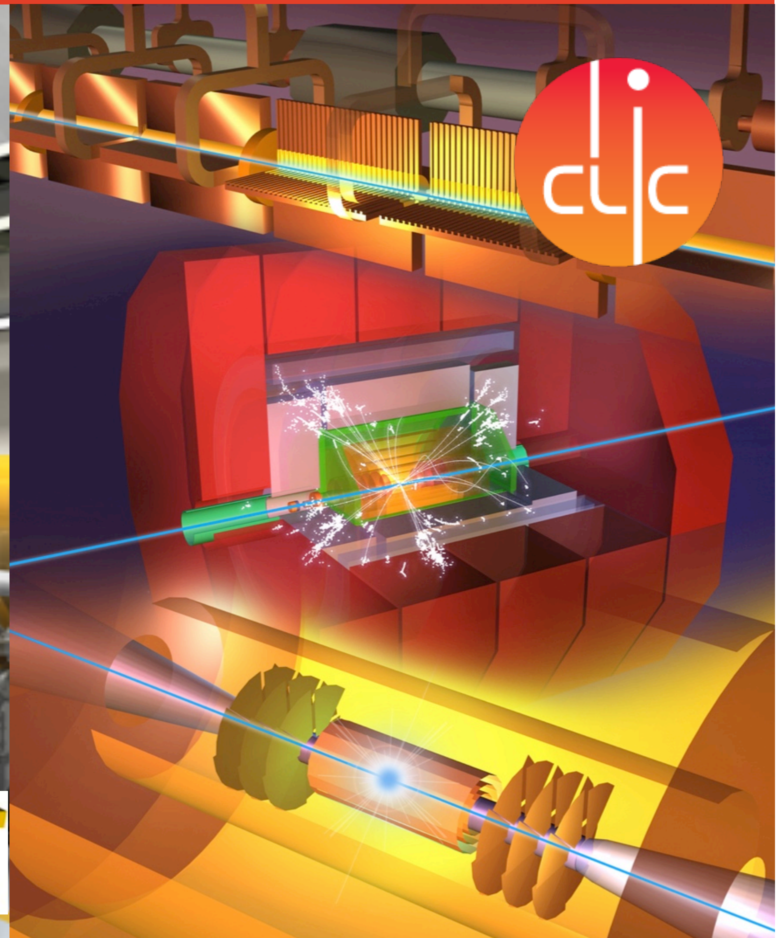
Linear e^+e^- colliders

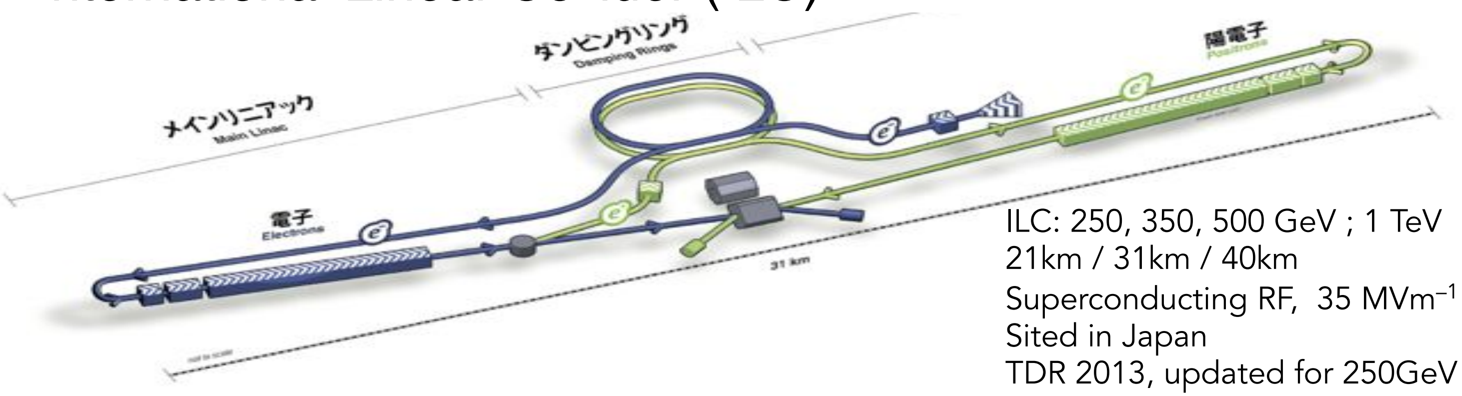


PPAP Community Meeting, 7 July 2023, Birmingham

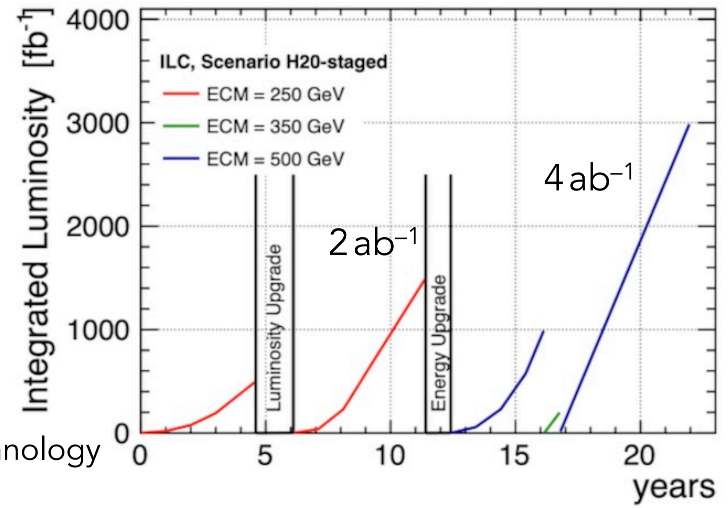
Aidan Robson, University of Glasgow

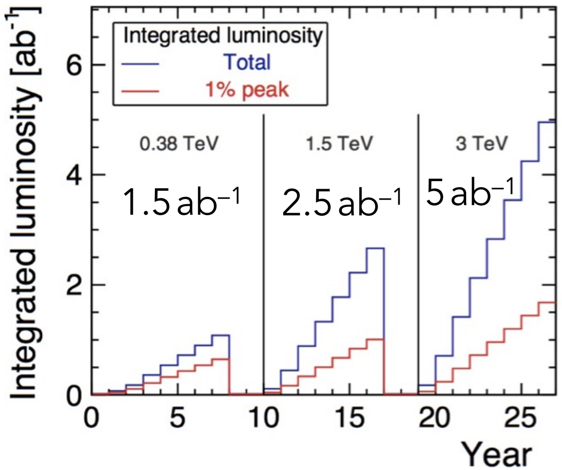
Linear Colliders

International Linear Collider (ILC)



