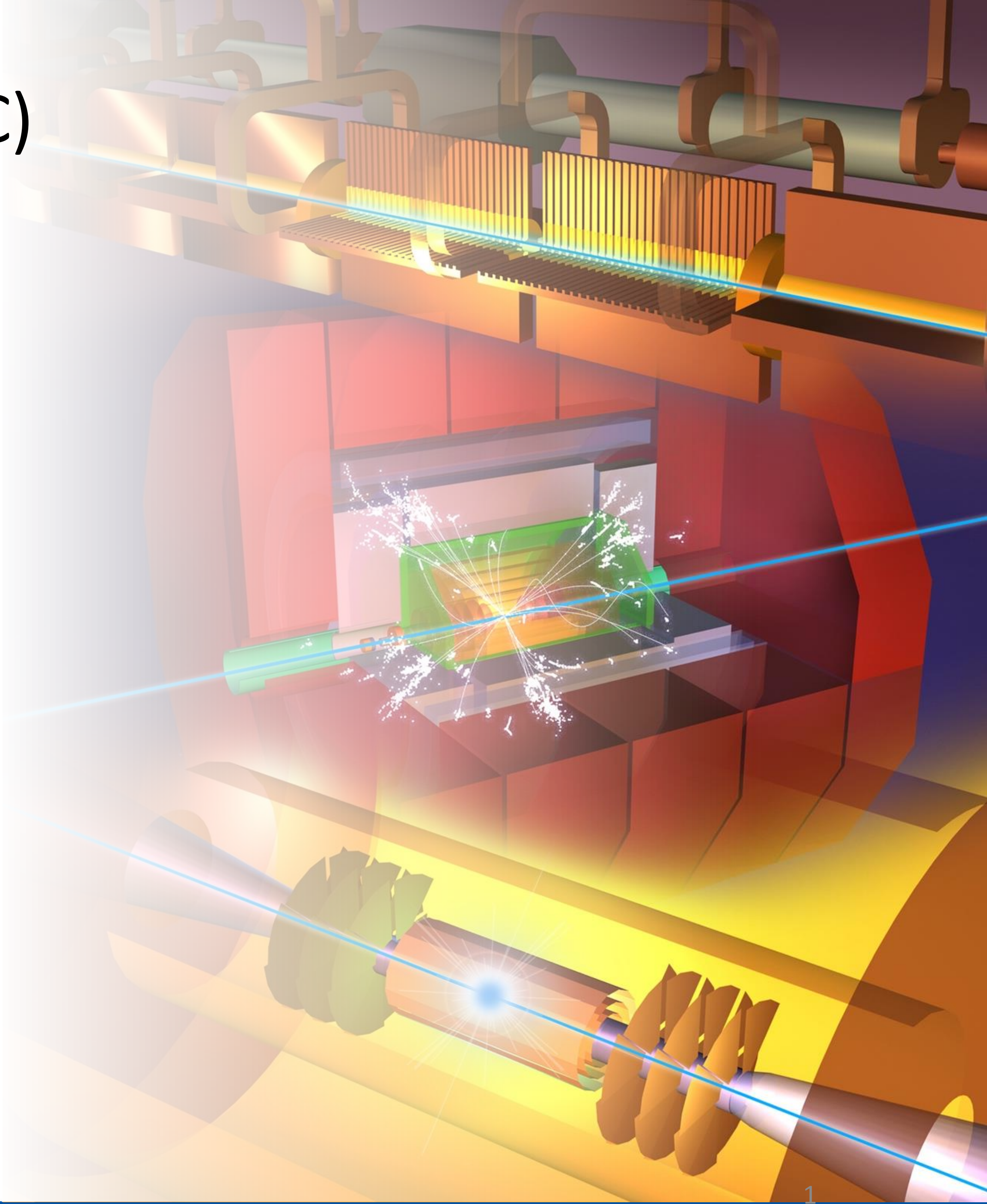
The Compact Linear Collider (CLIC)

- Most recent status in Snowmass white paper (March 22) : https://arxiv.org/abs/2203.09186
- More details in Project Implementation Plan documents for the European Strategy Update 2018-19.
- Focus on ESPP update ~2026

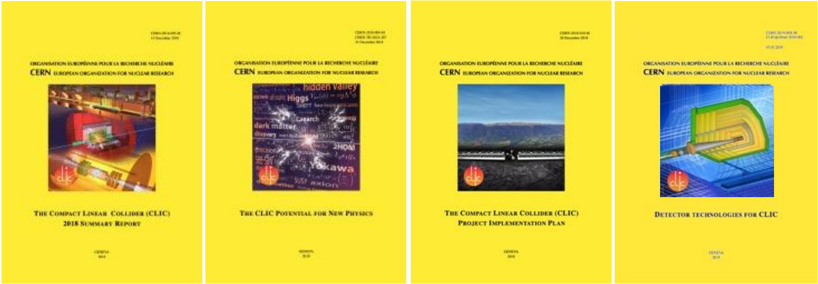


Status reports and studies

Two formal submissions to the ESPPU 2018

3-volume CDR 2012 *Updated Staging Baseline 2016*

4 CERN Yellow Reports 2018



Details about the accelerator, detector R&D, physics studies for Higgs/top and BSM

Available at:
clic.cern/european-strategy

Several LoIs have been submitted on behalf of CLIC and CLICdp to the Snowmass process:

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

Snowmass white paper:
https://arxiv.org/abs/2203.09186

Broadly speaking: "Updated accelerator part of 2018 Summary Report"

The CLIC project

O. Brunner[a], P. N. Burrows[b], S. Calatroni[a], N. Catalan Lasheras[a], R. Corsini[a], G. D'Auria[c], S. Doebert[a], A. Faus-Golfe[d], A. Grudiev[a], A. Latina[a], T. Lefevre[a], G. Mcmonagle[a], J. Osborne[a], Y. Papaphilippou[a], A. Robson[e], C. Rossi[a], R. Ruber[f], D. Schulte[a], S. Stapnes[a]*, I. Syratchev[a], W. Wuensch[a]

[a]CERN, Geneva, Switzerland, [b]John Adams Institute, University of Oxford, United Kingdom, [c]Elettra Sincrotrone Trieste, Italy, [d]IJCLab, Orsay, France, [e]University of Glasgow, United Kingdom, [f]Uppsala University, Sweden

April 4, 2022

Abstract

The Compact Linear Collider (CLIC) is a multi-TeV high-luminosity linear e^+e^- collider under development by the CLIC accelerator collaboration, hosted by CERN. The CLIC accelerator has been optimised for three energy stages at centre-of-mass energies 380 GeV, 1.5 TeV and 3 TeV [21]. CLIC uses a novel two-beam acceleration technique, with normal-conducting accelerating structures operating in the range of 70 MV/m to 100 MV/m.

