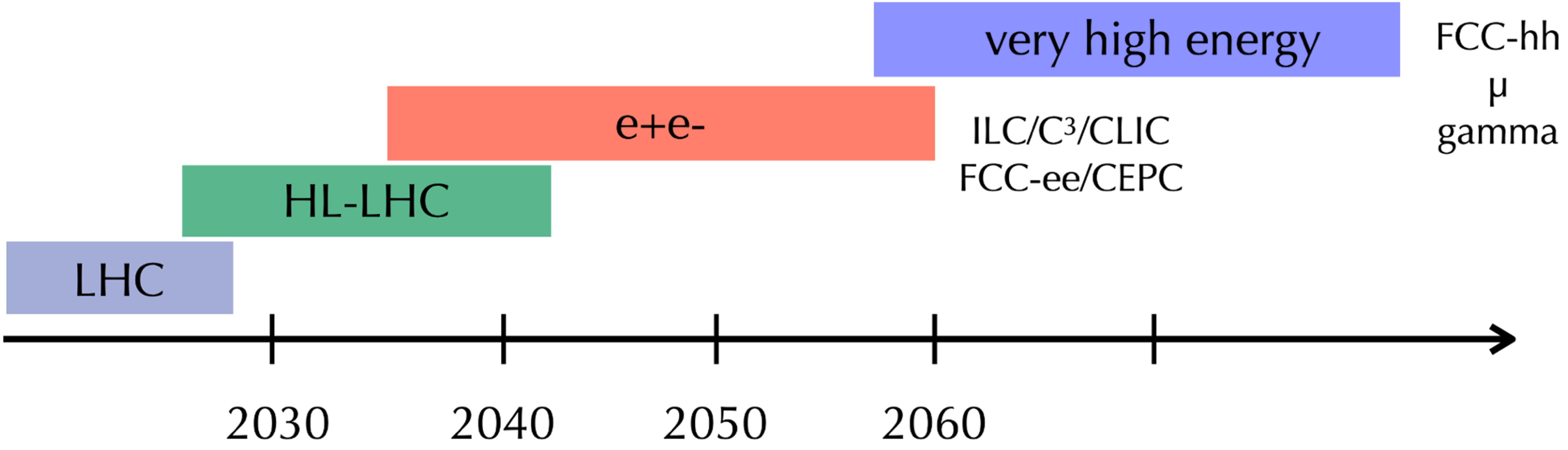
Energy Upgrades of a Linear Higgs Factory

2024 International Workshop on Future Linear Colliders

Emilio Nanni

July 8th, 2024

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

Decades Long Program of Higgs Physics and Discovery

Higgs Production at e^+e^-

ZH is dominant at **250 GeV**

Above **500 GeV**

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

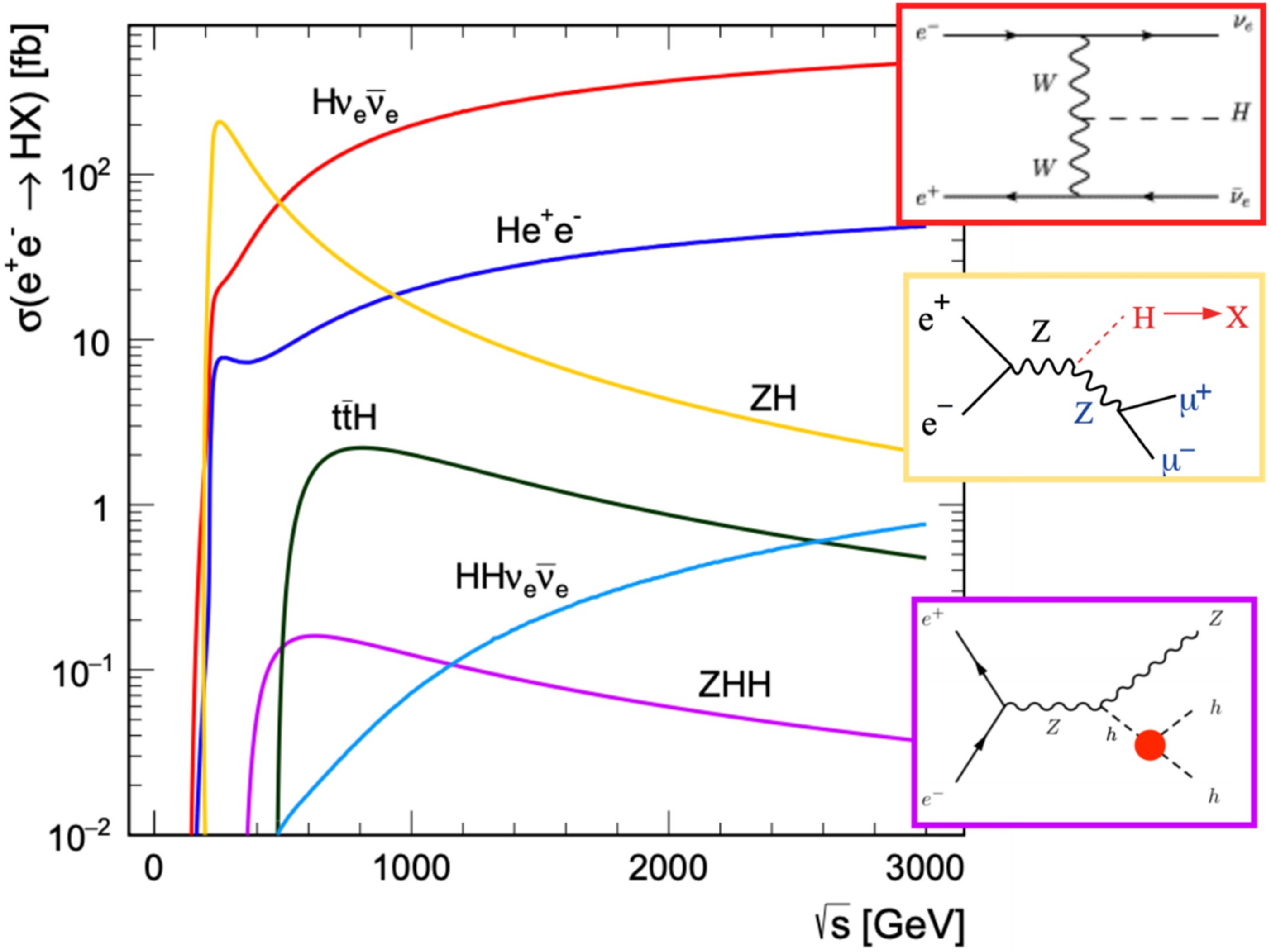
Global Vision for a Linear Collider Facility:

Mon July 8th

16:00-17:20 Ito Hall

Full Higgs Factory Program

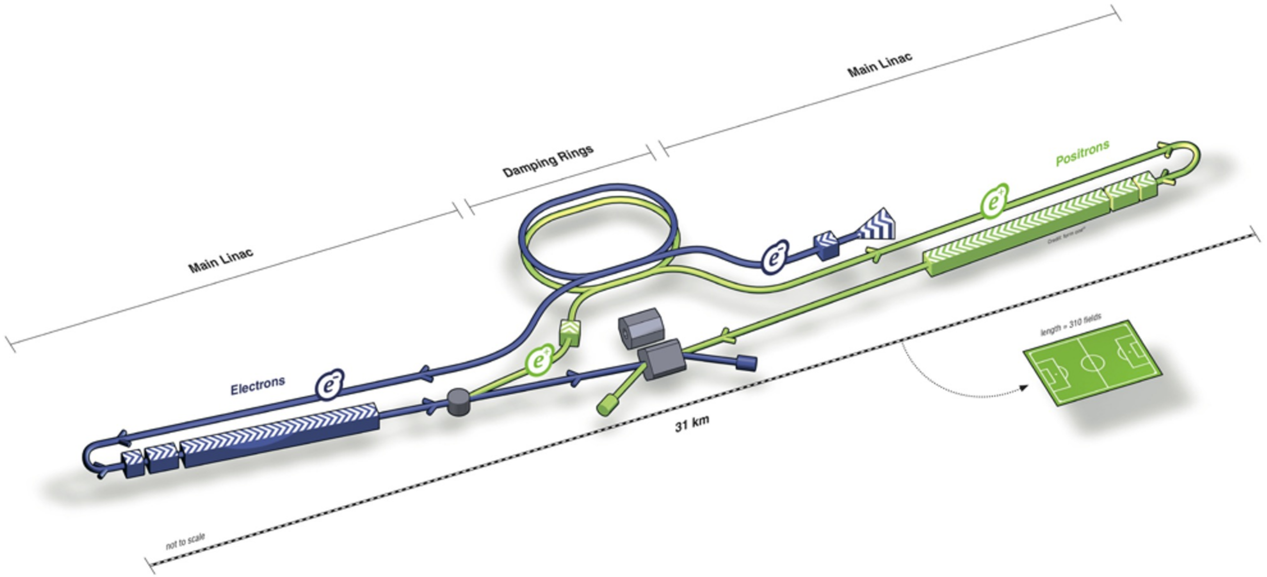
- 91 GeV to TeV scale
- BSM reach 100 TeV



Linear vs. Circular

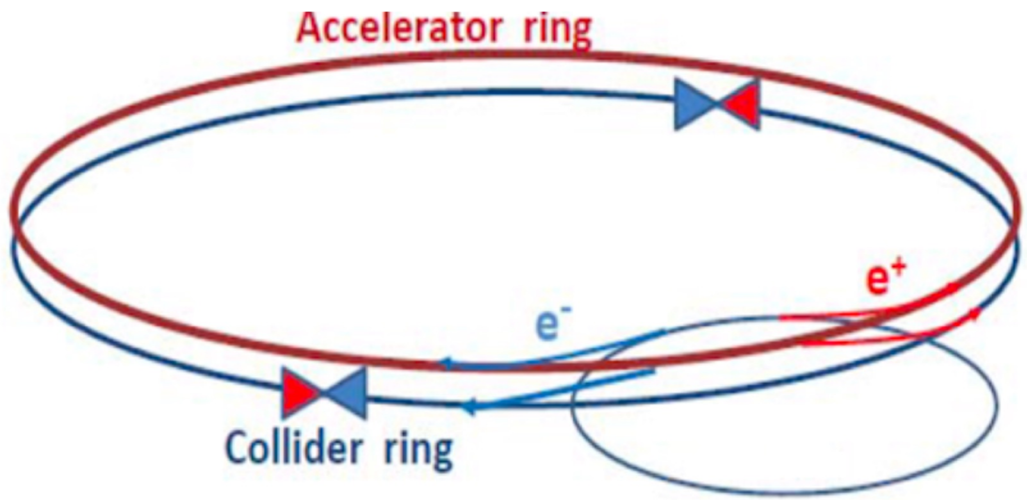
Linear e^+e^- colliders: ILC, C^3, CLIC

- Reach higher energies (~TeV), and can use polarized beams
- Relatively low radiation
- Collisions in bunch trains



Circular e^+e^- colliders: FCC-ee, CEPC

- Highest luminosity collider at Z/WW/ZH
- limited by synchrotron radiation above 350 – 400 GeV
- Beam continues to circulate after collision



Infrastructure, <u>Technology</u> and People Provide a Pathway for Future Discovery

Sustainable Scaling with Energy

Linear colliders maintain power efficiency with energy

Snowmass ITC comparison of collider parameters

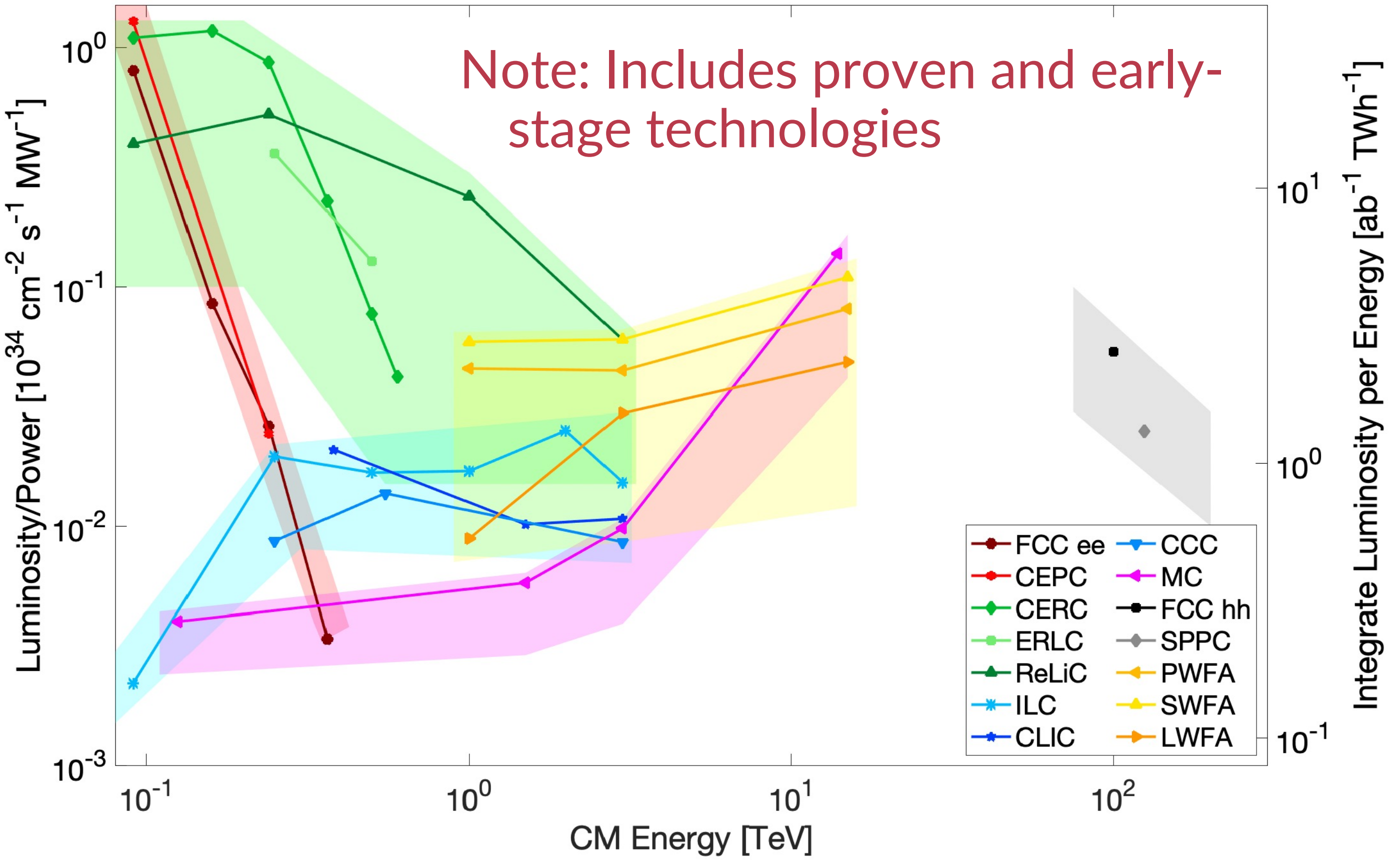
Inputs from 2021

Sustainability is an increasing focus of our community

Need community updates for EPPSU

Sustainability Session LCWS 2024:

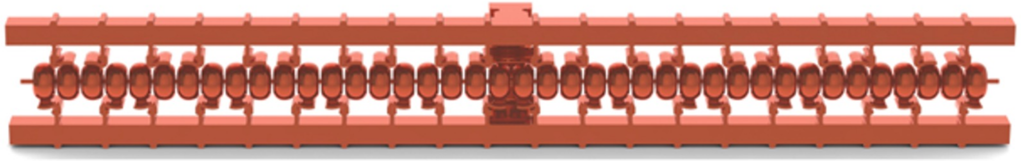
- Tuesday July 9th
- 15:45 - 17:45 Ito Hall https://agenda.linearcollider.org/event/10134/sessions/5589/#20240709



