Sustainability studies for the Cool Copper Collider

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Special Thanks to Brendon Bullard for Slides

CCTA Workshop
Sept. 1, 2023

arXiv > hep-ex > arXiv:2307.04084

High Energy Physics – Experiment

[Submitted on 9 Jul 2023]

A Sustainability Roadmap for C^3

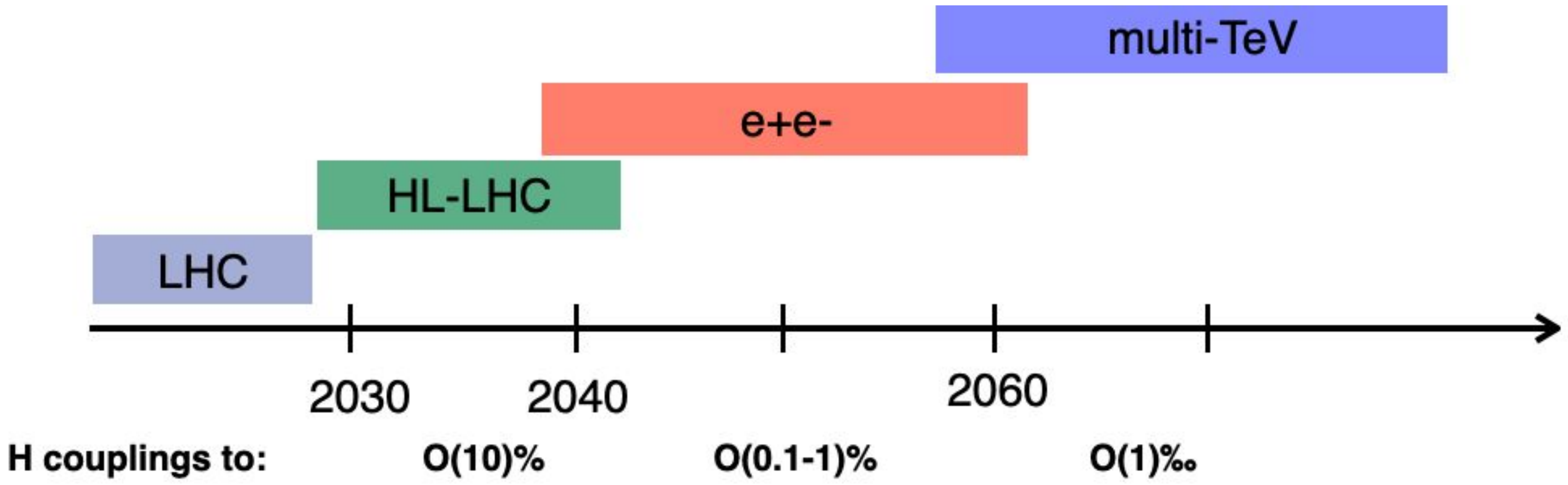
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University

U.S. DEPARTMENT OF ENERGY

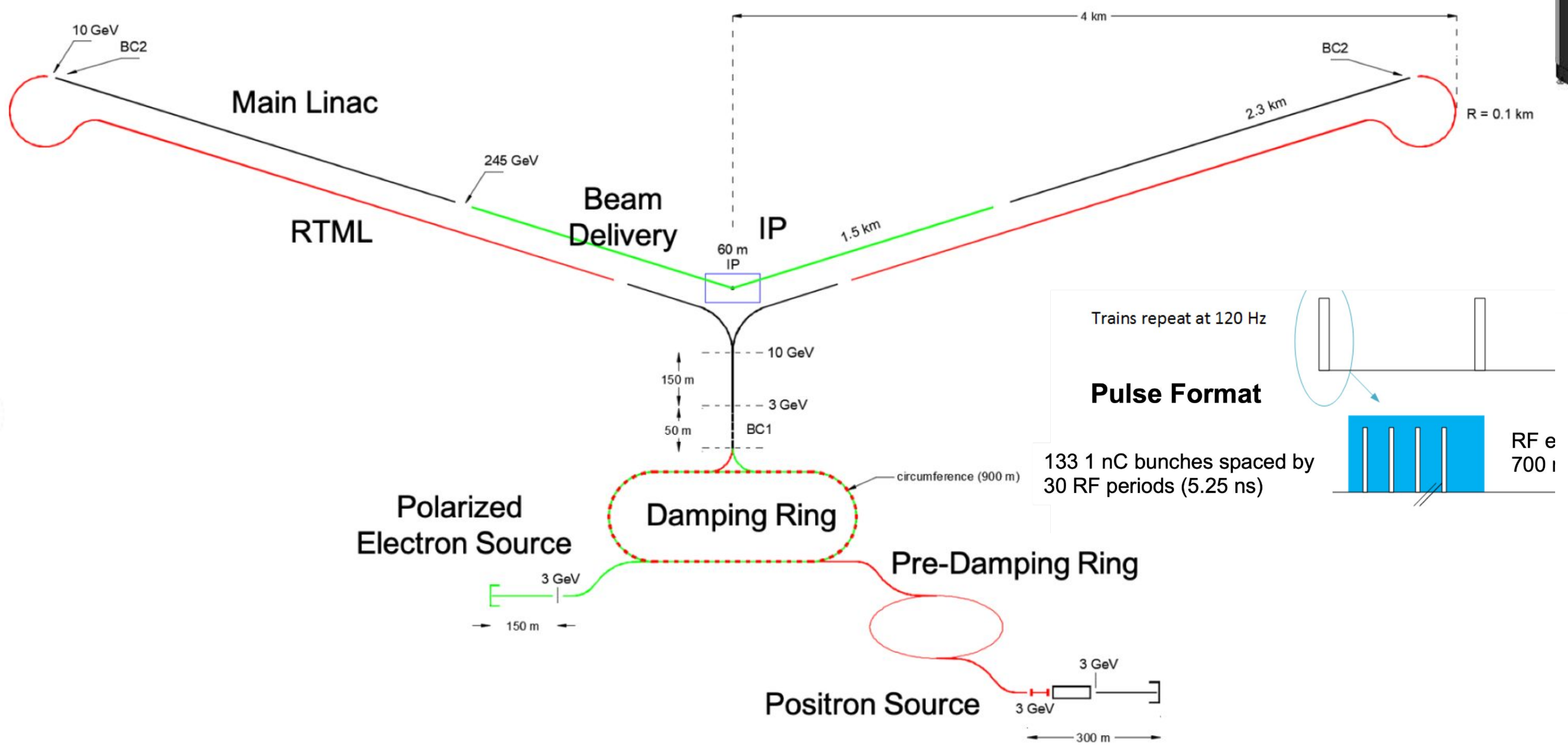
Introduction

- Community consensus that Higgs factory should be the next major collider after HL-LHC
- The Cool Copper Collider (C^3) is a linear e^+e^- collider concept with a compact 7-8 km footprint
  - Enabled by normal conducting copper RF cavities, low surface fields/breakdown rates → **high gradient!**
- Climate change poses significant threat to humanity and health of Earth's ecosystems
  - How can we continue to build and operate large colliders sustainably?
  - Evaluate emissions due to construction and operation, compare to other Higgs factory options on the basis of physics reach

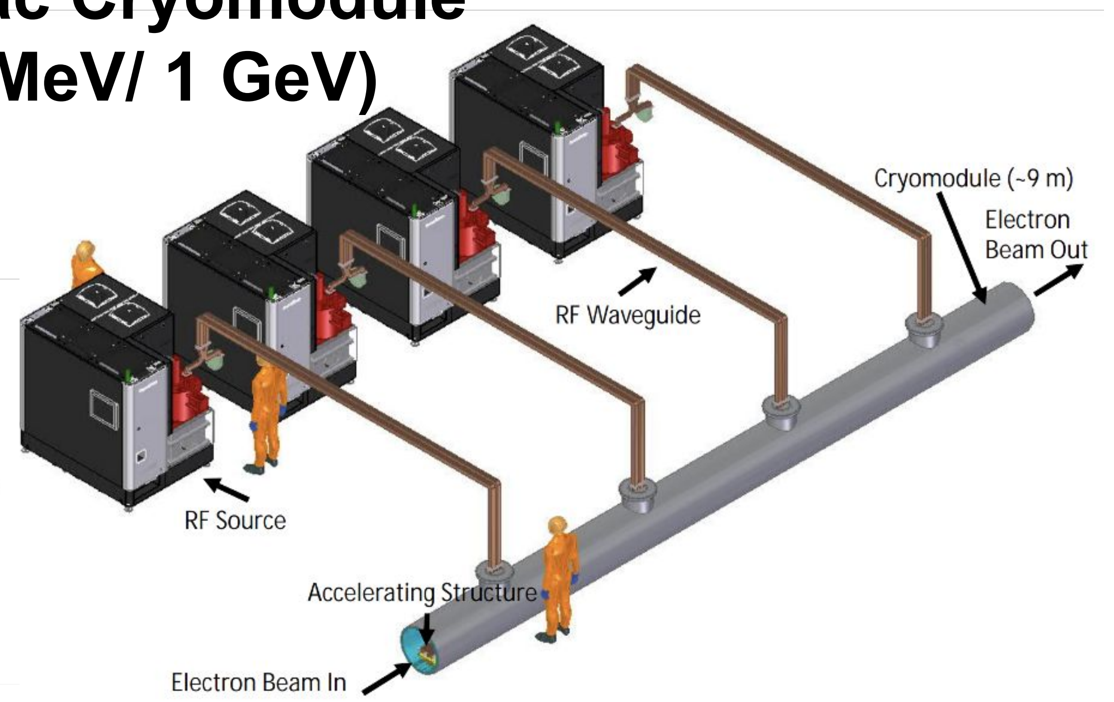


[The Energy Frontier 2021 Snowmass Report]

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



C^3 Main Linac Cryomodule 9 m (600 MeV/ 1 GeV)



Comparison of Parameters

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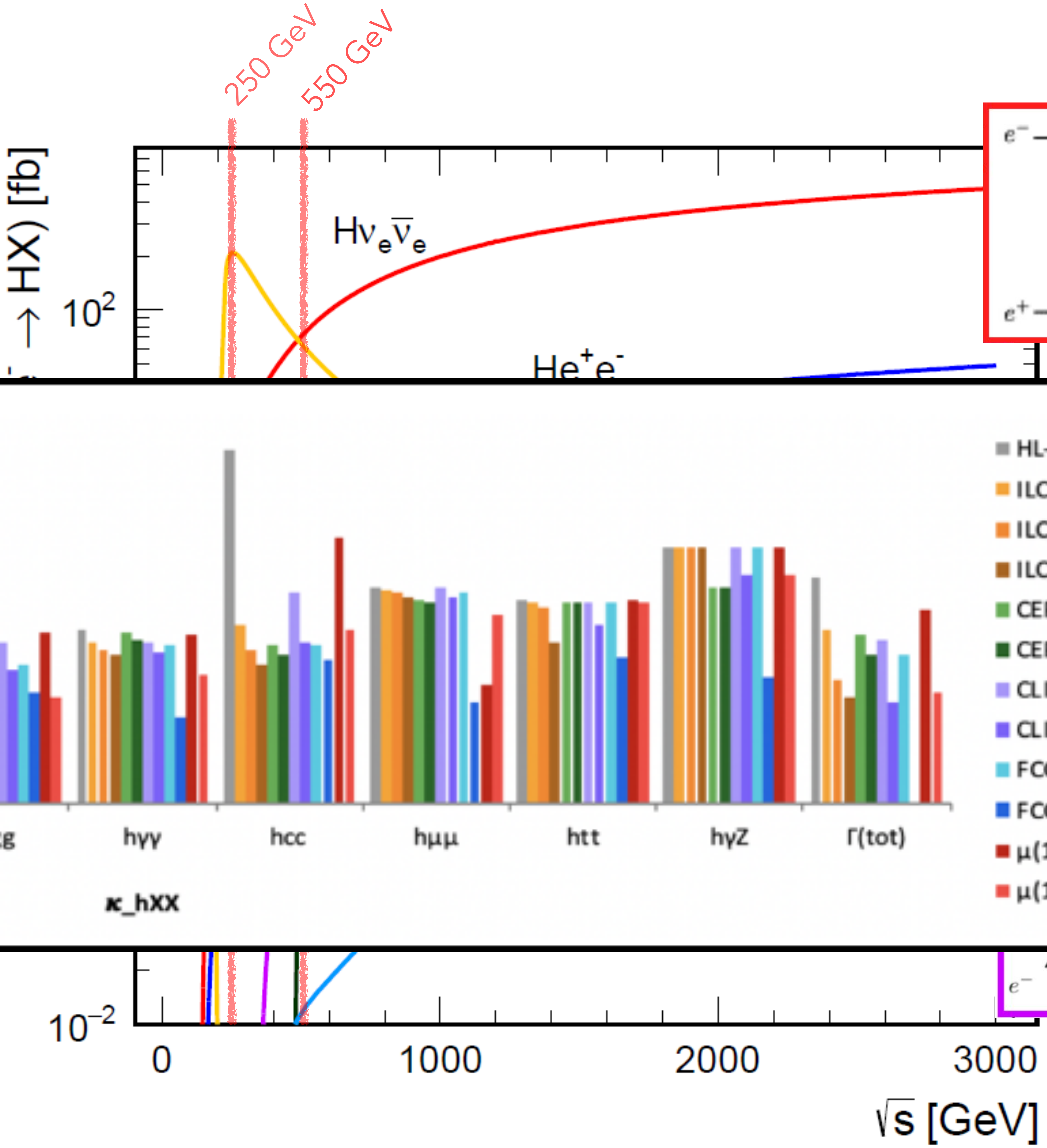
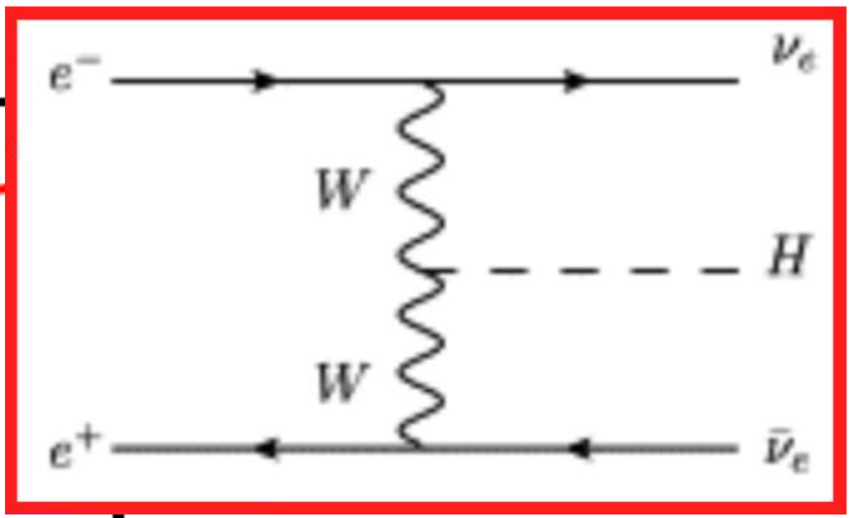
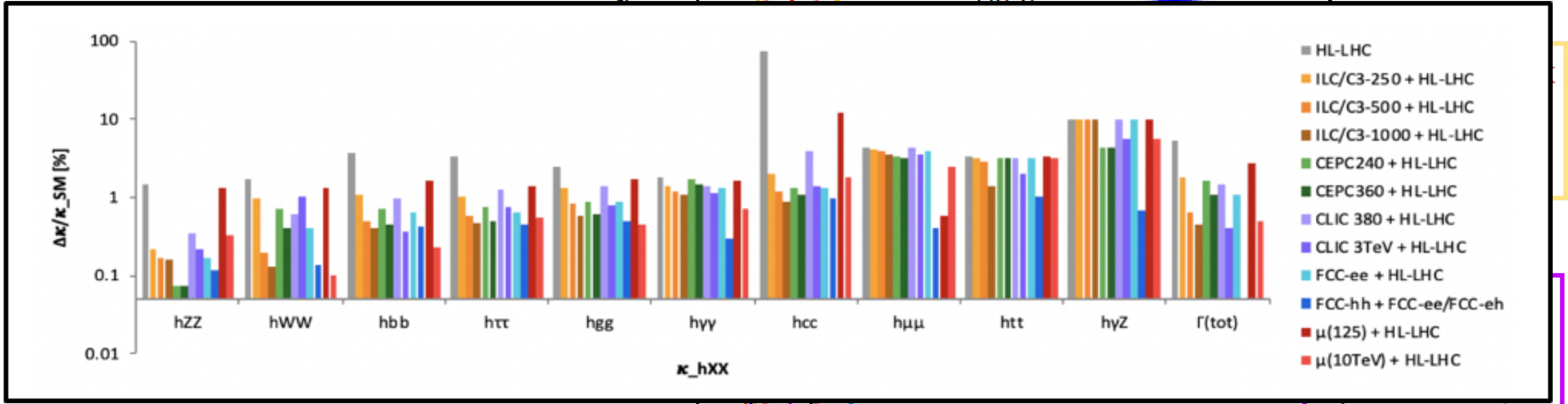
Collider	NLC	CLIC	ILC	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
Luminosity [x10^{34}]	0.6	1.5	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Length [km]	23.8	11.4	20.5 (31)	8	8
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	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
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014
Site Power [MW]	121	168	125	$\sim$150	$\sim$175
Design Maturity	CDR	CDR	TDR	pre-CDR	pre-CDR

Physics reach

All e+e- Higgs factories can operate in the 250 GeV ZH mode







Snowmass 2021 energy frontier report

Sensitivity comparison for each collider concept

- Taking into account effects of luminosity and polarization to evaluate measurement sensitivity:
  - C³/ILC-250 performs similarly to CLIC-380, C³/ILC-550 outperforms CLIC-380
  - C³/ILC-550 matches or exceeds physics reach of FCC in all coupling sensitivity metrics
  - **Compare colliders based on their total carbon footprint - weighted by precision of measurement**

		HL-LHC +				
Relative Precision (%)	HL-LHC	CLIC-380	ILC-250/C^3-250	ILC-500/C^3-550	FCC 240/360	CEPC-240/360
hZZ	1.5	0.34	0.22	0.17	0.17	0.072
hWW	1.7	0.62	0.98	0.20	0.41	0.41
$hb\bar{b}$	3.7	0.98	1.06	0.50	0.64	0.44
$h\tau^+\tau^-$	3.4	1.26	1.03	0.58	0.66	0.49
hgg	2.5	1.36	1.32	0.82	0.89	0.61
$hc\bar{c}$	-	3.95	1.95	1.22	1.3	1.1
$h\gamma\gamma$	1.8	1.37	1.36	1.22	1.3	1.5
$h\gamma Z$	9.8	10.26	10.2	10.2	10	4.17
$h\mu^+\mu^-$	4.3	4.36	4.14	3.9	3.9	3.2
$ht\bar{t}$	3.4	3.14	3.12	2.82/1.41	3.1	3.1
hhh	0.5	0.50	0.49	0.20	0.33	-
Γ_{tot}	5.3	1.44	1.8	0.63	1.1	1.1
Weighted average	-	0.94	0.86	0.45	0.59	0.49

$$\left\langle \frac{\delta\kappa}{\kappa} \right\rangle = \frac{\sum_i w_i \left(\frac{\delta\kappa}{\kappa}\right)_i}{\sum_i w_i}$$

$$w = \frac{\left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC}} - \left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC+HF}}}{\left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC+HF}}}$$

Snowmass Higgs physics topical group report

Tunnel construction for FCC-ee

- Snowmass climate impacts report analyzes FCC construction using bottom-up and top-down approaches
  - Only takes into account main tunnel (excludes access shafts, experimental halls, etc.)

