The Cool Copper Collider: An Advanced Concept for a Future e^+e^- Higgs Factory

Emilio Nanni

32nd International Symposium on Lepton Photon Interactions at High Energies
8/25/2025

Acknowledgements

arXiv > physics > arXiv:2503.20829

Physics > Accelerator Physics

[Submitted on 26 Mar 2025 (v1), last revised 6 Apr 2025 (this version, v2)]

ESPPU INPUT: C^3 within the "Linear Collider Vision"

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The Linear Collider Vision calls for a Linear Collider Facility with a physics reach from a Higgs Factory to the TeV-scale with e^+e^- collisions. One of the technologies under consideration for the accelerator is a cold-copper distributed-coupling linac capable of achieving high gradient. This technology is being pursued by the C^3 collaboration to understand its applicability to future colliders and broader scientific applications. In this input we share the baseline parameters for a C^3 Higgs-factory and the energy reach of up to 3 TeV in the 33 km tunnel foreseen under the Linear Collider Vision. Recent results, near-term plans and future R\&D needs are highlighted.

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PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: June 2, 2023
ACCEPTED: August 23, 2023
PUBLISHED: September 28, 2023

SNOWMASS'2021 ACCELERATOR FRONTIER

Status and future plans for C^3 R&D

Perspective | Open Access

Sustainability Strategy for the Cool Copper Collider

Martin Breidenbach, Brendon Bullard, Emilio Alessandro Nanni, Dimitrios Ntounis, and Caterina Vernieri

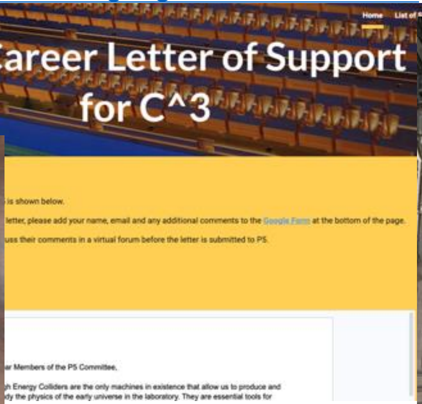
PRX Energy 2, 047001 – Published 26 October 2023

Community Events

https://web.slac.stanford.edu/c3/events

SLAC Feb. 12^{th}-13^{th}

https://sites.google.com/view/ec4c3

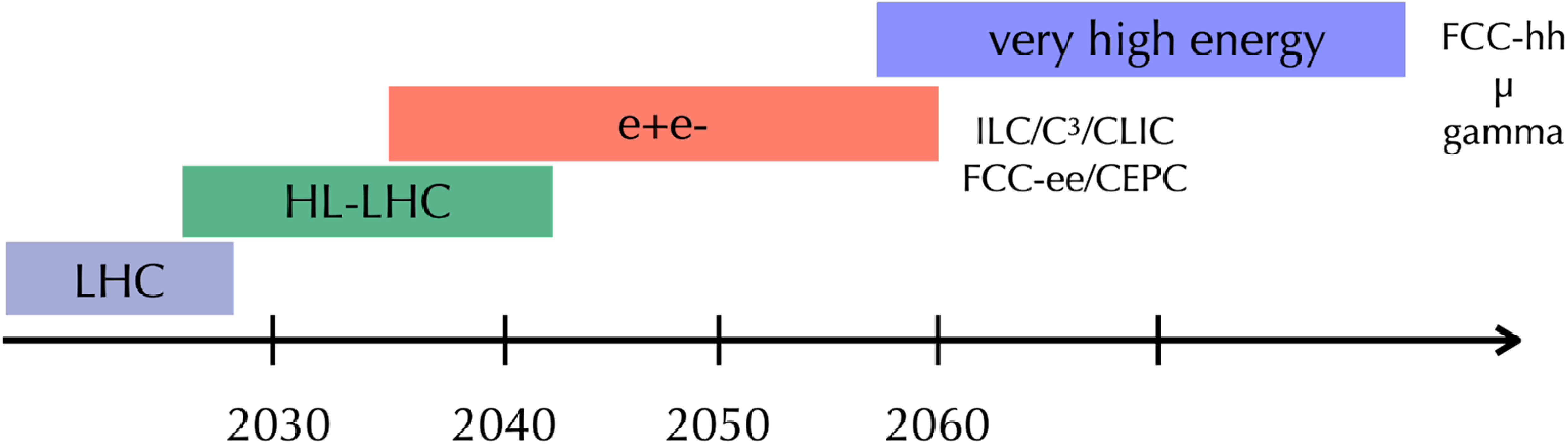


Next C3 Meeting at LCWS, Oct. 22^{nd} '25

More Details Here (Follow, Endorse, Collabora
https://web.slac.stanford.edu/c3/

Exploring the Energy Frontier…

What's Next for the Energy Frontier?



Wish list beyond HL-LHC:

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

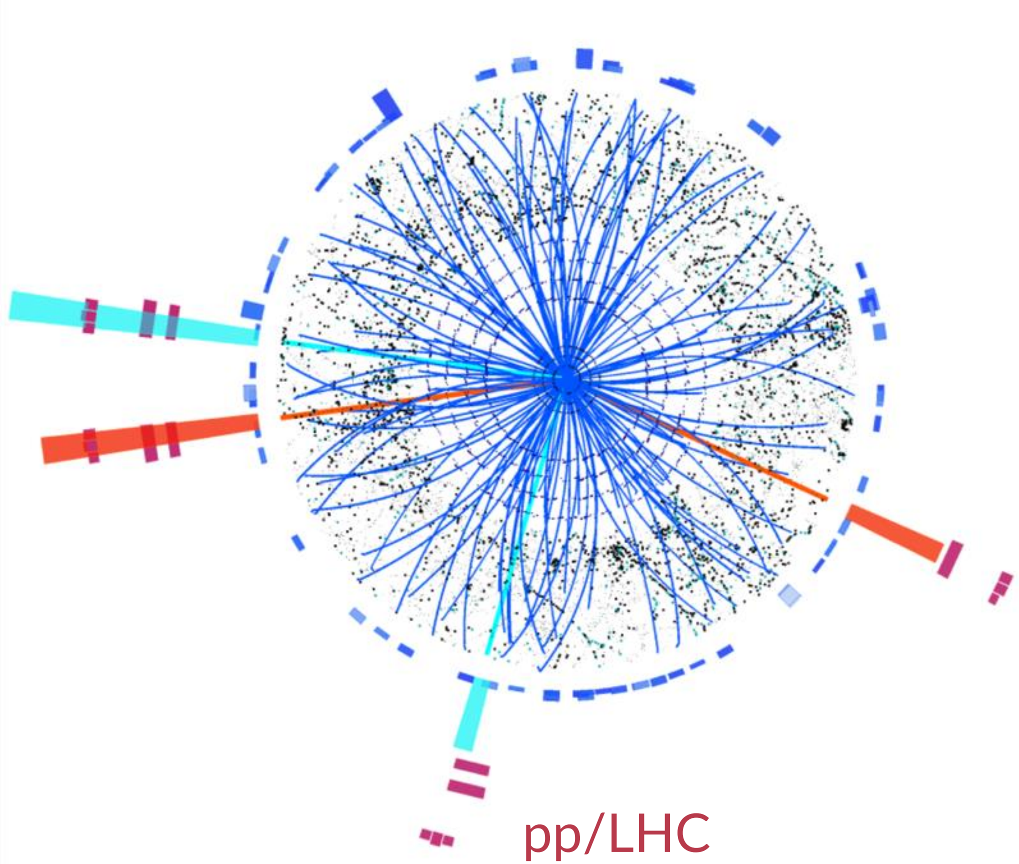
For the next e+e- Linear Collider

1. 5X the Beam Energy
2. 1000X the Luminosity (Effectively Beam Power Density)

