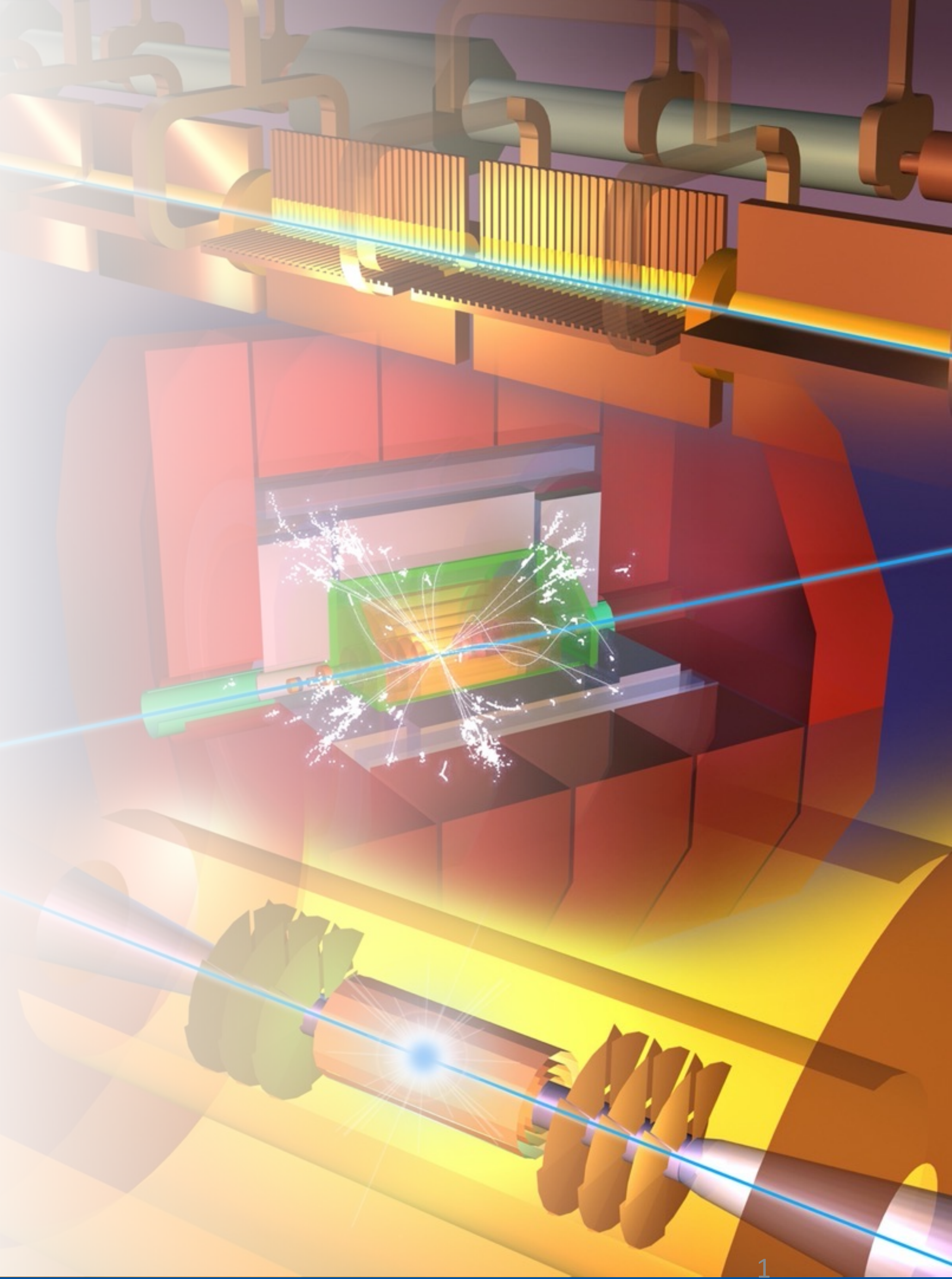
Steinar Stapnes
on behalf of CLIC

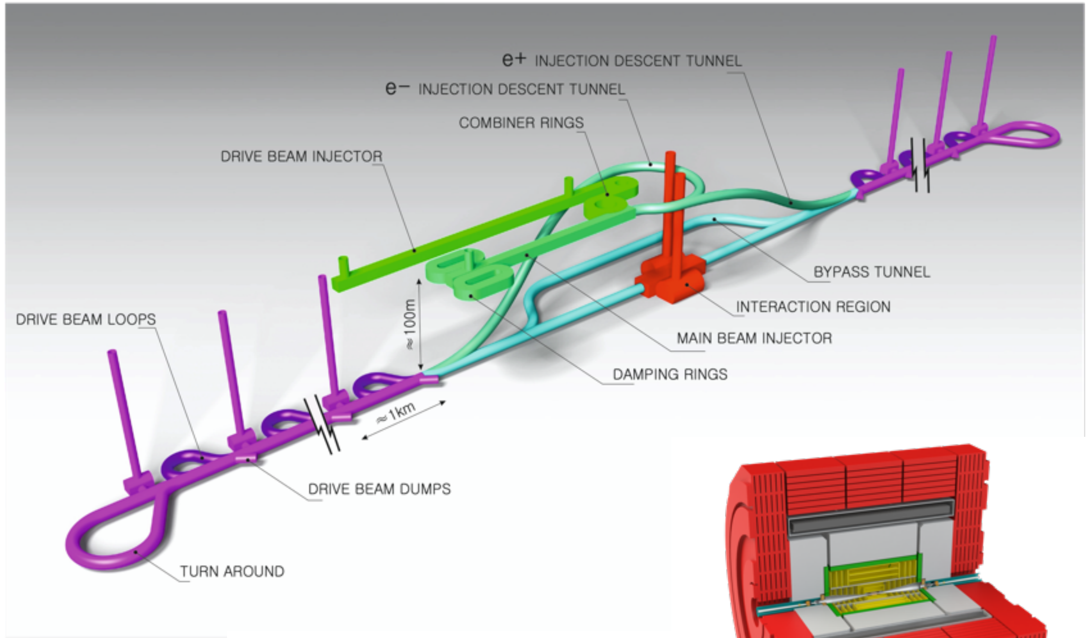
The Compact Linear Collider (CLIC)



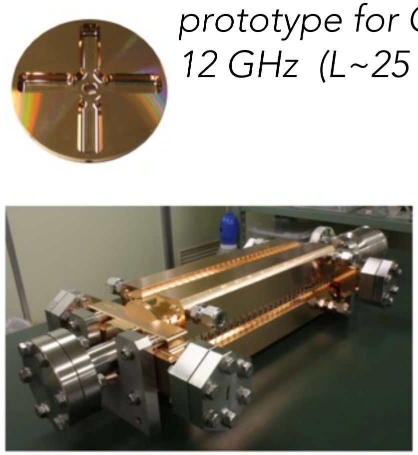
- Most recent status in Snowmass white paper (March 22) : https://arxiv.org/abs/2203.09186
- More details in Project Implementation Report documents for the European Strategy Update 2018-19.

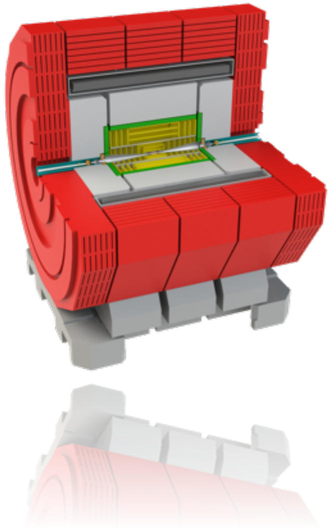
eeFACT2022
September 12th, 2022

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

Collaborations

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

CLIC detector and physics (CLICdp)
- 30 institutes from 18 countries
- Physics prospects & simulations studies
- Detector optimisation + R&D for CLIC

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

*Canada missing on map

CLIC parameters

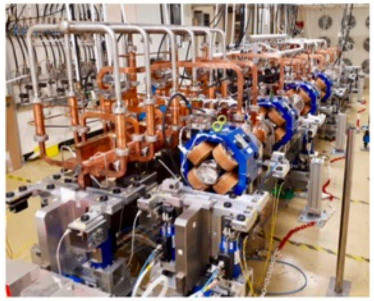
Table 1.1: Key parameters of the CLIC energy stages.

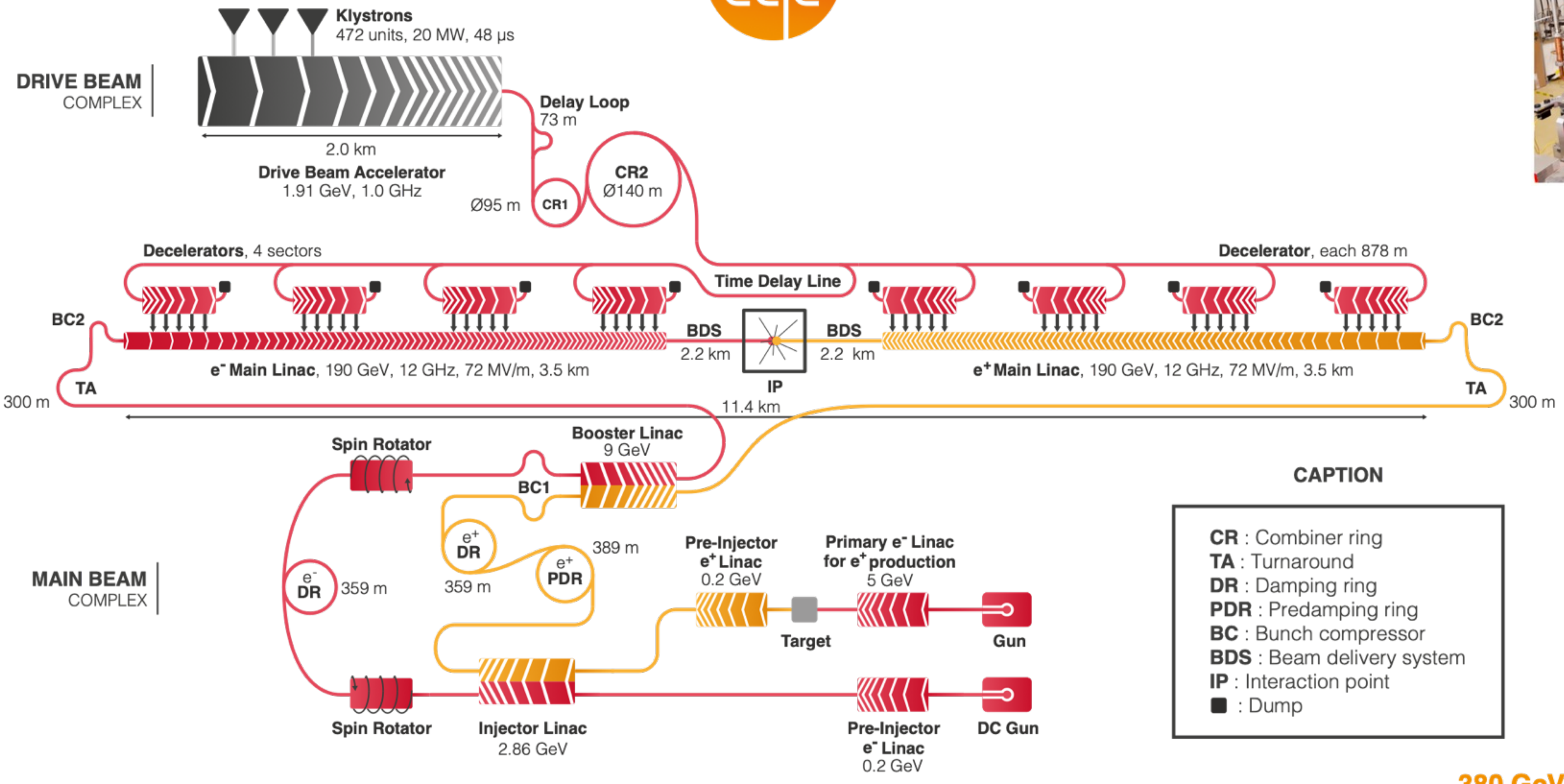
Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$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