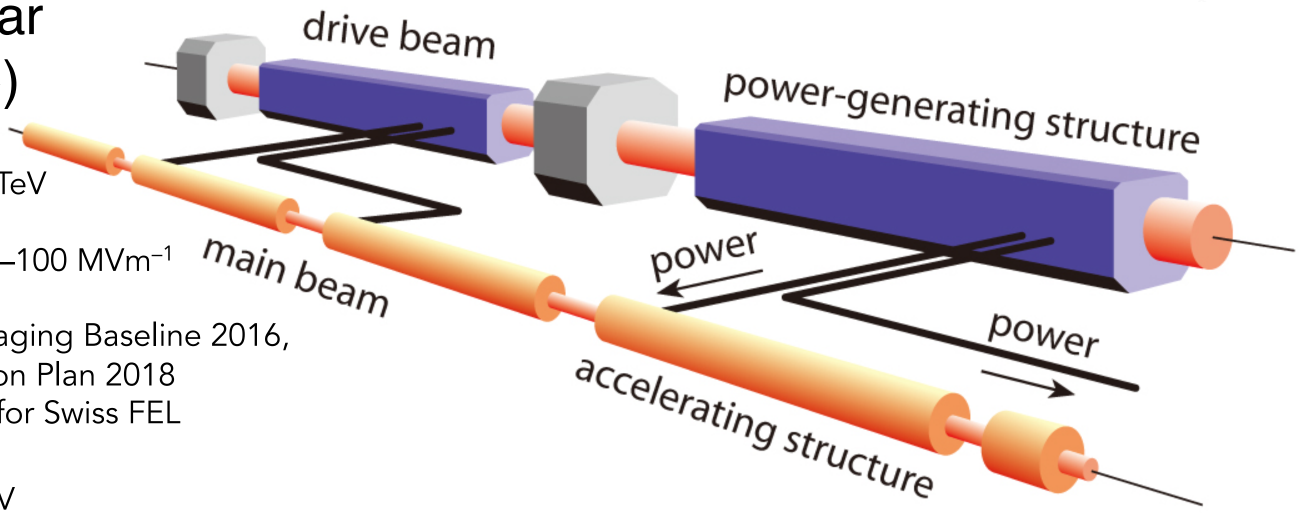
ILC: 250, 350, 500 GeV ; 1 TeV
21km / 31km / 40km
Superconducting RF, 35 MVm^{-1}
Sited in Japan
TDR 2013, updated for 250GeV
European XFEL demonstrates technology





Compact Linear Collider (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



Cool Copper Collider (C^3)

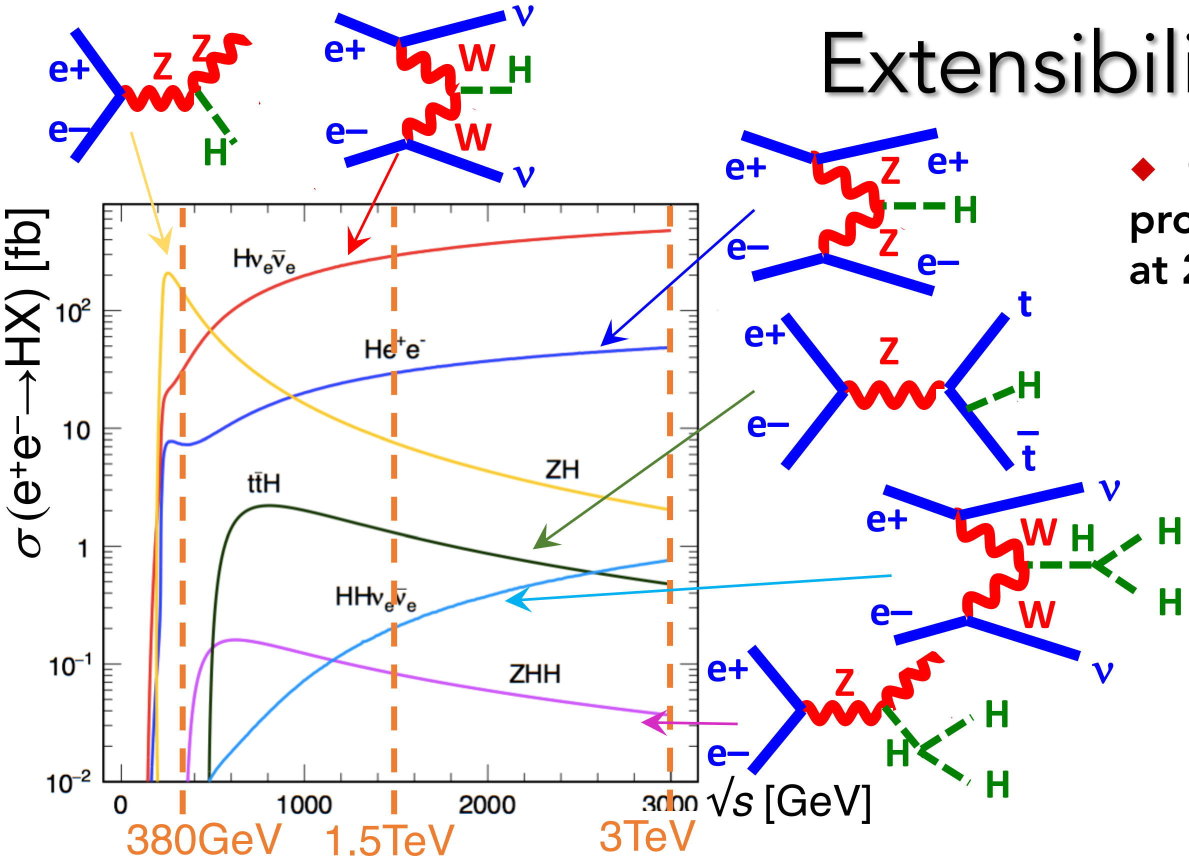
C^3: 250, 550 GeV
8km / 8km
Operation temperature 77K, 70–120 MVm^{-1}
Sited at Fermilab
Pre-CDR

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

Hybrid Asymmetric Linear Higgs Factory (HALHF)

