C^3 What is to be done?

Emilio Nanni & Caterina Vernieri
IDT WG3 Update
6/8/2023


Greetings from LCWS 2023!

Outline

1. Brief Review of C^3 Concept
2. Outstanding Technological Issues for the Accelerator
3. Demo Program
4. New Accelerator Results at LCWS
5. Comments Detectors from LCWS
7. Conclusion

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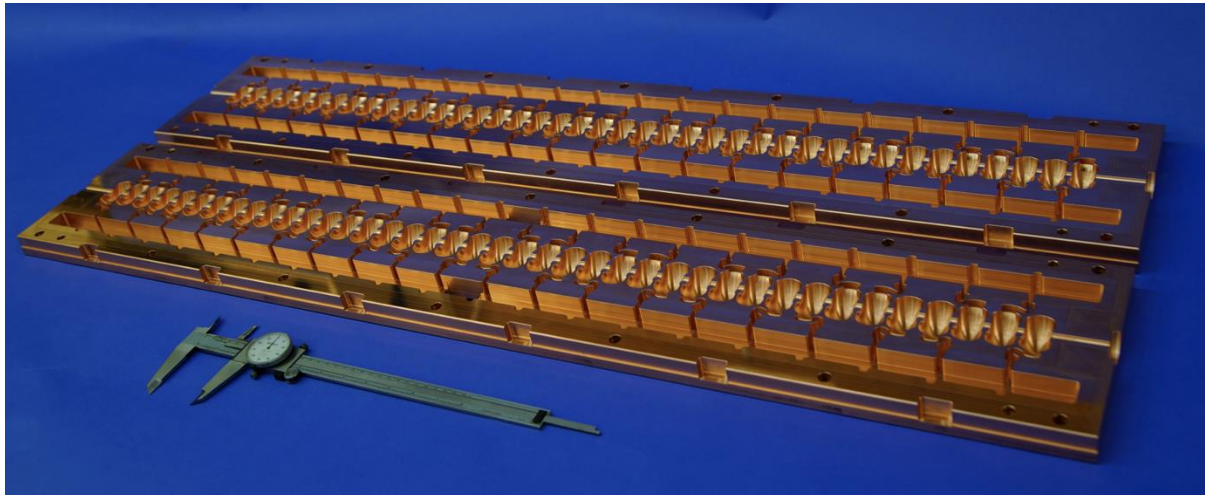
More Details Here (Follow, Endorse, Collaborate):
https://indico.slac.stanford.edu/event/7155/

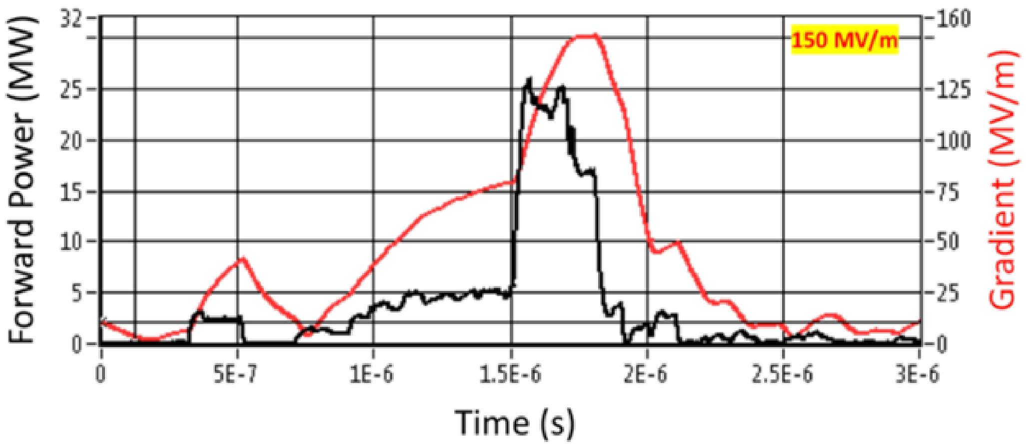
Cool Copper Collider

- 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

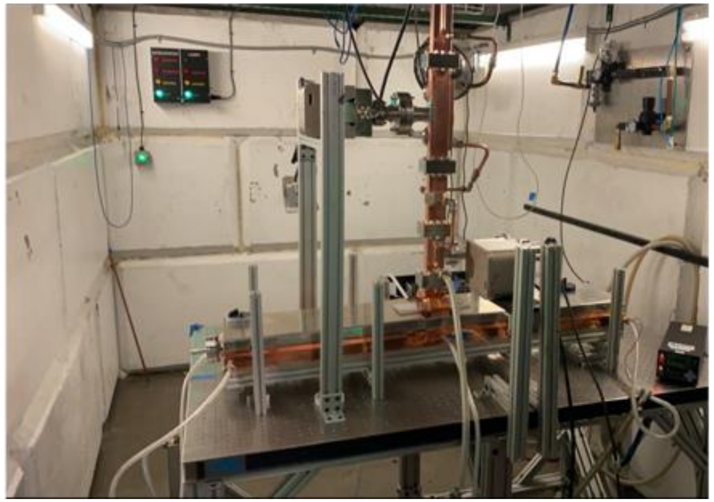


High Gradient Operation at 150 MV/m



Cryogenic Operation at X-band

High power Test at Radiabeam (C-band)



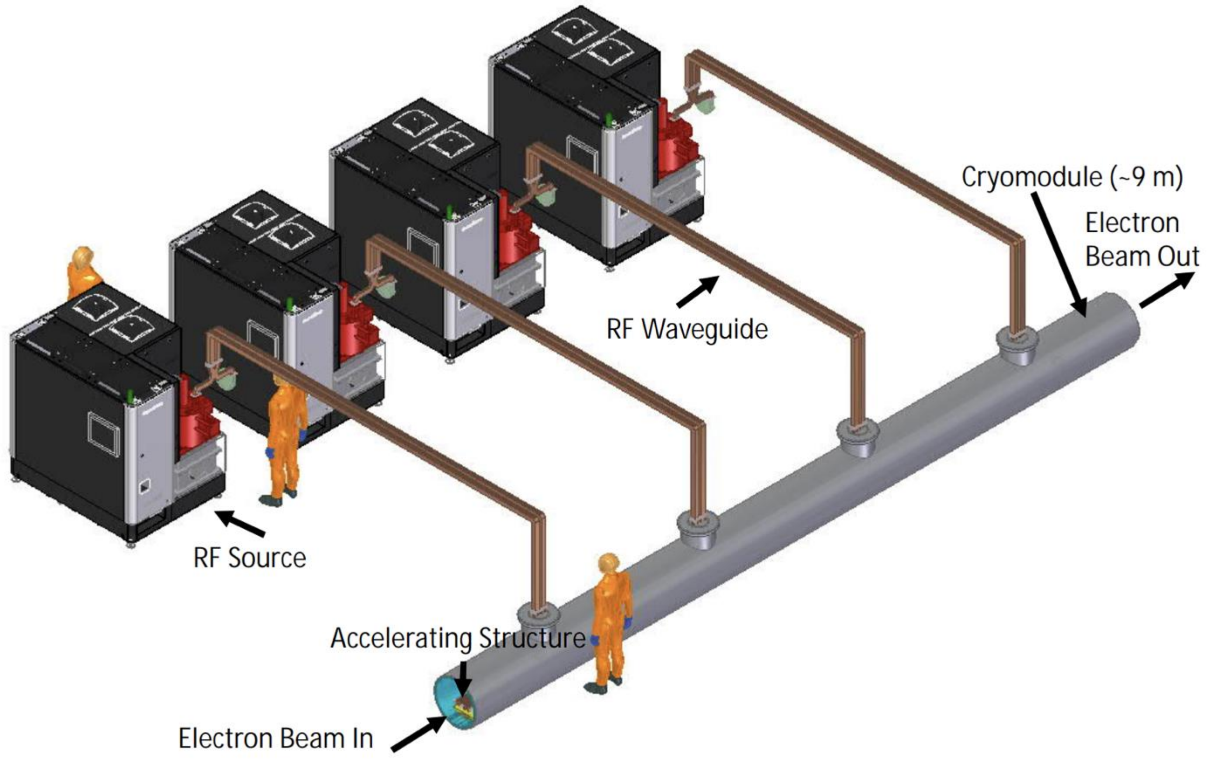
Tunnel Layout for Main Linac 250/550 GeV CoM

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

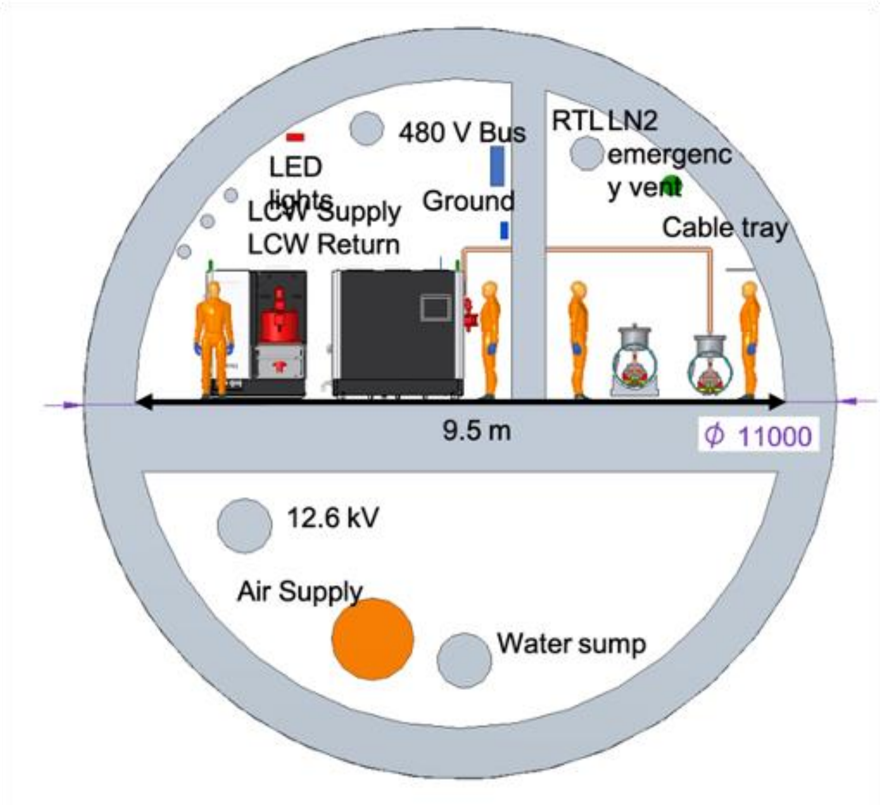
- Must minimize diameter to reduce cost and construction time

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)



Accelerator Complex

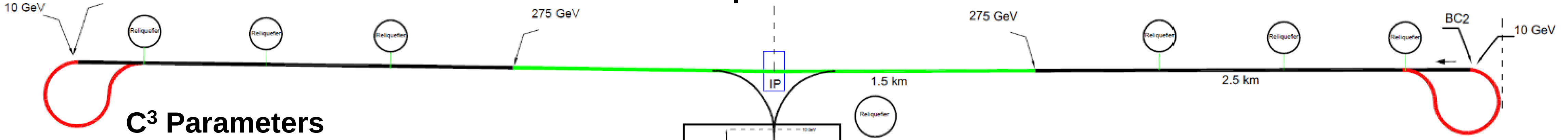
8 km footprint for 250/550 GeV CoM $\Longrightarrow$ 70/120 MeV/m

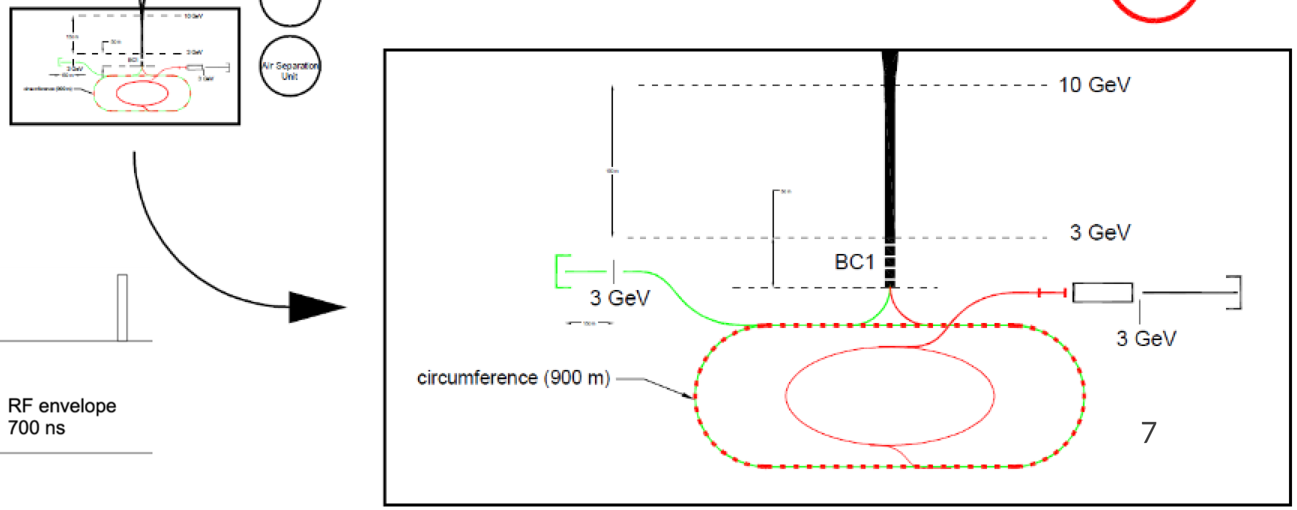
- 7 km footprint at 155 MeV/m for 550 GeV CoM – present Fermilab site

Large portions of accelerator complex 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

