C^3 Update for CLIC

Emilio Nanni

12/7/2022

Acknowledgements

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Strategy for Understanding the Higgs Physics: The Cool Copper Collider

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C^3 Demonstration Research and Development Plan

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

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

Starting from Last CLIC Meeting (May 2022)

Summary Still Accurate!

- Many years of collaboration through the high gradient community have proved successful at transforming the capability of accelerators and rf sources
- Many opportunities to collaborate between CLIC and C3
  - RF sources, manufacturing, rf pulse compression, beam dynamics, beam diagnostics…
  - As a concept C3 is built on the great work of CLIC and ILC
- Maybe one day we can return the favor….

New:

- …(Maybe one day we can return the favor) Not yet… still need your help….
- Recent focus areas:
  - Alignment
  - Stability
  - Sustainability
  - Demo Plan

Accelerator Complex

8 km footprint for 250/550 GeV CoM $\Longrightarrow$ 70/120 MeV/m

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

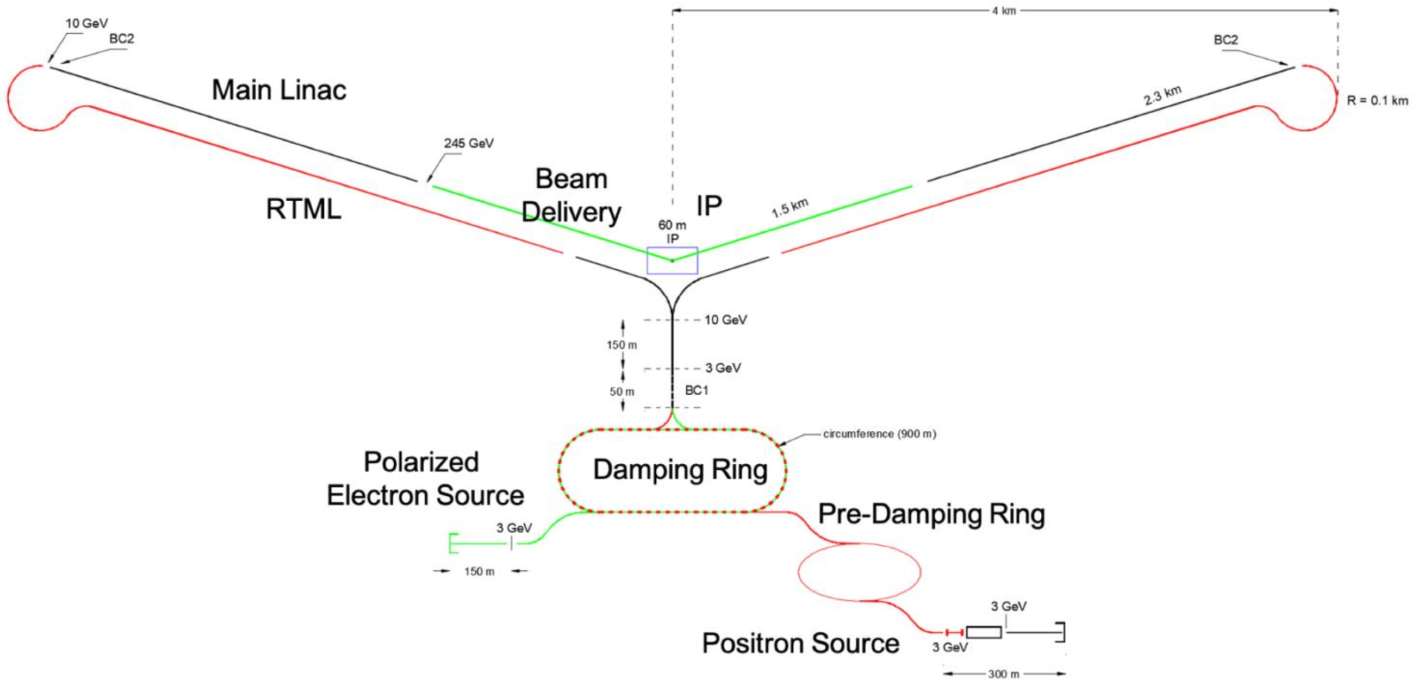
Large portions of accelerator complex are compatible between LC technologies

- 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
- Reliant on work done by CLIC and ILC to make progress

C^3 Parameters

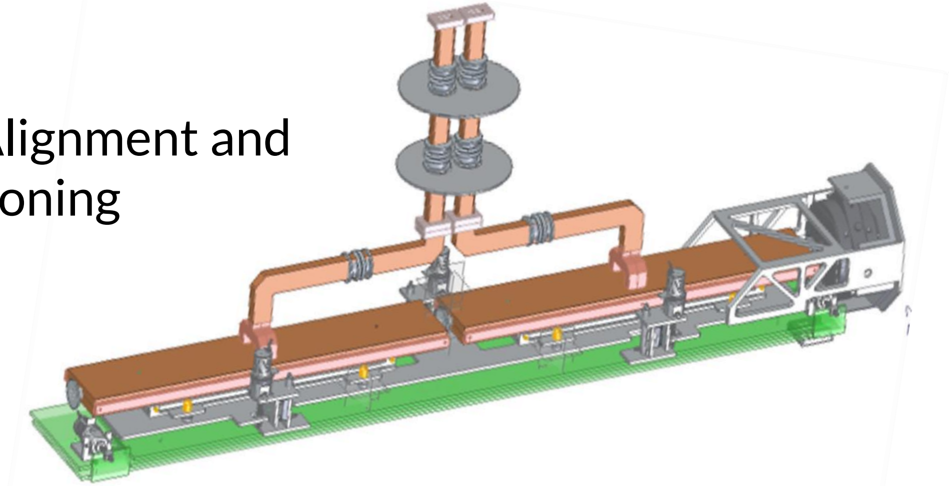
Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]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

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

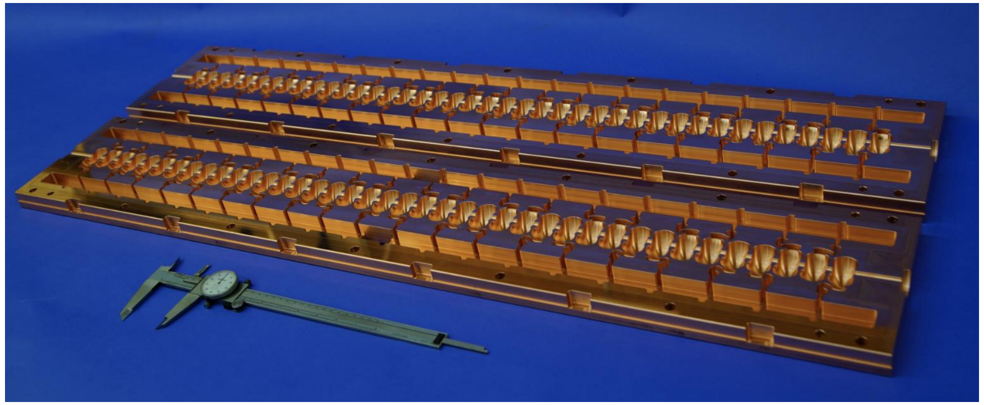


Ongoing Technological Development

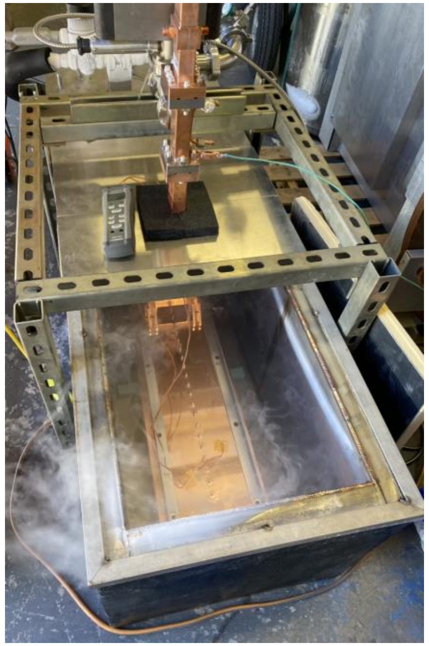
Preliminary Alignment and
Positioning



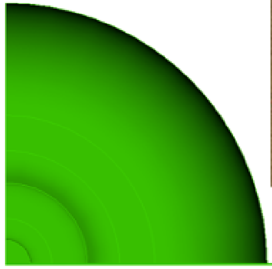
Modern Manufacturing
Prototype One Meter Structure

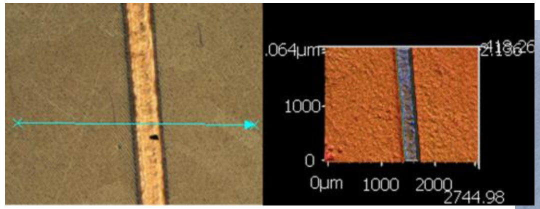


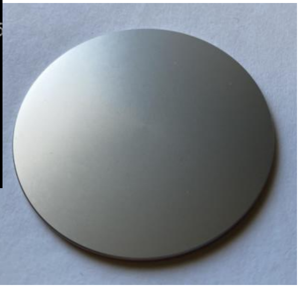
High Accelerating Gradients
Cryogenic Operation



Integrated Damping
Slot Damping with NiChrome Coating







C^3 Session @ Snowmass

08:00

- **C3 in the context of EF** — *Meenakshi Narain*
- **C3 Run Plan** — *Caterina Vernieri* — *332, HUB* — 08:10 - 08:20
- **Motivation for Energy Upgrades** — *Patrick Meade*
- **C3 in the Context of IF** — *Maxim Titov* — *332, HUB* — 08:30 - 08:40
- **Background Simulations** — *Lindsey Gray*
- **Dual Readout** — *Sarah Eno* — *332, HUB* — 08:50 - 09:00

09:00

- **Beam Dump Experiments** — *Douglas Tuckler*
- **Muon Experiments** — *Dylan Rankin* — *332, HUB* — 09:10 - 09:20
- **C3 in the Context of AF3/4** — *Angeles Faus-Golfe*
- **C3 Complex** — *Emilio Nanni* — *332, HUB* — 09:45 - 10:05

10:00

- **BDS/FF** — *Glen White* — *332, HUB* — 10:05 - 10:15
- **C3 in the Context of AF1** — *Mei Bai* — *332, HUB* — 10:30 - 10:40
- **C3 Demonstration R&D Plan** — *Faya Wang*

11:00

- **C3 in the Context of AF7** — *Sergey Belomestnykh* — *332, HUB* — 11:00 - 11:10
- **Survey of Ongoing and Near-Term R&D** — *Ankur Dhar et al.* — *332, HUB* — 11:10 - 12:00

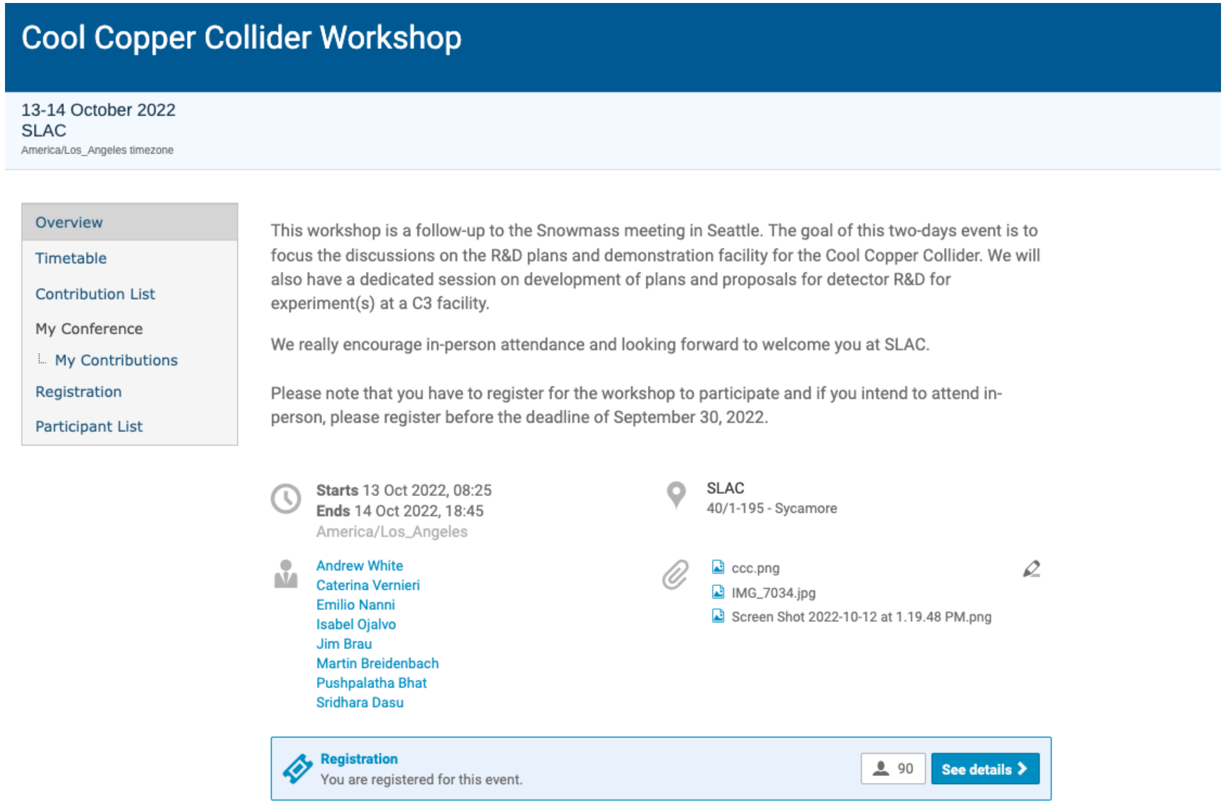
12:00

Snowmass

- Four hour session on Friday 7/22
- ~70 participants (35/35 in person/virtual)
- Engaged AF/EF/IF/ITF
- Announced follow up workshop Oct. 13/14th to finalize P5 Input

C^3 October Meeting

https://indico.slac.stanford.edu/event/7315/overview



Cool Copper Collider Workshop

13-14 October 2022
SLAC
America/Los_Angeles timezone

- Overview
- Timetable
- Contribution List
- My Conference
  - My Contributions
- Registration
- Participant List

This workshop is a follow-up to the Snowmass meeting in Seattle. The goal of this two-days event is to focus the discussions on the R&D plans and demonstration facility for the Cool Copper Collider. We will also have a dedicated session on development of plans and proposals for detector R&D for experiment(s) at a C3 facility.

We really encourage in-person attendance and looking forward to welcome you at SLAC.

Please note that you have to register for the workshop to participate and if you intend to attend in-person, please register before the deadline of September 30, 2022.

Starts 13 Oct 2022, 08:25
Ends 14 Oct 2022, 18:45
America/Los_Angeles

SLAC
40/1-195 - Sycamore

Andrew White
Caterina Vernieri
Emilio Nanni
Isabel Ojalvo
Jim Brau
Martin Breidenbach
Pushpalatha Bhat
Sridhara Dasu

ccc.png
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Screen Shot 2022-10-12 at 1.19.48 PM.png

Registration
You are registered for this event.
90
See details

Next Meeting In Feb. at LANL - Register here for announcements https://indico.slac.stanford.edu/event/7155/

Accelerator Design and Challenges

Accelerator Design

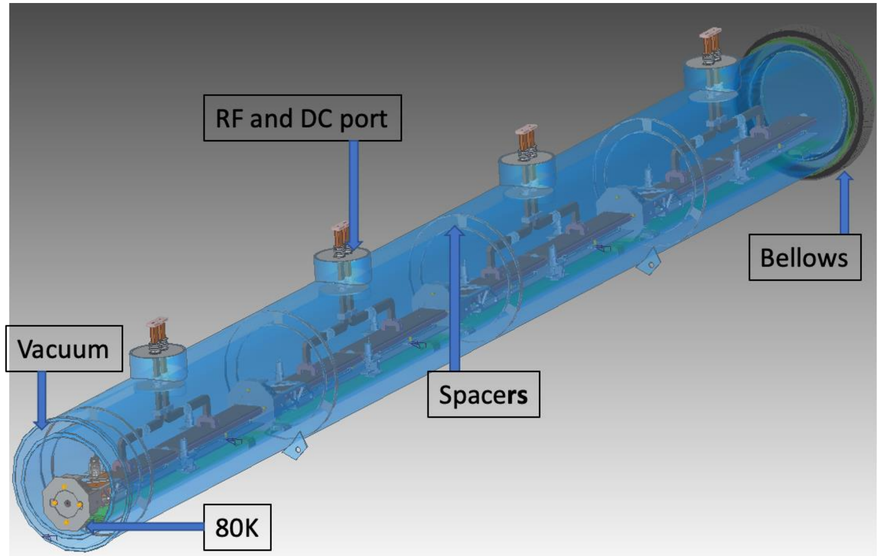
- Engineering and design of prototype cryomodule underway

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

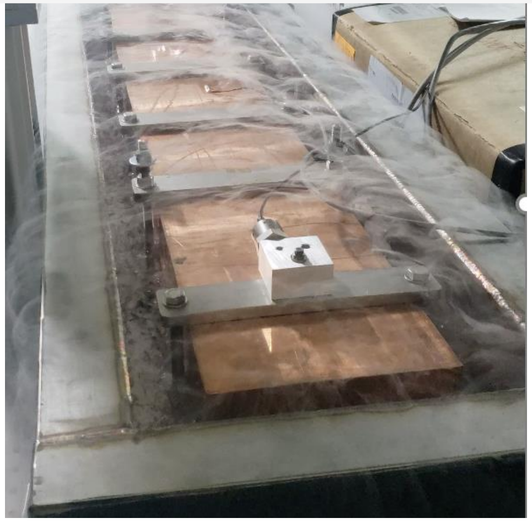
- Gradient – Scaling up to meter scale cryogenic tests
- Vibrations – Measurements with full thermal load
- Alignment – Working towards raft prototype
- Cryogenics – Two-phase flow simulations to full flow tests
- Damping – Materials, design and simulation
- Beam Loading and Stability - Thermionic beam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

Laying the foundation for a demonstration program to address technical risks beyond RDR (CDR) level

Cryomodule Concept



Vibration Studies



Cryomodule Design and Alignment

Up to 1 GeV of acceleration per 9 m cryomodule; ~90% fill factor with eight 1 m structures

Main linac will require 5 micron structure alignment

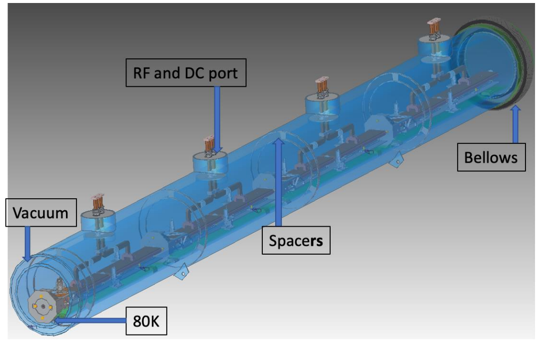
- Combination of mechanical and beam based alignment

Pre-alignment warm, cold alignment by wire, followed by beam based (Maybe RasNik, RasDif optical alignment better?)

- Mechanical motor runs warm or cold – no motion during power failure
- Piezo for active alignment

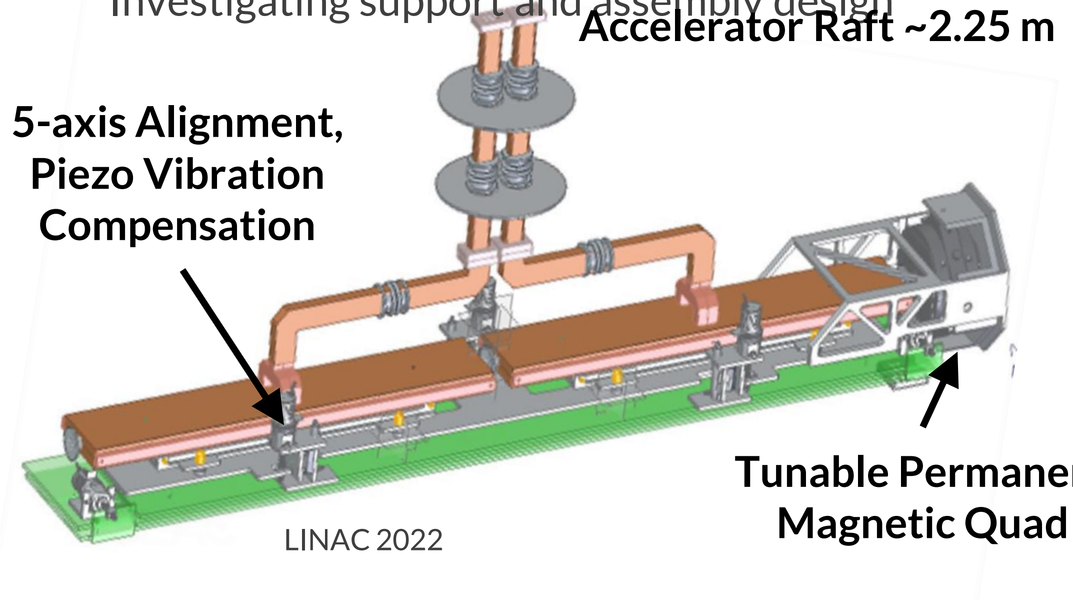
Investigating support and assembly design

