The Cool Copper Collider: An Advanced Concept for a Future Higgs Factory

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RAL Particle Physics Dept. Seminar
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SLAC NATIONAL ACCELERATOR LABORATORY

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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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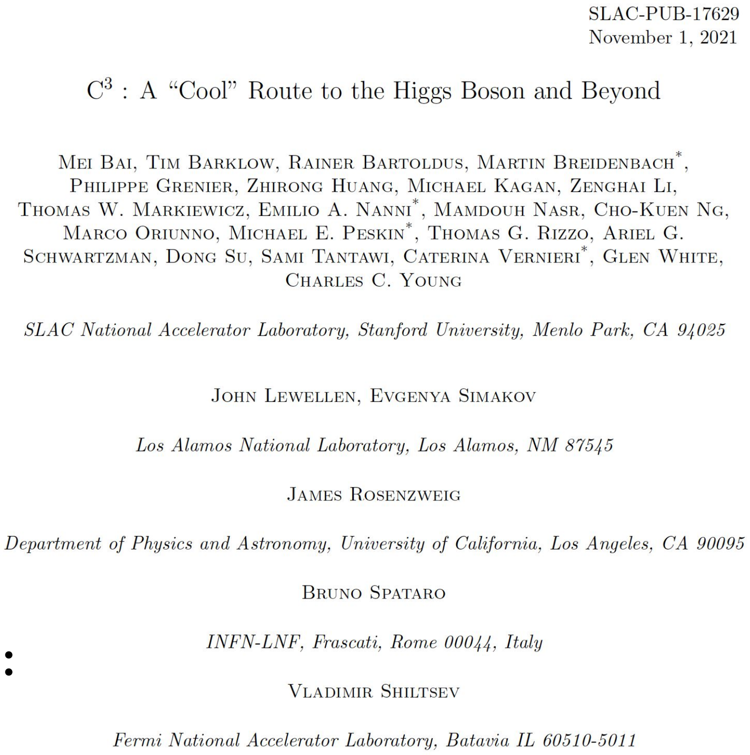

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C^3 : A “Cool” Route to the Higgs Boson and Beyond

Mei Bai, Tim Barklow, Rainer Bartoldus, Martin Breidenbach[*], Philippe Grenier, Zhirong Huang, Michael Kagan, Zenghai Li, Thomas W. Markiewicz, Emilio A. Nanni[*], Mamdouh Nasr, Cho-Kuen Ng, Marco Oriunno, Michael E. Peskin[*], Thomas G. Rizzo, Ariel G. Schwartzman, Dong Su, Sami Tantawi, Caterina Vernieri[*], Glen White, Charles C. Young

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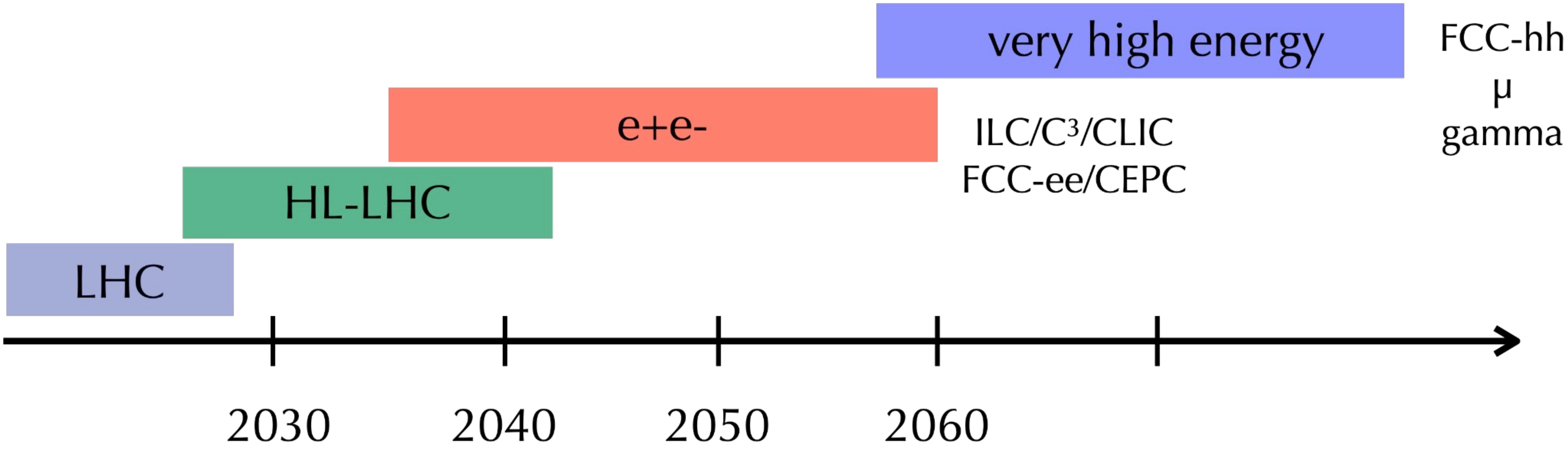
More Details Here (Follow, Endorse, Collaborate):

https://indico.slac.stanford.edu/event/7155/

What’s Next for the Energy Frontier?



very high energy

FCC-hh
μ
gamma

e+e-

ILC/C^3/CLIC
FCC-ee/CEPC

HL-LHC

LHC

2030 2040 2050 2060

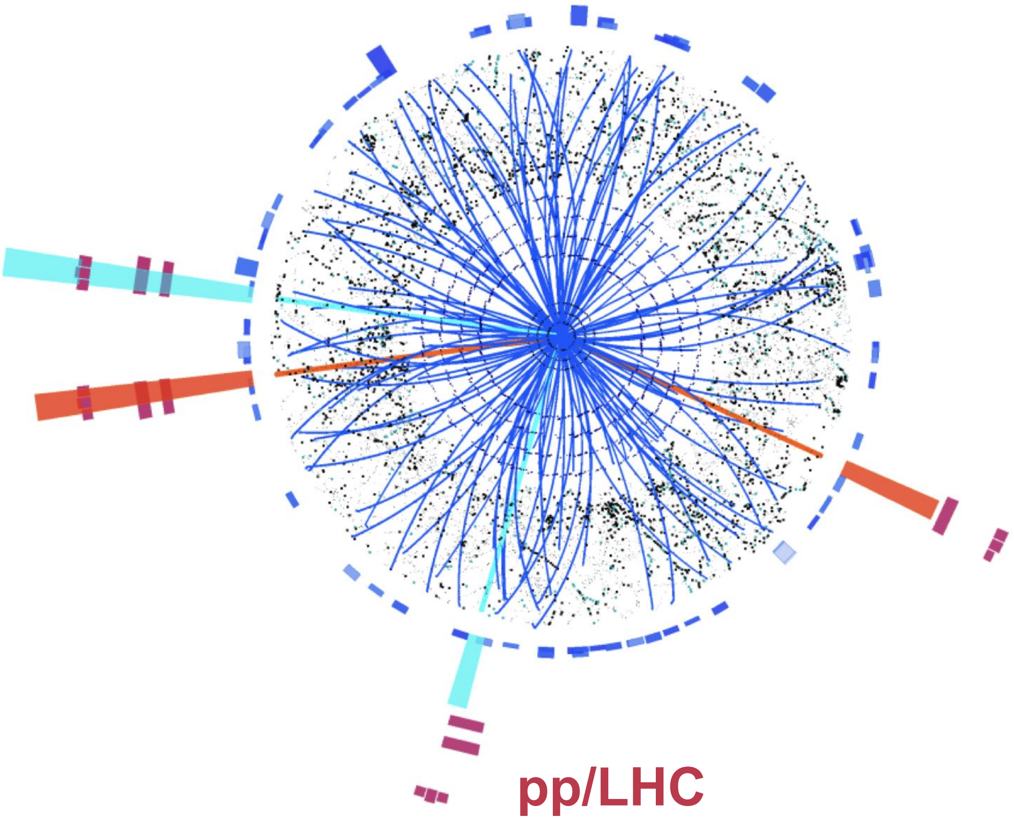
Wish list beyond HL-LHC:

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

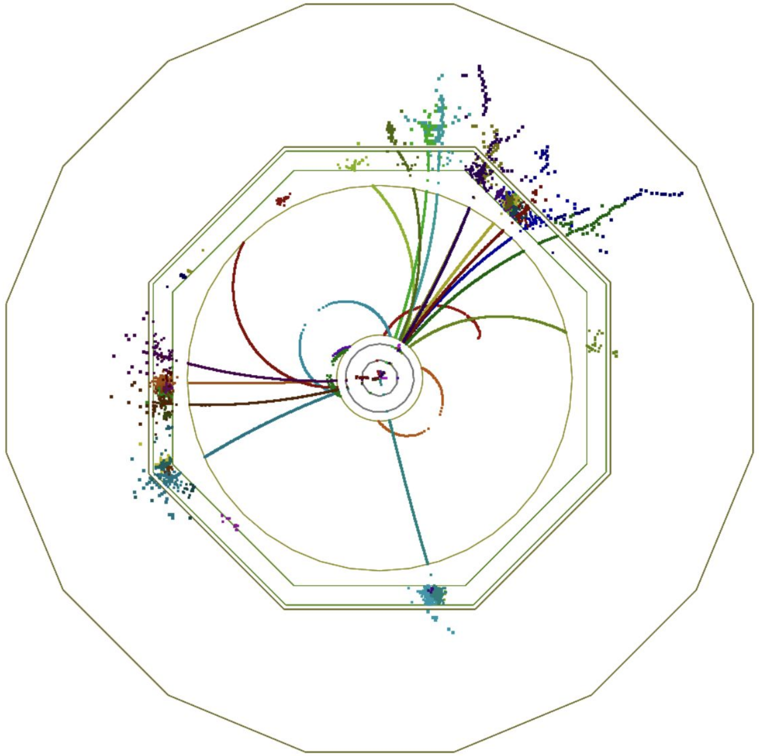
Why e^+e^-?

Initial state well defined & polarization ⟹ High-precision measurements

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



pp/LHC



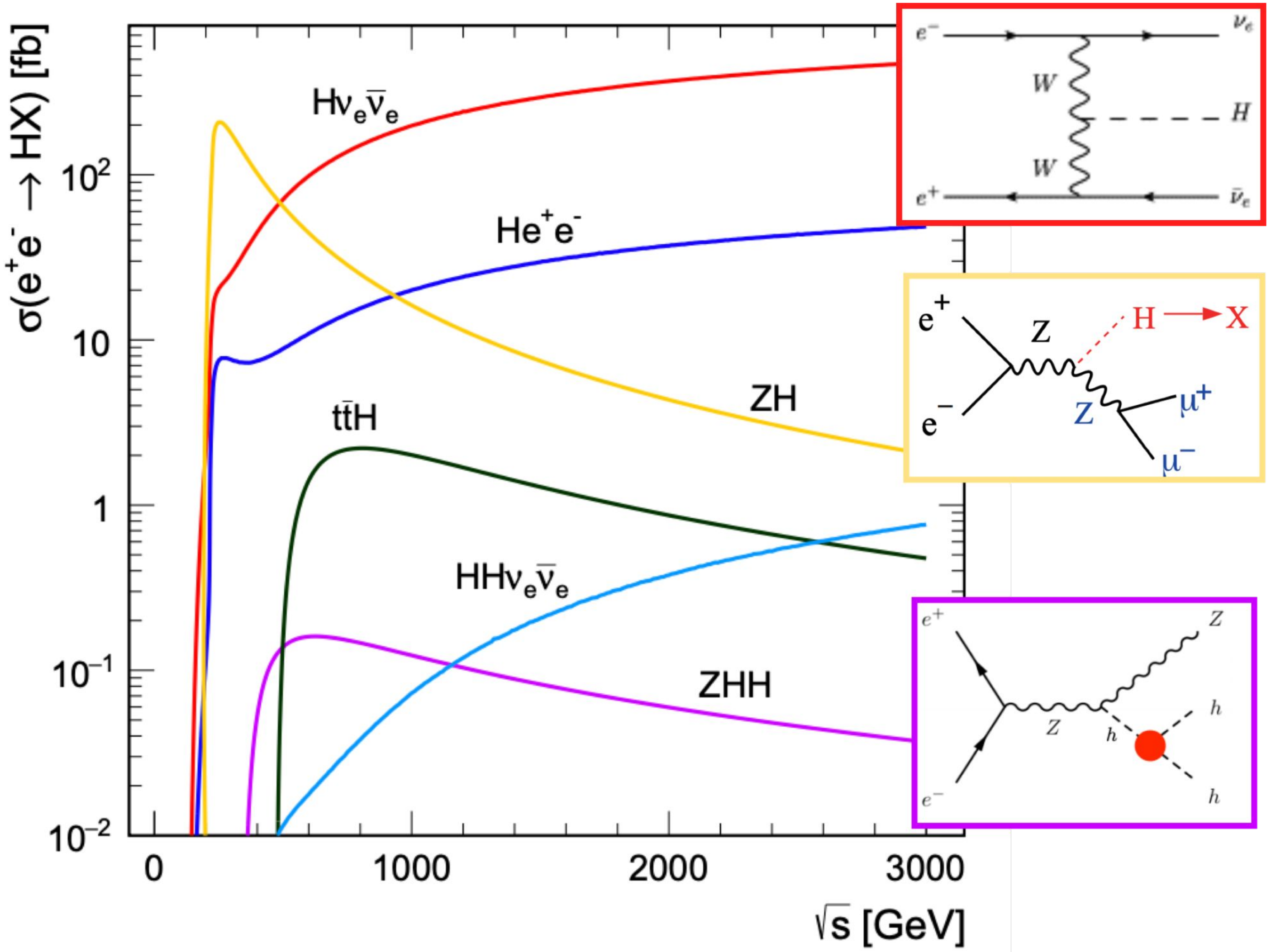
e^+e^-

Higgs Production at e^+e^-

ZH is dominant at **250 GeV**

Above **500 GeV**

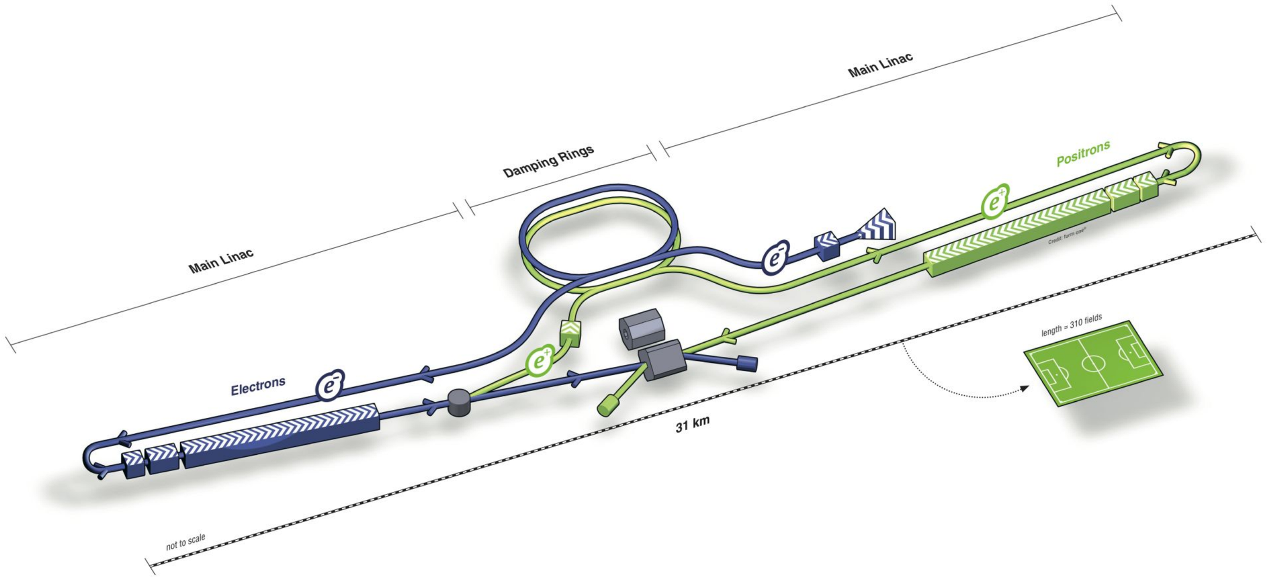
- Hvv dominates
- ttH opens up
- HH production accessible with ZHH



