High-energy e+e- colliders

Philip Burrows

Oxford University

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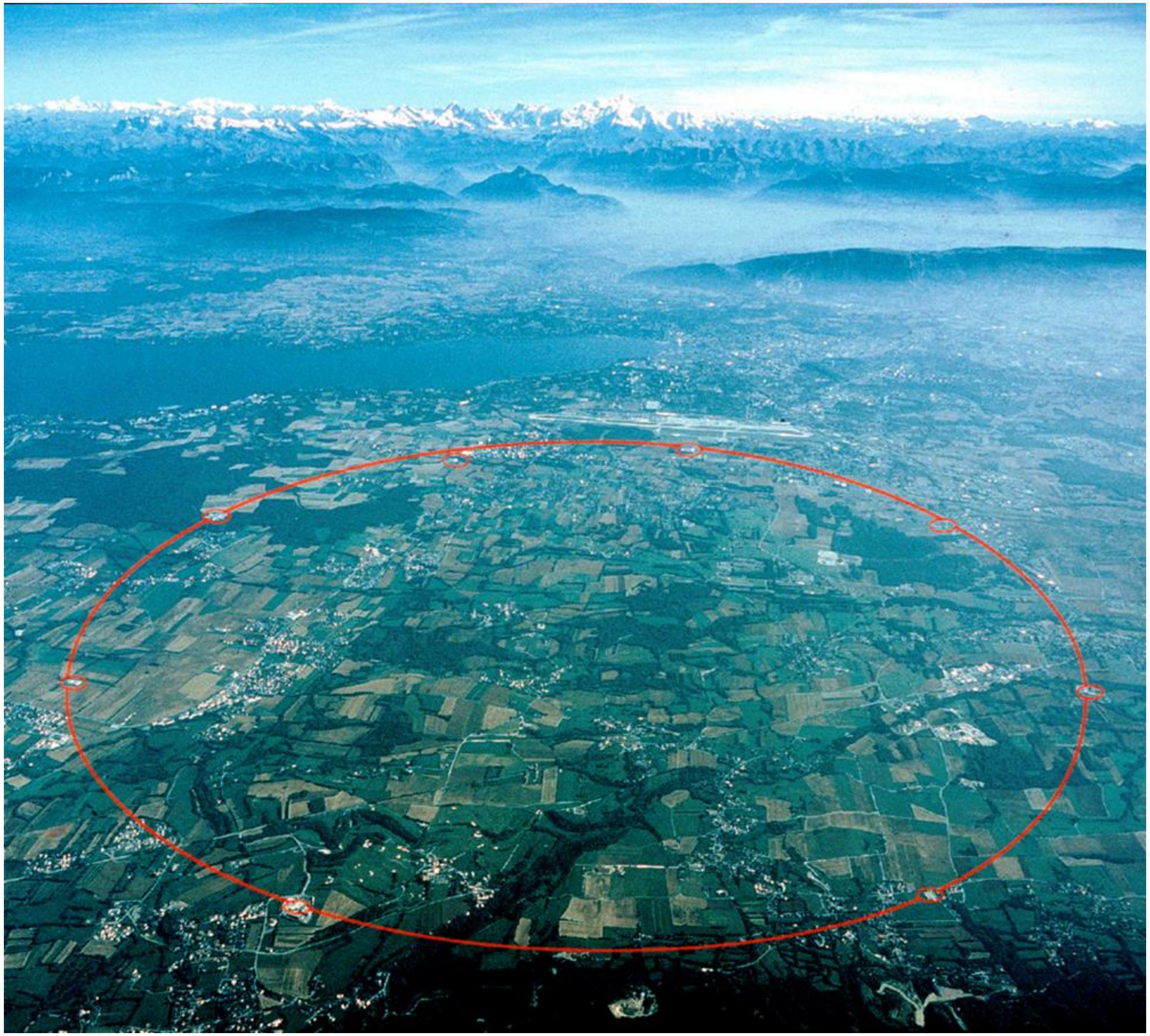
ILC: https://linearcollider.org
CLIC: https://clic.cern
FCC: https://home.cern/science/accelerators/future-circular-collider
CEPC: http://cepc.ihep.ac.cn/

Outline

- Introduction + overview
- FCCee / CEPC
- ILC
- CLIC
- UK R&D + technology capability
- Outlook

Large Electron-Positron Collider (LEP)



up to

c. 100 GeV

per beam

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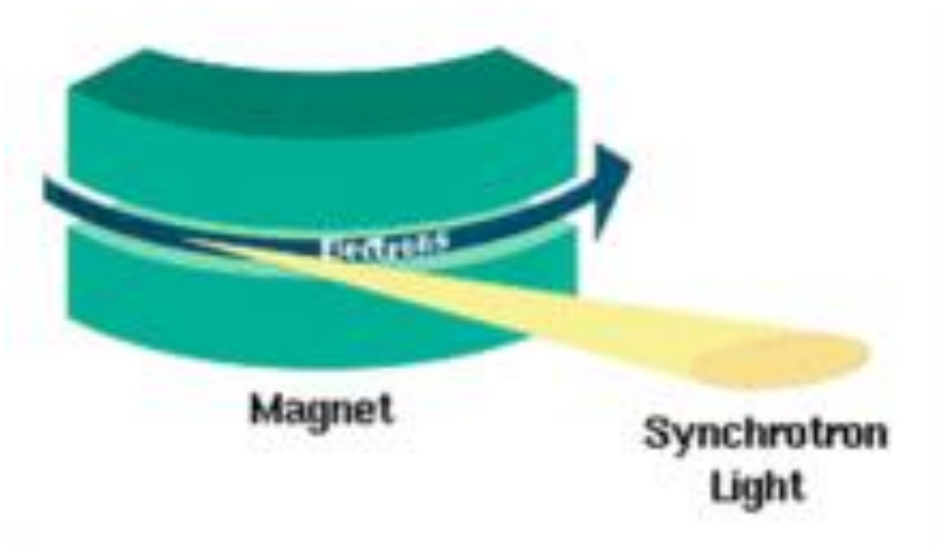
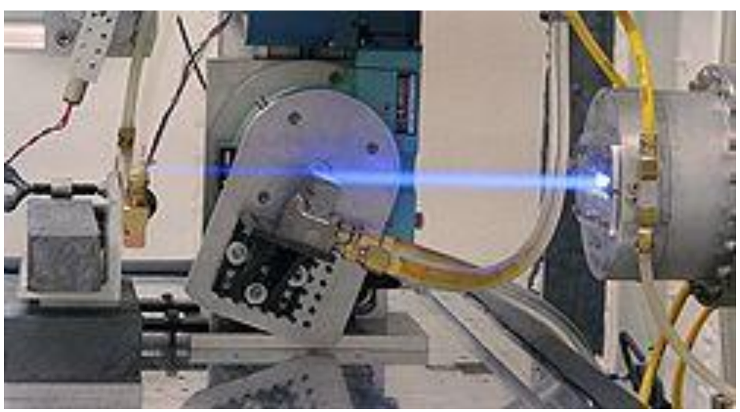
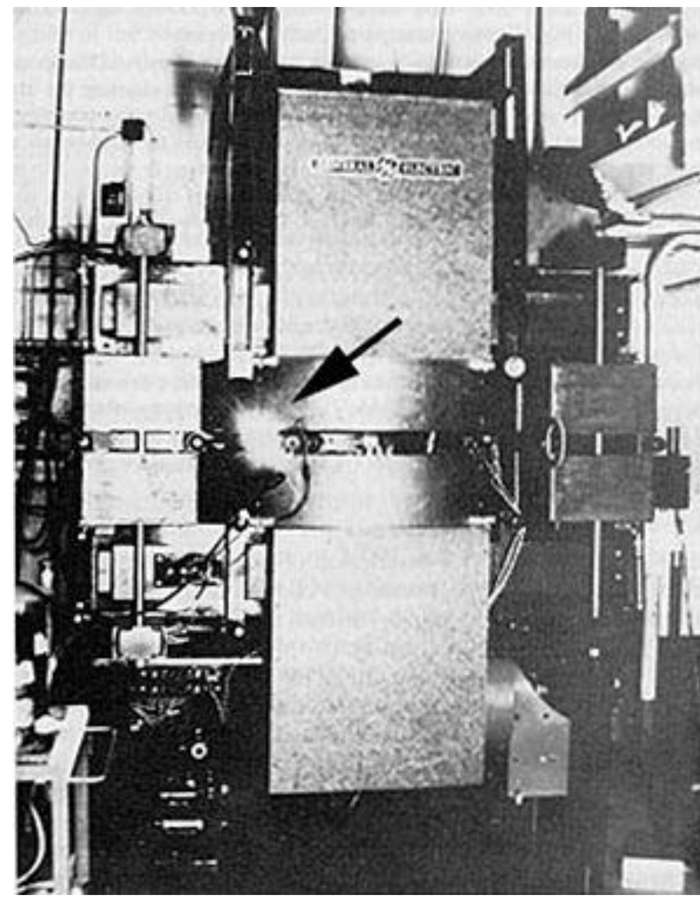
Synchrotron radiation



Discovered Elder et al 1947 (General Electric)





Synchrotron radiation

Power lost due to synchrotron radiation $P_{SR} \sim \gamma^4 / \rho^2$

$\gamma = E / m_0$, ρ = radius of trajectory

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For LEP (100 GeV, 27km)

each electron would lose ~ 3 GeV / turn

Synchrotron radiation

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$P = 10^{-6}$ Watts/electron → 18 MW total

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For LEP (100 GeV, 27km)

each electron would lose ~ 3 GeV / turn

$P = 10^{-6}$ Watts/electron → 18 MW total

→ compensate with RF cavities

Synchrotron radiation

Suppose we increase LEP beam energy (100 GeV) by factor 5: E → 500 GeV, in the same tunnel

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Synchrotron radiation

Suppose we increase LEP beam energy (100 GeV) by factor 5: E → 500 GeV, in the same tunnel

$P_{SR} \sim \gamma^4 / \rho^2$

γ increases by factor 5, so P increases by 5^4

this would give $P_{SR} = 5^4 * 18$ MW = 11 GW!

Compensate by increasing radius ρ?

Need 10 x ρ to reduce P_{SR} by 100 → 270km tunnel!

SLAC Linear Collider (SLC)

c. 50 GeV per beam

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SLAC Linear Collider (SLC)

Luminosity vs c.m. energy

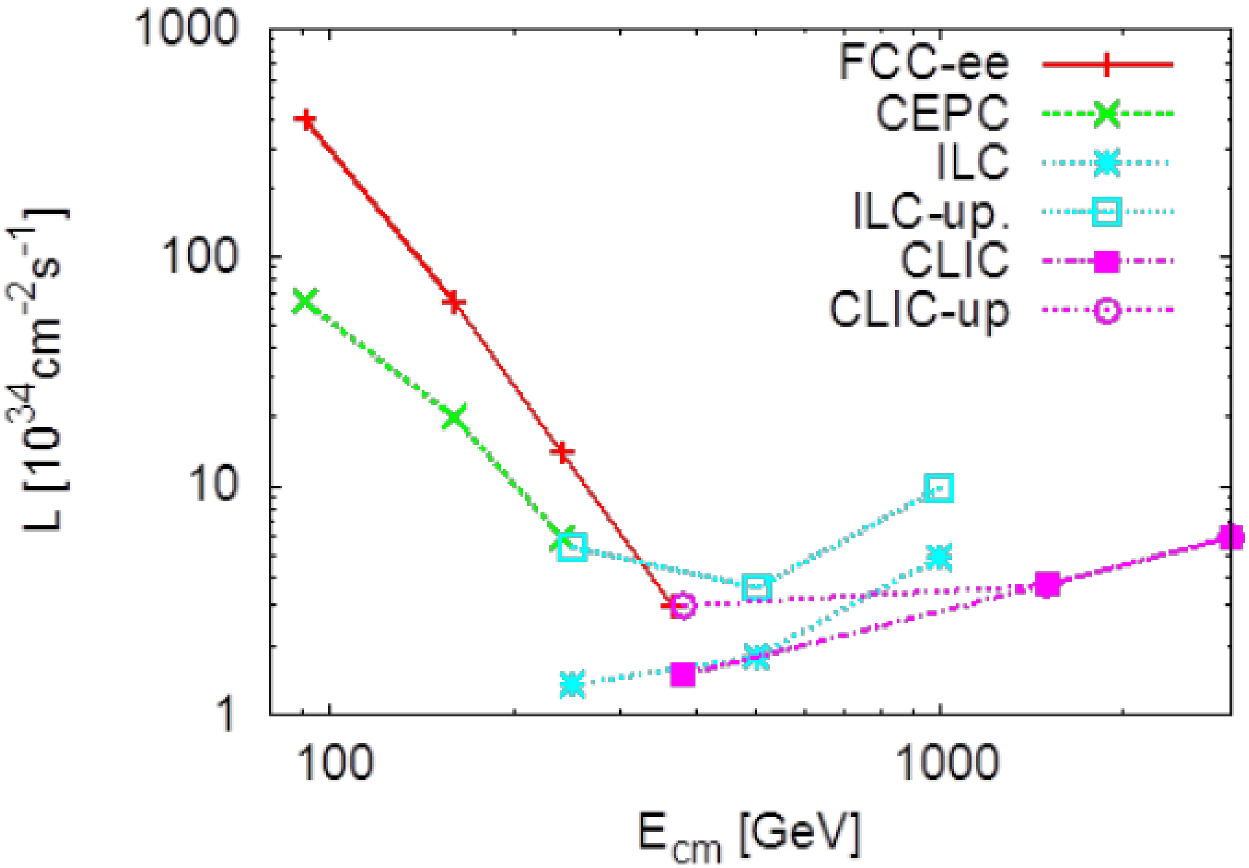

Fig. 10.2: Luminosity versus c.m. energy for e^+e^- Higgs Factories. Two IPs are assumed for the circular colliders FCC-ee and CEPC.

EPPSU 2020 Briefing Book
https://arxiv.org/abs/1910.11775

Collider options

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N_{Det}	$\mathscr{L}_{\mathrm{inst}}$/Det. $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\mathscr{L}$ $[\mathrm{ab}^{-1}]$	Time [years]	Ref.
HL-LHC	pp	14 TeV	–	2	5	6.0	12	[23]
HE-LHC	pp	27 TeV	–	2	16	15.0	20	[23]
FCC-hh	pp	100 TeV	–	2	30	30.0	25	[637]
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[637]
		$2M_W$	0/0	2	25	10	1-2	
		240 GeV	0/0	2	7	5	3	
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5	
		(1y SD before $2m_{top}$ run)					(+1)	
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[342]
		350 GeV	±80/±30	1	1.6	0.2	1	[346]
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5	
		(1y SD after 250 GeV run)					(+1)	
CEPC	ee	M_Z	0/0	2	17/32	16	2	[509]
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		240 GeV	0/0	2	3	5.6	7	
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[638]
		1.5 TeV	±80/0	1	3.7	2.5	7	
		3.0 TeV	±80/0	1	6.0	5.0	8	
		(2y SDs between energy stages)					(+4)	
LHeC	ep	1.3 TeV	–	1	0.8	1.0	15	[636]
HE-LHeC	ep	1.8 TeV	–	1	1.5	2.0	20	[637]
FCC-eh	ep	3.5 TeV	–	1	1.5	2.0	25	[637]

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e+e- collider options

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Luminosity around 250 GeV

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N_{Det}	$\mathscr{L}_{\text{inst}}$/Det. $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]	Ref.
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Luminosity around 350 GeV

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500 GeV and above

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Around 91 GeV

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FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[637]	**Tera Z**
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		
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		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		
		91 GeV			**0.2/0.4**				**Giga Z**
CEPC	ee	M_Z	0/0	2	17/32	16	2	[509]	
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
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Number of IPs

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		(2y SDs between energy stages)					(+4)	

4 also possible (FCC-ee)

2 also possible (ILC)

4 also possible (CEPC)

2 also possible (CLIC)

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Longitudinal beam polarisation

