C^3 – Cool Copper Collider:
A New Approach

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Acknowledgements

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

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ABSTRACT

We present a proposal for a cold copper distributed coupling accelerator that can provide a rapid route to precision Higgs physics with a compact 8 km footprint. This proposal is based on recent advances that increase the efficiency and operating gradient of a normal conducting accelerator. This technology also provides an e^+e^- collider path to physics at multi-TeV energies. In this article, we describe our vision for this technology and the near-term R&D program needed to pursue it.

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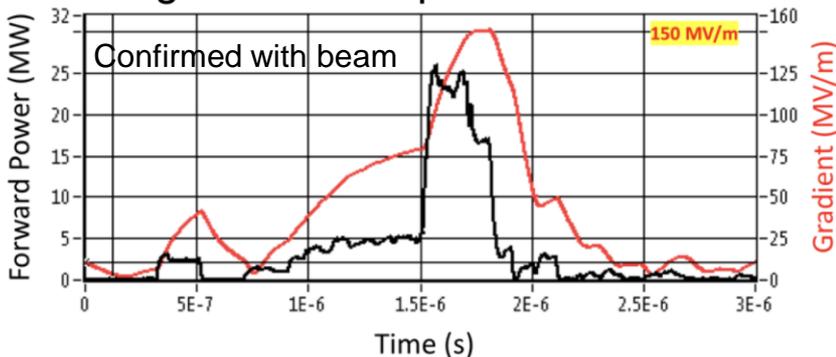Mitchell Schneider
Radiabeam
Brandon Weatherford

2

- C³ 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 (LN2 ~80K)
- Robust operations at high gradient: 120 MeV/m
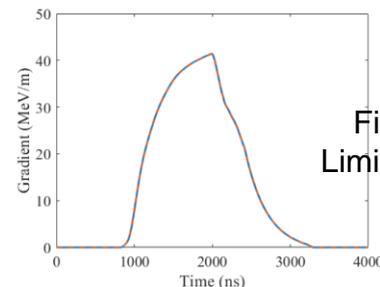- Scalable to multi-TeV operation
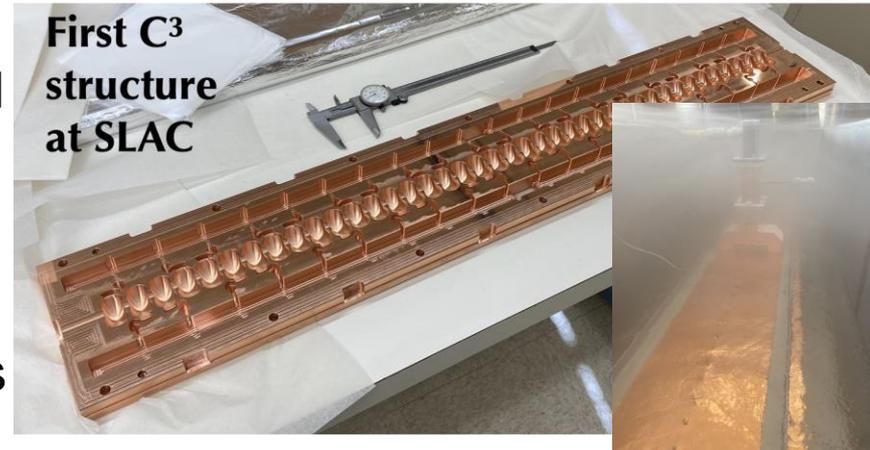
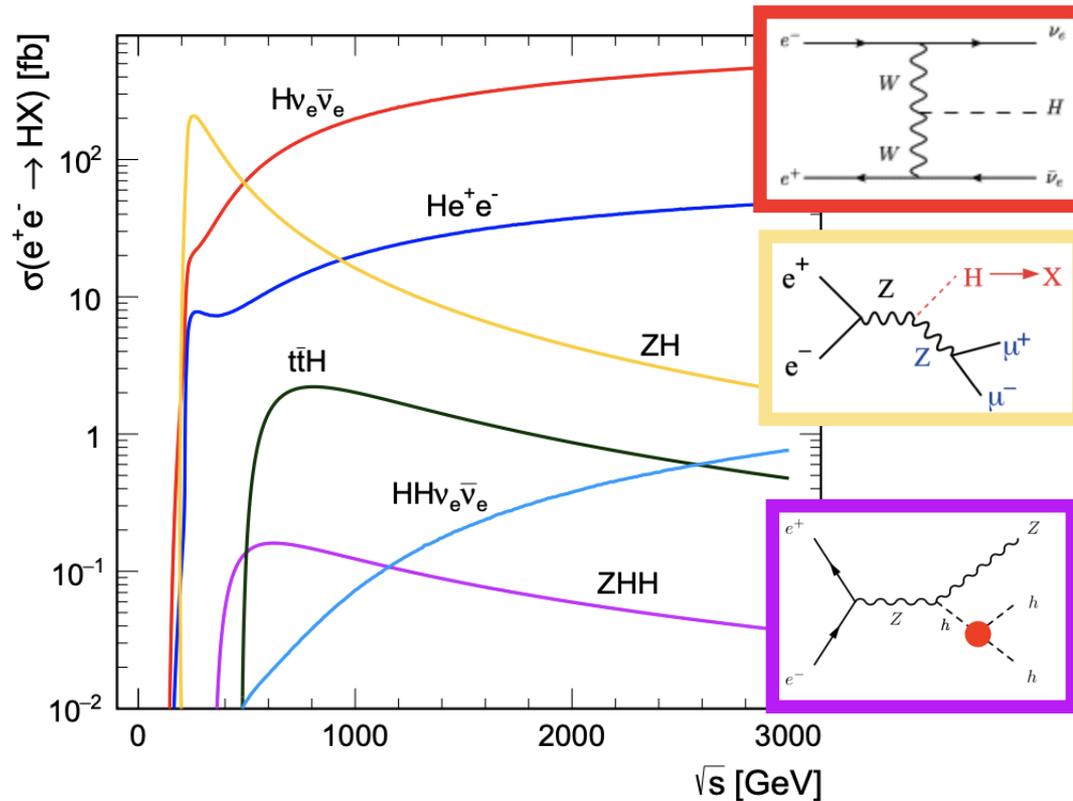First C³ structure at SLAC

