C3 sustainability parameters

web.slac.stanford.edu/c3/

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SLAC NATIONAL ACCELERATOR LABORATORY

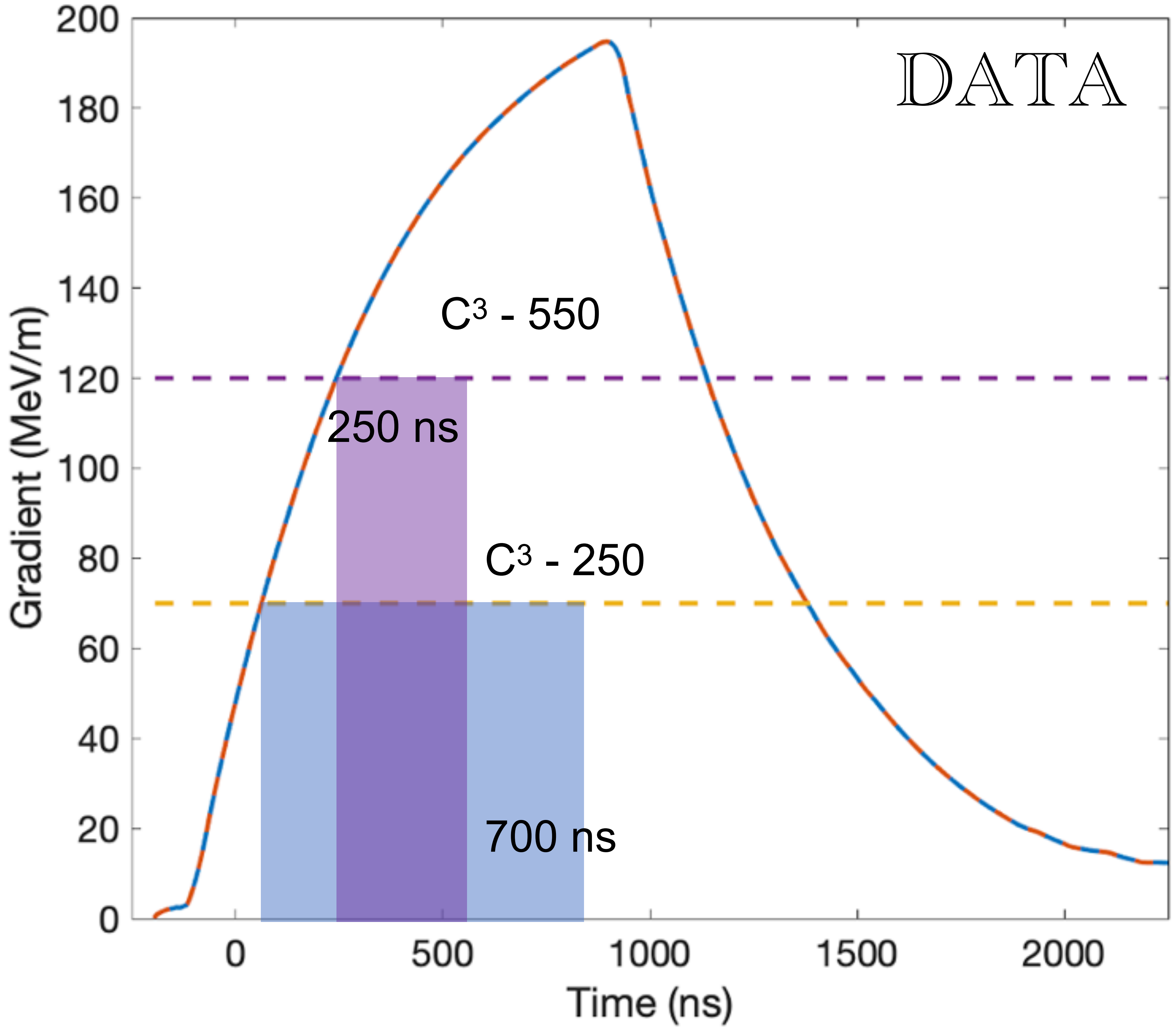
Stanford University

U.S. DEPARTMENT OF ENERGY

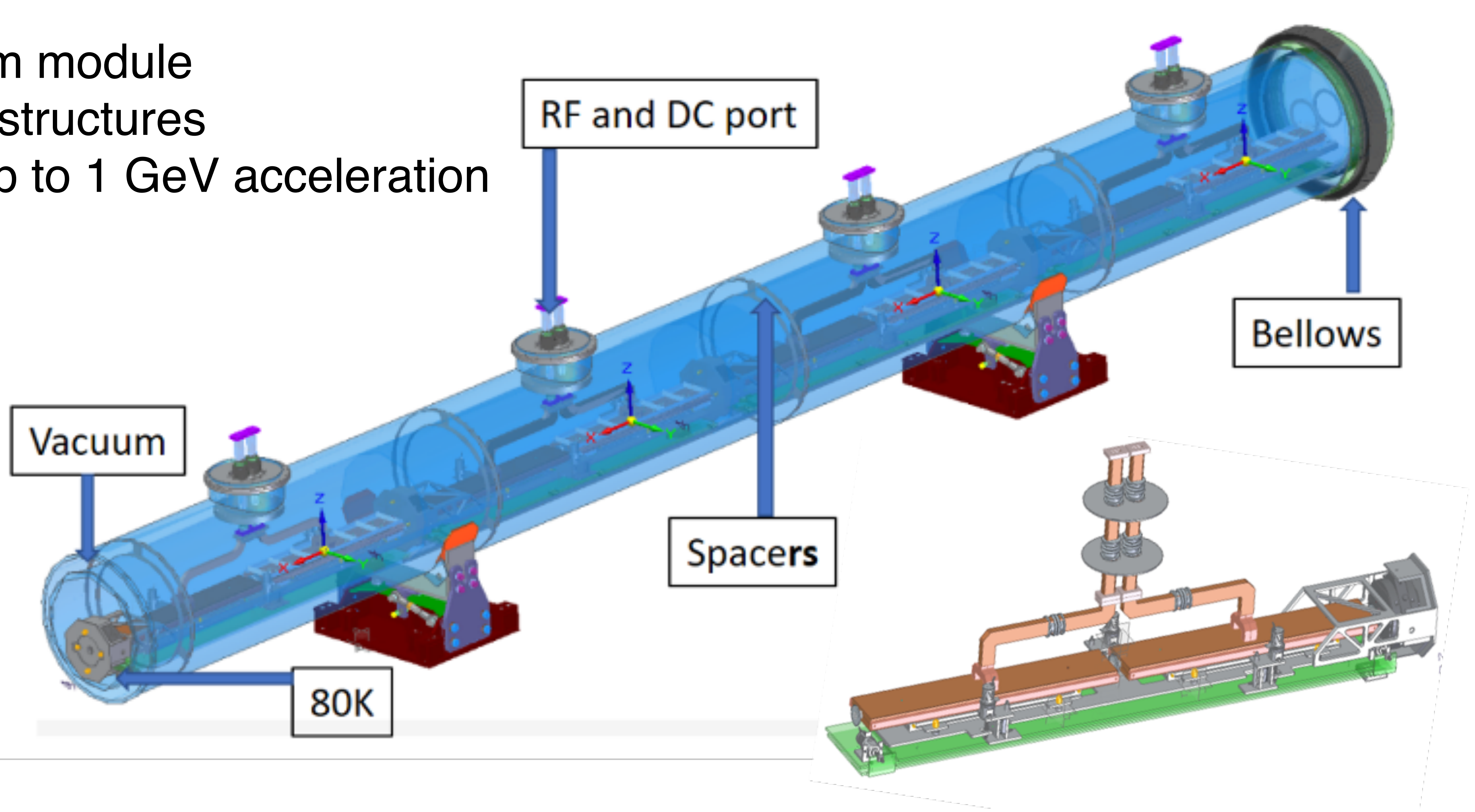
arXiv:2110.15800
Bulletin of the American Physical Society (2024)

C^3 Cool Copper Collider

- Target gradients of 70 MeV/m for C^3-250 and **120 MeV/m at 550 GeV**
- Beam parameters initially optimized to match the ILC luminosity within the same time frame



9m module
8 structures
Up to 1 GeV acceleration



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

C^3

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

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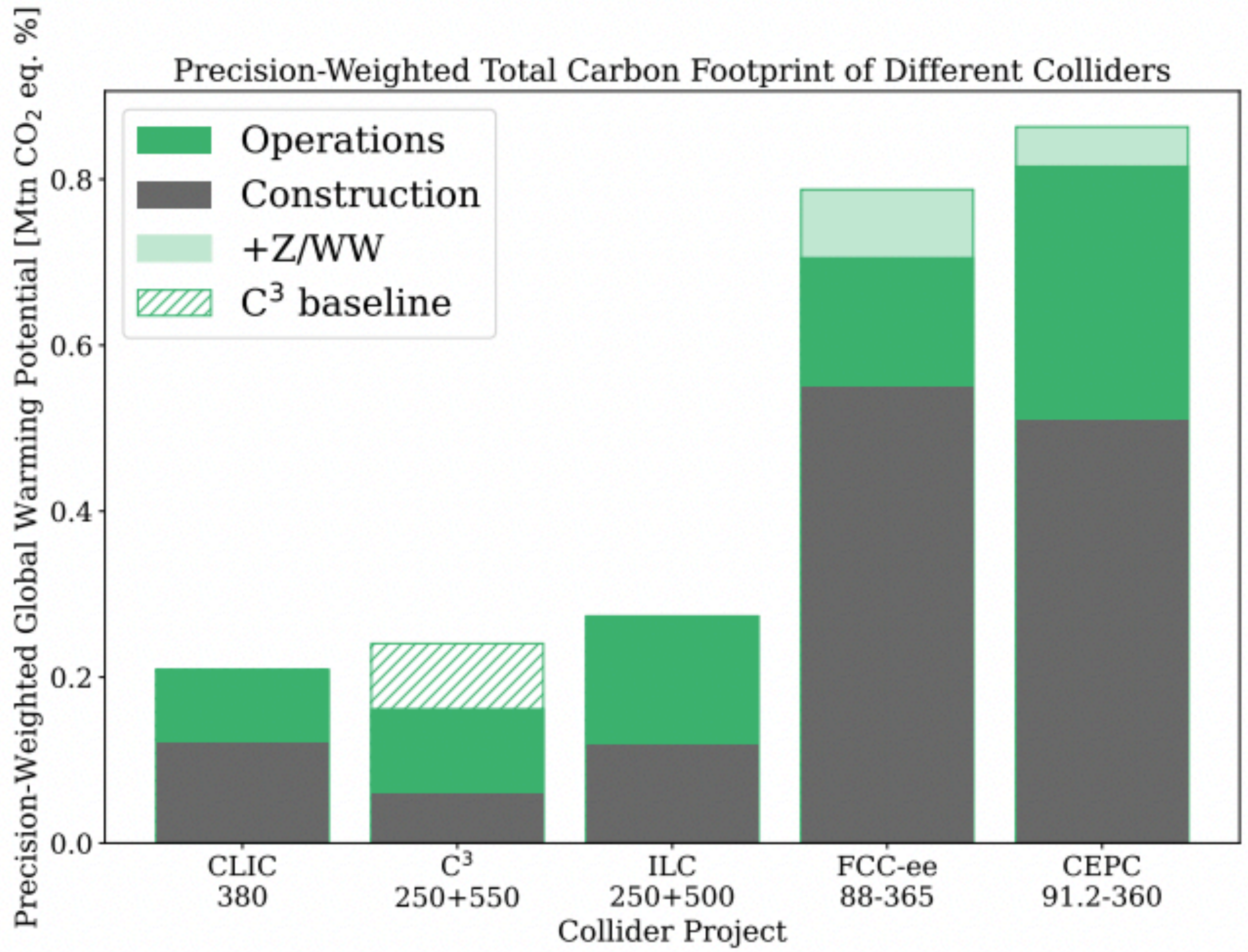
Double Flat Top	30
Halve Bunch Spacing	34
All Scenarios Combined	13