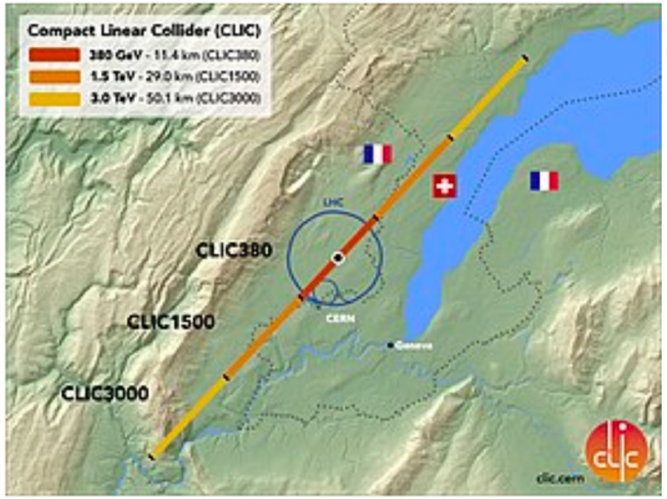
Linac Proposals or Technologies for Future Upgrades?

ILC 250/ 500 GeV

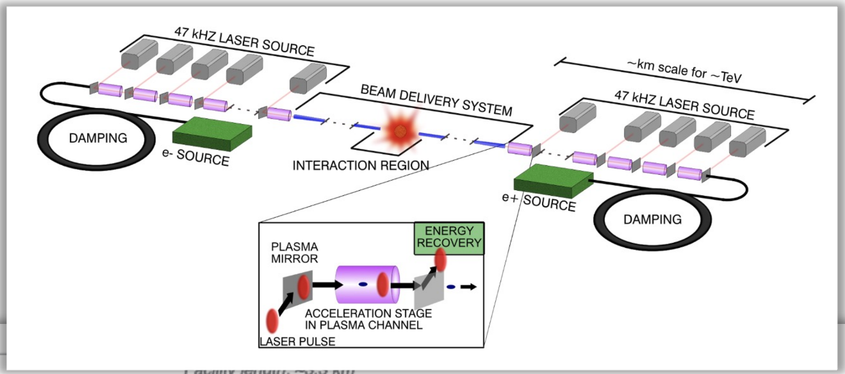
C³ 250/550 GeV … > TeV

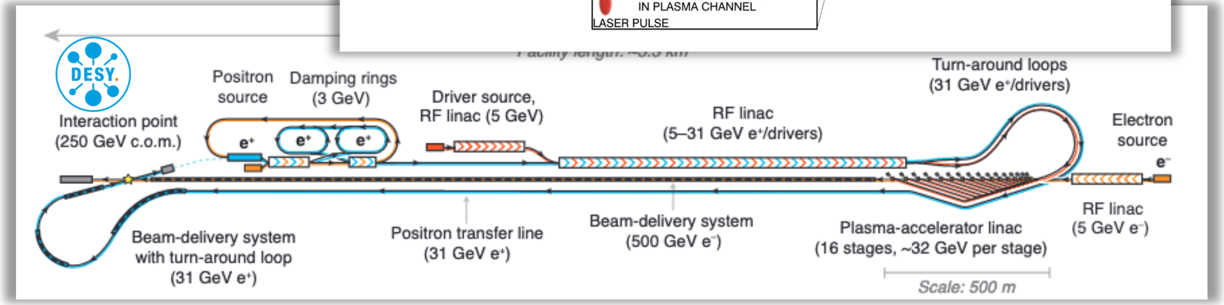


CLIC 380/1000/3000 GeV

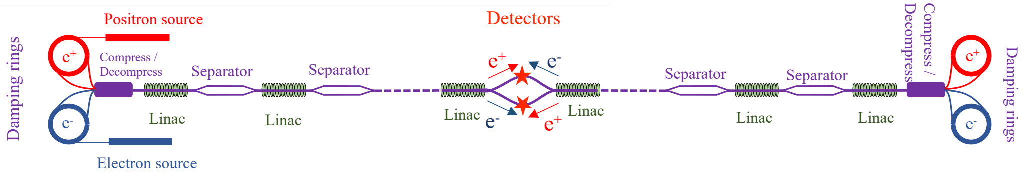


Wakefield Accelerators





Recirculating Linacs



LCWS 2024

ILC Baseline

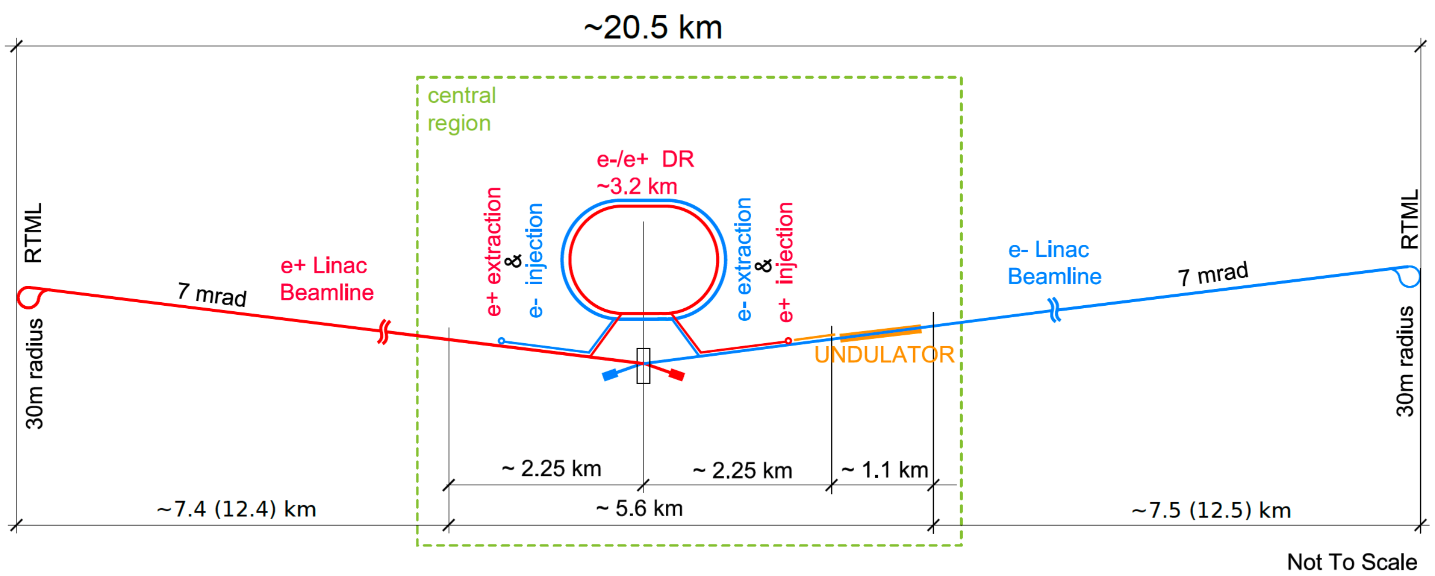
250 GeV Center of Mass Superconducting RF Linear Accelerator

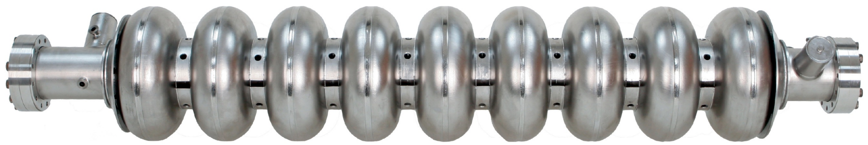
Established technology for main linac

Reusable Infrastructure:

- 2X 7.4 km large bore tunnel
- Electron and positron sources
- Damping rings
- Cryogenics
- Beam transport & turn arounds
- Beam delivery & final focus – upgradable or replaced

Existing HW reutilized (e.g. FELs)





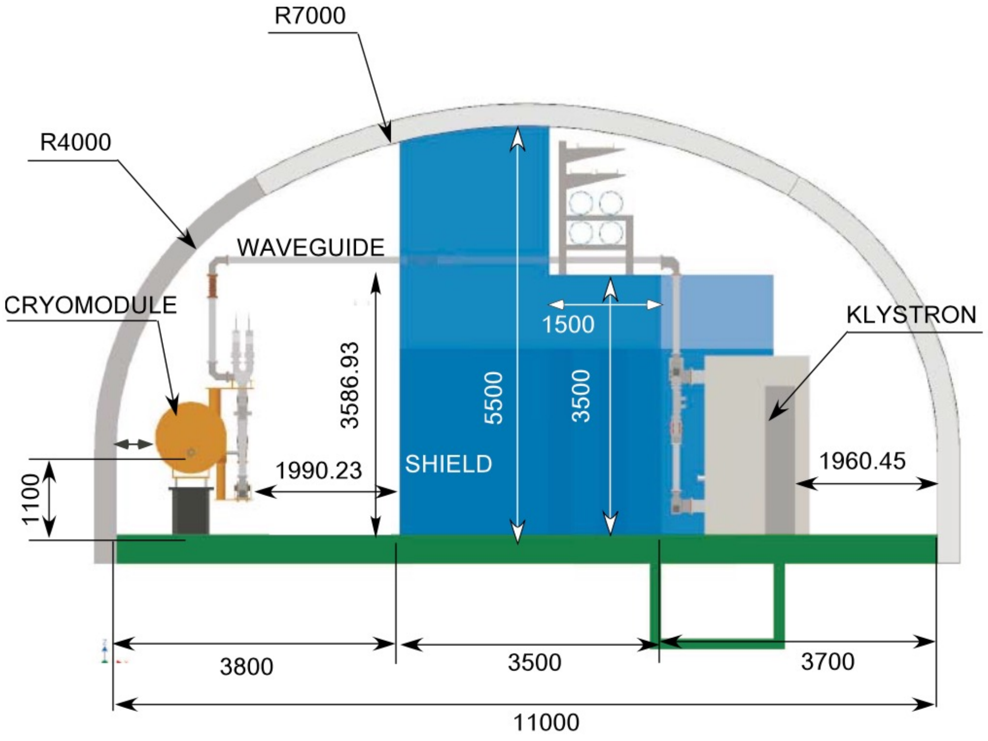
DESY-22-045, "The international linear collider: Report to snowmass 2021"

Why change technology? Energy Reach or Efficiency/Luminosity

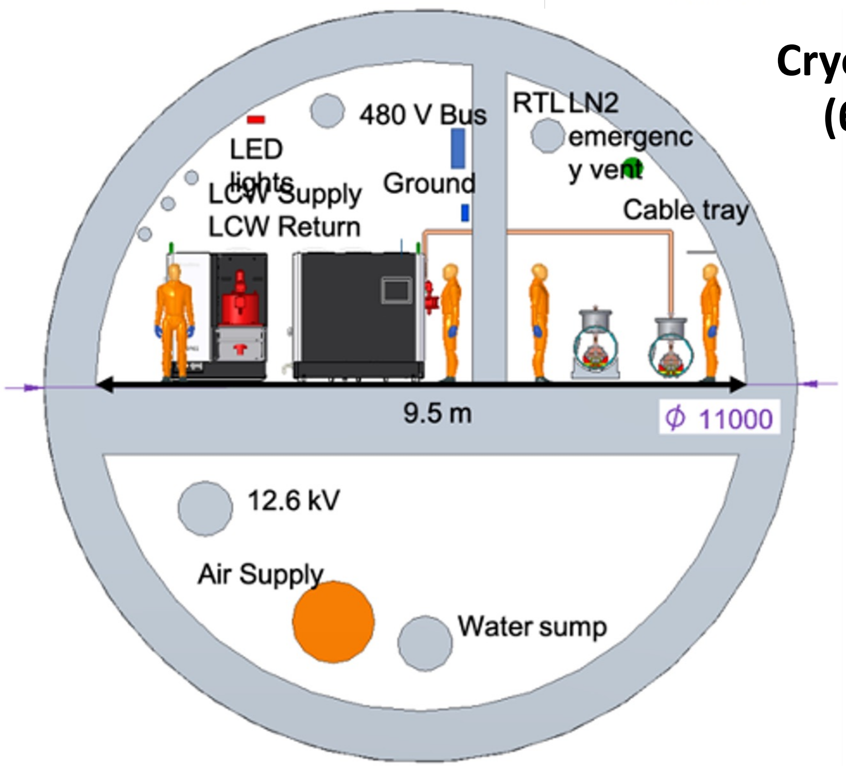
Constrain Imposed by Tunnel Dimensions

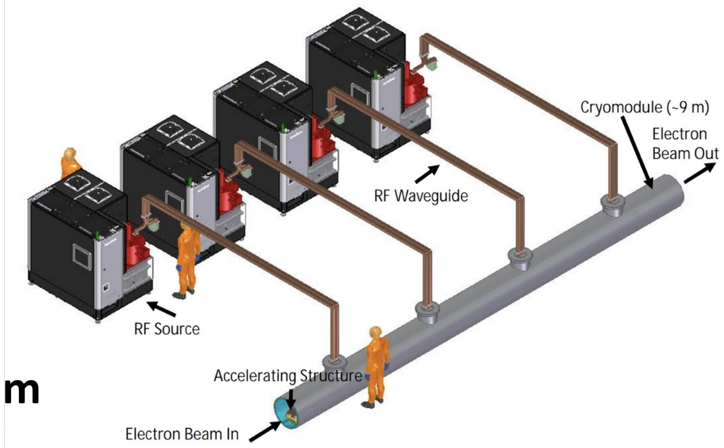
ILC provides a large tunnel suitable for multiple technologies

ILC
Usable Tunnel Width - 11 m



C³
Usable Tunnel Width - 9.5 m





Cryomodule Unit - 9 m
(630 MeV/1 GeV)

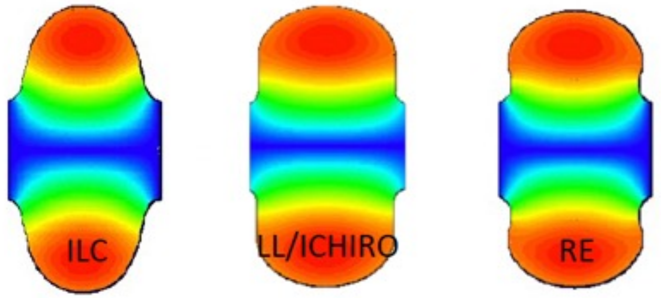
Pathways to Higher Energy

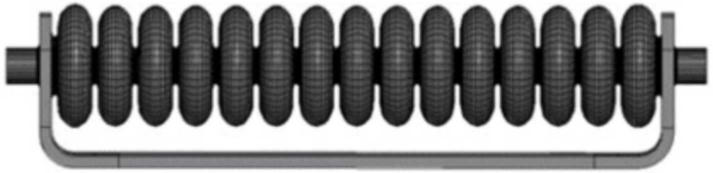
Assuming ILC 0.25 TeV – 20.5 km (2X 7.4 km for linac)