High power test at Radiabeam

First 300 K High Power Test
Limited Available RF - Next Cryo

High Gradient Operation at 150 MV/m

Confirmed with beam

150 MV/m

Cryogenic Operation at X-band

3

ZH is dominant at **250 GeV**

Above **500 GeV**
- Hνν dominates
- ttH opens up
- HH production accessible with ZHH

C. Vernieri

- 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)

Accelerator Complex

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

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

- Large portions of accelerator complex are compatible between LC technologies

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

C³ - Investigation of Beam Delivery Adapted from ILC/NLC
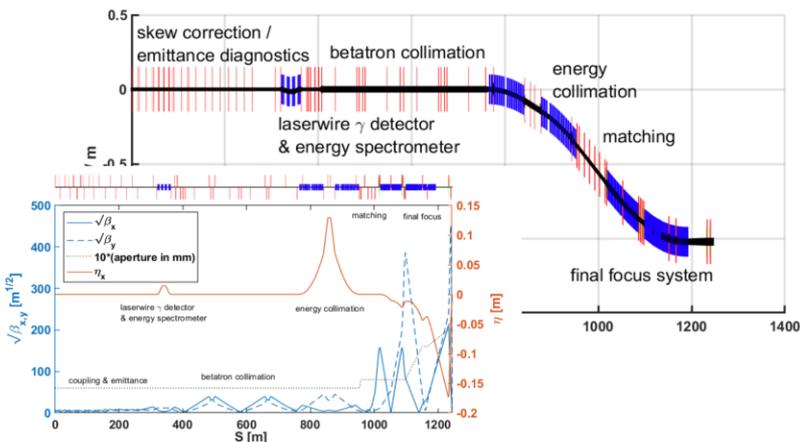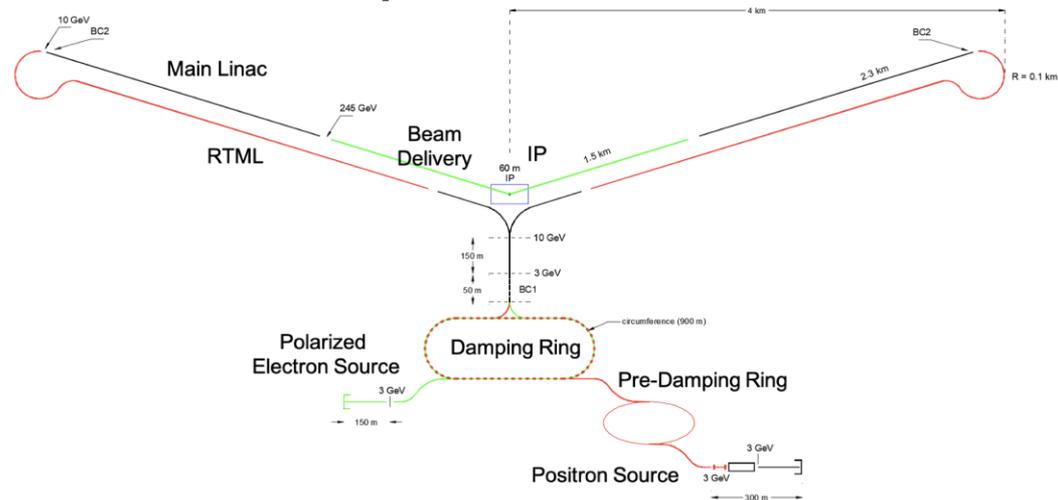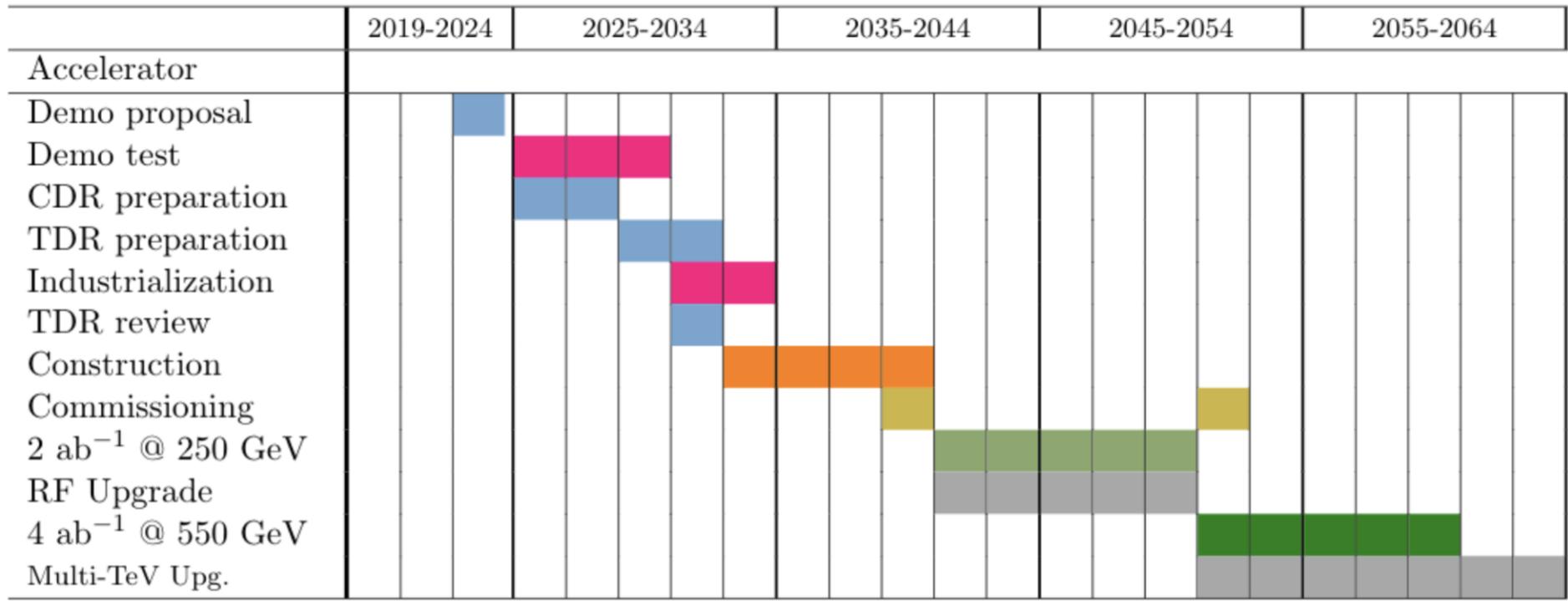