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

Extensibility



- **Common to all projects: ZH threshold at 250 or 380 GeV**

  Core Higgs programme sets requirements on detector performance: momentum resolution, jet energy resolution, impact parameter resolution etc

- **Top quark at threshold & continuum**

  Electron beam polarisation provides extra observables (Higgs/top/EWK/BSM) & controls systematics

- **TeV / multi-TeV @ linear**

  –> direct HH production, extra BSM reach etc

  –> detectors require e.g. deeper calorimeters

- **Flexibility** :

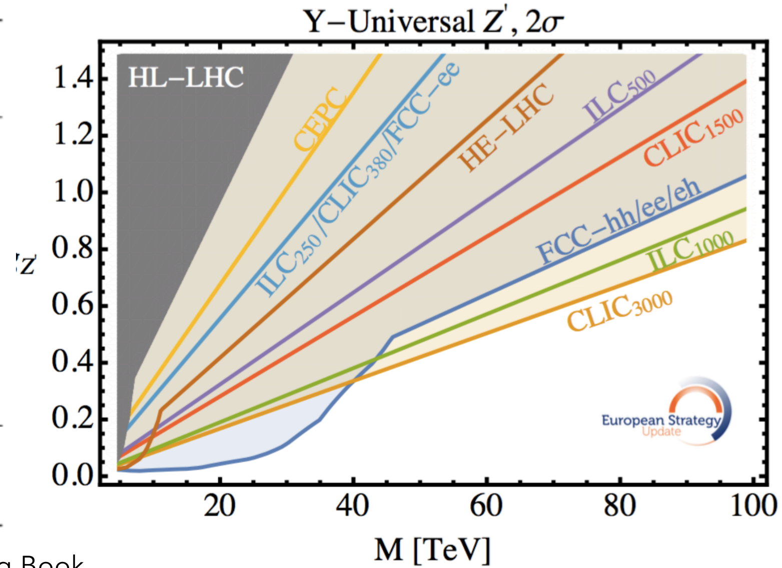
  –> project run-plans are optimised differently, but different approaches can result in similar sensitivities for core Higgs coupling measurements, e.g. CLIC baseline 380/1500 GeV vs CLIC just running longer at first stage

	Benchmark	HL-LHC	HL-LHC + CLIC		HL-LHC + FCC-ee	
			380 ($4\,ab^{-1}$)	380 ($1\,ab^{-1}$) + 1500 ($2.5\,ab^{-1}$)	240	365
g^{eff}_{HZZ}[%]	$SMEFT_{ND}$	3.6	0.3	0.2	0.5	0.3
g^{eff}_{HWW}[%]	$SMEFT_{ND}$	3.2	0.3	0.2	0.5	0.3
$g^{eff}_{H\gamma\gamma}$[%]	$SMEFT_{ND}$	3.6	1.3	1.3	1.3	1.2
$g^{eff}_{HZ\gamma}$[%]	$SMEFT_{ND}$	11.	9.3	4.6	9.8	9.3
g^{eff}_{Hgg}[%]	$SMEFT_{ND}$	2.3	0.9	1.0	1.0	0.8
g^{eff}_{Htt}[%]	$SMEFT_{ND}$	3.5	3.1	2.2	3.1	3.1
g^{eff}_{Hcc}[%]	$SMEFT_{ND}$	–	2.1	1.8	1.4	1.2
g^{eff}_{Hbb}[%]	$SMEFT_{ND}$	5.3	0.6	0.4	0.7	0.6
$g^{eff}_{H\tau\tau}$[%]	$SMEFT_{ND}$	3.4	1.0	0.9	0.7	0.6
$g^{eff}_{H\mu\mu}$[%]	$SMEFT_{ND}$	5.5	4.3	4.1	4.	3.8
$\delta g_{1Z}[\times 10^2]$	$SMEFT_{ND}$	0.66	0.027	0.013	0.085	0.036
$\delta\kappa_\gamma[\times 10^2]$	$SMEFT_{ND}$	3.2	0.032	0.044	0.086	0.049
$\lambda_Z[\times 10^2]$	$SMEFT_{ND}$	3.2	0.022	0.005	0.1	0.051

