Status of C3 R&D

The Higgs Boson at Future Colliders

web.slac.stanford.edu/c3/

Caterina Vernieri, Emilio Nanni

July 8, 2024

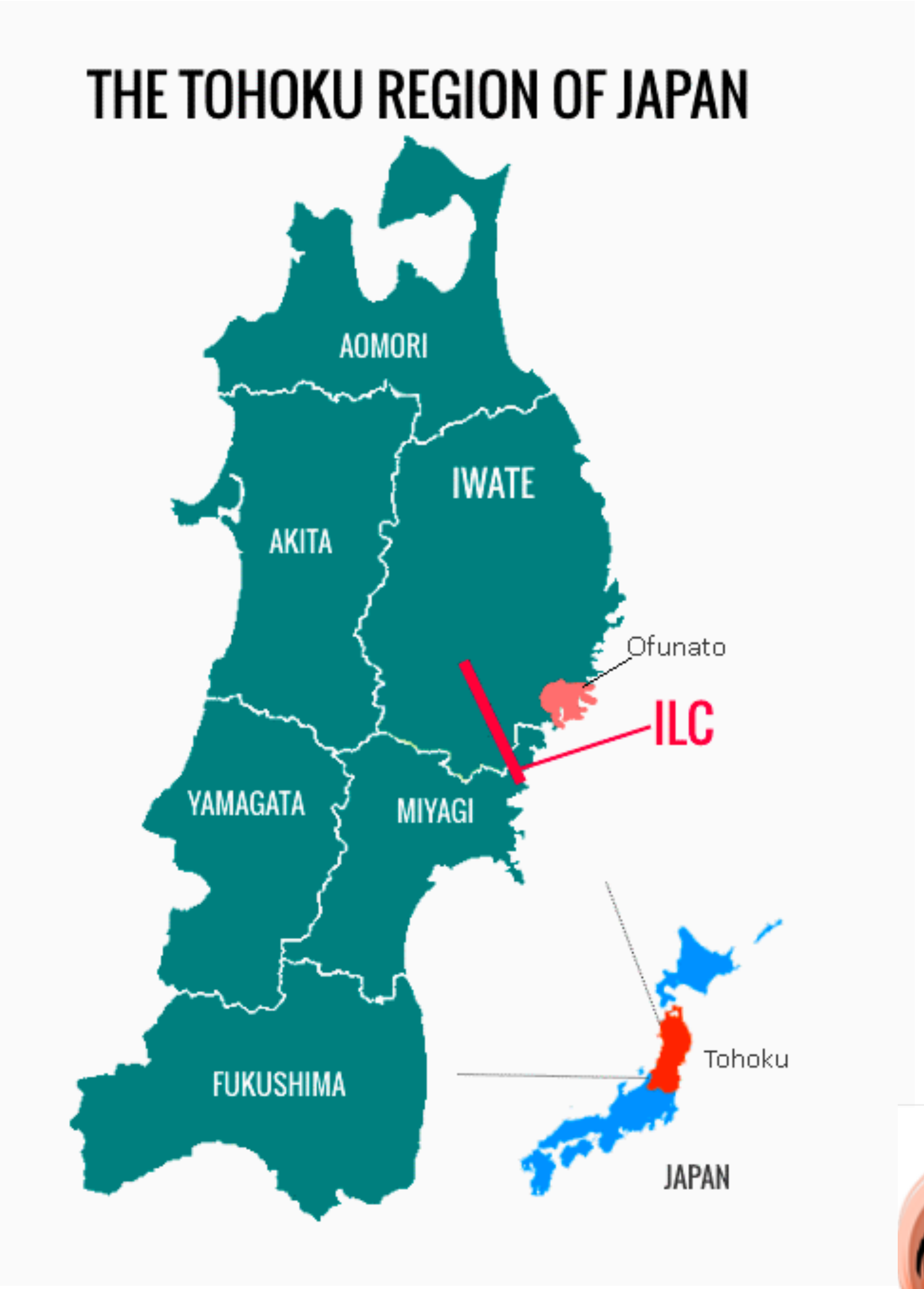
SLAC NATIONAL ACCELERATOR LABORATORY

LCWS2024 International Workshop on Future Linear Colliders

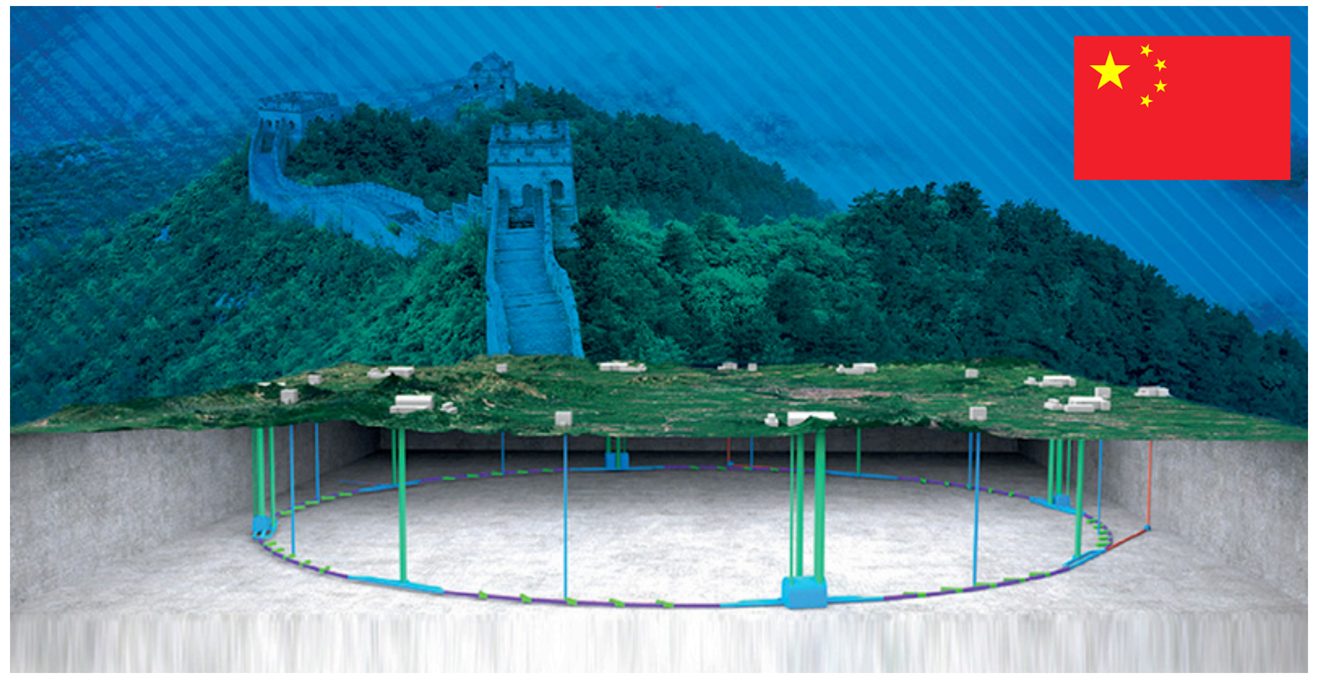
Stanford University | U.S. DEPARTMENT OF ENERGY

Higgs Factories

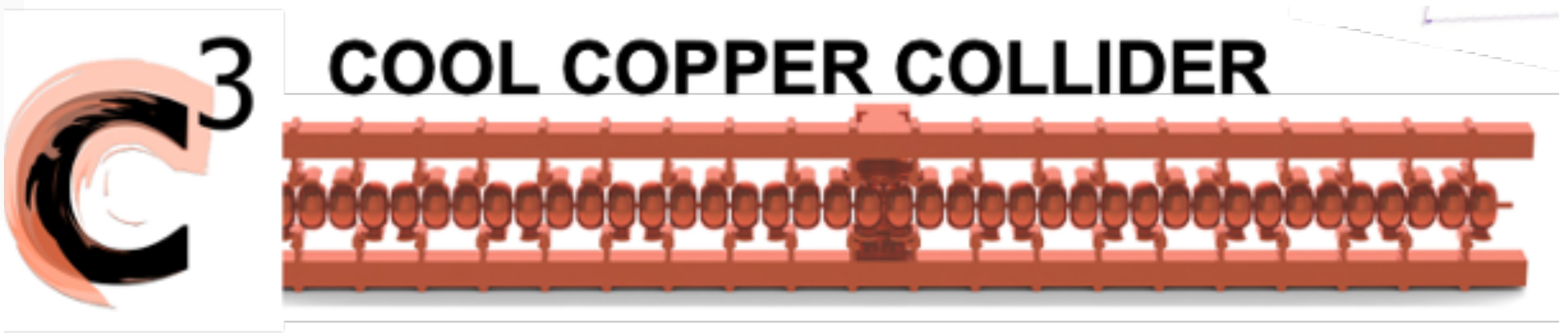
P5 report



250/500 GeV

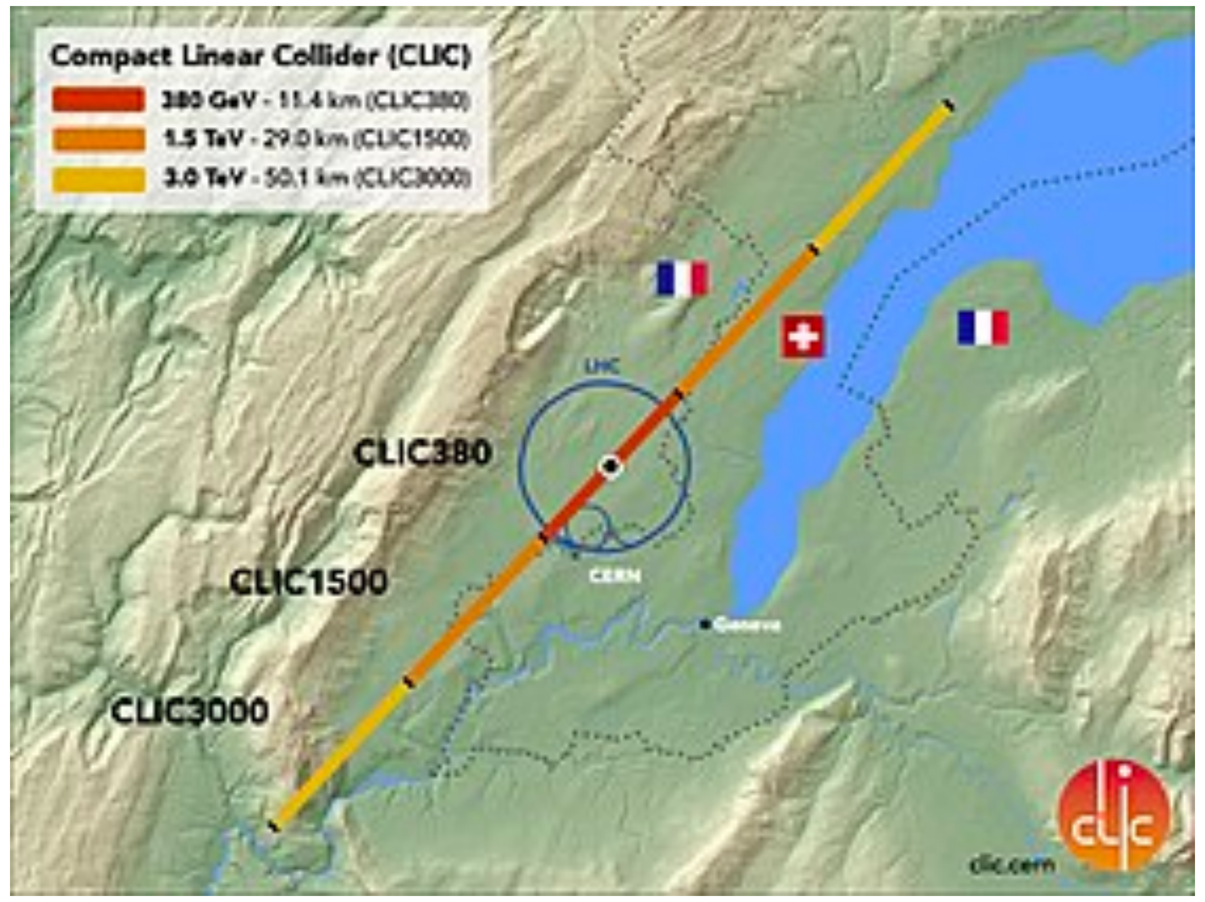


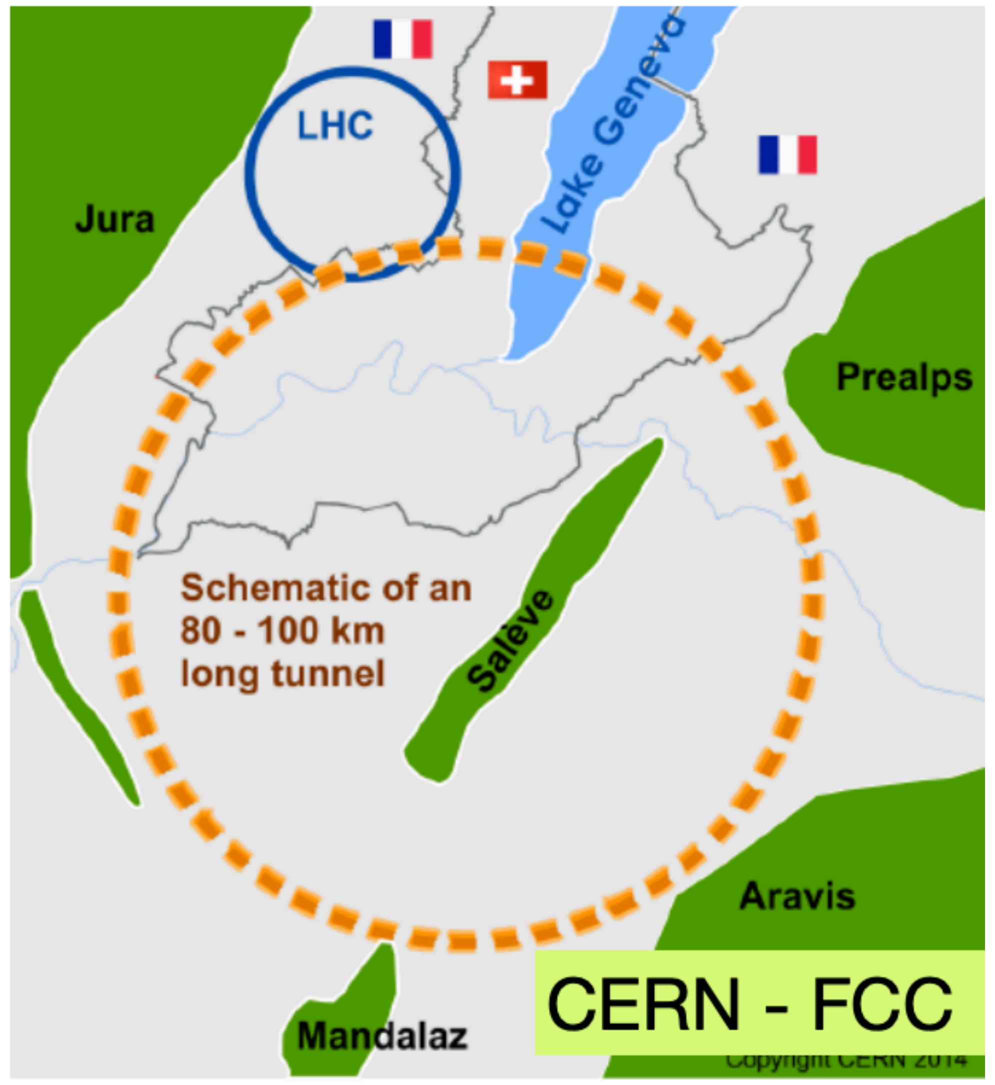
CEPC 240 GeV



250/550/… GeV

CLIC 380/1500/3000 GeV



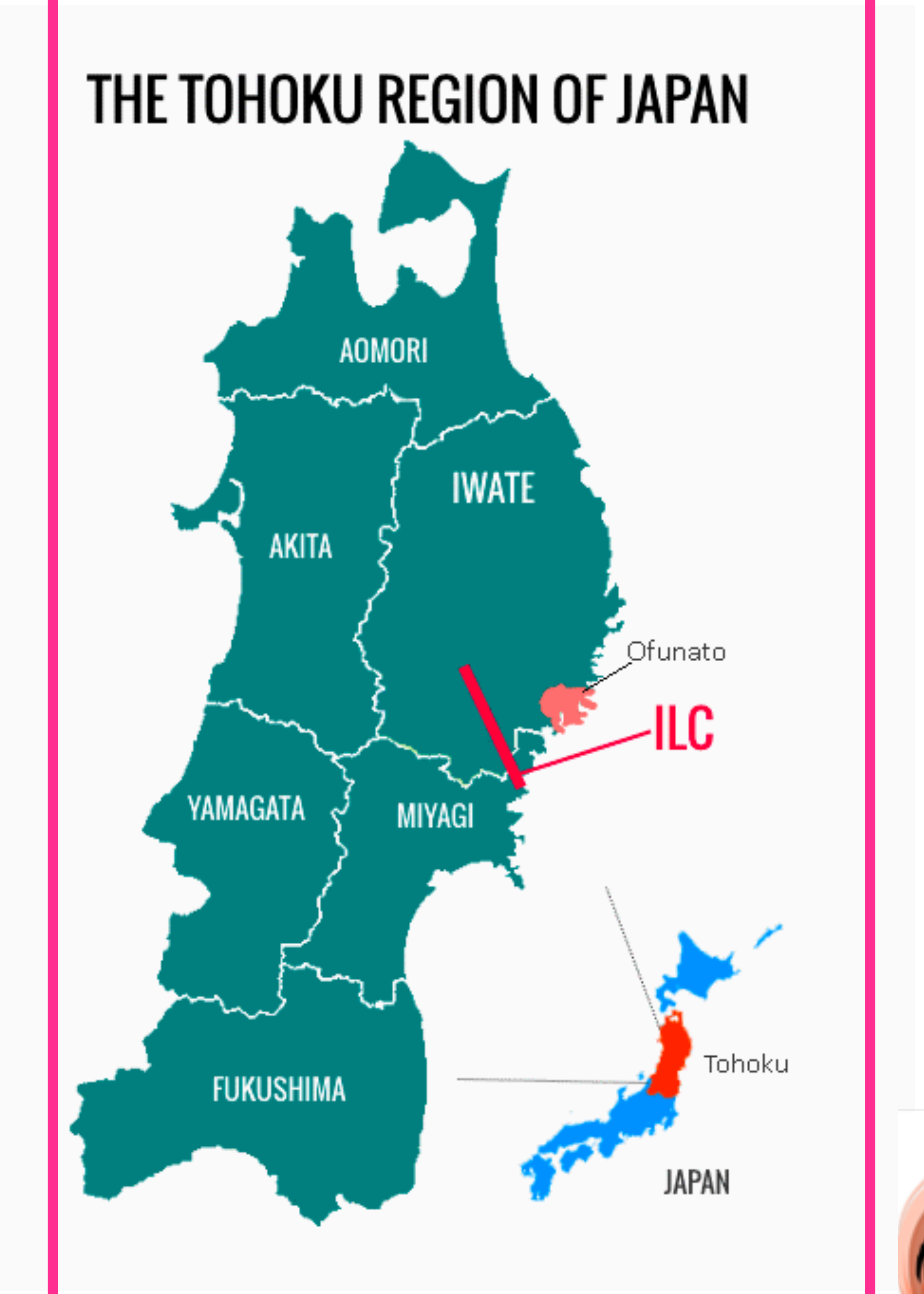


FCC-ee

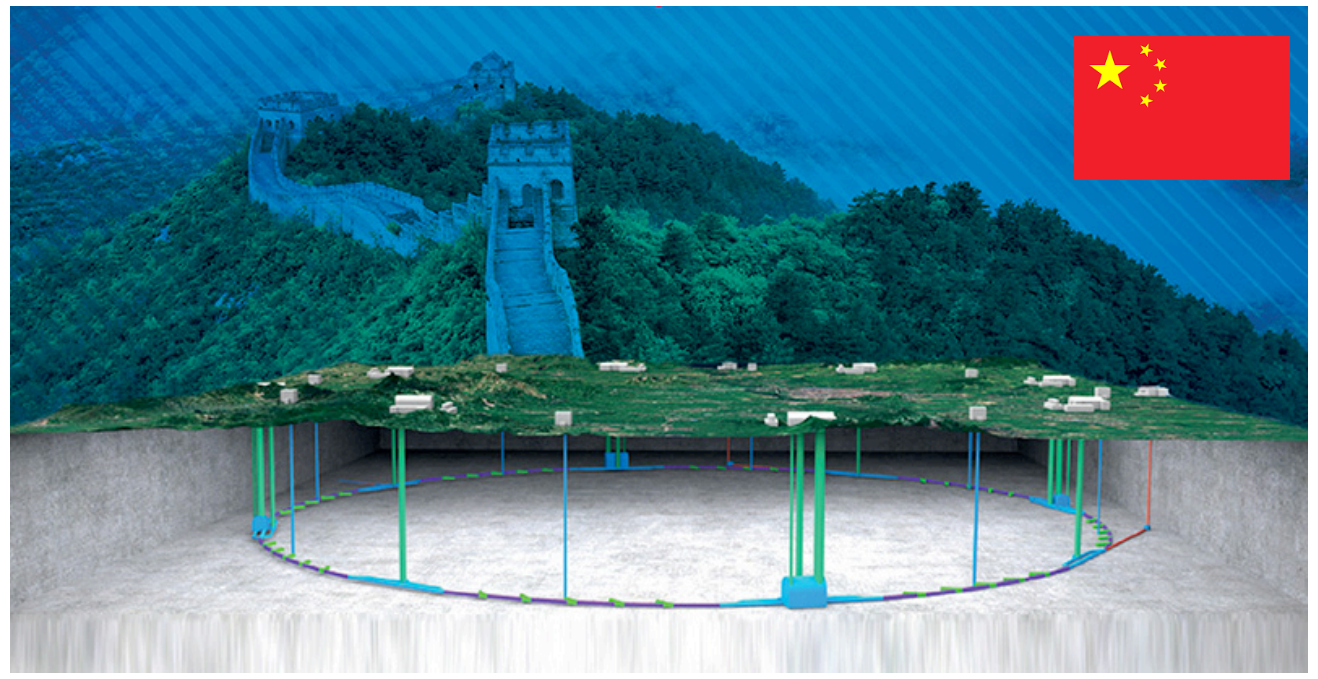
90/240/365 GeV

Higgs Factories

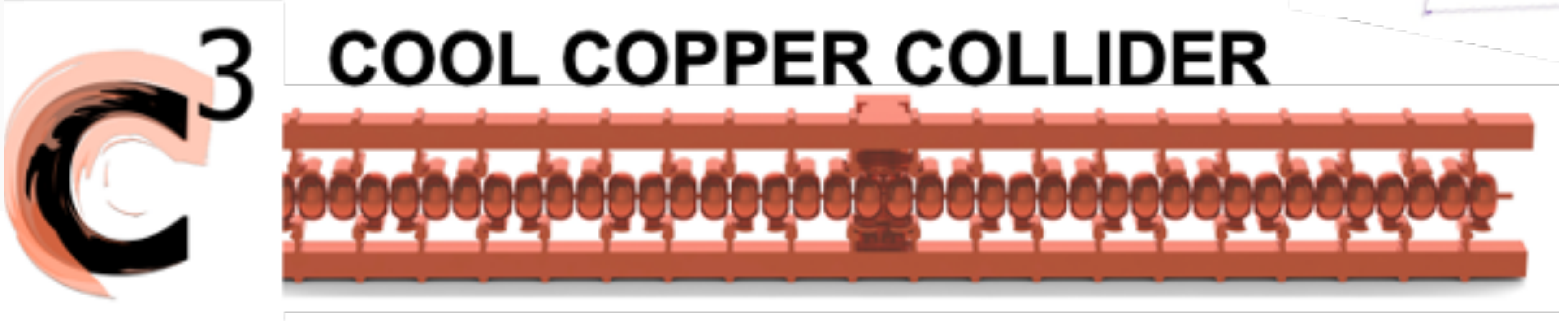
P5 report



250/500 GeV

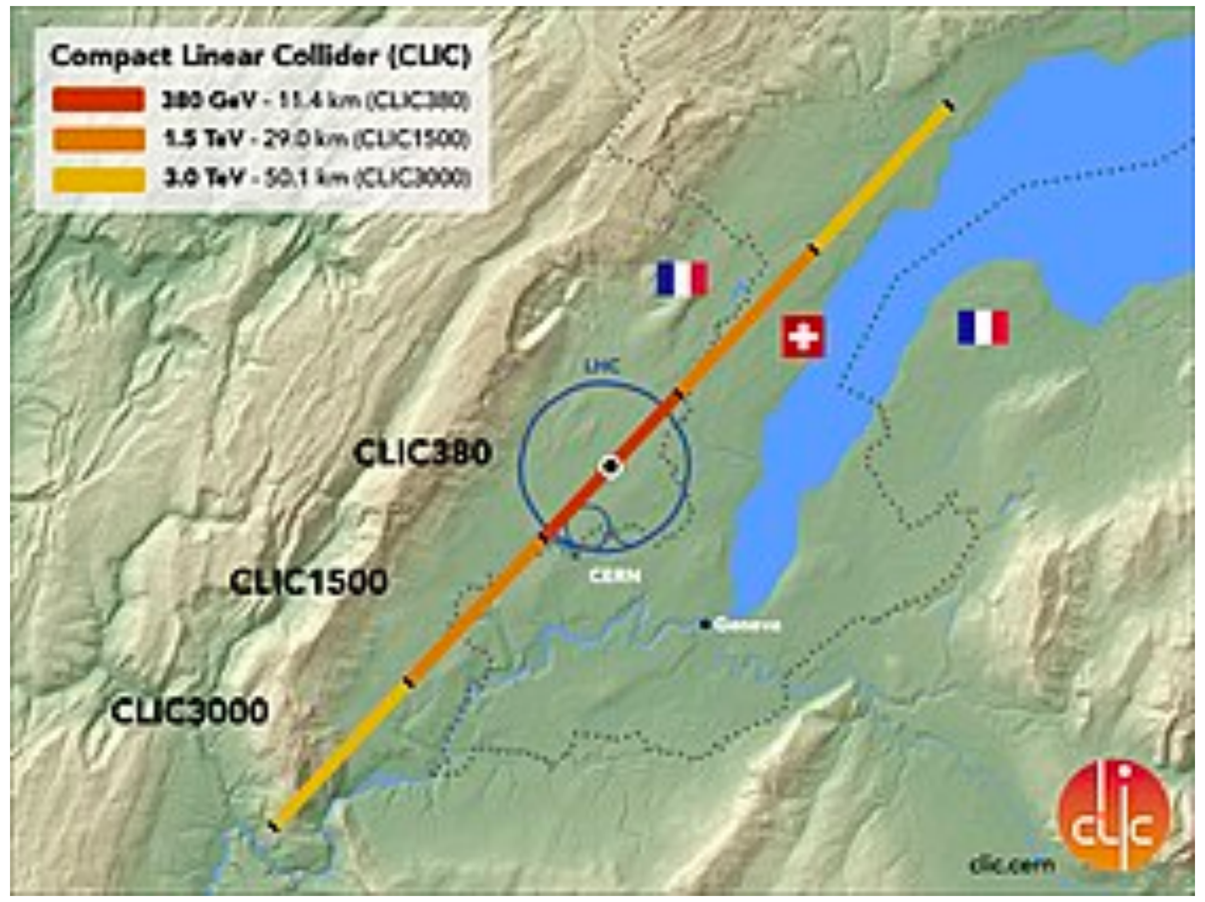


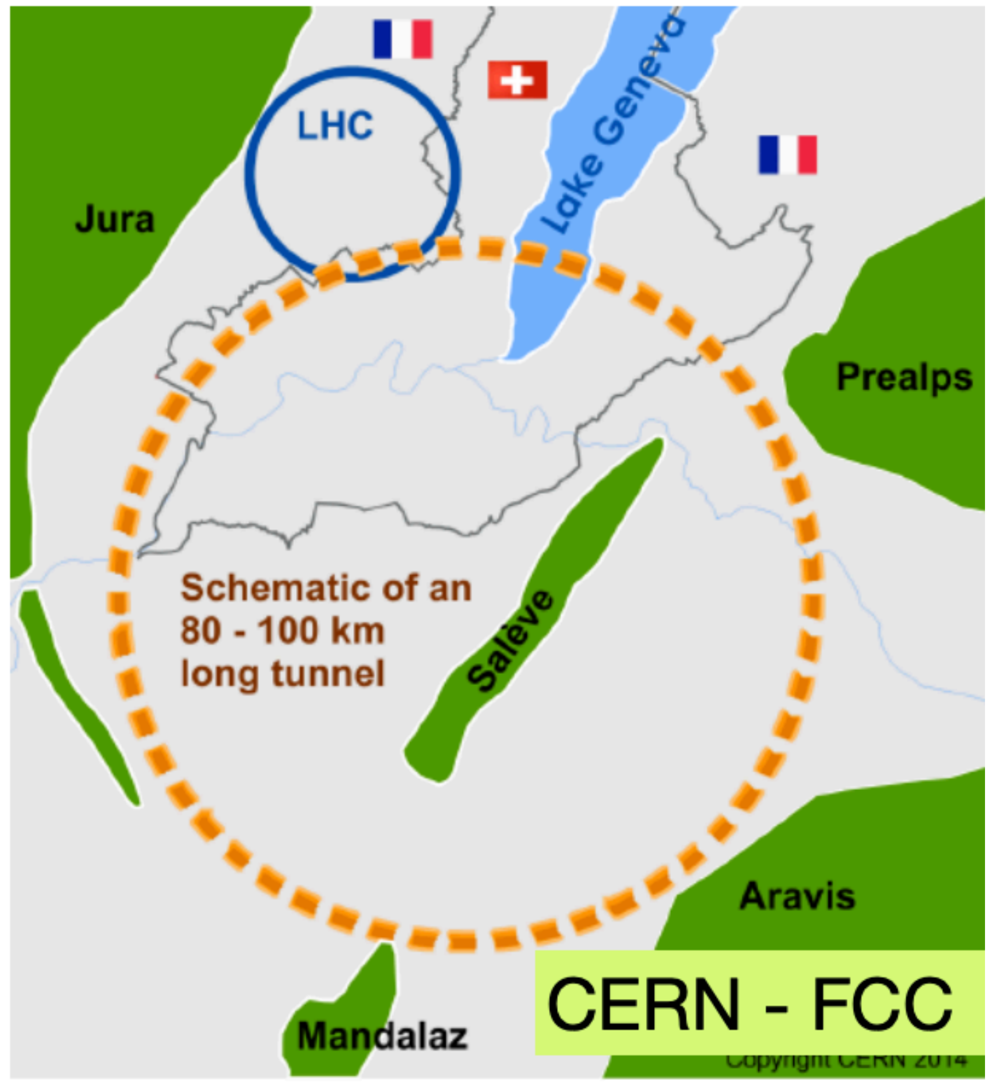
CEPC 240 GeV



250/550/… GeV

CLIC 380/1500/3000 GeV





FCC-ee

90/240/365 GeV

Post P5, motivating accelerator R&D

P5 report

Enabling the machines of the future

“Incorporate innovative concepts like cryogenic **cool copper** in the normal conducting RF program”