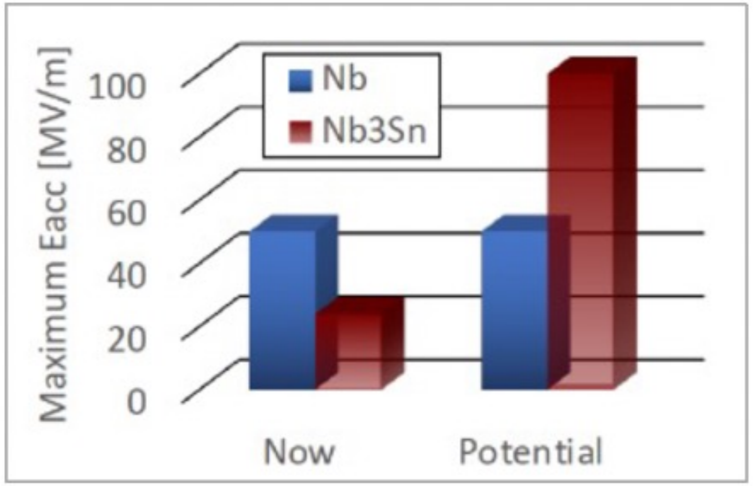
- 0.5 – 1 TeV
  - → SRF Materials and SRF Design
- 1 - 2 TeV
  - → Cold Copper and NCRF Design
  - → Two-Beam Accelerators
- O(10) TeV
  - → Wakefield Accelerators

SRF technology for ILC-250 beyond present limits

- Advanced shape standing wave SRF cavities – Low Loss (LL), ICHIRO,
- Reentrant (RE) – increase peak quench magnetic field by 10-20%, potentially bringing accelerating gradient limit to $\lesssim$ 60 MV/m
- Traveling wave (TW) SRF offers better cryogenic efficiency and higher accelerating gradient up to ~ 70 MV/m – possible application: ILC energy upgrade, HELEN collider, ACE at Fermilab
- Advanced SRF materials – Nb3Sn cavities can potentially reach ~ 90 MV/m







Cool Copper Collider

C^3 is based on a new rf technology

- Dramatically improving efficiency and breakdown rate

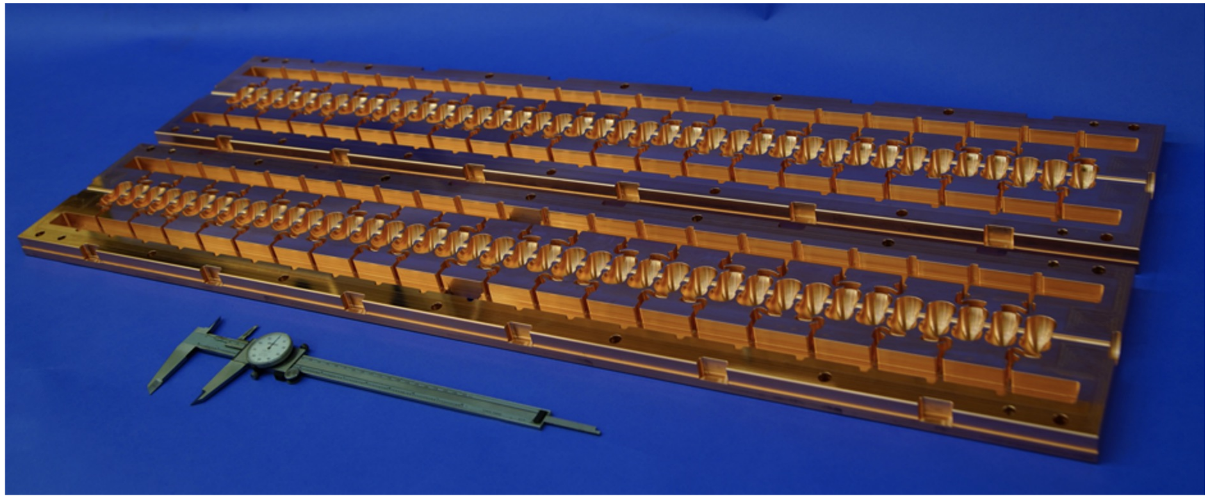
Distributed power to each cavity from a common RF manifold

Operation at cryogenic temperatures (LN_2 ~80 K)

