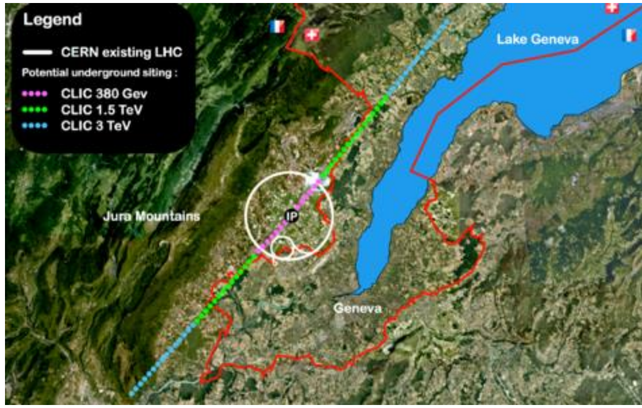
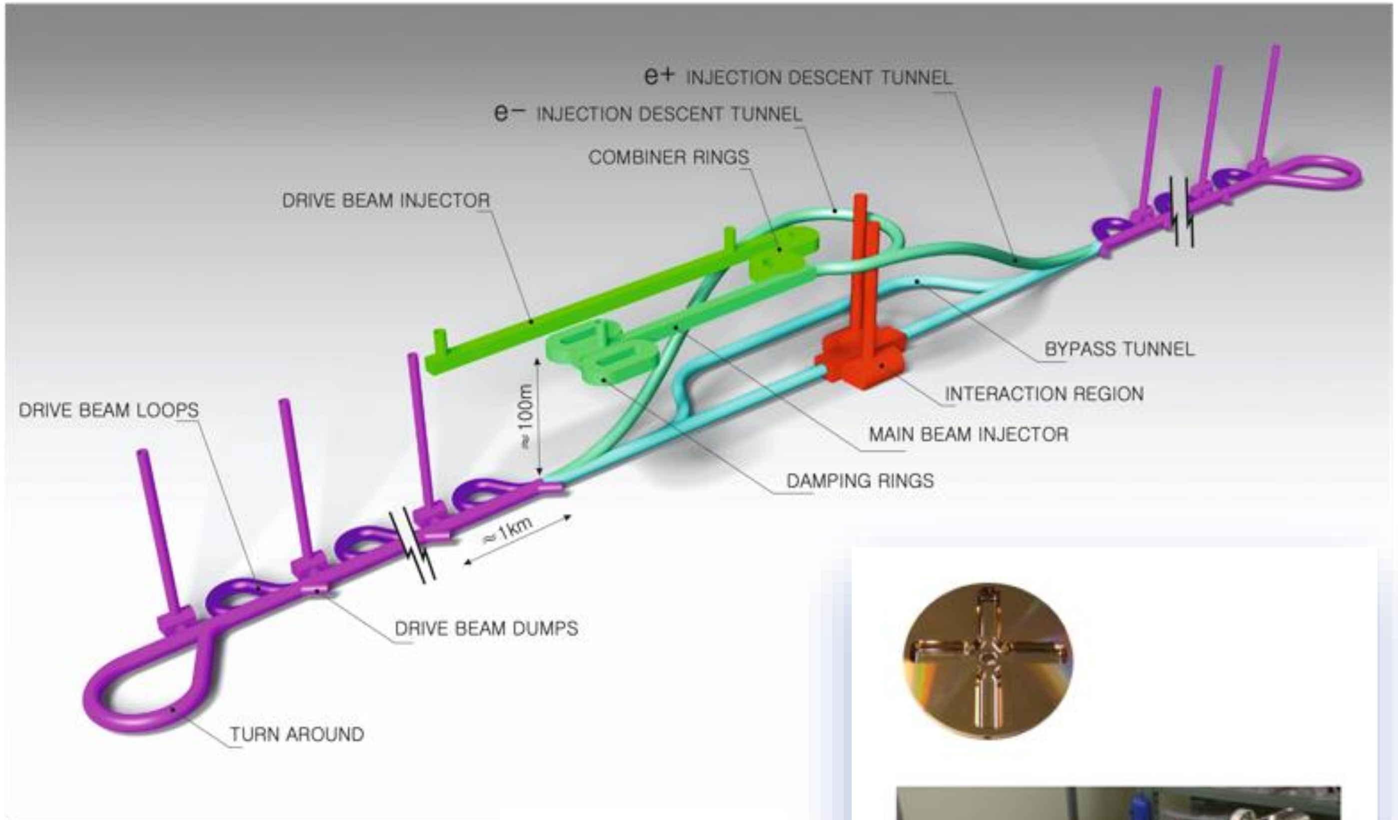
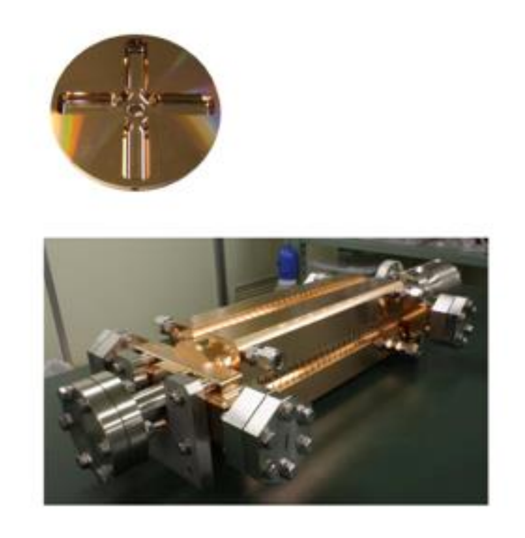
The Compact Linear Collider (CLIC)
- in previous ESPP -







Accelerating structure prototype for CLIC: 12 GHz (L~25 cm), 100 MV/m

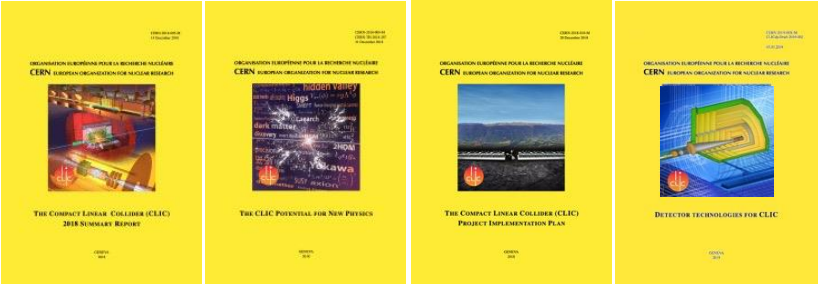
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision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

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]

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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.