Cryomodule Concept ~9m

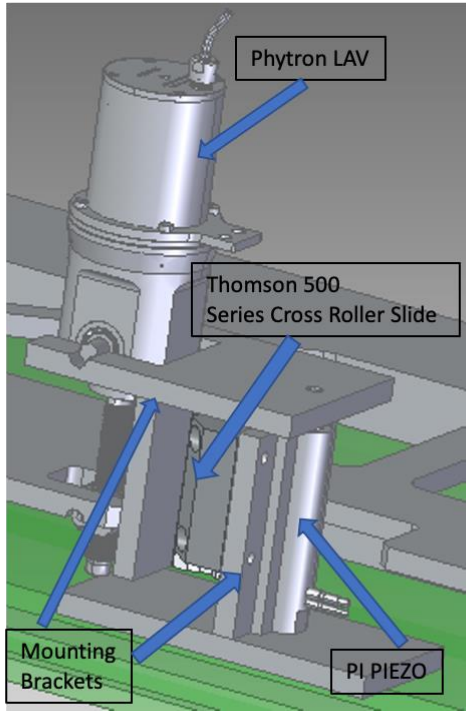


Accelerator Raft ~2.25 m

5-axis Alignment, Piezo Vibration Compensation

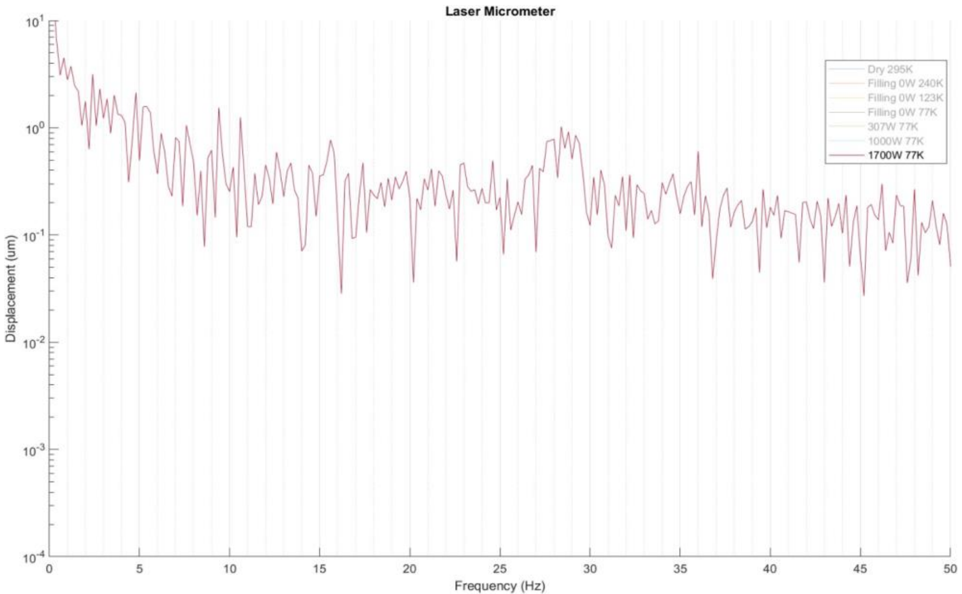


Tunable Permanent Magnetic Quad



Achieving Luminosity

- Our goal is to achieve MW class beam power for luminosity
- Requires we meet the emittance of CLIC given our bunch format
- Requires we meet CLIC tolerances to preserve emittance
  - Alignment components exist for operation at cryo – motors/piezos – 5 micron
  - Need very high stability of magnets -> Permanent magnets - we are working to understand if they are sufficiently isolated from structures which are vibrating
- Present bunch spacing large 3-5 ns - need to study…

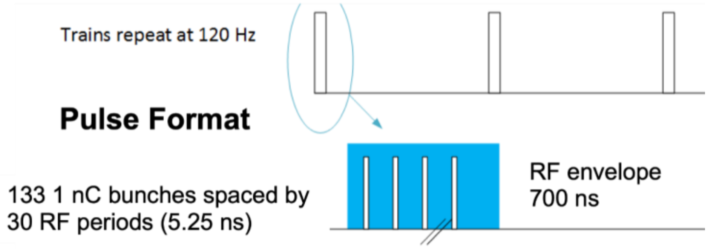


Large Scale Cryogenics

Very high confidence in performance of cryoplants – many commercial examples

We assume 15% plant efficiency; Air liquide quoted 16.4%up to 16.8%

Power Consumption and Sustainability



Temperature (K)	77
Beam Loading (%)	45
Gradient (MeV/m)	70
Flat Top Pulse Length (μs)	0.7
Cryogenic Load (MW)	9
Main Linac Electrical Load (MW)	100
Site Power (MW)	~150

Compatibility with Renewables Cryogenic Fluid Energy Storage

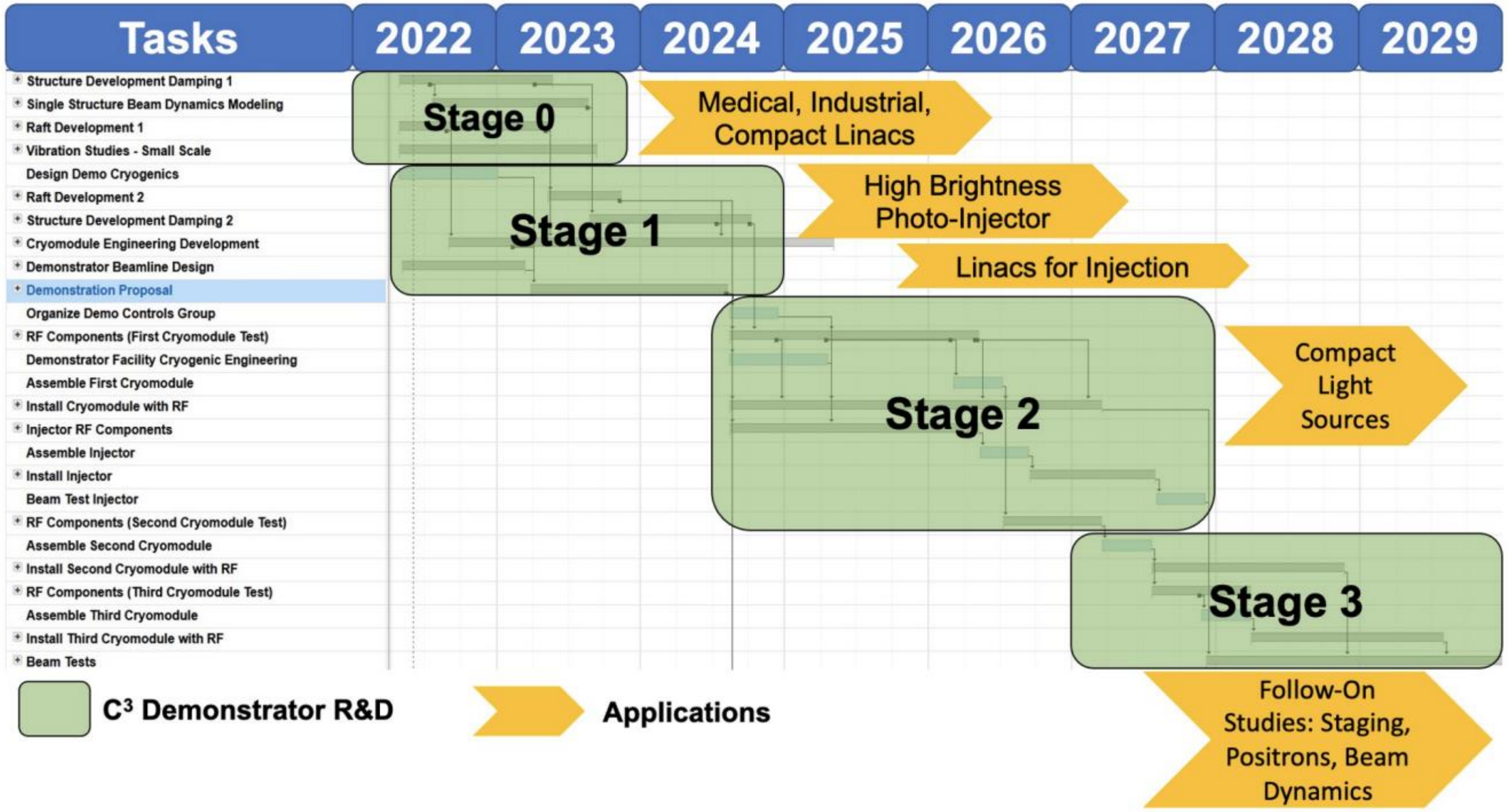
Highview Power

Intermittent and variable power production from renewables mediated with commercial scale energy storage and power production

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
Electrical Power For Cryo-Cooler	MW	60
Accelerator Complex Power	MW	~50
Site Power	MW	~150

C^3 Demonstration R&D Plan timeline



C^3 R&D, System Design and Project Planning are ongoing

- Early career scientists should help drive the agenda for an experiment they will build/use
- Many opportunities for other institutes to collaborate on:
  - beam dynamics, vibrations and alignment, cryogenics, rf engineering, controls, detector optimization, background studies, etc.

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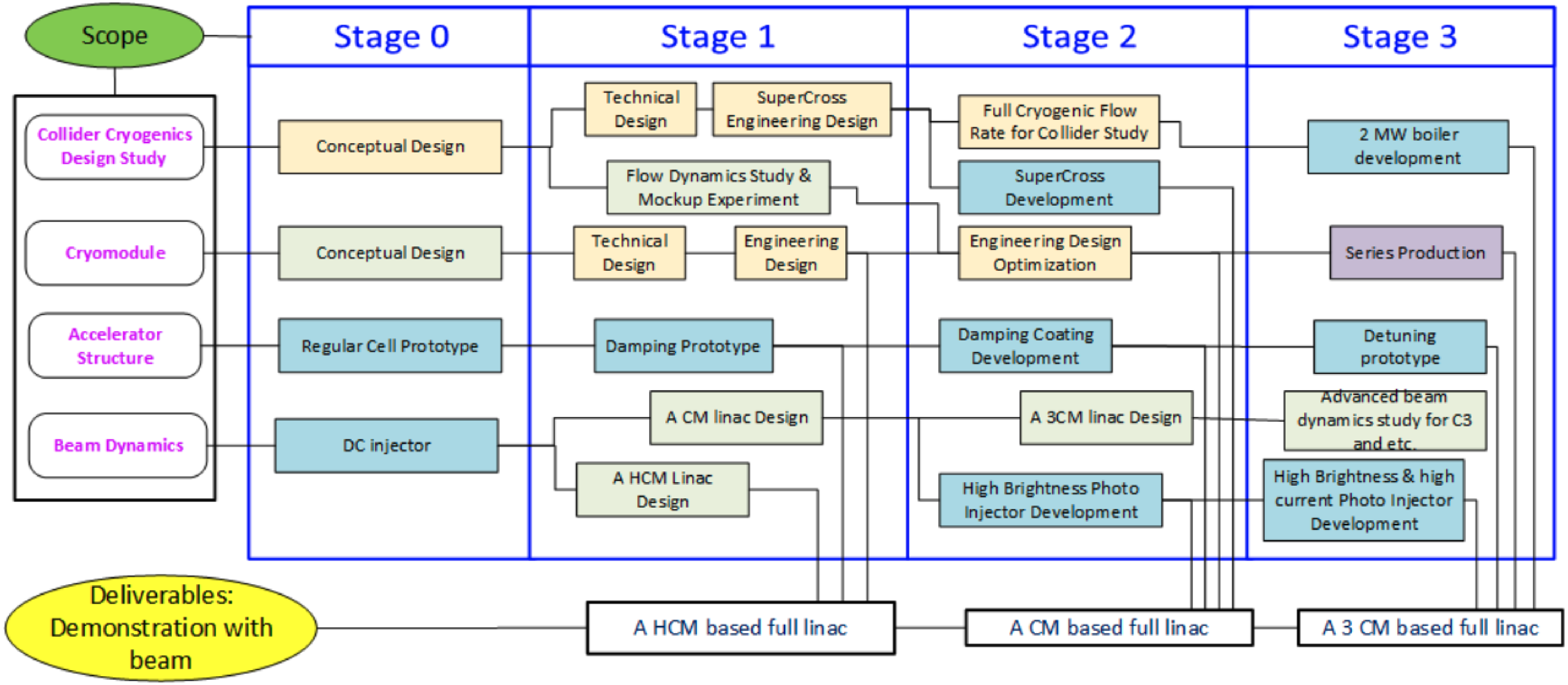
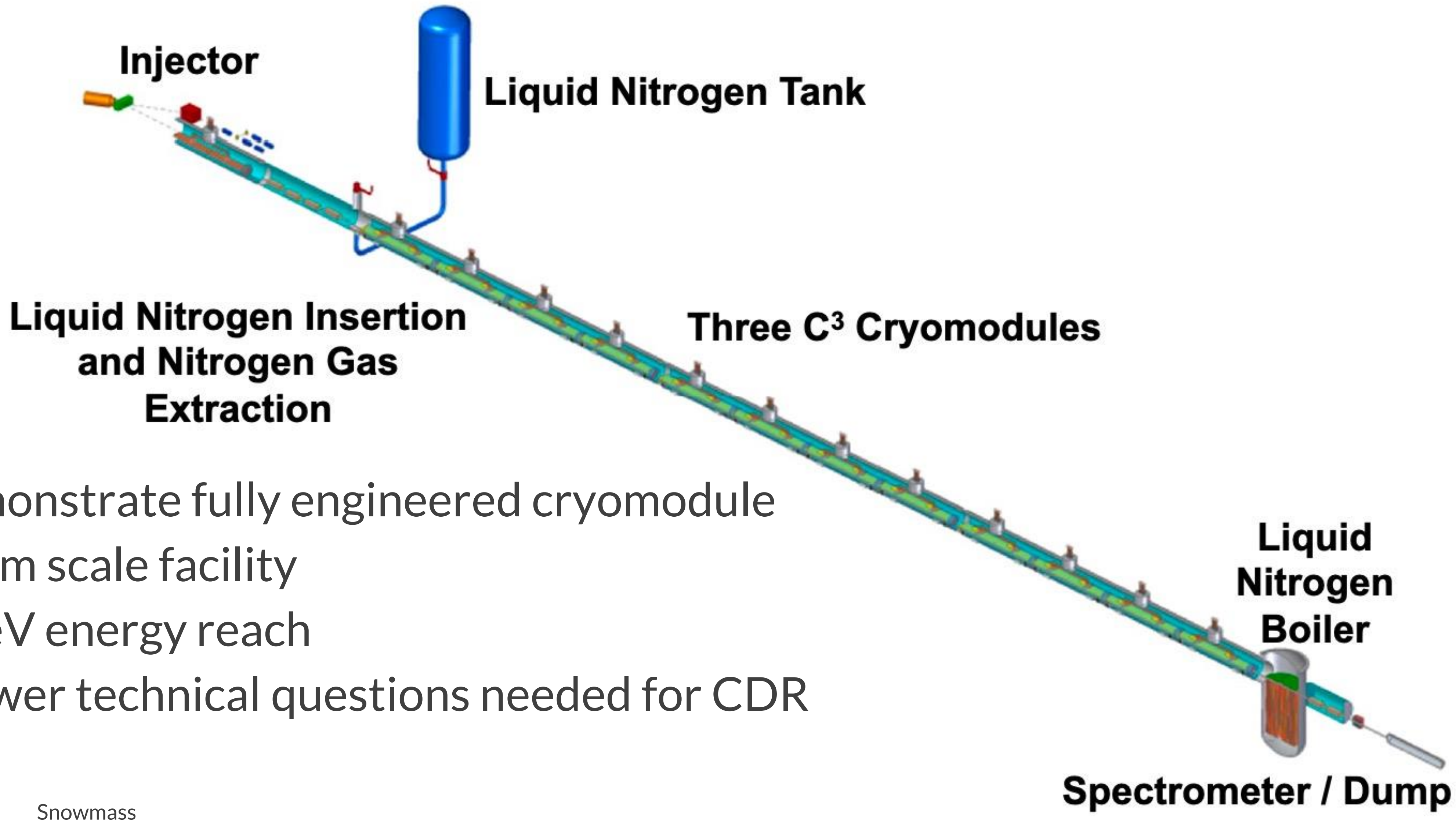
Accelerator Science & Engineering: Emilio Nanni nanni@slac.stanford.edu

C3 Demo Staged Plan

Ongoing Scoping Study in Preparation for P5

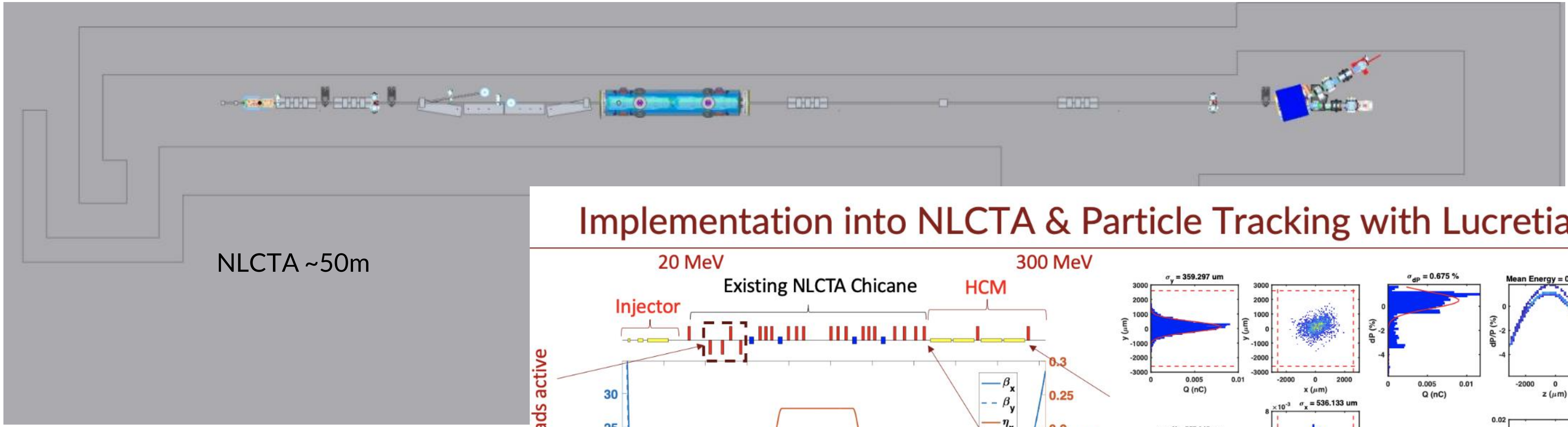


The Complete C³ Demonstrator

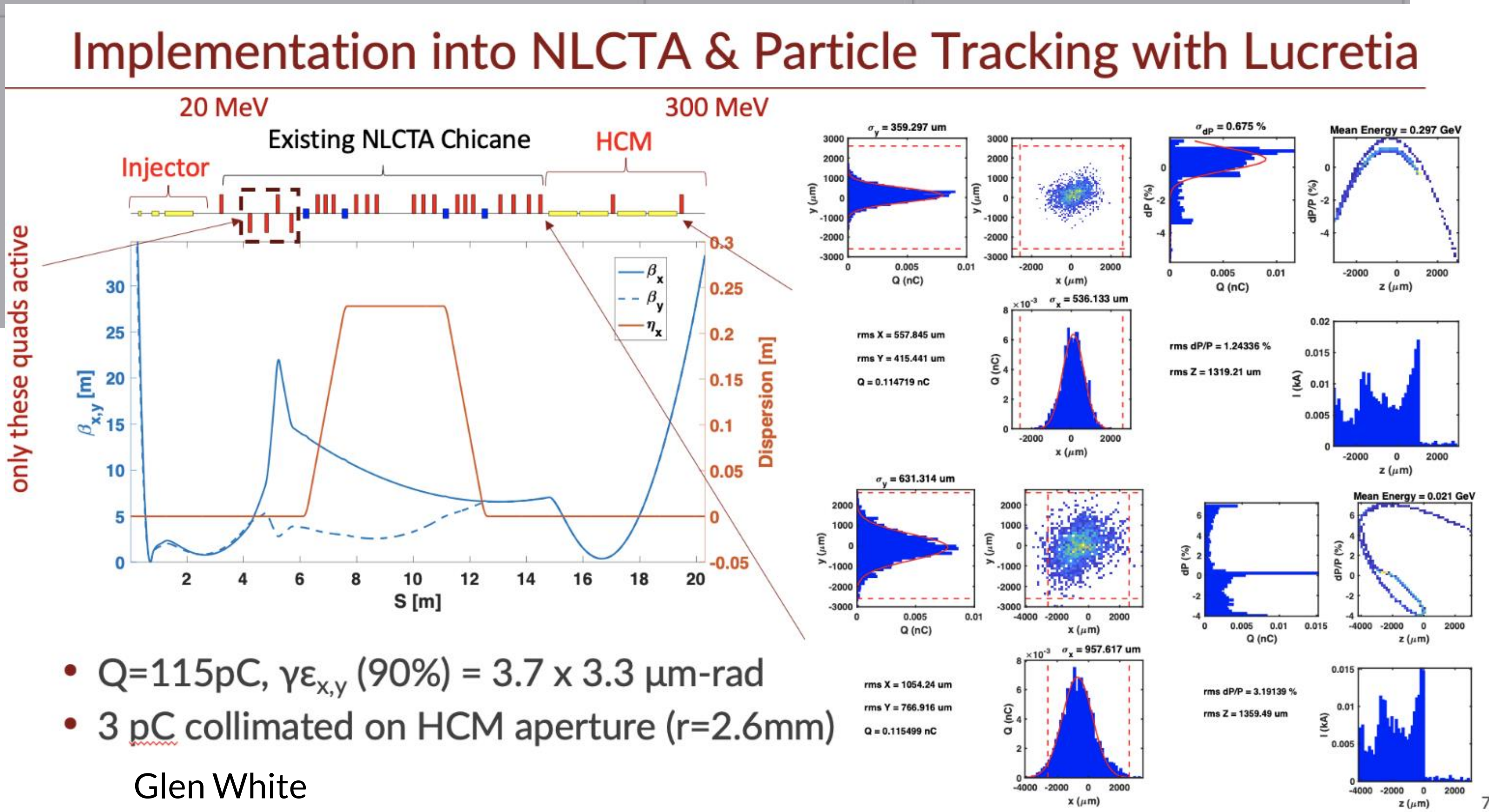


Demonstrate fully engineered cryomodule
~50 m scale facility
3 GeV energy reach
Answer technical questions needed for CDR

C3 Demo Studies - Stage 1 Half Cryomodule



- Focused on Stage 1 + 2
- Targeting a cost/time estimate to deliver to P5 based on NLCTA as an example site
- Stage 1 HCM DC Injector - 300 mA
- Stage 2 FCM Photo Injector - 1 nC; few bunch



Glen White

Conclusion

- C3 wants US participation in any future collider; we hope to deliver that message clearly to P5
- Please provide input feedback on our early career letter - https://sites.google.com/view/ec4c3/home
  - ALL are welcome to sign it and participate in crafting it

- LCWS May 15-19th 2023 at SLAC!

Questions?