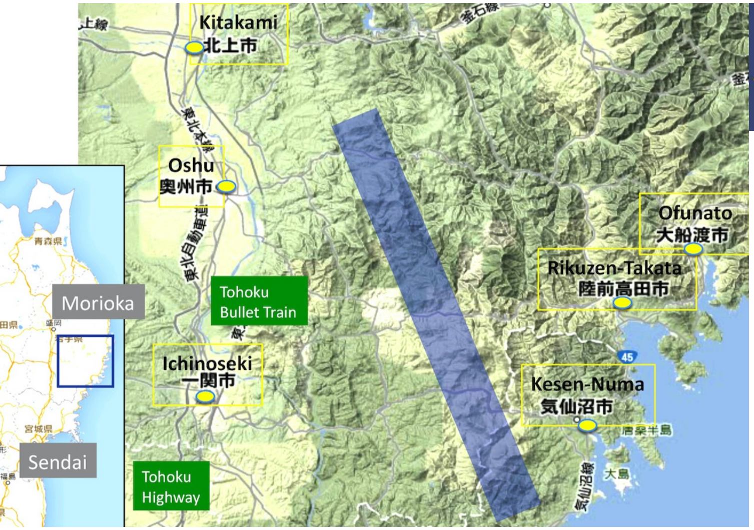
CLIC longer ($4ab^{-1}$) first stage

CLIC baseline: $1ab^{-1}$+1.5TeV

2001.05278 European Strategy Briefing Book



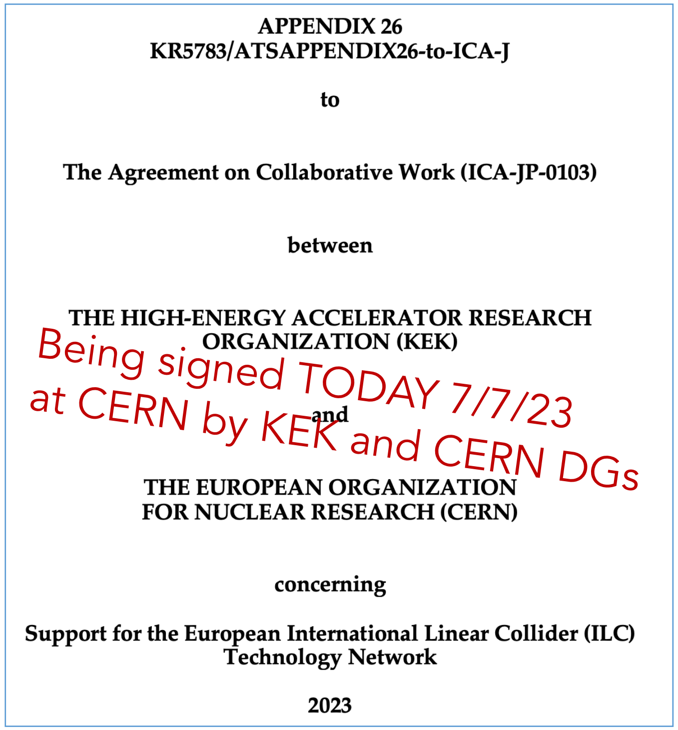
ILC Project



- ILC TDR 2013, several updates since then
- Site well understood; geological surveys done
- European XFEL demonstrated industrial cavity production
- Local support for hosting at Kitakami

- The International Development Team (IDT) was set up in 2020 to move towards the ILC Pre-lab
  –> UK representation Brian Foster, Phil Burrows, Aidan Robson
- Pre-lab envisaged to complete **engineering designs** for machine and civil construction and support **intergovernmental negotiation of organisation, governance, cost-sharing**

- Latest:
  ILC International Technology Network (ITN) is launching now
- Global collaboration programme focusing on time-critical accelerator R&D
  - SRF
  - e- & e+ Sources } Synergy with
  - Nano-beam } other colliders
- KEK budget for this R&D significantly increased this year and activity started since April; ITN allows flow of funds through bilateral agreements with regional host labs (and onwards)
- Some progress on discussing 'global project' governance etc


APPENDIX 26
KR5783/ATSAPPENDIX26-to-ICA-J

to

The Agreement on Collaborative Work (ICA-JP-0103)

between

THE HIGH-ENERGY ACCELERATOR RESEARCH ORGANIZATION (KEK)

and

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

concerning

Support for the European International Linear Collider (ILC) Technology Network

2023

Being signed TODAY 7/7/23 at CERN by KEK and CERN DGs

ILC International Technology Network (ITN)

- 17 ITN Work Packages →

SRF	WPP	1	Cavity production
	WPP	2	CM design
	WPP	3	Crab cavity
e-, e+ Sources	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
Nano-Beam	WPP	12	DR System design
	WPP	14	DR Injection/extraction
	WPP	15	Final focus
	WPP	16	Final doublet
	WPP	17	Main dump

- 5 European areas of activity:

Main UK interests

A1 SRF
- SRF: Cavities, and Cryomodule
- Crab-cavities → Daresbury; activity coordinated by UK
- Main Linac quads and cold BPMs

A2 Sources
- Pulsed magnet
- Wheel/target → Prototype rotating wheel done in UK

A3 Damping Ring including kickers → Strong synergy with Diamond 2 upgrade
- Low Emittance Ring lab

A4 ATF activities for final focus, nanobeams, MDI → John Adams Inst

A5 Implementation including Project Office
- Dump, CE, Cryo
- Sustainability
- EAJADE started (EU funding) → Oxford

Synergies also with CLIC

- Updated working timeline:

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

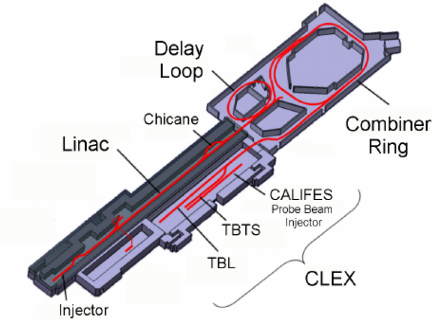
To first physics ~2038

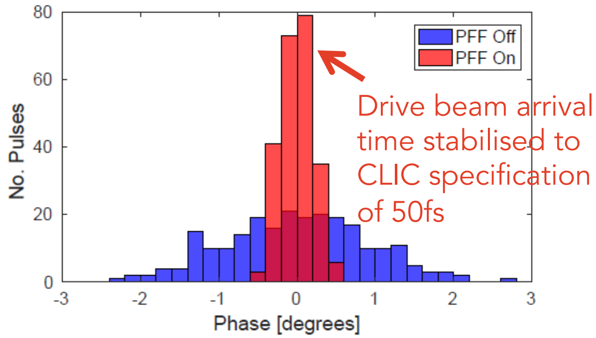
- Federation of Diet Members for the ILC has been reactivated, April 2023

CLIC Project

High-current drive beam bunched at 12 GHz

Produced at CLIC Test Facility CTF3



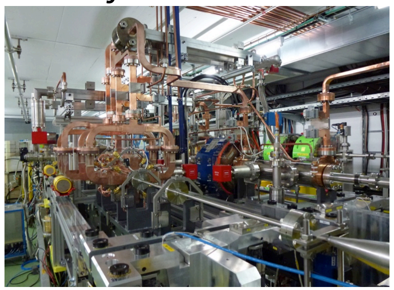


~100 MV/m gradient in main-beam cavities

Achieved in structures produced by different sources

Power transfer + main-beam acceleration

Demonstrated 2-beam acceleration



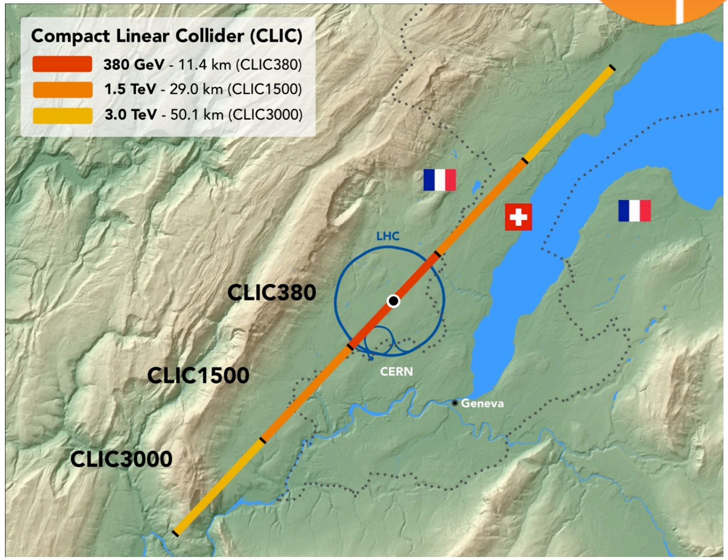
Alignment & stability

The CLIC strategy:

- Alignment; vibration damping; good beam measurement and feedback
- Tests in small accelerators of equipment and algorithms (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)

–> Key accelerator technologies have been demonstrated

CDR 2012 –> Updated Staging Baseline 2016 –> Project Implementation Plan 2018



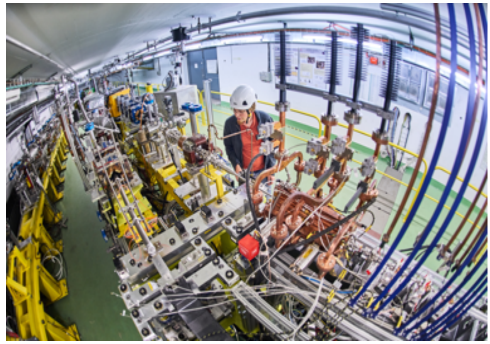
- Following the European Strategy Update, CLIC is maintained at CERN –> if the FCC feasibility study is not conclusive then CLIC could be implemented in an expeditious way
- 2021-25 programme continues CLIC as an option for a Higgs/top accelerator facility at CERN, and is pursuing high-gradient R&D and nanobeam technology more generally with a focus on non-particle physics applications
- A Project Readiness Report will be developed for 2025

CLIC Technologies & Developments

X-band technology:
- Design and manufacturing of X-band structures and components
- Study structures breakdown limits and optimization, operation and conditioning
- Baseline verification and explore new ideas
- Assembly and industry qualification
- Structures for applications, FELs, medical, etc

Technical and experimental studies, design & parameters:
- Module studies
- Beam dynamics and parameters
- Tests in CLEAR (wakefields, instrumentation) and other facilities (e.g. ATF2)
- High efficiency klystrons
- Injector studies suitable for X-band linacs

Luminosity margins and increases at 380 GeV
- Initial estimates of static and dynamic degradations from damping ring to IP gave: 1.5 x 10^{34} cm^{-2} s^{-1}
- Simulations taking into accord static and dynamic effects with corrective algorithms give 2.8 on average, and 90% of the machines above 2.3 x 10^{34} cm^{-2} s^{-1}

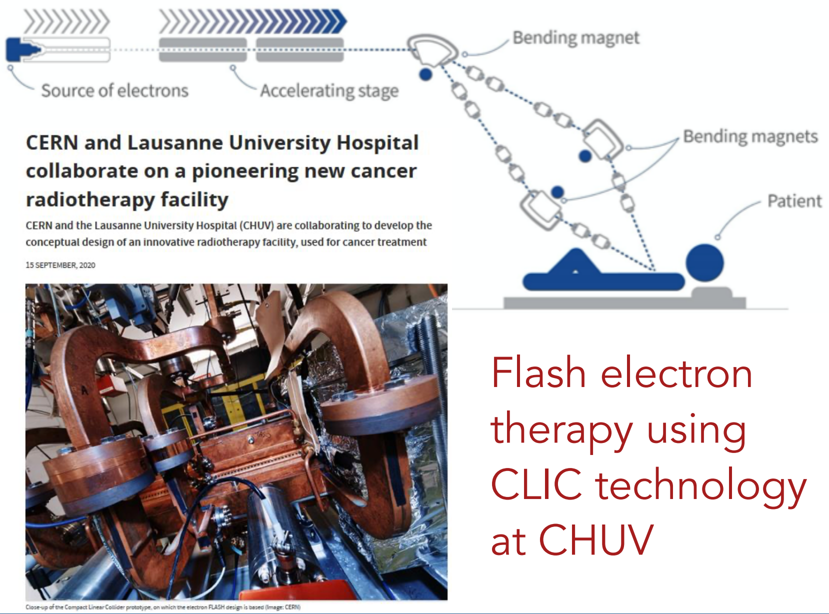


◆ **X-band technology readiness for the 380 GeV CLIC initial phase - more and more driven by use in small compact accelerators**

Application of X-band technology (examples):
- A compact FEL (CompactLight: EU Design Study 2018-21)
- Compact Medical linacs (proton and electrons)
- Inverse Compton Scattering Source (SmartLight)
- Linearizers and deflectors in FELs (PSI, DESY, more)
- 1 GeV X-band linac at LNF

SwissFEL uses CLIC-like structures at C-band

–> helping to include industrial partners etc towards a collider



Flash electron therapy using CLIC technology at CHUV

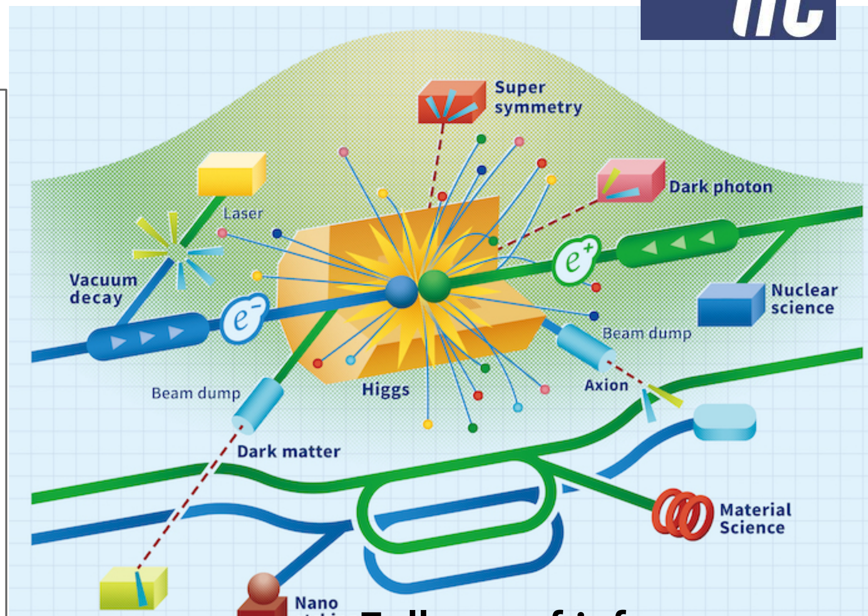
Sustainability

CLIC Power Efficiency:
Improving power efficiency for both initial phase & high energies

Power estimate bottom up (concentrating on 380 GeV systems)