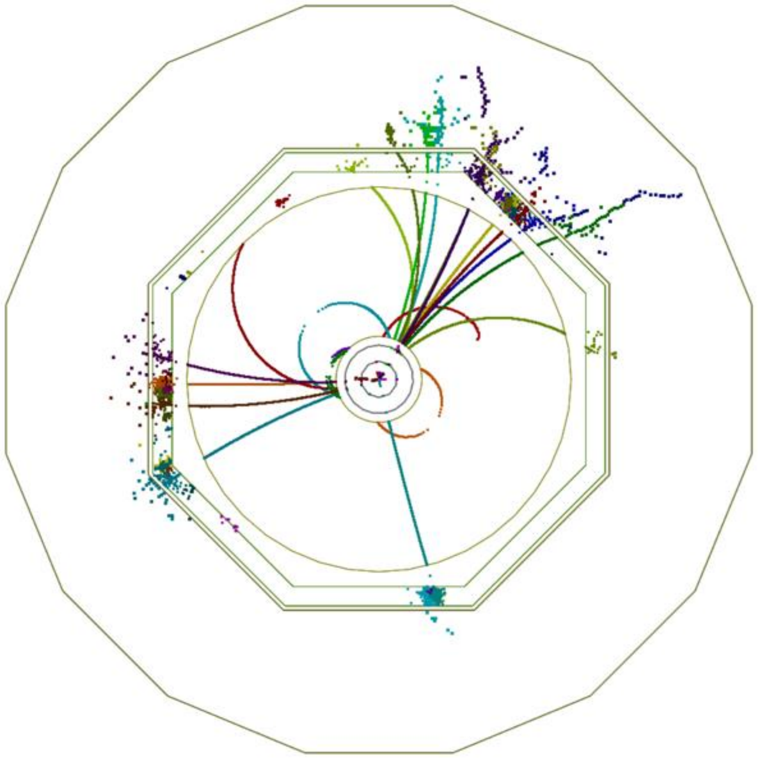
Why e^+e^-?