Linear vs. Circular

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

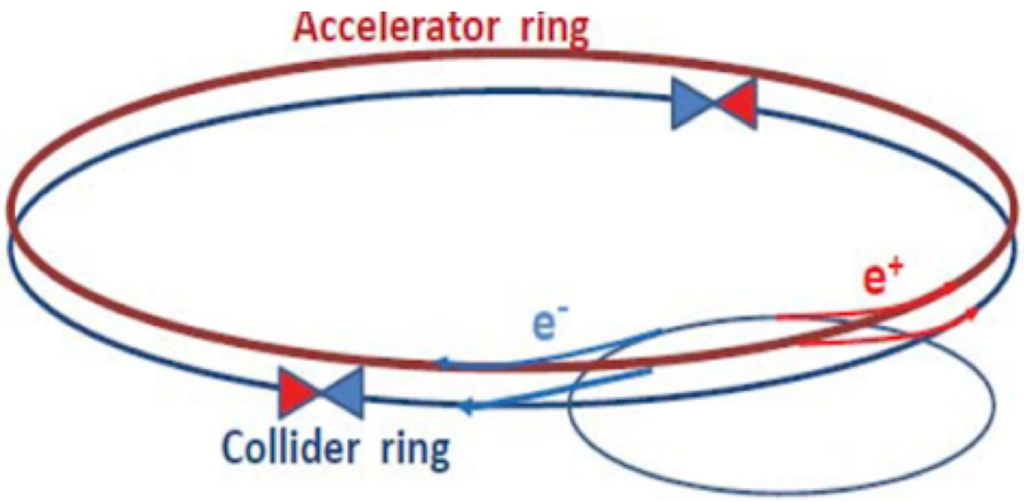
- Reach higher energies (~TeV), and can use polarized beams
- Relatively low radiation
- Collisions in bunch trains



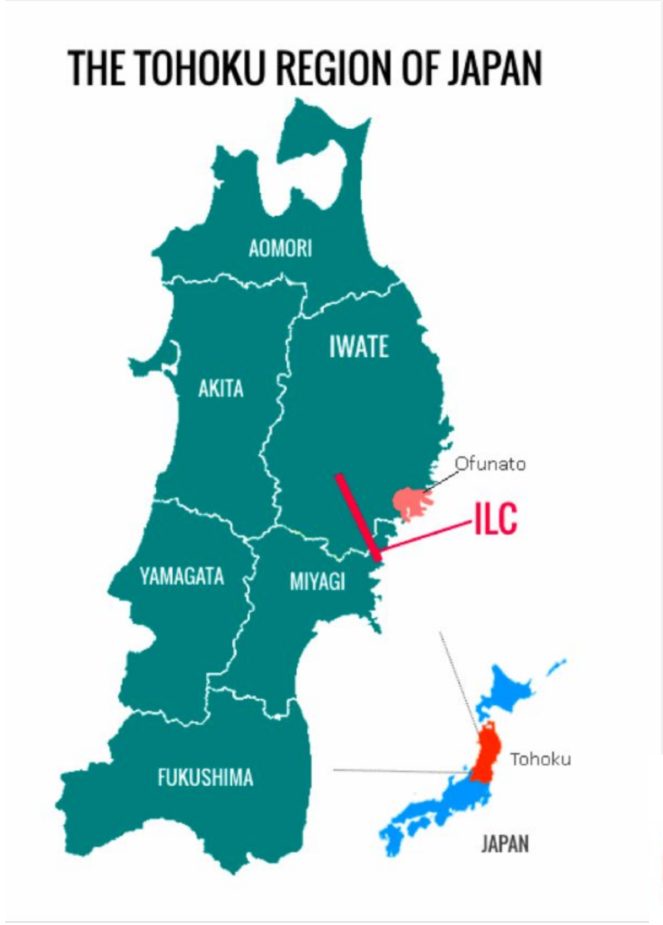
Credit: form one®

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

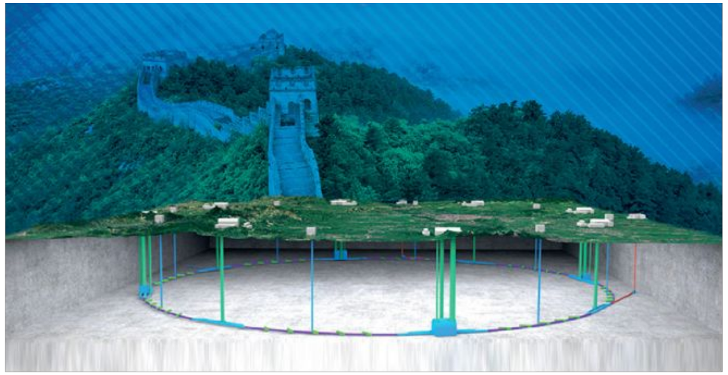
- Highest luminosity collider at Z/WW/ZH
- limited by synchrotron radiation above 350 – 400 GeV
- Beam continues to circulate after collision



Various Proposals

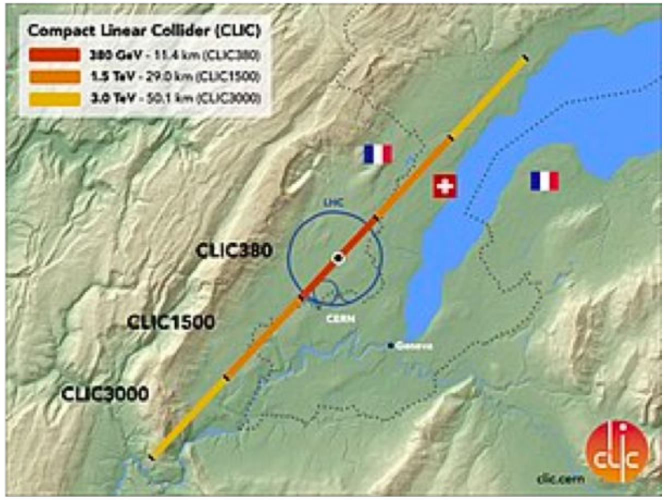


ILC
250/500 GeV

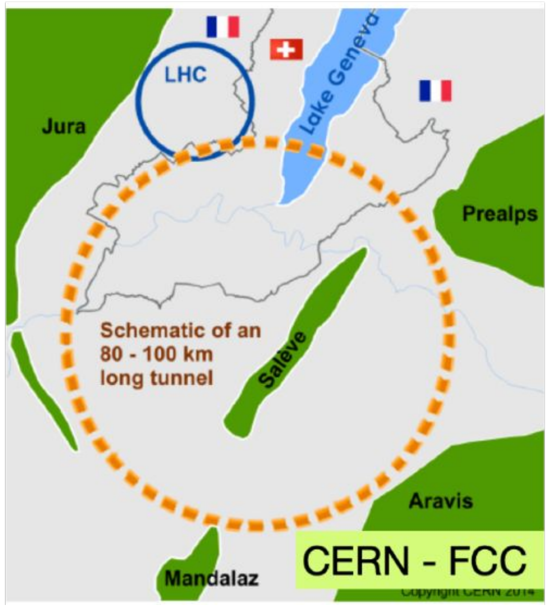


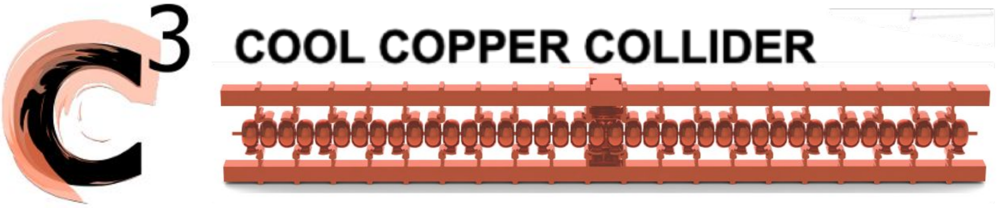
CEPC
240 GeV

CLIC 380/1000/3000 GeV



FCC-ee
240/365 GeV



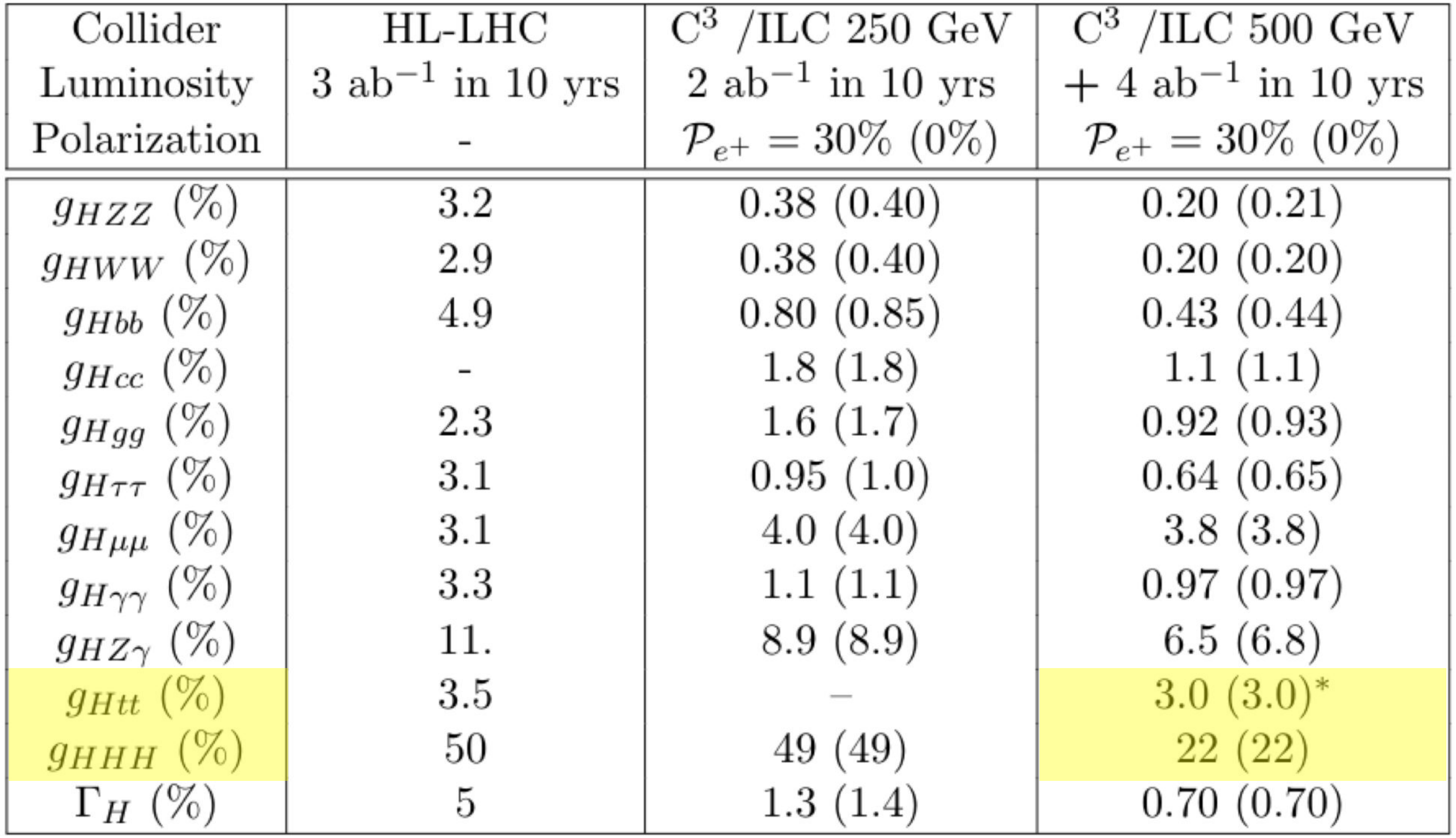


250/550 GeV
… > TeV

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



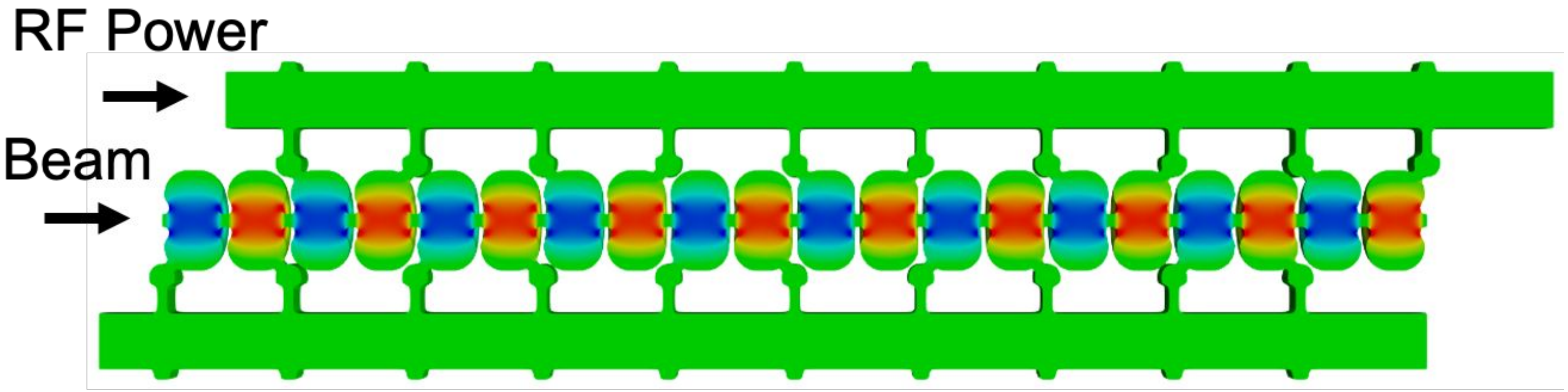
Collider	HL-LHC	C^3 /ILC 250 GeV	C^3 /ILC 500 GeV
Luminosity	3 ab^{-1} in 10 yrs	2 ab^{-1} in 10 yrs	+ 4 ab^{-1} in 10 yrs
Polarization	-	$\mathcal{P}_{e^+} = 30\%$ (0%)	$\mathcal{P}_{e^+} = 30\%$ (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80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

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

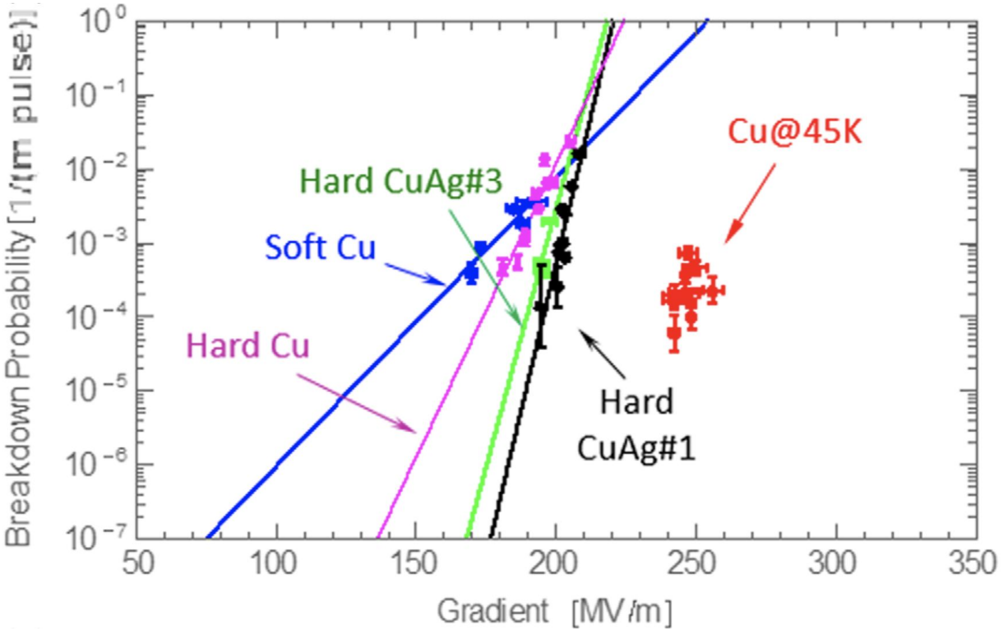
- Material strength is key factor
- Impact of high fields for a high brightness injector may eliminate need for one damping ring

Operation at 77 K with liquid nitrogen is simple and practical

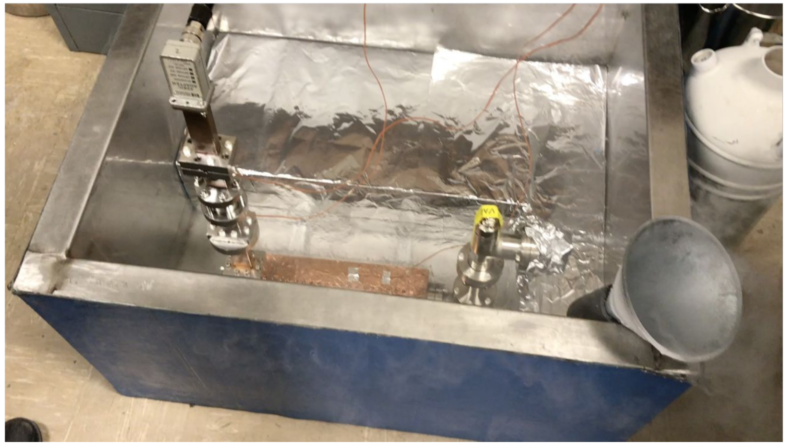
- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency

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

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



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



Cool Copper Collider

C^3 is based on a new rf technology

- Dramatically improving efficiency and breakdown rate

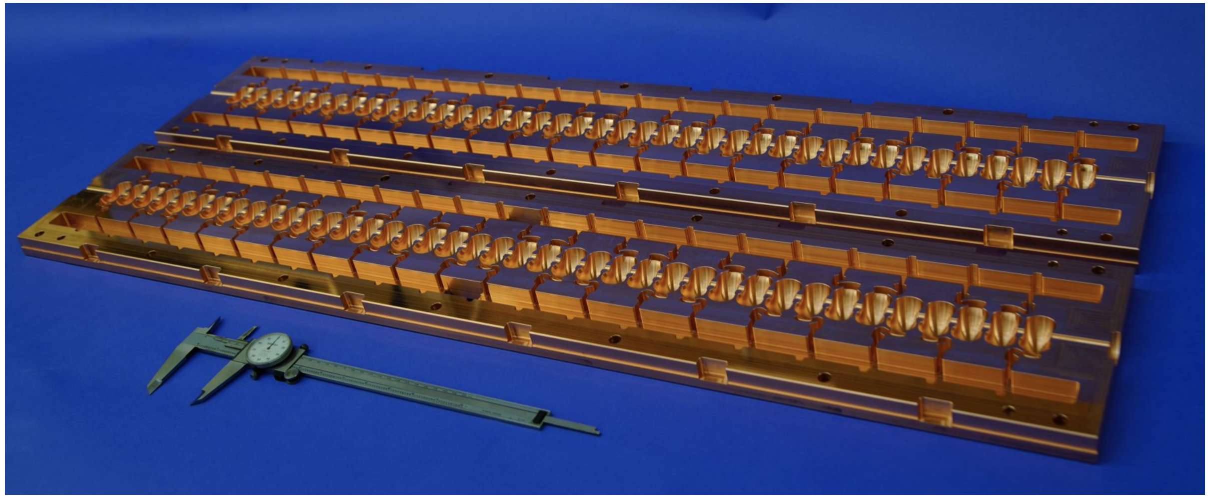
Distributed power to each cavity from a common RF manifold

Operation at cryogenic temperatures (LN$_2$ ~80 K)

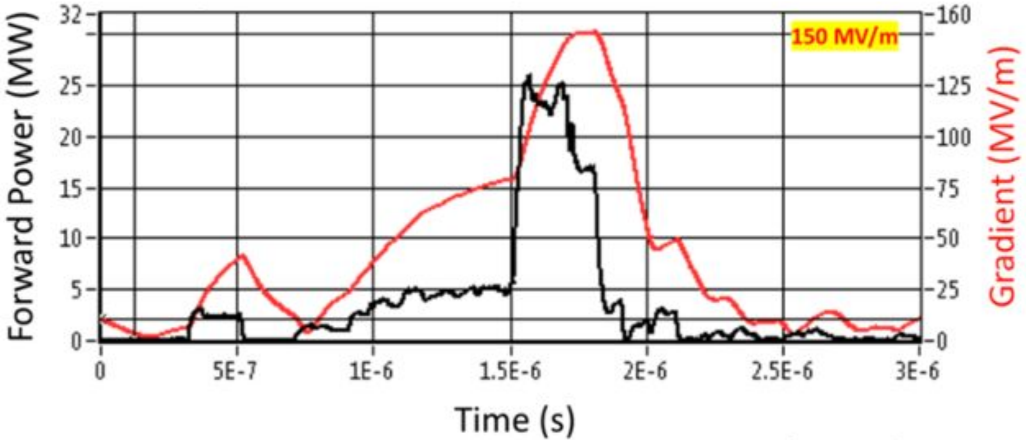
Robust operations at high gradient: 120 MeV/m

Scalable to multi-TeV operation

C^3 Prototype One Meter Structure

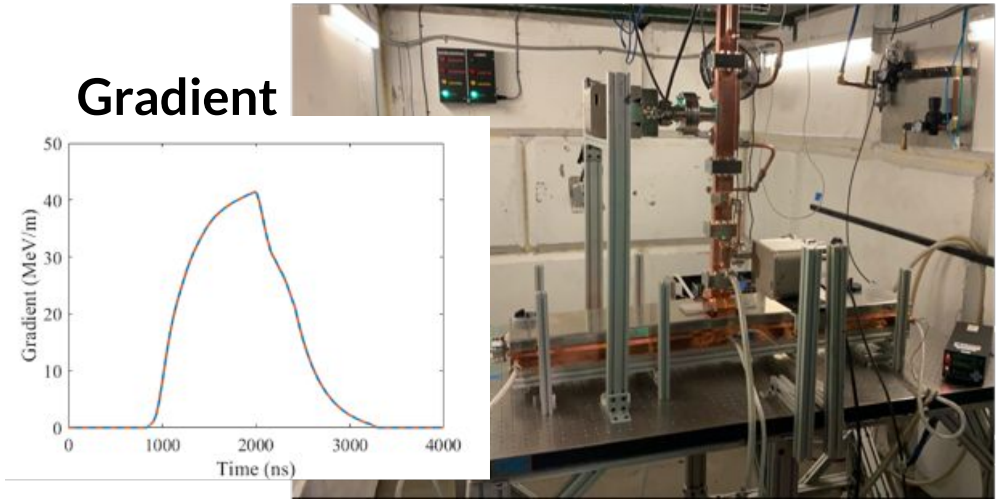


High Gradient Operation at 150 MV/m



Cryogenic Operation at X-band

High power Test at Radiabeam



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

Using established collider designs to inform initial parameters

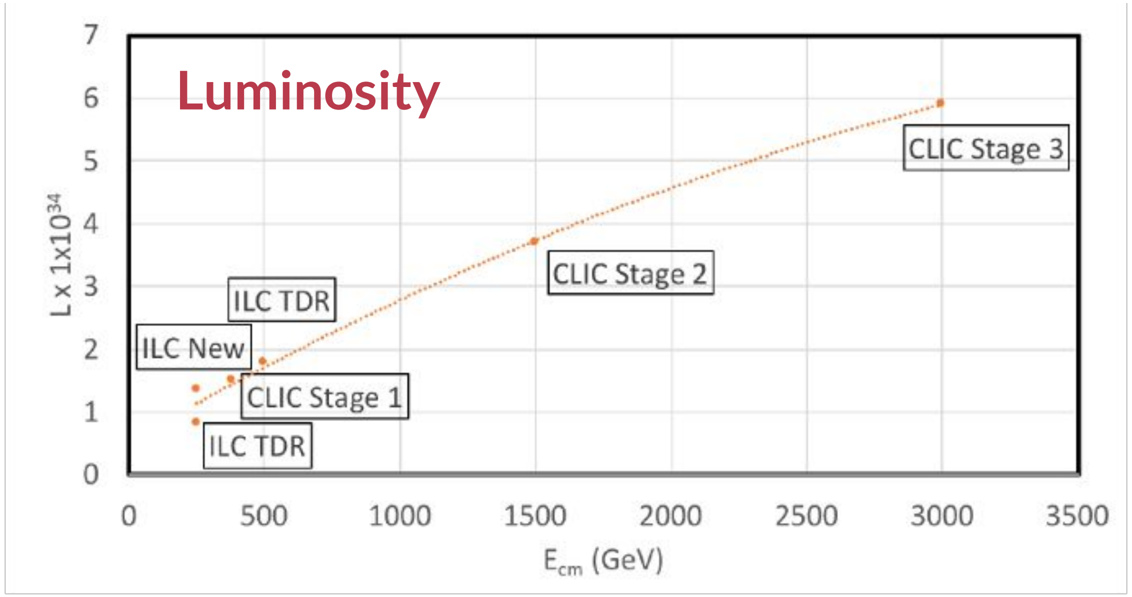
Quantifying impact of wakes requires detailed studies

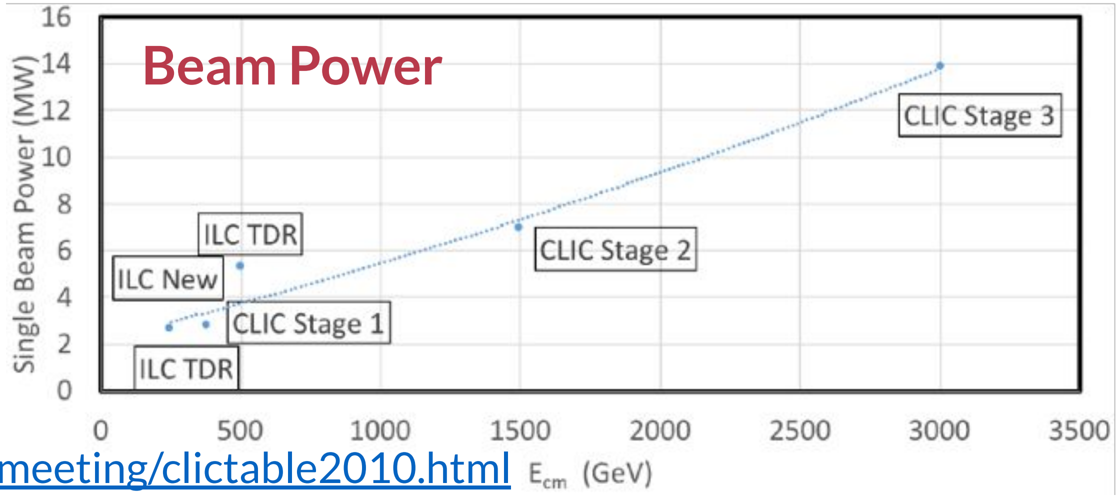
- Most important terms – aperture, bunch charge (and their scaling with frequency)

Target initial stage design at 250 GeV CoM

- 2 MW single beam power

Machine	CLIC	NLC	C^3
Freq (GHz)	12.0	11.4	5.7
a (mm)	2.75	3.9	2.6
Charge (nC)	0.6	1.4	1
Spacing (λ)	6	16	30/20
# of bunches	312	90	133/75





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

NLC, ZDR Tbl. 1.3,8.3

Accelerator Complex

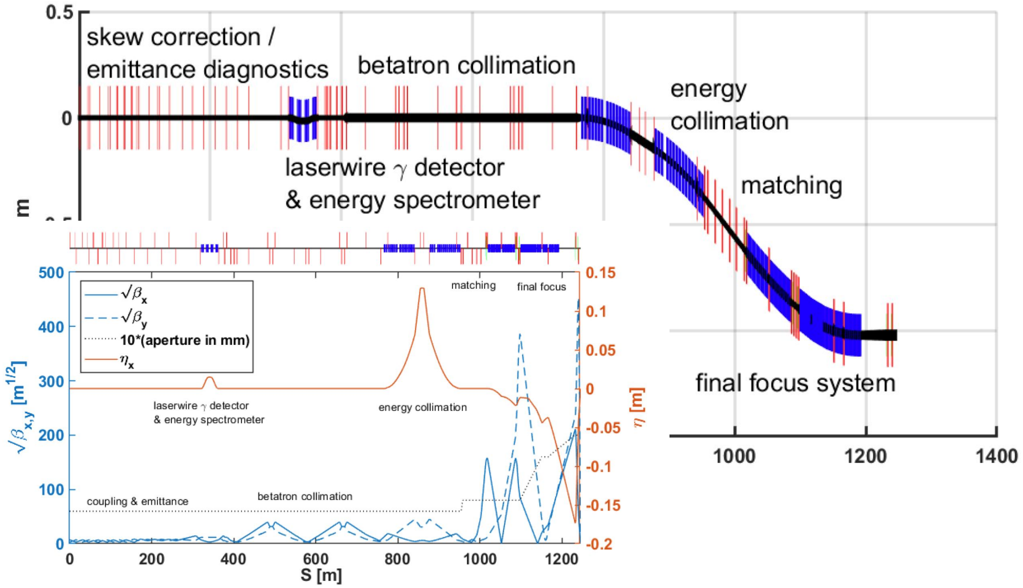
8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

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

Large portions of accelerator complex are compatible between LC technologies

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

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



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

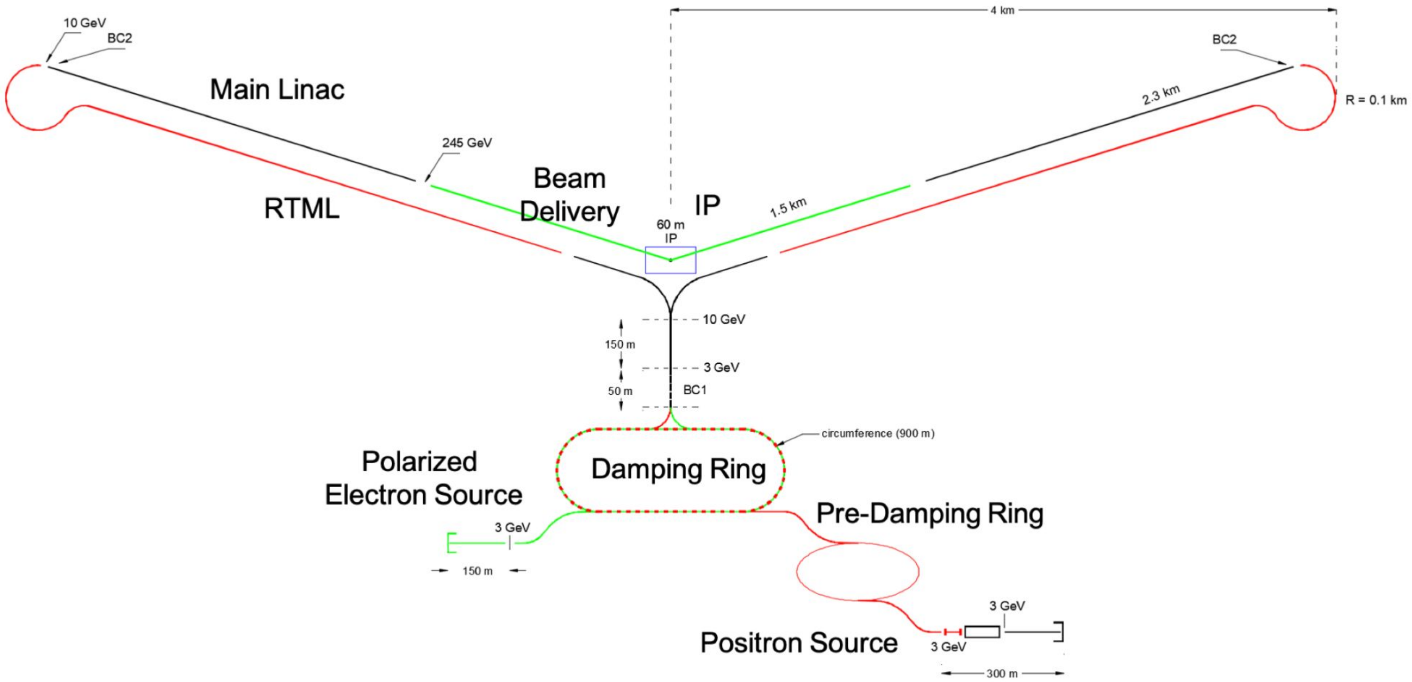
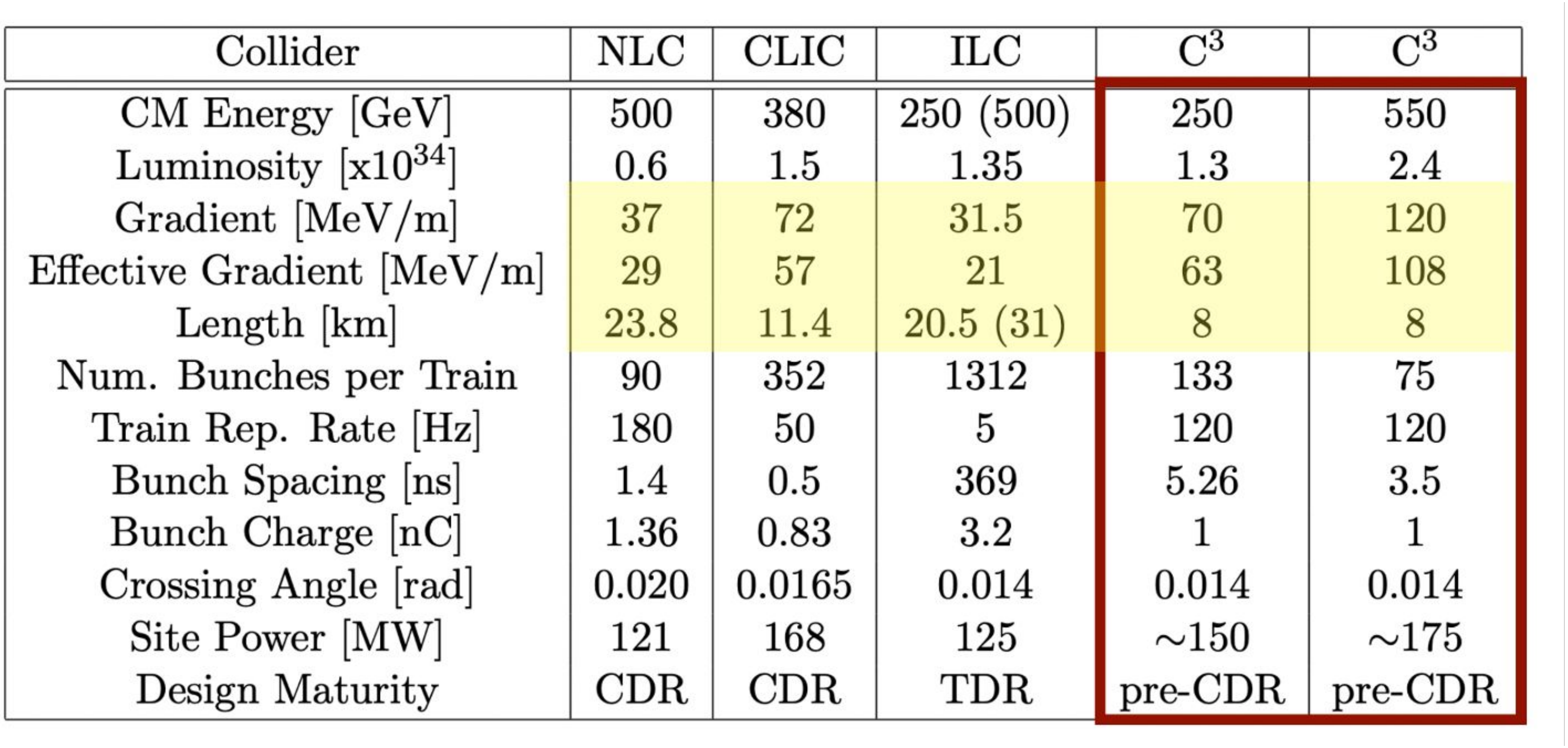


