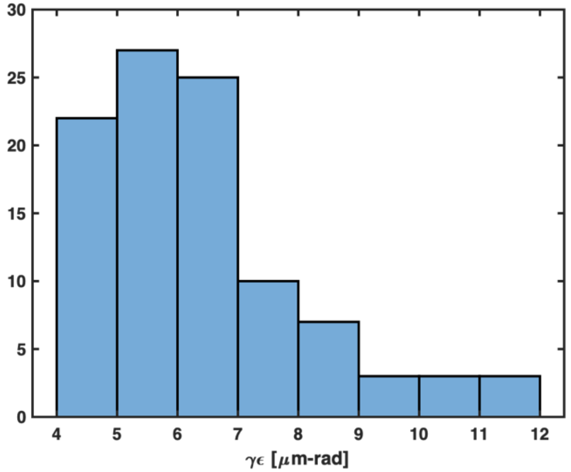
Wide Aperture S-band Injector Linac
$a/\lambda = 0.125$



- 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

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

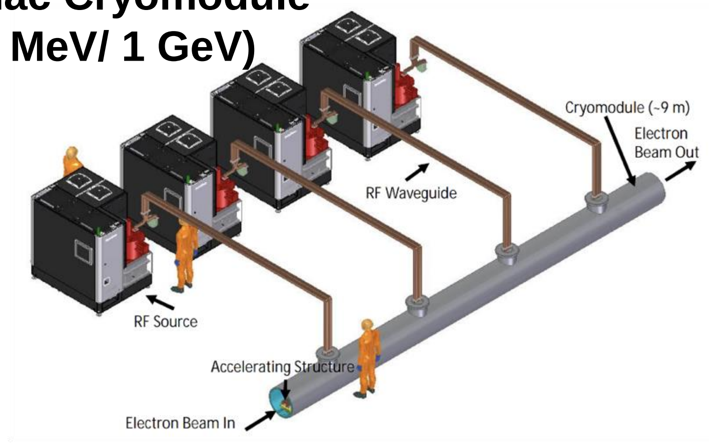
Accelerator Complex

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

Large portions of accelerator complex compatible between LC technologies

- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM), compatible w/ ILC-like detector
- Damping rings and injectors to be optimized with CLIC as baseline

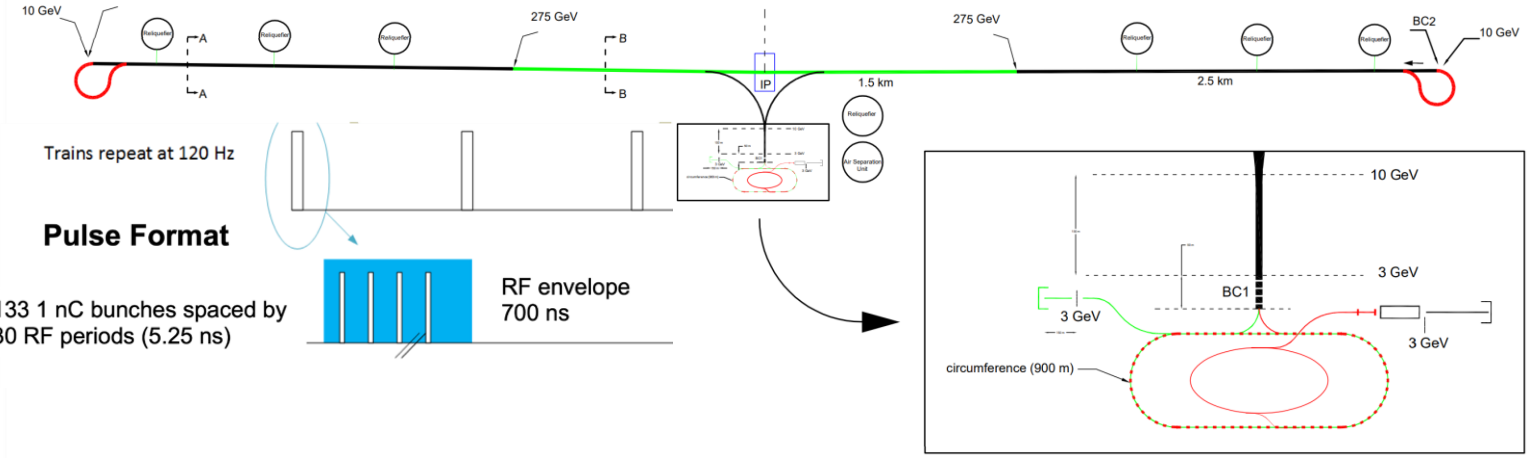
C^3 Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)



C^3 Parameters

Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

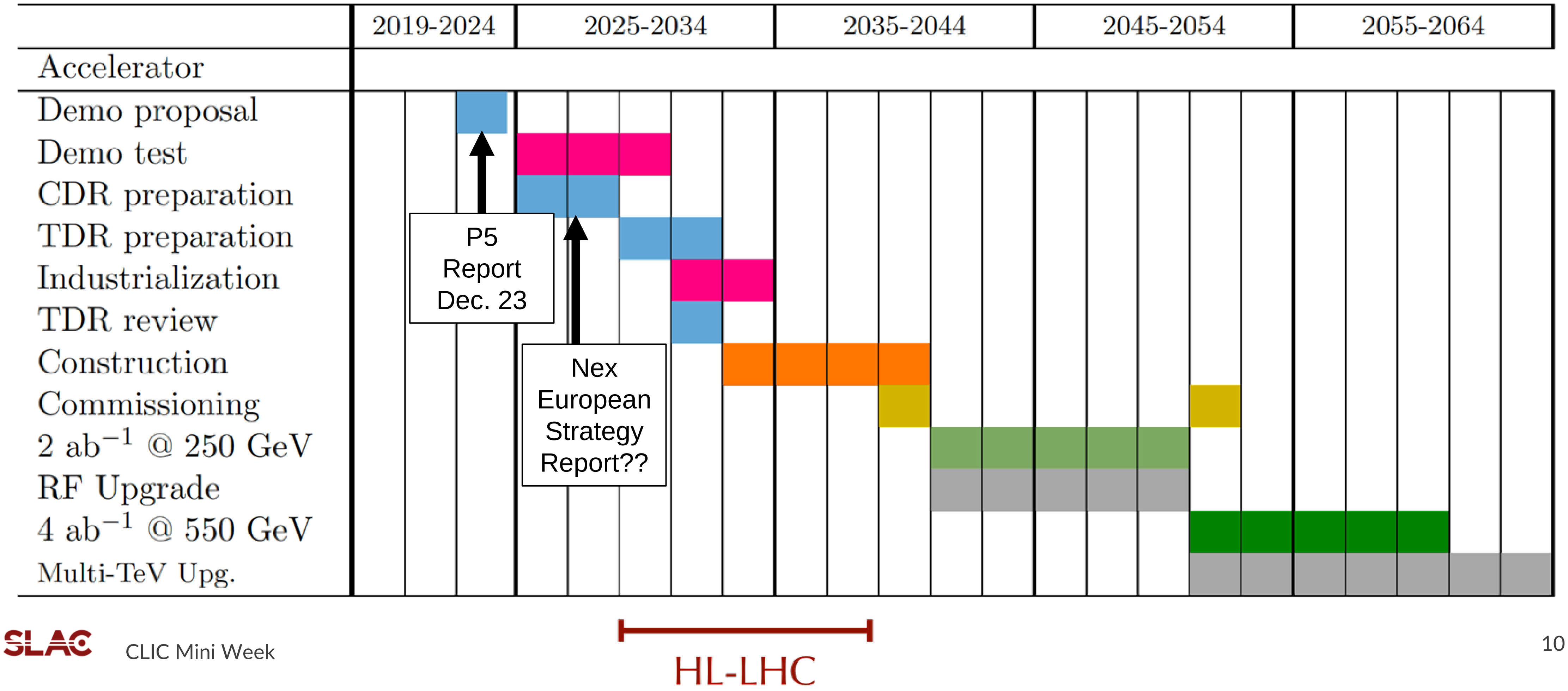
C^3 - 8 km Footprint for 250/550 GeV (to scale)



Technical Timeline for 250/550 GeV CoM

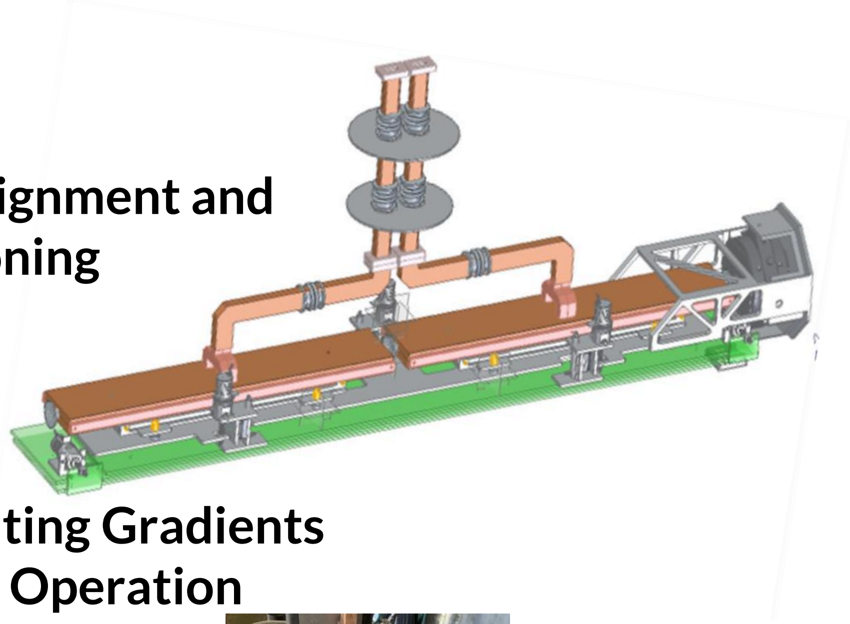
Technically limited timeline developed through the Snowmass process

Energy upgrade in parallel to operation with installation of additional RF power sources

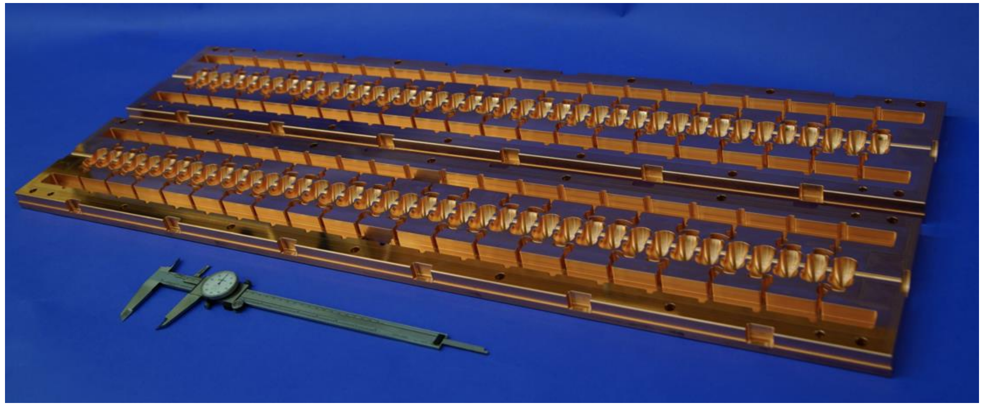


Ongoing Technological Development

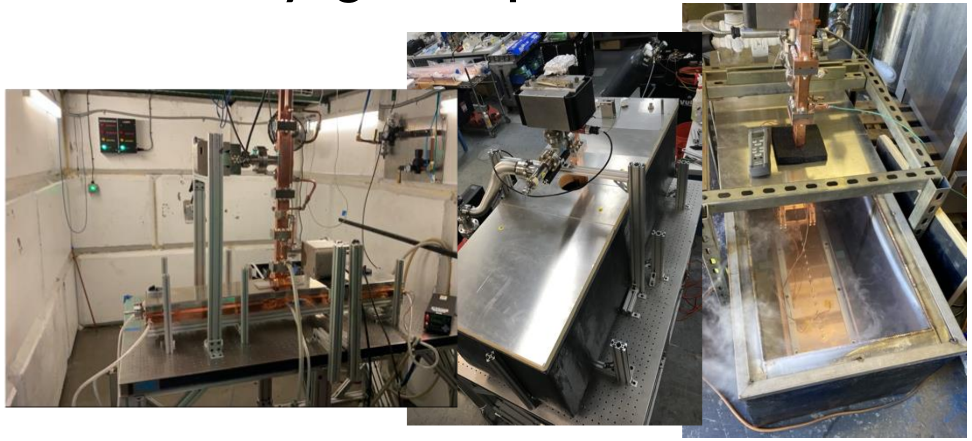
Preliminary Alignment and Positioning



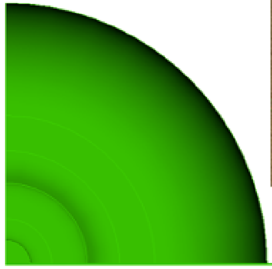
Modern Manufacturing
Prototype One Meter Structure

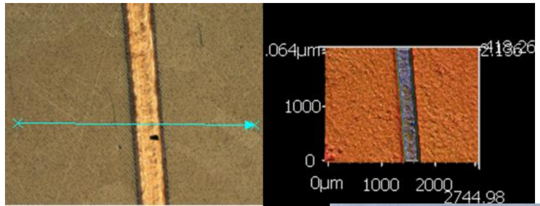


High Accelerating Gradients
Cryogenic Operation



Integrated Damping with NiChrome Coating



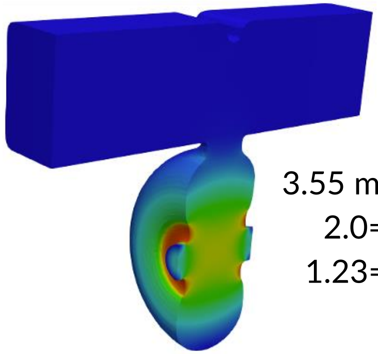


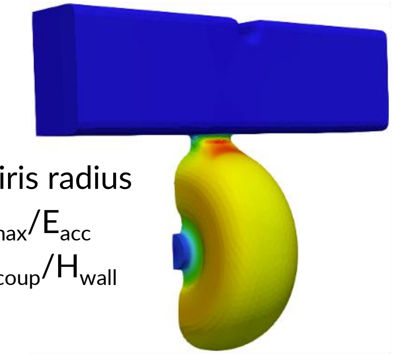
NiChrome sample for High Gradient Test Arrived at SLAC
NEXT: Hydrogen Furnace Fire and Ship to CERN!