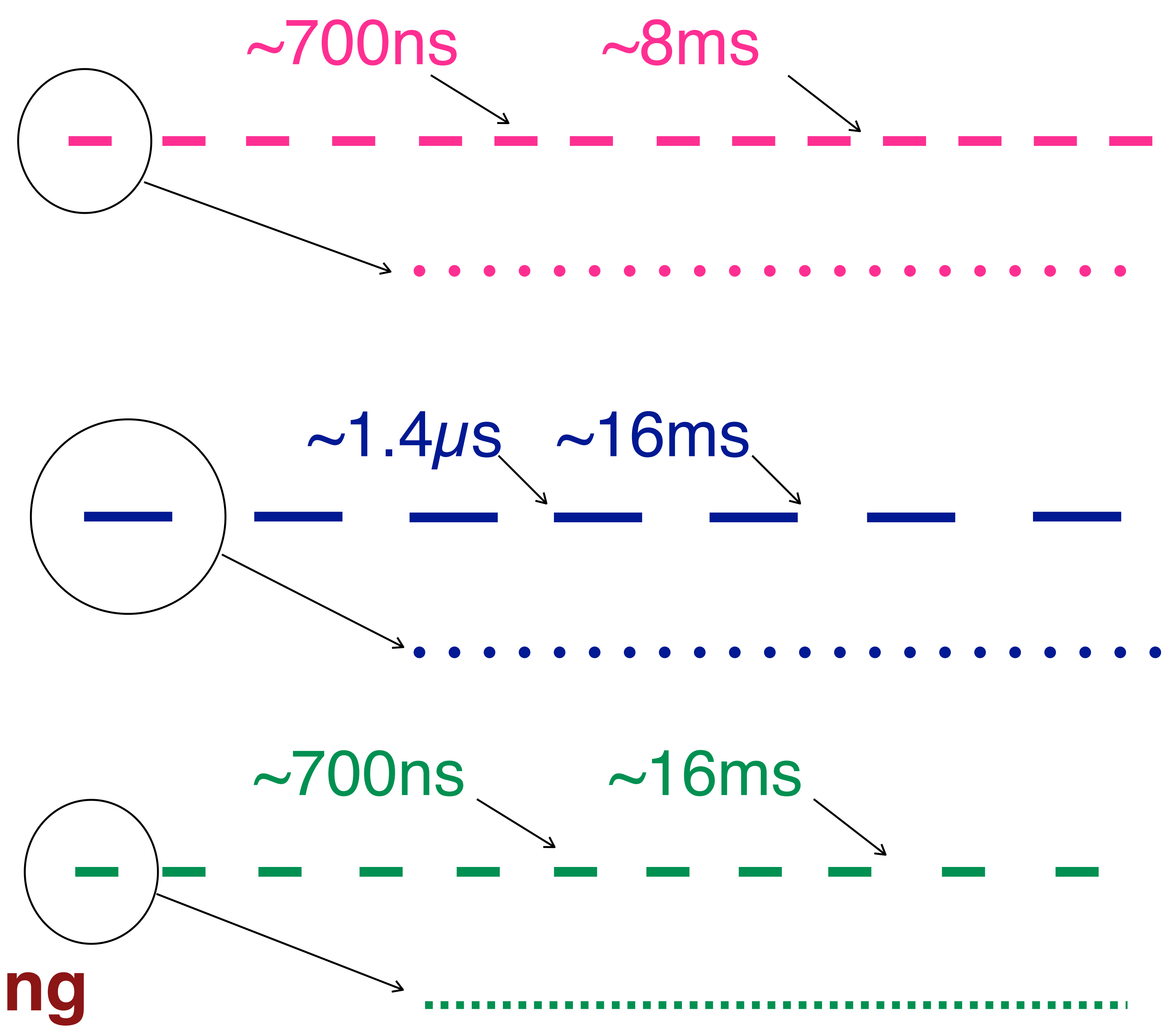
New “sustainable” parameter set ?

C^3 250 Bunch Format

Baseline

Double-flat top

Double-flat top
+
Halved bunch spacing



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

C^3 Trains at 60Hz, 1 train 266 bunches
Bunches are 5 ns apart

C^3 Trains at 60Hz, 1 train 266 bunches
Bunches are 2.65 ns apart

Constant luminosity

New “sustainable” parameter set

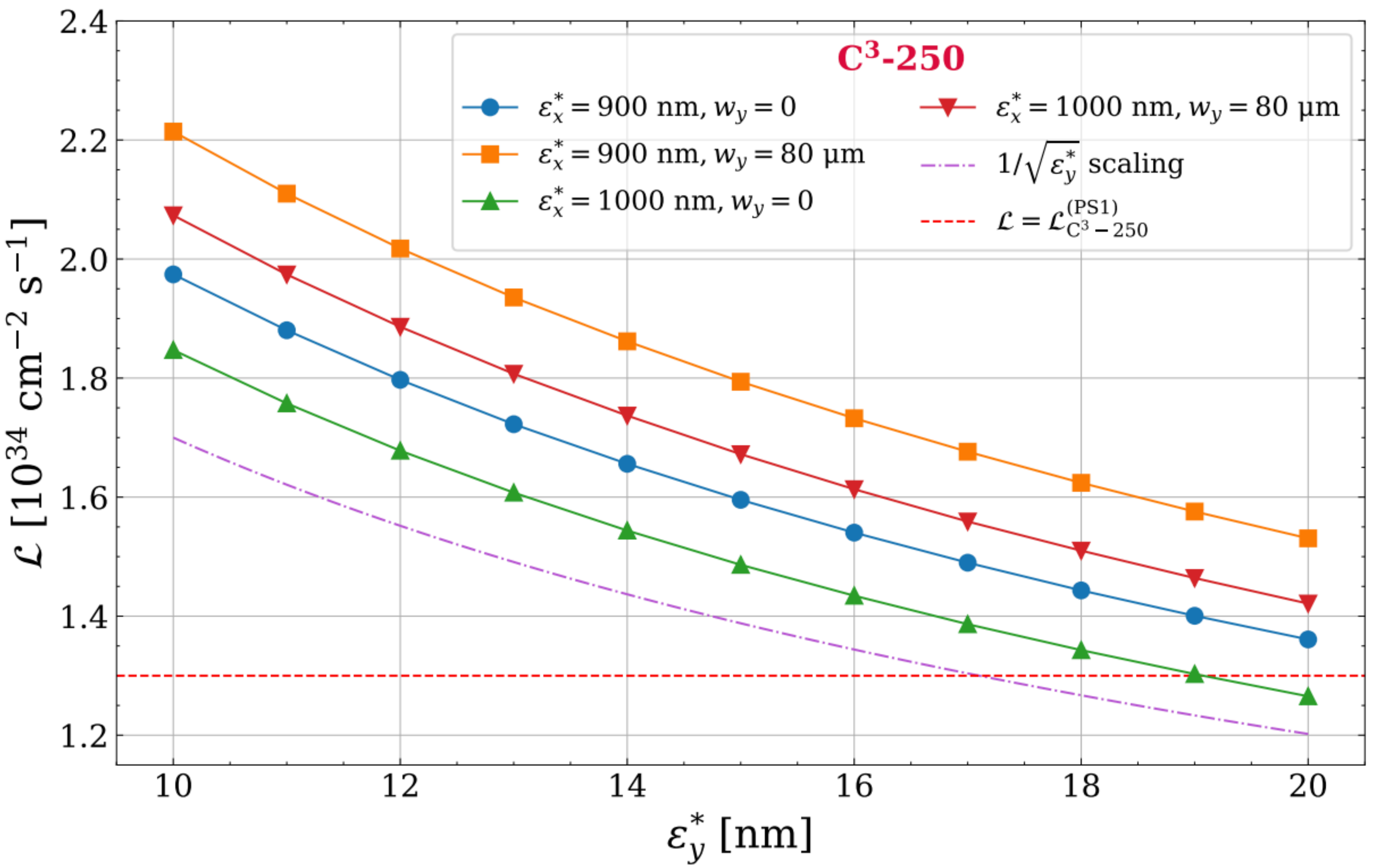
scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch 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

Optimized parameter sets

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

An improvement of around 40% while BIB is maintained at approximately the same levels.

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	$\mathscr{L}_{\text{geom}}$ $[10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}]$	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	$\mathscr{L}$ $[10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}]$	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



Studies on going to re-evaluate the BIB for the sustainability parameter set

Optimized parameter sets

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

An improvement of around 40% while BIB is maintained at approximately the same levels.

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

Parameter	Symbol [unit]	C^3-250 (PS1)	C^3-250 (PS2)
Center-of-mass Energy	$\sqrt{s_0}$ [GeV]	250	
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Nor	[illegible]	[illegible]	[illegible]
RM	[illegible]	[illegible]	[illegible]
RM	[illegible]	[illegible]	[illegible]
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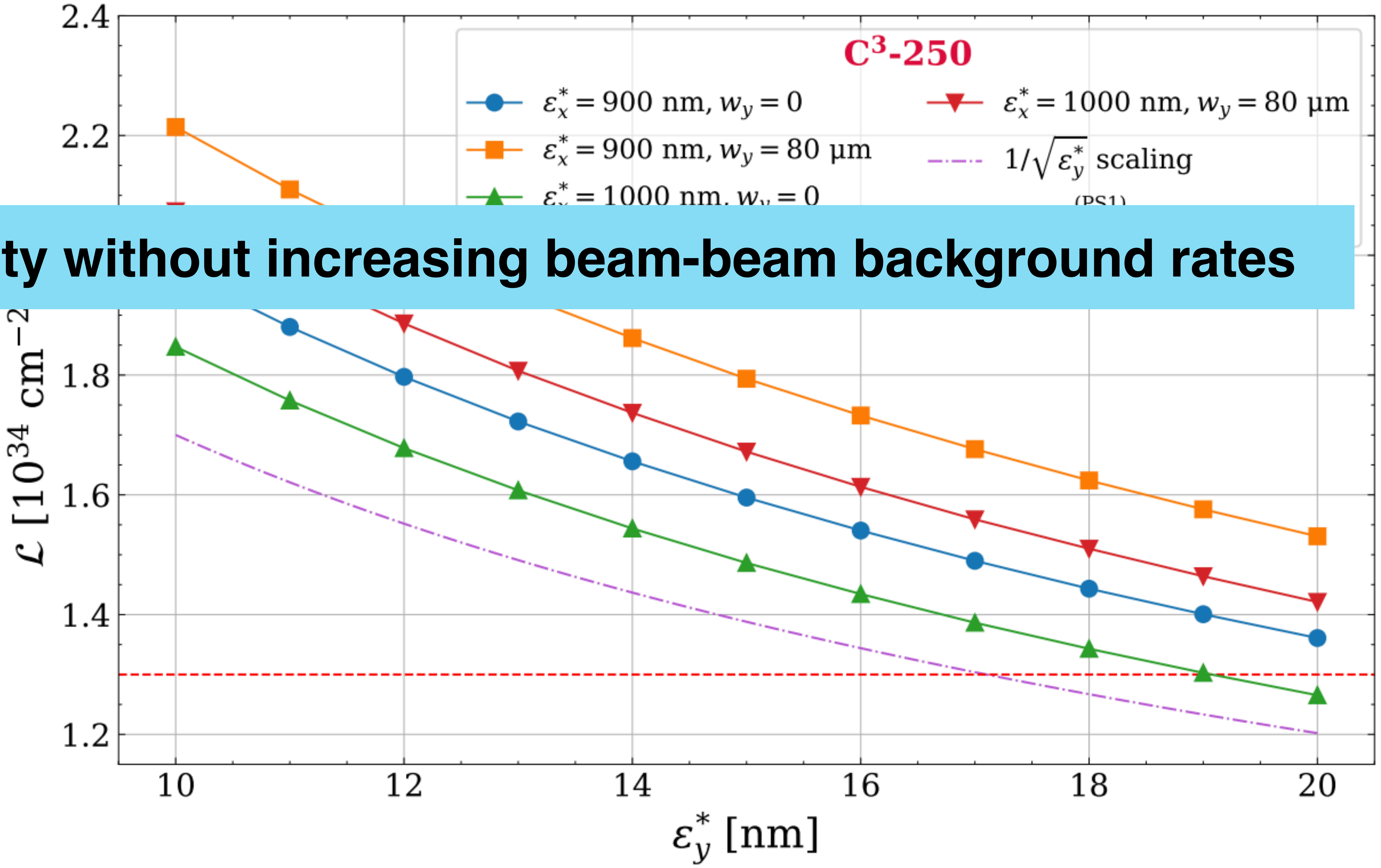
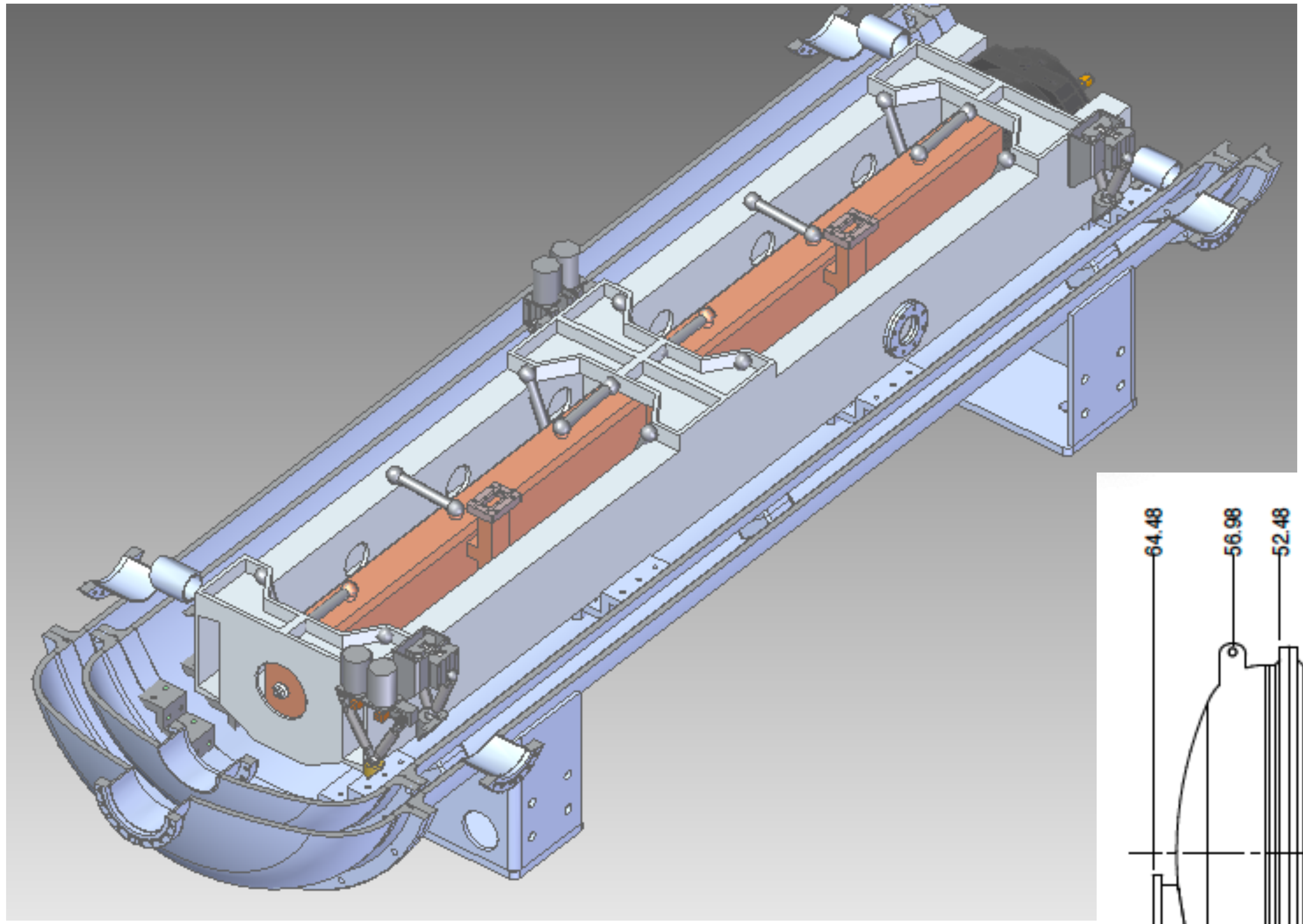