Table of Parameters

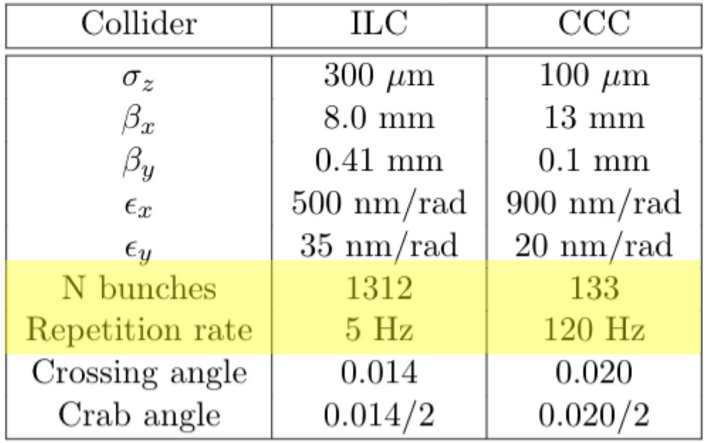


Collider	NLC	CLIC	ILC	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
Luminosity [x10^{34}]	0.6	1.5	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Length [km]	23.8	11.4	20.5 (31)	8	8
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5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

Beam Format and Detector Design Requirements

ILC timing structure: Fraction of a percent duty cycle

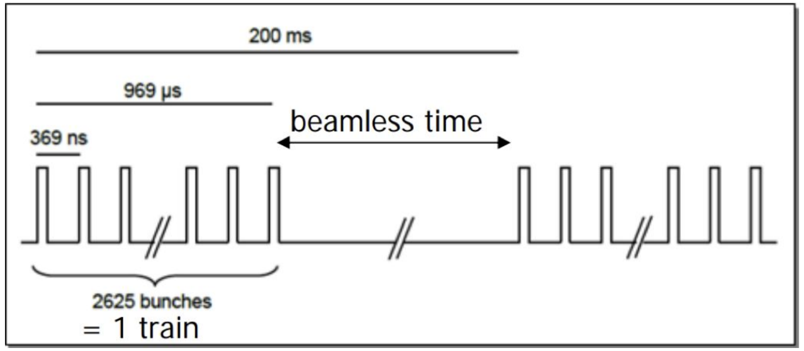
- **Power pulsing possible**, significantly reduce heat load
  - Factor of 50-100 power saving for FE analog power
- Tracking detectors **don't need active cooling**
  - Significantly reduction for the material budget
- **Triggerless readout** is the baseline



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

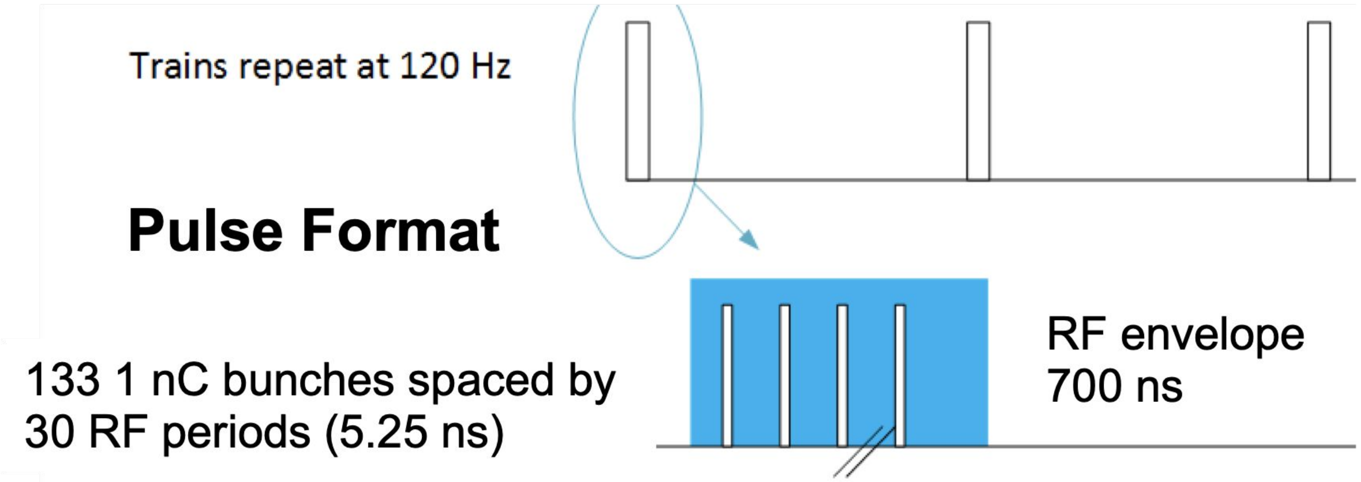
C^3 time structure is compatible with SiD-like detector overall design and ongoing optimizations

ILC timing structure



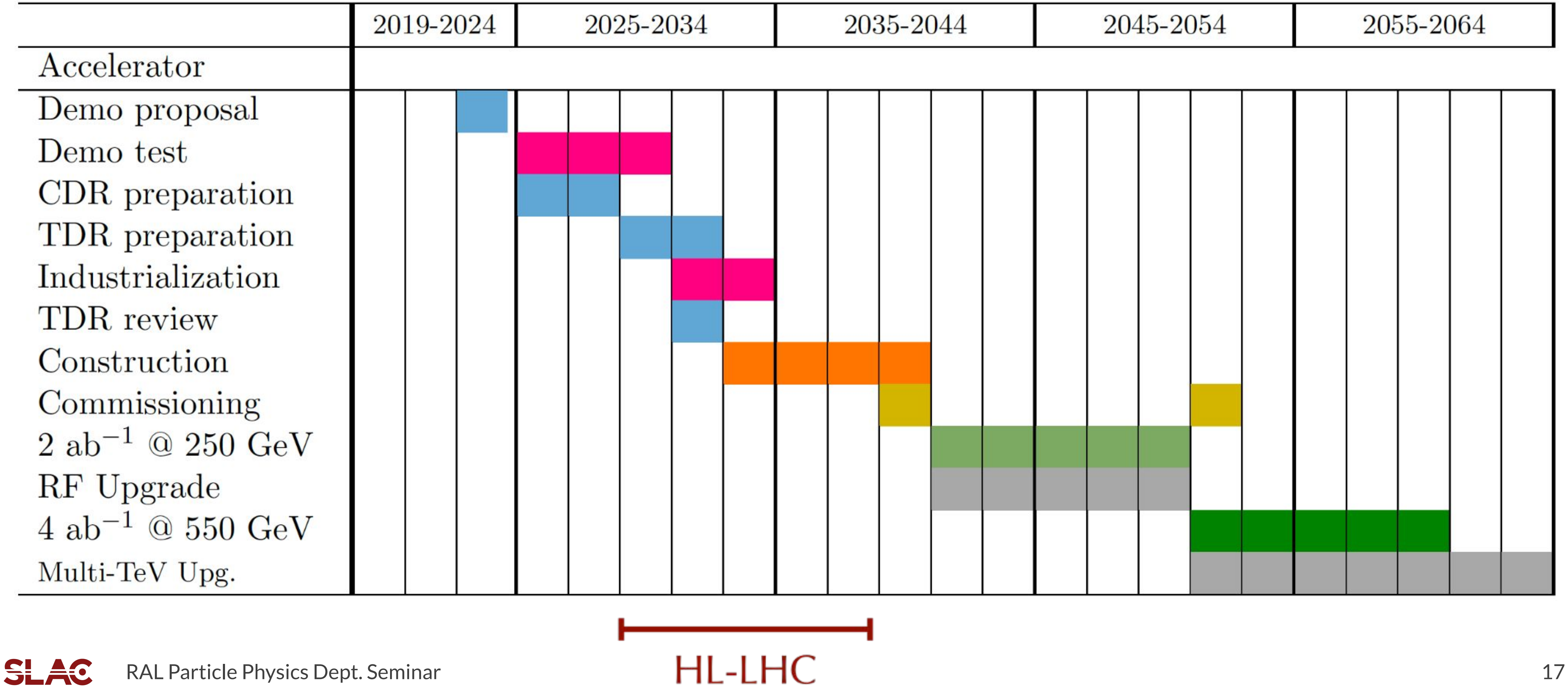
1 ms long bunch trains at 5 Hz
2820 bunches per train
308ns spacing

C^3 timing structure



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



	2019-2024			2025-2034					2035-2044					2045-2054					2055-2064				
Accelerator																							
Demo proposal			🟦																				
Demo test				🟥	🟥	🟥																	
CDR preparation				🟦	🟦																		
TDR preparation						🟦	🟦																
Industrialization							🟥	🟥															
TDR review							🟦																
Construction								🟧	🟧	🟧	🟧												
Commissioning											🟨						🟨						
2 ab^{-1} @ 250 GeV												🟩	🟩	🟩	🟩	🟩							
RF Upgrade												▨	▨	▨	▨	▨							
4 ab^{-1} @ 550 GeV																	🟩	🟩	🟩	🟩	🟩		
Multi-TeV Upg.																	▨	▨	▨	▨	▨	▨	▨

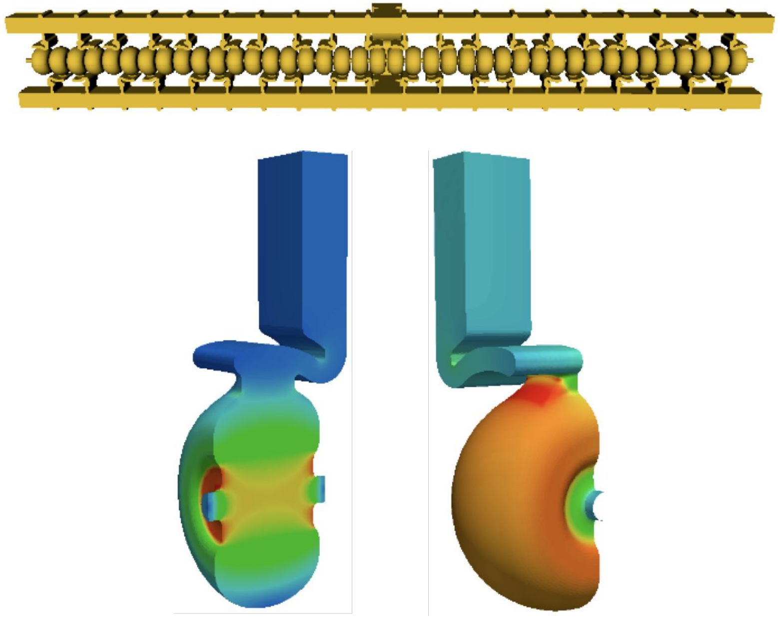
Ongoing Prototype Structure Development

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

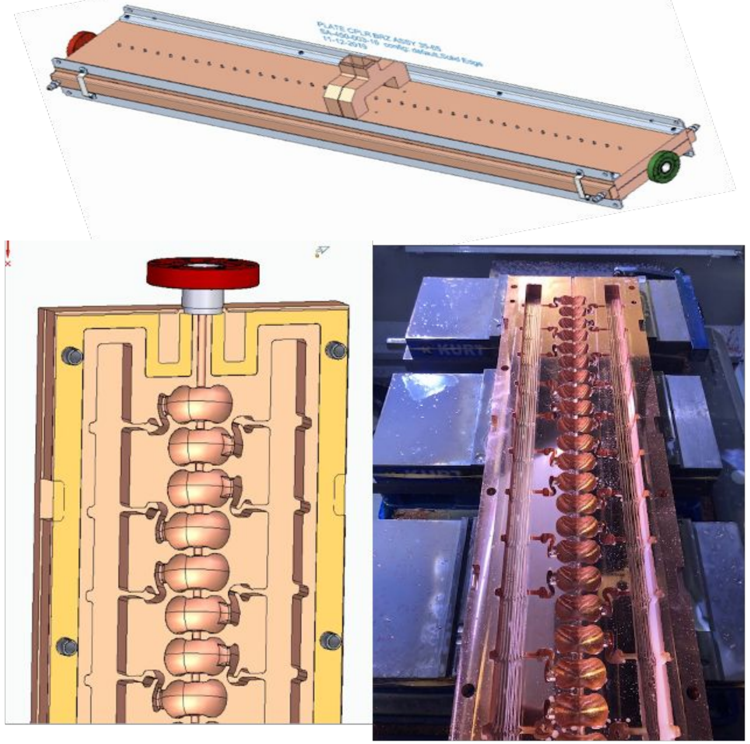
Main linac utilizes meter-scale accelerating structures, technology demonstration underway

Implement optimized rf cavity designs to control peak surface fields

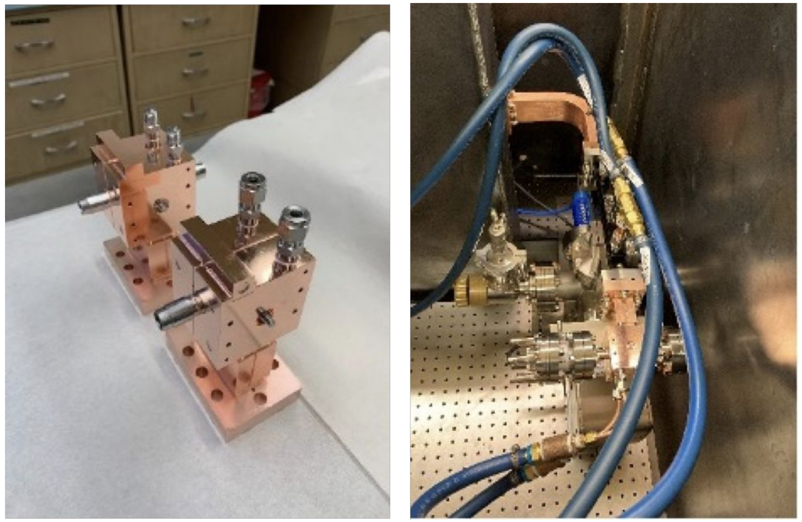
One meter (40-cell) C-band design with reduce peak E and H-field