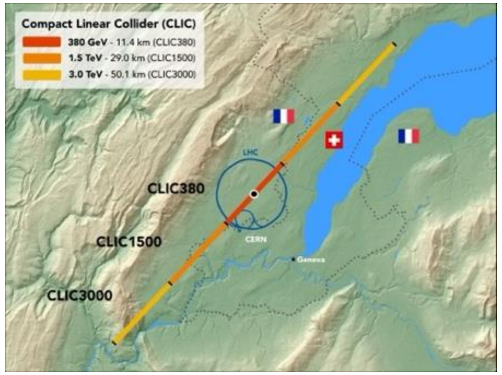
The report describes recent achievements in accelerator design, technology development, system tests and beam tests. Large-scale CLIC-specific beam tests have taken place, for example, at the CLIC Test Facility CTF3 at CERN [39], at the Accelerator Test Facility ATF2 at KEK [53, 67], at the FACET facility 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].

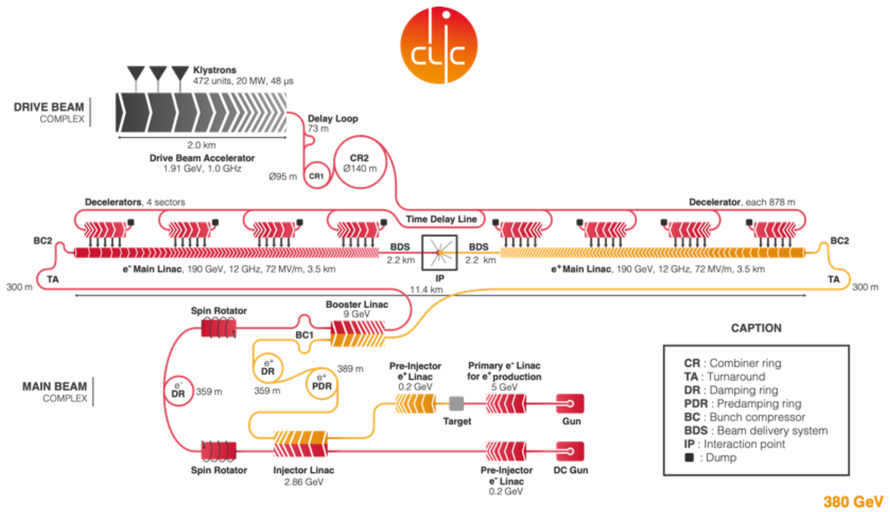
Detailed studies of the physics potential and detector for CLIC, and R&D on detector technologies, have been carried out by the CLIC detector and physics (CLICdp) collaboration. CLIC provides excellent sensitivity to Beyond Standard Model physics, through direct searches and via a broad set of precision 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.

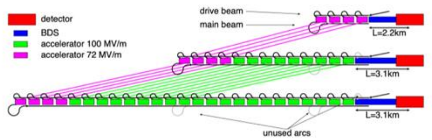
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

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

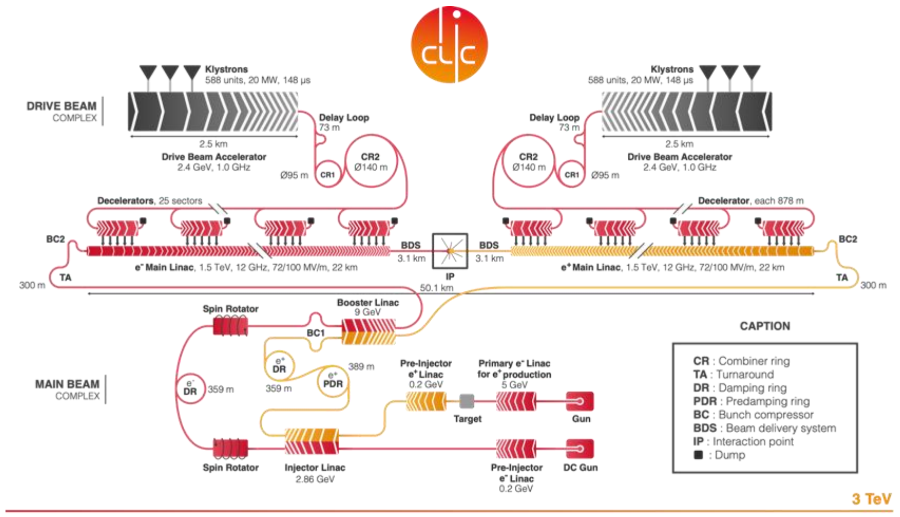
CLIC from 380 GeV to 3 TeV







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



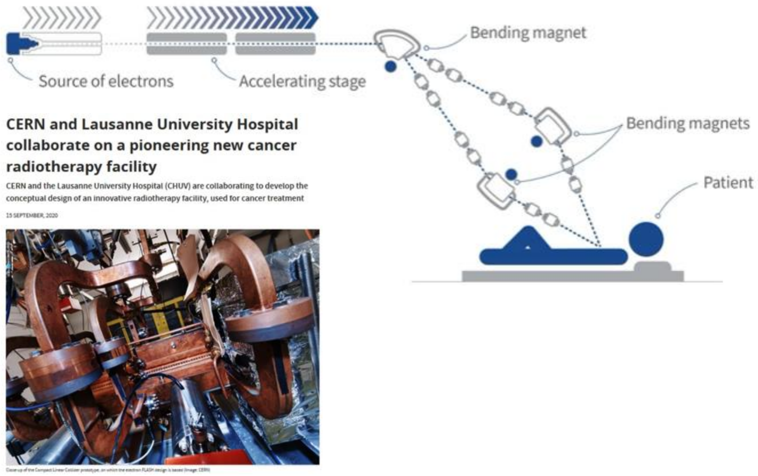
CLIC - Scheme of the Compact Linear Collider (CLIC)