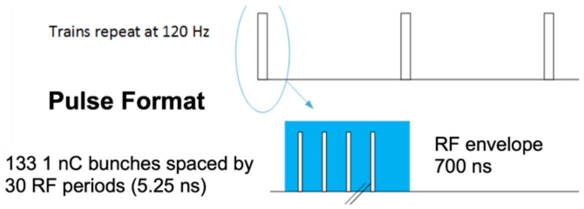
C^3 - 8 km Footprint for 250/550 GeV





C^3 Parameters

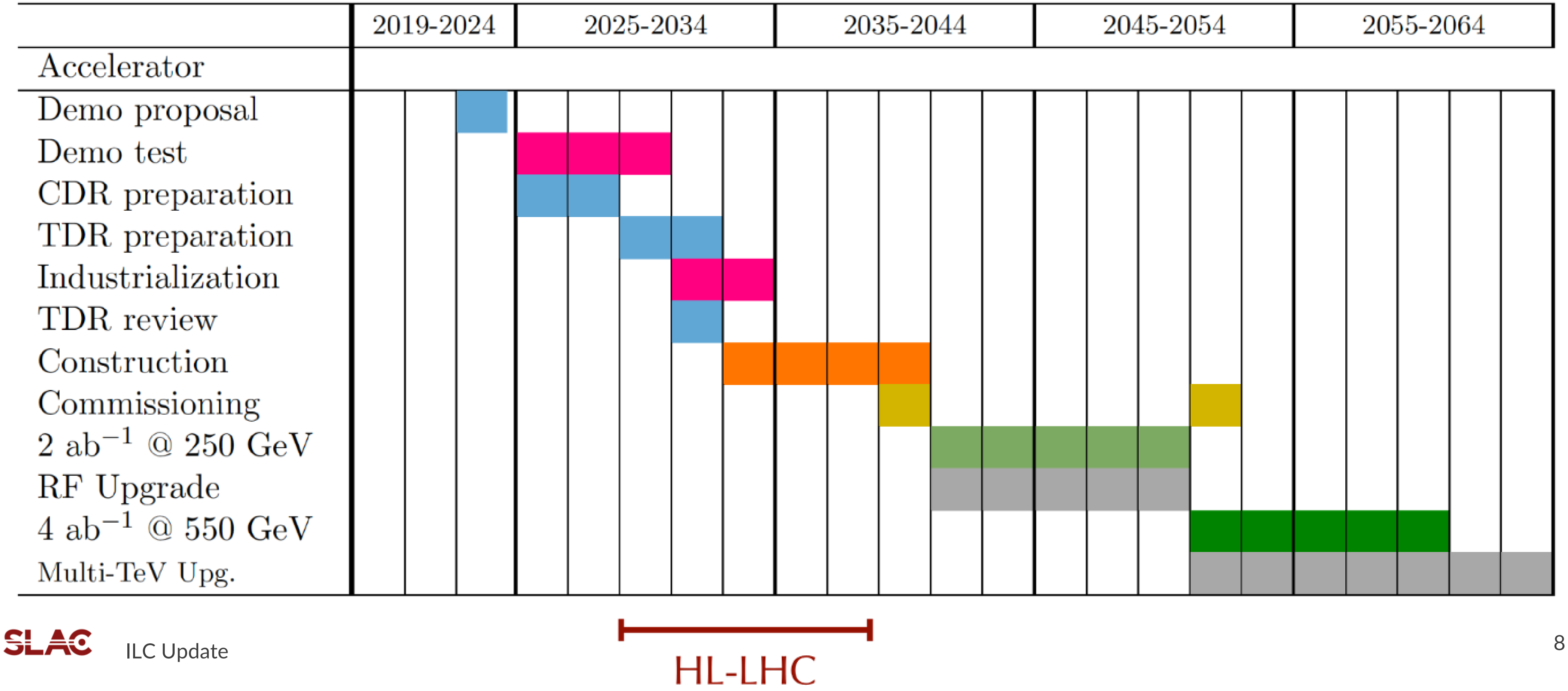
Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]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



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



Accelerator Design and Challenges

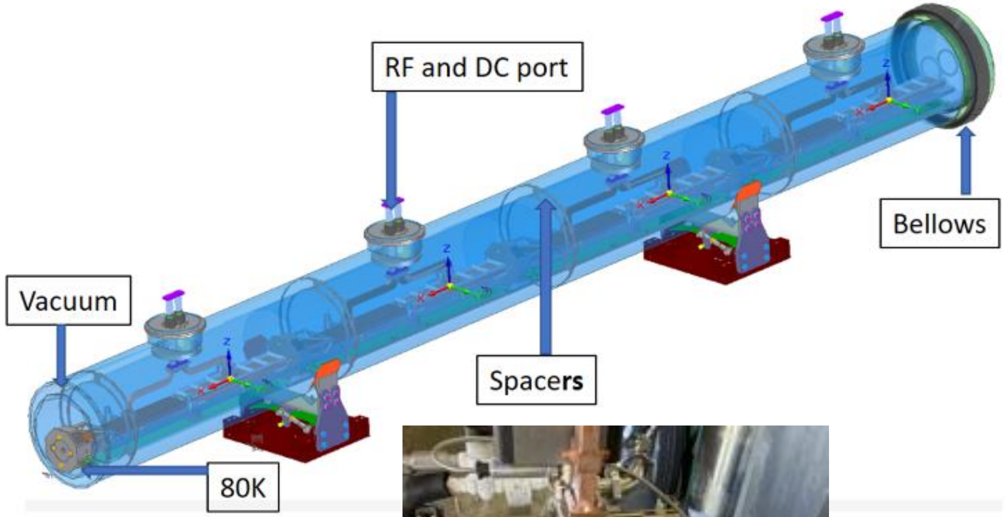
Accelerator Design

- 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

Cryomodule Concept



Vibration Studies

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:

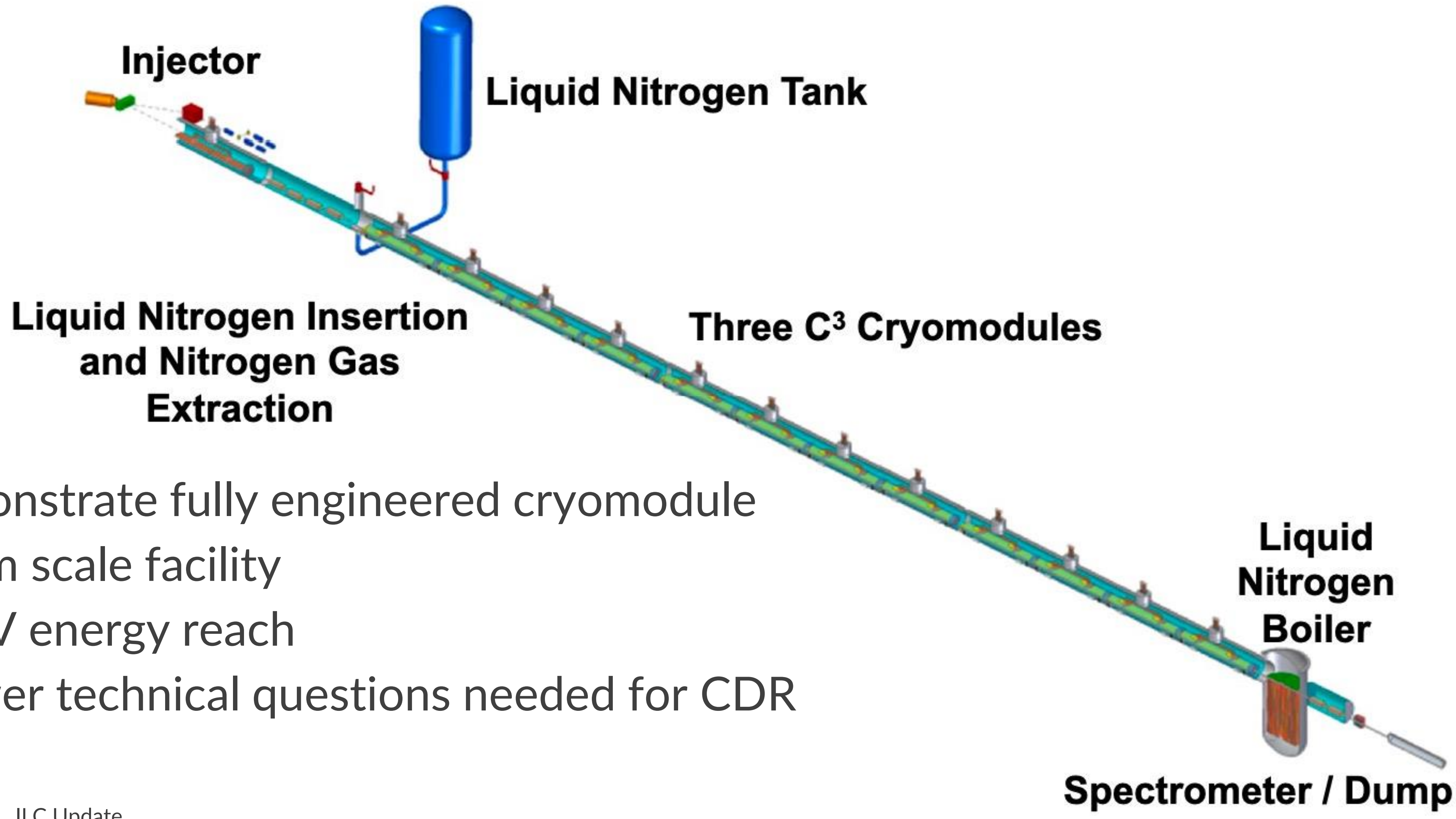
- **Demonstrate operation of fully engineered and operational cryomodule**
  - Simultaneous operations of min. 3 cryomodules
- Demonstrate operation during cryogenic flow equivalent to main linac at full liquid/gas flow rate
- Operation with a multi-bunch photo injector - high charges bunches to induce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