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

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



pp/LHC



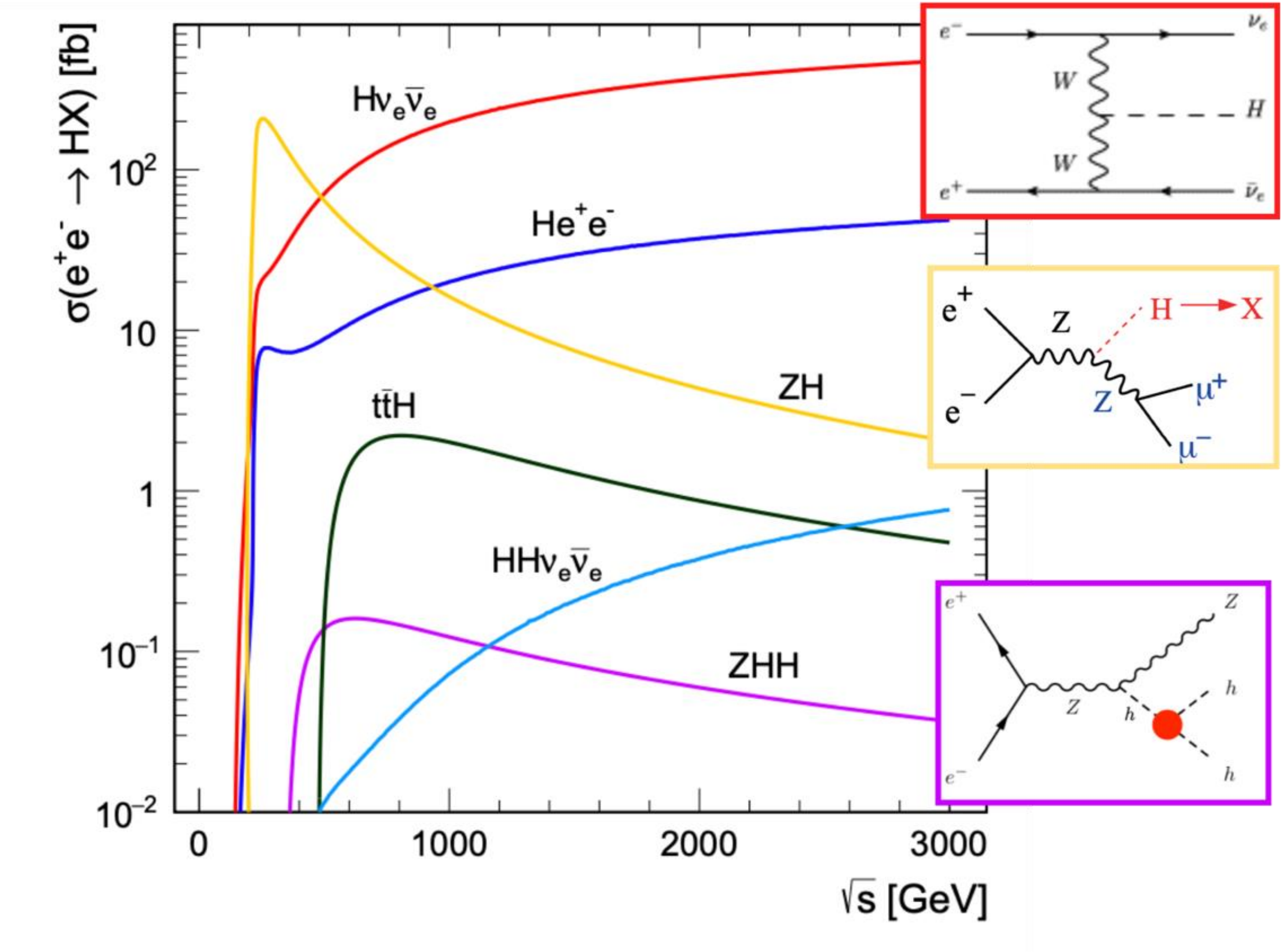
e^+e^-

Higgs Production at e^+e^-

ZH is dominant at 250 GeV

Above 500 GeV

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

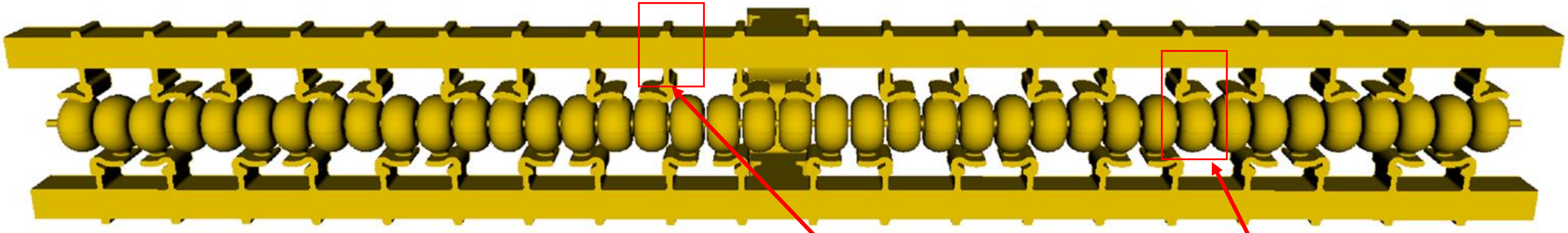


A novel route to a linear e^+e^- collider…

Breakthrough in the Performance of RF Accelerators

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

Full system design requires modern virtual prototyping



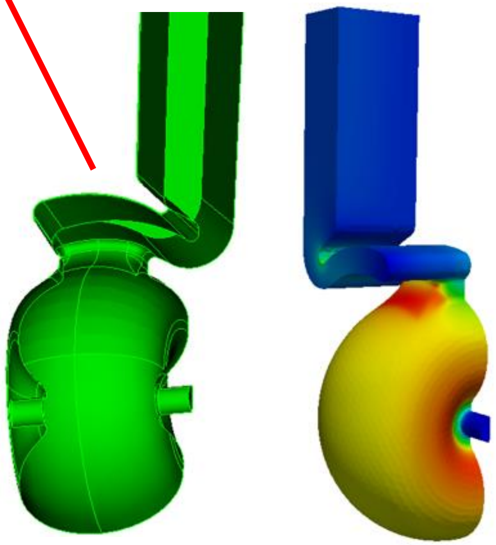
Vacuum space for rf cavities and manifold

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

Optimization of cell for efficiency (shunt impedance)

- Control peak surface electric and magnetic fields

Key to high gradient operation



arXiv:1807.10195 (2018)
PRAB 23.9 (2020): 092001

Cryo-Copper: Enabling Efficient High-Gradient Operation

Cryogenic temperature elevates performance in gradient

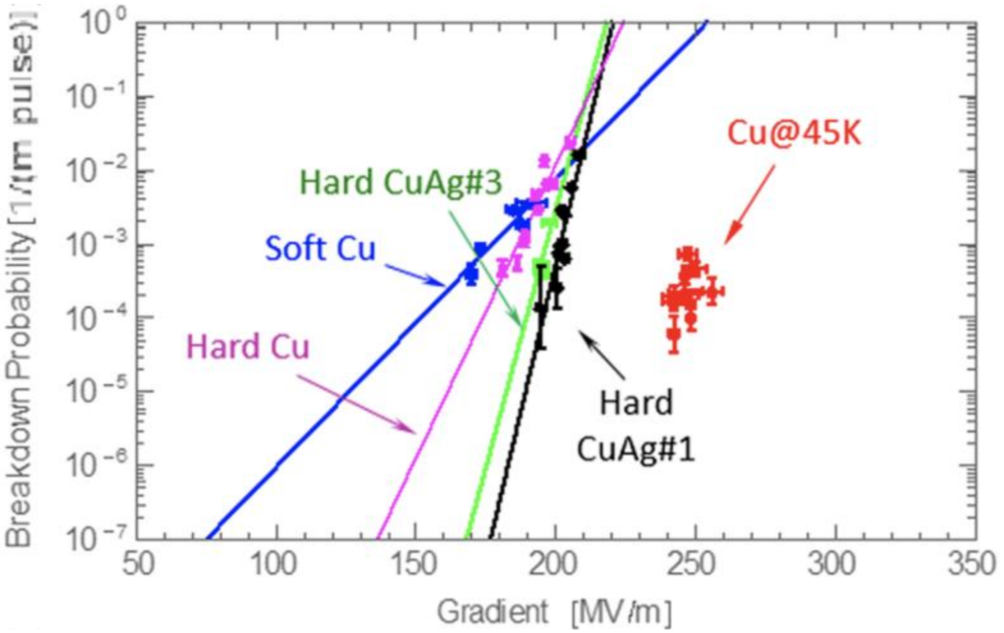
- Material strength is key factor
- Impact of high fields for a high brightness injector may eliminate need for one damping ring

Operation at 77 K with liquid nitrogen is simple and practical

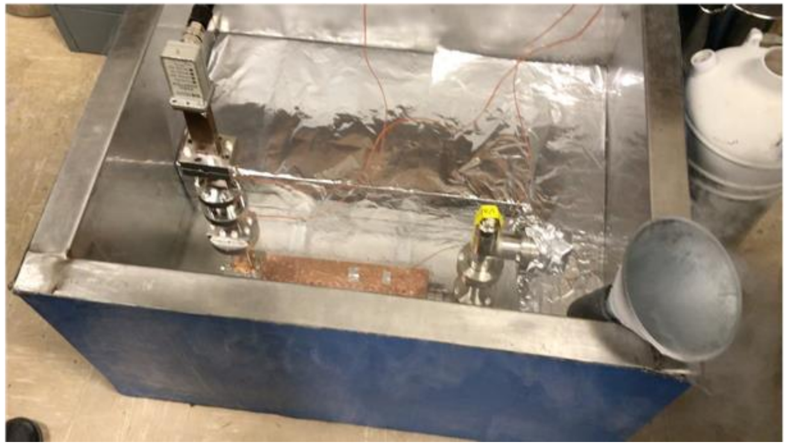
- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency

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

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



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



RF Power Requirements

70 MeV/m 250 ns Flattop (extendible to 1400 ns)

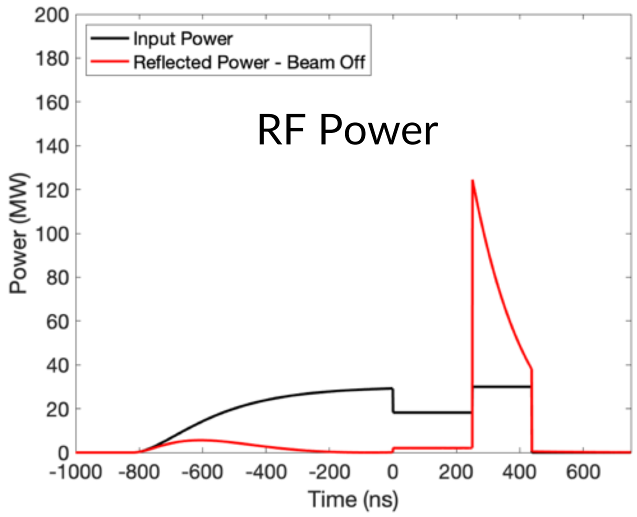
~2 microsecond rf pulse, ~30 MW/m

Conservative 2.3X enhancement from cryo

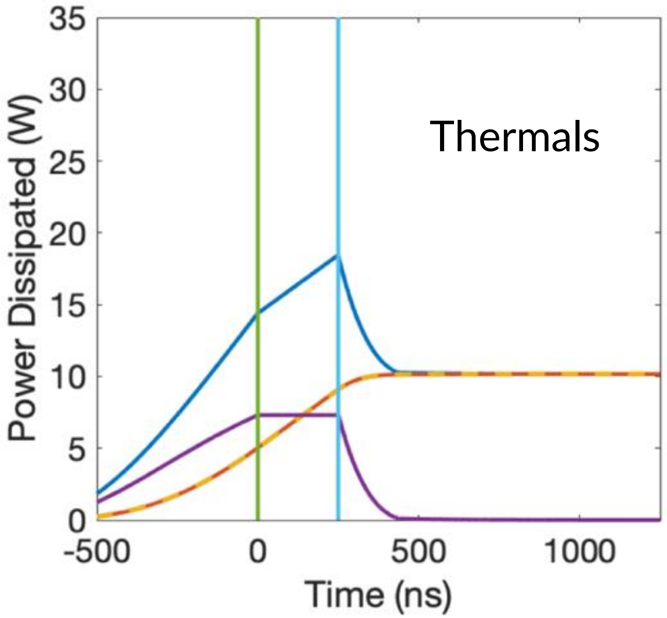
- No pulse compression

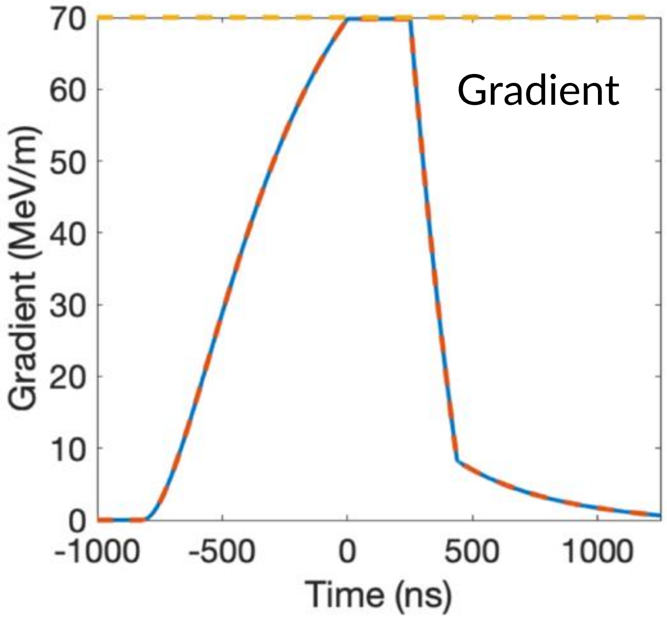
Ramp power to reduce reflected power

Flip phase at output to reduce thermals



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





Accelerator Complex

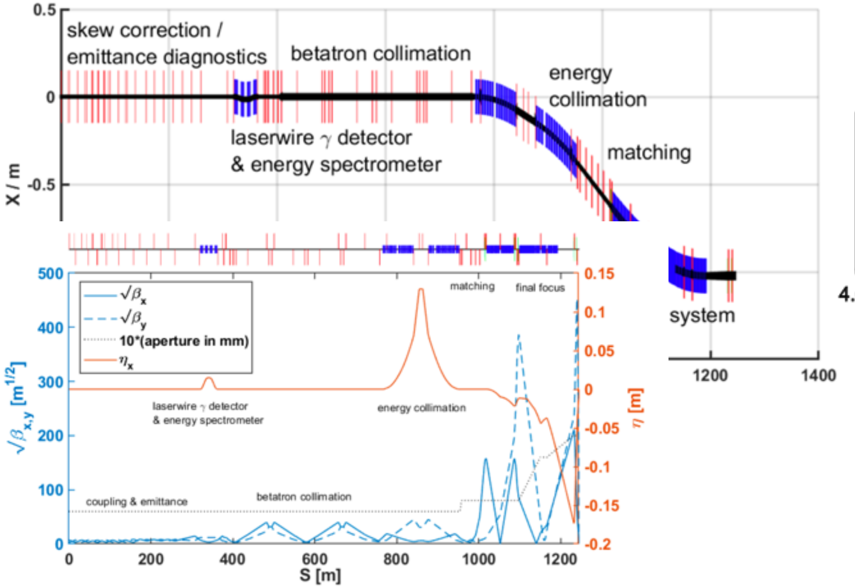
8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

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

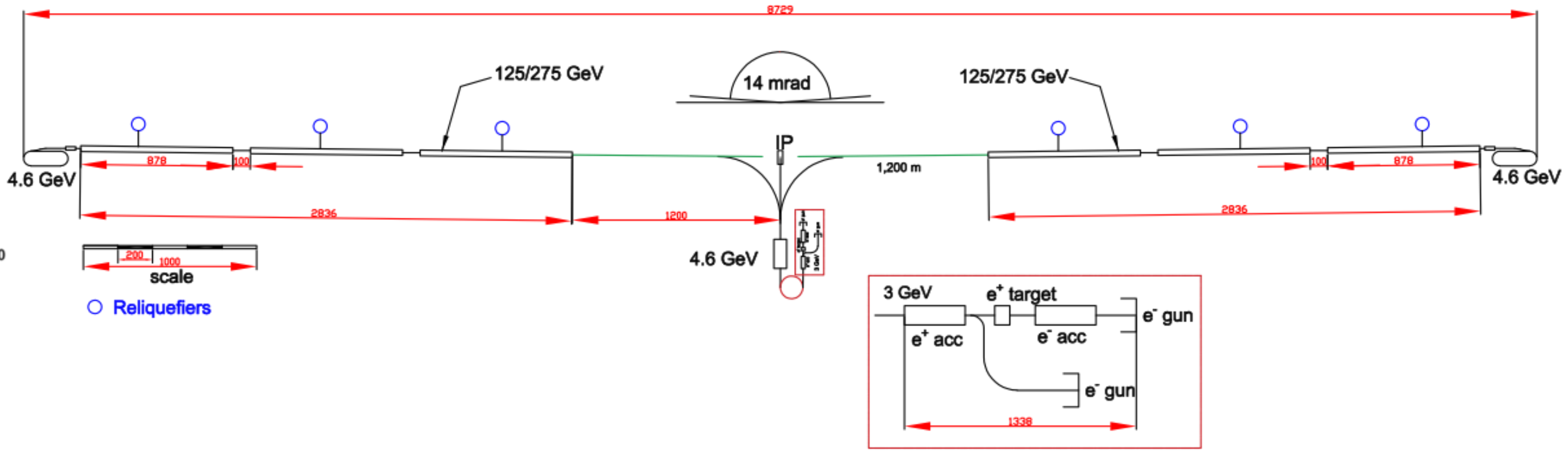
Large portions of accelerator complex are compatible between LC technologies

- 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)



