Future high-energy linear colliders

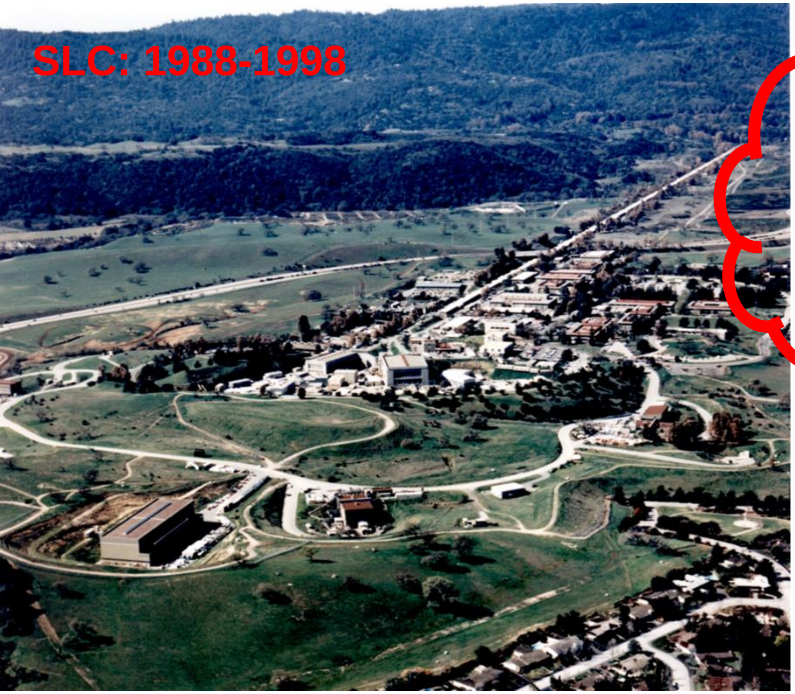
Philip Burrows

Oxford University

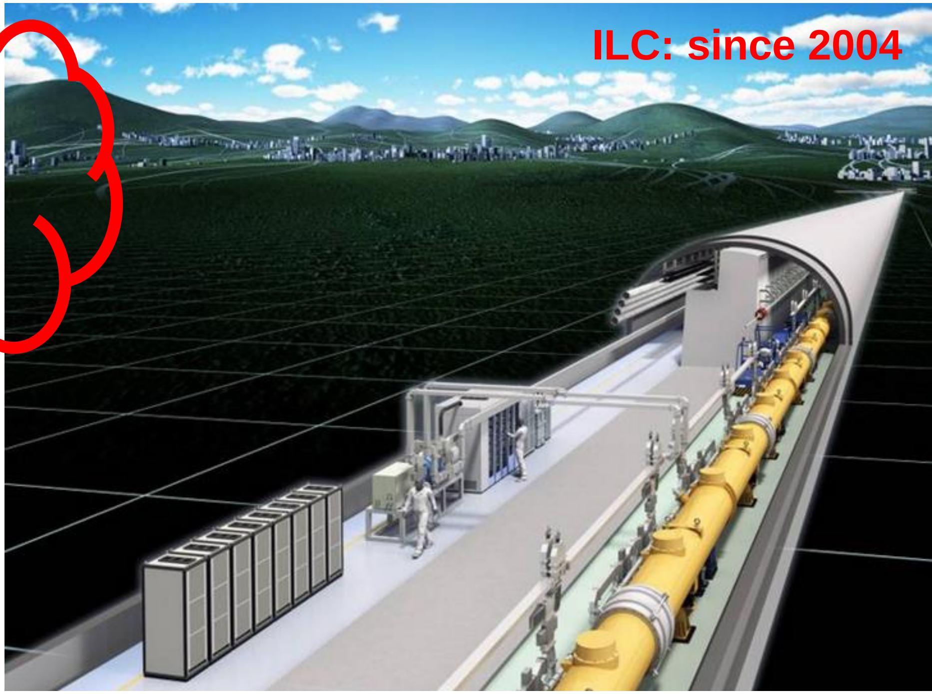
Director, John Adams Institute for Accelerator Science

ILC: https://linearcollider.org
CLIC: https://clic.cern

Linear Colliders



1990s:
NLC
JLC
TESLA



Outline

- Reminder: why linear?
- ILC
- CLIC
- Summary

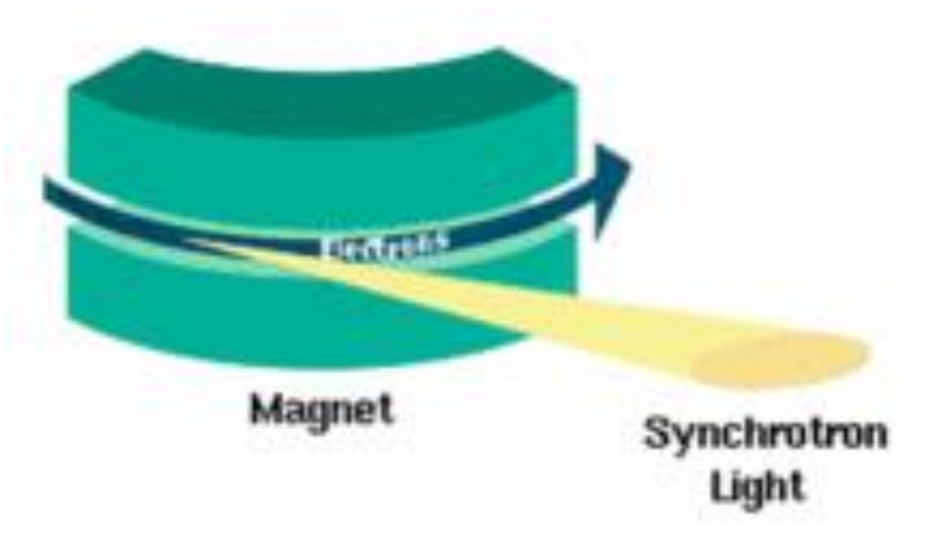
Why Linear?