The Complete C^3 Demonstrator



Demonstrate fully engineered cryomodule

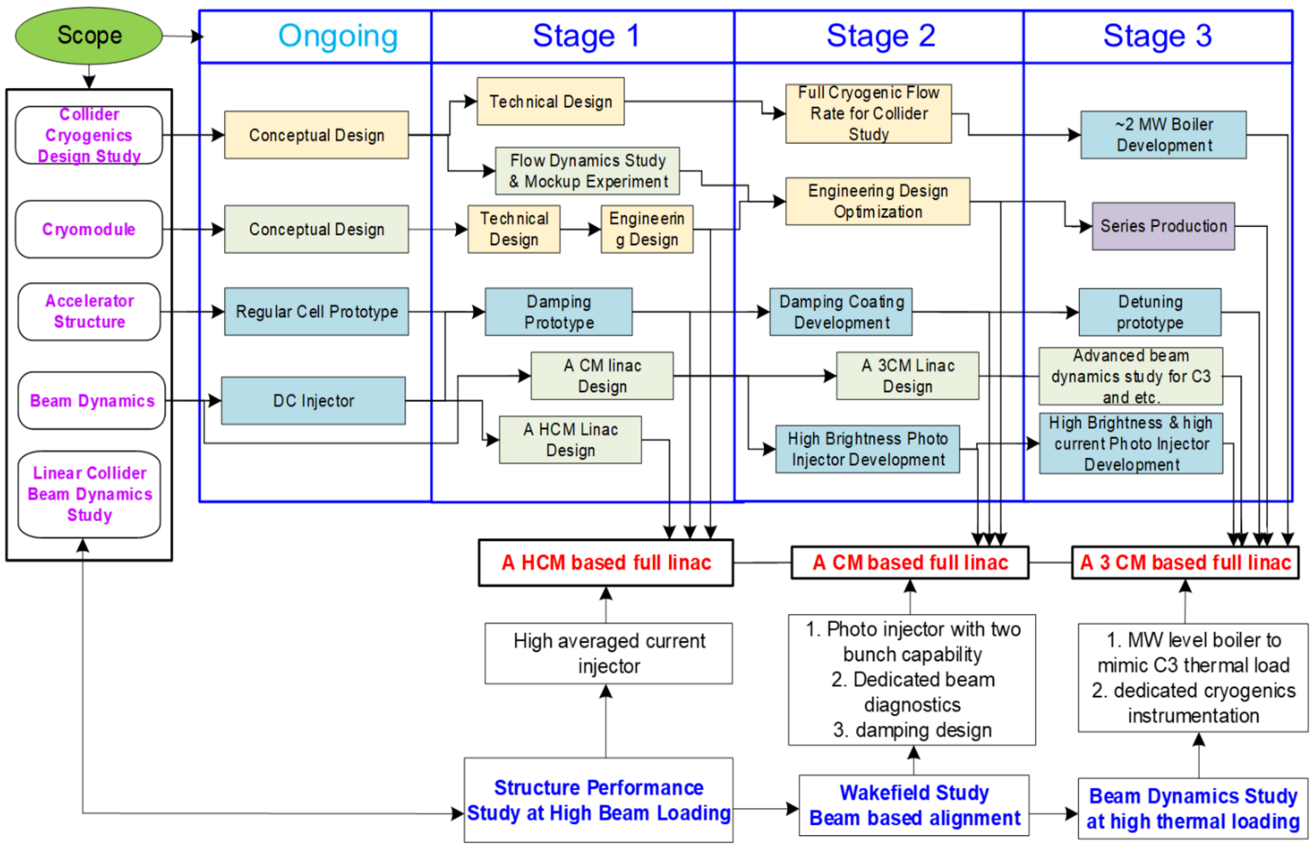
~50 m scale facility

3 GeV energy reach

Answer technical questions needed for CDR

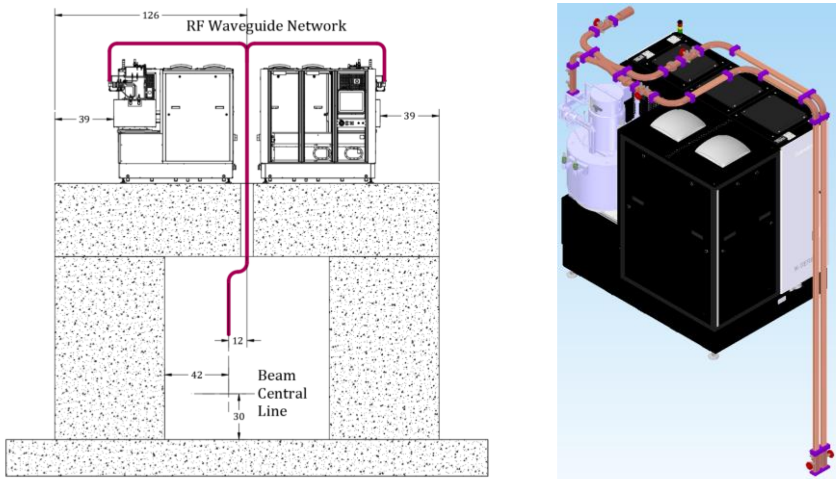
C^3 Demonstration R&D Plan

Demo Plan



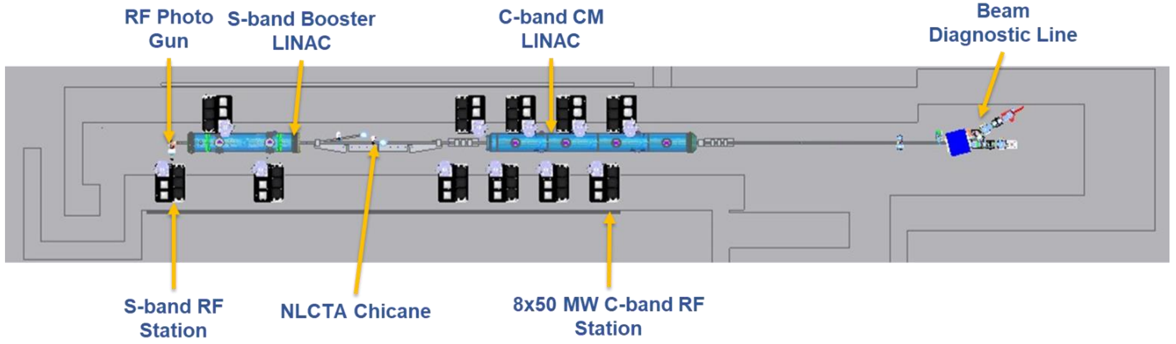
F. Wang, NCRF W 17th May 8:30

High Power RF Distribution



A. Krasnykh, BD W 17th May 11:20

Demo Beam Dynamics



J. Wu, BD Th 18th May 16:30

Power Consumption and Sustainability

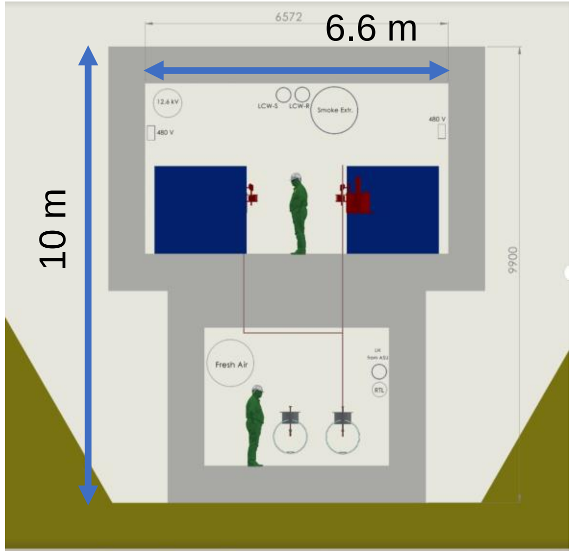
- **Sustainability - construction + operations CO_2 emissions per % sensitivity on couplings**
  - Polarization and high energy to improve sensitivity
  - Construction CO_2 emissions → minimize excavation and concrete
  - Operations → limit power, decarbonization of the grid and dedicated renewable sources

B. Bullard, S&A Th 18th May 10:30

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

Surface Tunnel



Linac Parameters

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

SLAC

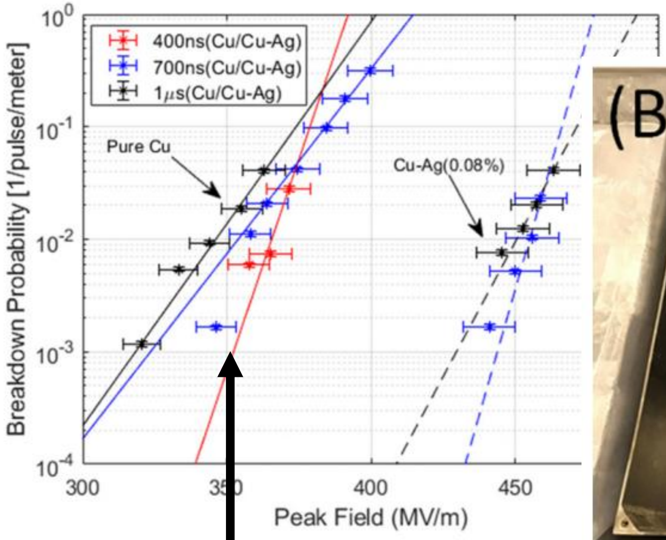
RF Design to High Gradient and High Power Testing

High gradient testing at LANL

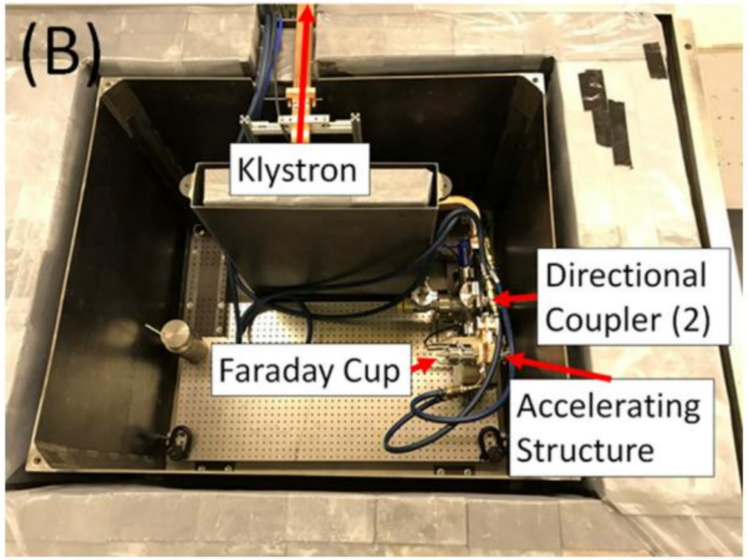
- Single cell structures
- Up to 8 MW per cavity (>240 MeV/m)

High power testing at Radiabeam

- Meter scale structures and components
- ~22 MW delivered in bunker -> 50 MW upgrade in progress



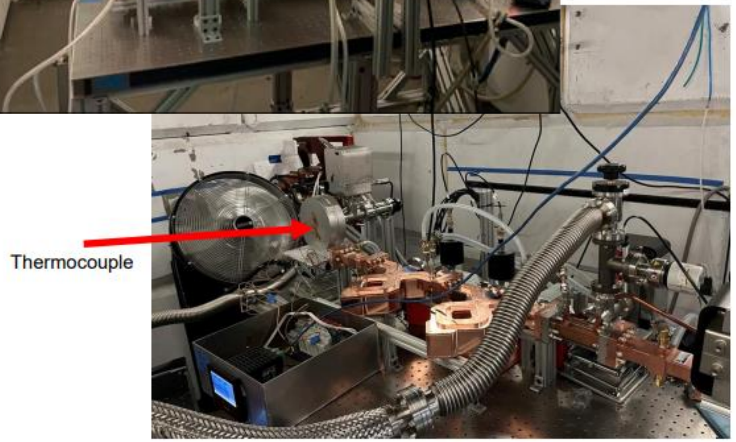
~190 MeV/m



Appl. Phys. Lett. 121, 254101 (2022); doi: 10.1063/5.0132706

One Meter Structure

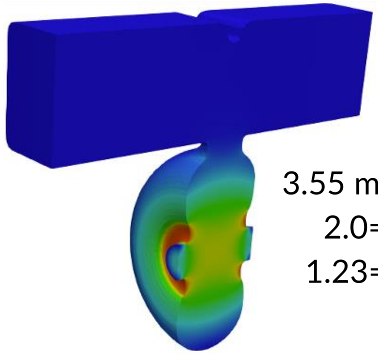
Additive Spiral Load (Inspired by CLIC)



Alignment and Vibrations

System level optimization essential for achieving performance

RF Structure Optimization

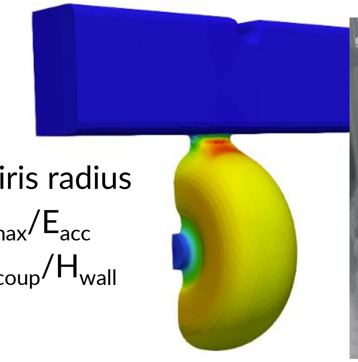


Electric Field

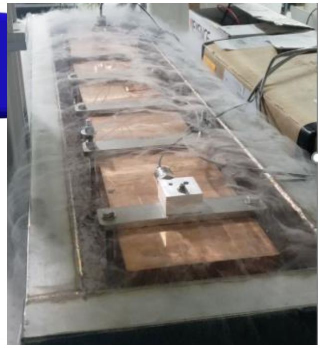
3.55 mm iris radius

$2.0 = E_{max}/E_{acc}$

$1.23 = H_{coup}/H_{wall}$



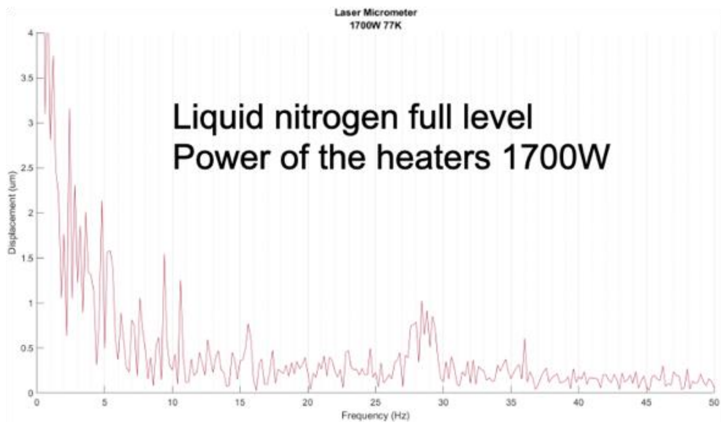
Magnetic Field



M. Shumail, Z. Li

Z. Li, NCRF W 17th May 10:30

Vibration Analysis



Z. George, V. Borzenets

Two-Phase Fluid Simulations

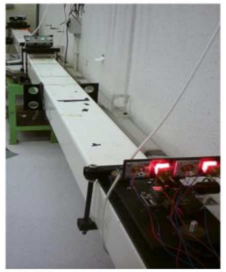
FAMU-FSU College of Engineering

K. Shoele

Precision Short and Long Range Alignment

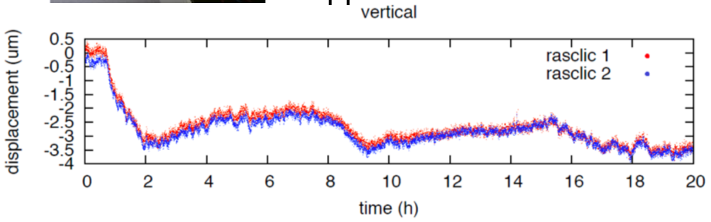
H. Van Der Graaf

Nikhef



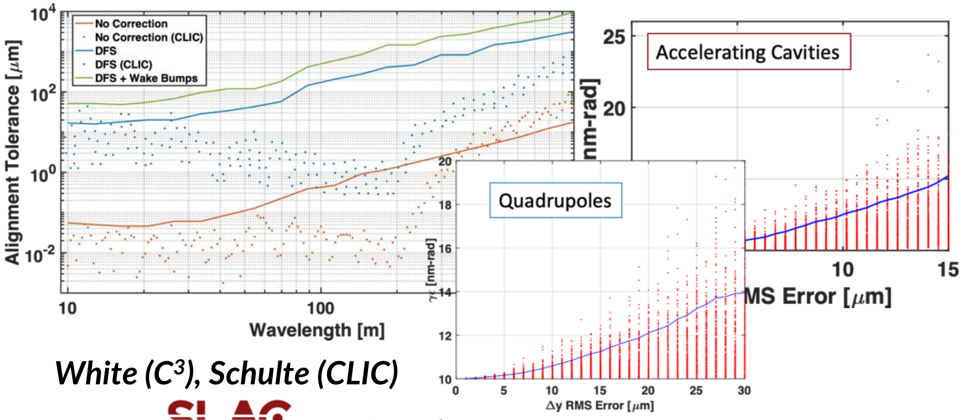
100 nm resolution

Approved effort to test cold



H. van der Graaf, CF W 17th May 14:30

Main Linac Beam Dynamics



White (C³), Schulte (CLIC)

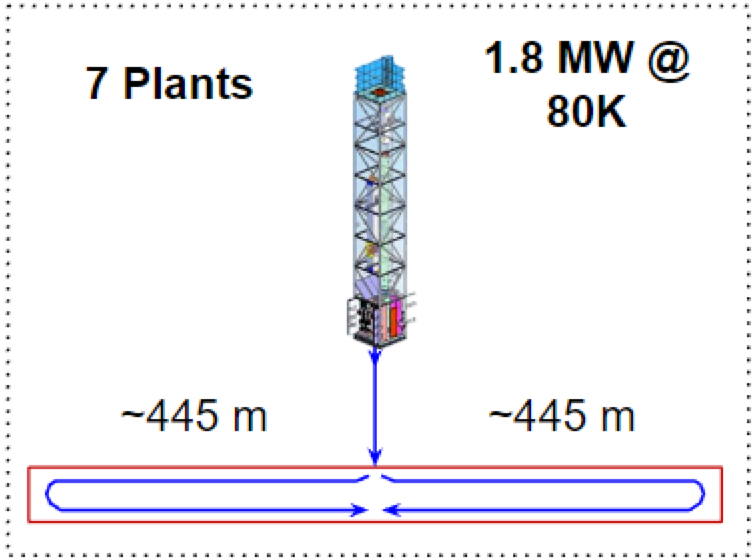
Alignment Parameters	Units	Value
Raft Components	μm	5
Short Range (~10m)	μm	30
Long Range (>200m)	μm	1000
Structure Vert. Vibration	μm	9
Quad Vert. Vibration	nm	15
BPM Resolution	μm	0.1
BPM-Quad Alignment	μm	2