Studies on going to re-evaluate the BIB for the sustainability parameter set

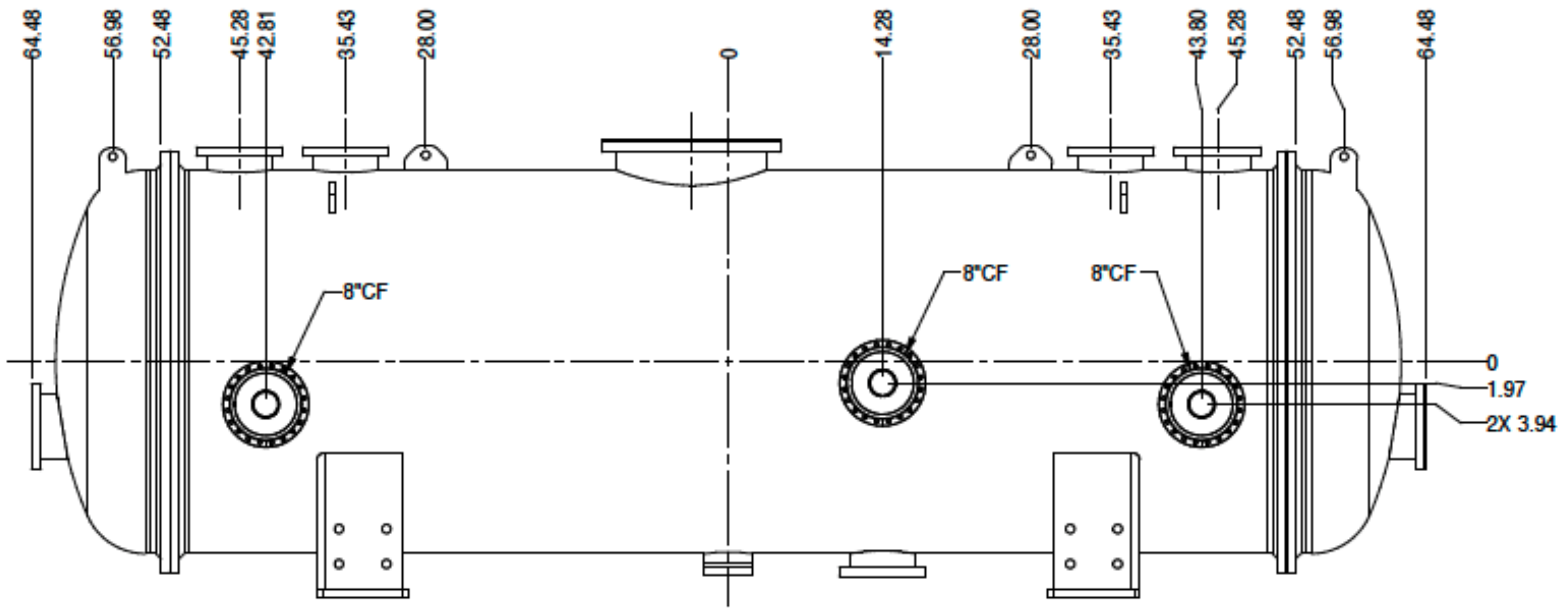
Quarter cryomodule

An important first step towards multi-structure operations

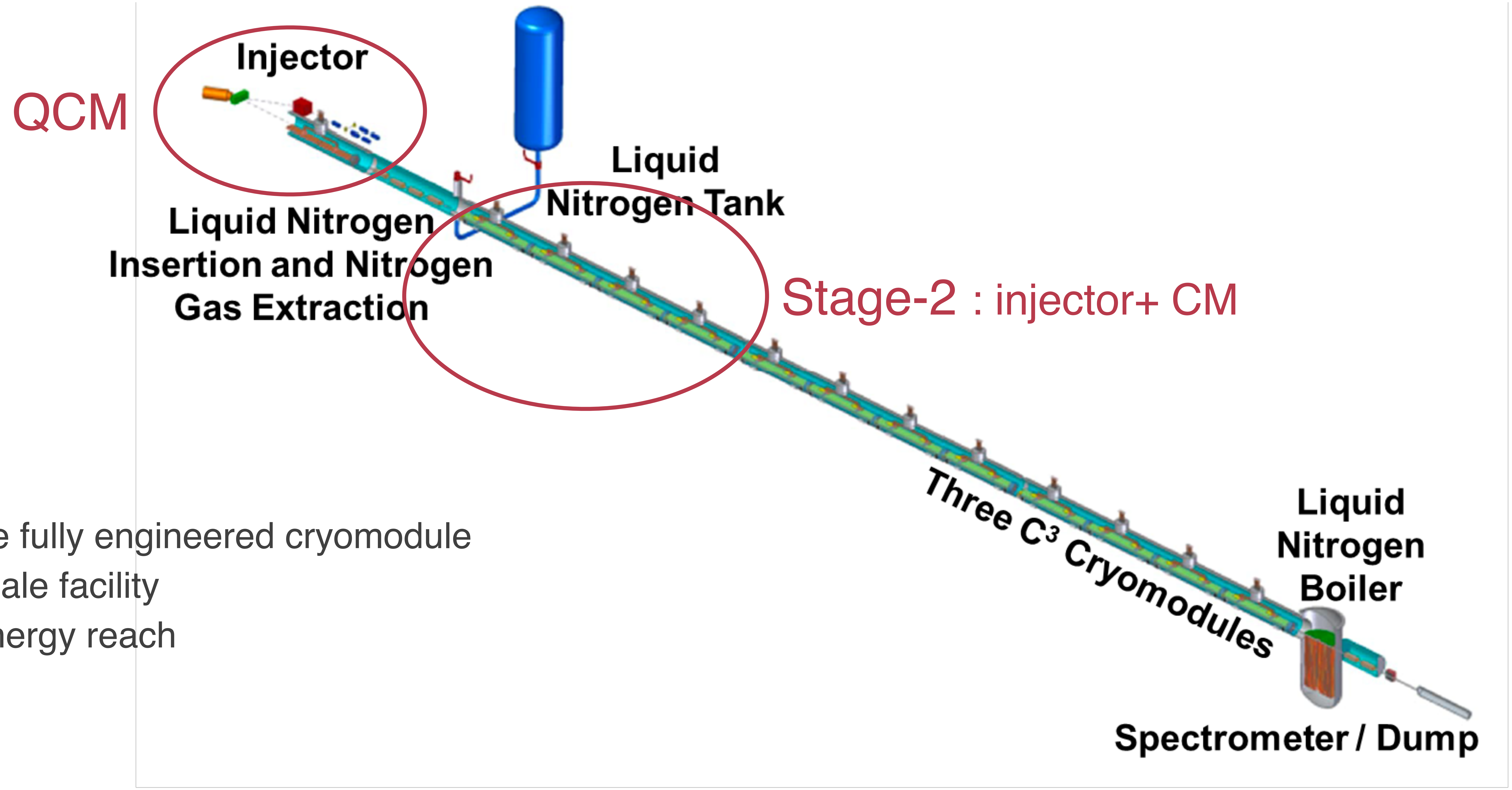


Order placed and expected delivery by Fall **2024**

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



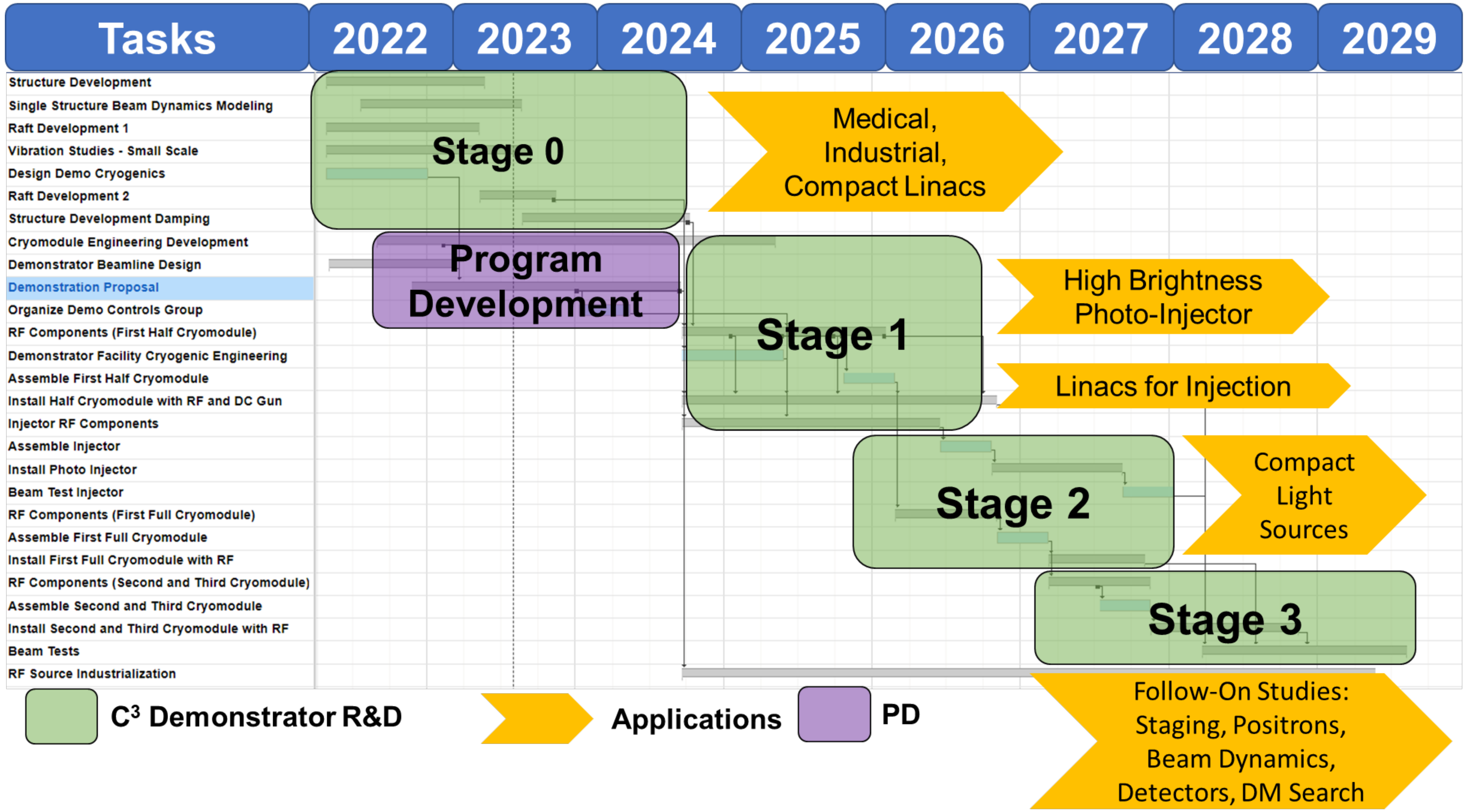
The Complete C³ Demonstrator



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

Demonstration R&D Plan Timeline *

* Technically Limited



Area Recommendation 8 P5 report

Demonstration R&D Plan Timeline *

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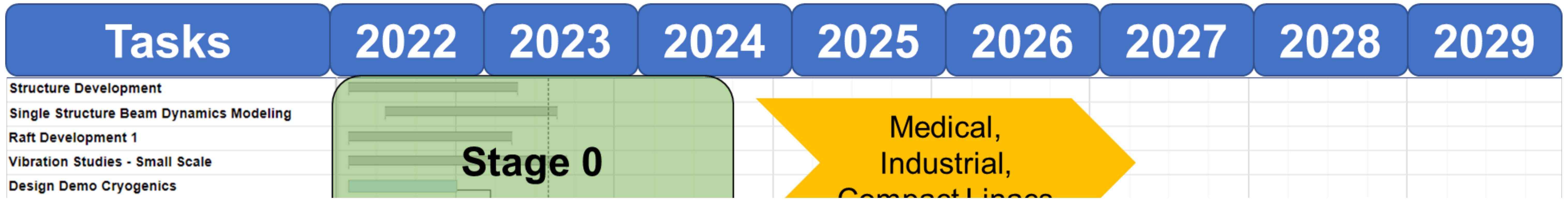