Area Recommendation 8: Future test facilities could include the **second stage cool copper** test for high gradient RF technology

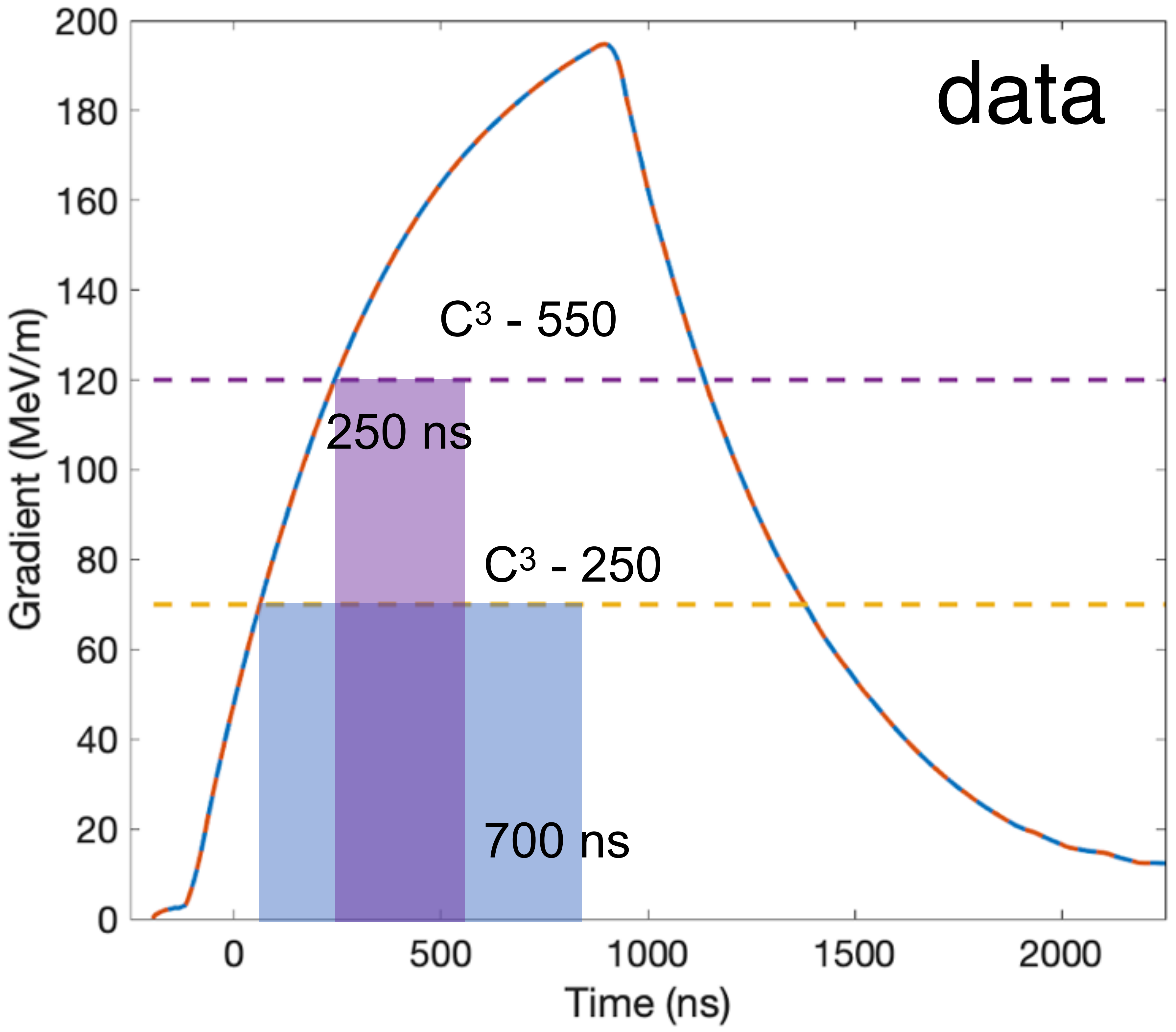
Accelerator technologies play a key role in **sustainability**

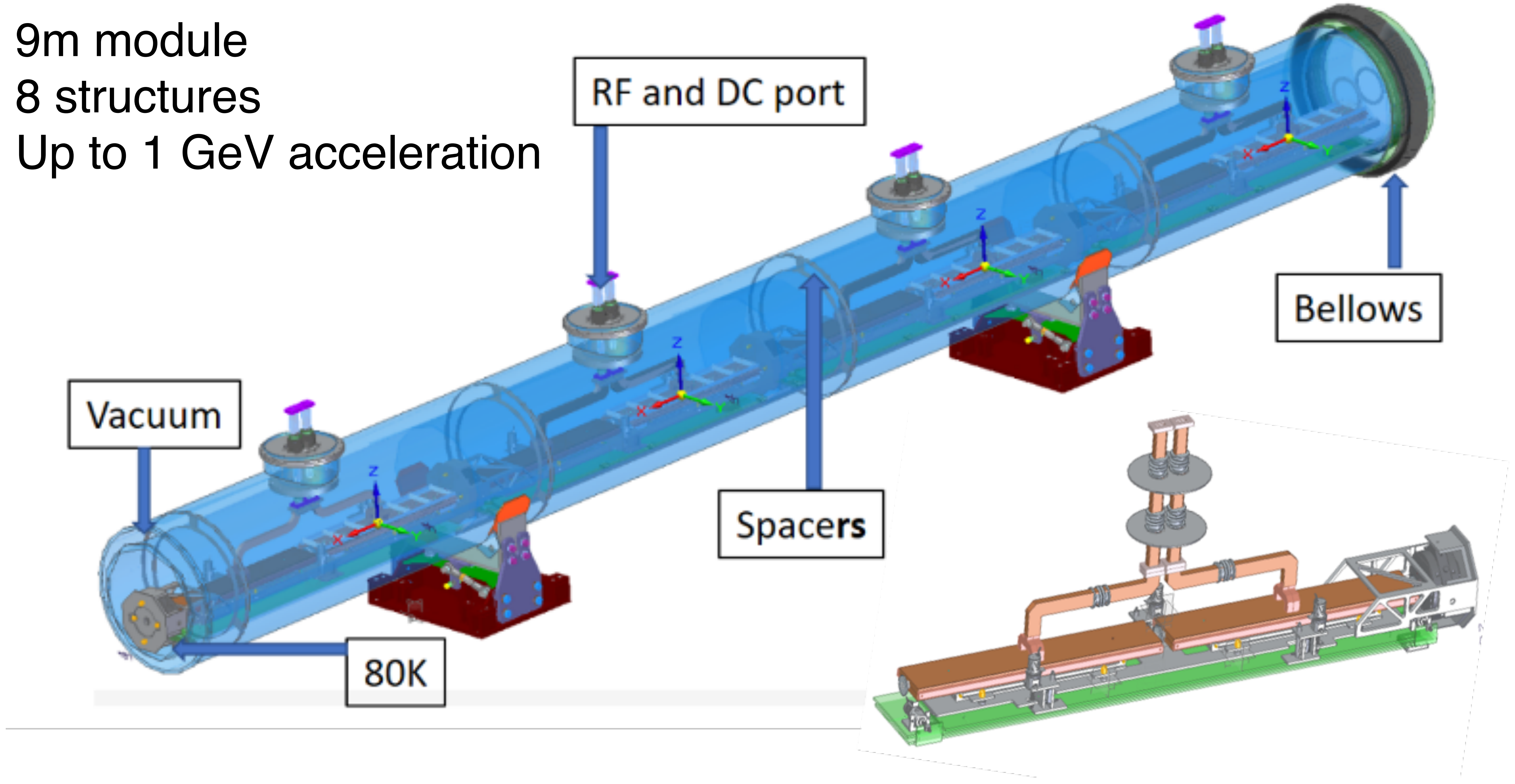
- “Accelerator structure improvements can also play an important role, including higher quality factor, and concepts like **cool copper**.”
- **Area Recommendation 20**: HEPAP, potentially in collaboration with international partners, should conduct a dedicated study aiming at developing a sustainability strategy for particle physics.

arXiv:2110.15800
Bulletin of the American Physical Society (2024)

C³ Cool Copper Collider

- Planning for operations at high gradient **at 550 GeV, 120 MeV/m**
  - **Start at 70 MeV/m for C³-250**
- Beam parameters optimized to record the same ILC luminosity within the same time frame and match physics goals





Accelerator Complex

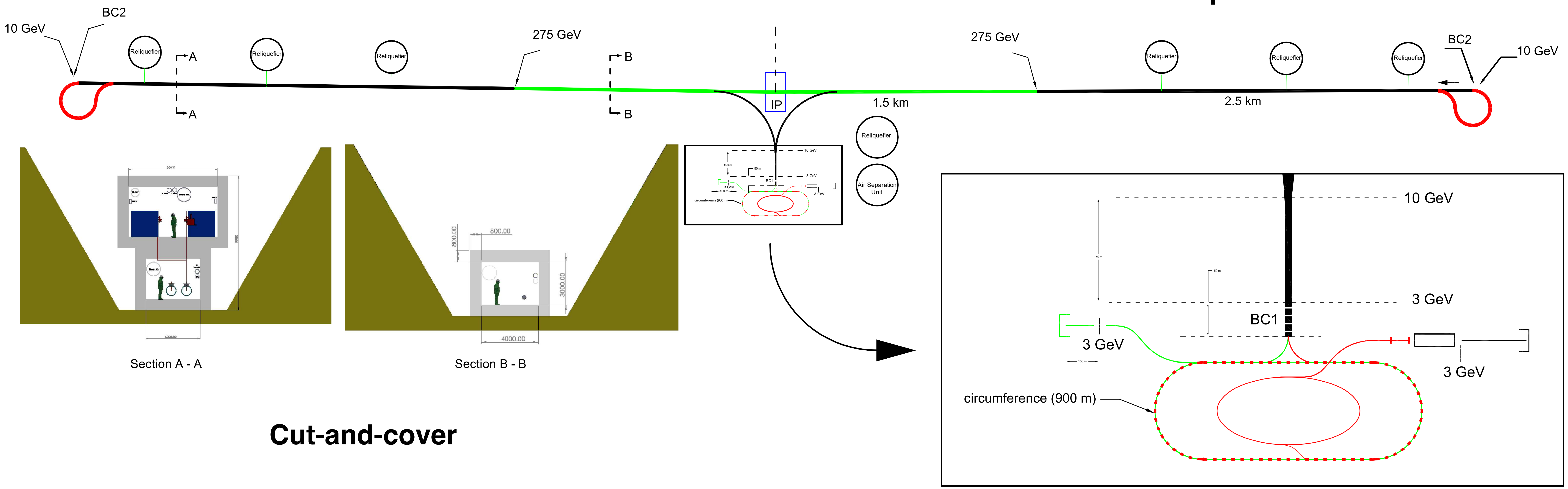
8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

- 7 km footprint at 155 MeV/m for 550 GeV CoM

Large portions of accelerator complex compatible between LC technologies

- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM)
- Damping rings and injectors to be optimized with CLIC as baseline

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



Cut-and-cover

One word on Sustainability

PRX Energy 2 047001

Construction + operations CO_2 emissions per % sensitivity on couplings

- Polarization and high energy to account for physics reach
- Construction CO_2 emissions → minimize excavation and concrete with cut and cover approach
- Main Linac Operations → limit power, decarbonization of the grid and dedicated renewable sources

Scenario	RF System (MW)	Cryogenics (MW)	Total (MW)	Reduction (MW)
Baseline 250 GeV	40	60	100	-
RF Source Efficiency Increased 15%	31	60	91	9
RF Pulse Compression	28	42	70	30
Double Flat Top	30	45	75	25
Halve Bunch Spacing	34	45	79	21
All Scenarios Combined	13	24	37	63

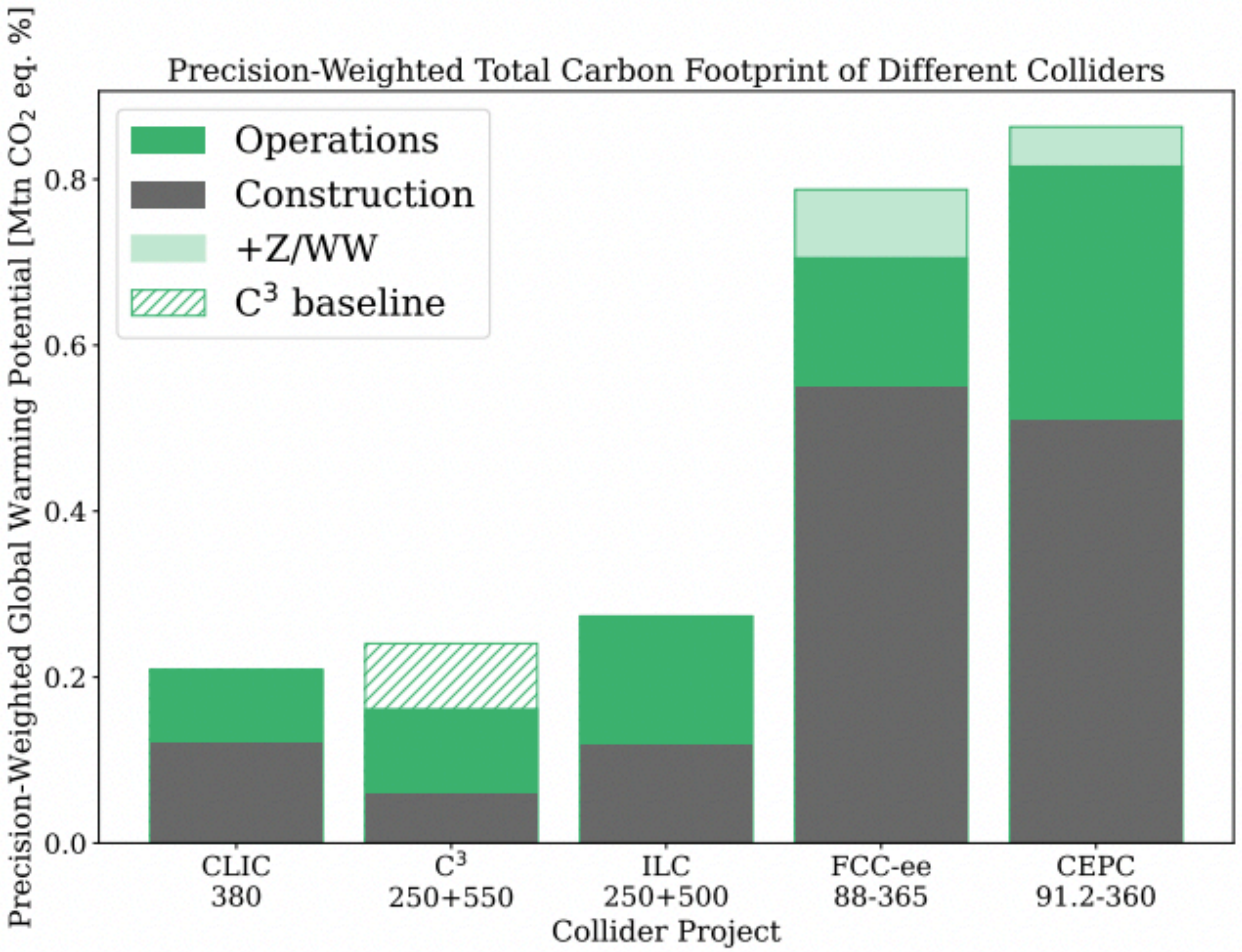
One word on Sustainability

PRX Energy 2 047001

Construction + operations CO_2 emissions per % sensitivity on couplings

- Polarization and high energy to account for physics reach
- Construction CO_2 emissions → minimize excavation and concrete with cut and cover approach
- Main Linac Operations → limit power, decarbonization of the grid and dedicated renewable sources

Scenario	RF Sys (MW
Baseline 250 GeV	40
RF Source Efficiency Increased 15%	31
RF Pulse Compression	28
Double Flat Top	30
Halve Bunch Spacing	34
All Scenarios Combined	13

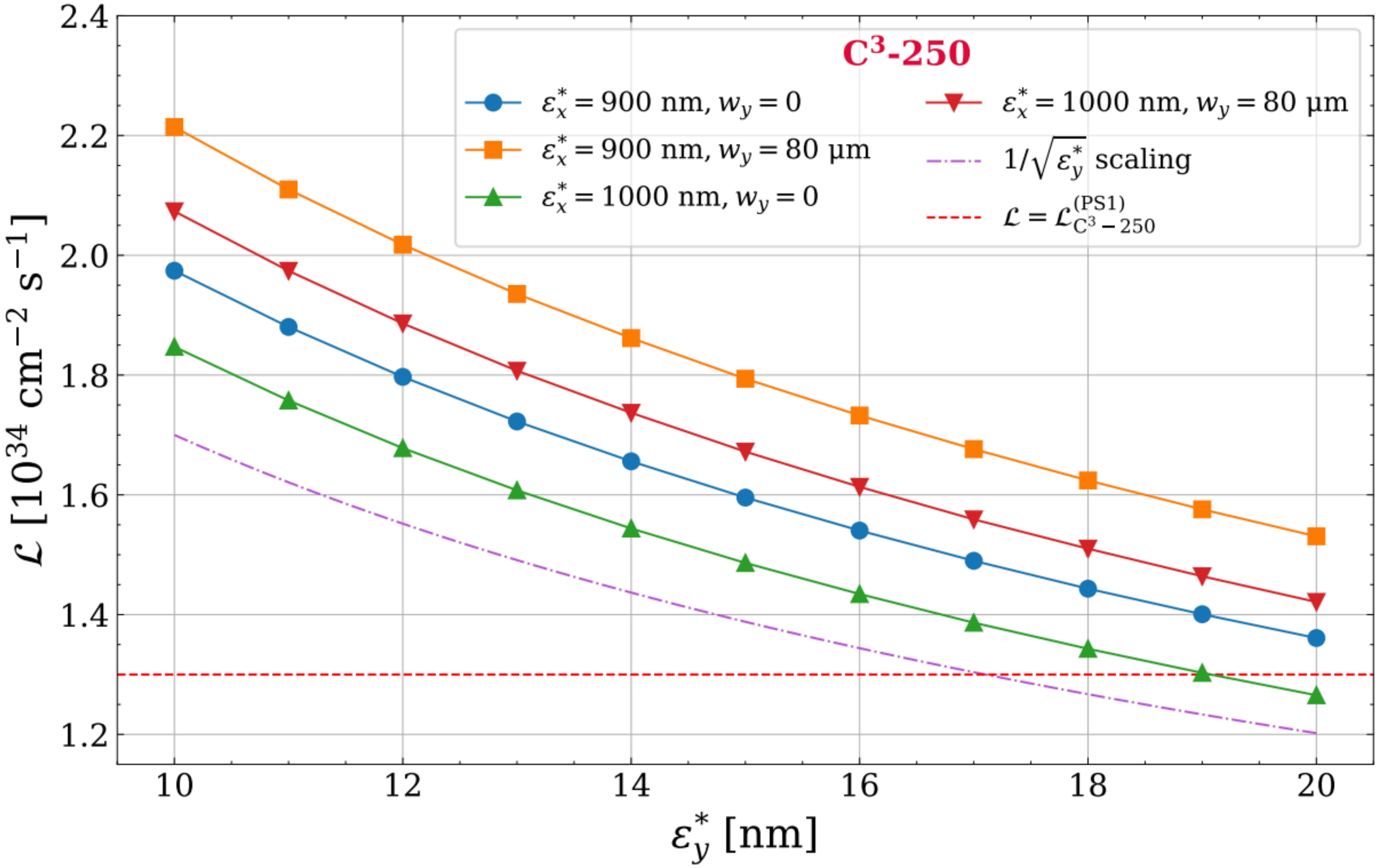


Optimized parameter sets

Phys. Rev. Accel. Beams 27, 061001, 2024

An improvement of about ~40% while maintaining BIB at the same level

Parameter	Symbol [unit]	C^3-250 (PS1)	C^3-250 (PS2)
Center-of-mass Energy	$\sqrt{s_0}$ [GeV]	250	
RMS bunch length	σ_z^* [µm]	100	
Horizontal beta function at IP	β_x^* [mm]	12	
Vertical beta function at IP	β_y^* [mm]	0.12	
Normalized horizontal emittance at IP	ϵ_x^* [nm]	900	1000
Normalized vertical emittance at IP	ϵ_y^* [nm]	20	12
RMS horizontal beam size at IP	σ_x^* [nm]	210	221
RMS vertical beam size at IP	σ_y^* [nm]	3.1	2.4
Vertical waist shift	w_y [µm]	0	80
Geometric Luminosity	$\mathscr{L}_{\text{geom}}$ [10^{34} cm^{-2} s^{-1}]	0.75	0.92
Horizontal Disruption	D_x	0.32	0.29
Vertical Disruption	D_y	21.5	26.5
Average Beamstrahlung Parameter	$\langle\Upsilon\rangle$	0.065	0.062
Total Luminosity	$\mathscr{L}$ [10^{34} cm^{-2} s^{-1}]	1.35	1.90
Peak luminosity fraction	$\mathscr{L}_{0.01}/\mathscr{L}$ [%]	73	74
Enhancement Factor	H_D	1.8	2.1
Average Energy loss	δ_E [%]	3.3	3.1
Photons per beam particle	n_γ	1.4	1.3
Average Photon Energy fraction	$\langle E_\gamma/E_0\rangle$ [%]	2.5	2.4
Number of incoherent particles/BX	N_{incoh} [10^4]	4.7	5.9
Total energy of incoh. particles/BX	E_{incoh} [TeV]	58	71



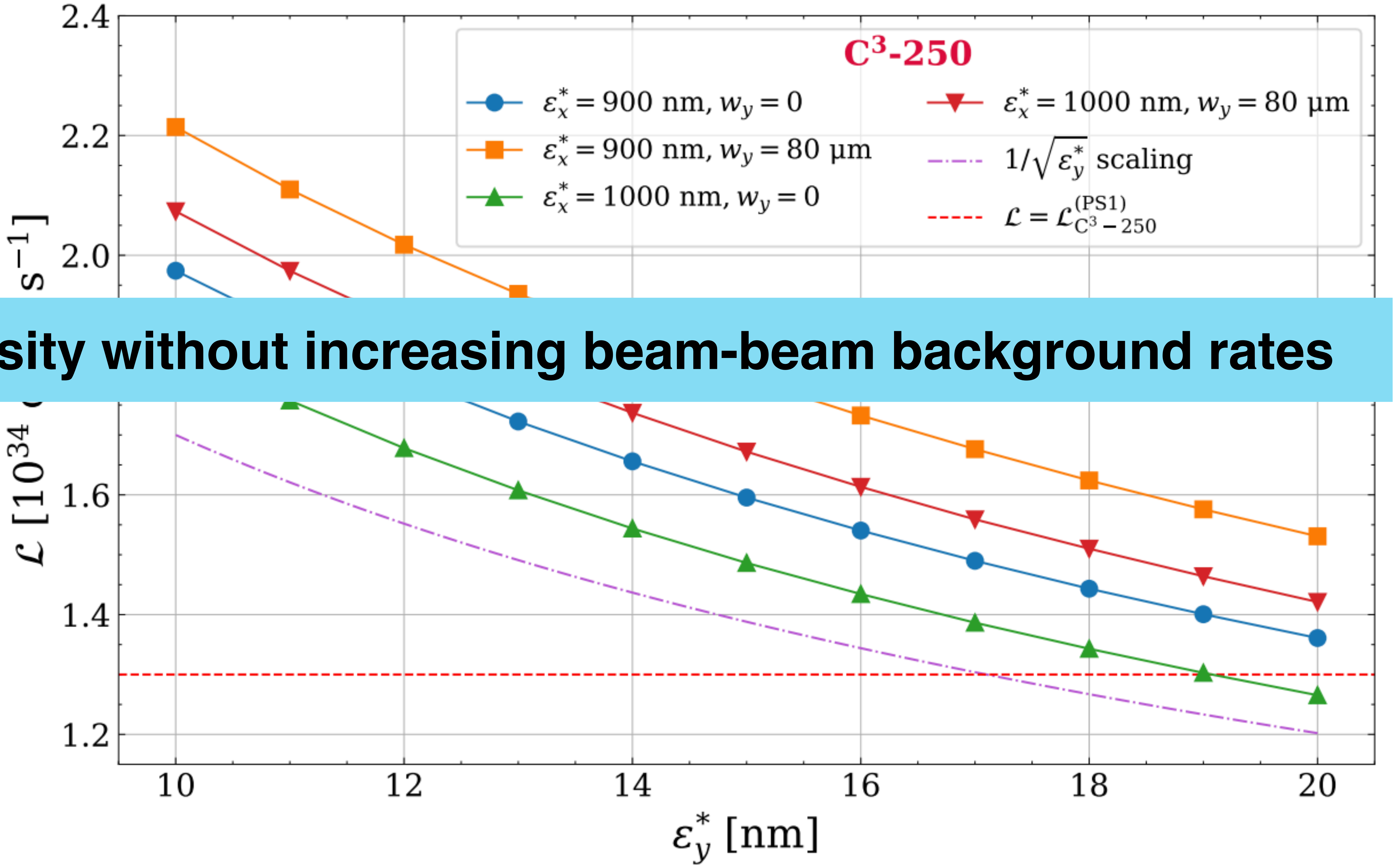
More in Dimitri's talk

Optimized parameter sets

Phys. Rev. Accel. Beams 27, 061001, 2024

An improvement of about ~40% while maintaining BIB at the same level

Parameter	Symbol [unit]	C^3-250 (PS1)	C^3-250 (PS2)
Center-of-mass Energy	$\sqrt{s_0}$ [GeV]	250	
RMS bunch length	σ_z^* [µm]	100	
Horizontal beta function at IP	β_x^* [mm]	12	
Vertical beta function at IP	β_y^* [mm]	0.12	
Normalized horizontal emittance at IP	ϵ_x^* [nm]	900	1000
Normalized vertical emittance at IP	ϵ_y^* [nm]	20	12
RMS horizontal beam size at IP	σ_x^* [nm]	210	221
RMS vertical beam size at IP	σ_y^* [nm]	3.1	2.4
Vertica[illegible]	[illegible]	[illegible]	[illegible]
Geome[illegible]	[illegible]	[illegible]	[illegible]
Horizontal Disruption	D_x	0.32	0.29
Vertical Disruption	D_y	21.5	26.5
Average Beamstrahlung Parameter	$\langle \Upsilon \rangle$	0.065	0.062
Total Luminosity	$\mathscr{L}$ [10^{34} cm^{-2} s^{-1}]	1.35	1.90
Peak luminosity fraction	$\mathscr{L}_{0.01}/\mathscr{L}$ [%]	73	74
Enhancement Factor	H_D	1.8	2.1
Average Energy loss	δ_E [%]	3.3	3.1
Photons per beam particle	n_γ	1.4	1.3
Average Photon Energy fraction	$\langle E_\gamma/E_0 \rangle$ [%]	2.5	2.4
Number of incoherent particles/BX	N_{incoh} [10^4]	4.7	5.9
Total energy of incoh. particles/BX	E_{incoh} [TeV]	58	71