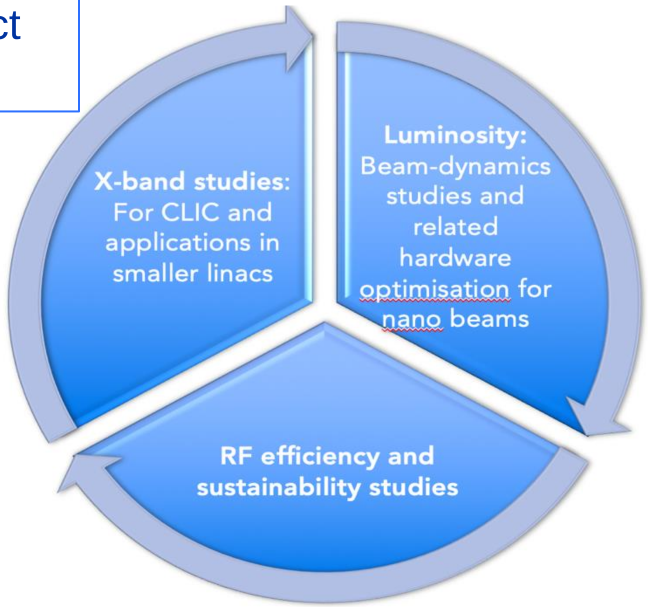
Table 1.1: Key parameters of the CLIC energy stages.

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

On-going and recent CLIC studies - 2019-25

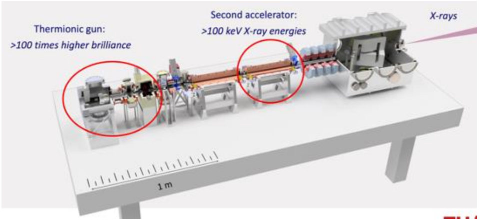
The X-band technology readiness for the 380 GeV CLIC initial phase - manufacturability and developments driven by use in small compact accelerators for industrial experience



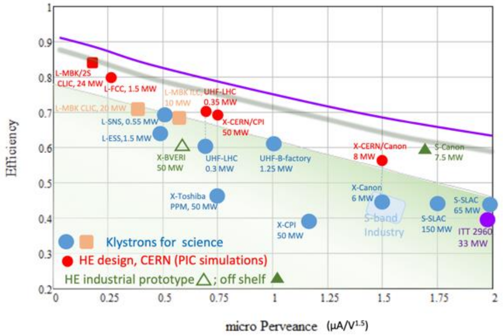


Optimizing the luminosity at 380 GeV at 2.3 x 10^{34} cm^{-2} s^{-1}– already implemented for Snowmass paper, further work to provide margins will continue (HW and SW)

Project summary for Snowmass: https://arxiv.org/pdf/2203.09186.pdf



Improving the **power efficiency** for both the initial phase (already in Snowmass report) and at high energies, including more **general sustainability studies** (in many cases done together with ILC – see later)

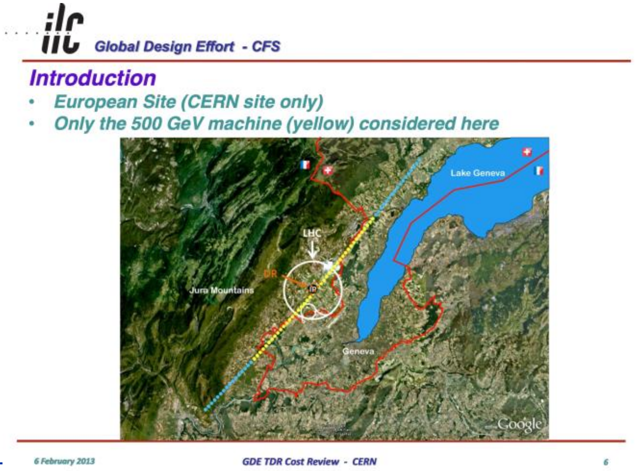


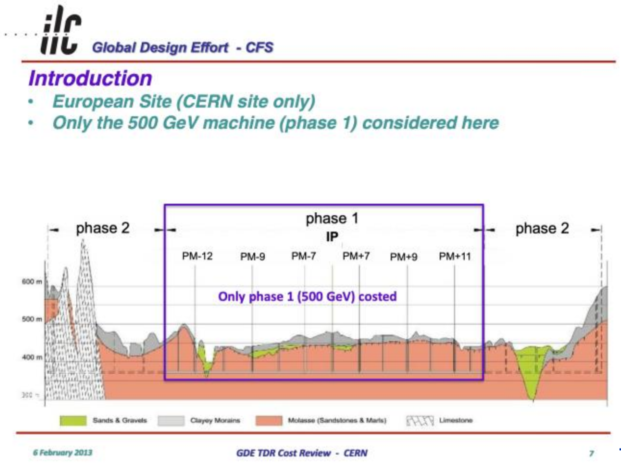
CERN


PAST
FUTURE

Linear Collider Inputs to the EPPSU – from LCWS

- Expect each LC project (ILC, CLIC, C3, HALHF, …) to make "Project Submissions”
  - project overviews with accelerator bias
- Joint LC Submissions
  - physics at a LC from 90 GeV to multi-TeV (use references to existing documents, but highlight specifically
    - need for >= 500 GeV and polarised beams
    - new results since Snowmass
  - a joint vision for a Linear Collider Facility incl. upgrades, beyond collider etc — at any location in the world
- Expect some Detector Concepts (ILD, SiD, …) to make a “Detector Concept Submissions”
- “LC facility” submission (i.e. starting with ILC and upgrade) at CERN



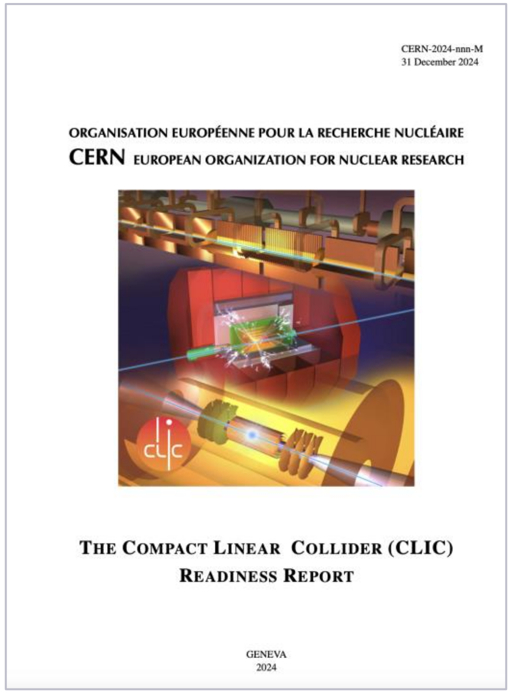


Adapted from Jenny List

The CLIC ESPP update main report

Preparing “Project Readiness Report” as a step toward a TDR

Assuming ESPP in ~ 2025-6, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.


