C3 Demonstration Facilities

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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.

arXiv:2110.15800

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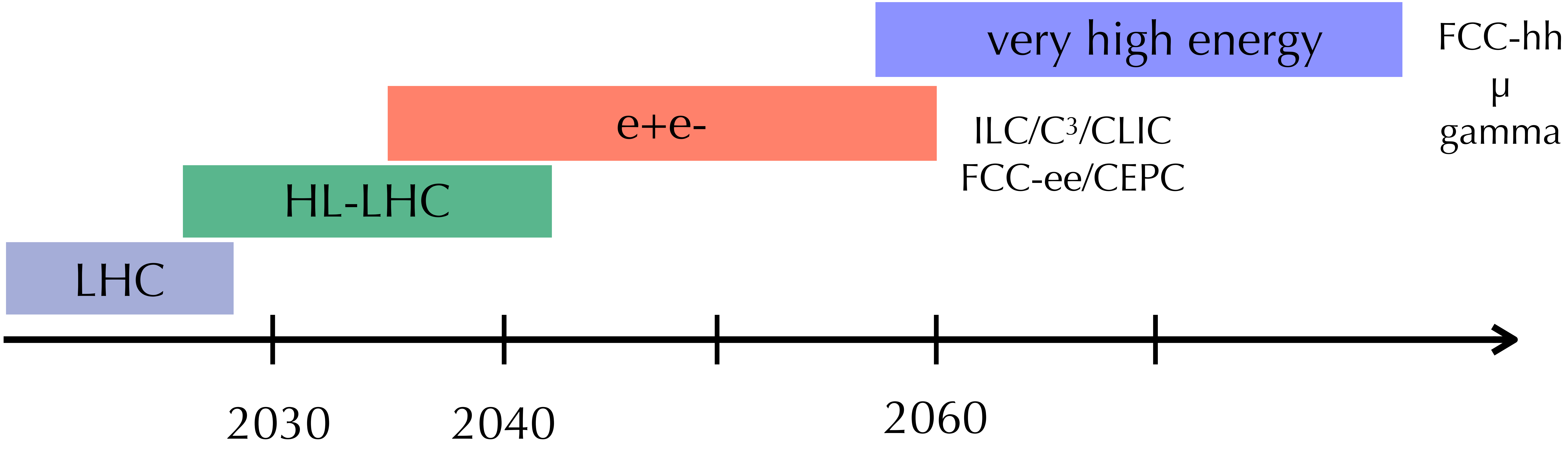
What's next?

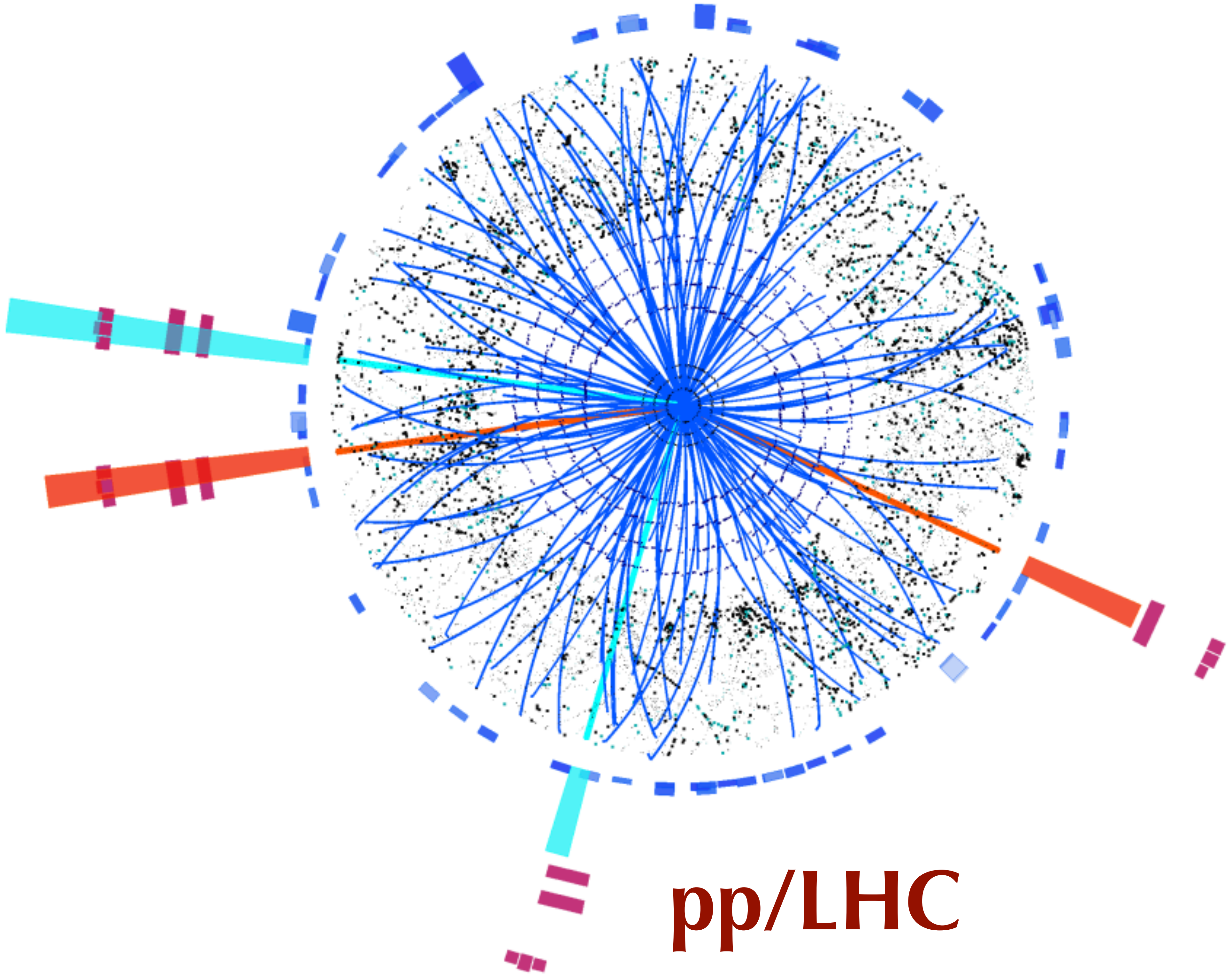


Wish list beyond HL-LHC:

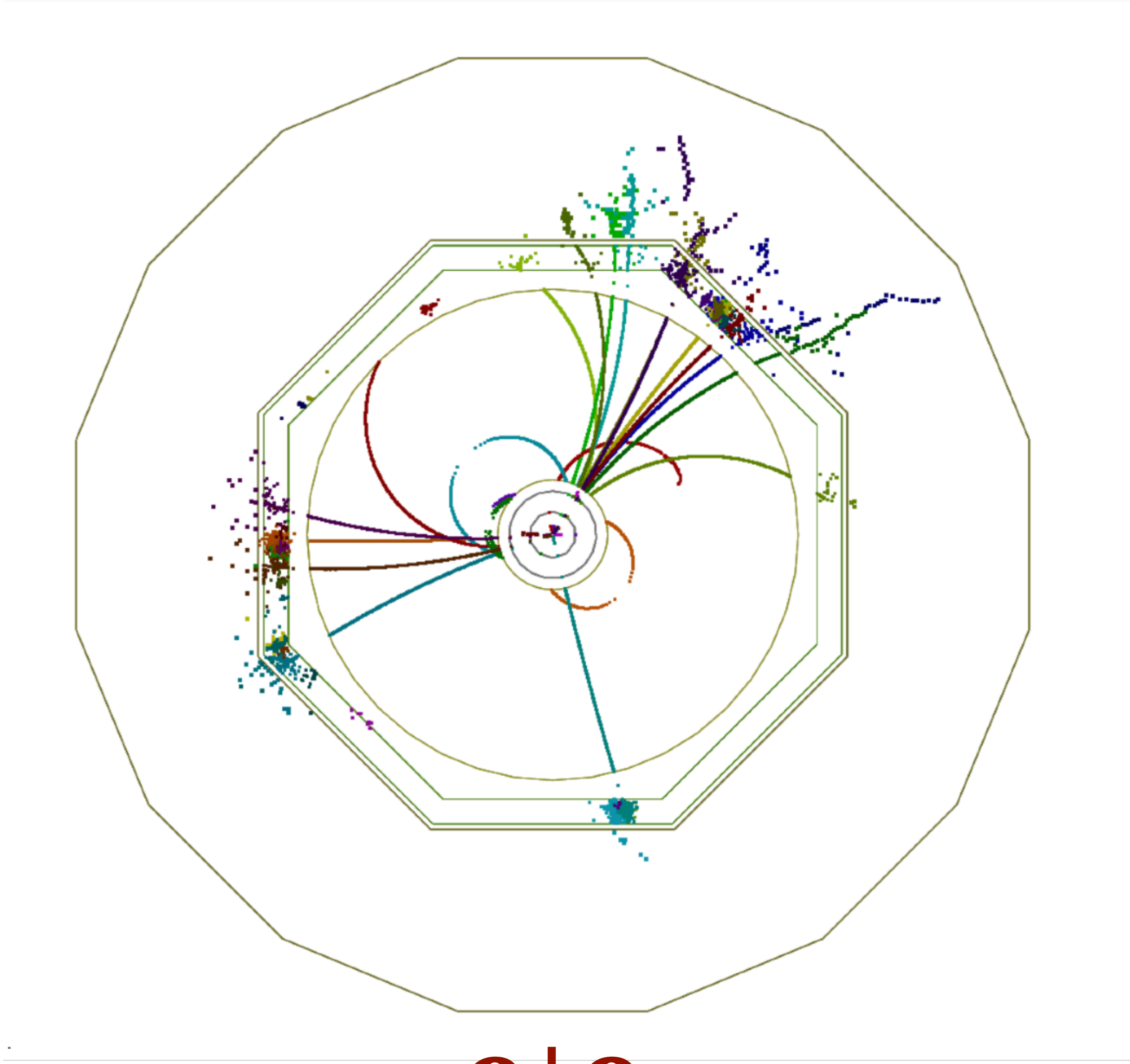
1. **Establish Yukawa couplings to light flavor $\Longrightarrow$ needs precision**
2. **Establish self-coupling $\Longrightarrow$ needs high energy**

Why e^+e^-?

- Initial state well defined & polarization $\Longrightarrow$ High-precision measurements
- Higgs bosons appear in 1 in 100 events $\Longrightarrow$ Clean experimental environment and trigger-less readout

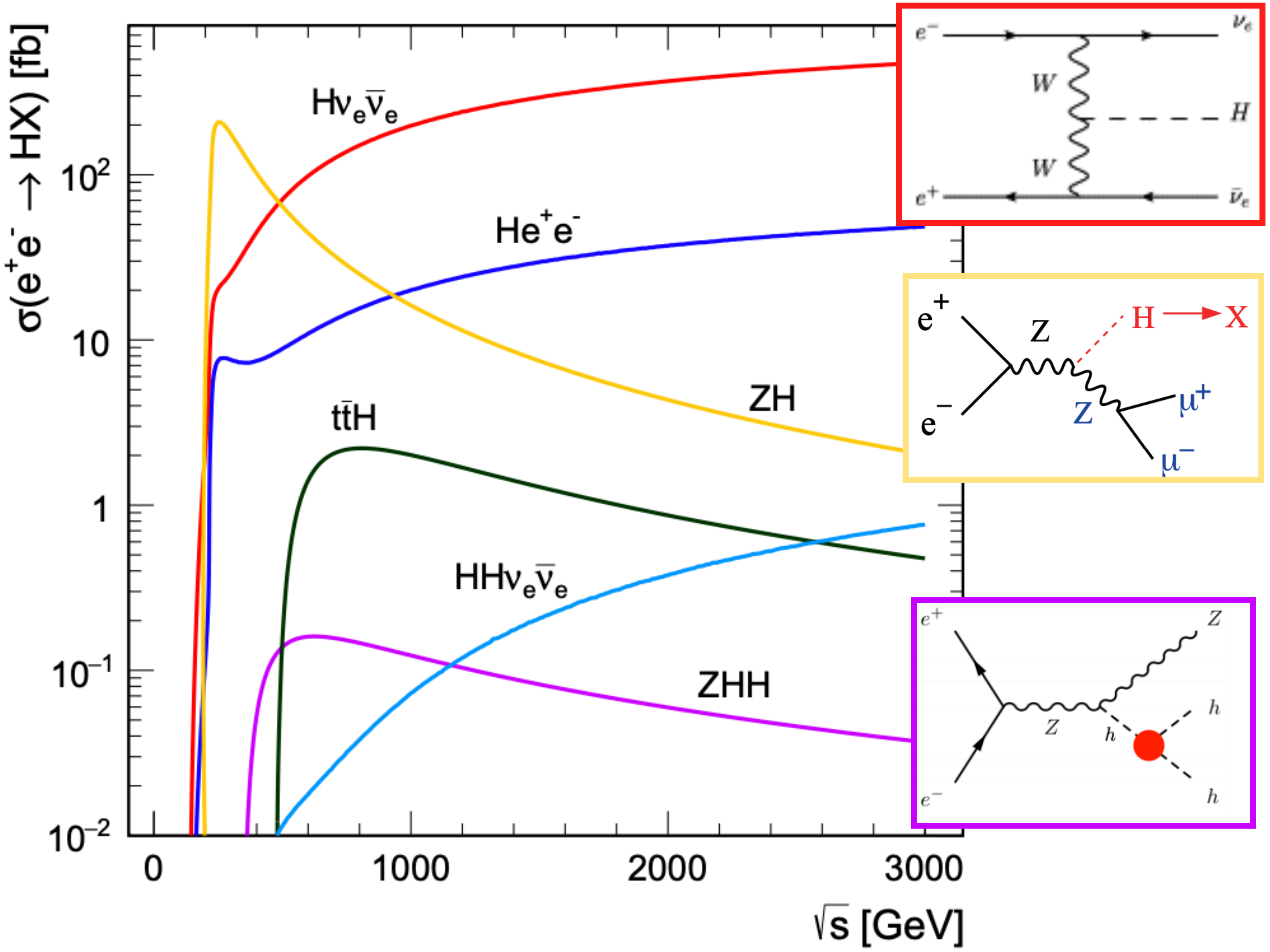


pp/LHC



e^+e^-

Higgs at e+e-



- ZH is dominant at **250 GeV**
- Above **500 GeV**
  - Hvv dominates
  - ttH opens up
  - HH production accessible with ZHH