Alignment and Vibrations

System level optimization essential for achieving performance

RF Structure Optimization





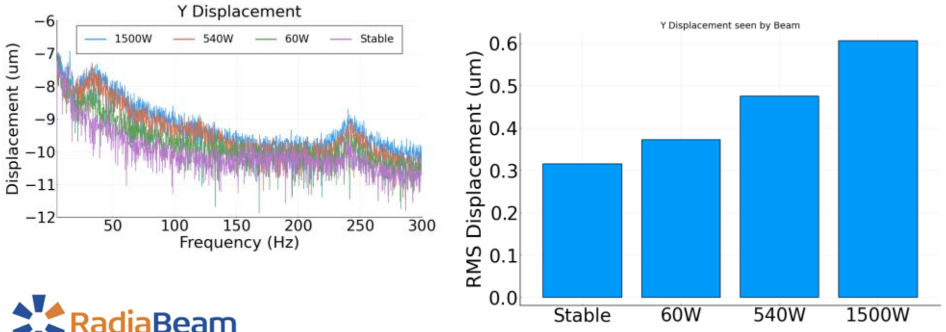
3.55 mm iris radius
$2.0 = E_{max}/E_{acc}$
$1.23 = H_{coup}/H_{wall}$

Electric Field

Magnetic Field

M. Shumail, Z. Li

Vibration Measurements and Analysis



RadiaBeam

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

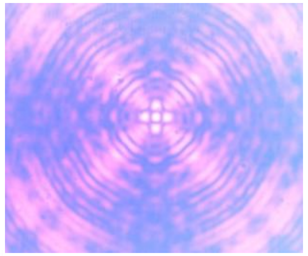
Two-Phase Fluid Simulations

FAMU-FSU College of Engineering

K. Shoele

Precision Short and Long Range Alignment

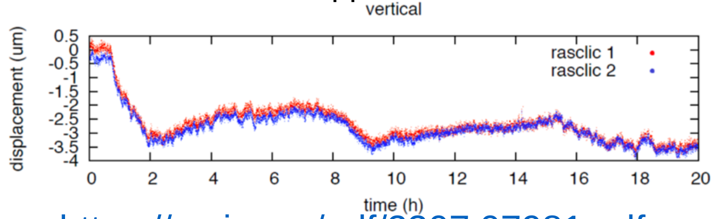
H. Van Der Graaf



Nikhef

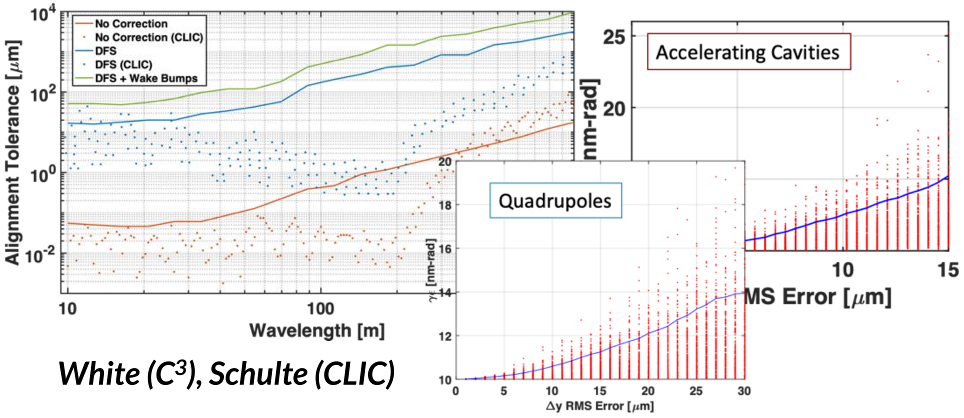
100 nm resolution

Approved effort to test cold



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

Main Linac Beam Dynamics



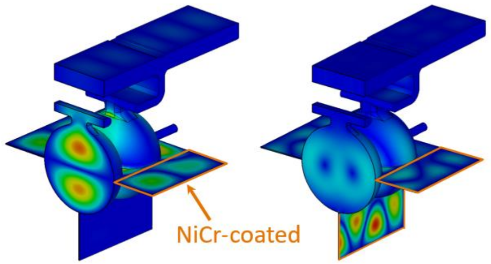
White (C[3]), Schulte (CLIC)

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

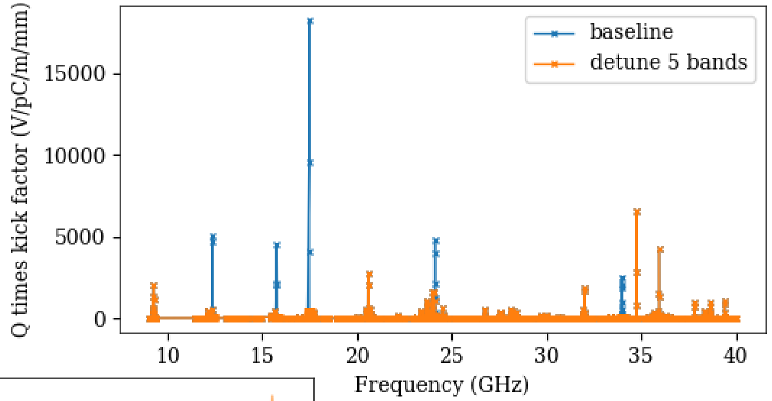
Emittance Preservation with HOM Suppression

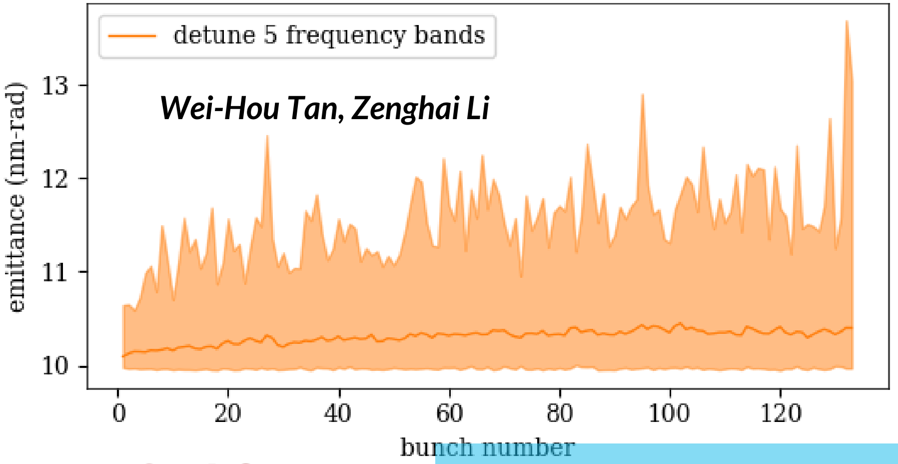


TM110 (9.27 GHz) TM211 (12.28 GHz)

H. Xu et al., LANL

Damped / Damped-Detuned Spectrum

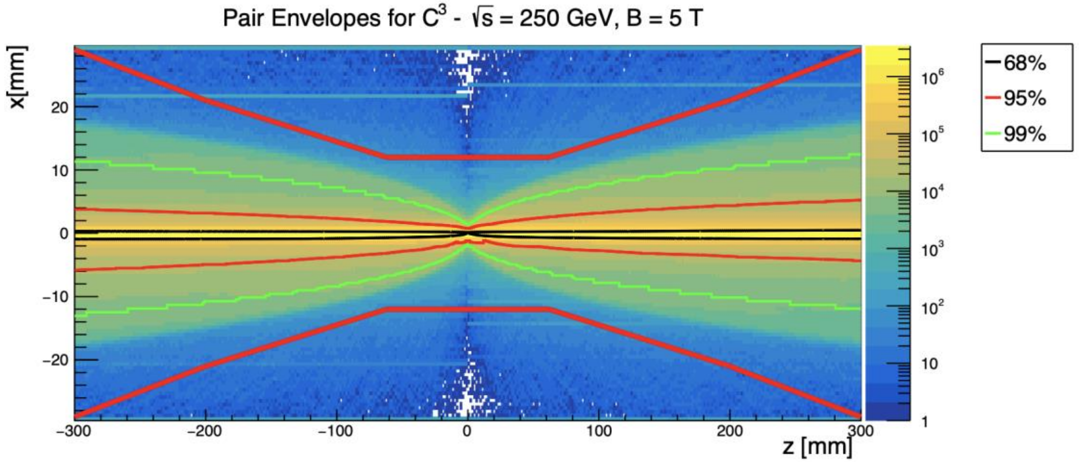




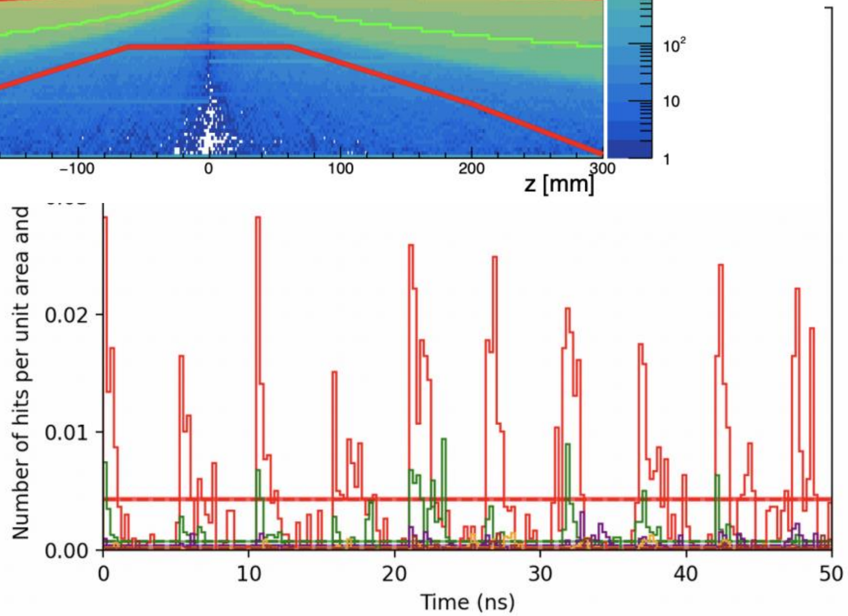
Compatible with ILC-like Detector

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, …

Two Cell Assembly for High Power Test

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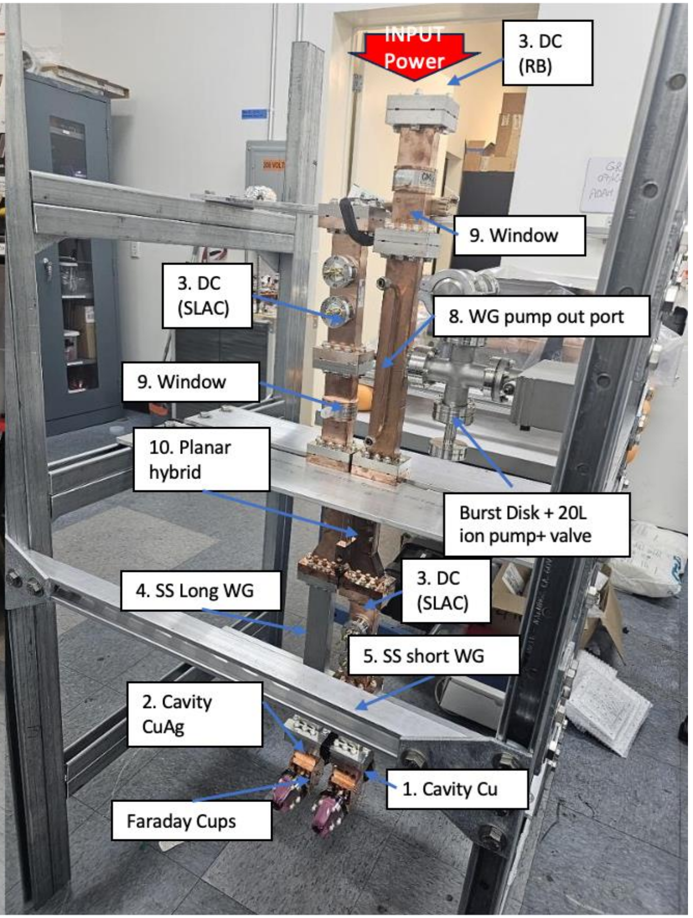
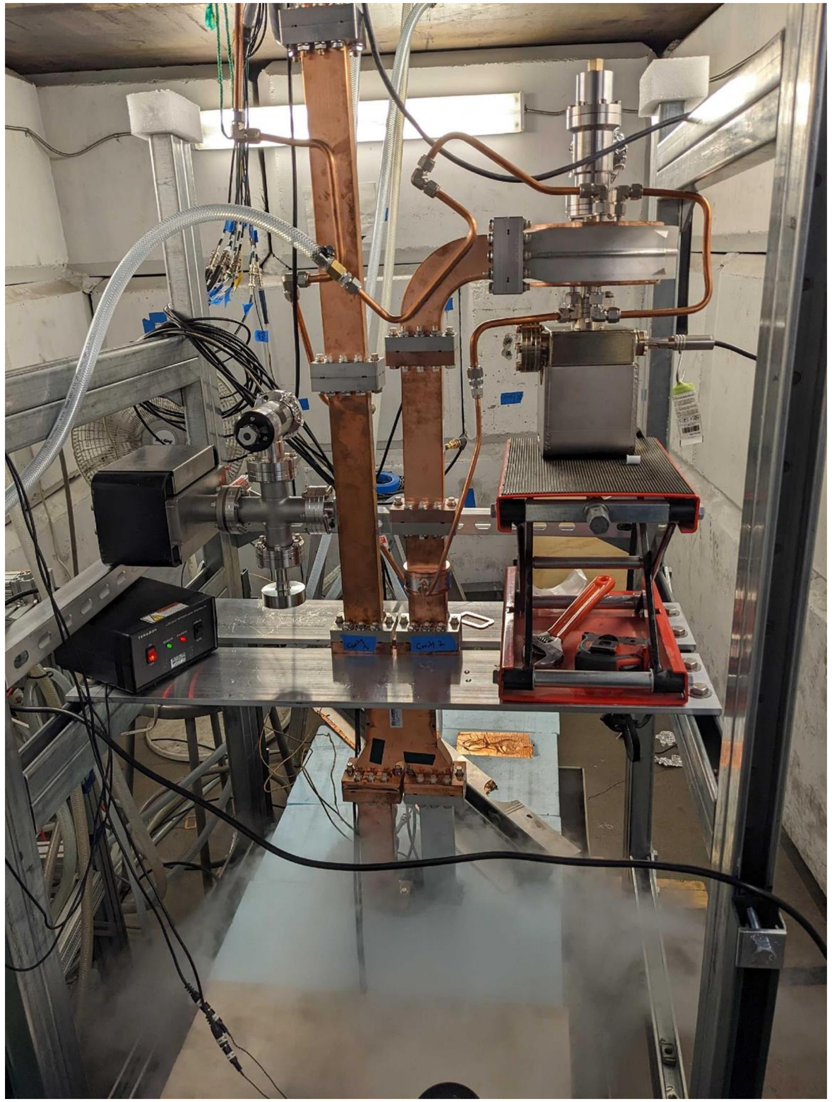
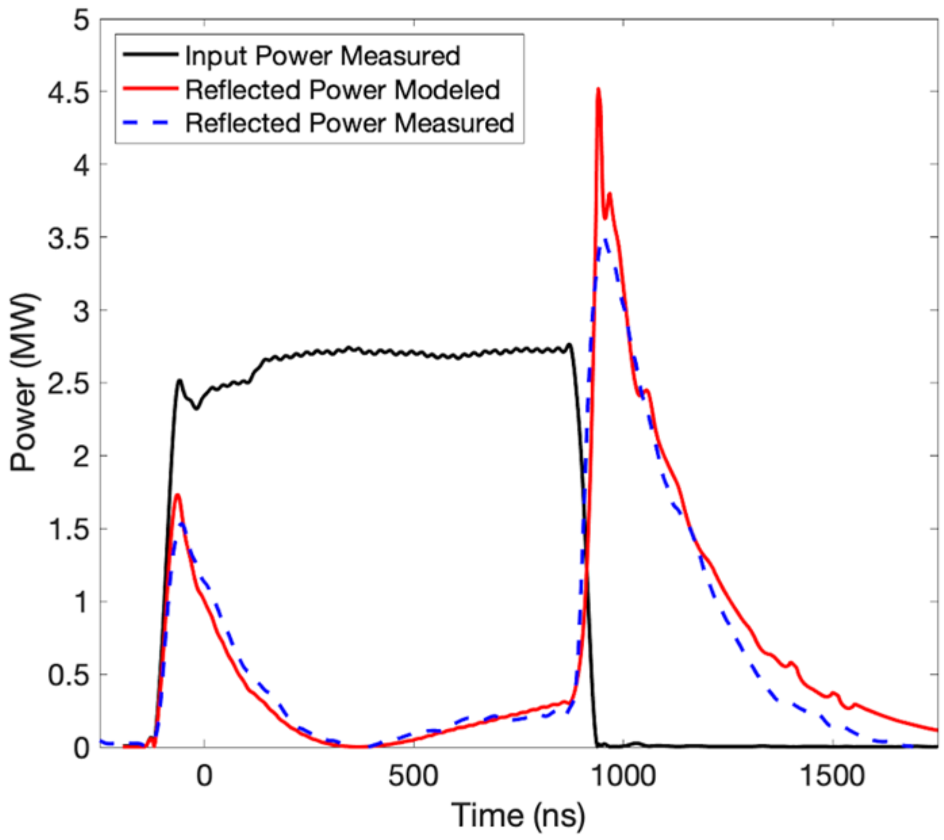
Radiabeam