LEP

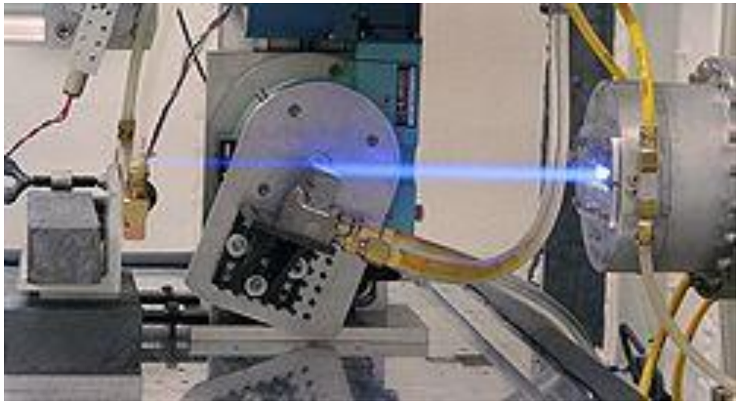
c. 100 GeV

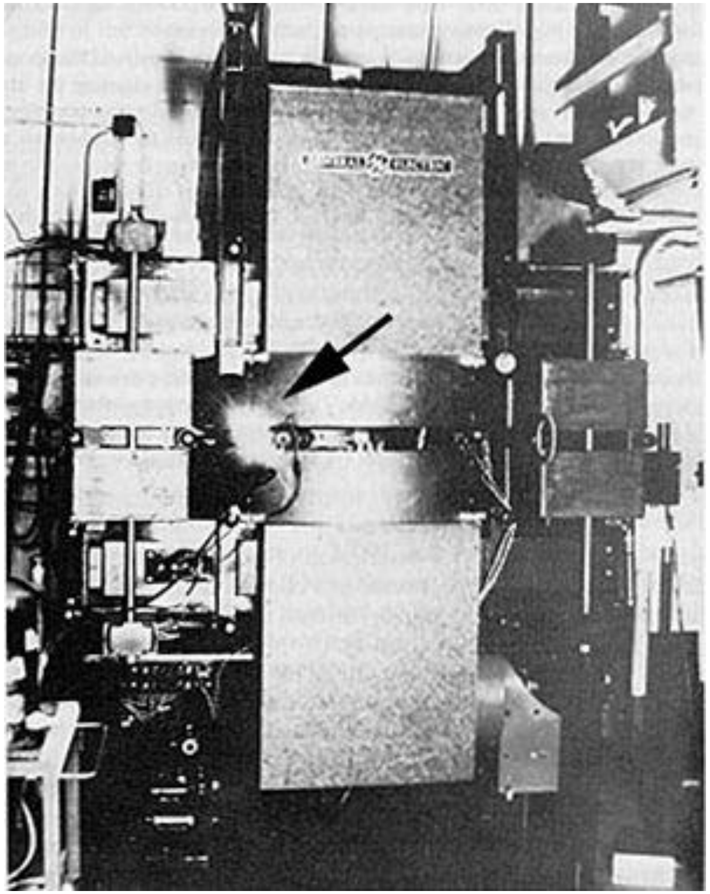
per beam

Synchrotron radiation



Discovered Elder et al 1947 (General Electric)





Synchrotron radiation

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

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→ compensate with RF cavities

Synchrotron radiation

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

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

Synchrotron radiation

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

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)

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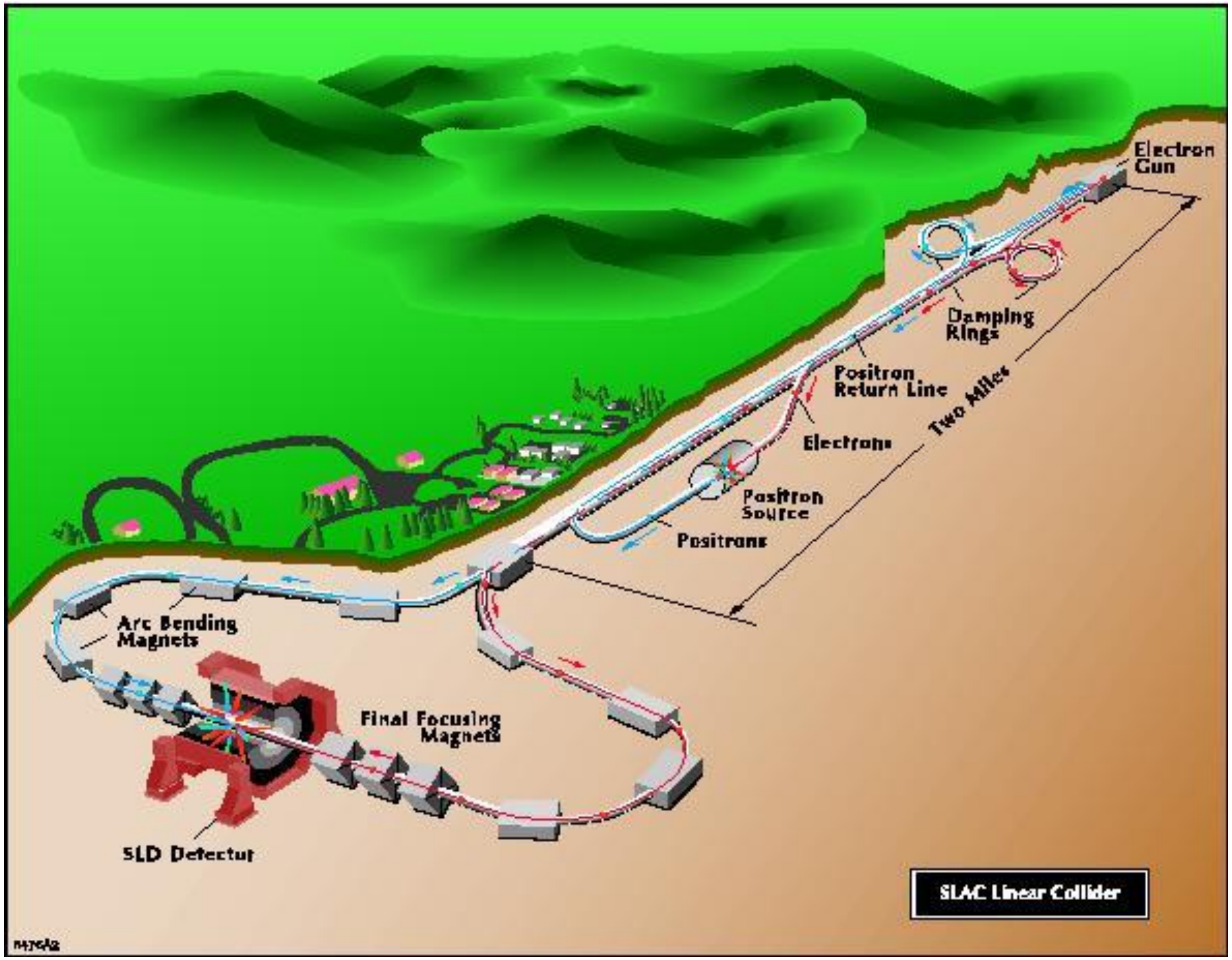


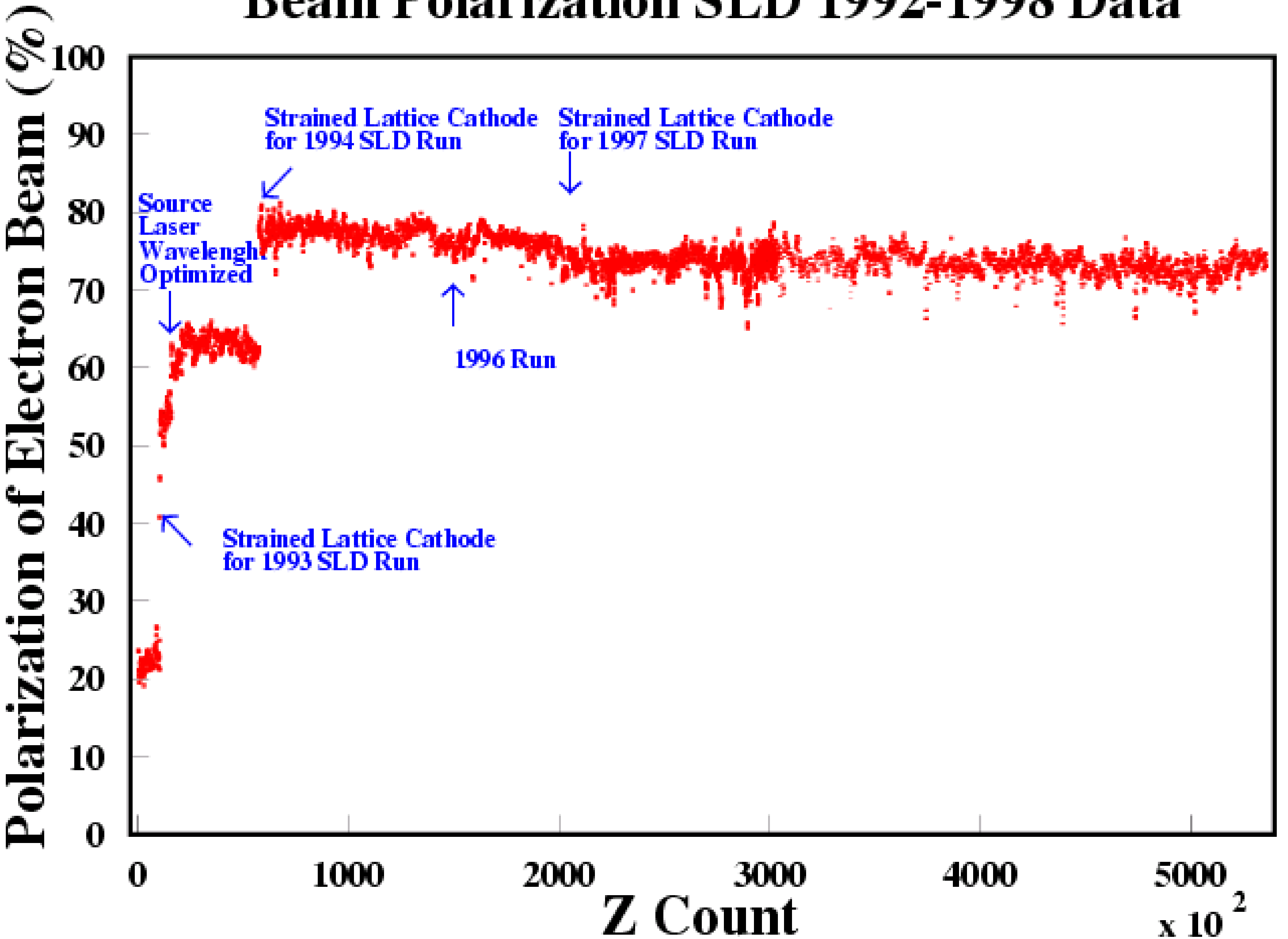
Built in the 1980s within the existing SLAC linear accelerator