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

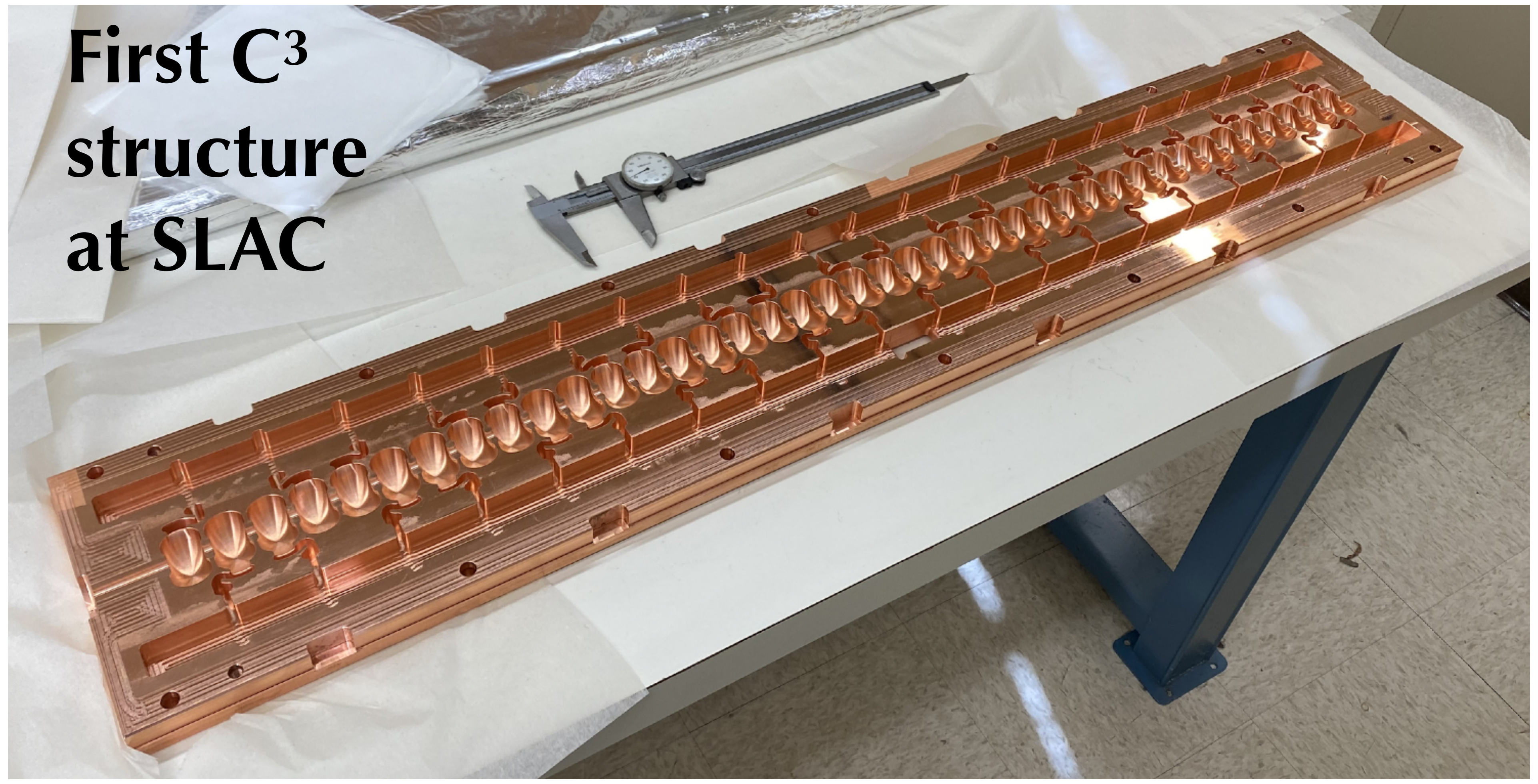
Collider Luminosity Polarization	HL-LHC 3 ab^{-1} in 10 yrs -	C^3 /ILC 250 GeV 2 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)	C^3 /ILC 500 GeV + 4 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80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

An novel route to a linear e+e- collider…

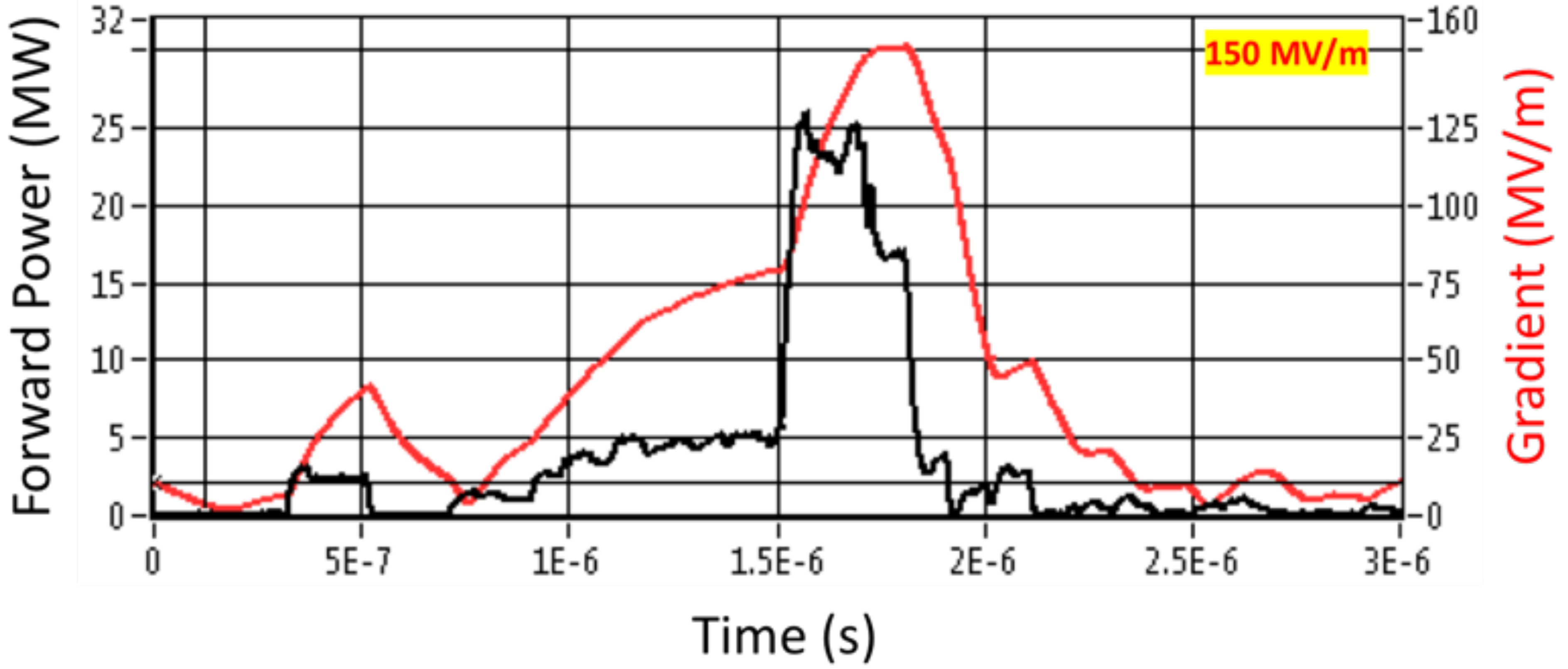
C^3 - Cool Copper Collider

arXiv:2110.15800

- C^3 is based on a new SLAC 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