Accelerator layout

Snowmass 2021

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

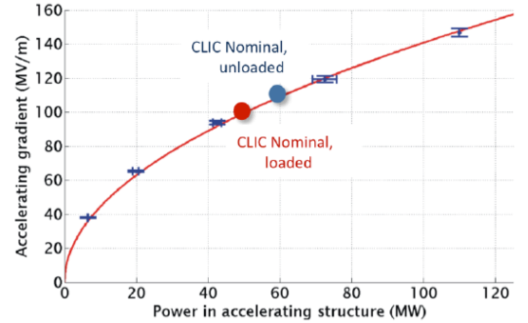




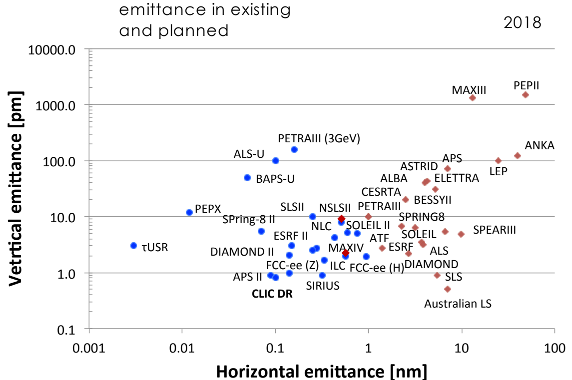
Accelerator challenges/technologies

Snowmass 2021

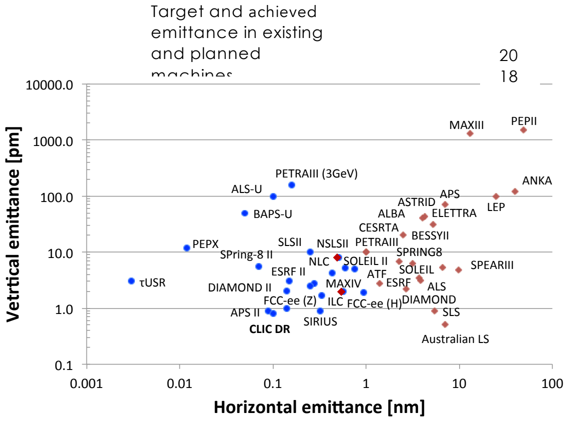
- CLIC baseline – a drive-beam based machine with an initial stage at 380 GeV
- Four main challenges
  1. High-current drive beam bunched at 12 GHz
  2. Power transfer and main-beam acceleration, efficient RF power
  3. Towards 100 MV/m gradient in main-beam X-band cavities
  4. Alignment and stability ("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

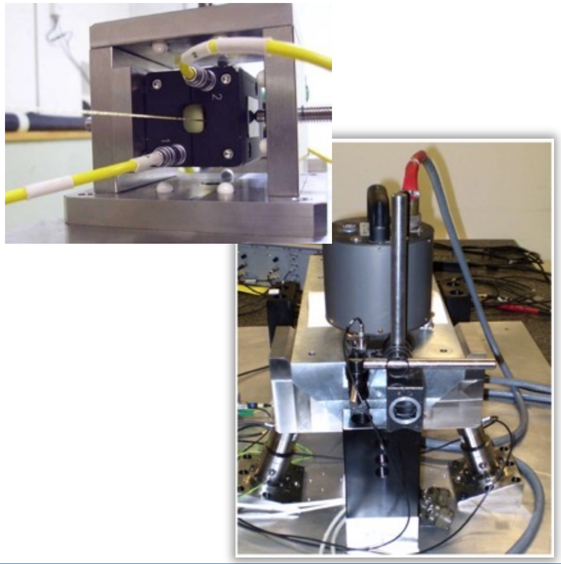


Target and achieved emittance in existing and planned



Low emittance generation and preservation



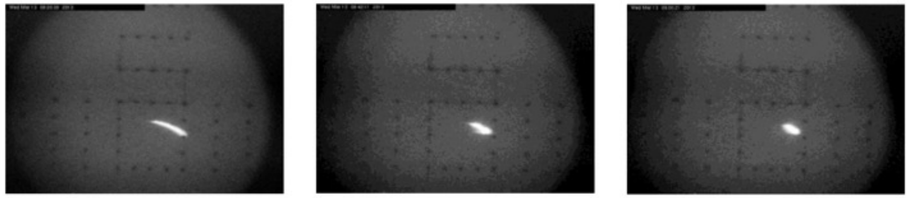


Low emittance damping rings

Preserve by

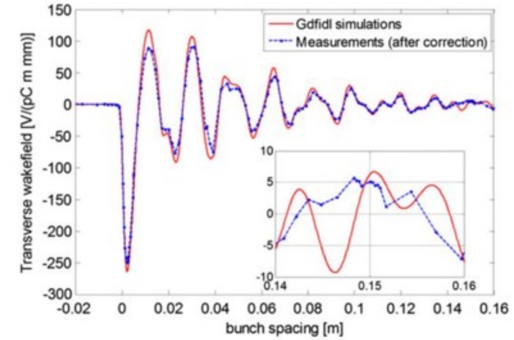
- Align components (10 μm over 200 m)
- Control/damp vibrations (from ground to accelerator)
- Beam based measurements
  – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks

- Experimental tests in existing accelerators of equipment and algorithms
  (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)

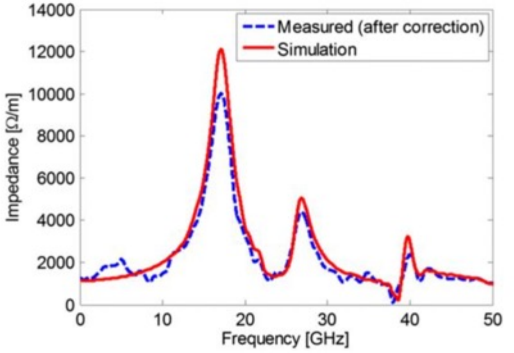


iteration 0 iteration 1 iteration 3

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)



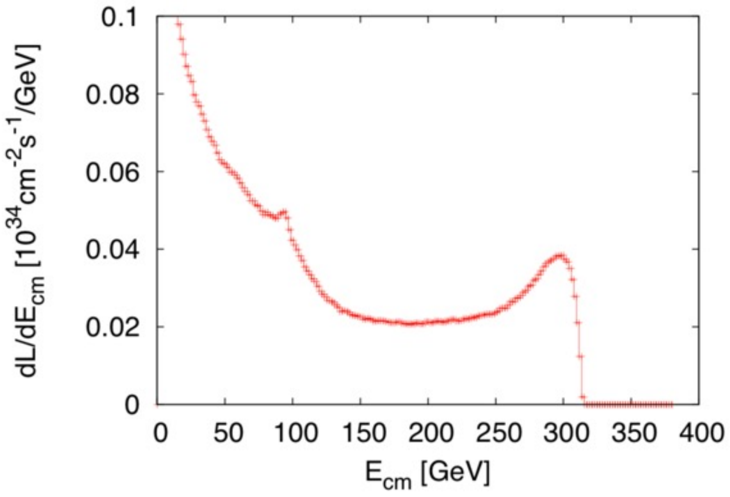
(b)

Wake-field measurements in FACET

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

Luminosities studies 2019-21

- 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)



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

X-band technology

CPI 50MW 1.5us klystron
Scandinova Modulator
Rep Rate 50Hz
Beam test capabilities

Ongoing test:
CPI2 repair validation and interferometry tests

CPI 50MW 1.5us klystron
Scandinova Modulator
Rep Rate 50Hz

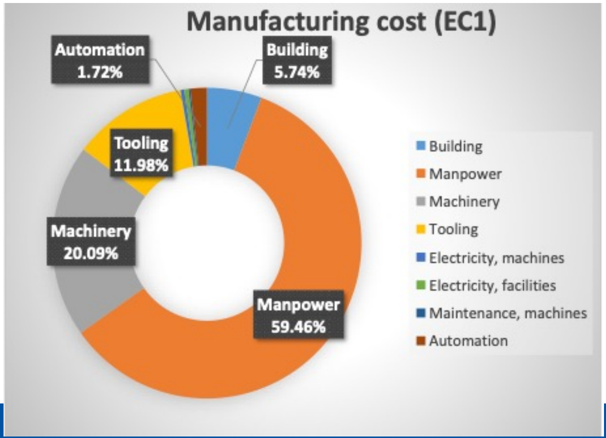
Ongoing test:
CLIC TD26 CLEX SuperStructure

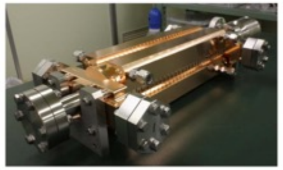
2x Toshiba 6MW 5us klystron
2x Scandinova Modulators
Rep Rate 400Hz

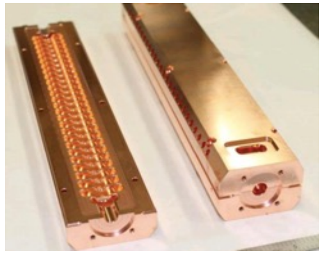
Ongoing test:
SARI X-band deflector
High power window

S-box (3GHz) also being set up again to test KT structure, PROBE and the new injector

Industrial survey 2019-20:
Based on the companies feedback, the preparation phase to the mass production could take about five years. Capacity clearly available.