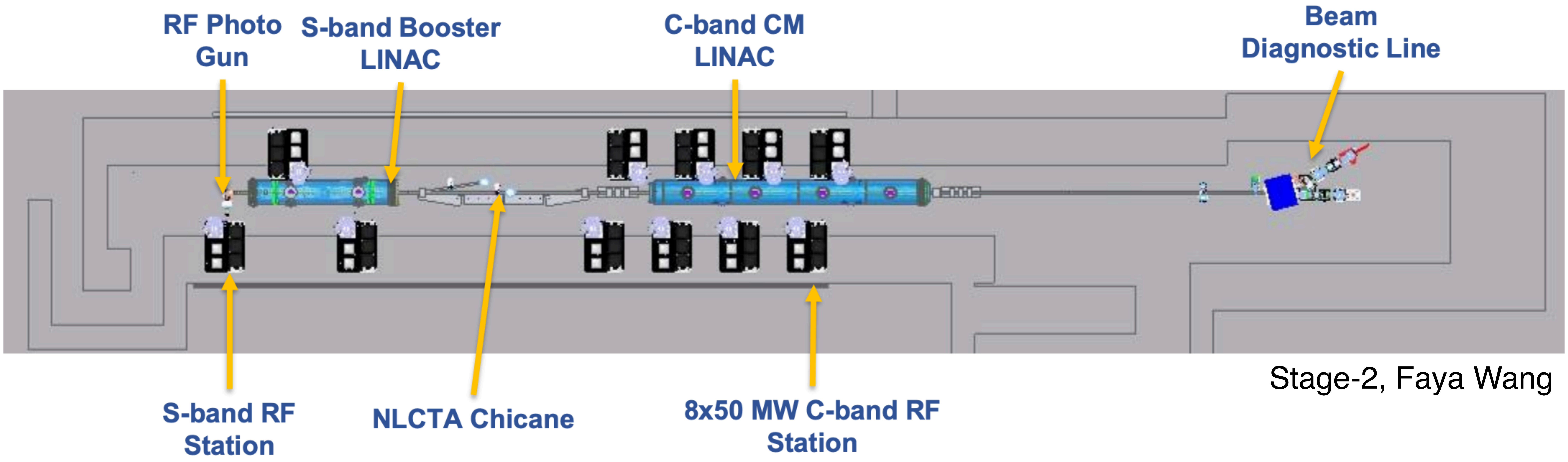

Stage-2, Faya Wang

Demonstration R&D Plan Timeline *

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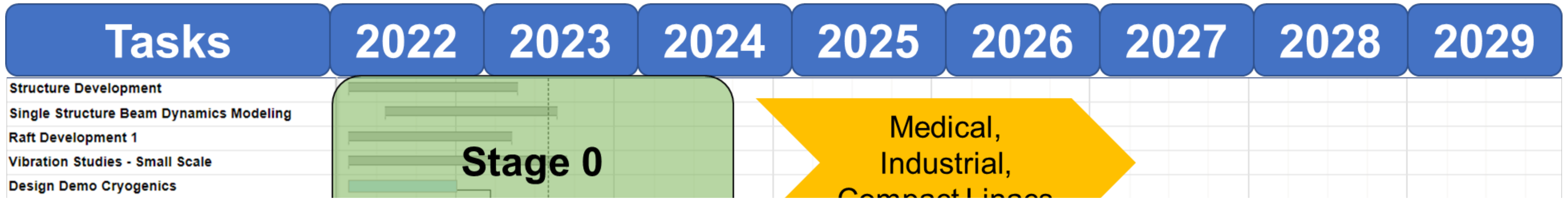

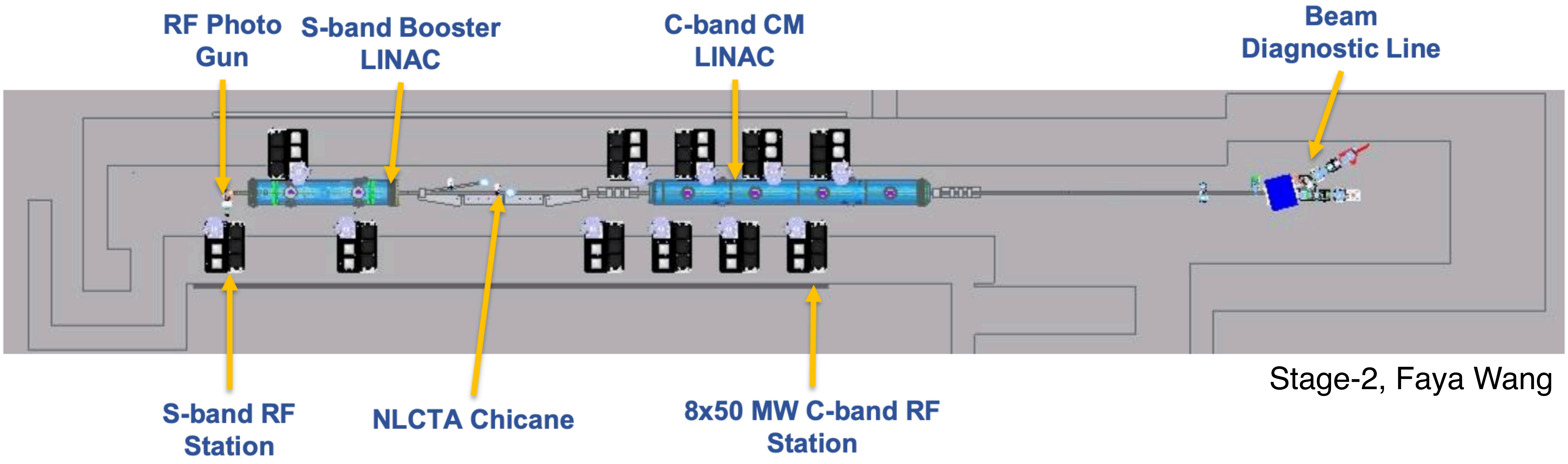

Stage-2, Faya Wang

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

Demonstration R&D Plan Timeline *

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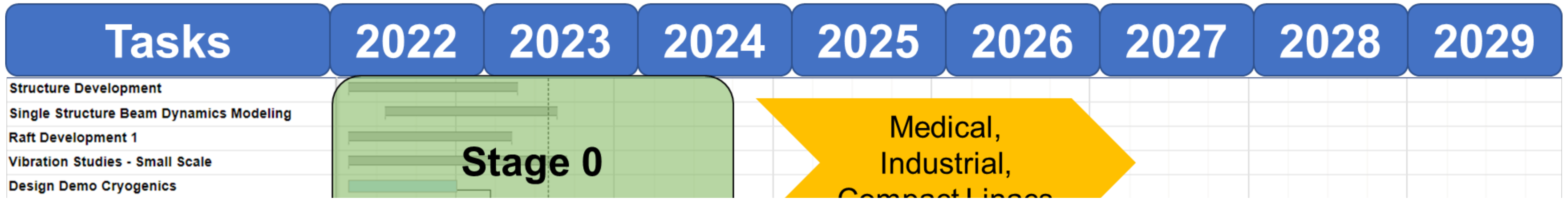

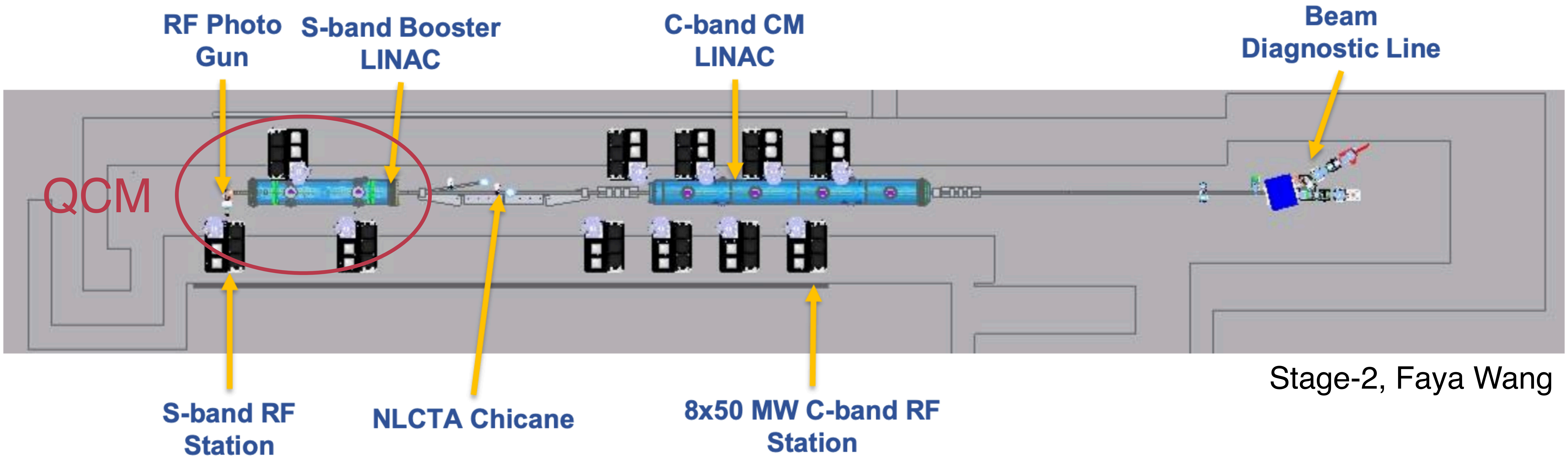

Stage-2, Faya Wang

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

Conclusions & Next steps

- **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!