Operated 1988-98 at c.o.m energy ~91 GeV on the Z^0 resonance

- established LC concepts

- longitudinal e- beam polarization @ IP

Beam Polarization SLD 1992-1998 Data



The SLAC Linear Collider

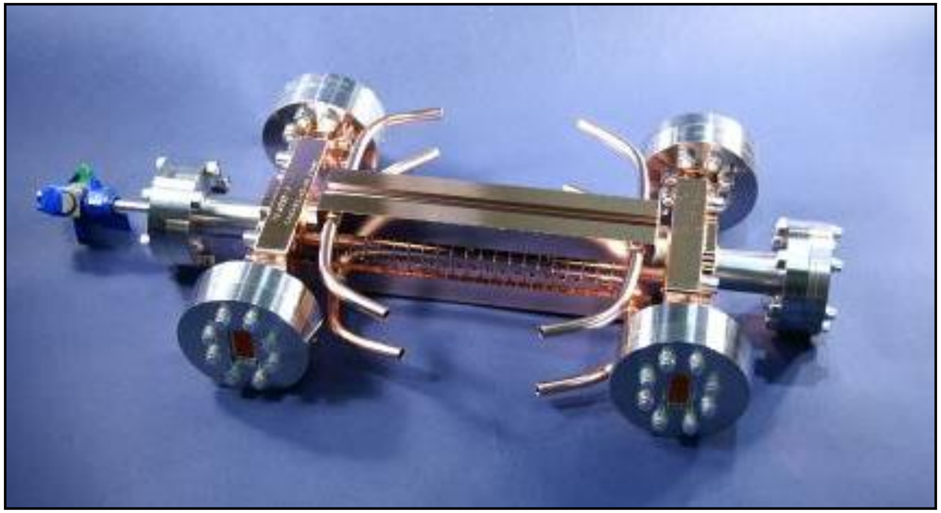
State-of-the-art accelerating cavities

ILC: 35 MV / m

(1.3 GHz)

CLIC: 100 MV / m

(12 GHz)



Luminosity

$$L = H\,N_1\,N_2\,f_{rep}\,/\,(\,4\pi\,\sigma_x\,\sigma_y\,)$$

ILC

Luminosity (ILC 250)

$$L = H\, N_1\, N_2\, f_{rep} \,/\, (\, 4\pi\, \sigma_x\, \sigma_y\,)$$

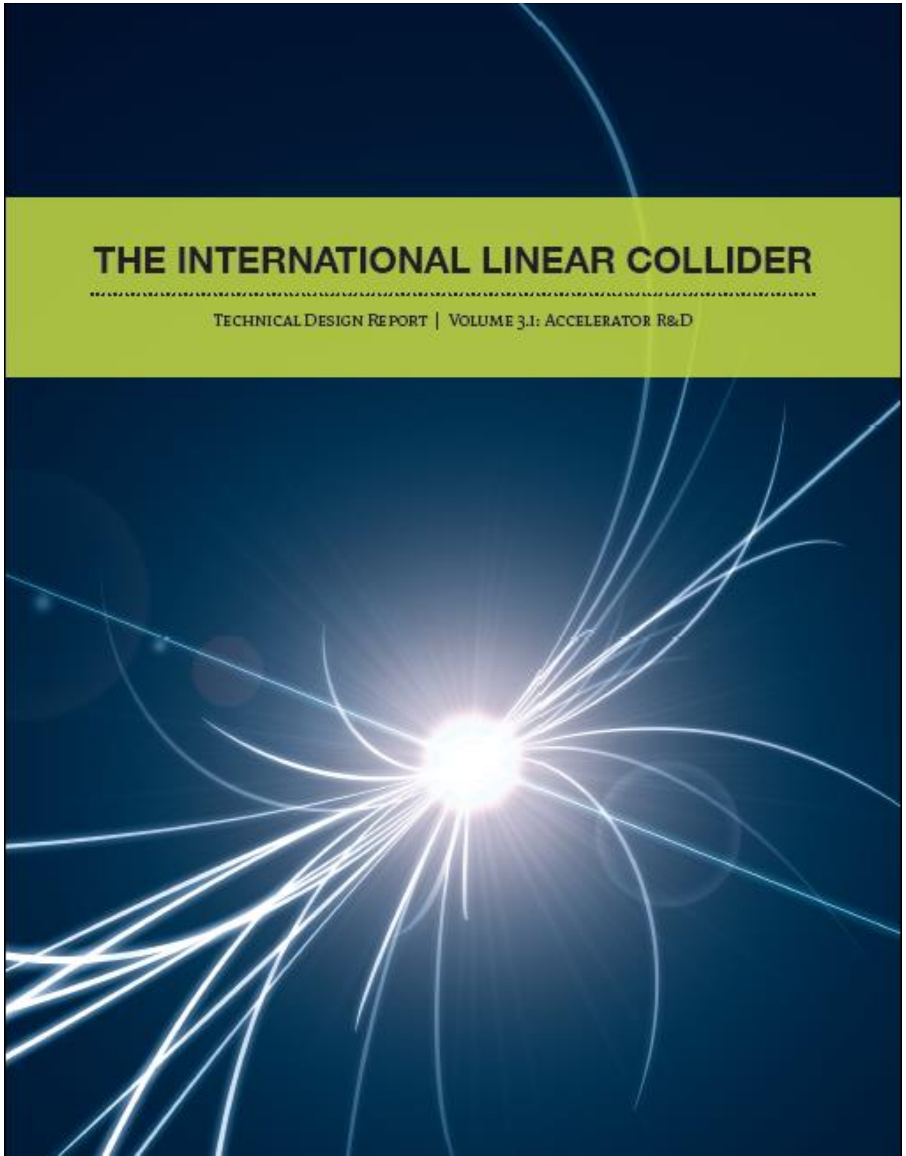
$N_1 = N_2$	≈	2×10^{10} e+/e- per bunch
f_{rep}	=	1312×5
$\sigma_{x,y}$	≈	500×8 nm ^{2}
L	=	$4\ 10^{10}\ 10^{10}\ 1300 \times 5 \,/\, (\, 4\pi\ 8 \times 500\ 10^{-7}\ 10^{-7}\,)$
	≈	10^{34} / cm^2 / s