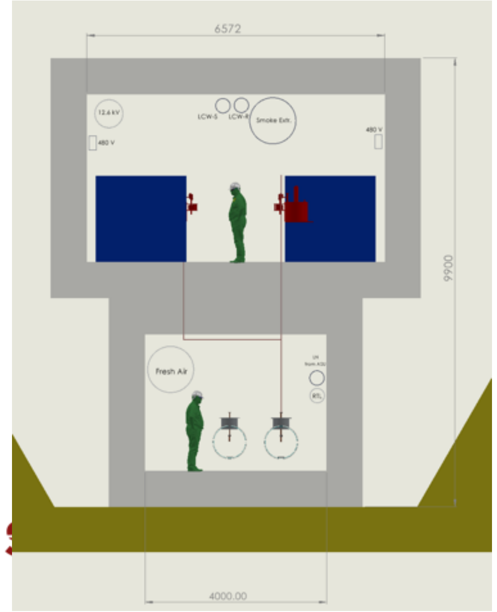
C^3 - 8 km Footprint for 250/550 GeV



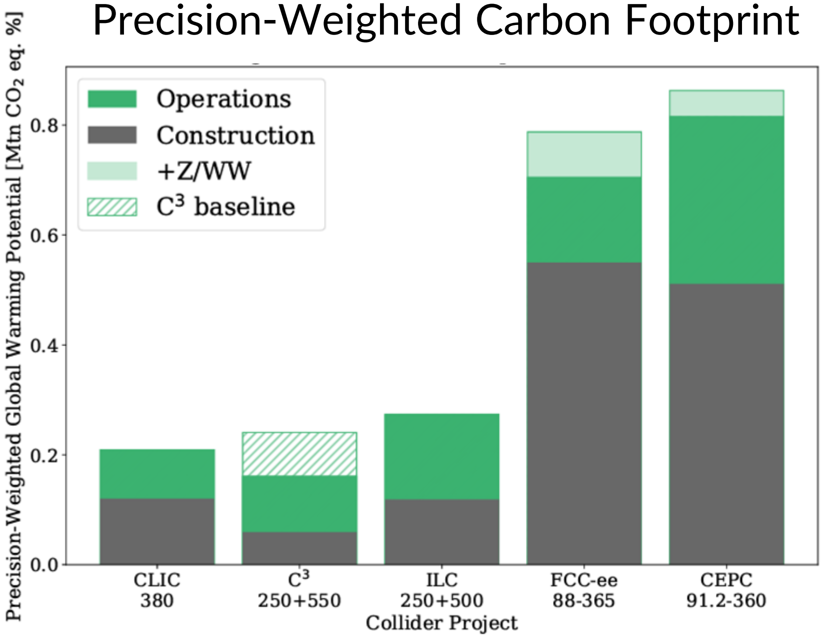
Power Consumption and Sustainability

- Compact footprint <8 km for both underground and surface sites
  - Underground – less constraints on energy upgrade
  - Surface – lower cost and faster to first physics
- 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

Surface-Site Mockup



Precision-Weighted Carbon Footprint



250 GeV CoM - Luminosity - 1.3×10^{34}

Parameter	Units	Value
Reliquification Plant Cost	M$/MW	18
Single Beam Power (125 GeV linac)	MW	2
Total Beam Power	MW	4
Total RF Power	MW	18
Heat Load at Cryogenic Temperature	MW	9
Electrical Power for RF	MW	40
Cryoplant Electrical Power	MW	60
Accelerator Complex Power	MW	~50
Site Power	MW	~150

PRX Energy 2.4 (2023): 047001

Table of Parameters

- Updated parameters from LCWS 2024

Scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch Charge [nC]	1	1	1	1
Crossing Angle [rad]	0.014	0.014	0.014	0.014
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	~150	~175	~110	~125

C^3 in the Context of ESPPU and LC Vision

LCVision ESPPU documents

… and relation to other inputs

Linear Collider Vision

arxiv paper & ESPPU submission

LC Physics Case & long-term vision — arxiv:2503.19983

LCF @ CERN — arxiv:2503.24049

ESPPU submission & back-up document

Technologies and upgrades

- ILC in Japan (IDT) — arxiv:2504.11292
- CLIC at CERN — arxiv:2503.24168 arxiv:2503.21857
- C^3 — arxiv:2503.20829
- HALHF — arxiv:2503.23489 arxiv:2503.19880 ESPPU submission 255
- 10 TeV Wakefield — arxiv:2503.20214 arxiv:2504.01434
- Beyond Collider — https://cds.cern.ch/record/2927631

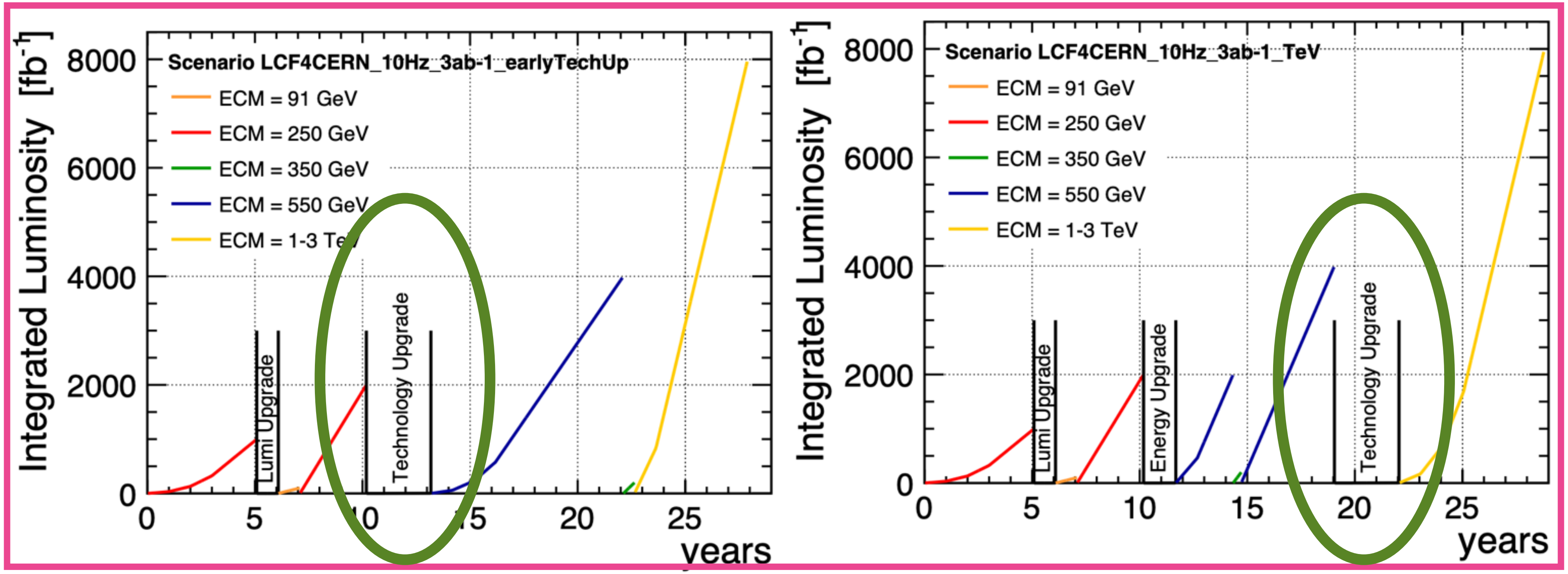
Routes to Higher Energy

A flexible strategy for a LCF

A Linear Collider

- can be built with today's technologies
- combines adequate precision with large energy range providing new insights and consistency checks

What can be done after an initial 10…20 year program by making use of advanced accelerator concepts and technologies?