Beam parameters optimized for C^3 luminosity without increasing beam-beam background rates

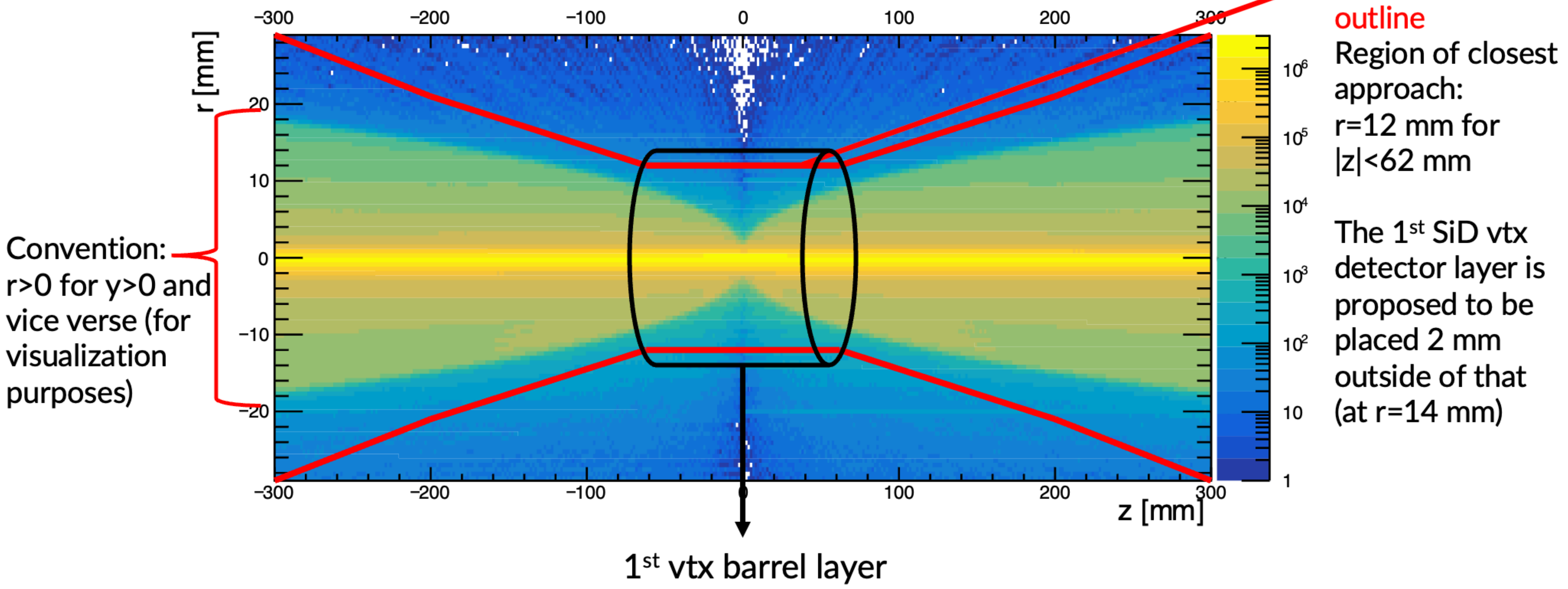
More in Dimitri's talk

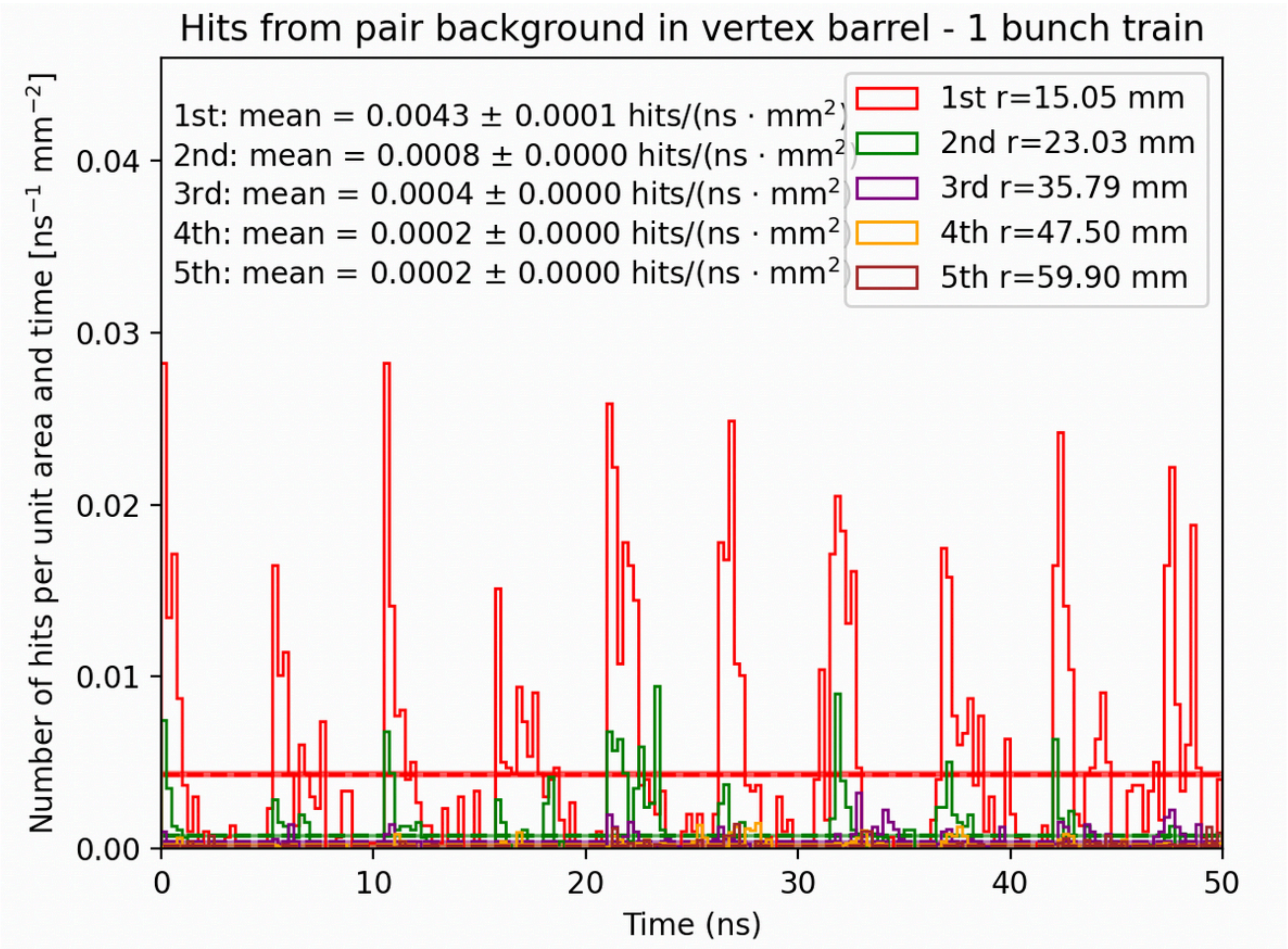
Importance of beam-beam background

More in Dimitris' talk

The effects of beam-beam interactions have to be careful simulated for physics and detector performance

Time distribution of hits per unit time and area: ~ $4.4 \cdot 10^{-3}$ hits/(ns·mm^2) ≃ 0.03 hits/mm^2 /BX
in the 1st layer of the vertex barrel SiD-like detector for ILC/C^3



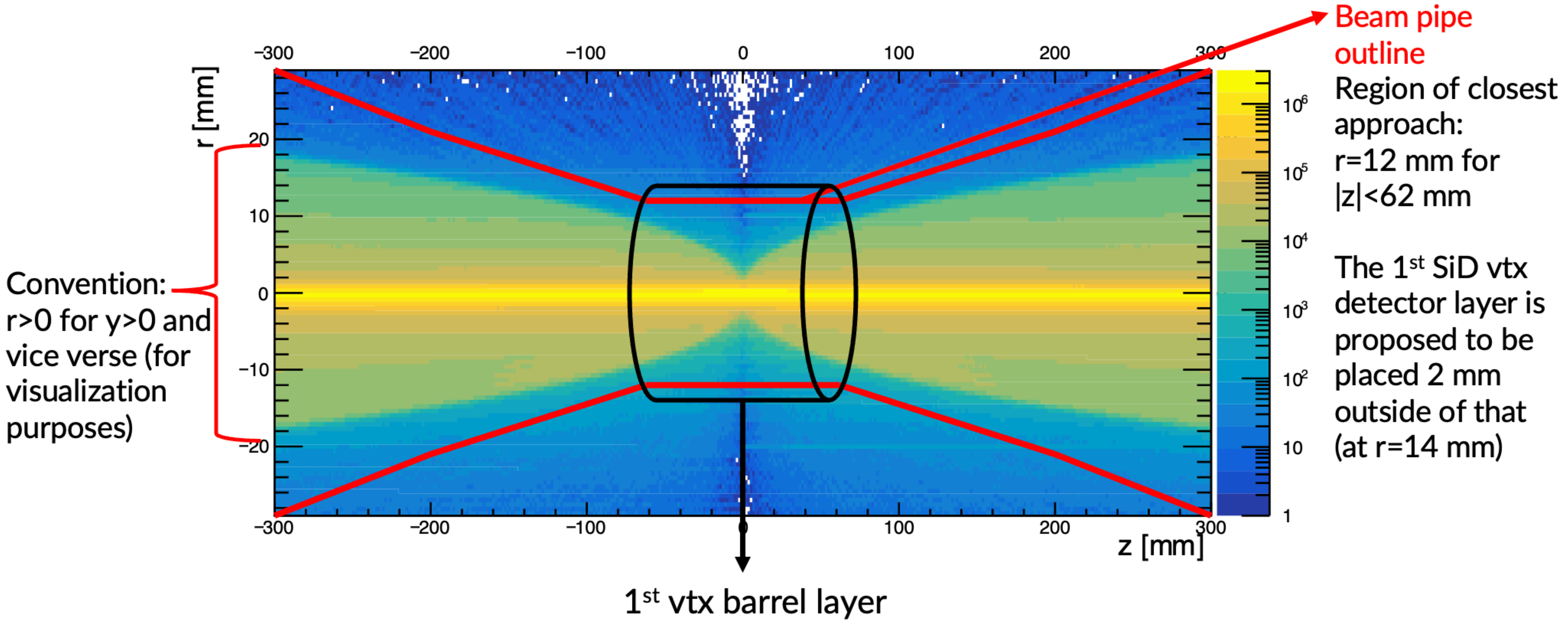


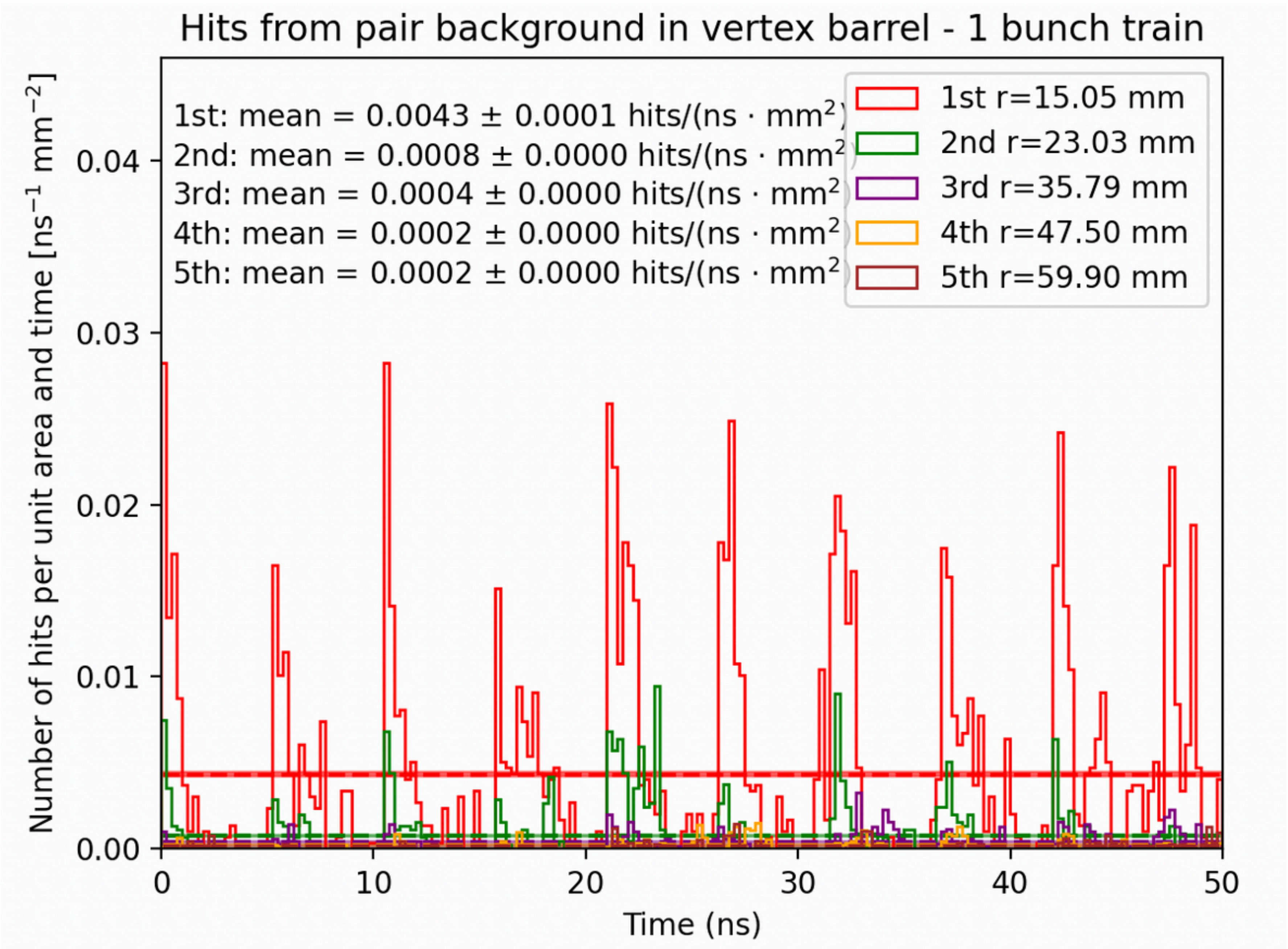
Importance of beam-beam background

More in Dimitris' talk

The effects of beam-beam interactions have to be careful simulated for physics and detector performance

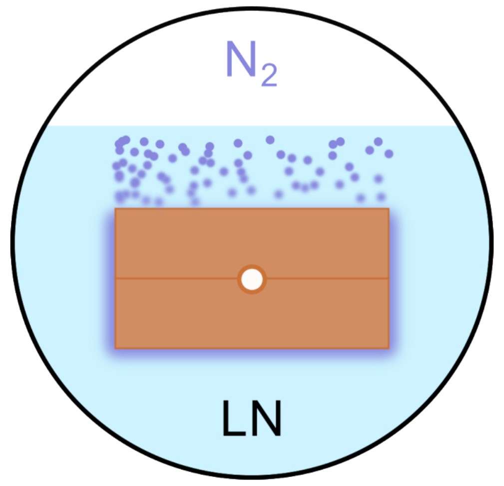
Time distribution of hits per unit time and area: ~ $4.4 \cdot 10^{-3}$ hits/(ns·mm²) ≃ 0.03 hits/mm² /BX
in the 1st layer of the vertex barrel SiD-like detector for ILC/C³





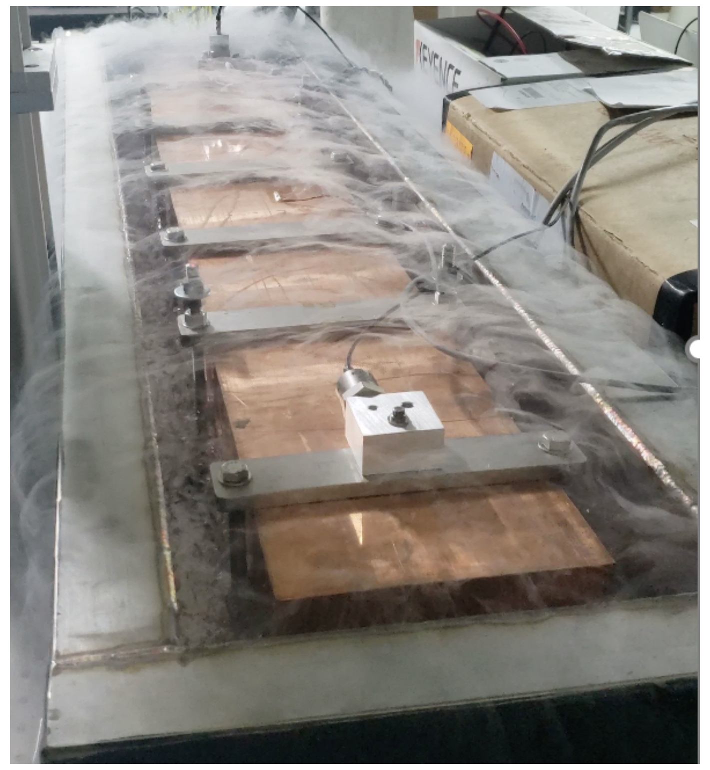
Synergistic studies among all HF options to inform detector design and ongoing optimizations

Technical progress and challenges



Over the last year, significant progress to tackle several challenges:

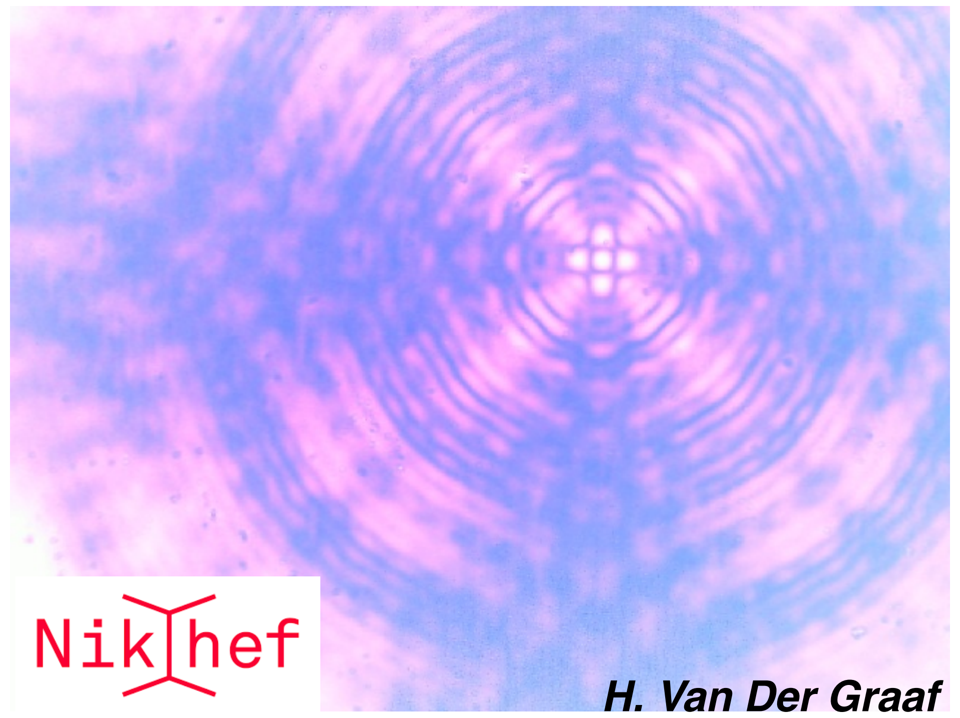
- **Gradient** – Scaling up to meter scale cryogenic tests (Emilio,Dennis)
- **Vibrations** – Measurements with full thermal load (Ankur)
- **Alignment** – Working towards raft prototype (Harry)
- **Cryogenics** – Two-phase flow simulations to full flow tests
- **Damping** – Materials, design and simulation (Wei-Hou, Shumail, Zhengai)
- **Beam Loading and Stability** - Beam test
- **Scalability** – Cryomodules and integration (Andy)
- **LLRF Control** with RF System on Chip (Ankur)

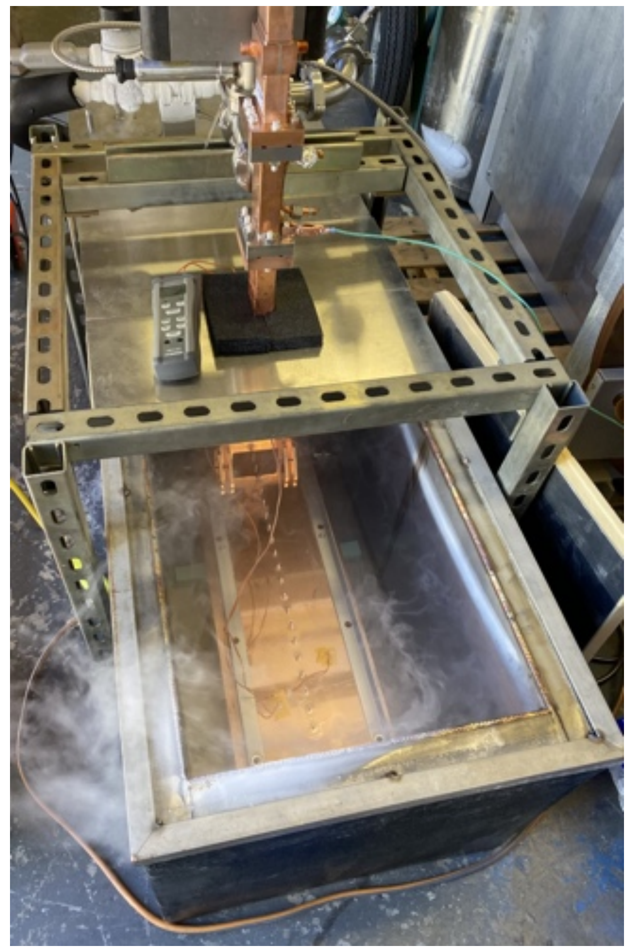


Vibration Studies

Laying the foundation for a demonstration program to address technical risks

See Ankur's talk for details

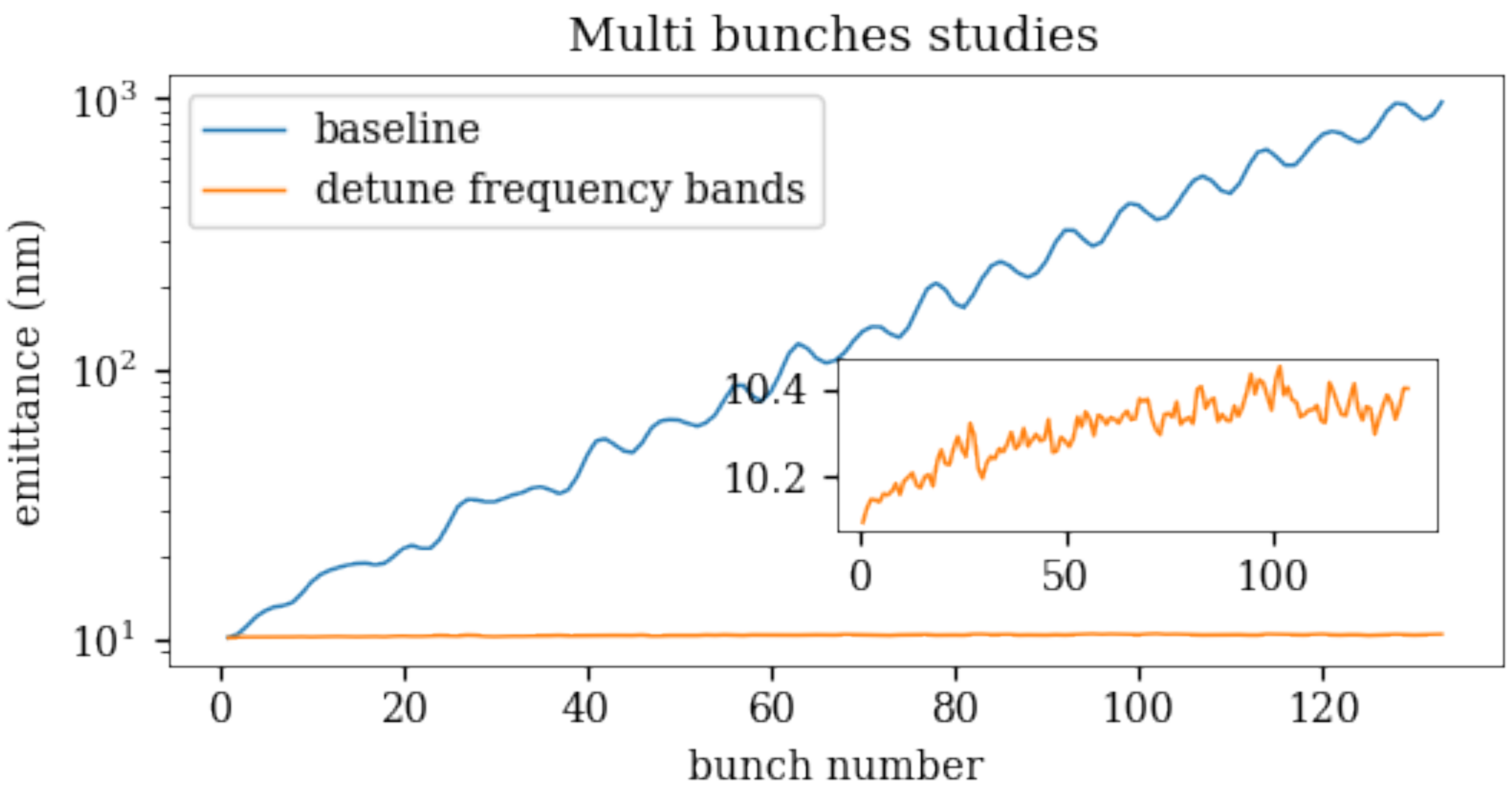


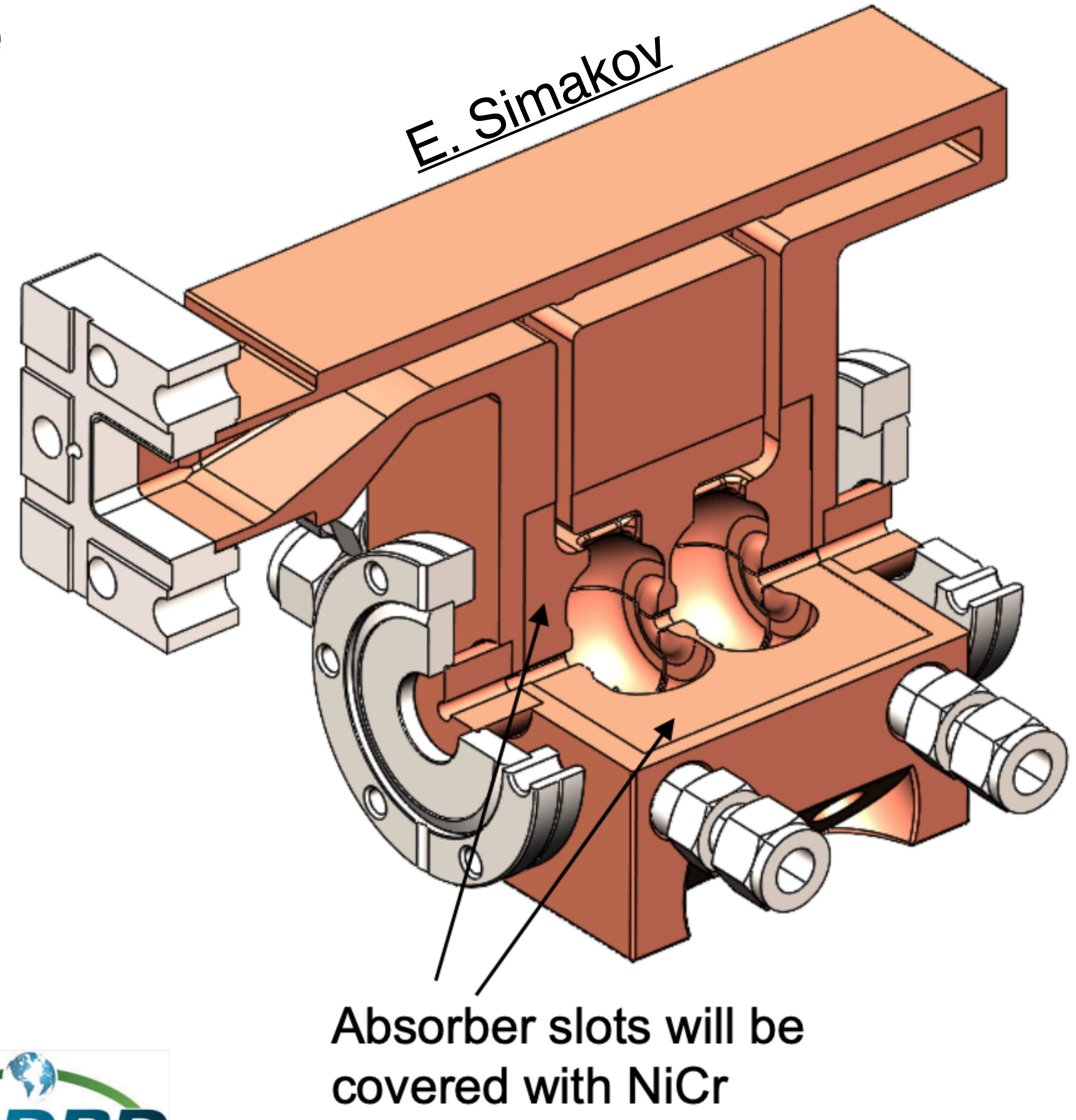


RadiaBeam

One highlight: damping & detuning

- Multi-bunch simulation studies have been conducted to identify required damping and detuning to mitigate long-range HOMs
- Single bunch studies also used for studying alignment tolerance
- Ni-Cr coatings for two-cells structures have been tested