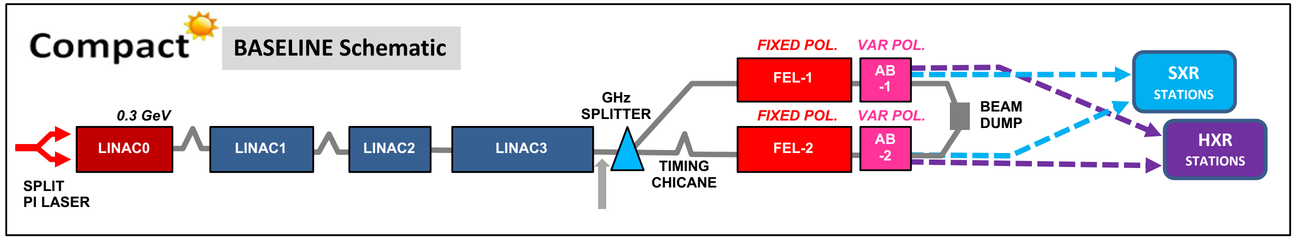


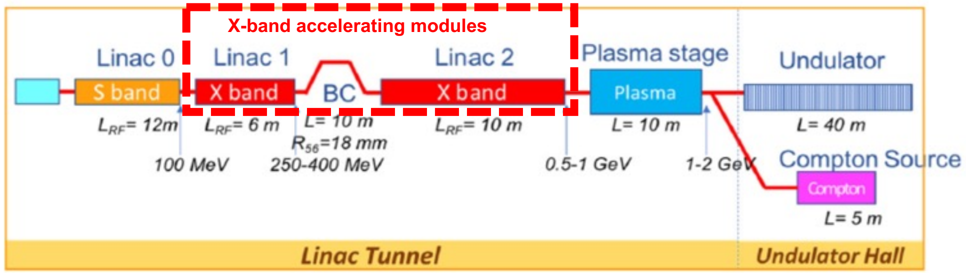
Structures and components production programme to study designs, operation/conditioning, manufacturing, industry qualification/experience

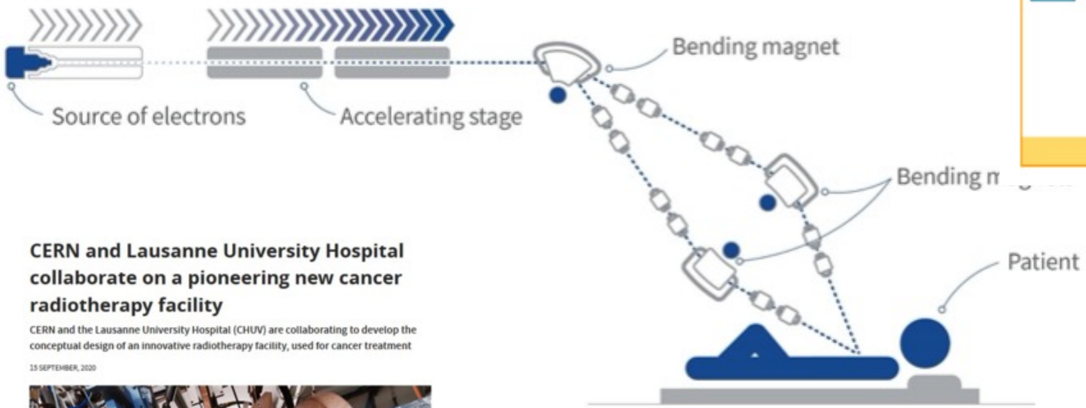
Applications – injector, X-band modules, RF

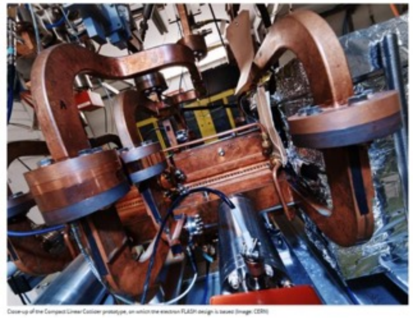
- CompactLight Design Studies 2018-21 (right) (EU design study with 26 partners)
- INFN/LNF ~1 GeV linac
- Flash RT, at CHUV
- “Design Studies” for ICS
- AERES, IFAST and TNA project

Overview at [LINK]()





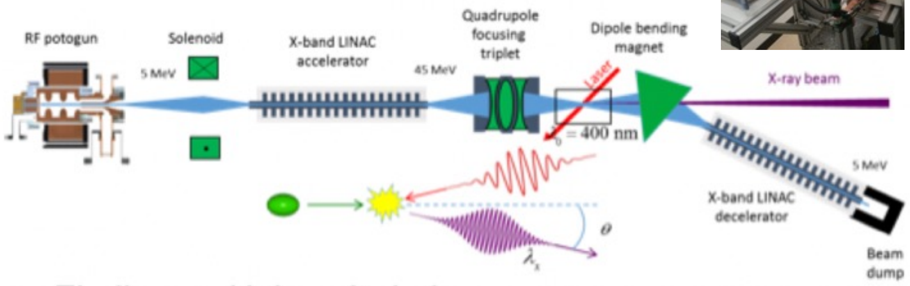


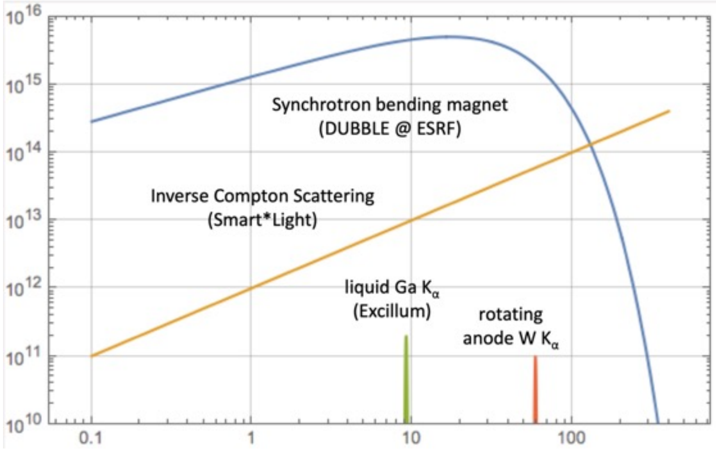


CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment

15 SEPTEMBER, 2020

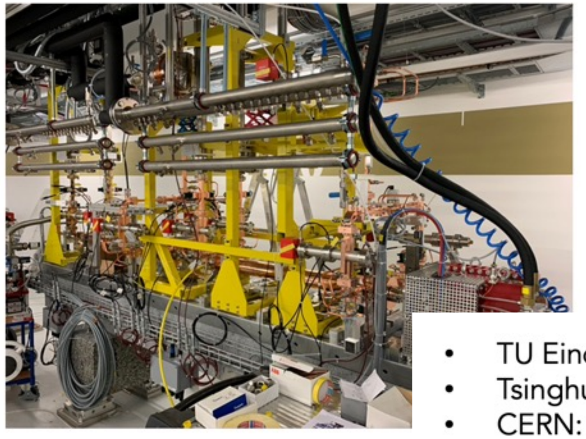




X-band use

Beam facilities: Operational and Commissioning

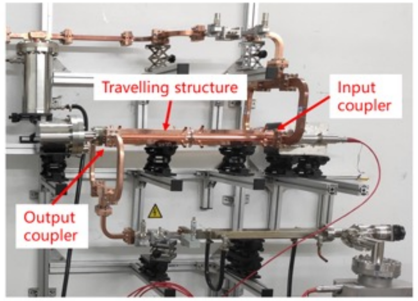
- Trieste, FERMI: Linearizer
- SwissFEL: Linearizer and PolariX deflector
- SARI: Linearizer, deflectors
- CERN: XBox-1 with CLEAR, accelerator
- DESY: FLASHForward and FLASH2, PolariX deflectors
- SLAC: NLCTA, XTA
- Argonne: AWA



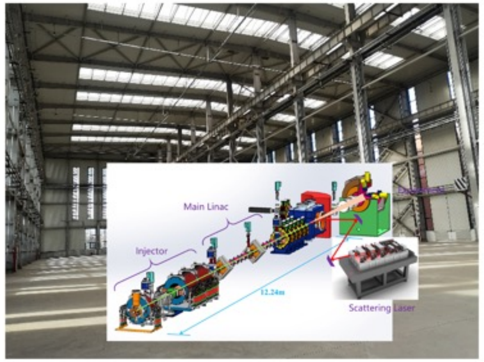
Post-undulator PolariX TDS for ATHOS bean

Beam facilities: Preparation

- 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

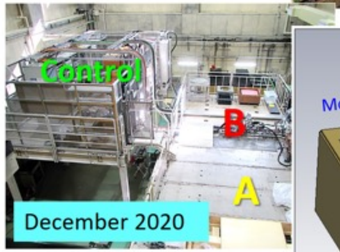


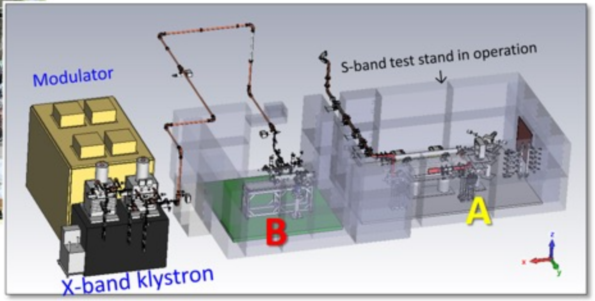
VIGAS



RF facilities: Operational and Commissioning (and construction)

- KEK: NEXTEF
- CERN: XBox-2,3 and SBox
- Tsinghua: TPot
- Valencia: IFIC VBox
- Trieste: FRMI S-Band
- SLAC: Cryo-systems
- LANL: CERF-NM
- INFN Frascati: TEX
- Melbourne: AusBox