C³ - 8 km footprint for 250/550 GeV

Table of 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	$\sim$150	$\sim$175
Length [km]	23.8	11.4	20.5 (31)	8	8
L* [m]	2	6	4.1	4.3	4.3

Timeline for C³ 250/550

- Technically limited timeline following community engagement through the full Snowmass process to define the parameters of the C³ proposal

Accelerator	2019-2024	2025-2034	2035-2044	2045-2054	2055-2064
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.					

HL-LHC

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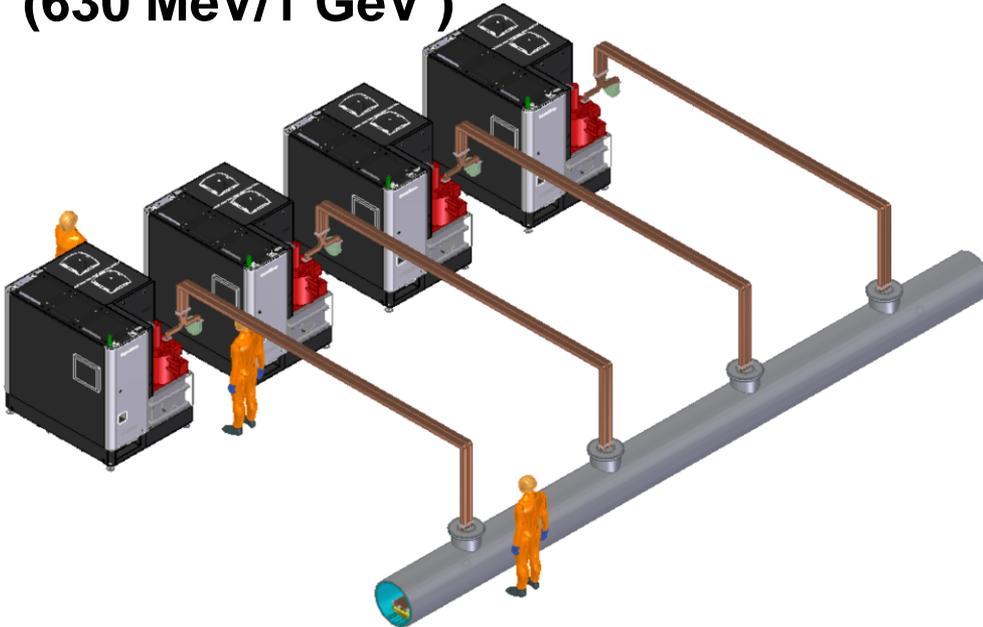
Usable Tunnel Width - 9.5 m
 (Same tunnel width as ILC)
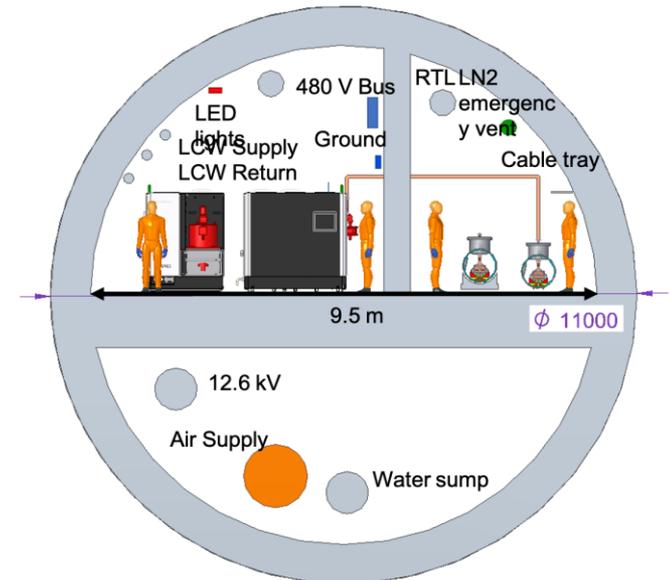
Cryogenics