The report describes recent achievements in accelerator design, technology development, system tests and beam tests. Large-scale CLIC-specific beam tests have taken place, for example, at the CLIC Test Facility CTF3 at CERN [39], at the Accelerator Test Facility ATF2 at KEK [53, 67], at the FACET facility at SLAC [35] and at the FERMI facility in Trieste [36]. Crucial experience also emanates from the expanding field of Free Electron Laser (FEL) linacs and recent-generation light sources. Together, they demonstrate that all implications of the CLIC design parameters are well understood and reproducible in beam tests and prove that the CLIC performance goals are realistic. An alternative CLIC scenario for the first stage, where the accelerating structures are powered by X-band klystrons, is also under study. The implementation of CLIC near CERN has been investigated. Focusing on a staged approach starting at 380 GeV, this includes civil engineering aspects, electrical networks, cooling and ventilation, installation scheduling, transport, and safety aspects. All CLIC studies have put emphasis on optimising cost and energy efficiency, and the resulting power and cost estimates are reported. The report follows very closely the accelerator project description in the CLIC Summary Report for the European Particle Physics Strategy update 2018-19 [22].

Detailed studies of the physics potential and detector for CLIC, and R&D on detector technologies, have been carried out by the CLIC detector and physics (CLICdp) collaboration. CLIC provides excellent sensitivity to Beyond Standard Model physics, through direct searches and via a broad set of precision measurements of Standard Model processes, particularly in the Higgs and top-quark sectors. The physics potential at the three energy stages has been explored in detail [2, 3, 17] and presented in submissions to the European Strategy Update process.

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

*Compiled and edited by the CLIC Accelerator Steering Group on behalf of the CLIC Accelerator Collaboration, corresponding author: steinar.stapnes@cern.ch

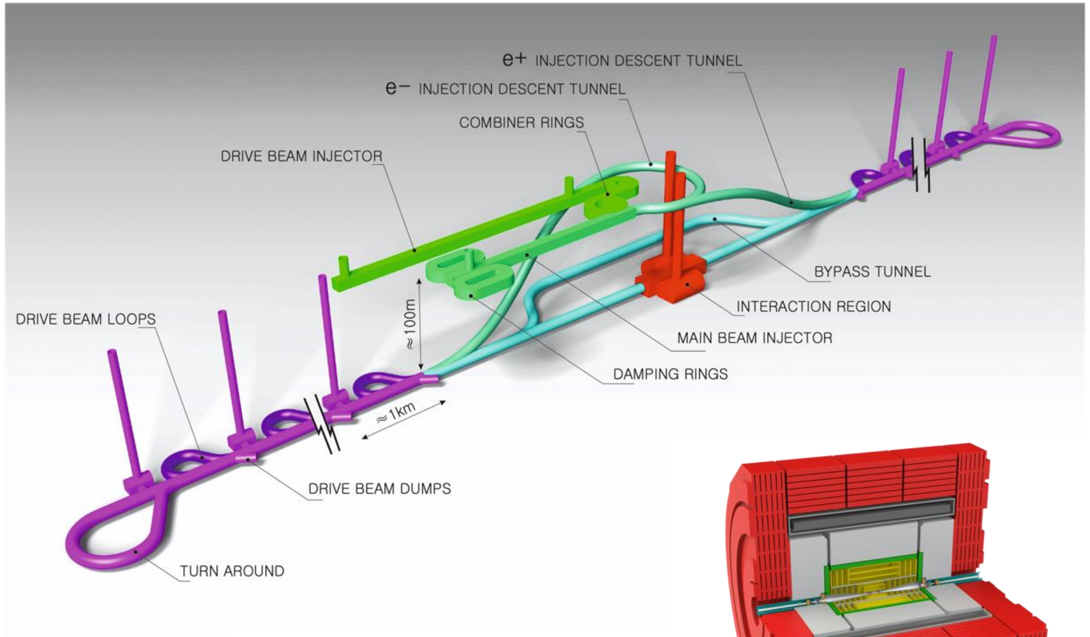
Readiness Report around ~2025-26

Update wrt Project Implementation Plan document 2018

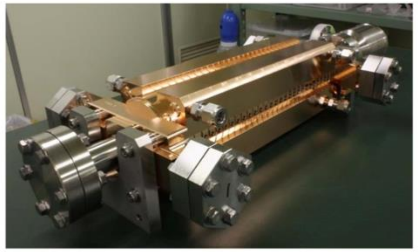
Key updates:

- Luminosity numbers, covering beam-dynamics, nanobeam studies and hardware, and positron production - at all energies
    - Risk reduction (wrt performance), bumps, redundancies
- Energy/power/sustainability: 380 well underway, 3 TeV to be done, L-band klystrons
- Sustainability issues, more work on running/energy models, carbon (construction/operation/disassembly)
- X-band progress – for CLIC, smaller machines, industry availability, including RF network
- RF design optimization/development – including injectors, R&D for higher energies, gradient (cool/HTS/etc.), power, beam parameters - links to plasma (if it can be made)
- Cost update. Changes wrt to 2018, plus impact of going green.
- Physics "update", use for "diversity" types of physics, LDM etc.
- Low cost/power klystron version, with fewer klystrons, 250 GeV

The Compact Linear Collider (CLIC)



Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)



- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

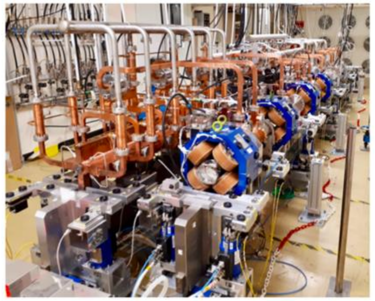
- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