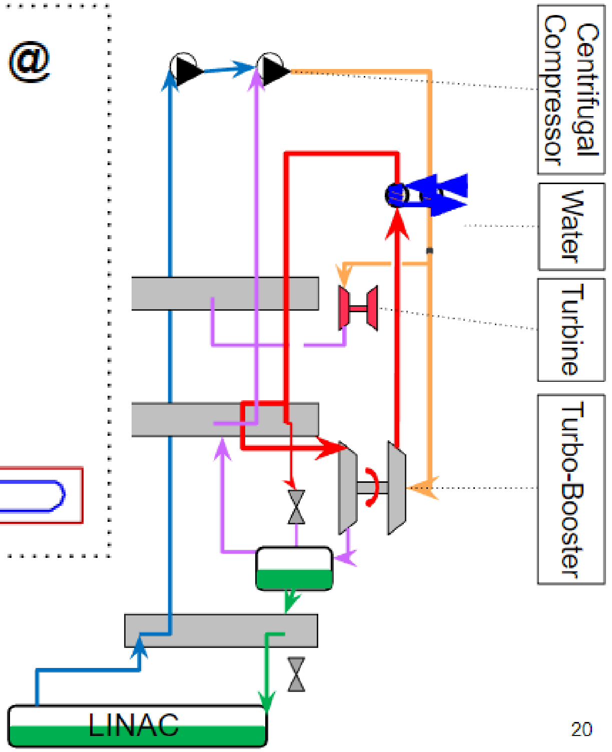
G. White, Beam Dynamics W 17th May 10:30

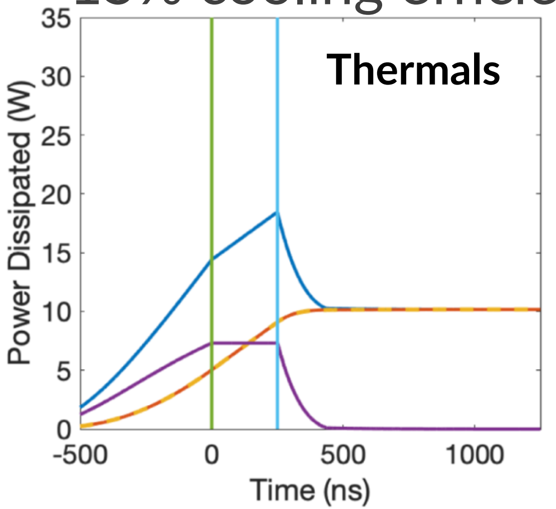
RF Power Requirements and Cryogenics

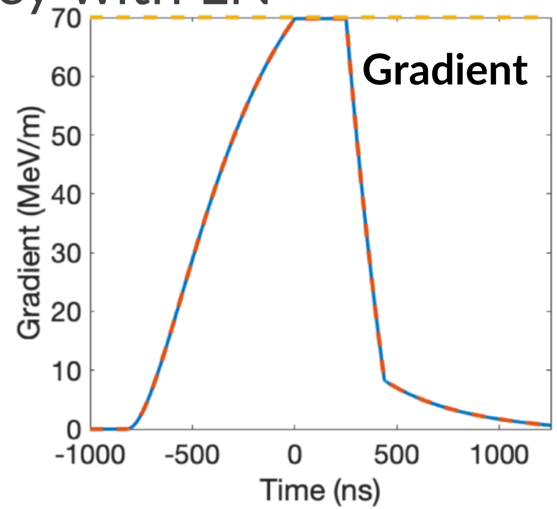
70 MeV/m 250 ns Flattop (extendible to 700 ns)
~1 microsecond rf pulse, ~30 MW/m
2.3X enhancement from cryo
- No pulse compression

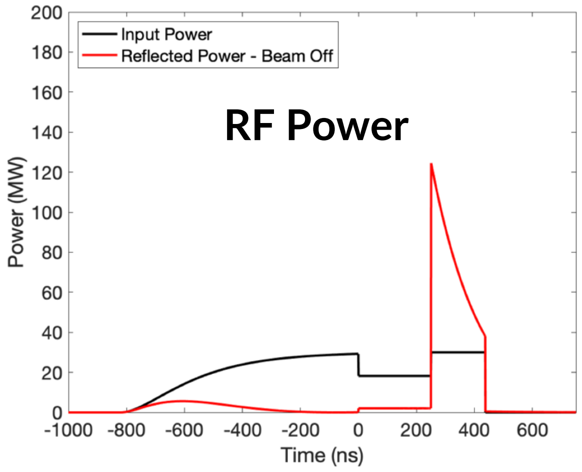
Ramp power to reduce reflected power
Flip phase at output to reduce thermals
<2.5 kW/m of structure for C3-250/550
15% cooling efficiency with LN











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

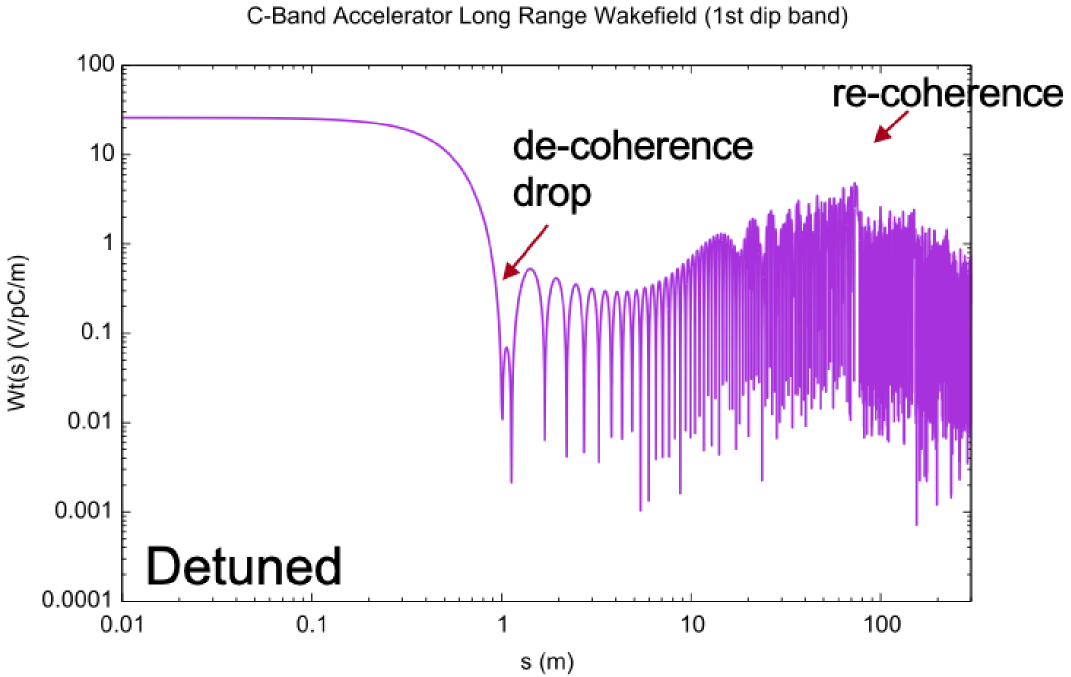
Gaussian Detuning Provides Required 1st Band Dipole Suppression for Subsequent Bunch, Damping Also Needed

Dipole mode wakefields immediate concern for bunch train

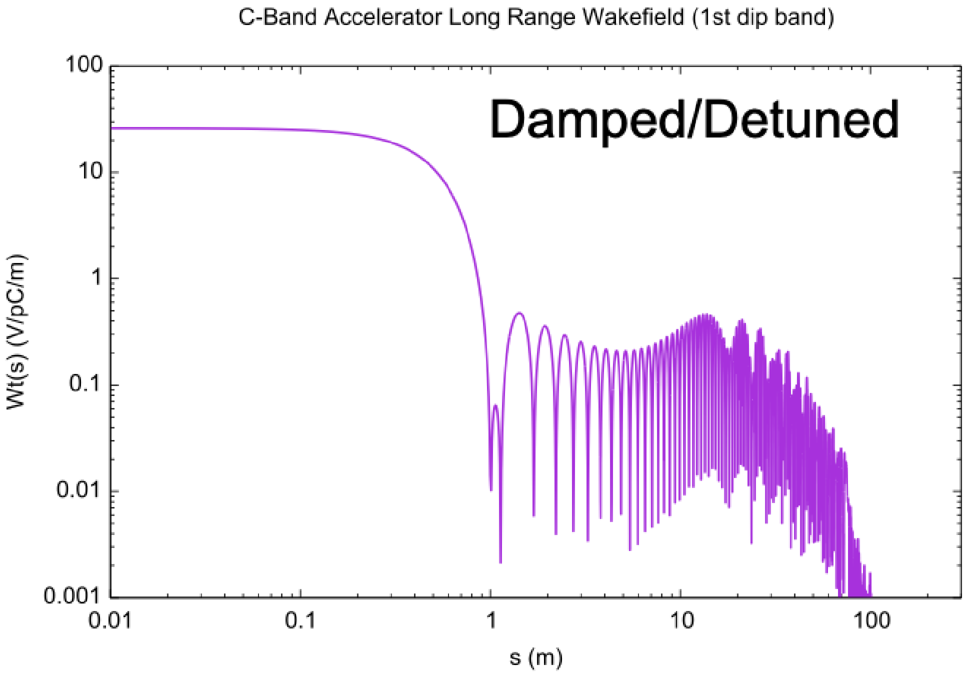
4σ Gaussian detuning of 80 cells for dipole mode (1st band) at f_c=9.5 GHz, w/ $\Delta f/f_c$=5.6%

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

- Damping needed to suppress re-coherence



(Only copper surface loss damping included)



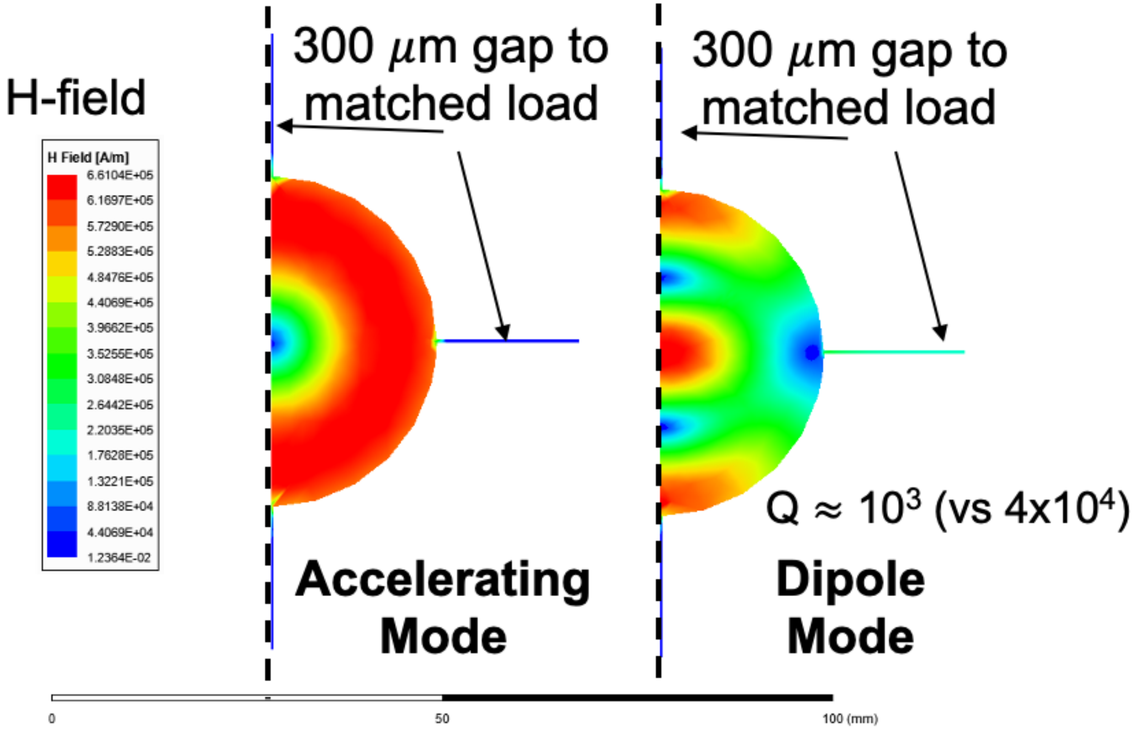
(1.0e3 Q total HOM damping included)

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

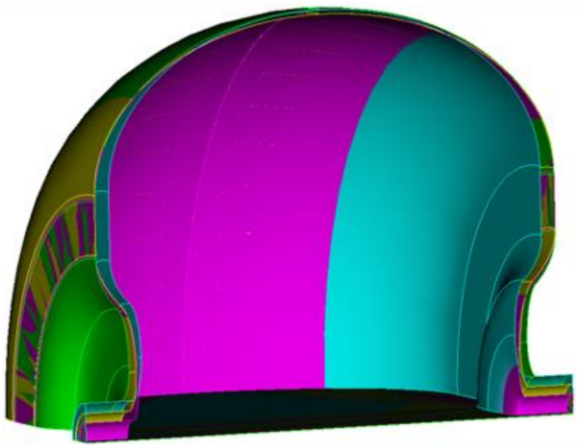
Individual cell feeds necessitate adoption of split-block assembly

Perturbation due to joint does not couple to accelerating mode

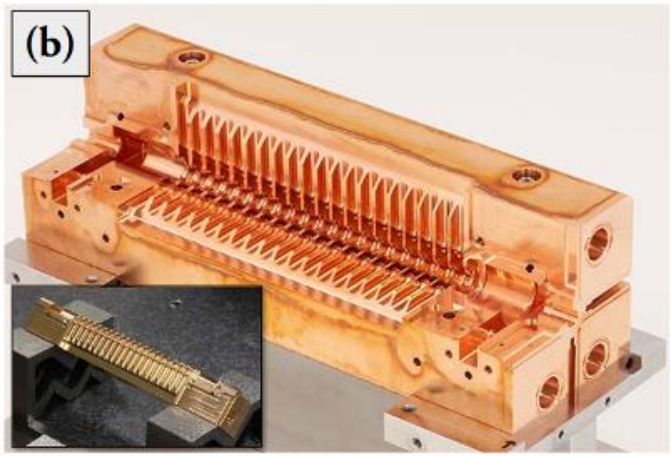
Exploring gaps in quadrature to damp higher order mode