C3 as upgrade for LCF

the route to 3 TeV

- studied in context of LCVision
- **LCF injector complex and damping rings compatible with C3:**
  - larger LCF DRs = lower risk
  - replace fast->slow kickers (kick whole trains)
  - bunch compressor length / emittance sufficient

=> substantial part of infrastructure could be reused

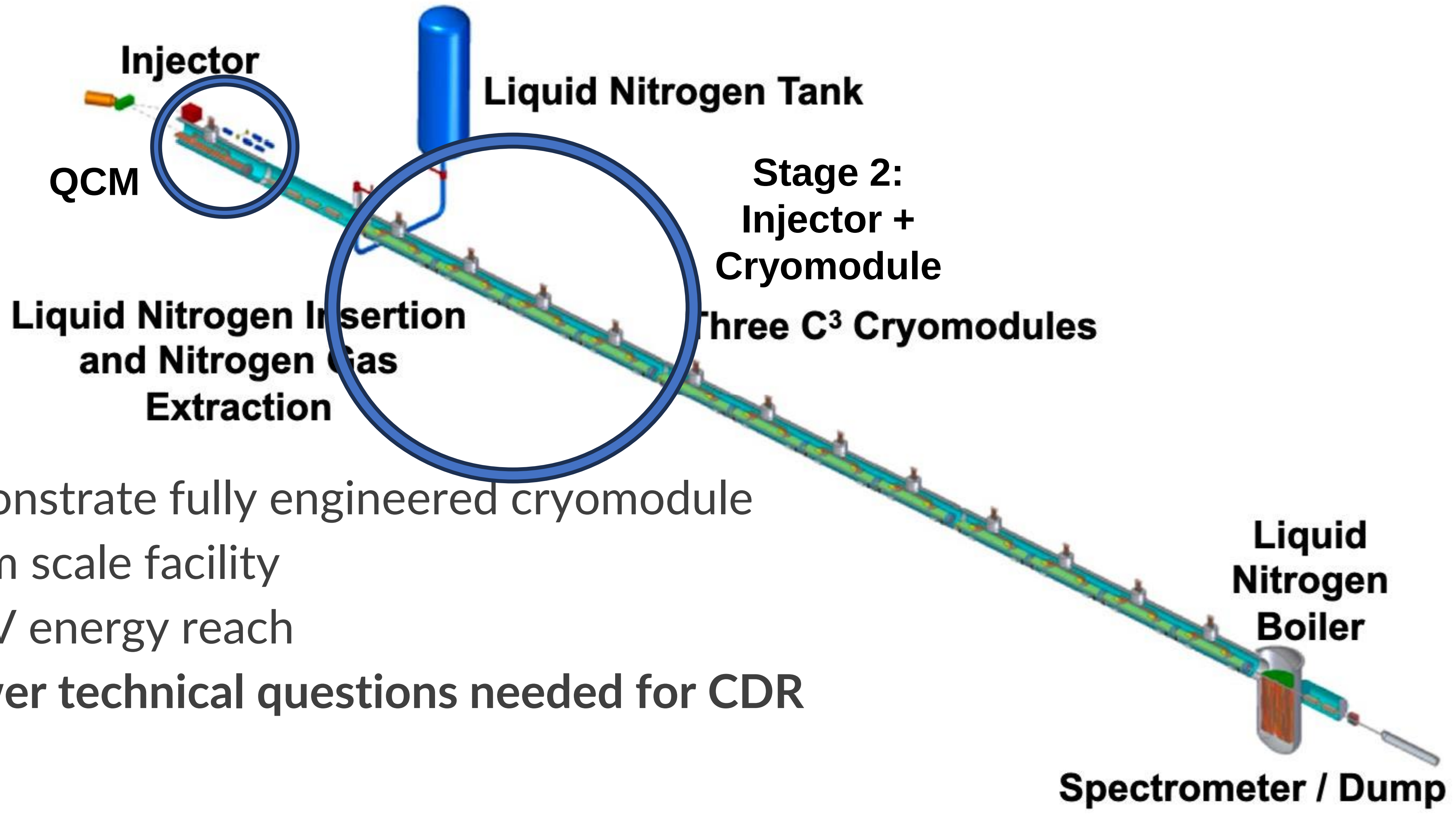
- cryo-plants need modification
- SRF cryomodules could be sold / donated for XFELs / medical linacs /.. round the world
- to be considered in design of beam delivery systems and dumps

Parameter	Unit	Value	Value	Value
Centre-of-Mass Energy	GeV	1000	2000	3000
Site Length	km	20	20	33
Main Linac Length (per side)	km	7.5	7	10.5
Accel. Grad.	MeV/m	75	155	155
Flat-Top Pulse Length	ns	500	195	195
Cryogenic Load at 77 K	MW	14	20	30
Est. AC Power for RF Sources	MW	68	65	100
Est. Electrical Power for Cryogenic Cooling	MW	81	116	175
Est. Site Power	MW	200	230	320
RF Pulse Compression		N/A	3X	3X
RF Source efficiency (AC line to linac)	%	50	80	80
Luminosity	$\times 10^{34}$ cm^{-2}s^{-1}	$\sim$4.5	$\sim$9	$\sim$14
Single Beam Power	MW	5	9	14
Injection Energy Main Linac	GeV	10	10	10
Train Rep. Rate	Hz	60	60	60
Bunch Charge	nC	1	1	1
Bunch Spacing	ns	3	1.2	1.2

Sustainability: C3 can be 2-4x more power efficient in TeV regime than CLIC / ILC
Very exciting R&D target for the next decade!