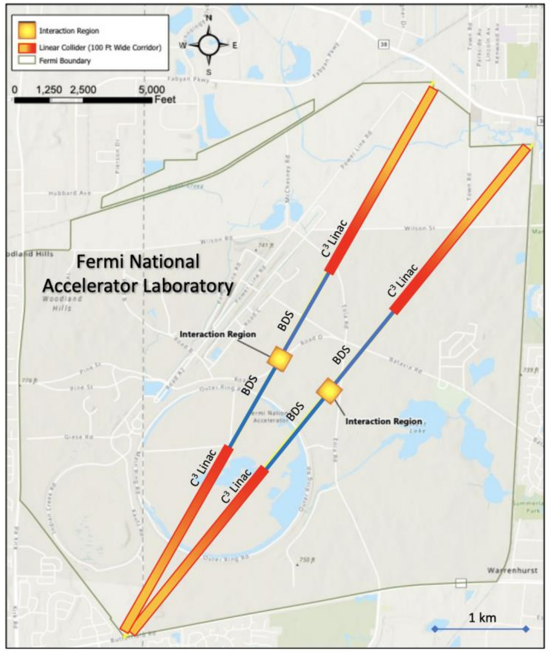
Backup

Civil Construction and Siting

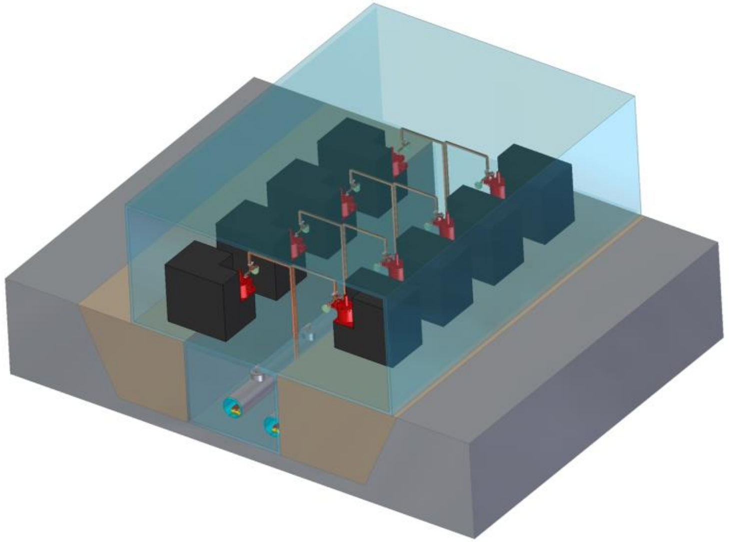
- Compact footprint <8 km for 550 GeV allows for many siting options
- Evaluating both underground and surface sites
  - Underground – less constraints on energy upgrade
  - Surface – lower cost and faster to first physics

National Lab and Green Field are Possibilities

Fermilab Site Filler

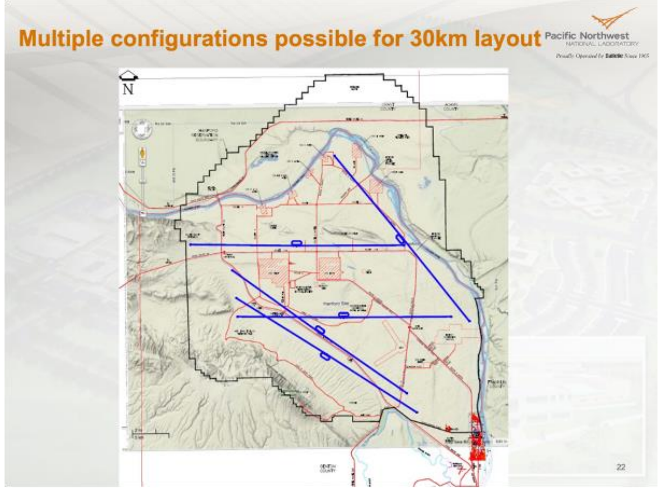


Surface-Site Mockup (Tunnel in White Paper)



- Rapid Excavation / Parallel Installation
- No Vertical Shafts

Hanford Site



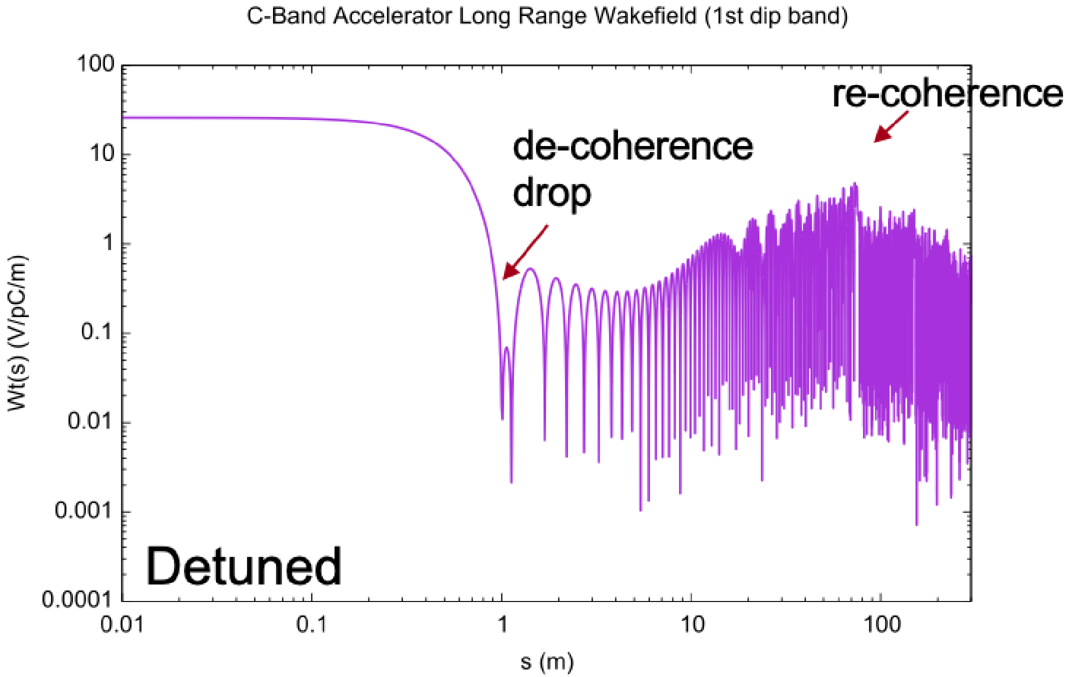
Gaussian Detuning Provides Required 1st Band Dipole Suppression for Subsequent Bunch, Damping Also Needed

Dipole mode wakefields immediate concern for bunch train

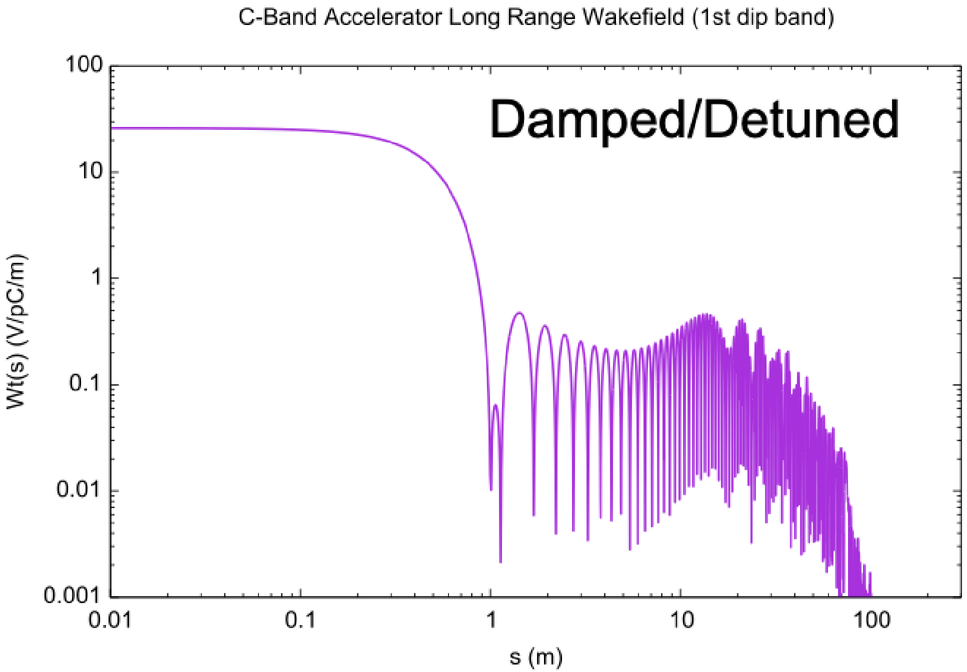
4σ Gaussian detuning of 80 cells for dipole mode (1st band) at f_c=9.5 GHz, w/ $\Delta f/f_c$=5.6%

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

- Damping needed to suppress re-coherence



(Only copper surface loss damping included)



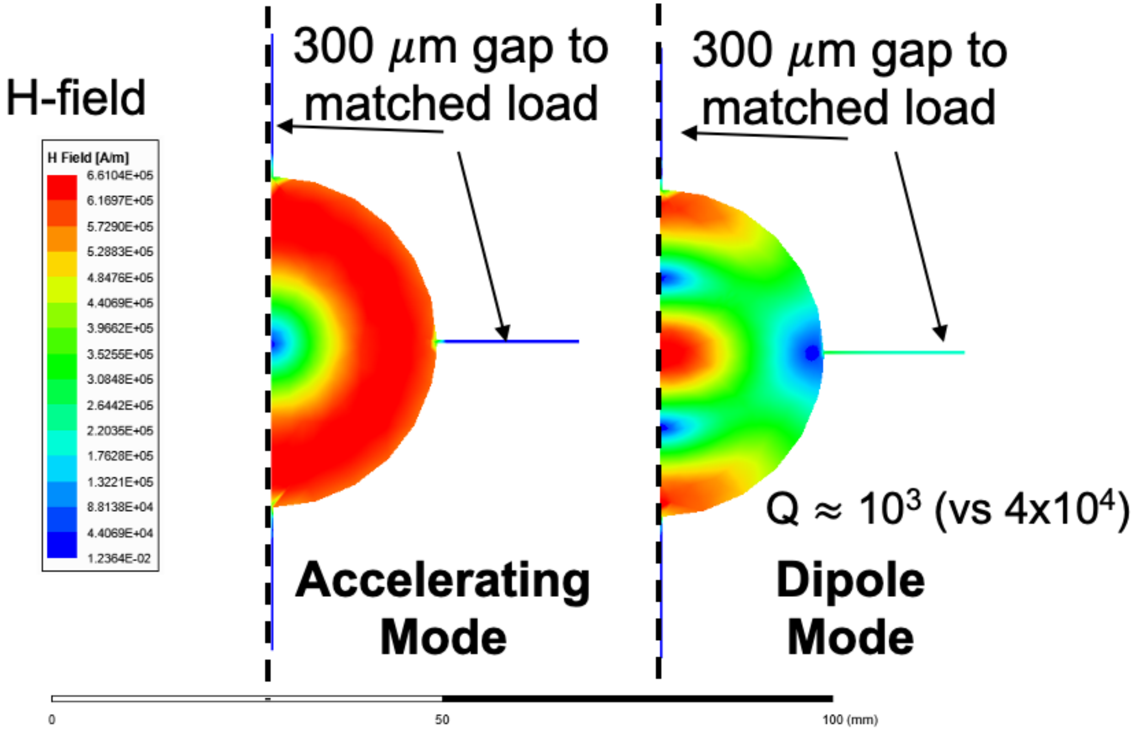
(1.0e3 Q total HOM damping included)

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

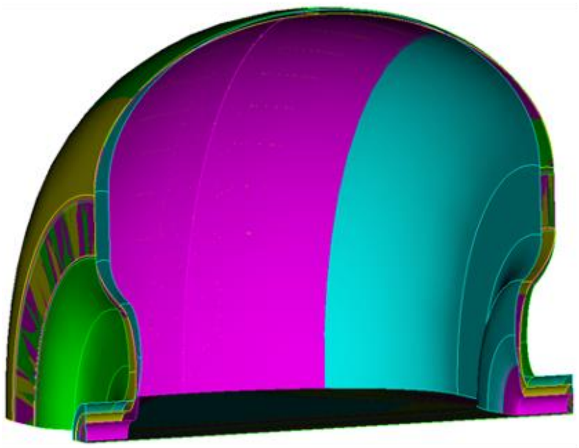
Individual cell feeds necessitate adoption of split-block assembly

Perturbation due to joint does not couple to accelerating mode

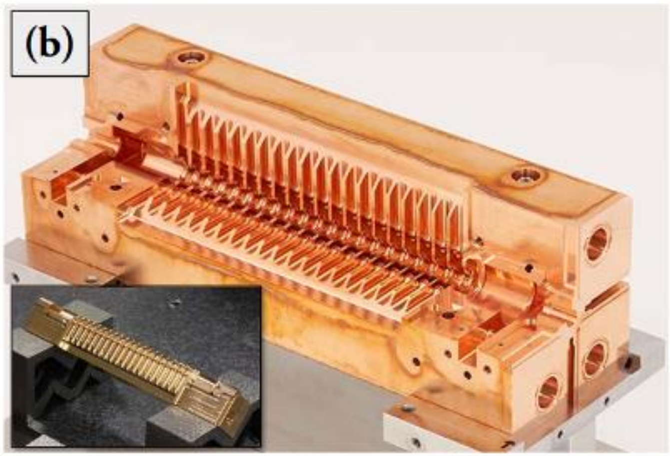
Exploring gaps in quadrature to damp higher order mode



Detuned Cavity Designs



Quadrant Structure



Abe et al., PASJ, 2017, WEP039

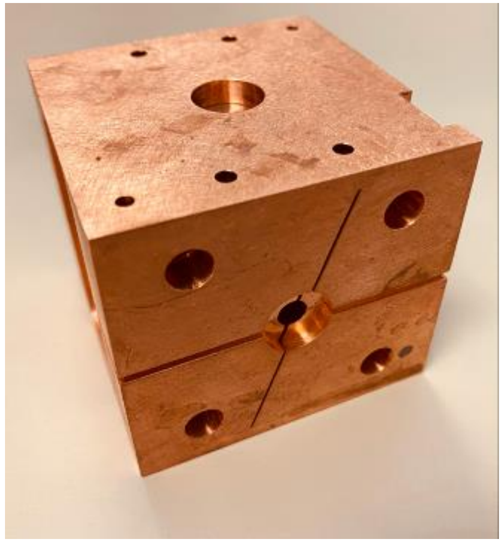
Implementation of Slot Damping

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

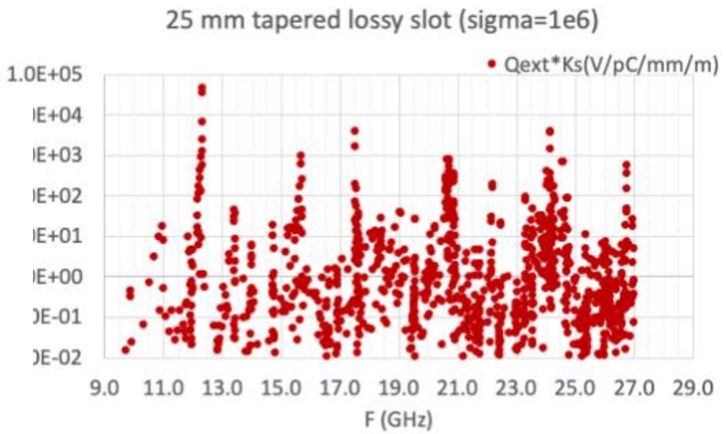
NiCr coated damping slots in development

Seeeking options with chemical plating

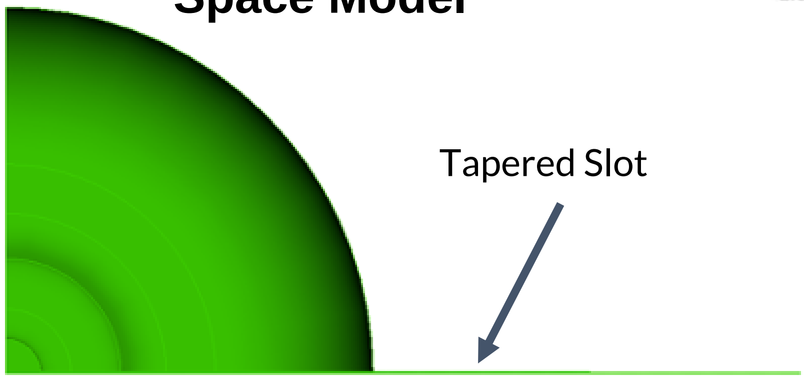
Damping Slot Prototype

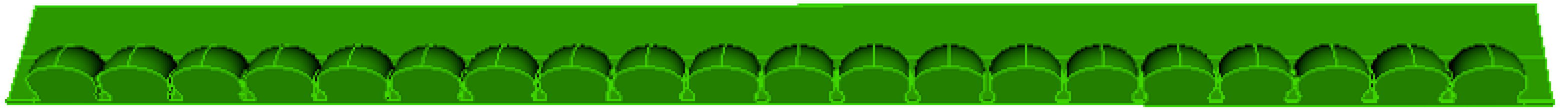


Kick Factor * Q

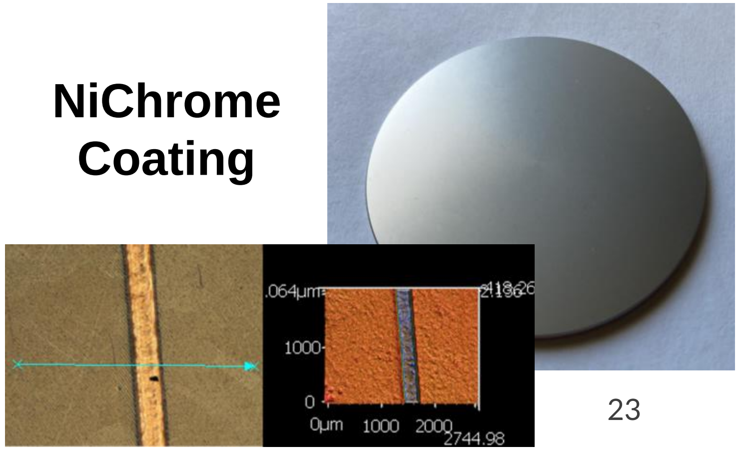


Vacuum Space Model





NiChrome Coating



RF Sources

- Picture is more nuanced – we assume 65% for the klystron, 50% for the rf source
- We assume PPM focusing
- These efficiencies and higher have been demonstrated - in particular with expensive depressed collectors
- Promising HEIKA work needs to continue
- RF source design not in demo – how do we support this? (industry, other applications)
- Not in our baseline: RF pulse compression could help a lot by reducing fill time

75XP-3

https://indico.cern.ch/event/39372/contributions/1829827/attachments/787979/1080133/AVlieks-X-Band_Klystron_Development_at_SLAC-final.pdf

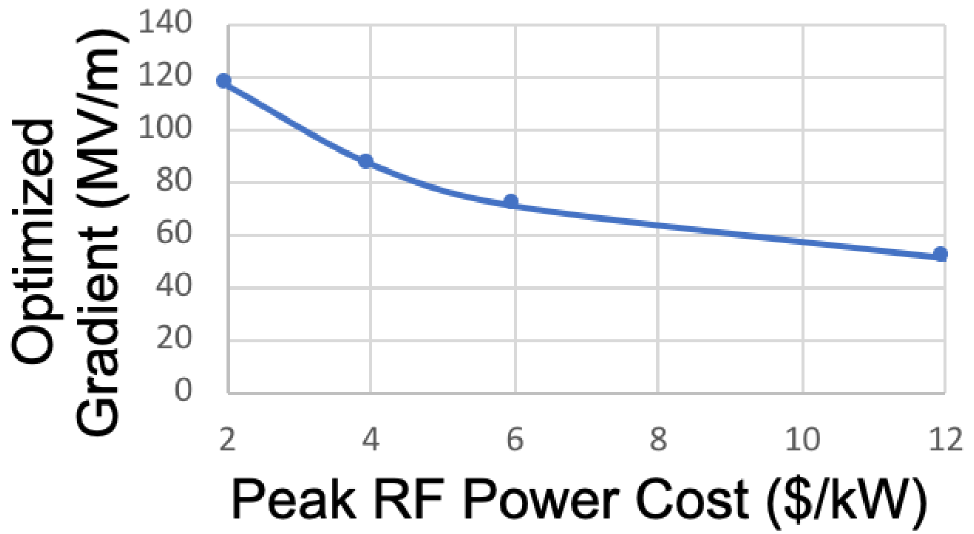
RF Source R&D Over the Timescale of the Next P5

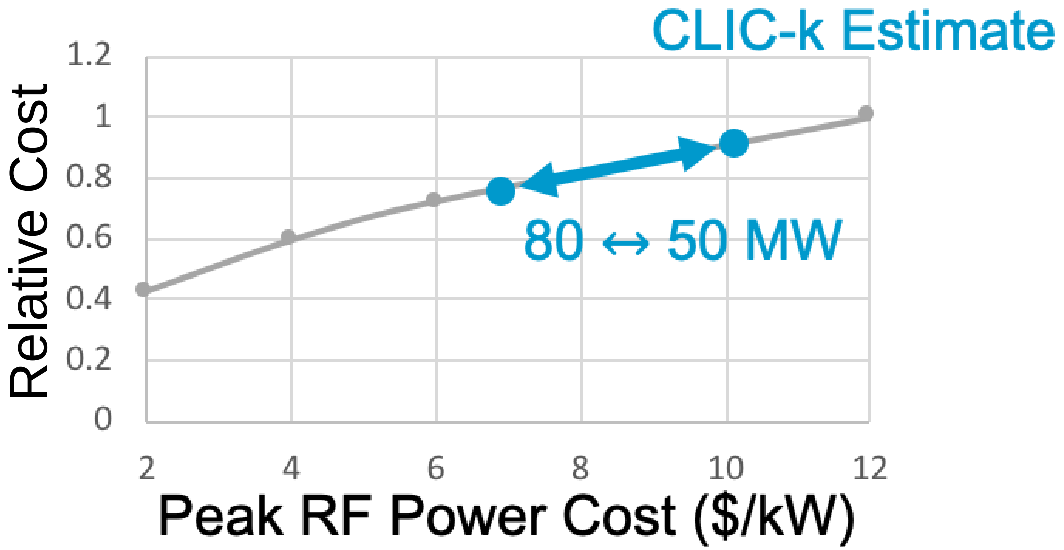
RF source cost is the key driver for gradient and cost

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 2 TeV CoM





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

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

RF Sources Available vs. Near Term Industrial Efforts

RF sources and modulators capable of powering C³-250 commercially available

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

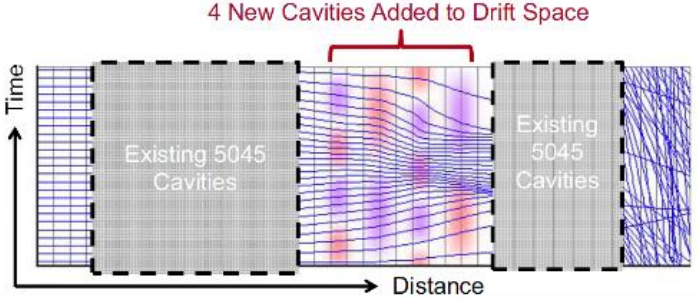
Los Alamos NATIONAL LABORATORY EST. 1943

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

BVEI X-band 50 MW 57% COM Prototype

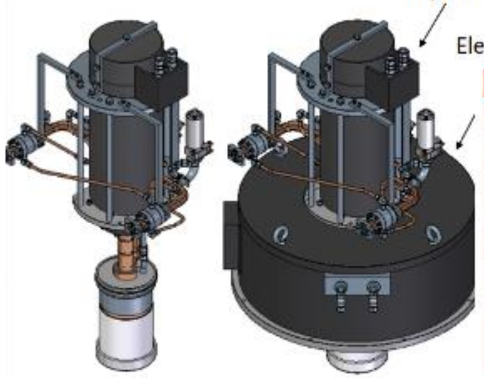
SLAC BAC Prototype

S-band Retrofit +10% efficiency, 73 MW



Near Term Industry

20-MW X-band Klystron



Perveance : 1.25

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.