Bottom-up approach

Driven by manufacture of concrete

FCC inner/outer diameter 5.5/6.5m

Concrete is 15% cement, which releases 1 ton CO_2 per ton

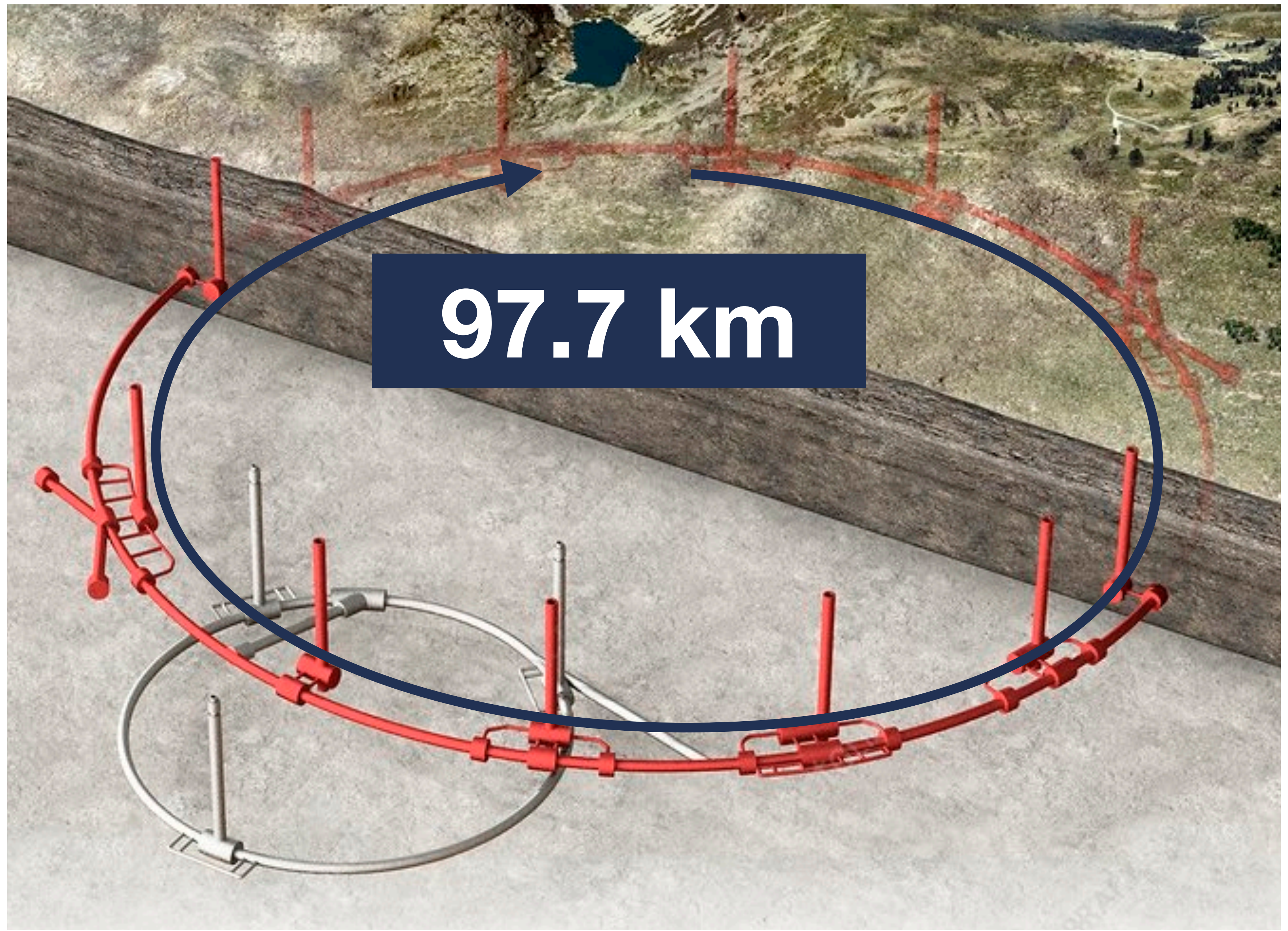
237 kton CO_2 (for 7 mil m^3 spoil, concrete density 1.72 ton/m^3)

Top-down approach

Includes secondary emissions (e.g. construction machinery)

Rough estimates of 5-10k kg CO_2 per meter of tunnel length

With 5k kg CO_2/m, yields **500 kton CO_2**

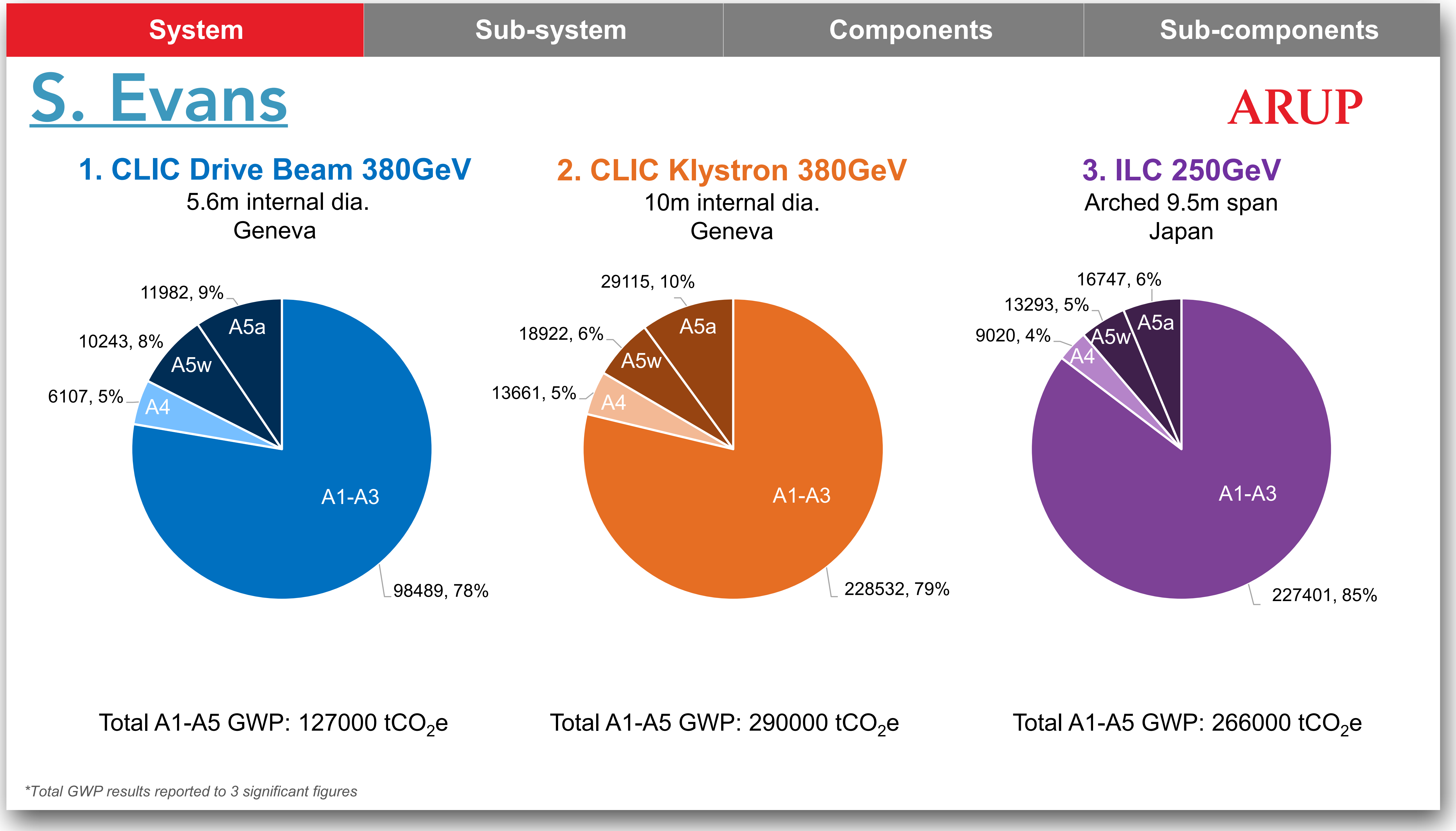


More recent update on FCC civil engineering (L. Broomiley)

Roughly factor of 2 difference between base material emissions and secondaries

Collider project inputs

- ARUP analysis indicates 80% of construction emissions arise from materials (A1-A3), remaining from material transport and construction process
  - More thorough than Snowmass report - rely on it for inputs for other Higgs factory parameters!
  - Approximate global warming potential (GWP) for tunnels ~6 tn/m for CLIC/ILC, apply for circular collider concepts



Project	Main tunnel length (km)	GWP (tCO_2e)		
		Main tunnel	+ Other	+ A4,A5
FCC	90.6	*545*	*700 (+30%)*	*875 (+25%)*
CEPC	100	*600*	*780 (+30%)*	*975 (+25%)*
ILC	13	80	200	270
CLIC	11	70	105	125

Design of additional tunnels (shafts, klystron gallery, caverns) will be used to improve rough +30/+25% estimates

Thanks to Steinar Stapnes for helpful discussions and feedback!

C^3 Excavation models

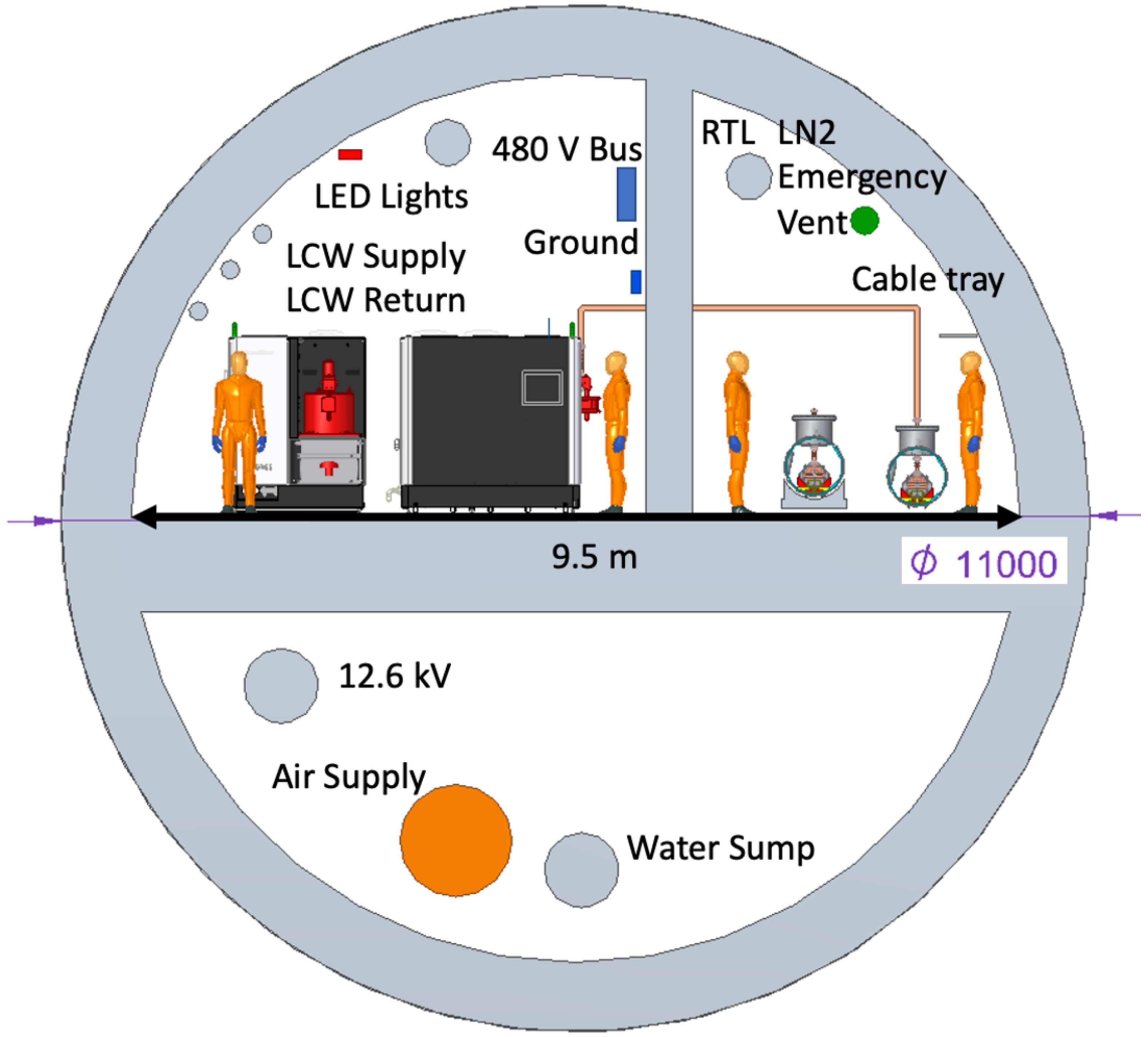
Bored tunnel

Total of 600k m^3 total excavation, **225k m^3 concrete**

- 200k m^3 of excavation comes from tunnel volume, *concretes include all site requirements!*

Releases 58 kton CO_2 from concrete

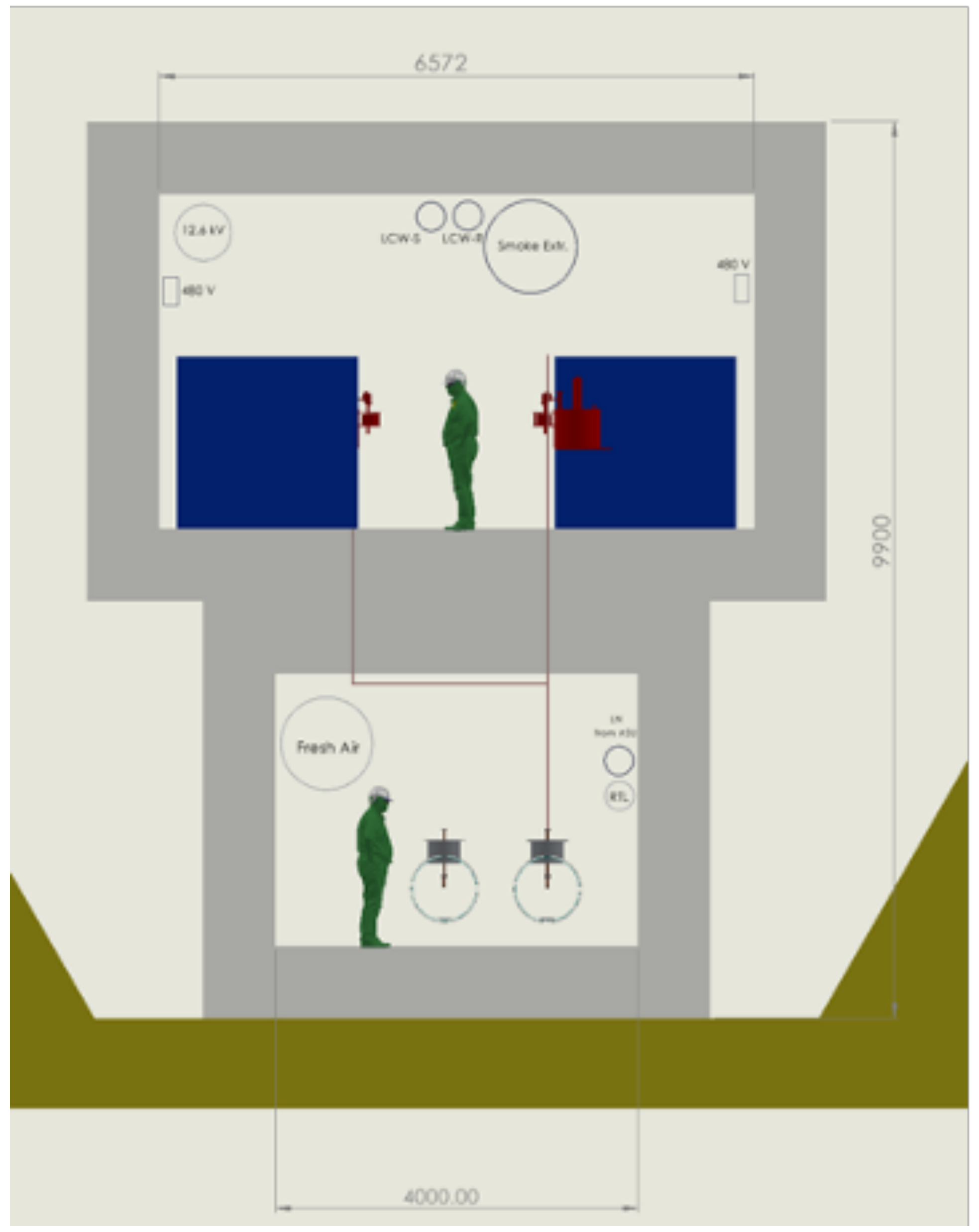
Double it to account for top-down vs. bottom-up **(120 kton CO_2)**