Scaling fabrication techniques in length and including controlled gap



LANL Test of single cell SLAC C-band structure



Cryomodule Design and Alignment

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

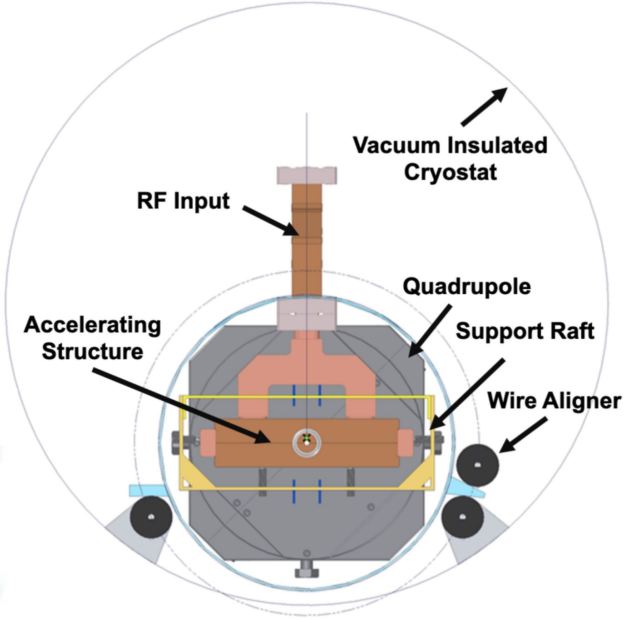
Main linac will require 5 micron structure alignment

- Combination of mechanical and beam based alignment

Pre-alignment warm, cold alignment by wire, followed by beam based

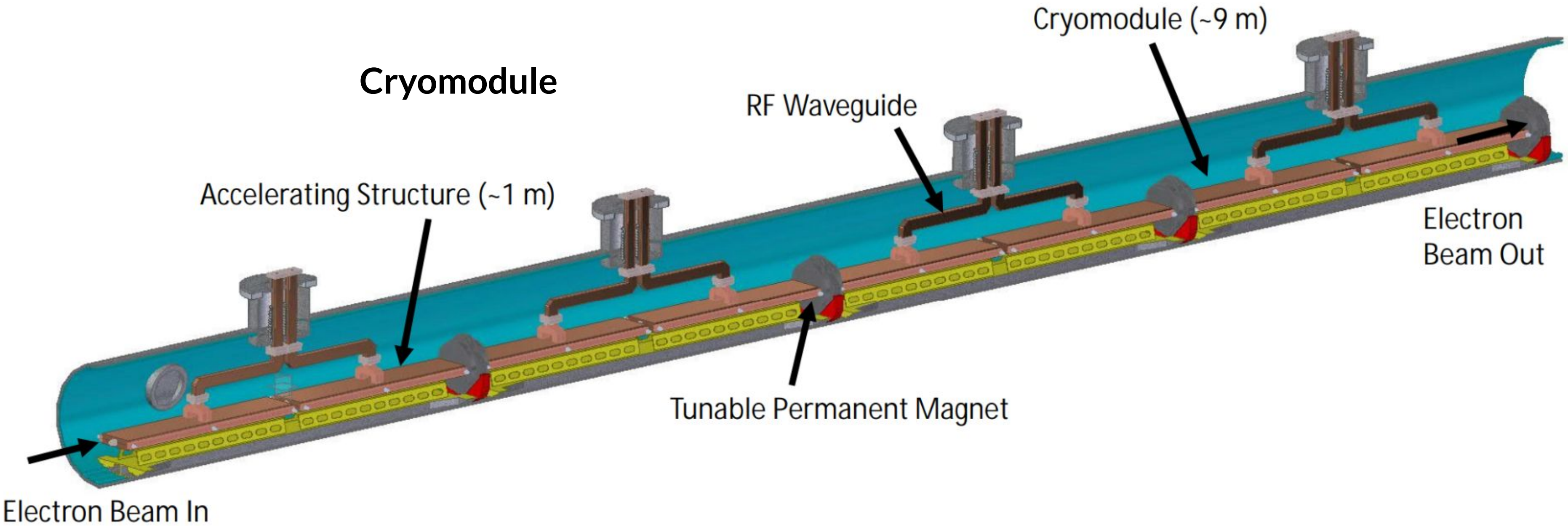
- Mechanical motor runs warm or cold – no motion during power failure
- Piezo for active alignment

Investigating support and assembly design



Cryomodule Cross Section

Cryomodule



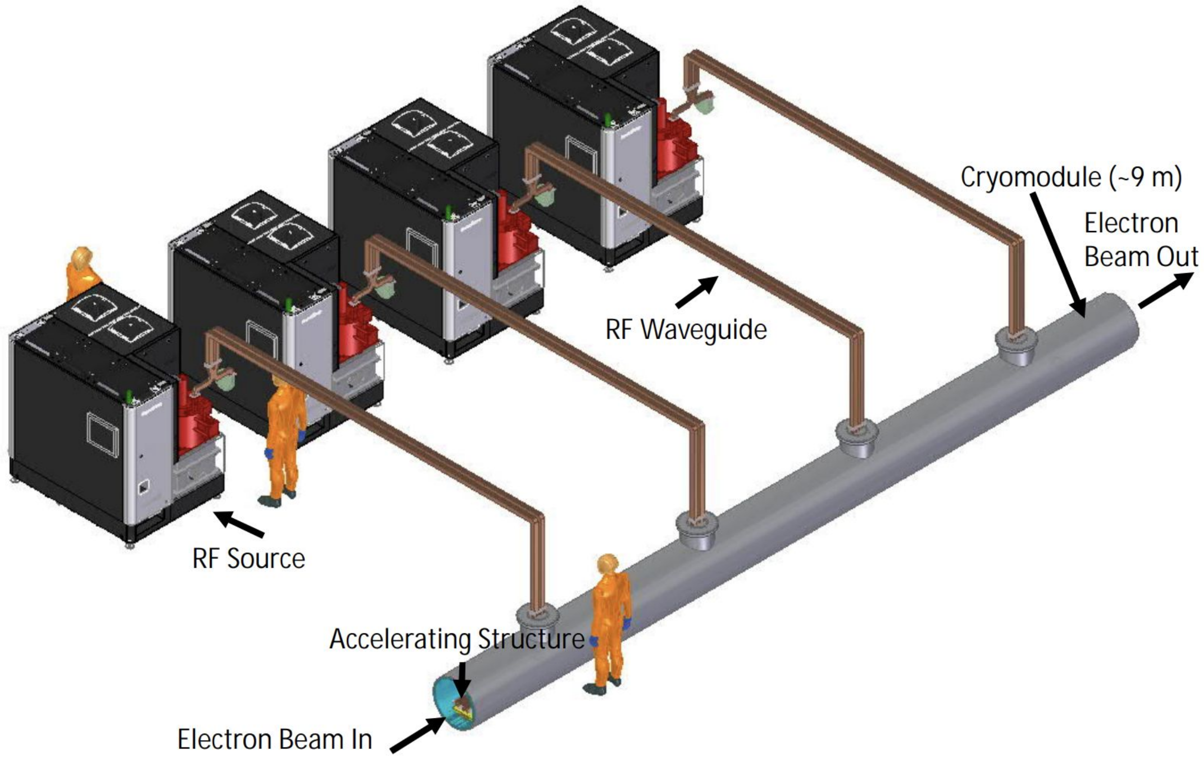
Tunnel Layout for Main Linac 250/550 GeV CoM

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

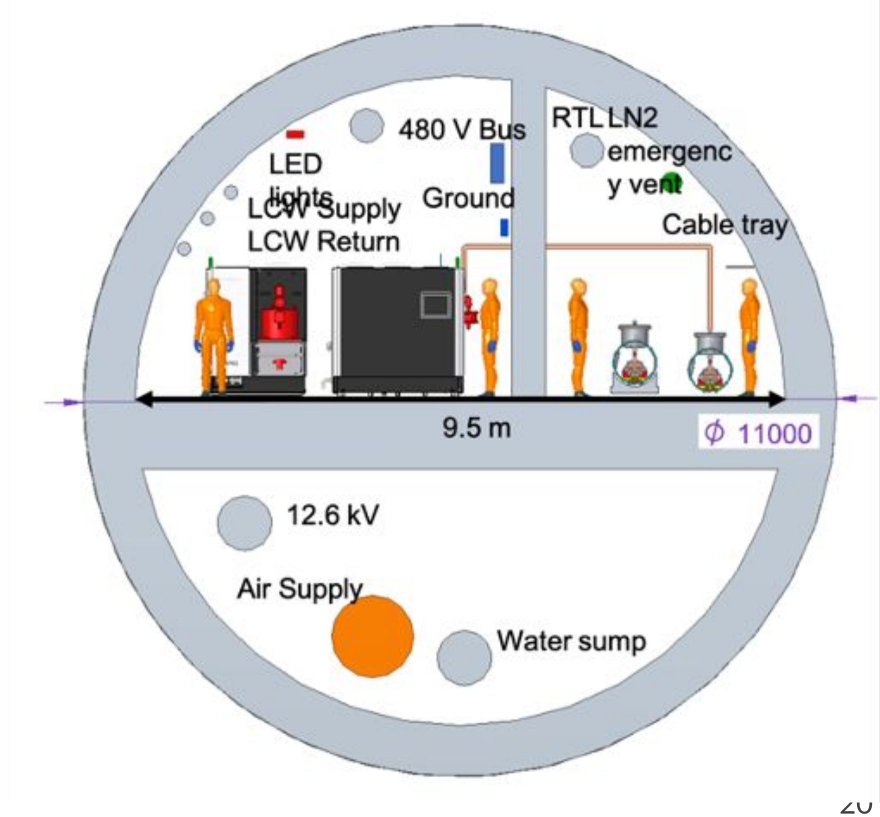
- Must minimize diameter to reduce cost and construction time

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

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



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

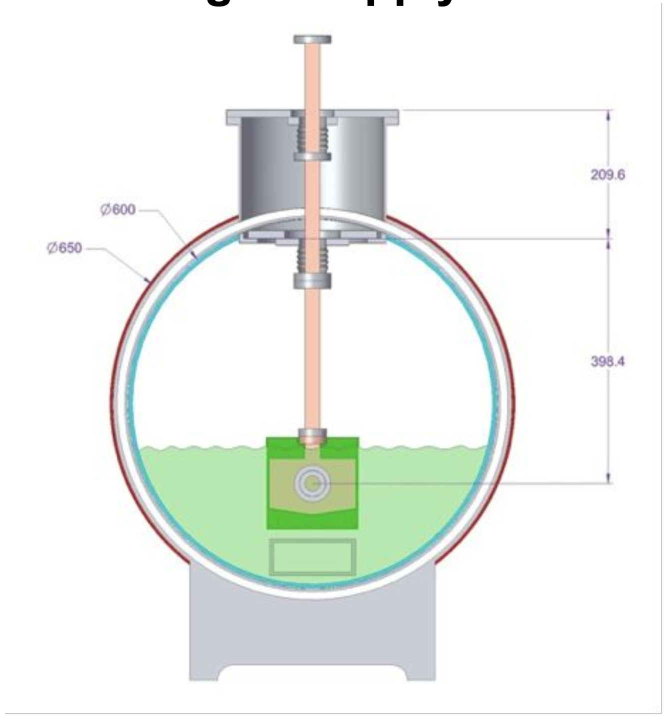


Cryomodule Design Scalable from 250 GeV to multi-TeV

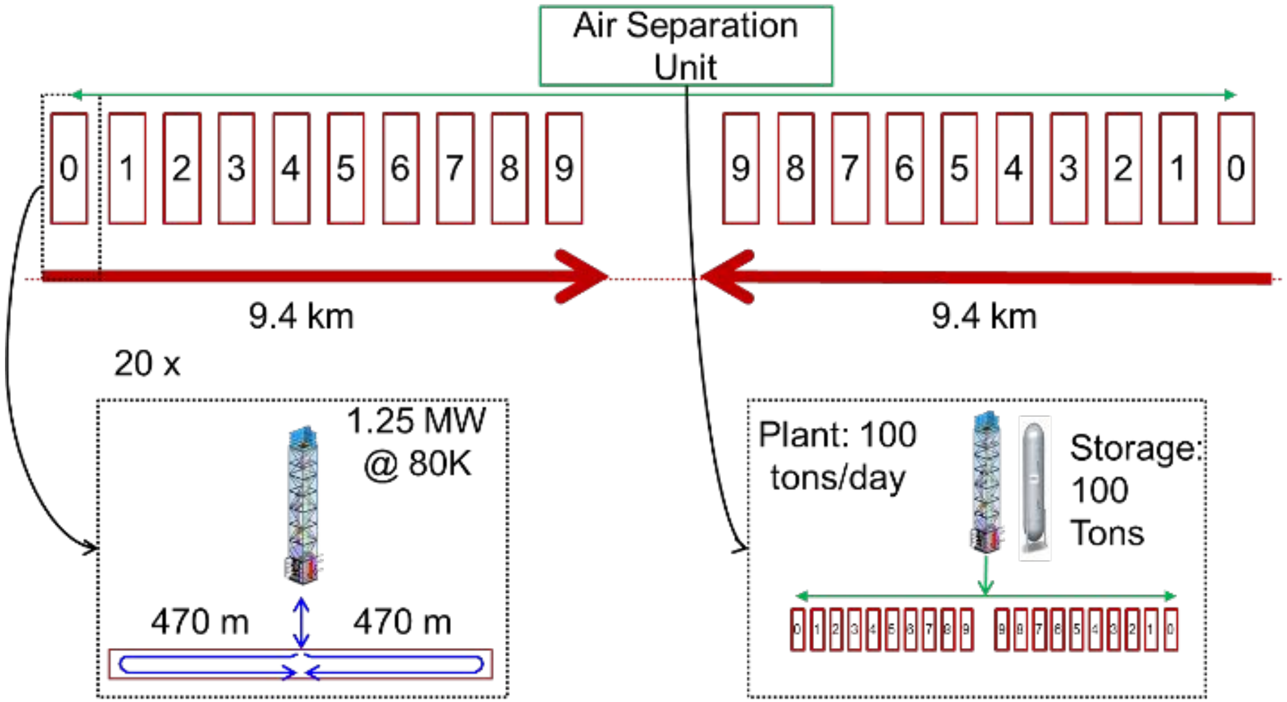
X-band structure demonstrated full average power over short length (0.25 m)

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



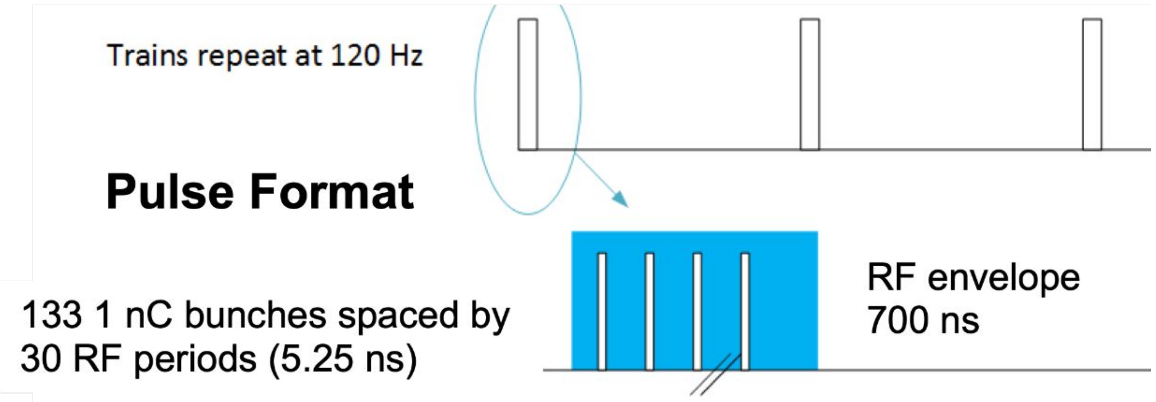
Main Linac Power Consumption

250 GeV CoM

Luminosity - 1.3×10^{34}

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

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



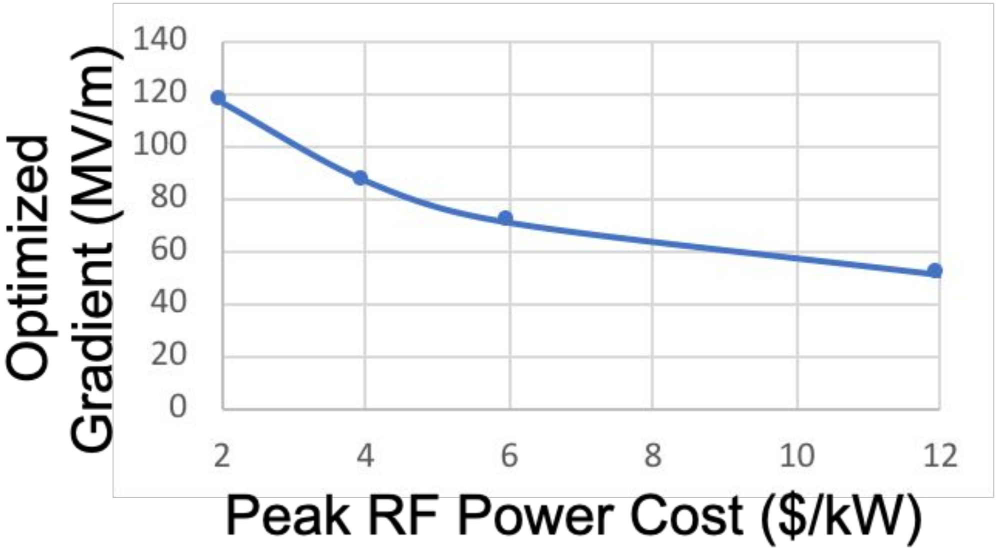
RF Source R&D Over the Timescale of the Next P5