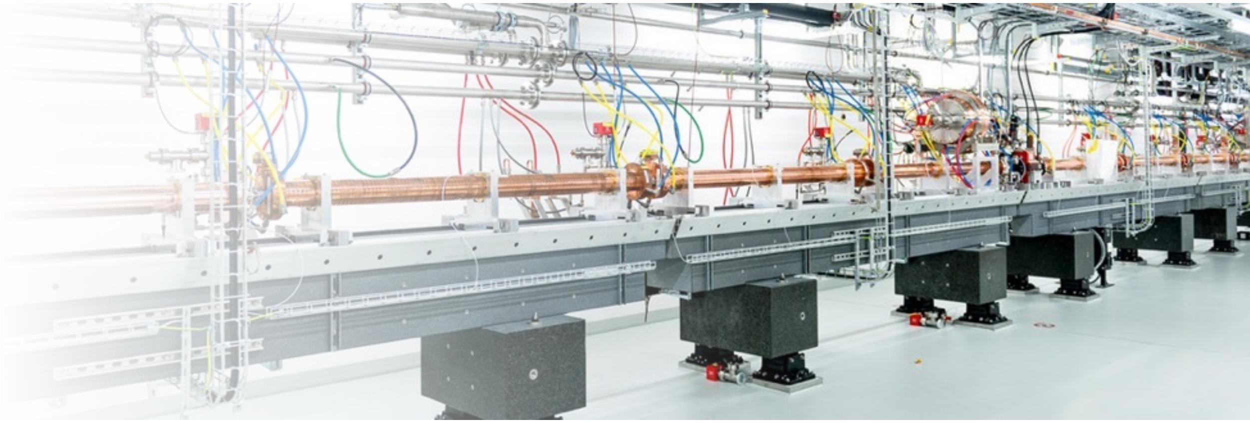


Larger NC linacs (most relevant operational ones are C-band based)

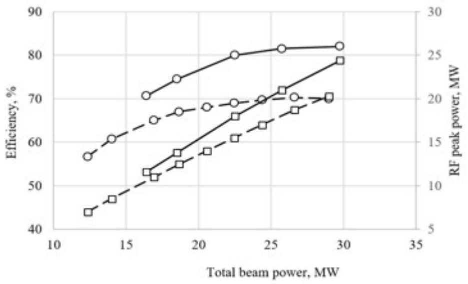
SwissFEL: C-band linac

- 104 x 2 m-long C-band (5.7 GHz) structures (beam up to 6 GeV at 100 Hz)
- Similar μm-level tolerance
- Length ~ 800 CLIC structures
- Being commissioned
- X-band structures from PSI perform well

Photo: SwissFEL/PSI





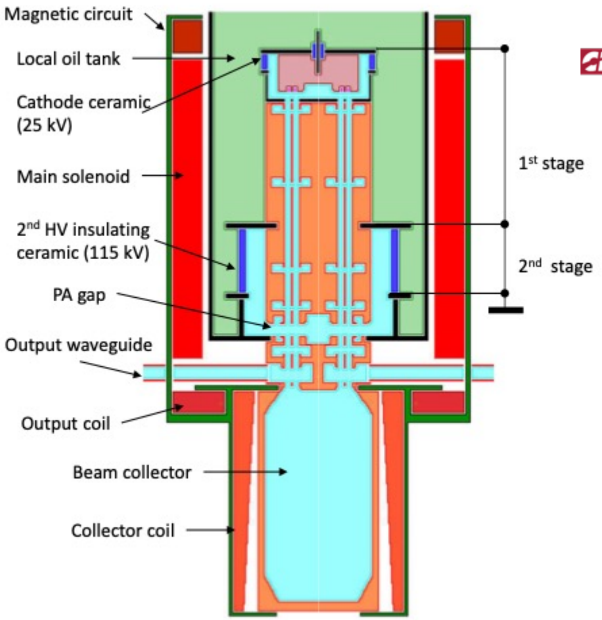


Location: CERN Bldg: 112

High Eff. Klystrons

L-band, X-band (for applications/collaborators and test-stands

Drivebeam klystron: The klystron efficiency (circles) and the peak RF power (squares) simulated for the CLIC TS MBK (solid lines) and measured for the Canon MBK E37503 (dashed lines) vs total beam power. See more later.
Publication: https://ieeexplore.ieee.org/document/9115885



High Efficiency X-band klystrons retrofit upgrades (in collaboration with CPI and Canon).

50 MW	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	58
Efficiency, %	36.2	68 / KlyC
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.35/0.6
RF circuit length, m	**0.32**	**0.32**

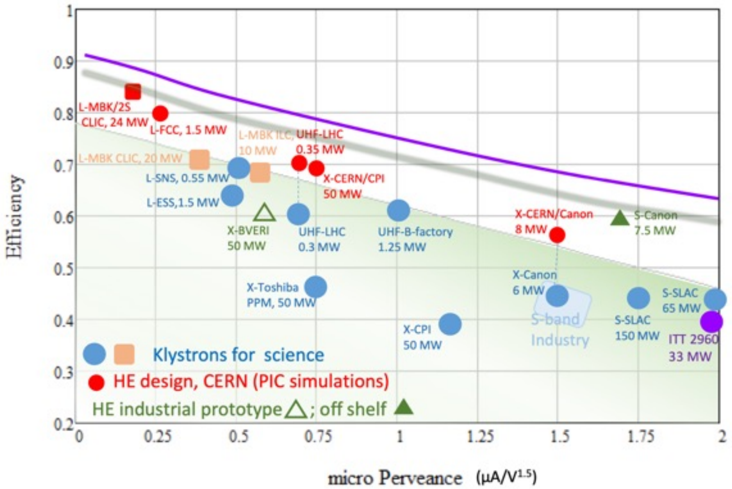
8-10 MW	E37113 at factory	HEX COM_M (CERN/Canon)
Voltage, kV	154	154
Current, A	93	90
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	58
Efficiency, %	42	57/ FCI
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.4
RF circuit length, m	**0.127**	**0.127**

20/1/2021 RF development meeting 15

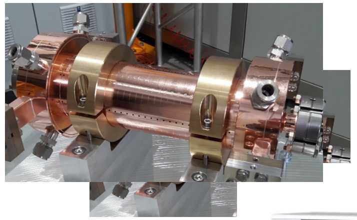
High Efficiency implementations:

- New small X-band klystron – recent successful prototype
- Large X-band with CPI
- L-band two stage, design done, prototype desirable

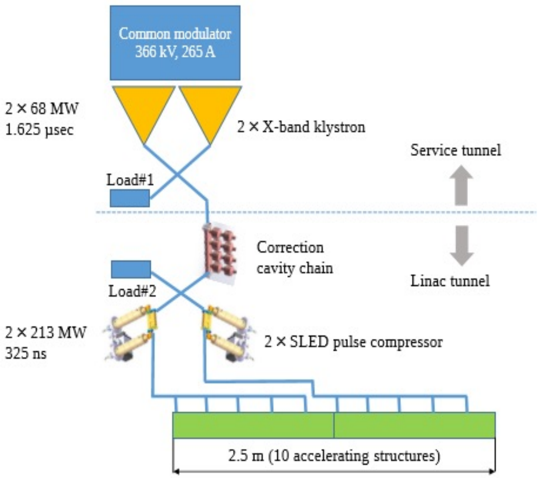
Also important, redesign of damping ring RF system – no klystron development foreseen



CLIC 380 GeV with X-band klystrons

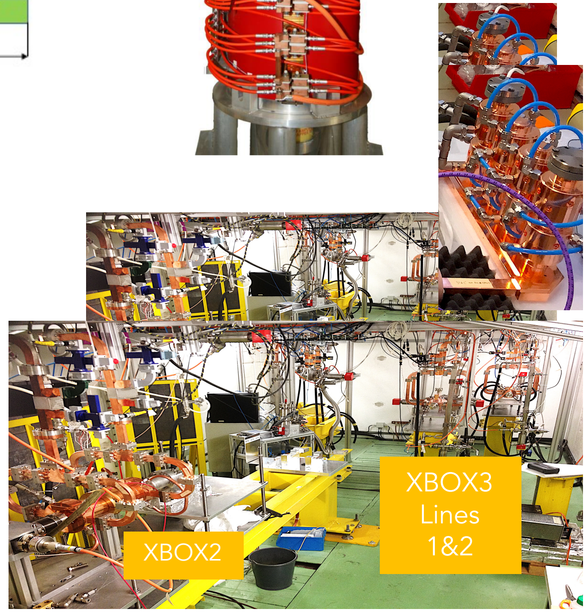


- Design made, many parts prototyped and available (and used in the smaller linacs mentioned on pages 9-10)
- Need larger tunnel for klystron gallery (CE study also made for this option)
- Also in this case the upgrades would require a drivebeam

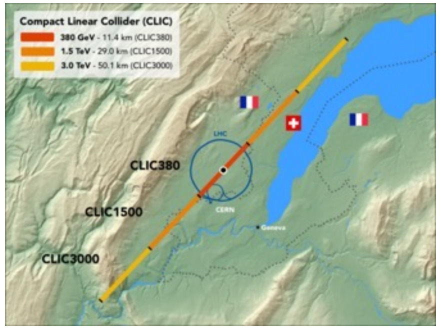


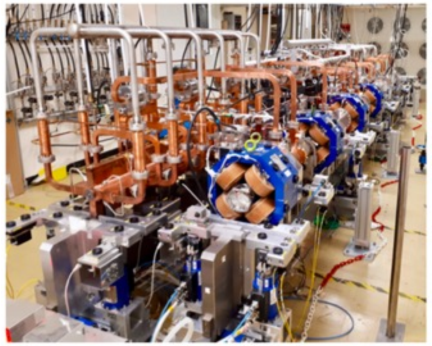
- Challenges: number of klystrons a factor 10 higher than in drive-beam version (~5500), lifetime a concern, costs (RF costs per 2m module approaching 1 MCHF)