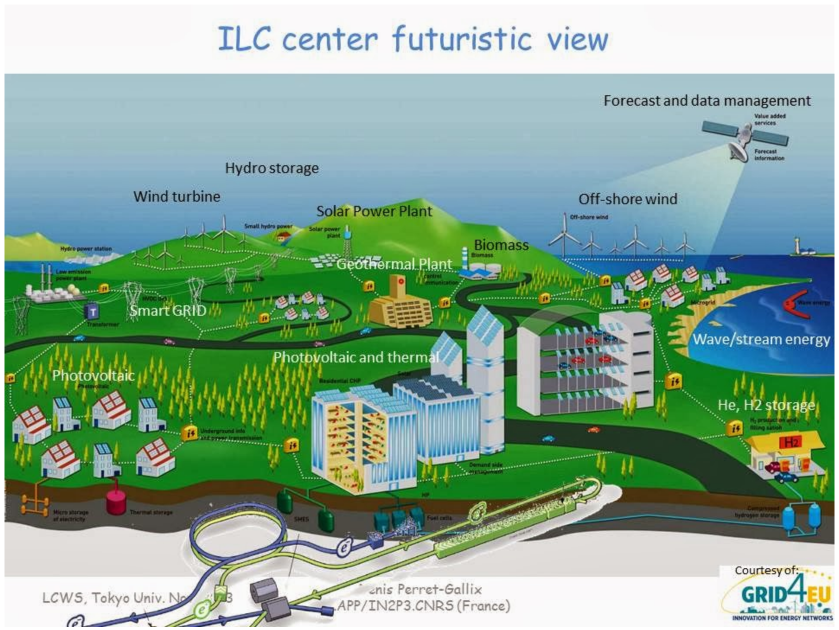
- Very large reductions since CDR, much more optimized drivebeam complex and more efficient klystrons, injectors more optimized, main target damping ring RF significantly reduced, recent L-band klystron studies, and also better estimates of nominal settings.

Power 110MW; energy consumption ~0.6 TWh yearly, CERN is currently (when running) at 1.2 TWh (~90% in accelerators)



Full use of infrastructures

Towards 'Green ILC':



Lifecycle assessment:
Study by Arup on carbon footprint and other environmental impacts, done to international standards

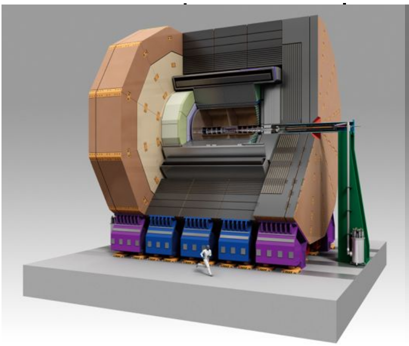
Assesses Global Warming Potential of underground civil engineering – raw materials, transport, construction activities (not the accelerator components). Bottom line:

CLIC 380GeV:
 127kton CO_2-eq (two-beam option)
 290kton CO_2-eq (klystron option)

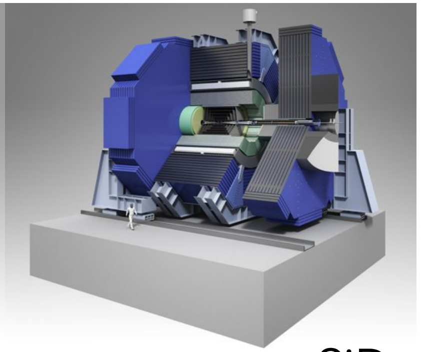
ILC 250GeV:
 266kton CO_2-eq

–> also points out potentials to reduce
Report being finalised this week –> will be available soon

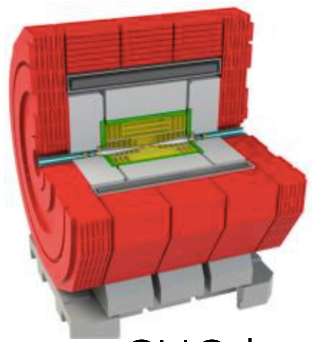
Detectors & software



ILD



SiD



CLICdet

Projects have individual specific requirements from accelerator environment but also many common aspects:
- – detector concepts
- – detector technologies
- – software tools
- – physics studies

UK has strong history & ongoing participation in ILD, SiD, CLICdp

- almost all LC studies based on Pandora C++ software development kit (Cambridge/Warwick)
- almost all LC studies use LCFIVertex flavour-tagging s/w (written in UK, now maintained in Japan)
- physics studies e.g. ZH hadronic recoil -> critical staging choices for linear colliders
- provided new ECAL simulation model for ILD
- provided complete new simulation model for SiD