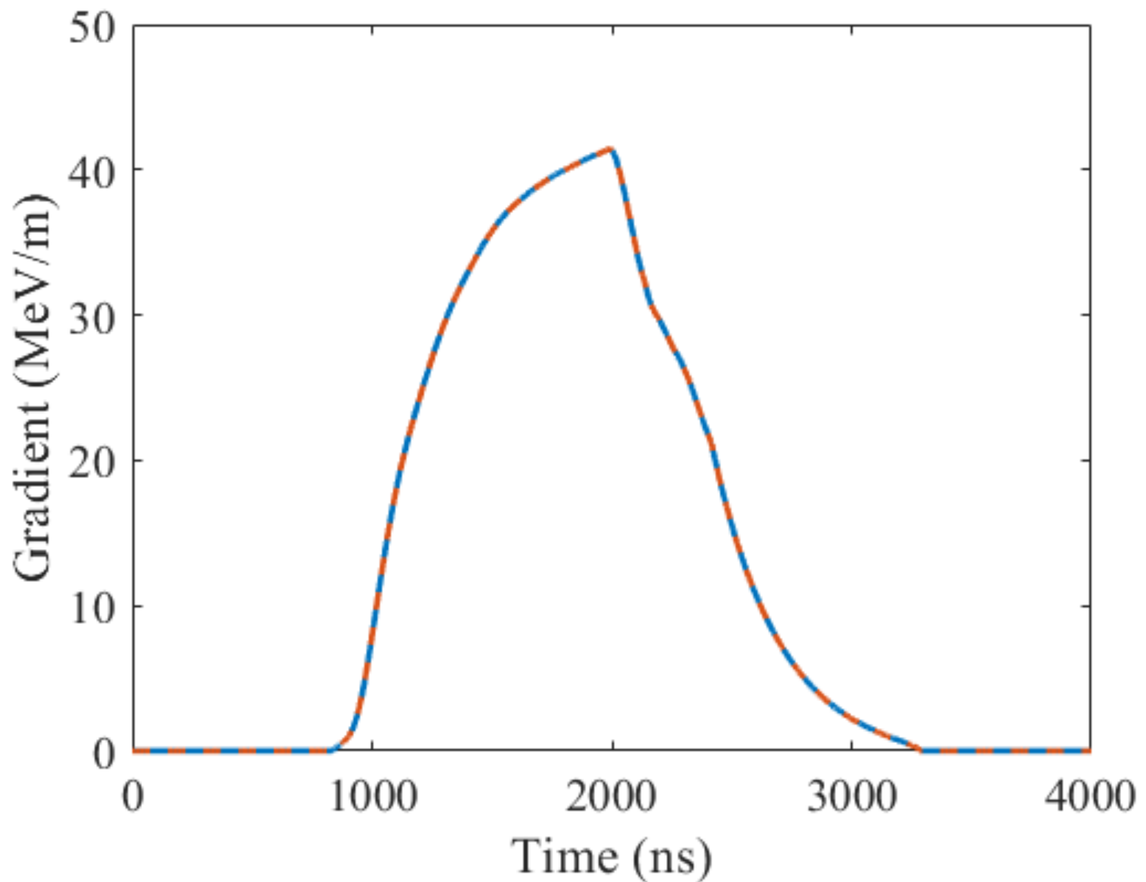


High Gradient Operation at 150 MV/m

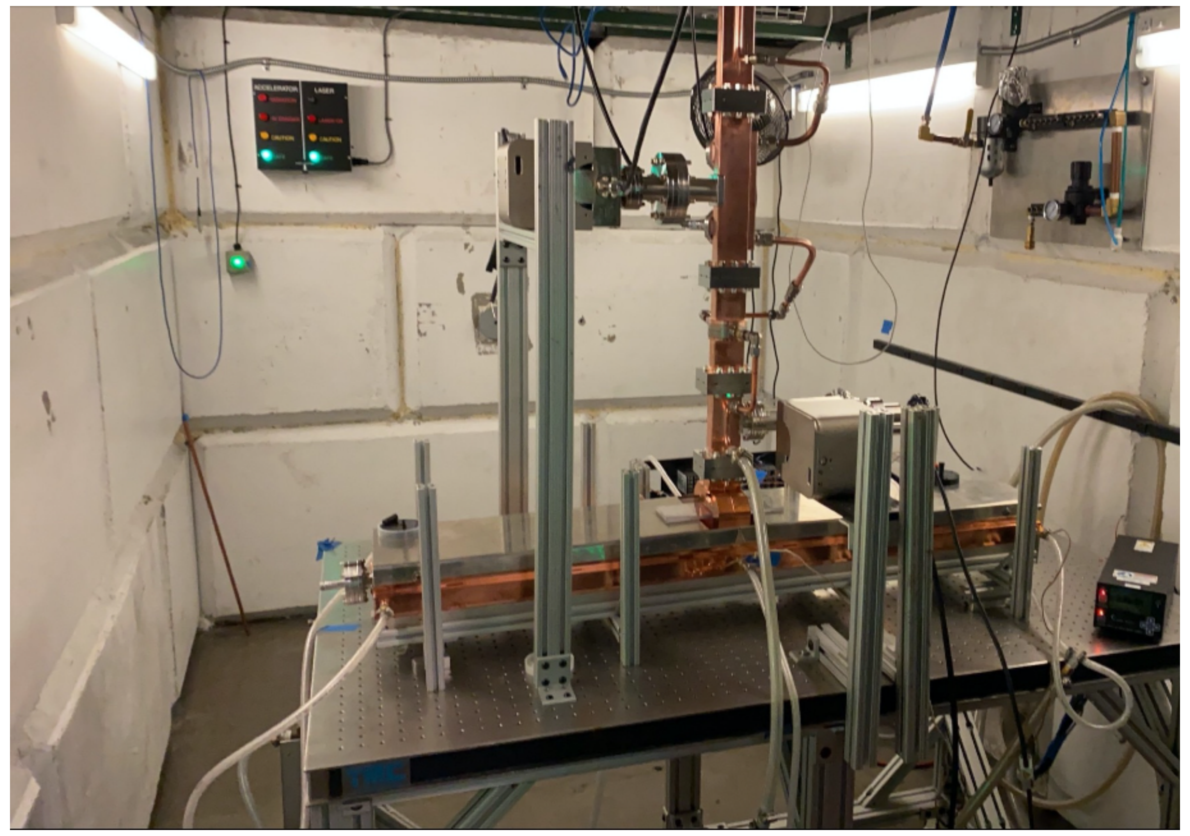


Cryogenic Operation at X-band

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



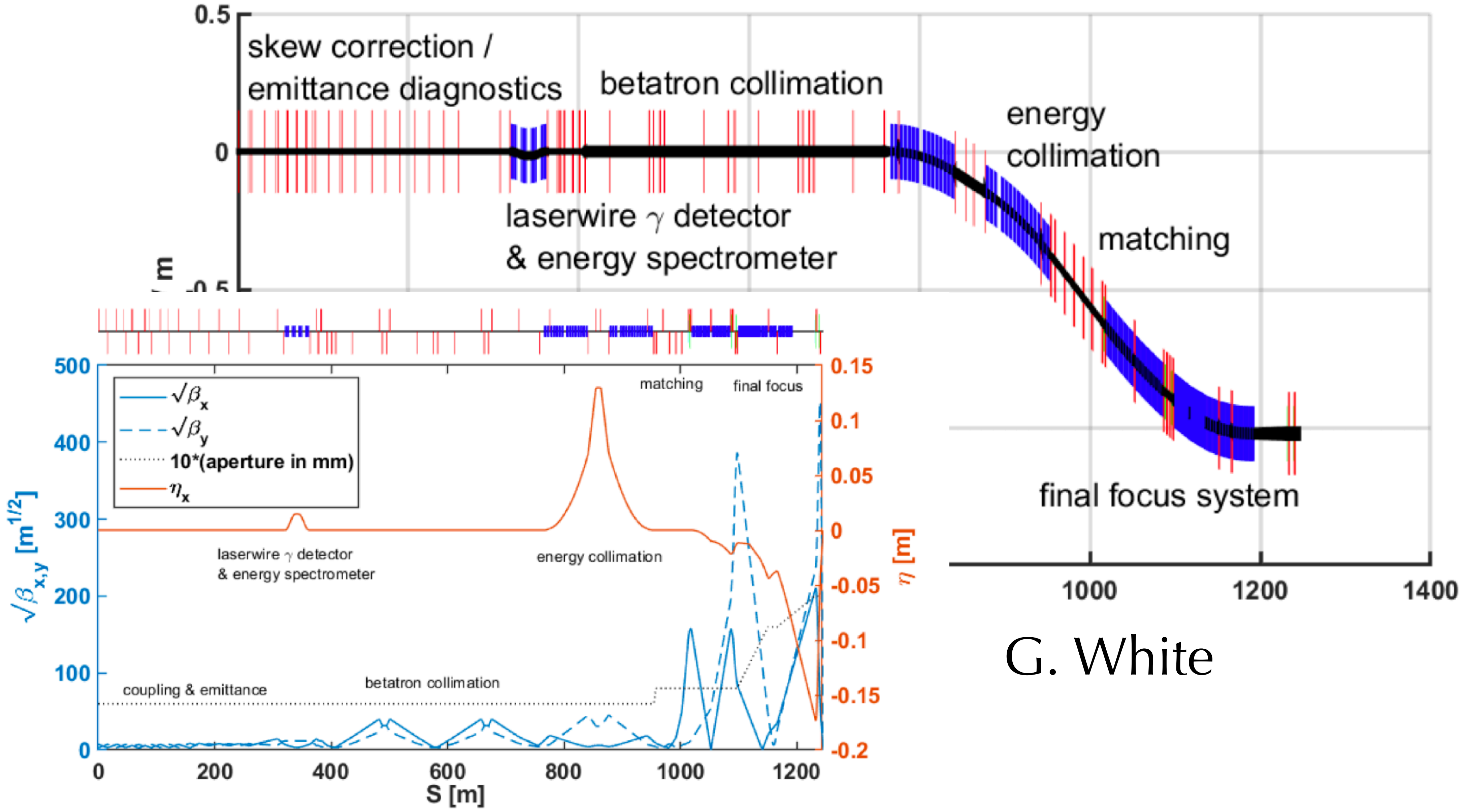
High power test at Radiabeam



Leverage the Development of Beam Generation and Delivery Systems for C³

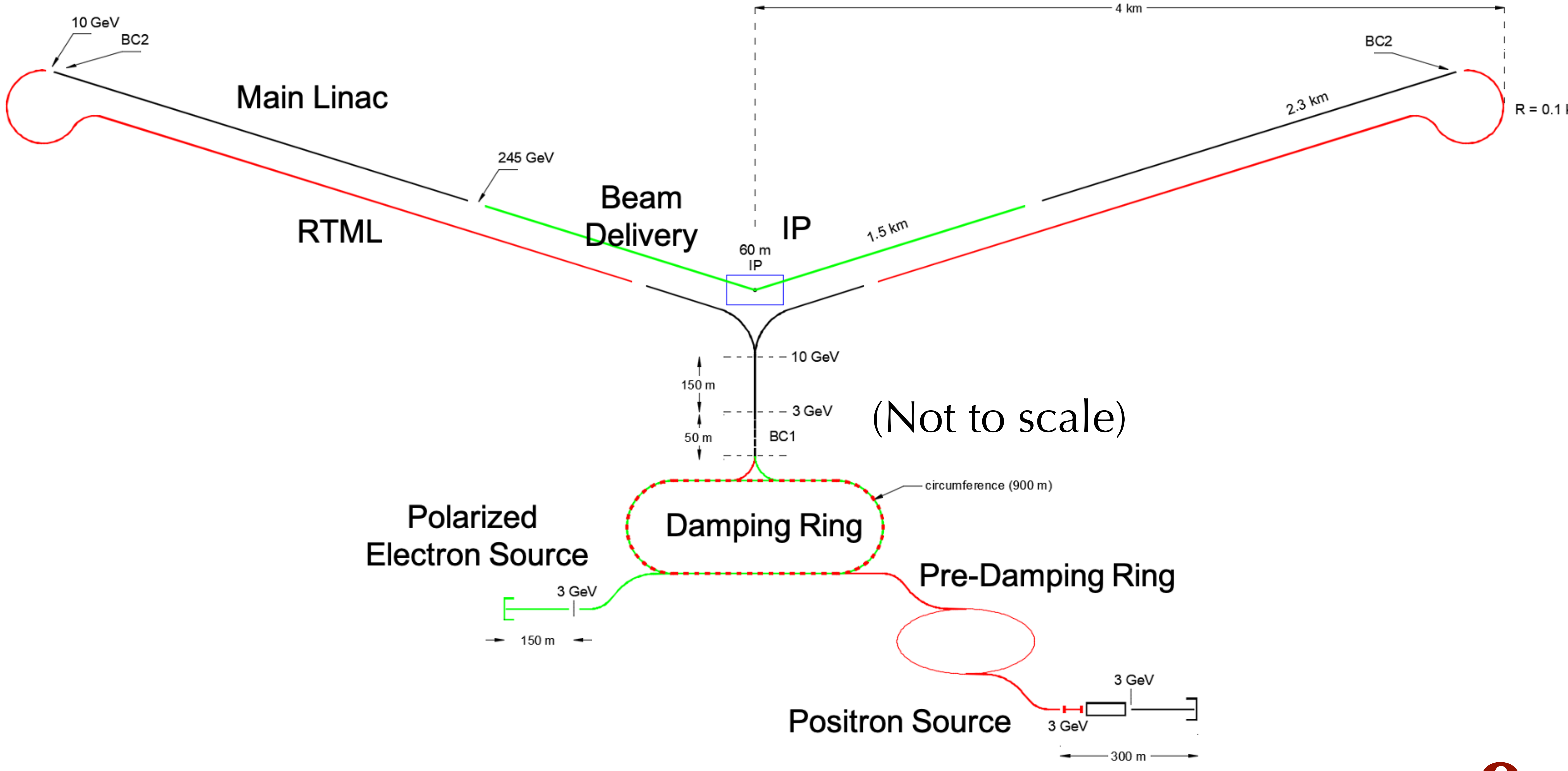
- Large portions of accelerator complex are compatible between LC technologies
  - Beam delivery and IP modified from ILC
  - Damping rings modified from CLIC
  - Injectors to be optimized with CLIC as baseline