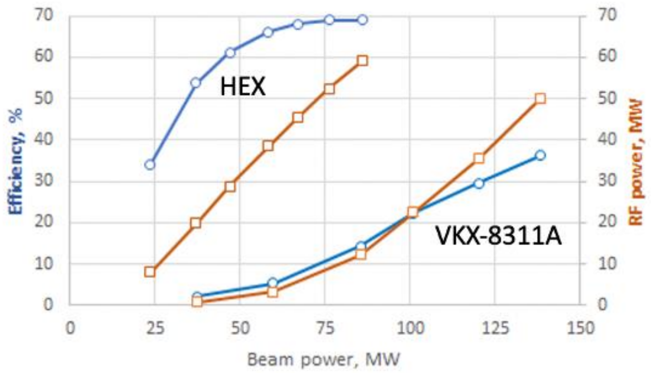
Two tubes have been built and tested up to 20MW

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

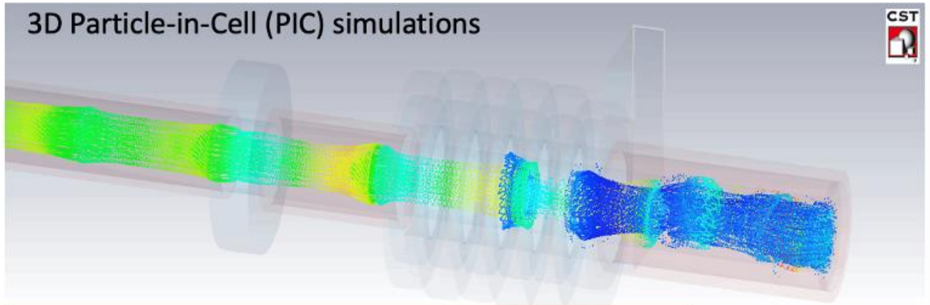


- Re-used solenoid.
- Increased life time (> factor 2)
- Reduced modulator power (~ factor 2)
- Increased power gain (10 dB)
- Reduced solenoidal field

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

Luminosity, Power and Sustainability

- C3 electrical power budgets
- Underlying assumptions:
  - Leverage power estimates from CLIC / ILC
  - What is different about C3?
    - Cooling
    - RF Sources
- The biggest challenges for achieving the design luminosity
  - Emittance, emittance, emittance

Proposal name	C3 - Cool Copper Collider
Beam energy [GeV]	125
Average beam current [A or mA]	0.016 mA
SR power [MW]	n/a
Collider cryo power [MW]	60
Collider RF power [MW]	40
Collider magnet power [MW]	16
Cooling & ventilation power [MW]	10
General services power [MW]	10
Injector cryo power [MW]	6
Injector RF power [MW]	4
Injector magnet power [MW]	4
Pre-injector power (where applicable) [MW]	n/a
Detector power (if included) [MW]	n/a
Data center power (if included) [MW]	n/a
Total power [MW]	150
Luminosity [10^(34) /cm^2/s]	1.3
Total integrated luminosity / year [1/fb/yr]	0.21 ab-1
Effective physics time per year asumed/needed to achieve integrated annual luminosity [10^7 s]	1.6
Energy Consumption / year [TWh]	0.67

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

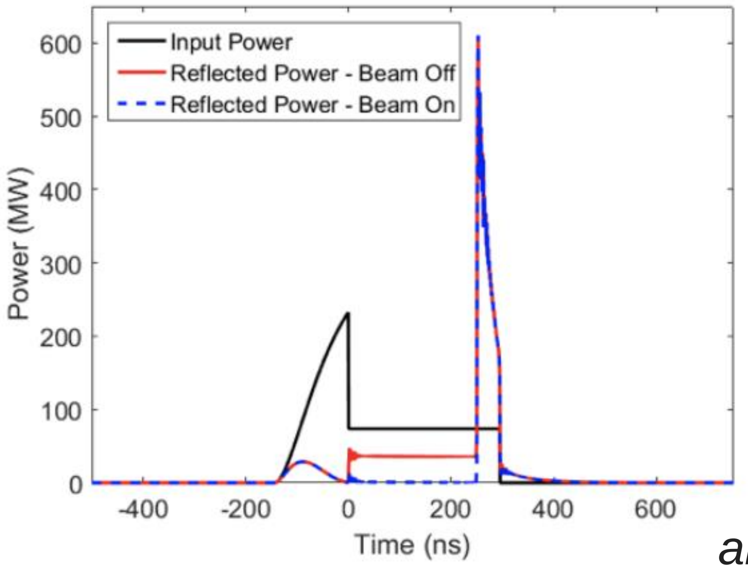
Parameter	Units	Baseline	High-Lumi
Energy CoM	GeV	250	250
Gradient	MeV/m	70	70
Beam Current	A	0.2	1.6
Beam Power	MW	2	16
Luminosity	$x10^{34}$	1.3	10.4
Beam Loading		45%	87%
RF Power	MW/m	30	125
Site Power	MW	~150	~180

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

Reducing Power

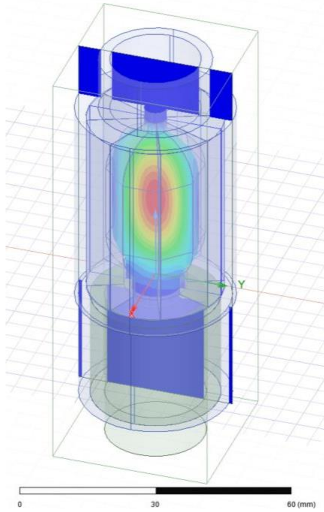
- RF pulse compression can reduce thermal losses
- Save up to 25% of main linac power (25MW) for 250 GeV
- Need to reach multi-TeV but could be implemented earlier
- Need very high Q (large compressor); HTS coatings may make more practical

Compressed pulse filling structure



arXiv:1807.10195 (2018)

HTS Pulse Compressor
REBCO Coatings



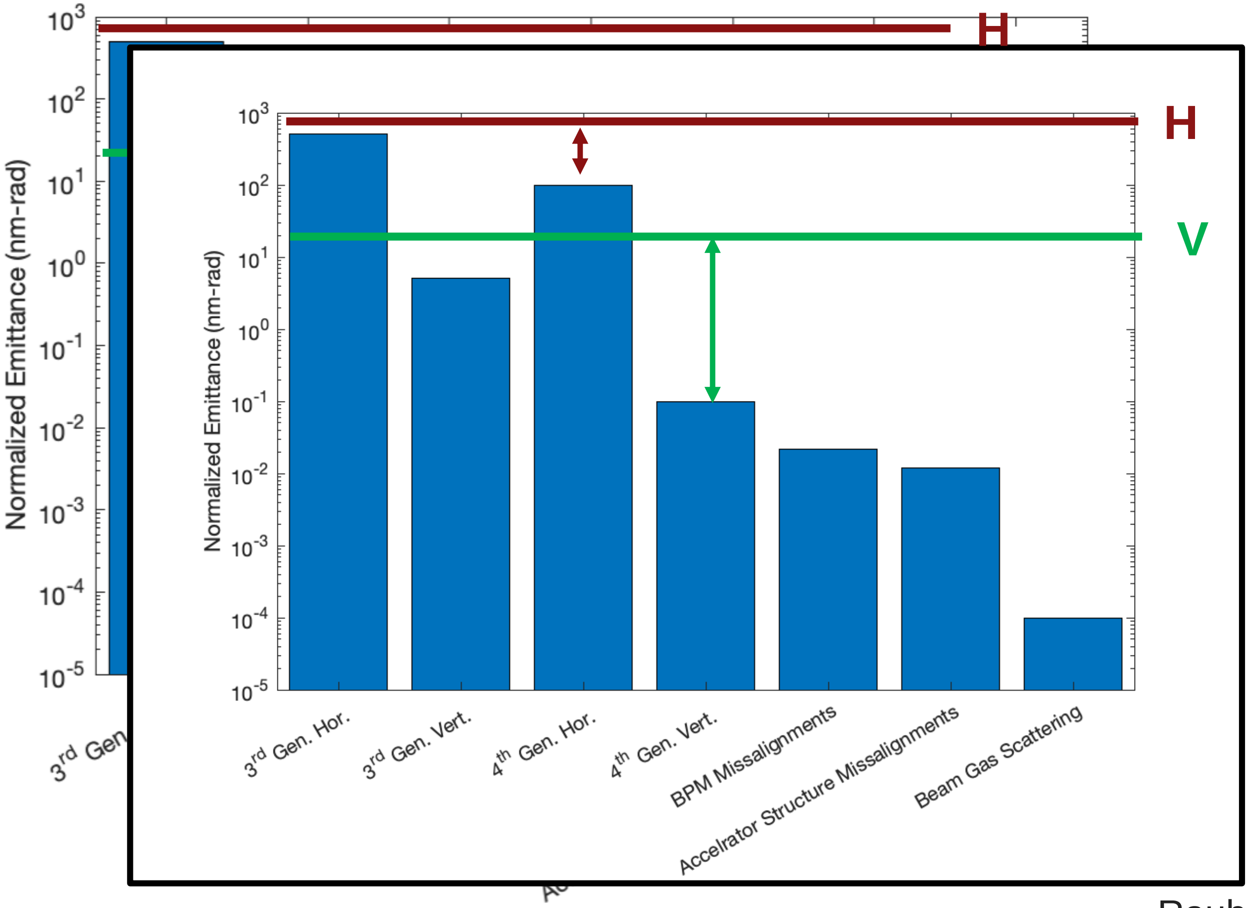
Qo ~ 400k

Le Sage, CERN
Collaborators

Back to Emittance

Spurred on by discussion with P. Raimondi

Tolerances are a big question and we need to prove them in the demo….

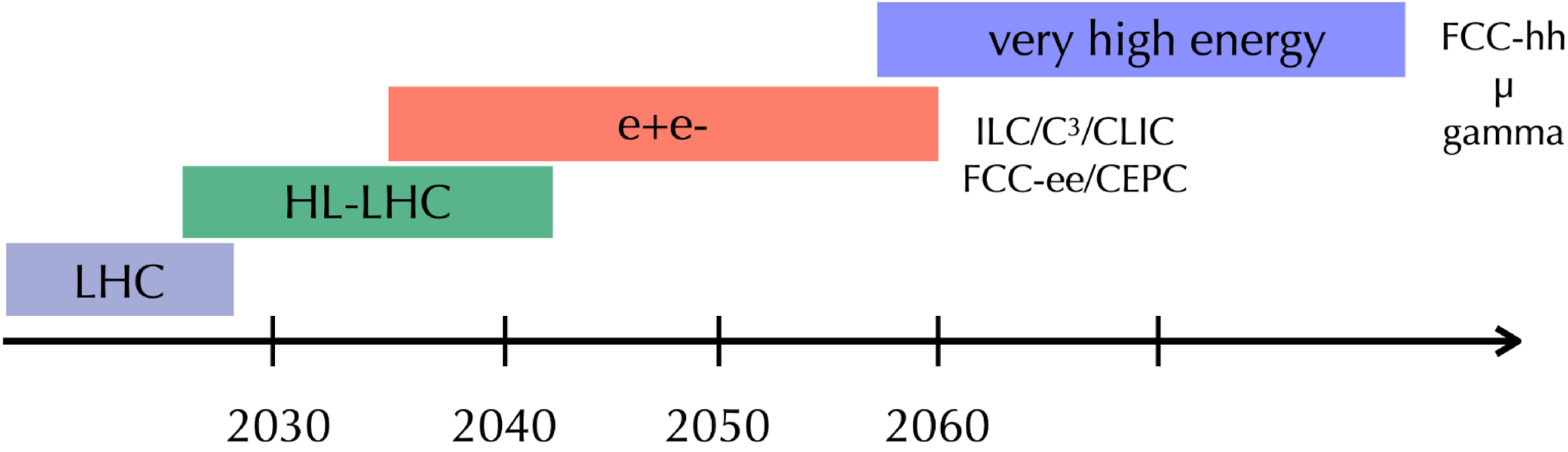


- 1 micron alignment tolerances

Caution: Requires serious investigation of beam dynamics - great topic for C³ Demonstration R&D

Raubenheimer, T. O. (2000). Estimates of emittance dilution and stability in high-energy linear accelerators. *Physical Review Special Topics-Accelerators and Beams*, *3*(12), 121002.

What's Next for the Energy Frontier?



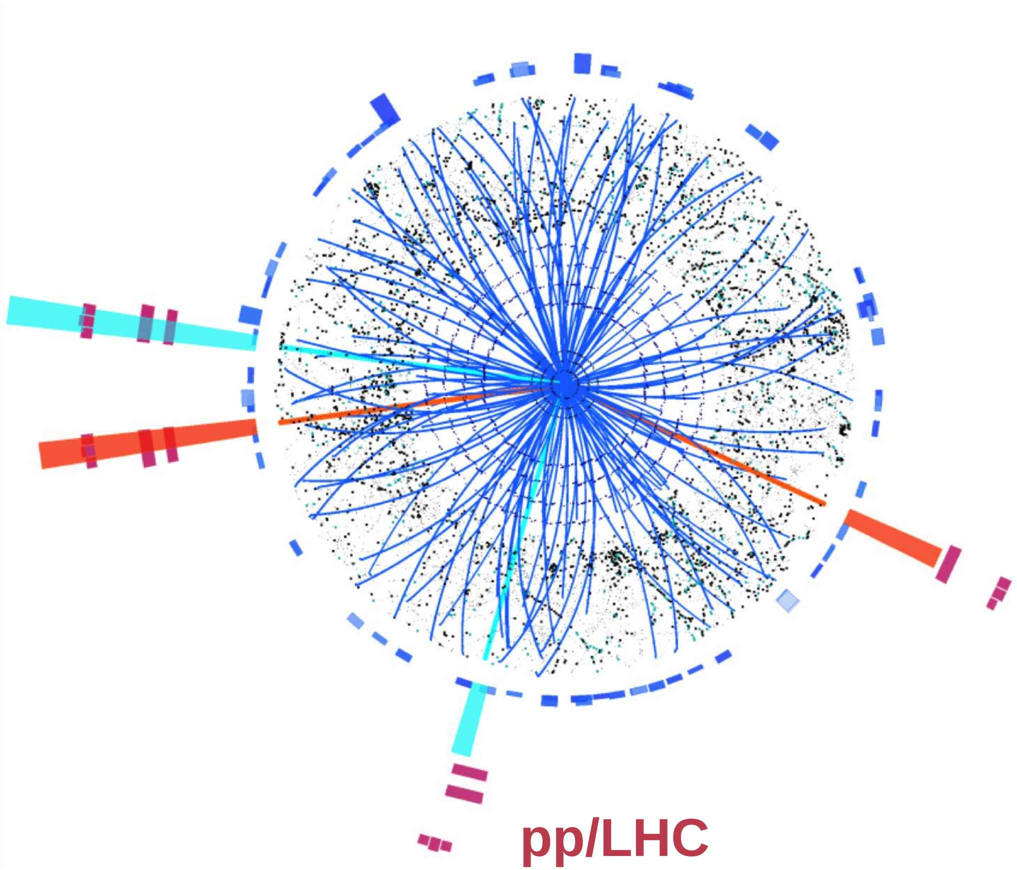
Wish list beyond HL-LHC:

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

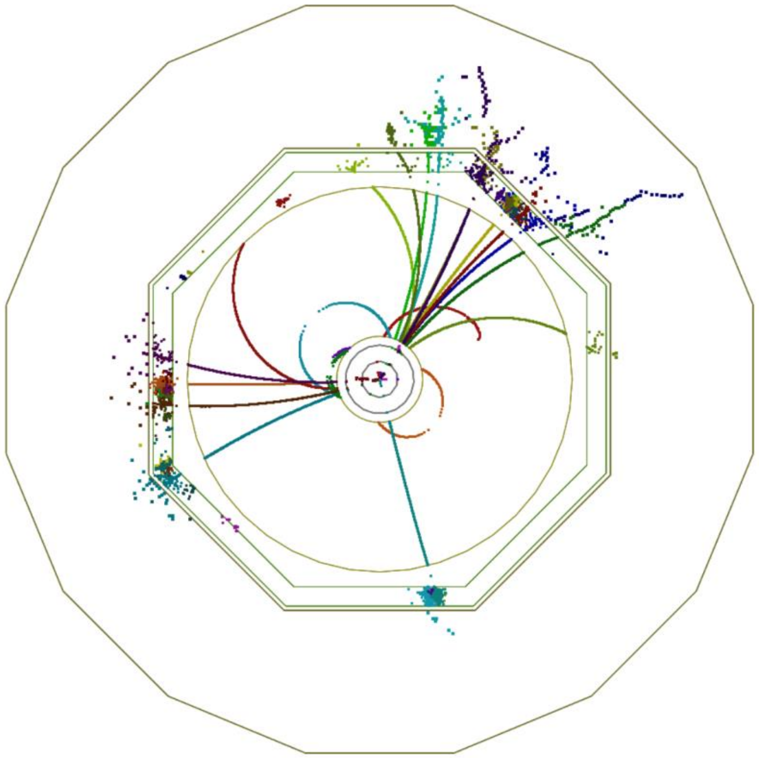
Why e^+e^-?

Initial state well defined & polarization $\Longrightarrow$ High-precision measurements

Higgs bosons appear in 1 in 100 events $\Longrightarrow$ Clean environment and trigger-less readout



pp/LHC



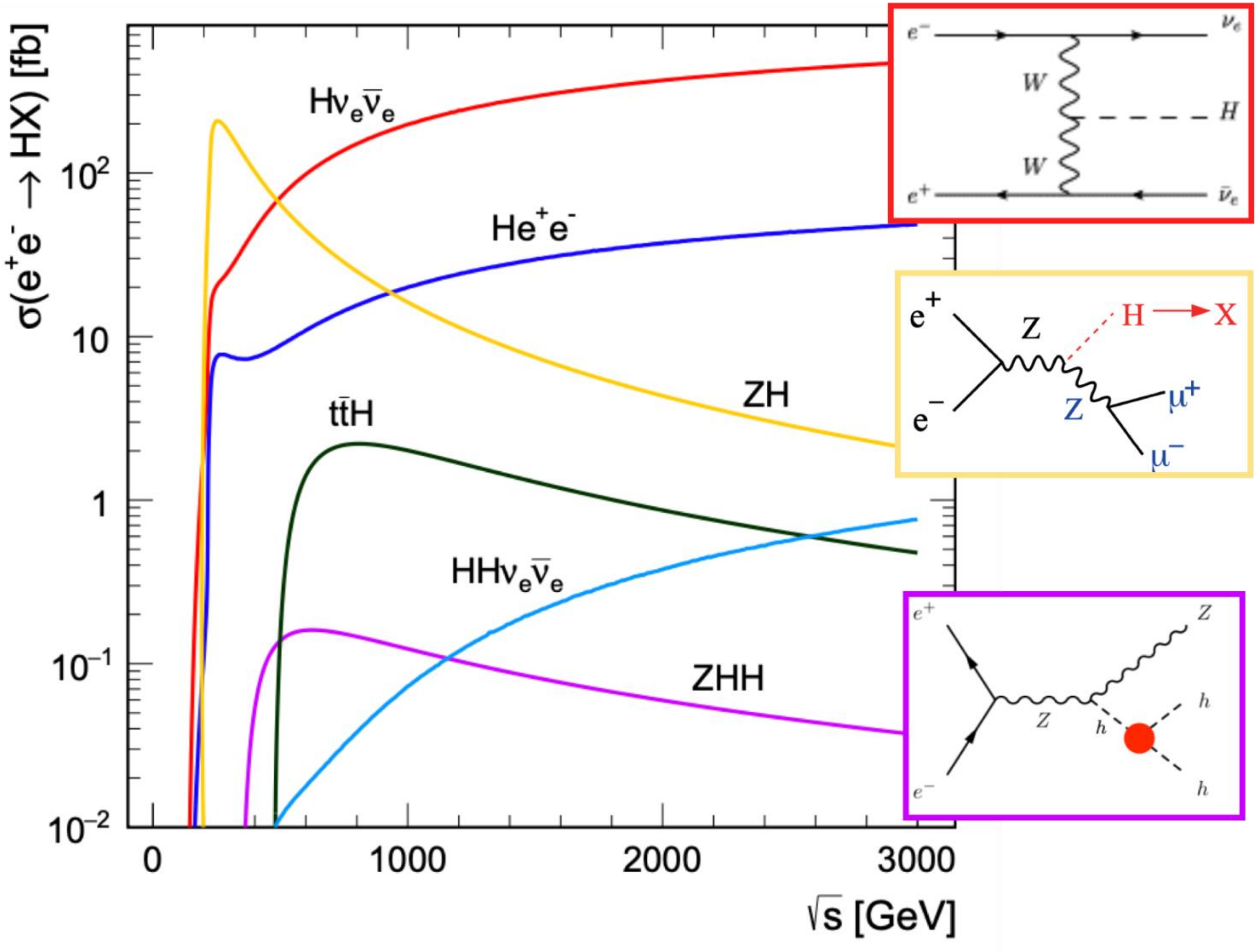
e^+e^-

Higgs Production at e^+e^-

ZH is dominant at **250 GeV**

Above **500 GeV**

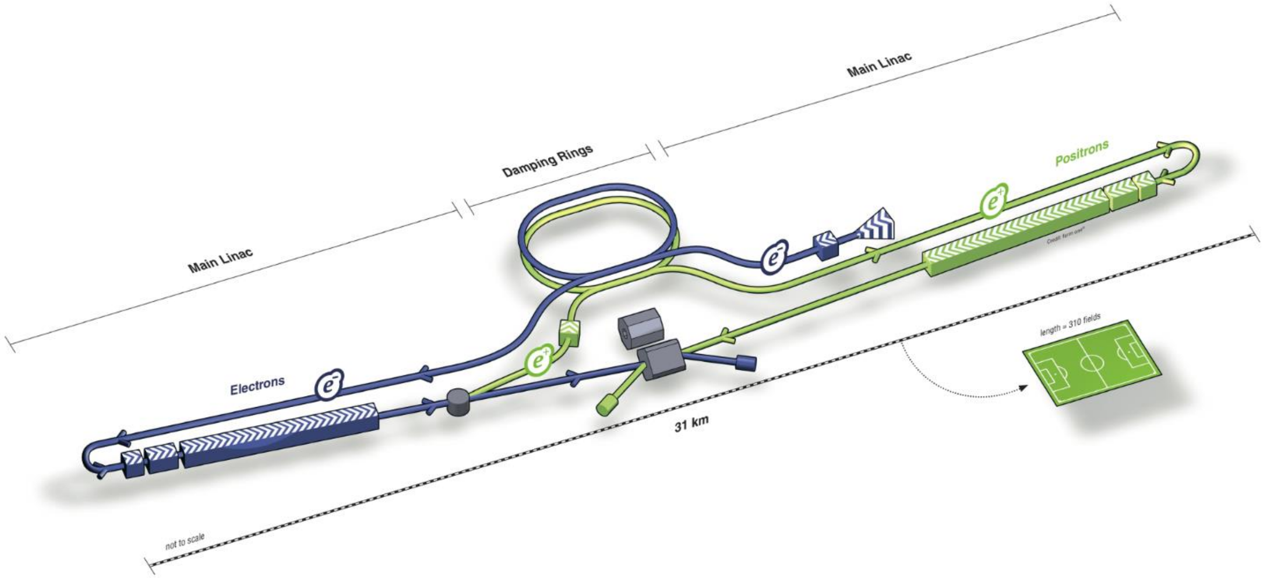
- Hvv dominates
- ttH opens up
- HH production accessible with ZHH
- An **orthogonal dataset** at 550 GeV to cross-check a deviation from the SM
- From 500 to 550 GeV a factor 2 improvement to the **top-Yukawa** coupling
- O(20%) precision on the Higgs **self-coupling**