- Consider redesign to reduce the klystron challenge



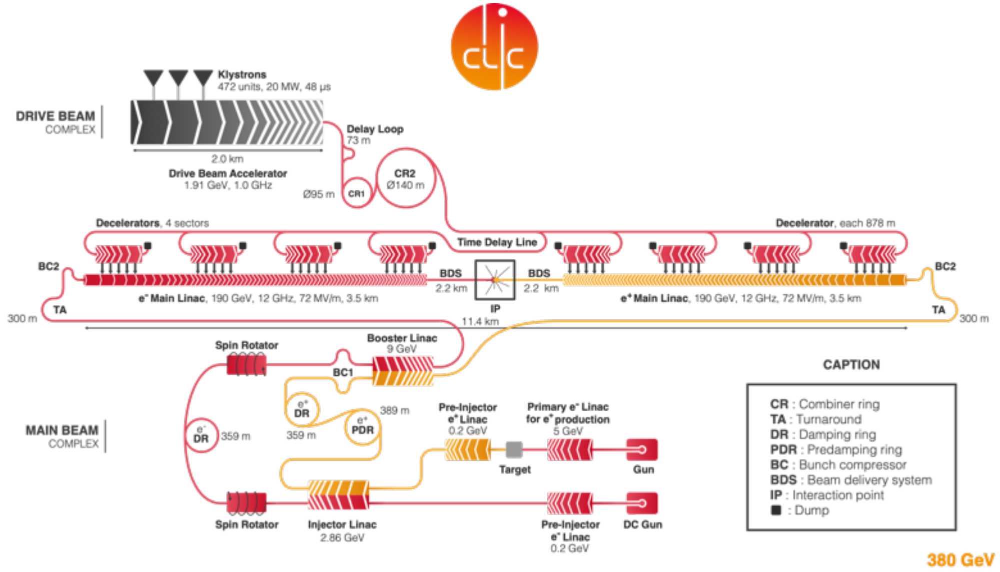
CLIC can easily be extended into the multi-TeV region

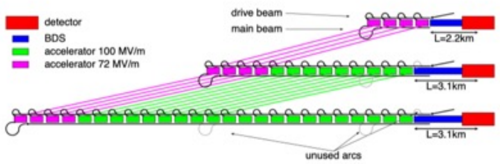




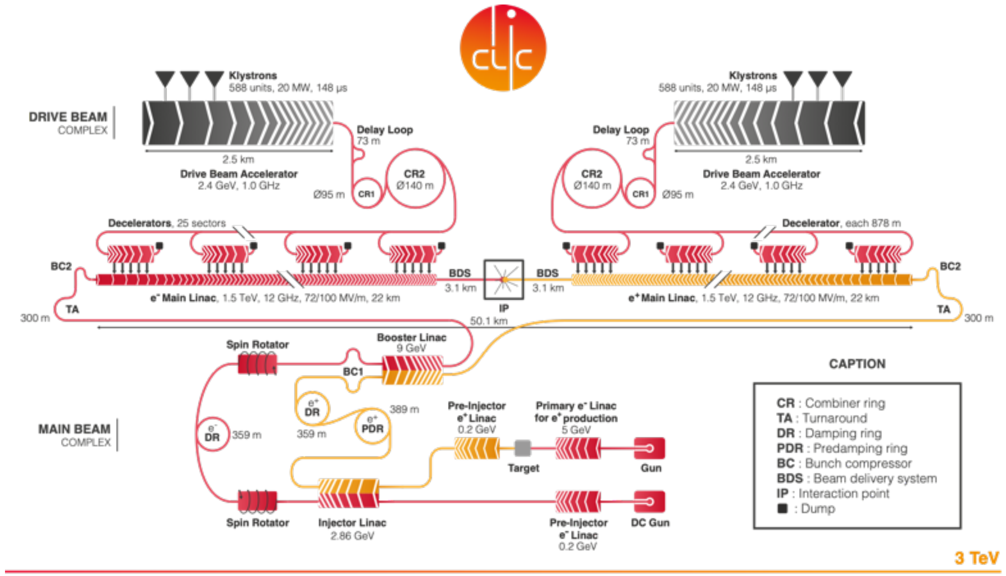
What are the critical elements:
- Physics
- Gradient and power efficiency
- Costs

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 - Scheme of the Compact Linear Collider (CLIC)

Pushing the acc. technology – R&D

CLIC core studies:

Normal conducting accelerating structures are limited in gradient by three main effects (setting aside input power):

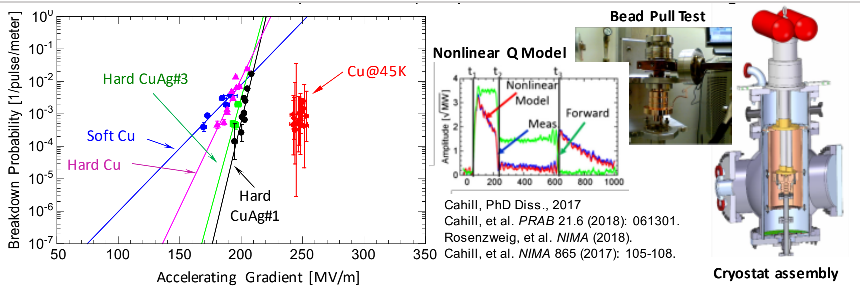
- Field emission
- Vacuum arcing (breakdown)
- Fatigue due to pulsed surface heating

Studying these processes gives important input into:

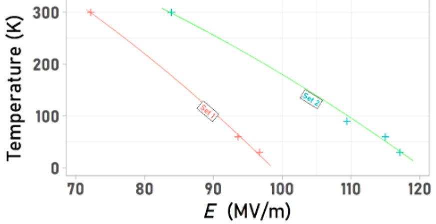
- RF design – Optimizing structures also coupled with beam dynamics
- Technology – Material choice, process optimization
- Operation – Conditioning and recovery from breakdown

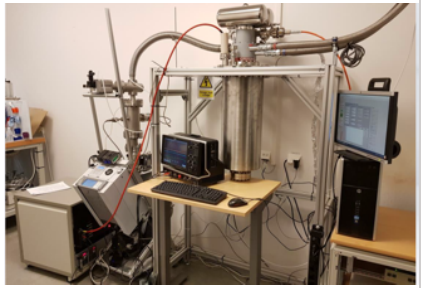
Designs for CLIC steadily improving, but also RFQ, Muon collider, XFEL, ICS, etc
Important experimental support

Multi-TeV energies:
High gradient, high wall-plug to beam efficiency, nanobeam parameters increasingly demanding

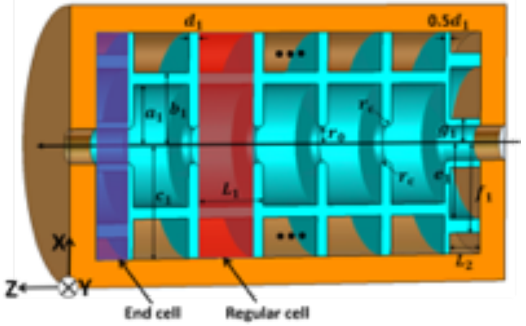


Cryo-cooled copper cavity, SLAC

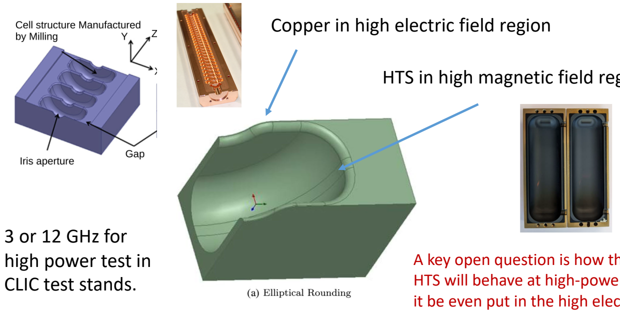




Cryo-cooled copper pulsed dc electrodes, Uppsala/CERN



Implementation



3 or 12 GHz for high power test in CLIC test stands.

A key open question is how the HTS will behave at high-power. Can it be even put in the high electric field region?

Cryogenic systems extended: Combining high-gradients in cryo-copper and high-temperature superconductors for high-efficiency and reduced peak RF power requirements.

Power and Energy

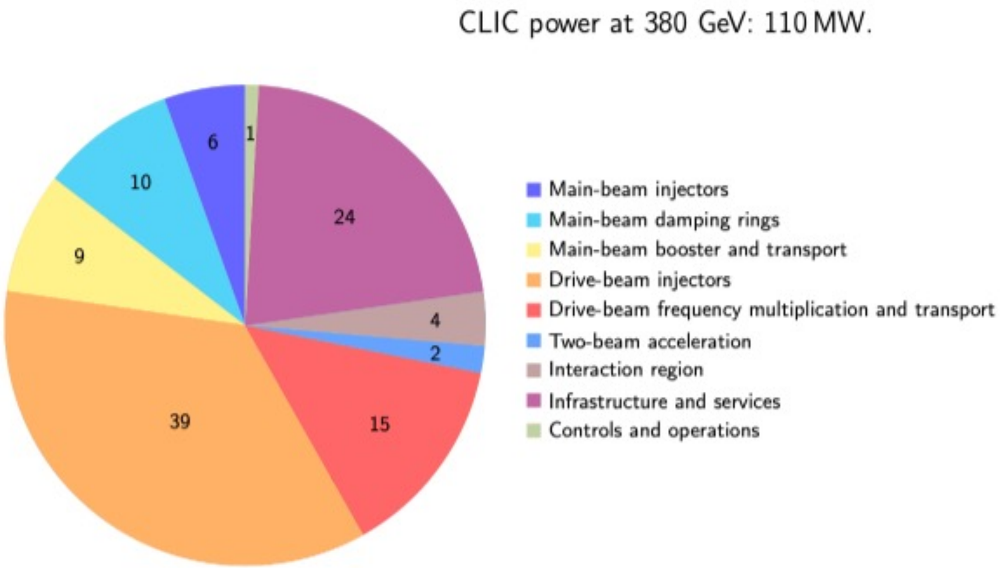


Fig. 4.8: Breakdown of power consumption between different domains of the CLIC accelerator in MW at a centre-of-mass energy of 380 GeV. The contributions add up to a total of 110 MW. (image credit: CLIC)

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)

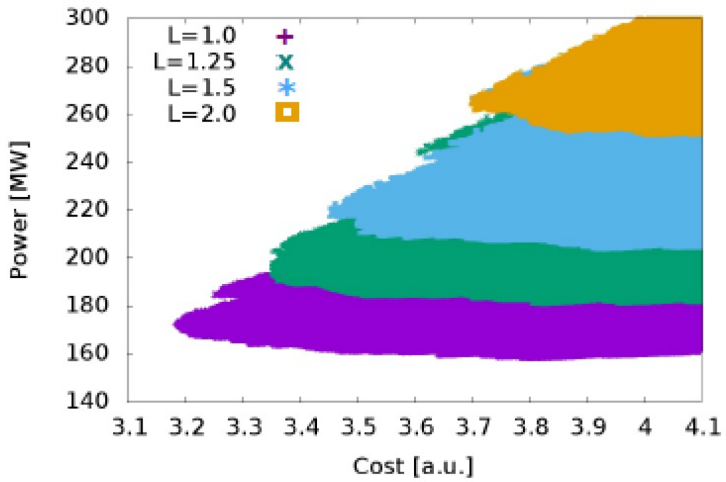
- Very large reductions since the CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimized, main target damping ring RF significantly reduced, recent L-band klystron studies

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

Sustainability and Carbon footprint studies

Snowmass 2021



Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum*

Design Optimisation:
The designs of CLIC, including key performance parameters as accelerating gradients, pulse lengths, bunch-charges and luminosities, have been optimised for cost but also increasingly focussing on reducing power consumption.