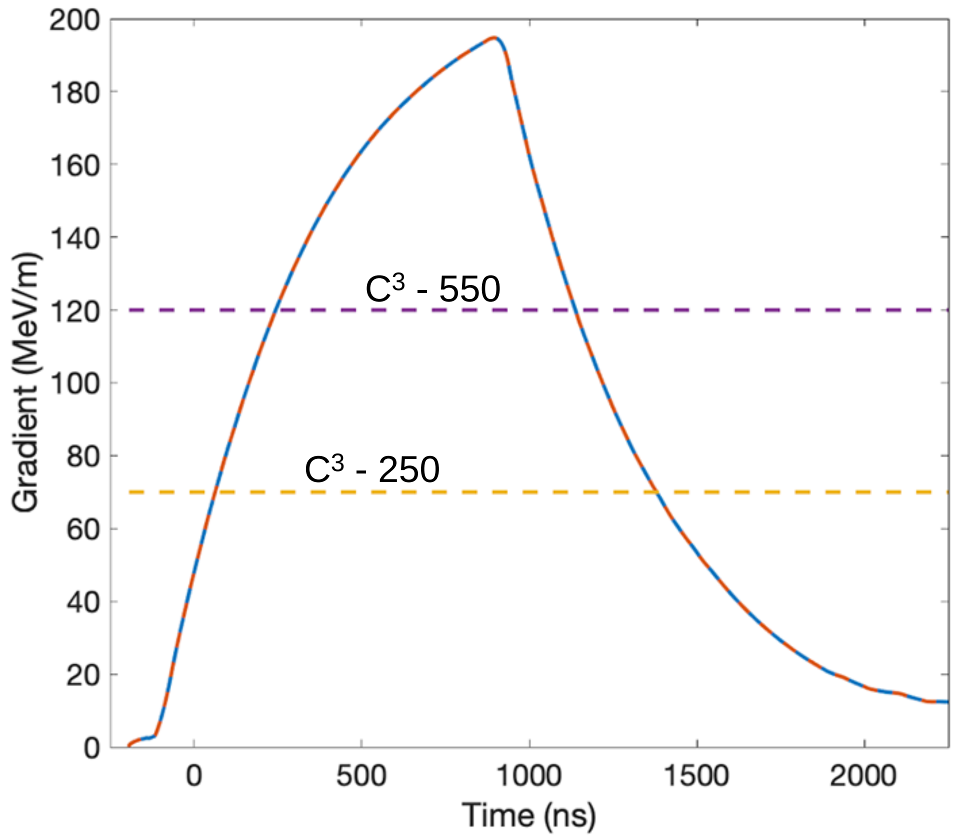




Typical (~~Highest Gradient~~) Performance

- Measured and modeled response for CuAg Cavity



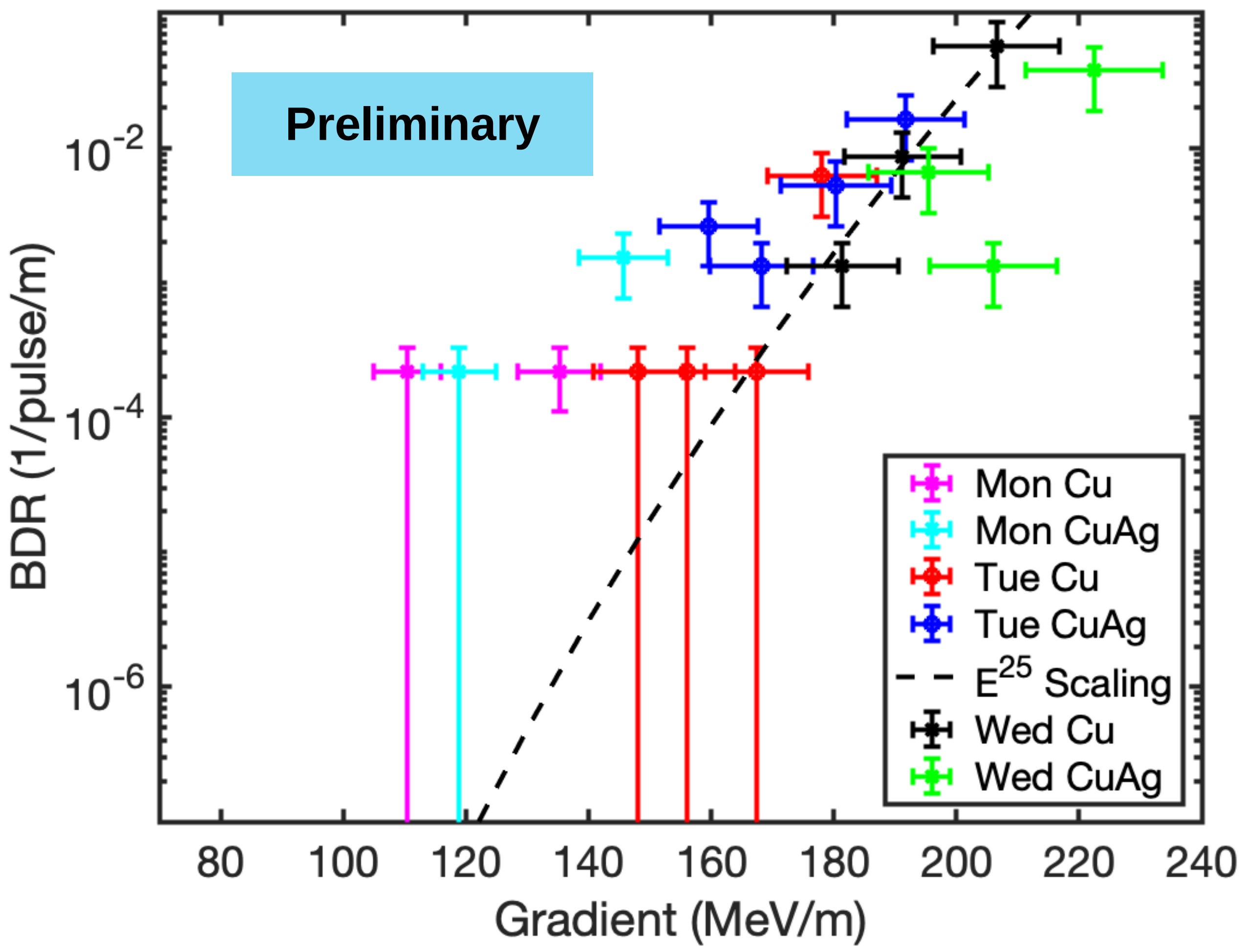


Breakdown Statistics

- Challenging due to short structure length – most data points O(1 hr)
- BDR of Cu and CuAg remarkably similar (very different than room temp)
- Showing day to day improvement

- Collected 5 more days of data – full analysis on going

- Very promising for longer flat top at 120 MeV/m

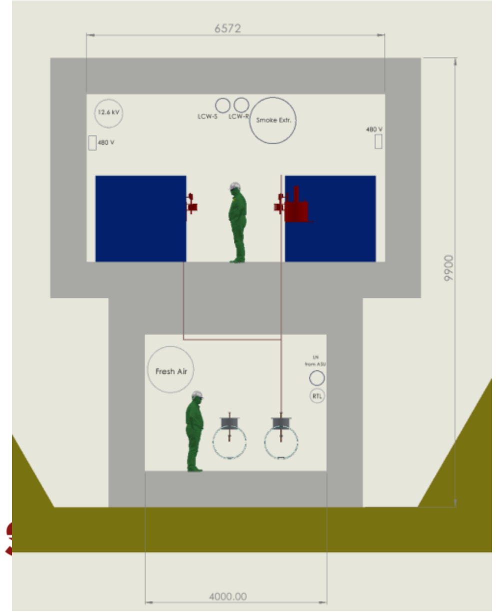


Special Thanks: A. Diego, M. Schneider, M. Boyce and A. Dhar

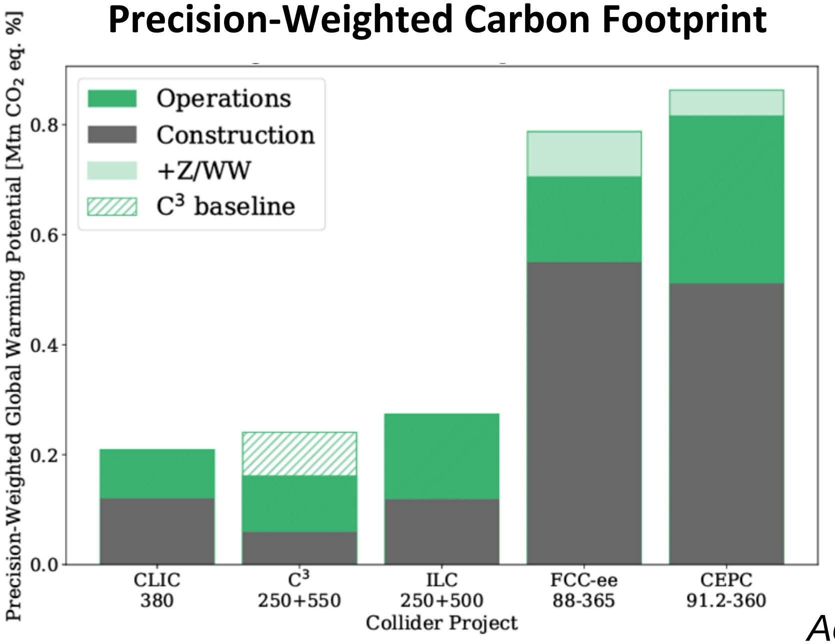
Power Consumption and Sustainability

- 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



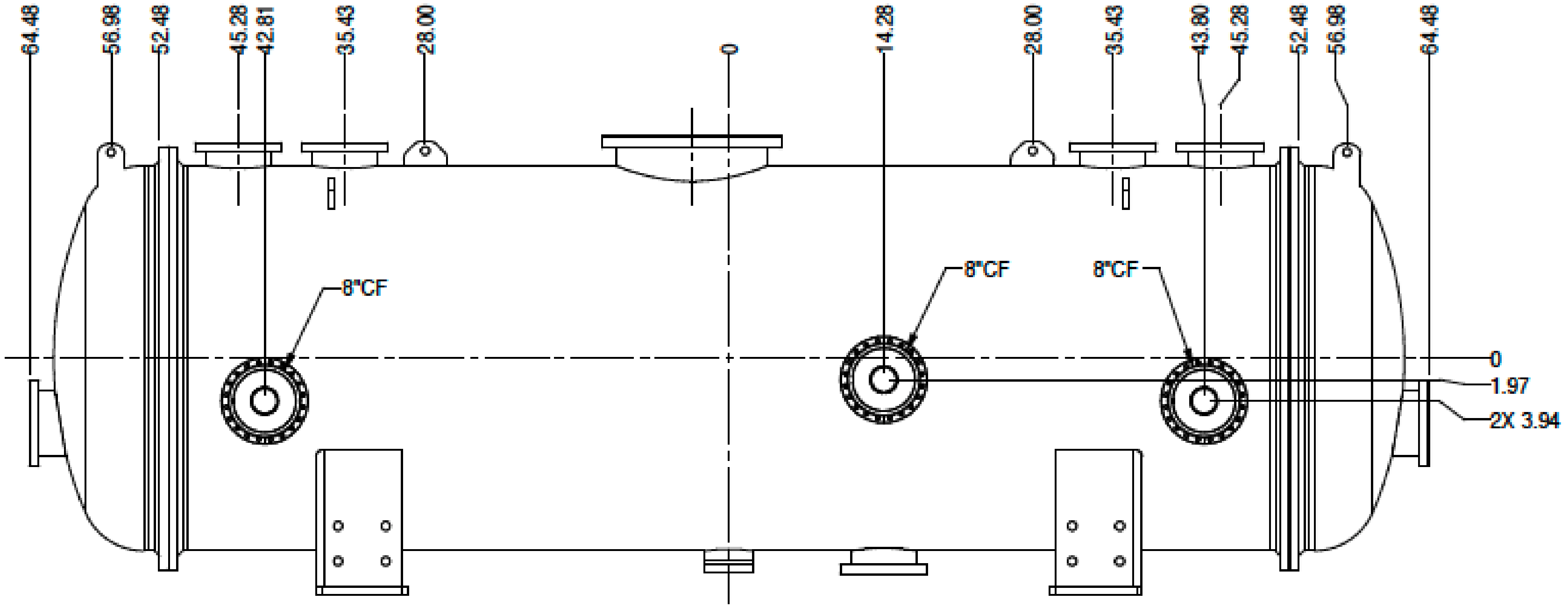
250 GeV CoM - Luminosity - $1.3x10^{34}$

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

Accepted PRX Energy, https://arxiv.org/abs/2307.04084

Quarter Cryomodule (QCM)

- Vacuum insulation, raft length up to 2.5 m
- Requisition is with procurement
- All drawings, technical documents complete
- Working with purchasing on RFP, aim to release prior to winter break