C³ Acknowledgements

WEBSITE web.slac.stanford.edu/c3/

SLAC-PUB-17661
April 12, 2022

Strategy for Understanding the Higgs Physics:
The Cool Copper Collider

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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

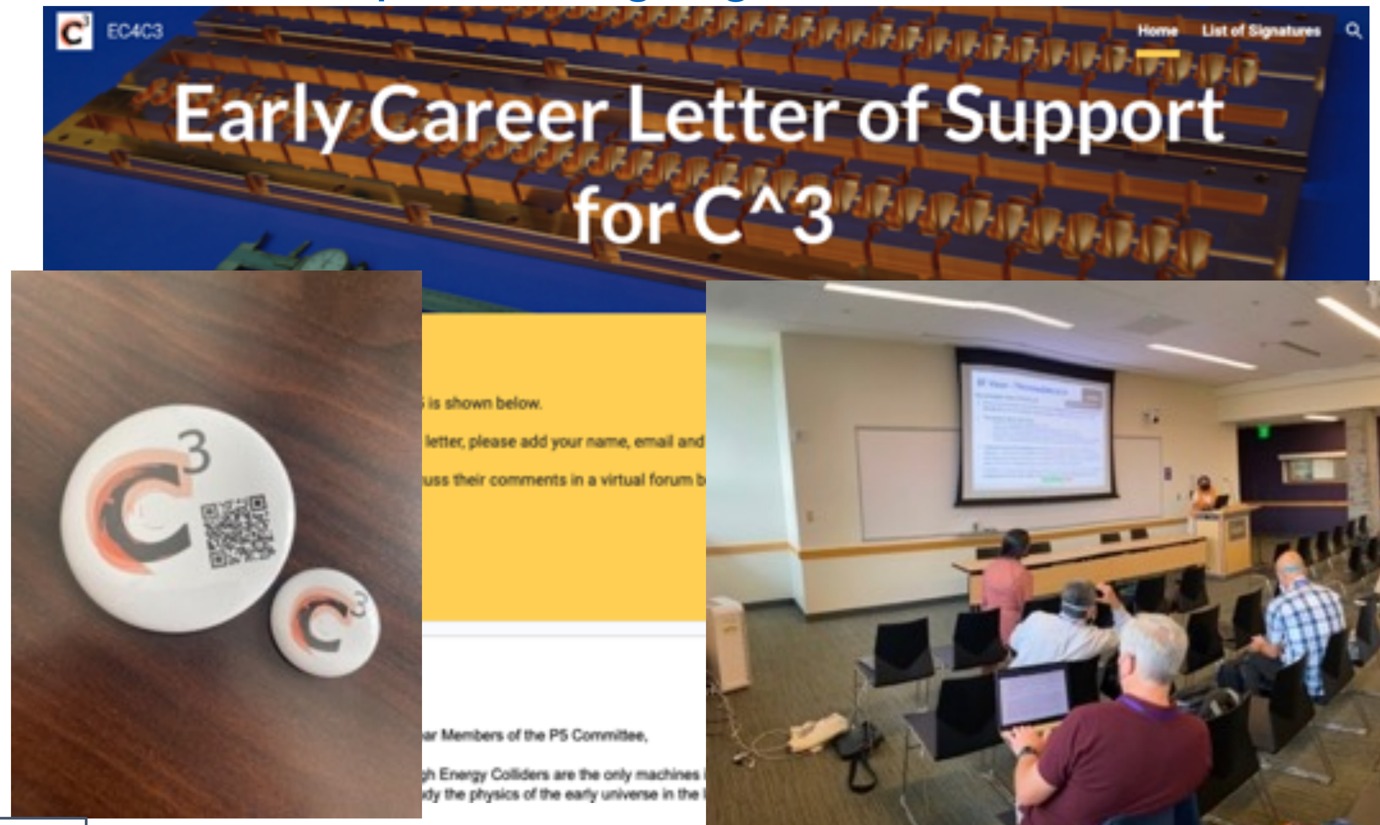
Martin Breidenbach, Brendon Bullard, Emilio Alessandro Nanni, Dimitrios Ntounis, and Caterina Vernieri
PRX Energy **2**, 047001 – Published 26 October 2023

Community Workshops:

Virtual, Fermilab, SLAC, LANL & Cornell University

220 Participants 60 Institutions

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

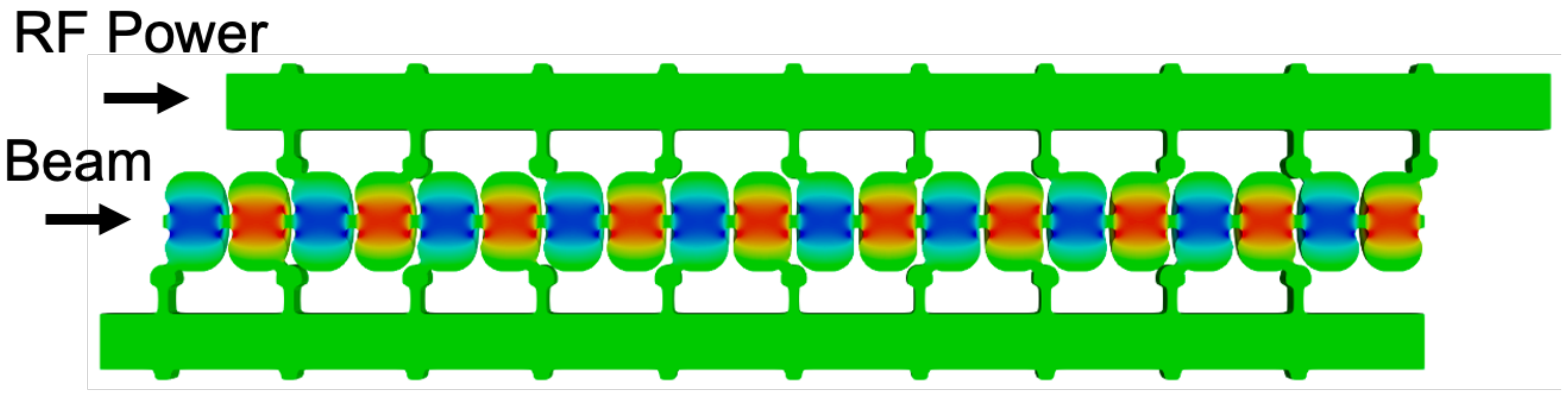


Next Meeting at LCWS July. 12th '24 @ Tokyo Univ.