Detuned Cavity Designs



Quadrant Structure

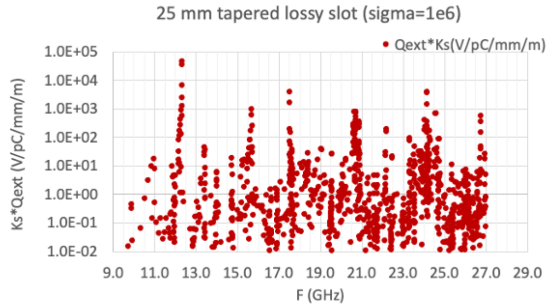


Abe et al., PASJ, 2017, WEP039

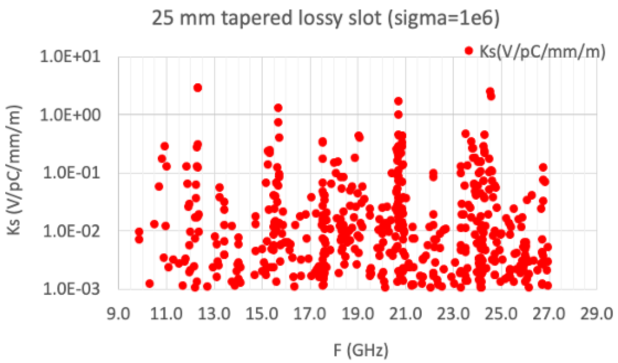
Implementation of Slot Damping

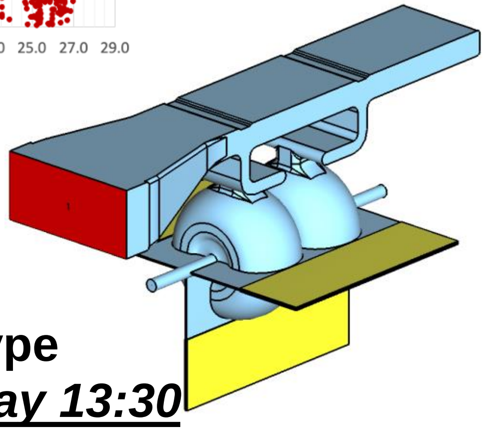
Need to extend to 40 GHz / Optimize coupling / Modes below 10^4 V/pC/mm/m
NiCr coated damping slots in development

Kick Factor * Q



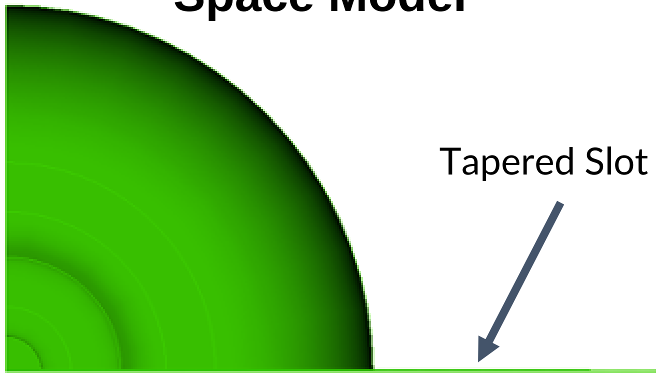
Kick Factor



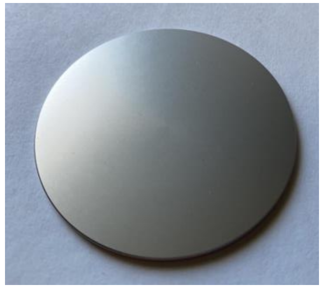


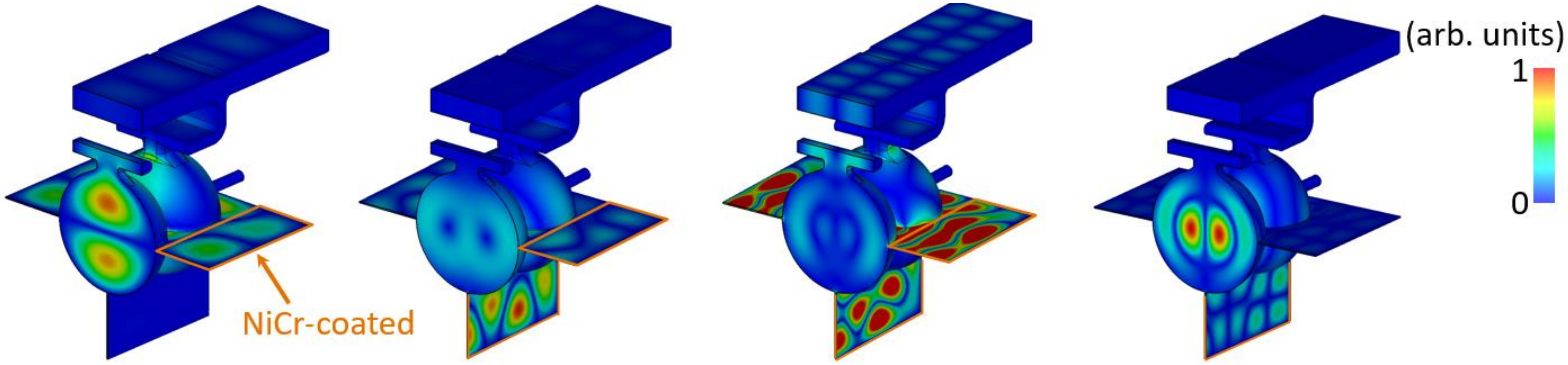
Two Cell Prototype
H. Xu, NCRF W 17th May 13:30

Vacuum Space Model



NiCr Tested at 80K





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

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

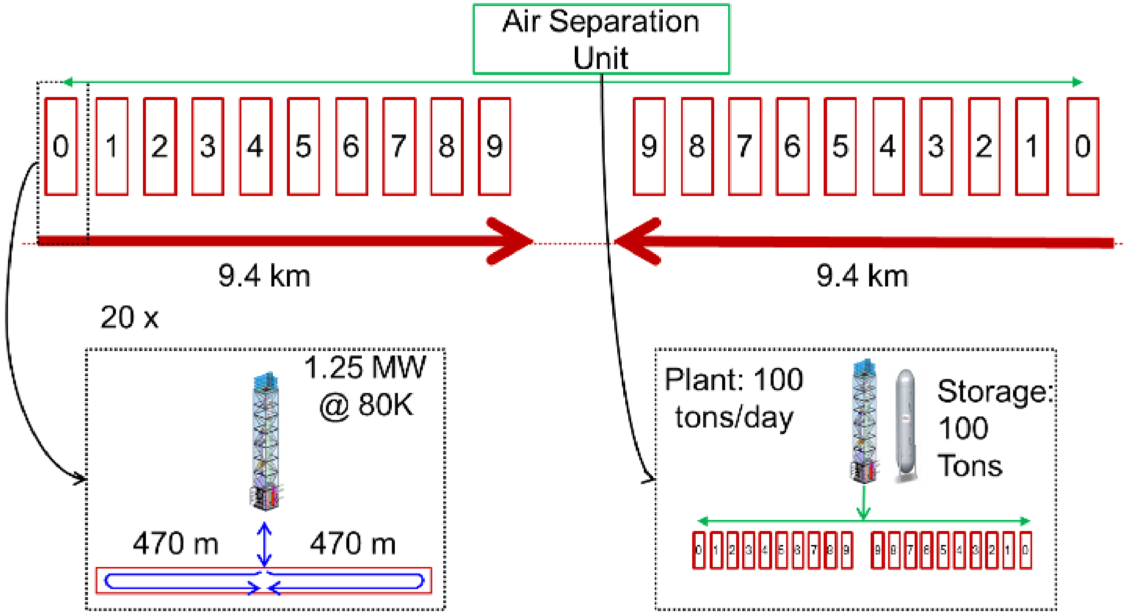
Parameter	Units	Baseline	High-Lumi
Energy CoM	GeV	250	250
Gradient	MeV/m	70	70
Beam Current	A	0.2	1.6
Beam Power	MW	2	16
Luminosity	$x10^{34}$	1.3	10.4
Beam Loading		45%	87%
RF Power	MW/m	30	125
Site Power	MW	~150	~180

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

Energy

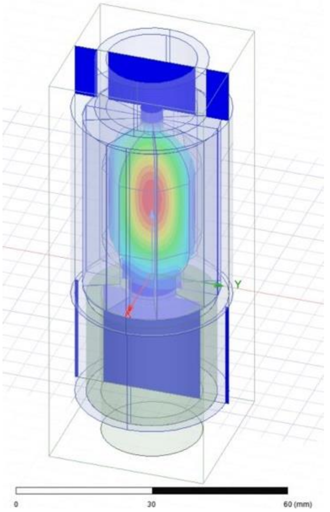
- Scalability studied to 3 TeV
- Requires rf pulse compression for reasonable site power
- Higher gradient option (155 MeV/m) in consideration

Cryogenics Scale to multi-TeV



arXiv:1807.10195 (2018)

HTS Pulse Compressor
REBCO Coatings



Qo ~ 400k

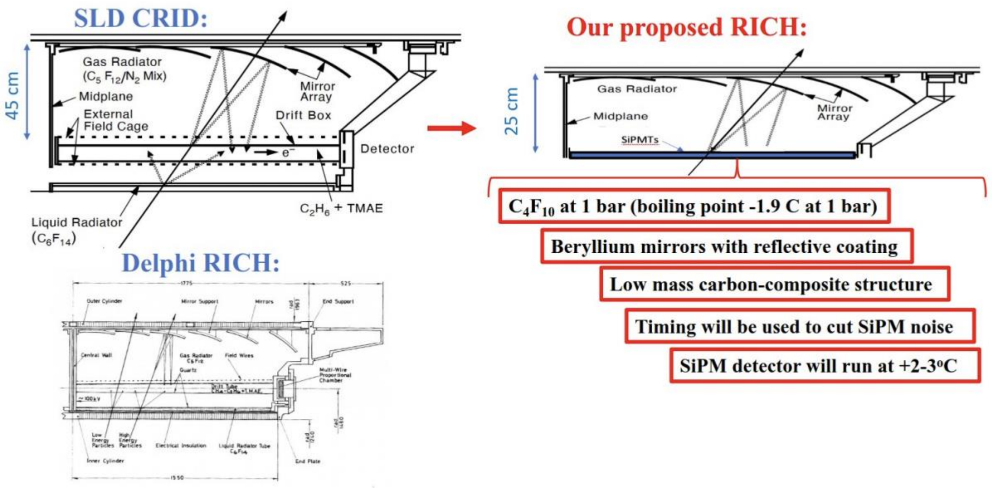
Le Sage, CERN Collaborators

G. Le Sage, S&A Th 18th May 11:30

Detector R&D topics

Some of the R&D topics emerged during LCWS

- Precise timing
  - For PID (10-50ps)
  - For improved tracking (ns) with MAPS
  - For Calorimetry PF
- Highly integrated sensors MAPS for tracking and calorimetry
- Different PID approaches
  - i.e. gaseous *compact* RICH
- Smart sensors/ASICs
- Better and modern software frameworks
  - Simulation and Reconstruction, leveraging LHC expertise



ILC Update Program Related to C^3

ID	Title	Date	Session	Track	Presenters	Email
3	Distributed Coupling Linac for Efficient Acceleration of High Charge Electron Bunches	17 May 2023, 11:00	Accelerator: Normal Conducting RF	Normal Conducting RF	Ankur Dhar	adhar@slac.stanford.edu
4	Physics with the XFEL Compton γγ Collider (XCC) Higgs Factory	17 May 2023, 13:30	Physics and Detectors: Track 1	Track 1: Physics at e+e- colliders	Timothy Barklow	timb@slac.stanford.edu
6	C3	15 May 2023, 10:30	Joint Plenary	Joint	Caterina Vernieri	caterina@slac.stanford.edu
13	A design of the C-band RF photoinjector cavity for testing photocathodes under extreme fields	17 May 2023, 14:40	Accelerator: Normal Conducting RF	Normal Conducting RF	Haoran Xu	haoranxu@lanl.gov
14	Two-cell high-gradient C-band RF accelerator cavity for high power HOM absorber testing	17 May 2023, 11:20	Accelerator: Normal Conducting RF	Normal Conducting RF	Haoran Xu	haoranxu@lanl.gov
20	C3 Main Linac Beam Dynamics	17 May 2023, 10:30	Accelerator: Beam Dynamics	Beam Dynamics	Glen White	whitegr@slac.stanford.edu
21	C3 demonstration plan and applications	17 May 2023, 08:30	Accelerator: Normal Conducting RF	Normal Conducting RF	Faya Wang	fywang@slac.stanford.edu
28	RF sources and power distribution for the C3-demo and beyong	17 May 2023, 13:30	Accelerator: Normal Conducting RF	Normal Conducting RF	Anatoly Krasnykh	krasnykh@slac.stanford.edu
30	Cryogenic Design for C3 Main Linacs	17 May 2023, 14:15	Accelerator: Conventional Facilities	Conventional Facilities	Martin Breidenbach	mib@slac.stanford.edu
31	A nanosecond pulse technology for injection/extraction systems	17 May 2023, 16:10	Accelerator: Beam Dynamics	Normal Conducting RF	Anatoly Krasnykh	krasnykh@slac.stanford.edu
41	C-Band Distributed Coupling Structure Design and Wakefield Damping	17 May 2023, 10:30	Accelerator: Normal Conducting RF	Normal Conducting RF	Zenghai Li	lizh@slac.stanford.edu
46	Pair Production and Hadron Photoproduction Backgrounds at C3	18 May 2023, 13:30	Physics and Detectors: Track 2	Track 2: Analysis and Reconstruction	Elias Mettner	emettner@wisc.edu
47	Muon Backgrounds from Beam Interactions with the Accelerator Structure at C3	18 May 2023, 13:45	Physics and Detectors: Track 2	Track 2: Analysis and Reconstruction	Dimitris Ntounis	dntounis@stanford.edu
51	High Temperature Superconducting RF cavity	18 May 2023, 11:30	Accelerator: Sustainability & Applications	Sustainability and Applications	Gregory Le Sage	lesage@slac.stanford.edu
52	Sustainability studies for the Cool Copper Collider	18 May 2023, 10:30	Accelerator: Sustainability & Applications	Sustainability and Applications	Brendon Bullard	bbullard@slac.stanford.edu
55	Rasnik as alignment system for linac submodules	17 May 2023, 14:30	Accelerator: Conventional Facilities	Conventional Facilities	Harry van der Graaf	vdgraaf@nikhef.nl
88	Cool Copper Collider Demonstrator Beam Dynamics and Diagnostics	18 May 2023, 15:30	Accelerator: Beam Dynamics	Beam Dynamics	Juhao Wu	jhwu@slac.stanford.edu
111	An Integrated Simulation Tool for Dark Current Radiation Effects using ACE3P and Geant4	17 May 2023, 16:00	Accelerator: Normal Conducting RF	Normal Conducting RF	Lixin Ge	lge@slac.stanford.edu
120	Application of CrYogenic Brightness-Optimized Radiofrequency Gun (CYBGORG) for Future Collider Studies	17 May 2023, 14:20	Accelerator: Normal Conducting RF	Normal Conducting RF	Gerard Lawler	gelawler@protonmail.com
207	Wakefield Damping in a Distributed Coupling Accelerating Structure for CLIC	17 May 2023, 16:30	Accelerator: Normal Conducting RF	Normal Conducting RF	Evan Ericson	eje344@mail.usask.ca

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

Questions?