Cut and cover

Preferred option for reduced construction costs and emissions (but not required)

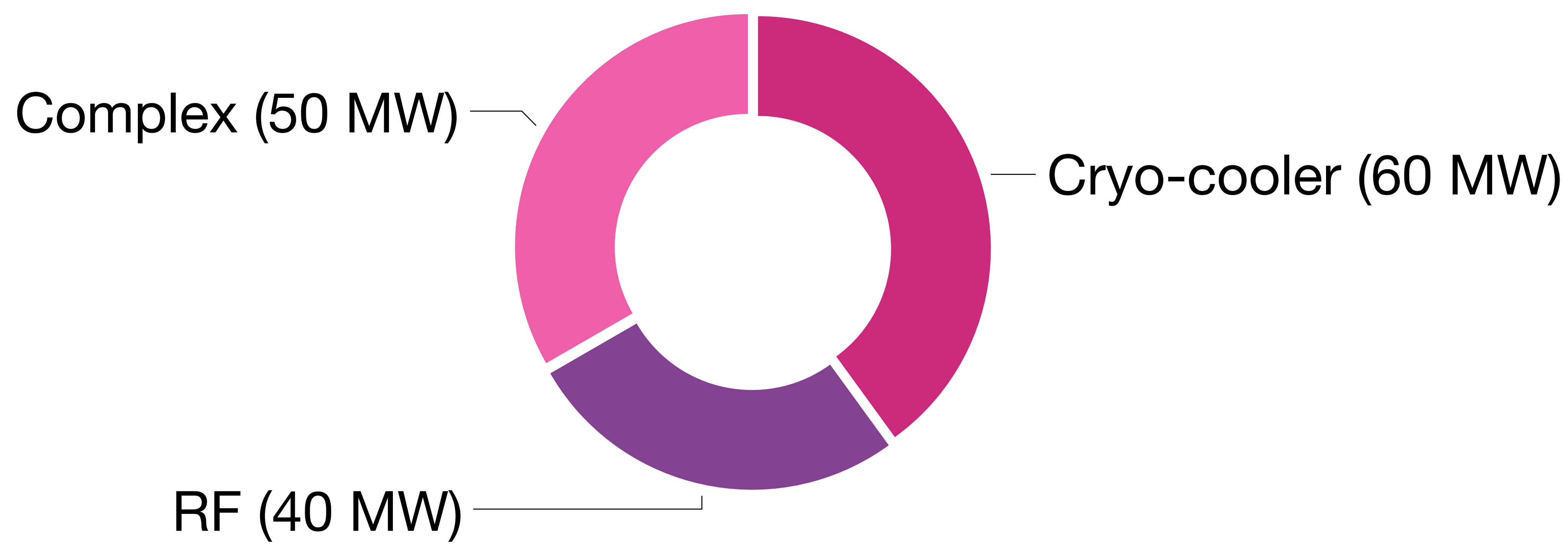
- Much of the displaced earth is pushed on top (shielding), only ~40k m^3 must be transported away
- Same amount of concrete required as for tunnel, assume emissions can be reduced to **65 kton CO_2**



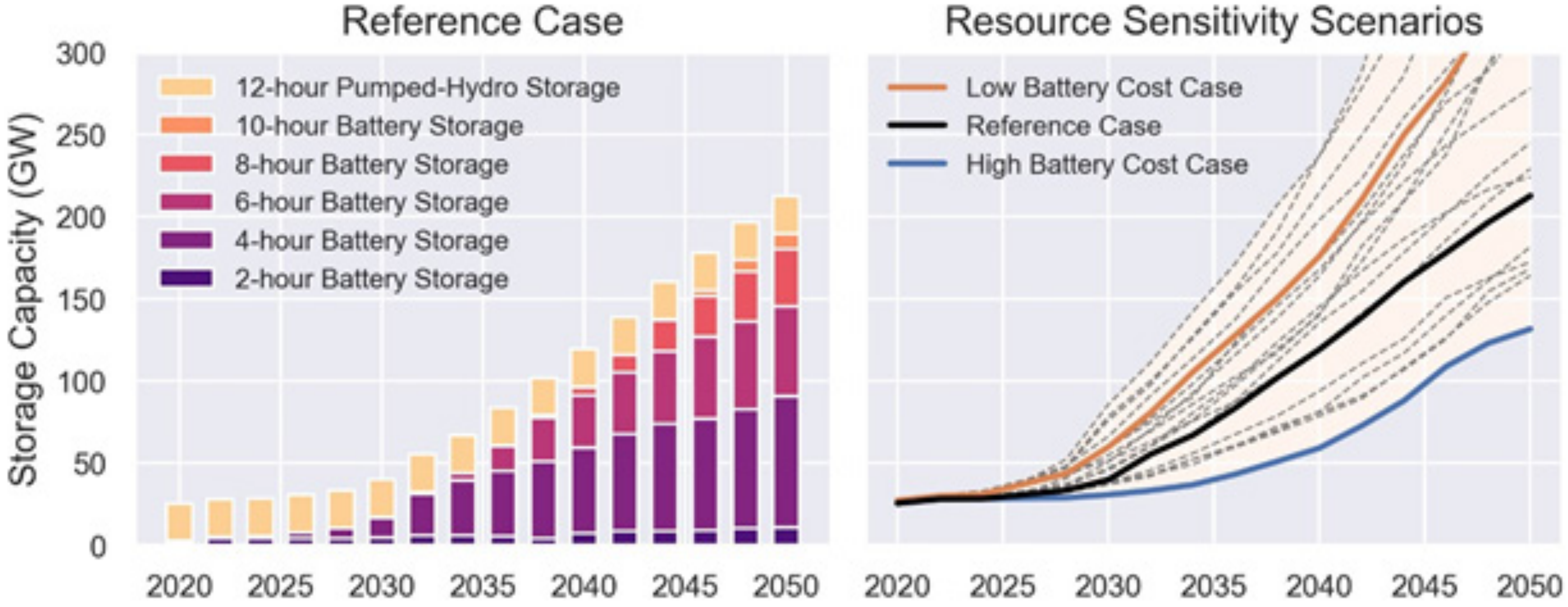
Operations emissions

- Driven by carbon footprint of energy production used during operations
  - Site power requirements have room for optimization, consider nominal beam parameters
  - **Carbon intensity** (equivalent emissions of gCO_2/kWh) key parameter, depends on location/power sources
  - "The United States has set a goal to reach 100 percent carbon pollution-free electricity by 2035" (from April 2021 US emissions target report - **is this a realistic assumption?**

Estimated power consumption for C³-250

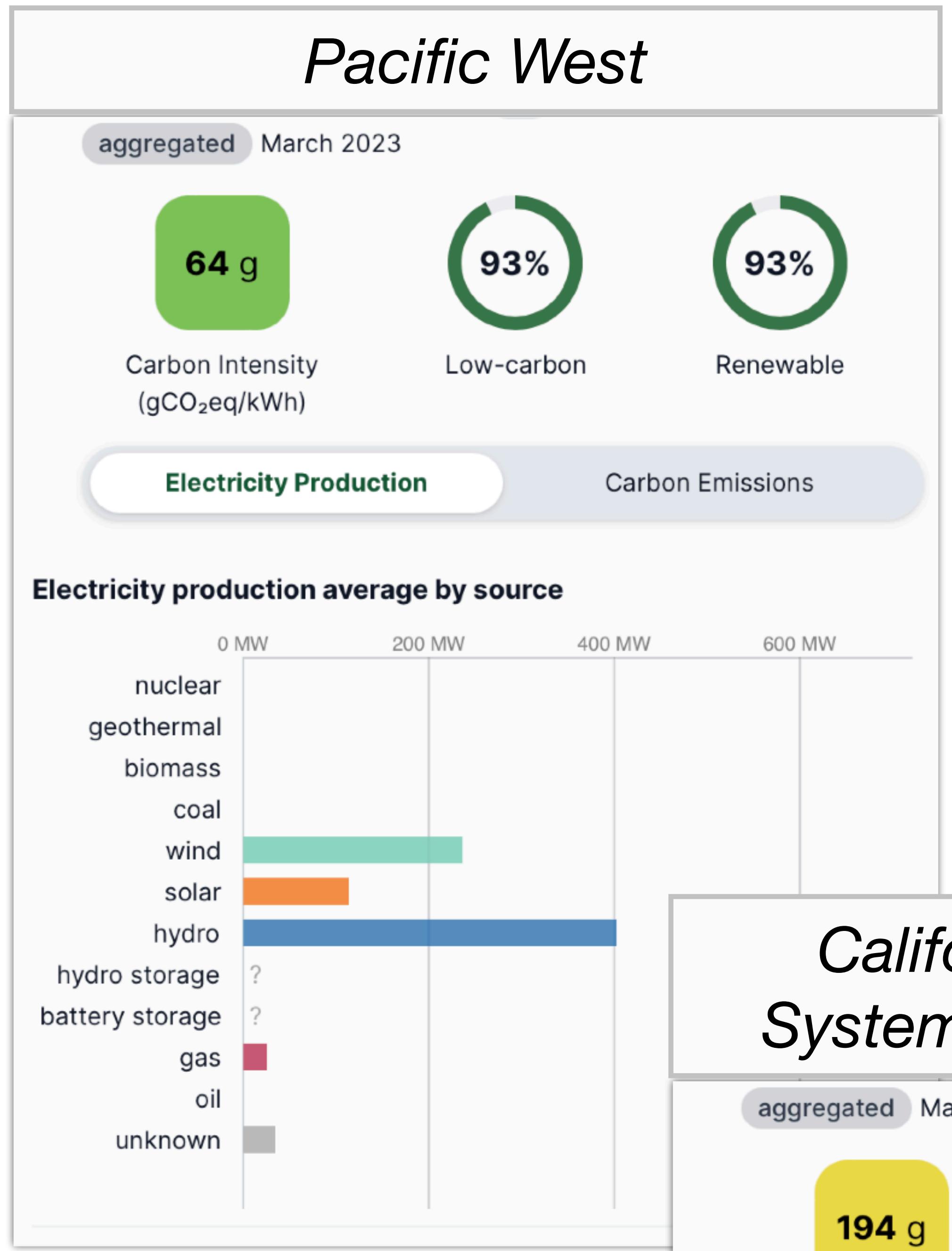


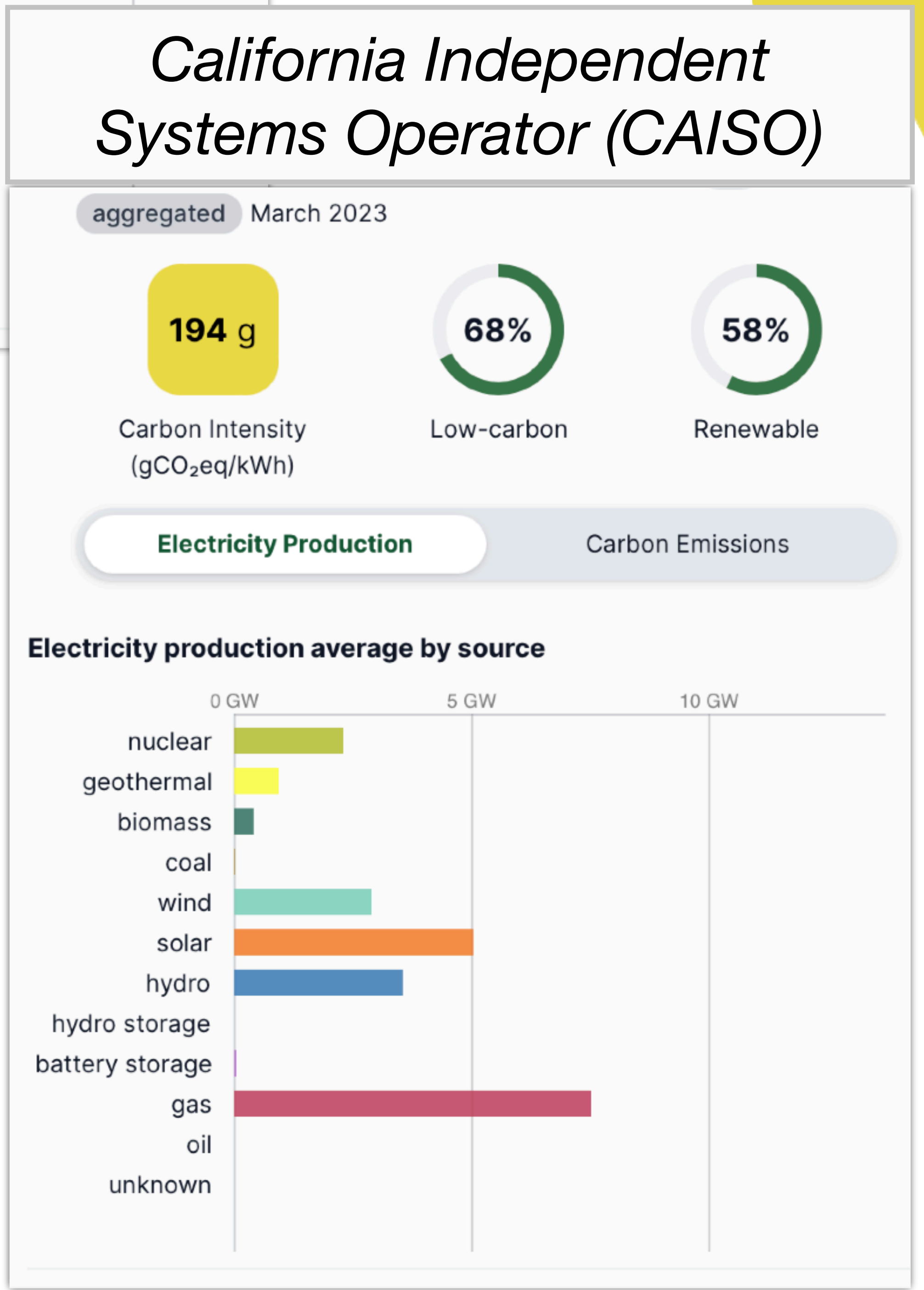
National grid storage capacity expected to reach 120 GWh by 2040 - 8 hours of storage at 150 MW < 1% of grid capacity