C³ - Investigation of Beam Delivery Adapted from ILC/NLC



G. White

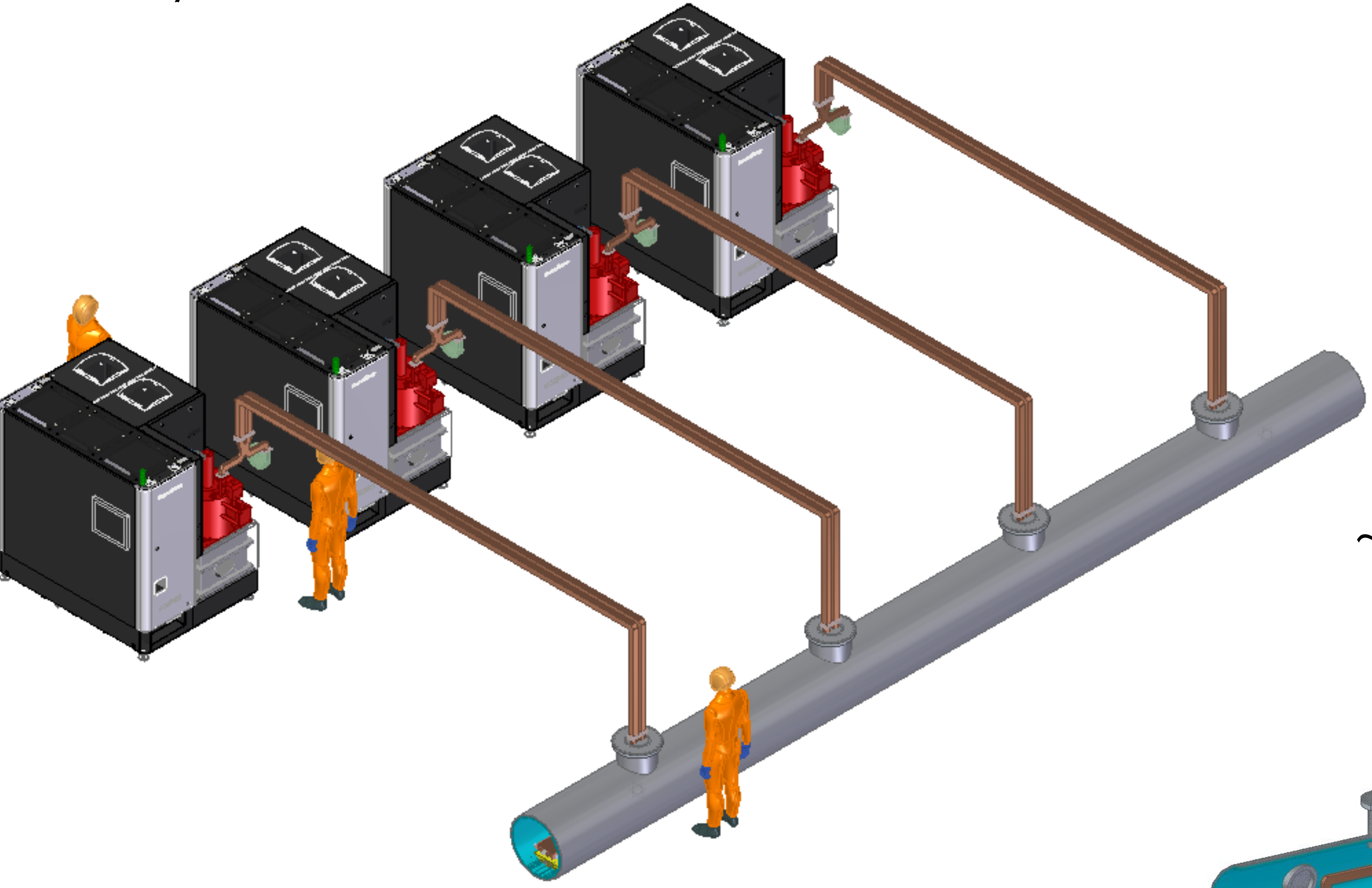
C³ - 8 km footprint for 250/550 GeV

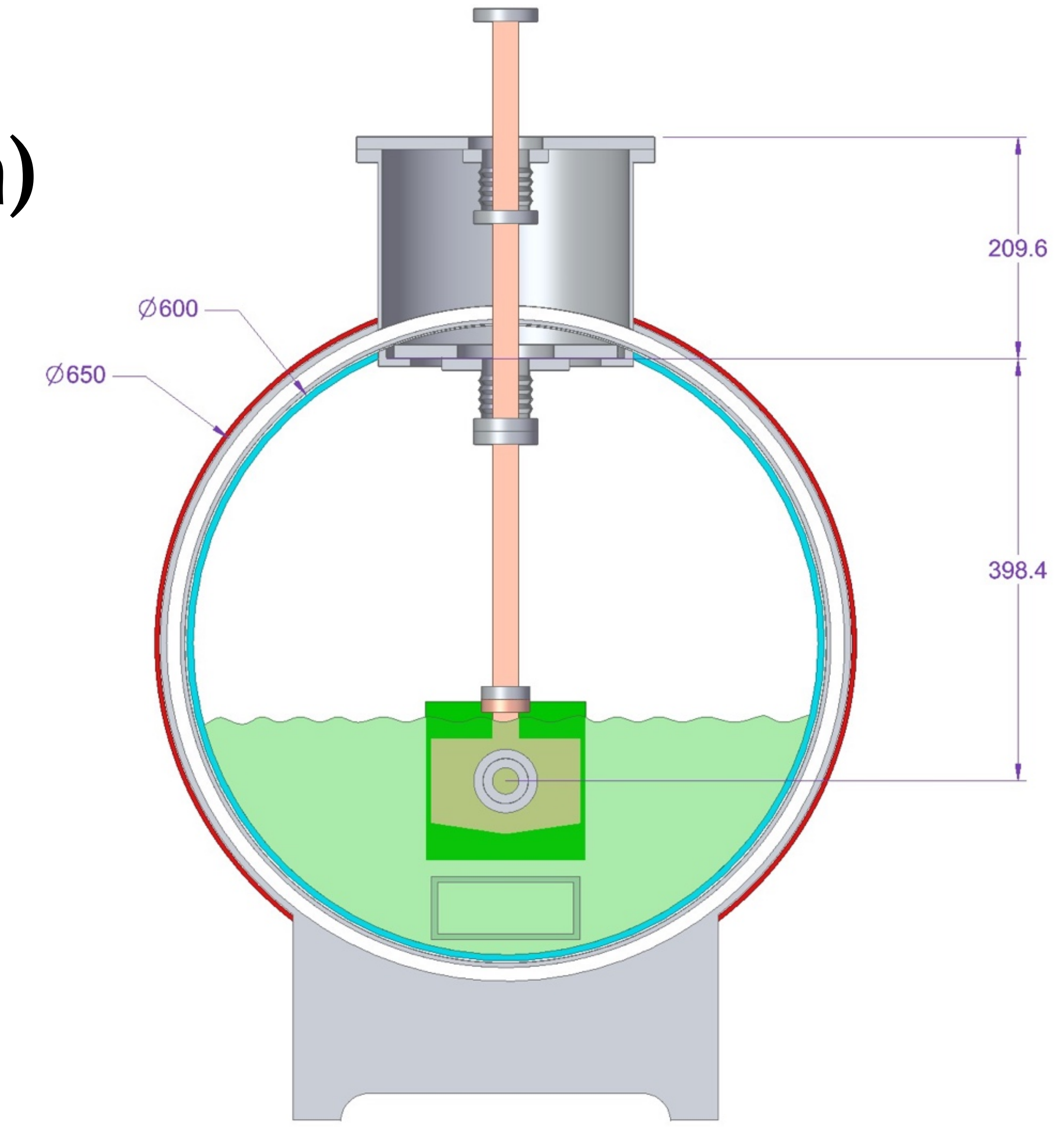


(Not to scale)

Main Linac Configuration

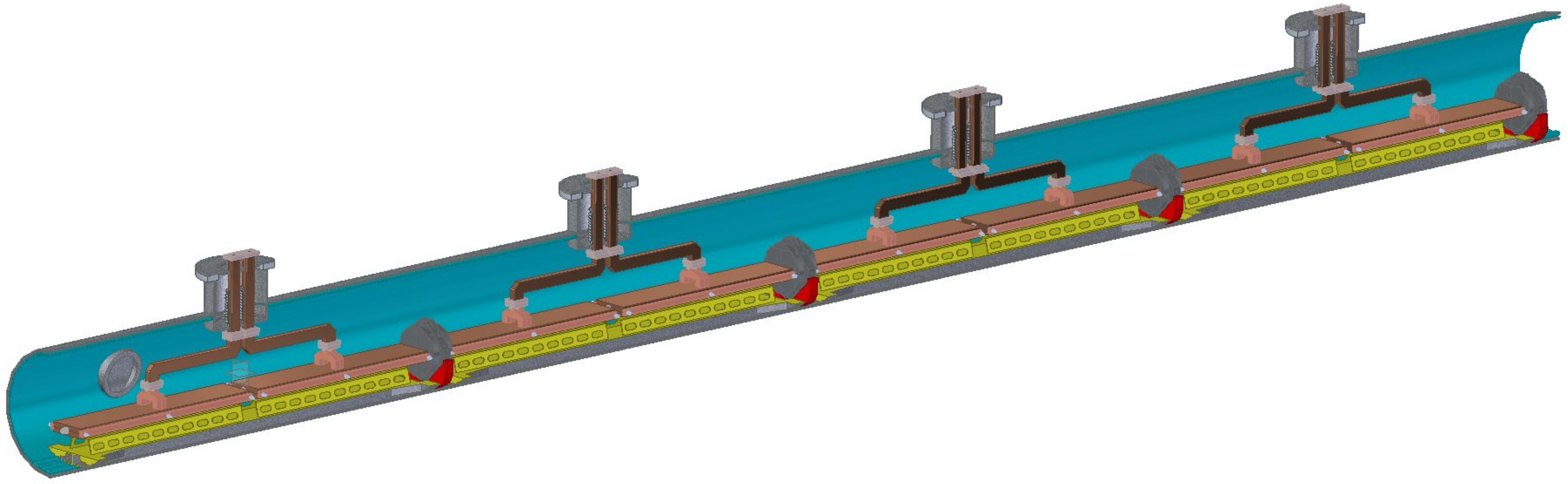
Cryomodule unit - 9 m (630 MeV -> 1 GeV; 70 -> 120 MeV/m)



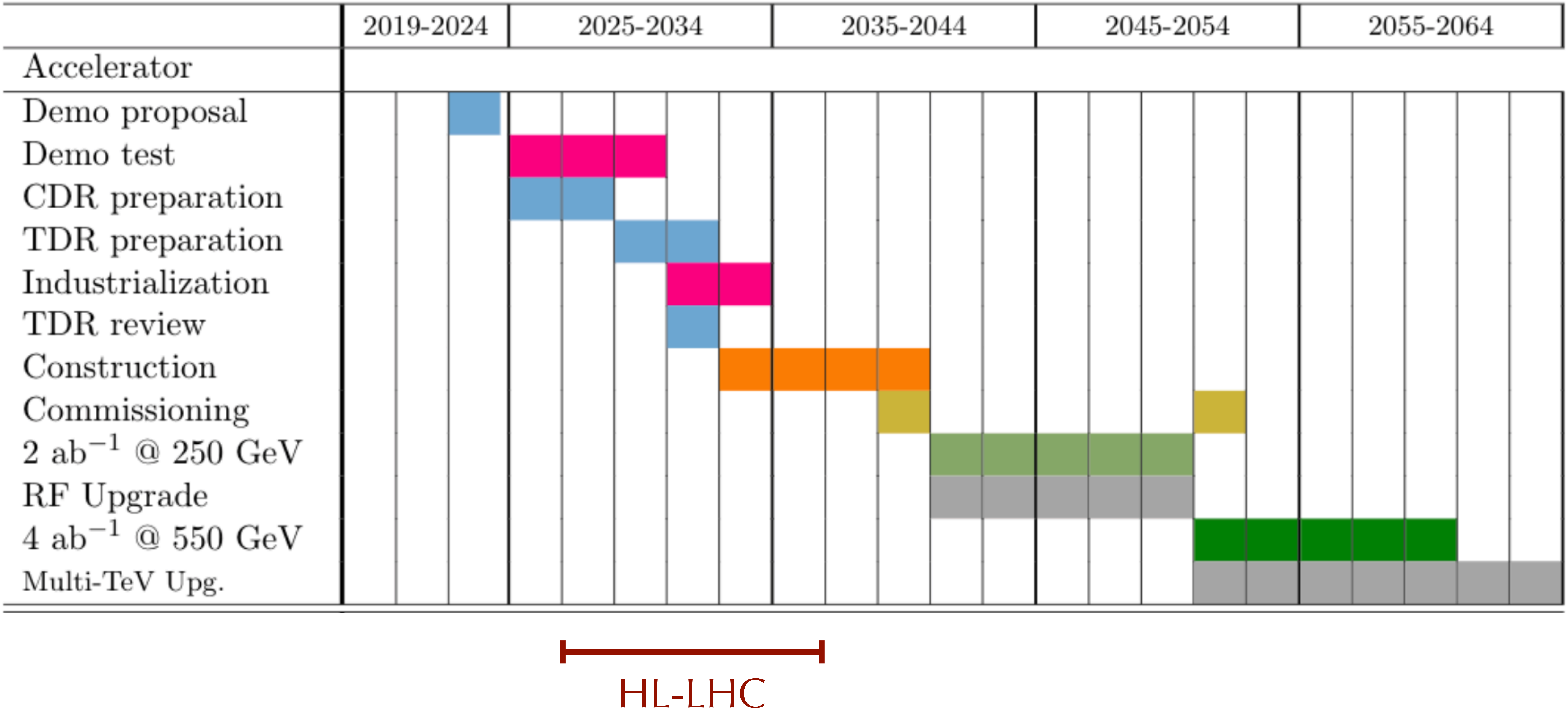


Shared nitrogen supply and return

~9m Cryomodule (90% fill factor)



C^3 timeline



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.
HL-LHC

Demo facility needs and possibilities….

Investigating C^3 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) in single bunch mode
    - Must understand margins for 120 - targeting power for (155 + margin) 170 MeV/m
    - 18 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 - already have mature designs created for the ILC and CLIC.
  - Our current baseline uses these directly although we will look for further cost-optimizations for the specific needs of the C^3

Demonstrator R&D Topics

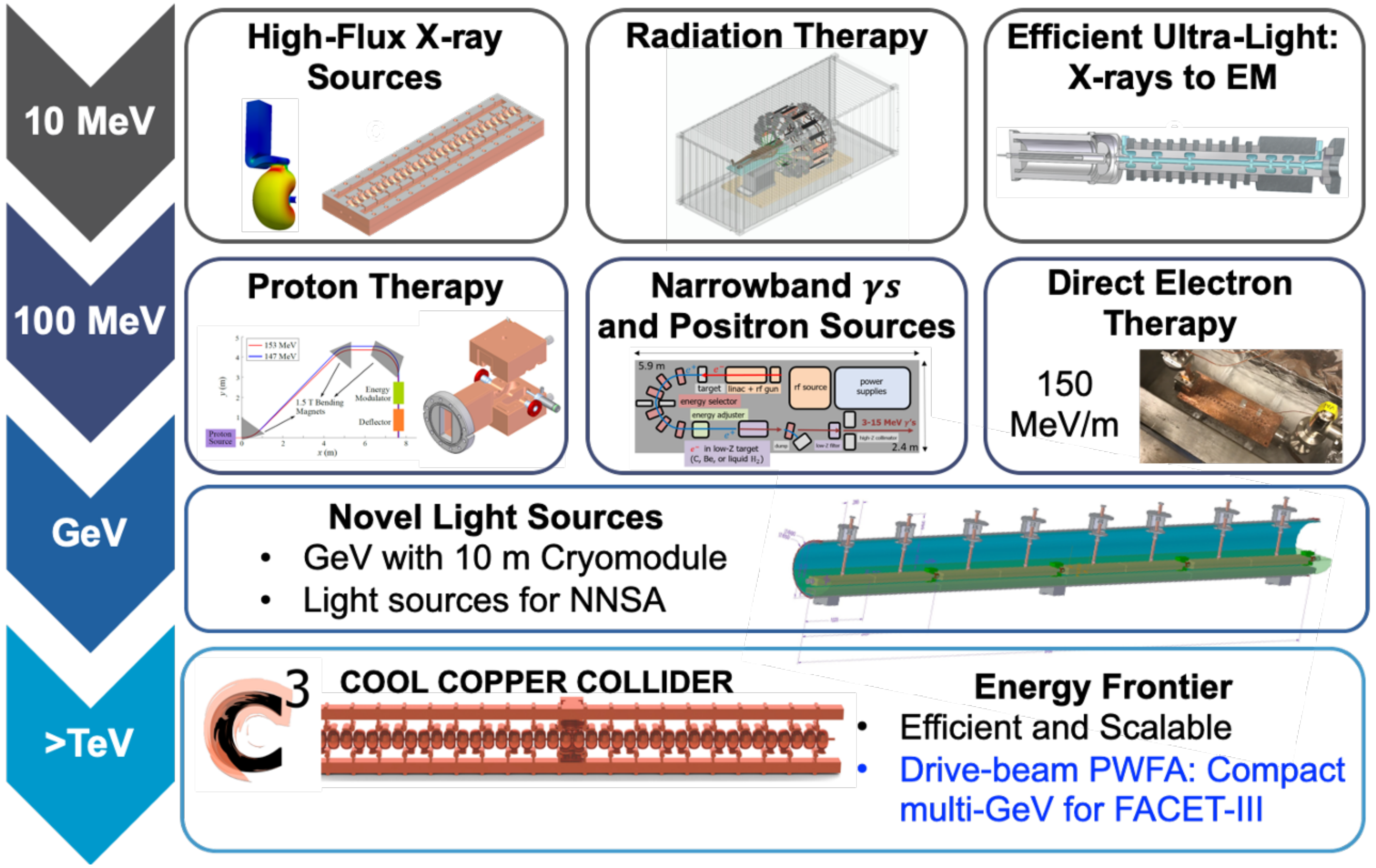
- Direct Demonstrator Facility (>=50 m, 100 Hz, 133X 1nC)
  - Cryomodule Cryogenics and Beamline Design
  - Cryomodule Assembly
  - Beam dynamics - lianc, damping rings, bunch compressors
  - RF High-brightness photo-injector for demonstrator
  - RF High-brightness polarized photo-injector
  - DC polarized 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