CERN-2024-nnn-M
31 December 2024

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE COMPACT LINEAR COLLIDER (CLIC)
READINESS REPORT

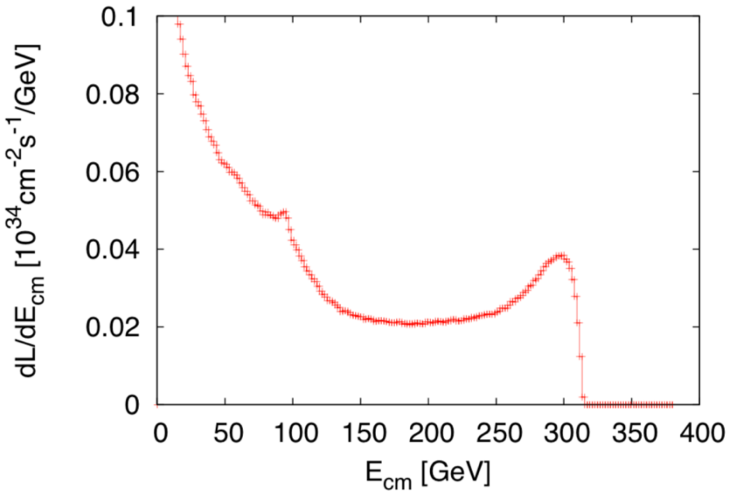
GENEVA
2024

However several important changes compared to what is presented earlier:

- Energy scales: 380 GeV and 2 TeV with one drivebeam, consider also 100 Hz running at 250 GeV (i.e. two parallel experiments, two BDSs)
- Several updates on parameters (injectors, damping rings, drive-beam) based on new designs, results and prototyping (e.g. klystrons, magnets) - however no fundamental changes beyond staying at one drivebeam
- Technology results updates, including more on use of them in other projects (e.g. alignment, instrumentation, X-band RF is small linacs)
- Update costing and power – for costing interplay between inflation and CHF exchanges – and for example power at 2 TeV never estimated
- LCAs
- More details needed for next phase (i.e. prep phase)

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, 2.3×10^{32} – 0.4×10^{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)



These numbers are already included in the Snowmass report 2021

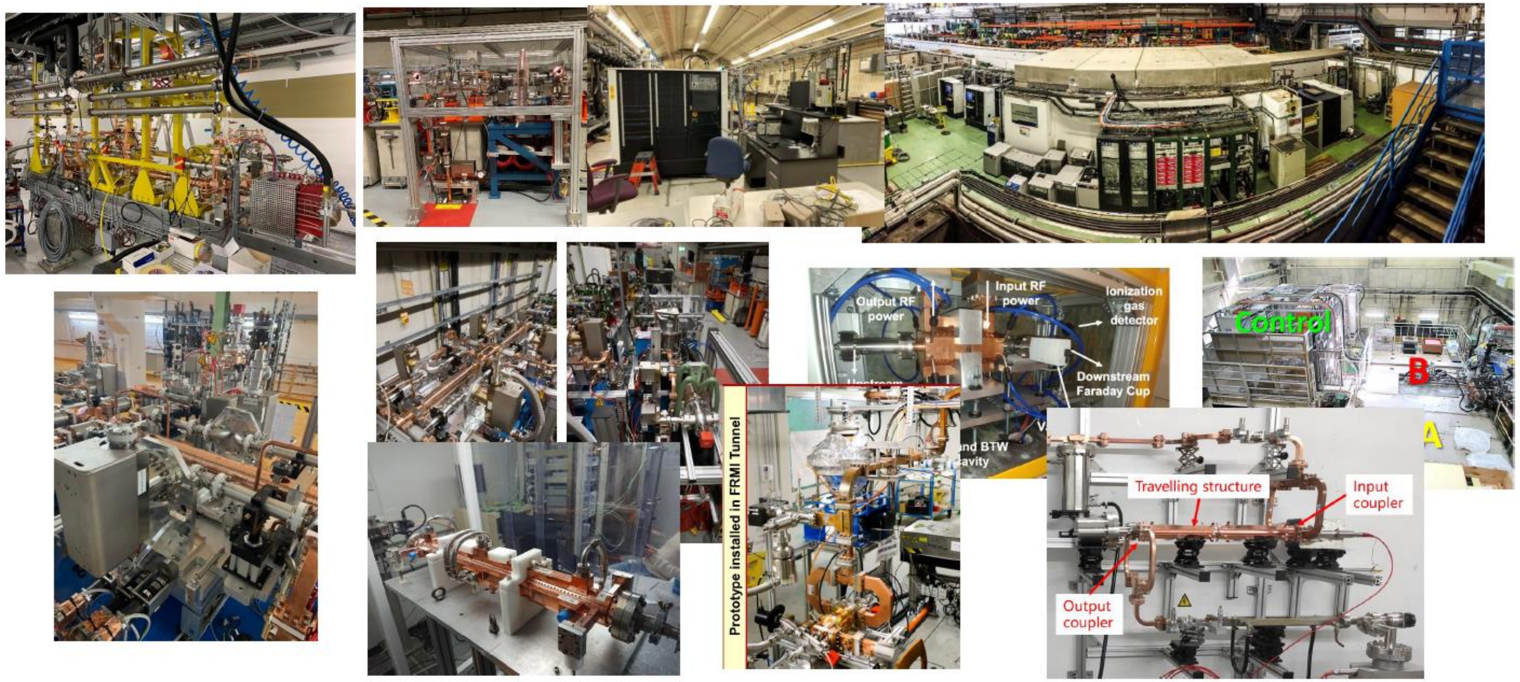
CLIC is heavily prototyped

The CLIC accelerator studies are mature:

- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of “all” key elements

Update with most recent results, update with examples of use in other projects, X-band project overview (details in separate paper)

X-band RF technology – outside CLIC



Compact Linacs have many uses:

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

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

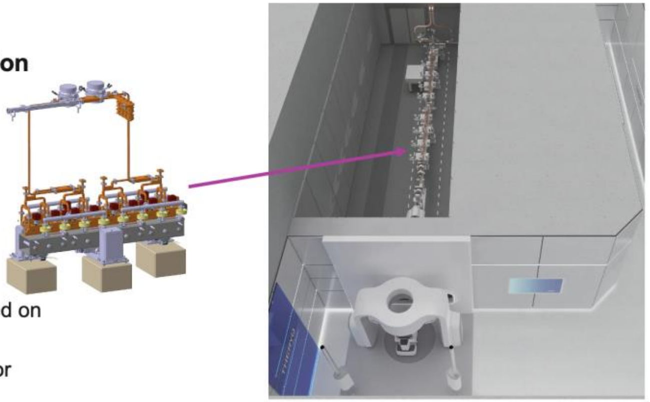
Trieste, Fermi	Linearizer
SwissFEL	Linearizer and Polarix deflector
SARI:	Linearizer, deflectors
CERN:	Xbox-1 with CLEAR, accelerator
DESY:	PolariX deflectors in FELs
SLAC:	NLCTA, XTA
Argonne	AWA
Arizona	CXLS, ICS

KEK	NEXTEF
CERN	XBox-2,3 and SBox
Tsinghua	TPot
Valencia	IFIC VBox
Trieste	FERMI 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
+ more	

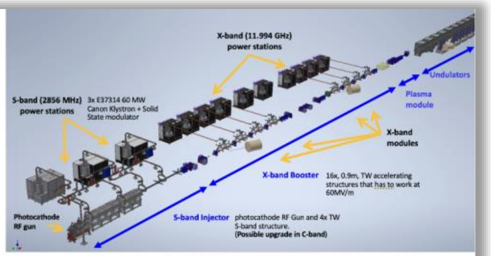
Medical - DEFT (Deep Electron Flash Therapy)

- **CERN-CHUV-THERYQ collaboration**
  - VHEE (100 – 250 MeV)
  - FLASH (>40 Gy/s, < 100 ms)
  - Clinical trials planned for 2025
- **Accelerator technology**
  - S-band photoinjector
  - X-band accelerating structures mounted on girders
  - X-band klystrons with pulse compressor

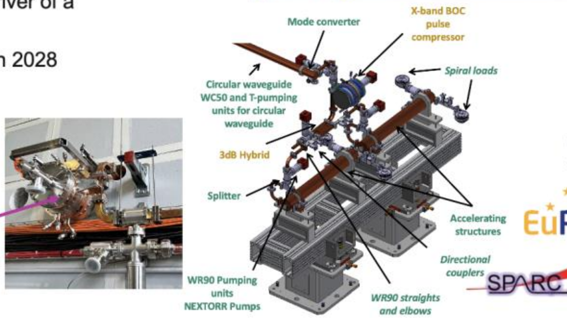


CERN CHUV THERYQ

Research - EuPRAXIA@SPARC_LAB



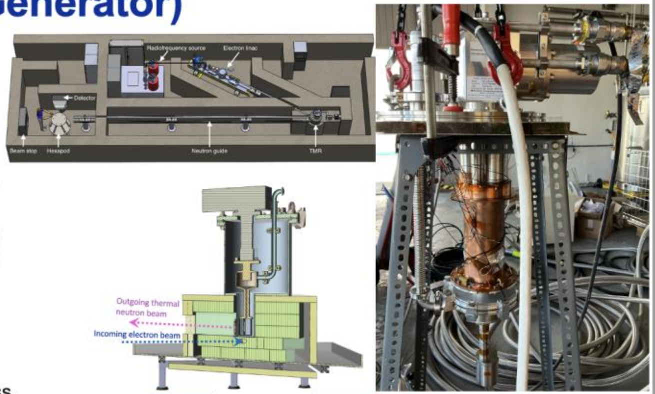
- **41 laboratory collaboration, hosted at INFN Frascati**
  - FEL facility driven by plasma acceleration
  - 1 GeV X-band electron linac driver of a plasma wakefield accerator
  - Expected ready for operation in 2028
- **Accelerator technology**
  - S-band injector
  - 50 MW X-band klystrons
  - X-band pulse compressor
  - X-band accelerating structures



INFN EuPRAXIA SPARC LAB

Industrial - VULCAN (Versatile ULtra-Compact Advanced Neutron Generator)

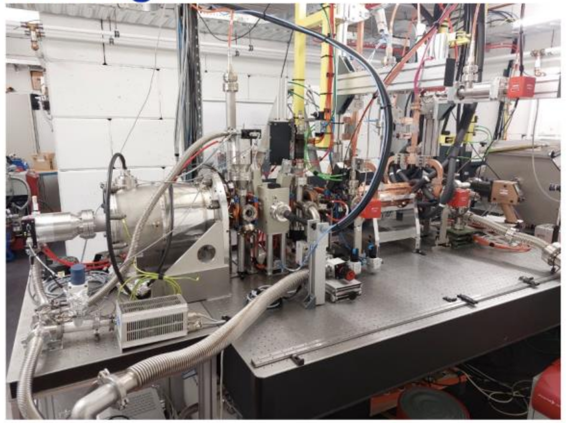
- **CERN-DAES-DTI-Xnovotech collaboration**
  - 35 MeV, kW-scale electron linac
  - Target-moderator-reflector for converting electrons to thermal neutrons
  - Stress-strain measurements, battery & fuel-cell investigations
  - Proof of concept testing in CLEAR this year, complete prototype construction by mid-late 2020s
- **Accelerator technology**
  - High-gradient accelerating structures and pulse compressor optimized for compactness, cost, beam power and efficiency
  - High-power, high-efficiency klystrons



CERN DAES xnovotech

Research / Industrial - Smart*Light

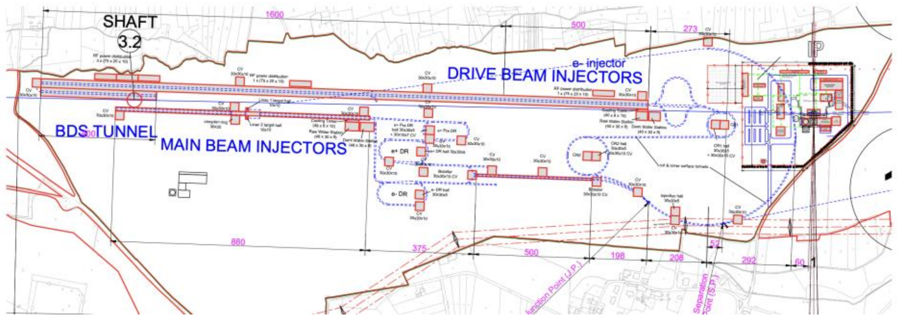
- **Dutch-Flemish collaboration, at Eindhoven University of Technology**
  - Inverse Compton Scattering
  - 30 MeV electrons producing 40 keV X-rays through laser interaction
  - Upgrading to Smart*Light 2.0 with 60 MeV and 100x higher repetition rate
  - Table-top device in operation
- **Accelerator technology**
  - Single X-band accelerating structure
  - 6 MW X-band klystron with pulse compressor

