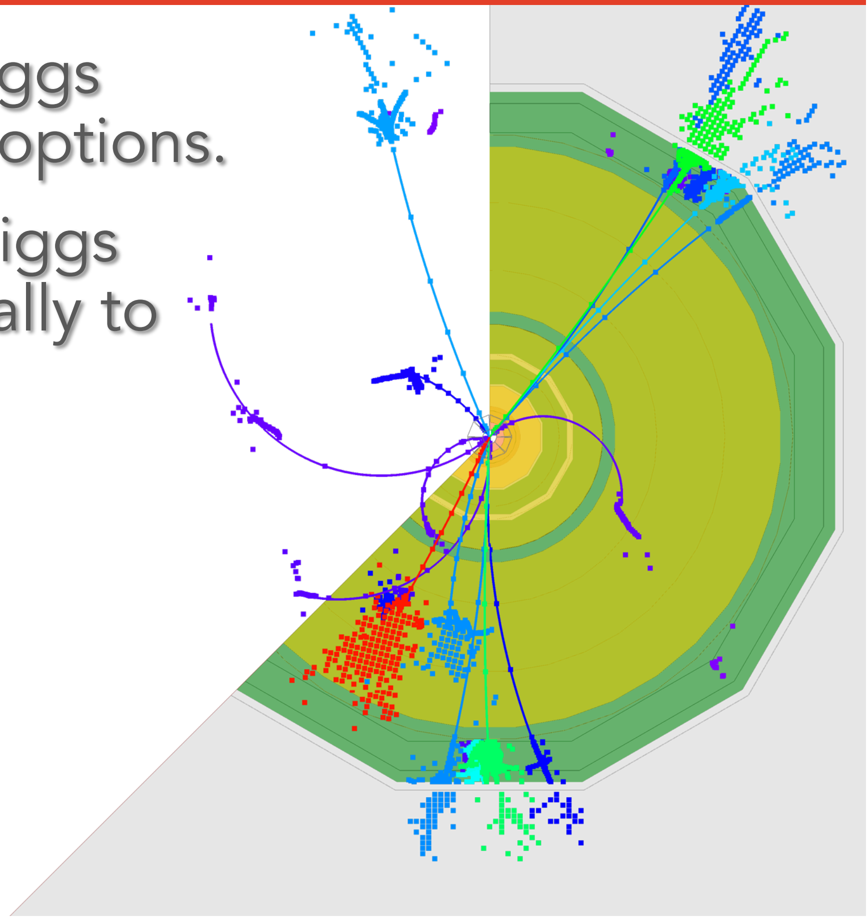
Linear Collider Higgs Factories

Projects input towards UK Strategy

Please contact Aidan Robson with updates/corrections. This version: 1/11/2024

A linear collider facility can deliver the core Higgs precision programme with attractive upgrade options.

A linear facility can be less costly than other Higgs factory options, and complementary scientifically to other Higgs factory options.



- ILC in Japan
- ILC at CERN
- CLIC
- C^3
- HALHF

Key physics deliverables

250 GeV (/380 GeV)

- precision Higgs mass and couplings; total ZH cross-section
- Higgs –> invisible (Dark Sector portal)
- two-fermion (ff) and WW programmes
- optional: WW threshold scan

  - several couplings at few-0.1% level: Z, W, g, b, tau
  - some more at ~1%: gamma, c

Z pole, few billion Z bosons

- EWPOs 10–100x better than today

  - benefit from beam polarisation

350 GeV

- precision top mass from threshold scan

500–600 GeV

- Higgs self-coupling in ZHH
- top-quark EW couplings
- top Yukawa coupling including CP structure
- improved Higgs, WW and ff
- probe Higgsinos up to ~300GeV
- probe Heavy Neutral Leptons up to ~600GeV