NREL Storage Futures Study

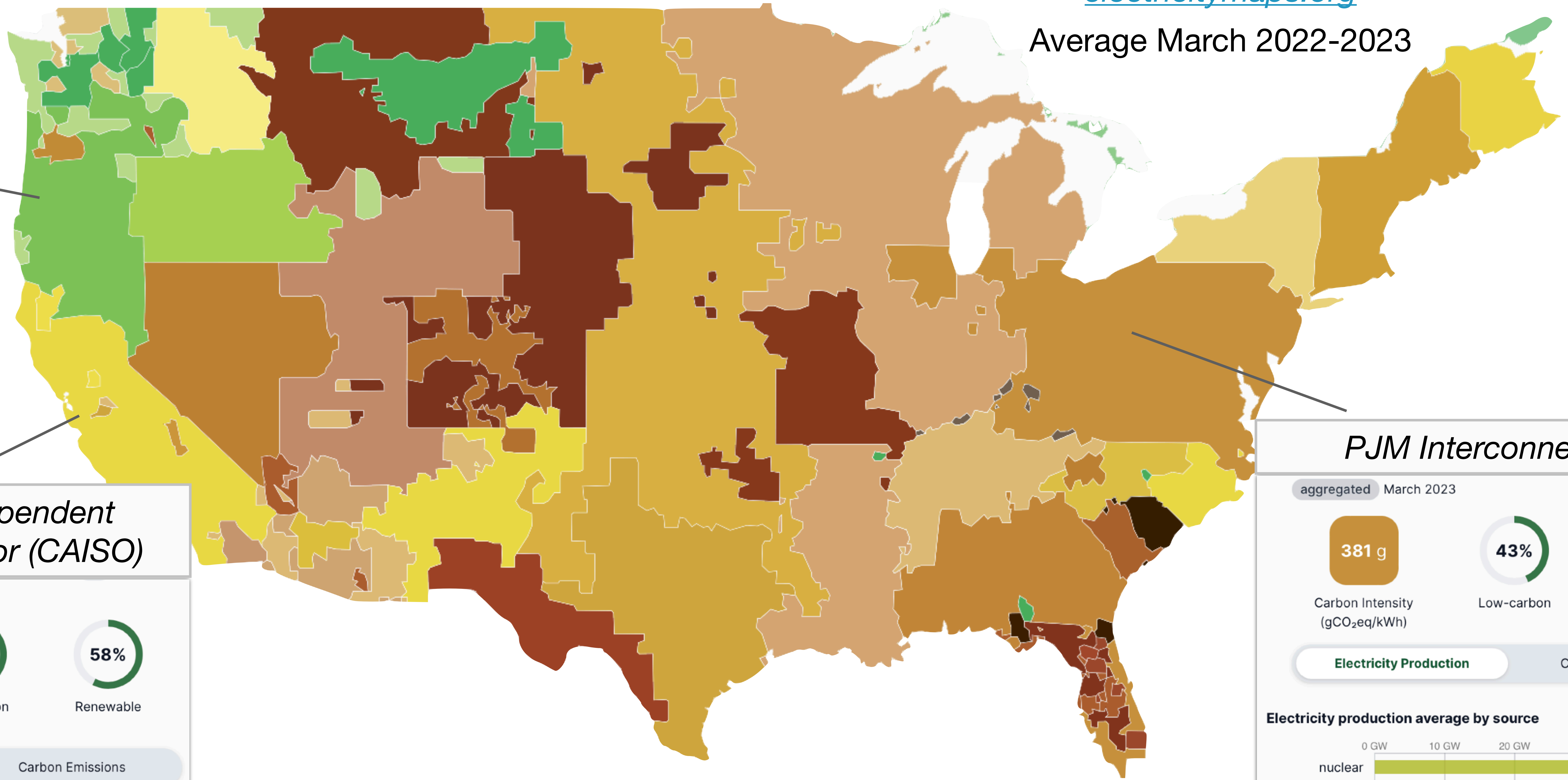
Siting options for C^3

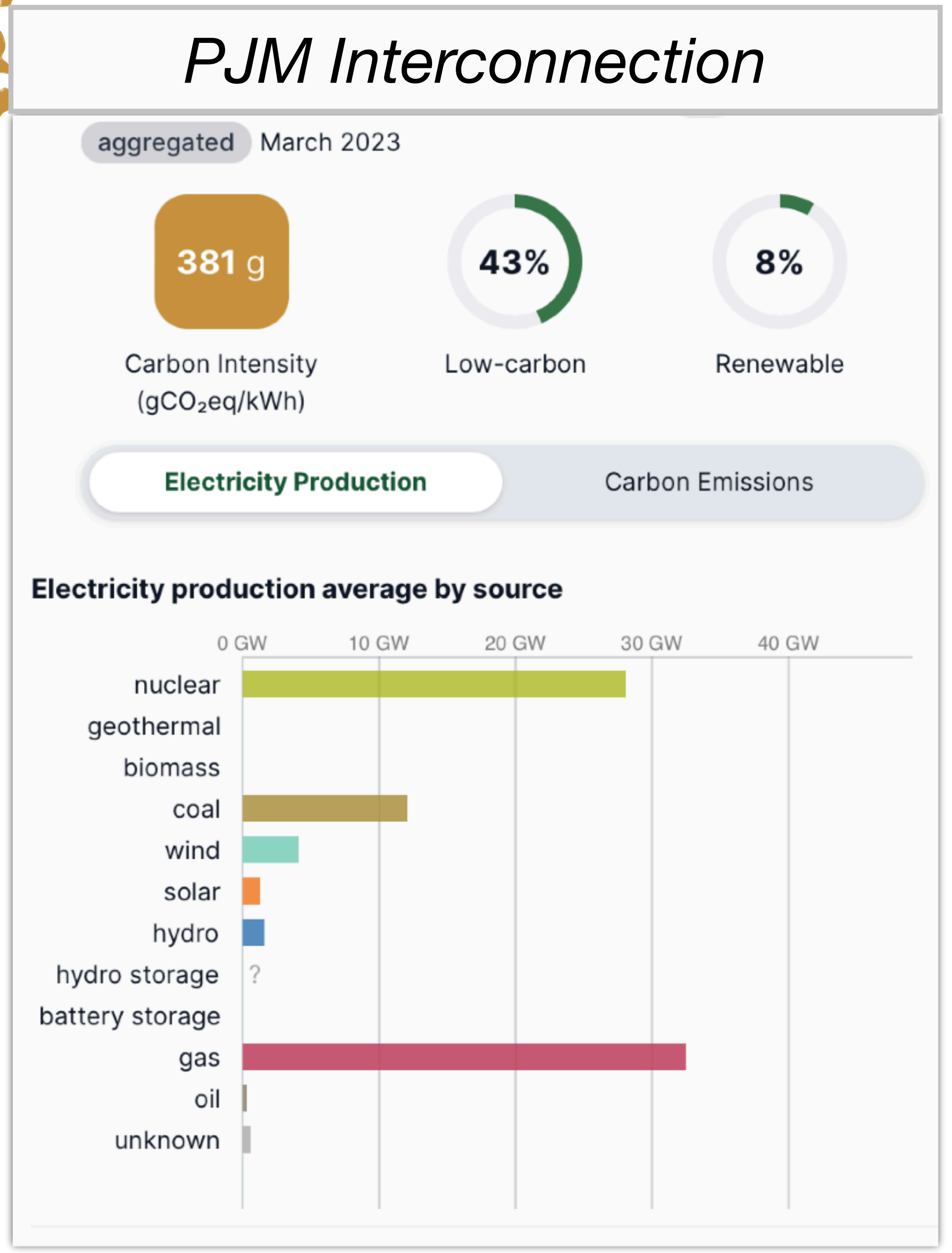




electricitymaps.org

Average March 2022-2023





C^3 has flexibility in site choice

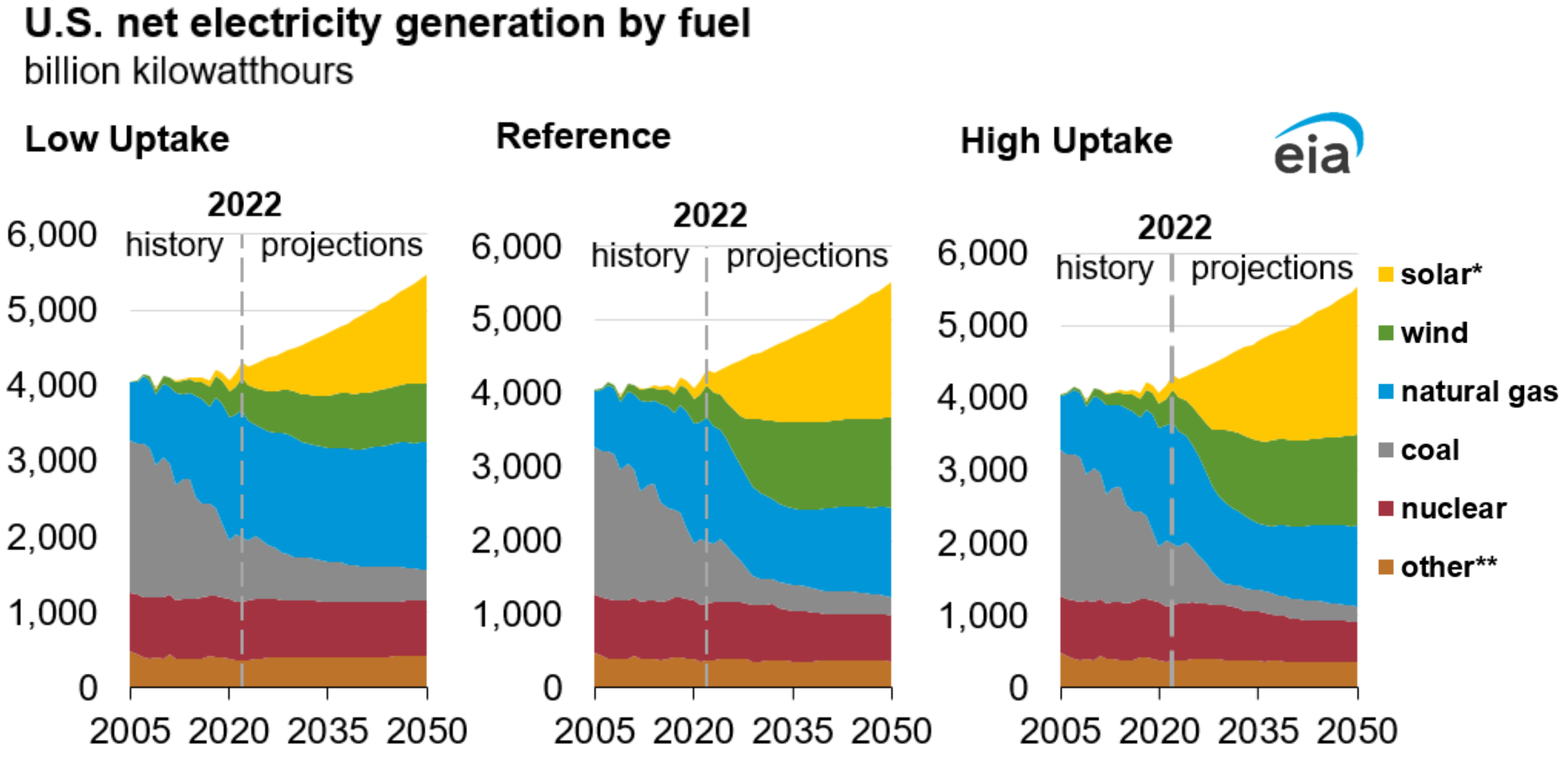
Carbon intensity for electricity generation varies across US, driven by **hydro** in Northwest, **solar** in Southwest, and **nuclear** in Northeast

Not representative of C^3 operations beginning in ~2040! Need projections

PJM 2022 estimate used in Janot, Blondel 2022

Carbon intensity projections

US Energy Information Agency (EIA), Annual Report 2023



Project carbon intensities in 2022 into 2040 based on **Low Uptake** scenario of energy source portfolio (national level)

CAISO: 194 → 70 gCO_2/kWh

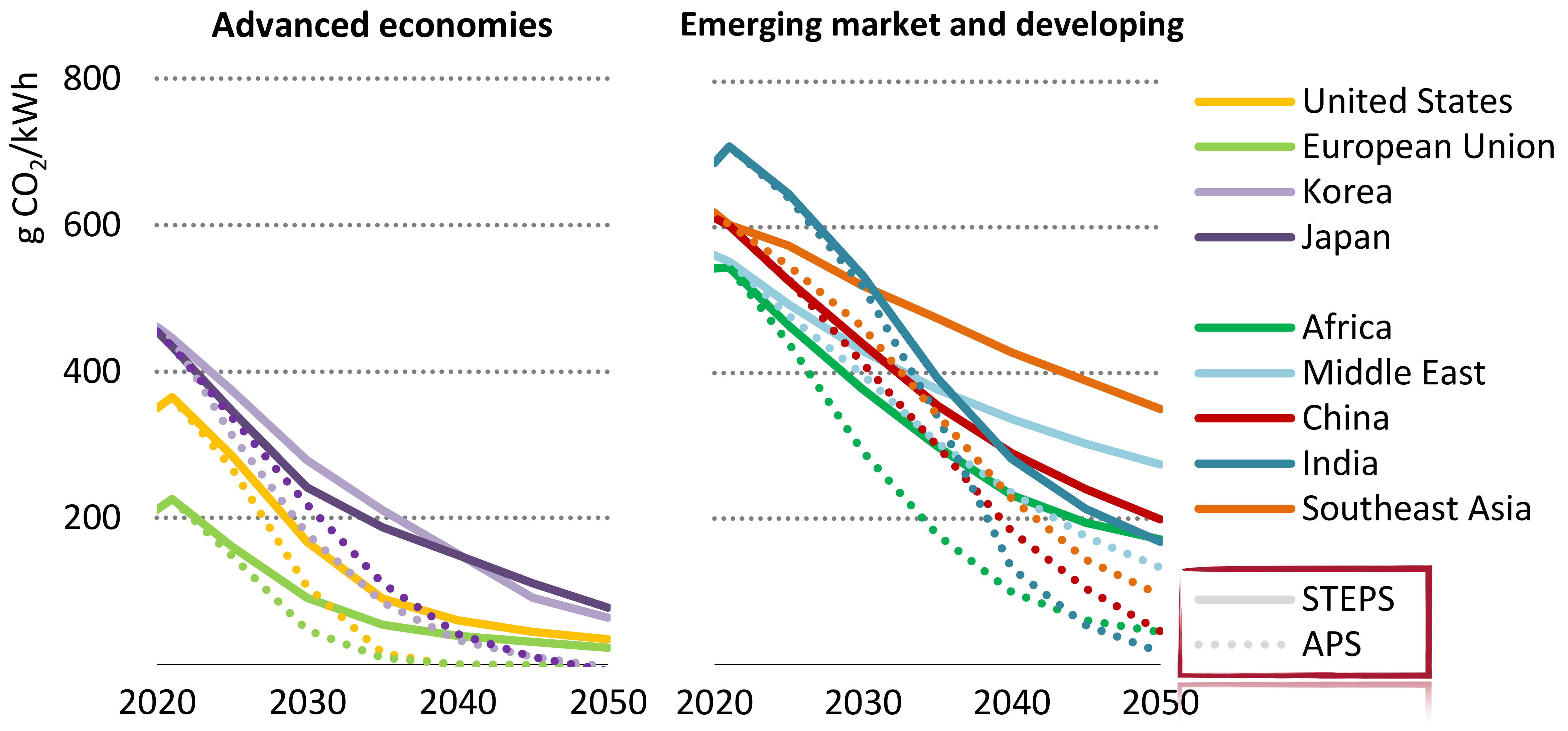
PJM: 381 → 130 gCO_2/kWh

World Energy Outlook 2022, International Energy Agency

Stated Policies Scenario (STEPS)	*Announced Pledges Scenario (APS)*	*Net Zero Emissions by 2050 (NZE)*

More aggressive decarbonization scenario →

Figure 6.14 ▷ Average CO_2 intensity of electricity generation for selected regions by scenario, 2020-2050



US: **45** gCO_2/kWh

EU: **40** gCO_2/kWh

Japan: **150** gCO_2/kWh

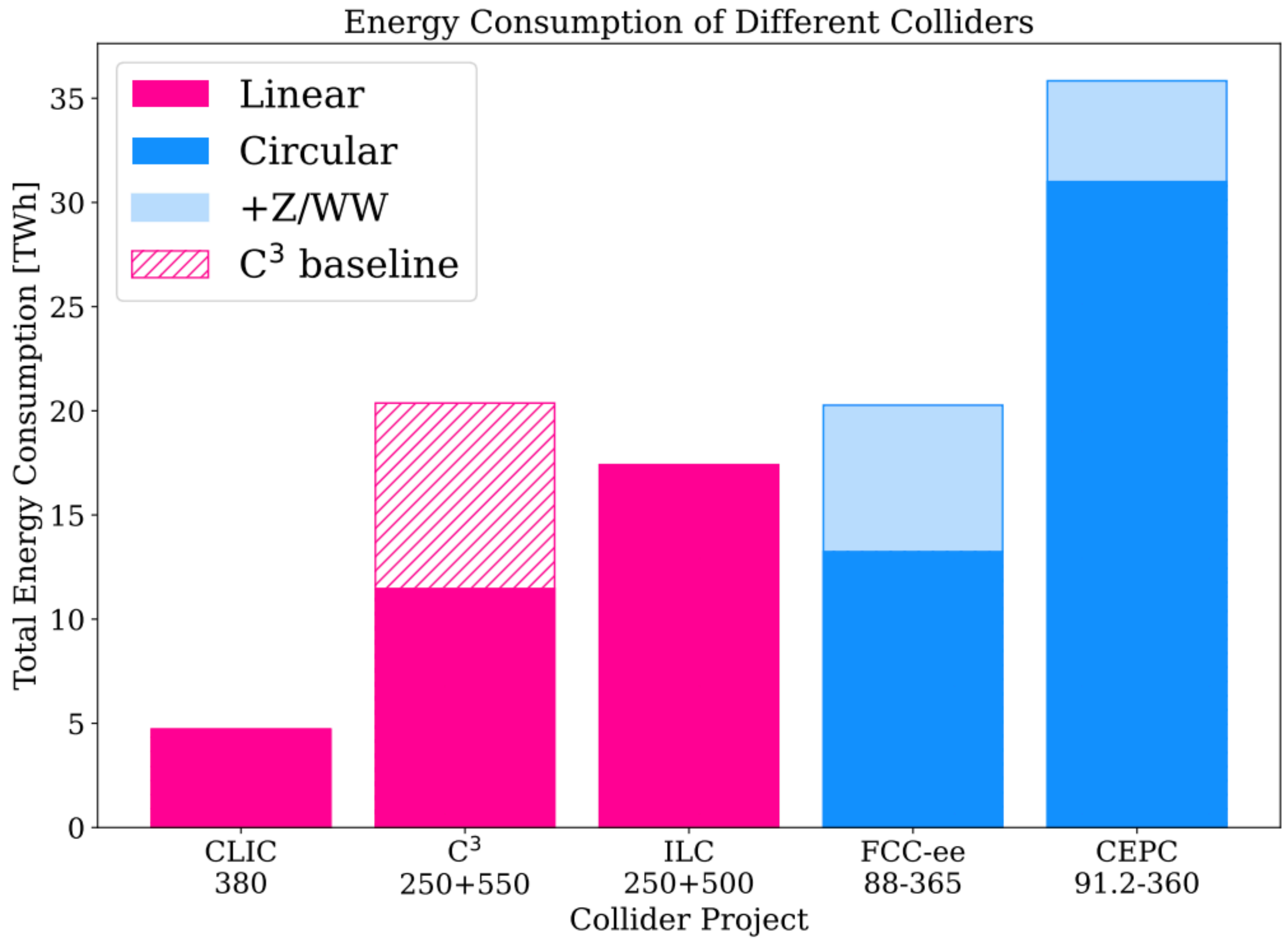
China: **300** gCO_2/kWh

→ ***both estimations using projections from US and international agencies give comparable projections***