Linear vs. Circular

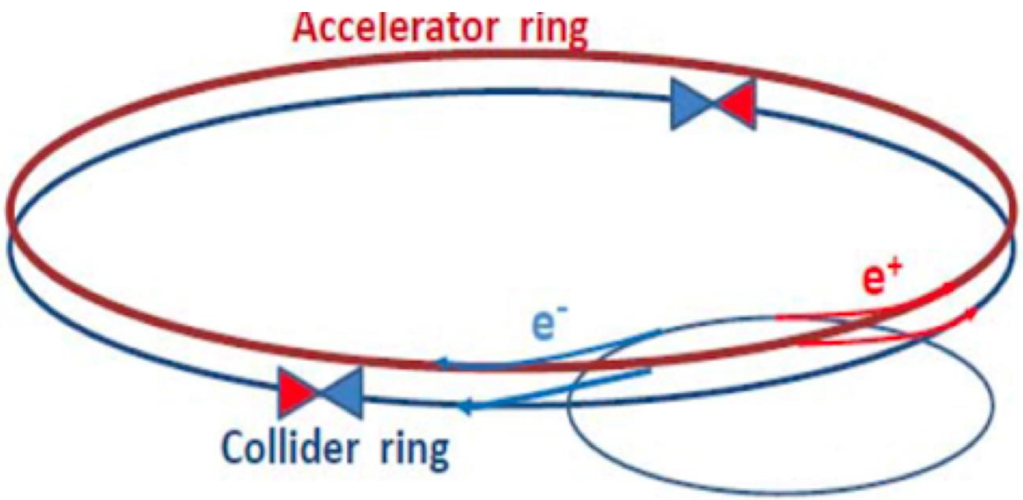
Linear e^+e^- colliders: ILC, C^3, CLIC

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

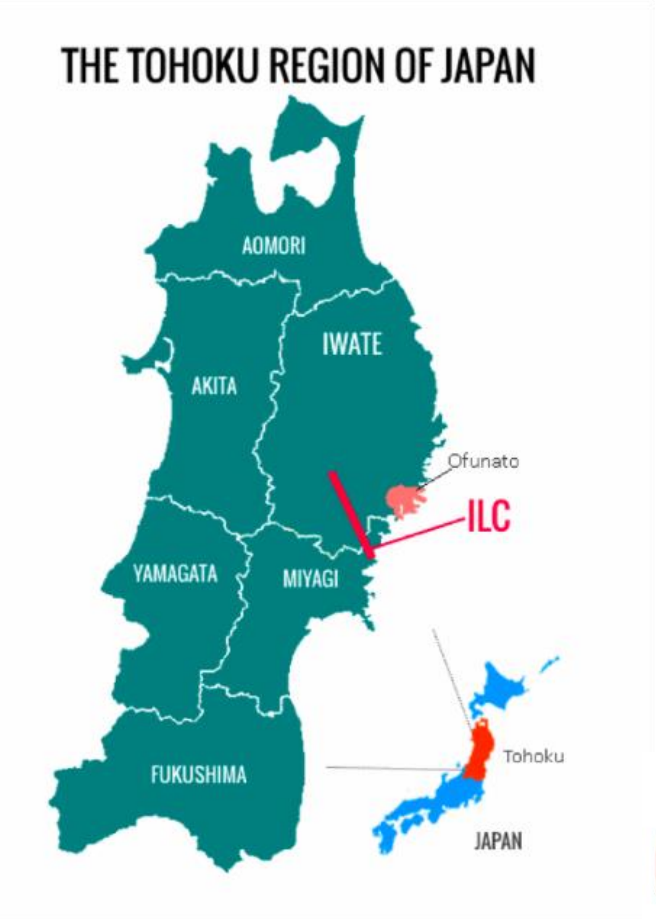


Circular e^+e^- colliders: FCC-ee, CEPC

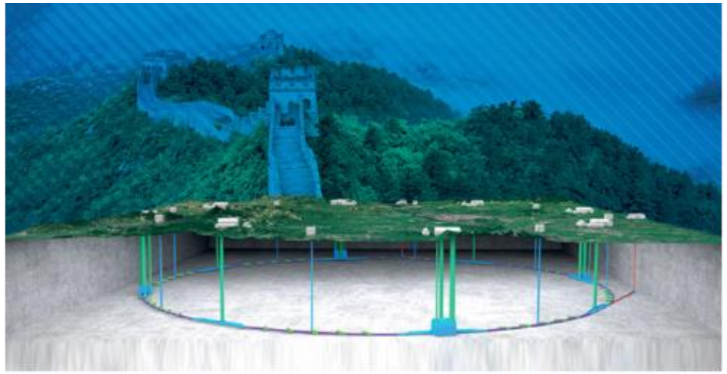
- Highest luminosity collider at Z/WW/ZH
- limited by synchrotron radiation above 350 – 400 GeV
- Beam continues to circulate after collision



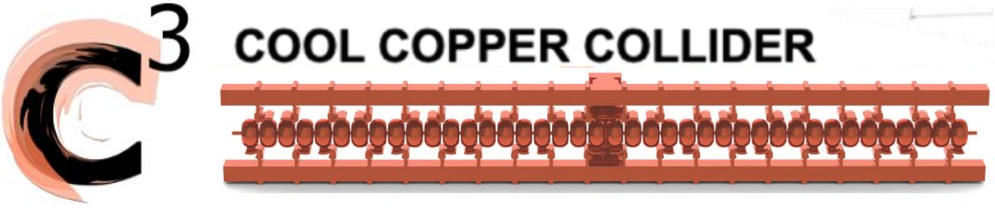
Various Proposals



ILC
250/500 GeV

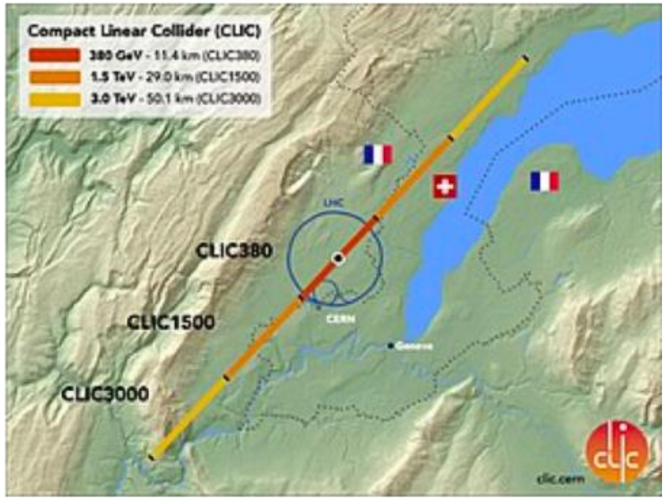


CEPC
240 GeV

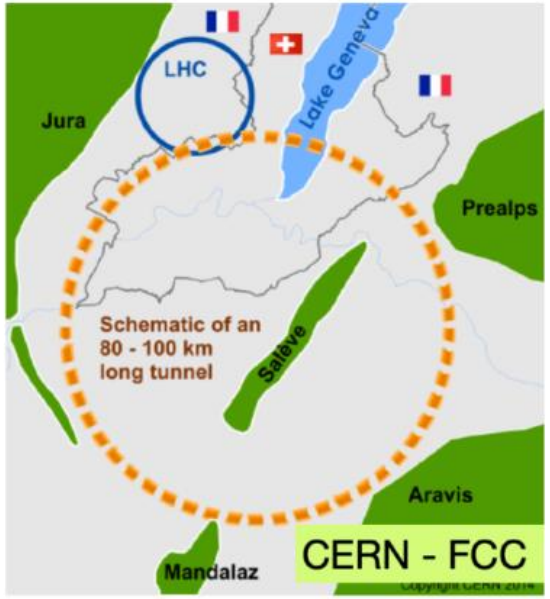


250/550 GeV
… > TeV

CLIC 380/1000/3000 GeV



FCC-ee
240/365 GeV

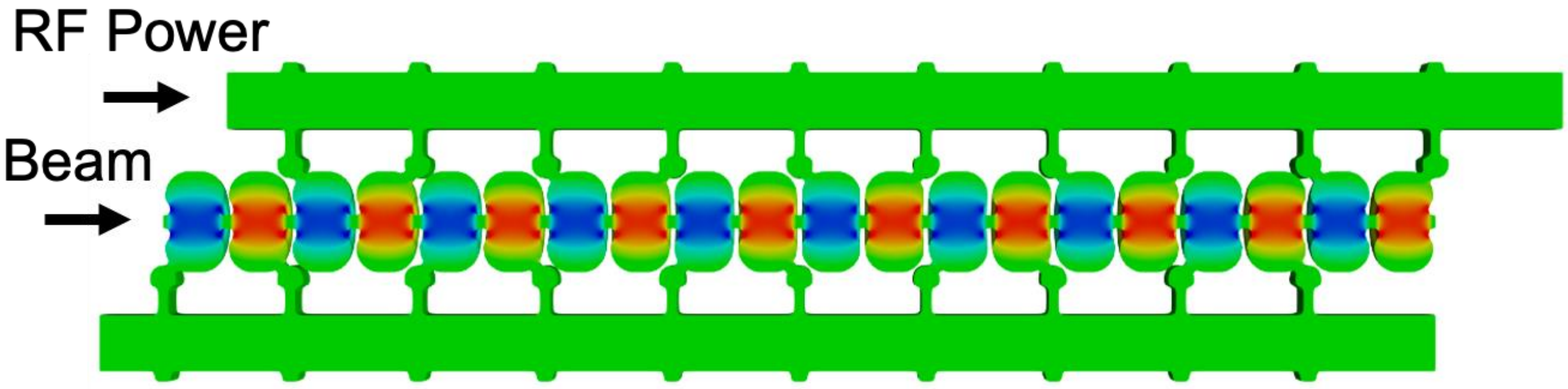


A novel route to a linear e^+e^- collider…

Breakthrough in the Performance of RF Accelerators

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

Full system design requires modern virtual prototyping



Electric field magnitude produced when RF manifold feeds alternating cells equally

Optimization of cell for efficiency (shunt impedance)

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

- Control peak surface electric and magnetic fields

Key to high gradient operation

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

Cryo-Copper: Enabling Efficient High-Gradient Operation

Cryogenic temperature elevates performance in gradient

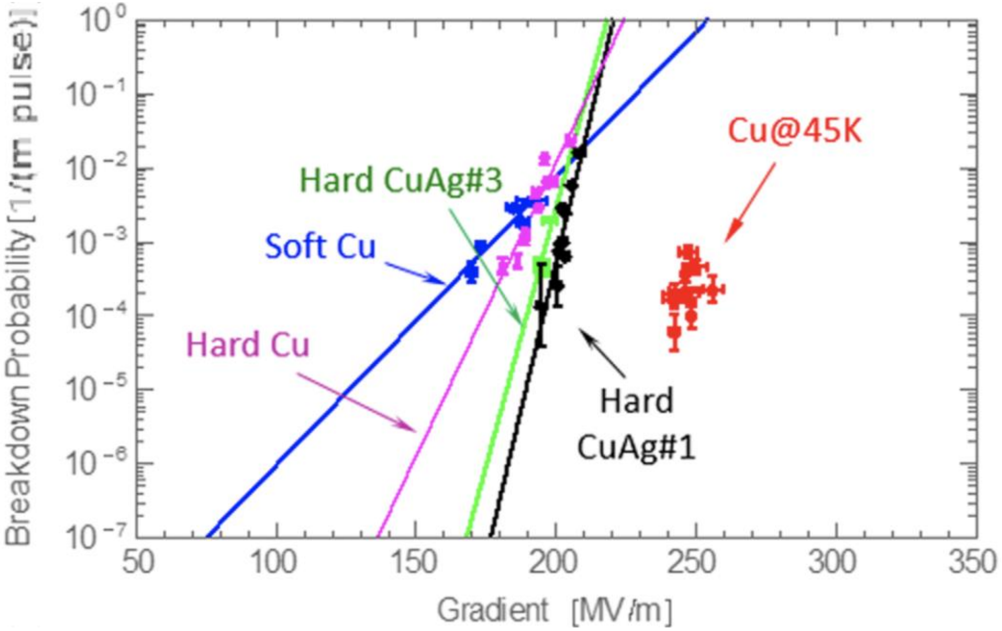
- Material strength is key factor
- Impact of high fields for a high brightness injector may eliminate need for one damping ring

Operation at 77 K with liquid nitrogen is simple and practical

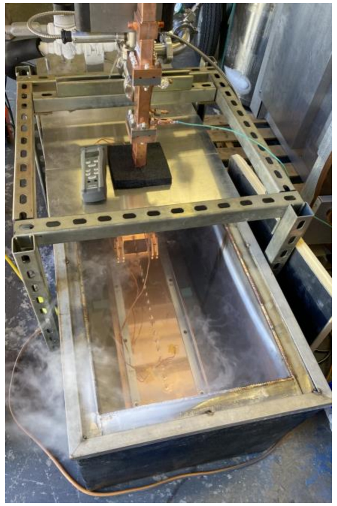
- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency

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

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



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



Cool Copper Collider

C^3 combines these advances

- Dramatically improving efficiency and breakdown rate

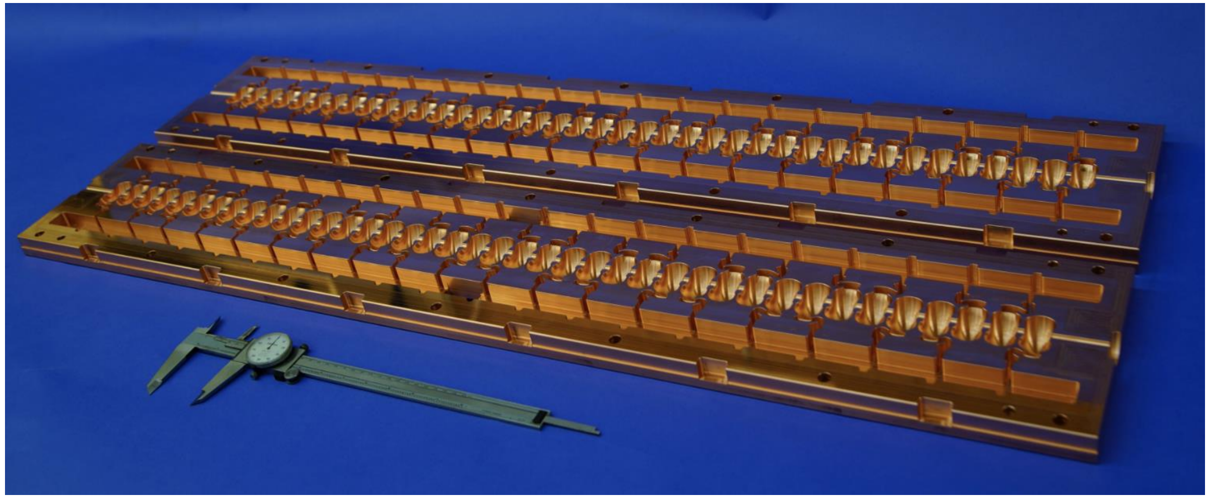
Distributed power to each cavity from a common RF manifold

Operation at cryogenic temperatures (LN_2 ~80 K)

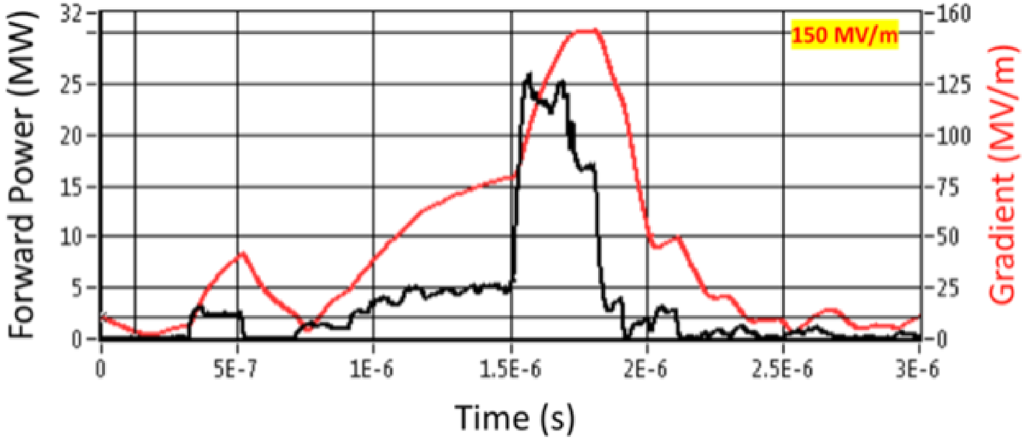
Robust operations at high gradient: 120 MeV/m

Scalable to multi-TeV operation

C^3 Prototype One Meter Structure

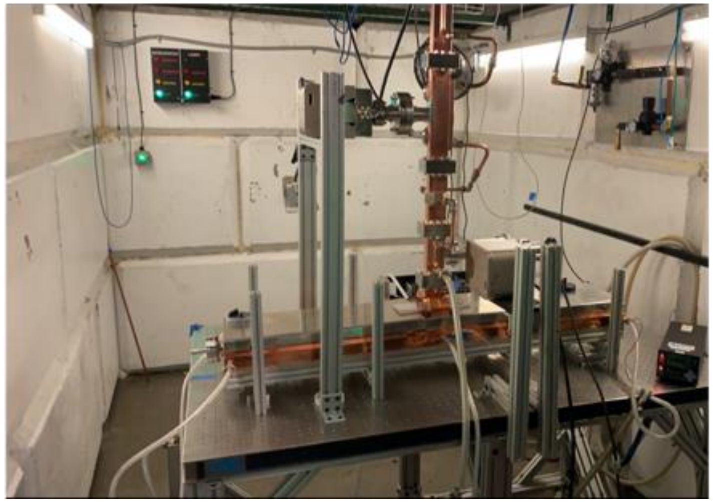


High Gradient Operation at 150 MV/m

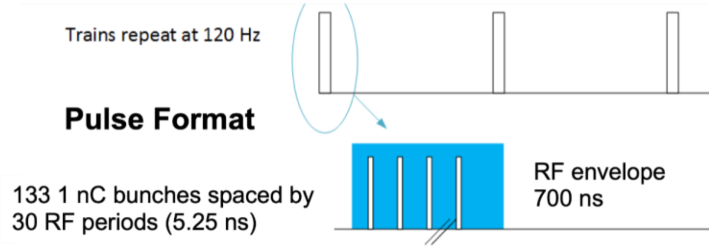


Cryogenic Operation at X-band

High Power Test at Radiabeam (Room Temp and Cryo)



Power Consumption and Sustainability



Temperature (K)	77
Beam Loading (%)	45
Gradient (MeV/m)	70
Flat Top Pulse Length (μs)	0.7
Cryogenic Load (MW)	9
Main Linac Electrical Load (MW)	100
Site Power (MW)	~150

Compatibility with Renewables Cryogenic Fluid Energy Storage

Intermittent and variable power production from renewables mediated with commercial scale energy storage and power production

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 ML	MW	40
Electrical Power For Cryo-Cooler	MW	60
Accelerator Complex Power	MW	~50
Site Power	MW	~150

C^3 Accelerator Complex

8 km footprint for 250/550 GeV CoM $\Longrightarrow$ 70/120 MeV/m

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

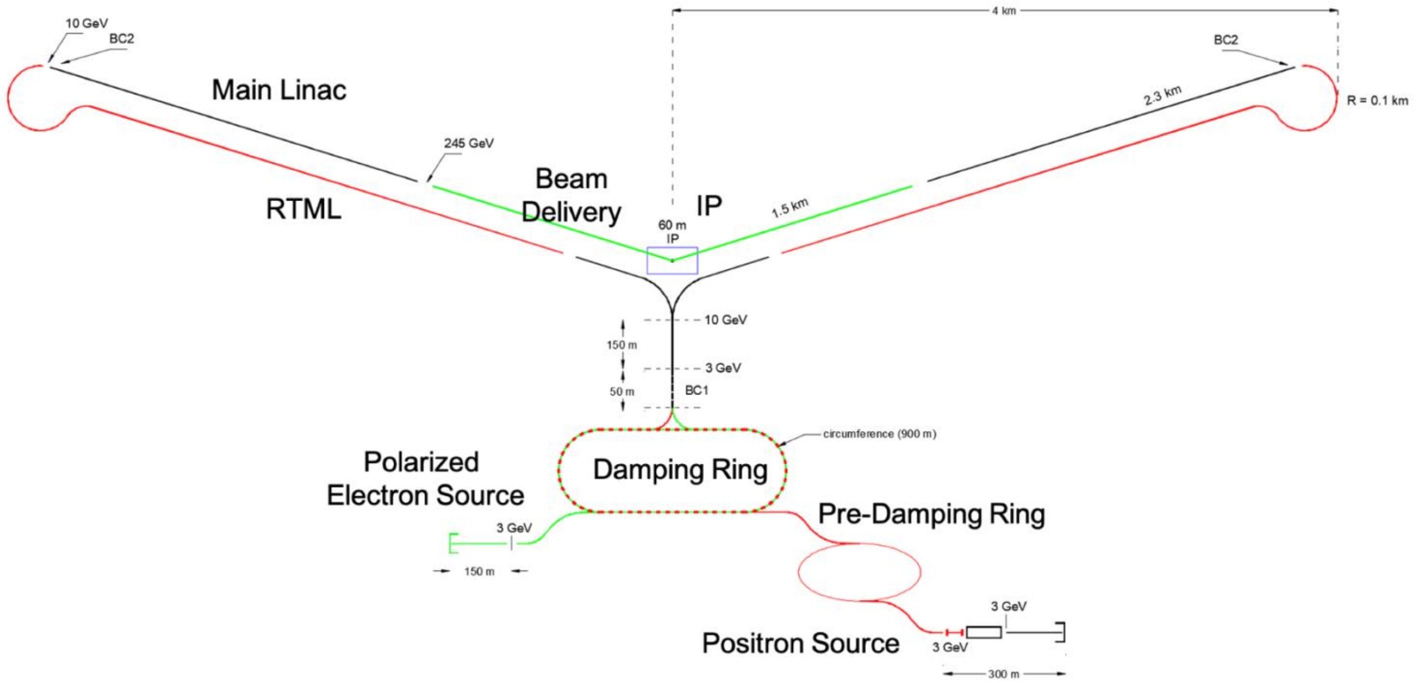
Large portions of accelerator complex are compatible between LC technologies