  - many not accessible at HL-LHC

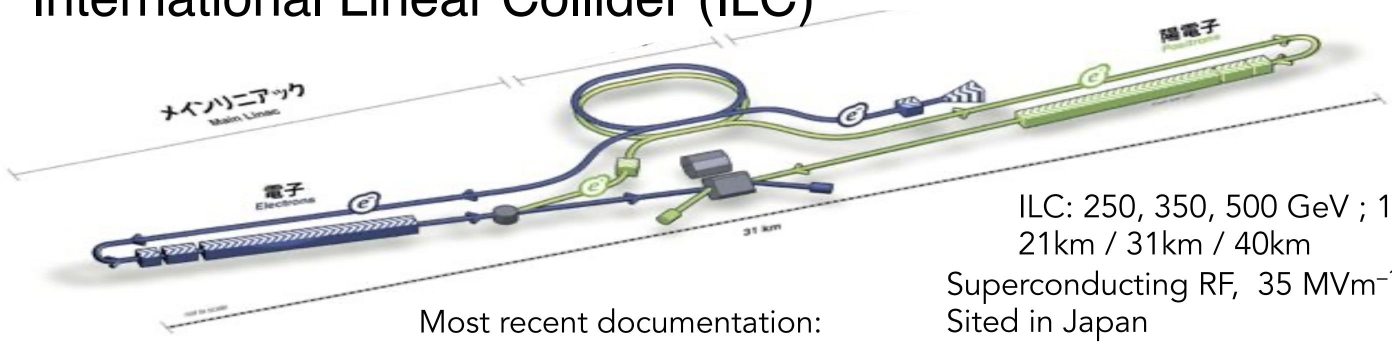
≥500 GeV e+e– collisions are only achievable at a linear collider facility

800–1000 GeV

- Higgs self-coupling in VBF
- further improvements in tt, ff, WW
- probe Higgsinos up to ~500GeV
- probe Heavy Neutral Leptons up to ~1000GeV
- searches…

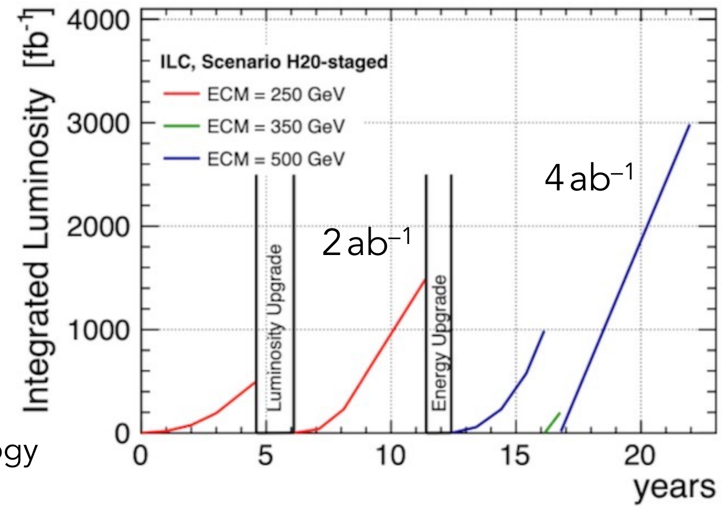
1. ILC in Japan

International Linear Collider (ILC)



Most recent documentation:
ILC Report to Snowmass 2022
https://arxiv.org/abs/2203.07622

ILC: 250, 350, 500 GeV ; 1 TeV
21km / 31km / 40km
Superconducting RF, 35 MVm^{-1}
Sited in Japan
TDR 2013, updated for 250GeV
European XFEL demonstrates technology



$\sqrt{s}$	**250 GeV**	**91 GeV** (not baseline)	**350 GeV**	**500 GeV**
Int L (ab^{-1})	2	0.1	0.2	4
Duration (yr)	11	1.5	0.75	9
Wall power (MW)	111 / 138 ▲ (▲after lumi upgrade)	94/115		173/215
Length (km)	20.5	20.5	31	31
Environmental cost of construction (kt CO_2 eq)	266 *			

Baseline: 1 interaction point

Time to first collisions:
5 years preparation phase
9 years construction (21km)

(* ARUP Life Cycle Assessment for civil construction only; addition of accelerator components is underway)
https://edms.cern.ch/ui/#!master/navigator/document?D:101320218:101320218:subDocs