(Note: Silicon Valley Clean Energy can provide 175 MW of clean energy in 2-3 year timeframe)

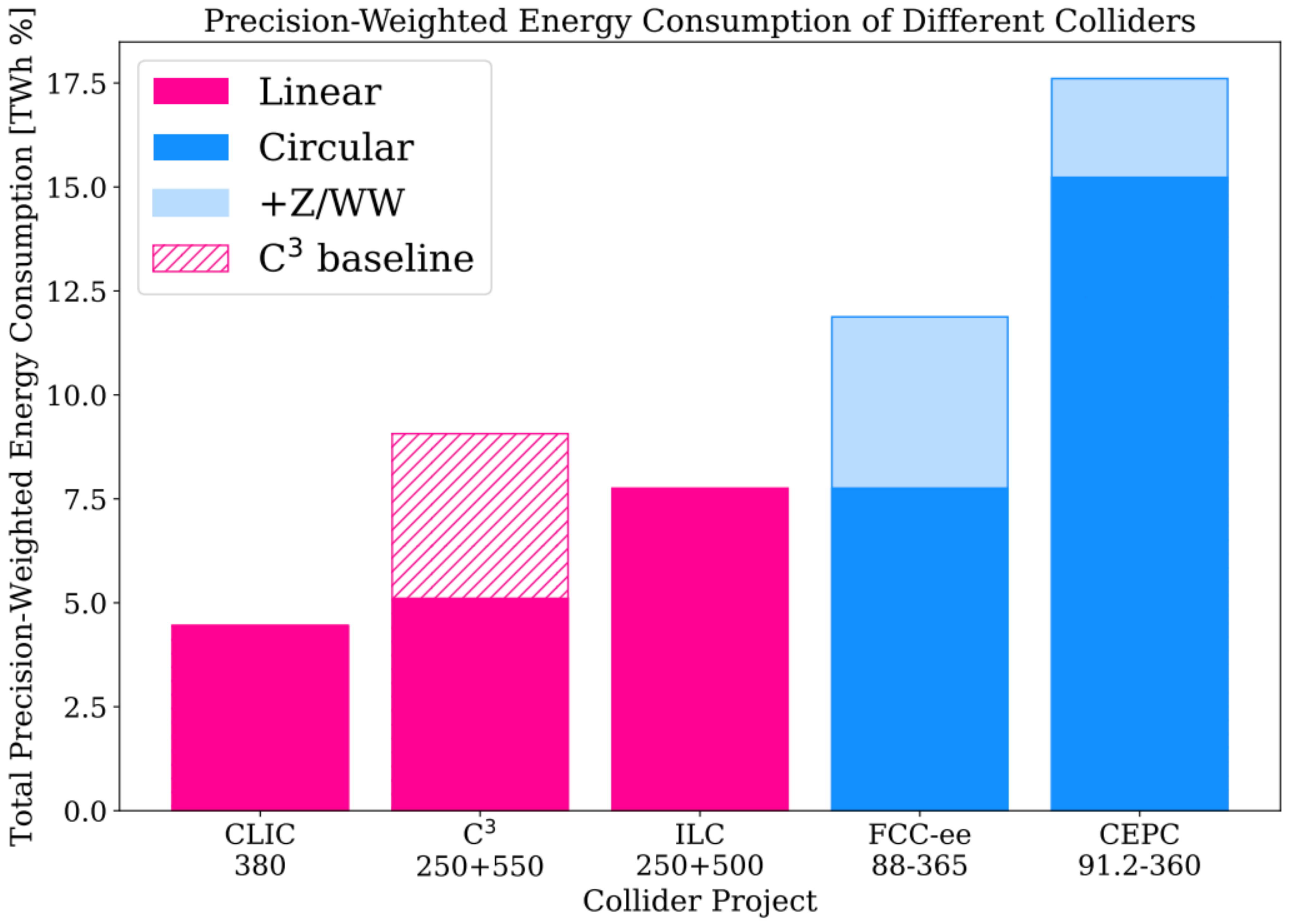
Energy consumption and emissions

Total energy consumption over full run time



C^3 and CEPC consumption driven by long run times

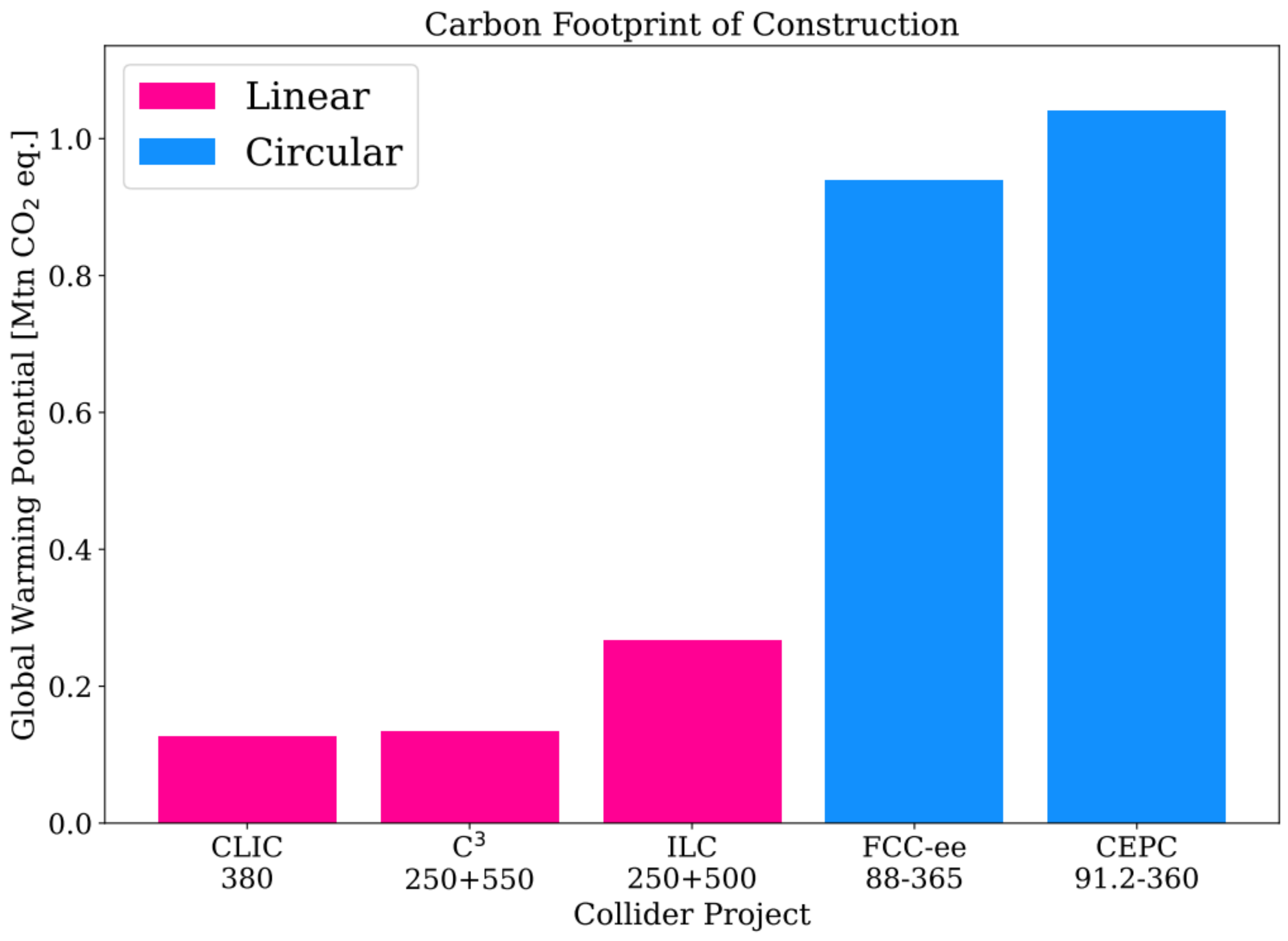
Precision Weighted Consumption



Differentiation in environmental impact driven by scientific output

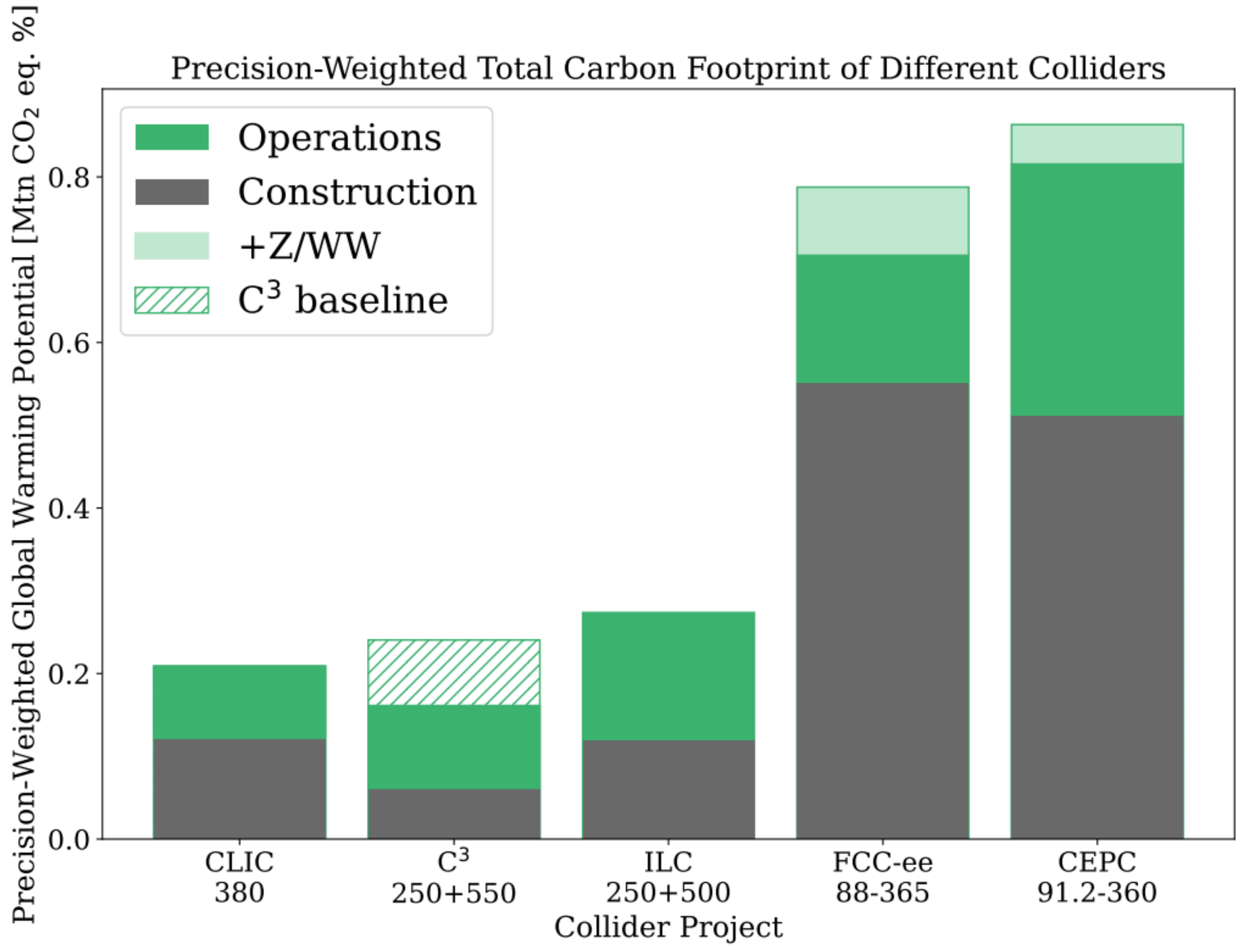
Impacts of construction

Emissions from construction



Project	Main tunnel length (km)	GWP (kton CO_2e)		
		Main tunnel	+ other structures	+ A4-A5
FCC	90.6	578	751	939
CEPC	100	638	829	1040
ILC	13.3	97.6	227	266
CLIC	11.5	73.4	98	127
C^3	8.0	133	133	146

Precision weighted total carbon impact

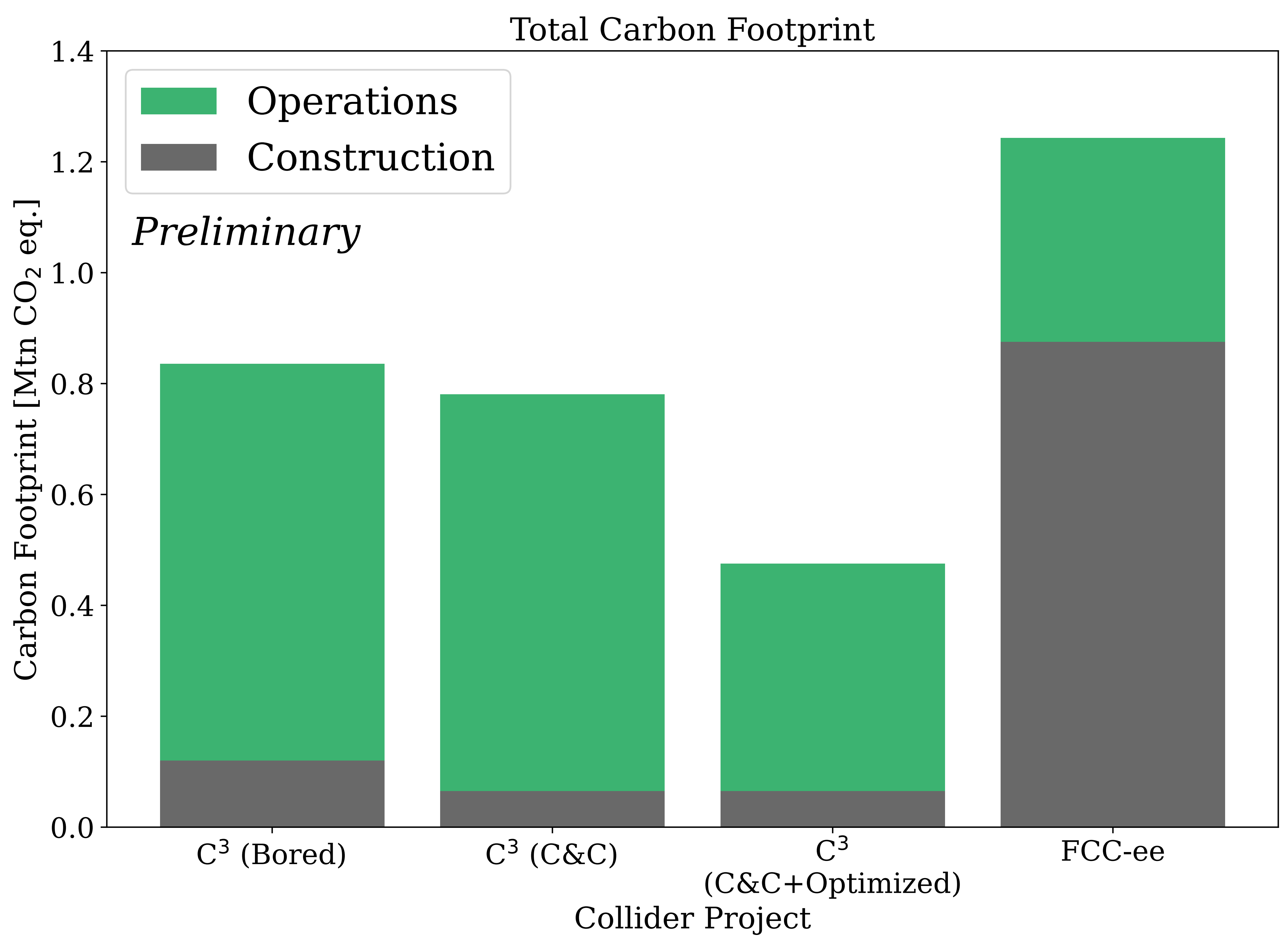


C^3 power optimizations

Possible options for beam power reduction with several different approaches

Impact on luminosity and ultimate physics performance not yet evaluated

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



Emissions due to operations have clear road toward further reduction since clean energy in California is already accessible, *operations emissions of C^3 can be virtually eliminated* (limited by emissions from manufacturing solar panels)

Carbon capture in concrete can offset emissions, but scalability not yet demonstrated

→ **great potential for green Higgs factory with C^3!**

Bunch Spacing

- Beam power can be increased for additional luminosity **or higher current shorter RF pulse**
- C3 has a relatively low current for 250 GeV CoM (0.19 A) - Could we push to match CLIC at 1.66 A? (8.5X increase?)
- Pulse length and rep. rate are also options (rep. rate is challenging from a power perspective)