Technical Developments:
Technical developments targeting reduced power consumptions at system level high efficiency klystrons, and super conducting and permanents magnets for damping rings and linacs.

Renewable energy (carbon footprint):
Is it possible to fully supply the annual electricity demand of the CLIC-380 by installing local wind and PV generators (study in 2018 for 200 MW collider: this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators, at a cost of slightly more than 10% of the CLIC 380 GeV cost). Can cover fully the power needs 50-60% of a normal running year (studied at 200 MW, more for a 110 MW CLIC)

Running when energy is available and cheap:
CLIC is normal conduction, single pass, can change off-on-off quickly, at low power when not pulsed. Specify state-change (off-standby-on) times and power uses for each – see if clever scheduling using low cost periods when for example renewables are abundant, can reduce the energy bill and make the facility more sustainable.

Other:
Tunnel heat recovery study, full CO2 estimate to be done, future studies joint with ILC

Snowmass 2021

Running on renewables

- It is possible to supply the annual electricity demand of the CLIC-380 by installing local wind and PV generators (this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators, at a cost of slightly more than 10% of the CLIC 380 GeV cost)
  - At the time of the study 200 MW was conservatively used, in reality only ~110 MW are needed
- Self-sufficiency during all times can not be reached and 54% of the time CLIC could run independently from public electricity supply with the portfolio simulated.
- About 1/3 of the generated PV and wind energy will be available to export to the public grid even after adjusting the load schedule of CLIC.
- However, the renewables are most efficient in summer, when prices (until recently) are lower

More information (link)

CLIC: Study on Regenerative Energy Use

- CLIC Study: consider 5 operating modes:
  - Off (shutdown)
  - Standby and intervention – scheduled or unscheduled
  - Low power running (50% lumi)
  - Full operation (note at that time assumed to need 200 MW, now reduced)
- Study assumes target of 130 days of full operation equivalent running
- Considers impact of various running strategies on energy costs

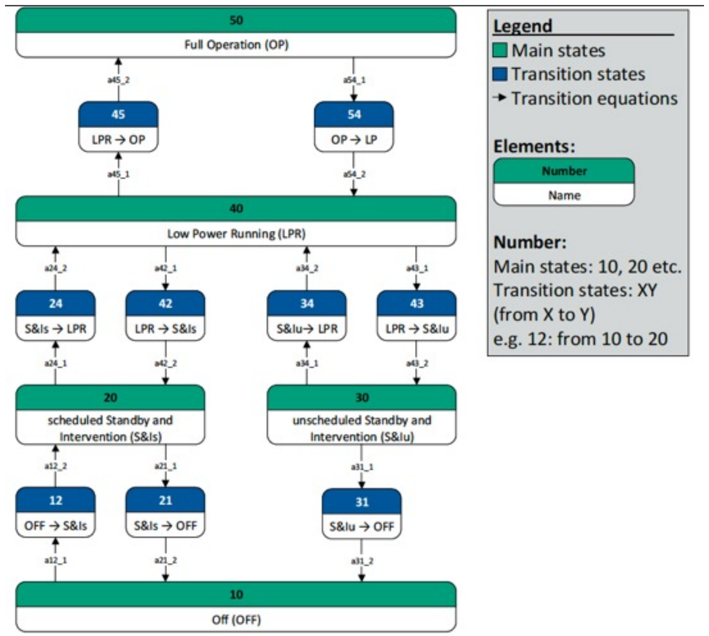


Figure 1-1: Schematic representation of the finite state machine

https://edms.cern.ch/document/2065162/1

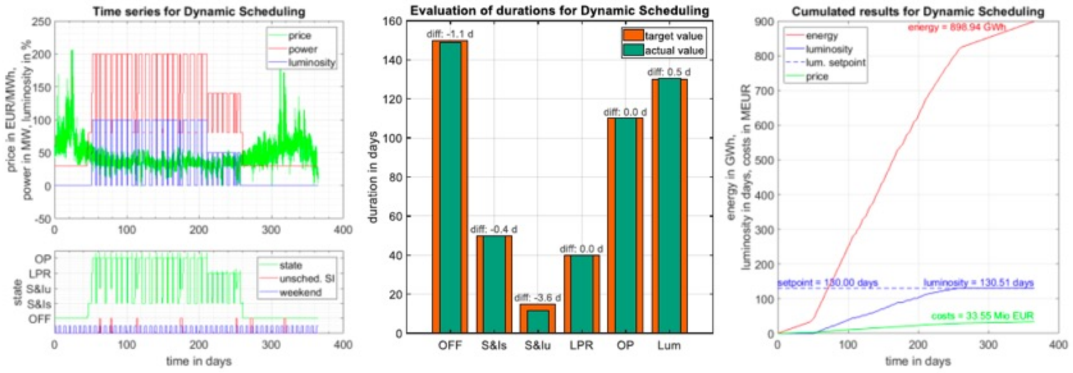
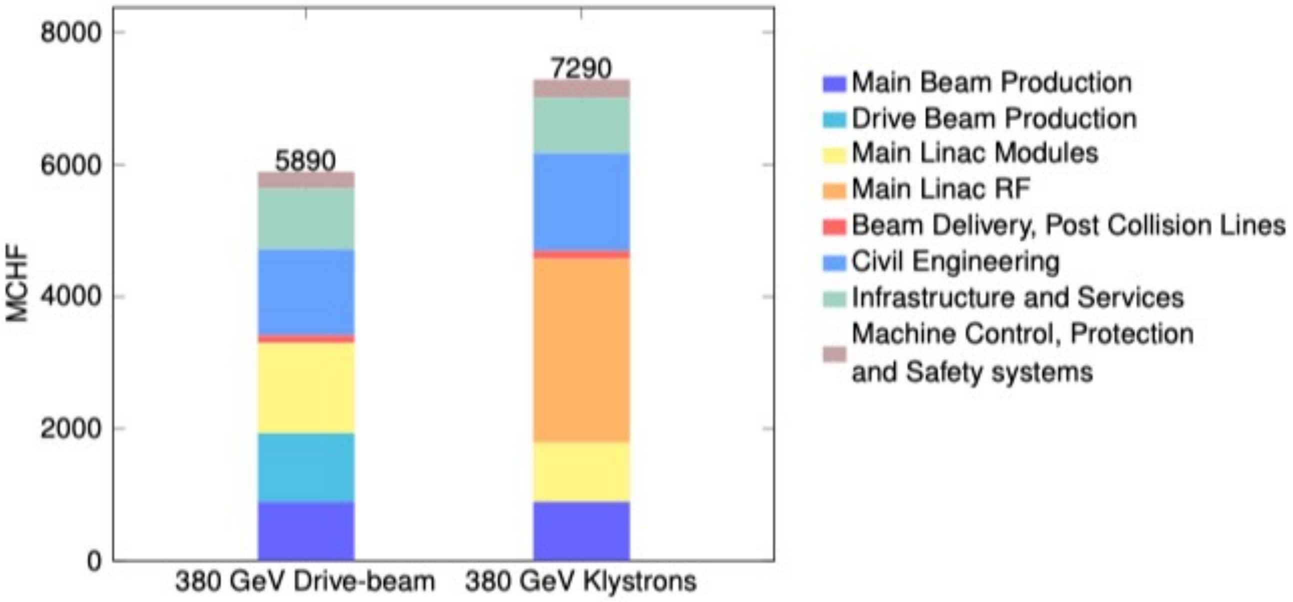


Figure 1-18: Example plots of a simulation run (left: time series, middle: bar graph with durations, right: cumulated times)

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	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**

$$\text{CLIC 380 GeV Drive-Beam based:} \quad 5890^{+1470}_{-1270}\,\text{MCHF};$$

$$\text{CLIC 380 GeV Klystron based:} \quad 7290^{+1800}_{-1540}\,\text{MCHF}.$$

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

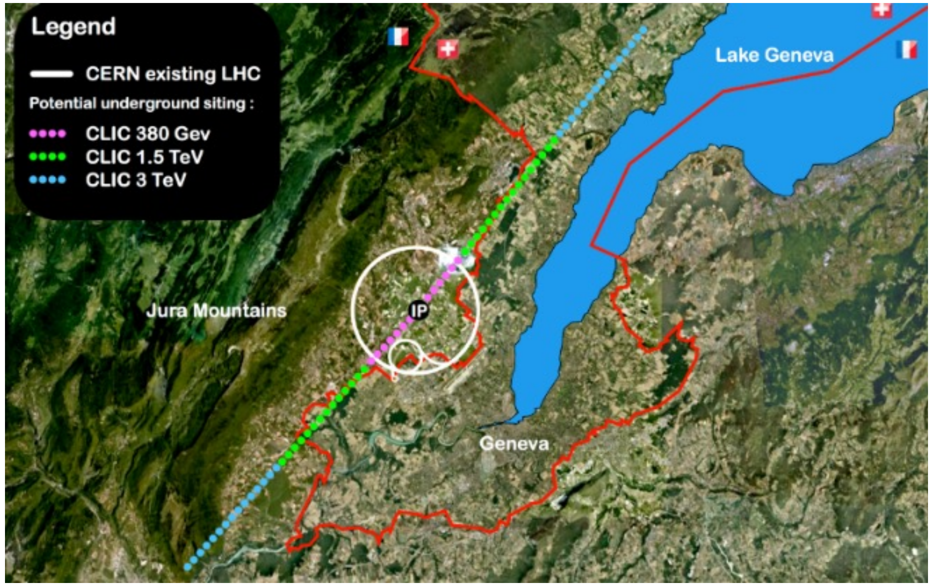
Operation:

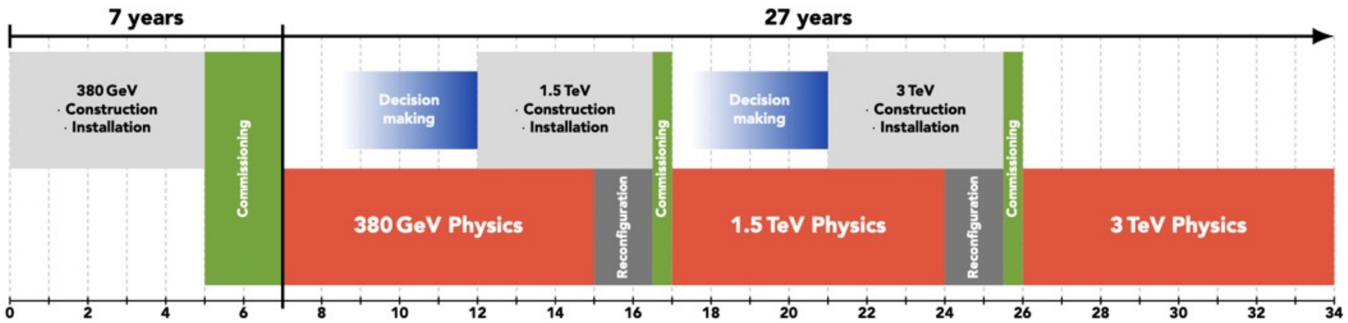
- 116 MCHF (see assumptions in box below)
- Energy costs

– 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.