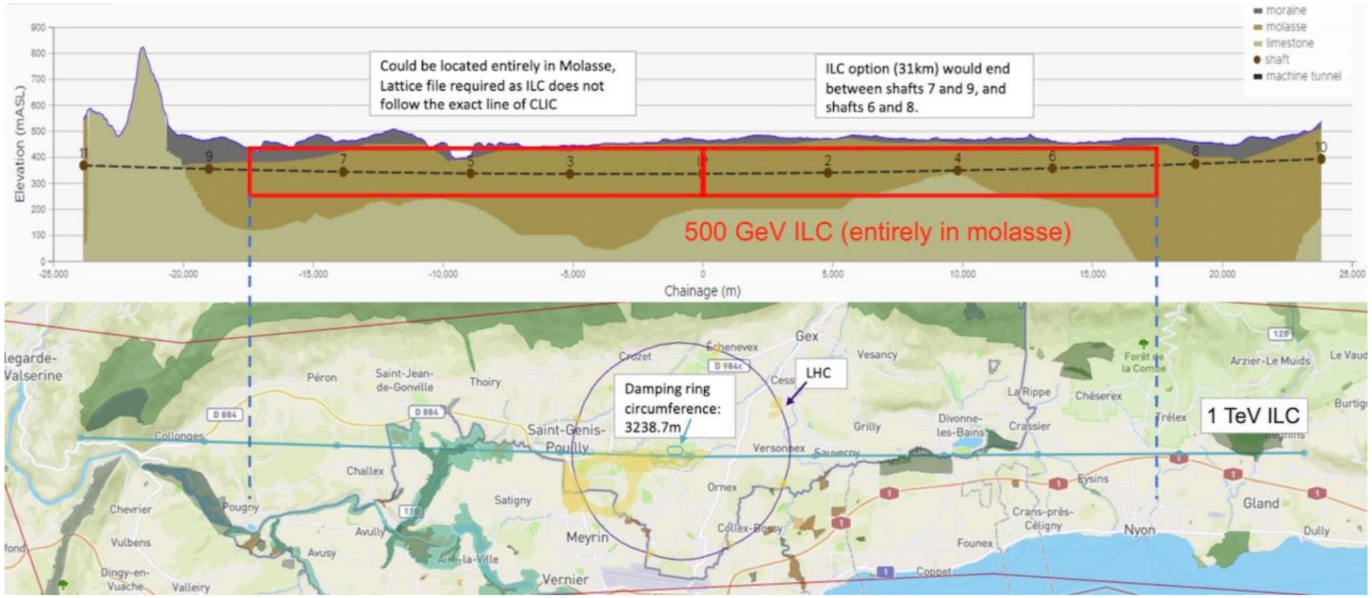
Financial cost:
Value estimate for the ILC accelerator at 250 GeV is 4780 – 5260 MILCU in 2012 prices, plus 17165 kh of institutional labour.
In 2018 this was updated to 2017 prices including labour: 635.0 – 702.8 GYen
In 2018 the operation costs were estimated to be 36.6 – 39.2 GYen (around 318–341 MEuro) per year
A full cost update is underway and will be available in January 2025.

2. ILC at CERN

ILC siting at CERN is being revisited from the time of the TDR and the CLIC siting studies

Machine parameters are assumed similar to ILC in Japan, but baseline is 2 interaction points

CERN-specific CFS costing is underway



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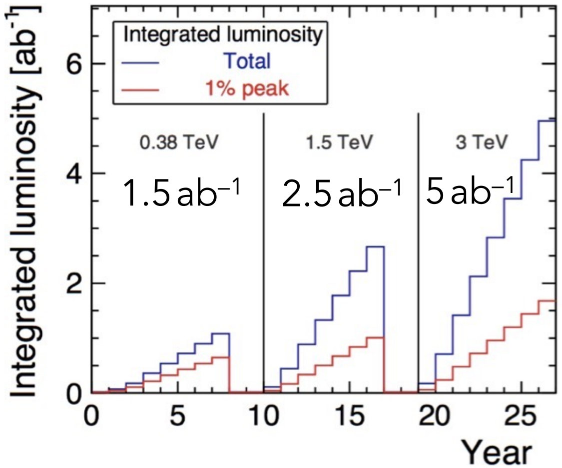
Baseline: 2 interaction points

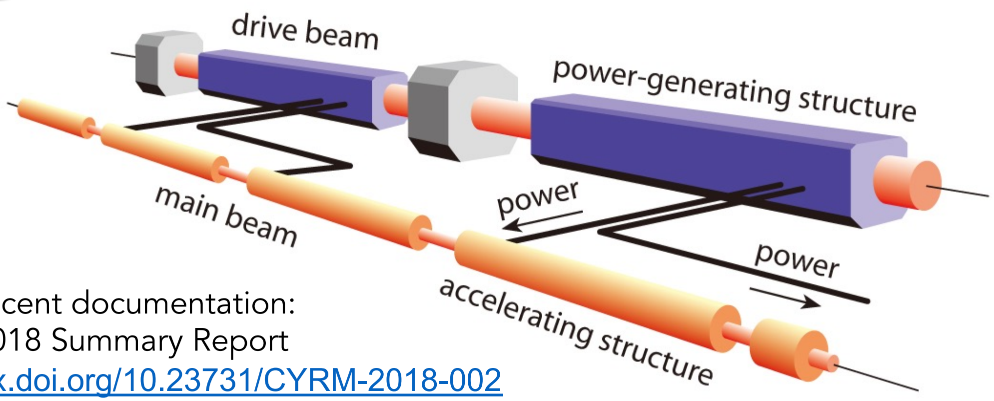
Time to first collisions:
assumed similar to ILC in Japan:
5 years preparation phase
9 years construction (21km)

Financial cost:
A full costing is underway and will be available in January 2025.