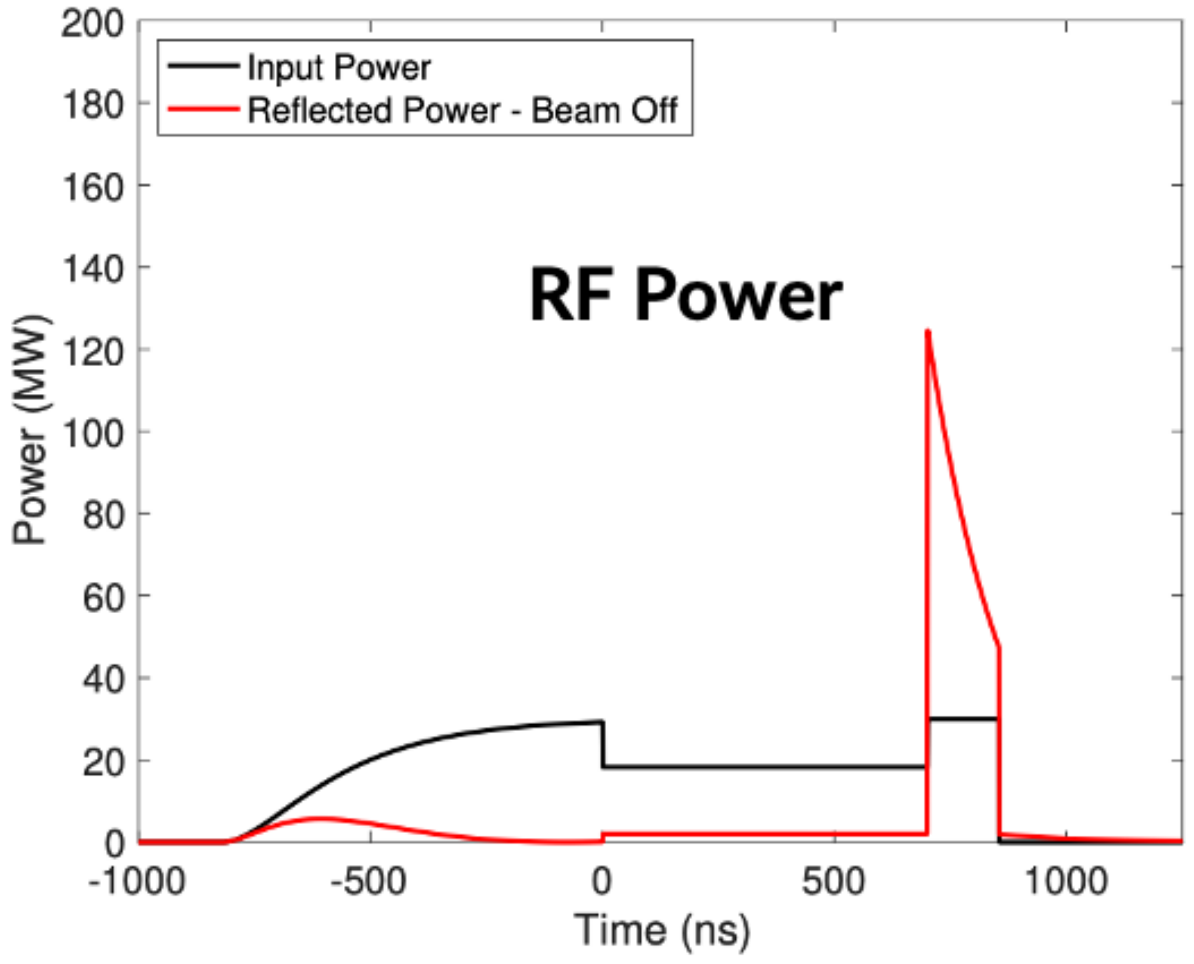
Caution: Requires serious investigation of beam dynamics - great topic for C^3 Demonstration R&D

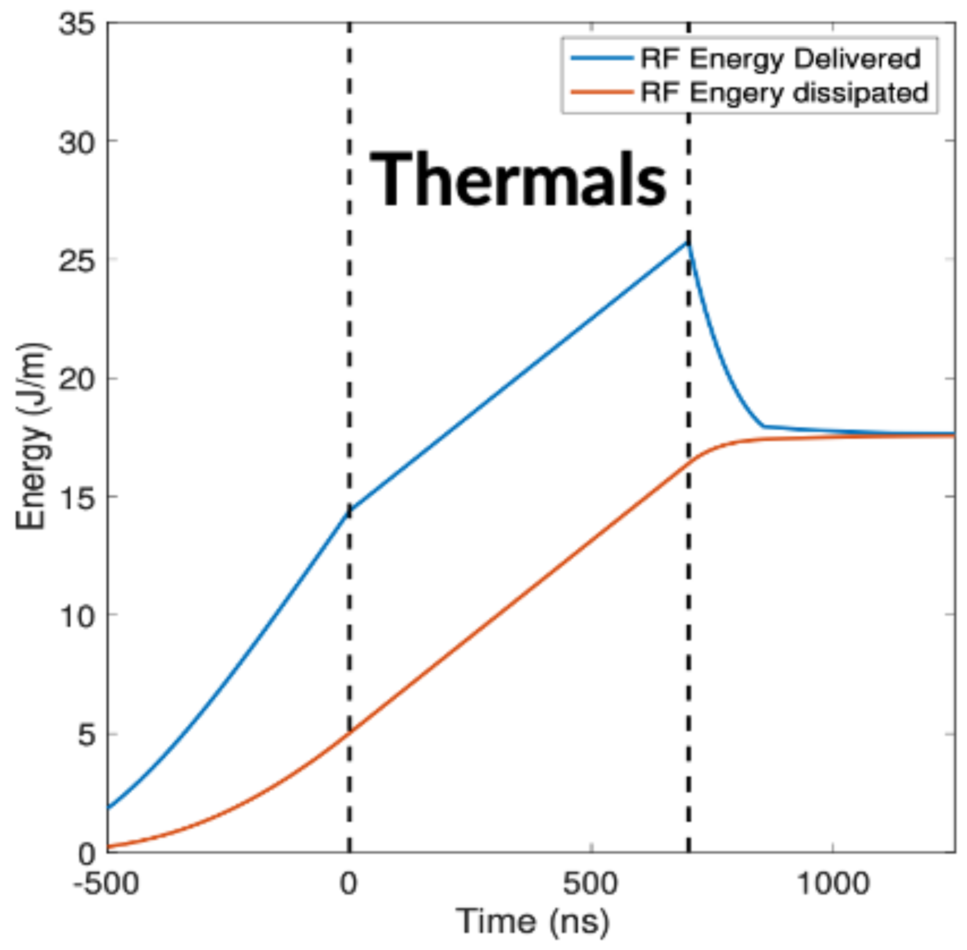
- Impact:
  - More damping may be needed
  - Higher power per meter - part of upgrade to 550 GeV
  - Detector - 3ns bunch spacing good, 1 ns spacing ok
  - **<1 ns bunch spacing significant impact on detector**

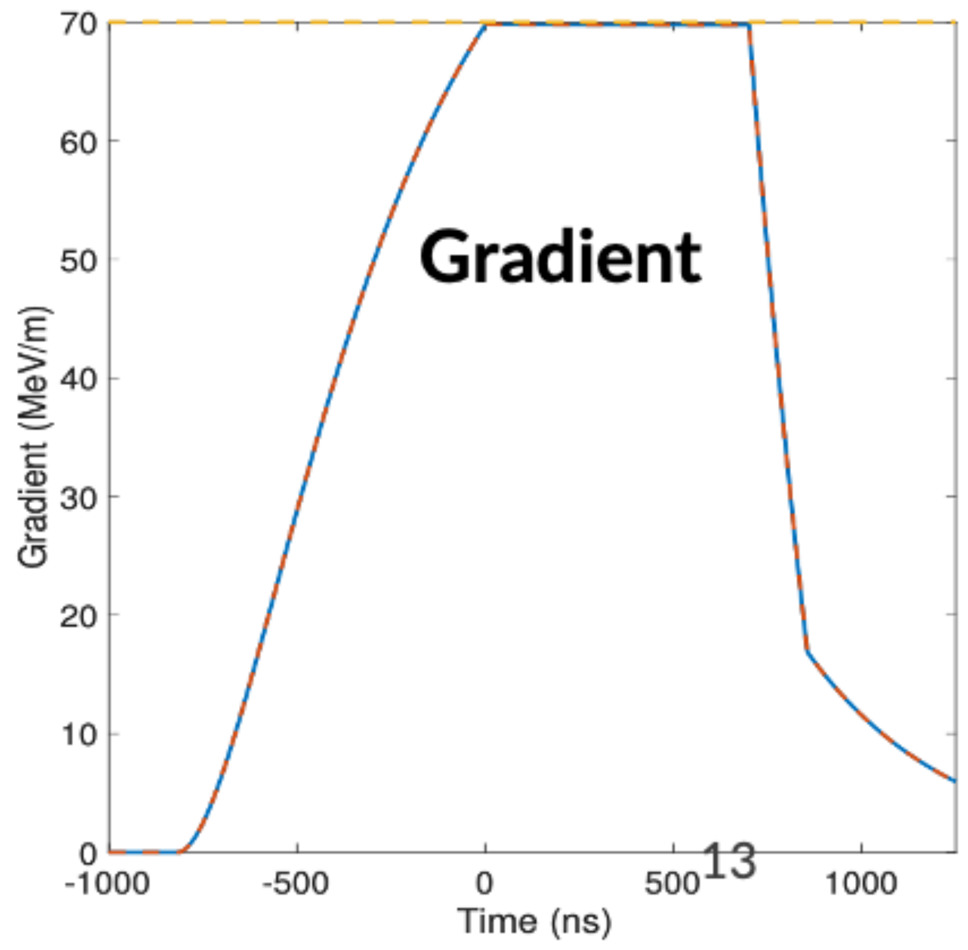
Parameter	Units	Baseline	High-Lumi
Energy CoM	GeV	250	250
Gradient	MeV/m	70	70
Beam Current	A	0.2	1.6
Beam Power	MW	2	16
Luminosity	$x10^{34}$	1.3	10.4
Beam Loading		45%	87%
RF Power	MW/m	30	125
Site Power	MW	~150	~180

Pulse Length

- Baseline -> **Thermal load 2200 W/m @ 120 Hz**
  - 70 MeV/m 700 ns (120 MeV/m 250 ns) flattop
  - ~1.5 microsecond rf pulse, ~30 (80) MW/m
    - **With 45% beam loading**
    - **High RF-beam efficiency even with low current 0.2 A (0.33 A)**
  - Conservative 2.3X enhancement from cryo
    - **No pulse compression**
  - Ramp power to reduce reflected power
  - Flip phase at output to reduce thermals
  - <2.5 kW/m at 120 Hz







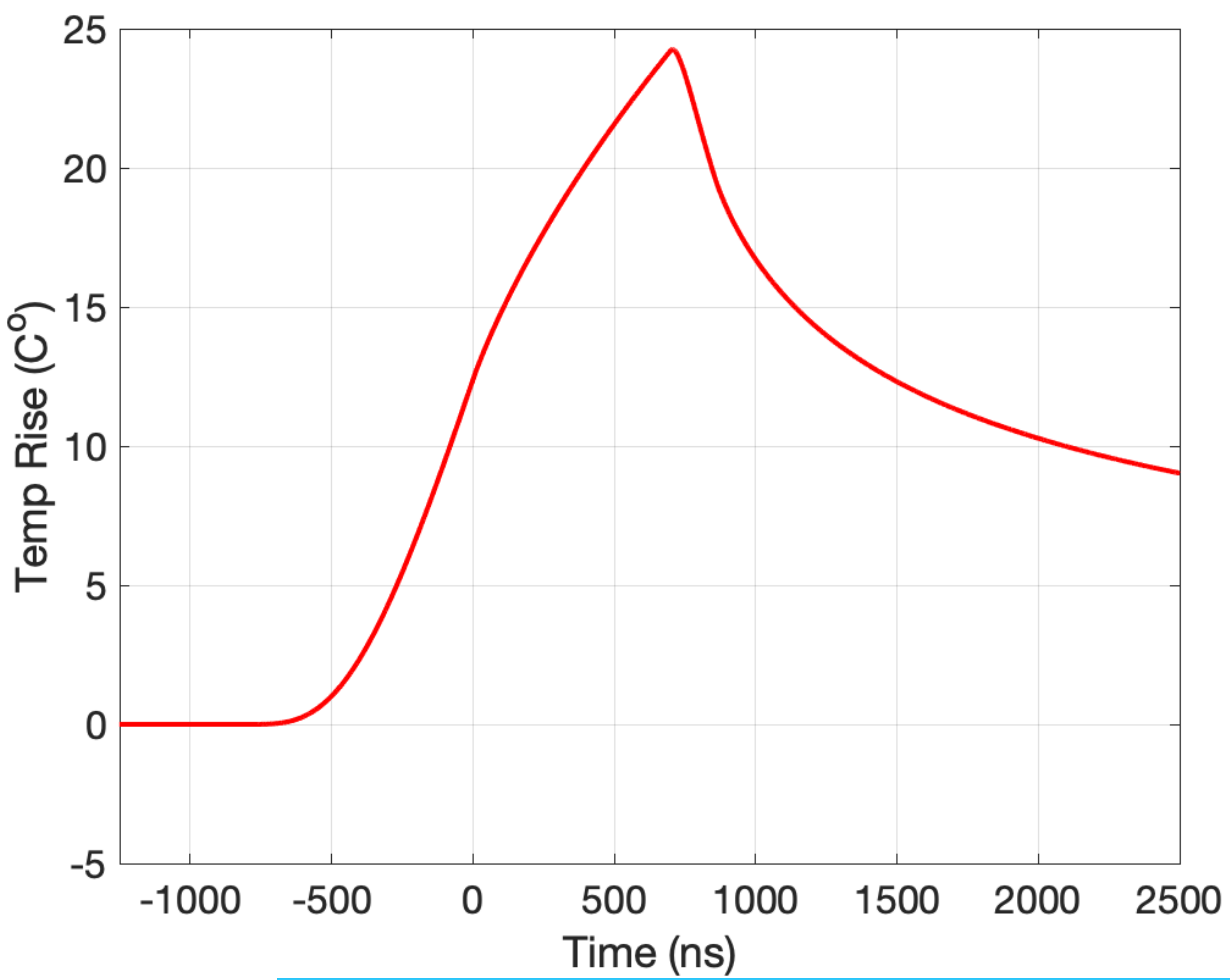
SLAC FLS 2023

Pulse Length

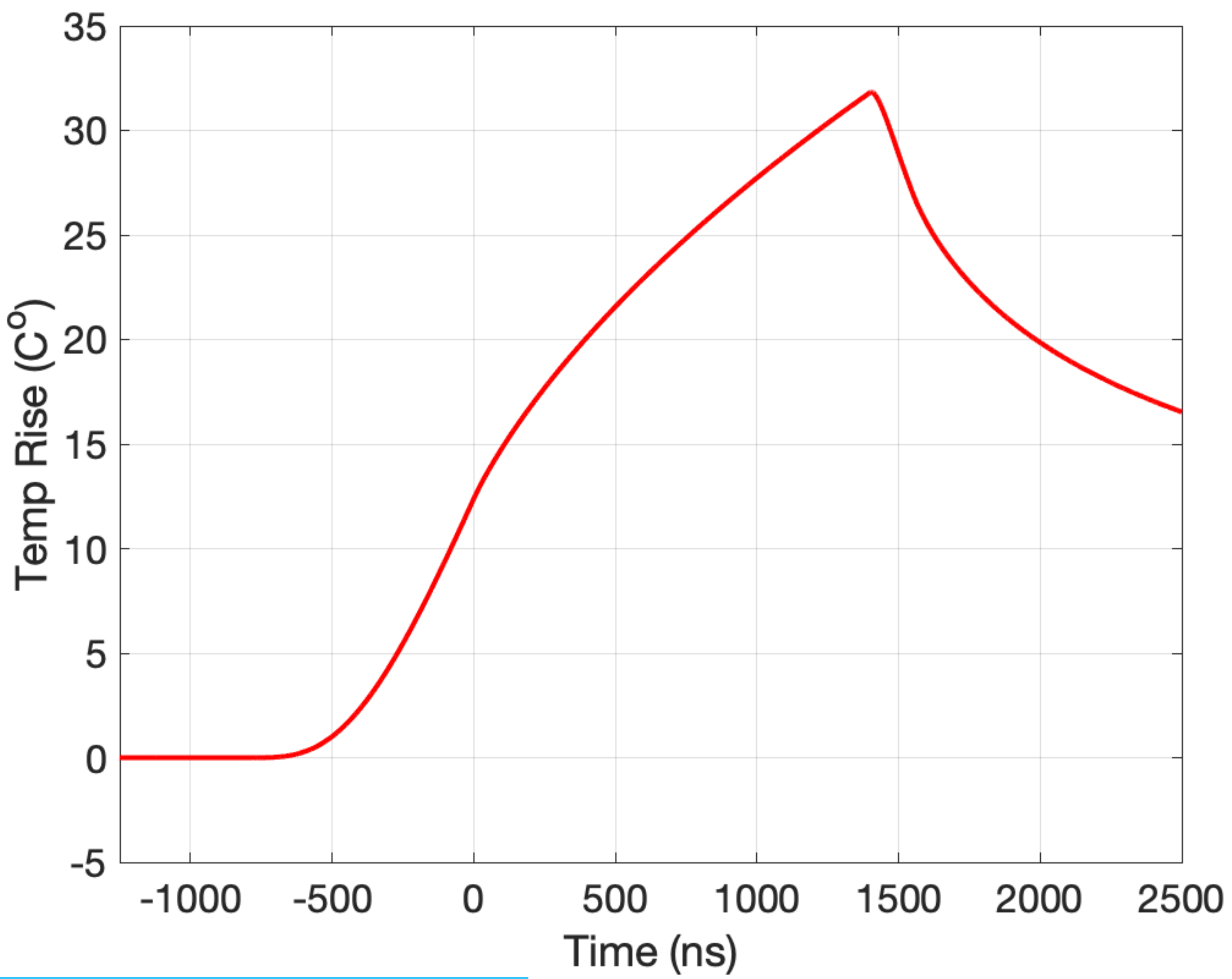
SLAC

- Double the pulse length and half the repetition rate?
- Reduce to 1700 W/m, but pulsed heating goes up (both below 50K)