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N_{Det}	$\mathscr{L}_{\mathrm{inst}}$/Det. $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\mathscr{L}$ $[\mathrm{ab}^{-1}]$	Time [years]	Ref.
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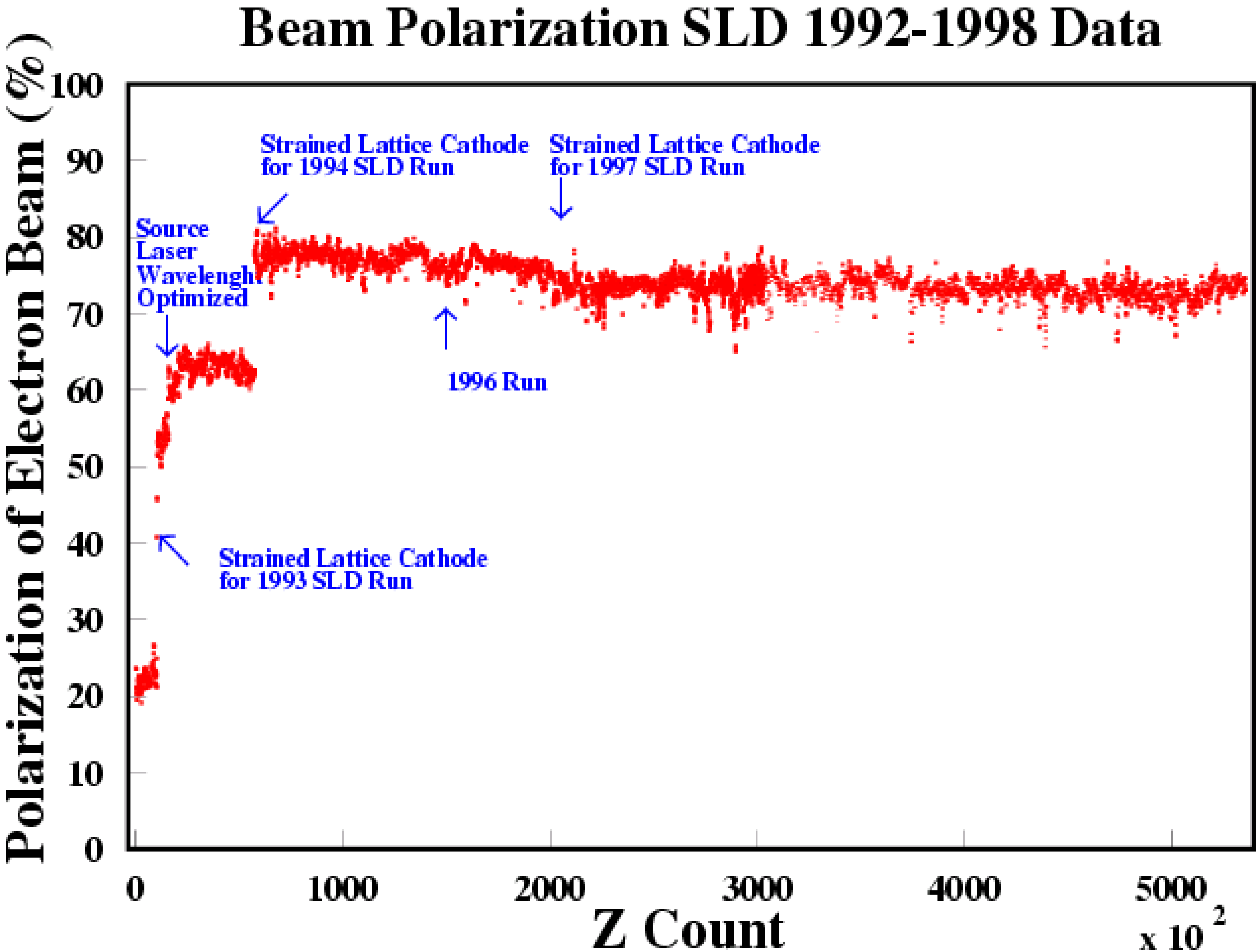
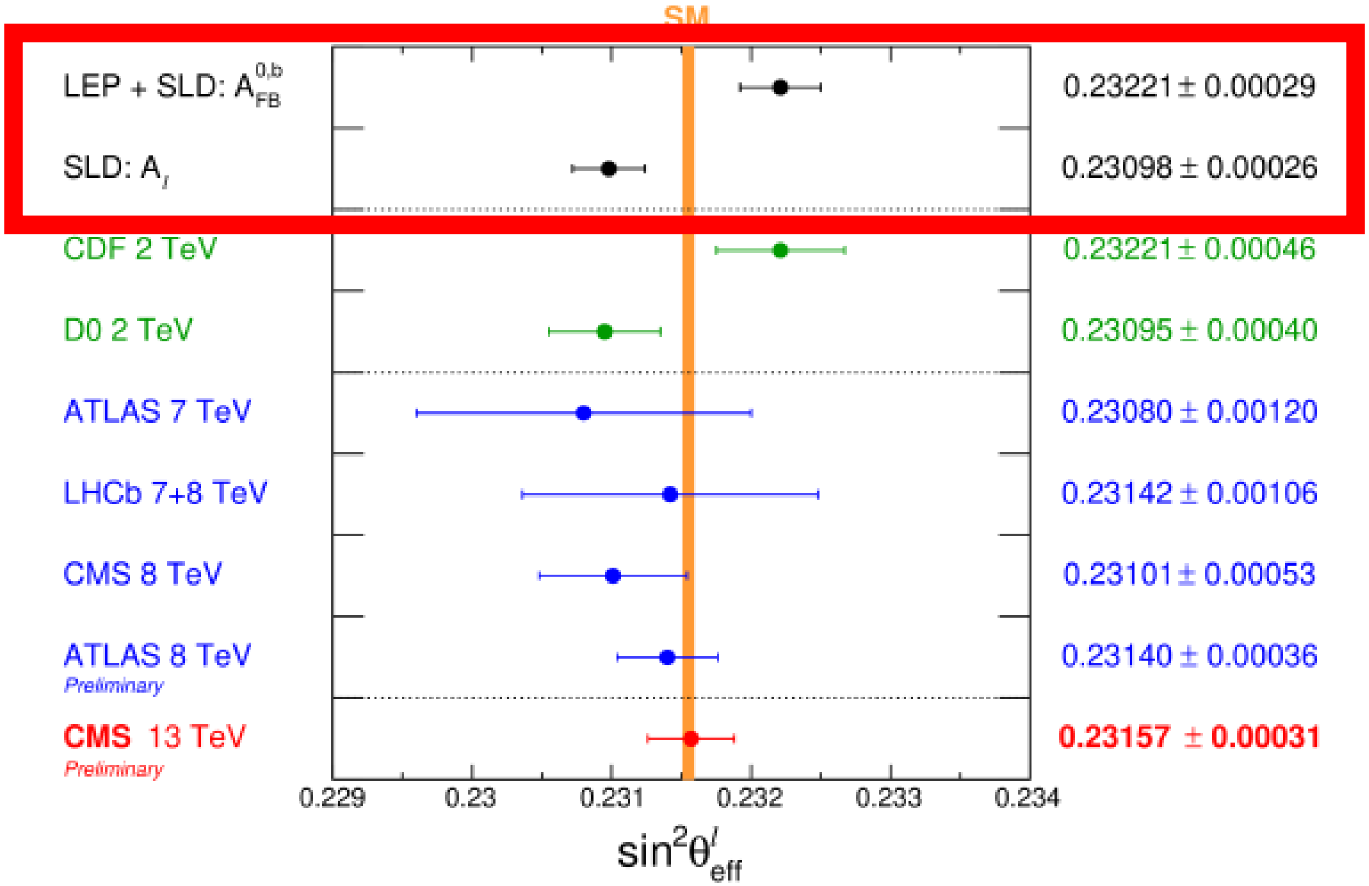
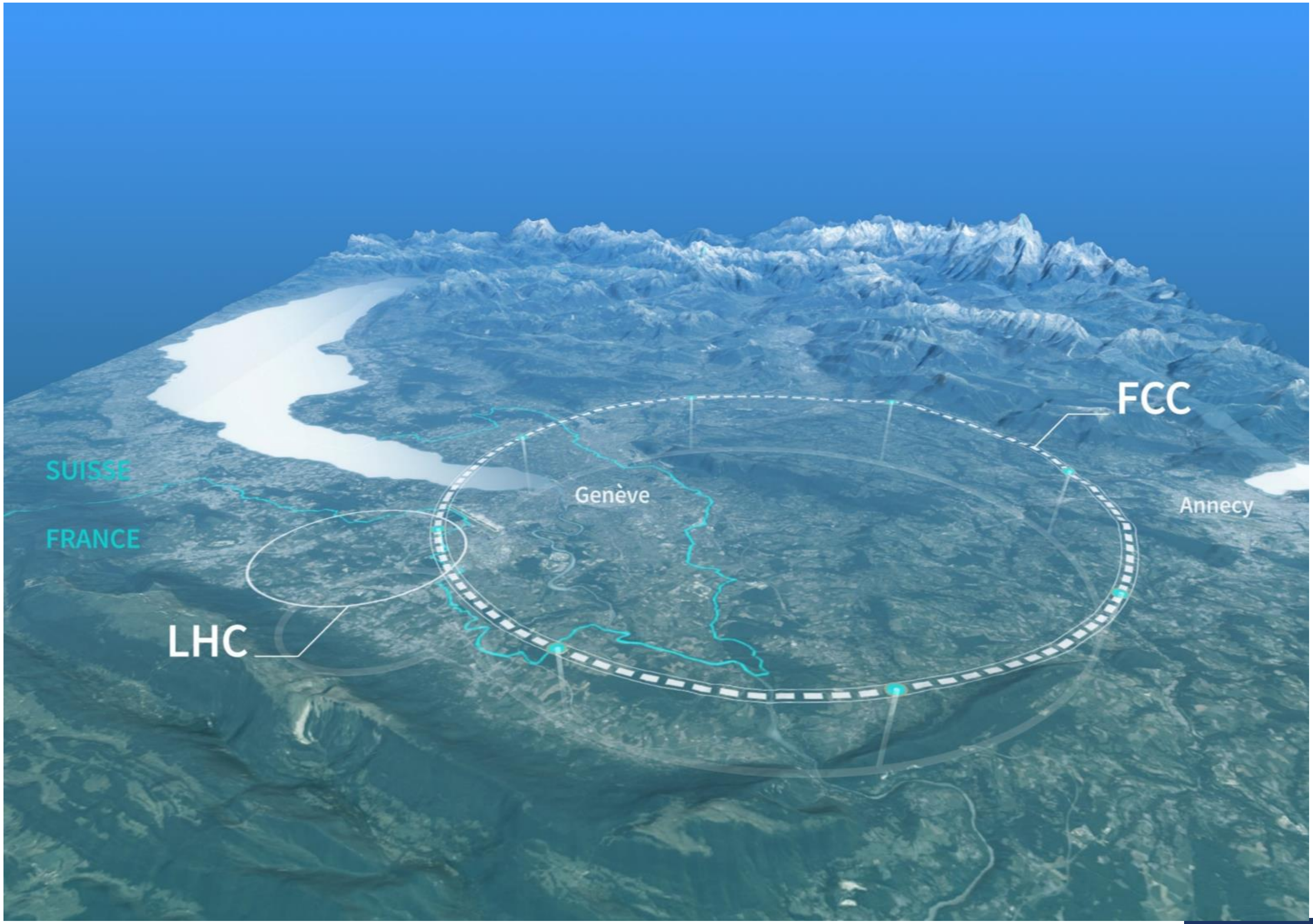

Beam Polarization SLD 1992-1998 Data
Polarization of Electron Beam (%)
Z Count
x 10^2
Strained Lattice Cathode for 1994 SLD Run
Strained Lattice Cathode for 1997 SLD Run
Source Laser Wavelenght Optimized
1996 Run
Strained Lattice Cathode for 1993 SLD Run
0
10
20
30
40
50
60
70
80
90
100
0
1000
2000
3000
4000
5000

Beam polarisation is an essential tool

most precise measurement at colliders

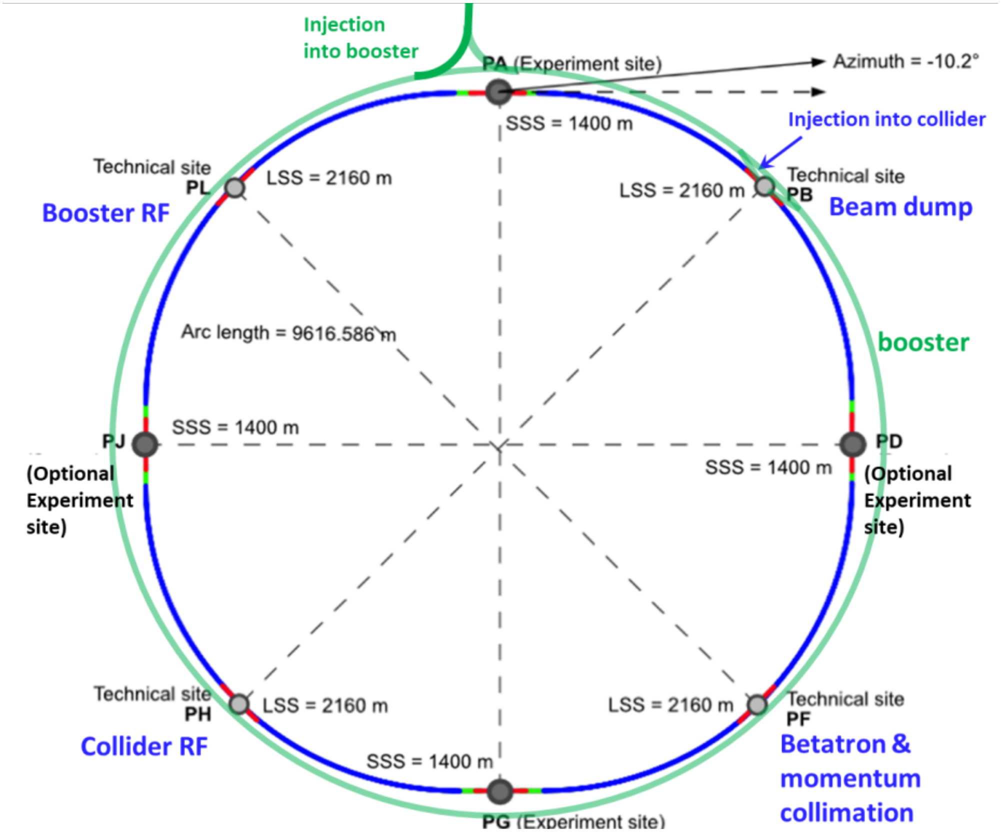


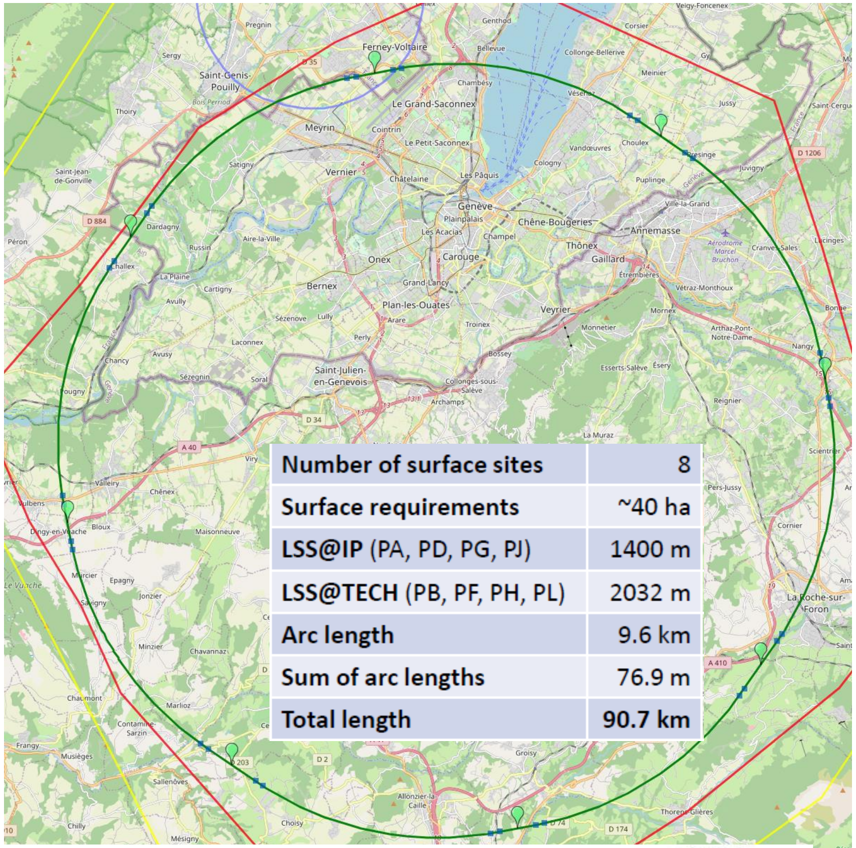
Future Circular Collider



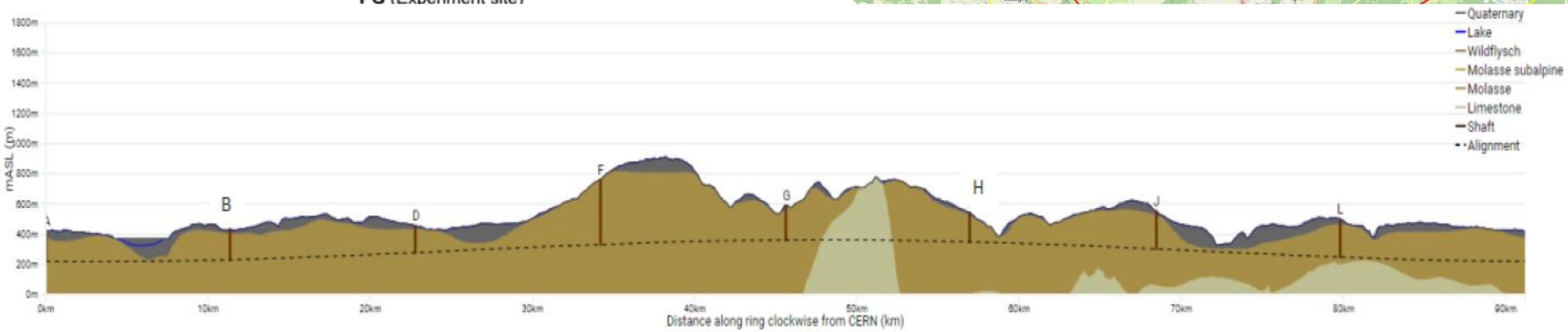
Future Circular Collider

Feasibility Study due to report March 2025





Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	90.7 km



FCC baseline run plan

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5×10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2×10^6 H	5 years 2×10^6 tt pairs

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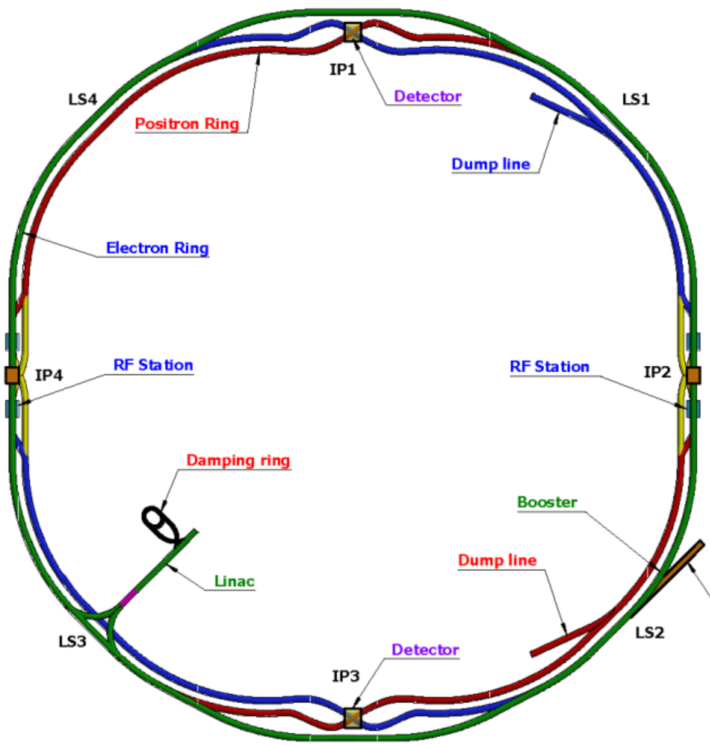
CEPC



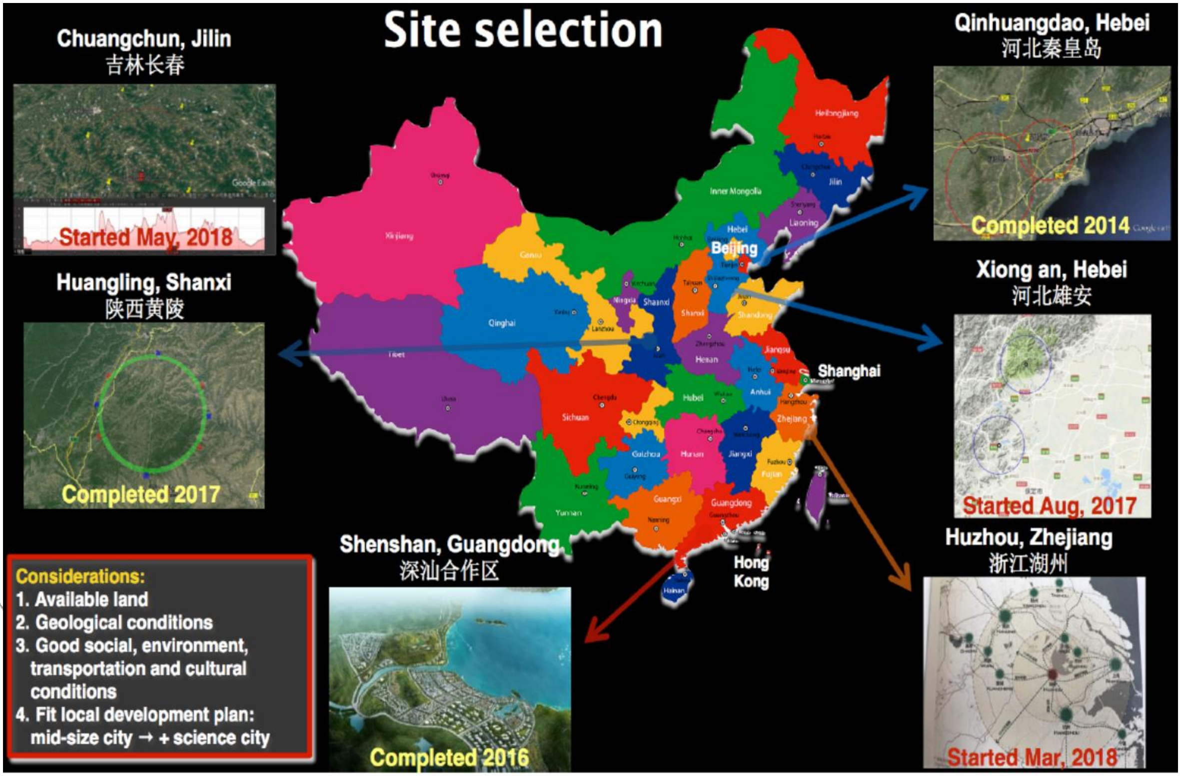
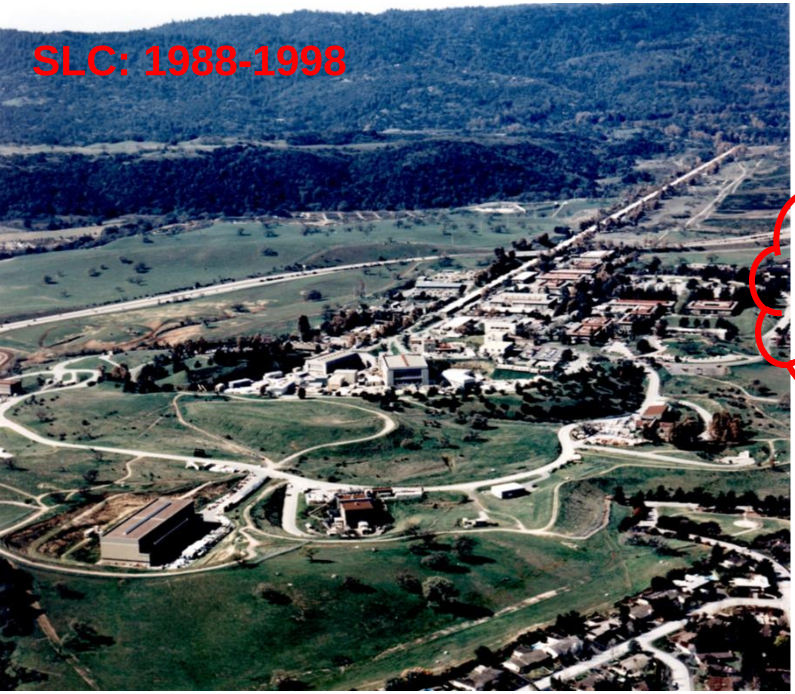