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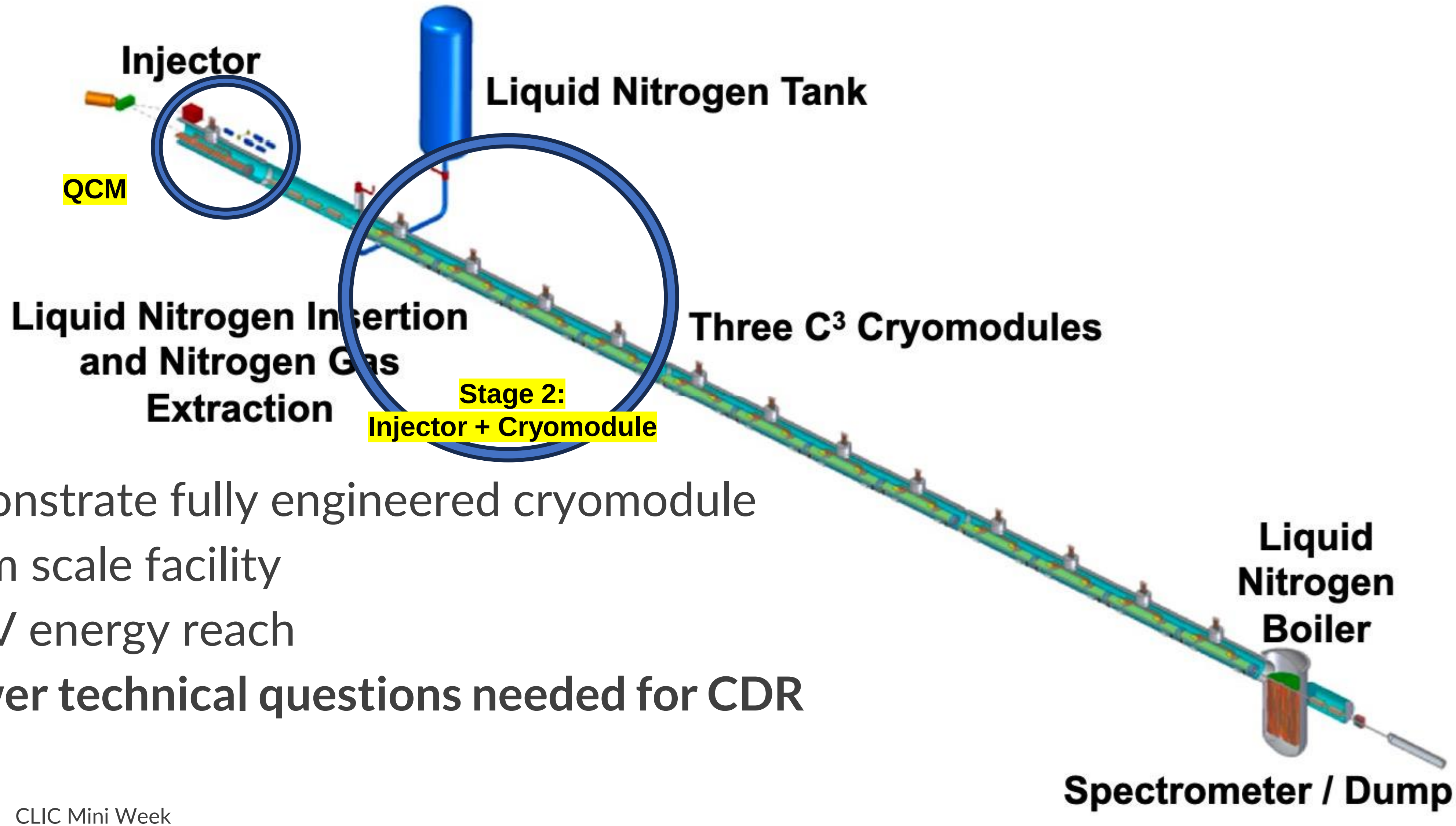
Outlook

The Complete C^3 Demonstrator



Demonstrate fully engineered cryomodule

~50 m scale facility

3 GeV energy reach

Answer technical questions needed for CDR

Conclusions

- C^3 provides a rapid route to precision Higgs physics with a compact 8 km footprint
  - Higgs physics run by 2040
  - US-hosted facility possible
- C^3 time structure is compatible with ILC-like detector design and optimizations ongoing
- C^3 upgrade to 550 GeV with only added rf sources
  - Higgs self-coupling and expanded physics reach
- C^3 is scalable to multi-TeV
- C^3 Demo advances technology beyond CDR level
  - 5 year program, followed by completion of TDR and industrialization
  - Three stages with quantitative metrics and milestones for decision points
  - Direct and synergistic contributions to near-term collider concepts

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

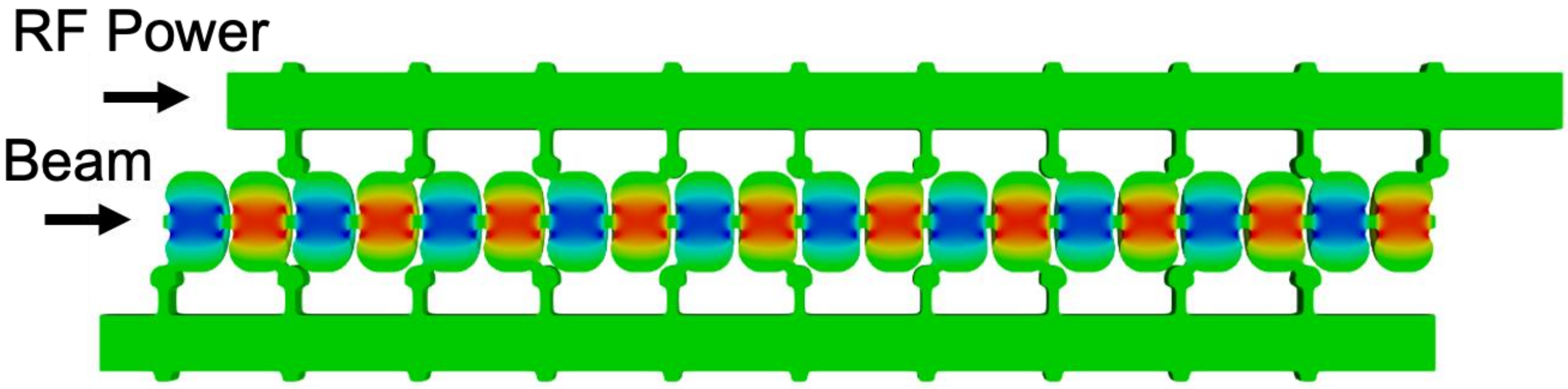
Questions?

Additional Material

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) $R_s = G^2/P$ [MΩ/m]

- Control peak surface electric and magnetic fields

Key to high gradient operation

Tantawi, Sami, et al. *PRAB* 23.9 (2020): 092001.

Cryo-Copper: Enabling Efficient High-Gradient Operation

Cryogenic temperature elevates performance in gradient

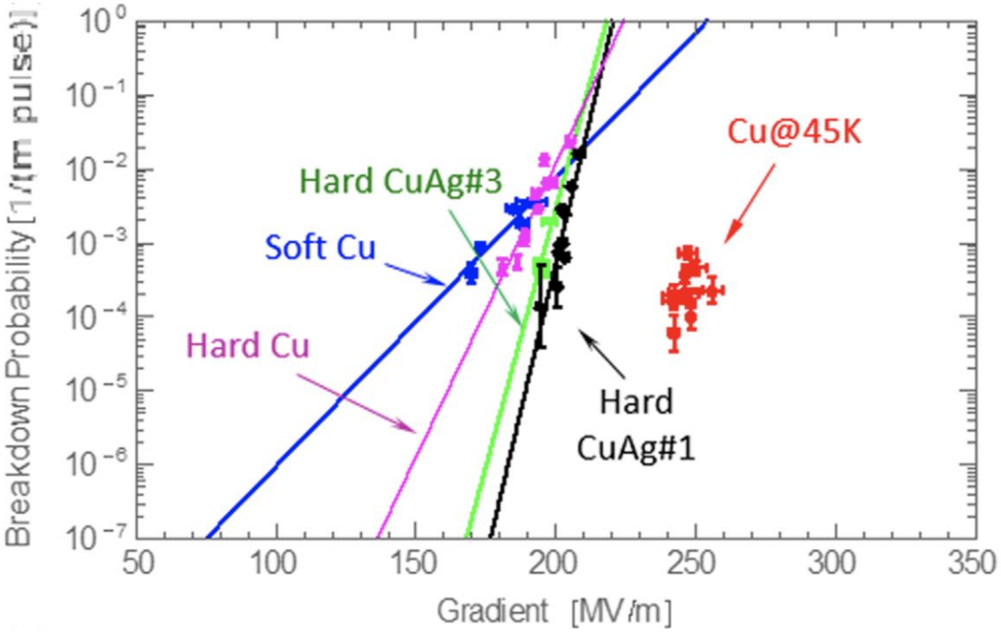
- Increased material strength is key factor
- Increase electrical conductivity reduces pulsed heating in the material

Operation at 77 K with liquid nitrogen is simple and practical

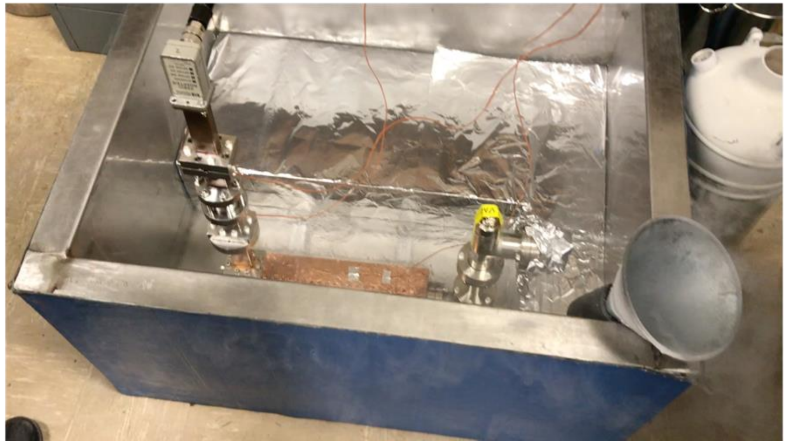
- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency

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

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



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



Cool Copper Collider

C^3 is based on a new rf technology

- Dramatically improving efficiency and breakdown rate

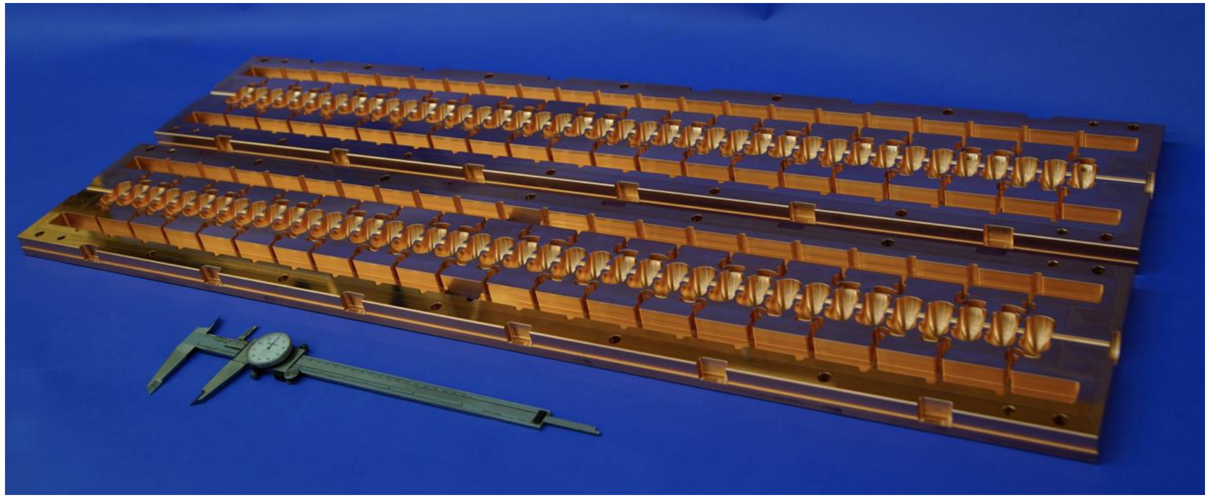
Distributed power to each cavity from a common RF manifold

Operation at cryogenic temperatures (LN_2 ~80 K)

Robust operations at high gradient: 120 MeV/m

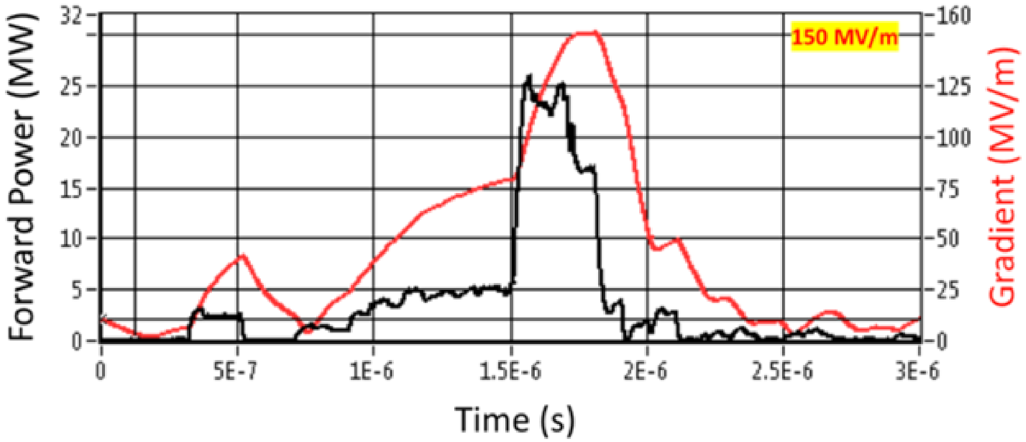
Scalable to multi-TeV operation

C^3 Prototype One Meter Structure



Cryogenic Operation at X-band

High Gradient Operation at 150 MV/m



Nasr, et al., *PRAB* 24.9 (2021): 093201.

High power Test at Radiabeam

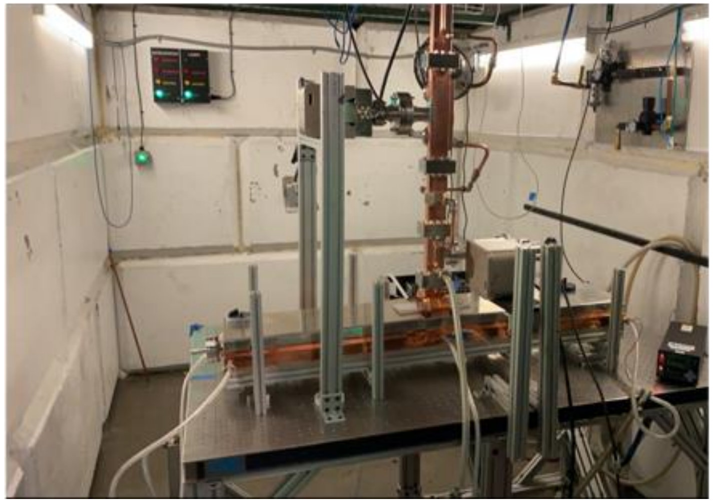


Table of Parameters

Collider	NLC	CLIC	ILC	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
Luminosity [x10^{34}]	0.6	1.5	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Length [km]	23.8	11.4	20.5 (31)	8	8
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	120	120
Bunch Spacing [ns]	1.4	0.5	369	5.26	3.5
Bunch Charge [nC]	1.36	0.83	3.2	1	1
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014
Site Power [MW]	121	168	125	$\sim$150	$\sim$175
Design Maturity	CDR	CDR	TDR	pre-CDR	pre-CDR

Full Parameters

Collider	NLC[28]	CLIC[29]	ILC[5]	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
σ_z [μm]	150	70	300	100	100
β_x [mm]	10	8.0	8.0	12	12
β_y [mm]	0.2	0.1	0.41	0.12	0.12
ϵ_x [nm-rad]	4000	900	500	900	900
ϵ_y [nm-rad]	110	20	35	20	20
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	120	120
Bunch Spacing [ns]	1.4	0.5	369	5.26	3.5
Bunch Charge [nC]	1.36	0.83	3.2	1	1
Beam Power [MW]	5.5	2.8	2.63	2	2.45
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014
Crab Angle	0.020/2	0.0165/2	0.014/2	0.014/2	0.014/2
Luminosity [x10^{34}]	0.6 (w/ IP dil.)	1.5 (max is 4)	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Shunt Impedance [MΩ/m]	98	95		300	300
Effective Shunt Impedance [MΩ/m]	50	39		300	300
Site Power [MW]	121	168	125	~150	~175
Length [km]	23.8	11.4	20.5 (31)	8	8
L* [m]	2	6	4.1	4.3	4.3