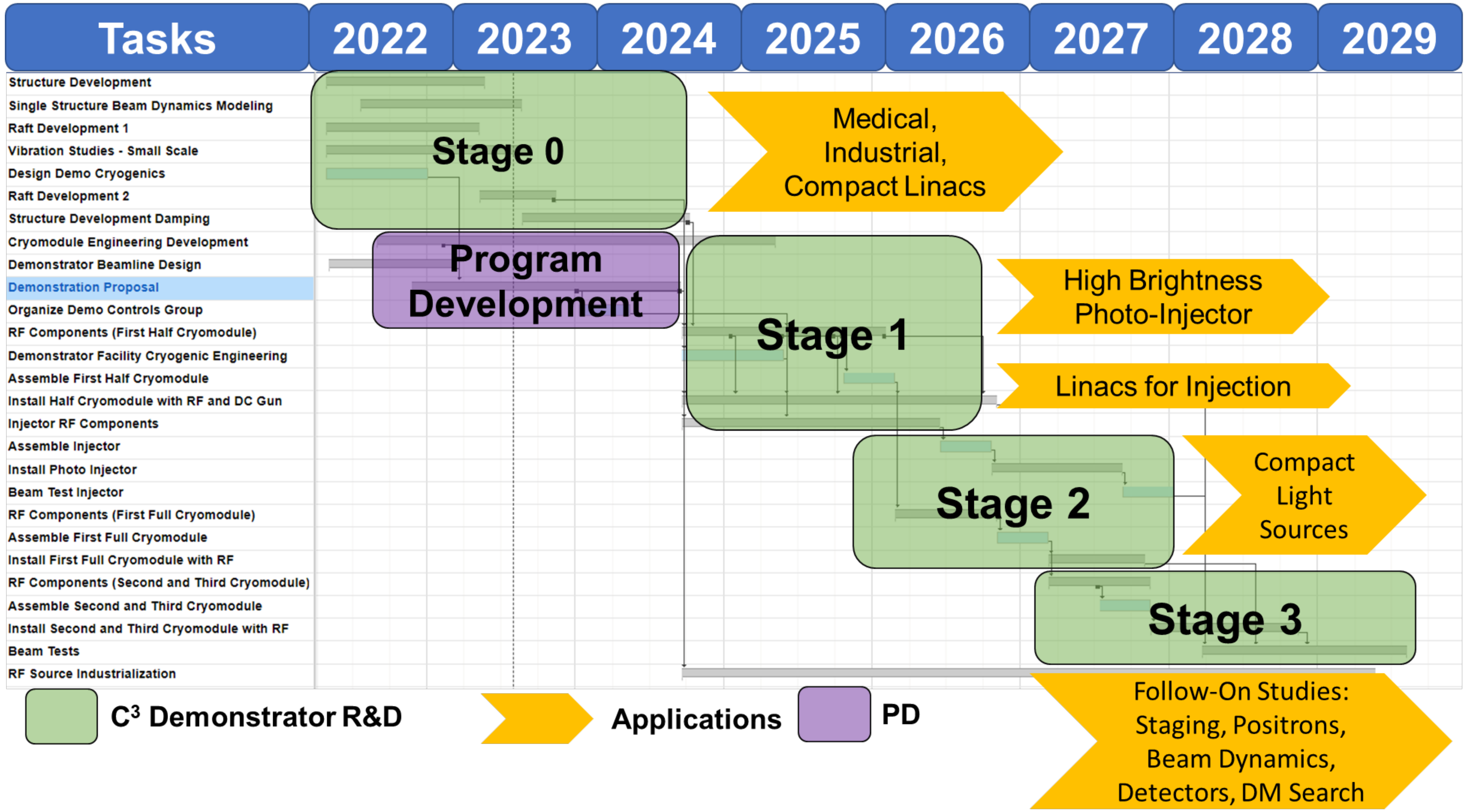




See Ankur & Zhengai talks for details

Demonstration R&D Plan Timeline *

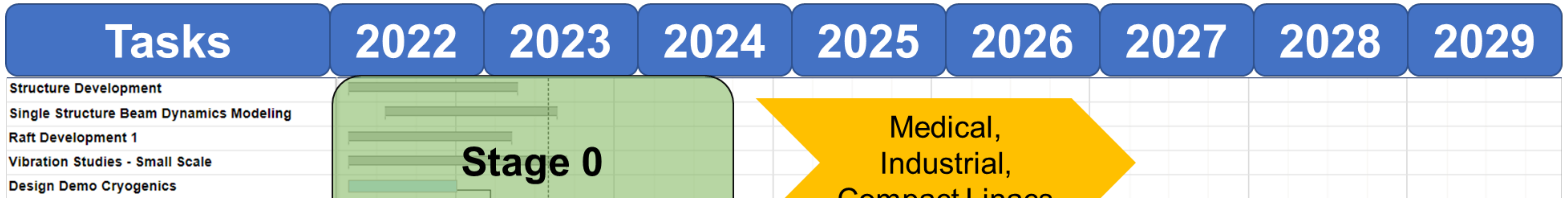
* Technically Limited

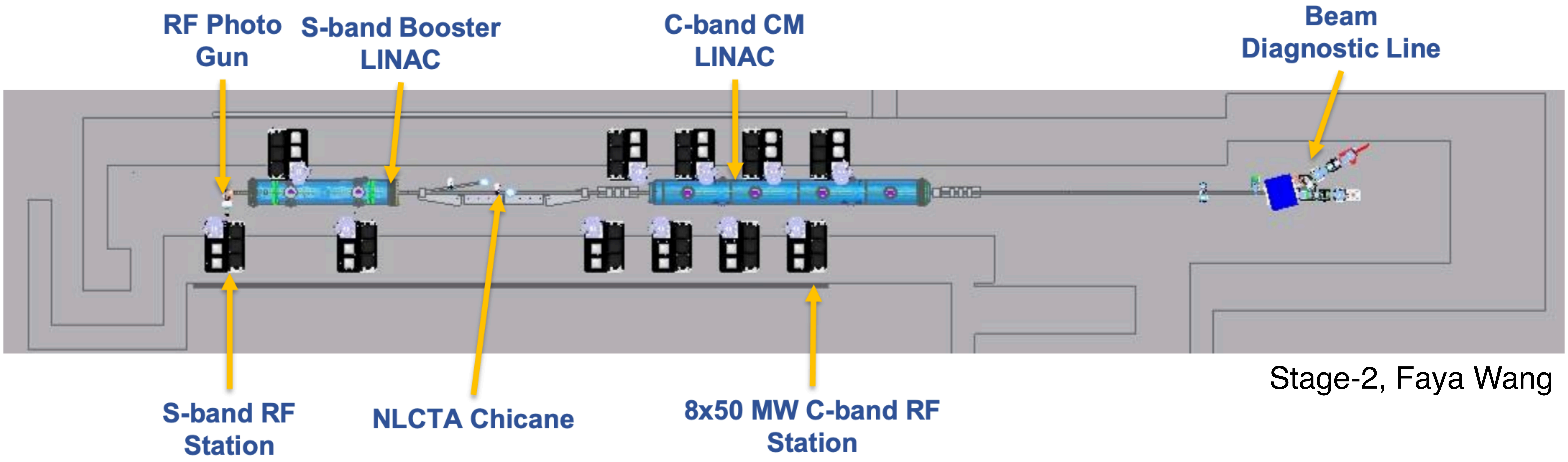


Area Recommendation 8 P5 report

Demonstration R&D Plan Timeline *

* Technically Limited

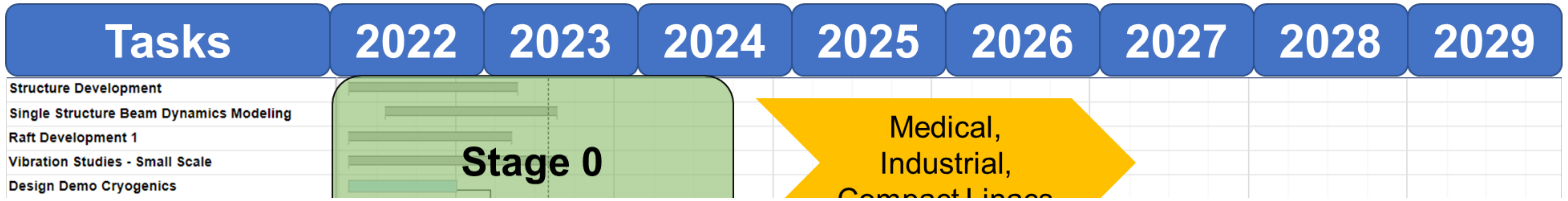


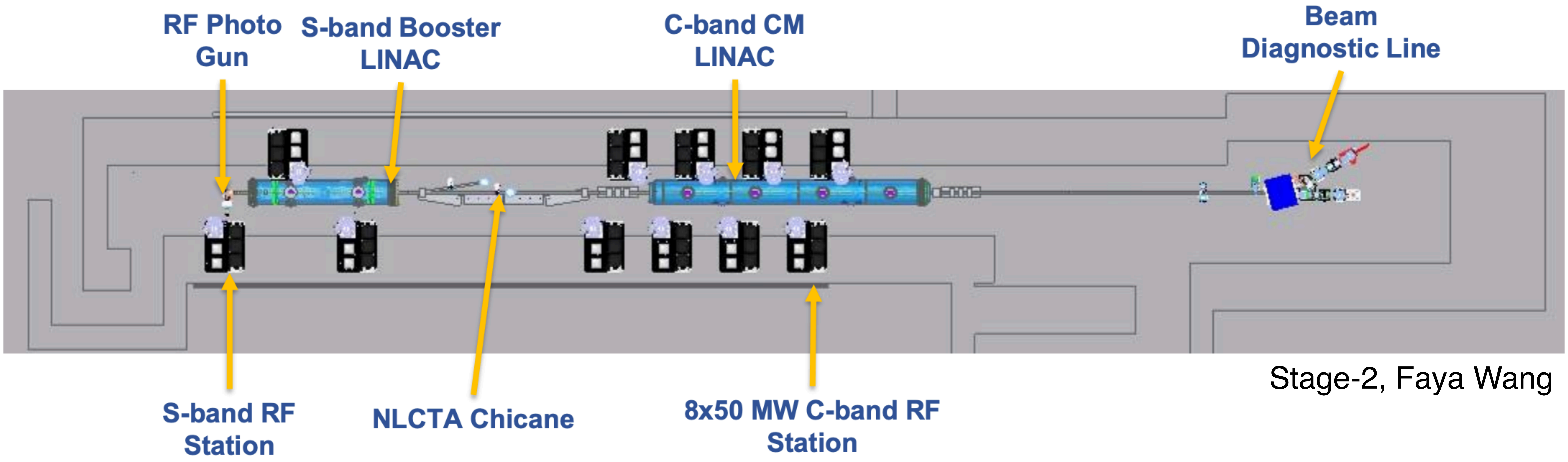


Stage-2, Faya Wang

Demonstration R&D Plan Timeline *

* Technically Limited



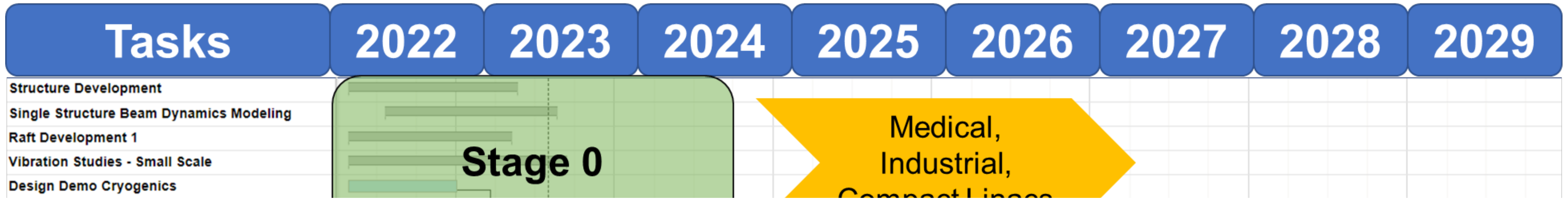


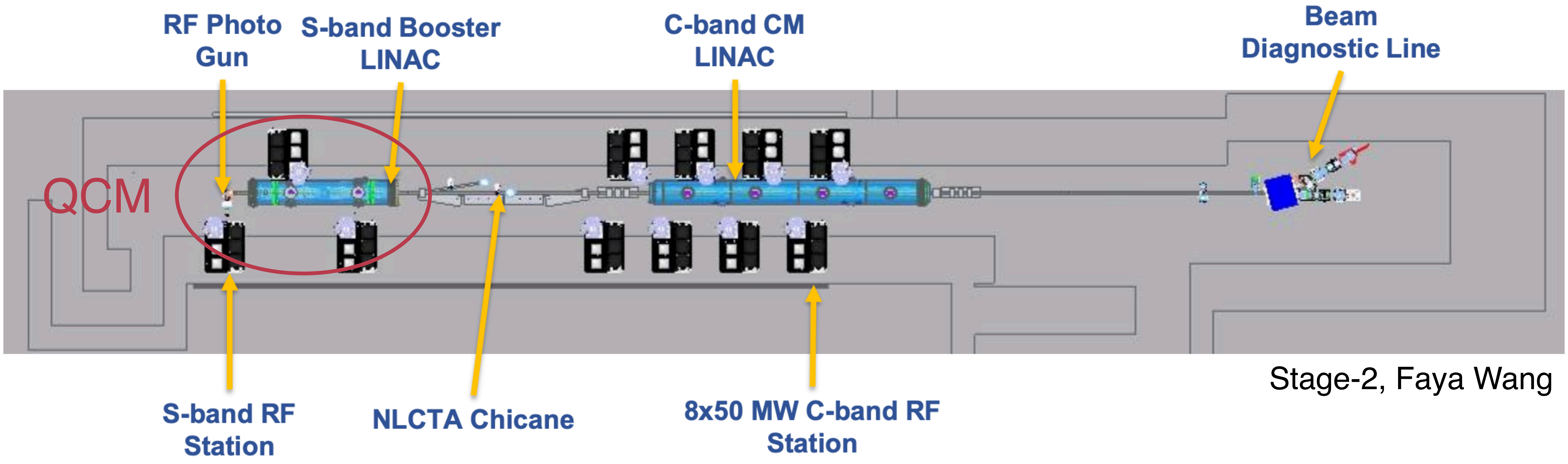
Stage-2, Faya Wang

Stage 1/2 will answer the most pressing technical questions - beam loading, damping, alignment, required to assess technical risks

Demonstration R&D Plan Timeline *

* Technically Limited





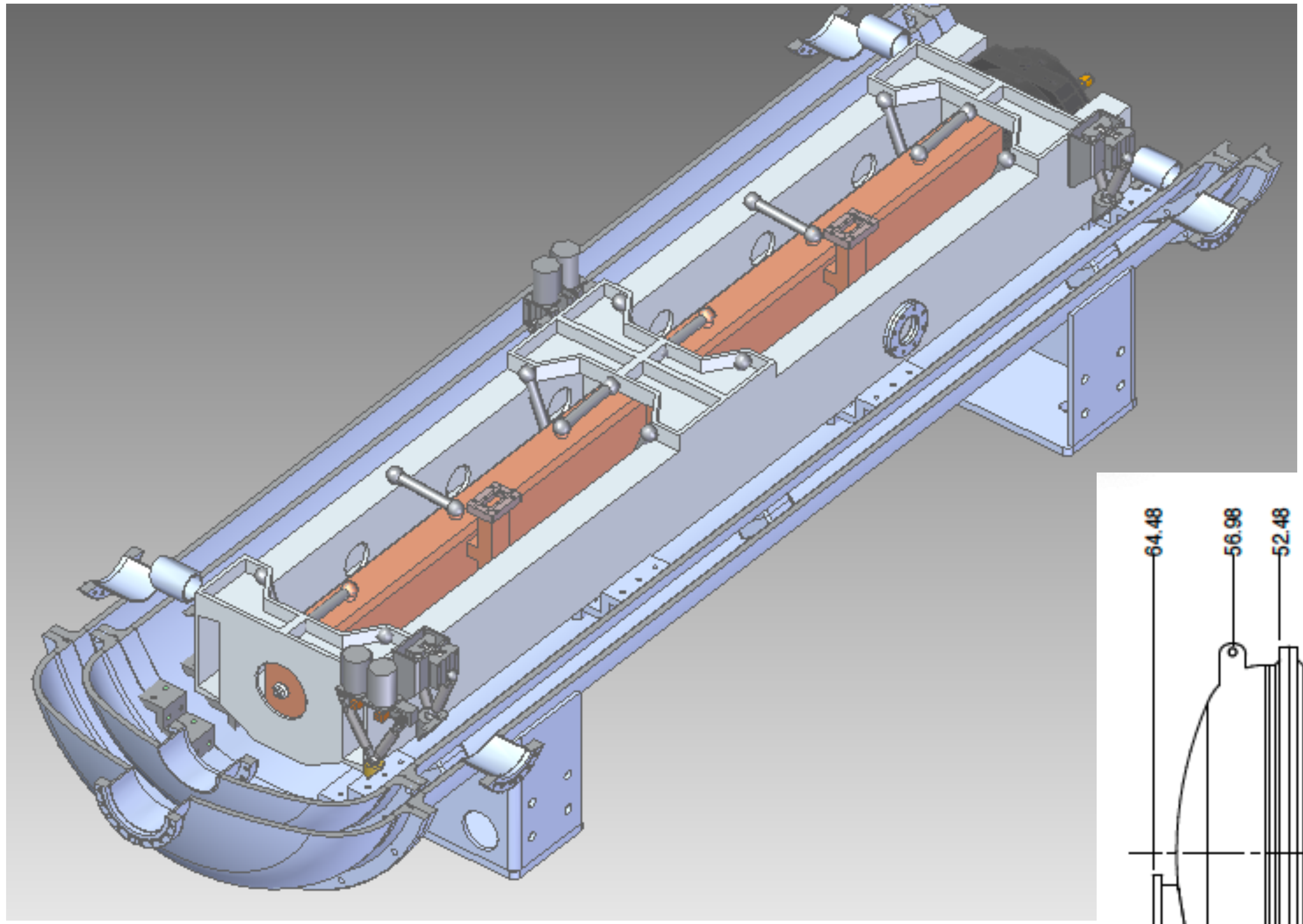
Stage-2, Faya Wang

Stage 1/2 will answer the most pressing technical questions - beam loading, damping, alignment, required to assess technical risks

Quarter cryomodule

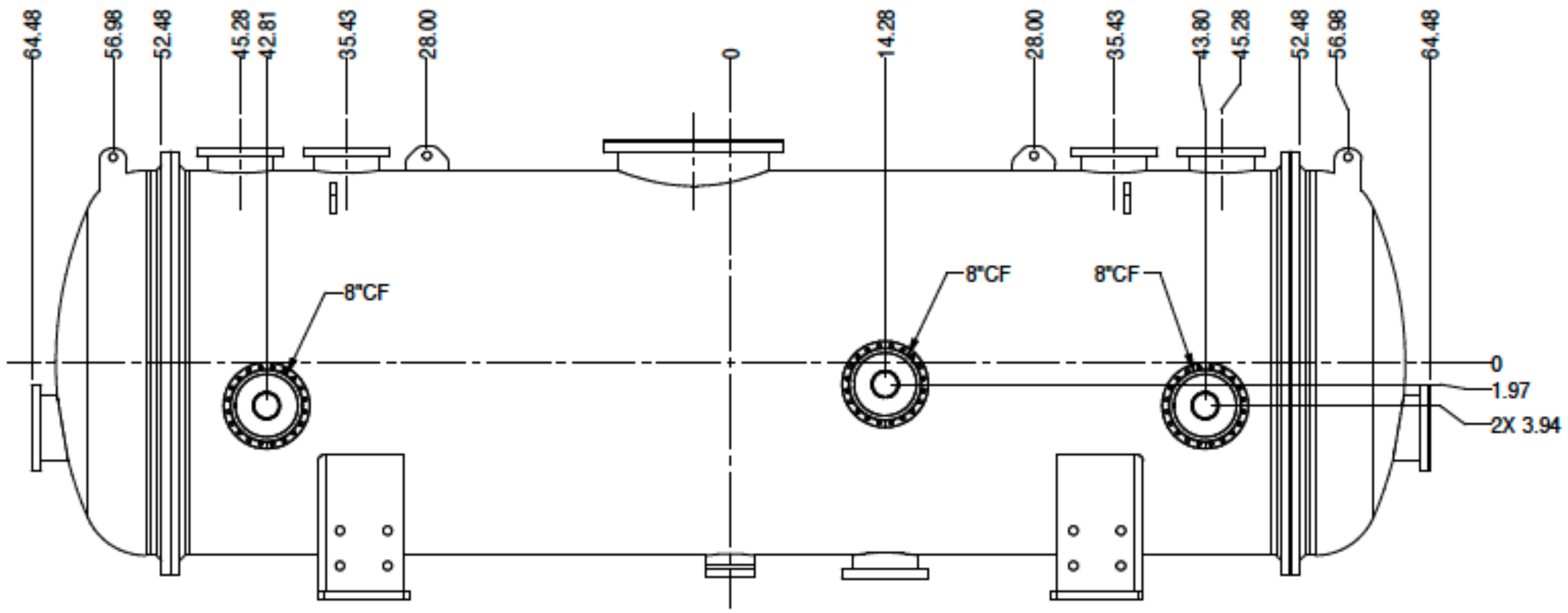
[Andy's talk]

An important first step towards multi-structure operations

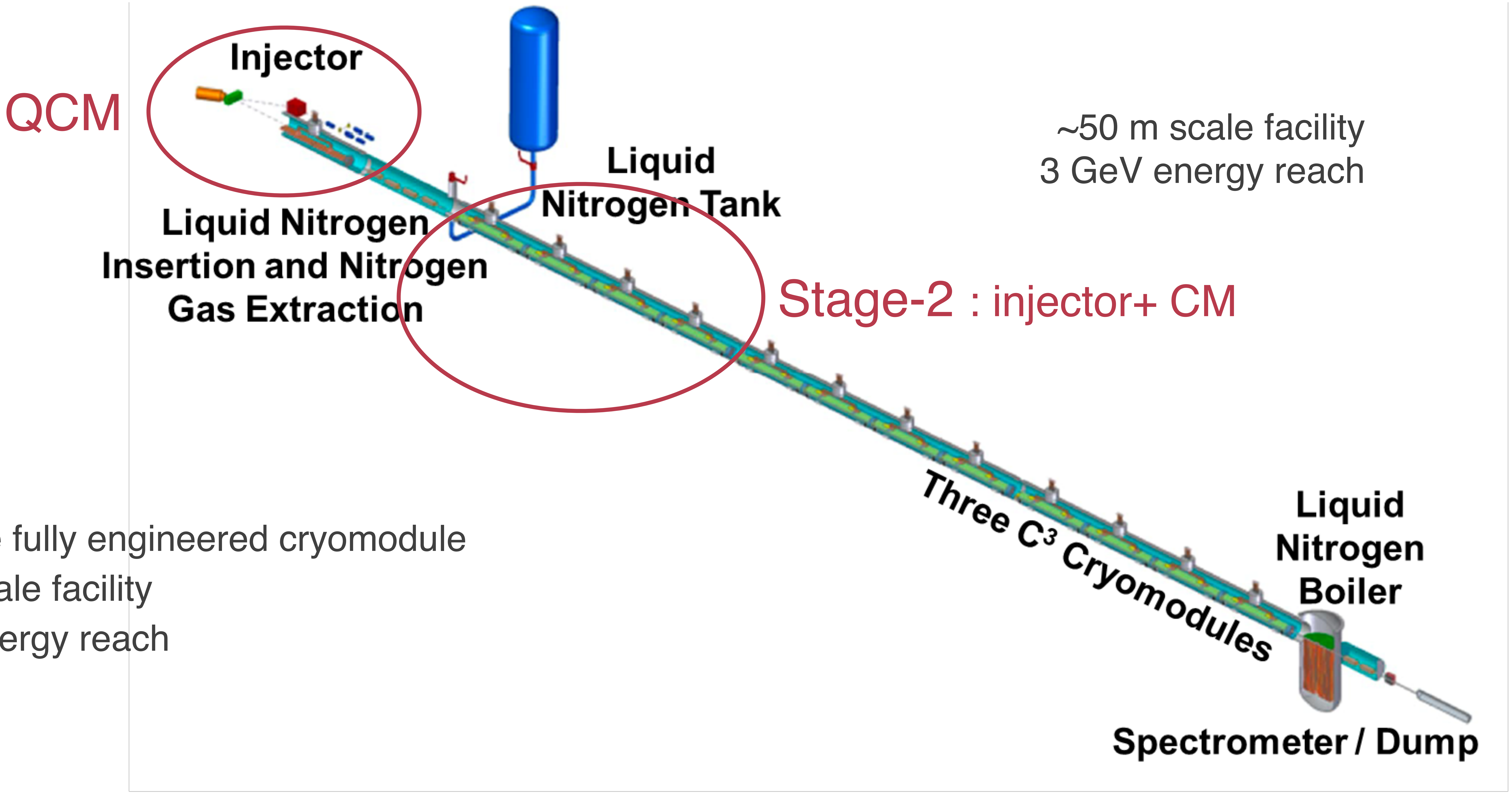


Order placed and expected delivery by Fall **2024**

- Outfit for alignment and vibration testing
- Follow-on experiments with structures at high gradient and beam acceleration