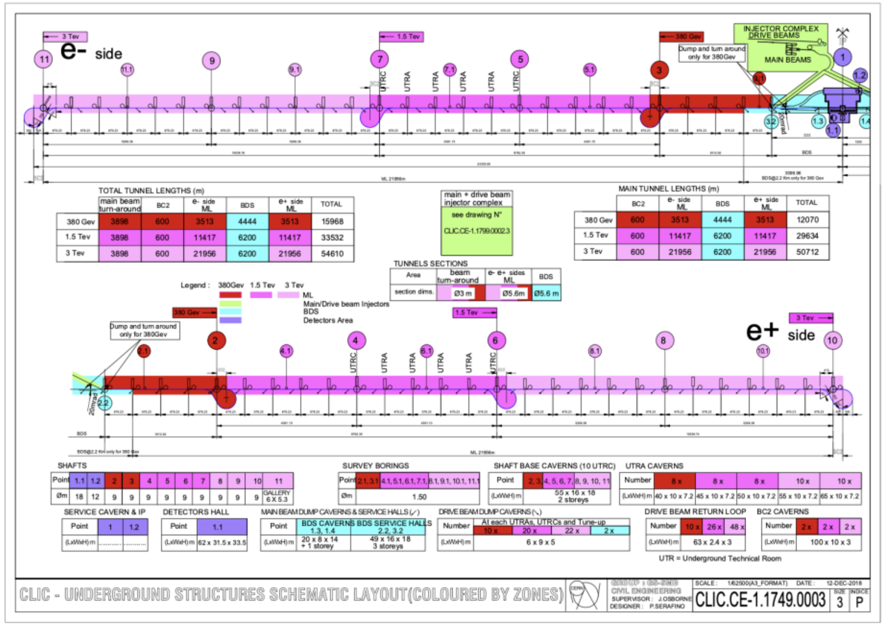


TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

CE and layout

	Update wrt PiP	Comments
Lengths	380 GeV, for 250 (same as 380?) and 2 TeV (length to be defined), revise main drawings from PiP. Check turn around lengths.	Check surface conflicts. Laser straight.
Widths	5.6m ML and BDS. Klystron version unchanged	Check also turn arounds and transfer tunnels
Second experiment	2 BDS, extra caverns	Check crossing angels and cost estimate, understand FF support and beamdumps
Surface	Check DB, transfers, injectors and DRs	Fit into Prevessin, even with two experiments ?
Costing	Check CLIC versus FCC – can we extract unit costs ? Almost done (ref Carlo's work)	Compare with FCC and internal review
Prep. Time, etc	Model from FCC	Prep. time estimate
LCA	On-going	Consistent with CE drawings





Power and Energy

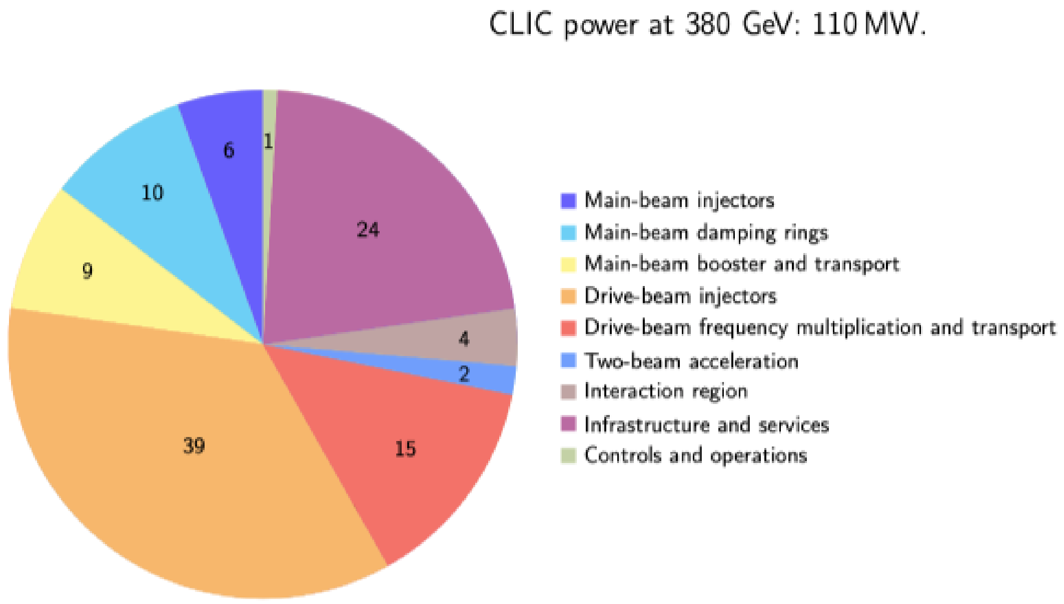


Fig. 4.8: Breakdown of power consumption between different domains of the CLIC accelerator in MW at a centre-of-mass energy of 380 GeV. The contributions add up to a total of 110 MW. (image credit: CLIC)

Table 4.2: Estimated power consumption of CLIC at the three centre-of-mass energy stages and for different operation modes. The 380 GeV numbers are for the drive-beam option and have been updated as described in Section 4.4, whereas the estimates for the higher energy stages are from [57].