C^3 Demonstration R&D Plan

C^3 demonstration R&D needed to advance technology beyond CDR level

Minimum requirement for Demonstration R&D Plan:

- **Demonstrate operation of fully engineered and operational cryomodule**
  - Simultaneous operations of min. 3 cryomodules
- 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 (and higher > 155 MeV/m) w/ single bunch
  - Must understand margins for 120 - targeting power for (155 + margin) 170 MeV/m
  - 18X 50 MW C-band sources - off the shelf units
- **Fully damped-detuned accelerating structure**
- Work with industry to develop C-band source unit optimized for installation with main linac

This demonstration directly benefits development of compact FELs, beam dynamics, high brightness guns, *etc.*

The other elements needed for a linear collider - the sources, damping rings, and beam delivery system – more advanced from the ILC and CLIC – need C^3 specific design

- Our current baseline uses these directly; will look for further cost-optimizations for of C^3

Upgrade Options

Luminosity

- Beam power can be increased for additional luminosity
- C^3 has a relatively low current for 250 GeV CoM (0.19 A) - Could we push to match CLIC at 1.66 A? (8.5X increase?)
- Pulse length and rep. rate are also options

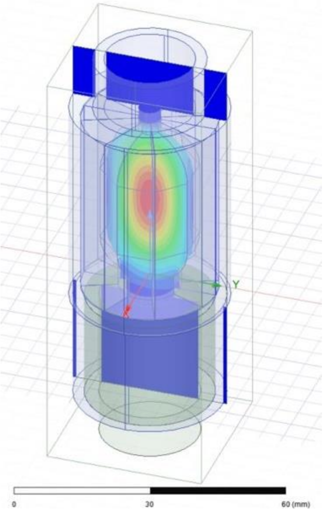
Parameter	Units	Baseline	High-Lumi
Energy CoM	GeV	250	250
Gradient	MeV/m	70	70
Beam Current	A	0.2	1.6
Beam Power	MW	2	16
Luminosity	$x10^{34}$	1.3	10.4
Beam Loading		45%	87%
RF Power	MW/m	30	125
Site Power	MW	~150	~180

Caution: Requires serious investigation of beam dynamics - great topic for C^3 Demonstration R&D

Energy

- Scalability studied to 3 TeV
- Requires rf pulse compression for reasonable site power
- Higher gradient option (155 MeV/m) in consideration

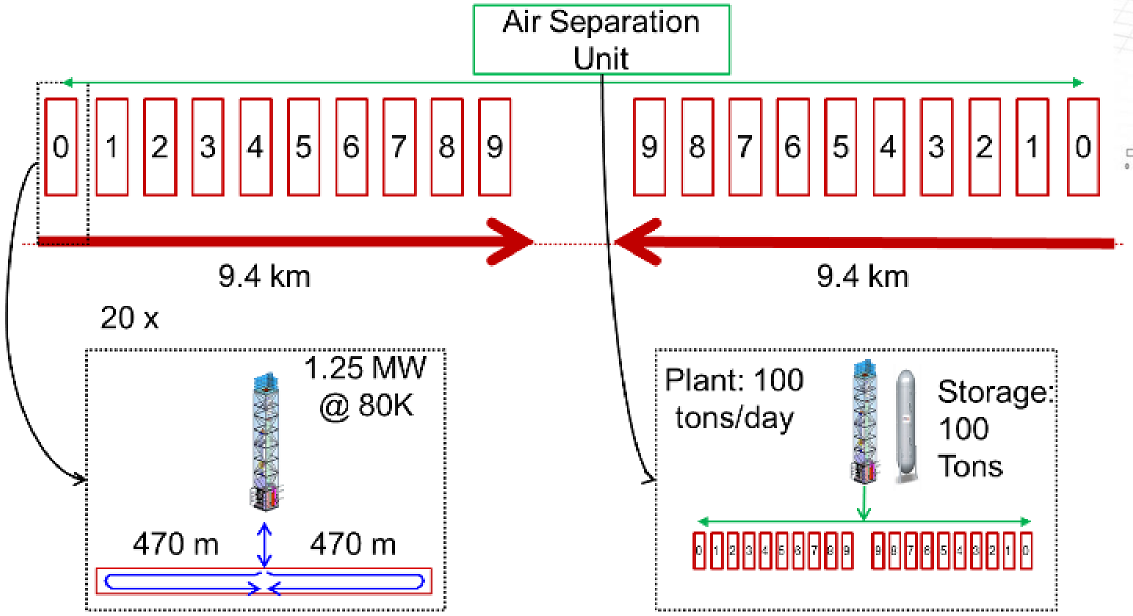
HTS Pulse Compressor
REBCO Coatings



Qo ~ 400k

Le Sage, CERN Collaborators

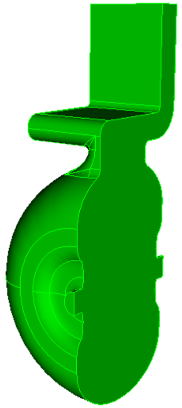
Cryogenics Scale to multi-TeV



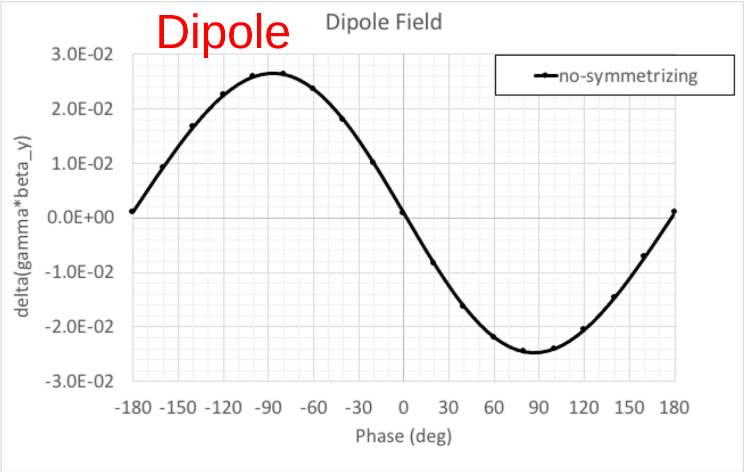
arXiv:1807.10195 (2018)

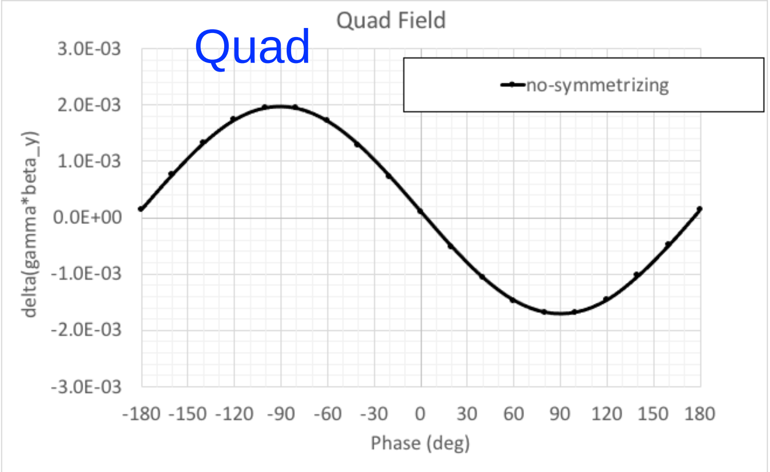
Further Cavity Optimization Possible

- Single side coupling iris induces dipole and quad fields
- Coupling hole symmetrization and racetrack shape incorporated to minimize dipole and quad fields

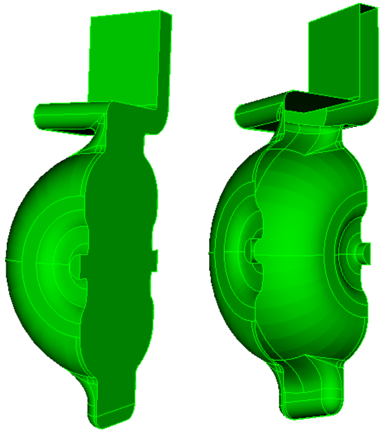


dipole, quad calculated at 50MV/m

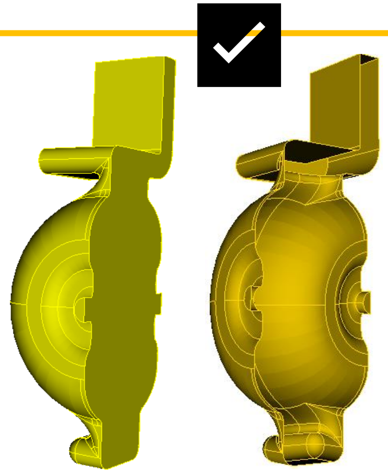




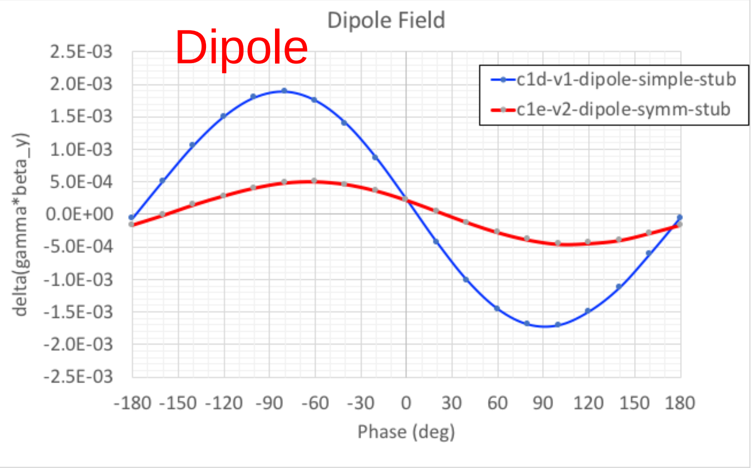
w/o symmetrization

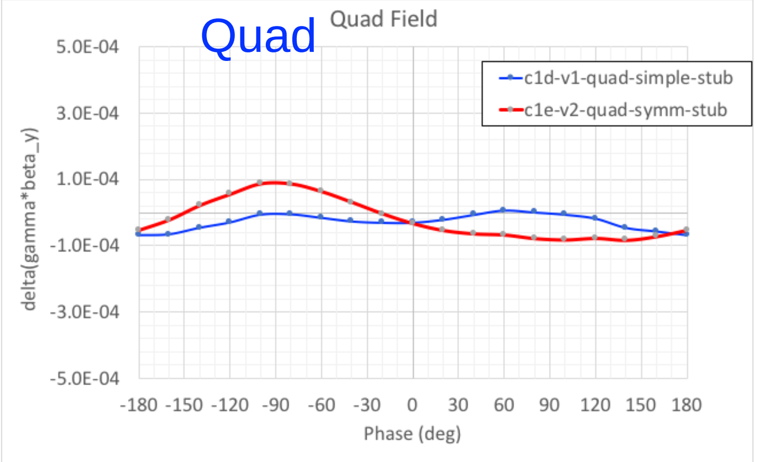


V1-simple-stub
(not ideal cancellation)



V2-symm-stub
(good cancellation)





with symmetrization 100X reduction

Zenghai Li

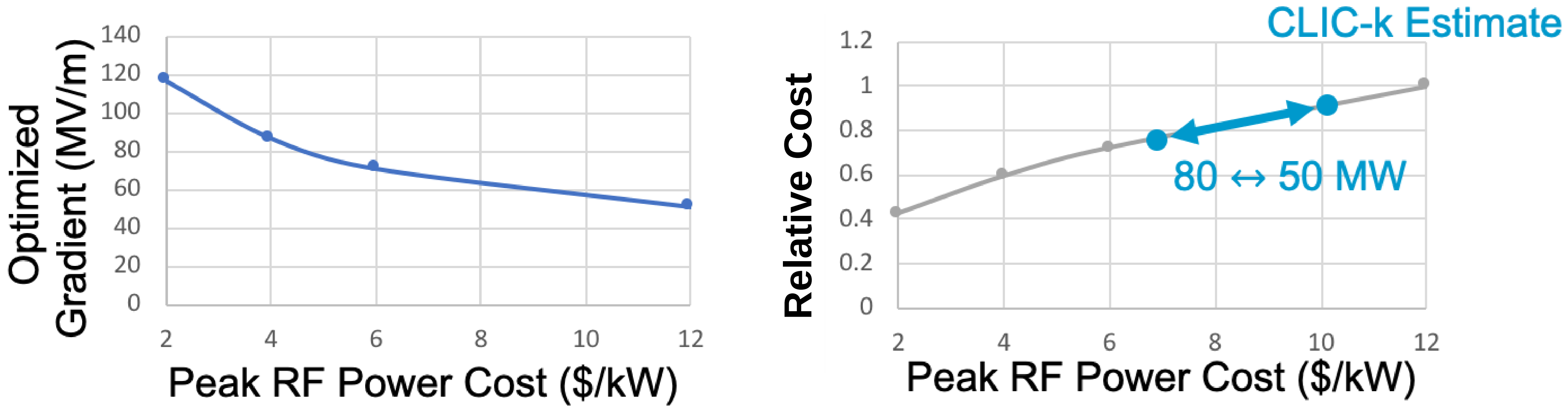
RF Source R&D Over the Timescale of the Next P5

RF source cost is the key driver for gradient and cost

Significant savings when items procured at scale of LC

Need to focus R&D on reducing source cost to drive economic argument for high gradient