Ignored ‘hour-glass’ + intra-bunch effects (H) …

These need to be taken into account for precise L calculation

ILC Technical Design Report (June 2013)

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



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

Part I:

ILC R&D IN THE TECHNICAL DESIGN PHASE

Part II:

THE ILC BASELINE DESIGN

Editors:

Phil Burrows, John Carwardine, Eckhard Elsen, Brian Foster, Mike Harrison, Hitoshi Hayano, Nan Phinney, Marc Ross, Nobu Toge, Nick Walker, Akira Yamamoto, Kaoru Yokoya

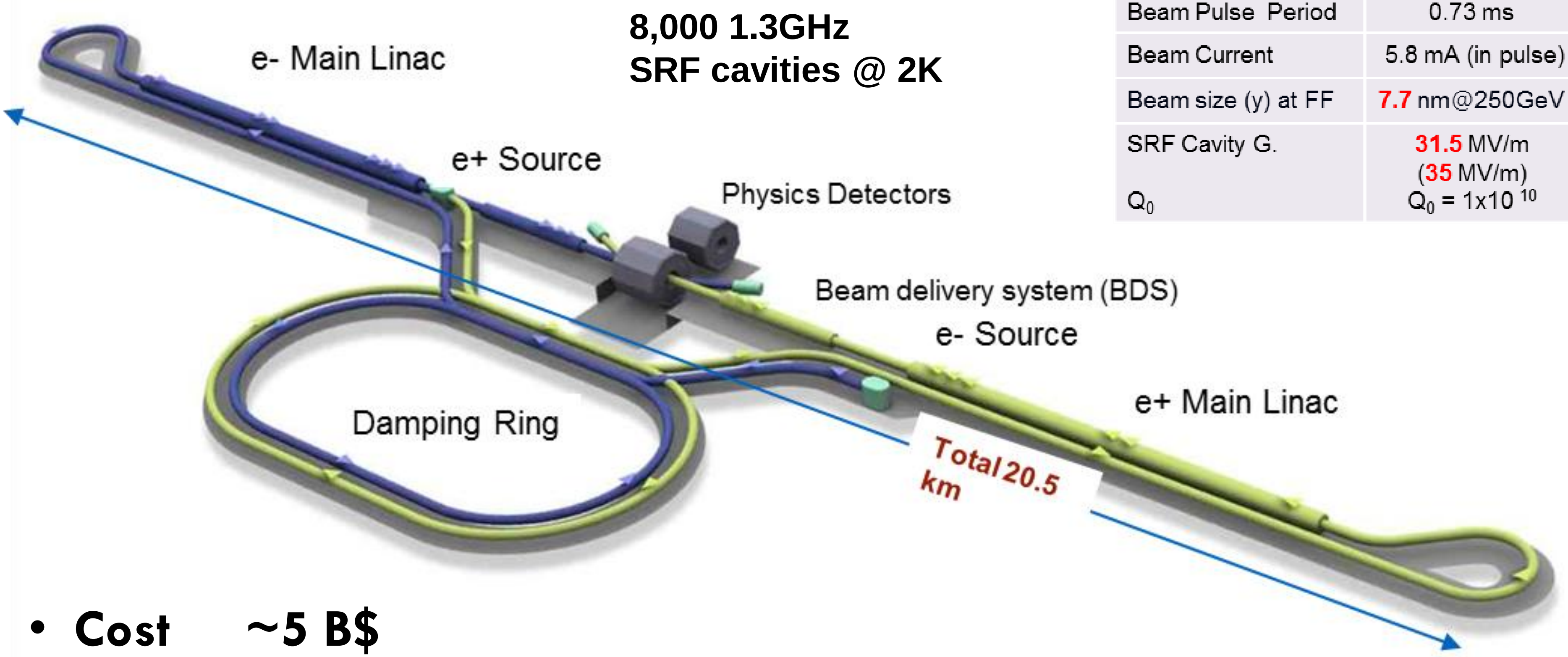
Technical Editors:

Maura Barone, Benno List

ILC today

8,000 1.3GHz
SRF cavities @ 2K

Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{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 = 1x10^{10}



- Cost ~5 B$
- Power ~110 MW

Ongoing developments

Huge global interest in ILC-like SC RF systems:

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

European XFEL @ DESY

Largest deployment of SCRF technology

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

Ongoing developments

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Nb cavity performance advancements made at many labs

New surface treatments + improved fabrication techniques → major improvements in gradient, Q, yield, cost

eg. N-infusion → 45 MV/m @ Q ~ 2 x 1010**

(ILC spec: 31.5 MV/m @ Q ~ 1 x 1010)**

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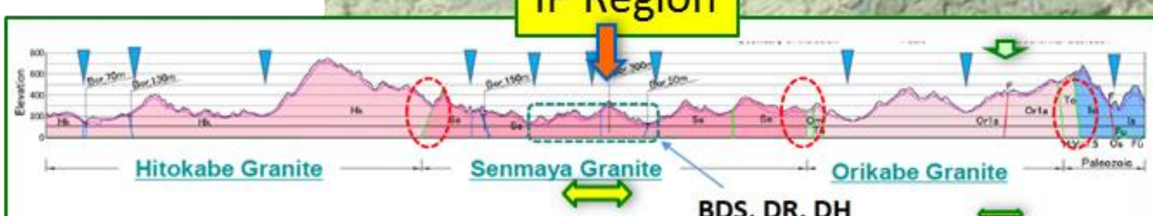
ILC Candidate Location: Kitakami, Tohoku

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

IP Region



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Extensive site studies in Japan: geology, civil, environment, safety …

Engineering design studies for beam dumps, positron source …

Ongoing optimisation of nanobeam production at ATF2

Detailed plan for 4-year work programme: engineering prototypes → Engineering Design Report + construction start

ILC upgrade options

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
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.