- 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

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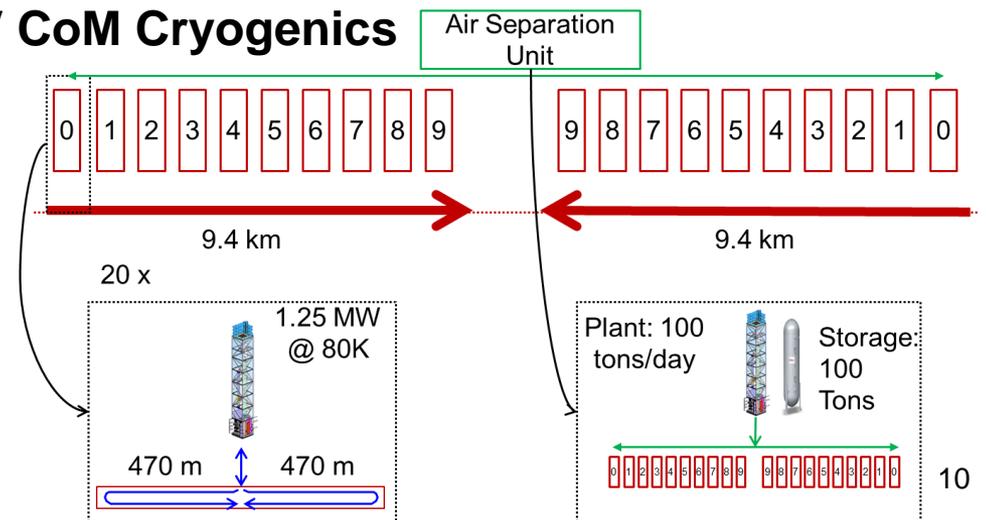$$\eta_{cs} = Cryogenic\ Structure$$
$$\eta_k = RF\ Source$$

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

Conservative estimate by Air Liquide
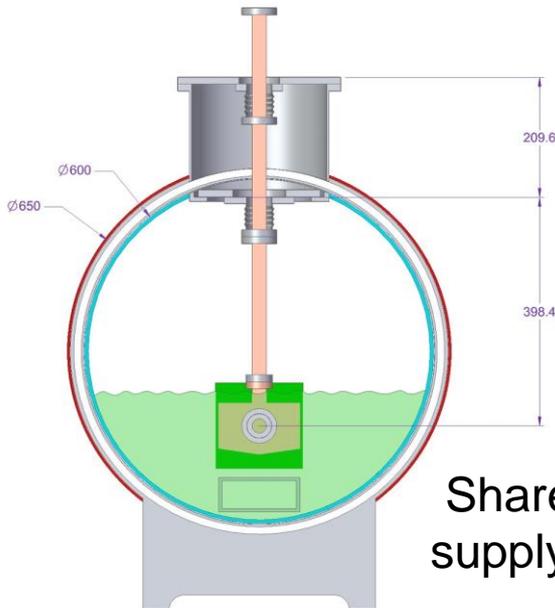
Shared nitrogen supply and return