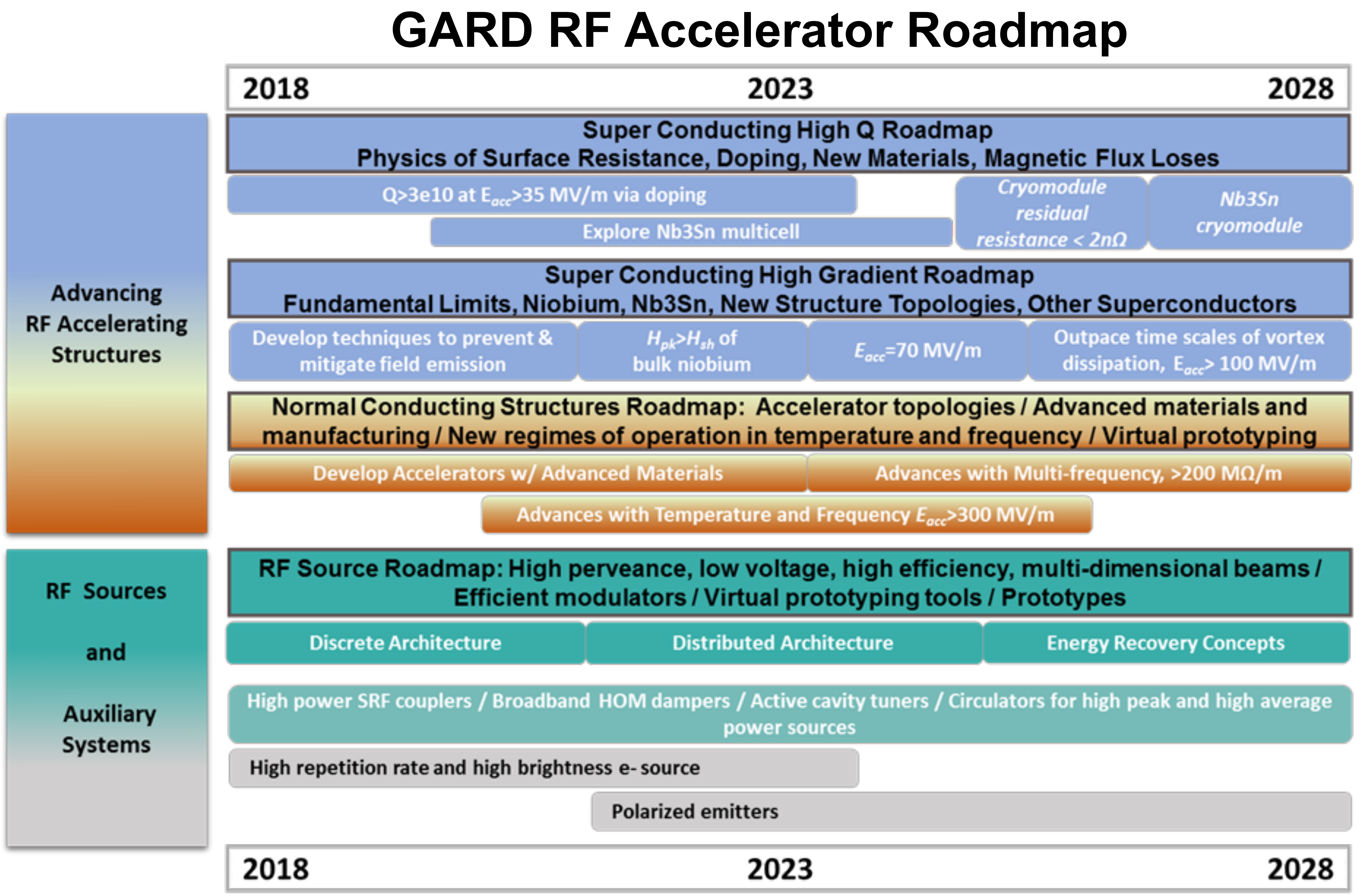
- Parallel R&D
  - Levitated Positron Target - Radiatively cooled
  - QD0/QD1
  - Advanced RF Source R&D
  - RF Distribution (pulse compressor)
  - Site Studies
  - Error Sensitivity Study
  - Polarimetry

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

CCC Demo in the Context of GARD RF Roadmap

- Exploring rf accelerator technology at many energy scales to enable near- and long-term capabilities
- Aim to achieve the goals laid out in the DOE GARD RF roadmap



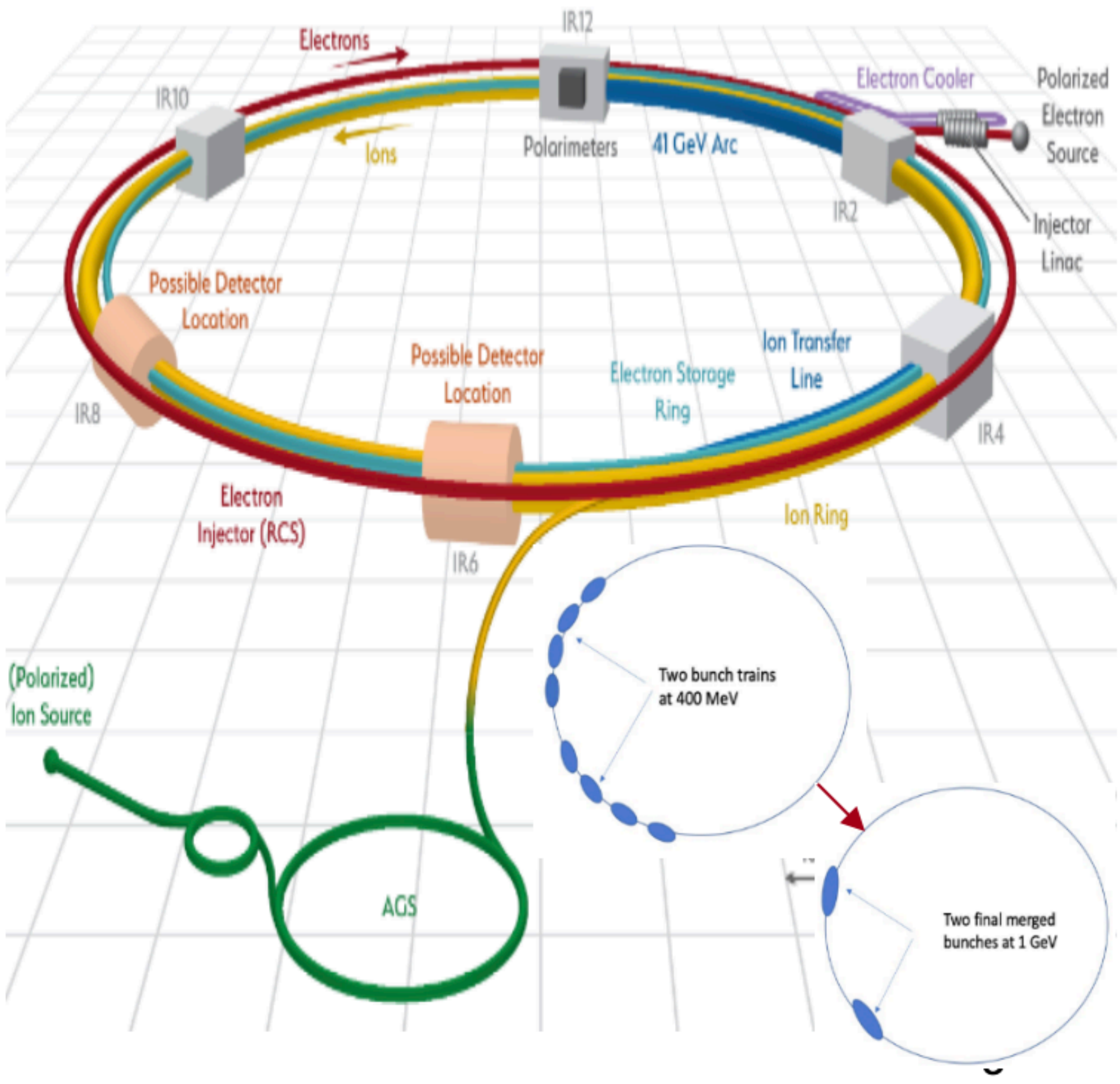


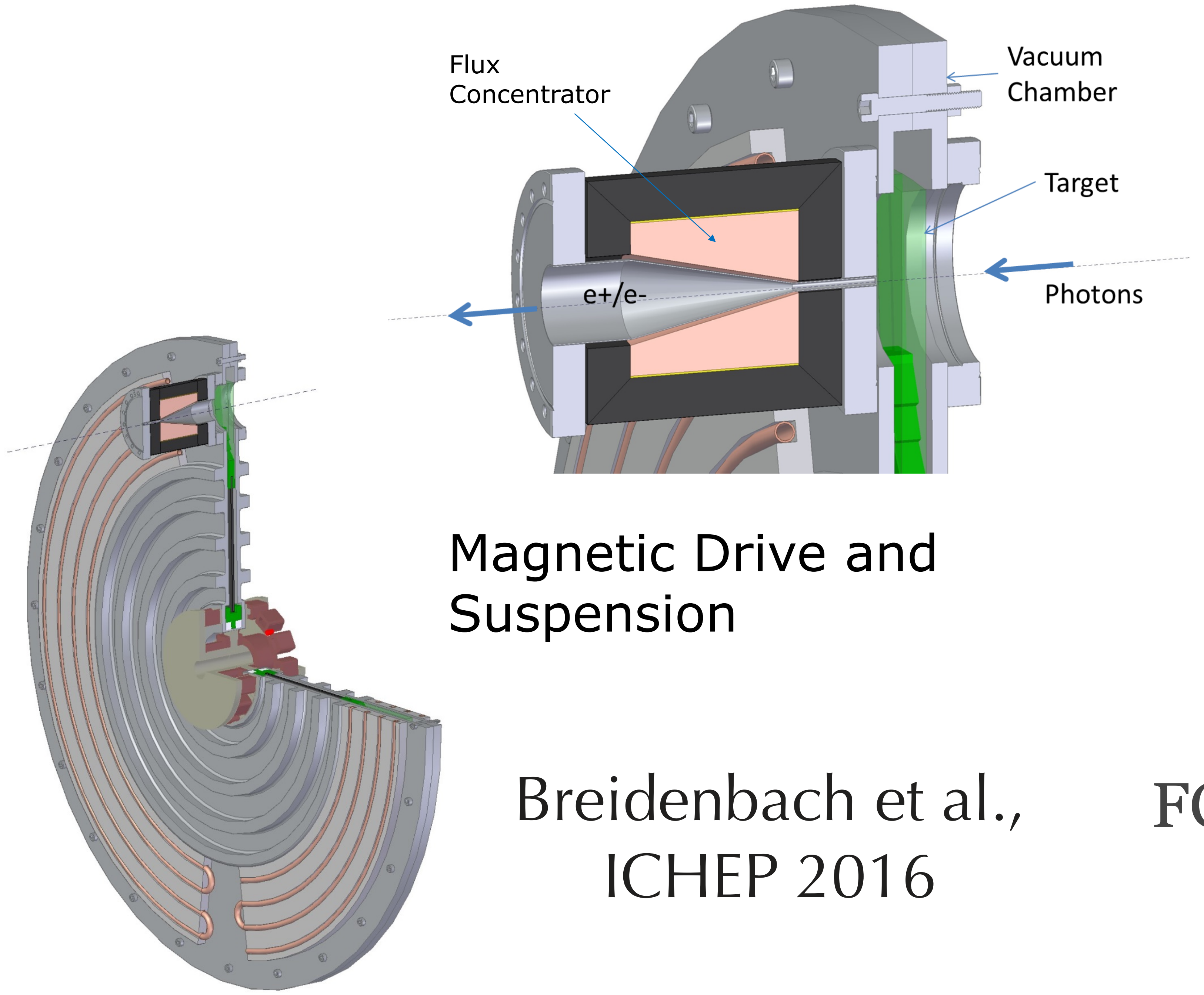
- CCC demonstration facility would play a significant role in addressing this roadmap and taking it forward

Synergy with Sources and Capture

- Electron and positron source technology highly synergistic between accelerator facilities
- CCC will require high charge bunch train
- Demo facility R&D topics
  - Cryogenic high brightness rf guns
  - Acceleration to few hundred MeV
  - Positron target, production, capture