3. CLIC



CLIC: 380 GeV ; 1.5, 3 TeV
11km / 29km / 50km
Room temperature, 72–100 MVm^{-1}
Sited at CERN
CDR 2012, Updated Staging Baseline 2016,
Project Implementation Plan 2018
Similar structures used for Swiss FEL



Most recent documentation:
CLIC 2018 Summary Report
http://dx.doi.org/10.23731/CYRM-2018-002

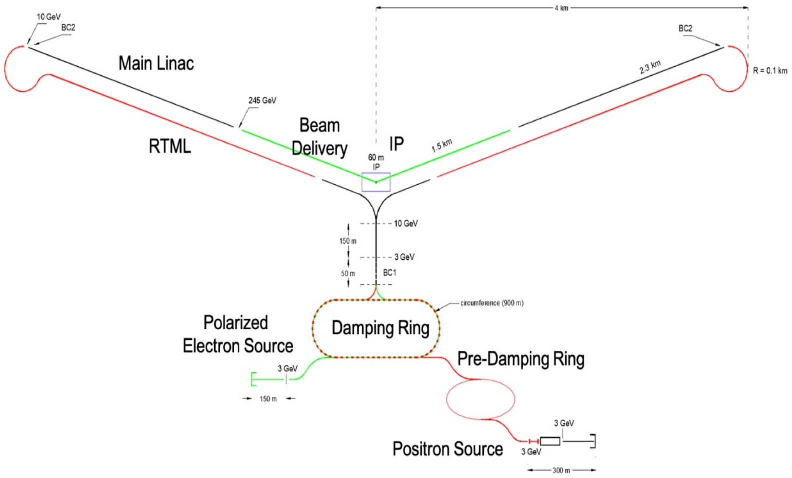
$\sqrt{s}$	**380 GeV**	**1.5 TeV**	**3 TeV**
Int L (ab^{-1})	1.5	2.5	5
Duration (yr)	8	7	8
Wall power (MW)	110		550
Length (km)	11	29	50
Environmental cost of construction (kt CO_2 eq)	127 *	169 *	205 *
Environmental cost of operation (kt CO_2 eq)	59 over 8 years	145 over 7 years	274 over 8 years

Baseline: 1 interaction point

Time to first collisions:
5 years preparation phase
8 years construction (11km)

(* ARUP Life Cycle Assessment for civil construction only; addition of accelerator components is underway)
https://edms.cern.ch/ui/#!master/navigator/document?D:101320218:101320218:subDocs

Financial cost:
Cost re-evaluated bottom-up 2017-18. 380GeV: 5.9 BCHF. To 1.5TeV: add 5.1 BCHF. To 3TeV: add 7.3 BCHF
Estimate of labour requirements for 380GeV construction: 11150 FTE-years
In 2018 a preliminary estimate of operation costs was 116 MCHF/yr, and 640FTE of operational support
CLIC Project Implementation Plan 2018 shows CLIC380 to be financeable from CERN budget over construction time



4. C^3

C^3: 250, 550 GeV
8km / 8km
Operation temperature 77K, 70–120 MVm^{-1}
Sited at Fermilab
Pre-CDR

C^3 Beam delivery / IP identical to ILC
Damping rings / injector similar to CLIC
Physics output very similar to ILC

Most recent documentation:
https://iopscience.iop.org/article/10.1088/1748-0221/18/07/P07053

$\sqrt{s}$	**250 GeV**	**550 GeV**
Int L (ab^{-1})	2	4
Duration (yr)	5	5
Wall power (MW)	~150	~175
Length (km)	8	8
Environmental cost of construction (kt CO_2 eq)	146 *	