Gradient/Cost Scaling vs. RF Source Cost for Main Linac



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

RF Power Requirements

70 MeV/m 250 ns Flattop (extendible to 700 ns)

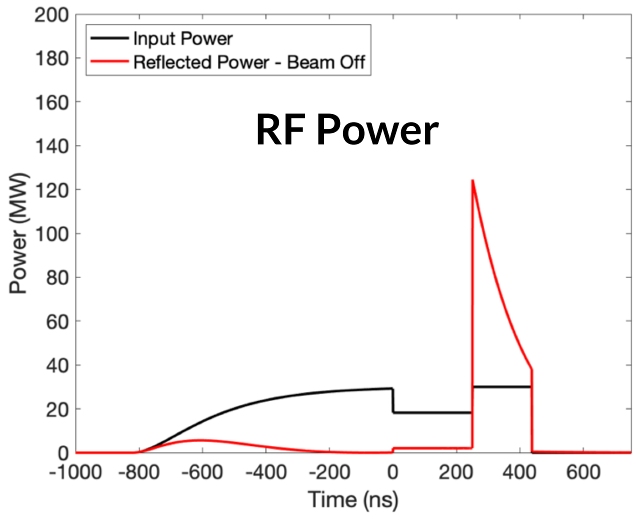
~1 microsecond rf pulse, ~30 MW/m

Conservative 2.3X enhancement from cryo

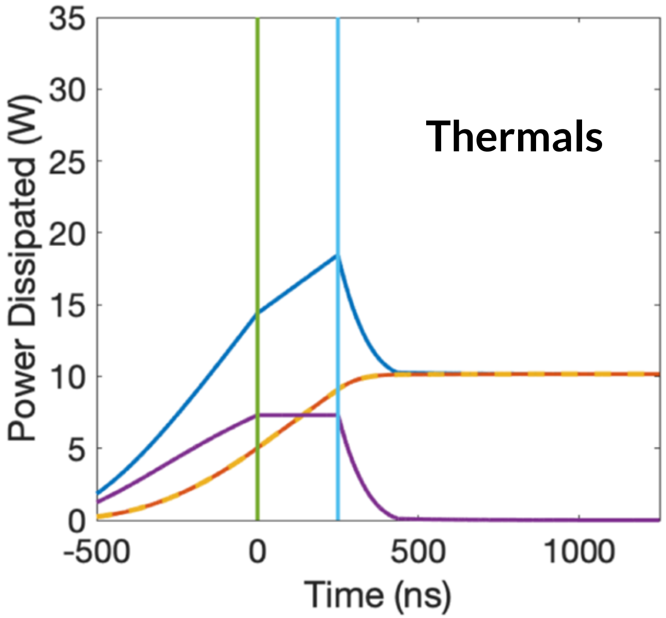
- No pulse compression

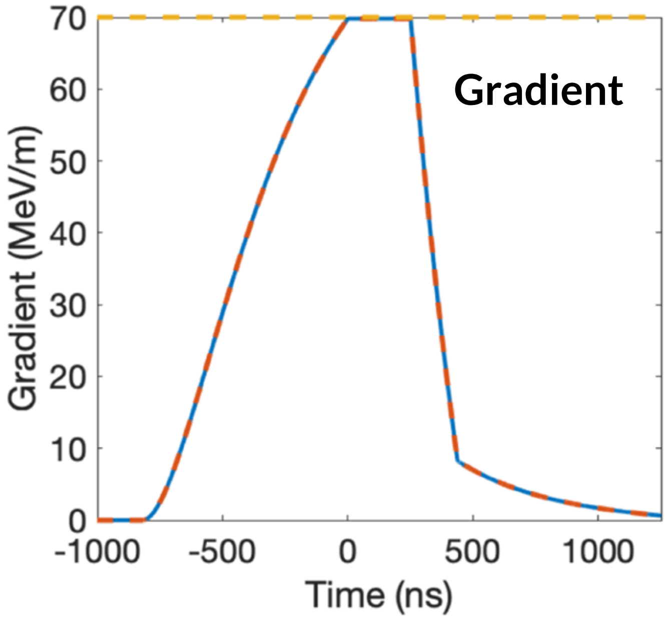
Ramp power to reduce reflected power

Flip phase at output to reduce thermals



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





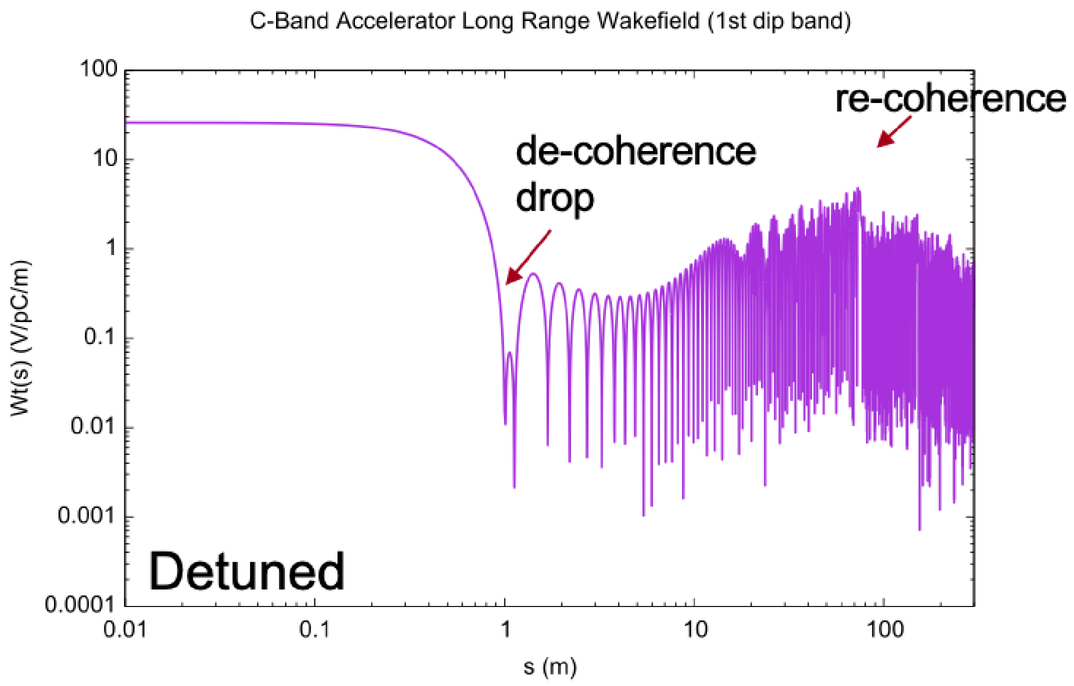
Gaussian Detuning Provides Required 1st Band Dipole Suppression for Subsequent Bunch, Damping Also Needed

Dipole mode wakefields immediate concern for bunch train

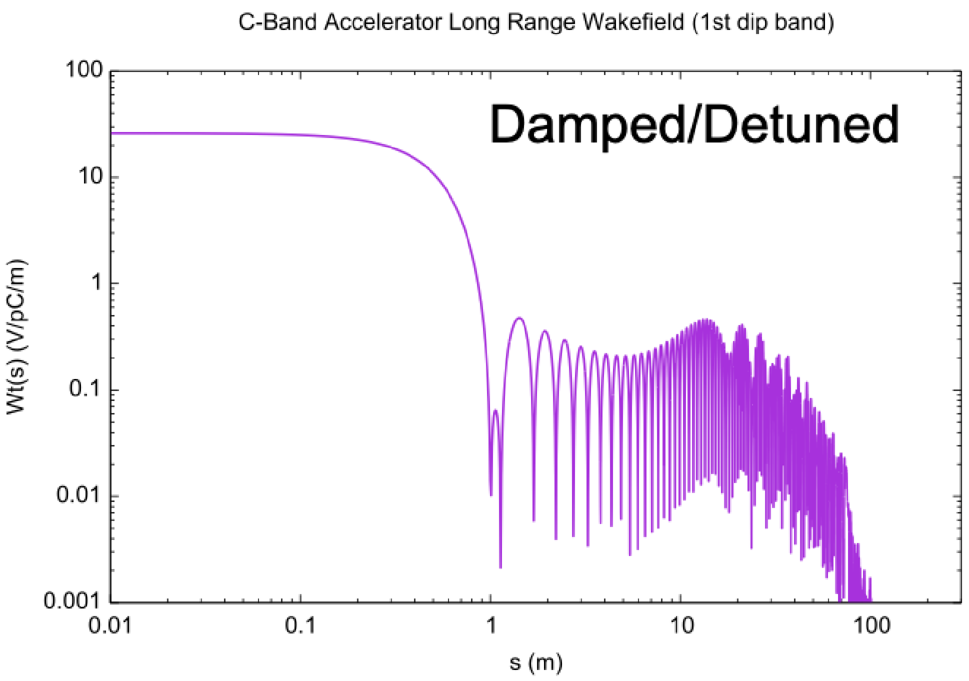
4σ Gaussian detuning of 80 cells for dipole mode (1st band) at f_c=9.5 GHz, w/ $\Delta f/f_c$=5.6%

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

- Damping needed to suppress re-coherence



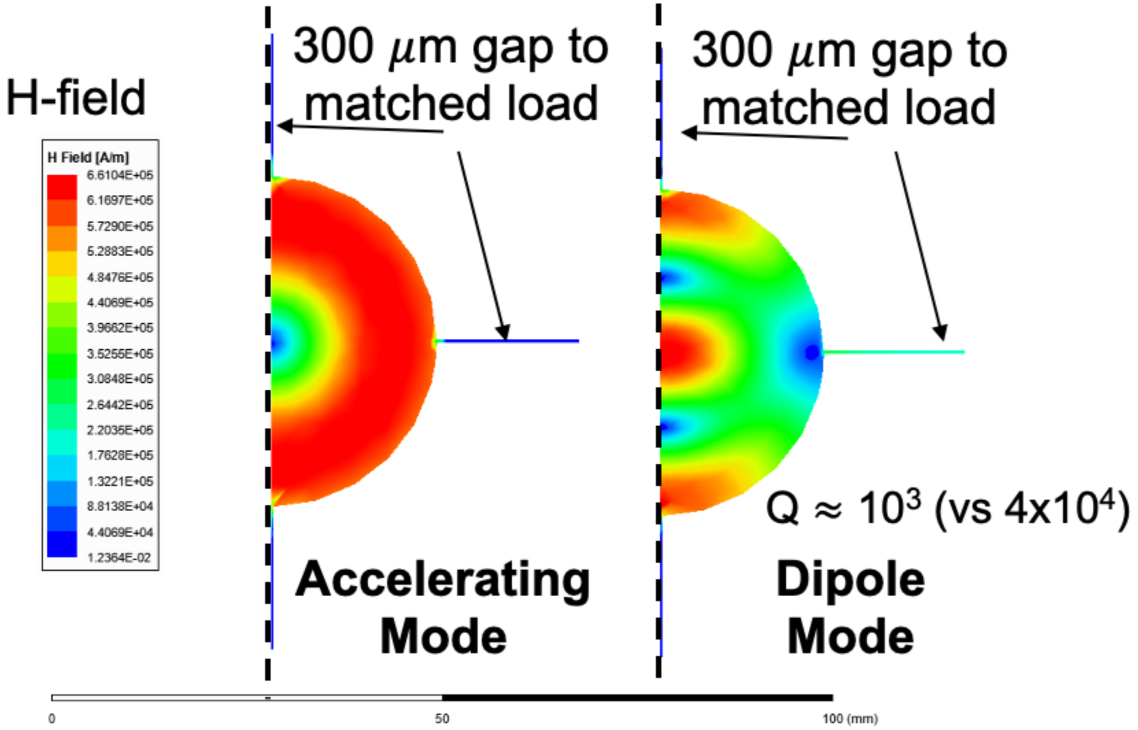
(Only copper surface loss damping included)



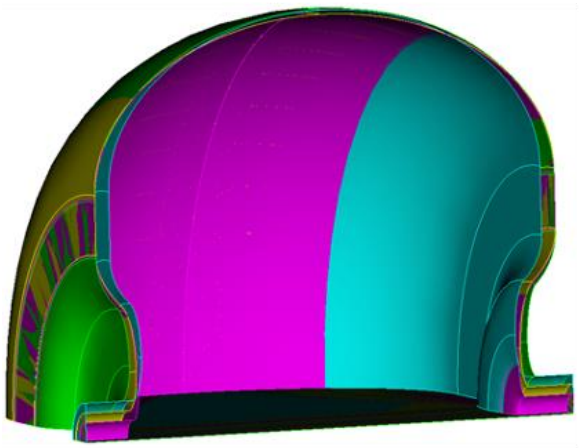
(1.0e3 Q total HOM damping included)

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

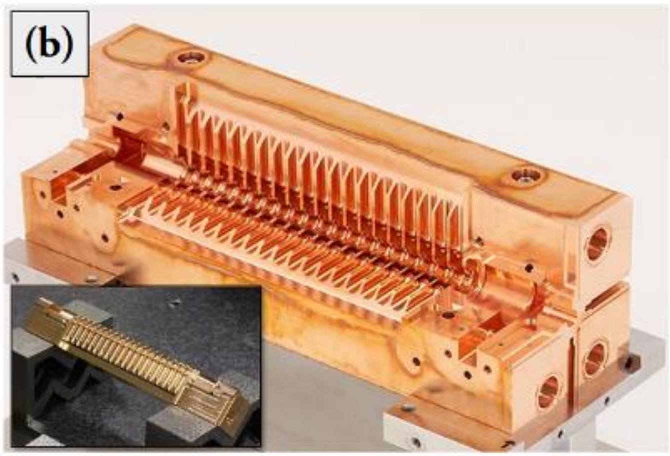
Individual cell feeds necessitate adoption of split-block assembly
Perturbation due to joint does not couple to accelerating mode
Exploring gaps in quadrature to damp higher order mode