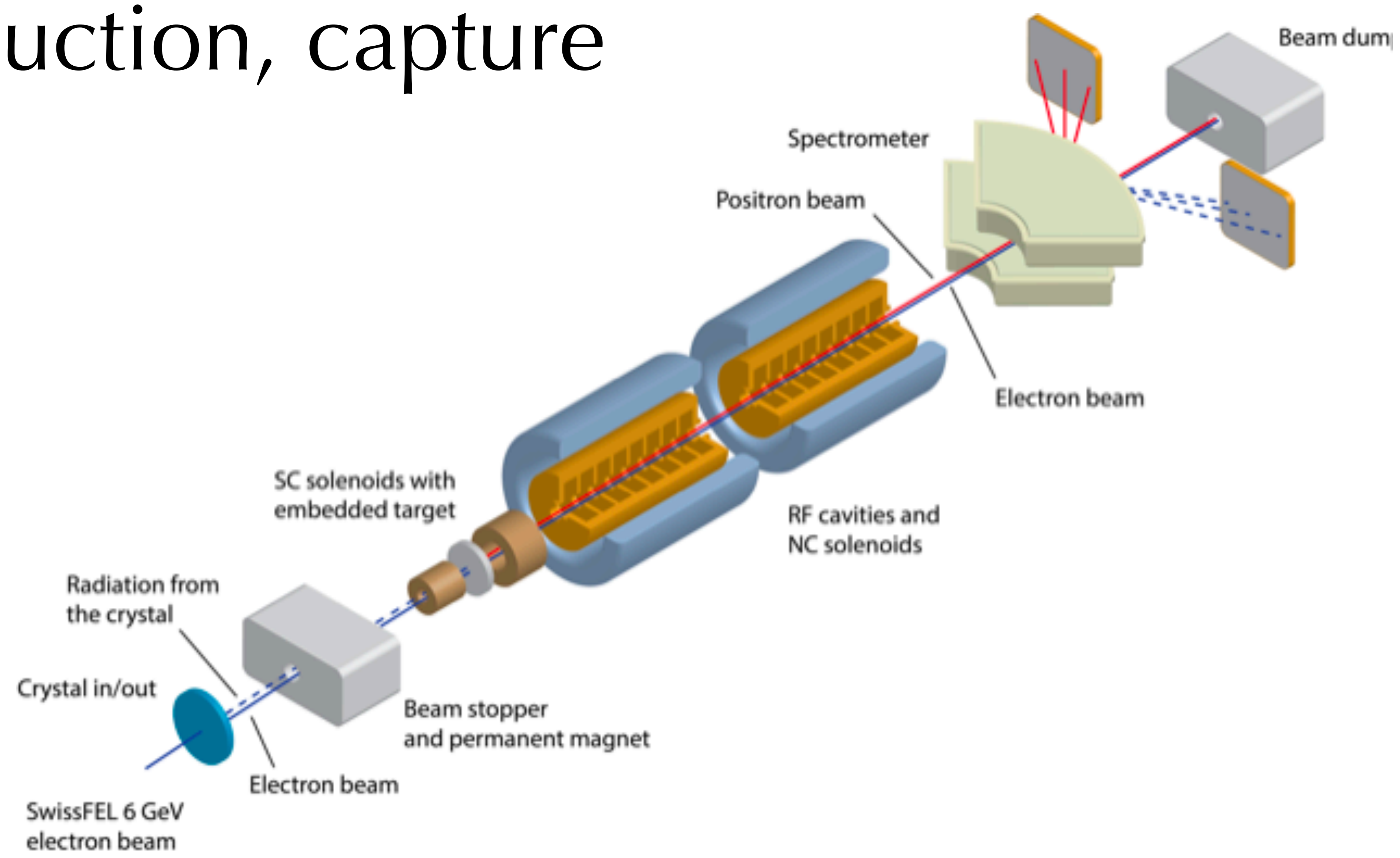
EIC schematic layout



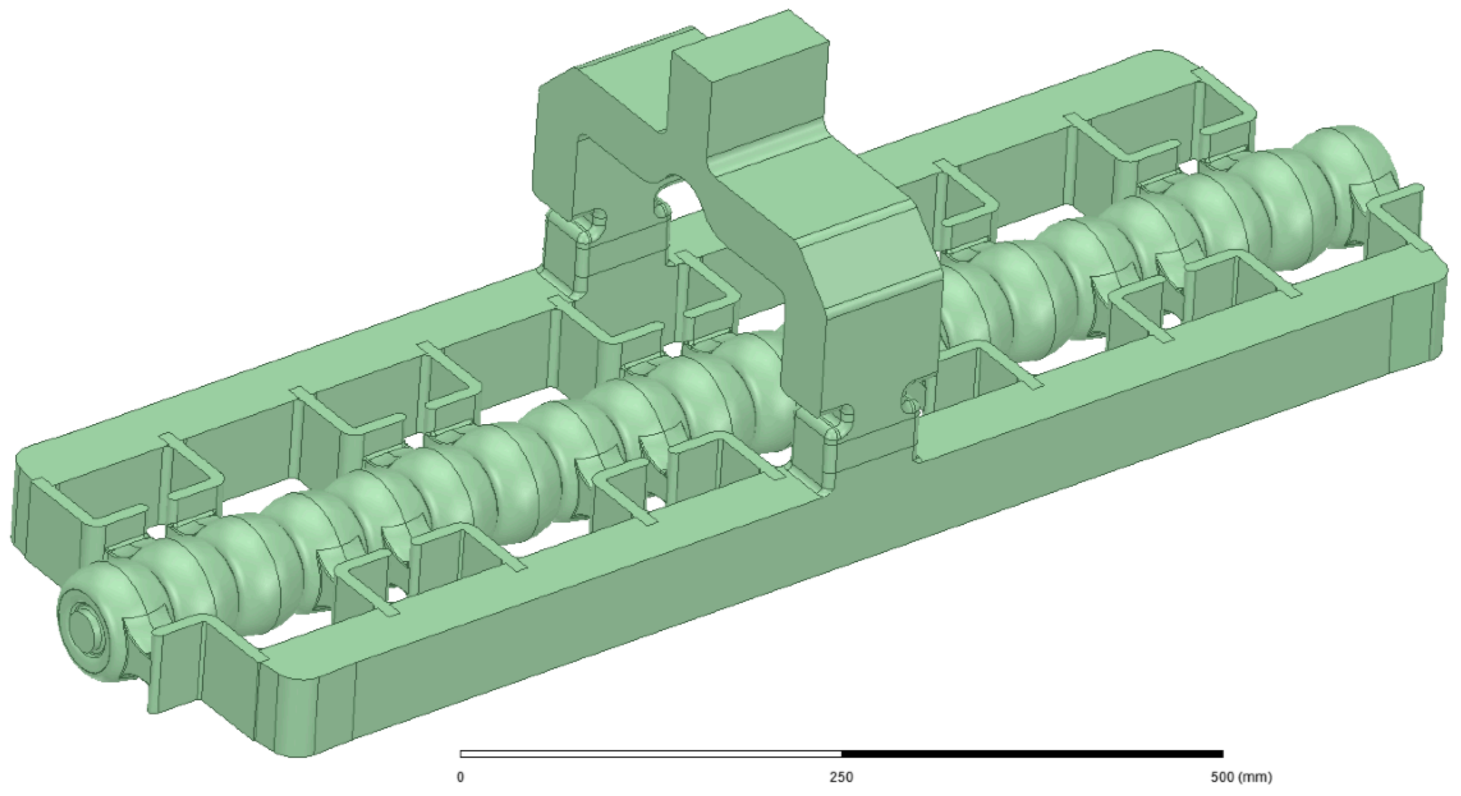


Magnetic Drive and Suspension

Breidenbach et al., ICHEP 2016



FCC-ee Injector design and PSI Positron Source

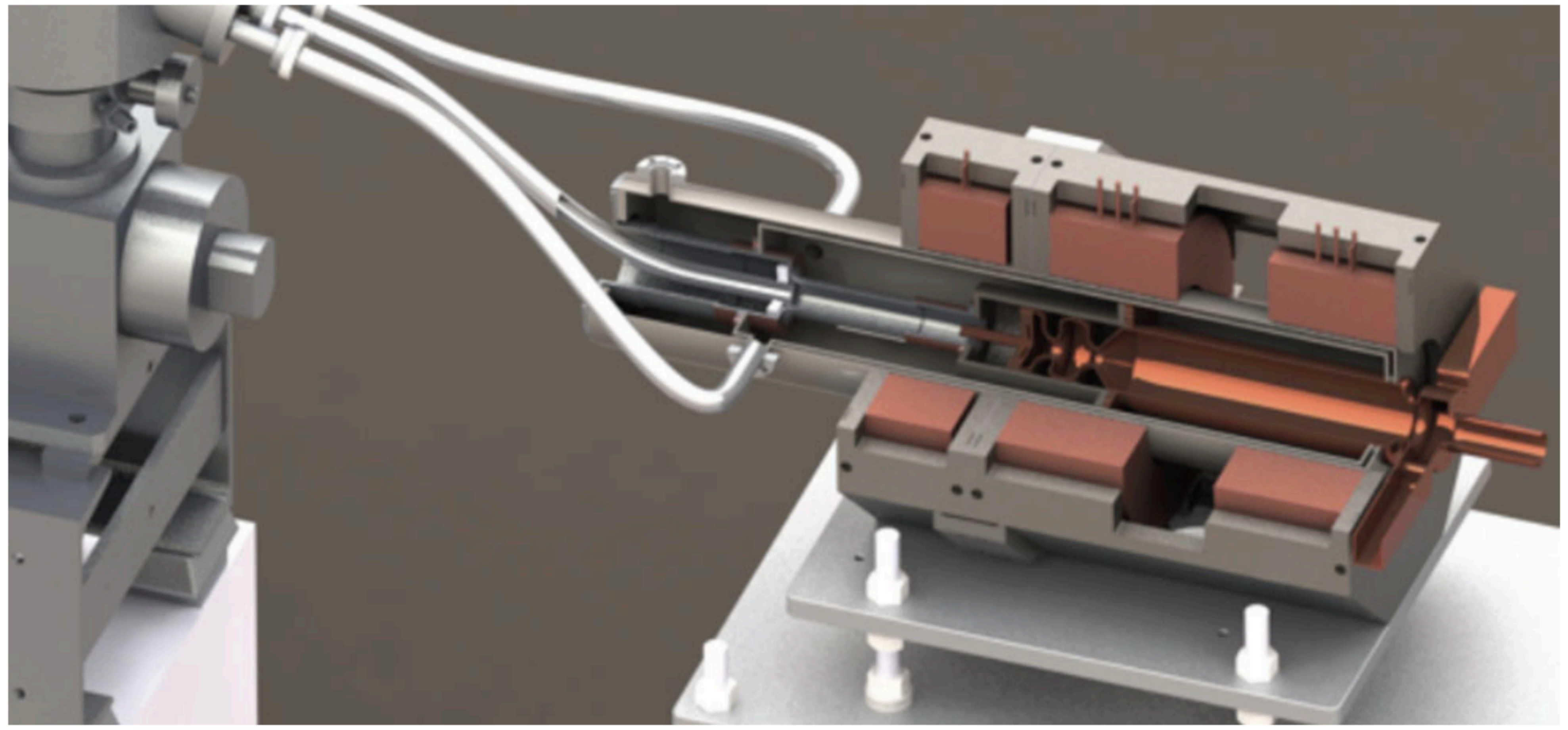


S-band Capture Linac (1 m)

Beam Dynamics and Advanced Accelerator Concepts

- CCC demo facility goal is to produce stable high charge bunch train
- High-brightness gun
  - Transport of low emittance beam
  - Bunch compression
  - FELs
  - ….
- Possible follow on R&D for PWFA:
  - Staging with multiple plasma cells
  - Ultra-high brightness beam generation
  - Demonstration of extremely short bunches
    - Up to Mega-Amp peak currents
  - Advanced ultrafast X-ray sources are possible
  - Plasma lens and final focus (Spencer Gessner talk)

PRAB 22, 023403 (2019)