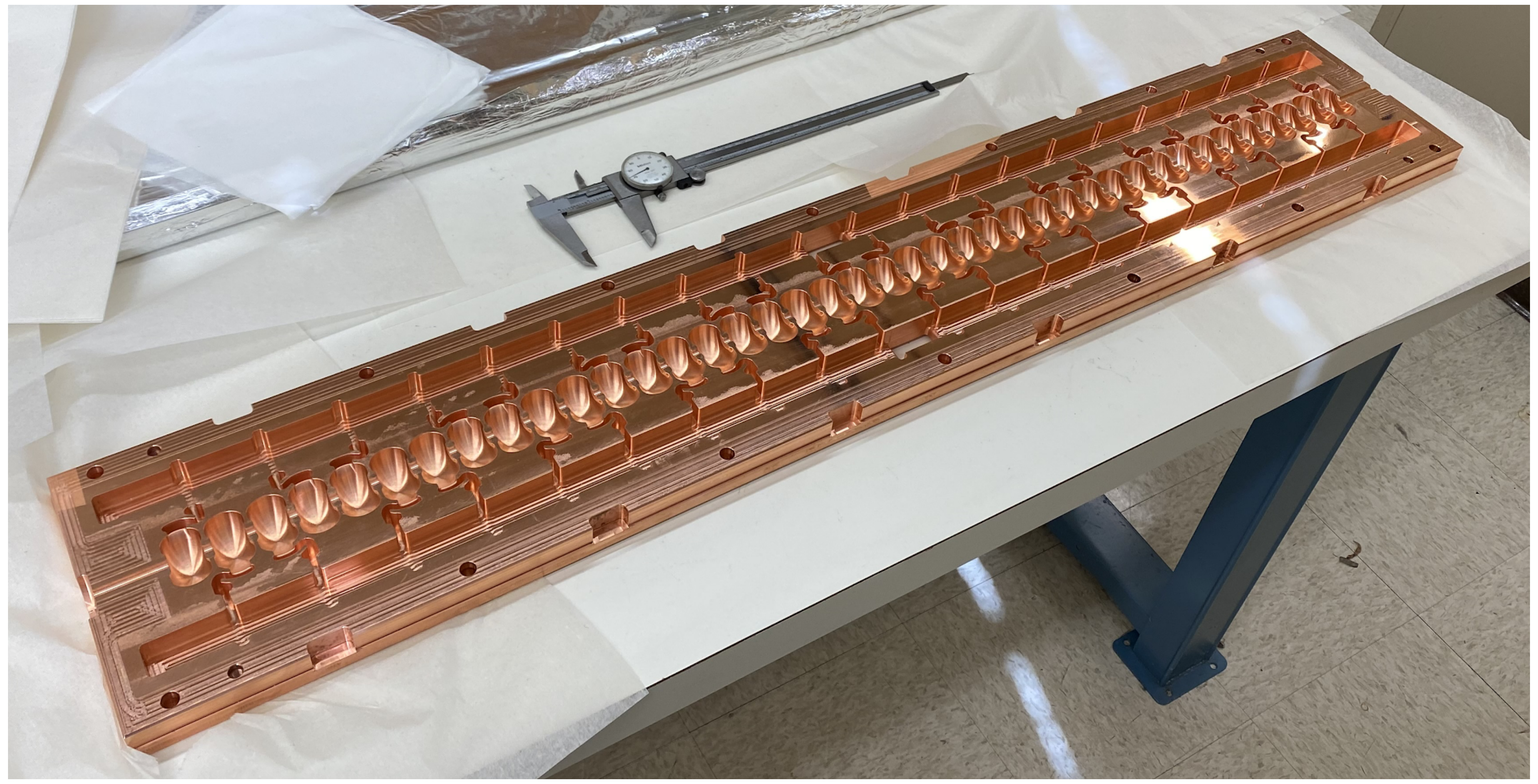
Recap: the Cool Copper technology

C³ 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

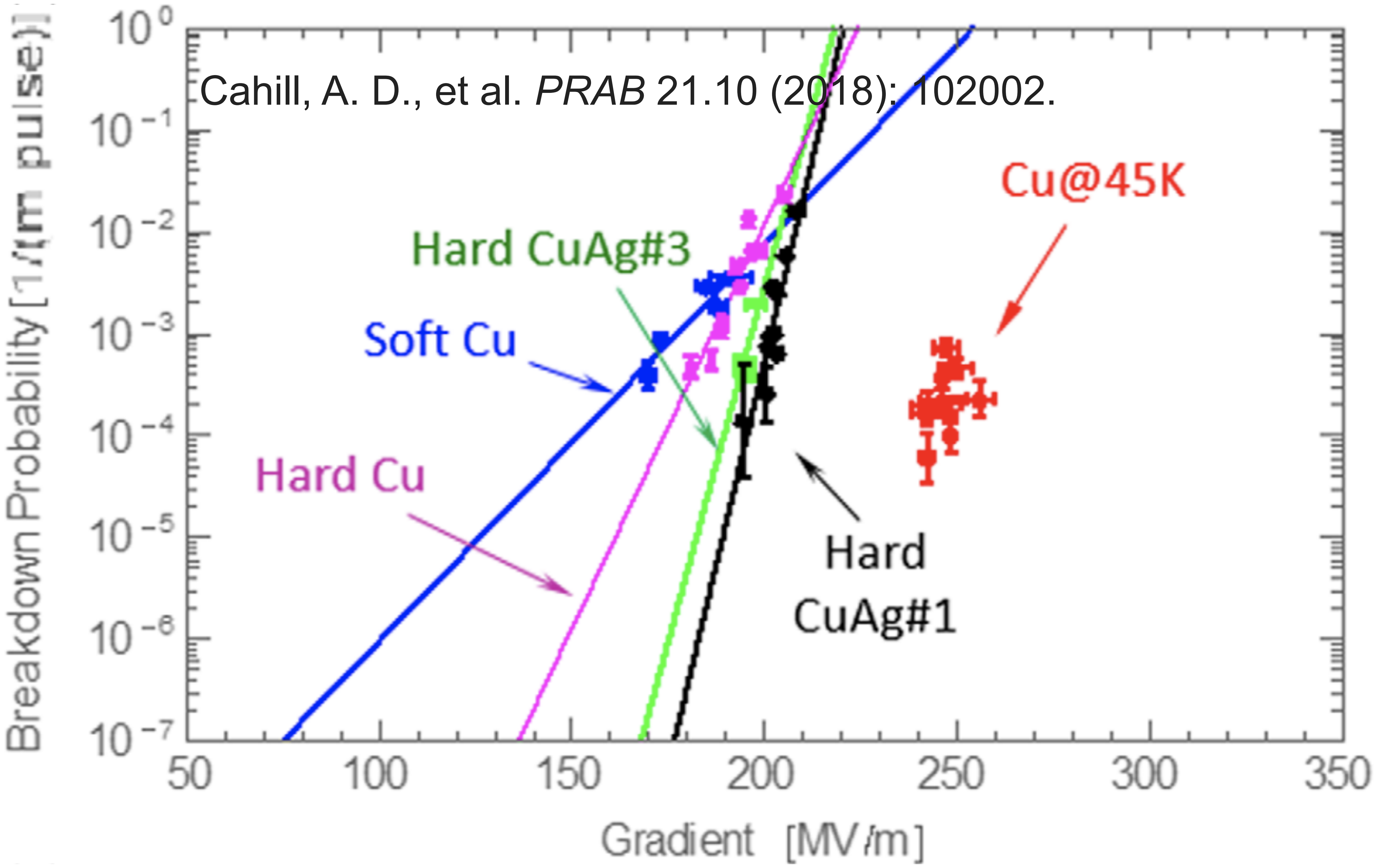


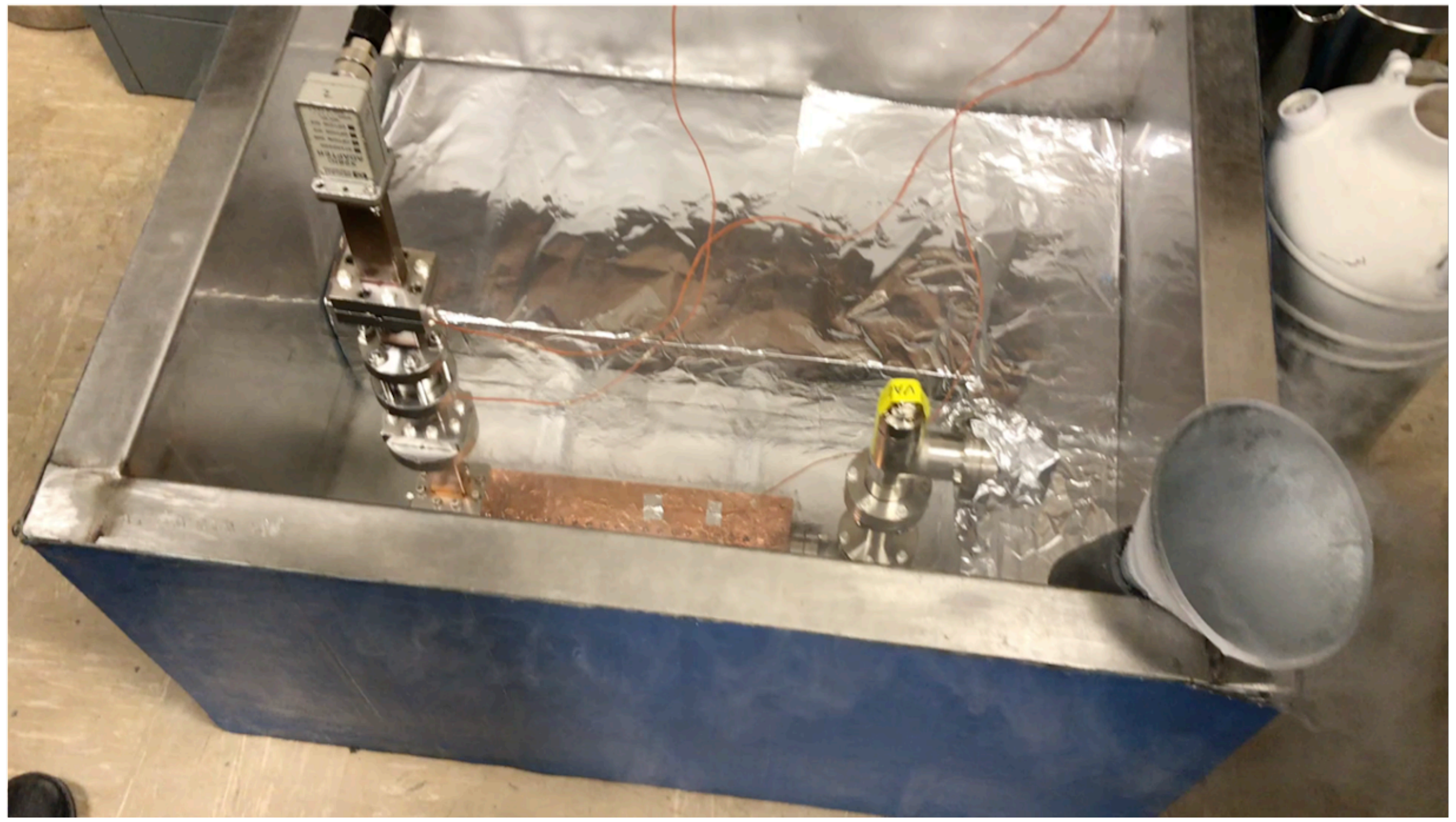
Electric field magnitude for equal power from RF manifold



First C³ structure at SLAC

Why cool?





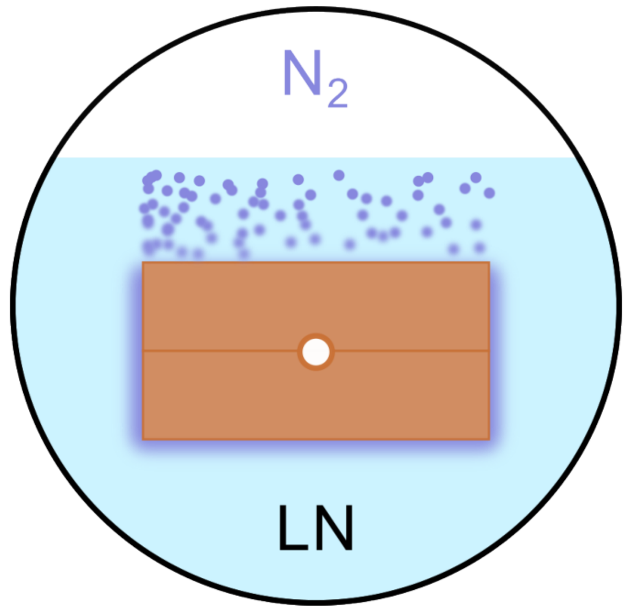
Nasr, et al. *PRAB* 24.9 (2021): 093201.

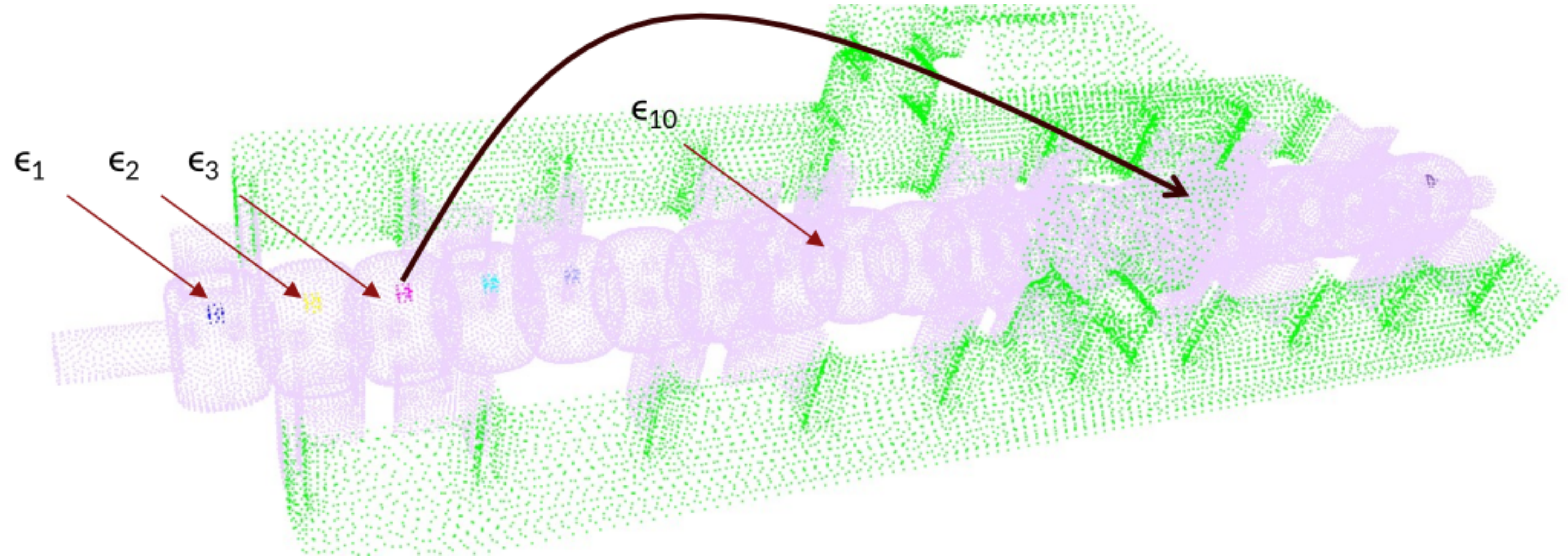
- Cryogenic temperature elevates performance in gradient
  - Increased material strength for gradient
  - Increase electrical conductivity reduces pulsed heating in the material
- Operation at 77 K with liquid nitrogen is simple and practical