- 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
- New opportunities to improve Beam Delivery and footprint

C^3 Parameters

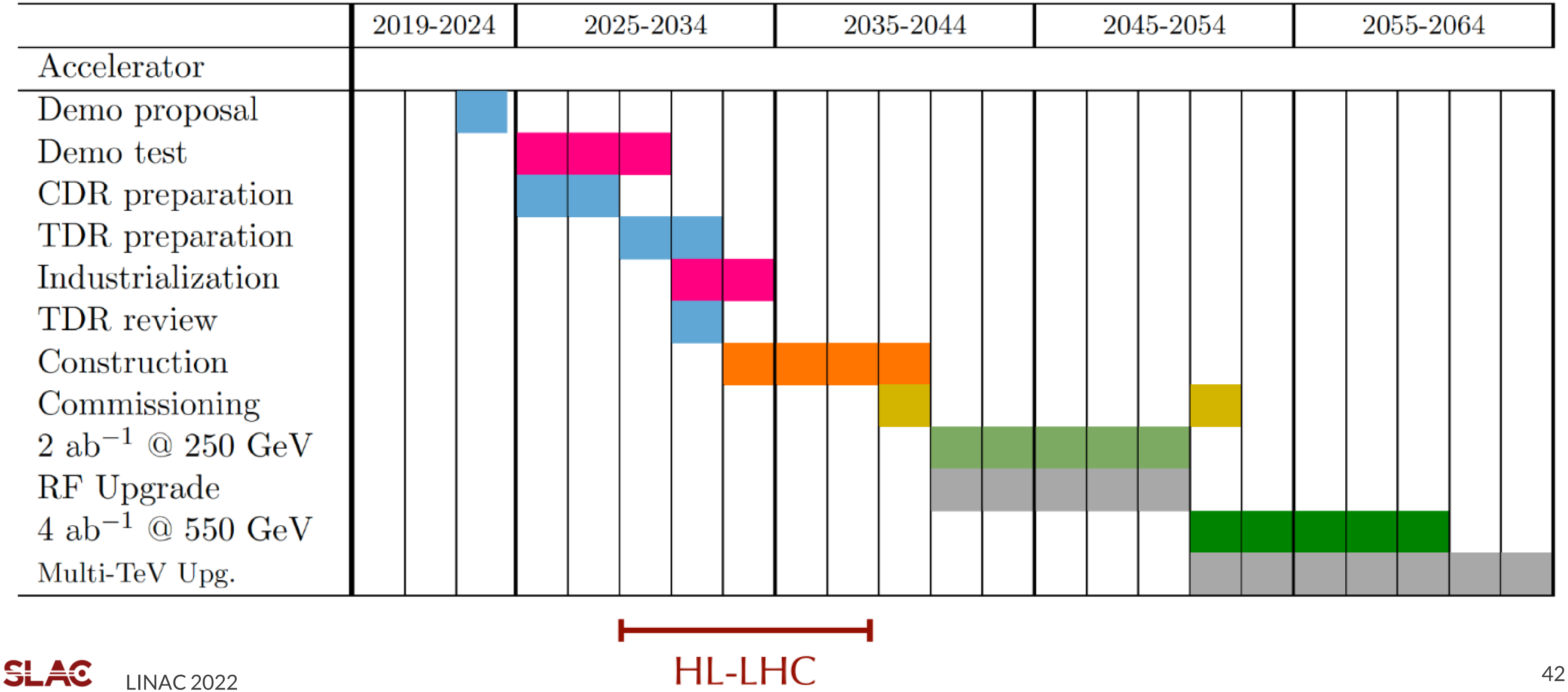
Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]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

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



Technical Timeline for 250/550 GeV CoM

Technically limited timeline following community engagement through the full Snowmass process to define the parameters of the C^3 proposal



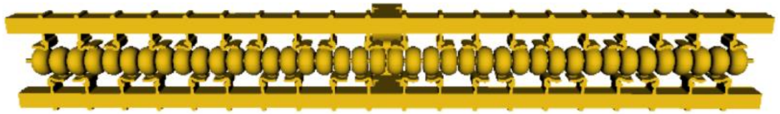
Ongoing Prototype Structure Development

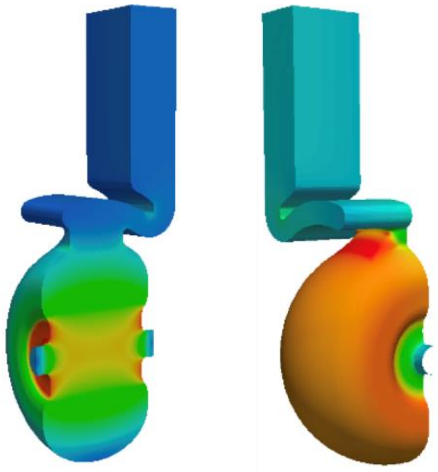
Incorporate the two key technical advances: Distributed Coupling and Cryo-Copper RF

Main linac utilizes meter-scale accelerating structures, technology demonstration underway

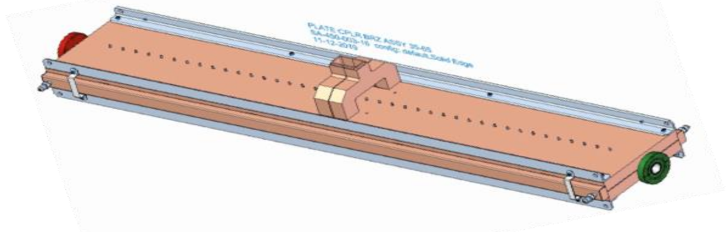
Implement optimized rf cavity designs to control peak surface fields

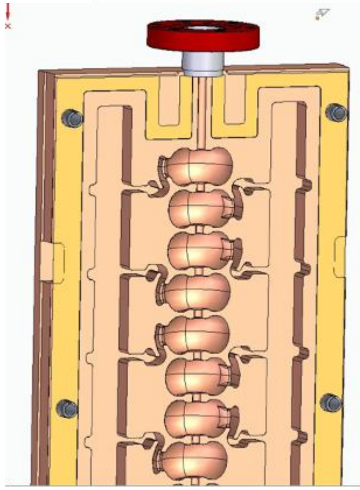
One meter (40-cell) C-band design with reduce peak E and H-field

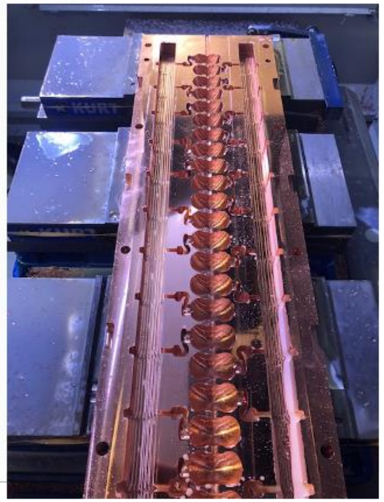




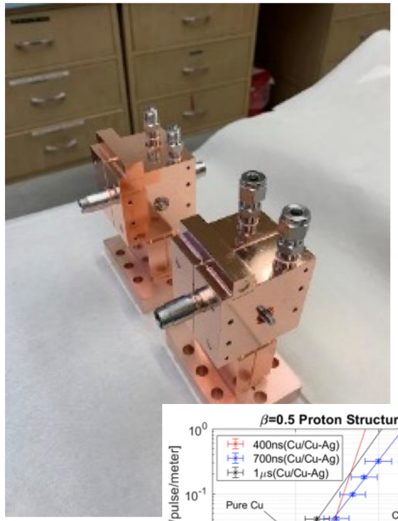
Scaling fabrication techniques in length and including controlled gap

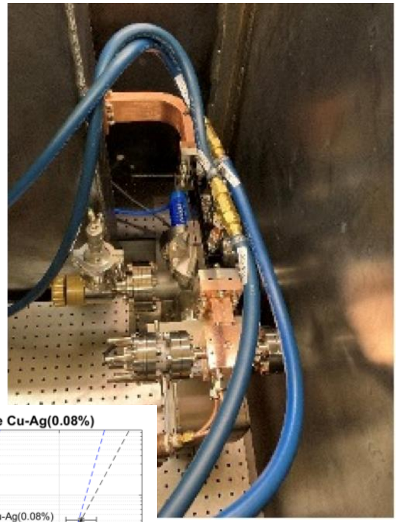


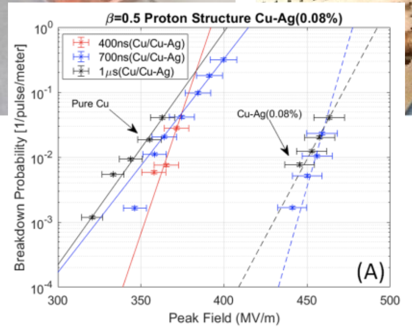




LANL Test of single cell SLAC C-band structure







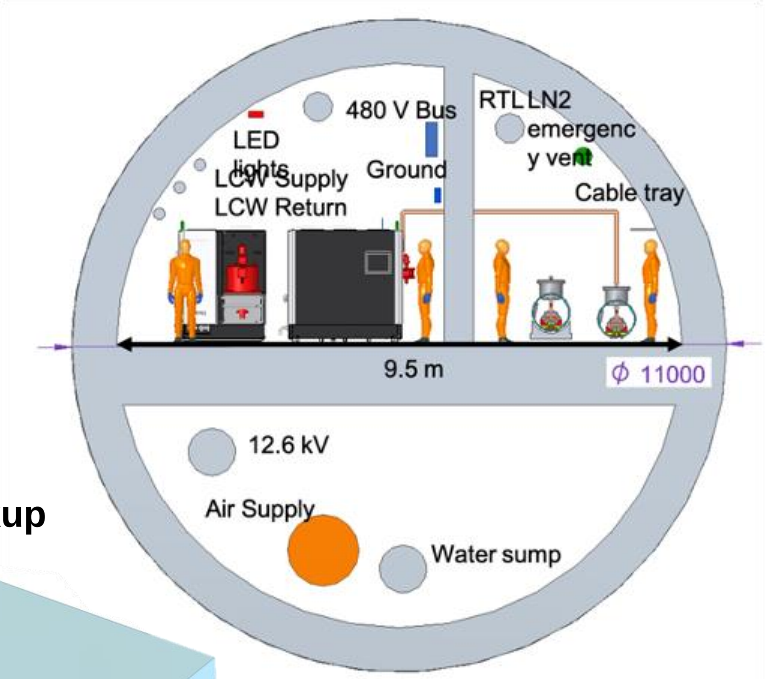
Tunnel Layout for Main Linac 250/550 GeV CoM

Need to optimize tunnel layout – first study looked at 9.5 m inner diameter in order to match ILC costing model

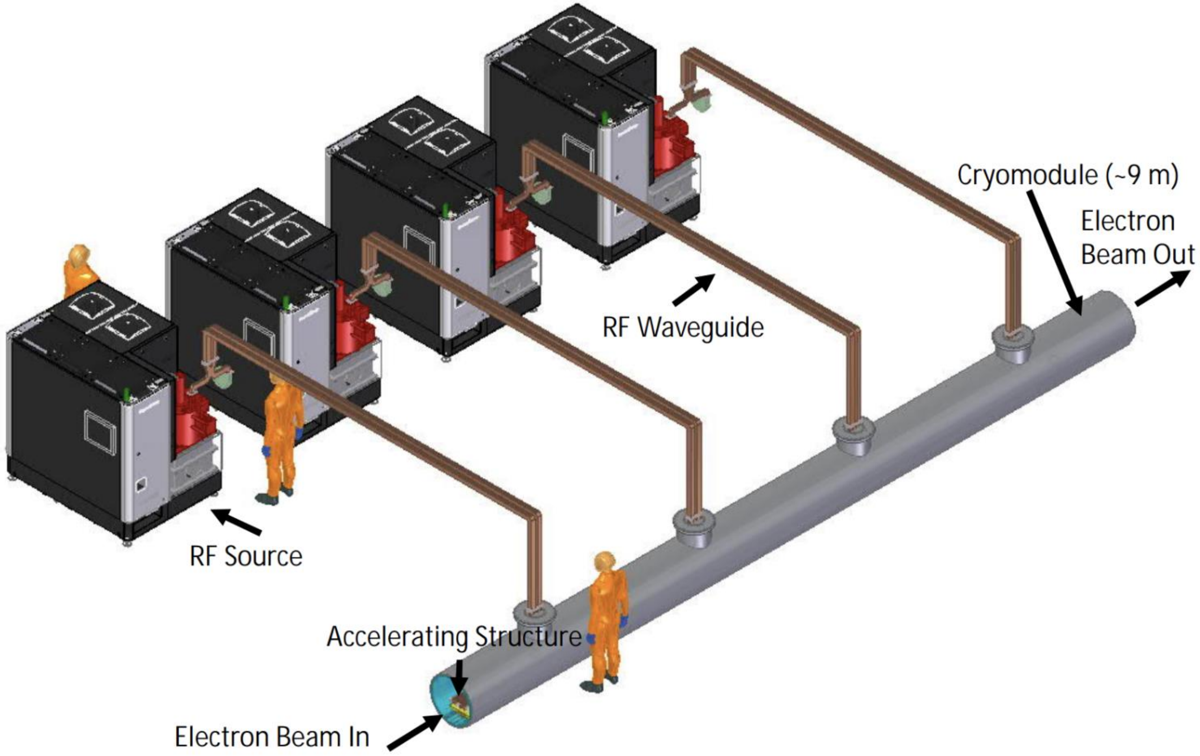
- Must minimize diameter to reduce cost and construction time

Surface site (cut/cover) provides interesting alternative – concerns with length of site for future upgrade

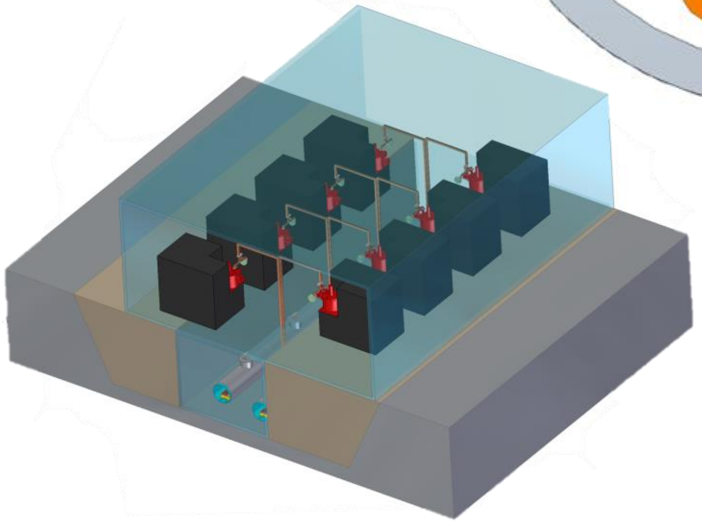
Usable Tunnel Width - 9.5 m
(Same tunnel width as ILC)



Cryomodule Unit - 9 m
(630 MeV/1 GeV)



Surface Site Mockup

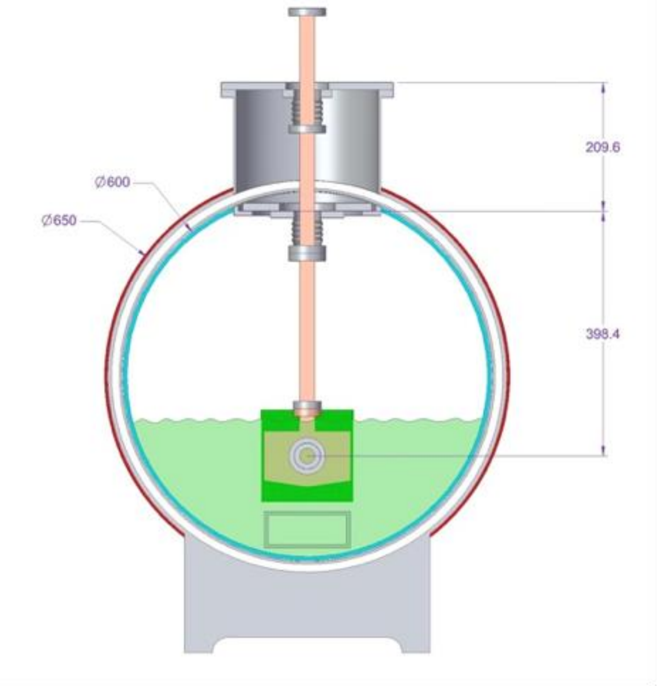


Cryomodule Design Scalable from 250 GeV to multi-TeV

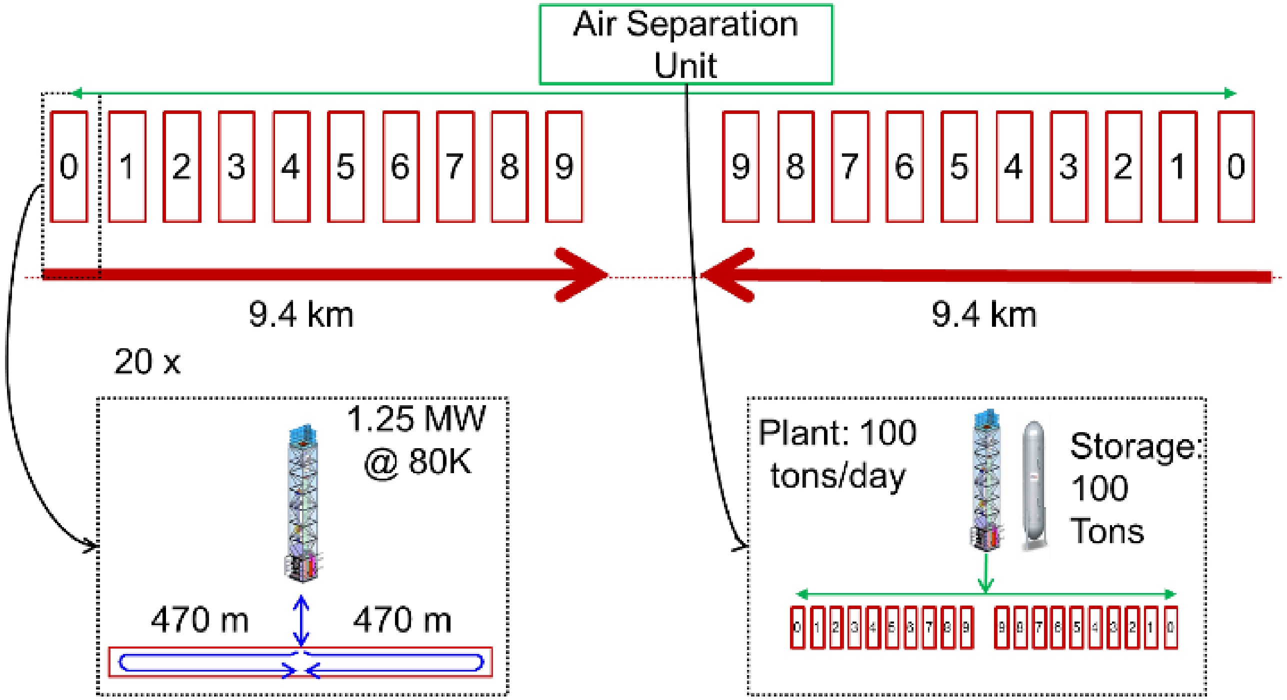
X-band structure demonstrated full average power over short length (0.25 m)

Cryomodule design developed for cryoplant layout to cool 1.2 MW/km thermal load at 77K

Shared Nitrogen Supply and Return



Cryogenics Scale to multi-TeV



Outlook

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:

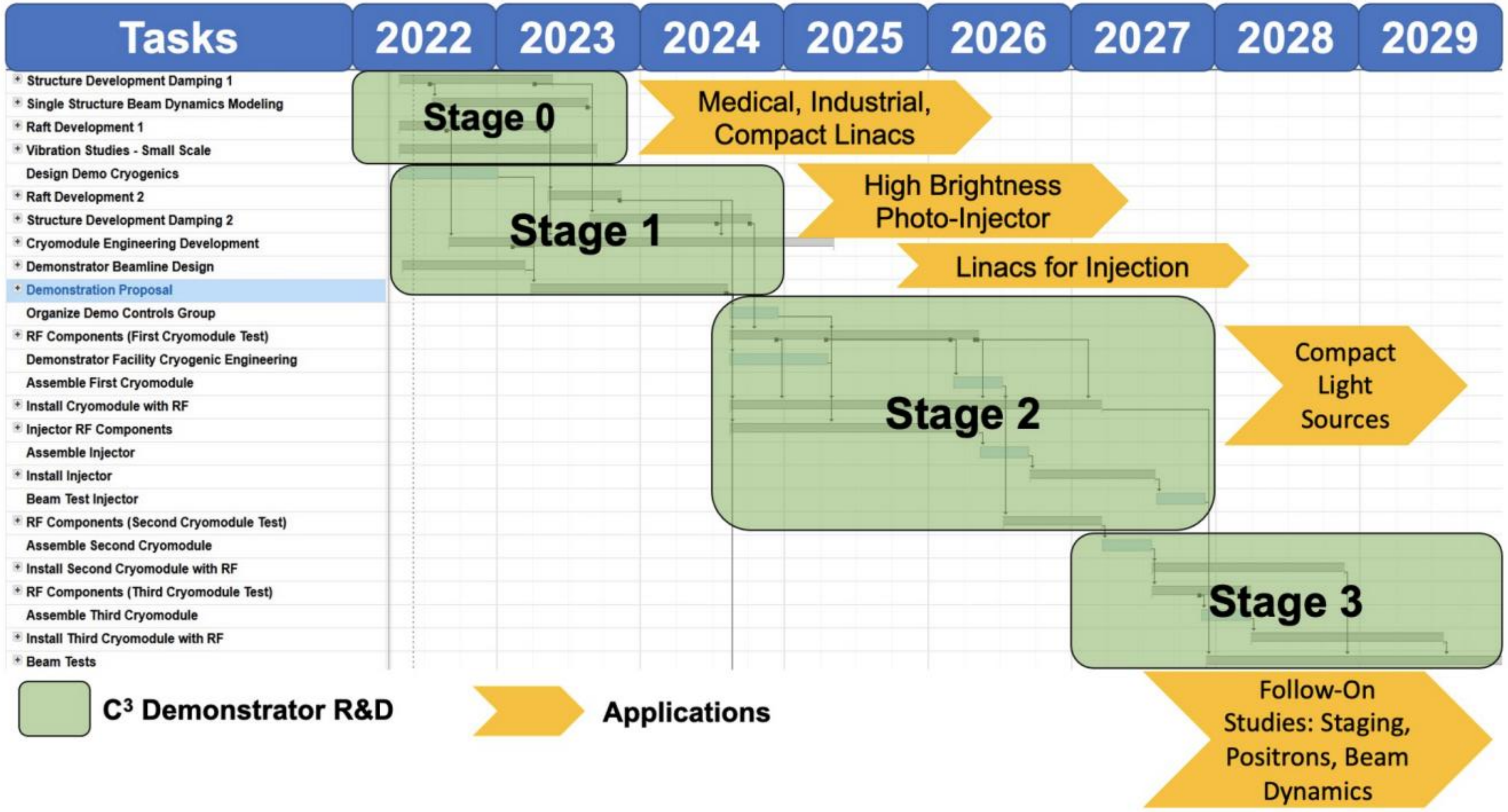
- **Demonstrate operation of fully engineered and operational cryomodule**
  - Simultaneous operations of min. 3 cryomodules
- Demonstrate operation during cryogenic flow equivalent to main linac at full liquid/gas flow rate
- Operation with a multi-bunch photo injector - high charges bunches to induce 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