The Complete C³ Demonstrator



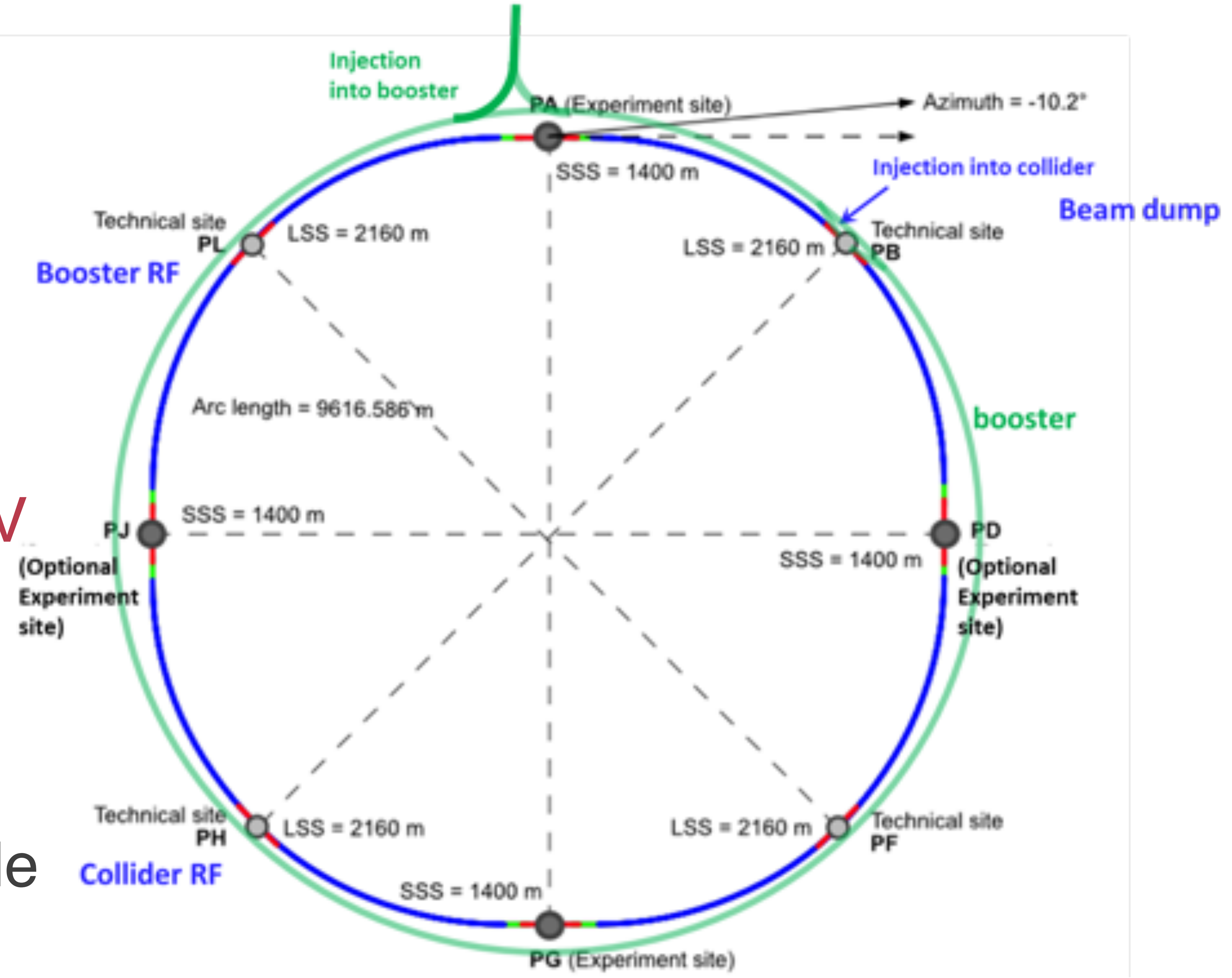
- Demonstrate fully engineered cryomodule
  - ~50 m scale facility
  - 3 GeV energy reach

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

- ILC - options for electron driven positron source based C^3 technology and high energy upgrades
- FCC-ee - common electron and positron injector linac from 6 to 20 GeV
  - **reduce length 3.5X OR reduce rf power 3.5X**
- 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

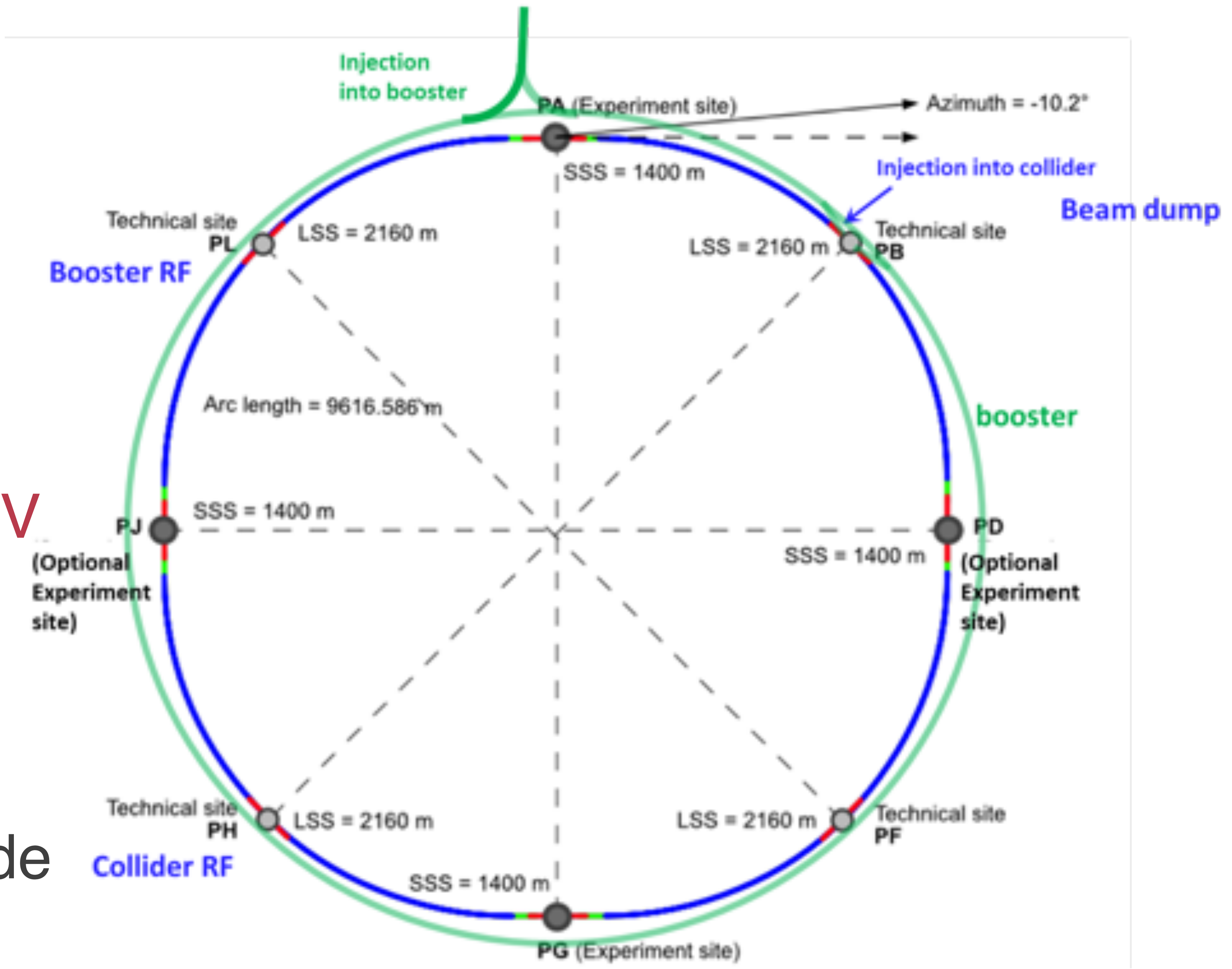


Synergies with Future Colliders

RF Accelerator Technology Essential for All Near-Term Collider Concepts

C³ Demo is positioned to contribute synergistically or directly to all near-term collider concepts

- ILC - options for electron driven positron source based C³ technology and high energy upgrades
- FCC-ee - common electron and positron injector linac from 6 to 20 GeV
  - **reduce length 3.5X OR reduce rf power 3.5X**
- Muon Collider - high gradient cryogenic copper cavities in cooling channel, alternative linac for acceleration after cooling
- AAC - C³ Demo utilized for staging, C³ facility multi-TeV energy upgrade reutilizing tunnel, $\gamma\gamma$ colliders



C³ cryomodule could yield to significant improvements to size and sustainability of FCC-ee high energy linac

Conclusions & Next steps

- Two Higgs Factory proposals on the table after P5, ILC and FCC-ee, to push our understanding of **Higgs properties** far **beyond HL-LHC sensitivity reach**
- **Accelerator R&D** could enable new capabilities to boost “sustainably” collider performance
  - C^3 technology could play a key role in current HF proposals
- C^3 accelerating structures have been successfully tested at high gradient
  - Damping slots have been tested and to be included in the next fabrication iteration
- R&D is on going and progress has been made to evaluate alignment and vibration tolerances.
  - **First Quarter Cryomodule**, with two structures, will assess them in detail
    - Expected delivery later this fall
- **Stage 1/2** will answer the most pressing technical questions: beam loading, damping, alignment

thank you!

C^3 Acknowledgements

WEBSITE web.slac.stanford.edu/c3/

SLAC-PUB-17661
April 12, 2022

Strategy for Understanding the Higgs Physics:
The Cool Copper Collider

JINST
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

SLAC-PUB-17629
November 1, 2021

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

Perspective | Open Access

Sustainability Strategy for the Cool Copper Collider

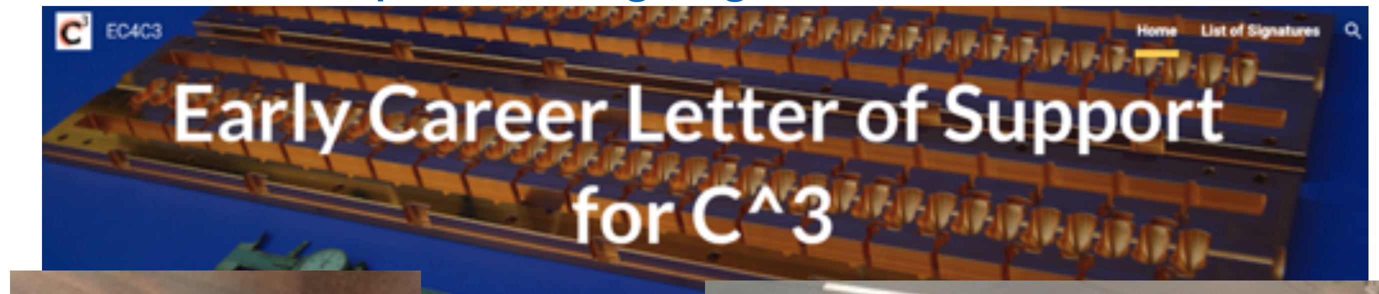
Martin Breidenbach, Brendon Bullard, Emilio Alessandro Nanni, Dimitrios Ntounis, and Caterina Vernieri
PRX Energy **2**, 047001 – Published 26 October 2023

Community Workshops:

Virtual, Fermilab, SLAC, LANL & Cornell University

220 Participants 60 Institutions

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

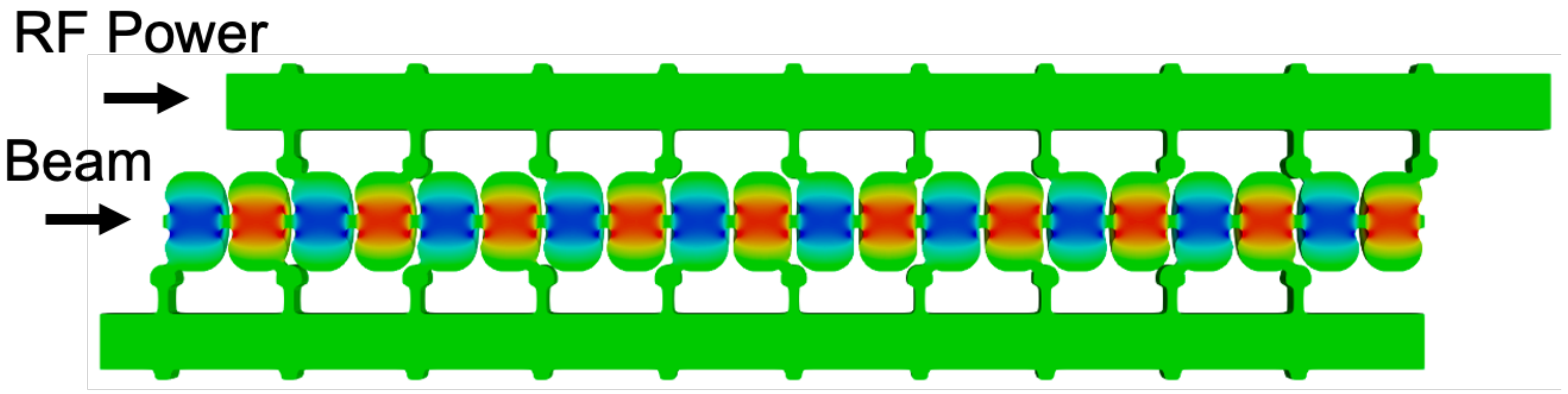


Next Meeting at LCWS July. 12th '24 @ Tokyo Univ.

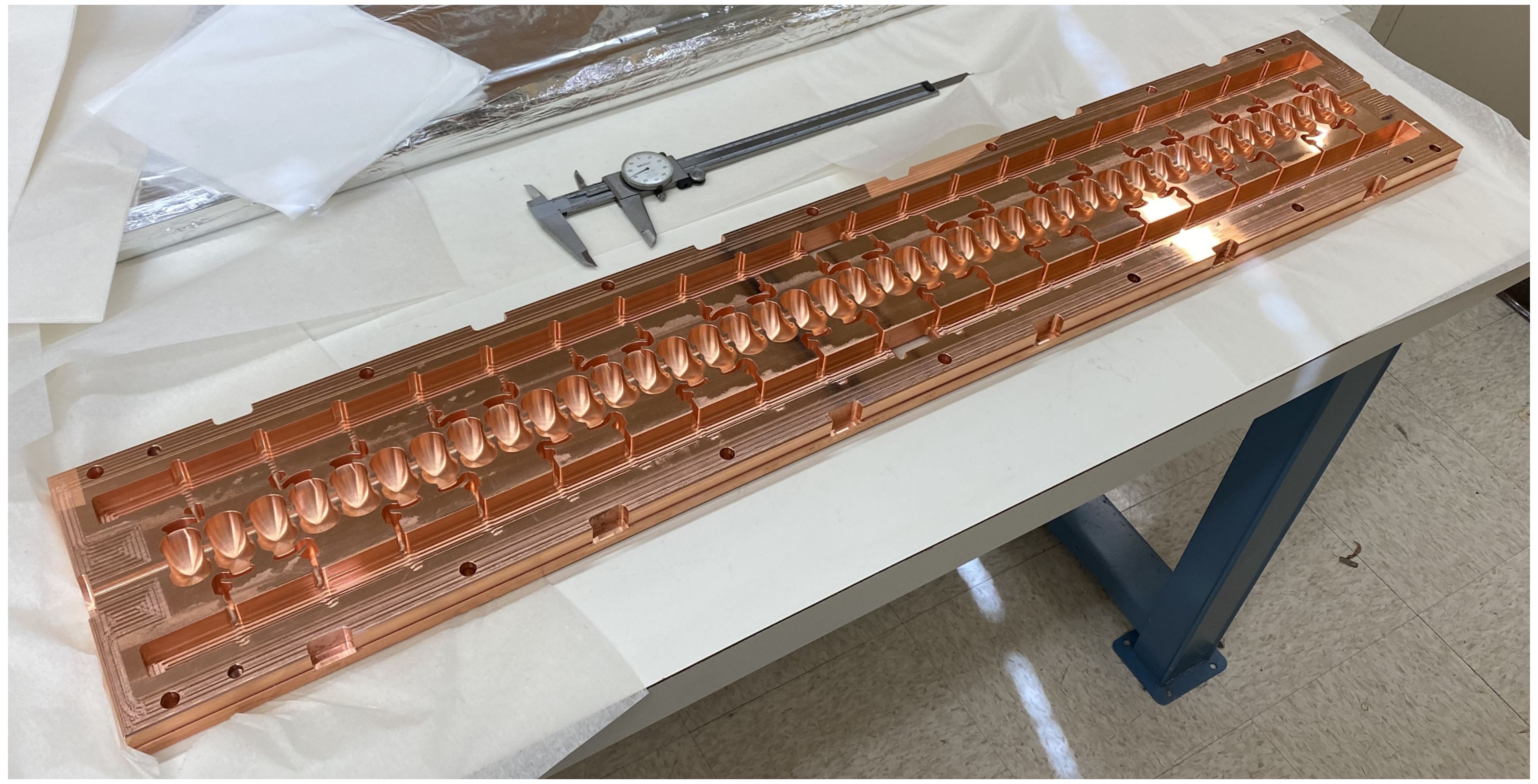
Recap: the Cool Copper technology

C^3 is a new linac **normal conducting technology**

- Distributed power to each cavity from a common RF manifold
  - modern super-computing for solution
  - Seemingly complex structure can easily and inexpensively be built with **modern CNC Machines**
- Cryogenic temperature elevates performance in gradient
  - Operation at 77 K with liquid nitrogen is simple and practical

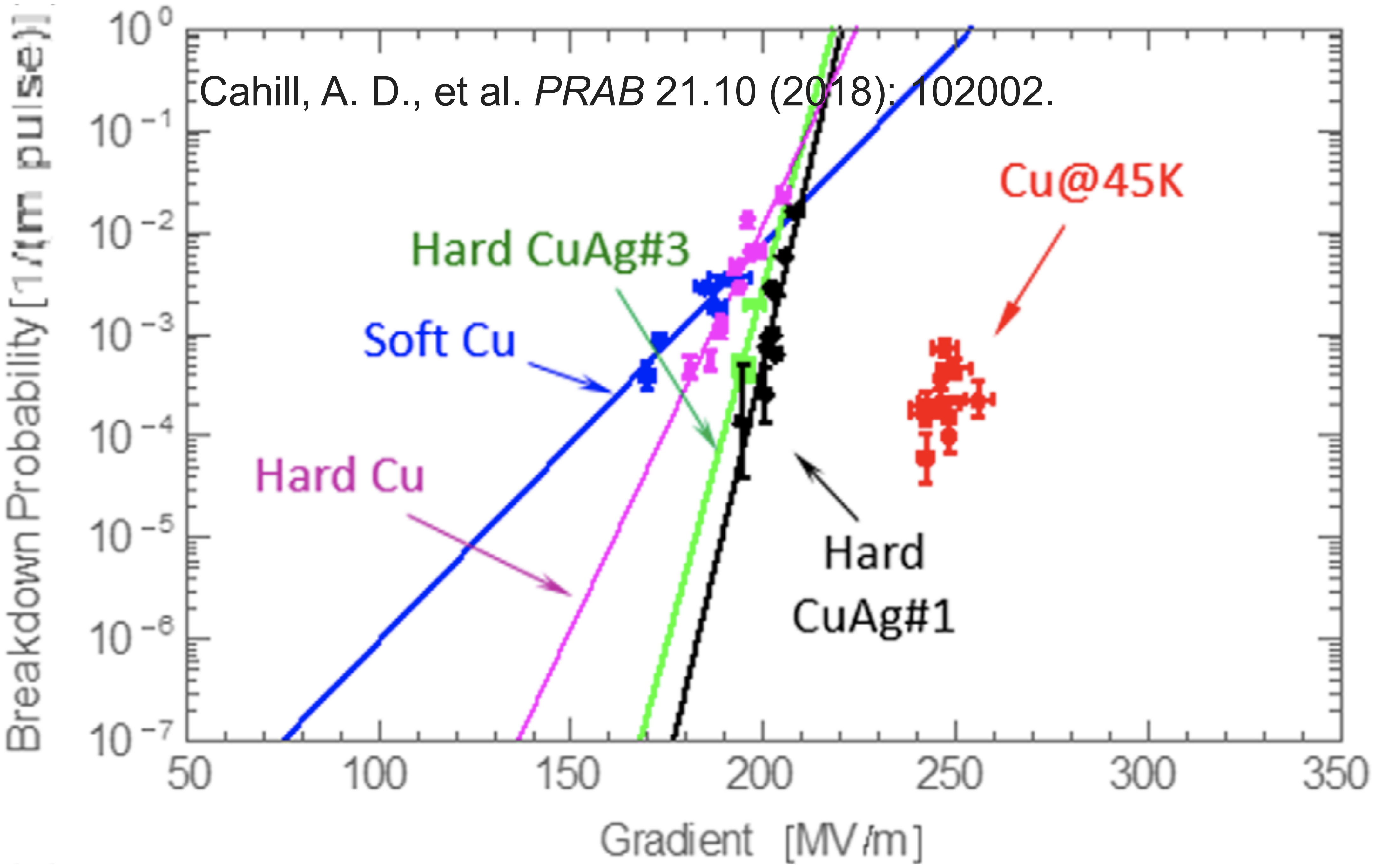


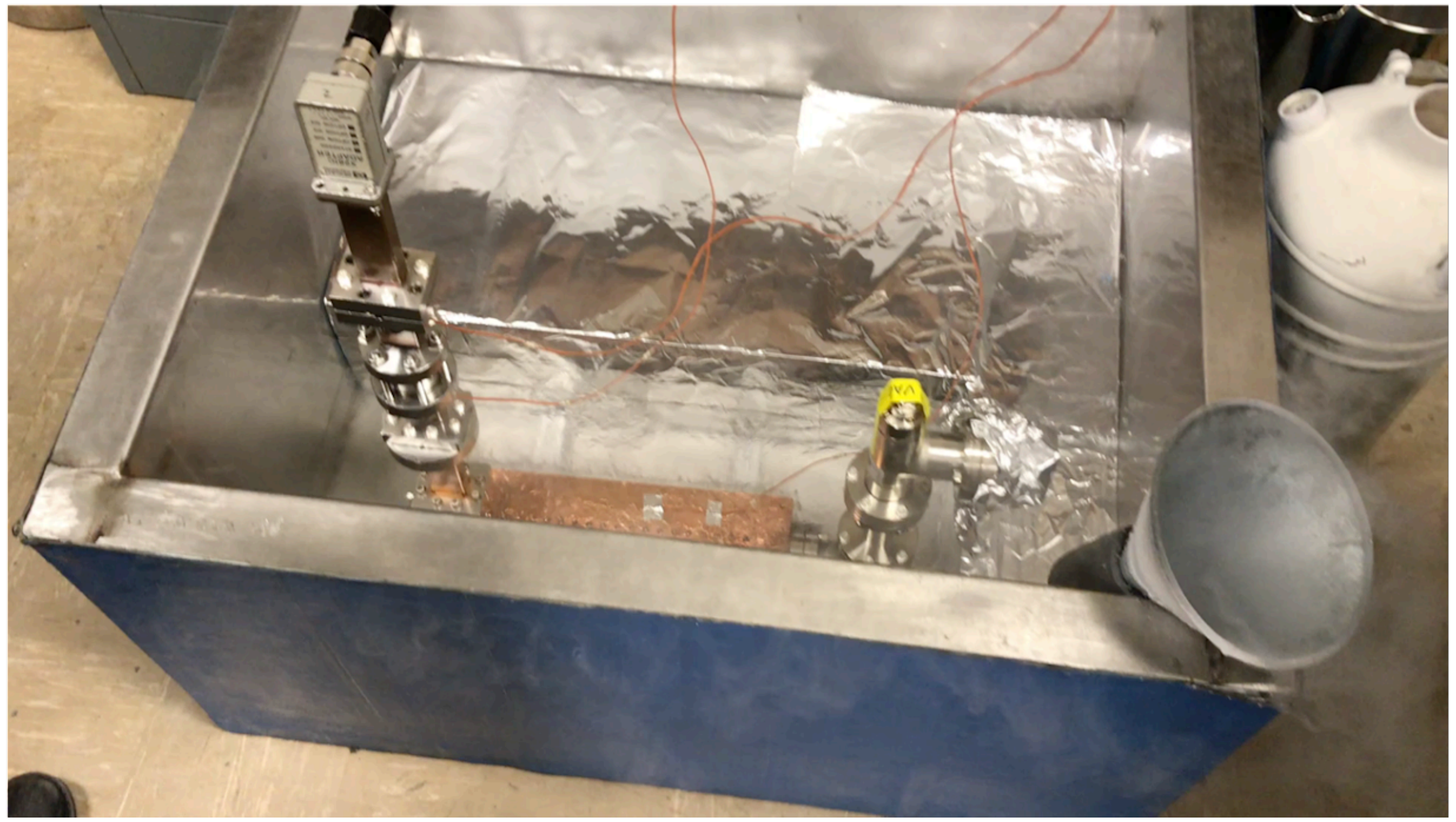
Electric field magnitude for equal power from RF manifold



First C^3 structure at SLAC

Why cool?





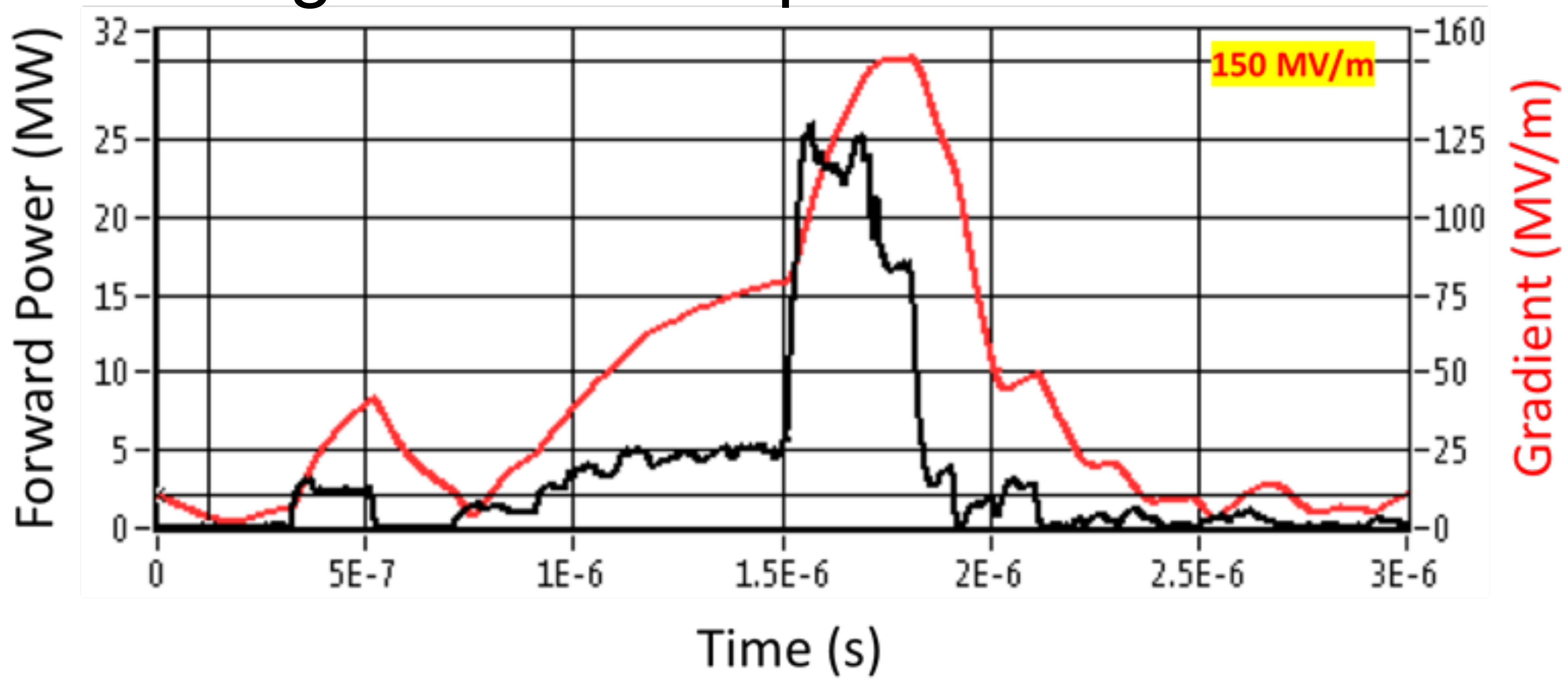
Nasr, et al. *PRAB* 24.9 (2021): 093201.