Table 3.2: CEPC operation plan (@ 50 MW)

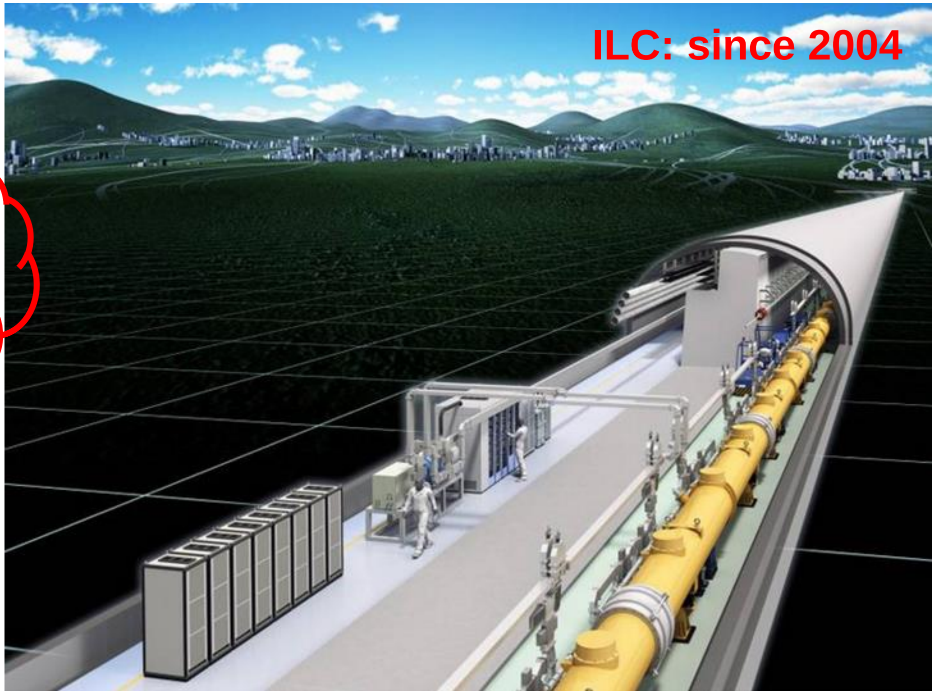
Particle	$E_{c.m.}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Integrated L per year (ab^{-1}, 2 IPs)	Years	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H	240	8.3	2.2	10	21.6	4.3×10^6
Z	91	192*	50	2	100	4.1×10^{12}
W	160	26.7	6.9	1	6.9	2.1×10^8
$t\bar{t}$**	360	0.8	0.2	5	1.0	0.6×10^6

TDR completed (Dec 2023)
Awaiting decision on inclusion in next 5-year plan 2026-2030
Could be operational mid 2030s

Linear Colliders

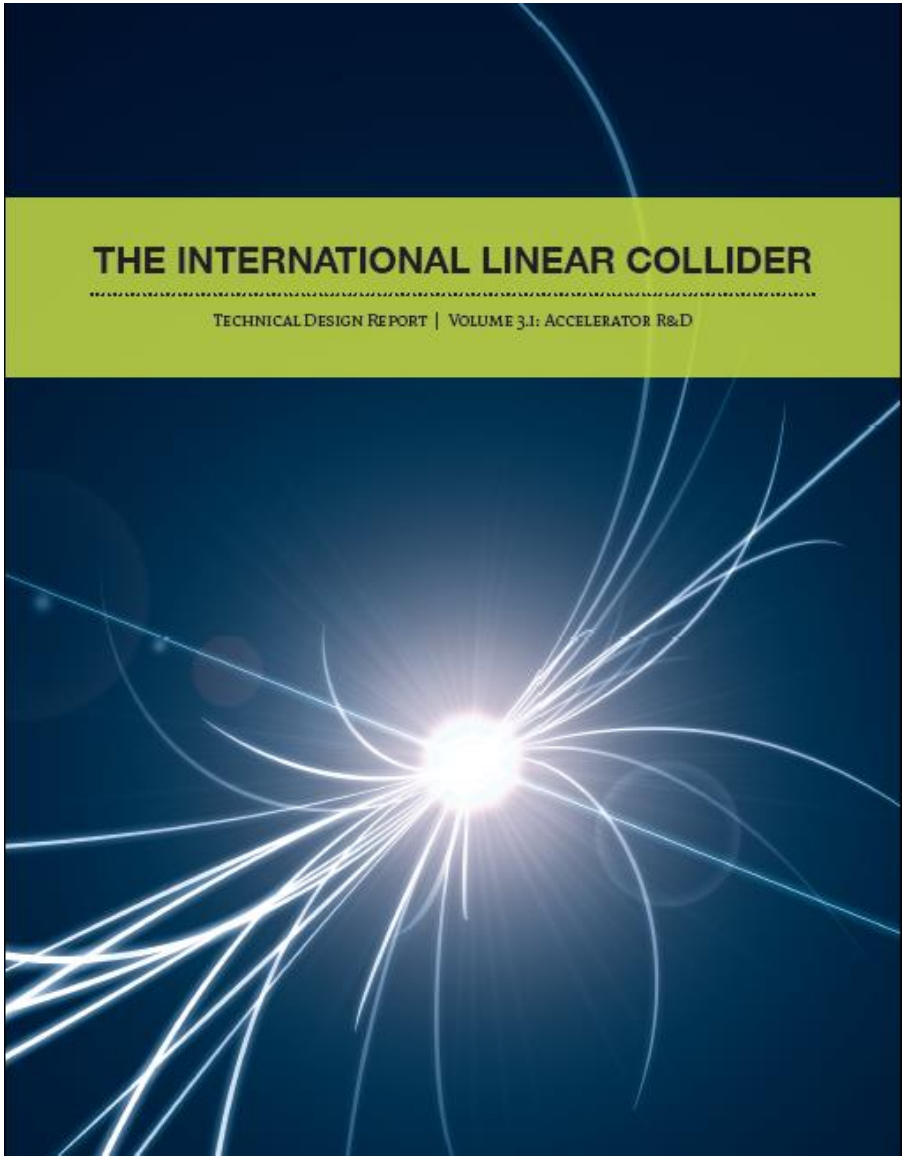


NLC
JLC
TESLA



ILC Technical Design Report (June 2013)

baseline 500 GeV: $6.7B (2010) + 13,000 person-years



https://linearcollider.org/technical-design-report/

Volume 3 – Accelerator
Part I: R&D in the Technical Design Phase
Part II: Baseline Design

Editors
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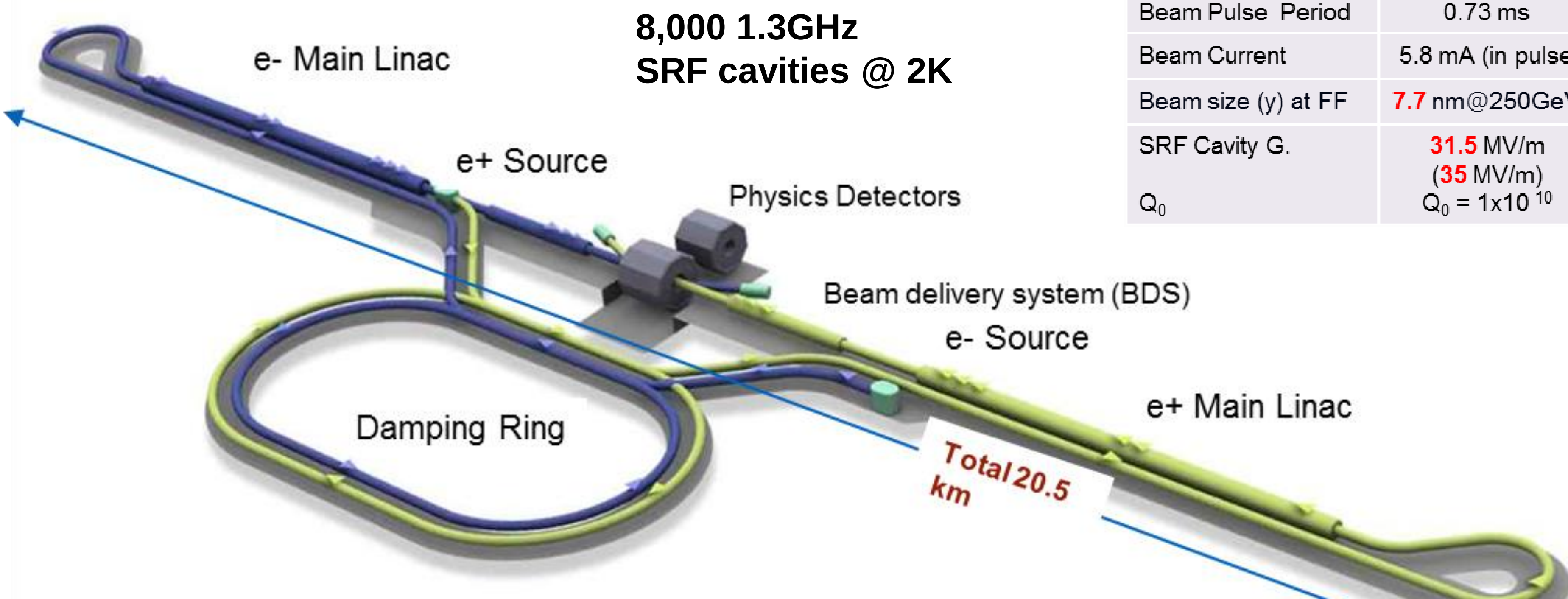
ILC 2017/8

Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	$1.35 \times 10^{34}\ cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) $Q_0 = 1 \times 10^{10}$

8,000 1.3GHz SRF cavities @ 2K



- **Cost ~ $5B (2010)**
- **Power ~ 111 MW**

UPDATE IN PROGRESS FOR EPPSU MARCH 25

European XFEL @ DESY

Largest deployment of SCRF technology

- **100 cryomodules**
- **800 cavities**
- **17.5 GeV**
- **First beams 2016**

Candidate site proposed by Japanese researchers

Tohoku ILC Project Development Center
(https://tipdc.org/)

ILC project status

- April 2022: ICFA extended International Development Team (IDT) mandate

- April 2023 MEXT increased ILC budget at KEK, IDT has identified 'time-critical' work packages and initiated collaboration among KEK and international partners

  → ILC Technology Network

- 'International Expert Panel' reviewed models for realising a large global project such as ILC; informal conversations involving funding agencies

- Cost update in progress (for input to European Strategy ~ March 2025):

  250, 350, 500/550 GeV stages

  inflation, exchange rate changes

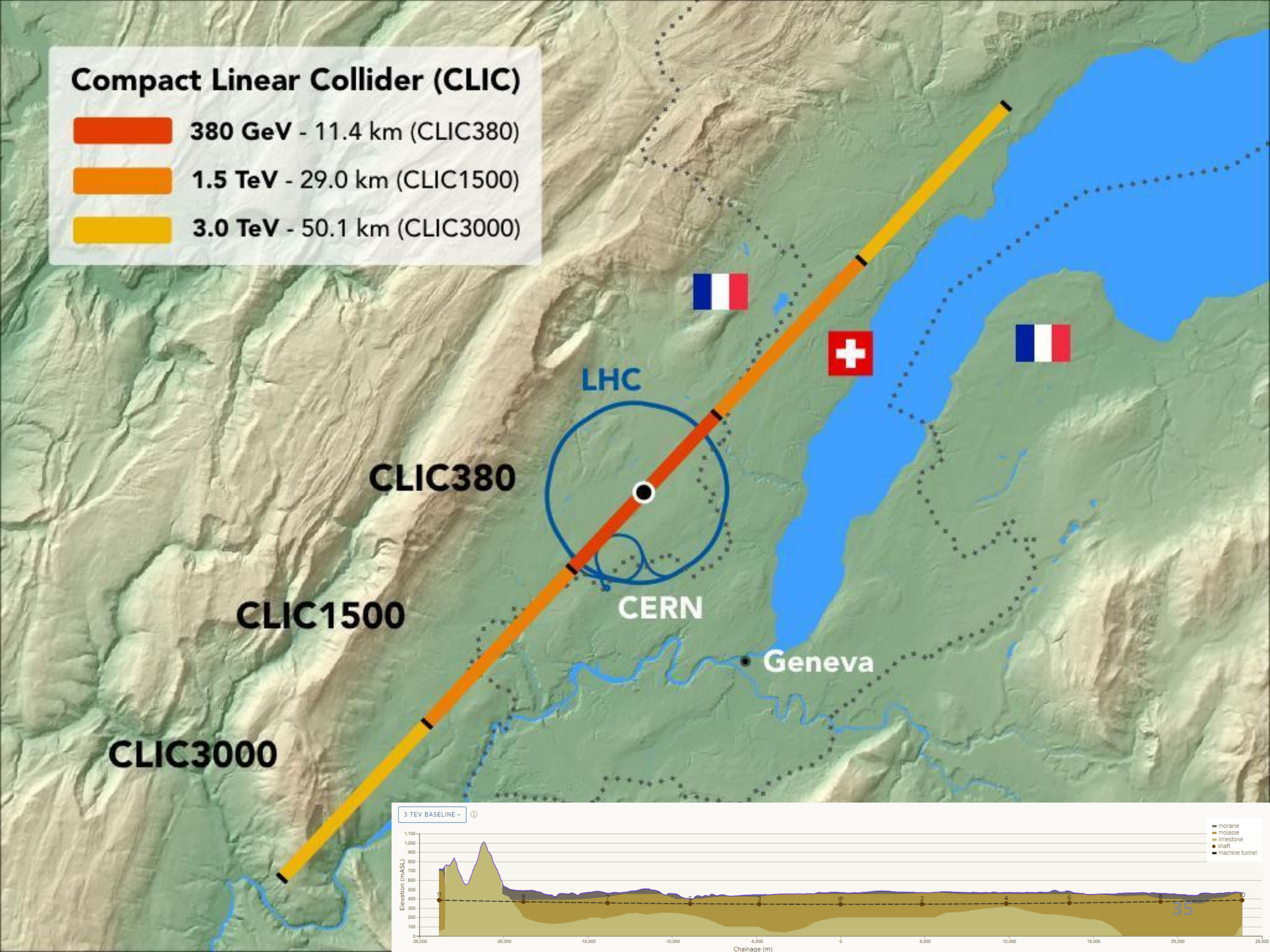
  cryomodules: experience from EU-XFEL, LCLS-II-HE + industry

  → cost in 2023 US$ using methodology that allows currency translation

CLIC overview

- **Timeline:** e+e- linear collider at CERN for the era beyond HL-LHC
- **Compact:** novel and unique two-beam accelerating technique based on high-gradient room-temperature X-band RF cavities:

  first stage: 380 GeV, ~11km long, 20,500 cavities
- **Expandable:** staged collision energies from 380 GeV (Higgs/top) up to 3 TeV


Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva
3 TEV BASELINE
moraine
molasse
limestone
shaft
machine tunnel
Elevation (mASL)
Chainage (m)
11
9
7
5
3
IP
2
4
6
8
10

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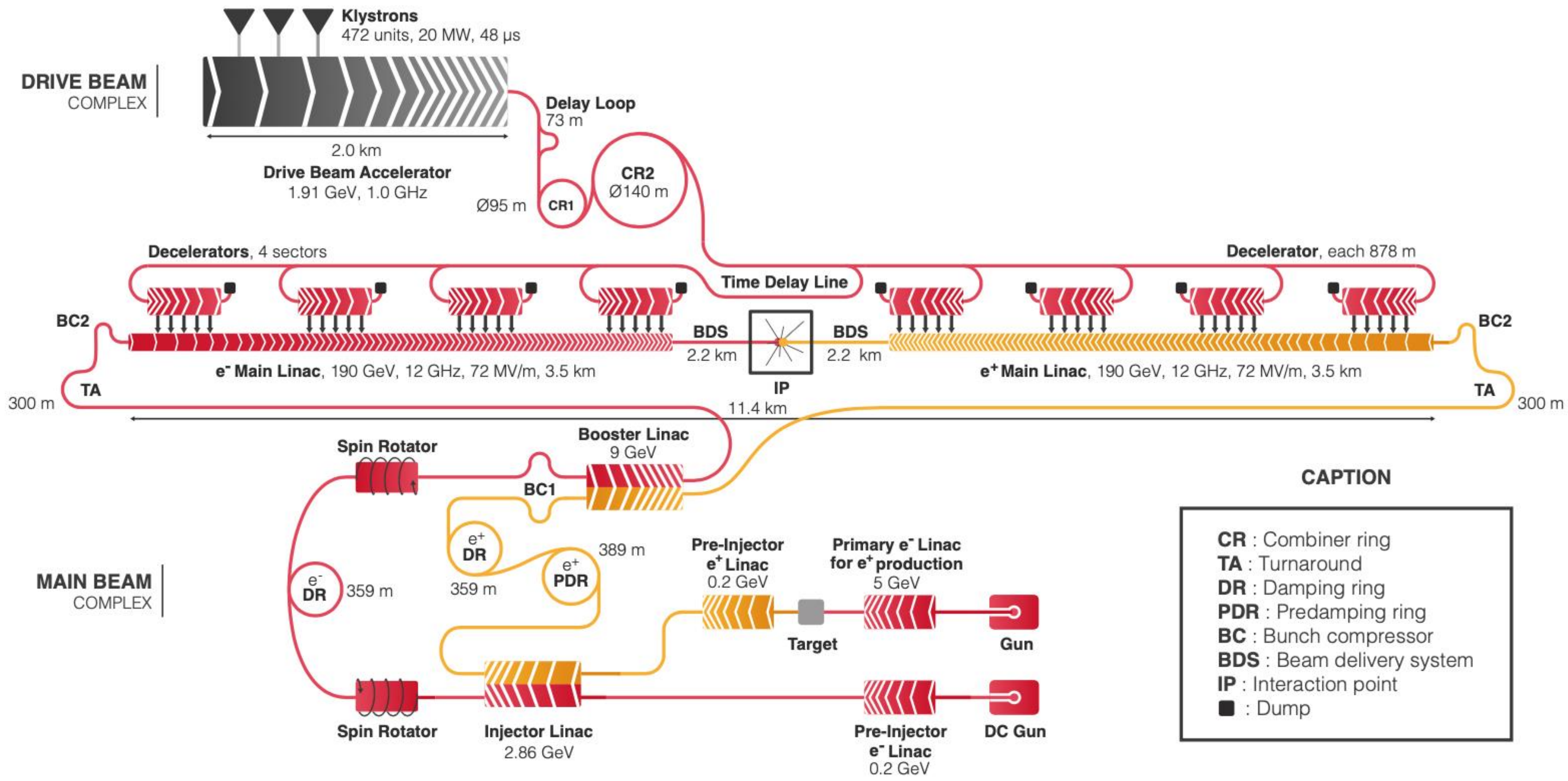
  first stage: 380 GeV, ~11km long, 20,500 cavities
- **Expandable:** staged collision energies from 380 GeV (Higgs/top) up to 3 TeV