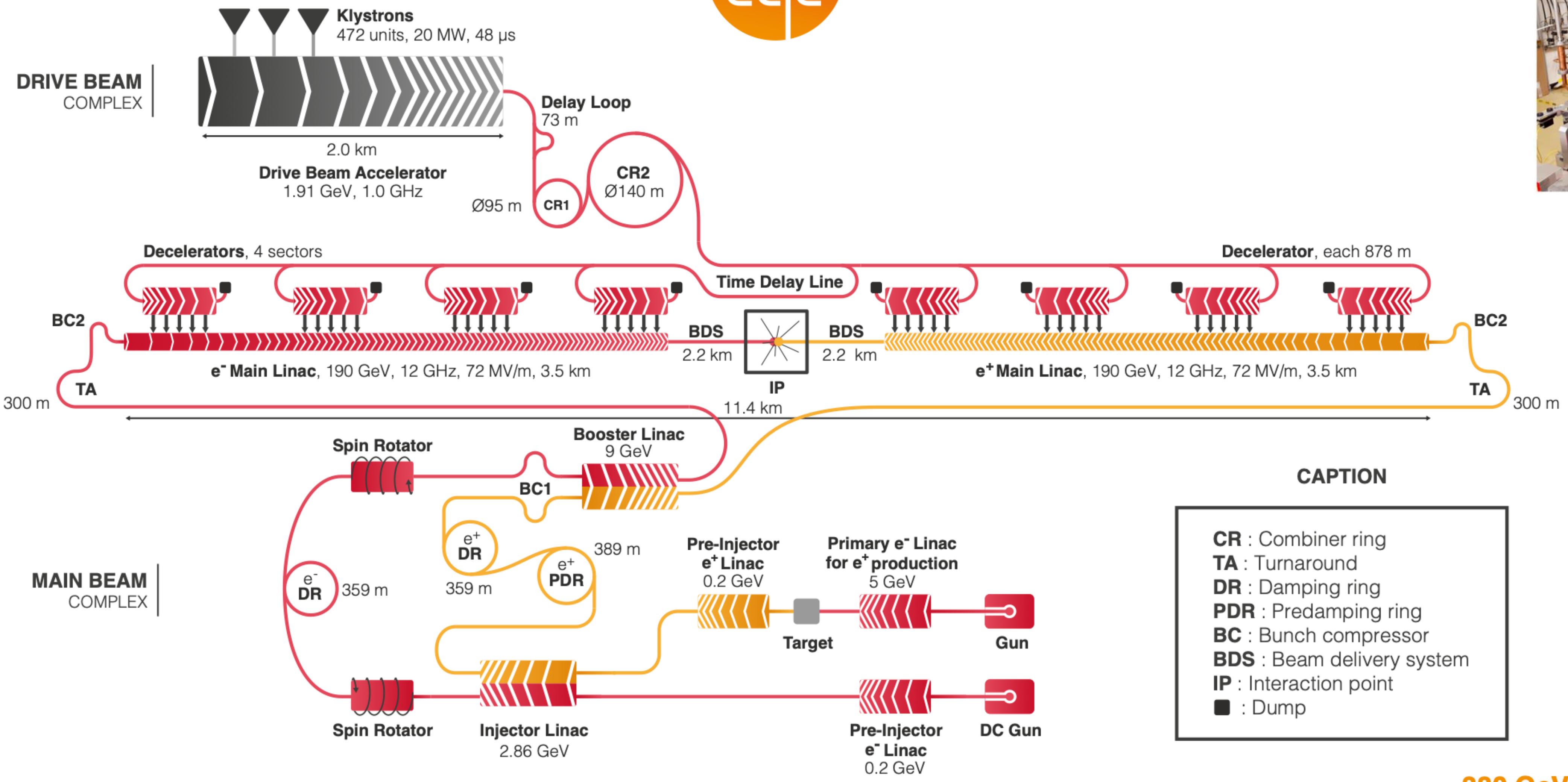
- **Cost:** 5.9 BCHF for 380 GeV
- **Power/Energy:** 110 MW at 380 GeV (~0.6 TWh annually), corresponding to 50% of CERN’s energy consumption today

- Comprehensive **Detector and Physics** studies

Accelerator layout

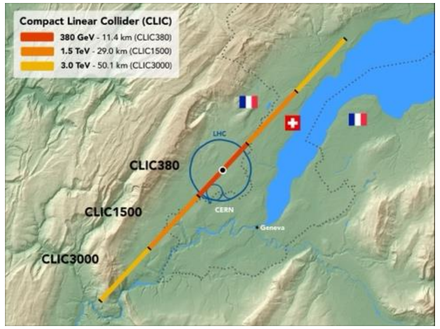
1. Drive beam accelerated to ~2 GeV using conventional klystrons
2. Intensity increased using a series of delay loops and combiner rings
3. Drive beam decelerated and produces high-RF
4. Feed high-RF to the less intense main beam using waveguides

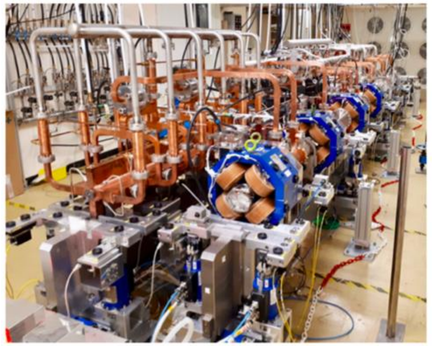




380 GeV

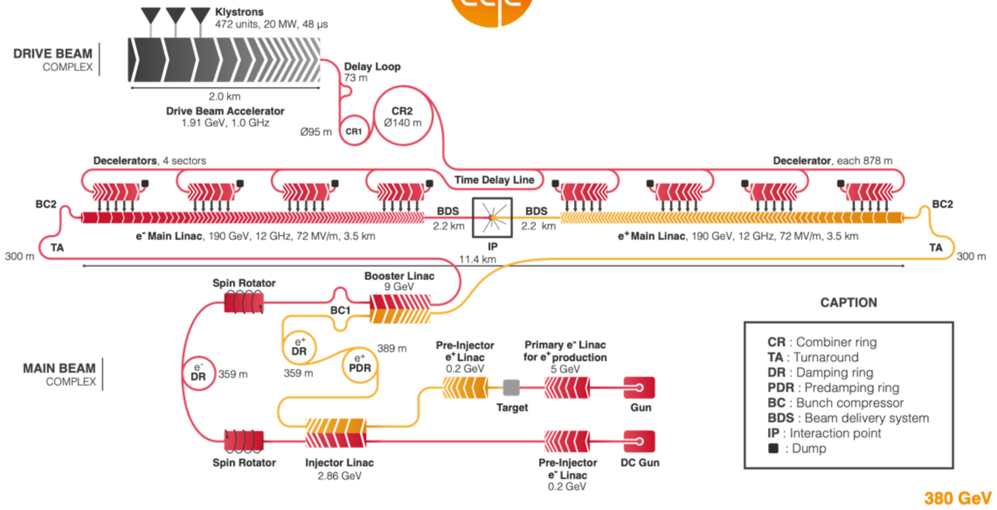
CLIC can easily be extended into the multi-TeV region

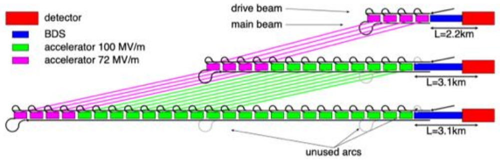




What are the critical elements:

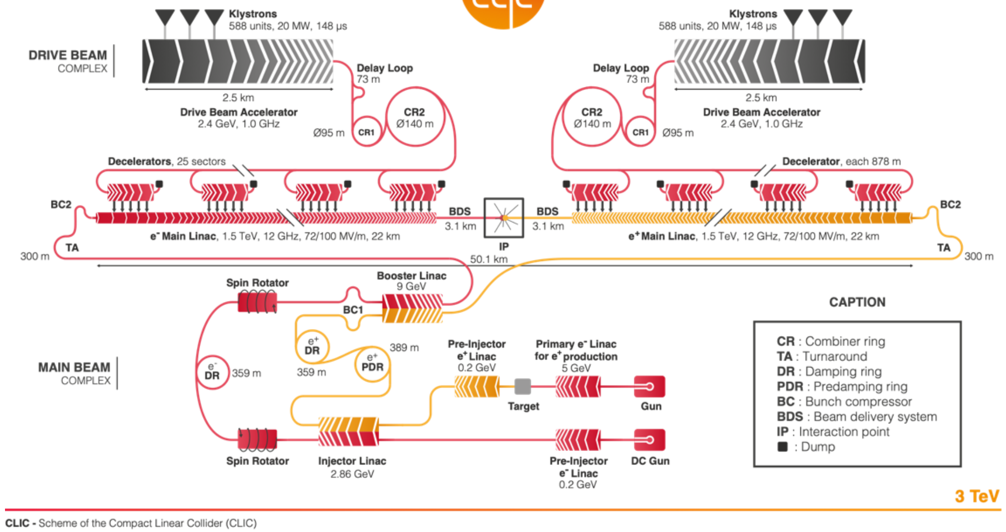
- Physics
- Gradient and power efficiency
- Costs



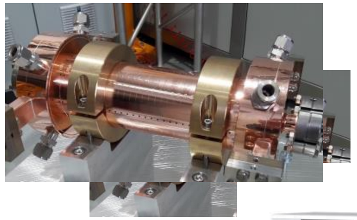


1. Drive beam accelerated to ~2 GeV using conventional klystrons
2. Intensity increased using a series of delay loops and combiner rings
3. Drive beam decelerated and produces high-RF
4. Feed high-RF to the less intense main beam using waveguides

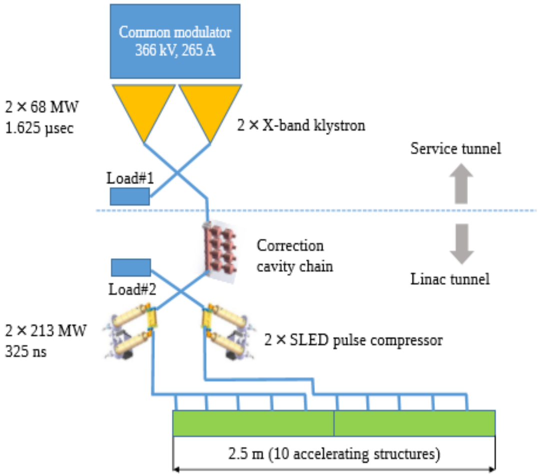
Extend by extending main linacs, increase drivebeam pulse-length and power, and a second drivebeam to get to 3 TeV



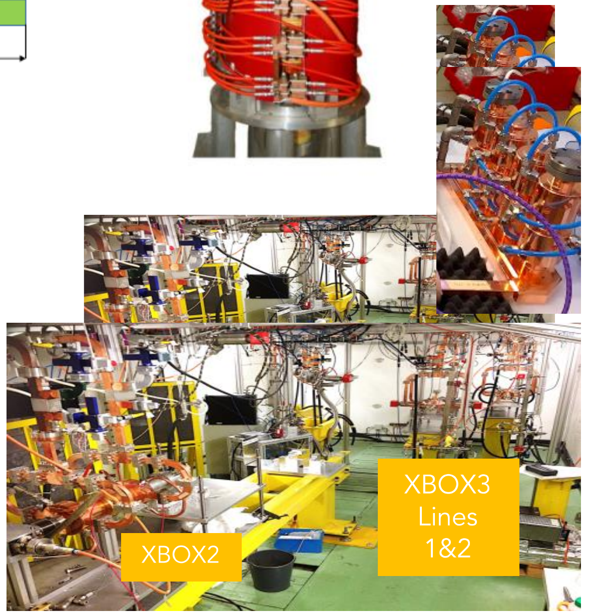
CLIC 380 GeV with X-band klystrons



- Design made, many parts prototyped and available (and used in the smaller linacs mentioned on pages 9-10)
- Need larger tunnel for klystron gallery (CE study also made for this option)
- Also in this case the upgrades would require a drivebeam

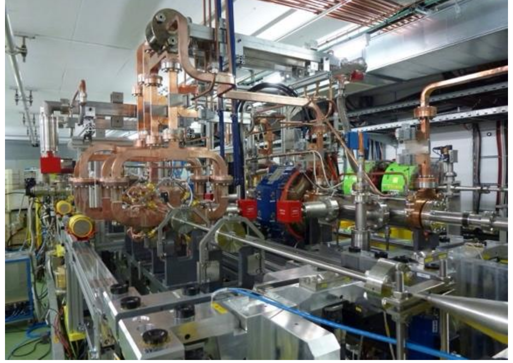


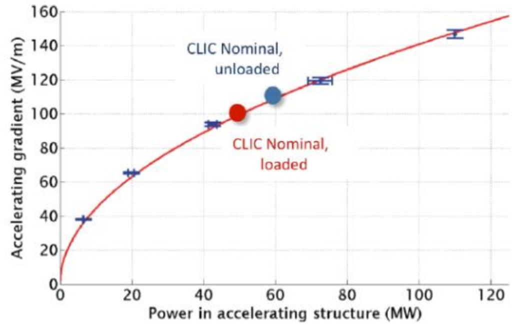
- Challenges: number of klystrons a factor 10 higher than in drive-beam version (~5500), lifetime a concern, costs (RF costs per 2m module approaching 1 MCHF)
- Redesign to reduce the klystron challenge – fewer, current design not optimized since 2018 ?