- Cryogenic temperature elevates performance in gradient
  - Increased material strength for gradient
  - Increase electrical conductivity reduces pulsed heating in the material
- Operation at 77 K with liquid nitrogen is simple and practical

Expected gradient

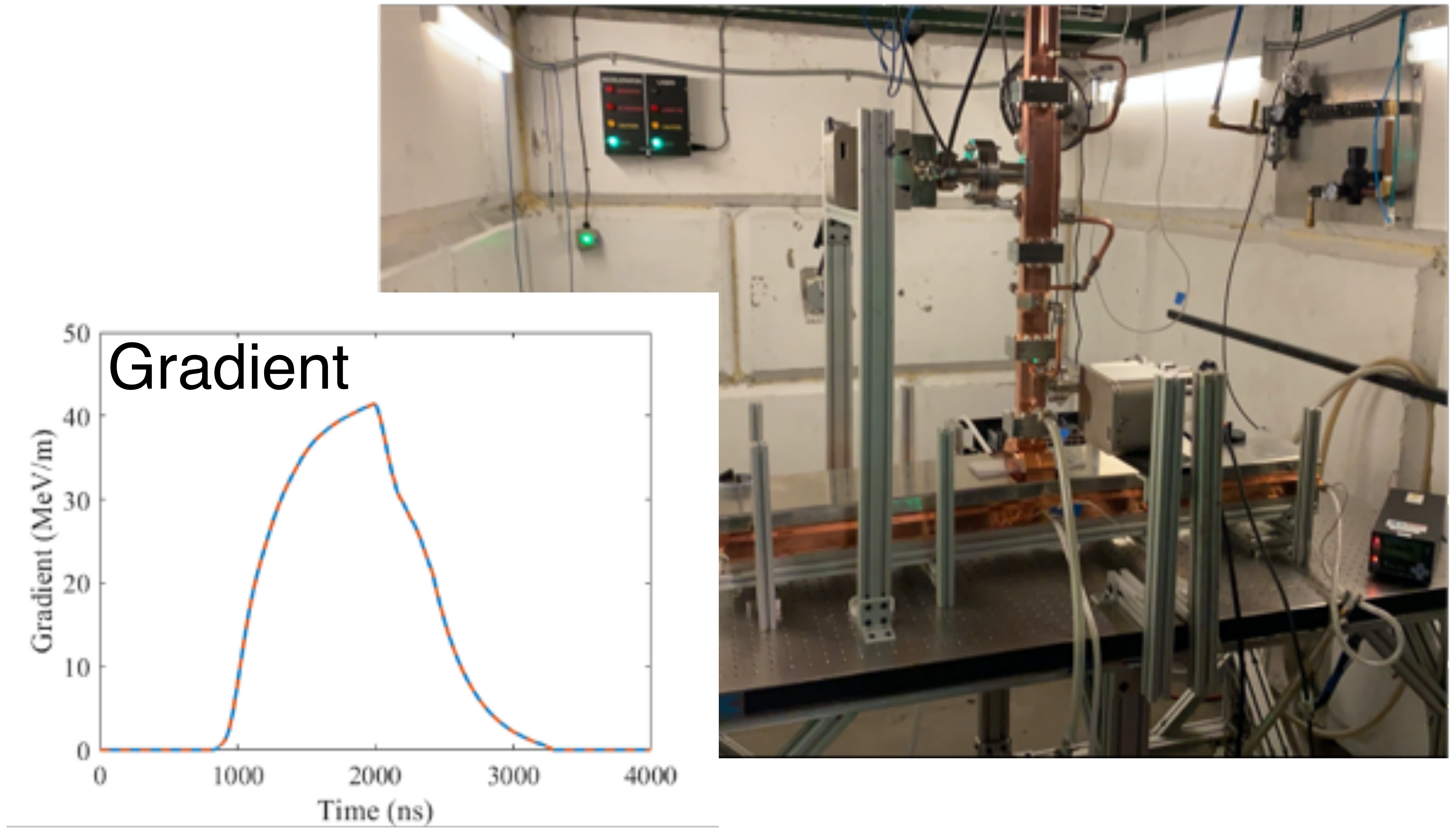
- Robust operations at high gradient: 120 MeV/m
  - Start at 70 MeV/m for C^3-250
- Scalable to multi-TeV operations

High Gradient Operation at 150 MV/m



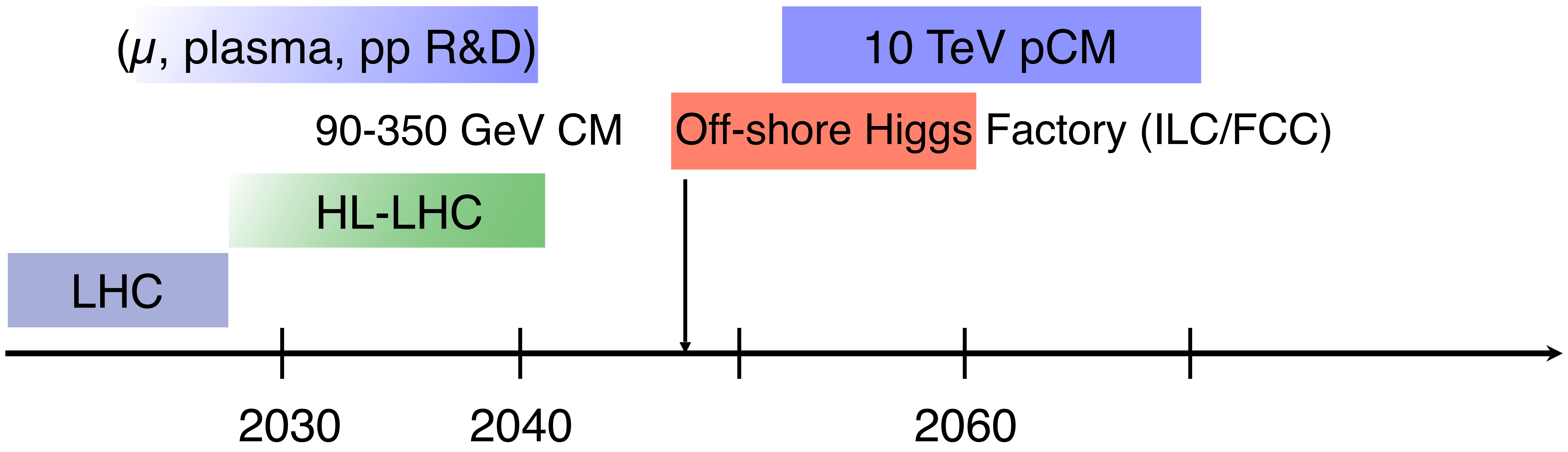
Cryogenic Operation at X-band

High Power Test at Radiabeam



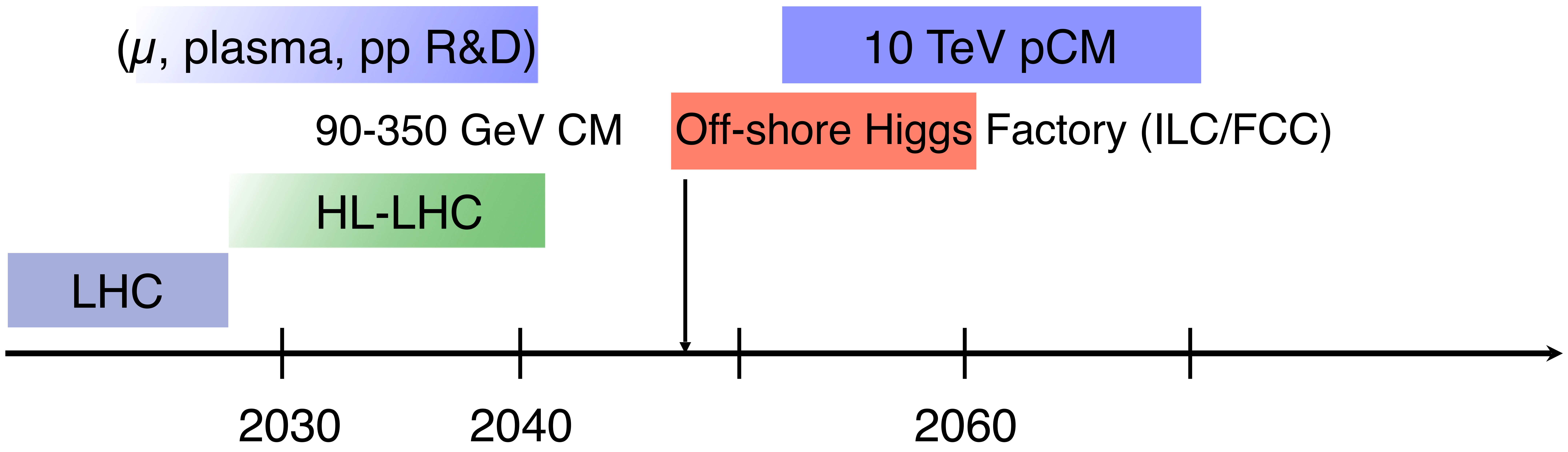
post-P5 roadmap

P5 report



post-P5 roadmap

P5 report

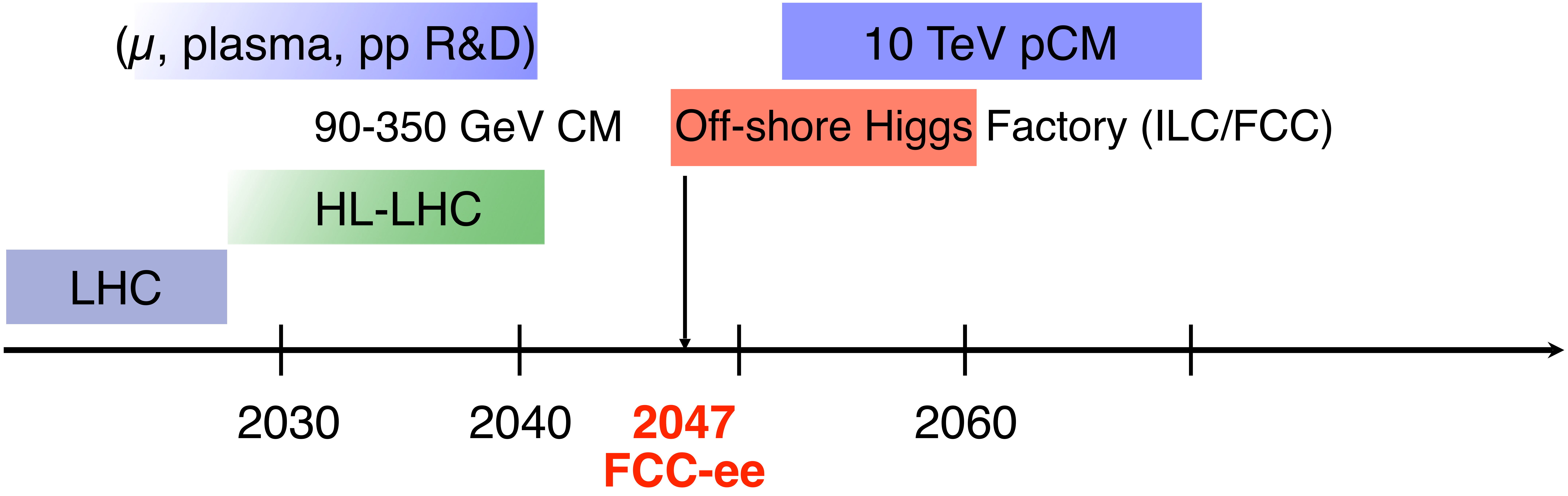


H couplings to: **O(5-10)%** **O(0.1-1)%**

H self-coupling to: **O(50)%** **O(20)%** **O(1)%**

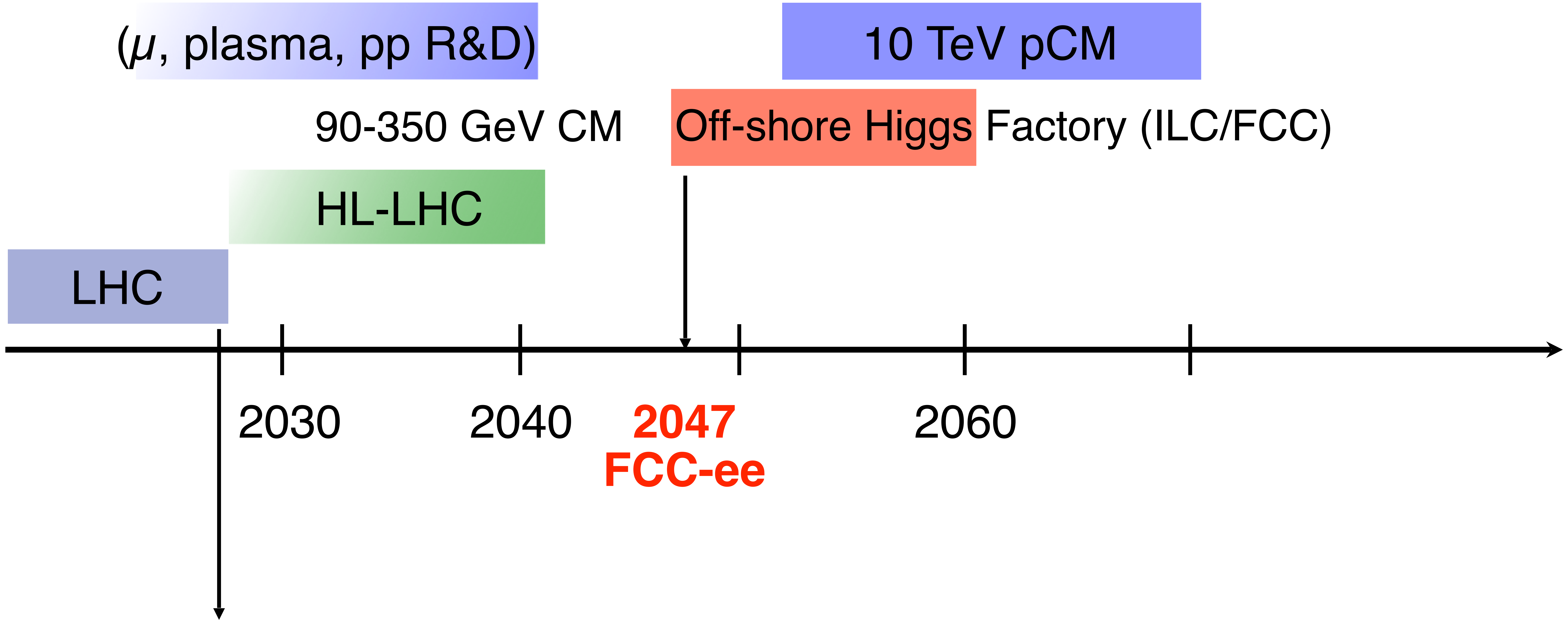
post-P5 roadmap

P5 report



post-P5 roadmap

P5 report

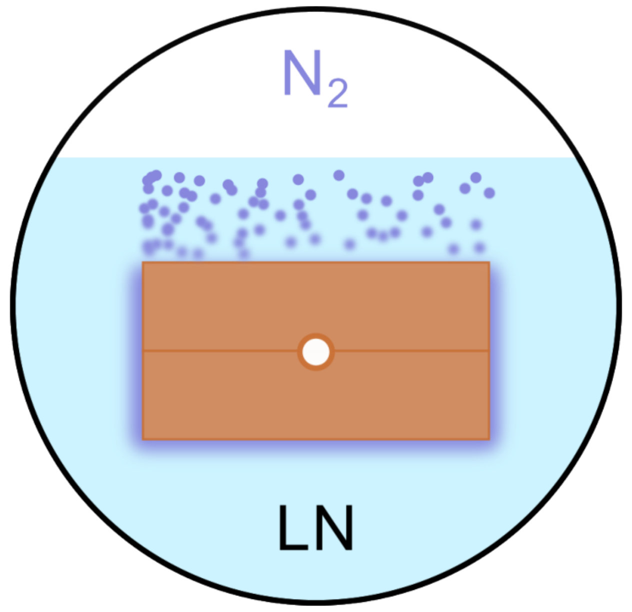


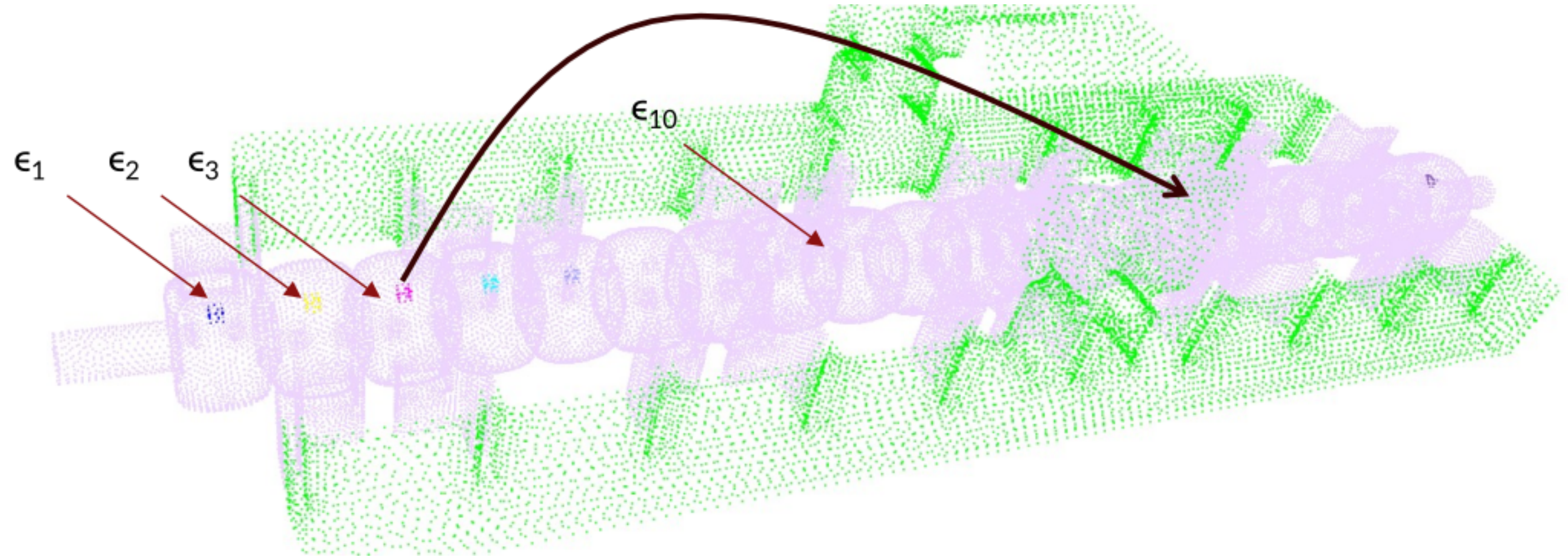
European Strategy for Particle Physics Update
FCC feasibility study report

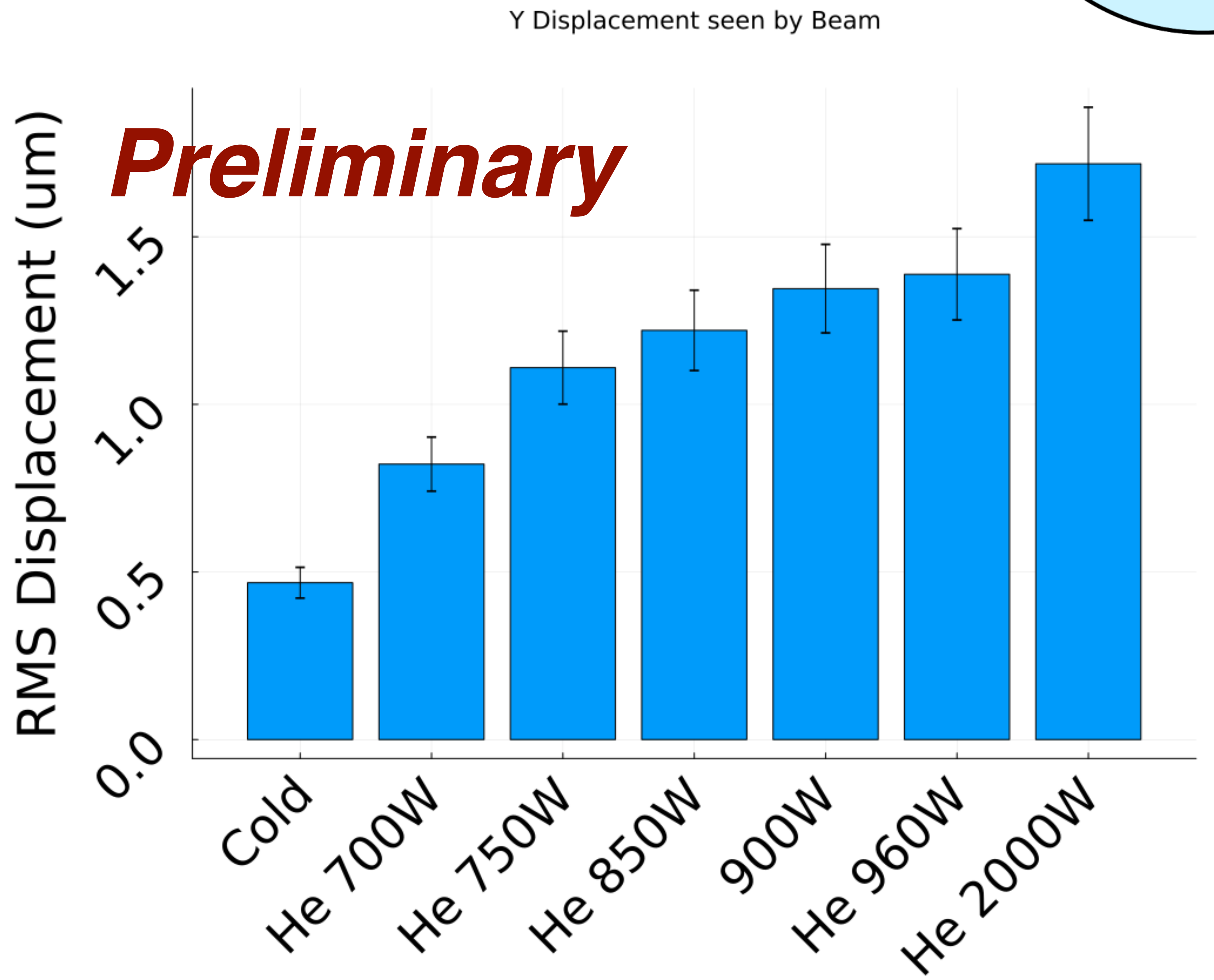
A couple of highlights

More in Ankur's talk

- S-Band injector linac development: low emittance for up to 14 nC bunches while accelerating them at 18 MV/m
  - Targeting Efficient Acceleration of High Charge Bunches
  - S-Band structure assembly and tuning is complete
- Prototype C3 Linac with a resistive heater was used to test vibration within LN up to 2 kW

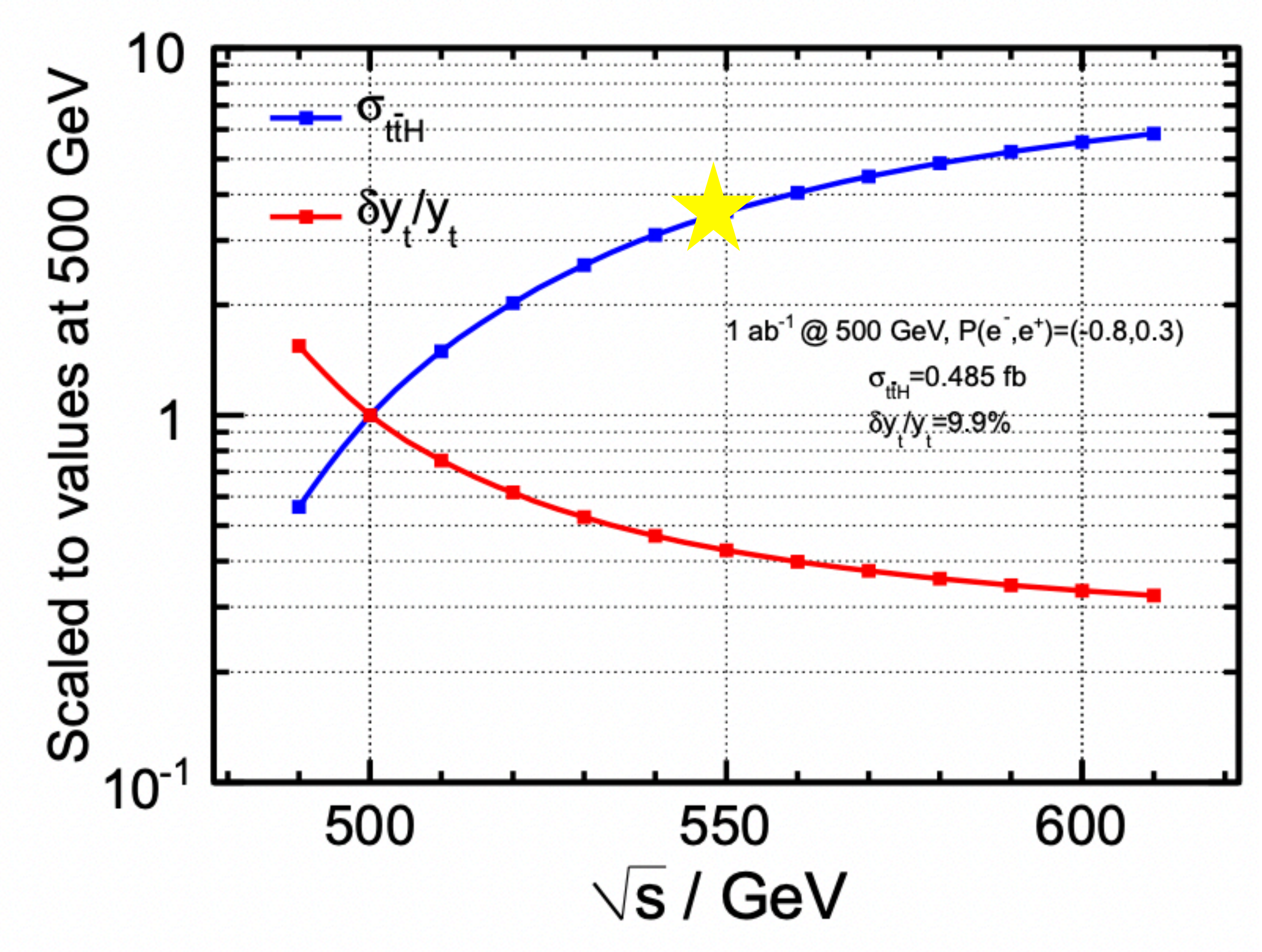






Why 550 GeV?