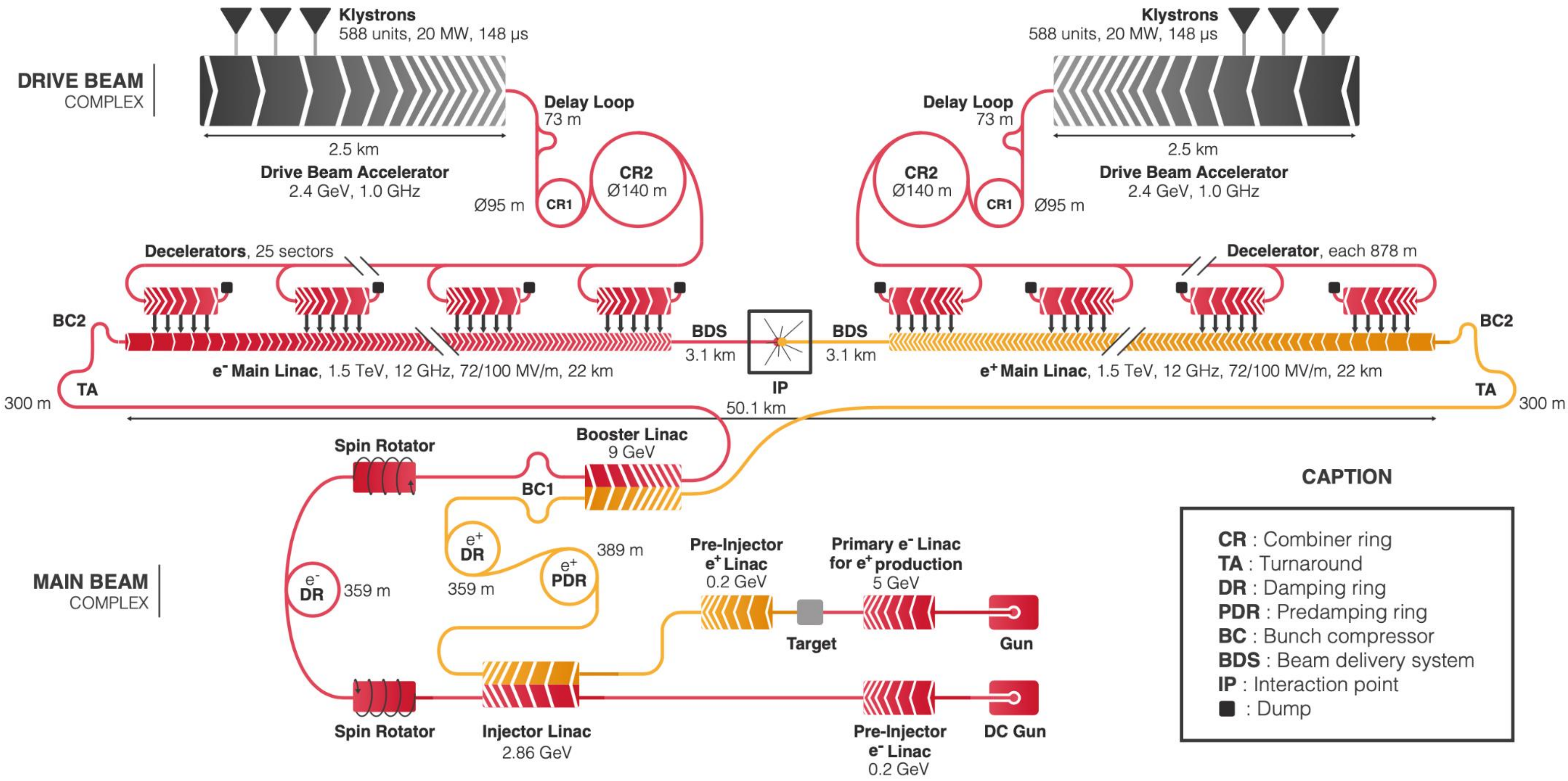
- **Conceptual Design Report published in 2012**
- **Project Implementation Plan released in 2018:** **Cost: 5.9 BCHF for 380 GeV**
- **Status report: Snowmass 'white paper' 2022:** https://arxiv.org/abs/2203.0918
- **Preparing CLIC Readiness Report for 2026 European PP Strategy Update**

CLIC 380 GeV layout



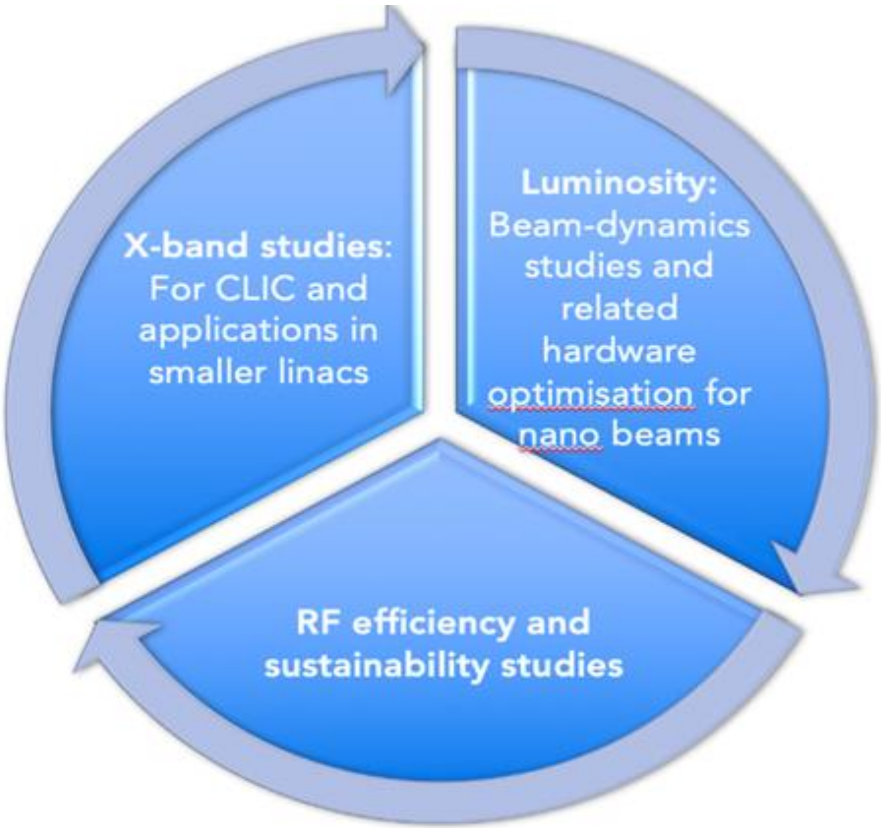
Baseline electron polarisation ±80%

CLIC 3 TeV layout



Baseline electron polarisation ±80%

CLIC project readiness → 2025/26

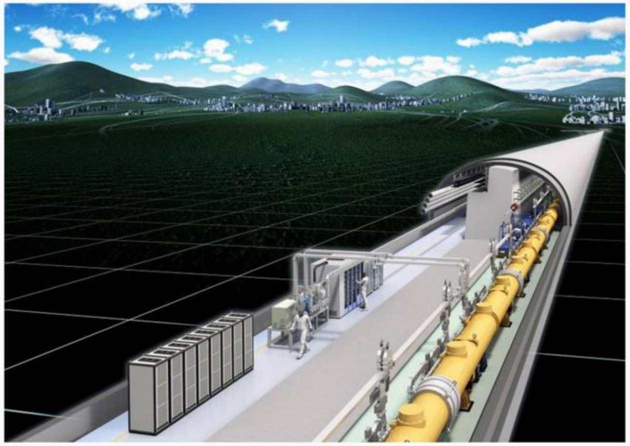


CLIC Readiness Report will include:

- **380 GeV + 2 TeV (single drive beam); also 250 GeV @ 100Hz**
- **Luminosity performance update, including beam dynamics, nanobeam studies, and positron production (all energies)**
- **Energy, power, sustainability …**
- **Sustainability issues: running/energy models, CO2-eq Life Cycle Assessment (LCA): construction + operation + decommissioning**
- **RF design optimization/development – including injectors, R&D for higher gradients - links to wakefield acceleration where relevant**
- **Cost update w.r.t. to 2018, including impacts of more sustainable design**

UK + future e+e- colliders

UK strongly committed to European Strategy priority of an e+e- 'Higgs Factory'



2004-12: £18M investment in Global Design Effort → ILC TDR

UK capability:
- **Positron source**
- **Damping rings**
- **Beam Delivery + Mach/Det Interface**
- **Beam dumps**

International Development Team

ILC Technology Network (with CERN)

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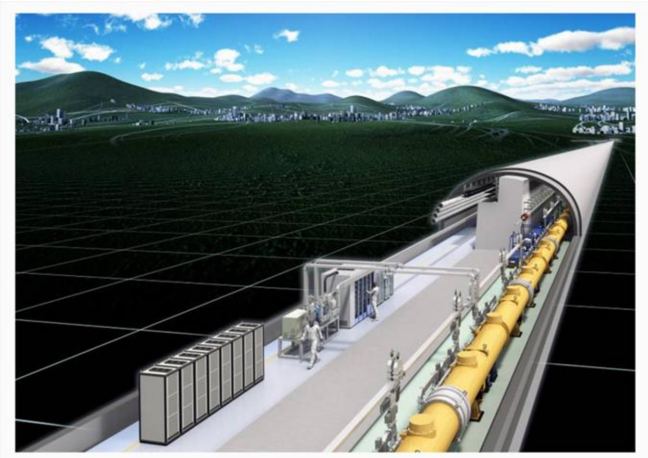

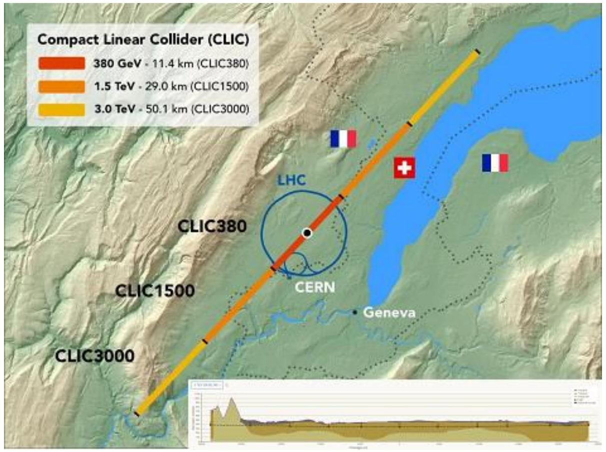

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2011-18: £14M investment joint with CERN → CLIC CDR + PIP

UK capability:
- Permanent magnets
- Linac RF systems
- Beam Delivery + Mach/Det Interface
- Instrumentation

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CLIC Project Readiness Report

Input to EPPSU 2026

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John Adams Institute for Accelerator Science

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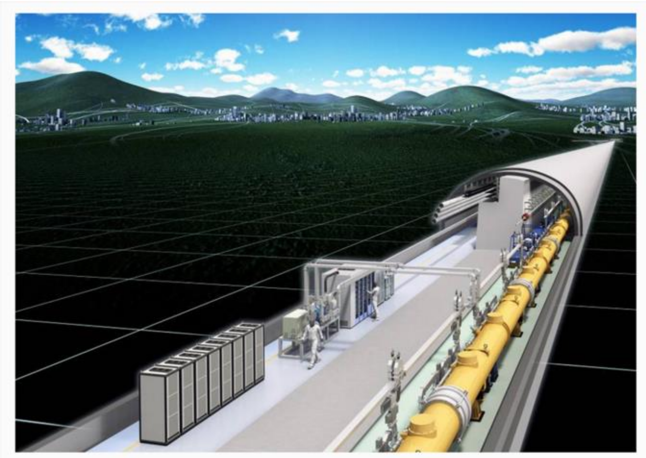

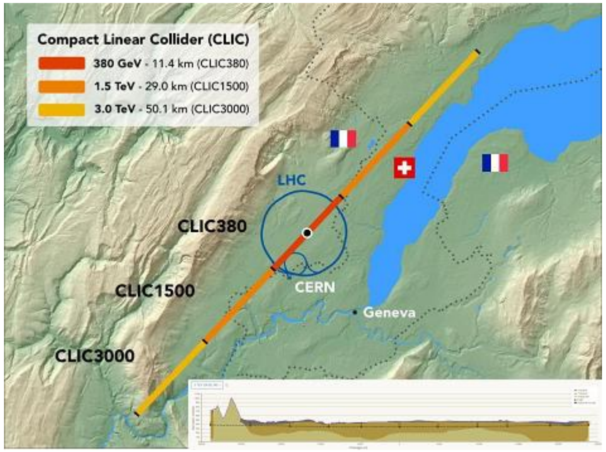

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→ deployed on HL-LHC, AWAKE, FCCee, Diamond, UK-XFEL

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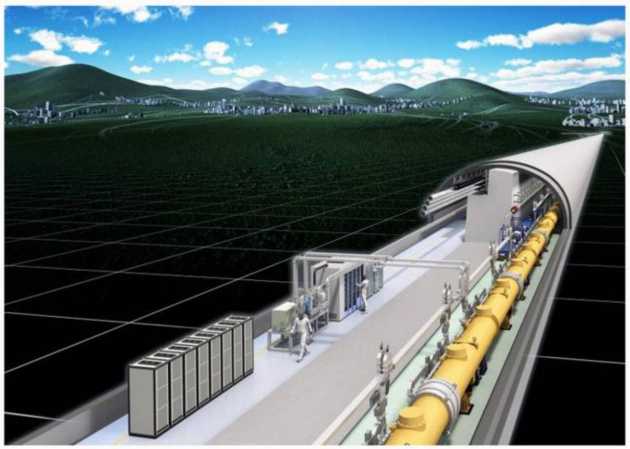

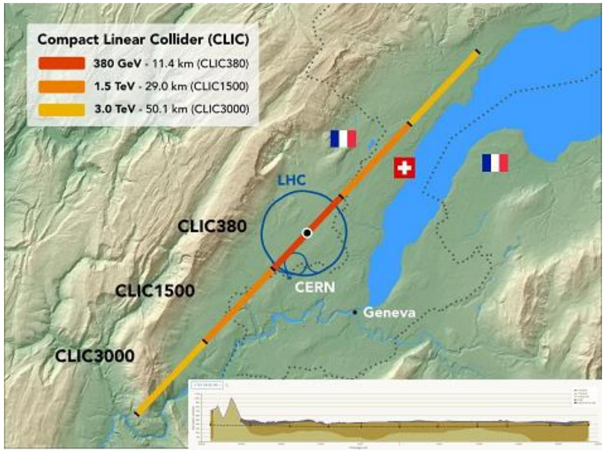

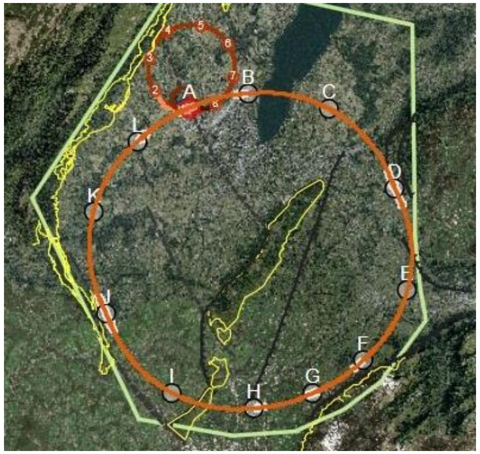

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2015-19: EuroCircol: Beam dynamics + lattice design

2021-25: FCCIS

→ deployed on HL-LHC, AWAKE, FCCee, Diamond, UK-XFEL

International Development Team

ILC Technology Network (with CERN)

CLIC Project Readiness Report

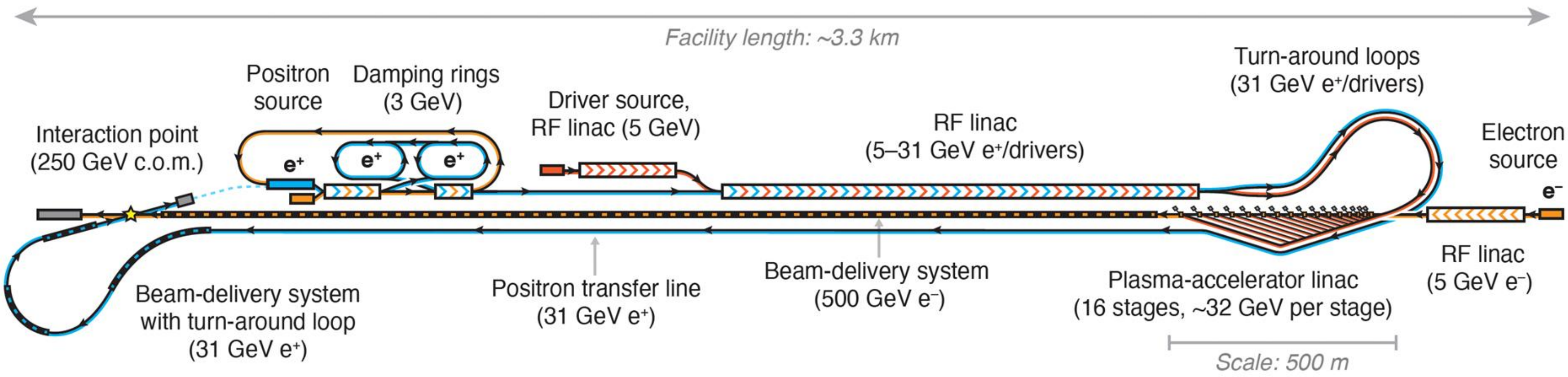
Input to EPPSU 2026

Feasibility study:

JAI working on main ring BPMs and collision feedback system

Hybrid Asymmetric Linear Higgs Factory (HALHF)

Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)
Lindstrøm, D'Arcy and Foster, arXiv:2312.04975



Directly capitalises on UK expertise in wakefield acceleration and linear collider systems

→ Richard D'Arcy's talk

Outlook

Circular e+e- collider designs spanning 91 GeV → 360 GeV are at an advanced stage:

FCC(ee) Feasibility Study will report March 2025

CERN resources identified in MTP for 'pre-TDR' phase prior to any decision to proceed

DG / FCC schedule foresees a Council decision ~ 2028, FCCee operation ~ 2048 → 2066

CEPC TDR completed, in consideration for implementation in next '5-year plan'

Linear Colliders offer a flexible, staged approach to energy frontier in e+e- collisions:

straightforward energy upgrade path 250 GeV → 500+ GeV and 1 TeV and beyond

linear facility reusable as technology improves, eg. ILC → CLIC → plasma wakefield ...