C³ Demonstration R&D Plan timeline

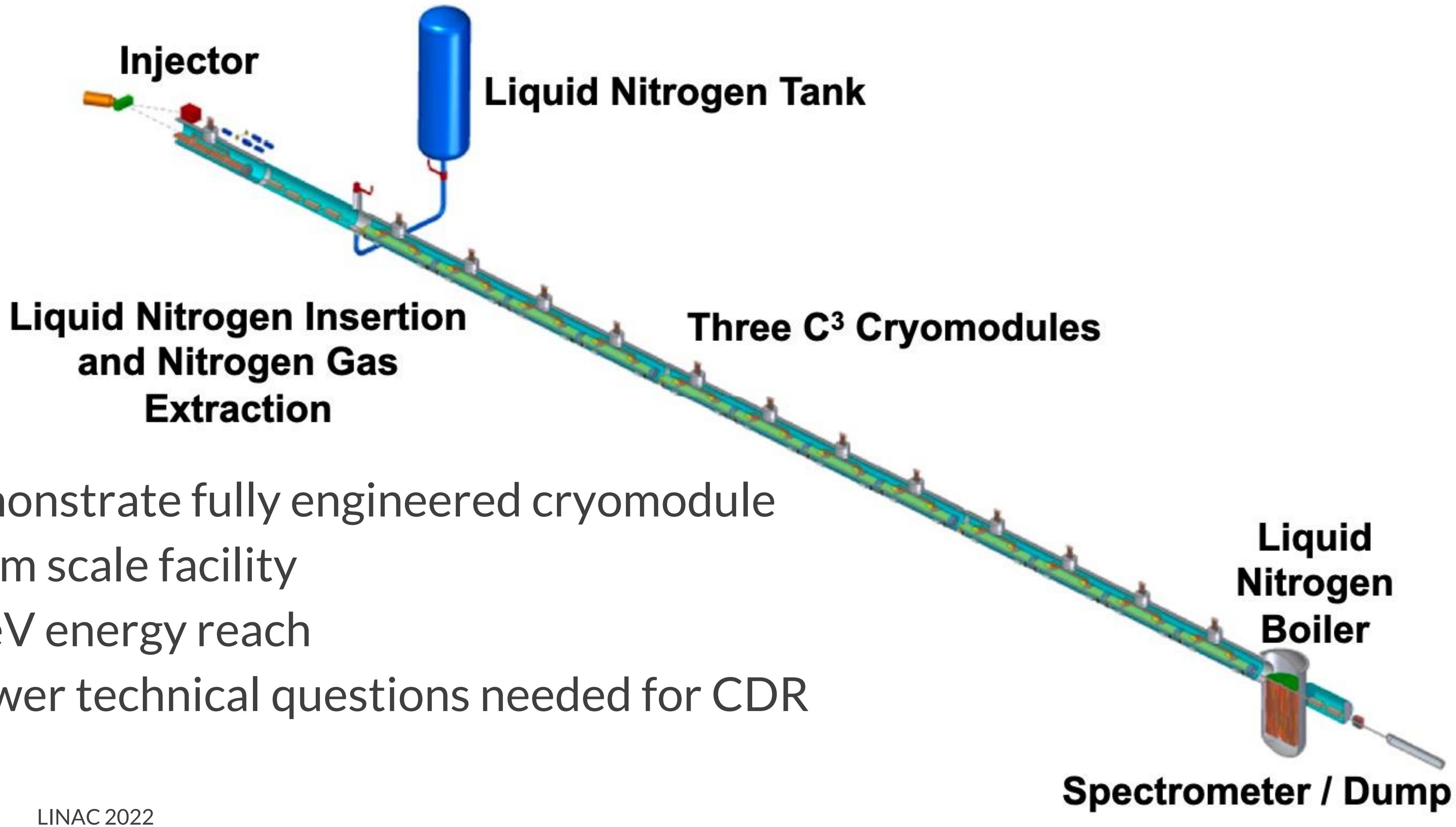


C³ R&D, System Design and Project Planning are ongoing

- Early career scientists should help drive the agenda for an experiment they will build/use
- Many opportunities for other institutes to collaborate on:
  - beam dynamics, vibrations and alignment, cryogenics, rf engineering, controls, detector optimization, background studies, etc.

High Energy Physics: Caterina Vernieri caterina@slac.stanford.edu
Accelerator Science & Engineering: Emilio Nanni nanni@slac.stanford.edu

The Complete C^3 Demonstrator



Demonstrate fully engineered cryomodule

~50 m scale facility

3 GeV energy reach

Answer technical questions needed for CDR

Conclusion

Next C^3 Workshop in Planning – Oct. 13-14th @ SLAC

https://indico.slac.stanford.edu/event/7315/

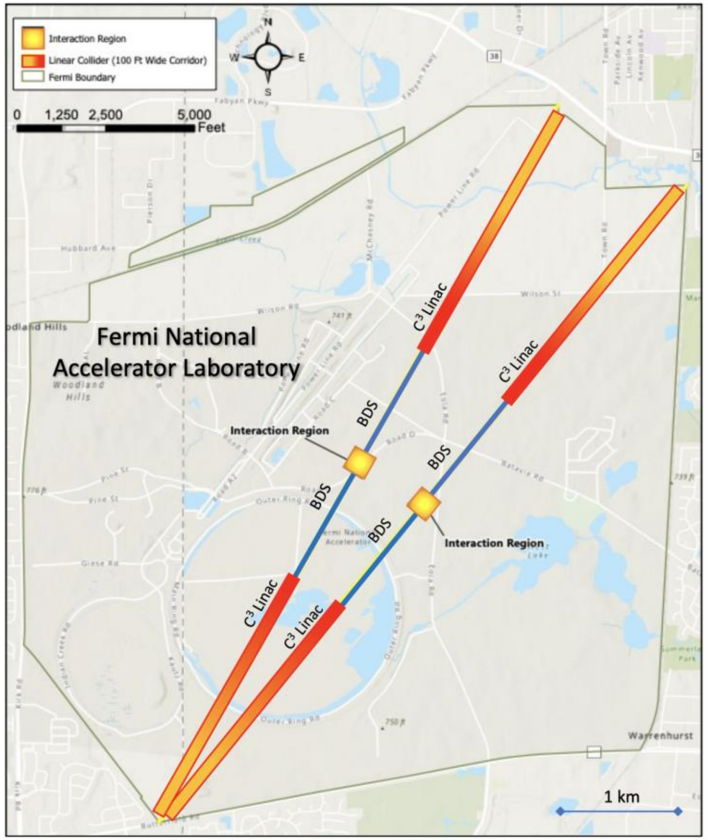
C^3 can provide a rapid route to precision Higgs physics with a compact 8 km footprint

- Higgs physics run by 2040
- Possibly, a US-hosted facility

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 multi-TeV e+e- collider



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

Accelerator Design and Challenges

Accelerator Design

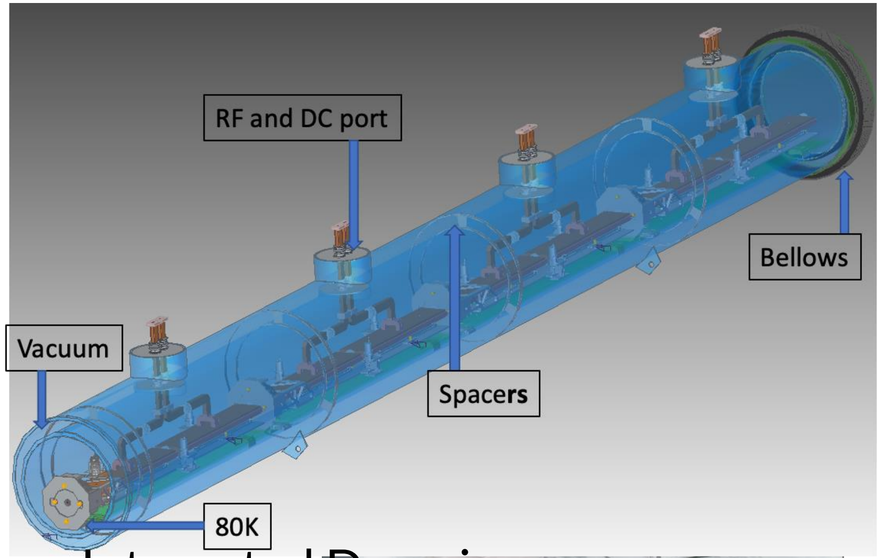
- Engineering and design of prototype cryomodule underway

Focused on challenges identified with community through Snowmass

- 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 - Thermionic beam test
- Scalability – Cryomodules and integration

Laying the foundation for a demonstration program to address technical risks beyond RDR (CDR) level

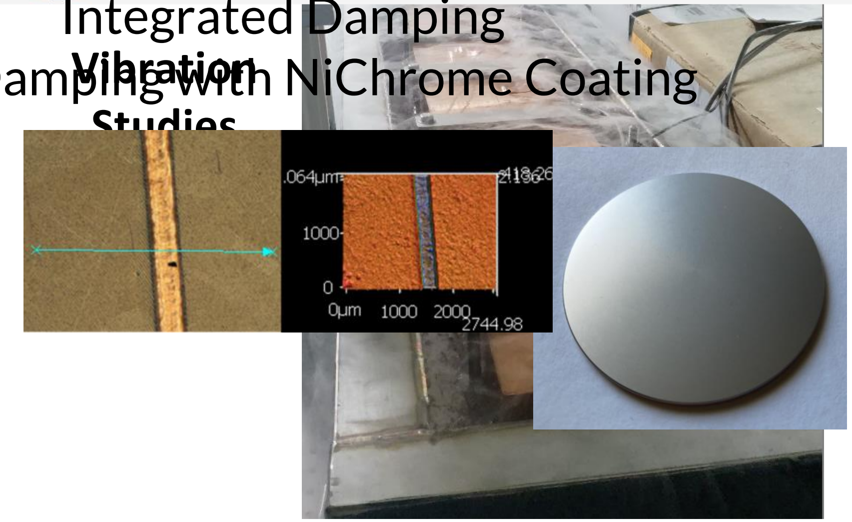
Cryomodule Concept



Integrated Damping

Vibration Studies

Slot Damping with NiChrome Coating



RF Power Requirements

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

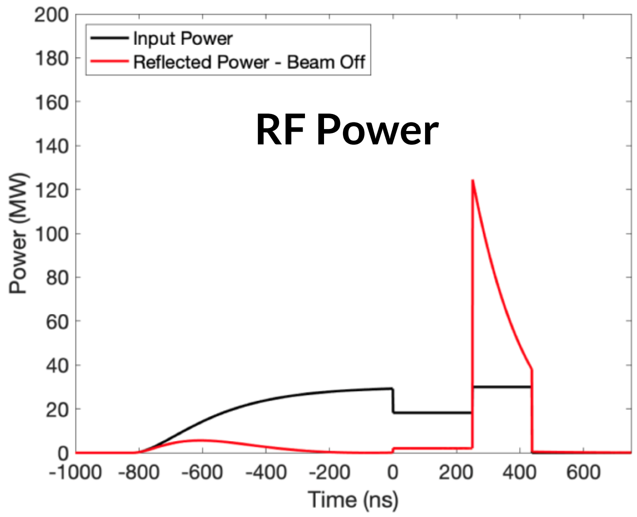
~1 microsecond rf pulse, ~30 MW/m

Conservative 2.3X enhancement from cryo

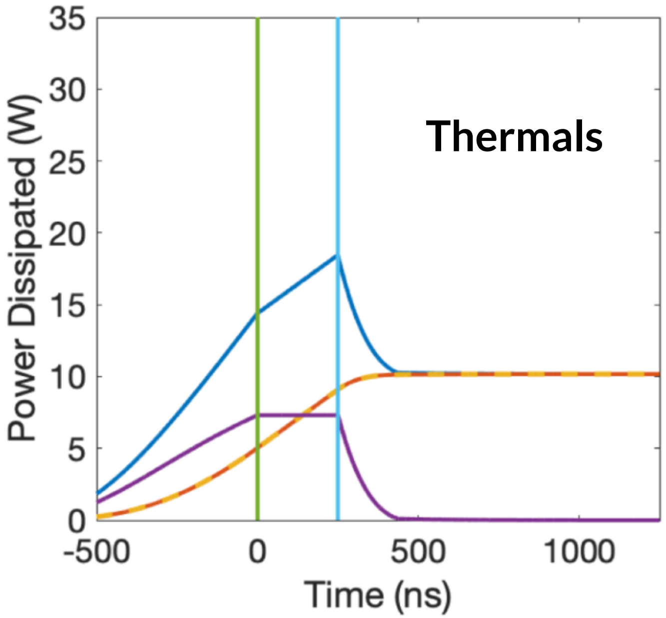
- No pulse compression

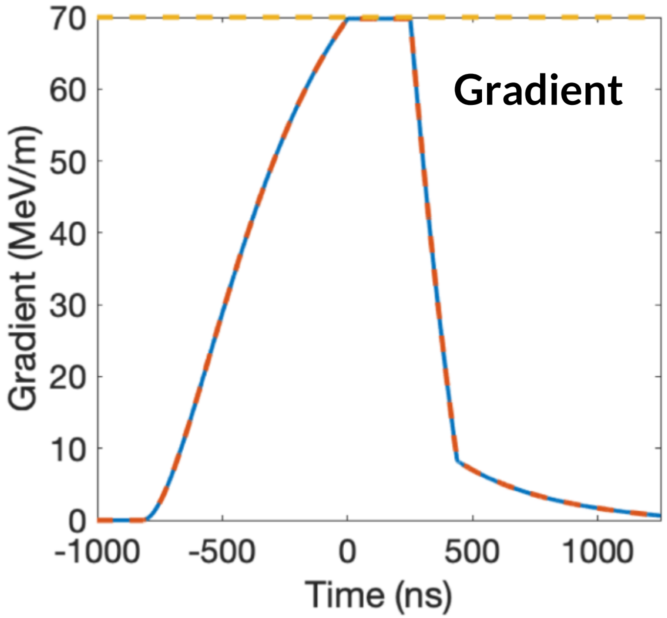
Ramp power to reduce reflected power

Flip phase at output to reduce thermals



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





Beam Format and Detector Design Requirements

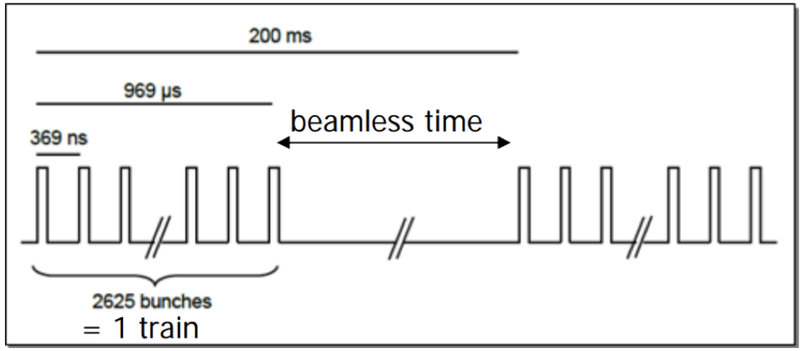
ILC timing structure: Fraction of a percent duty cycle

- **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

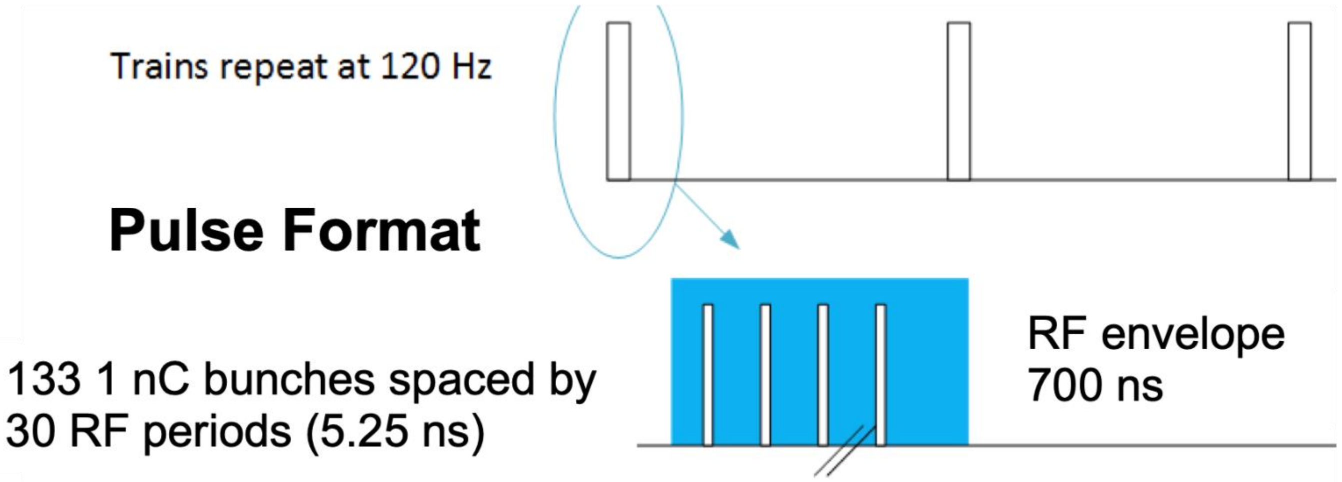
C^3 time structure is compatible with SiD-like detector overall design and ongoing optimizations

ILC timing structure



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

C^3 timing structure



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

Why 550 GeV?

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

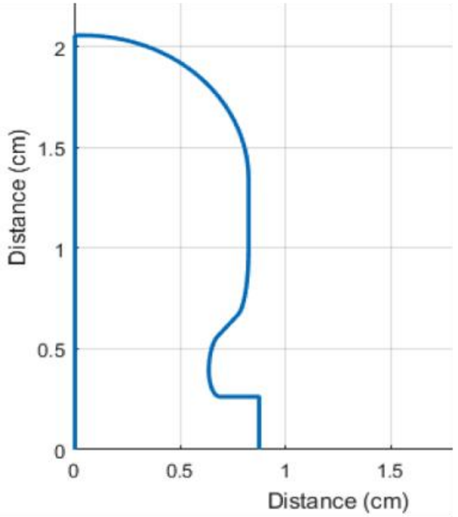
- An **orthogonal dataset** at 550 GeV to cross-check a deviation from the SM predictions observed at 250 GeV
- From 500 to 550 GeV a factor 2 improvement to the **top-Yukawa** coupling
- O(20%) precision on the Higgs **self-coupling** would allow to exclude/demonstrate at 5σ models of electroweak baryogenesis

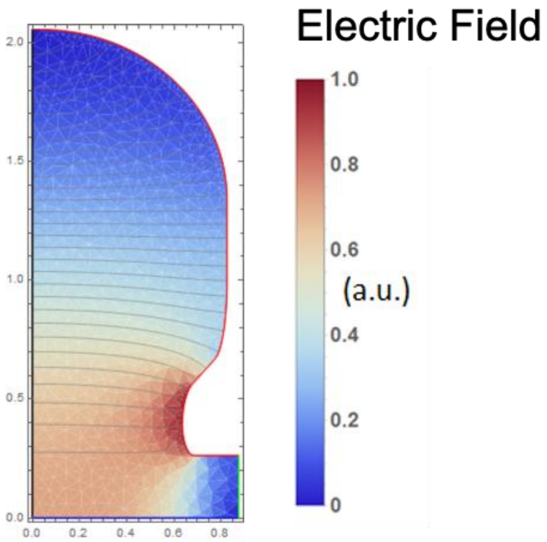
Collider Luminosity Polarization	HL-LHC 3 ab^{-1} in 10 yrs -	C^3 /ILC 250 GeV 2 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)	C^3 /ILC 500 GeV + 4 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80 (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)

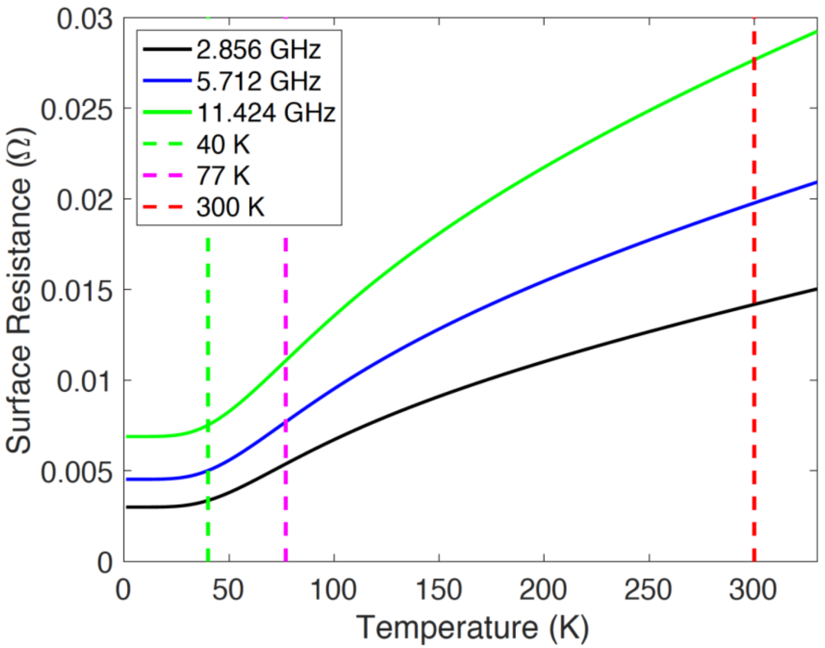
Optimized Cavity Geometries for Standing Wave Linac