Cryogenic RF Gun

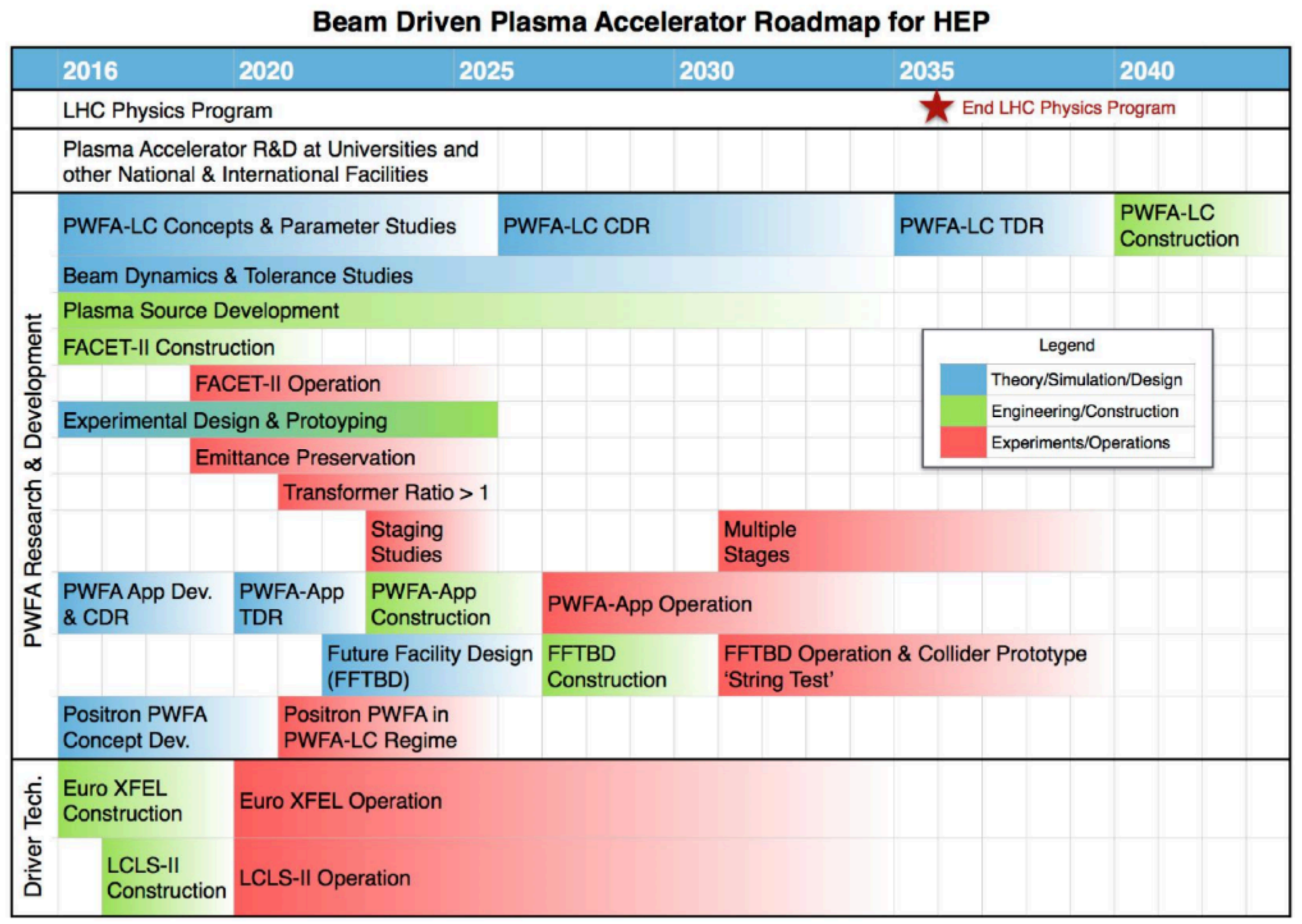
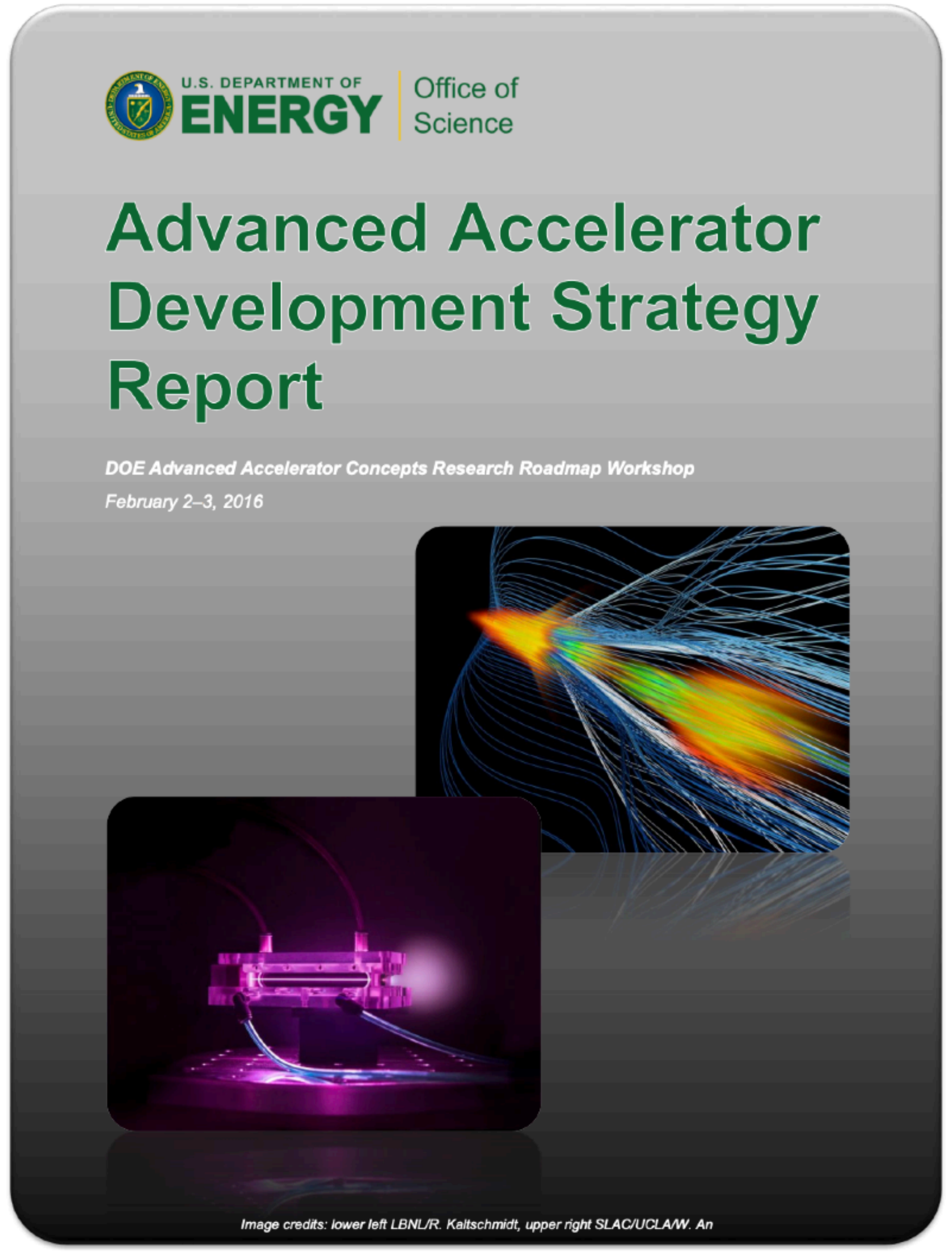


Figure 4: High level R&D roadmap for particle beam driven plasma accelerators.



Integration of AI/ML and Online Accelerator Modeling / Control

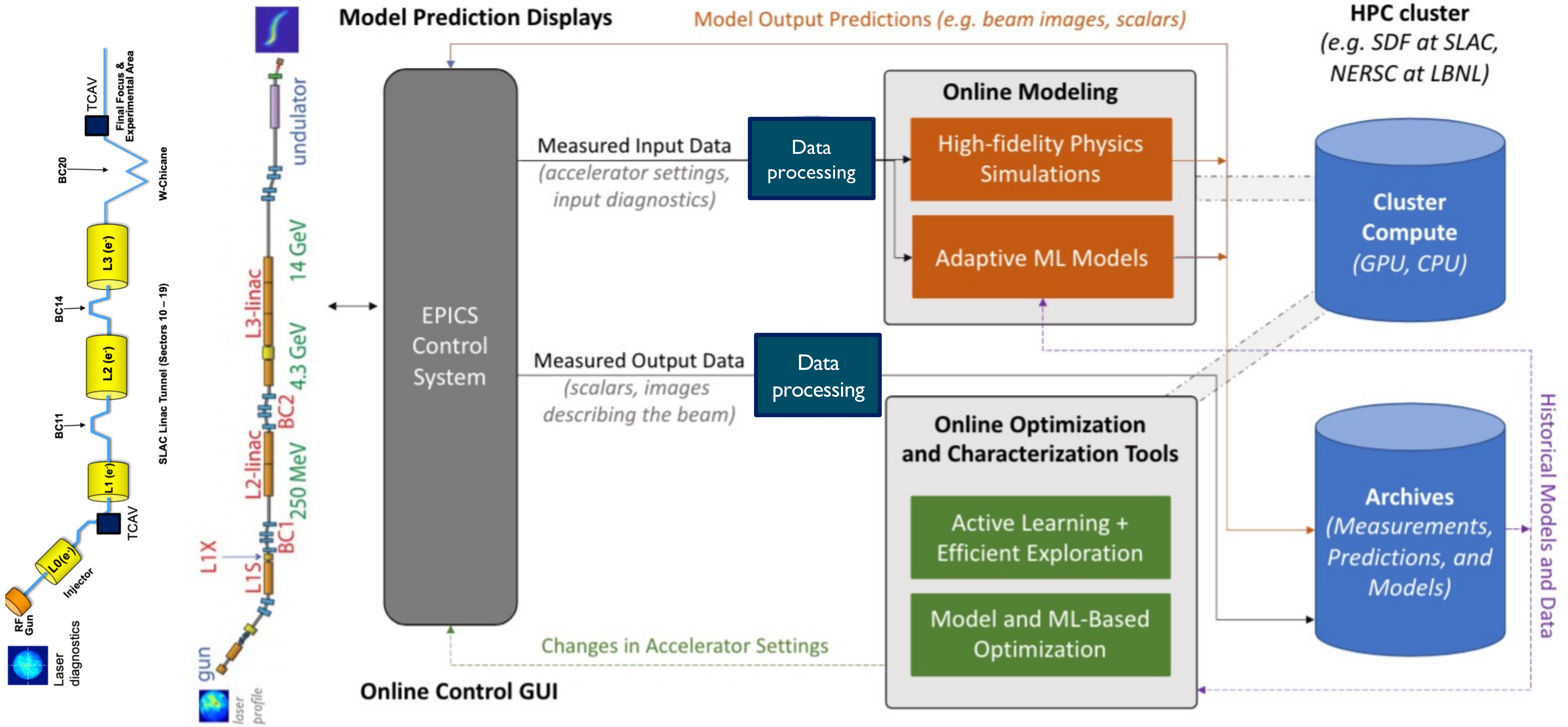
- Many proof-of-principle results for AI/ML modeling and control of accelerators → *usually in limited ranges of operating conditions or addressing isolated problems (e.g. only optimization, only modeling)*
- **Now need to address integration into dedicated operation:**

-Need a comprehensive *facility-agnostic* software/hardware ecosystem that can couple HPC, online simulation, and AI/ML

-Need to assess/address robustness challenges of dedicated operation and coupling different types of AI/ML tasks together

-Coupling of AI/ML, traditional algorithms, and human-in-the-loop operations *(provide useful/ actionable information rather than add to information overload)*

→ *Prototyping a comprehensive AI/ML ecosystem for online modeling/control at smaller-scale test facilities would (1) provide substantial benefit in bringing this technology to maturity and (2) provide a roadmap for scaling it up to larger facilities*



See: Auralee Edelen, AI/ML for Particle Accelerator, X-Ray Beamlines and Electron Microscopy, https://indico.fnal.gov/event/50731/timetable/

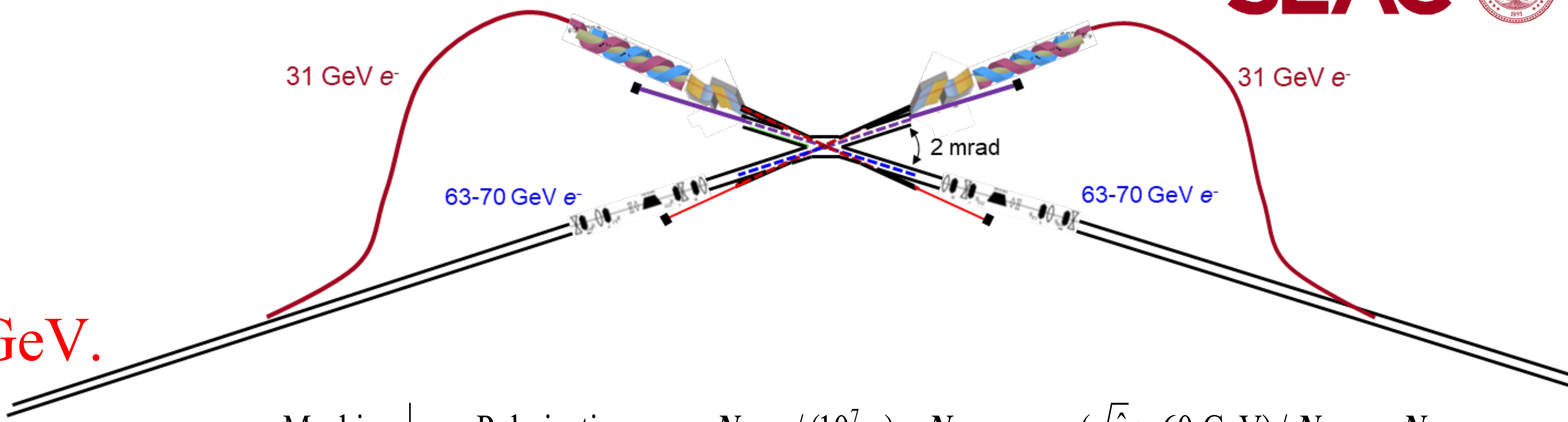
XCC – XFEL Compton Collider

Run $\gamma\gamma \to \boldsymbol{H}$ at $\sqrt{s_{\gamma\gamma}} = 125$ GeV half the time

and $e^{-}\gamma \to e^{-}\boldsymbol{H}$ at $\sqrt{s_{e\gamma}} = 140$ GeV the other half

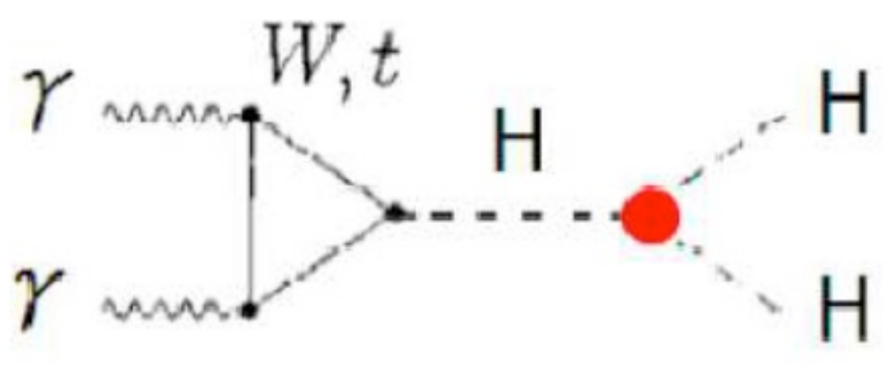
to calibrate the $\sigma \times \mathrm{BR}$ measurements at $\sqrt{s_{\gamma\gamma}} = 125$ GeV.