complementary to long-term future hadron or muon colliders

'LC Vision' in preparation for EPPSU

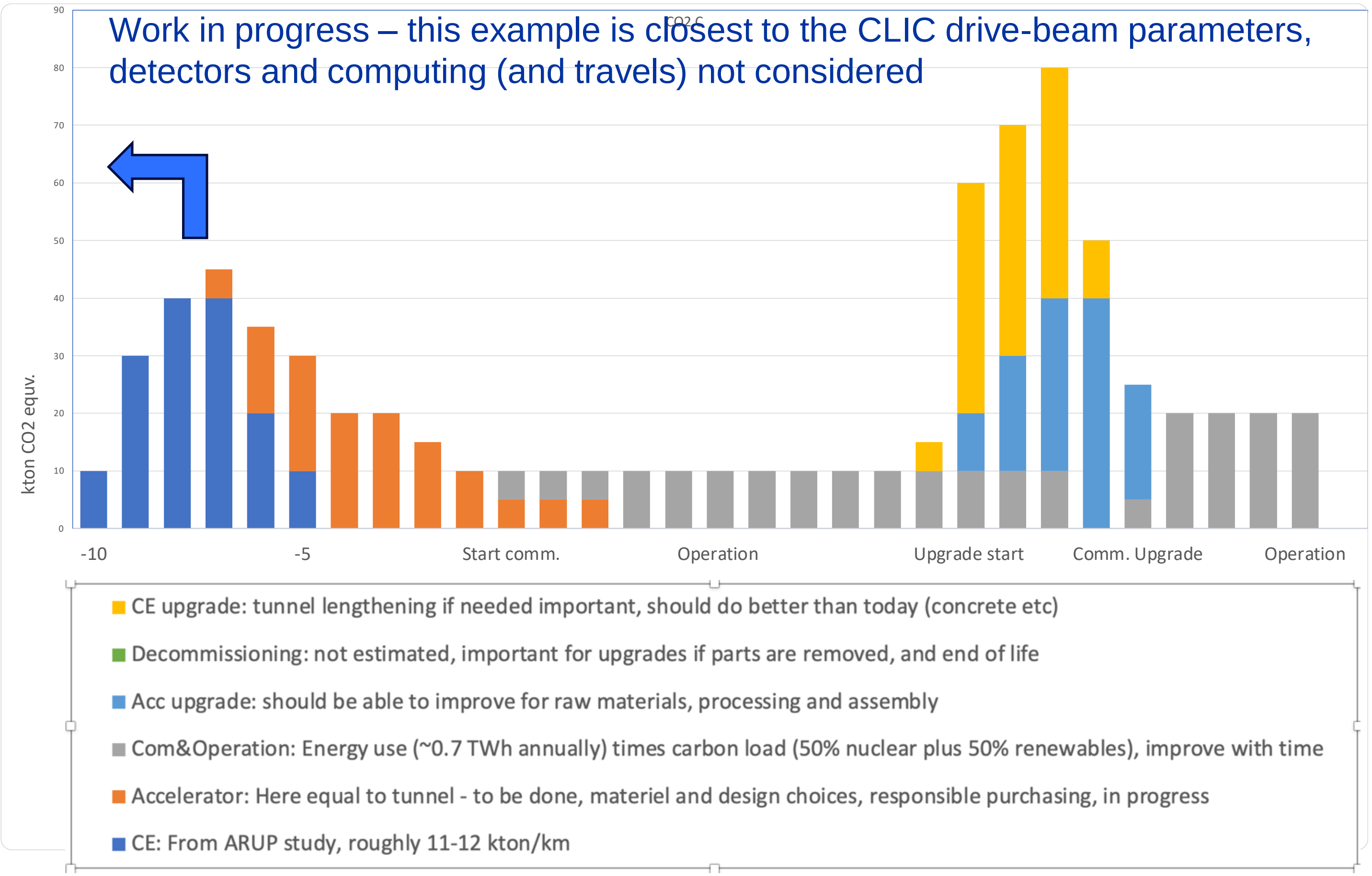
→ Cost and environmental sustainability will be important factors in decision-making

Towards CLIC Carbon Accounting via Life Cycle Assessment

This plot (blue part) is for 11 km of tunnel, scales with length

Now working on machine parts (orange), here assumed hardware = civil engineering impact

Work in progress – this example is closest to the CLIC drive-beam parameters, detectors and computing (and travels) not considered

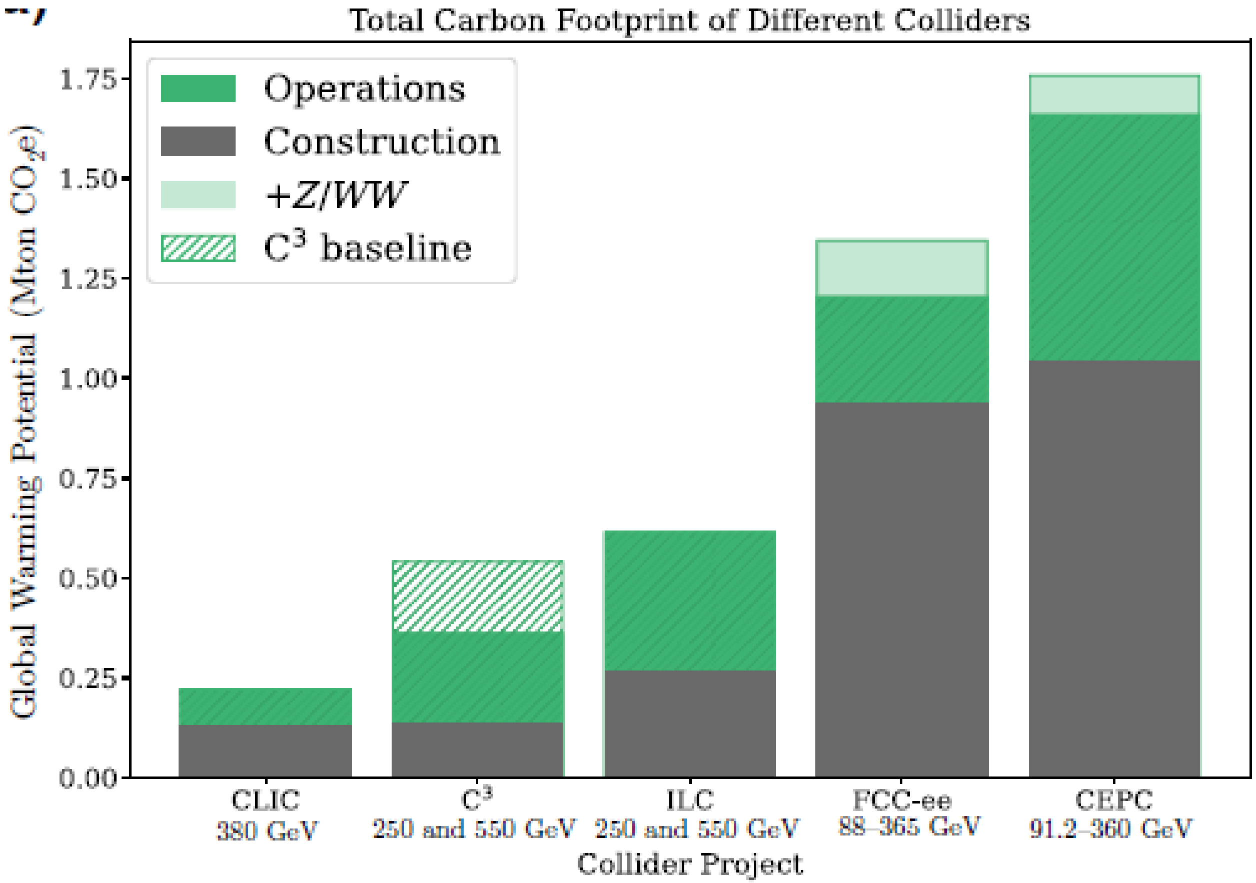


Steinar Stapnes

Environmental impact

Will be a major consideration for any new facility

Eg. Study by Breidenbach et al, PRX Energy 2 047001 (Oct 2023):



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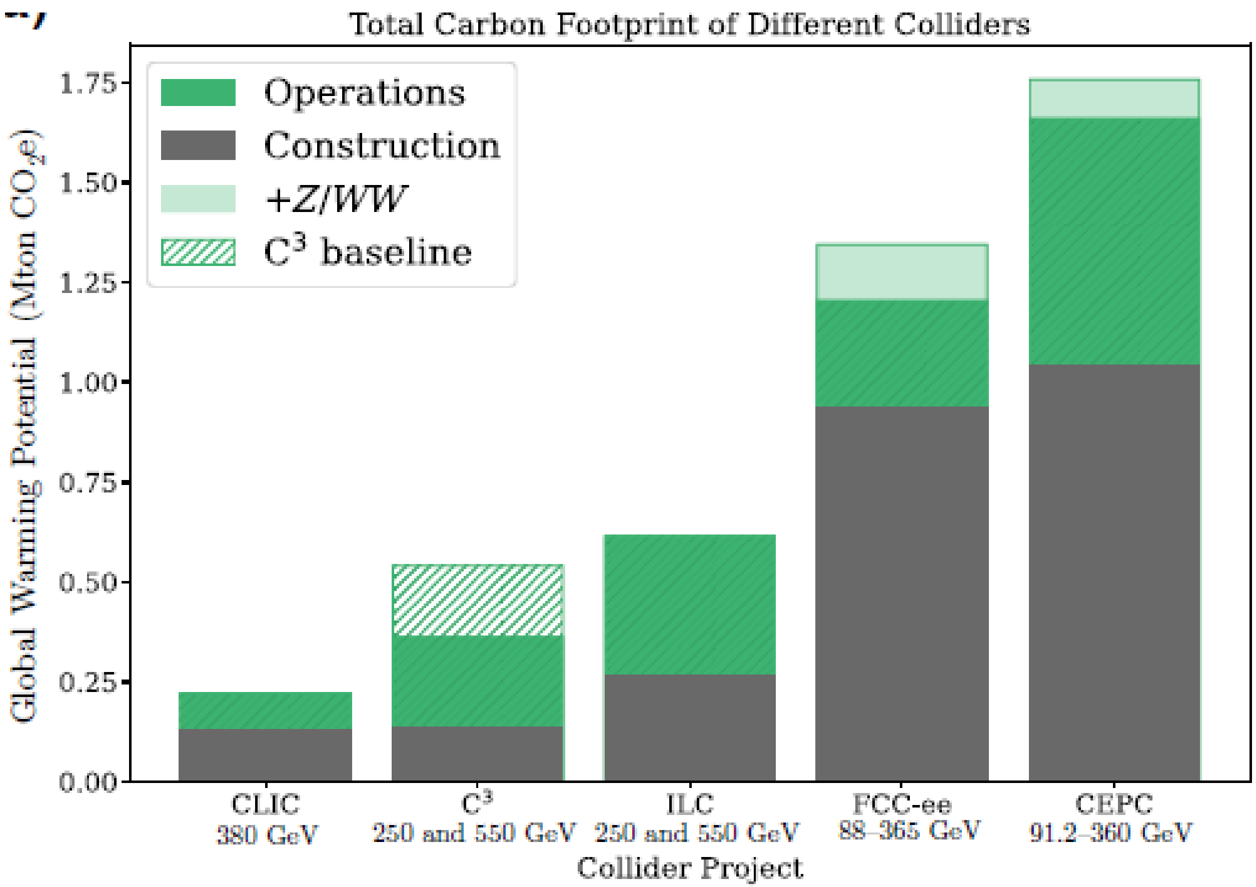


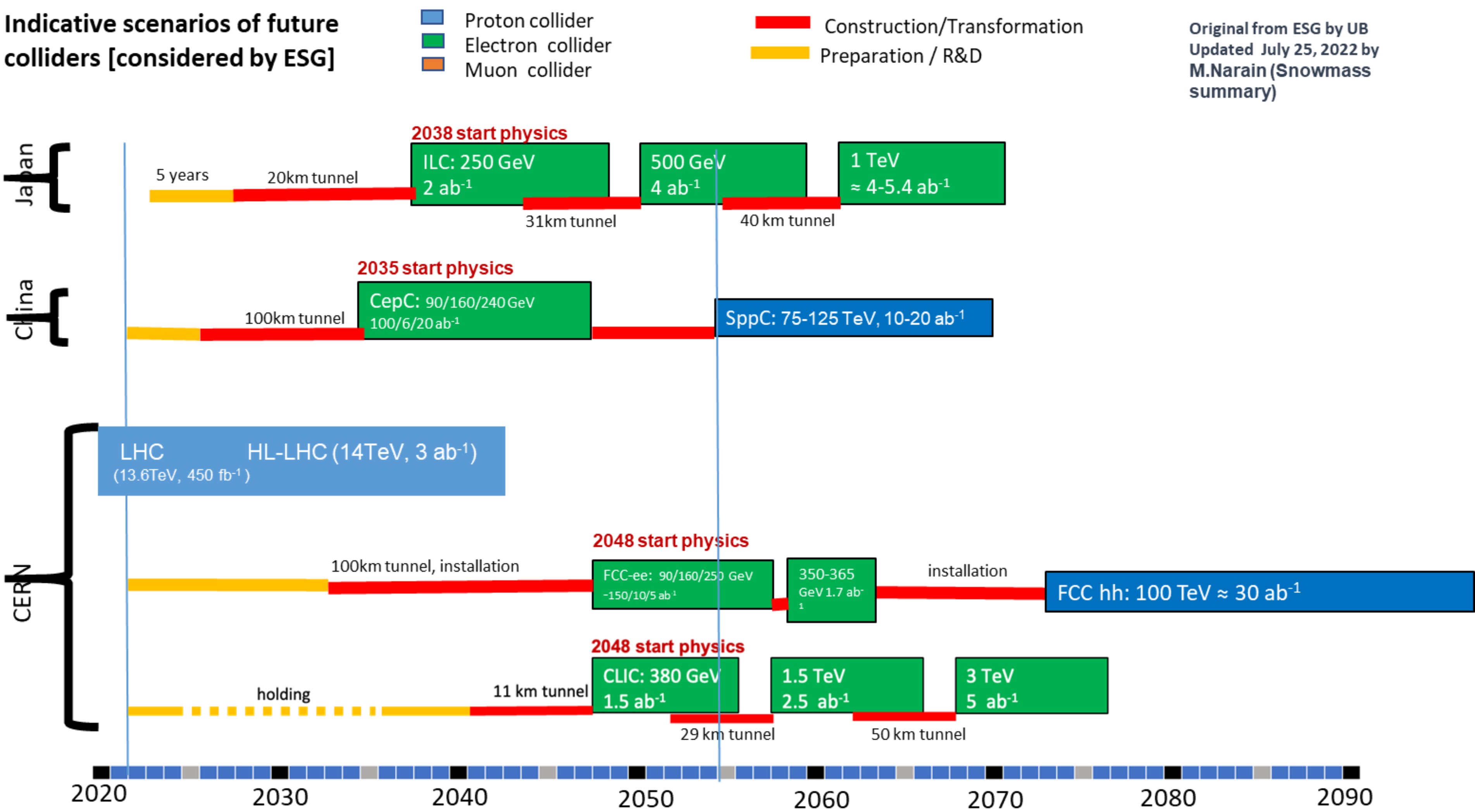
Detailed life-cycle assessment (LCA)

Consistent basis

Using industry standards for CO2eq costs for construction, operation + decommissioning

LCA in progress for ILC, CLIC, FCCee

Schedules?


Indicative scenarios of future colliders [considered by ESG]
Proton collider
Electron collider
Muon collider
Construction/Transformation
Preparation / R&D
Original from ESG by UB
Updated July 25, 2022 by
M.Narain (Snowmass summary)
Japan
5 years
20km tunnel
2038 start physics
ILC: 250 GeV
2 ab-1
31km tunnel
500 GeV
4 ab-1
40 km tunnel
1 TeV
≈ 4-5.4 ab-1
China
100km tunnel
2035 start physics
CepC: 90/160/240 GeV
100/6/20 ab-1
SppC: 75-125 TeV, 10-20 ab-1
CERN
LHC
(13.6TeV, 450 fb-1)
HL-LHC (14TeV, 3 ab-1)
100km tunnel, installation
2048 start physics
FCC-ee: 90/160/250 GeV
~150/10/5 ab-1
350-365
GeV 1.7 ab-1
installation
FCC hh: 100 TeV ≈ 30 ab-1
holding
11 km tunnel
2048 start physics
CLIC: 380 GeV
1.5 ab-1
29 km tunnel
1.5 TeV
2.5 ab-1
50 km tunnel
3 TeV
5 ab-1
2020
2030
2040
2050
2060
2070
2080
2090

Thanks to many colleagues

Extra material

Costs?

All numbers provisional – expect updates for ESPPU:

FCCee: Feasibility Study interim report (Oct 2023) - CERN core cost:

240 GeV, 2 IPs, no detectors	**12.8 BChF**
350 GeV, 4 IPs, no detectors	**15 BChF**

ILC: TDR cost (2010 US$):

500 GeV, 1 IP, no detector (2013)	**$6.7B capital + 13,000 years labour**
250 GeV, 1 IP, no detector (2018)	**$5B capital**

CLIC: Project Implementation Plan (2018) - CERN core cost:

380 GeV, 1 IP, no detector	**5.9 BChF**

Extra material:

ILC

ILC baseline

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	Upgrades		
						500	250	1000
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ^*_{z}	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_{\text{x}}$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_{\text{y}}$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

Table 4.1: Summary table of the ILC accelerator parameters in the initial 250 GeV staged configuration and possible upgrades. A 500 GeV machine could also be operated at 250 GeV with 10 Hz repetition rate, bringing the maximum luminosity to $5.4 \cdot 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ [26]. *): For operation at the Z-pole additional beam power of 1.94/3.88 MW is necessary for positron production.

ILC upgrade options

Luminosity I

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
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Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
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ILC upgrade options

Luminosity II

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	Upgrades		
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Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
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ILC upgrade options

Energy I + II

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RMS bunch length	σ^*_{z}	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

Table 4.1: Summary table of the ILC accelerator parameters in the initial 250 GeV staged configuration and possible upgrades. A 500 GeV machine could also be operated at 250 GeV with 10 Hz repetition rate, bringing the maximum luminosity to $5.4 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [26]. *): For operation at the Z-pole additional beam power of 1.94/3.88 MW is necessary for positron production.

ILC upgrade options

Energy III

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ_{z}^*	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ_{x}^*	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ_{y}^*	nm	7.7	7.7	14.6	5.9	7.7	2.7
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Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

Table 4.1: Summary table of the ILC accelerator parameters in the initial 250 GeV staged configuration and possible upgrades. A 500 GeV machine could also be operated at 250 GeV with 10 Hz repetition rate, bringing the maximum luminosity to $5.4 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [26]. *): For operation at the Z-pole additional beam power of 1.94/3.88 MW is necessary for positron production.

Ongoing ILC technology developments

- **Huge global interest in ILC-like SC RF systems:**

  eg. European XFEL, LCLS-II, Shanghai XFEL …

- **Nb cavity performance advancements made at many labs**
- **Improved fabrication techniques + surface treatments → prospects for higher gradient, Q, yield, also reductions in cost, cryo power …**

  advanced Nb sheet production

  advanced surface treatments

  longer-term: thin-film coatings on Cu → 4K vs. 2K operation

- **ILC Technology Network ('ITN') advancing technical progress on linac RF, sources, damping rings, beam delivery system, dumps …**

ITN kickoff meeting @ CERN Oct 2023

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ILC indicative schedule

IDT Scope for ILC Realization

-success oriented and asuming no major incident-

Technology Network Phase | **Preparatory Phase** | **Construction Phase** ~10 years for the construction and commissioning

2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	• • •

R&D and effort to gain a common view and understanding.

ILC preparation laboratory and intergovernmental discussion

2021 May

Technical Preparation and Work Packages (WPs) during ILC Pre-lab

Work Packages (WPs) for ILC Pre-Lab

2022 June

Time-critical WPs for the ILC construction

WP-Primes for Time Critical

http://doi.org/10.5281/zenodo.4742018

https://agenda.linearcollider.org/event/9649/attachments/38003/60567/Time-Critical_WPsV8b.pdf

ILC Technology Network (ITN)

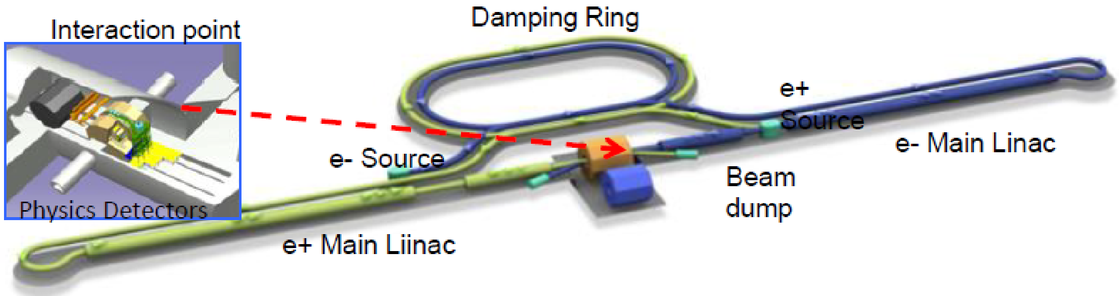
-- global collaboration program---

- **Acc. R&Ds** focusing on
  - SRF
  - e- & e+ Sources
  - Nano-beam

KEK obtained a budget for these R&Ds and started the activity from 2023.