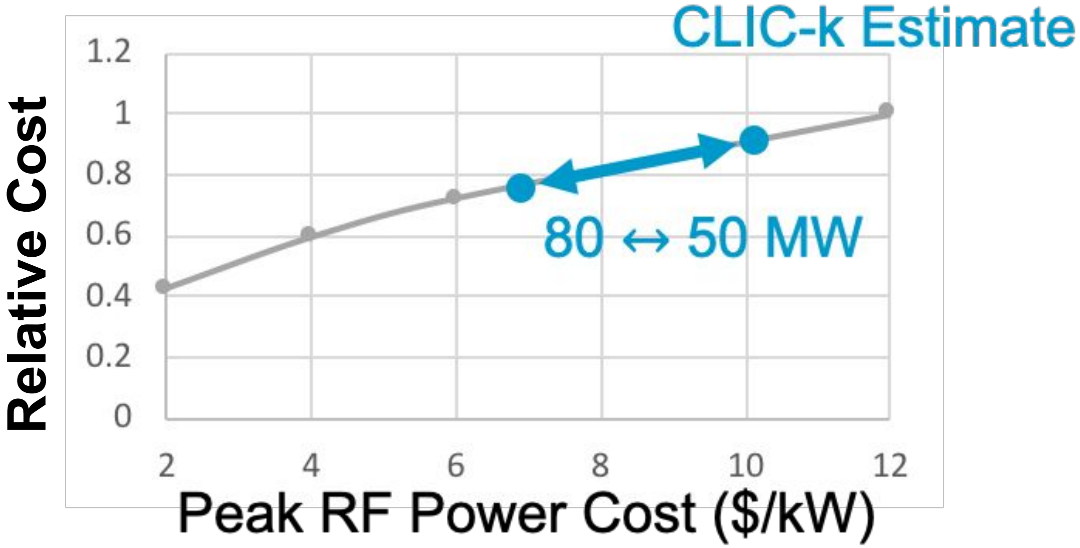
RF source cost is the key driver for gradient and cost

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

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 CCC-250 commercially available

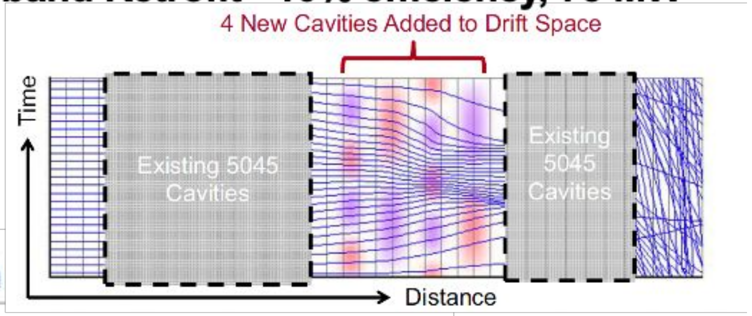
Plan to leverage significant developments in performance (HEIKA) of high power rf sources – requires industrialization

Los Alamos NATIONAL LABORATORY EST.1943

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

BVEI X-band 50 MW 57% COM Prototype

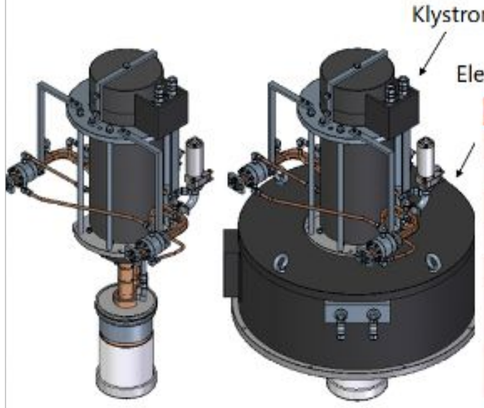
SLAC BAC Prototype
S-band Retrofit +10% efficiency, 73 MW



Near Term Industry

20-MW X-band Klystron

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

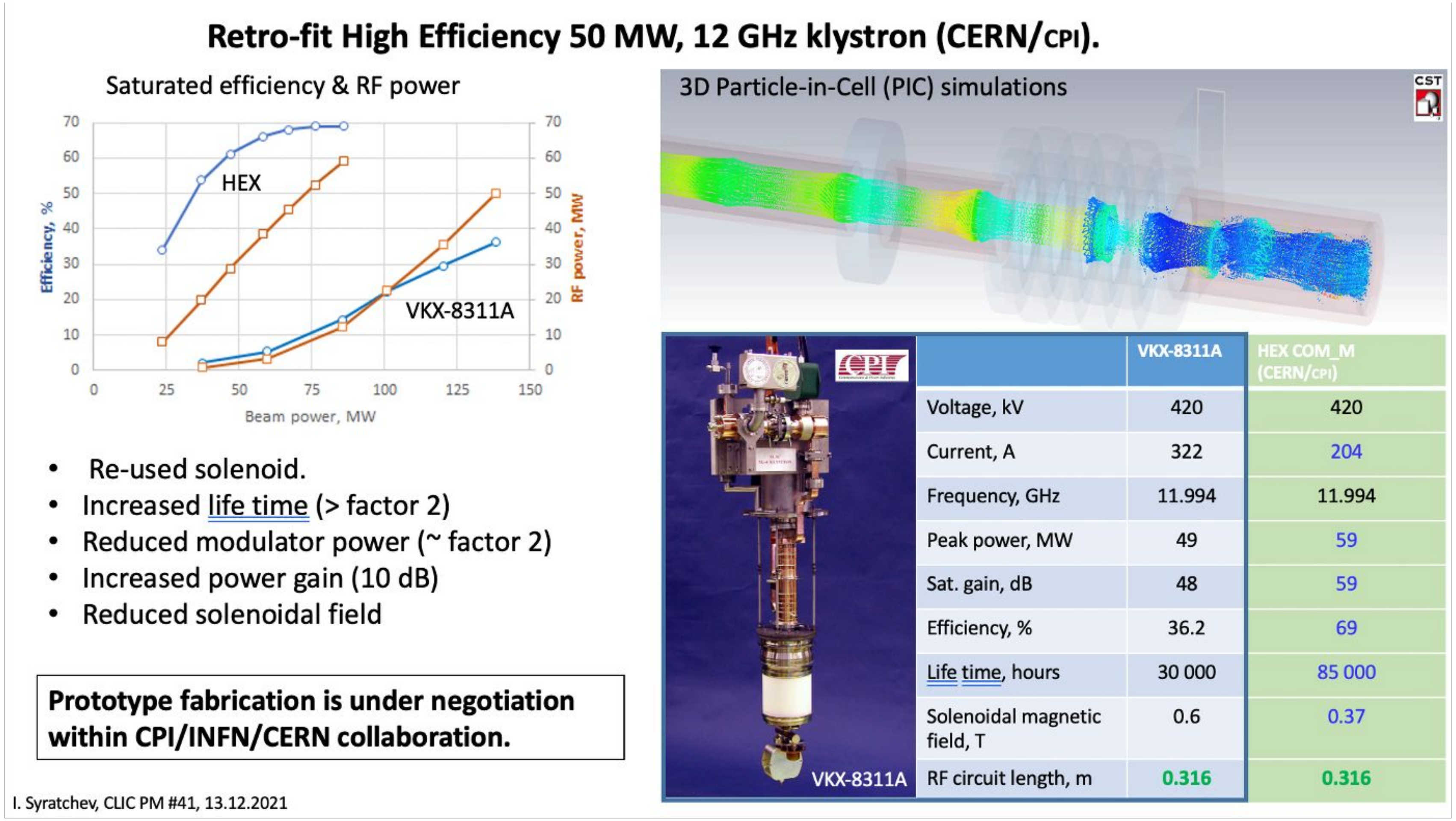
* Actual efficiency is estimated to be 46 - 48%.

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).

- 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.

	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. Syratchev, CLIC PM #41, 13.12.2021

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

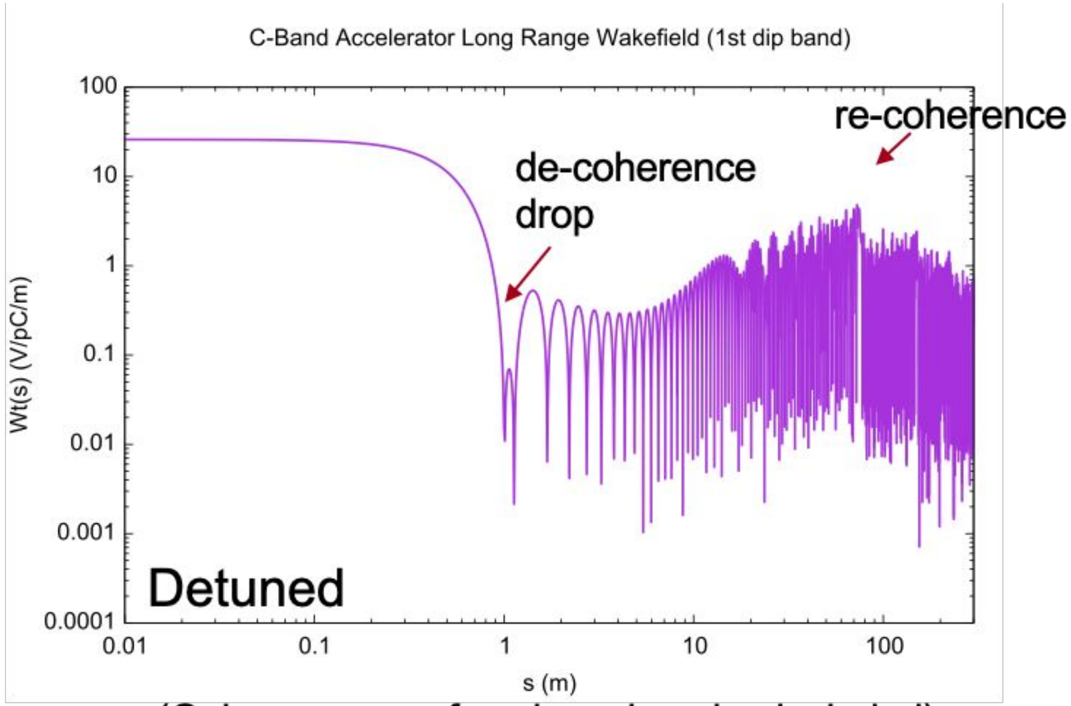
Gaussian Detuning Provides Required 1st Band Dipole Suppression for Subsequent Bunch, Damping Also Needed

Dipole mode wakefields immediate concern for bunch train

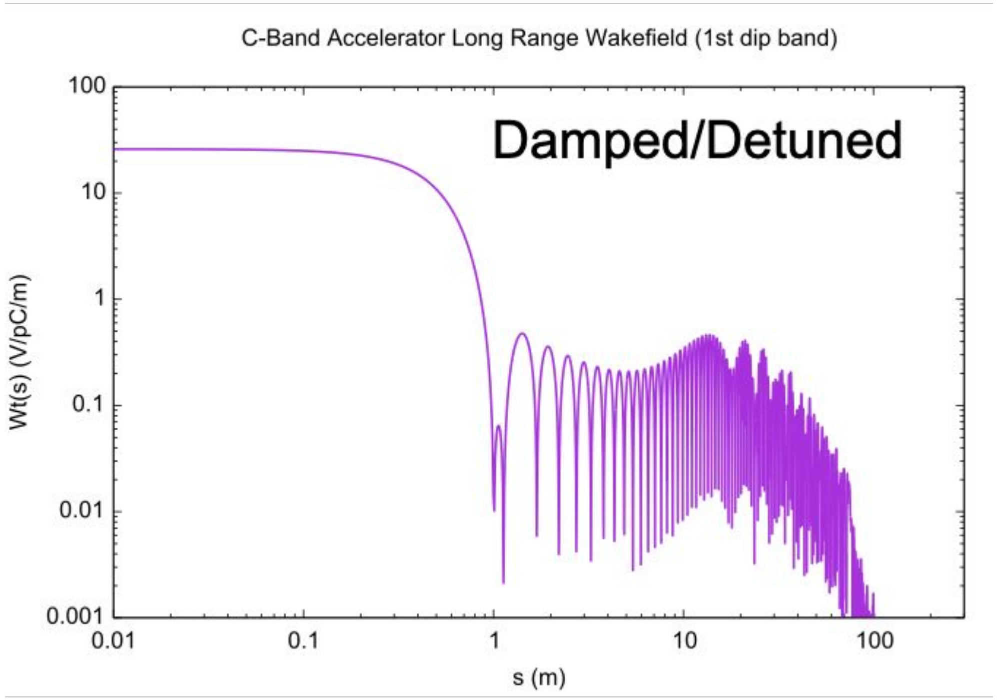
4σ Gaussian detuning of 80 cells for dipole mode (1st band) at f_c=9.5 GHz, w/ $\Delta f/f_c$=5.6%

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

- Damping needed to suppress re-coherence



(Only copper surface loss damping included)



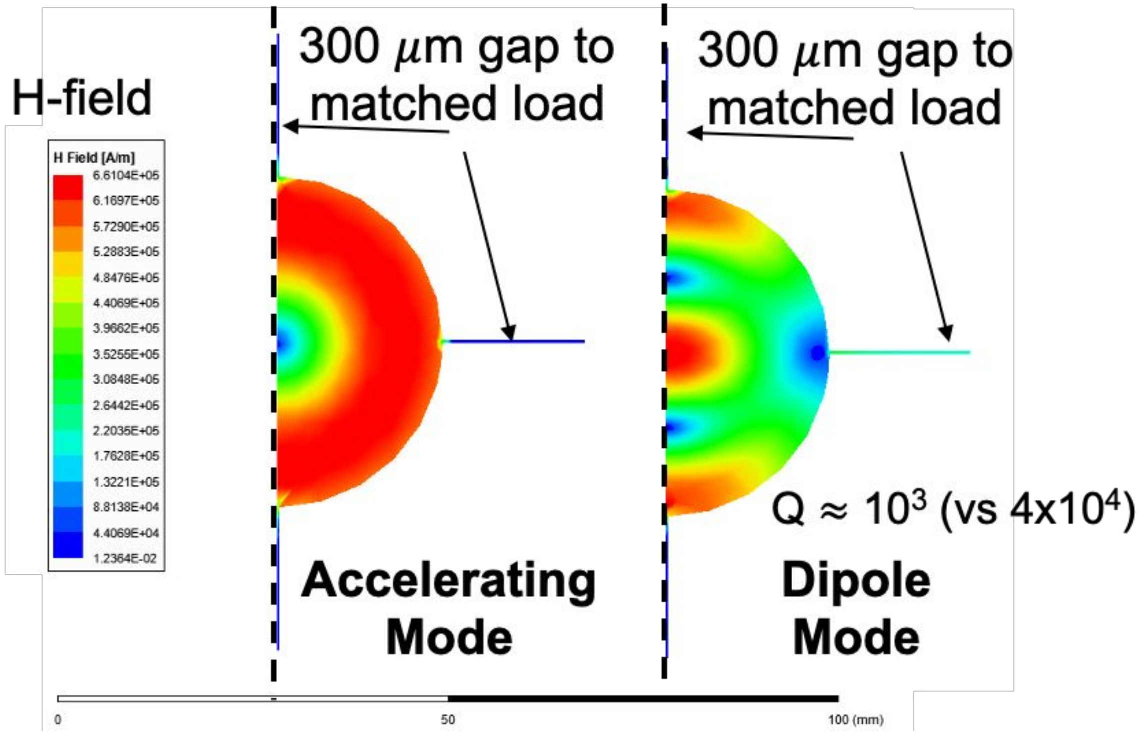
(1.0e3 Q total HOM damping included)