Accelerator challenges/technologies

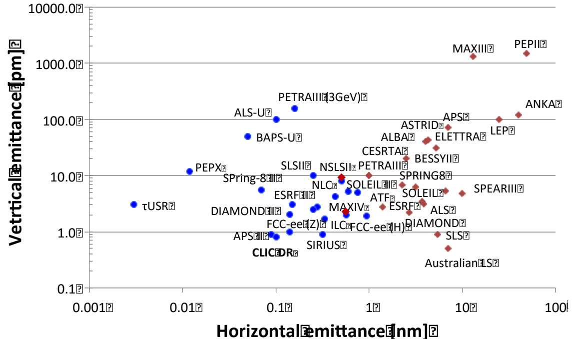
- CLIC baseline – a drive-beam based machine with an initial stage at 380 GeV
- Four main challenges
    1. High-current drive beam bunched at 12 GHz
    2. Power transfer and main-beam acceleration, efficient RF power
    3. Towards 100 MV/m gradient in main-beam X-band cavities
    4. Alignment and stability ("nano-beams")
- The CTF3 (CLIC Test Facility at CERN) programme addressed all drive-beam production issues
- Other critical technical systems (alignment, damping rings, beam delivery, etc.) addressed via design and/or test-facility demonstrations
- X-band technology developed and verified with prototyping, test-stands, and use in smaller systems and linacs
- Two C-band XFELS (SACLA and SwissFEL – the latter particularly relevant) now operational: large-scale demonstrations of normal-conducting, high-frequency, low-emittance linacs





Target and achieved emittance in existing and planned

2018



Extensive prototyping over the last ~5-10 years

The CLIC accelerator studies are mature:

Optimised design for cost and power

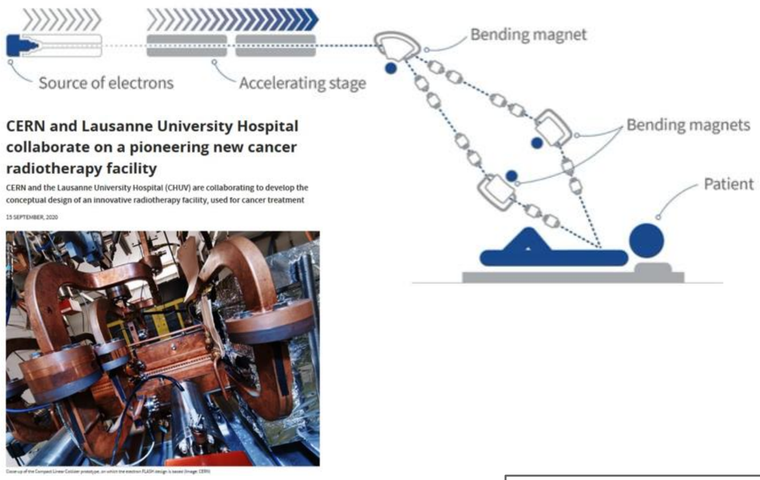
Many tests in CTF3, FELs, lightsources and test-stands

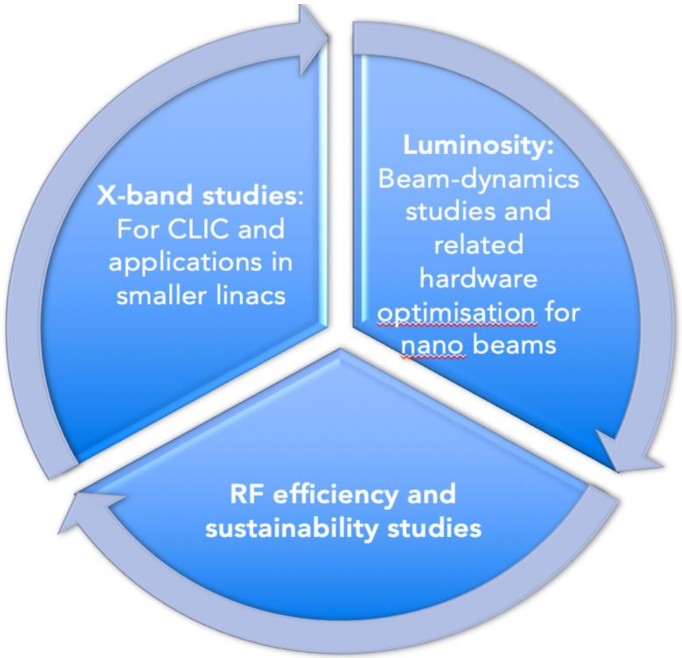
Technical developments of "all" key elements

On-going CLIC studies towards next ESPP update

Project Readiness Report as a step toward a TDR
Assuming ESPP in ~ 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

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



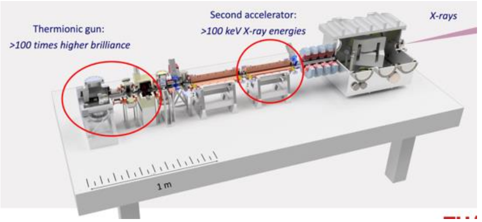


Optimizing the luminosity at 380 GeV – already implemented for Snowmass paper, further work to provide margins will continue.

Luminosity margins and increases:

- 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}** (this is the value currently used)

Common LC studies in ATF3 part of this, and also on positron, sources, DRs and beam-dynamics.



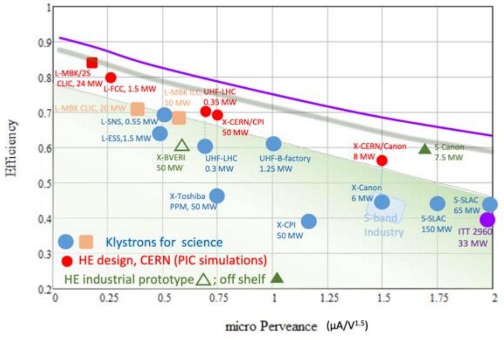
Improving the power efficiency for both the initial phase and at high energies, including more general sustainability studies

Power estimate bottom up (concentrating on 380 GeV systems)

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

Energy consumption ~0.6 TWh yearly, CERN is currently (when running at 1.2 TWh.

More work needed on LCA (carbon and other issues).



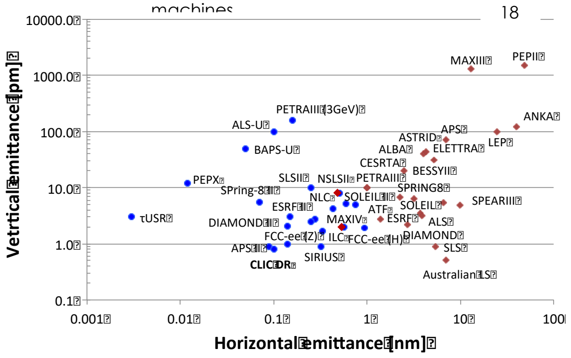
CLIC parameters

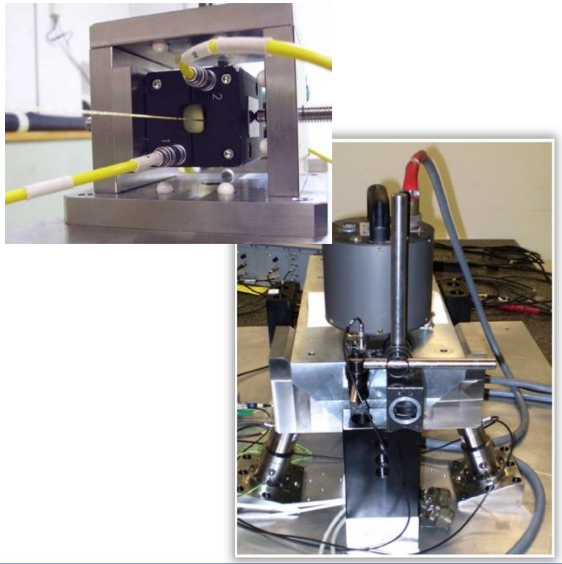
Table 1.1: Key parameters of the CLIC energy stages.