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ILC upgrade options

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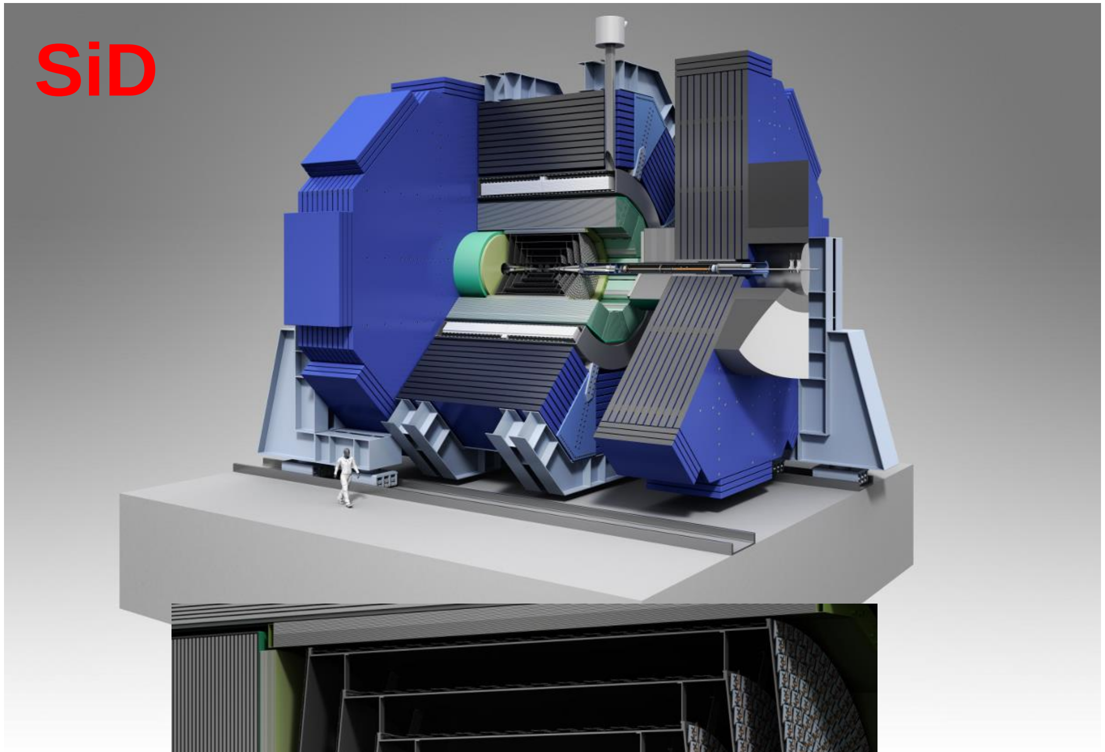
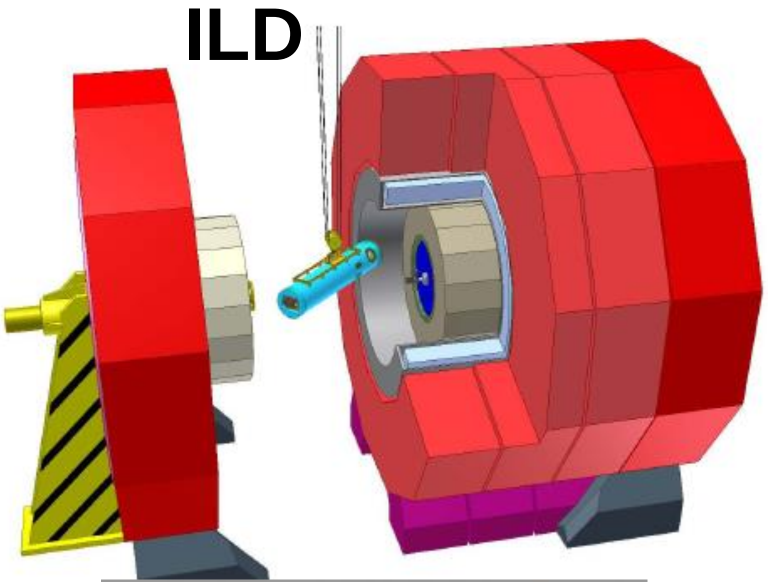
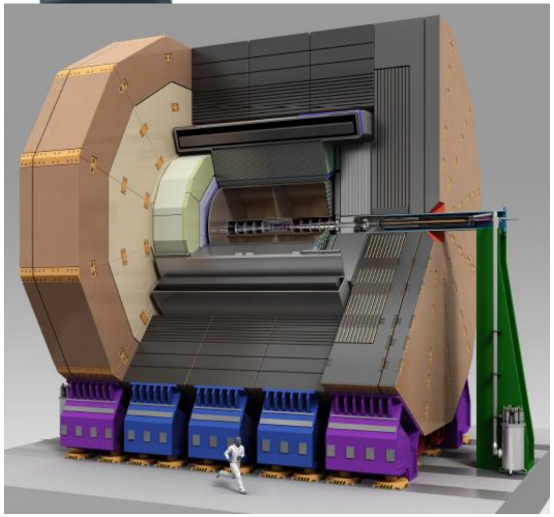
ILC Detectors







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ICFA ILC plan

2020: ICFA set up International Development Team (IDT) 'towards … timely realisation of ILC'

1 + 4-year 'Pre-lab' to finalise technical prototypes, prepare Engineering Design Report, secure cooperation among funding agencies, and prepare for construction start

	IDT	ILC Pre-Lab				ILC Lab.										
	PP	P1	P2	P3	P4	1	2	3	4	5	6	7	8	9	10	Phys. Exp.
Preparation CE/Utility, Survey, Design Acc. Industrialization prep.																
Construction																
Civil Eng.																
Building, Utilities																
Acc. Systems																
Installation																
Commissioning																
Physics Exp.																

Following a four-year ILC Pre-Lab phase, ILC construction will continue for about ten years.

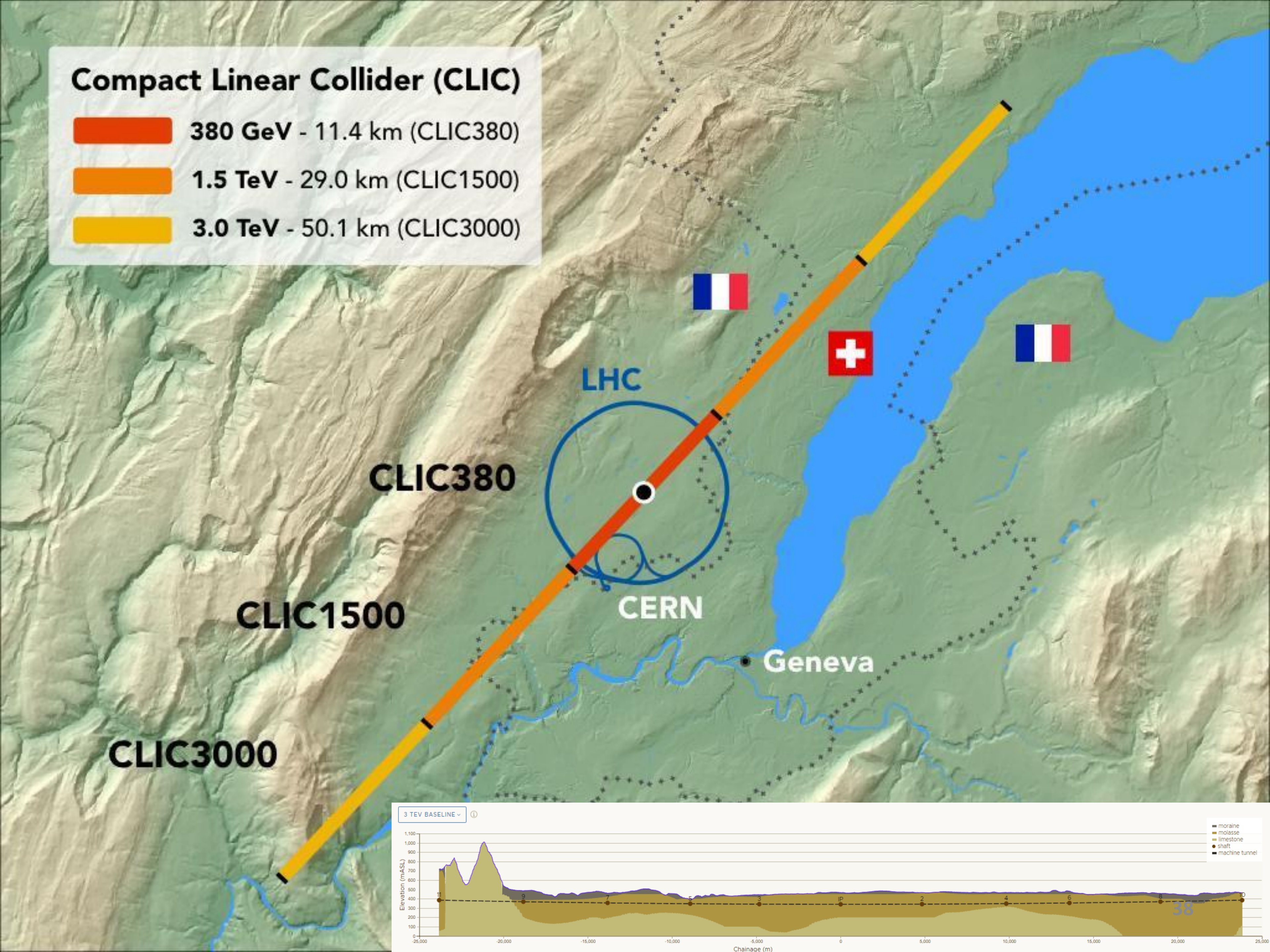
John Adams Institute for Accelerator Science