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







Accelerator Complex

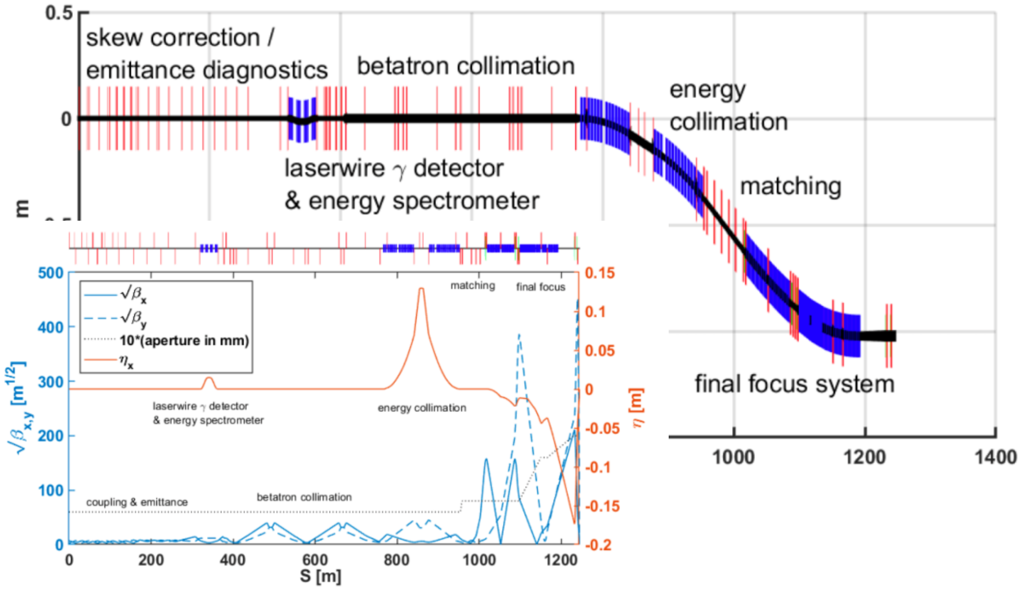
present these electrical power budgets and their underlying assumptions, and also – in your assessment - the biggest challenges for achieving the design luminosity8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

- 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 i

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



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

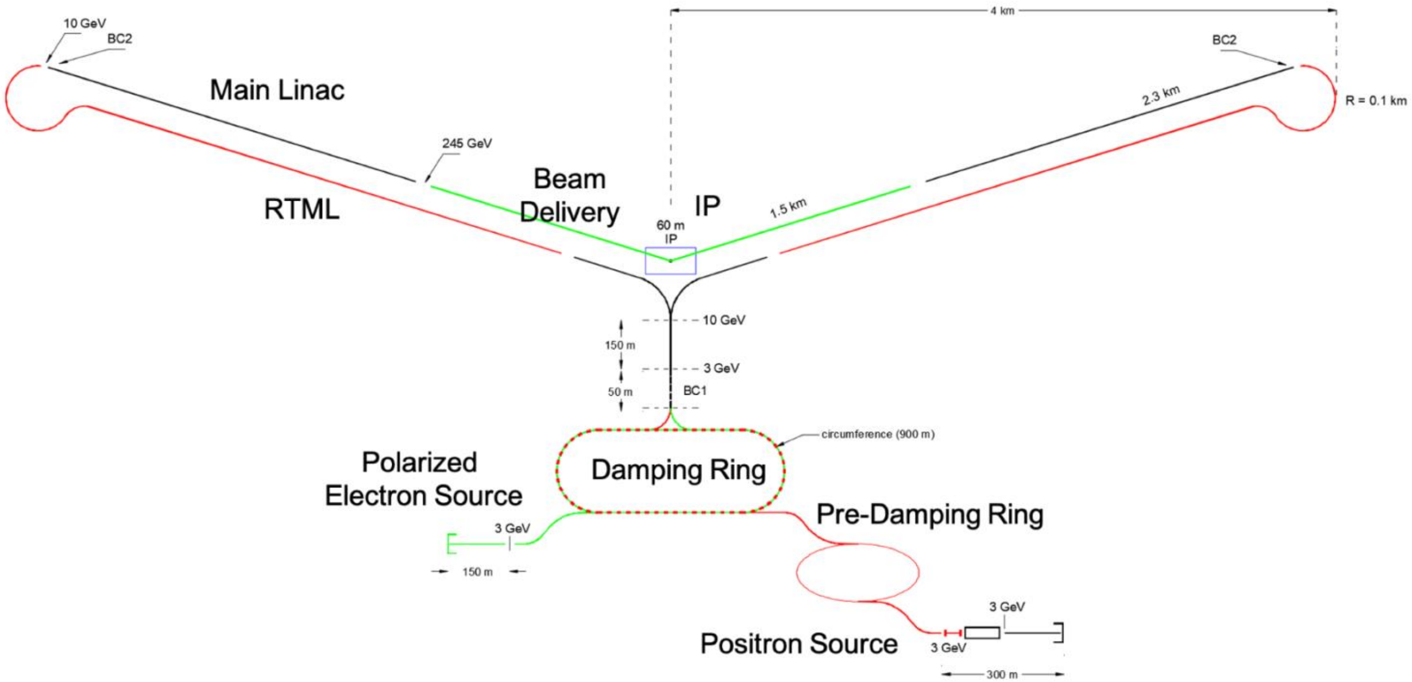


Table of Parameters

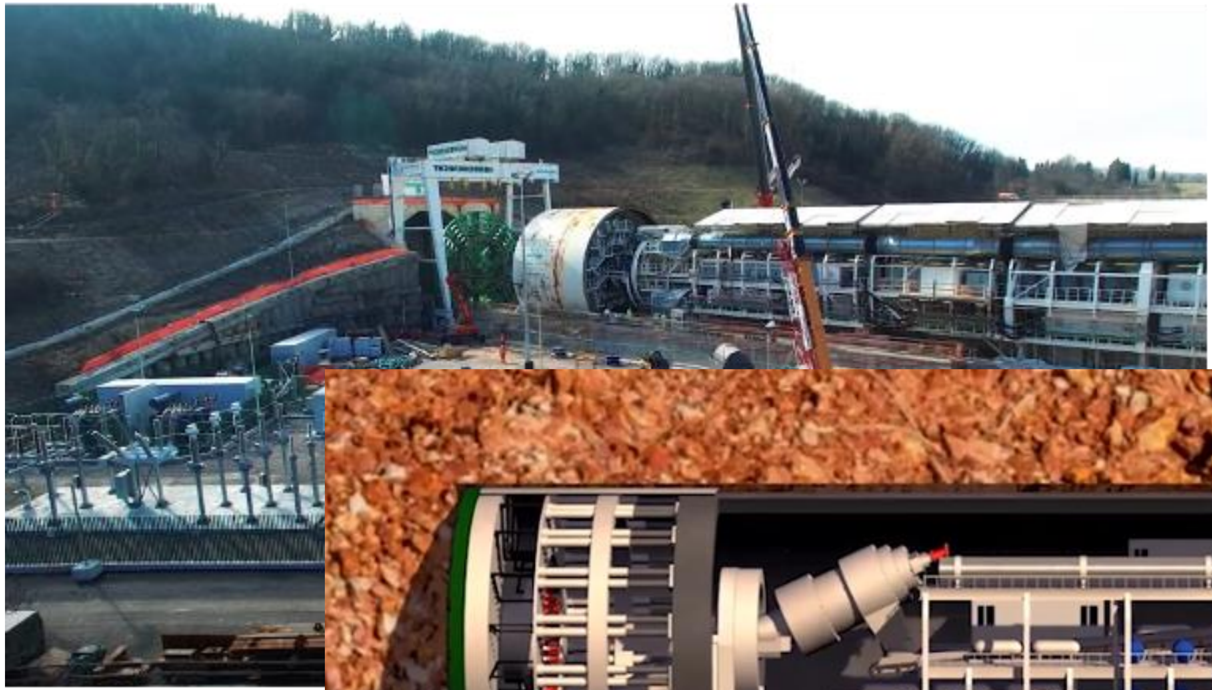
Collider	NLC	CLIC	ILC	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
Luminosity [x10^{34}]	0.6	1.5	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Length [km]	23.8	11.4	20.5 (31)	8	8
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	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

State of the Art Tunnel Construction

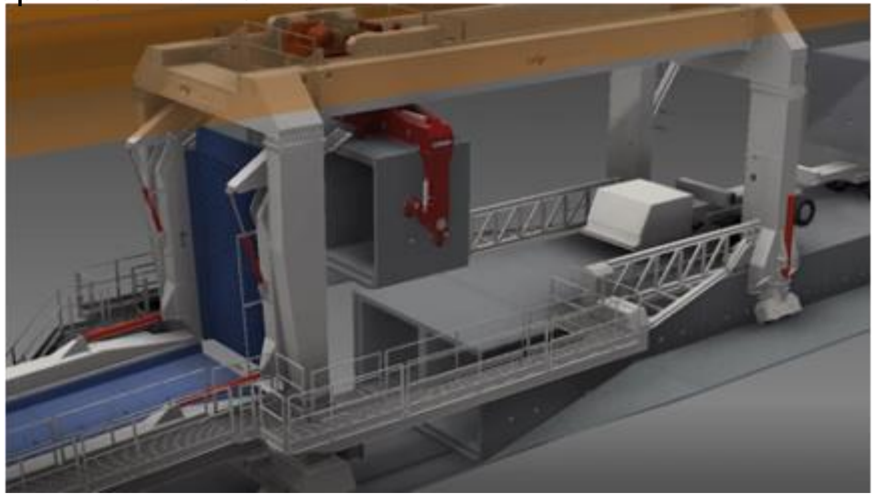
Workshop!

Santa Lucia 8 km Tunnel – 16 m diameter boring machine – 3 yrs

Pre-fab concrete lining and service tunnel during excavation



Drop-In Service Tunnel



Tunnel Lining

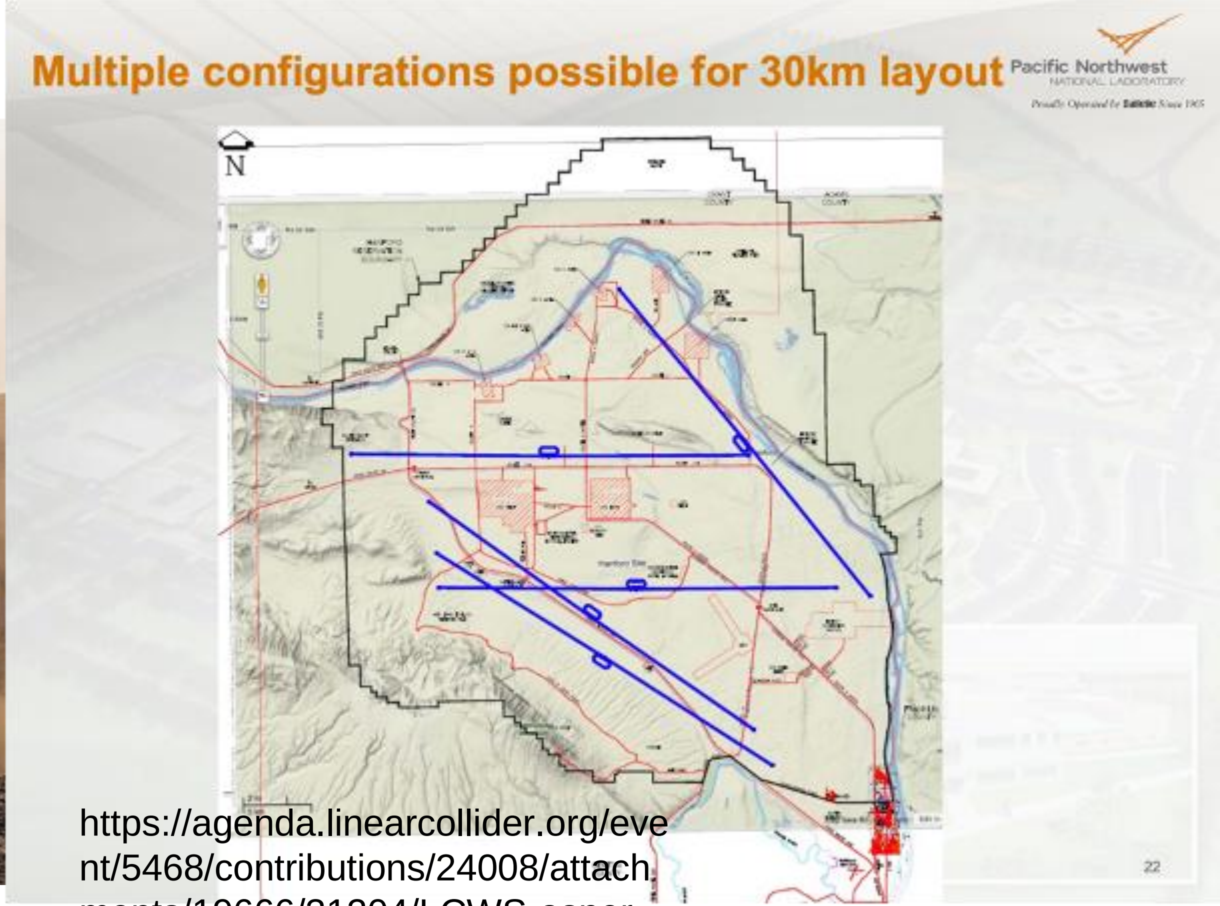
Cut and Cover Construction

Workshop!

At 8 km surface site becomes a possibility – limited locations could implement an energy upgrade

Could have significant cost / construction timeline impact

Was explored in the context of ILC



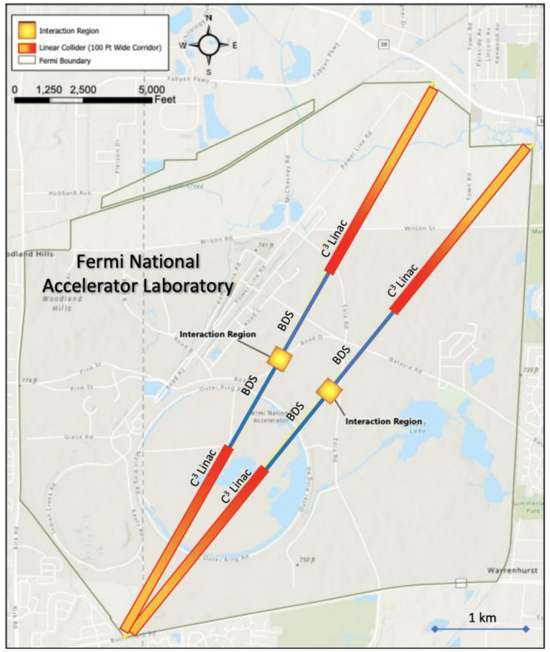
https://agenda.linearcollider.org/event/5468/contributions/24008/attachments/19666/31204/LCWS-asner-v2.pdf

Civil Construction and Siting

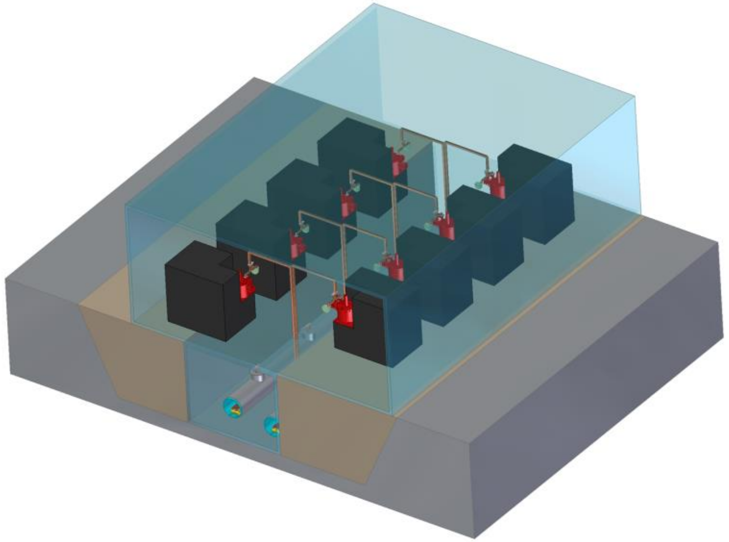
- Compact footprint <8 km for 550 GeV allows for many siting options
- Evaluating both underground and surface sites
  - Underground – less constraints on energy upgrade
  - Surface – lower cost and faster to first physics

National Lab and Green Field are Possibilities

Fermilab Site Filler

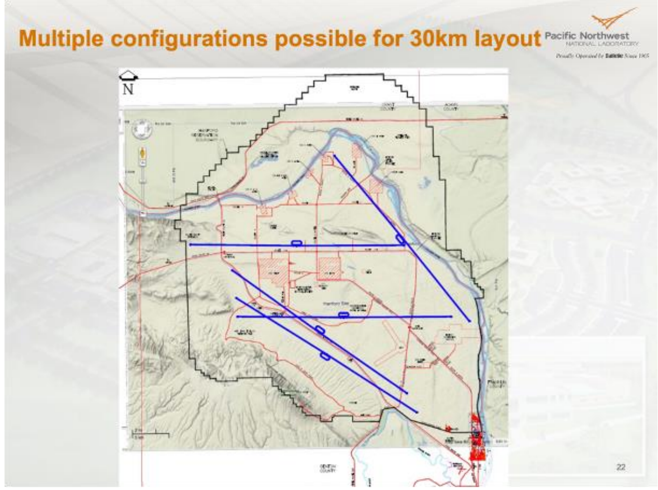


Surface-Site Mockup (Tunnel in White Paper)



- Rapid Excavation / Parallel Installation
- No Vertical Shafts

Hanford Site



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

Using established collider designs to inform initial parameters

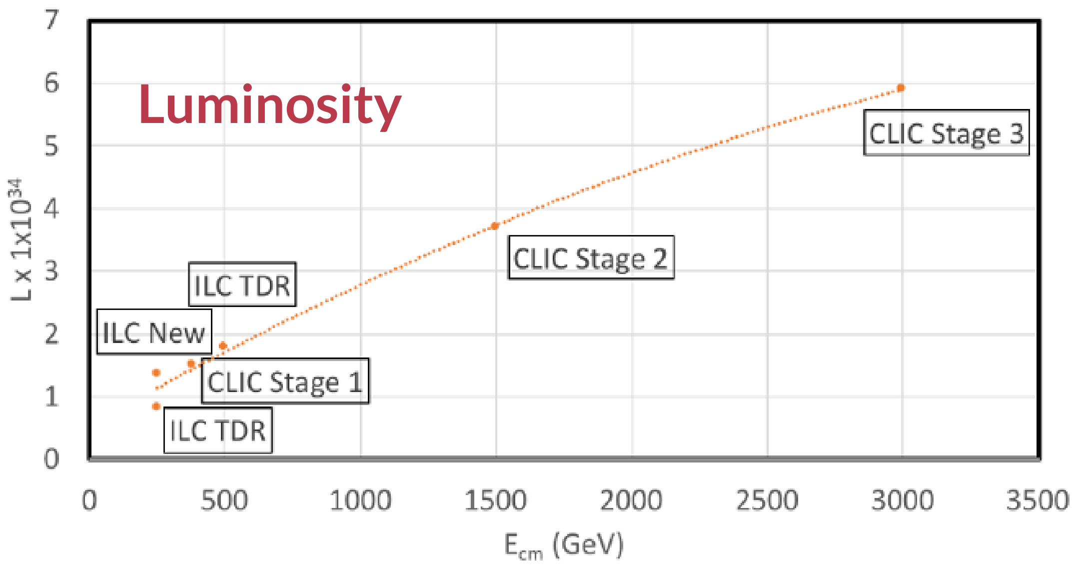
Quantifying impact of wakes requires detailed studies

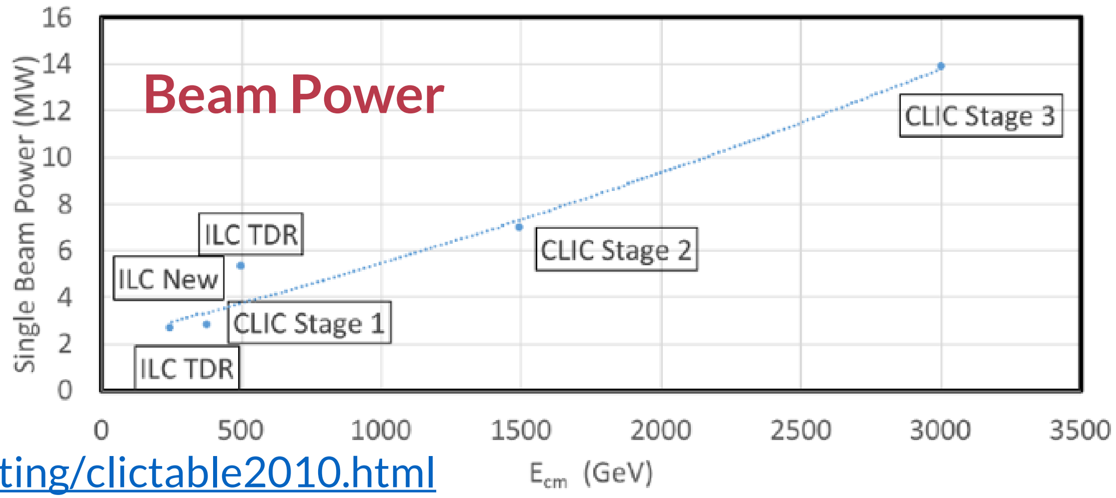
- Most important terms – aperture, bunch charge (and their scaling with frequency)

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	133/75



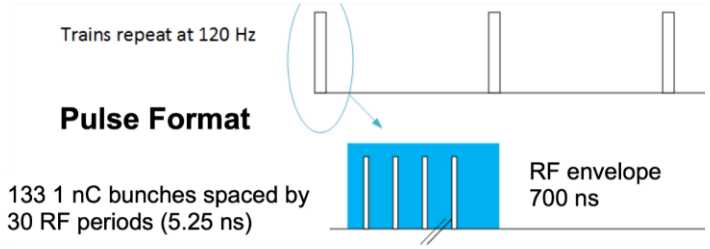


SLAC

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

NLC, ZDR Tbl. 1.3,8.3

Power Consumption and Sustainability



Temperature (K)	77
Beam Loading (%)	45
Gradient (MeV/m)	70
Flat Top Pulse Length (μs)	0.7
Cryogenic Load (MW)	9
Main Linac Electrical Load (MW)	100
Site Power (MW)	~150

Compatibility with Renewables Cryogenic Fluid Energy Storage

Highview Power

Intermittent and variable power production from renewables mediated with commercial scale energy storage and power production

250 GeV CoM - Luminosity - $1.3\text{x}10^{34}$

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 ML	MW	40
Electrical Power For Cryo-Cooler	MW	60
Accelerator Complex Power	MW	~50
Site Power	MW	~150