A factor two in the top-yukawa coupling wrt 500 GeV

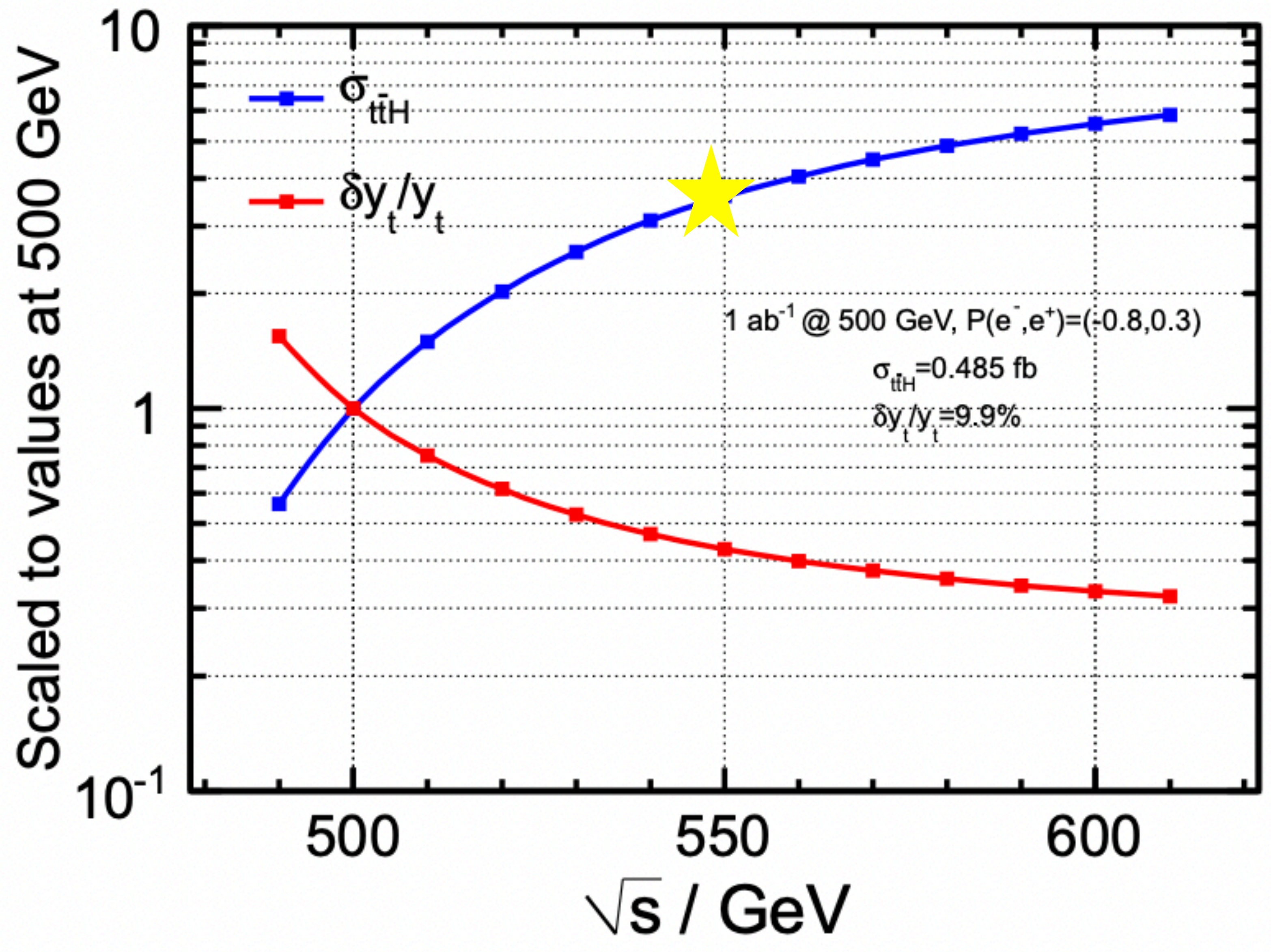


Collider Luminosity Polarization	HL-LHC 3 ab^{-1} in 10 yrs -	C^3 /ILC 250 GeV 2 ab^{-1} in 10 yrs $\mathcal{P}_{e^+}$ = 30% (0%)	C^3 /ILC 500 GeV + 4 ab^{-1} in 10 yrs $\mathcal{P}_{e^+}$ = 30% (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80 (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:1908.11299
arXiv:1506.07830

Why 550 GeV?

A factor two in the top-yukawa coupling wrt 500 GeV



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)

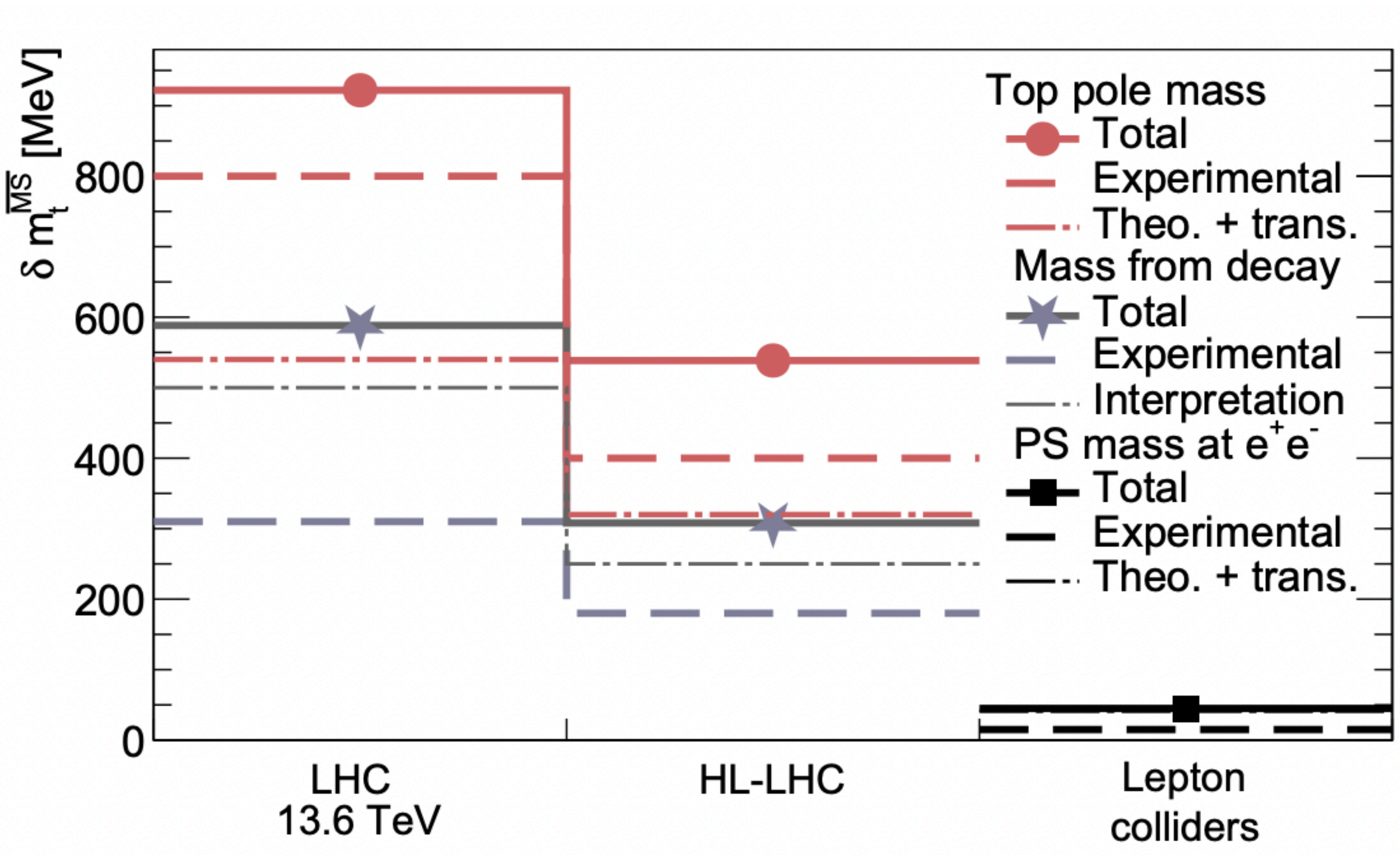
O(20%) precision on the Higgs self-coupling would allow to exclude/ demonstrate at 5σ models of electroweak baryogenesis

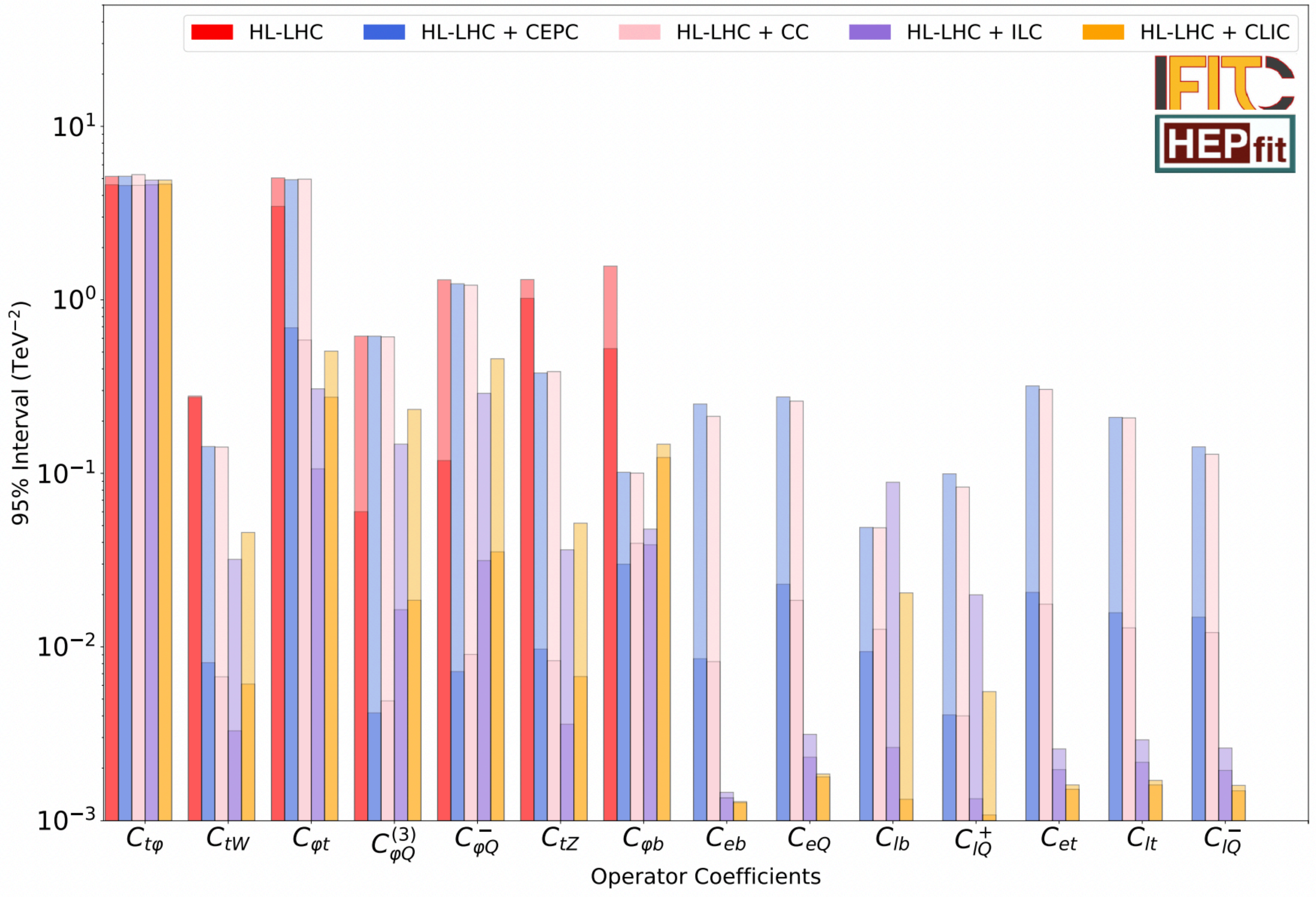
arXiv:2205.02140
arXiv:2209.07510

Top physics at e+e-

Unique opportunities for theoretically clean precision observables

- The measurement of the tt cross-section with a threshold scan can determine the top mass with 50 MeV uncertainty
- Global fits demonstrate e+e- sensitivity of10-100 times above HL-LHC for some operators top electroweak couplings at energies > 500 GeV





Current benchmarks and next steps

The goal of measuring Higgs properties with sub-% precision translates into ambitious requirements for detectors at e+e-

- Requirements mostly driven by (Higgs) specific benchmarks
- Technological advances can open new opportunities and additional physics benchmarks (i.e. H→ss) can add more stringent requirements

Physics goal	Detector	Requirement
hZZ sub-%	Tracker	σ_{p_T}/p_T=0.2% for $p_T < 100$ GeV
		$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/$ GeV for $p_T > 100$ GeV
	Calorimeter	4% particle flow jet resolution
		EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2
		EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
		shower timing resolution 10 ps
$hb\bar{b}/hc\bar{c}$	Tracker	$\sigma_{r\phi} = 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1}\mu$m
		5μm single hit resolution

Arxiv:2209.14111 Arxiv:2211.11084 DOE Basic Research Needs Study on Instrumentation

	Topic	Lead group	Relevant $\sqrt{s}$ [GeV] 91	161	240–250	350–380	$\geq$ 500
1	HtoSS	HTE			✓	✓	✓
2	ZHang	HTE (GLOB)			✓	✓	✓
3	Hself	GLOB			✓	✓	✓

Current benchmarks and next steps

The goal of measuring Higgs properties with sub-% precision translates into ambitious requirements for detectors at e^+e^-

- Requirements mostly driven by (Higgs) specific benchmarks
- Technological advances can open new opportunities and additional physics benchmarks (i.e. H→ss) can add more stringent requirements

Physics goal	Detector	Requirement
hZZ sub-%	Tracker	σ_{p_T}/p_T=0.2% for $p_T < 100$ GeV
		$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/$ GeV for $p_T > 100$ GeV
	Calorimeter	4% particle flow jet resolution
		EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2
		EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
		shower timing resolution 10 ps
$hb\bar{b}/hc\bar{c}$	Tracker	$\sigma_{r\phi} = 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1} \mu$m
		5μm single hit resolution

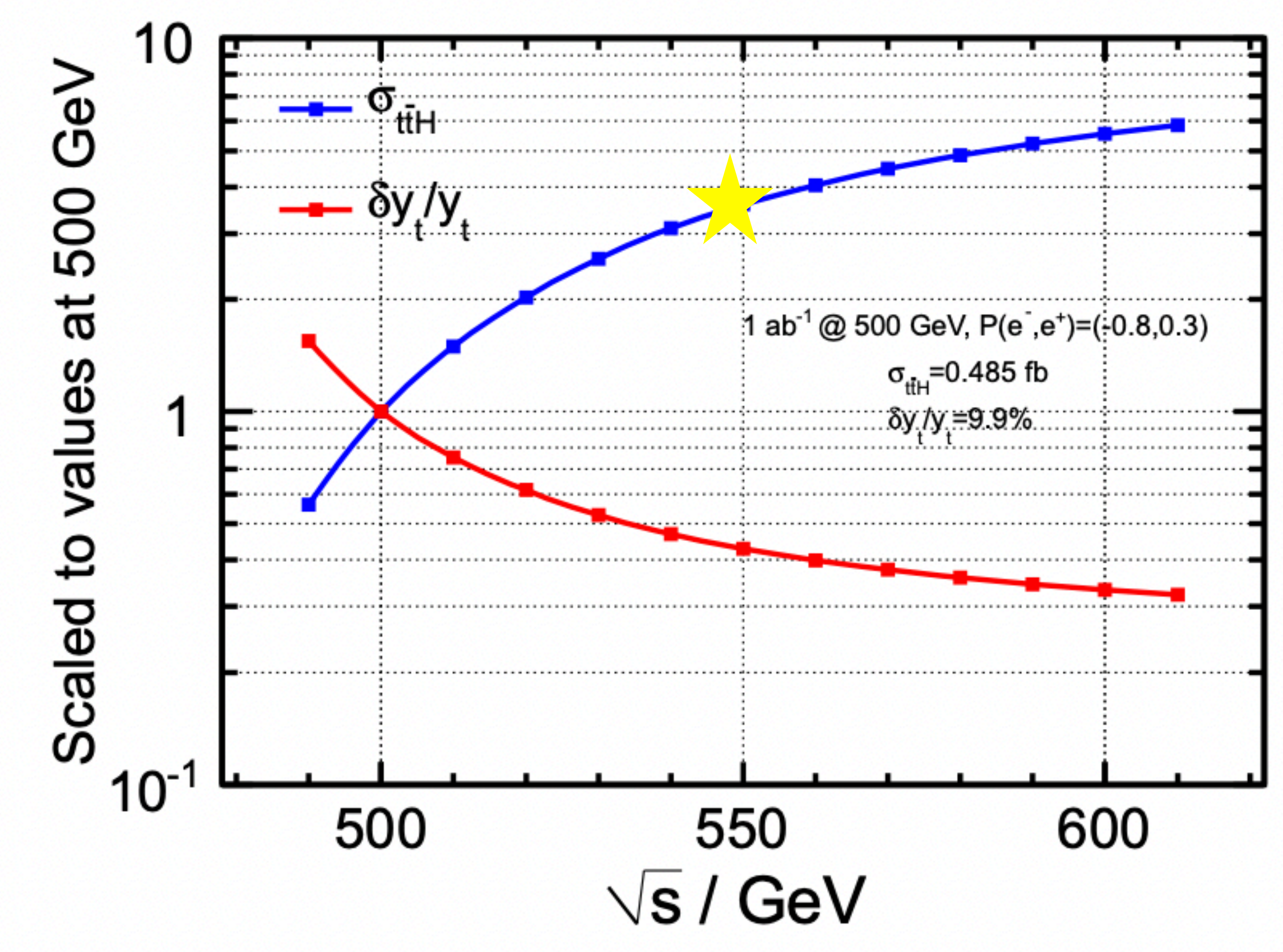
Arxiv:2209.14111 Arxiv:2211.11084 DOE Basic Research Needs Study on Instrumentation

Topic		Lead group	Relevant $\sqrt{s}$ [GeV] 91	161	240–250	350–380	≥ 500
1	HtoSS	HTE			✓	✓	✓
2	ZHang	HTE (GLOB)			✓	✓	✓
3	Hself	GLOB			✓	✓	✓

Focus topics for the ECFA study on Higgs / Top / EW factories *should* provide further detector design guidelines (2401.07564) by Spring 2025

Why 550 GeV?

A factor two in the top-yukawa coupling



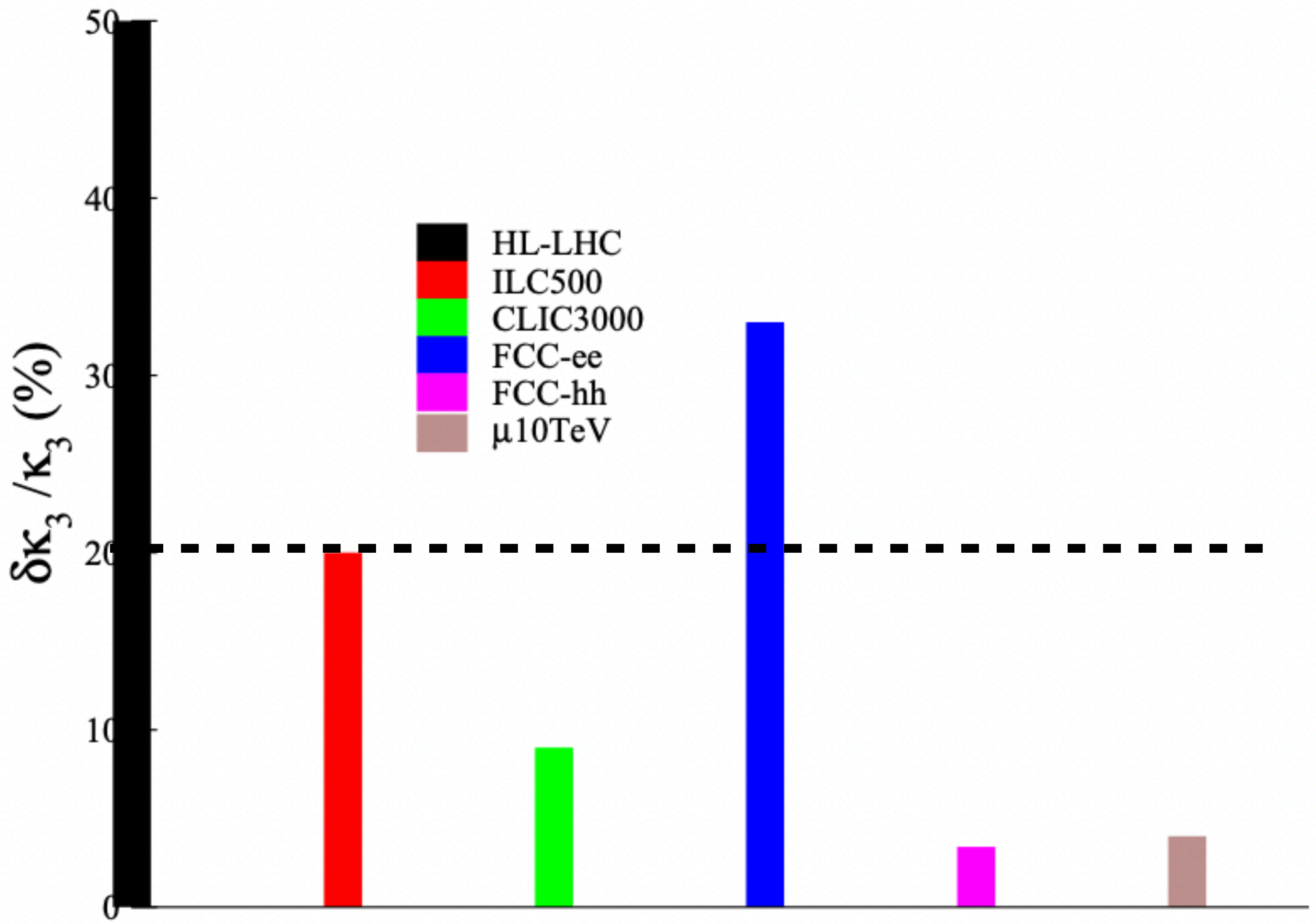
Collider Luminosity Polarization	HL-LHC 3 ab^{-1} in 10 yrs -	C^3 /ILC 250 GeV 2 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)	C^3 /ILC 500 GeV + 4 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80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

The Higgs self-coupling

arXiv:2209.07510

HL-LHC projections are conservative, as they have still to be updated since 2018

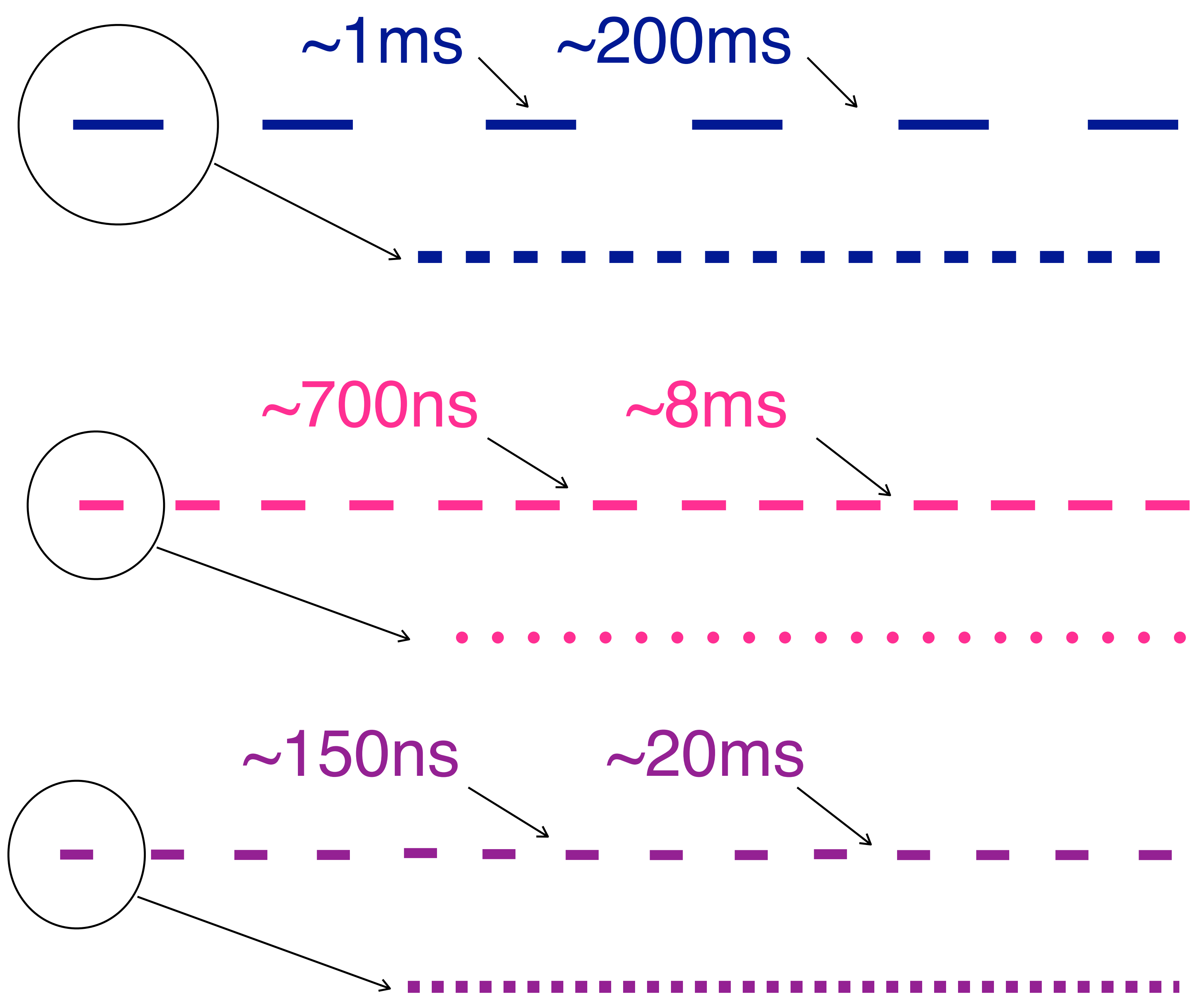
collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC$_{250}$/C^3-250 [51, 52]	49%	–	49%
ILC$_{500}$/C^3-550 [51, 52]	38%	20%	20%
CLIC$_{380}$ [54]	50%	–	50%
CLIC$_{1500}$ [54]	49%	36%	29%
CLIC$_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%



O(20%) precision on the Higgs self-coupling would allow to exclude/ demonstrate at 5σ models of electroweak baryogenesis

Beam Format and Detector Design Requirements

arXiv:2003.01116
FCC Mid Term Report



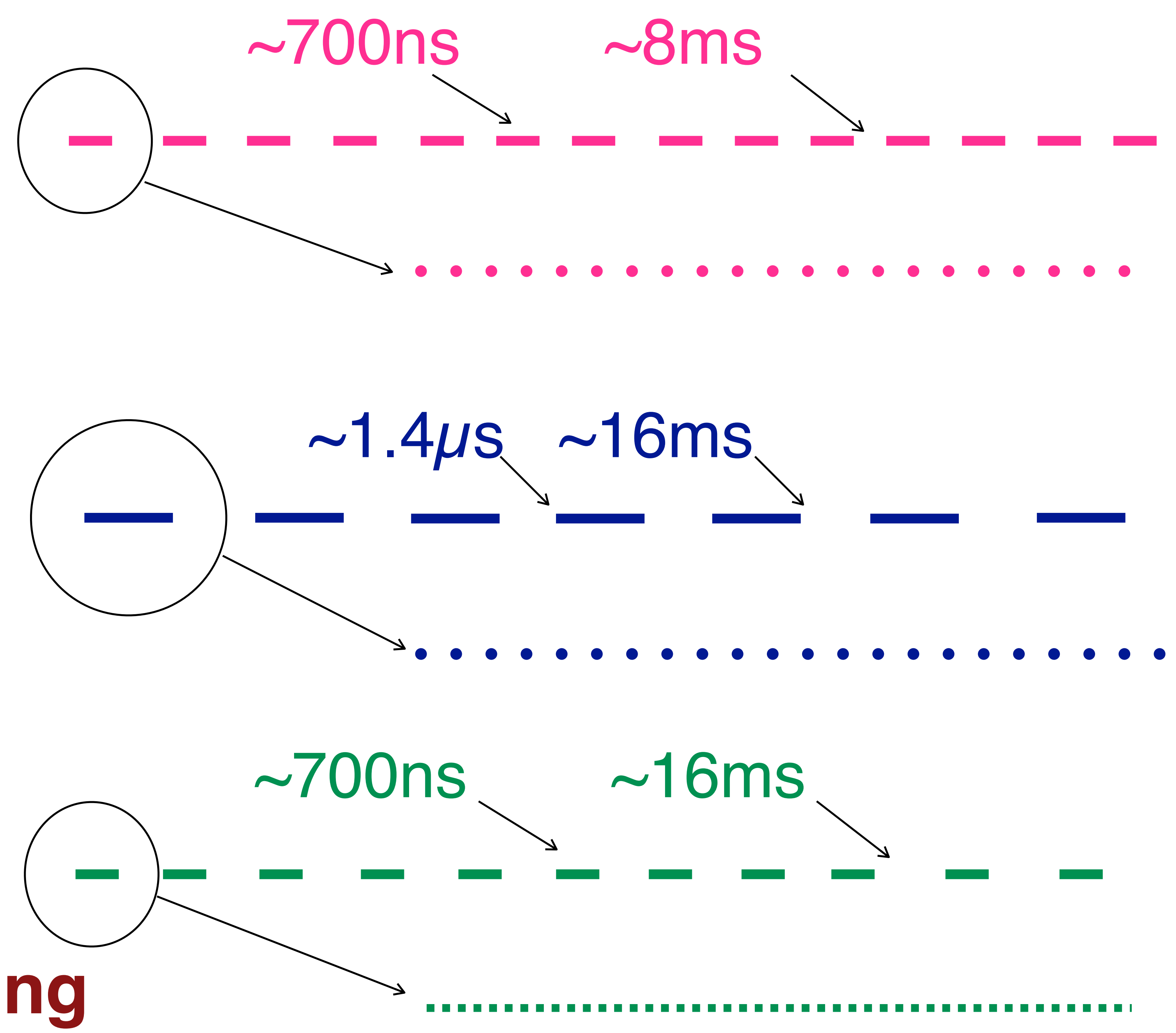
ILC Trains at 5Hz, 1 train 1312 bunches
Bunches are 369 ns apart

C^3 Trains at 120Hz, 1 train 133 bunches
Bunches are 5 ns apart

CLIC Trains at 50Hz, 1 train 312 bunches
Bunches are 0.5 ns apart

- **Very low duty cycle at LC** (0.5% ILC, 0.08% C^3) allows for trigger-less readout and power pulsing
  - Factor of 100 power saving for front-end analog power
- Impact of beam-induced background to be mitigated through MDI and detector design
- **O(1-100) ns bunch identification capabilities** (hit-time-stamping) can further suppress beam-backgrounds and keep occupancy low - same as for FCC-ee

New “sustainable” parameter set ?