2 TeV CoM Cryogenics

10

Cryomodule Design and Alignment

- 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

1 m Accelerator
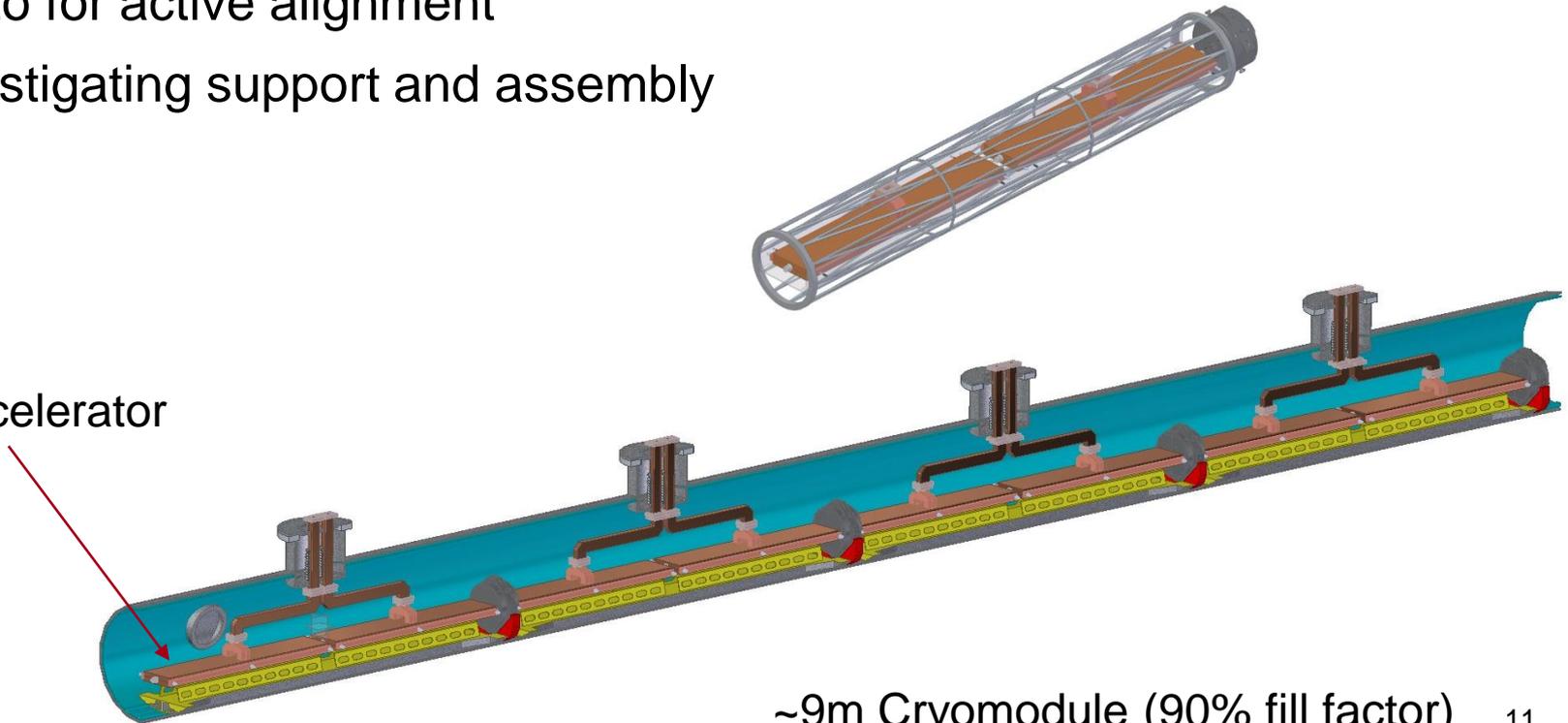
~9m Cryomodule (90% fill factor)

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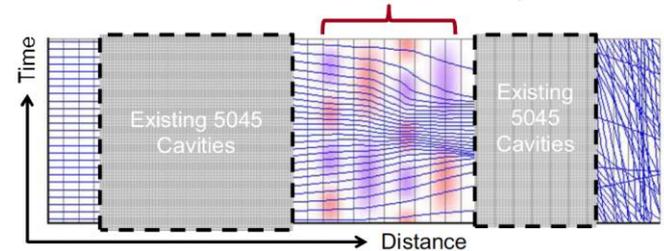
SLAC BAC Prototype
S-band Retrofit +10% efficiency, 73 MW

4 New Cavities Added to Drift Space

BVEI X-band 50 MW 57% COM Prototype

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

Near Term Industry

20-MW X-band Klystron (Recent on the market)