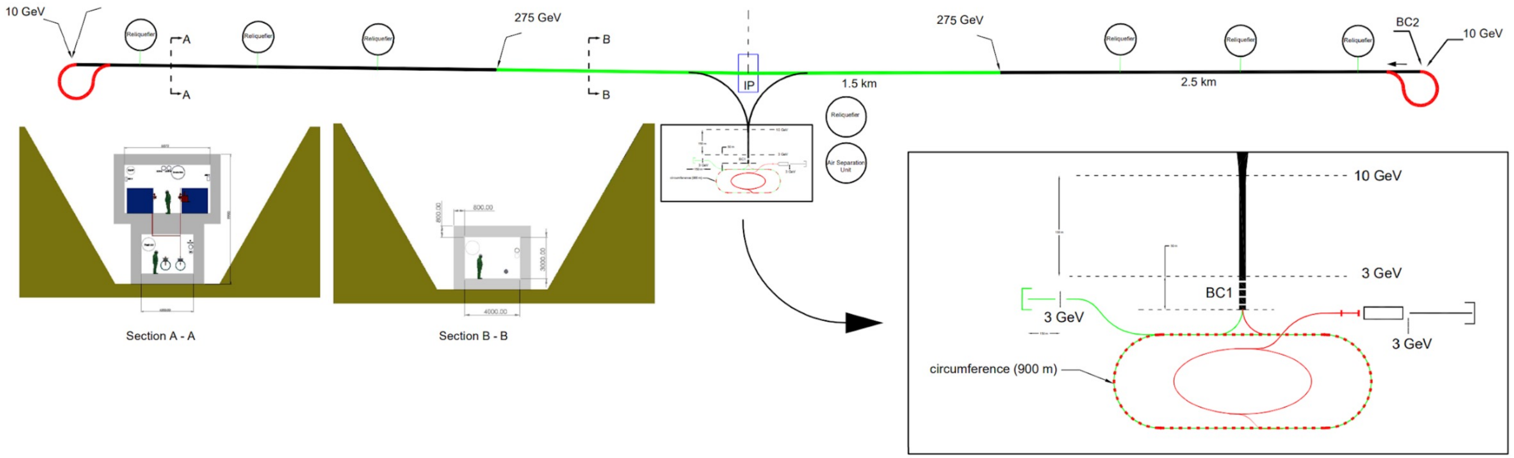
Potential for High gradient: 155 MeV/m

Scalable to multi-TeV operation

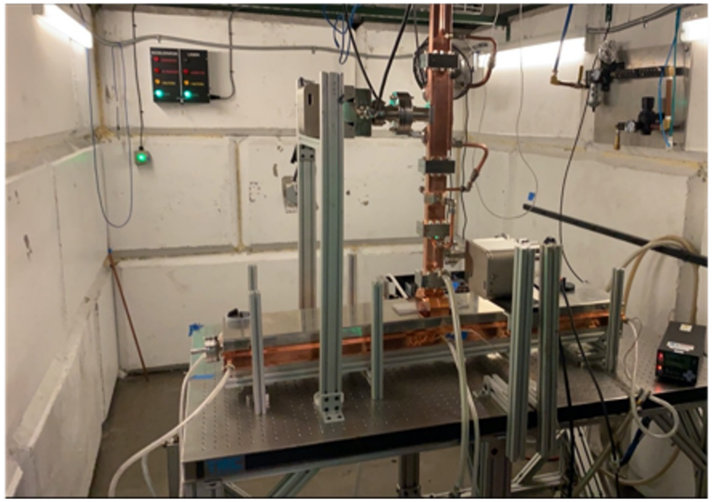
C^3 Prototype One Meter Structure



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

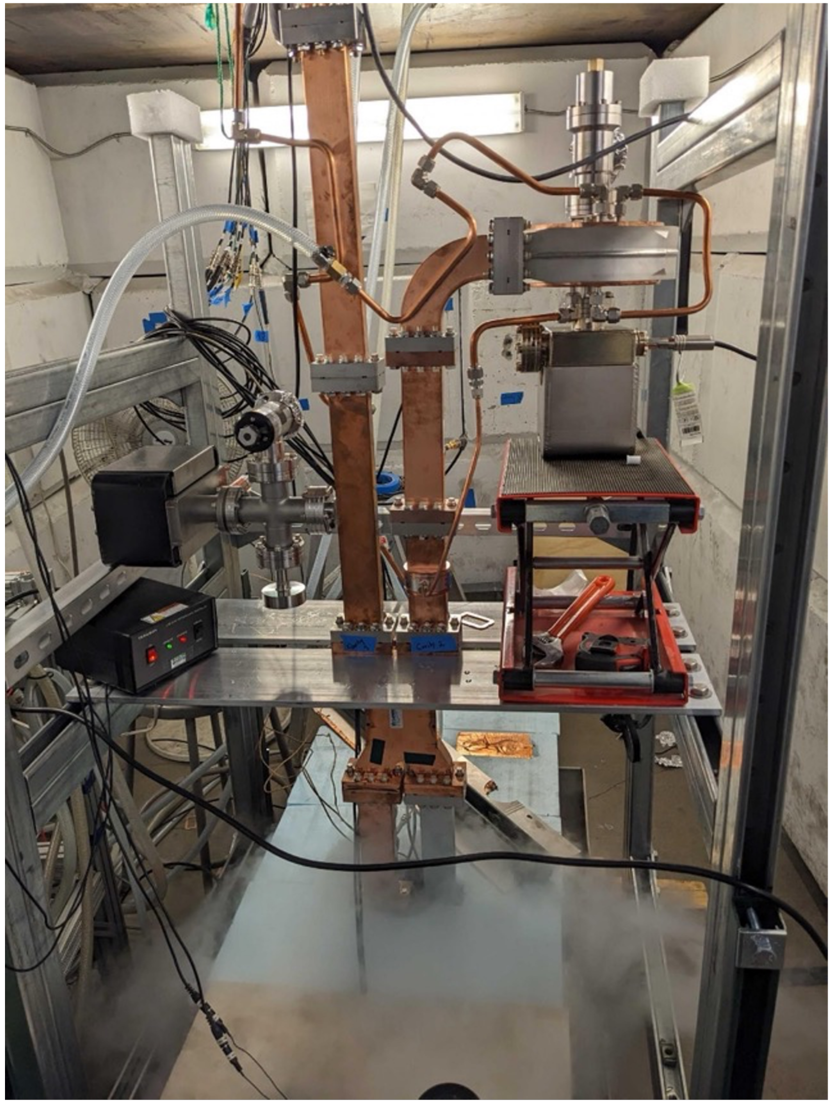


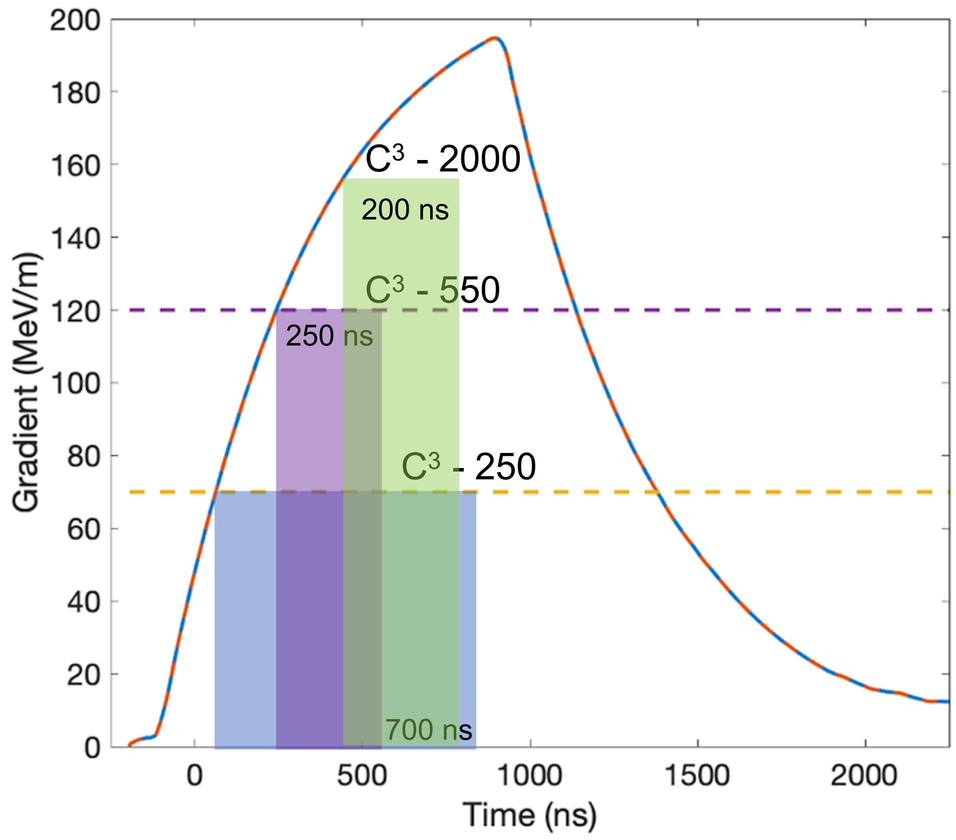
High power Test at Radiabeam



Exceeding Gradients and Pulse Lengths Required for C^3

- Measured and modeled response for single cell cavity





Energy Upgrade of ILC 250

Cryoplants replaced or modified

Injectors and damping rings reusable with fast kickers and extraction of bunch trains

Sustainability: Adoption of lower repetition rate, higher beam loading will improve power consumption

B. Bullard - Sustainability Session: Tuesday 16:15

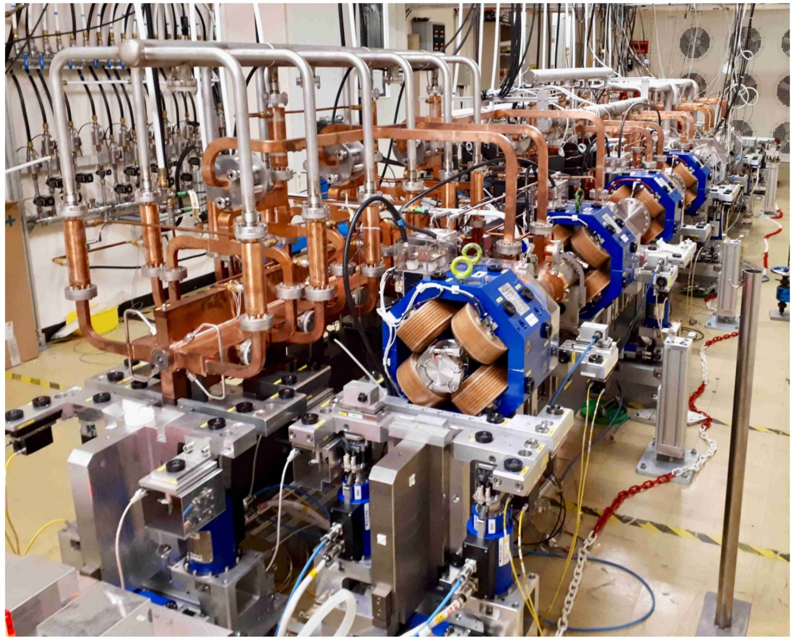
Parameter	Unit	Value	Value
Center of Mass Energy	GeV	1000	2000
Site Length	km	20	20
Main Linac Length (per side)	km	7.5	7
Accel. Grad.	MeV/m	75	155
Flat-Top Pulse Length	ns	500	195
Cryogenic Load at 77 K	MW	14	20
Est. AC Power for RF Sources	MW	68	65
Est. Electrical Power for Cryogenic Cooling	MW	81	116
RF Pulse Compression		N/A	3X
RF Source efficiency (AC line to linac)	%	50	80
Luminosity	$\mathrm{x}10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	∼4.5	∼9
Single Beam Power	MW	13.5	9
Injection Energy Main Linac	GeV	10	10
Train Rep. Rate	Hz	60	60
Bunch Charge	nC	1	1
Bunch Spacing	ns	3	1.2