Detuned Cavity Designs



Quadrant Structure



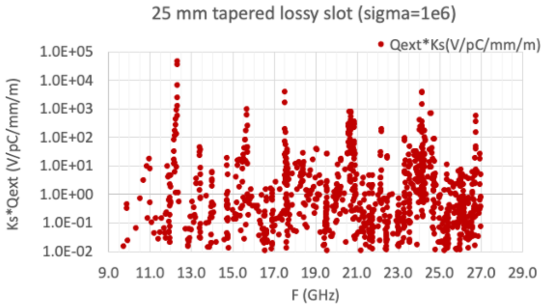
Abe et al., PASJ, 2017, WEP039

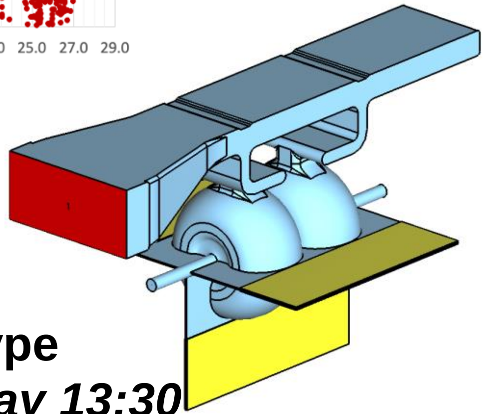
Implementation of Slot Damping

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

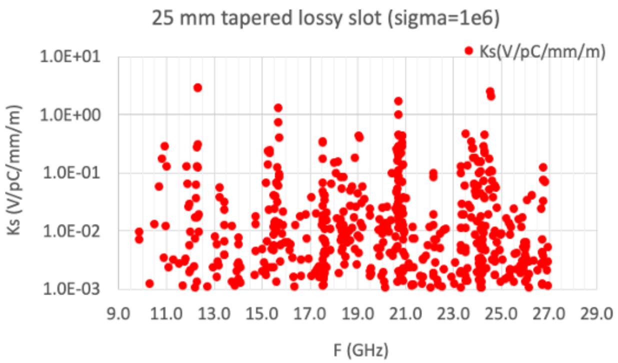




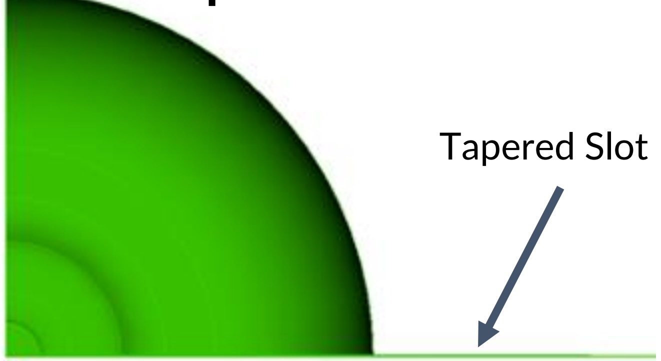
Two Cell Prototype

H. Xu, NCRF W 17th May 13:30

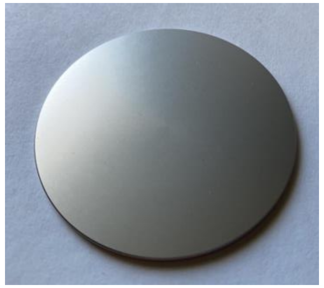
Kick Factor

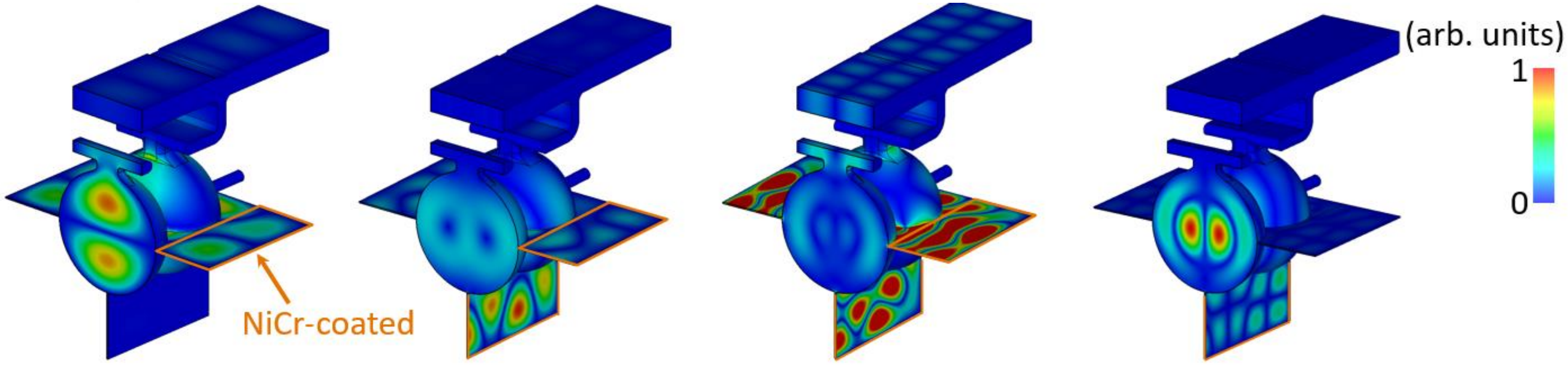


Vacuum Space Model



NiCr Tested at 80K





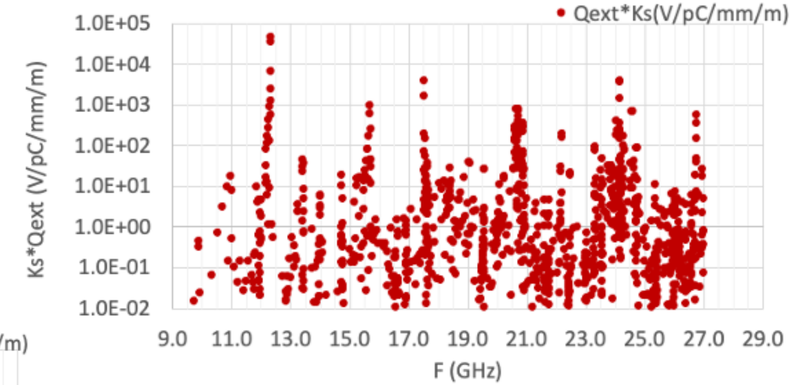
TM110 (9.27 GHz) TM211 (12.28 GHz) TM120 (15.67 GHz) TM121 (17.65 GHz)

Implementation of Slot Damping

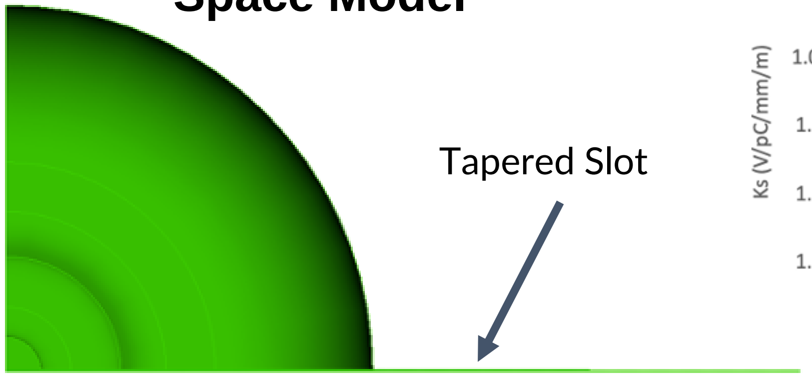
Need to extend to 40 GHz / Optimize coupling / Modes below 10^4 V/pC/mm/m

NiCr coated damping slots in development

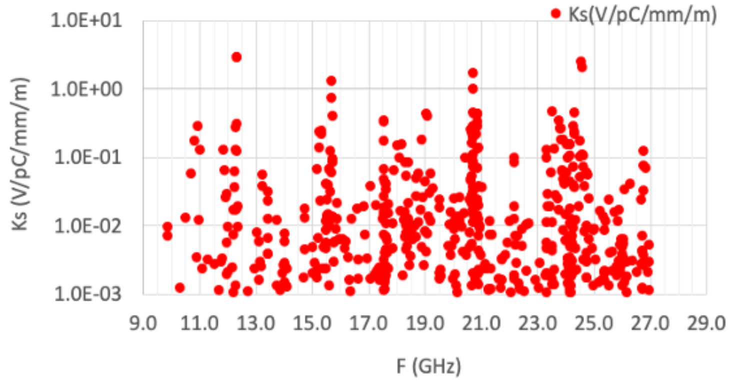
Kick Factor * Q

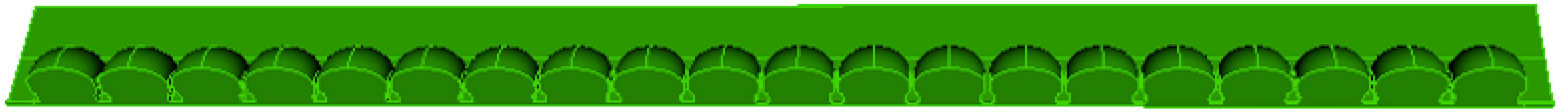


Vacuum Space Model

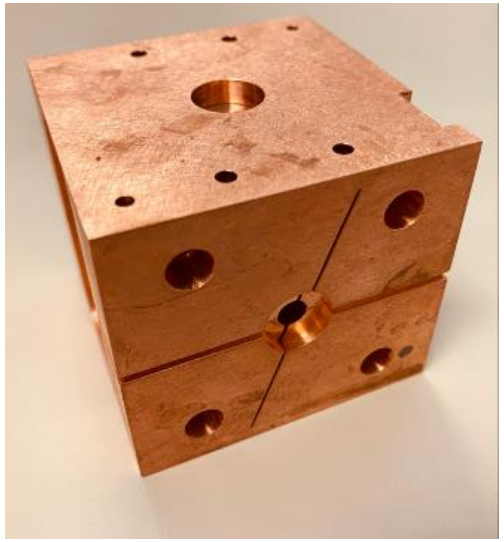


Kick Factor





Damping Slot Prototype



RF Power Requirements and Cryogenics

70 MeV/m 250 ns Flattop (extendible to 700 ns)

~1 microsecond rf pulse, ~30 MW/m

2.3X enhancement from cryo

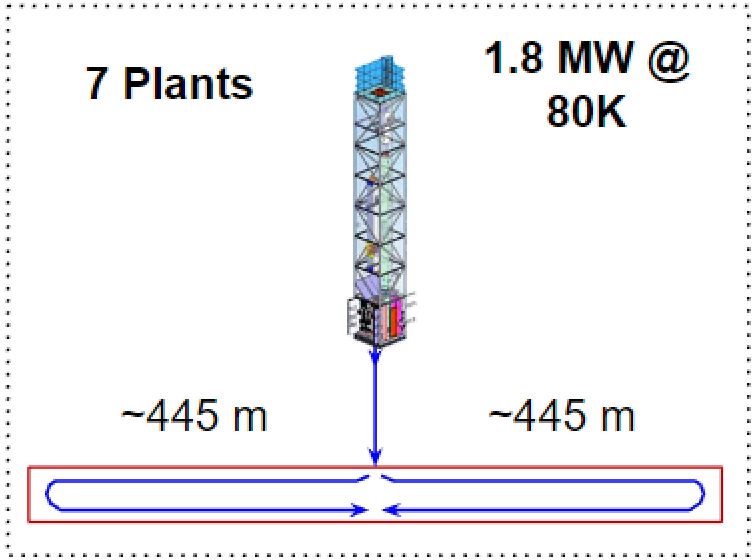
- No pulse compression

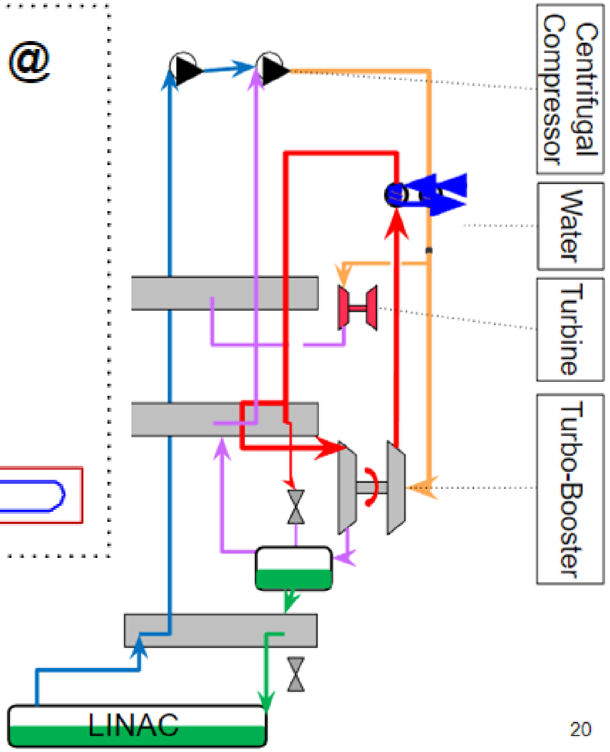
Ramp power to reduce reflected power

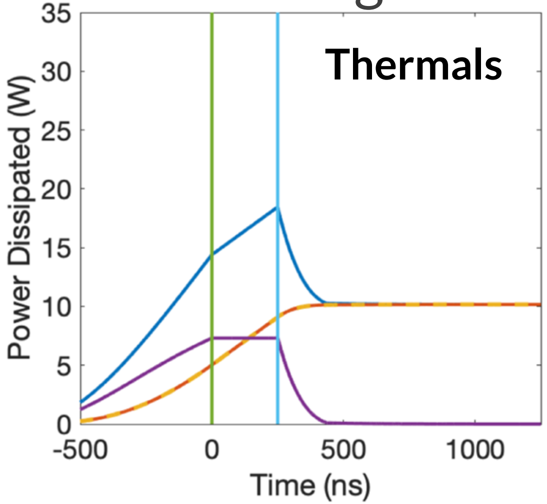
Flip phase at output to reduce thermals

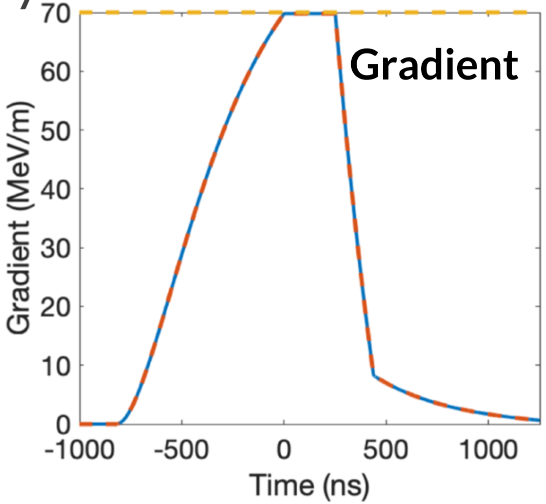
<2.5 kW/m of structure for C3-250/550

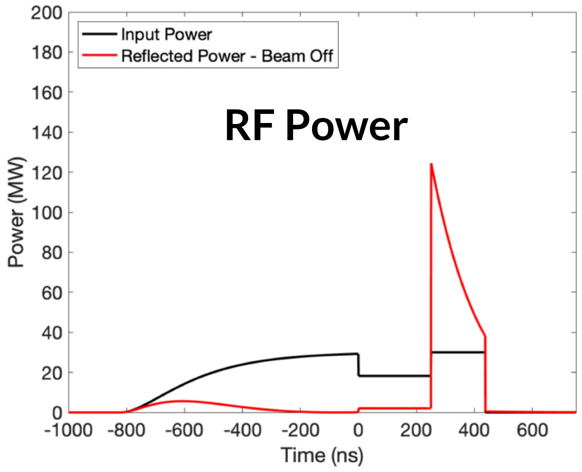
15% cooling efficiency with LN











M. Breidenbach, CF
W 17th May 14:15

Beam Format and Detector Design Requirements

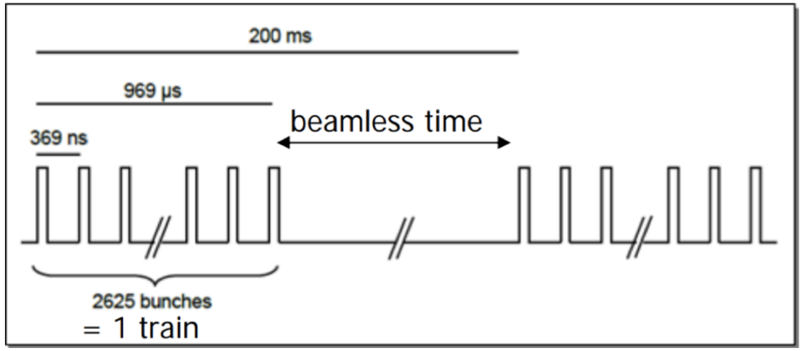
ILC timing structure: Fraction of a percent duty cycle

- **Power pulsing possible**, significantly reduce heat load
  - Factor of 50-100 power saving for FE analog power
- Tracking detectors **don't need active cooling**
  - Significantly reduction for the material budget
- **Triggerless readout** is the baseline

Collider	ILC	CCC
σ_z	300 μm	100 μm
β_x	8.0 mm	13 mm
β_y	0.41 mm	0.1 mm
ϵ_x	500 nm/rad	900 nm/rad
ϵ_y	35 nm/rad	20 nm/rad
N bunches	1312	133
Repetition rate	5 Hz	120 Hz
Crossing angle	0.014	0.020
Crab angle	0.014/2	0.020/2

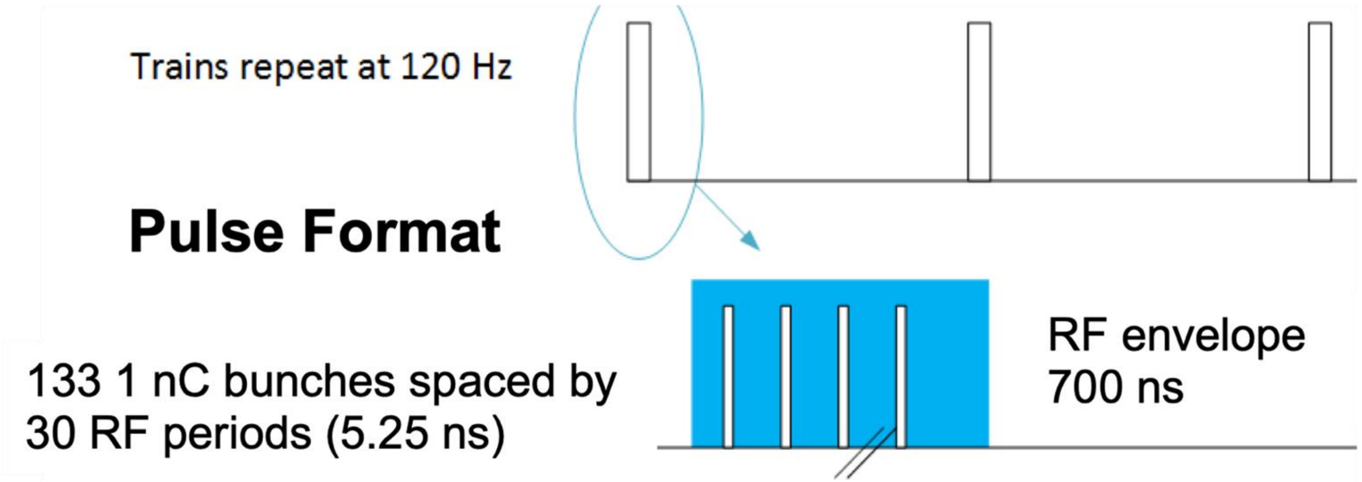
C^3 time structure is compatible with ILC-like detector overall design and ongoing optimizations

ILC timing structure



1 ms long bunch trains at 5 Hz
2820 bunches per train
308ns spacing

C^3 timing structure



Why 550 GeV?