C^3 Demo

The Complete C^3 Demonstrator



Demonstrate fully engineered cryomodule

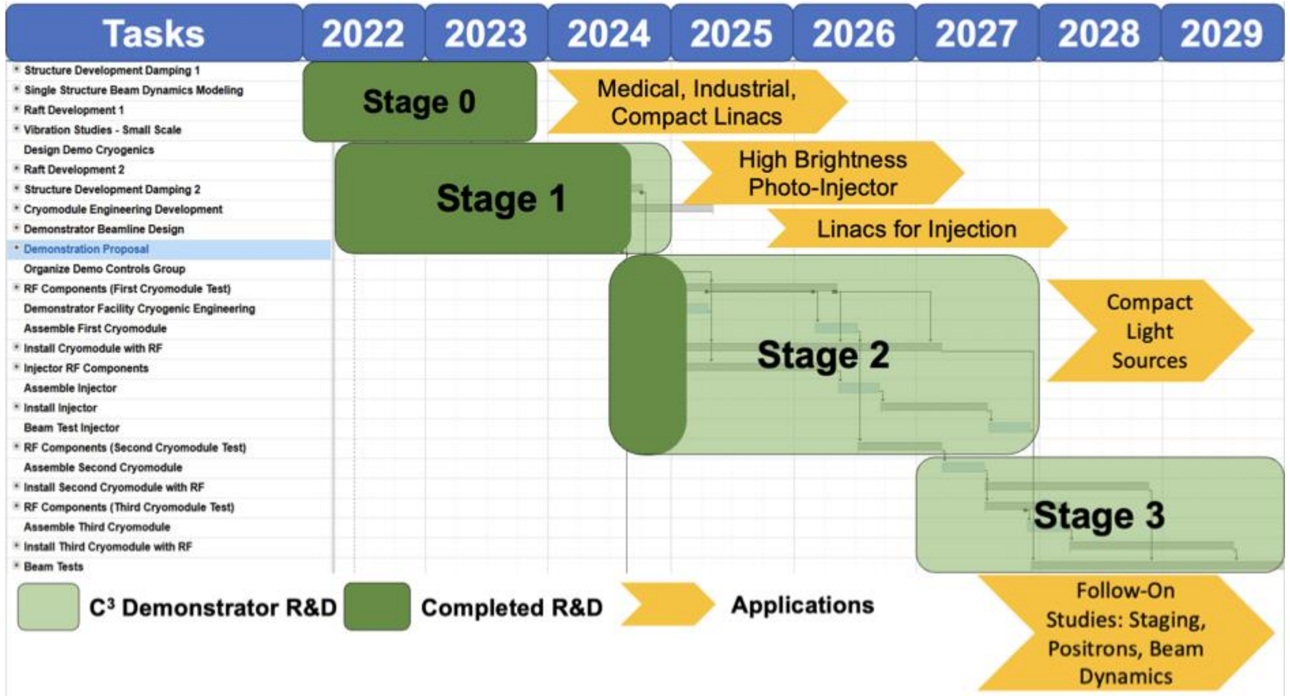
~50 m scale facility

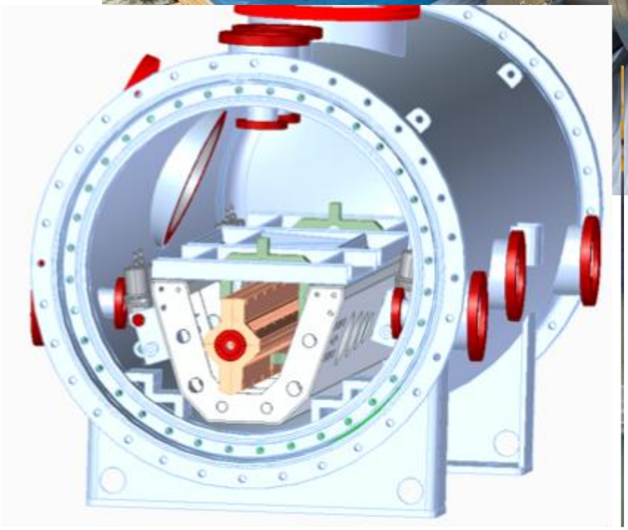
3 GeV energy reach

Answer technical questions needed for CDR

Quarter Cryomodule (QCM)

- Vacuum insulation, raft length up to 2.5 m
- First step into realizing Stage 2 goals
- Outfit for alignment and vibration testing
- Follow-on experiments with structures at high gradient and beam acceleration (see next talk)