700 ns, 70 MeV/m



1400 ns, 70 MeV/m

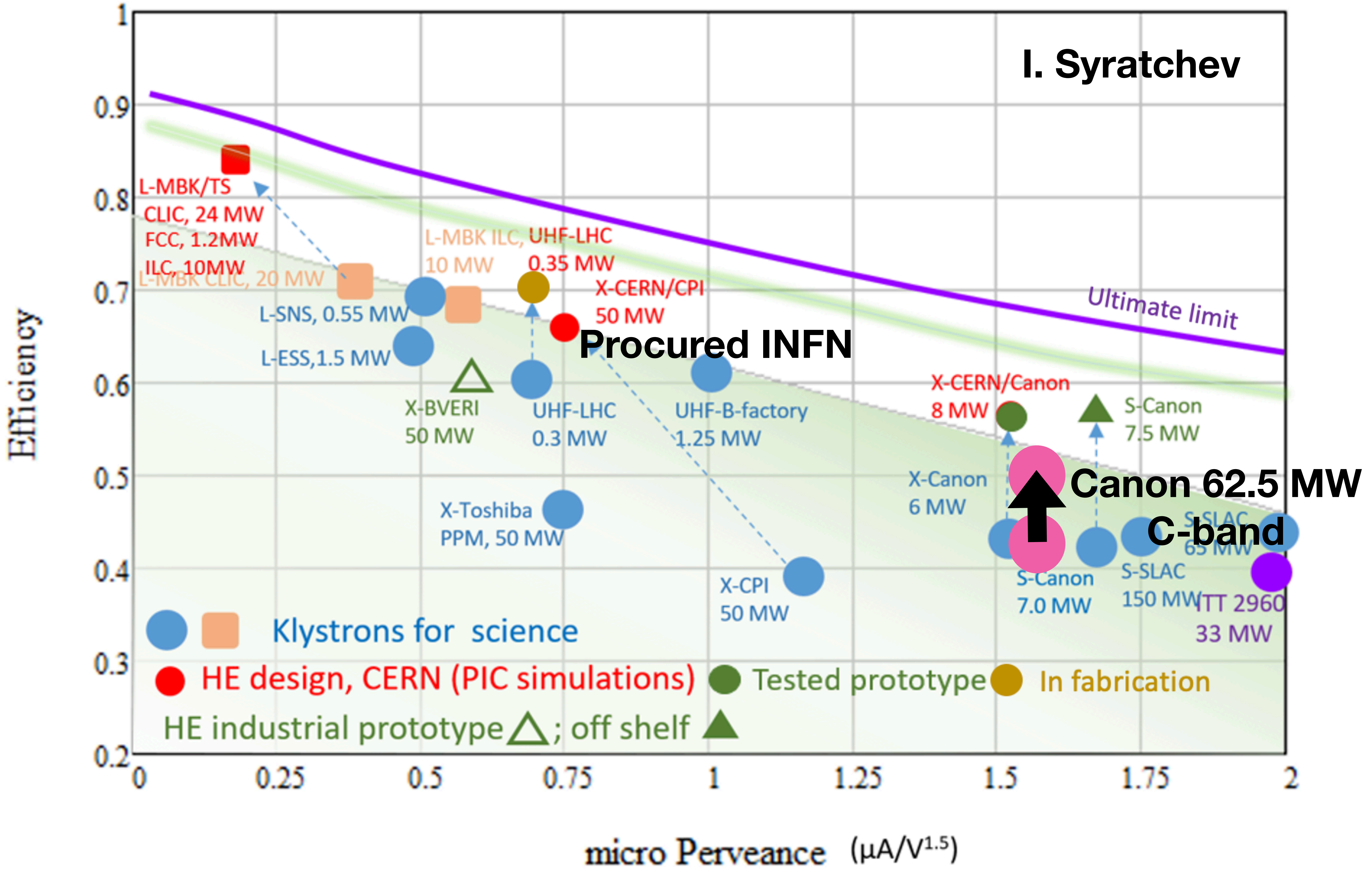


Combining reduced bunch spacing and increased bunch length provides ~50% savings for main linac (50 MW reduction)

RF Source Efficiency

- Need to include: Modulator, klystron and magnets
- Recent progress reported at CCTA
- Permanent magnet solenoid will have significant impact

High Efficiency klystrons project at CERN is targeted to improve efficiency and performance of these devices for various applications.



https://indico.slac.stanford.edu/event/7467/contributions/6129/

Pulse Compression

✦ Reduce fill time of accelerator, increase pulse length of rf source -> Need high Qo

Normal Conducting Pulse Compressor

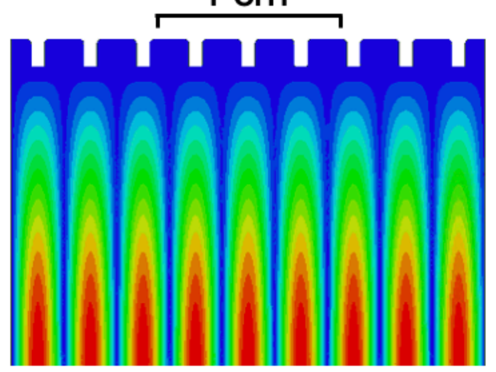
Compact RF pulse compression

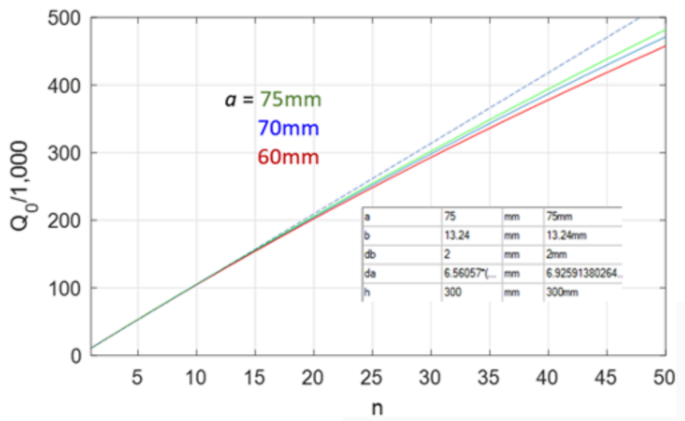
Powering the FLASH-VHEE linac

- Two polarized modes in a single high-Q cavity
- HE_{11}-mode in the corrugated cylindrical cavity achieves a Q_0 of 405,000 with a cavity length of 0.87 m.

K200 Solid State Modulator System from ScandiNova and Canon Klystron
- 11.424 GHz
- Peak power 6 MW
- Pulse length 4 μs

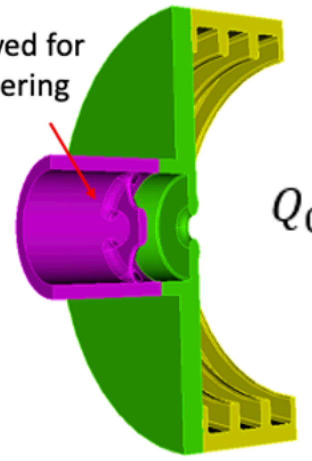
4 cm



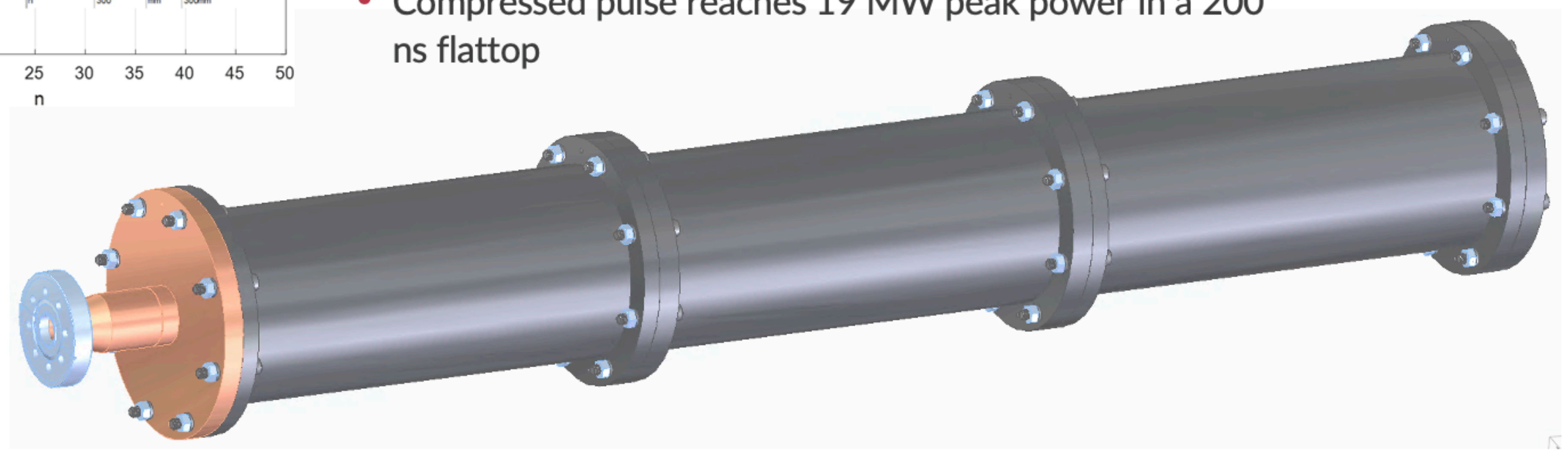


- Coupler designed with an intermediary low-Q TE_{11} cavity
  - small aperture to the compressor minimizes the perturbation to the HE_{11} mode
  - four irises into the low-Q cavity enhance the coupling factor
- Compressed pulse reaches 19 MW peak power in a 200 ns flattop

Improved for engineering design



$$Q_0 = \frac{2391.448 a^3 f^{5/2} L}{a^3 f^2 + 121.126 L}$$



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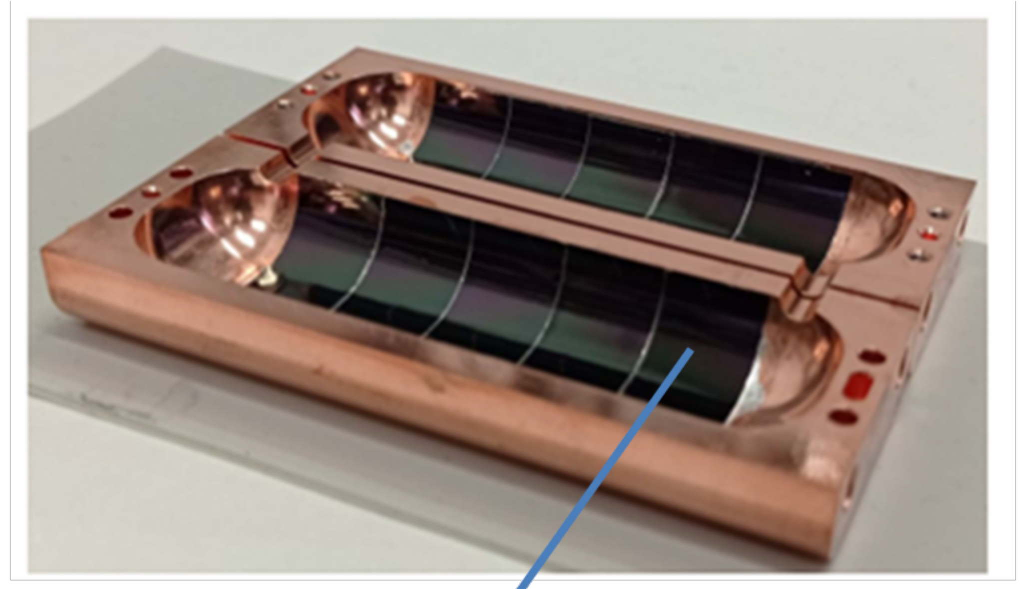
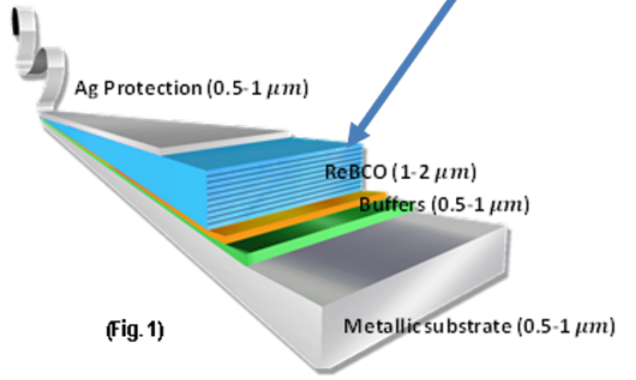
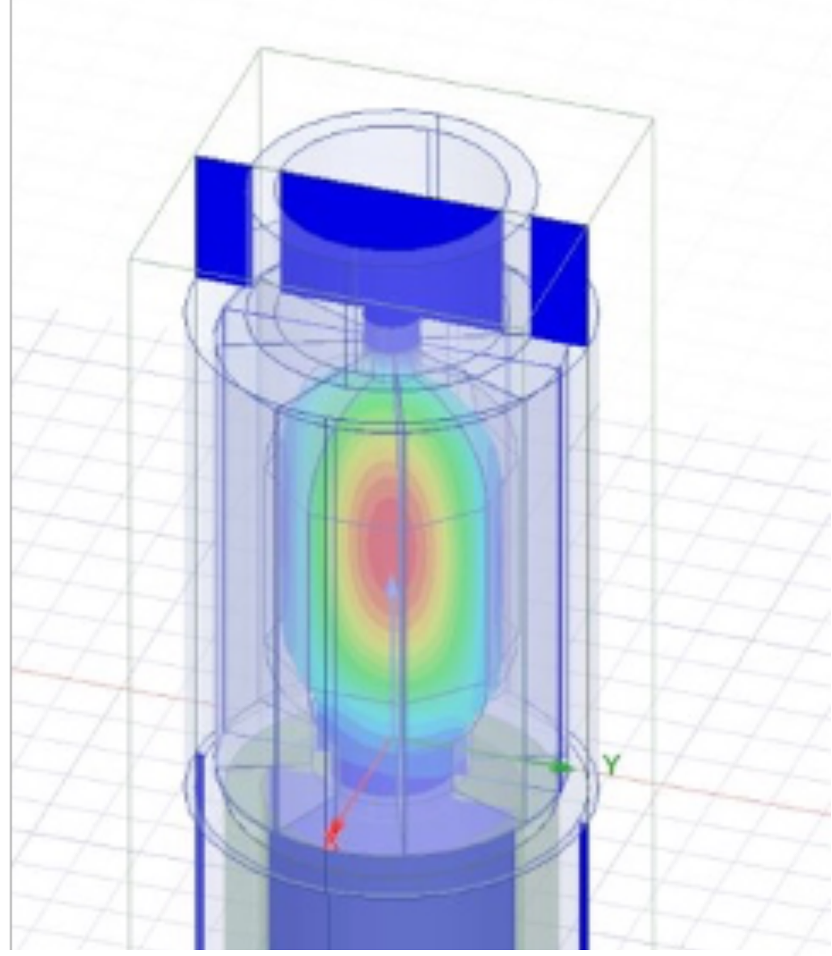
https://indico.slac.stanford.edu/event/7467/contributions/5839/

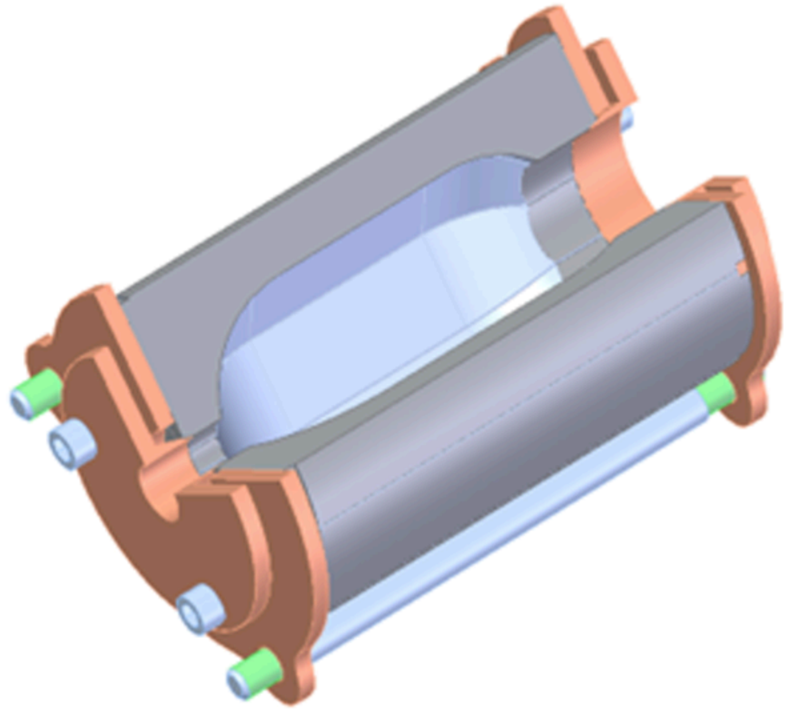
High Temperature Superconductor Pulse Compressor







J. Golm et al., *IEEE TAS, 32, No. 4, (2022) 1500*



doi/jacow-ipac2023-wepa183/index.html

Conclusions

- C^3 is a candidate for a compact linear e^+e^- Higgs factory with low carbon impact
- Lower energy consumption over circular colliders to achieve same (or better) physics goals
  - C^3 physics reach enhanced by polarized electrons, ability to access $\sqrt{s}$ = 550 GeV running mode
- Significantly reduced emissions associated to construction than alternative Higgs factory concepts
  - Emissions from conventional concrete manufacturing, **factor 4-8 lower emissions for C^3 than FCC**
- Can be built anywhere, but compelling to build in US due to expected grid electrification
  - By 2040, carbon intensity of electricity generation to be on par with EU, far below Japan and China
- More precision in auxiliary systems to refine operations estimates

Thank you for your attention - stay tuned!