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

Low emittance generation and preservation

Target and achieved emittance in existing and planned machines 2018





Low emittance damping rings

Preserve by

- Align components (10 µm over 200 m)
- Control/damp vibrations (from ground to accelerator)
- Beam based measurements
  – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks
- Experimental tests in existing accelerators of equipment and algorithms
  (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)

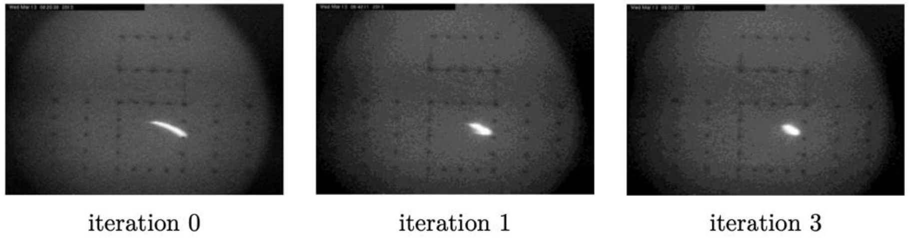
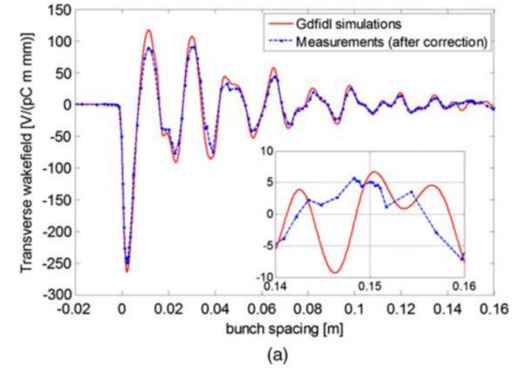
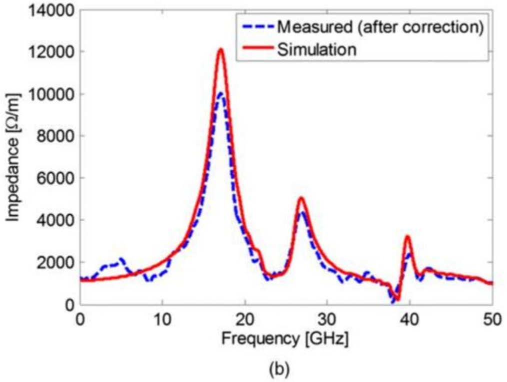


Figure 8.10: Phosphorous beam profile monitor measurements at the end of the FACET linac, before the dispersion correction, after one iteration step, and after three iteration steps. Iteration zero is before the correction.



(a)



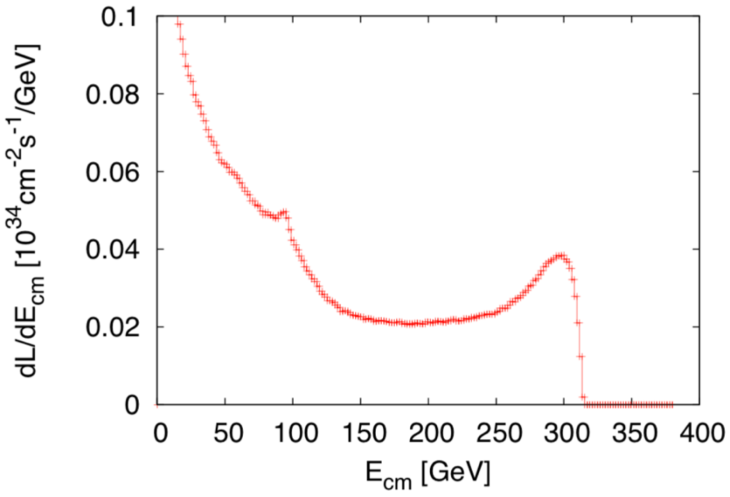
(b)

Wake-field measurements in FACET

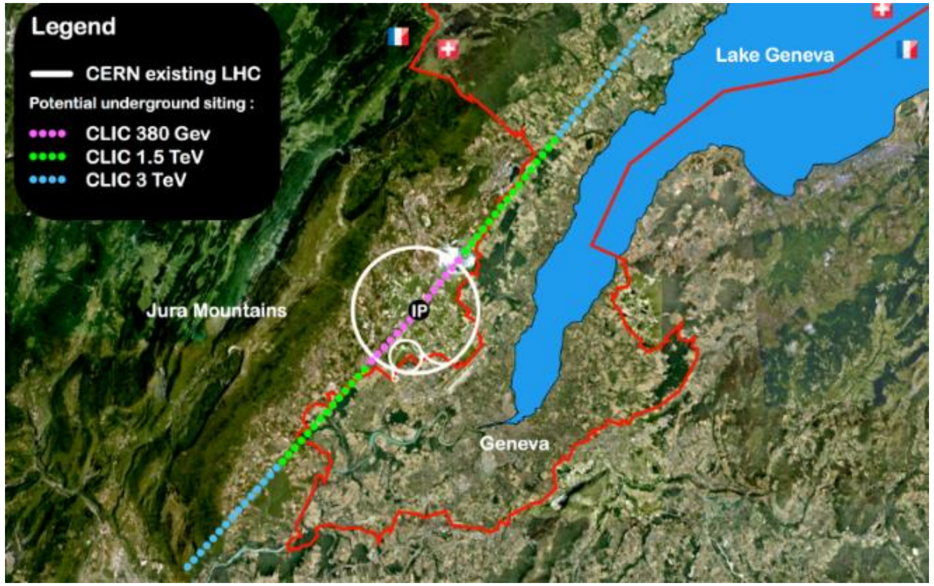
(a) Wakefield plots compared with numerical simulations.
(b) Spectrum of measured data versus numerical simulation.