Collision energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	110	25	9
1500	364	38	13
3000	589	46	17

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 (~90% in accelerators)

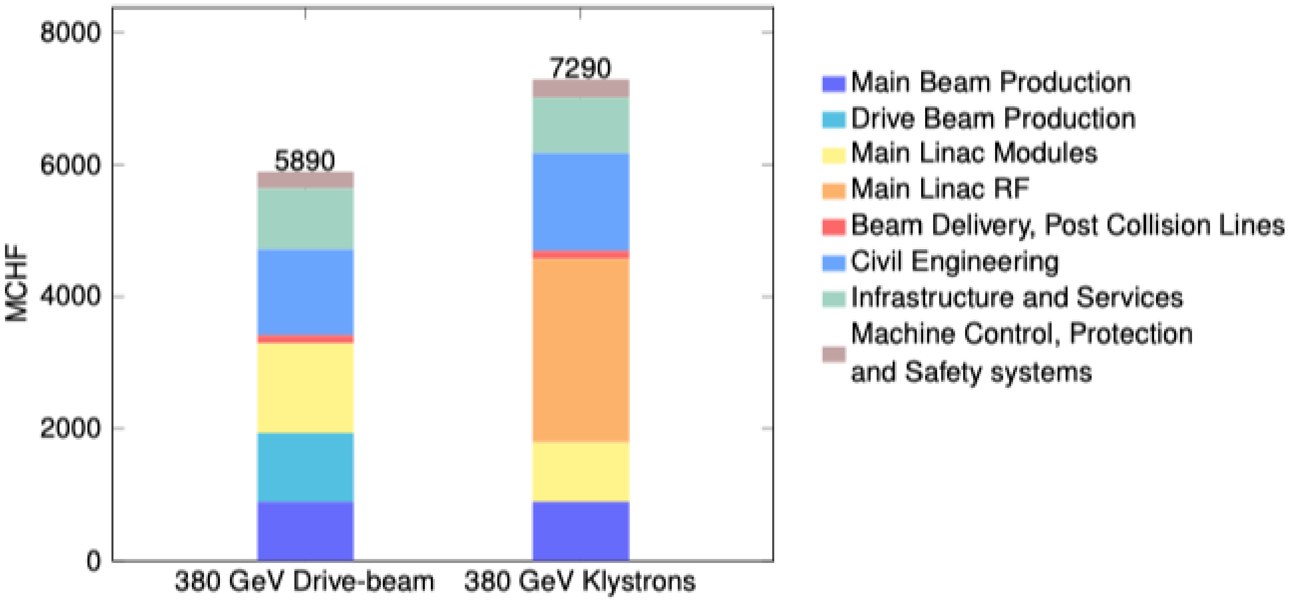
1.5 TeV and 3 TeV numbers still from the CDR (but included in the reports), to be re-done the next ~2 years

Savings of high efficiency klystrons, DR RF redesign or permanent magnets not included at this stage, so numbers will be reduced

Cost - I

Machine has been re-costed bottom-up in 2017-18

- Methods and costings validated at review on 7 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:

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

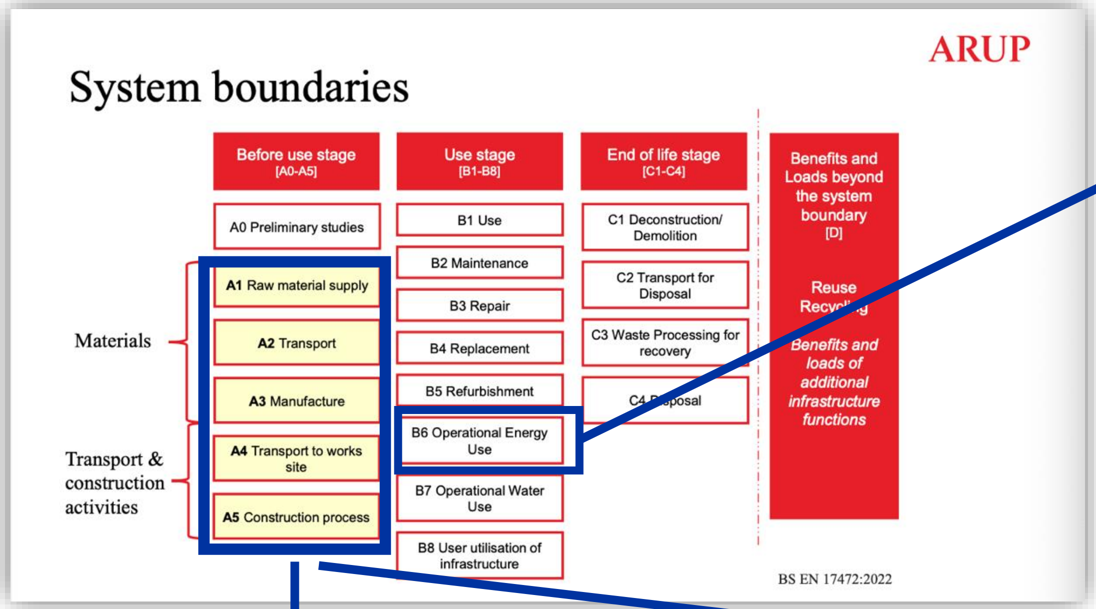
Operation:

- 116 MCHF (see assumptions in box 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)

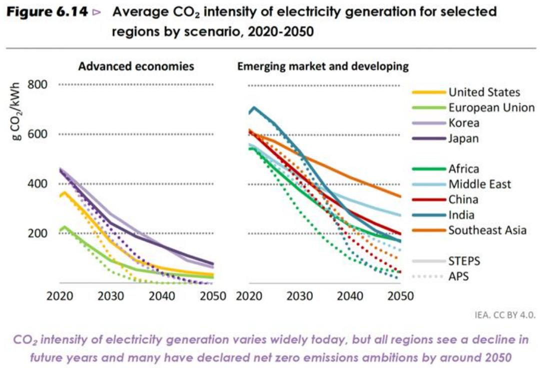
  These replacement/operation costs represent 116 MCHF per year.