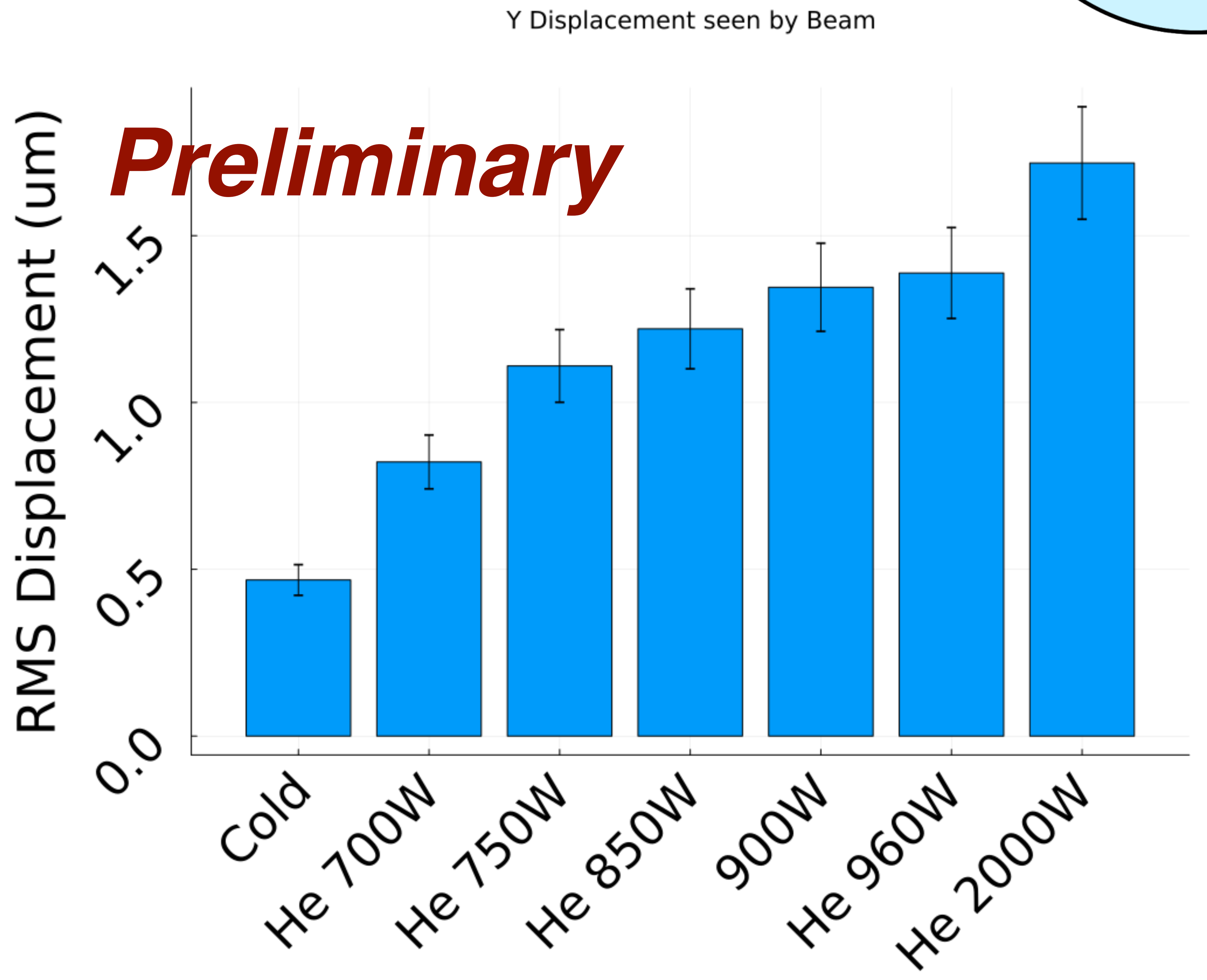
A couple of highlights

More in Ankur's talk

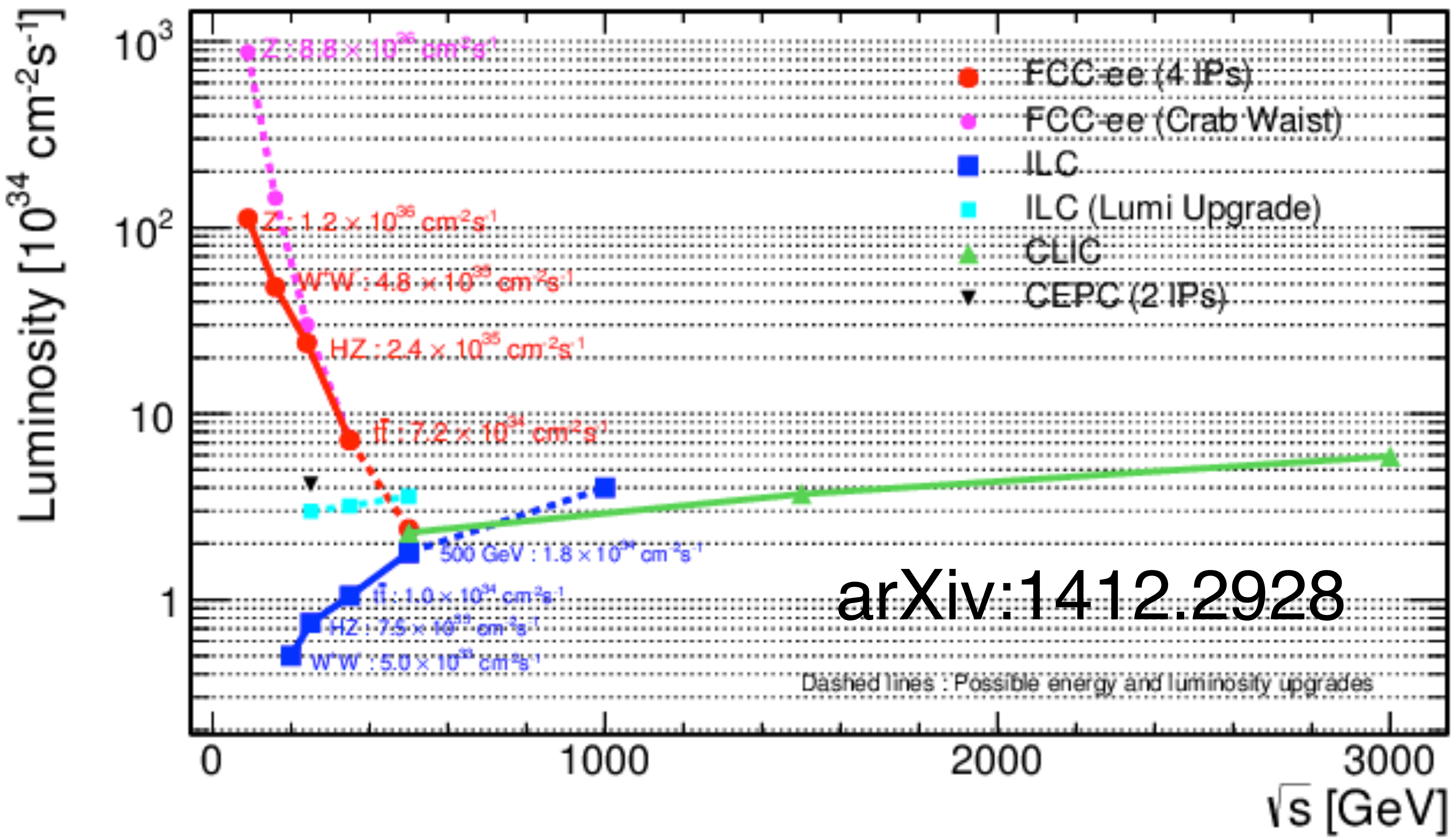
- S-Band injector linac development: low emittance for up to 14 nC bunches while accelerating them at 18 MV/m
  - Targeting Efficient Acceleration of High Charge Bunches
  - S-Band structure assembly and tuning is complete
- Prototype C3 Linac with a resistive heater was used to test vibration within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