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

Individual cell feeds necessitate adoption of split-block assembly

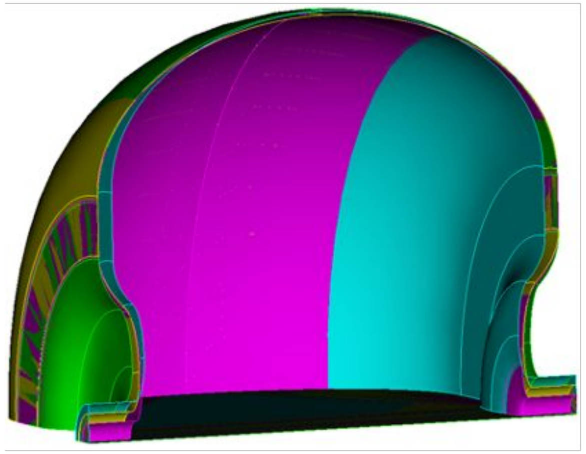
Perturbation due to joint does not couple to accelerating mode

Exploring gaps in quadrature to damp higher order mode

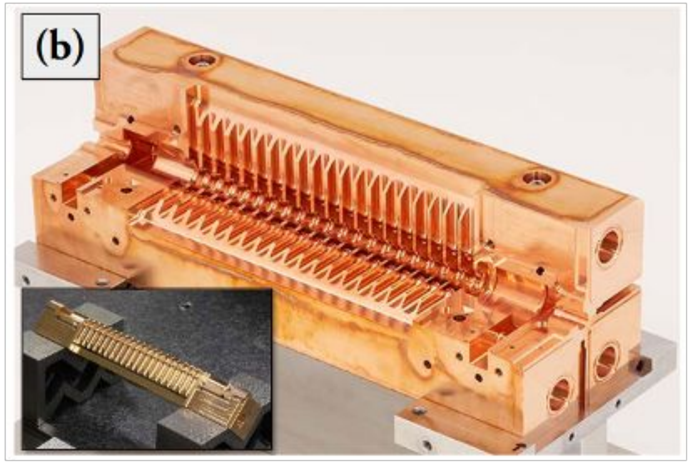


$Q \approx 10^3$ (vs $4\text{x}10^4$)

Detuned Cavity Designs



Quadrant Structure



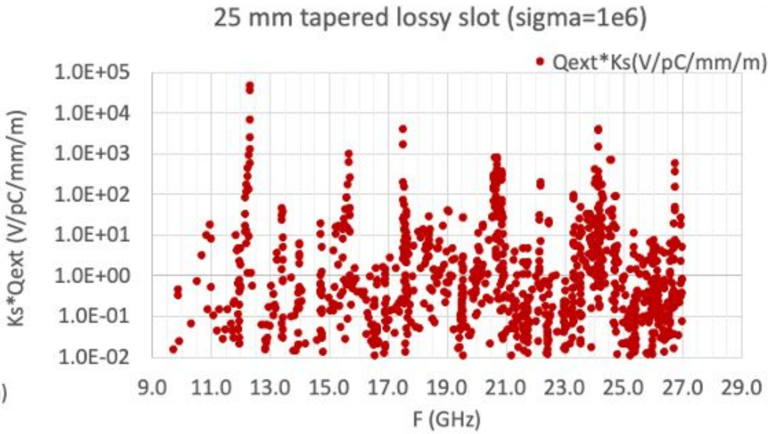
Abe et al., PASJ, 2017, WEP039

Implementation of Slot Damping

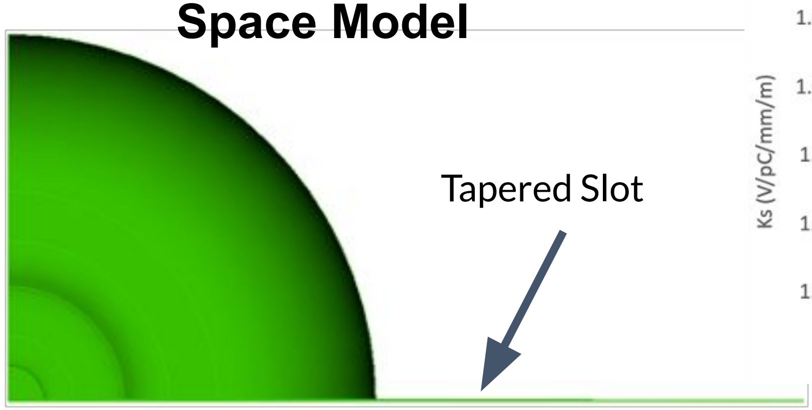
Need to extend to 40 GHz / Optimize coupling / Modes below 10^4 V/pC/mm/m

NiCr coated damping slots in development

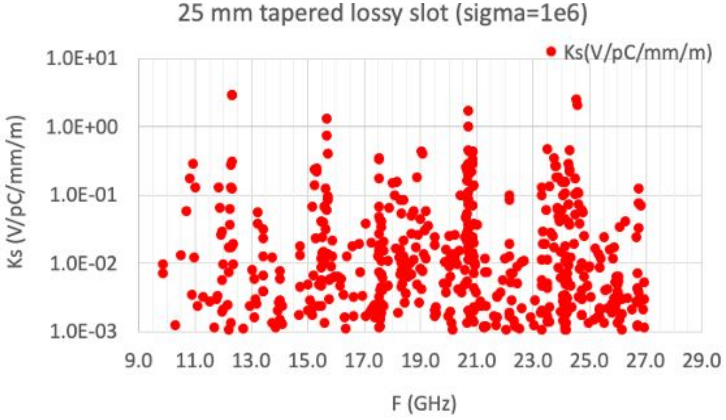
Kick Factor * Q



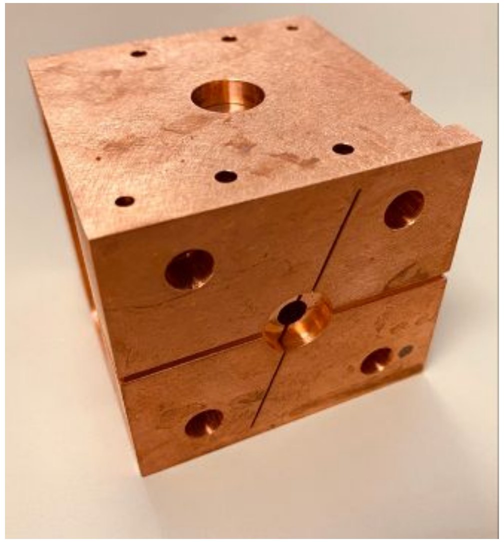
Vacuum Space Model



Kick Factor



Damping Slot Prototype



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:

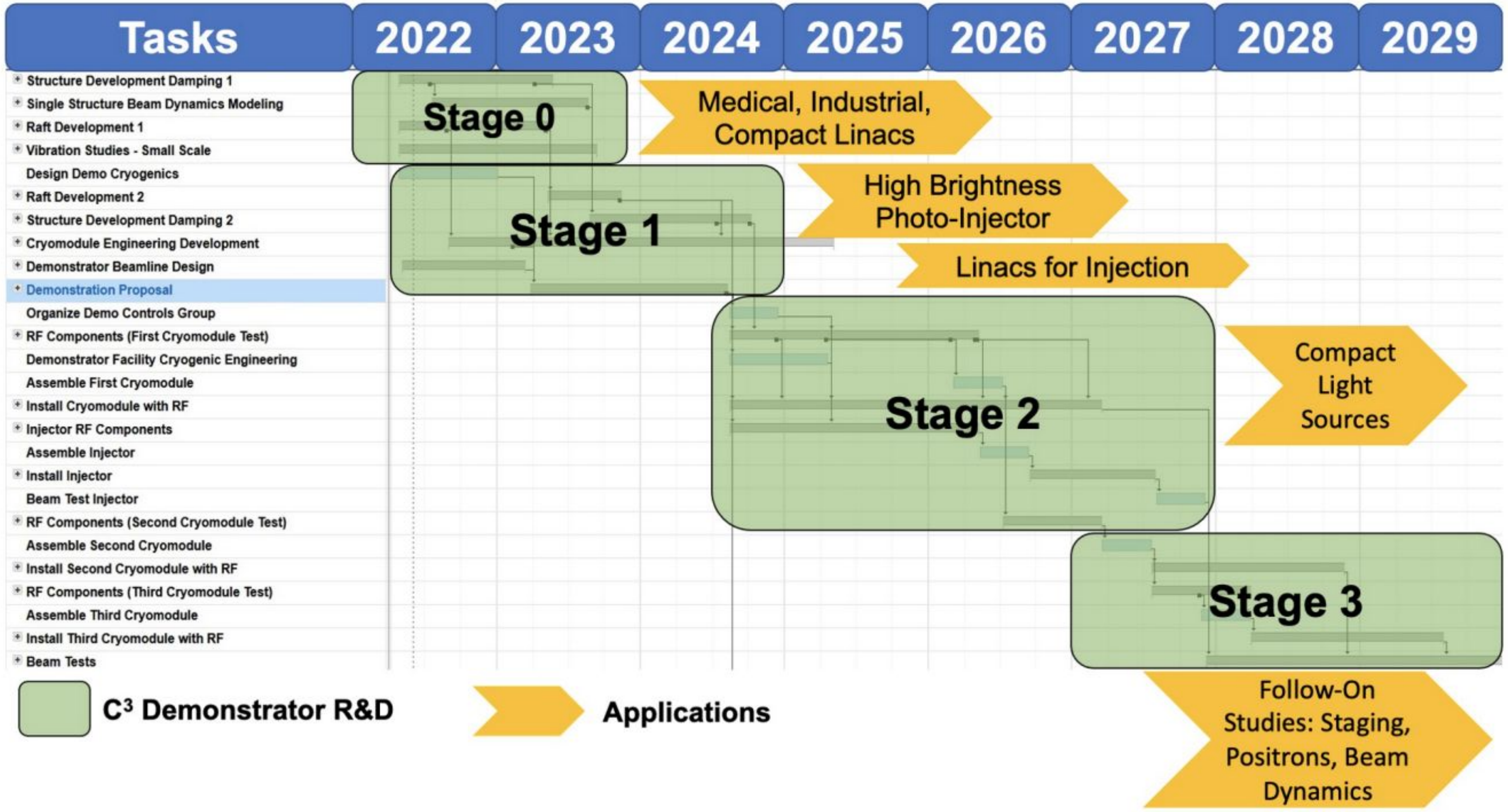
- **Demonstrate operation of fully engineered and operational cryomodule**
  - Simultaneous operations of min. 3 cryomodules
- Demonstrate operation during cryogenic flow equivalent to main linac at full liquid/gas flow rate
- Operation with a multi-bunch photo injector - high charges bunches to induce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

C^3 Demonstration R&D Plan timeline

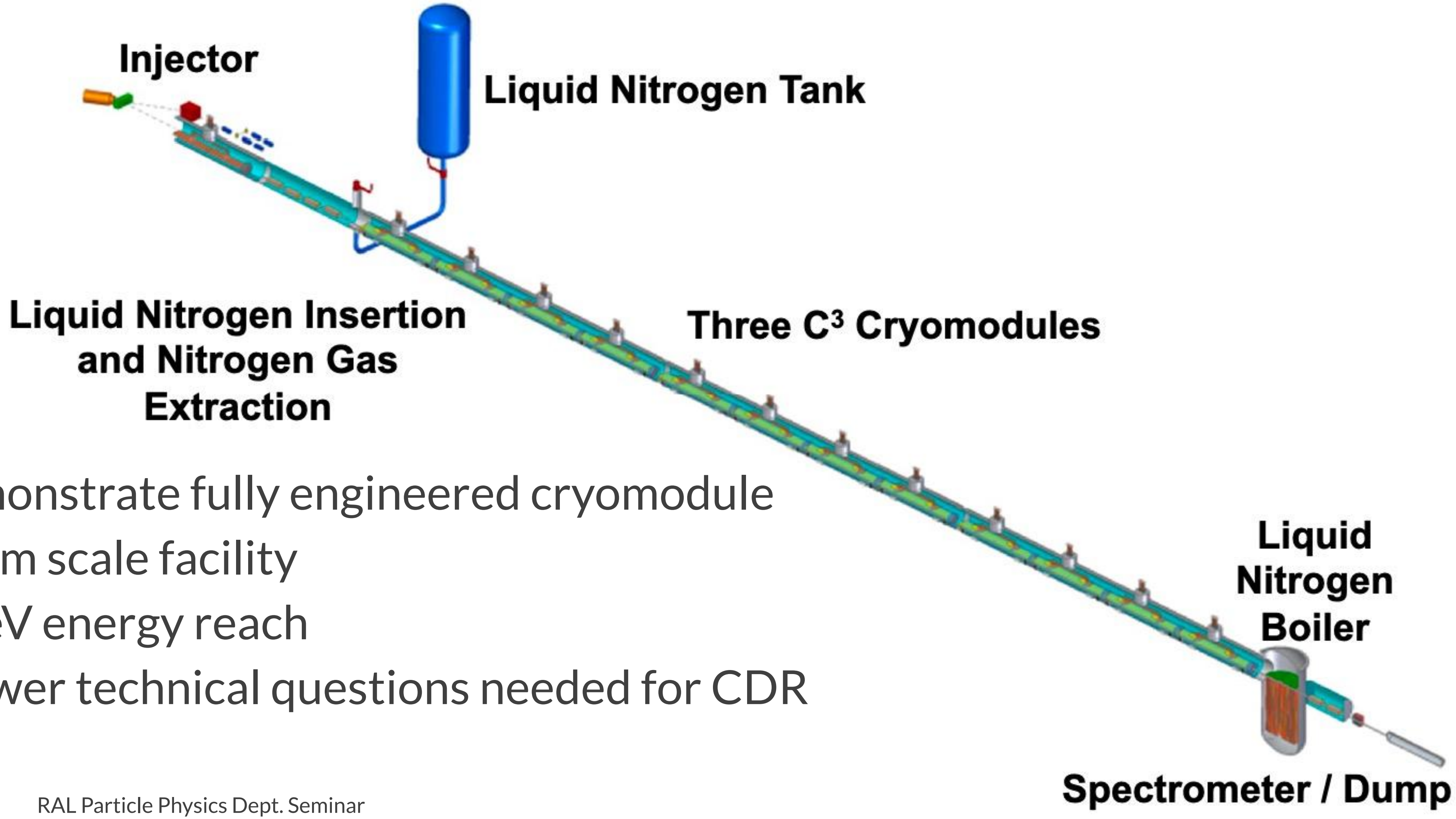


C^3 R&D, System Design and Project Planning are ongoing

- 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.

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 - May 17-18th @ Fermilab (https://forms.gle/QoepjKu1j9AuDf6j8)

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.

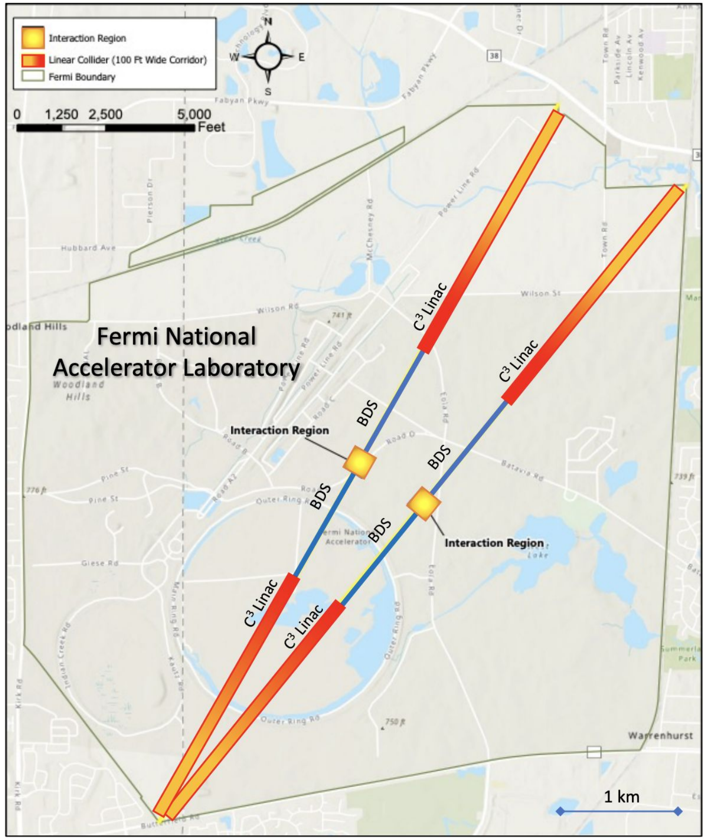
C^3 can be quickly be upgraded to 550 GeV

C^3 can be extended to a 3 TeV e+e- collider with capabilities similar to CLIC

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

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

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



More Details Here (Follow, Endorse, Collaborate):

https://indico.slac.stanford.edu/event/7155/

Questions?