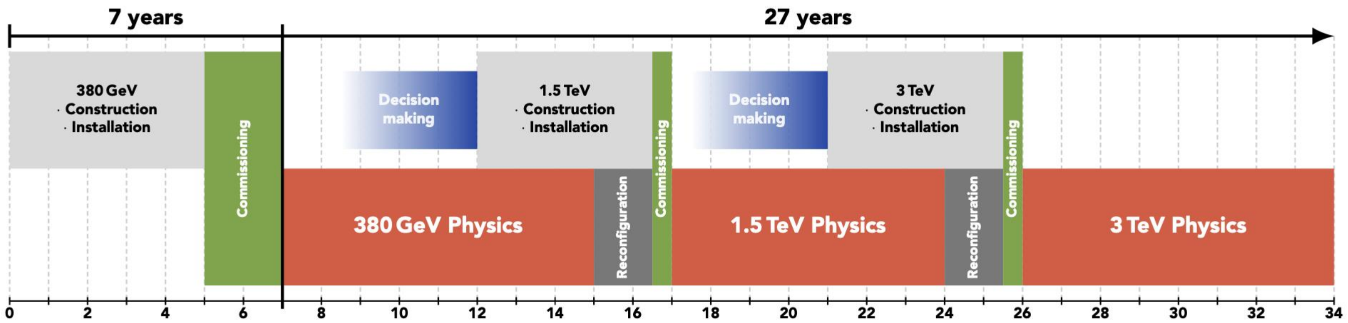
Luminosities studies 2019-22

- Luminosity margins and increases
  - Initial estimates of static and dynamic degradations from damping ring to IP gave: 1.5 x 10^{34} cm^{-2} s^{-1}
  - Simulations give 2.8 on average, and 90% of the machines above **2.3 x 10^{34} cm^{-2} s^{-1}**
  - A "perfect" machine will give : 4.3 x 10^{34} cm^{-2} s^{-1}
  - In addition: doubling the frequency (50 Hz to 100 Hz) would double the luminosity, at a cost of ~55% and ~5% power and cost increase
- Z pole performance, 2.3x10^{32} – 0.4x10^{34} cm^{-2} s^{-1}
  - The latter number when accelerator configured for Z running (e.g. early or end of first stage)
- Gamma – Gamma spectrum (example)



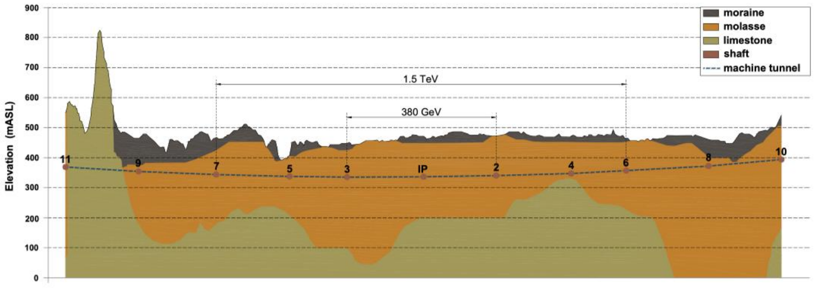
CLIC CE, stages and schedules





Technology Driven Schedule from start of construction shown above.

A preparation phase of ~5 years is needed before (estimated resource need for this phase is ~4% of overall project costs)

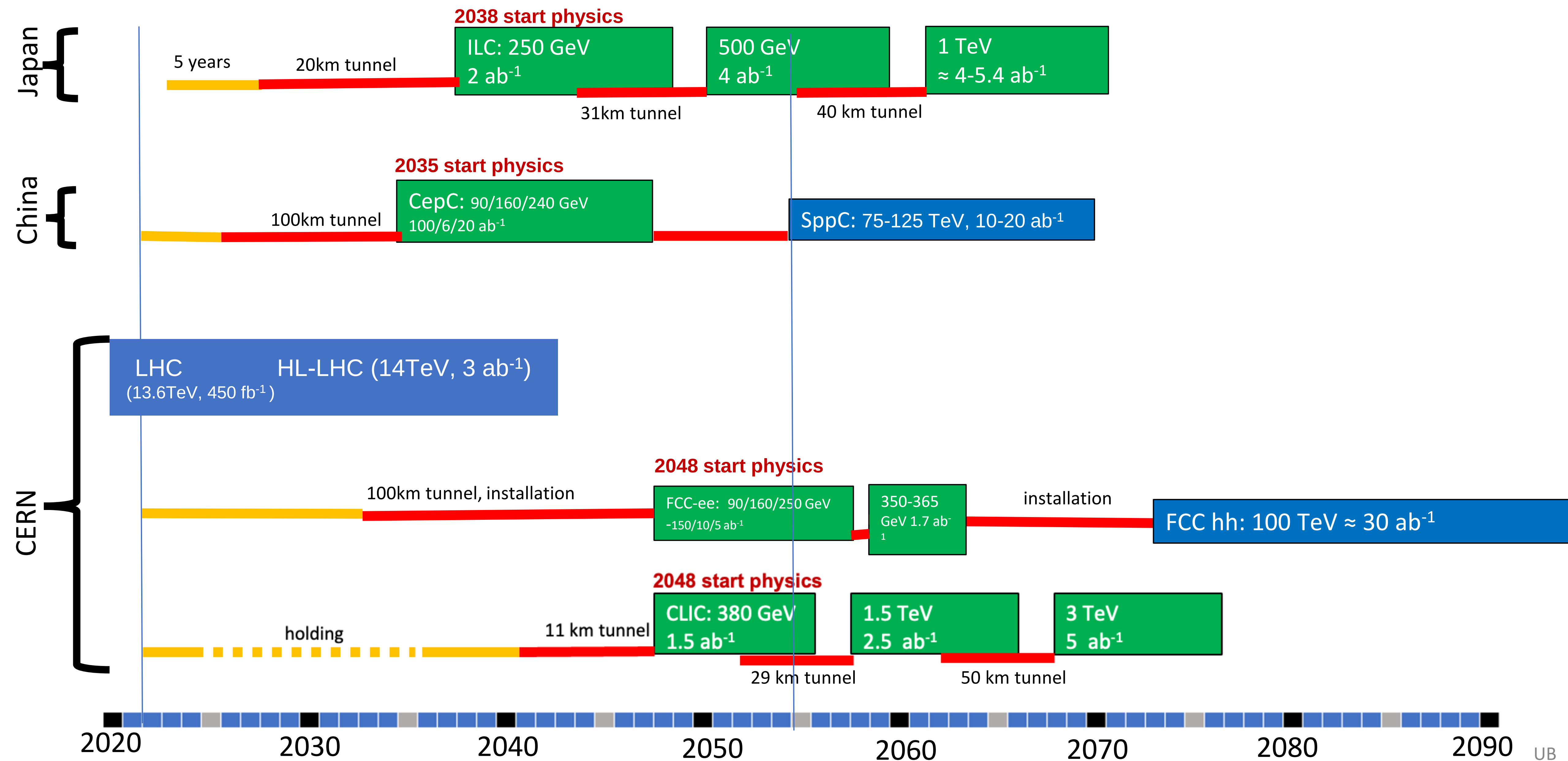


Indicative scenarios of future colliders [considered by ESG]

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)



Proposed Strategy for CLIC cost review

CLIC PIP 2018 – 380 GeV

Domain	Sub-Domain	Cost [MCHF]	
		Drive Beam	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*		
	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

Review Areas that may produce a relevant impact on cost:

Civil Engineering
Injectors
Damping Rings
RF (Modulators + Klystrons)
Cooling and Ventilation
Additional Detector (push – pull)

Invest 0.3FTE in the development of a more user friendly Interface to the existing Costing Tool ?