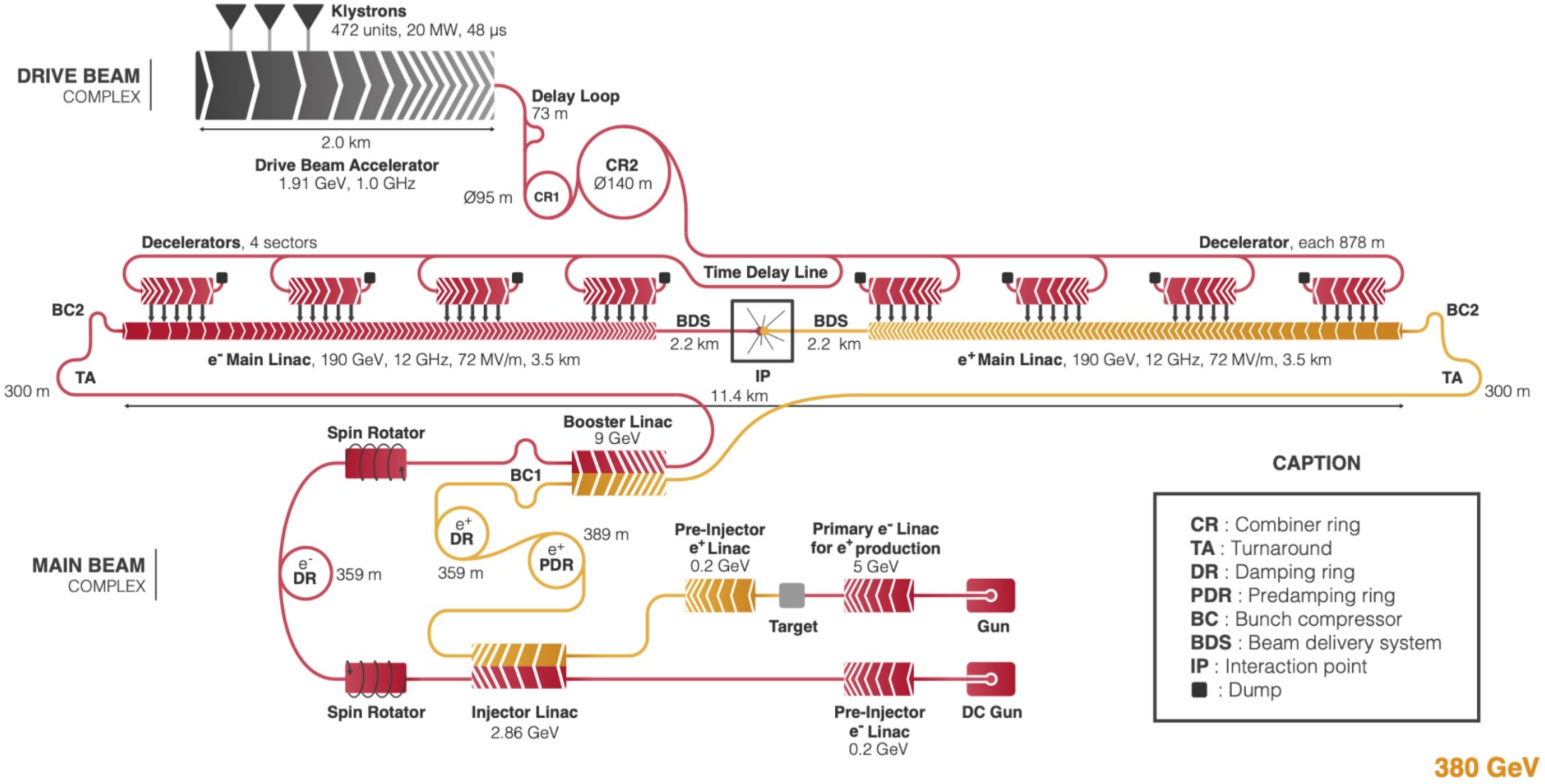
CLIC Two Beam Acceleration

High gradient achievable with CLIC accelerator technology

Efficient high power and low energy drive linac

Power extraction parallel to the main linac



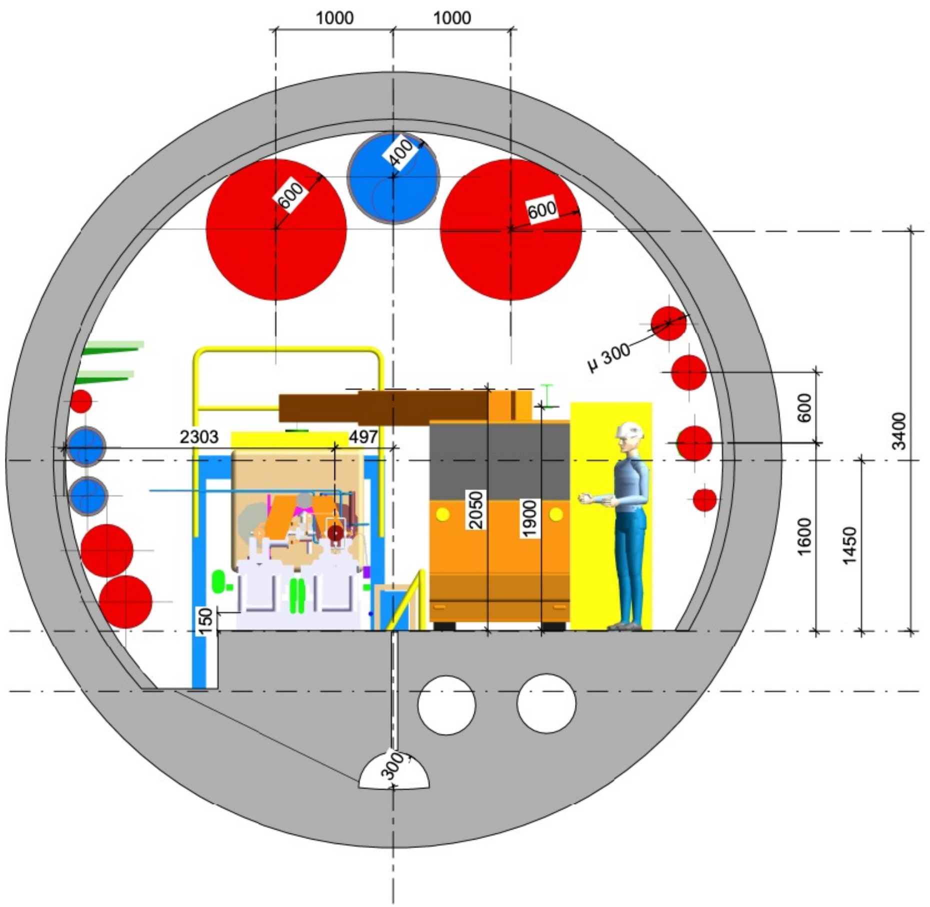


arxiv.org/pdf/2203.09186

CLIC Gradients for TeV Upgrade

CLIC modules operate at 100 MeV/m and fit easily in ILC main linac tunnel

Additional drive beam turnaround one possible complication



Nominal CLIC Parameters

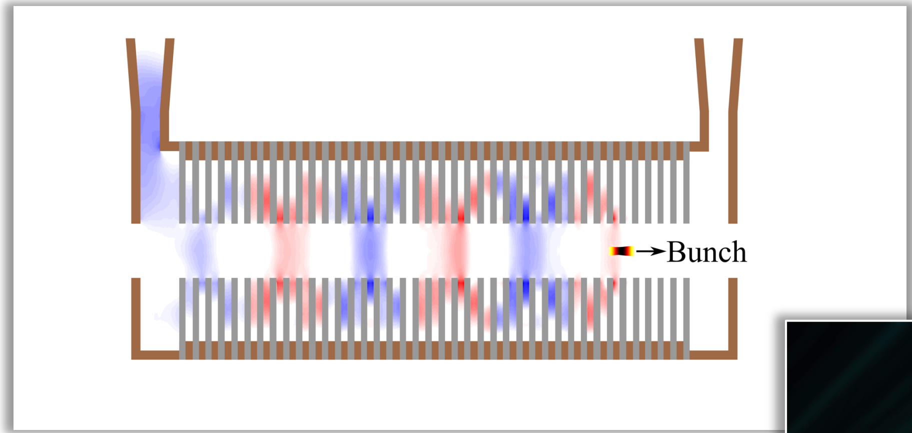
Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	10^9	5.2	3.7	3.7
Bunch length	µm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