Additional Material

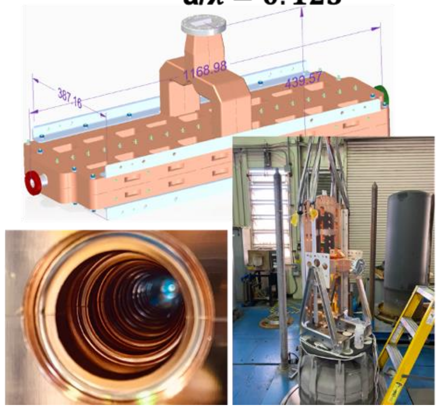
Synergies with Future Colliders

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

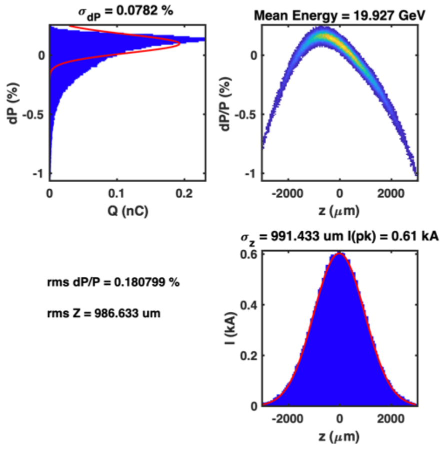
- CLIC - components, damping, fabrication techniques
- ILC - options for electron driven positron source based C^3 technology
- Muon Collider - high gradient cryogenic copper cavities in cooling channel, alternative linac for acceleration after cooling
- AAC - C^3 Demo utilized for staging, C^3 facility 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**

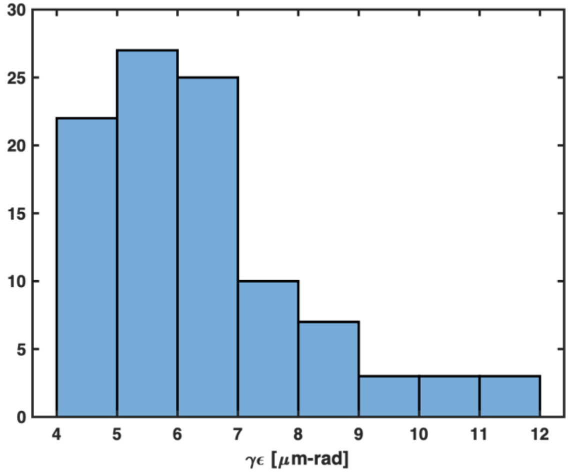
Wide Aperture S-band Injector Linac
$a/\lambda = 0.125$



- 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

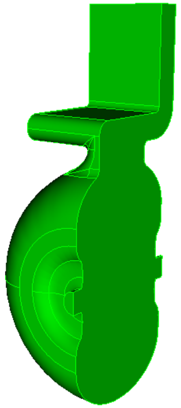
90% seeds < 8 um-rad with lattice errors

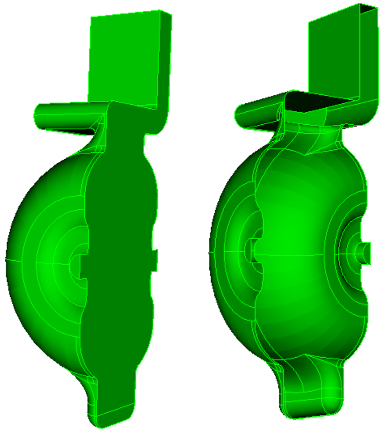




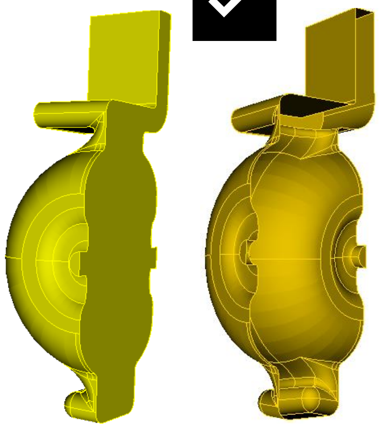
Further Cavity Optimization Possible

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



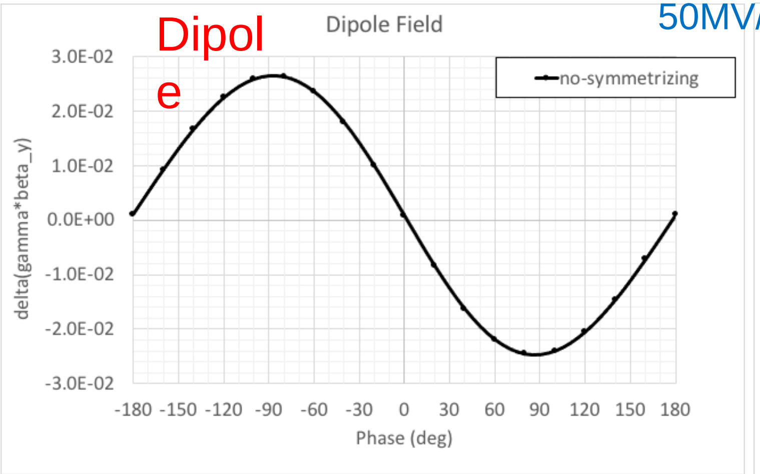


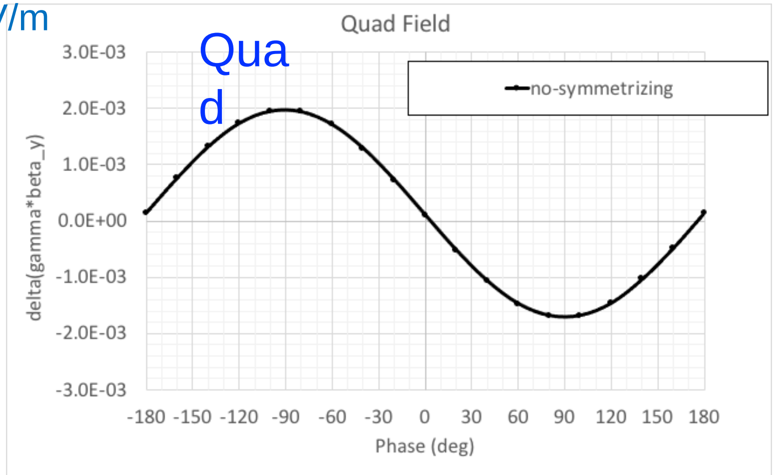
V1-simple-stub (not ideal cancellation)



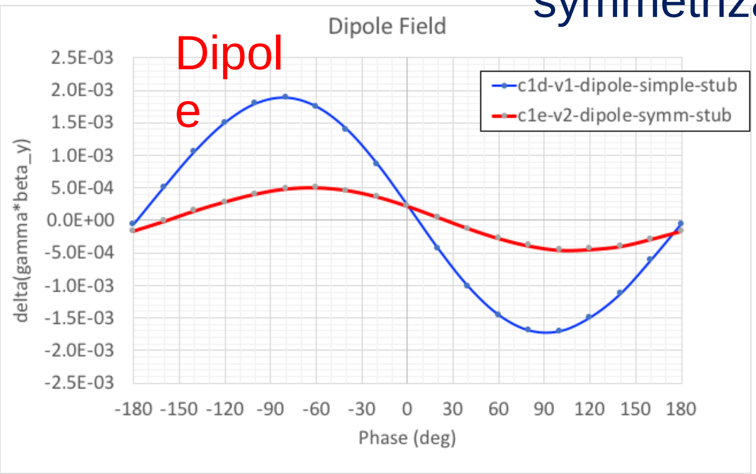
V2-symm-stub (good cancellation)

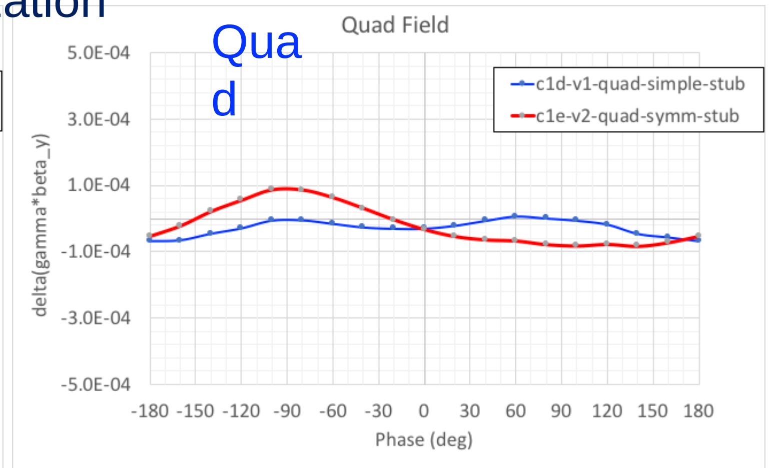
dipole, quad calculated at 50MV/m





w/o symmetrization





with symmetrization 100X reduction

Zenghai Li

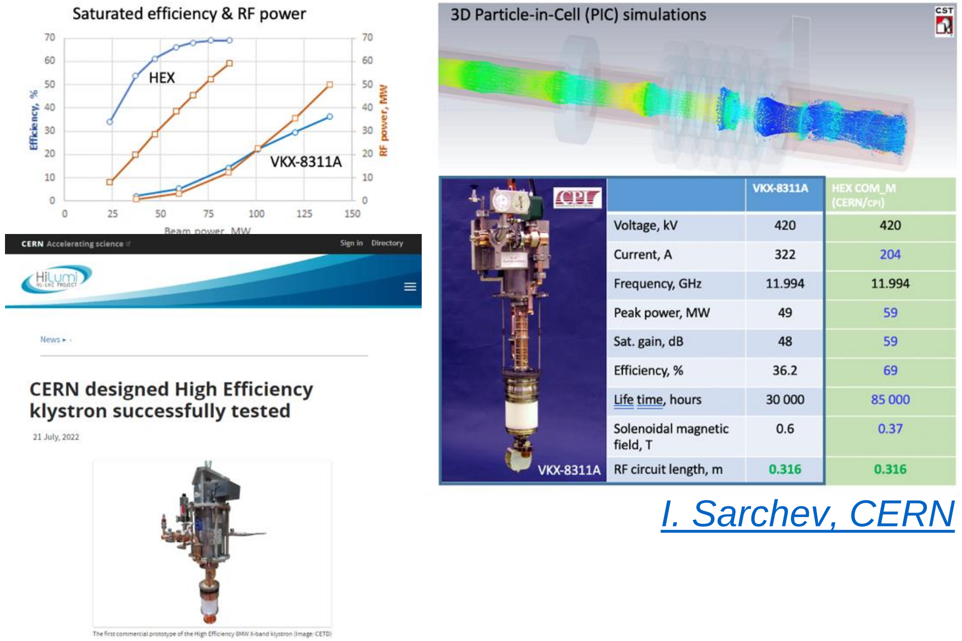
Global Contributions

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)

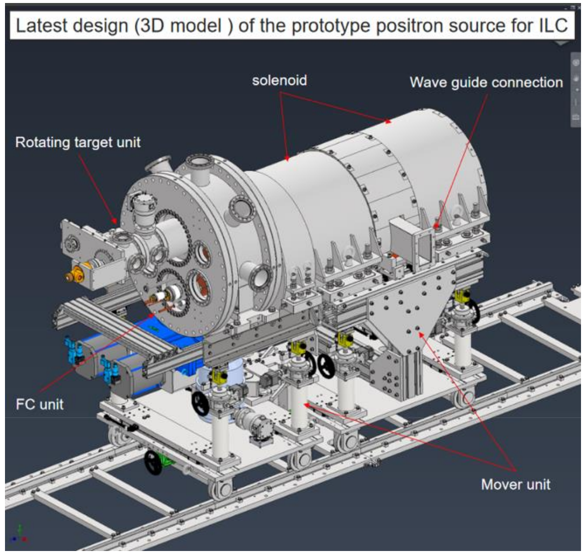
Retro-fit High Efficiency 50 MW, 12 GHz klystron (CERN/CPI).