First Draft of cost review due by June 2024 ?

CE DB “Light” Review performed

Civil Engineering Works	Cost [EUR] 2018 PIP Estimate	Cost [EUR] Inflated PIP Estimate	Cost [CHF] 2018 PIP Estimate	Cost [CHF] Inflated PIP Estimate	Cost [CHF] Costing Tool
Underground Structures	667'689'418	767'425'257	754'489'042	748'316'368	804'881'315
Surface Structures	369'011'864	424'132'864	416'983'407	413'571'956	418'420'204
Site Developement	34'383'126	39'519'092	38'852'933	38'535'067	59'196'914
Temporary works	2'398'476	2'756'747	2'710'277	2'688'104	2'848'189
TOTAL	**1'073'482'884**	**1'233'833'960**	**1'213'035'659**	**1'203'111'495**	**1'285'346'621**

In 2018 1 EUR = 1.13 CHF
2018 – 2023 CE index= + 15%
2018 – 2023 IPP index= + 2.9%
In 2023 1 EUR = 0.9751 CHF

Overview
Timetable
Registration

CLIC Website
Privacy Information

CLIC Project Office
clic.project.office@cern.ch

Timetable

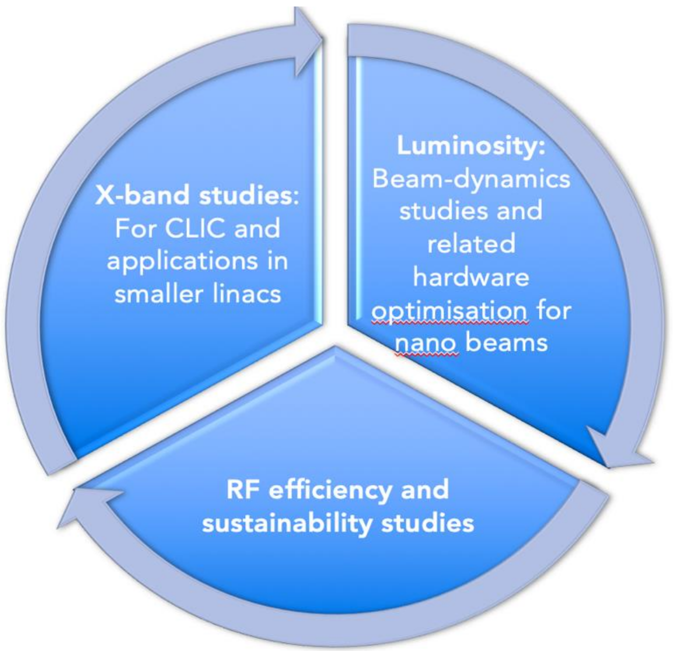
Mon 11/12 | Tue 12/12 | Wed 13/12 | All days

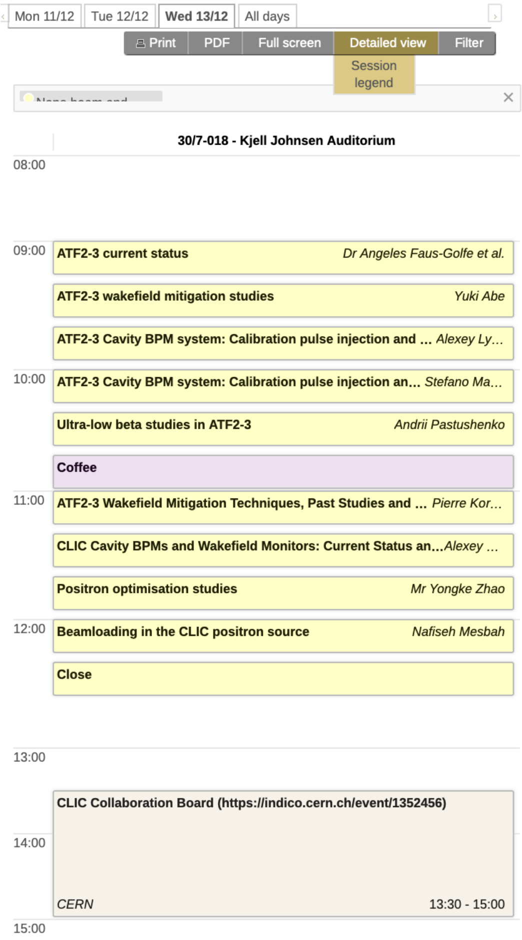
Print | PDF | Full screen | Detailed view | Filter
Session legend

Project planning : CLIC towards

30/7-018 - Kjell Johnsen Auditorium

Time	Contribution	Location	Speaker	Schedule
12:00				
13:00				
	CLIC project status and mini-week goals	*CERN*	*Steinar Stapnes*	13:30 - 13:55
14:00	**ILC status and plans**	*CERN*	*Dr Benno List*	14:00 - 14:20
	HALHF plans	*CERN*	*Brian Foster*	14:25 - 14:45
	FCC-ee injector studies	*CERN*	*Alexej Grudiev*	14:50 - 15:10
15:00	**LC physics potential**	*CERN*	*Aidan Robson*	15:15 - 15:35
	Coffee	*CERN*		15:40 - 16:00
16:00	**Emittance tuning knobs for CLIC ML**	*CERN*	*Andrii Pastushenko*	16:00 - 16:20
	Power estimats	*CERN*	*Alexej Grudiev*	16:25 - 16:45
	RTML optimisation	*CERN*	*Mr Yongke Zhao*	16:50 - 17:10
17:00	**Sustainability studies for LC - CLIC and ILC**	*CERN*	*Steinar Stapnes*	17:15 - 17:35
	Highlights from the 2023 HGWS	*CERN*	*Walter Wuensch*	17:40 - 18:00
18:00				





Power and Sustainability, see talks later

Summary and thanks

- CLIC studies focused on core technologies, X-band and nanobeam, for next ESPP update well underway.
  - Many common studies with ILC – the traditional ones but also recently related to sustainability, also common interactions with C^3
  - Keep focus on both 380 GeV and multi-TeV performance and R&D
- Greatly helped by studies of smaller linacs and systems using X-band technology – important for collaboration and industry capabilities

- Thanks to many CLIC accelerator colleagues for slides and input