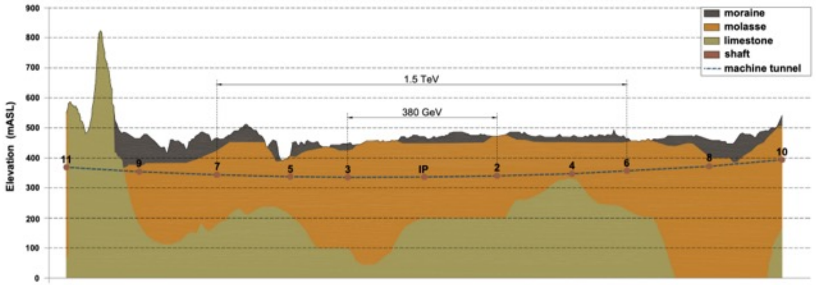
CLIC CE, stages and schedules

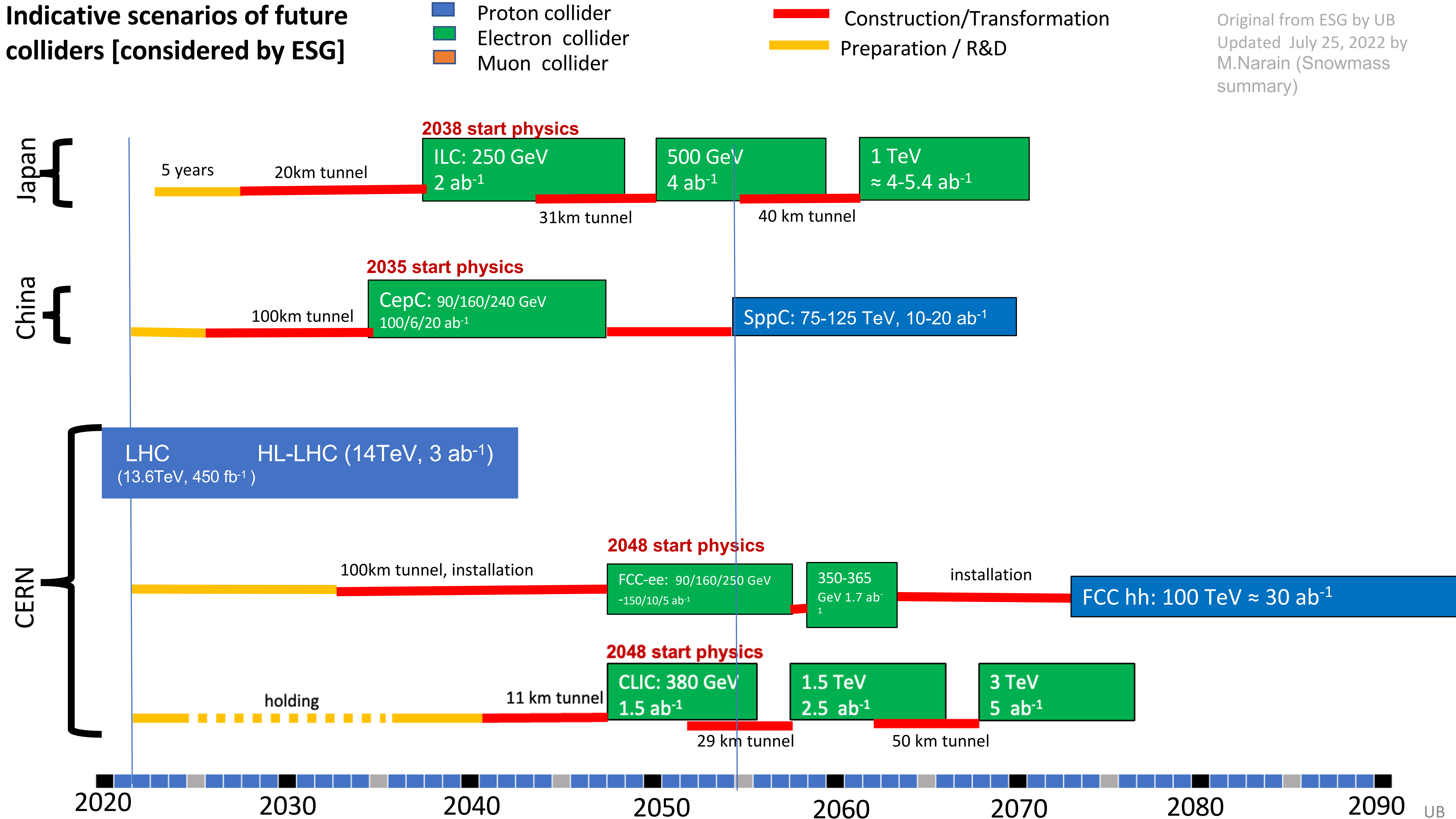




Technology Driven Schedule from start of construction shown above.

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

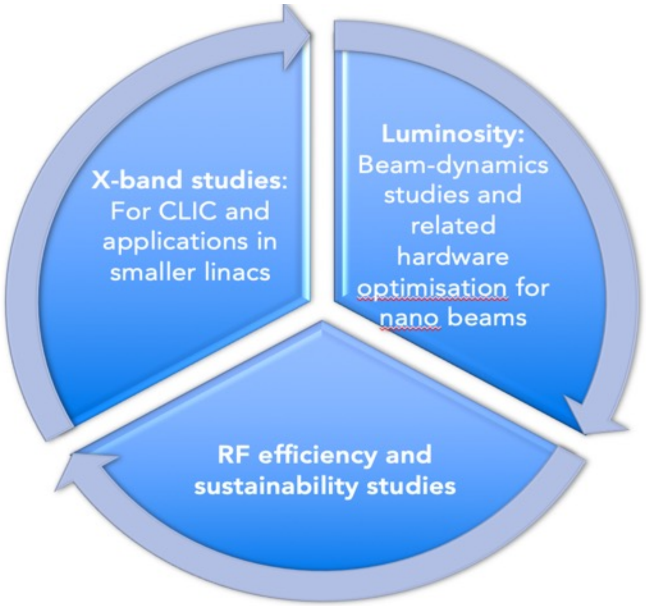




Indicative scenarios of future colliders [considered by ESG]
Proton collider
Electron collider
Muon collider
Construction/Transformation
Preparation / R&D
Original from ESG by UB
Updated July 25, 2022 by M.Narain (Snowmass summary)
Japan
2038 start physics
5 years
20km tunnel
ILC: 250 GeV
2 ab^{-1}
500 GeV
4 ab^{-1}
1 TeV
≈ 4-5.4 ab^{-1}
31km tunnel
40 km tunnel
China
2035 start physics
100km tunnel
CepC: 90/160/240 GeV
100/6/20 ab^{-1}
SppC: 75-125 TeV, 10-20 ab^{-1}
CERN
LHC
(13.6TeV, 450 fb^{-1})
HL-LHC (14TeV, 3 ab^{-1})
2048 start physics
100km tunnel, installation
FCC-ee: 90/160/250 GeV
-150/10/5 ab^{-1}
350-365
GeV 1.7 ab^{-1}
installation
FCC hh: 100 TeV ≈ 30 ab^{-1}
2048 start physics
holding
11 km tunnel
CLIC: 380 GeV
1.5 ab^{-1}
1.5 TeV
2.5 ab^{-1}
3 TeV
5 ab^{-1}
29 km tunnel
50 km tunnel
2020
2030
2040
2050
2060
2070
2080
2090
UB

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 - see earlier slides, 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
- Improving the power efficiency for both the initial phase and at high energies, including more general sustainability studies - see specific slides on this topic above

CLIC Project Readiness 2025-26

Goals for the studies by ~2025, key improvements:

- Luminosity numbers, covering beam-dynamics, nanobeam, and positrons - at all energies. Performance risk reduction, system level studies
  - Substantial progress already documented in Snowmass report and associated references, remains a focus for beamdynamics, nanobeam related technical developments and positron production studies

- Energy/power: 380 GeV well underway, 3 TeV to be done, L-band klystron efficiency
  - In Snowmass report for 380 GeV

- Sustainability issues, more work on running/energy models and carbon footprint
  - Initial studied in Project Implementation Plan (PiP) 2018, just referred to briefly in Snowmass report

- X-band progress – for CLIC, smaller machines, industry availability, including RF network
  - Addressed by establishing improved baseline, CompactLight Design Study very important and many smaller setup. No complete documentation in PiP 2018 or Snowmass report 2022.

- R&D for higher energies, gradient, power, prospects beyond 3 TeV
  - Links also to power, nanobeam and beamdynamics

- Cost update, only discuss changes wrt Project Implementation Plan in 2018
  - Possible impact of sustainability optimization, inflation ?