arxiv.org/pdf/2203.09186

S. Gessner, P5 Town Hall 2023

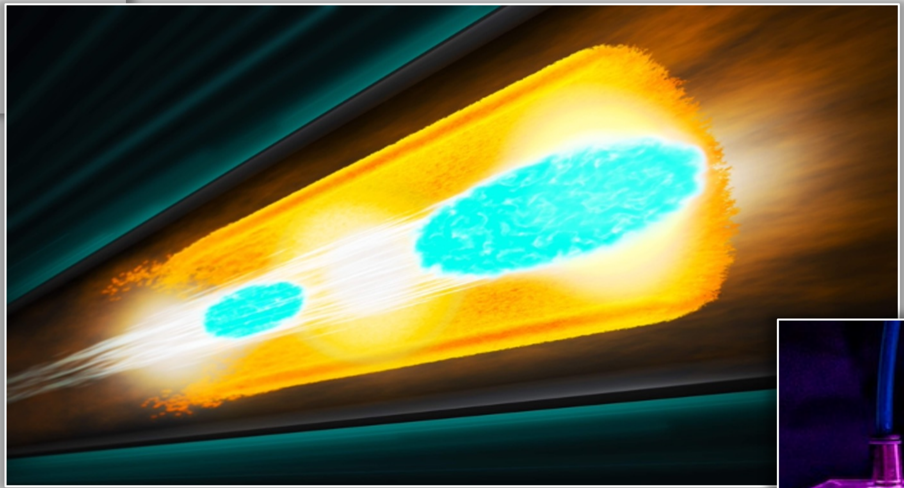
Wakefield Accelerator Technologies

Structure Wakefield Accelerators @

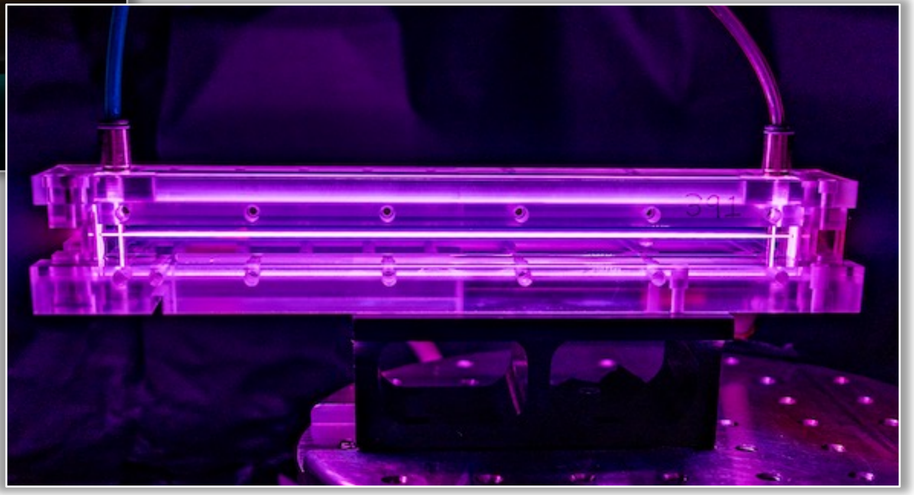


Argonne, SLAC, and LBNL are the stewards of SWFA, PWFA, and LWFA technology in the US, with university participation.

Beam Driven Plasma @ SLAC



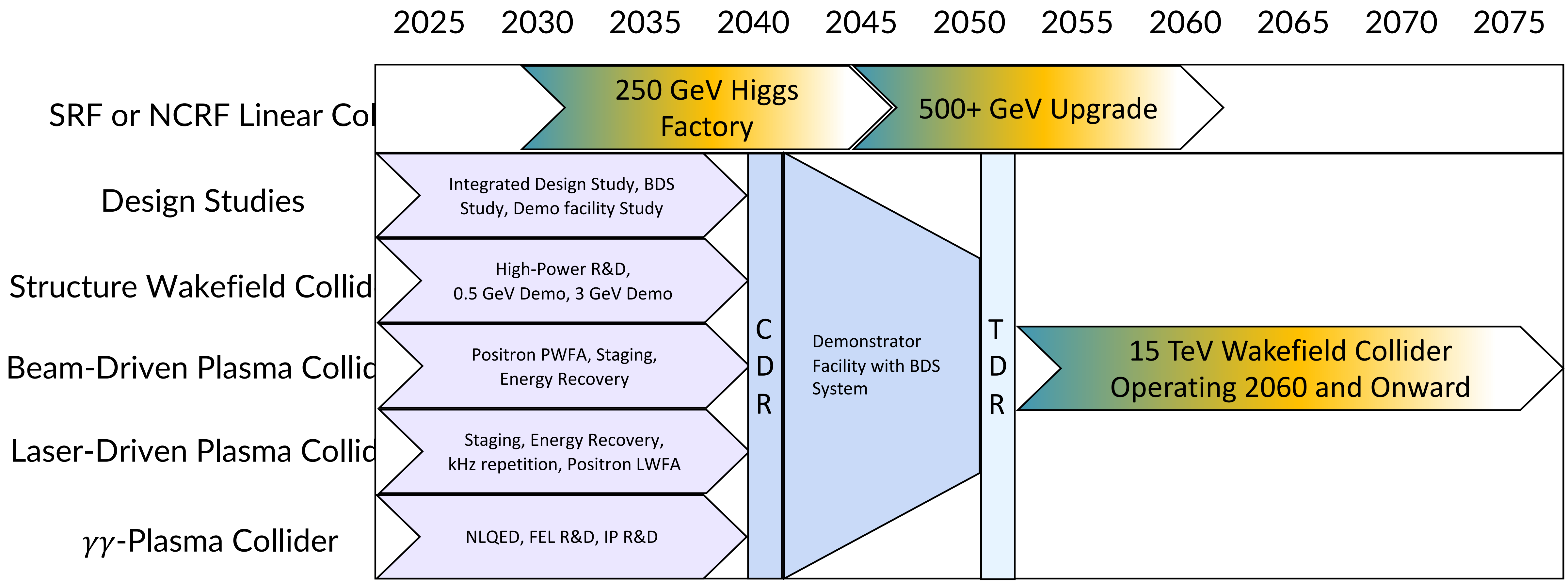
Laser Driven Plasma @ BERKELEY LAB



Key advantages:

Ultra-large gradients (1-100 GeV/m)
Ultra-short bunches (suppress beamstrahlung)

The Path to 10+ TeV



Wakefield Accelerators can be developed in parallel with the operation of Linear Collider Higgs Factories to provide a staged upgrade path to the energy frontier.

ACC Sessions at LCWS 2024 https://agenda.linearcollider.org/event/10134/sessions/5585/#20240709

Conclusions

Fundamental strength of a linear collider facility is the ability to increase energy

Achievable with the same technology and extension of length

Achievable improvement or replacement of main linac technology

- *e.g.* ILC 250 GeV with 20 km footprint can reach 2 TeV with C^3 technology

Vigorous Accelerator R&D needed to unlock this potential

Please Attend and Participate in the "Global Vision for a Linear Collider Facility"

https://agenda.linearcollider.org/event/10134/contributions/55143/