CLIC

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 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)

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 RF cavities:

  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 2018

  Cost: 5.9 BChF for 380 GeV (stable w.r.t. CDR)

  Power: 168 MW at 380 GeV (significantly reduced since CDR)

- Comprehensive Detector and Physics studies

CLIC Collaborations

https://clic.cern

CLIC accelerator:

- **~50 institutes from 28 countries**
- **CLIC accelerator studies, design and development**
- **Construction + operation of CLIC Test Facility, CTF3**

CLIC detector and physics (CLICdp):

- **30 institutes from 18 countries**
- **Physics prospects & simulation studies**
- **Detector optimisation + R&D for CLIC**

+ strong participation in the CALICE and FCAL Collaborations and in AIDA-2020/AIDAinnova

CLIC Collaborations

CLIC European Strategy Inputs

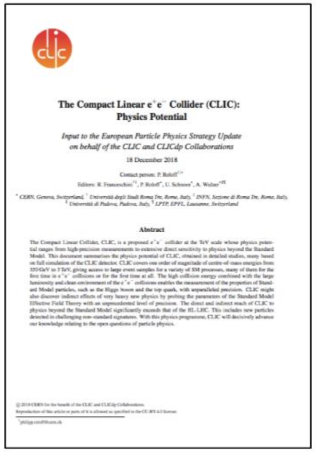
http://clic.cern/european-strategy


The Compact Linear e+e− Collider (CLIC): Accelerator and Detector

Input to the European Particle Physics Strategy Update on behalf of the CLIC and CLICdp Collaborations

18 December 2018

Abstract


The Compact Linear e+e− Collider (CLIC): Physics Potential

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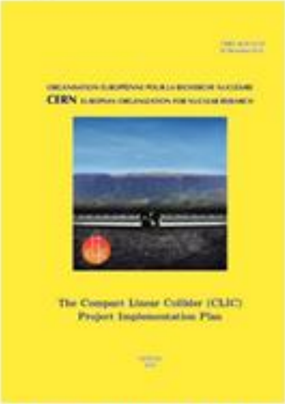
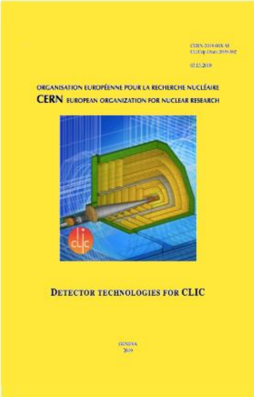
Abstract

CERN-2018-005-M

CERN-2018-009-M



CERN-2018-010-M



CERN-2019-001

CLIC Snowmass Inputs

Several LoIs have been submitted on behalf of CLIC and CLICdp

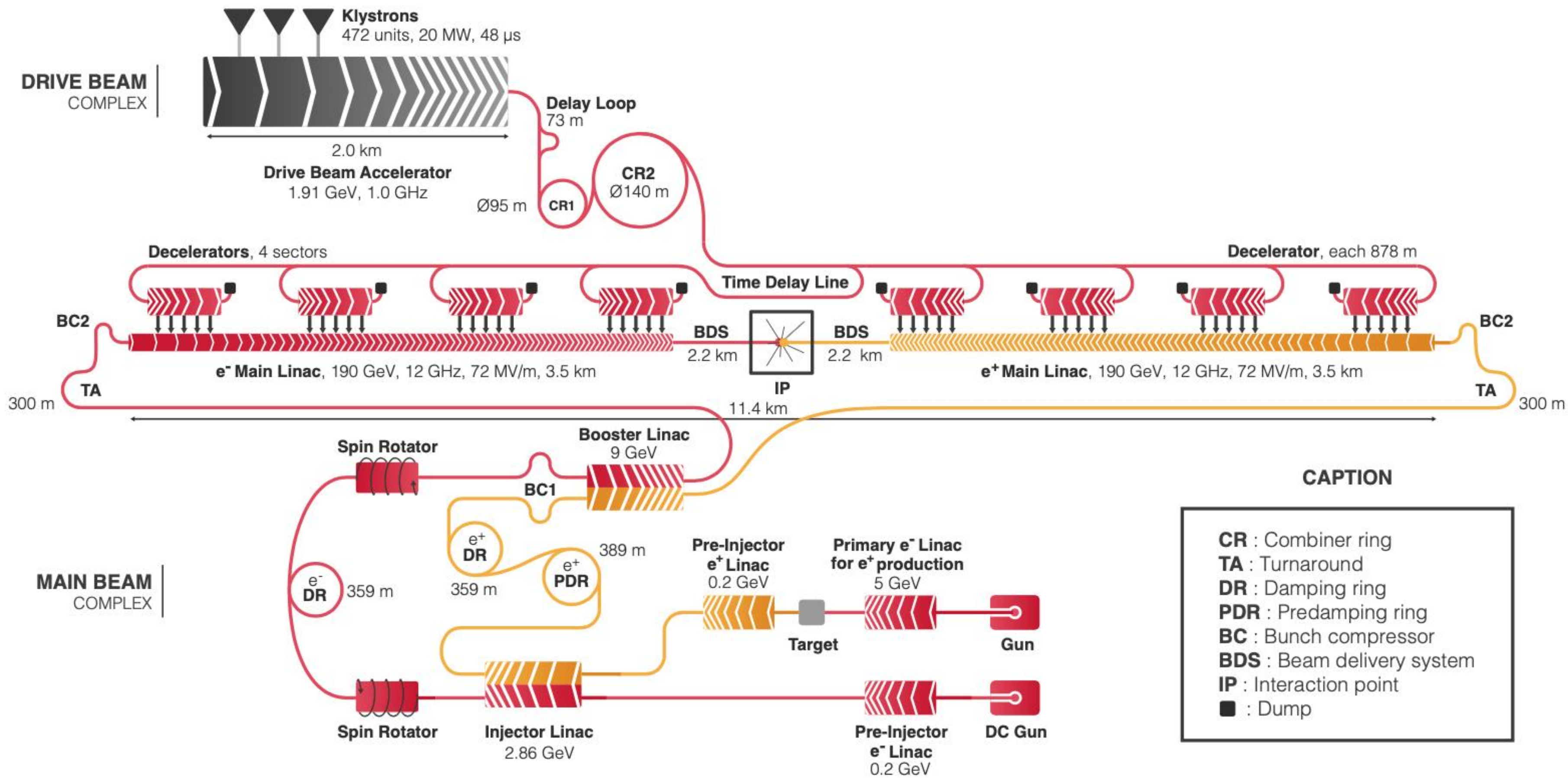
The CLIC accelerator study: Link
Beam-dynamics focused on very high energies: Link
The physics potential: Link
Detector: Link

CLIC parameters

Table 1.1: Key parameters of the CLIC energy stages.