Backup

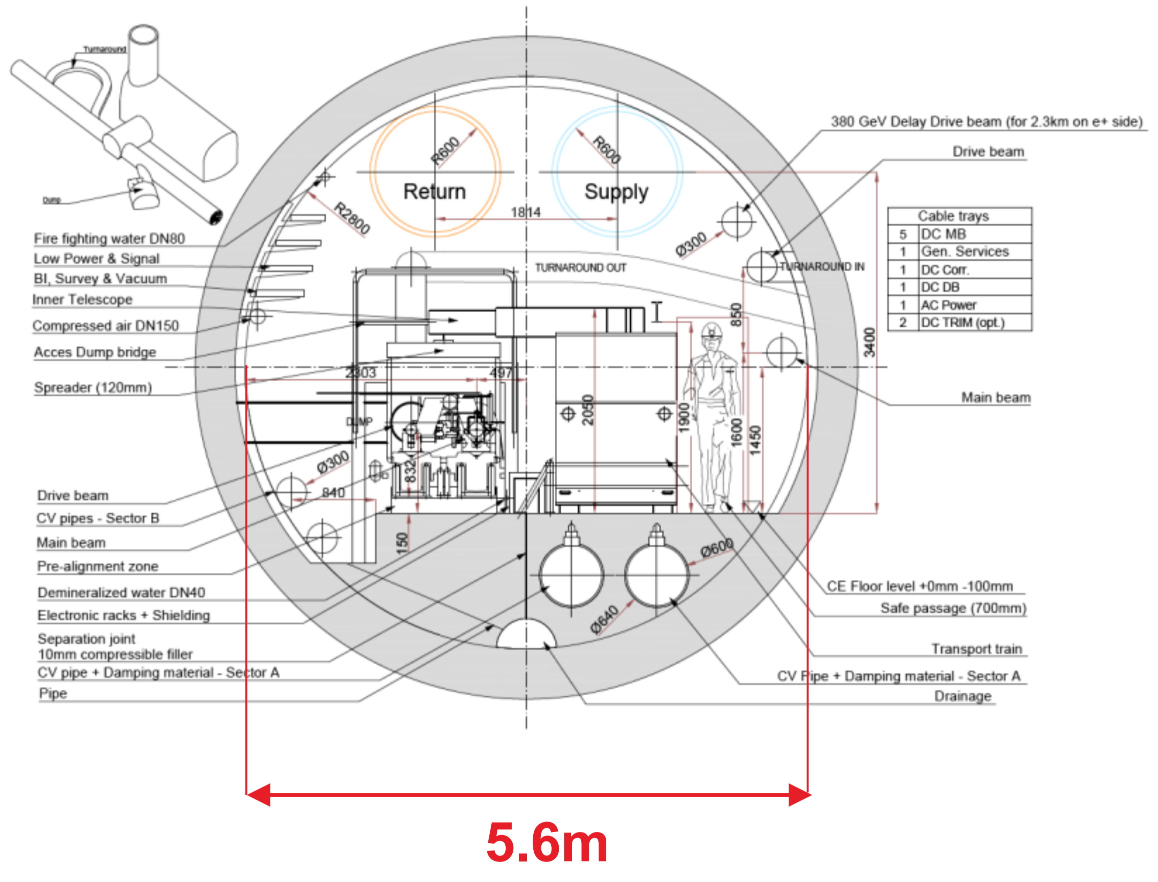
Collider project inputs

ARUP

Linear Collider Options

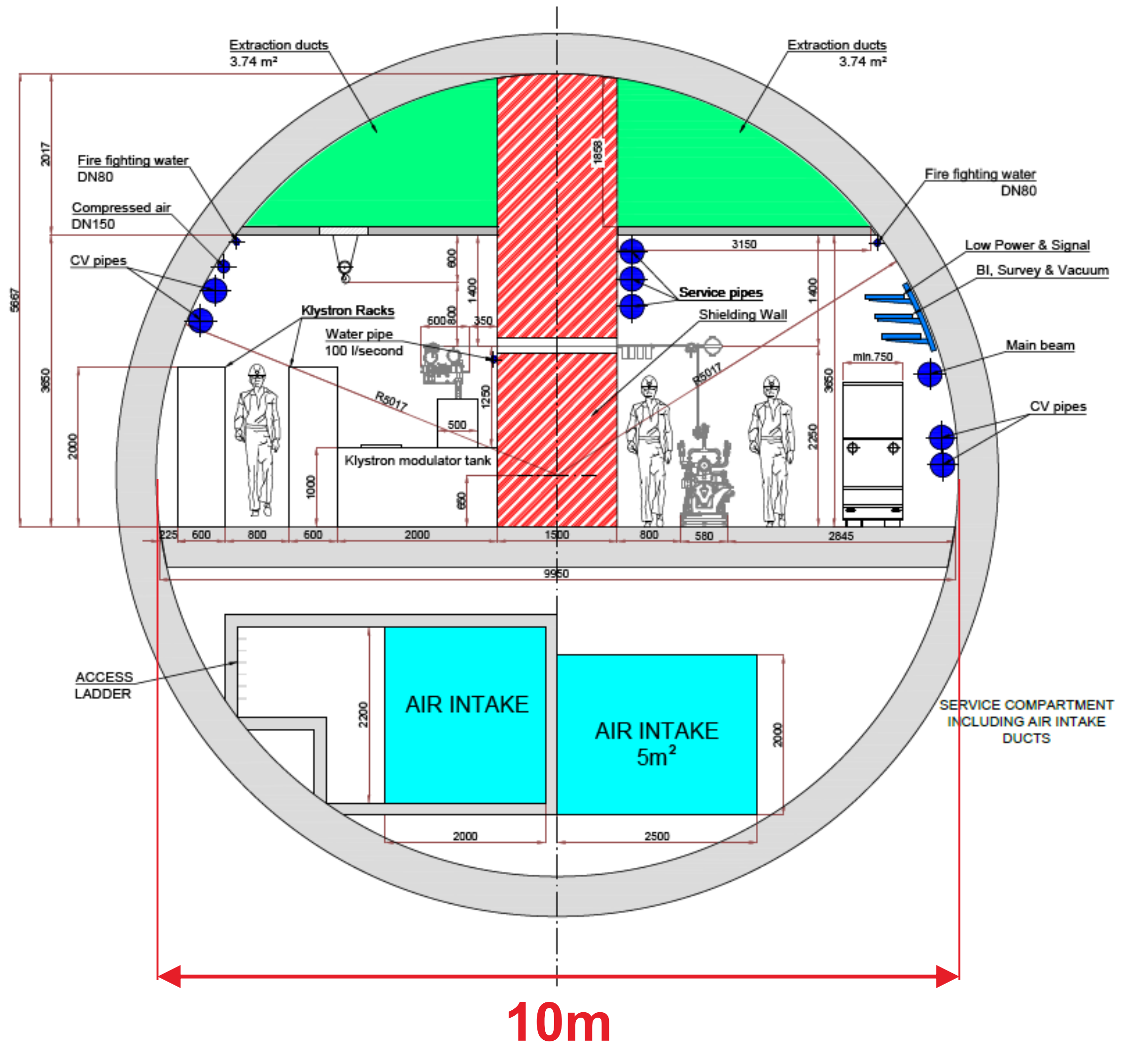
S. Evans

1. CLIC Drive Beam
5.6m internal dia. Geneva.
(380GeV, 1.5TeV, 3TeV)



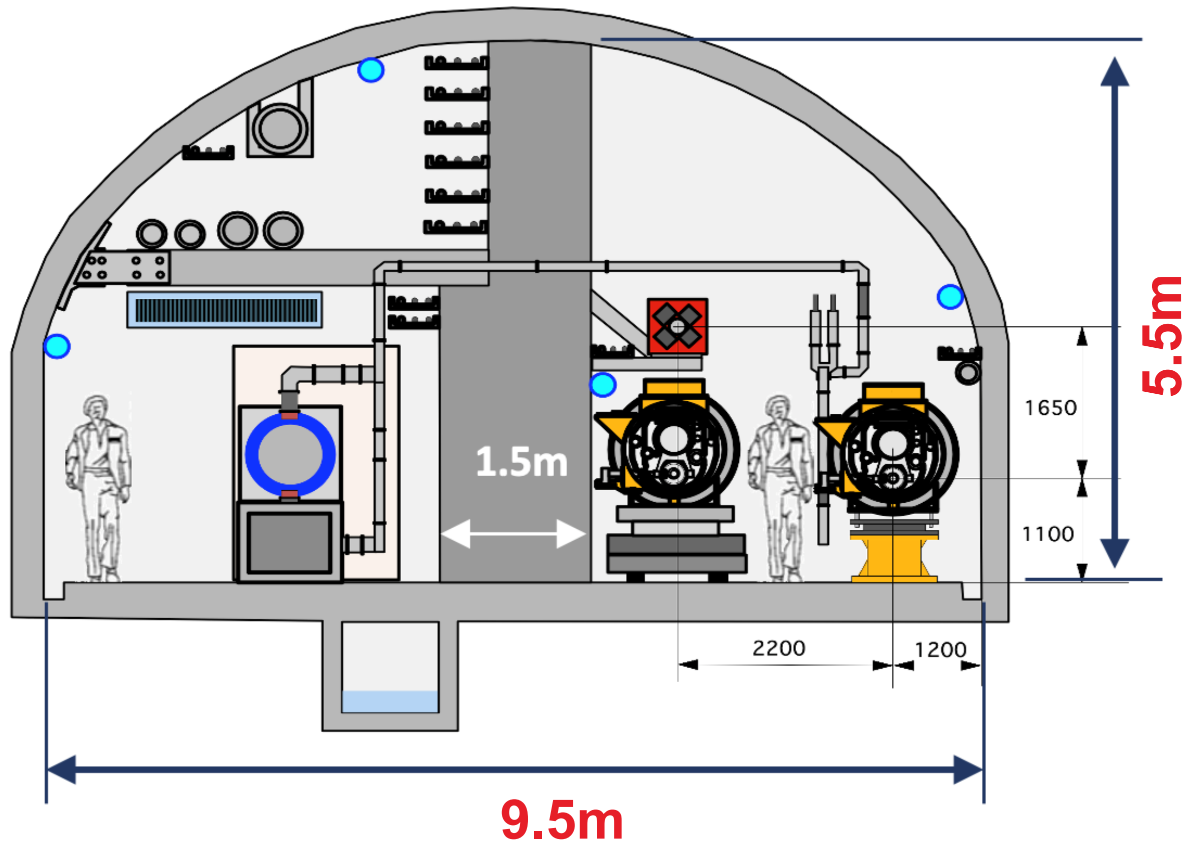
Reference: CLIC Drive Beam tunnel cross section, 2018

2. CLIC Klystron
10m internal dia. Geneva.
(380GeV)



Reference: CLIC Klystron tunnel cross section, 2018

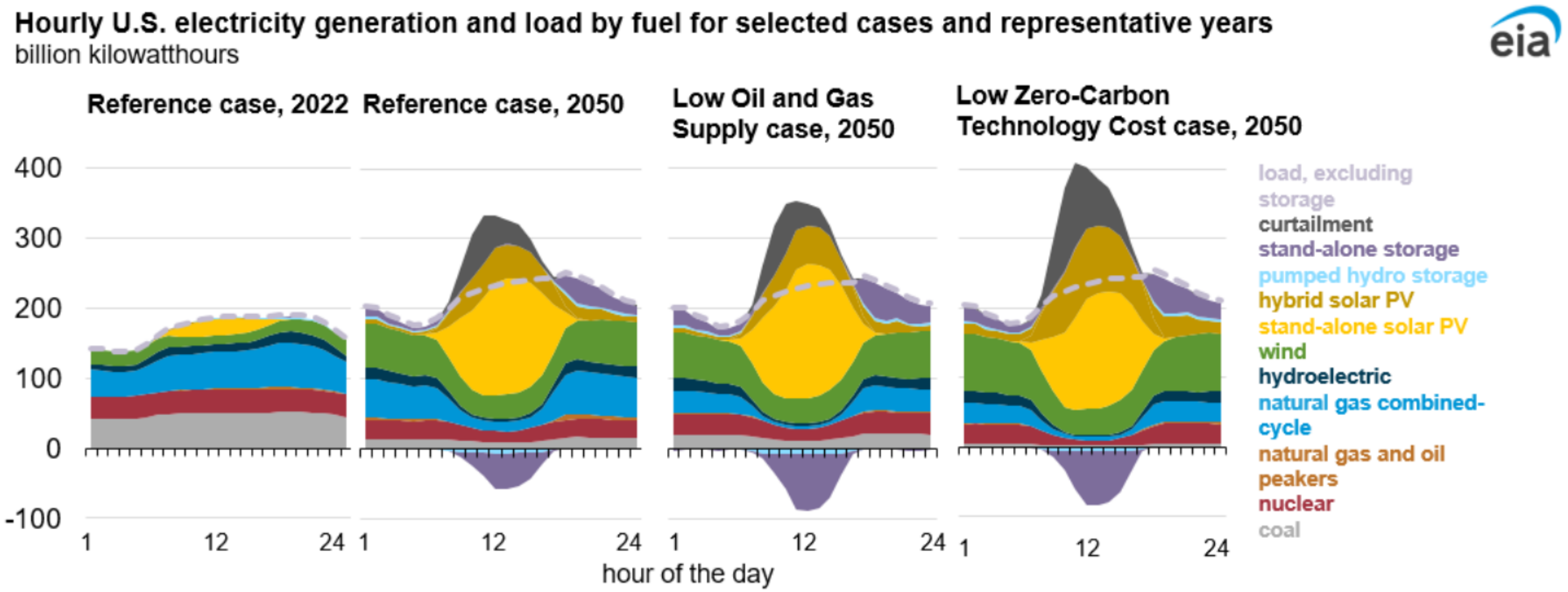
3. ILC
Arched 9.5m span. Japan.
(250GeV)



Reference: Tohoku ILC Civil Engineering Plan, 2020

Projected daily energy load curves by region (US)

Energy outlook March 16 2023



Data source: U.S. Energy Information Administration, *Annual Energy Outlook 2023* (AEO2023)
Note: Negative generation represents charging of energy storage technologies such as pumped hydro storage and battery storage. Hourly dispatch estimates are illustrative and are developed to determine curtailment and storage operations; final dispatch estimates are developed separately and may differ from total utilization as this figure shows. Standalone solar photovoltaic (PV) includes both utility-scale and end-use PV electricity generation.

Additional operating parameters

Higgs factory	CLIC [29]	ILC [28]	C^3 [3]	CEPC [30],[31]	FCC-ee [32],[24]
Center-of-mass energies considered $\sqrt{s}$ [GeV]	380	250, 500	250, 550	240,360	240, 340-350, 365
Site Power P [MW]	110	111 at 250 GeV 173 at 500 GeV	$\sim$ 150 at 250 GeV $\sim$ 175 at 550 GeV	340	290 at 240 GeV $\sim$ 350 at $340-350, 365$ GeV
Annual collision time T_{annual} [10^7 s/year]	1.20	1.60	1.60	1.30	1.08
Operational Efficiency ϵ	0.75	0.75	0.75	0.60	0.75
Site power fraction during downtime κ	0.3	0.5	0.3	0.5	0.5
Running time T_{run} [years]	8	11 at 250 GeV 9 at 500 GeV	10 at 250 GeV 10 at 550 GeV	10 at 240 GeV 5 at 360 GeV	3 at 240 GeV 1 at $340-350$ GeV 4 at 365 GeV
Instantaneous Luminosity/IP $\mathcal{L}_{\text{inst}}$ [$\cdot 10^{34}$ cm^{-2} s^{-1}]	2.3	1.35 at 250 GeV 1.8 at 500 GeV	1.3 at 250 GeV 2.4 at 550 GeV	8.3 at 240 GeV 0.83 at 360 GeV	8.5 at 240 GeV 0.95 at $340-350$ GeV 1.55 at 365 GeV
Target Integrated Luminosity $\mathcal{L}_{\text{int}}$ [ab^{-1}]	1.5	2 at 250 GeV 4 at 500 GeV	2 at 250 GeV 4 at 550 GeV	20 at 240 GeV 1 at 360 GeV	5 at 240 GeV 0.2 at $340-350$ GeV 1.5 at 365 GeV