Klystron: E37116   Perveance : 1.25

Electromagnet: VT-68970

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

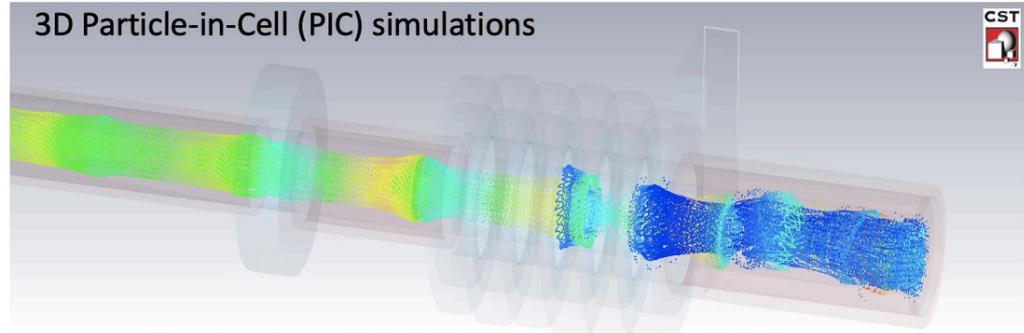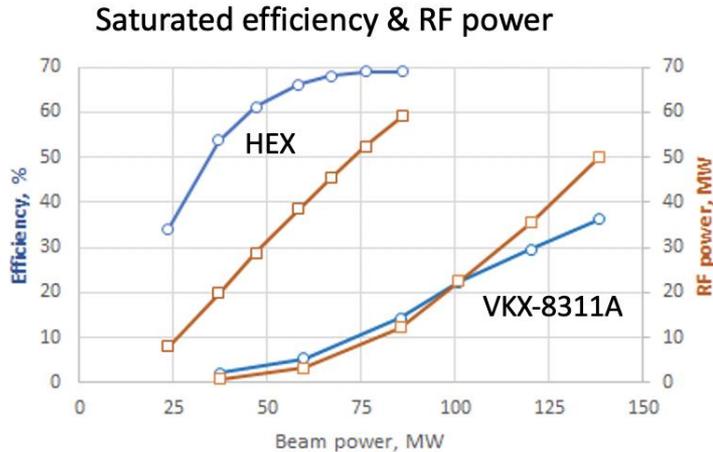* Actual efficiency is estimated to be 46 - 48%.

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

HEX

VKX-8311A

3D Particle-in-Cell (PIC) simulations

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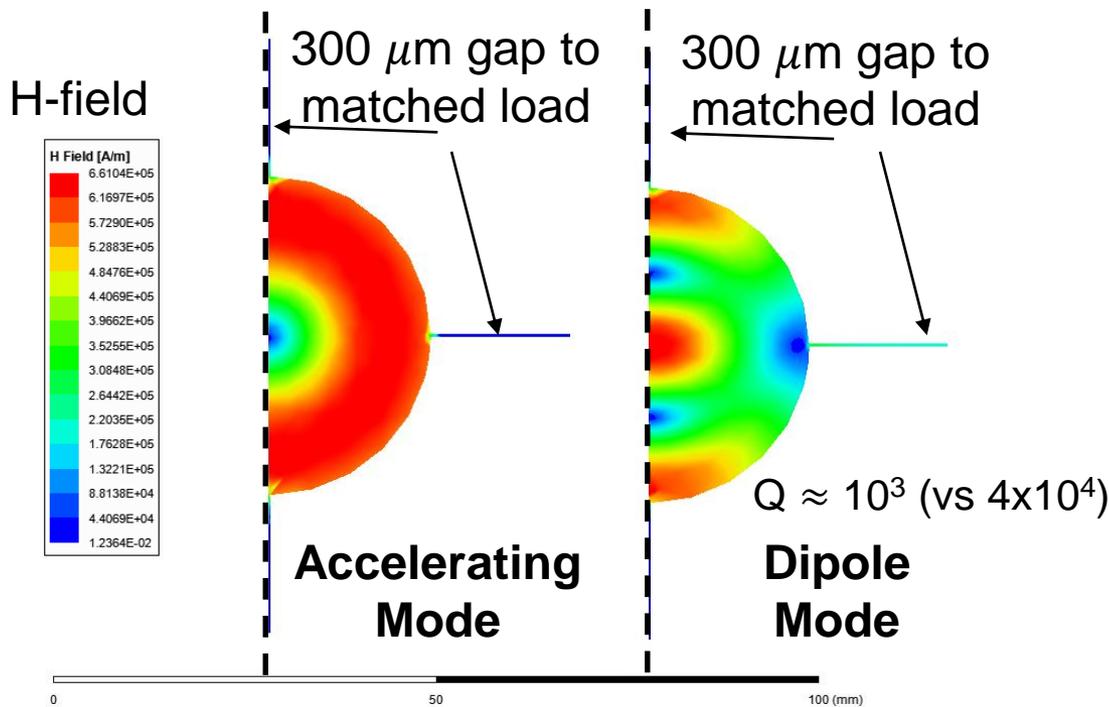- Increased power gain (10 dB)
- Reduced solenoidal field

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
<u>Life time</u>, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.37
RF circuit length, m	0.316	0.316

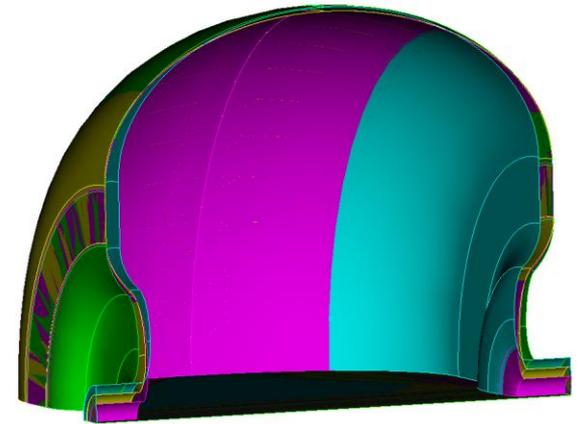I. Syratchev, CLIC PM #41, 13.12.2021

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

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

Design of Detuned Cavities

H-field

H Field [A/m]
6.6104E+05
6.1697E+05
5.7290E+05
5.2883E+05
4.8476E+05
4.4069E+05
3.9662E+05
3.5255E+05
3.0848E+05
2.6442E+05
2.2035E+05
1.7628E+05
1.3221E+05
8.8138E+04
4.4069E+04
1.2364E-02