We propose **250 GeV** with a relatively inexpensive upgrade to **550 GeV**

- An **orthogonal dataset** at 550 GeV to cross-check a deviation from the SM predictions observed at 250 GeV
- From 500 to 550 GeV a factor 2 improvement to the **top-Yukawa** coupling
- O(20%) precision on the Higgs **self-coupling** would allow to exclude/demonstrate at 5σ models of electroweak baryogenesis

Collider Luminosity Polarization	HL-LHC 3 ab^{-1} in 10 yrs -	C^3 /ILC 250 GeV 2 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)	C^3 /ILC 500 GeV + 4 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80 (0.85)	0.43 (0.44)
g_{Hcc} (%)	-	1.8 (1.8)	1.1 (1.1)
g_{Hgg} (%)	2.3	1.6 (1.7)	0.92 (0.93)
$g_{H\tau\tau}$ (%)	3.1	0.95 (1.0)	0.64 (0.65)
$g_{H\mu\mu}$ (%)	3.1	4.0 (4.0)	3.8 (3.8)
$g_{H\gamma\gamma}$ (%)	3.3	1.1 (1.1)	0.97 (0.97)
$g_{HZ\gamma}$ (%)	11.	8.9 (8.9)	6.5 (6.8)
g_{Htt} (%)	3.5	–	3.0 (3.0)*
g_{HHH} (%)	50	49 (49)	22 (22)
Γ_H (%)	5	1.3 (1.4)	0.70 (0.70)

arXiv:1708.08912
arXiv:1801.02840

One note on polarization

- There are extensive comparisons between the FCC-ee plan and the C^3/ILC runs that show they are rather compatible to study the Higgs Boson
- When analyzing Higgs couplings with SMEFT, 2 ab^{-1} of polarized running is essentially equivalent to 5 ab^{-1} of unpolarized running.
  - Electron polarization is essential for this. But, there is almost no difference in the expectation with and without positron polarization.
  - Positron polarization allows more cross-checks of systematic errors. We may wish to add it later.
  - Positron polarization brings a large advantage in multi-TeV running, where the most important cross sections are from $e^-_L e^+_R$

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

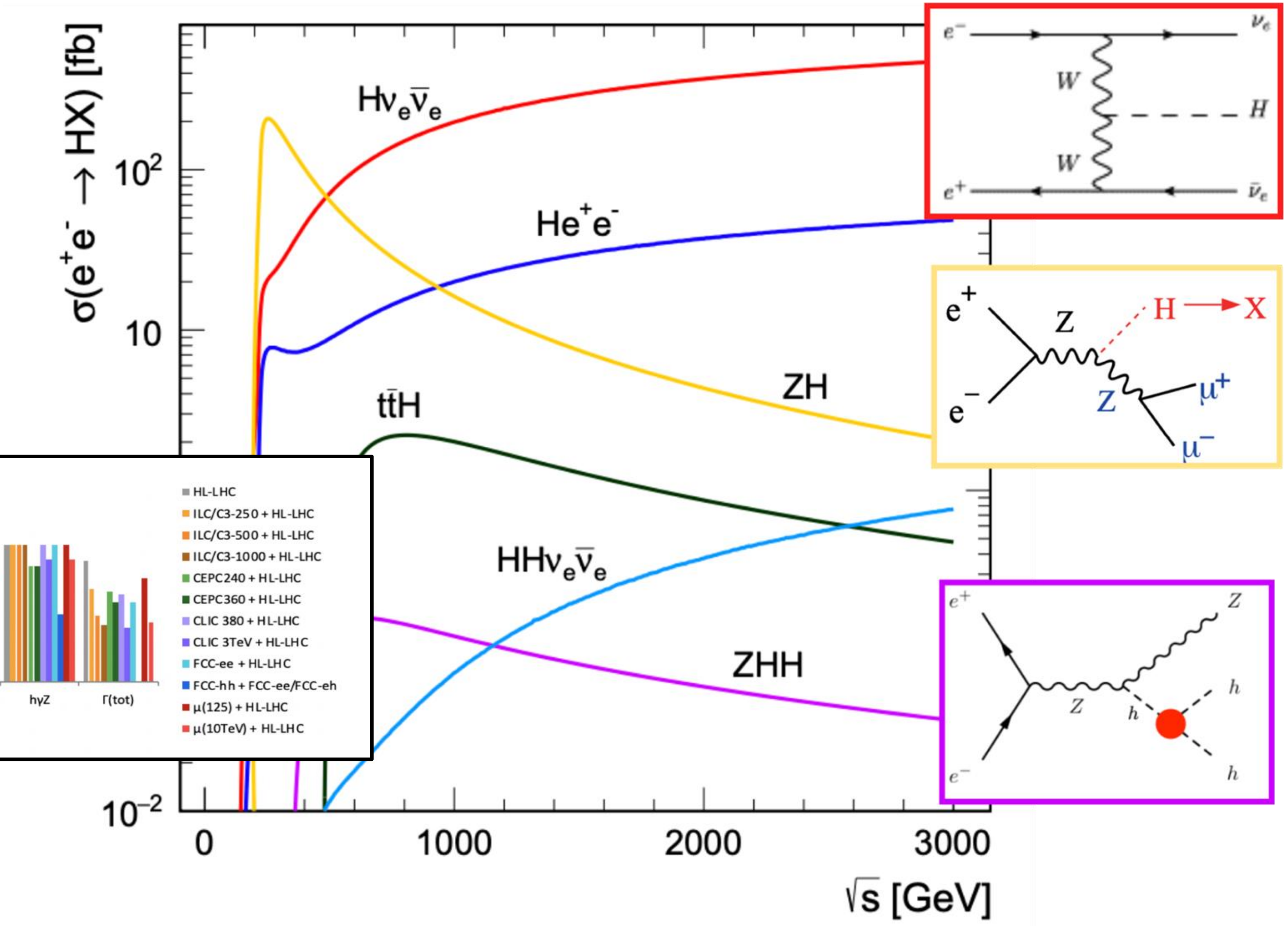
Physics: Higgs Production at e^+e^-

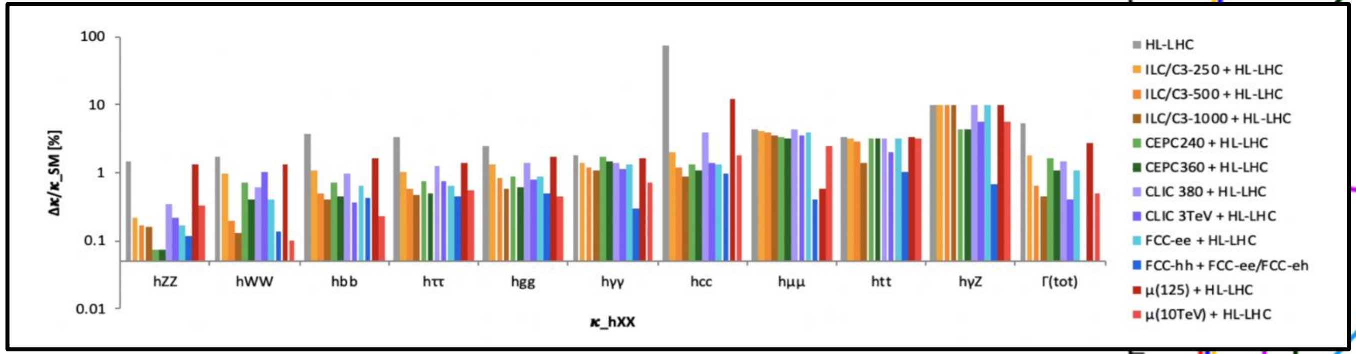
ZH is dominant at **250 GeV**

Above **500 GeV**

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

Delivers a rich physics program





The Energy Frontier 2021 Snowmass Report

Sustainability

- **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

		HL-LHC +				
Relative Precision (%)	HL-LHC	CLIC-380	ILC-250/C^3-250	ILC-500/C^3-550	FCC 240/360	CEPC-240/360
hZZ	1.5	0.34	0.22	0.17	0.17	0.072
hWW	1.7	0.62	0.98	0.20	0.41	0.41
$hb\bar{b}$	3.7	0.98	1.06	0.50	0.64	0.44
$h\tau^+\tau^-$	3.4	1.26	1.03	0.58	0.66	0.49
hgg	2.5	1.36	1.32	0.82	0.89	0.61
$hc\bar{c}$	-	3.95	1.95	1.22	1.3	1.1
$h\gamma\gamma$	1.8	1.37	1.36	1.22	1.3	1.5
$h\gamma Z$	9.8	10.26	10.2	10.2	10	4.17
$h\mu^+\mu^-$	4.3	4.36	4.14	3.9	3.9	3.2
$ht\bar{t}$	3.4	3.14	3.12	2.82/1.41	3.1	3.1
hhh	0.5	0.50	0.49	0.20	0.33	-
Γ_{tot}	5.3	1.44	1.8	0.63	1.1	1.1
Weighted average	-	0.94	0.86	0.45	0.59	0.49

Project	Main tunnel length (km)	GWP (kton CO_2e)		
		Main tunnel	+ other structures	+ A4-A5
FCC	90.6	578	751	939
CEPC	100	638	829	1040
ILC	13.3	97.6	227	266
CLIC	11.5	73.4	98	127
C^3	8.0	133	133	146

$$w = \frac{\left(\frac{\delta\kappa}{\kappa}\right)_{HL-LHC} - \left(\frac{\delta\kappa}{\kappa}\right)_{HL-LHC+HF}}{\left(\frac{\delta\kappa}{\kappa}\right)_{HL-LHC+HF}}$$

$$\left\langle \frac{\delta\kappa}{\kappa} \right\rangle = \frac{\sum_i w_i \left(\frac{\delta\kappa}{\kappa}\right)_i}{\sum_i w_i}$$

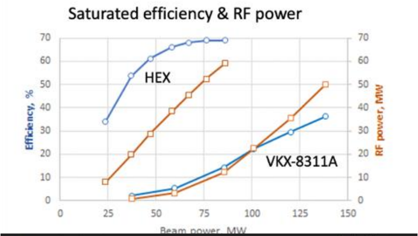
Global Contributions

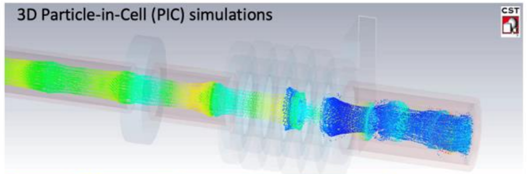
C^3 Technical Timeline Only Possible with the Exceptional Progress of ILC and CLIC

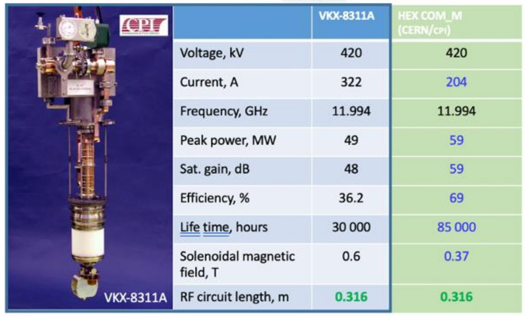
- Benefit from injector complex and beam delivery concepts
- Continue to benefit from technological improvement by ILC and CLIC

High Efficiency RF Sources (CLIC)

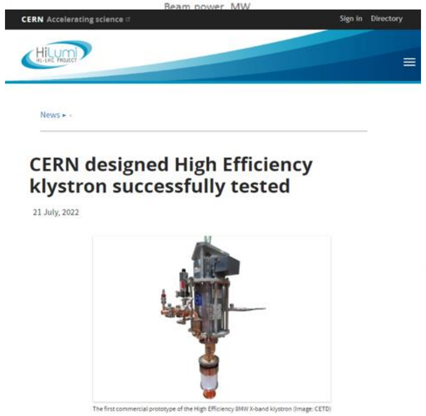
Retro-fit High Efficiency 50 MW, 12 GHz klystron (CERN/CPI).





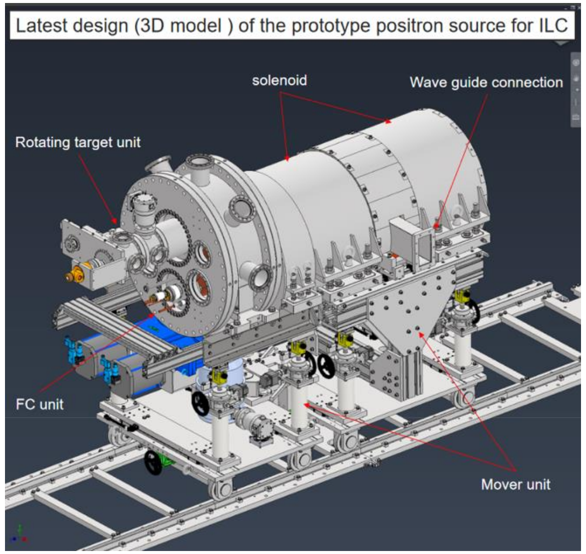


	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	59
Efficiency, %	36.2	69
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.37
RF circuit length, m	0.316	0.316



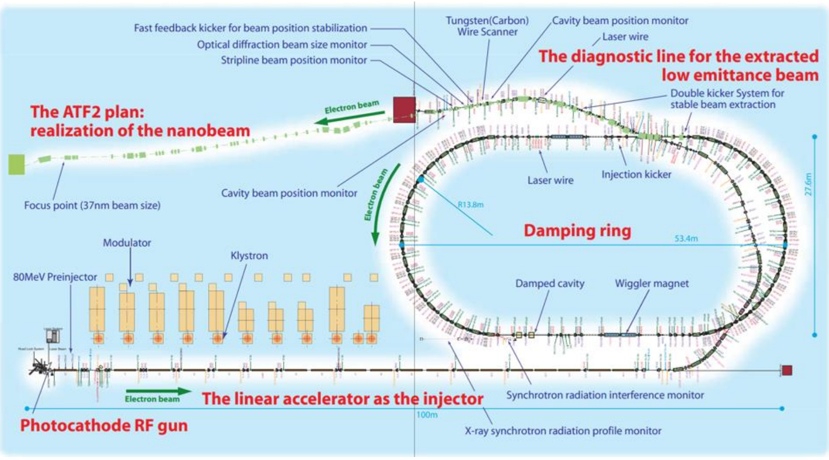
I. Sarchev, CERN

Electron Driven Positron Source



Courtesy of Y. Enomoto

Nanobeams for IP (ATF)



https://www-atf.kek.jp/atf/

Vibrant International Community for Future Colliders is Essential