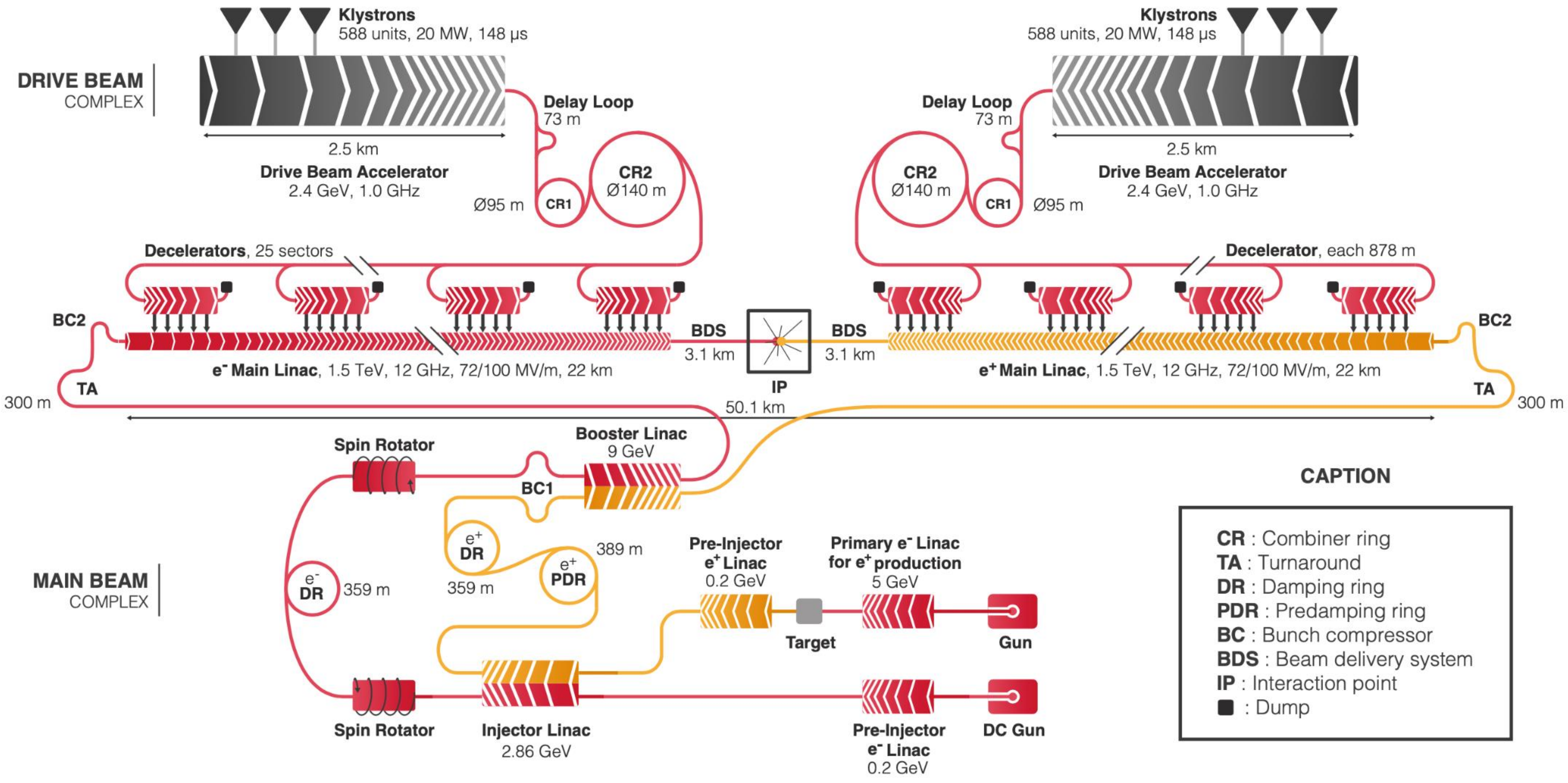
Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	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 380 GeV layout