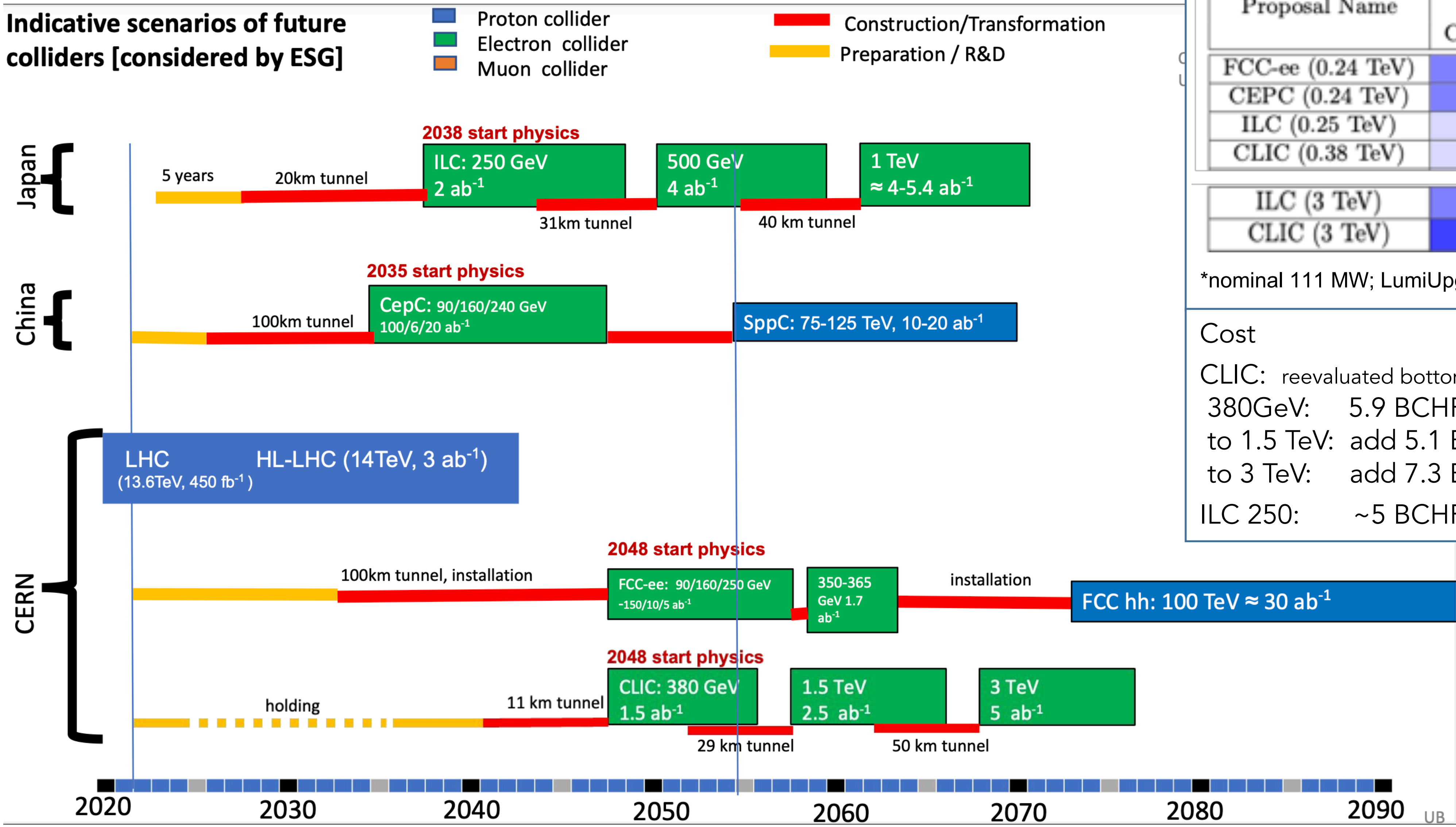
Recent focus on linked efforts: via DRDs on hardware and via ECFA to identify commonalities and complementarities, and to share expertise –> see separate slides

UK aligned hardware interests in silicon vertexing/tracking, calorimetry, DAQ

– contact maintained through loose ‘LCUK’ collaboration with representative from (almost) every UK group

- PhDs in last 6 years in Linear Colliders from:
  Cambridge [reconstruction, calorimeter optimization, Higgs & EWK studies]
  Edinburgh [Higgs studies]
  Glasgow [CLICpix]
  Sussex [DAQ & Higgs studies]
  Birmingham [digital calorimetry & top studies]
  Oxford [accelerator physics]

Timeline, cost, power



Power
from Snowmass implementation taskforce

MW

Proposal Name	Power Consumption
FCC-ee (0.24 TeV)	290
CEPC (0.24 TeV)	340
ILC (0.25 TeV)	140 *
CLIC (0.38 TeV)	110
ILC (3 TeV)	~400
CLIC (3 TeV)	~550

*nominal 111 MW; LumiUpgrade 138MW

Cost

CLIC: reevaluated bottom-up 2017–18
380GeV: 5.9 BCHF
to 1.5 TeV: add 5.1 BCHF
to 3 TeV: add 7.3 BCHF

ILC 250: ~5 BCHF

- Timelines are technologically limited – except the CERN projects, which are linked to completion of the HL-LHC, readiness and startup ~2045-48
- ILC and CEPC schedules are mature, but the projects need to pass approval processes in the near future to maintain these schedules

Linear Colliders vision

- ILC and CLIC are mature options for a Higgs factory
- Flexibility with a LC:
  - From initial Linear Collider: followed by energy increases and/or independent muon and/or hadron machines with radius and magnets to be determined. Can also overlap in time with hadron/muon machines.
    In the longer future the civil infrastructure can be used with novel acceleration techniques e.g. plasma
- User community:
  - One or two main collider experiments
    (ILC baseline is push-pull; CLIC380 has studied two IPs)
  - "Diversity programme" using injectors, single beams, "long range" effects for axion searches / LLPs etc
    (much more to explore)

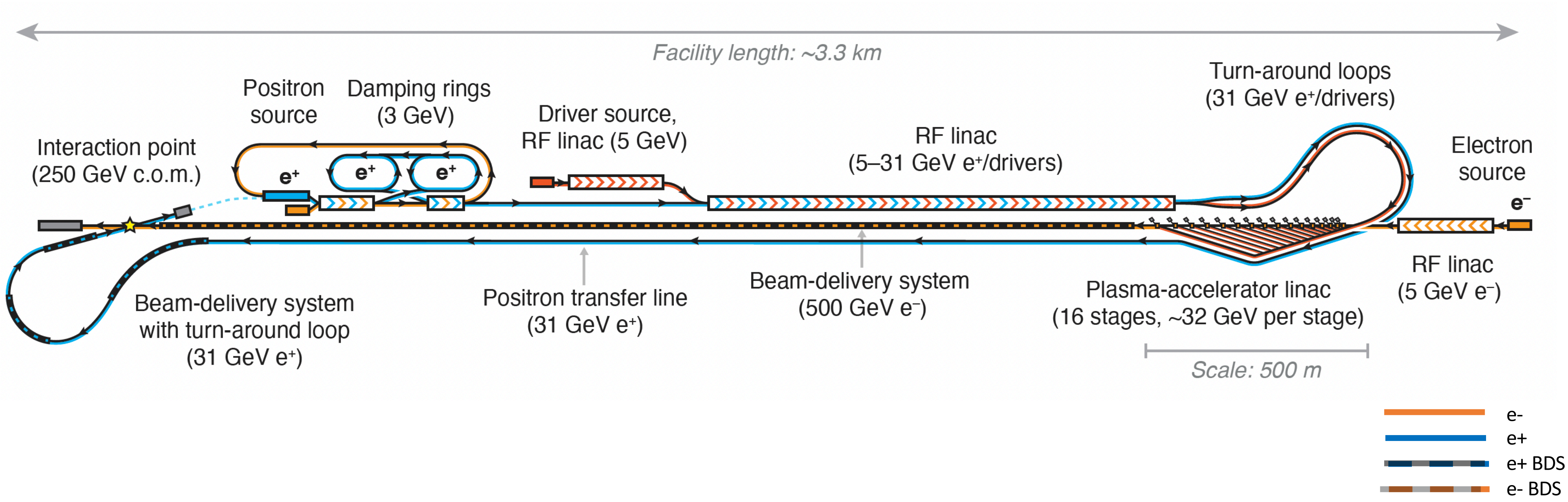
The LC "vision" is a balanced programme over the next 20-30 years for:

- a Higgs factory as soon as possible, upgradable
- R&D for the machine beyond, no constraints imposed by the LC
- a strong diversified programme using the LC complex
- and HL-LHC of course!