ITN scope

ILC Technology Network



Not only for the **ILC** but also for **various application**

- Creating particles — ***Sources***
  - polarized elections / positrons
- High quality beams — ***Damping ring***
  - Low emittance beams
    - Small beam size (small beam spread)
    - Parallel beam (small momentum spread)
- Acceleration — ***Main linac***
  - superconducting radio frequency (SRF)
- Getting them collided — ***Final focus***
  - nano-meter beams
- Go to ***Beam dumps***

SRF

e-, e+ Sources

Nano-Beam

WPP	1	Cavity production
WPP	2	CM design
WPP	3	Crab cavity
WPP	4	E- source
WPP	6	Undulator target
WPP	7	Undulator focusing
WPP	8	E-driven target
WPP	9	E-driven focusing
WPP	10	E-driven capture
WPP	11	Target replacement
WPP	12	DR System design
WPP	14	DR Injection/extraction
WPP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

LCWS2024 (Shin MICHIZONO)

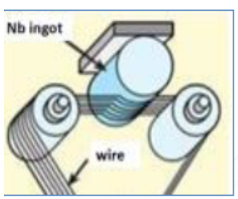
ITN SC RF cavity development

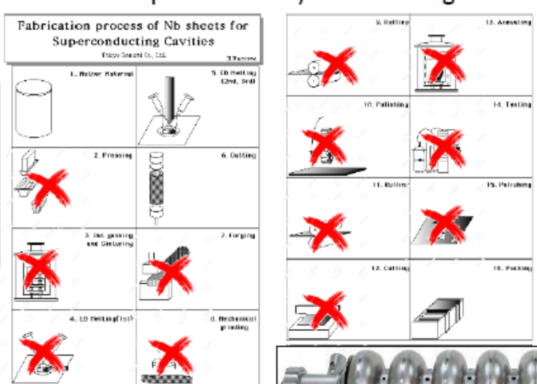
WP-prime 1: SRF Cavity
(Scoping the Industrial-Production Readiness)

- Research with single-cell cavities to establish the best production process including:
  - Advanced Nb sheet production method
  - Advanced surface treatment recipe(mainly developed by FNAL)
- Globally common design with compatible High Pressure Gas Safety (HPGS) regulation
- 24 nine-cell cavities are to be developed for industrial-production readiness
  - 8 cavities in each region
  - Production process encouraged to be optimized in each region
  - Cavity performance expected: E_{acc} = <35 MV/m> (+/− 20%), Q_0 = 1.0 x 10^{10}, Yield = ≥90%
- RF performance/success yield to be examined (including 2nd pass and further)
  - 3rd pass to be examined if effective

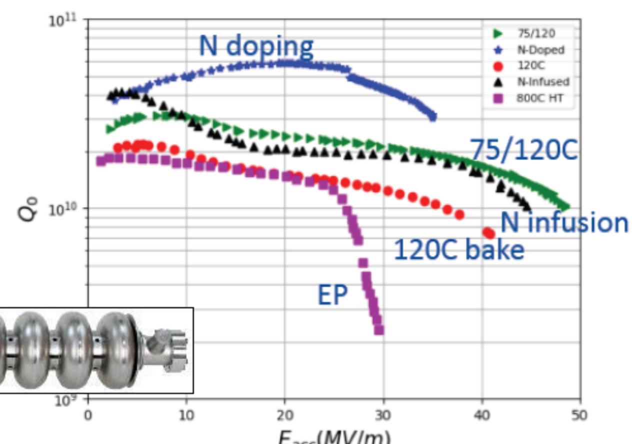
	# of cavities to be produced		
	Americas	Europe	JP/Asia
single-cell	2	2	2
nine-cell	8	8	8

Advanced Nb sheet production by direct slicing





Advanced surface treatment technologies pioneered by FNAL



Material/Sub-component
↓
QA of Material/Sub-C
↓
Cavity Production
↓
Surface Process
↓
Vertical Test = Cavity RF Test

Production process

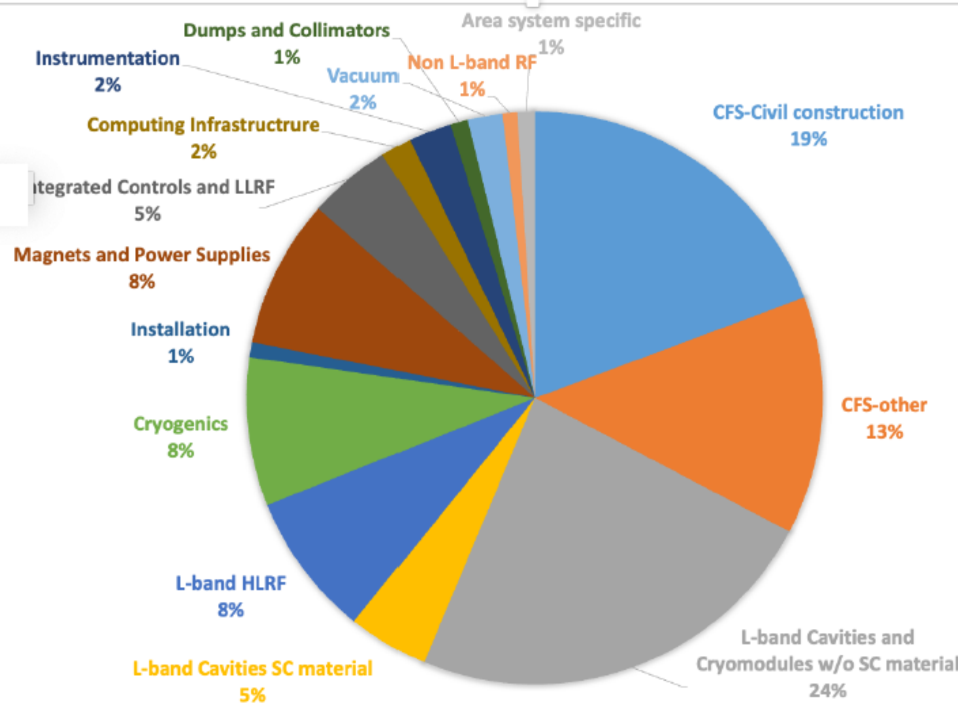
ILC cost update panel

Cost update task force members:

Gerry Dugan	(Cornell)
Benno List	(DESY)
Marc Ross	(SLAC)
Hiroshi Sakai	(KEK)
Nobuhiro Terunuma	(KEK)
Nick Walker	(DESY)
Akira Yamamoto*)	(KEK)
and from IDT EB	
Andy Lankford	(UCI)
Shinichiro Michizono	(KEK)
Steinar Stapnes	(CERN)

*)Task Force leader

Cost distribution for ILC250



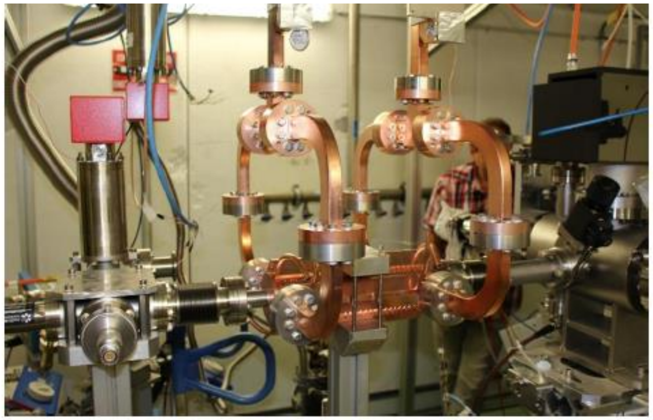
Extra material:

CLIC

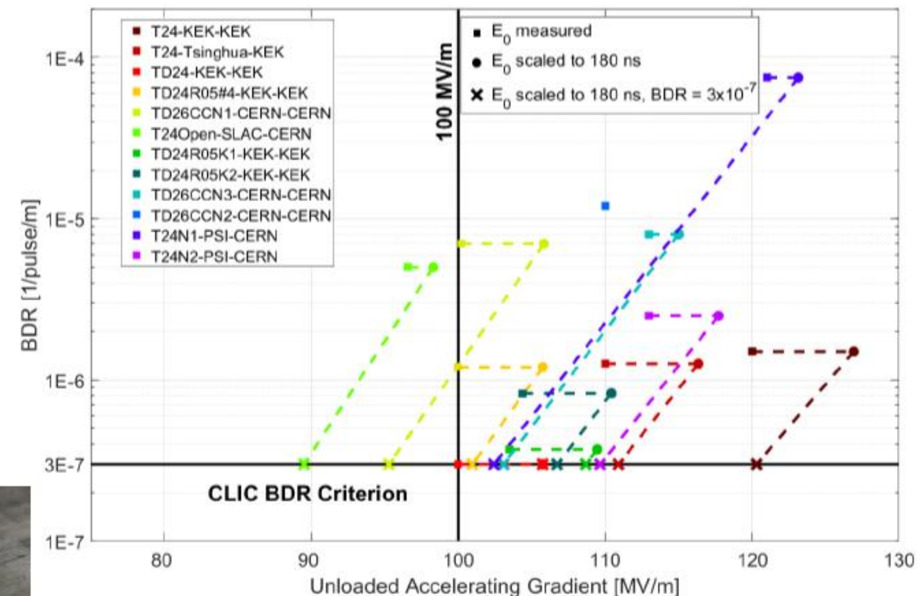
CLIC parameters

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	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	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	1×10^{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

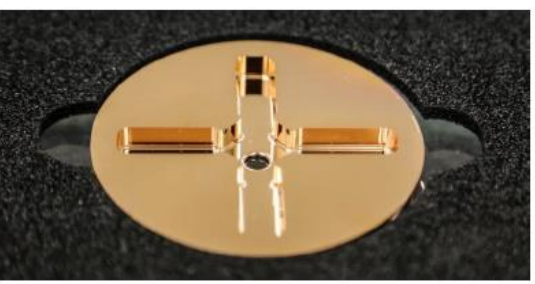
CLIC X-band structure development

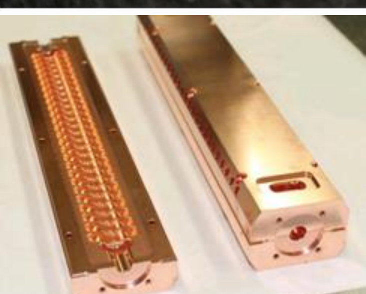


Test structure



Achieved accelerating gradients in tests



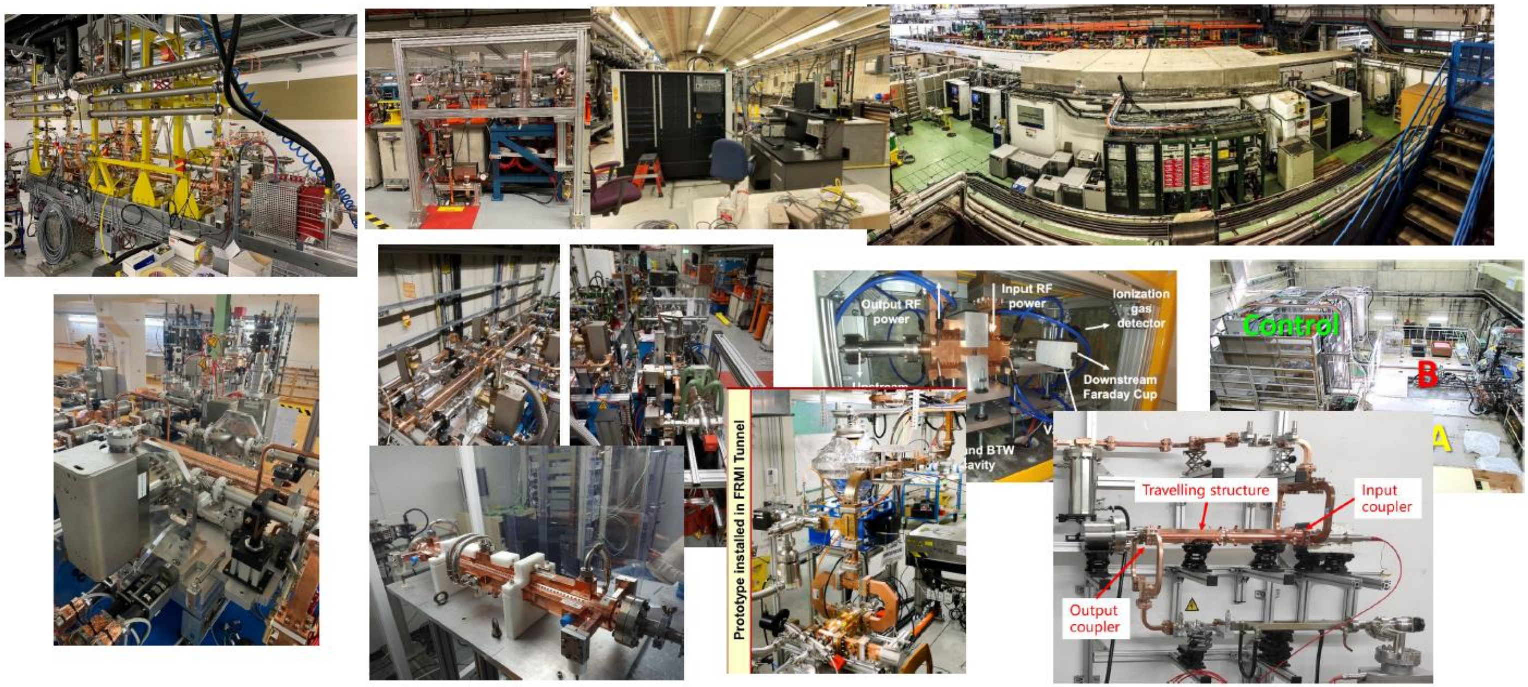


→ **Emphasis on industrialising processes via collaboration with manufacturers**
→ **Collaboration with C3**

Beyond CLIC: global X-band deployment

Compact linacs have many uses:

- **Research accelerators (e.g. FELs as main technology or special elements), in medical or industrial linacs**
- **Many/most of these developments are driven by CLIC collaborators, for their ”local” applications**



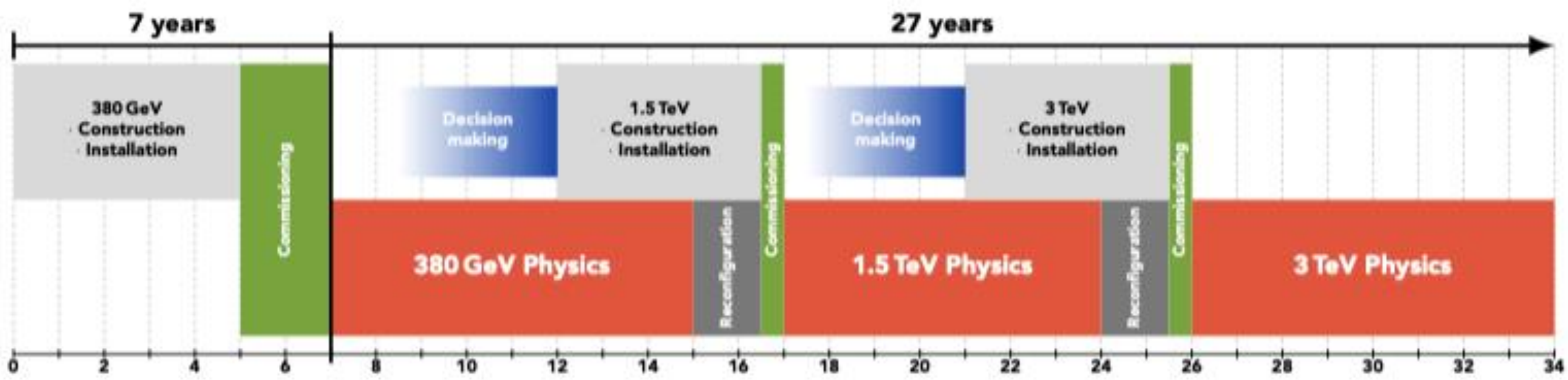
Main benefits for CLIC: much strengthened industrial base and strong increase in research/experience with X-band technology and associated components

- Trieste, FERMI: Linearizer
- SwissFEL: Linearizer and PolariX deflector
- SARI: Linearizer, deflectors
- CERN: XBox-1 with CLEAR, accelerator
- DESY: FLASHForward and FLASH2, PolariX deflectors
- SLAC: NLCTA, XTA
- Argonne: AWA

- KEK: NEXTEF
- CERN: XBox-2,3 and SBox
- Tsinghua: TPot
- Valencia: IFIC VBox
- Trieste: FRMI S-Band
- SLAC: Cryo-systems
- LANL: CERF-NM
- INFN Frascati: TEX
- Melbourne: AusBox

- TU Eindhoven: SMART*LIGHT, ICS
- Tsinghua: VIGAS, ICS
- CERN: AWAKE electron injector
- INFN Frascati: EuPRAXIA@SPARC_LAB, accelerator
- DESY: SINBAD/ARES, deflector
- CHUV/CERN: DEFT, medical accelerator
- Daresbury: CLARA, linearizer
- Trieste: FERMI energy upgrade

CLIC timeline

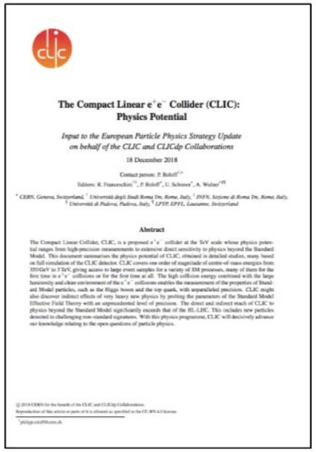


Technology-driven schedule from start of construction shown above.