Baseline

C³ Trains at 120Hz, 1 train 133 bunches
Bunches are 5 ns apart

Double-flat top

C³ Trains at 60Hz, 1 train 266 bunches
Bunches are 5 ns apart

Double-flat top
+
Halved bunch spacing

C³ Trains at 60Hz, 1 train 266 bunches
Bunches are 2.65 ns apart

Constant luminosity

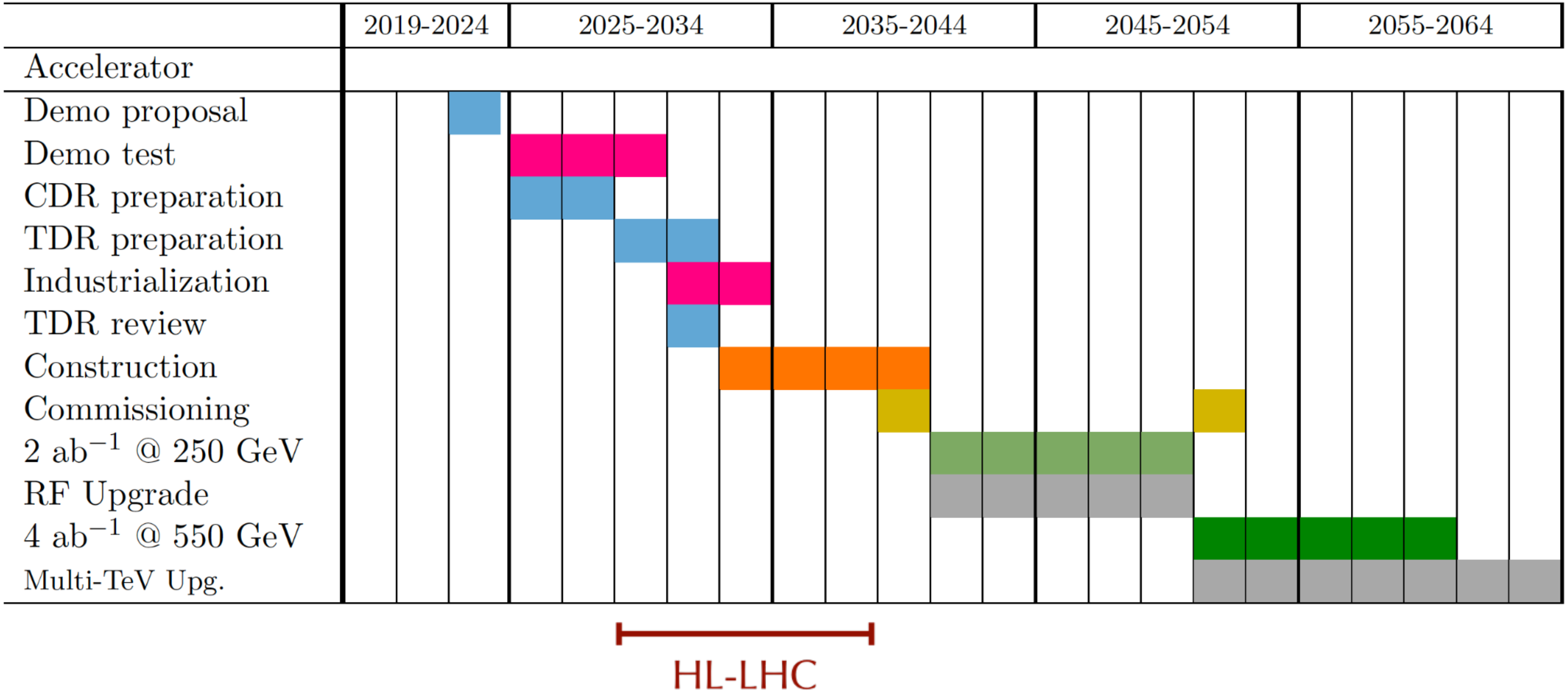
New “sustainable” parameter set ?

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

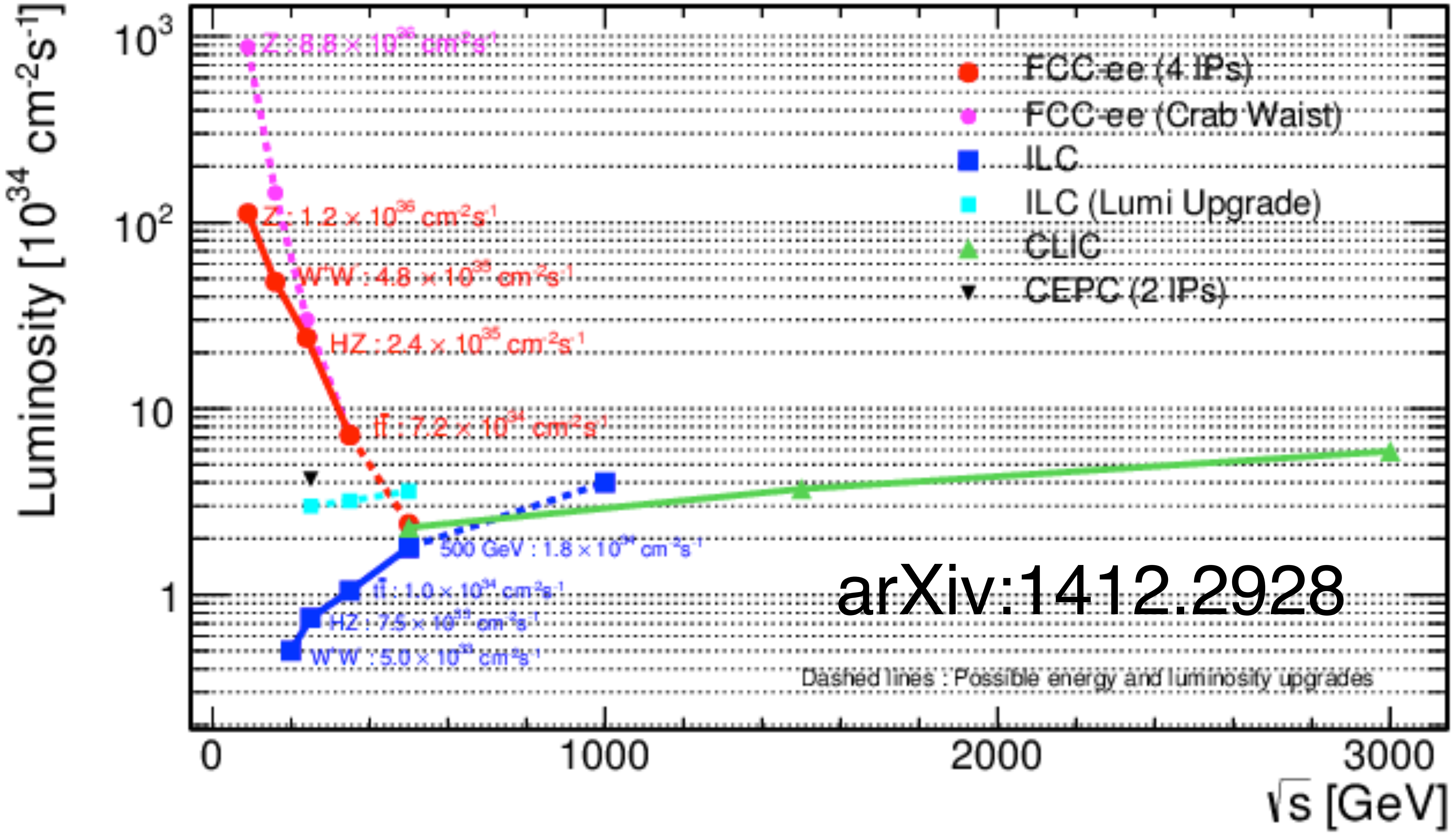
Technical Timeline for 250/550 GeV CoM

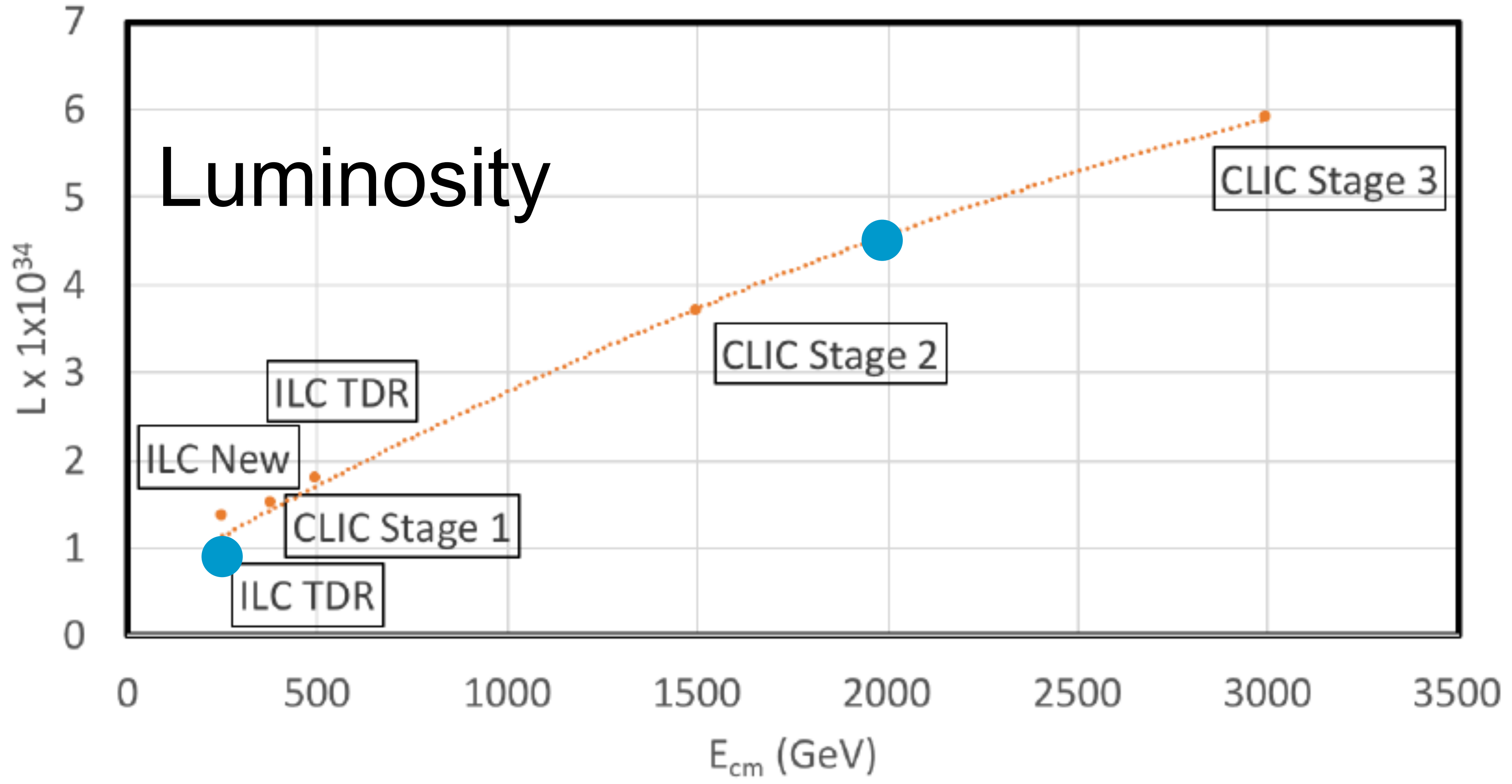
P5 Town Hall

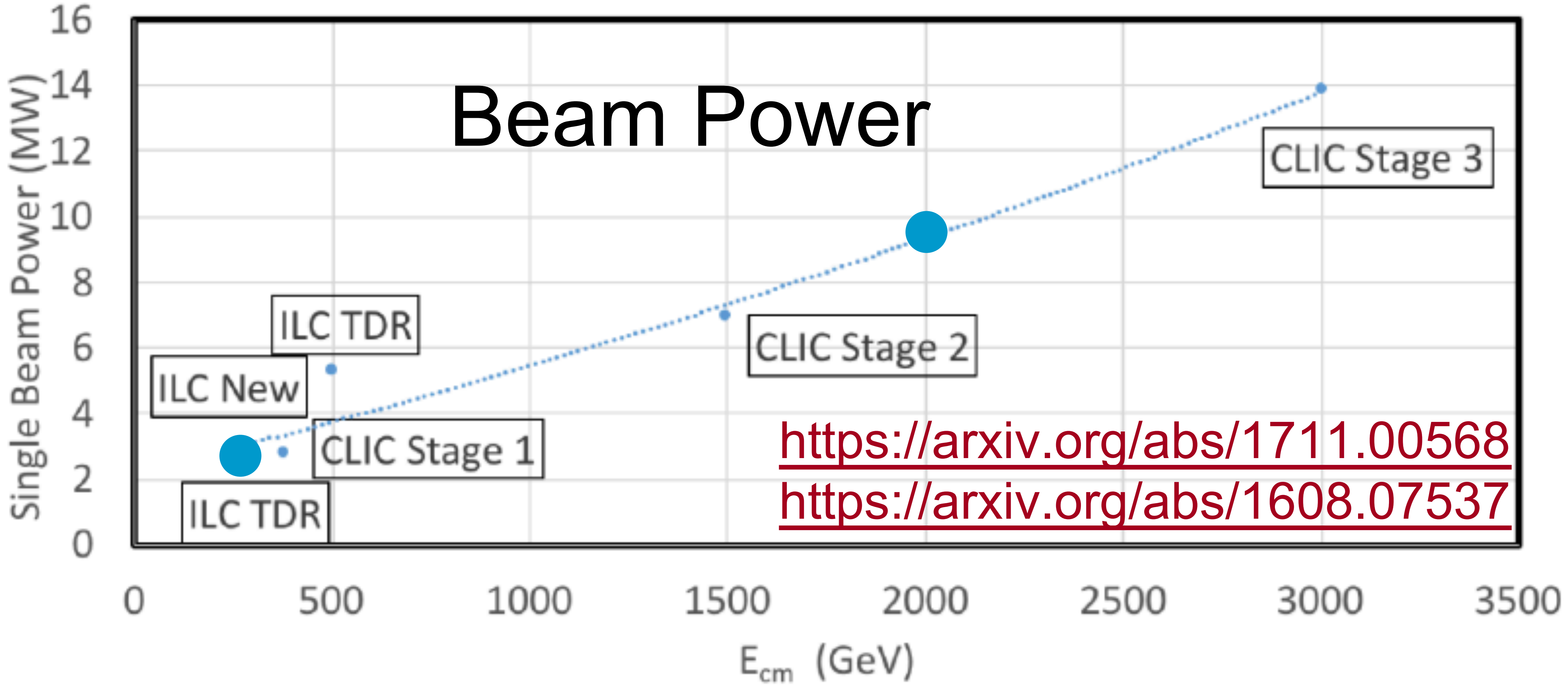
Energy upgrade in parallel to operation with installation of additional RF power sources



Luminosity optimization

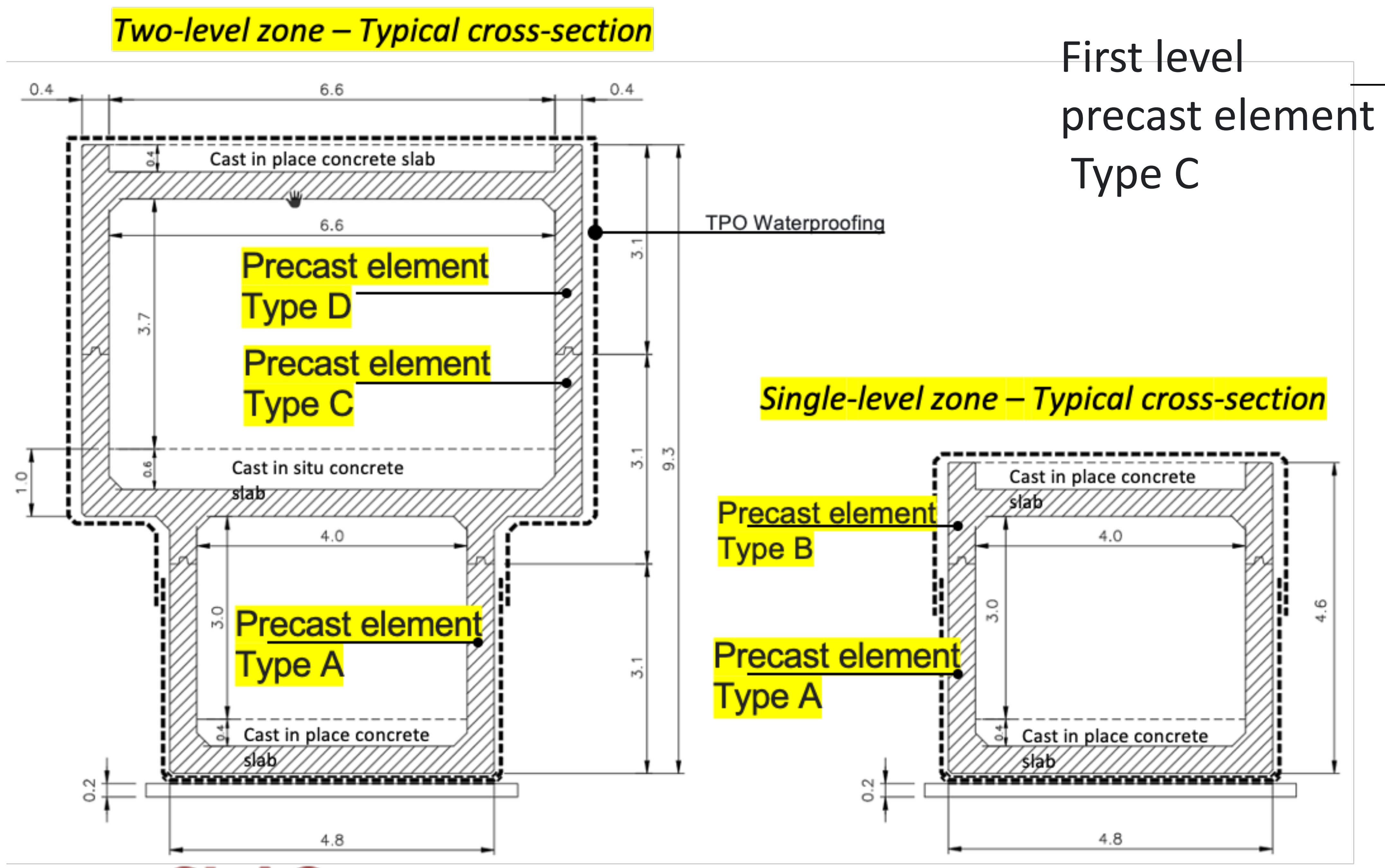




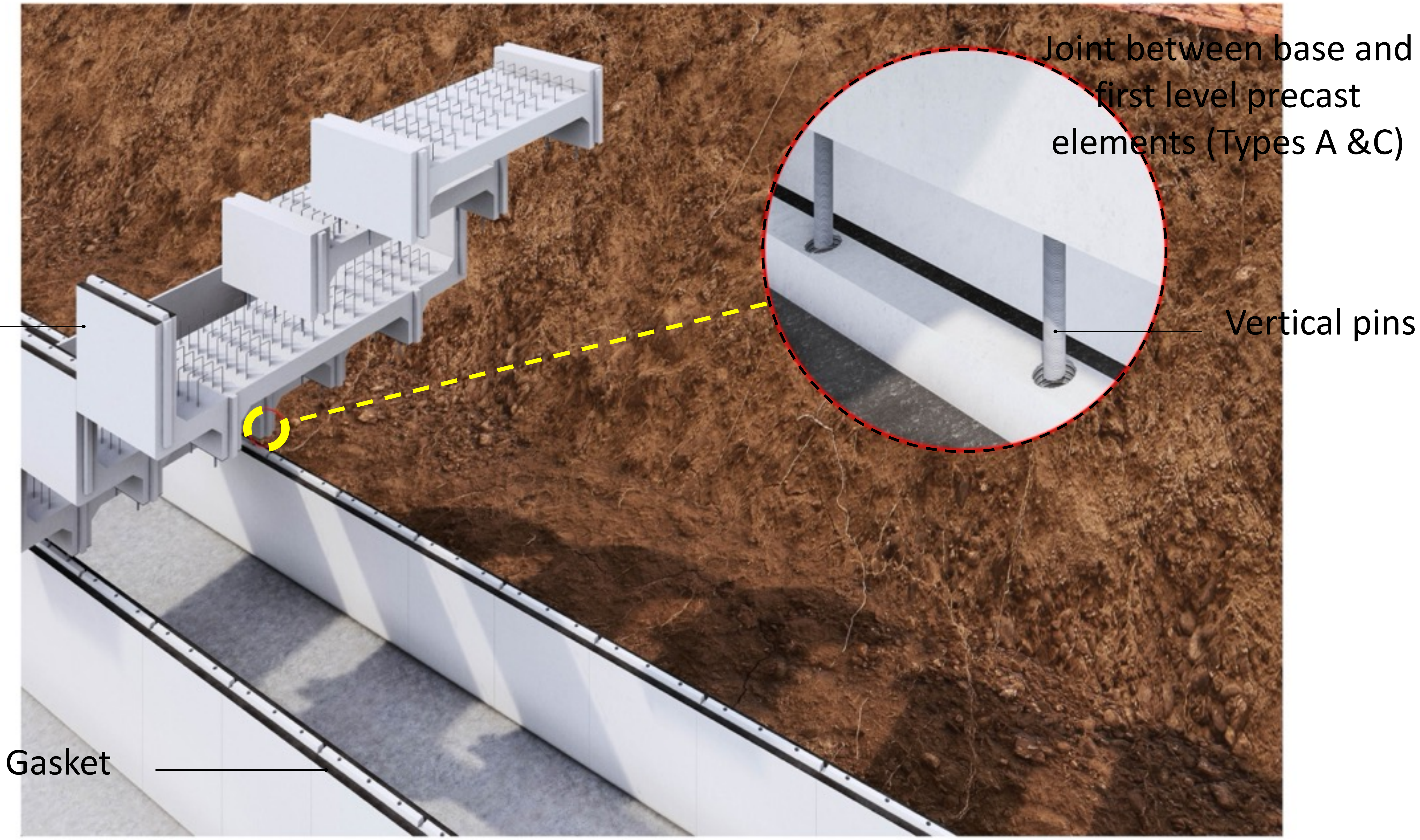


Rapid Construction with a Surface Site

- “Cut and cover” construction
- Precast concrete housing elements made on site
- Limited waster material – reuse material to cover tunnel
- Requires low density site e.g. Hanford

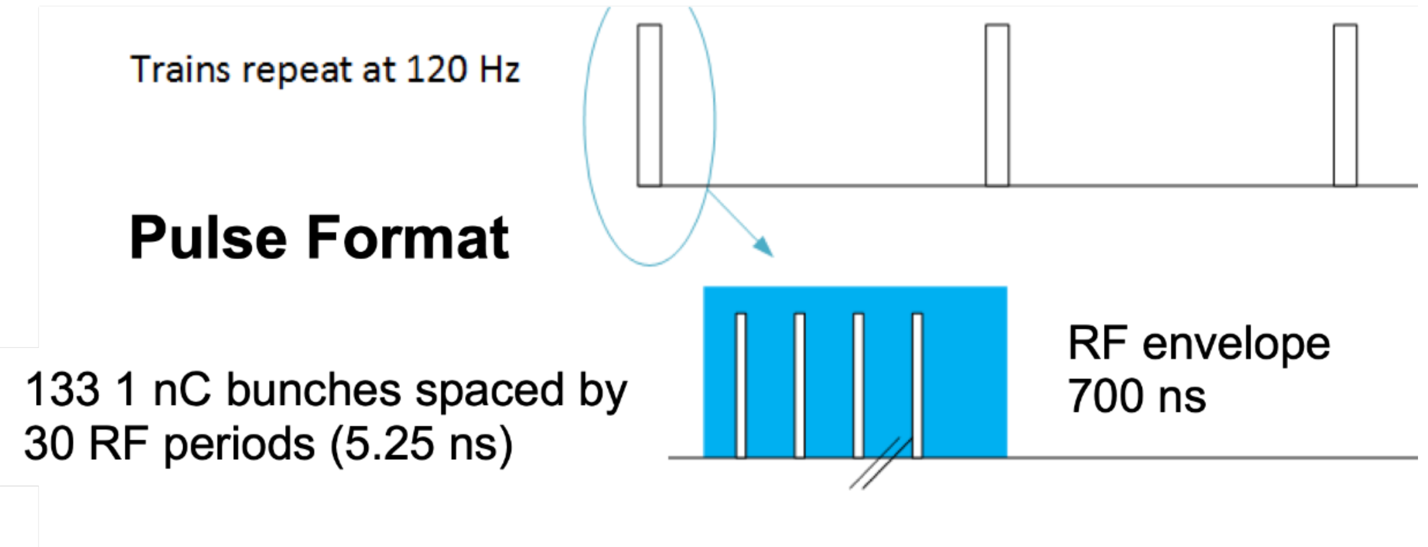


First level precast elements installation



Power Consumption and Sustainability

Snowmass



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

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
Electrical Power For Cryo-Cooler	MW	60
Accelerator Complex Power	MW	~50
Site Power	MW	~150

Compatibility with Renewables
Cryogenic Fluid Energy Storage

Highview Power

Intermittent and variable power production from renewables mediated with commercial scale energy storage and power production