Sustainability: Life Cycle Assessment (LCA)



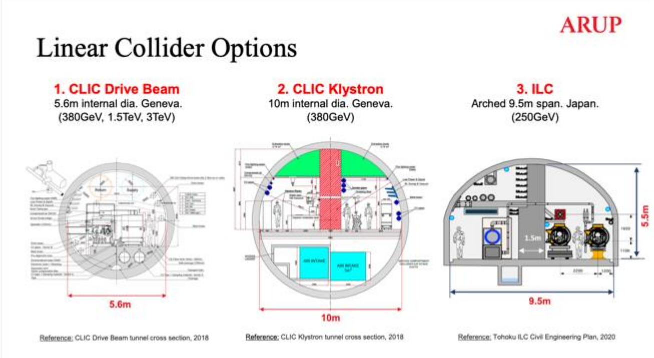
What is the carbon intensity of energy in ~2050 (operation):

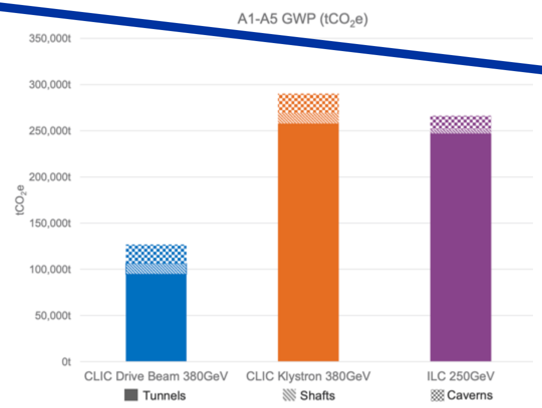
- 50% nuclear and 50% renewable give ~10-15g/kWh
- France summer-months are today ~40g/kWh
- Reductions predicted (LINK)



LCA report for **Civil Engineering**: LINK

Addressing the Civil Engineering impact





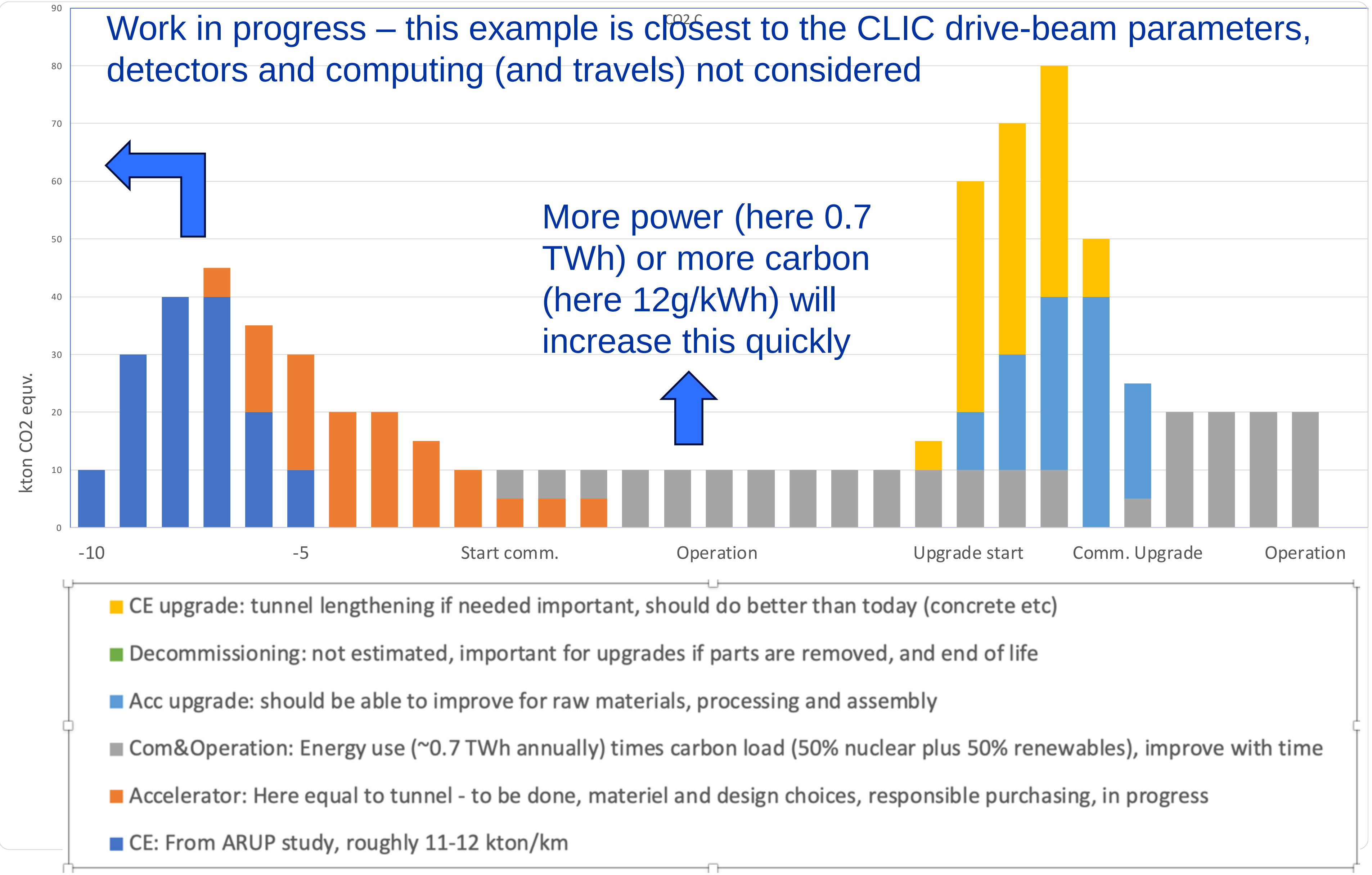
Next working on the machine parts, on top of the CE estimate

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

Towards Carbon Accounting with LCA

This plot (blue part) is for 11 km of tunnel, scales with length (ref. CE study prev. page)

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



Agenda today

CLIC Project Meeting #46

Tuesday 3 Sept 2024, 09:00 → 13:00 Europe/Zurich

6/2-004 (CERN)

Videoconference CLIC Project Meeting #46 — Join — 6/2-004

09:00	→ 09:20	**Introductions, preparing for the ESPP update** **Speaker**: Steinar Stapnes (CERN)	20m
09:30	→ 09:45	**Low and medium power HTS measurements.** **Speaker**: Jessica Golm (CERN)	15m
09:50	→ 10:05	**Studies of two BDSs** **Speaker**: Vera Cilento (CERN)	15m
10:10	→ 10:25	**Electron driven pulsed neutron source** **Speaker**: Laurence Matthew Wroe (CERN)	15m
10:30	→ 10:50	**Coffee Break**	20m
10:50	→ 11:05	**ATF3 studies and results** **Speaker**: Pierre Korysko (University of Oxford (GB))	15m
11:10	→ 11:25	**Condition studies** **Speaker**: Victoria Madeleine Bjelland	15m
11:30	→ 11:45	**Dielectric (DDA) structures** **Speaker**: Pablo Martinez Reviriego	15m
11:55	→ 12:00	**AOB and close**	5m

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