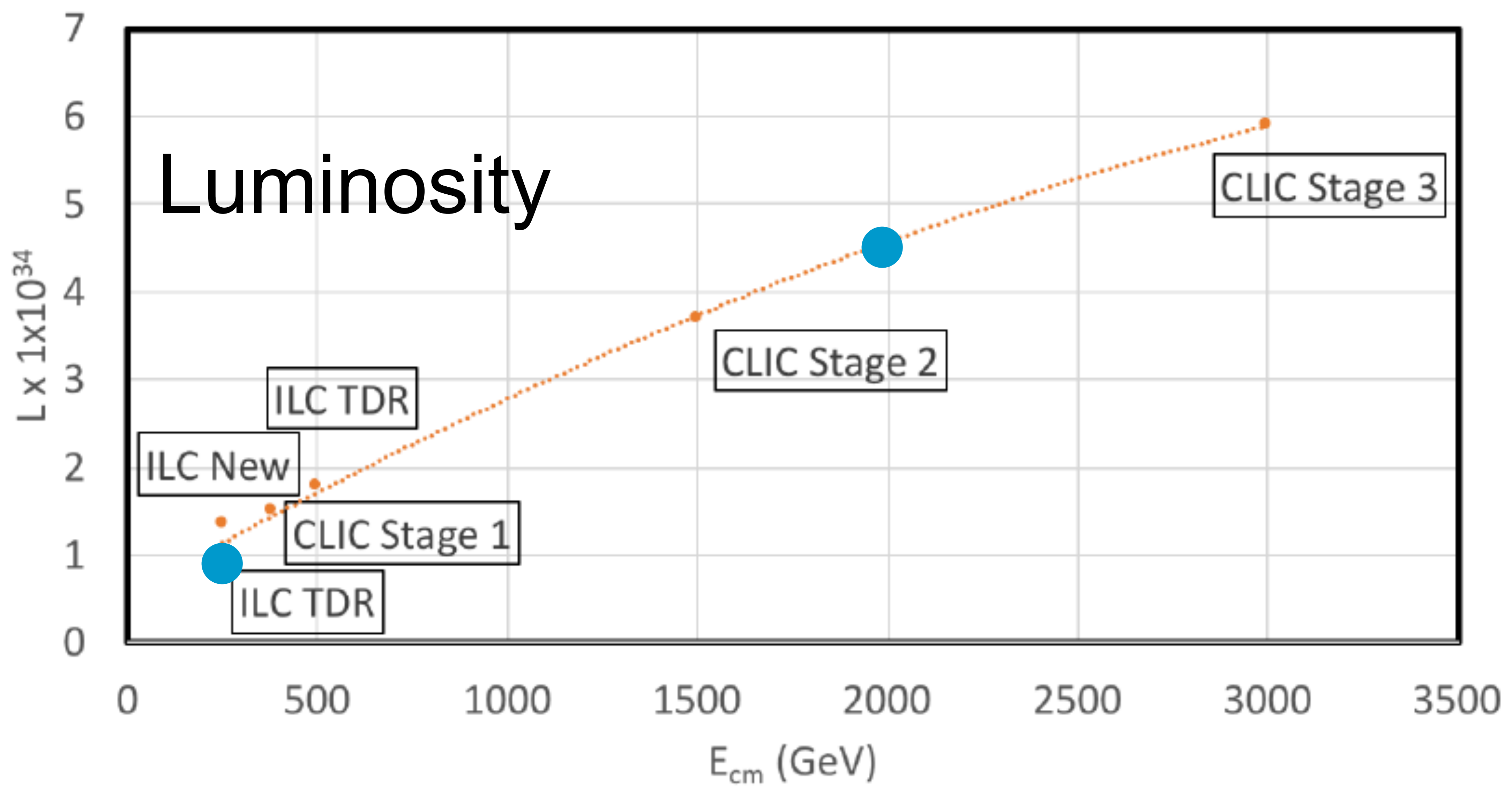


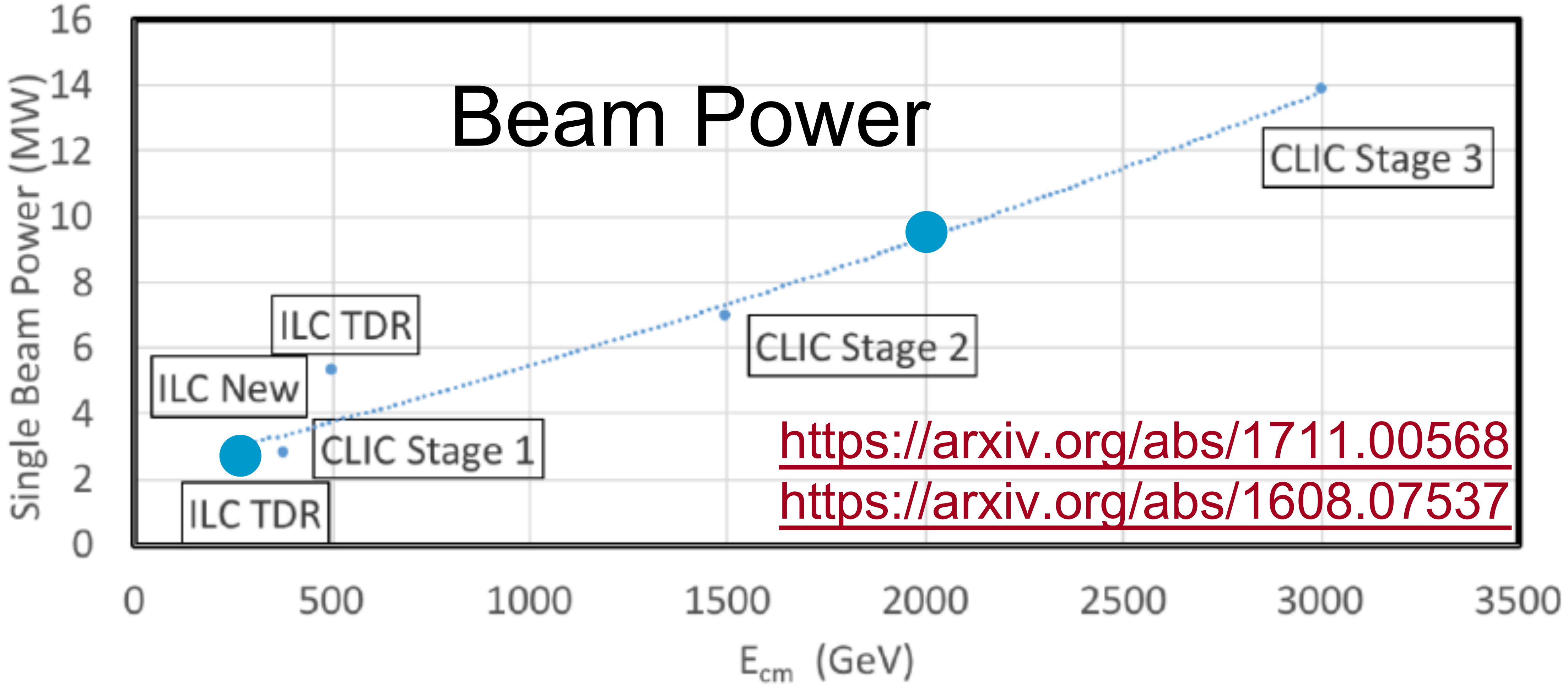




Luminosity optimization



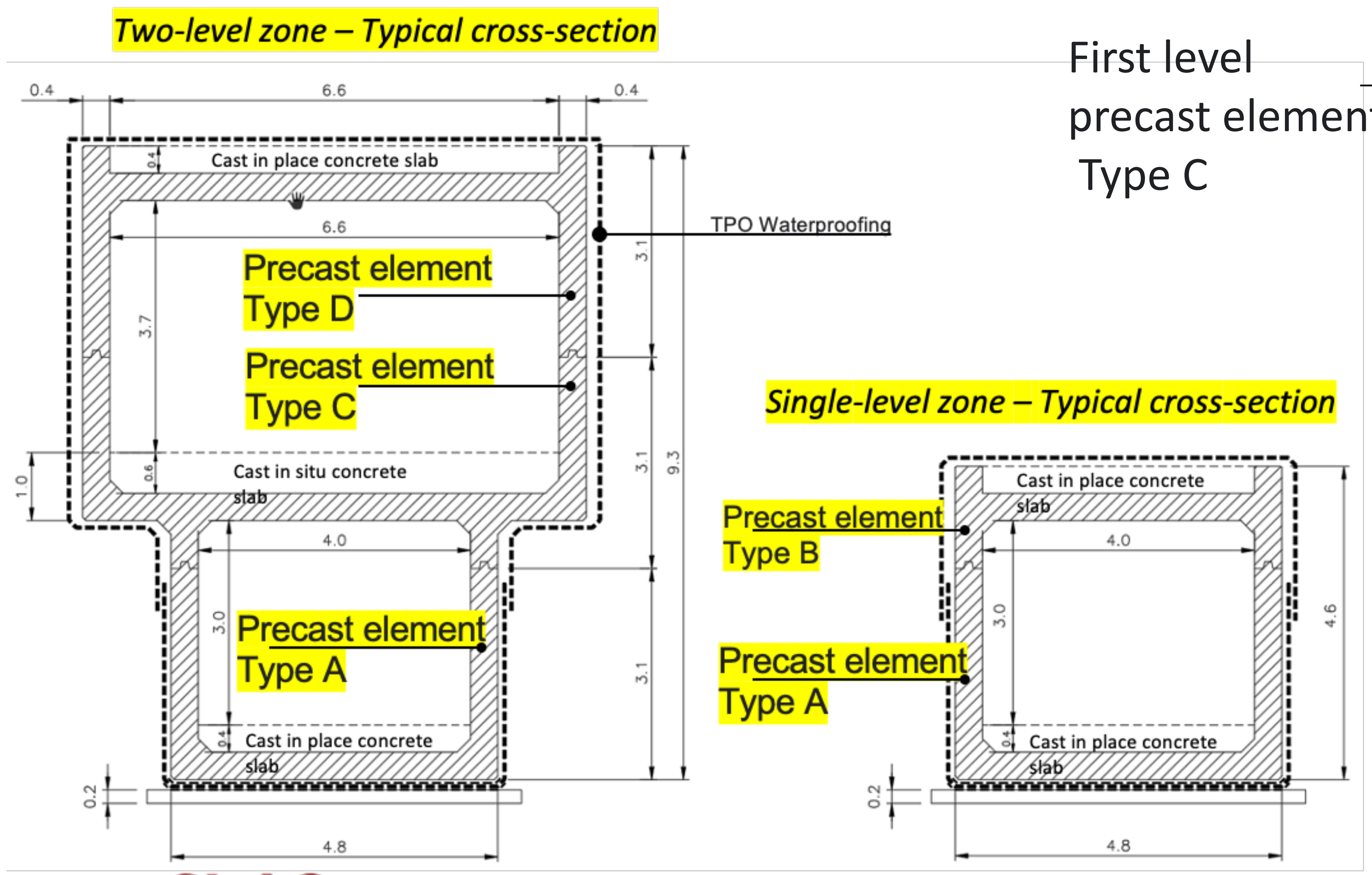




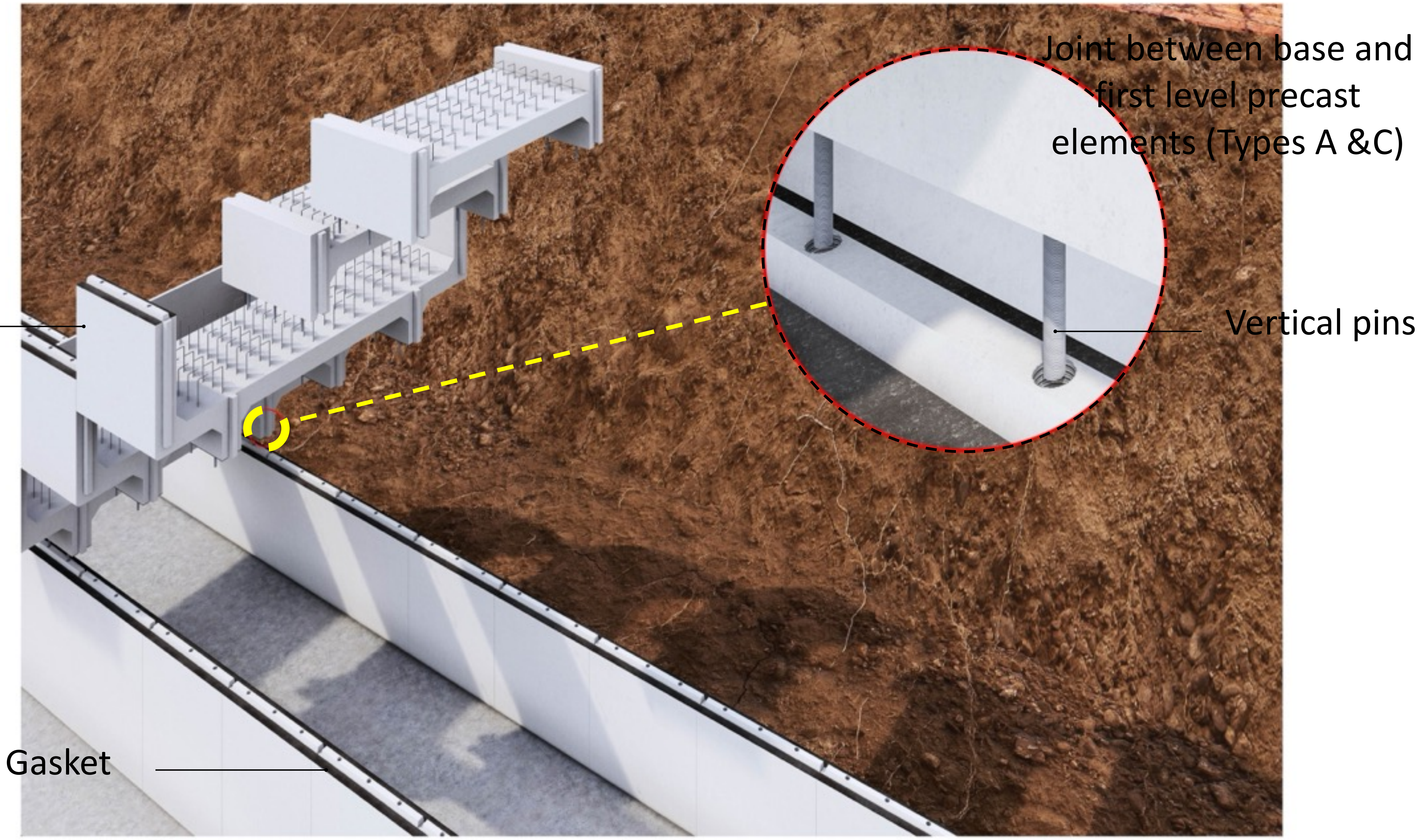
https://arxiv.org/abs/1711.00568
https://arxiv.org/abs/1608.07537

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

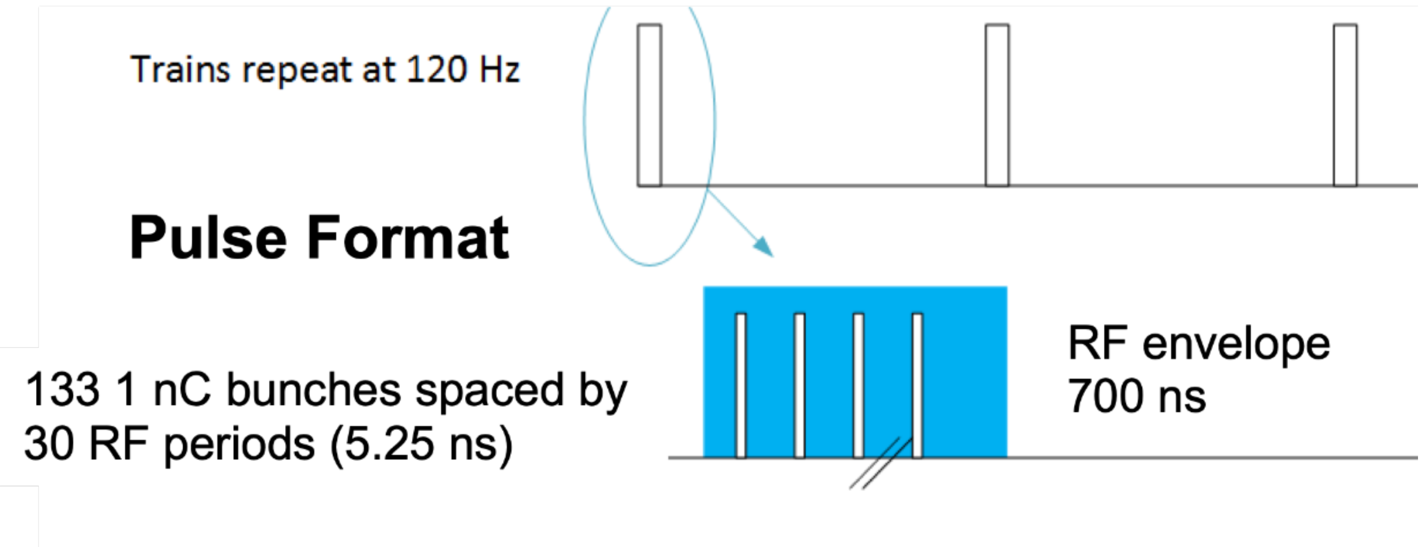


First level precast elements installation



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