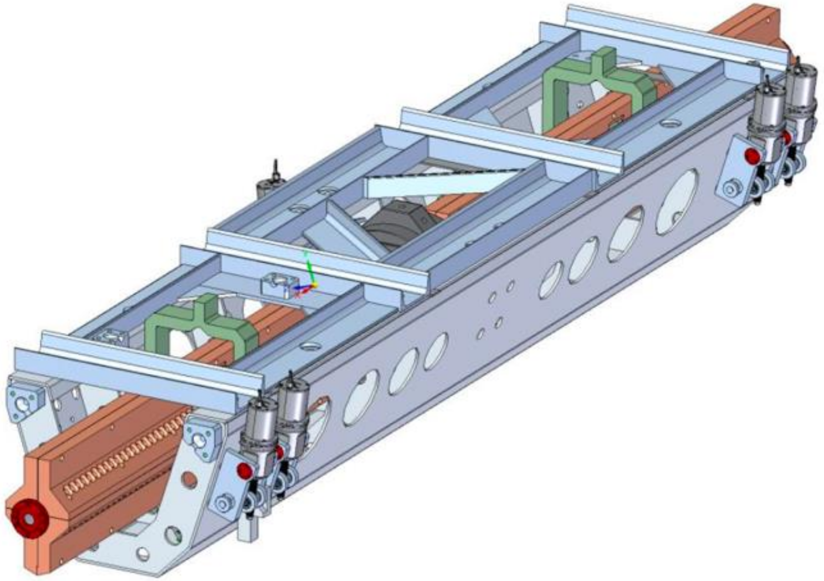


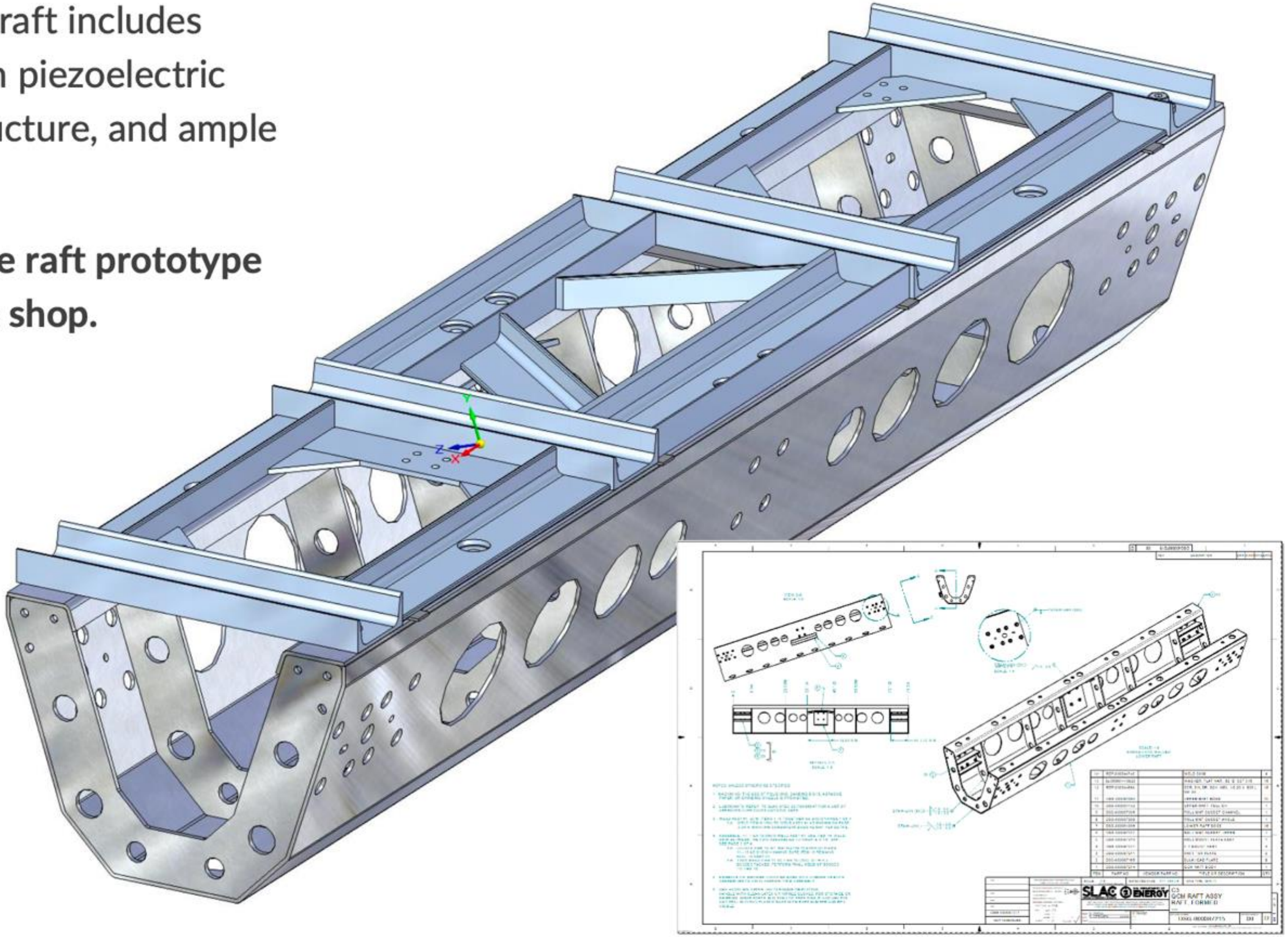


QCM with Raft

The raft is designed to support the accelerator structure during assembly and permanently once installed. The raft includes mounting points for alignment adjustment with piezoelectric motors, compliant mounting points for the structure, and ample flow channels for LN2.

The design and drawings are complete, and the raft prototype has been placed on order with a local machine shop.



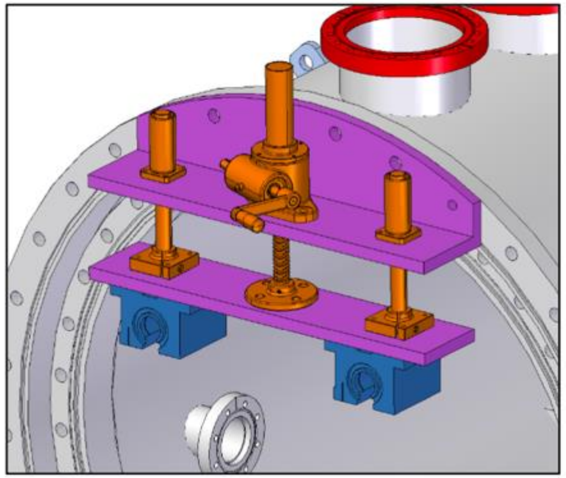


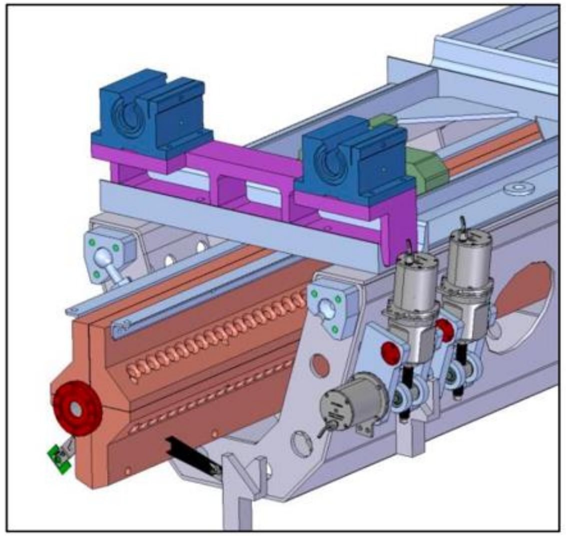
Raft Loading Setup

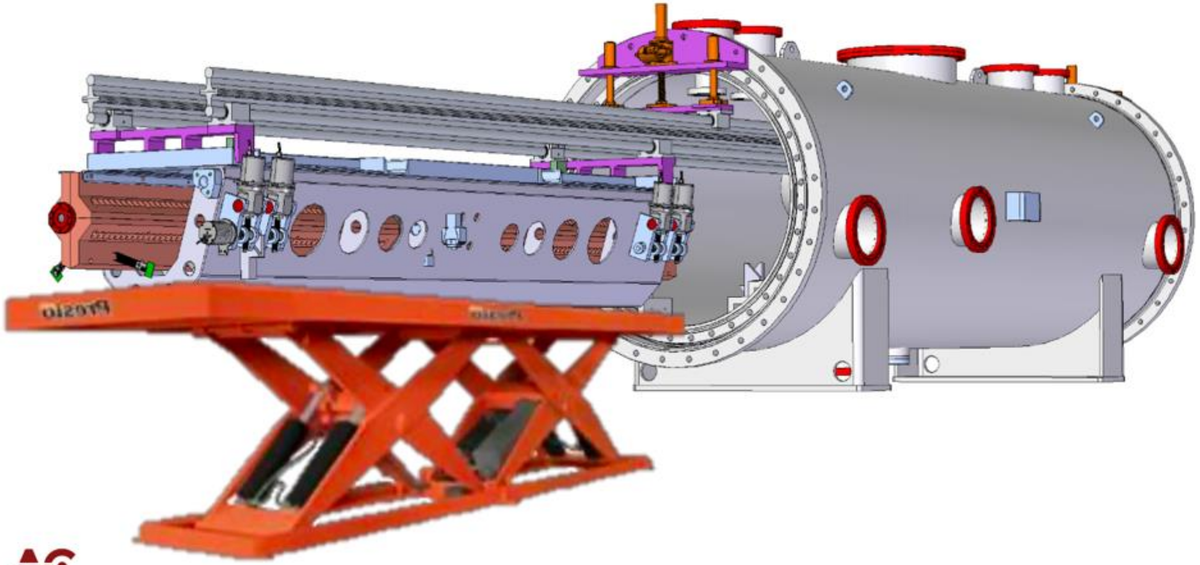
The loading setup enables horizontal installation of the raft and structure with vertical adjustment to clear mounting hardware.

Loading is done with adjustable height bearings which can be manually adjusted or controlled with stepper motors. All fixtures and bearings are removed once installed.

The design is still in the conceptual design phase.







SLAC

Conclusion

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

- Higgs physics run by 2040

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

Looking forward to discussions on LC Vision and C3 inputs to ESPPU

See Next Talk by Ankur Dhar on Cold-Copper Technology Update

Full slate of technical updates at LCWS 2025

More Details Here (Follow, Endorse, Collaborate):
https://web.slac.stanford.edu/c3/

Questions?