This produces model independent Higgs coupling measurements, just like the ILC.



Machine	Polarization	$N_{\mathrm{Higgs}}/(10^7\ \mathrm{s})$	$N_{\mathrm{Hadronic\ Events}}(\sqrt{\hat{s}} > 60\ \mathrm{GeV})/N_{\mathrm{Higgs}}$	$N_{\mathrm{minbias/BX}}$
XCC	$90\%\ e^-$	32,000	70	9.5
ILC	$-80\%\ e^-\ \ +30\%\ e^+$	42,000	230	1.3
ILC	$+80\%\ e^-\ \ -30\%\ e^+$	28,000	55	1.3

An energy upgrade to $\sqrt{s_{\gamma\gamma}} = 280$ GeV to study the Higgs potential with $\gamma\gamma \to \boldsymbol{HH}$ would require only 2.8 km of C^3 linac.

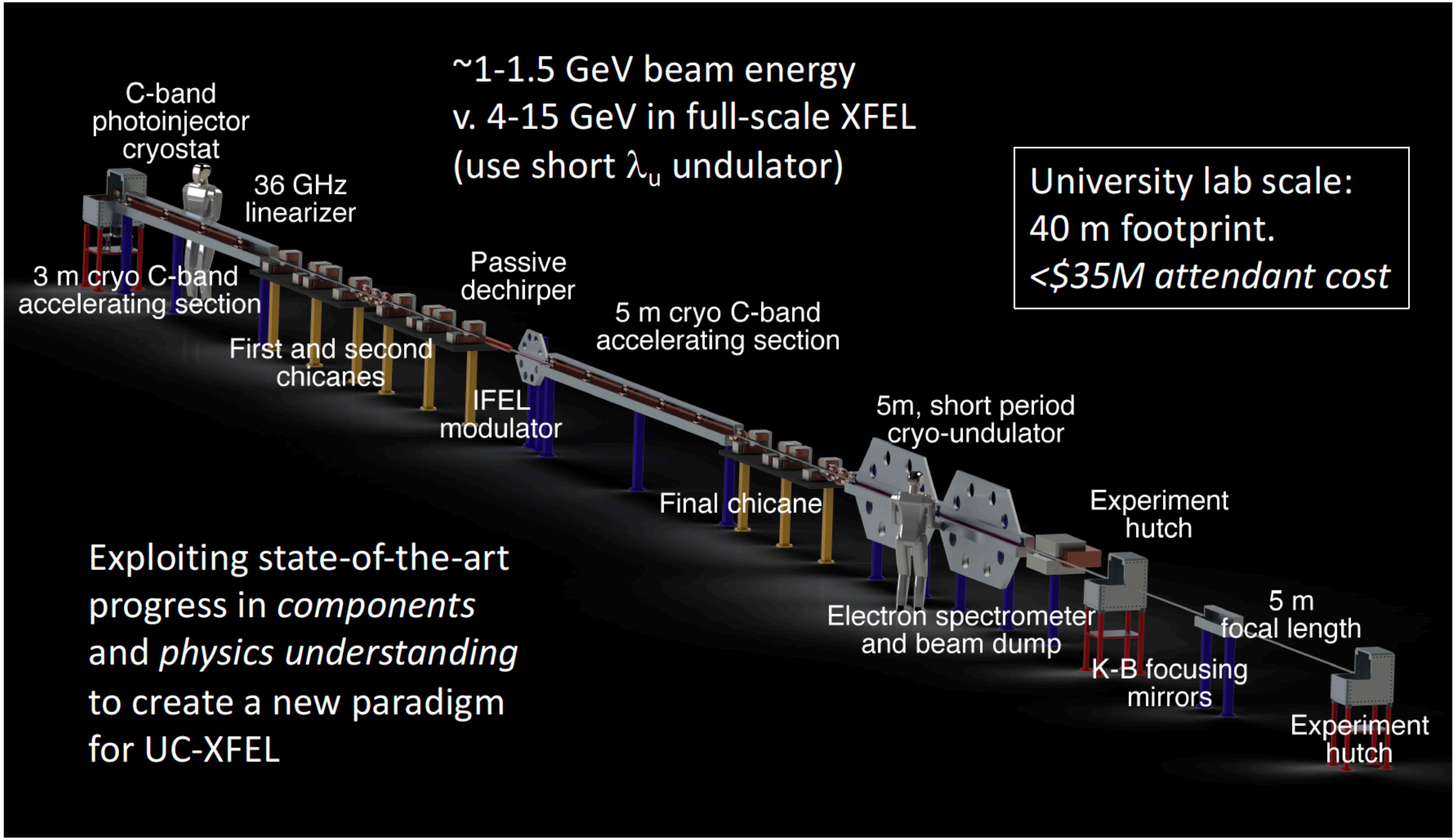


Demo Facility Overlap:

- Cryogenic rf gun for polarized electron
- Cryomodule operation w/ XCC bunch structure
- FEL development

FEL Applications - Ultra-Compact XFEL
Next Talk by J. Rosenzweig

UCLA



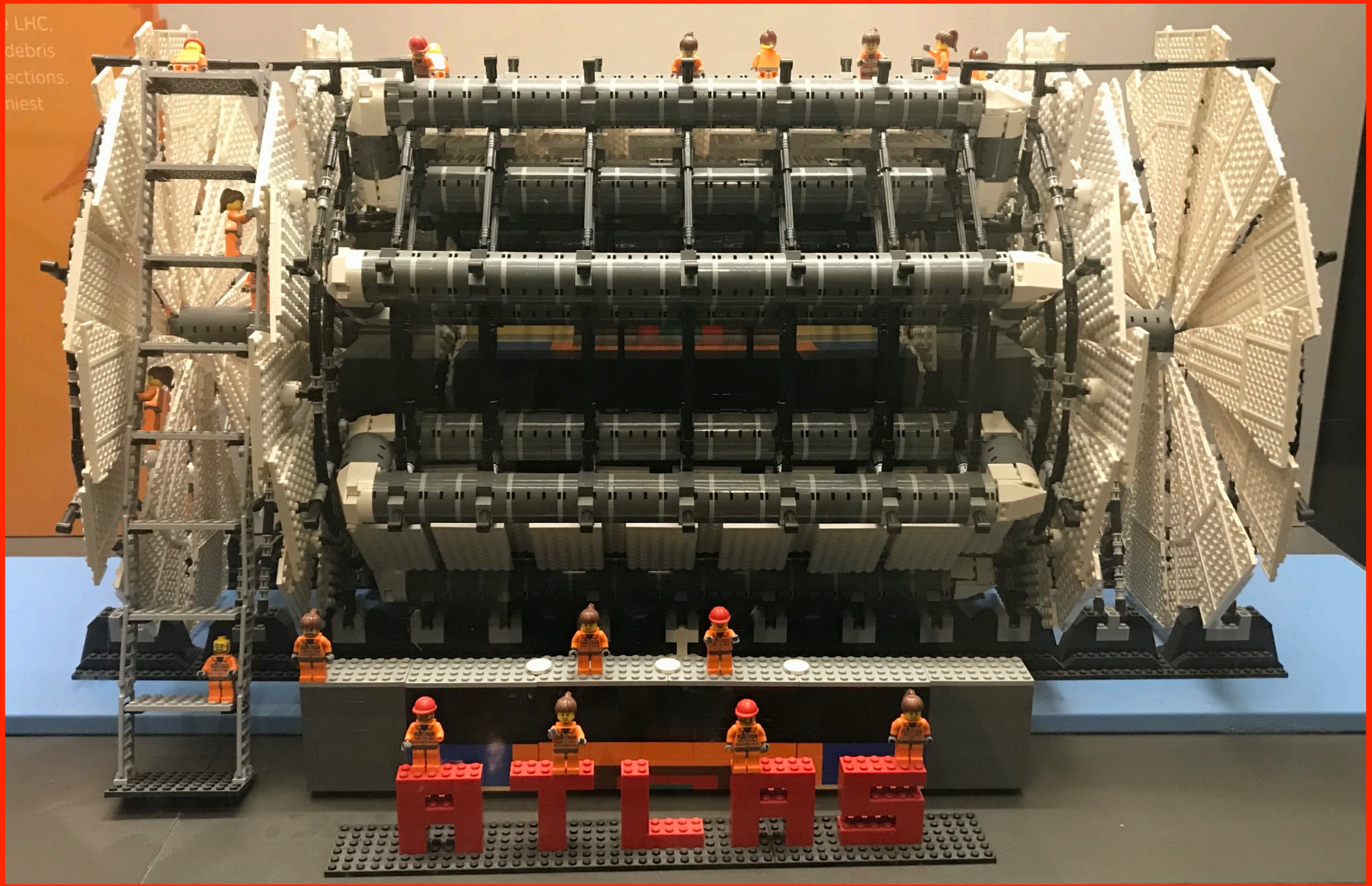
Getting Involved C^3 R&D & Conclusions

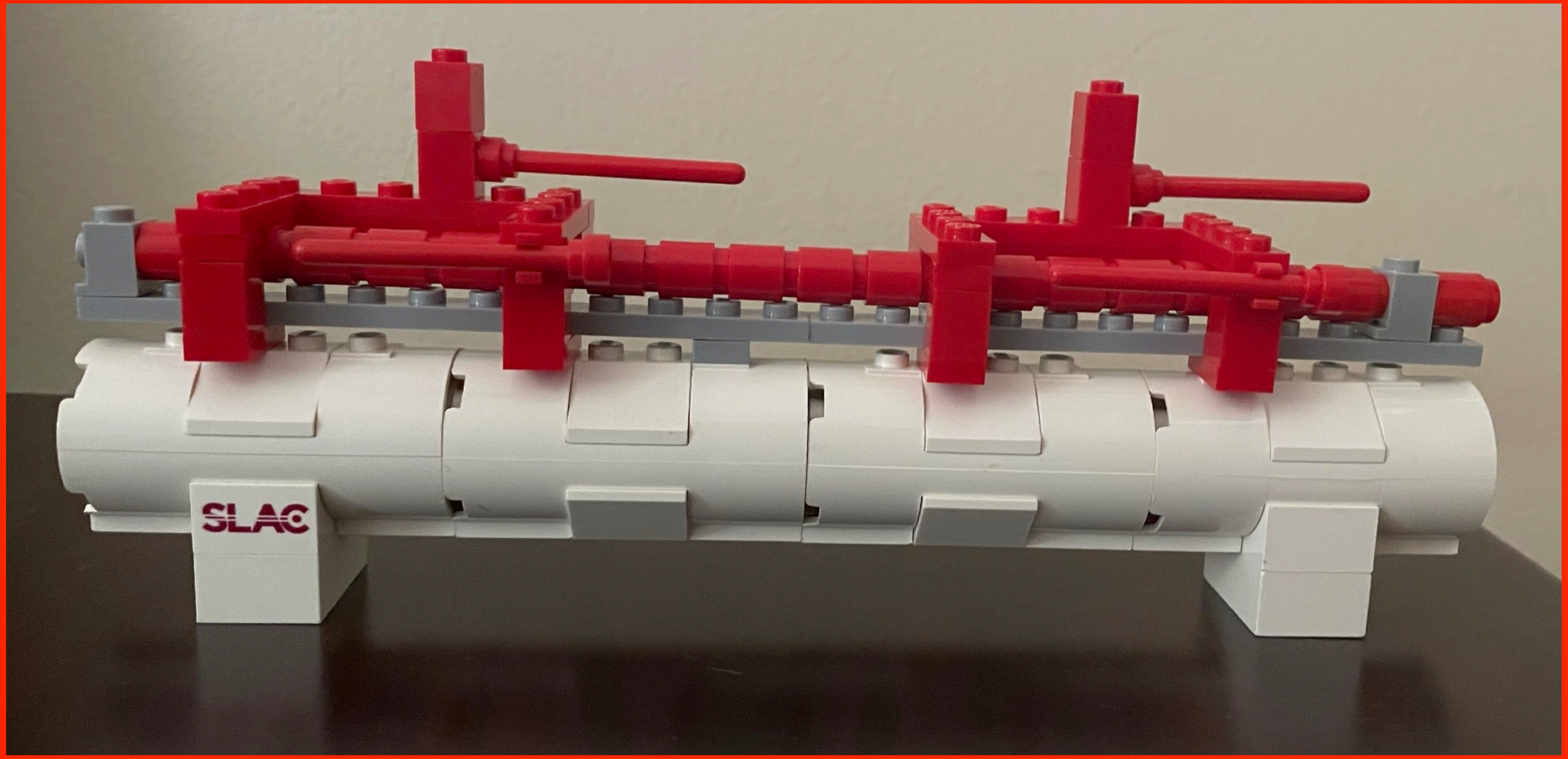
C^3 R&D, System Design and Project Planning are ongoing

- Help drive the agenda with many opportunities for other institutes to collaborate on:
  - (SiD) detector optimization, background studies, beam dynamics, vibrations and alignment, cryogenics, rf engineering, controls, etc.
- Research opportunities at SLAC for short-long term:
  - DOE SULI https://science.osti.gov/wdts/suli
  - DOE SCGSR https://science.osti.gov/wdts/scgsr

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 can be quickly and inexpensively 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
- Demonstration facility will play an exciting role in many Accelerator R&D topical areas





Extra