A preparation phase of ~5 years is needed beforehand
(estimated resource needed ~4% of overall project cost)

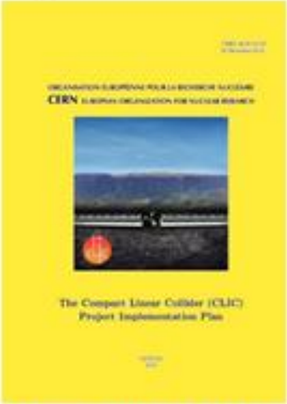
CLIC European Strategy 2020 Inputs

http://clic.cern/european-strategy

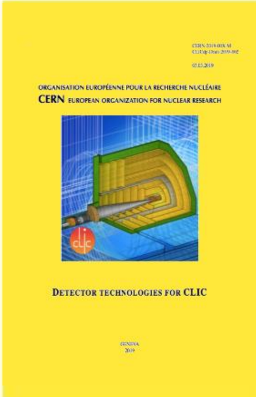


CERN-2018-005-M

CERN-2018-009-M



CERN-2018-010-M



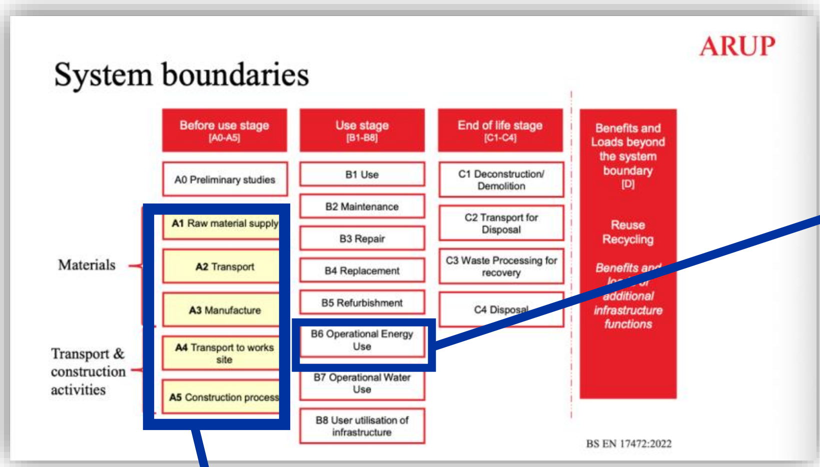
CERN-2019-001

CLIC Snowmass Inputs (2022)

Several LoIs have been submitted on behalf of CLIC and CLICdp

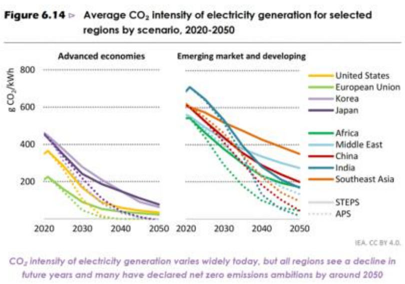
The CLIC accelerator study: Link
Beam-dynamics focused on very high energies: Link
The physics potential: Link
Detector: Link

Sustainability: towards a Life Cycle Assessment (LCA) for LCs



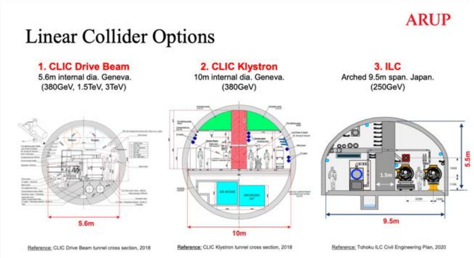
What is the carbon intensity of energy in ~2050 (operation):

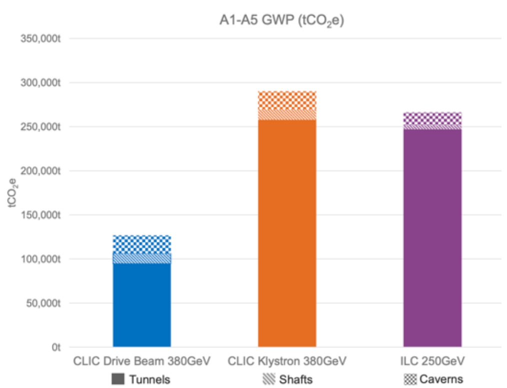
- 50% nuclear and 50% renewable give ~10-15g/kWh
- France summer-months are today ~40g/kWh
- ILC has a green implementation concept including compensation and contracting renewable energy
- Reductions predicted (LINK)



LCA report for Civil Engineering: LINK

Addressing the Civil Engineering impact



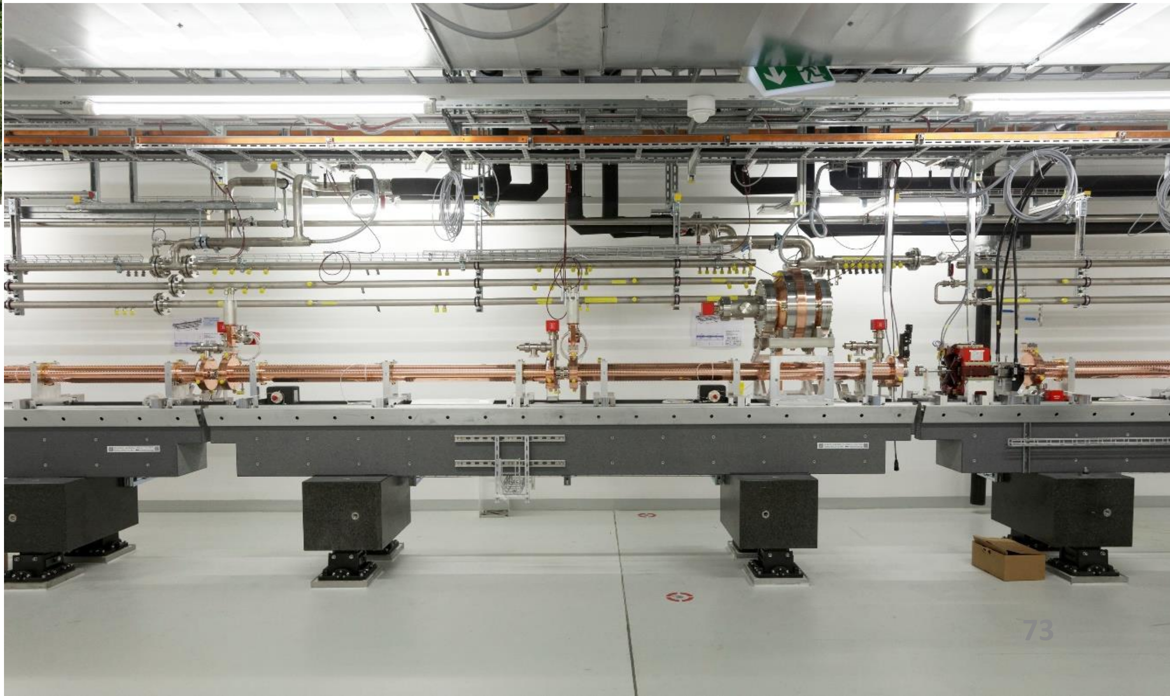


Around 11-12 kton/km main linac (CLIC DB and ILC)

Steinar Stapnes

SwissFEL

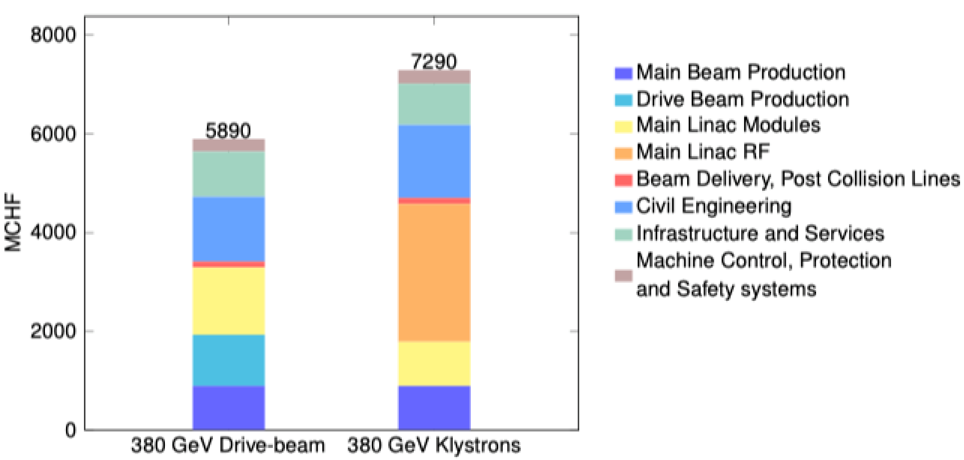
- **104 x 2m-long C-band structures (beam → 6 GeV @ 100 Hz)**
- **Similar um-level tolerances**
- **Length ~ 800 CLIC structures**



Cost (380 GeV)

Accelerator re-costed bottom-up

- **Methods and costings validated at review November 2018 – similar to LHC, ILC, CLIC CDR**
- **Technical uncertainty and commercial uncertainty estimated**



Domain	Sub-Domain	Cost [MCHF] Drive-Beam	Cost [MCHF] Klystron
Main Beam Production	Injectors	175	175
	Damping Rings	309	309
	Beam Transport	409	409
Drive Beam Production	Injectors	584	—
	Frequency Multiplication	379	—
	Beam Transport	76	—
Main Linac Modules	Main Linac Modules	1329	895
	Post decelerators	37	—
Main Linac RF	Main Linac Xband RF	—	2788
Beam Delivery and Post Collision Lines	Beam Delivery Systems	52	52
	Final focus, Exp. Area	22	22
	Post-collision lines/dumps	47	47
Civil Engineering	Civil Engineering	1300	1479
Infrastructure and Services	Electrical distribution	243	243
	Survey and Alignment	194	147
	Cooling and ventilation	443	410
	Transport / installation	38	36
Machine Control, Protection and Safety systems	Safety system	72	114
	Machine Control Infrastructure	146	131
	Machine Protection	14	8
	Access Safety & Control System	23	23
Total (rounded)		**5890**	**7290**

CLIC 380 GeV Drive-Beam based: 5890^{+1470}_{-1270} MCHF;

CLIC 380 GeV Klystron based: 7290^{+1800}_{-1540} MCHF.

Cost - II

Other cost estimates:

Construction:

- **Labour estimate: ~11500 FTE for 380 GeV**
- **From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of linacs)**
- **From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of linacs)**

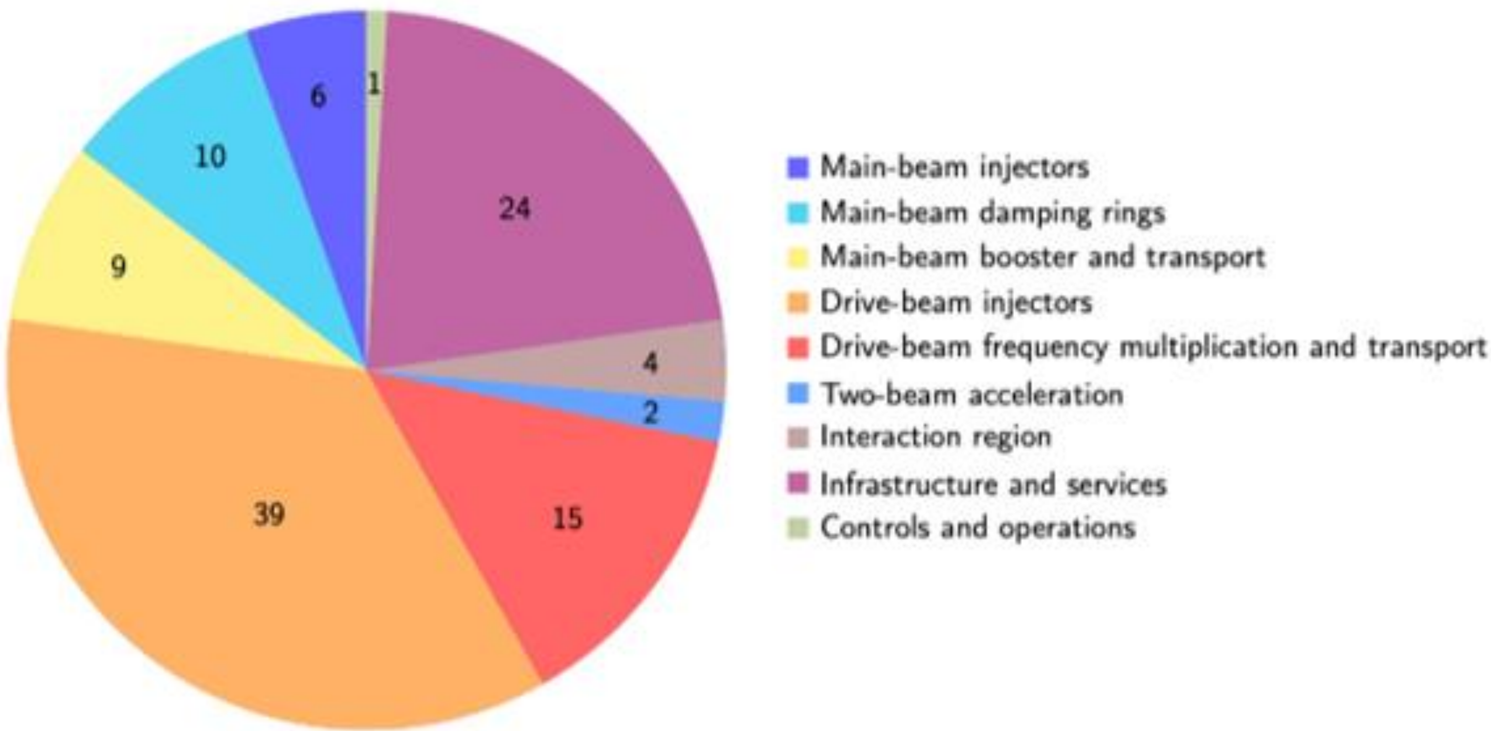
Operation:

- **116 MChF consumables + spares (see below)**
- **Energy costs**

– 1% for accelerator hardware parts (e.g. modules).
– 3% for the RF systems, taking the limited lifetime of these parts into account.
– 5% for cooling, ventilation and electrical infrastructures etc. (includes contract labour and consumables)

These replacement/operation costs represent 116 MCHF per year.

Power + energy: 380 GeV



Power = 110 MW

Annual energy consumption = 0.6 TWh (~ 50% of current CERN energy use)

Further savings possible: high-efficiency klystrons, permanent magnets …
Looking also more closely at 1.5 and 3 TeV numbers

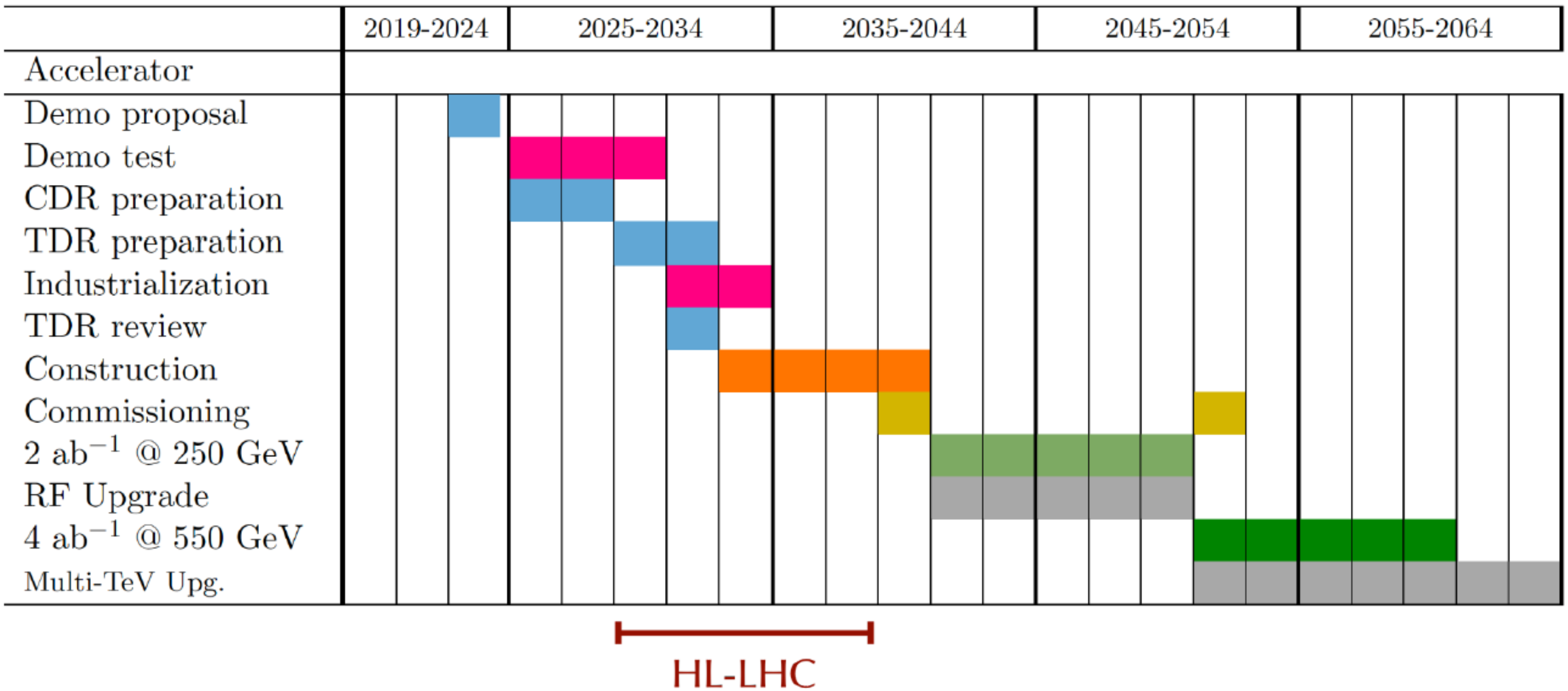
Extra material:

C3

Technical Timeline for 250/550 GeV CoM

P5 Town Hall

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



Cool Copper Collider (C3)

- **Design aim: 550 GeV c.o.m. energy w. 120 MV/m structures**

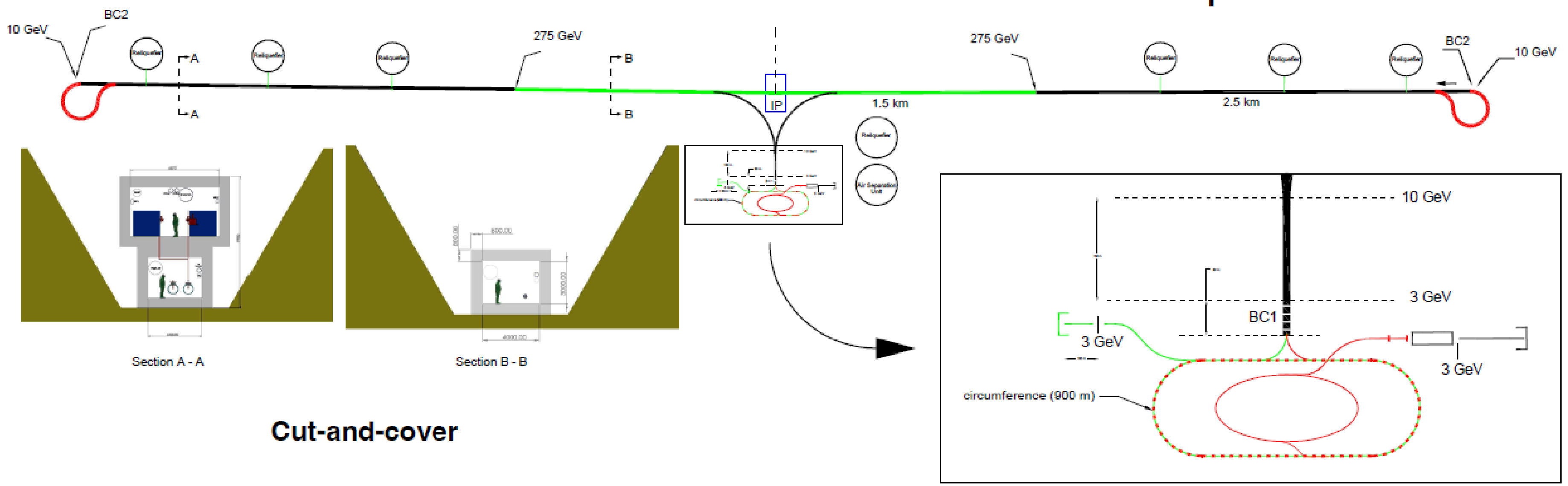
  start @ 250 GeV w. 70 MV/m structures

- **Beam parameters optimised for same integrated luminosity as ILC: 2 ab-1 in 10 years @ 250 GeV**
- **Benefits from synergies with ILC and CLIC:**