Backup

HALHF

Hybrid Asymmetric Linear Higgs Factory



- Overall facility length ~ 3.3 km – which will fit on ~ any of the major pp labs. (NB. There is a service tunnel as with ILC (not shown))

Talk at LCWS 2023: [LINK]
and paper:
https://arxiv.org/2303.10150

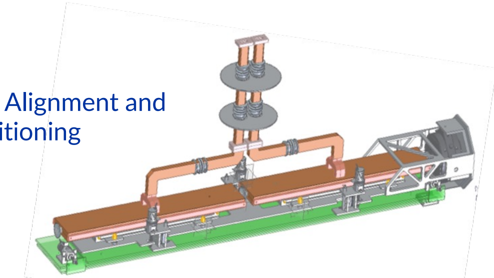
C[3] studies

8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

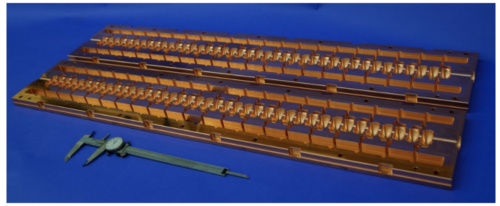
Large portions of accelerator complex are compatible between LC technologies

- Beam delivery and IP modified from ILC (1.5 km for 550 GeV CoM)
- Damping rings and injectors to be optimized with CLIC as baseline
- Reliant on work done by CLIC and ILC to make progress

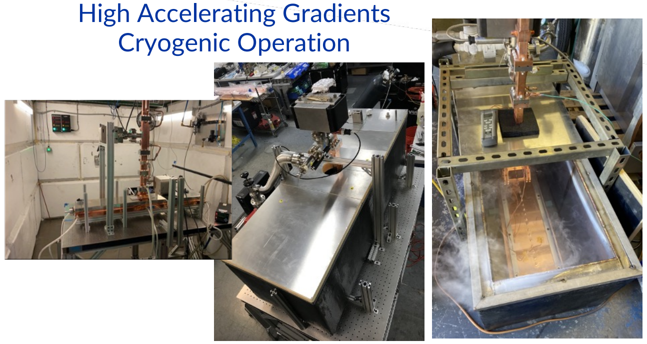
Preliminary Alignment and Positioning



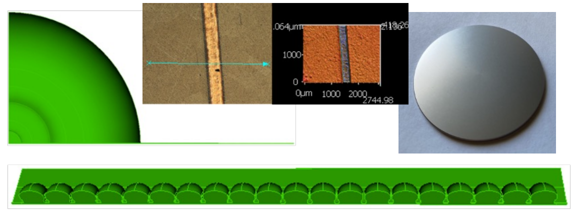
Modern Manufacturing
Prototype One Meter Structure

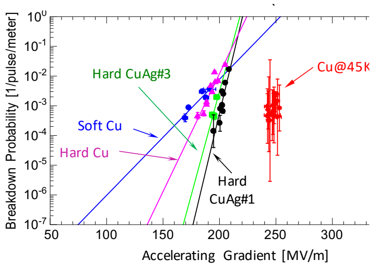


High Accelerating Gradients
Cryogenic Operation

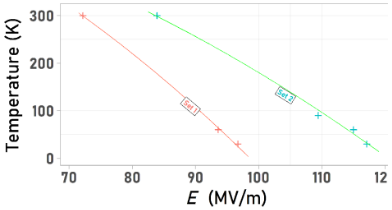


Integrated Damping
Slot Damping with NiChrome Coating



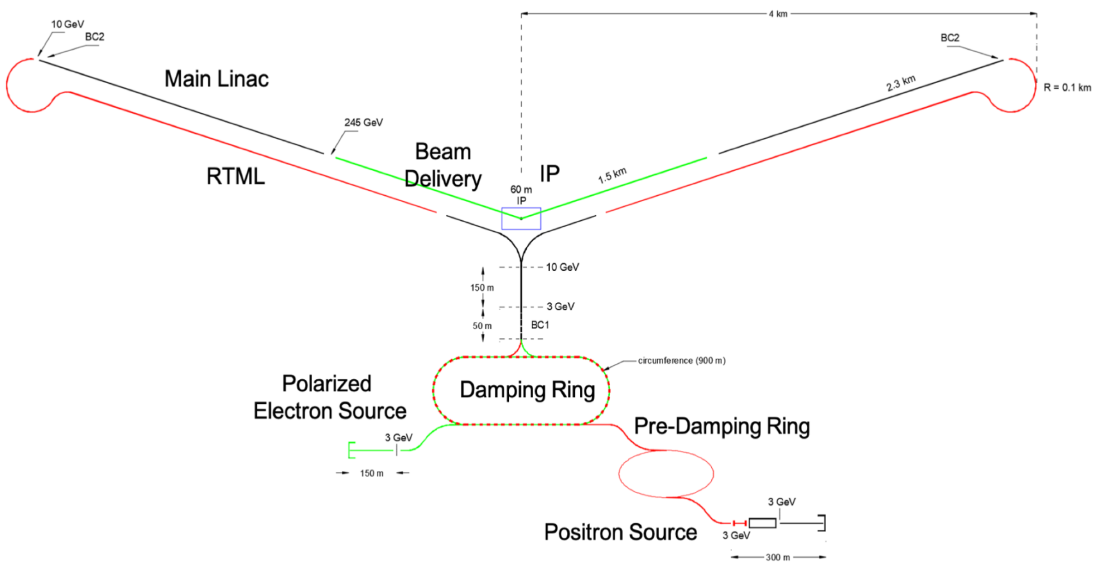


Cryo-cooled



Cryo-cooled copper pulsed electrodes, Uppsala/CERN

C³ - 8 km Footprint for 250/550 GeV



C³ Parameters

Collider	C[3]	C[3]
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

Currently looking for P5 support. Optimistic scenario: construction 2030; first collisions 2040