Baseline electron polarisation ±80%

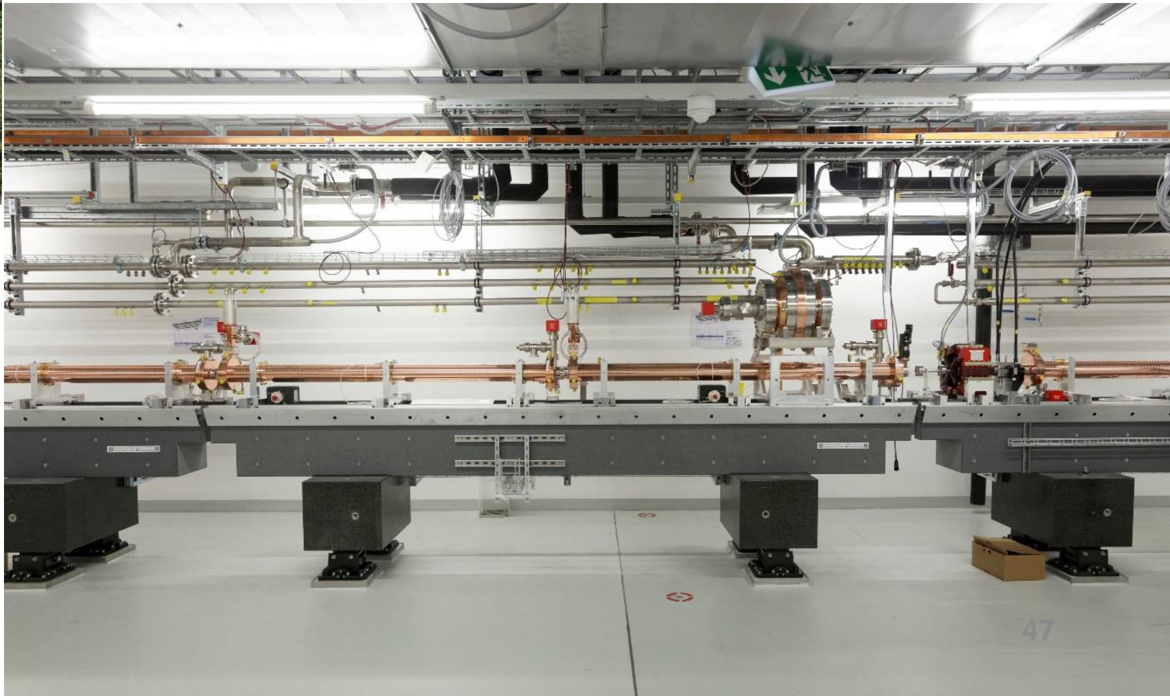
CLIC 3 TeV layout



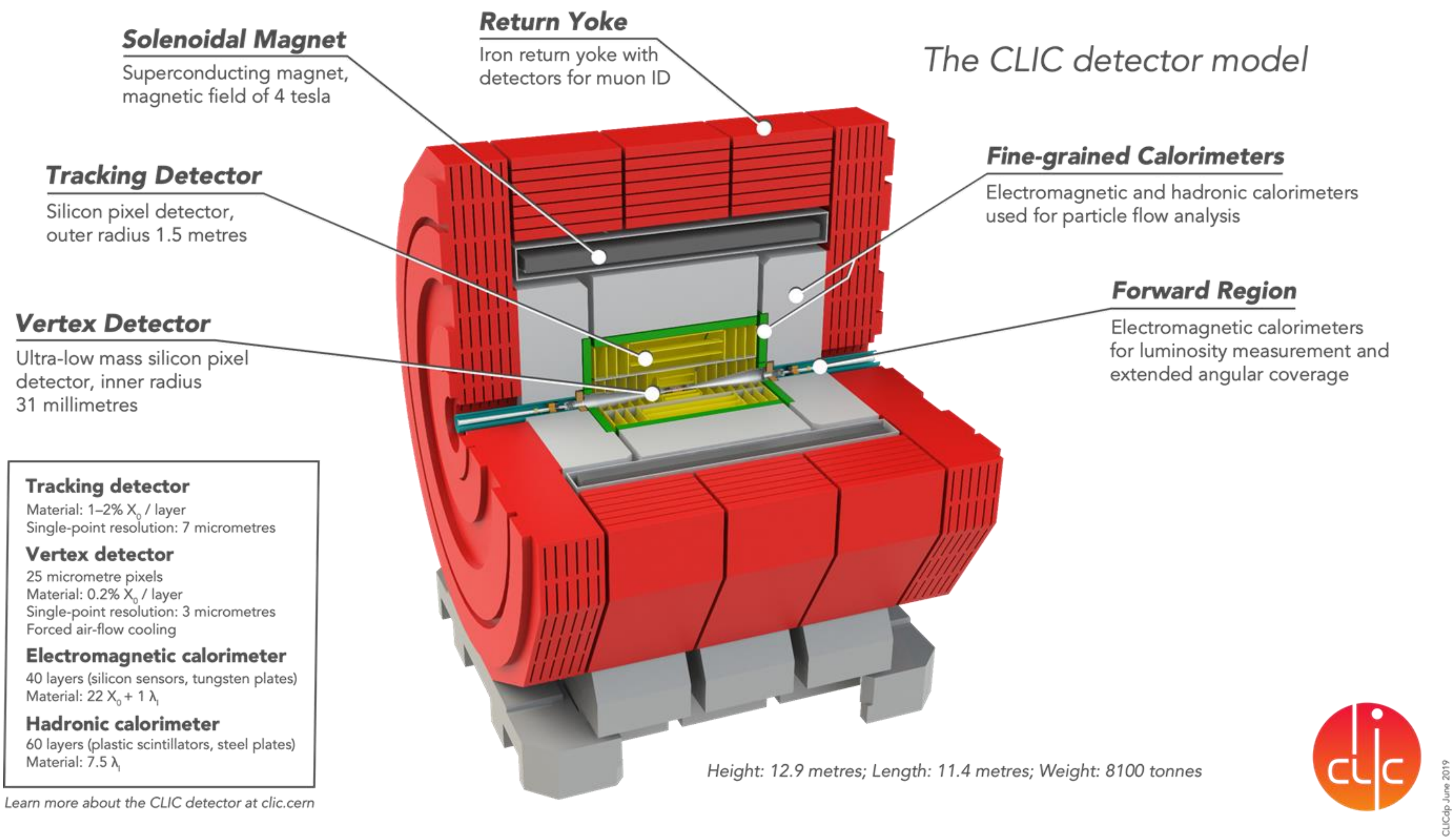
Baseline electron polarisation ±80%

SwissFEL

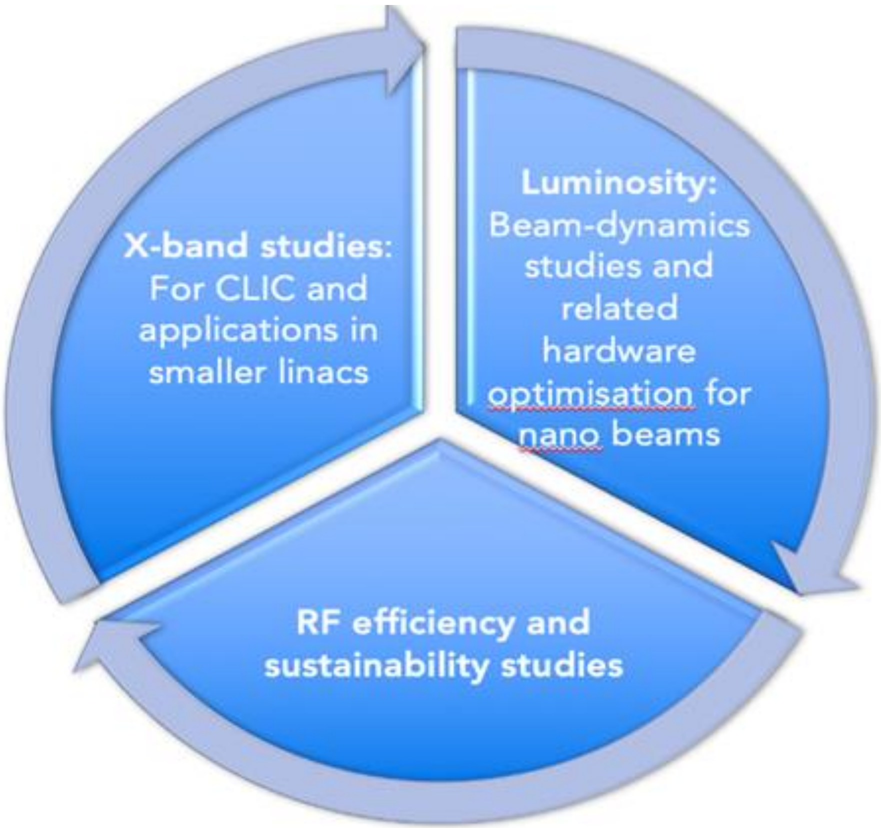
- **104 x 2m-long C-band structures (beam → 6 GeV @ 100 Hz)**
- **Similar um-level tolerances**
- **Length ~ 800 CLIC structures**



CLIC detector



CLIC project readiness → 2025/26



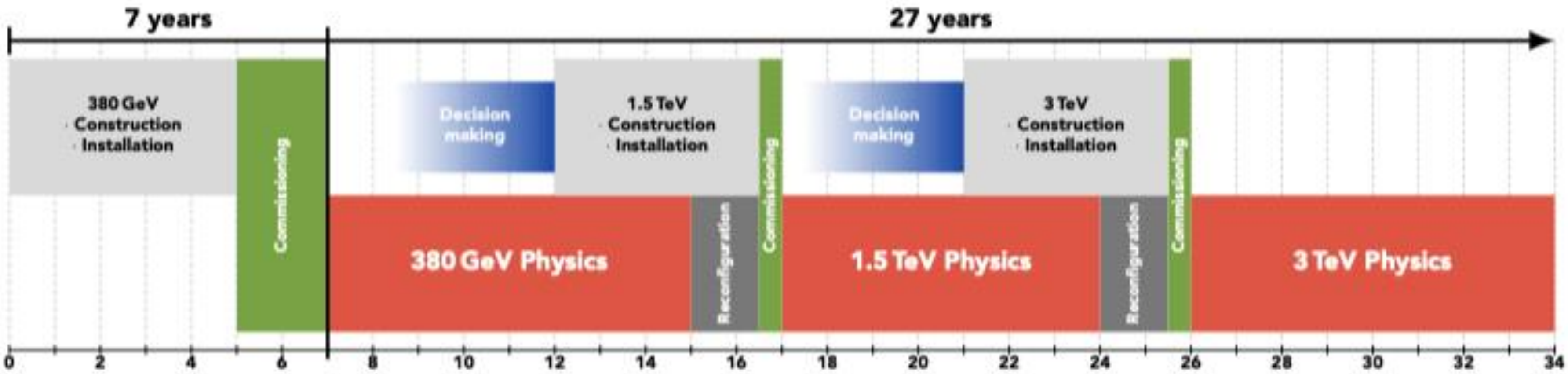
Project Readiness Report as a step toward a TDR – for next ESPP

Assuming ESPP in 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

Focusing on:

- **The X-band technology readiness for the 380 GeV CLIC initial phase**
- **Optimizing the luminosity at 380 GeV**
- **Improving the power efficiency for both the initial phase and at high energies**

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)

Summary

ILC + CLIC are technically-mature projects

large X-ray FEL systems in operation using both technologies

Concepts have been developed over decades via global efforts

ILC TDR 2013

CLIC CDR 2012, updated 2018

Both are consistent with European PP strategy

European Strategy Update 2020

The vision is to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges

3. **High-priority future initiatives a) An electron-positron Higgs factory is the highest-priority next collider.** For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy ...

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

b) **Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders.** It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other **high-gradient accelerating structures**, bright muon beams, energy recovery linacs.

Summary

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large X-ray FEL systems in operation using both technologies

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ILC TDR 2013

CLIC CDR 2012, updated 2018

Both are consistent with European PP strategy

Both affordable: costs comparable with LHC cost (today)

Manageable power: 110 MW (CLIC 380, ILC 250) similar to LHC

Intrinsically upgradeable for both luminosity and energy

LC offers a flexible, staged approach to energy frontier:

energy ~ length

facility reusable as gradient improves, eg. ILC → CLIC → PWFA …

complementary to long-term future hadron or muon colliders

Thanks to ILC + CLIC colleagues