	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

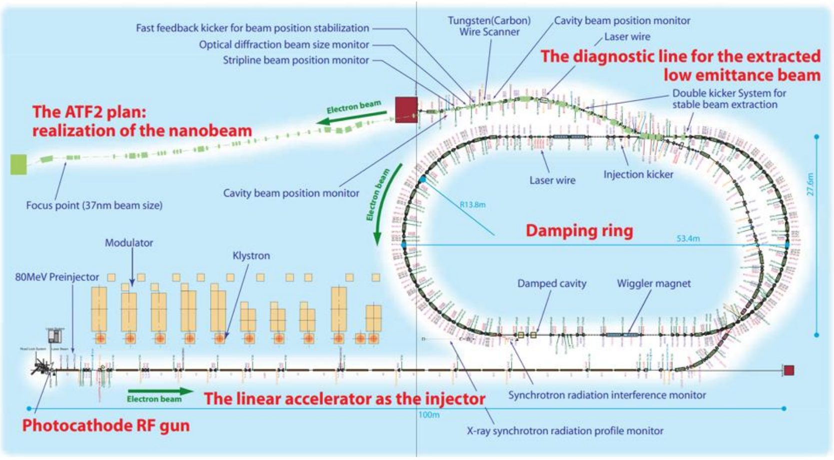
I. Sarchev, CERN

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

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

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

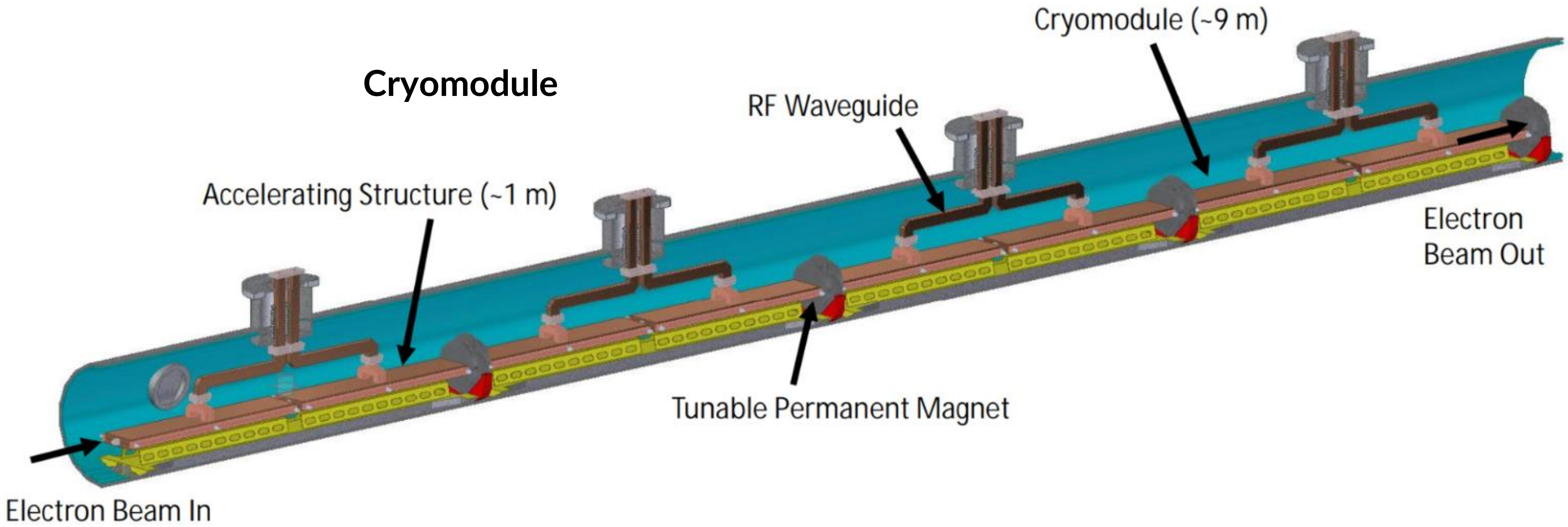
- Combination of mechanical and beam based alignment

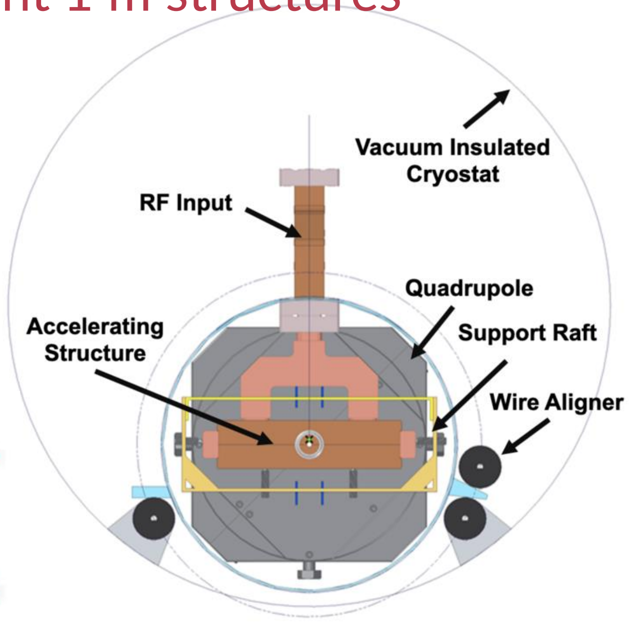
Pre-alignment warm, cold alignment by wire, followed by beam based

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

Investigating support and assembly design

Cryomodule





Cryomodule Cross Section

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

Using established collider designs to inform initial parameters

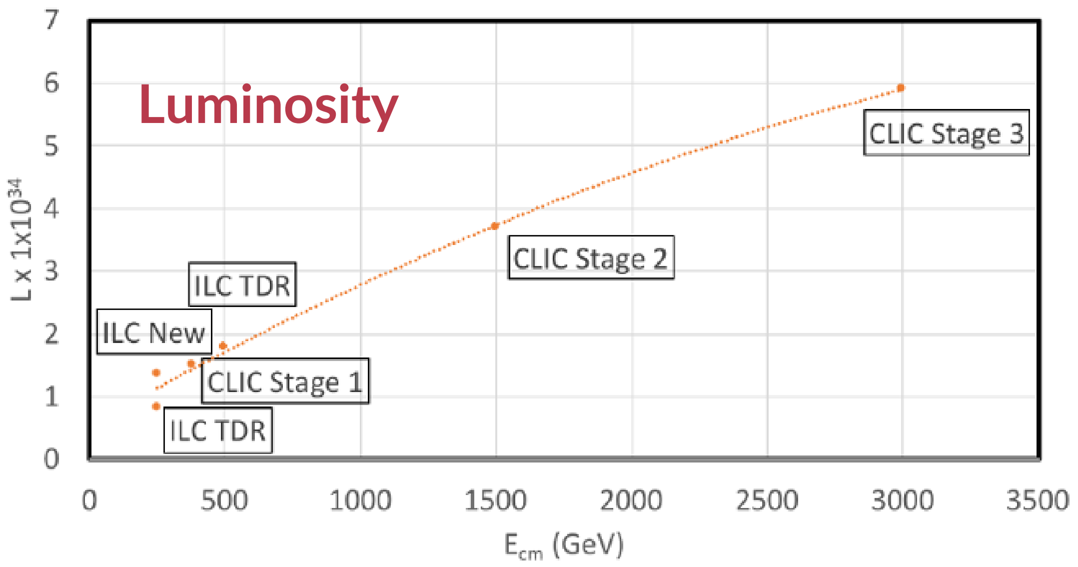
Quantifying impact of wakes requires detailed studies

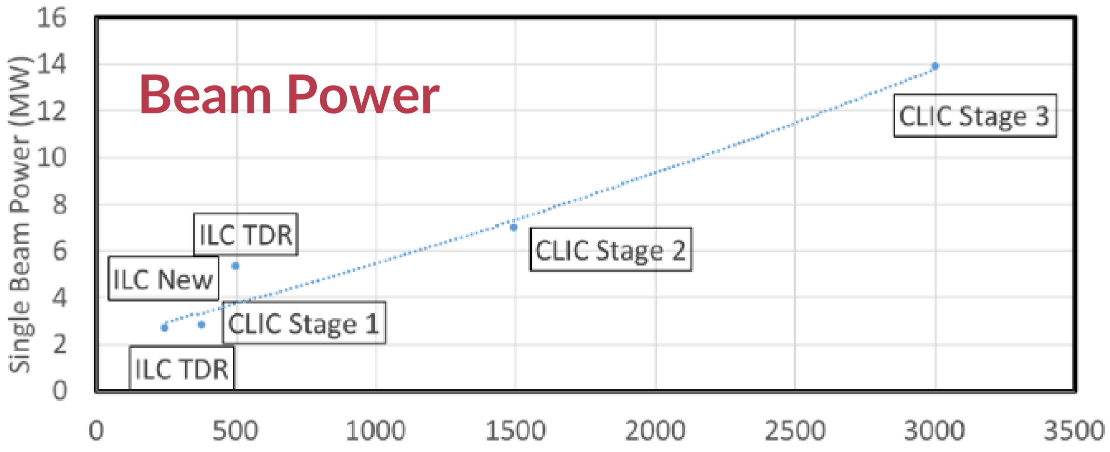
- Most important terms – aperture, bunch charge (and their scaling with frequency)

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





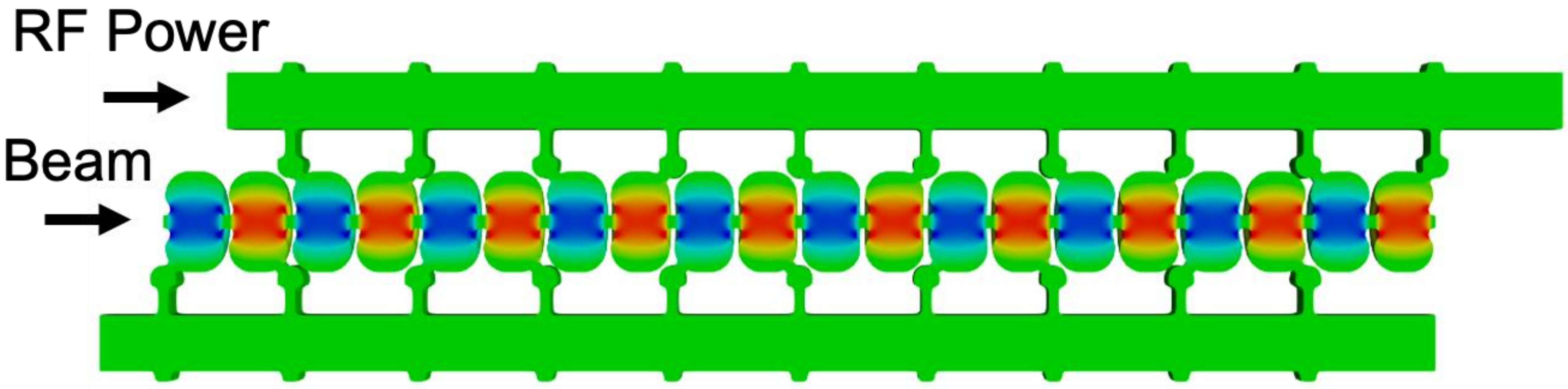
https://clic-meeting.web.cern.ch/clic-meeting/clictable2010.html

NLC, ZDR Tbl. 1.3,8.3

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

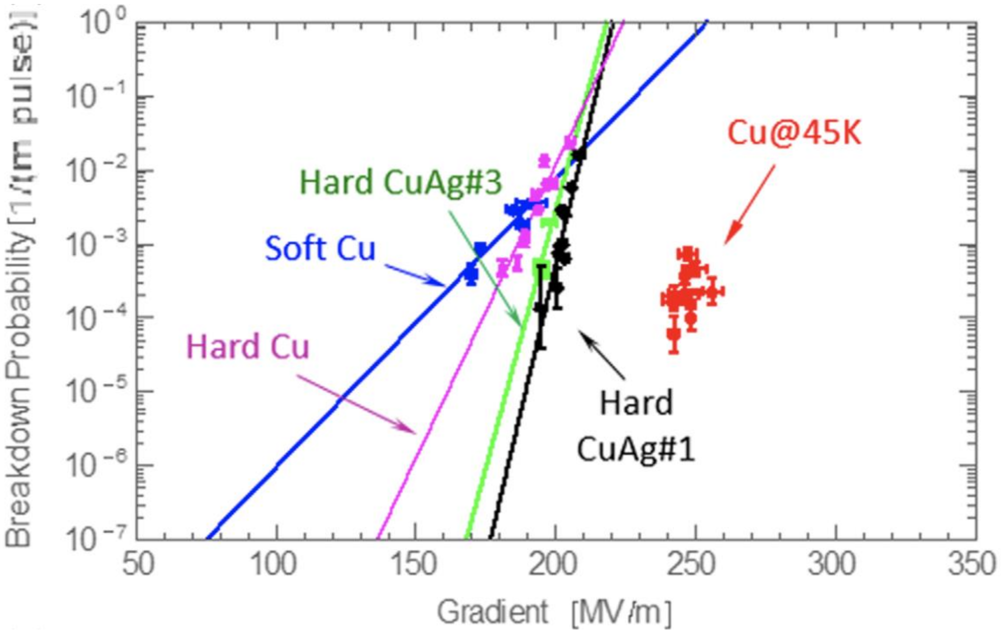
- Increased material strength is key factor
- Increase electrical conductivity reduces pulsed heating in the material

Operation at 77 K with liquid nitrogen is simple and practical

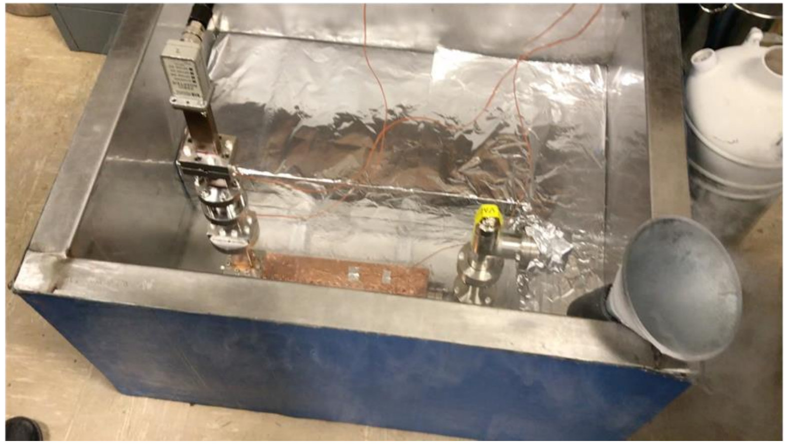
- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency

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

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



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



Beam Format and Detector Design Requirements

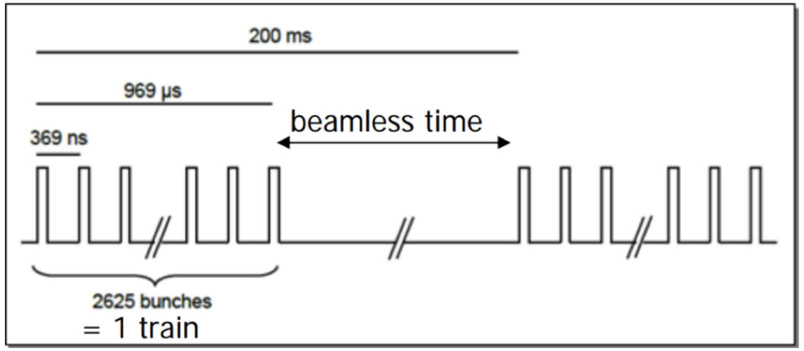
Collider	ILC	CCC
σ_z	300 μm	100 μm
β_x	8.0 mm	13 mm
β_y	0.41 mm	0.1 mm
ϵ_x	500 nm/rad	900 nm/rad
ϵ_y	35 nm/rad	20 nm/rad
N bunches	1312	133
Repetition rate	5 Hz	120 Hz
Crossing angle	0.014	0.020
Crab angle	0.014/2	0.020/2

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

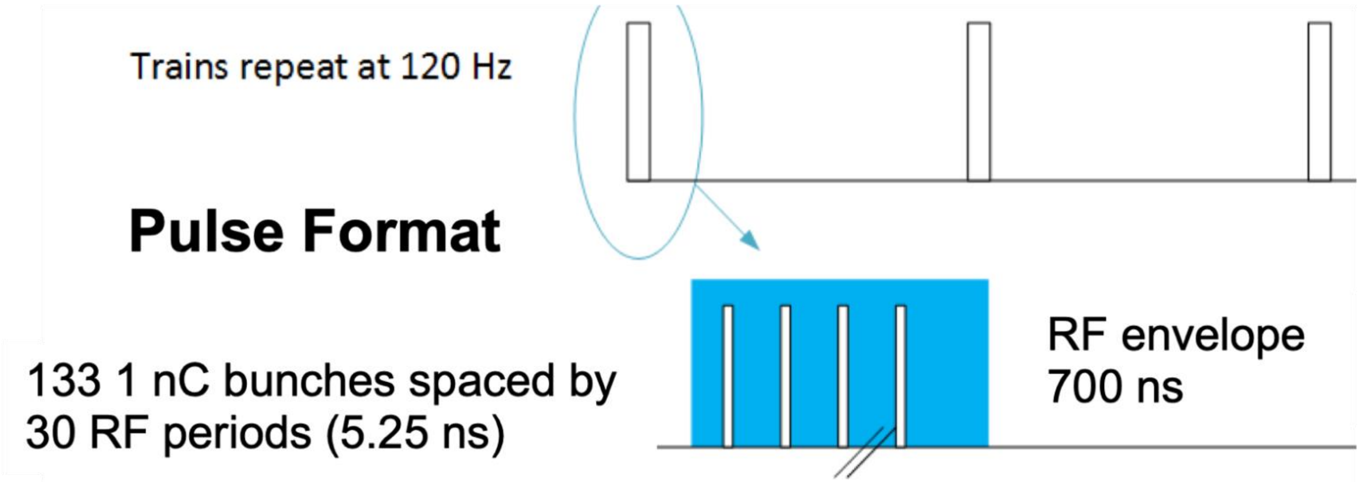
C^3 time structure is compatible with ILC-like detector overall design and ongoing optimizations

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 $e^-_L e^+_R$

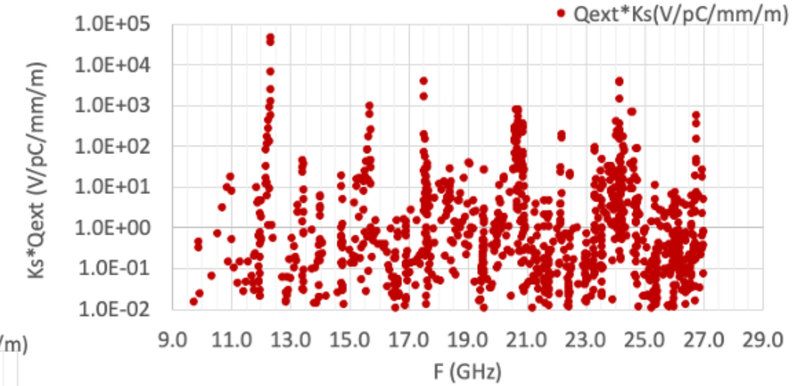
coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
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

Implementation of Slot Damping

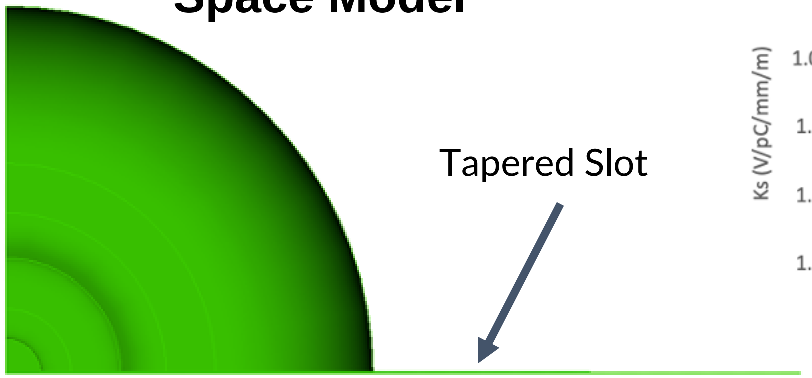
Need to extend to 40 GHz / Optimize coupling / Modes below 10^4 V/pC/mm/m

NiCr coated damping slots in development

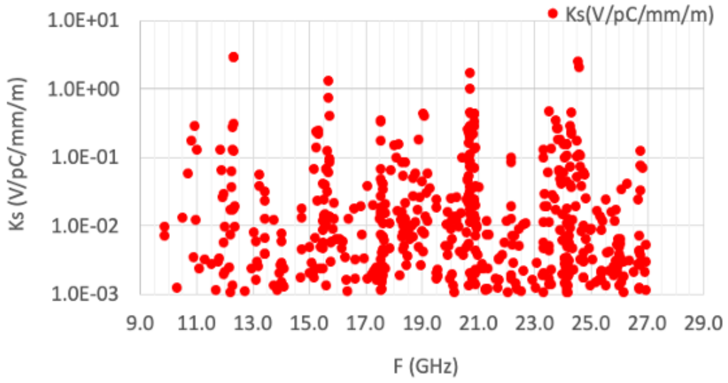
Kick Factor * Q

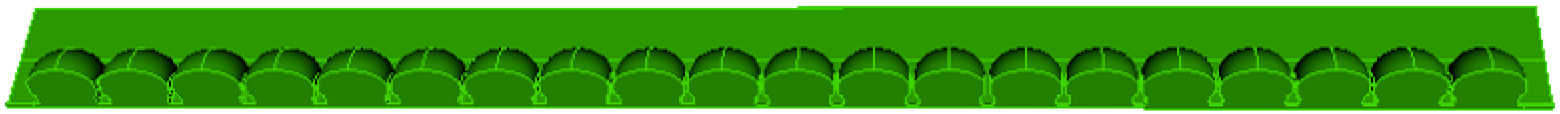


Vacuum Space Model

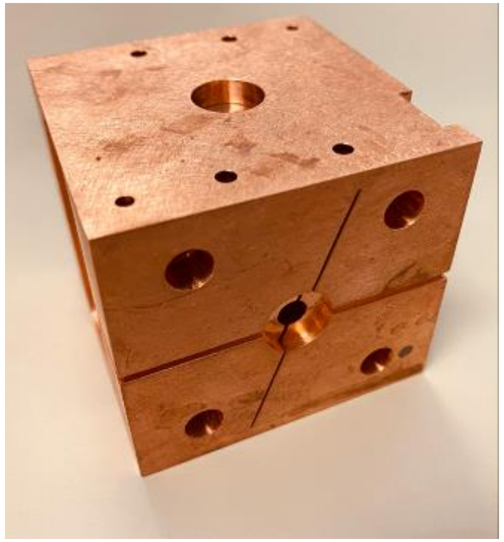


Kick Factor





Damping Slot Prototype



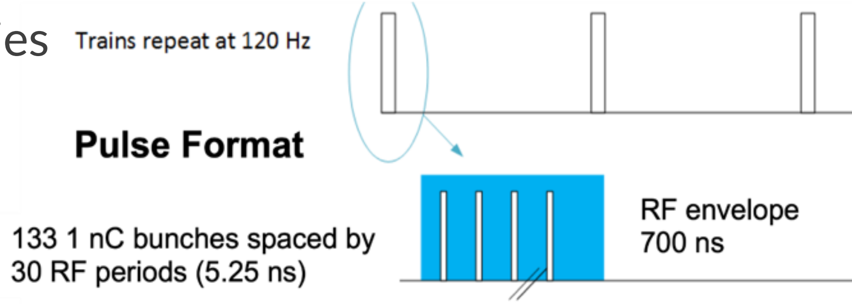
Accelerator Complex

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

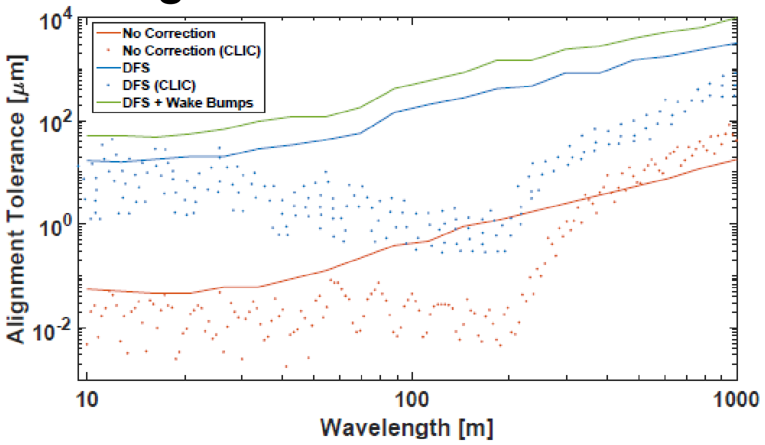
Large portions of accelerator complex compatible between LC technologies

- 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



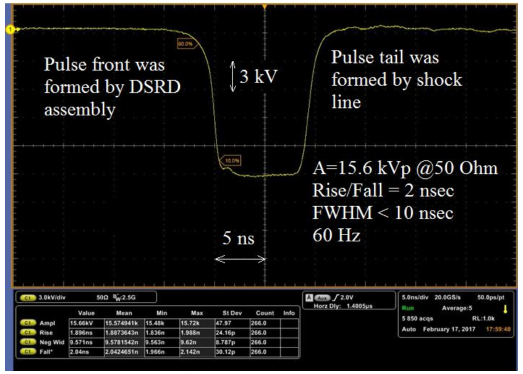
G. White, Beam Dynamics W 17th May 10:30

Alignment and DFS Studies

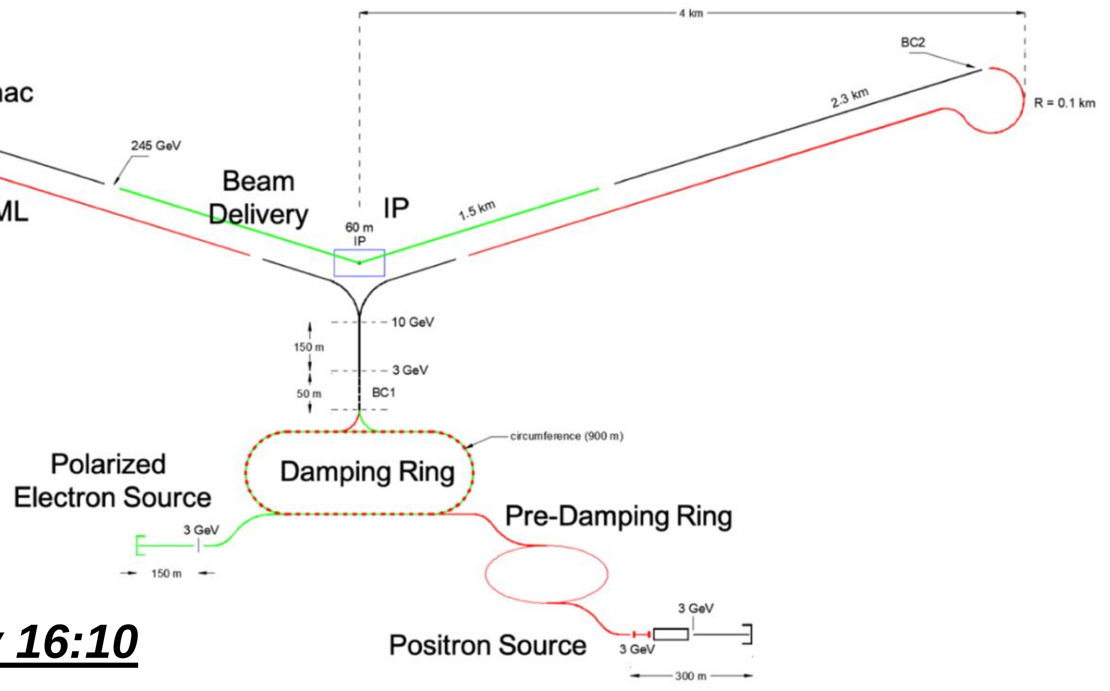


D. Schulte, CLIC Main Linac Beam Dynamics, ALEGRO Workshop, CERN 2019

DR Kickers



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



A. Krasnykh, Beam Dynamics W 17th May 16:10

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