300 μm gap to matched load

300 μm gap to matched load

$Q \approx 10^3$ (vs 4×10^4)

Accelerating Mode

Dipole Mode

Quadrant Structure

(b)

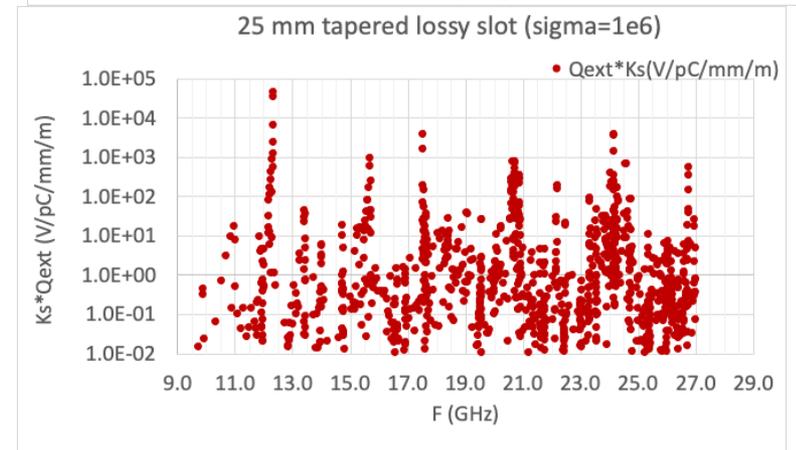Abe et al., PASJ, 2017, WEP039

14

0   50   100 (mm)
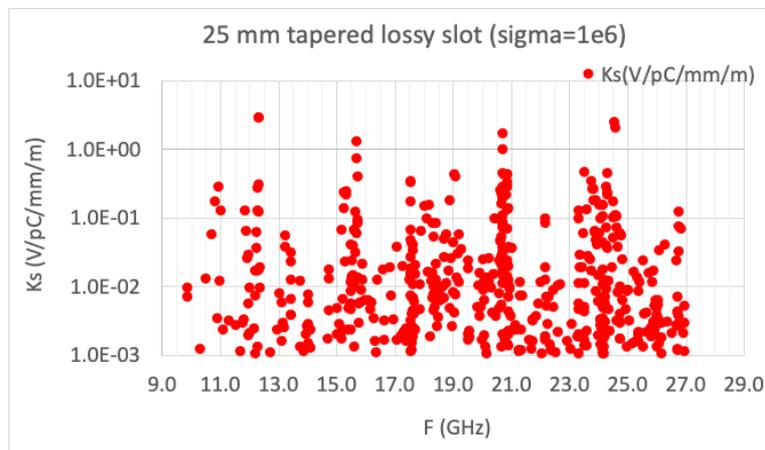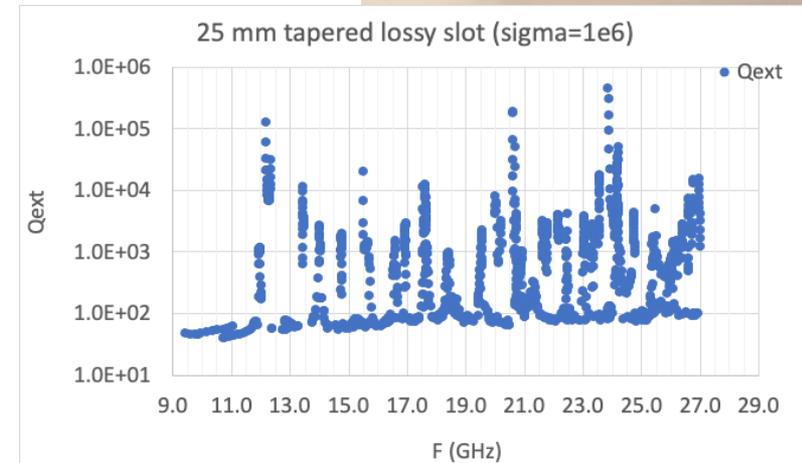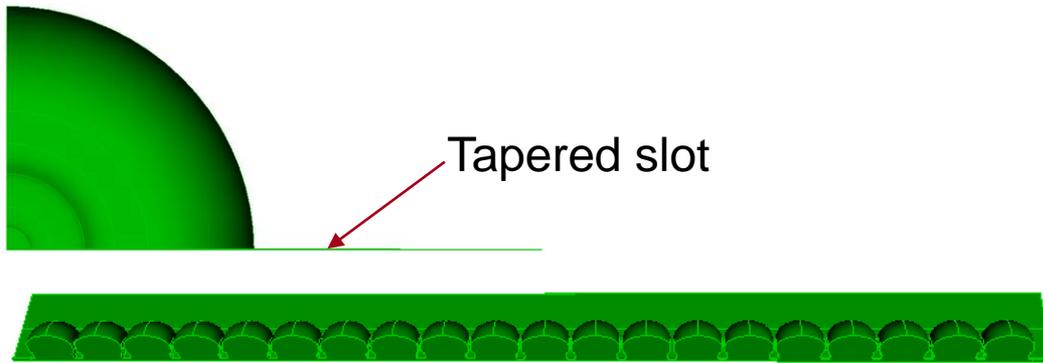
Implementation of Slot Damping