Backup

RF Power Requirements

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

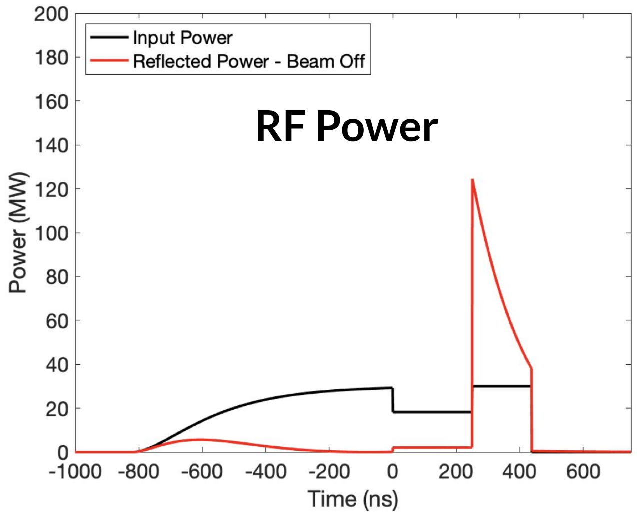
~1 microsecond rf pulse, ~30 MW/m

Conservative 2.3X enhancement from cryo

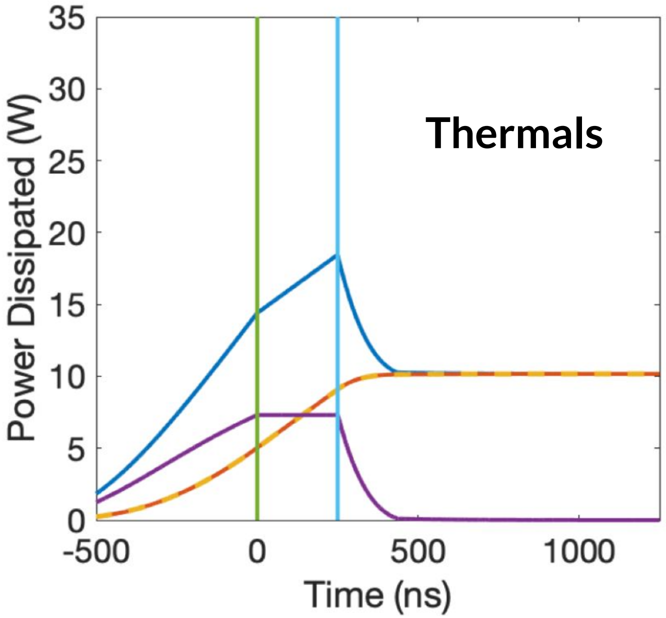
- No pulse compression

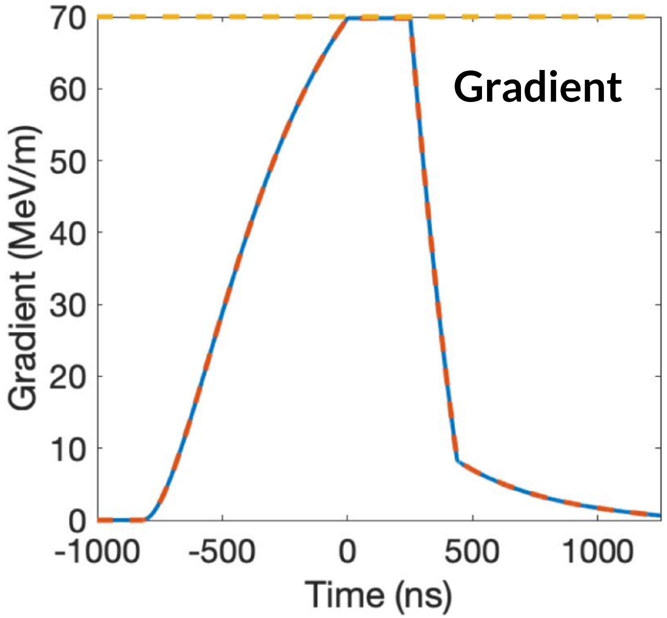
Ramp power to reduce reflected power

Flip phase at output to reduce thermals

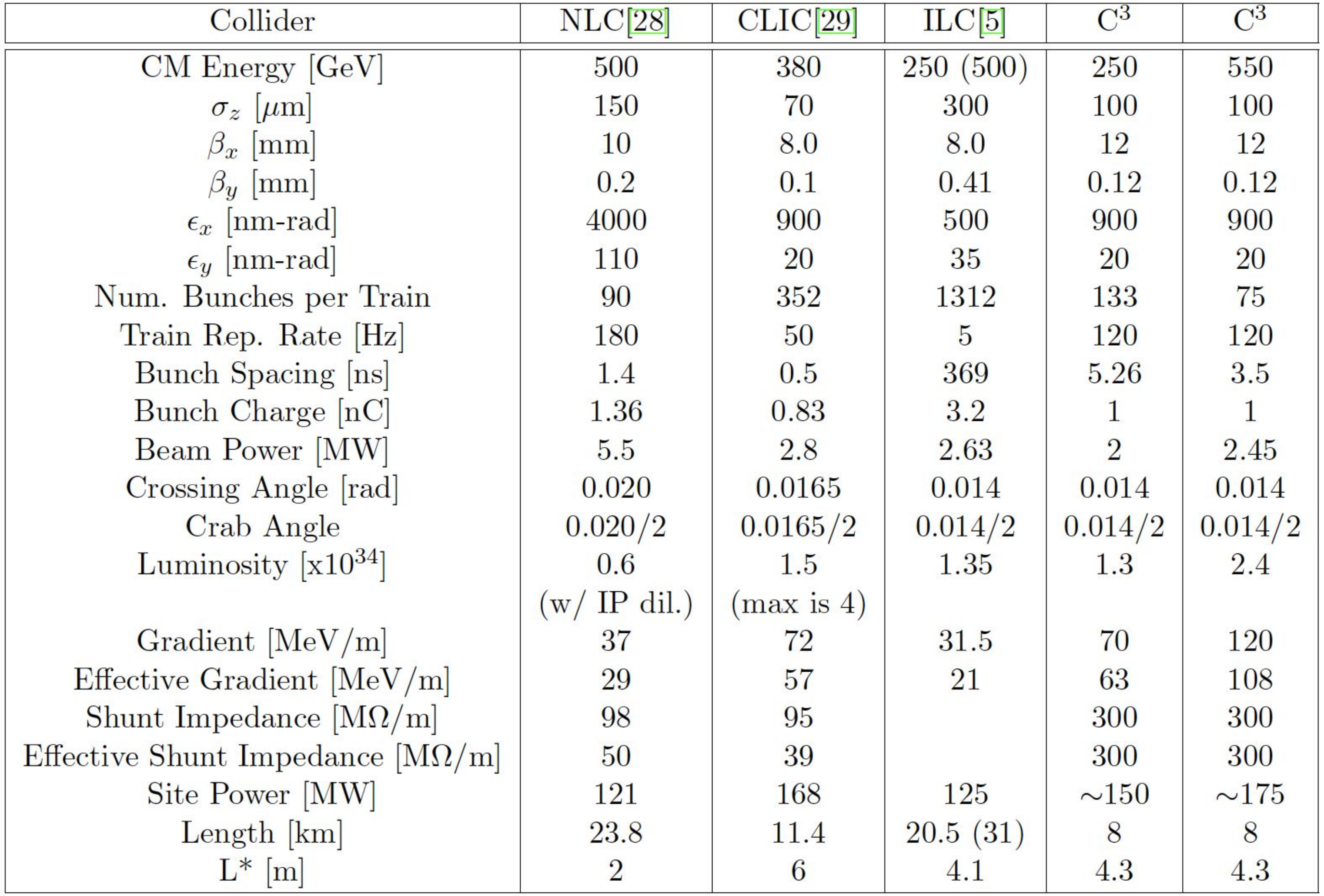


One 65 MW klystron every two meters -> Matches CLIC-k rf module power





Full Parameters

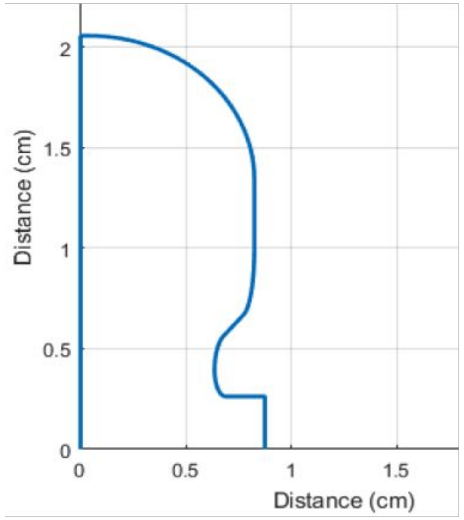


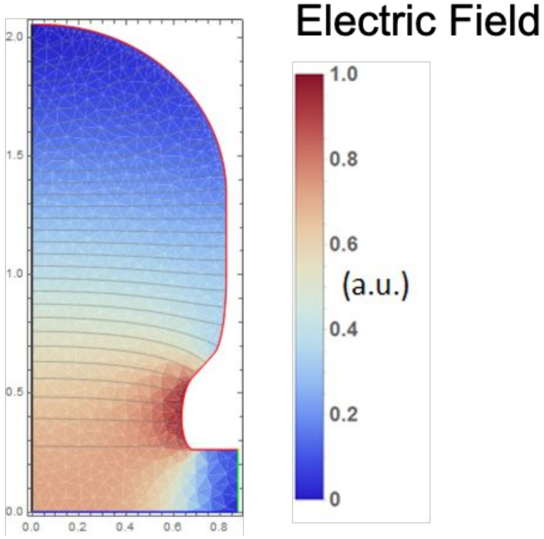
Collider	NLC[28]	CLIC[29]	ILC[5]	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
σ_z [μm]	150	70	300	100	100
β_x [mm]	10	8.0	8.0	12	12
β_y [mm]	0.2	0.1	0.41	0.12	0.12
ϵ_x [nm-rad]	4000	900	500	900	900
ϵ_y [nm-rad]	110	20	35	20	20
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	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

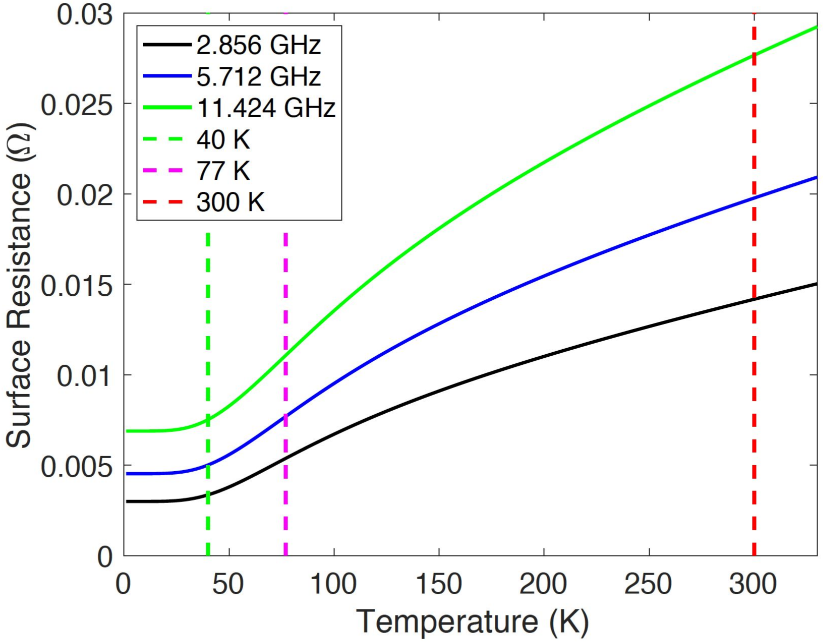
Optimized Cavity Geometries for Standing Wave Linac

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





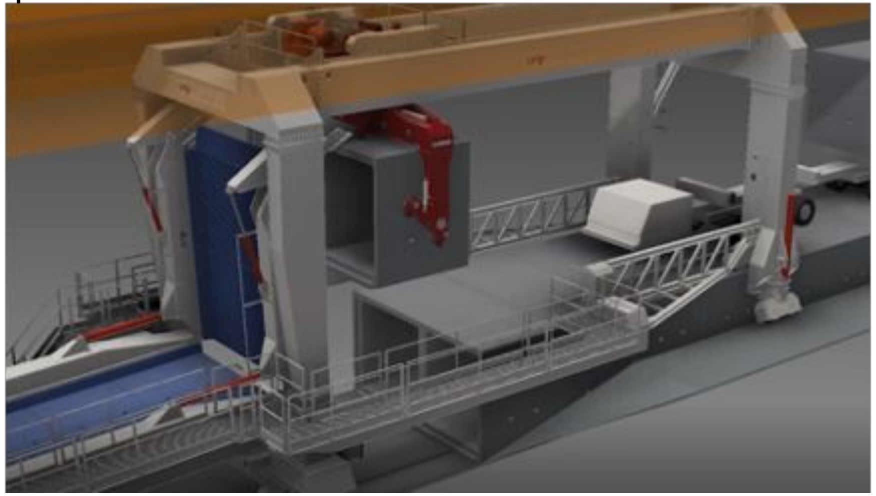


State of the Art Tunnel Construction

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

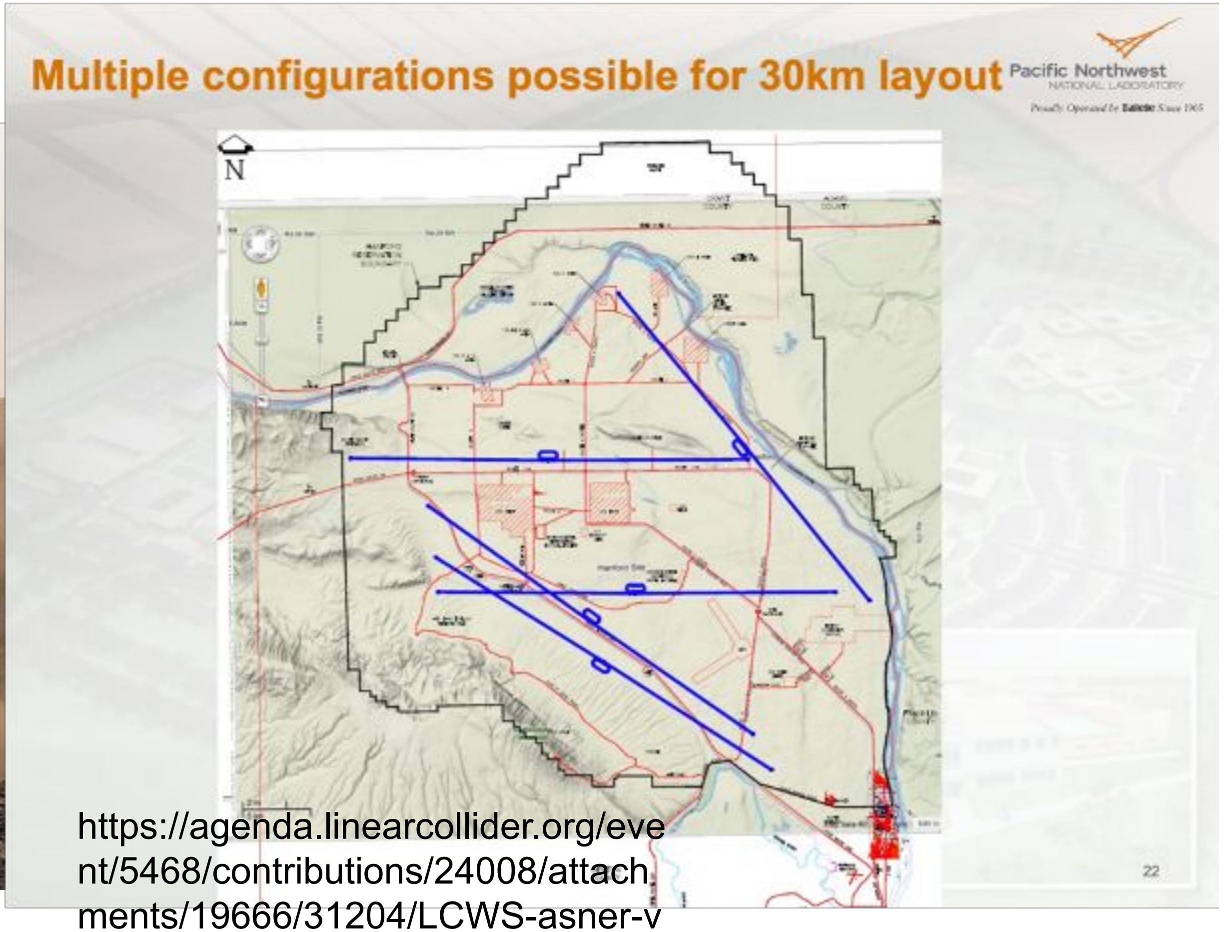
Cut and Cover Construction

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



Multiple configurations possible for 30km layout

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