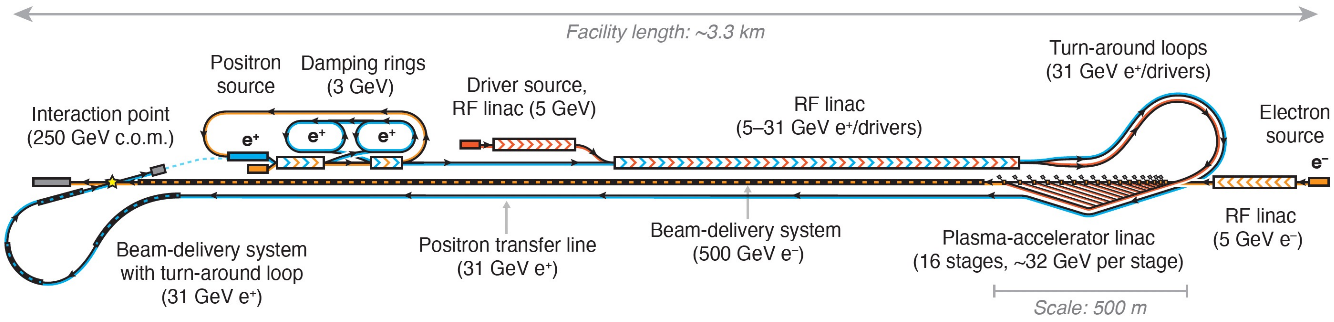
Baseline: 1 interaction point

Time to first collisions:
- 4 years preparation phase
- 4 years construction

(* By proponents, for civil construction only, adapted from ILC/CLIC Life Cycle Assessment)
https://journals.aps.org/prxenergy/abstract/10.1103/PRXEnergy.2.047001

Financial cost:
Capital cost estimate 2021: \$3.5–4 B https://arxiv.org/abs/2110.15800

5. HALHF



HALHF: 250 GeV (e^- 500GeV, e^+ 31GeV)
3.3km
25 MVm^{-1} conventional, 6.3GVm^{-1} plasma
Pre-CDR

Most recent documentation:
https://arxiv.org/abs/2303.10150

$\sqrt{s}$	**250 GeV**	**380 GeV**	**550 GeV**
Wall power (MW)	80	115	162
Length (km)	3.3	4.6	5.5
Environmental cost of construction (kt CO_2 eq)	49	64	83

Baseline: 1 interaction point

Time to first collisions:
10 years R&D + preparation phase
5 years construction

Projected luminosities can be compared with ILC/CLIC:

	HALHF	**ILC**	**CLIC**
$\sqrt{s}$	250 GeV	250 GeV	380 GeV
Inst. luminosity ($cm^{-2}s^{-1}$)	0.81×10^{34}	1.35×10^{34}	2.3×10^{34}
Lumi fraction in top 1%	57%	73%	57%

Financial cost:
Capital cost estimate 2023 in European accounting: $ 1.9B (250GeV), $ 2.5B (380GeV), $ 3.2B (550 GeV)

Linear Collider Facility @CERN

For many years CERN pioneered CLIC
- technology is demonstrated, and detailed design and costing exist
- first stage 380GeV (or 250GeV) can be built within CERN budget
  (see CLIC Project Implementation Plan 2018)

Equally could start with superconducting RF ("ILC @ CERN")
- proven and *industrialised* technology
- strong general interest in SCRF technology around the world
- significant industrial production capacity in Europe and elsewhere
- strong lab expertise outside CERN could help reduce the load on CERN
- CERN site was already studied for ILC TDR

–> opportunity to minimize the time until the next project

Full exploitation of a linear collider facility:
- consider beam-extraction / dump instrumentation / far detectors
  –> super-LUXE / super-LDMX / super-SHIP
- lines for detector and beam-instrumentation tests
- low-emittance beams of photons/muons/neutrons for various applications
- accelerator development towards demonstrators of upgrades of main facility

Linear Collider Facility @CERN upgrade options

A Linear Collider Facility operating as an initial-stage Higgs factory provides many potential upgrade options:

An SCRF machine can be upgraded by

1. extending tunnel; upgrading power – a 'straightforward', guaranteed fall-back
2. upgrading to higher-gradient cavities (which exist in the lab, though not yet industrially)

OR SCRF could be replaced by X-band copper cavities (like CLIC or C3)

– allows 2x (3x, 4x …?) the energy without a tunnel extension

–> reuse SCRF modules for other applications round the world

OR HALHF concept could be applied to e.g. 250 GeV ILC:

– plasma-accelerate electrons to 550 GeV

– upgrade positron linac from 125 to 137.5 GeV –> $\sqrt{s}$ = 550GeV

–> Higgs factory upgraded to tt / ttH / ZHH factory

OR move to energy-recovery linac like "ReLiC"

– energy and particle recovery by deceleration and re-cooling

– conceptual study indicates up to O(100) higher luminosity than CLIC/ILC could be conceivable

–> choice can be made depending on physics and wider accelerator technology landscape at the time