  Beam Delivery System and Interaction Region based on ILC

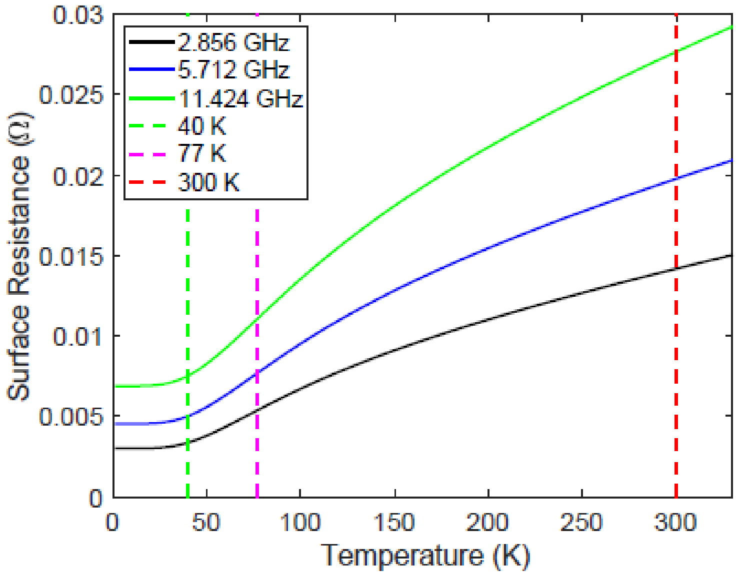
  Damping Rings and injectors use CLIC as a baseline

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



Cut-and-cover

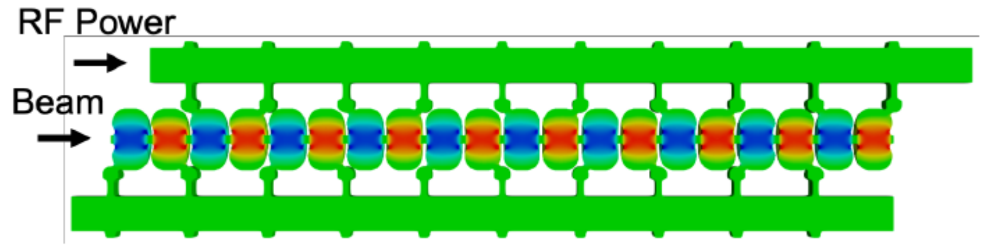
Cool Copper Collider (C3)



Design choice: C-band Cu RF cavities @ 77K (LN2)

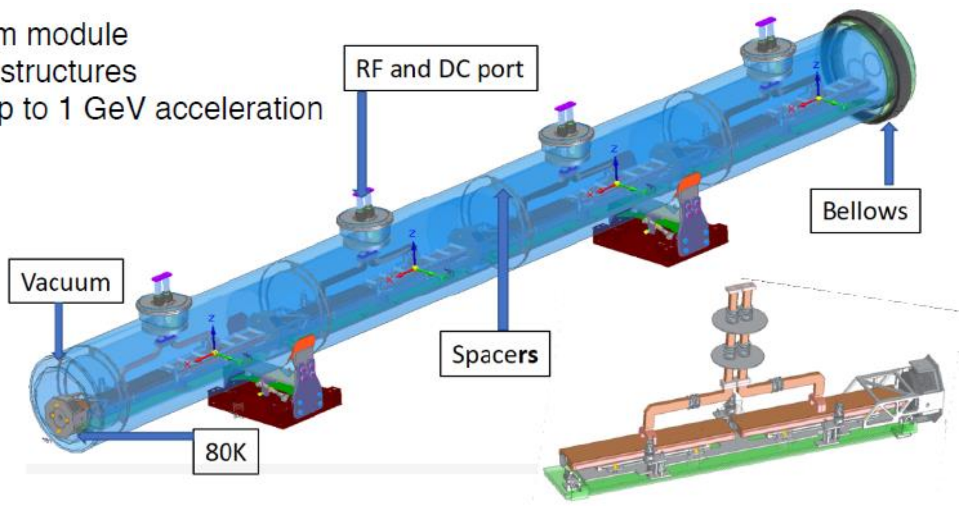
higher gradients ←→ lower RF power

higher RF → beam efficiency



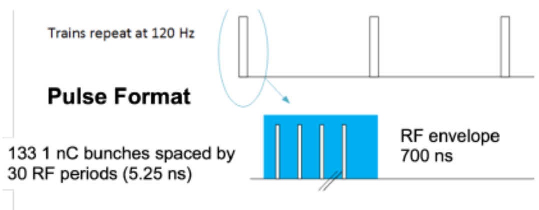
Electric field magnitude for equal power from RF manifold

9m module
8 structures
Up to 1 GeV acceleration



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

Compatibility with Renewables
Cryogenic Fluid Energy Storage

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

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

34

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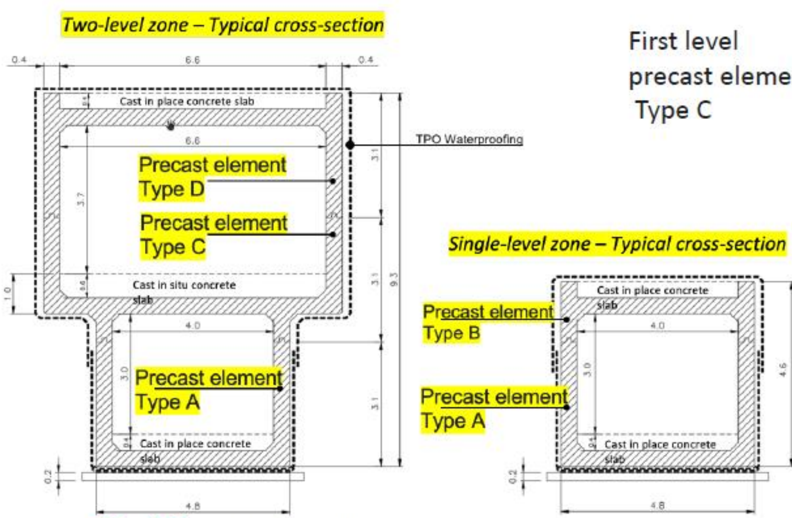
New “sustainable” parameter set ?

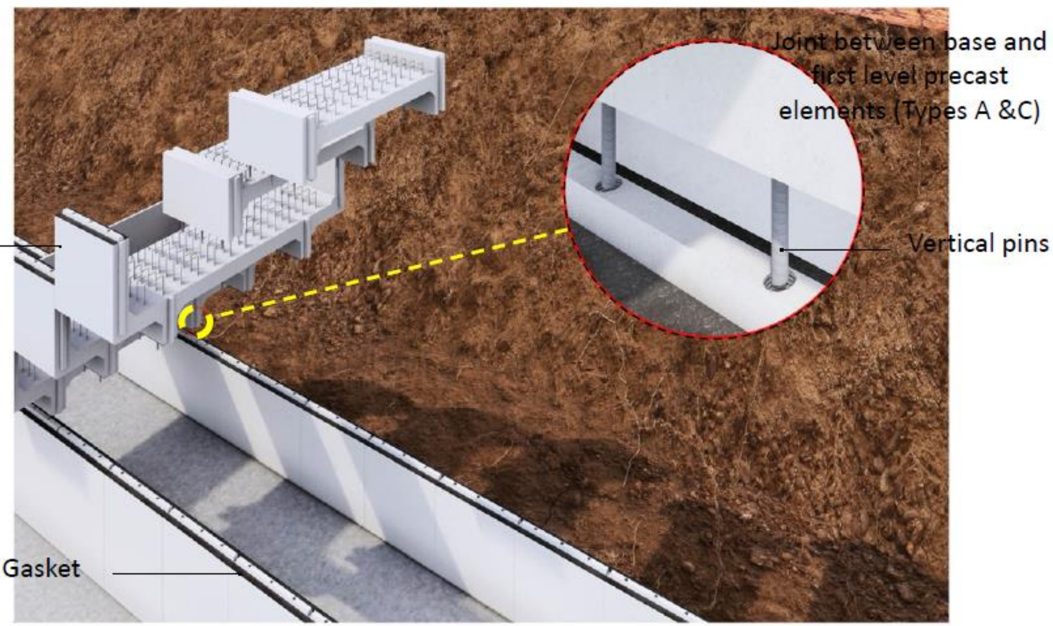
scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch 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]	$\sim$150	$\sim$175	$\sim$110	$\sim$125

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





C3 comparison

Collider	NLC[28]	CLIC[29]	ILC[5]	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
σ_z [μm]	150	70	300	100	100
β_x [mm]	10	8.0	8.0	12	12
β_y [mm]	0.2	0.1	0.41	0.12	0.12
ϵ_x [nm-rad]	4000	900	500	900	900
ϵ_y [nm-rad]	110	20	35	20	20
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
Beam Power [MW]	5.5	2.8	2.63	2	2.45
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014
Crab Angle	0.020/2	0.0165/2	0.014/2	0.014/2	0.014/2
Luminosity [x10^{34}]	0.6 (w/ IP dil.)	1.5 (max is 4)	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Shunt Impedance [MΩ/m]	98	95		300	300
Effective Shunt Impedance [MΩ/m]	50	39		300	300
Site Power [MW]	121	168	125	~150	~175
Length [km]	23.8	11.4	20.5 (31)	8	8
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UNIVERSITY OF OXFORD

John Adams Institute for Accelerator Science

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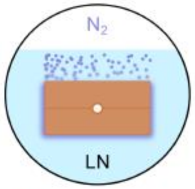
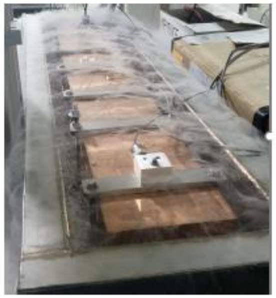
C^3 Technical progress and challenges



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

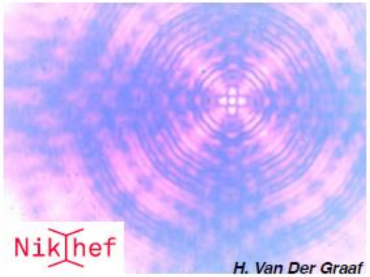
- **Gradient** – Scaling up to meter scale cryogenic tests (Emilio,Dennis)
- **Vibrations** – Measurements with full thermal load (Ankur)
- **Alignment** – Working towards raft prototype (Harry)
- **Cryogenics** – Two-phase flow simulations to full flow tests
- **Damping** – Materials, design and simulation (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

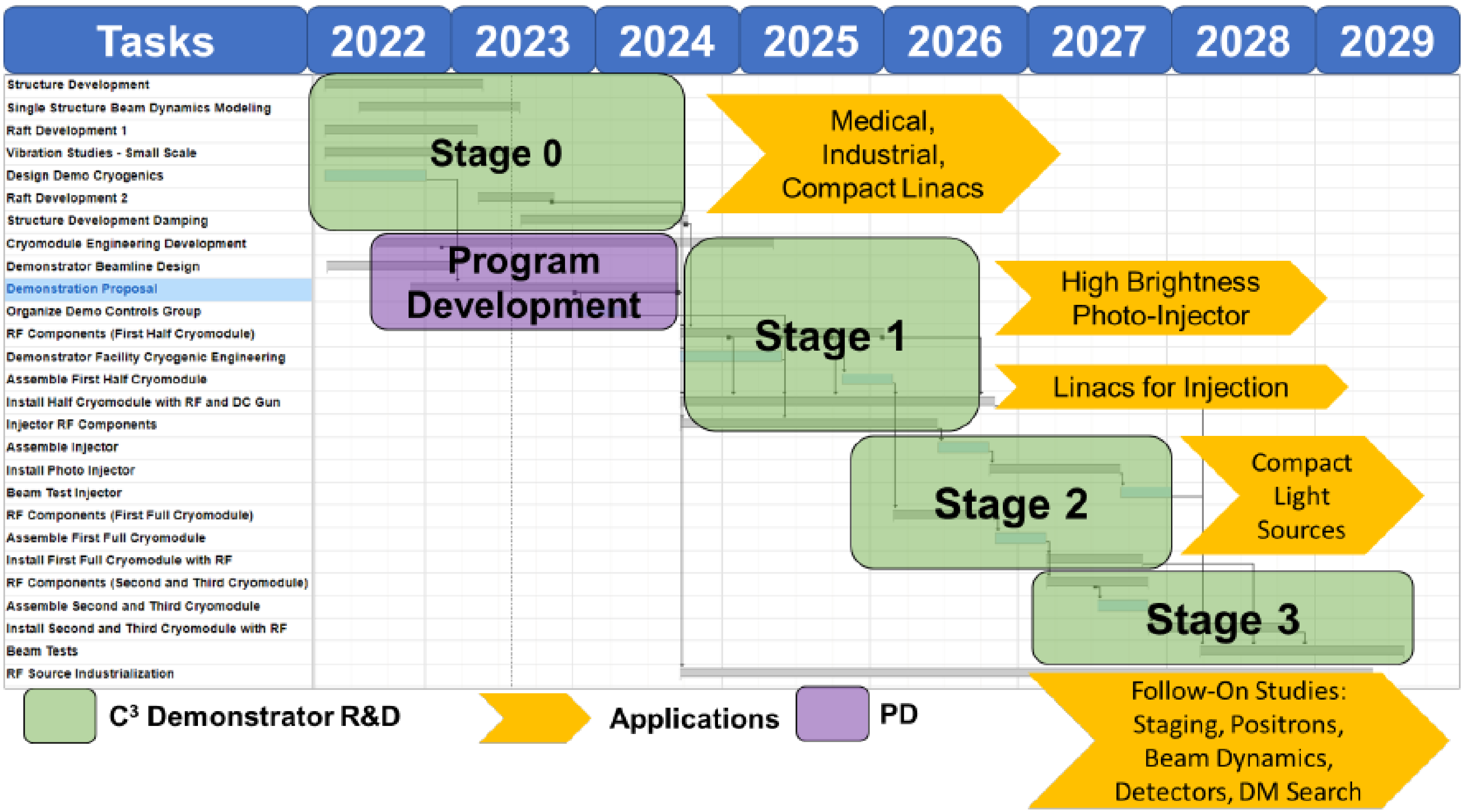
Laying the foundation for a demonstration program to address technical risks

See Ankur's talk for details



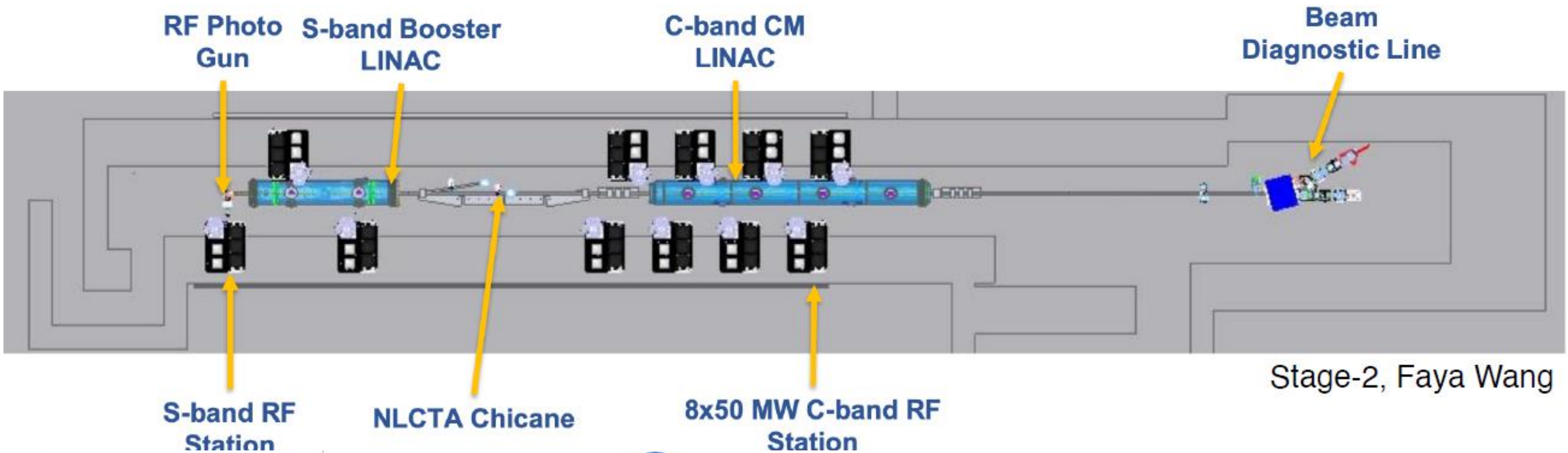
RadiaBeam

C^3 Demonstration R&D Plan Timeline *

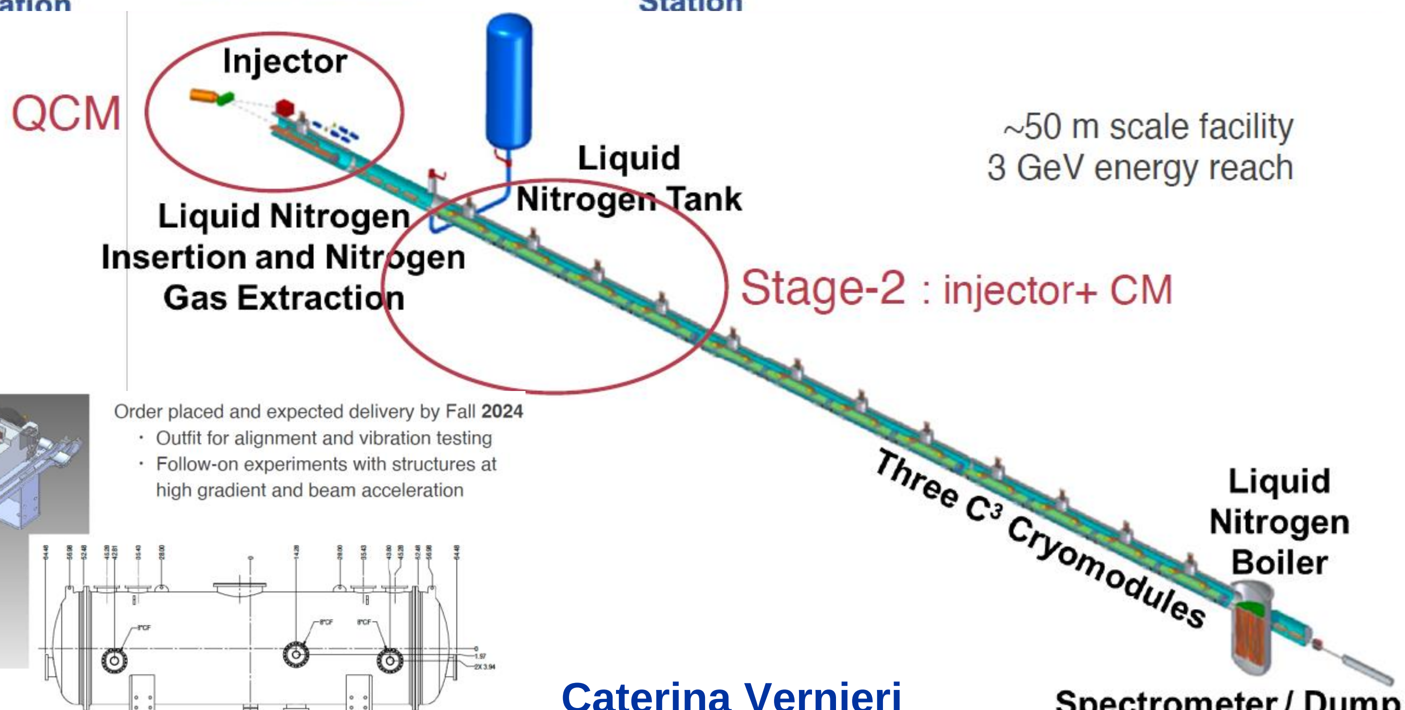


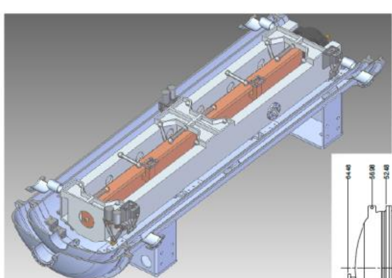
Caterina Vernieri

C3 demonstrator



Stage-2, Faya Wang





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

Caterina Vernieri

Development of accelerators