Slot Damping Prototype Working on NiCr Coating
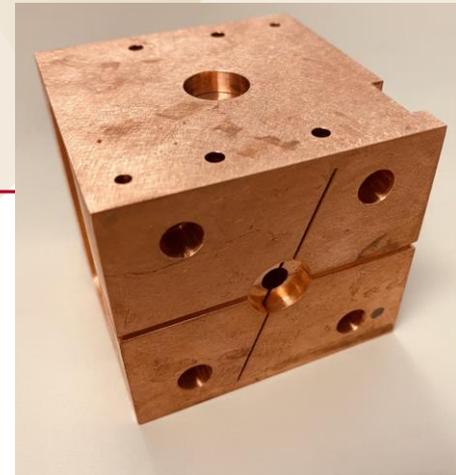
- Need to extend to 40 GHz / Optimize coupling / Modes below 10^4 V/pC/mm/m
- NiCr coated damping slots in development

Tapered slot

25 mm tapered lossy slot (sigma=1e6)

25 mm tapered lossy slot (sigma=1e6)

25 mm tapered lossy slot (sigma=1e6)

Demonstration Facility

C^3 demonstration facility to advance technology beyond CDR level

Minimum requirement for Demo Facility:

- **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 step is included in our timeline. The cost is O(100 M$).

- This demonstration directly benefits development of compact FELs for photon science.

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 although we will look for further cost-optimizations for the specific needs of the C^3

16

Demonstration Facility R&D Topics

Direct Demonstrator Facility (>=50 m, 120 Hz, 133X 1nC)

- Cryomodule Cryogenics and Beamline Design
- Cryomodule Assembly
- Beam dynamics - lianc, damping rings, bunch compressors
- RF High-brightness photo-injector for demonstrator
- RF High-brightness polarized photo-injector
- DC polarized gun and injector
- Low level rf - Klystron controls and rf signal control
- Raft alignment:
  - Warm/cold mechanical/piezoelectric feedback
- High Power RF Distribution (waveguide components, loads)
- End-to-end simulation

Parallel R&D

- Levitated Positron Target - Radiatively cooled
- QD0/QD1
- Advanced RF Source R&D
- RF Distribution (pulse compressor)
- Site Studies
- Error Sensitivity Study
- Polarimetry

Industrialization

- Cryogenics Quads
- Linac Fabrication
- Cryomodule Cryogenics and Beamline Design
- Cryomodule Production
- Klystron
- Modulator
- Tunnel
- Pre-Fab Surface Construction
- Large scale cryogenics

Additional Cost Reduction

- High-brightness polarized rf gun to remove one damping ring

- Low-voltage massively parallel rf sources – cost driver for the main linac and whole complex at TeV scale

- RF pulse compression – achieve nominal gradient faster and reduce thermal load on cryogenics

  - High temperature superconductor possible 10X improvement in Q-factor at LN temperature
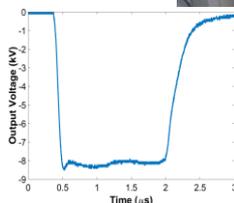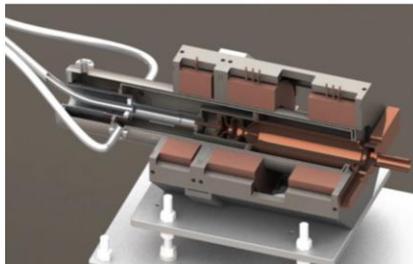
REBCO Tape Coated Cavity

High Brightness Gun PRAB 22, 023403 (2019)

Low-cost "Digikey Catalog" Marx Modulator

HTS tape

Tape attached at ICMAB by G. Telles, N. Lamas, X. Granados, T. Puig, J. Gutierrez

From: Jessica Golm, Sergio Caltroni, Walter Wuensch
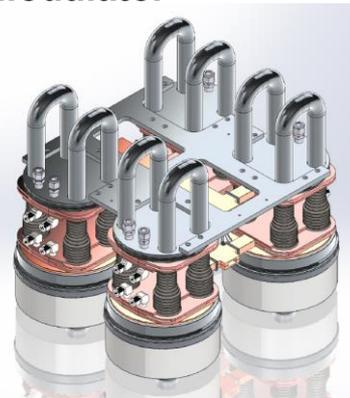
Modular Klystron Array operating at extremely low voltages

18

Questions?