- Low cost klystron version – reoptimize for power, cost and fewer klystrons

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

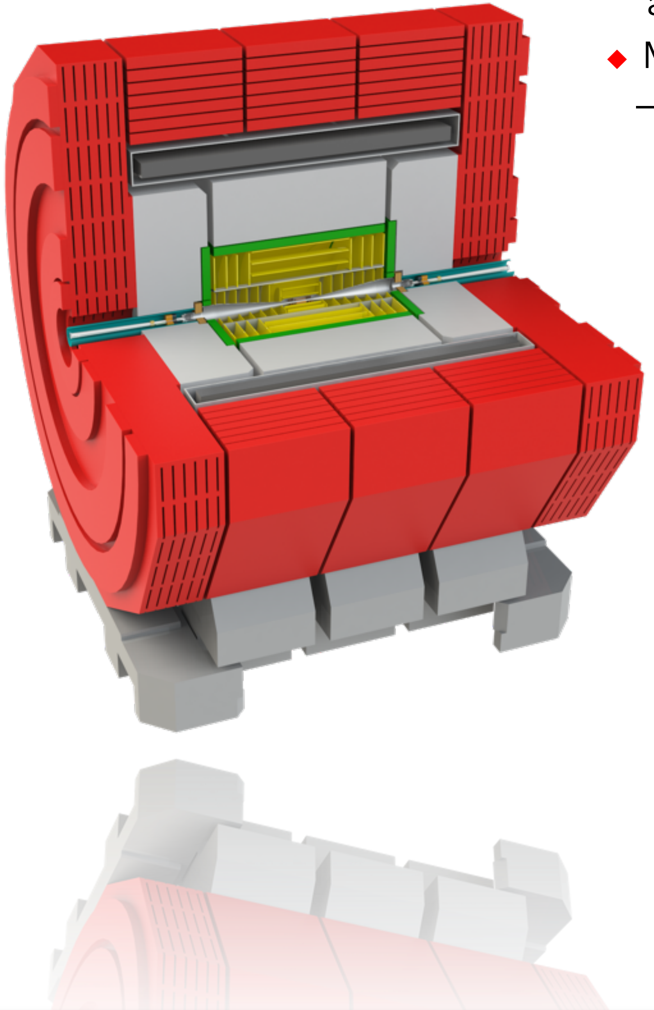
Summary and thanks

- CLIC studies focused on core technologies, X-band and nanobeam, for next ESU, well underway.
- 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
- Detector and physics studies continue at lower pace, also in many areas integrated or connected with ”Higgs-factory” studies, and wider Detector R&D efforts (not covered in this talk)

- Thanks to many CLIC accelerator colleagues for slides and input

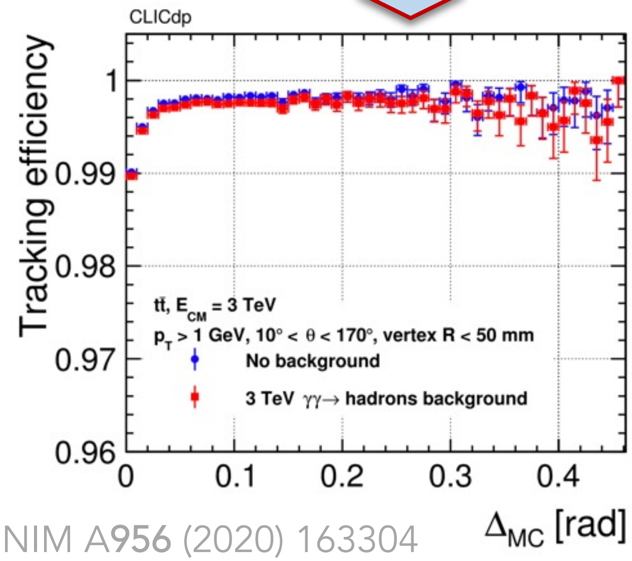
Extra slides

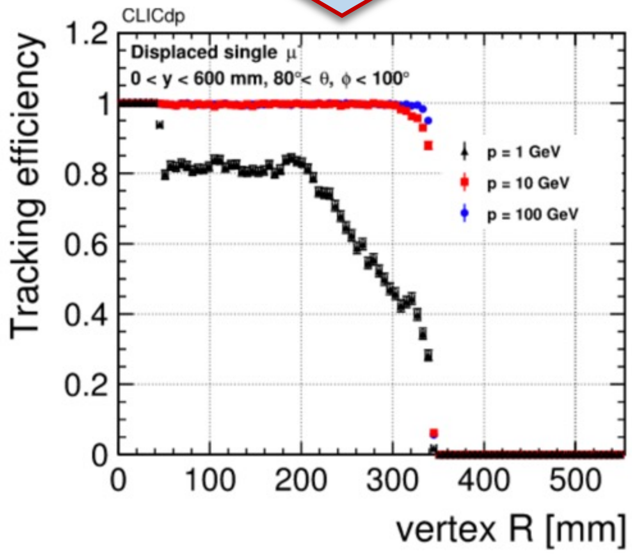
CLIC Detector



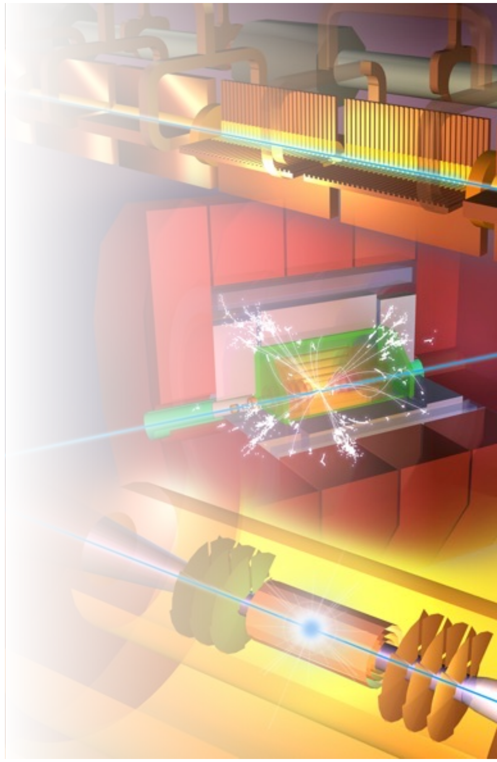
CLICdet:

- High-performing detector optimized for CLIC beam environment
- Full GEANT-based simulation, including beam-induced backgrounds, available for optimization and physics studies
- Mature reconstruction chain allows detailed performance characterisation – e.g. for tracking: effect of busy environment; displaced track reconstruction





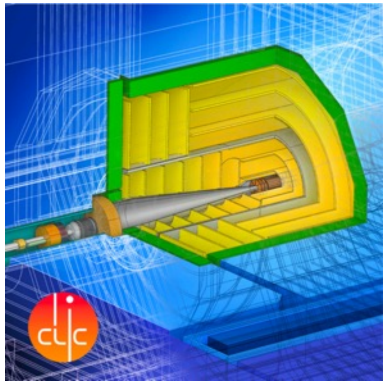
NIM A**956** (2020) 163304



Software framework:

- Originally in iLCSoft, the simulation/reconstruction is now fully embedded in the Key4HEP ecosystem –> a common target for all future collider options – existing reconstruction algorithms "wrappered" for the new framework

Detector R&D for CLICdet



Calorimeter R&D => within CALICE and FCAL

Silicon vertex/tracker R&D:

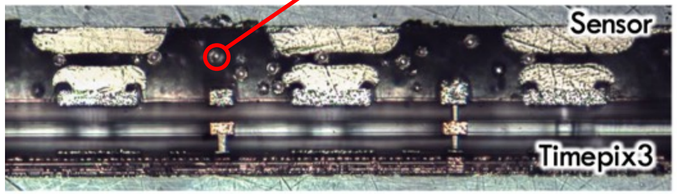
- Working Group within CLICdp and strong collaboration with DESY + AIDAinnova
- Now integrated in the CERN EP detector R&D programme

A few examples:

Hybrid assemblies:

◆ Development of bump bonding process for CLICpix2 hybrid assemblies with 25 µm pitch
https://cds.cern.ch/record/2766510

ACF conductor ball



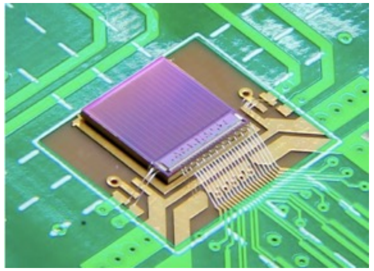
◆ Successful sensor+ASIC bonding using Anisotropic Conductive Film (ACF), e.g. with CLICpix2, Timepix3 ASICs. ACF now also used for module integration with monolithic sensors.
https://agenda.linearcollider.org/event/9211/contributions/49469/

Monolithic sensors:

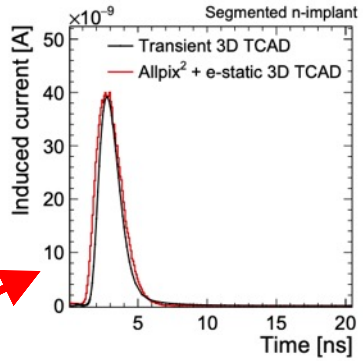
◆ Exploring sub-nanosecond pixel timing with ATTRACT FASTPIX demonstrator in 180 nm monolithic CMOS
https://agenda.linearcollider.org/event/9211/contributions/49445/

◆ Now performing qualification of modified 65 nm CMOS imaging process for further improved performance

CLICTD monolithic tracking sensor:

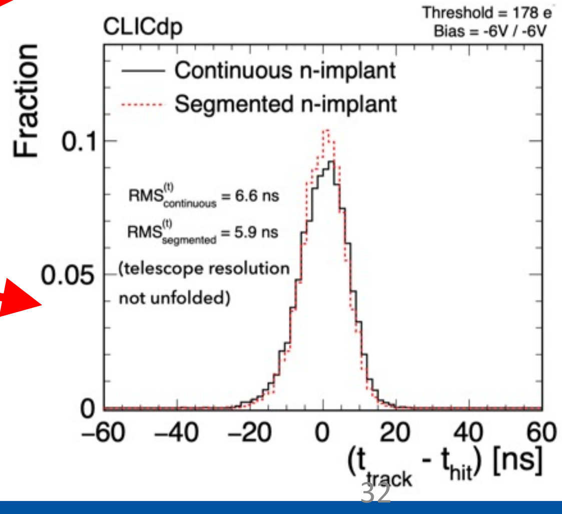


Detailed simulations, Allpix² transient Monte Carlo combined with electrostatic 3D TCAD.



Beam tests at DESY, e.g. 5.8 ns CLICTD time resolution achieved

https://agenda.linearcollider.org/event/9211/contributions/49443/



Physics Potential recent highlights 1:
Initial energy stage

- Ongoing studies on Higgs and top-quark precision physics potential

Higgs coupling sensitivity:

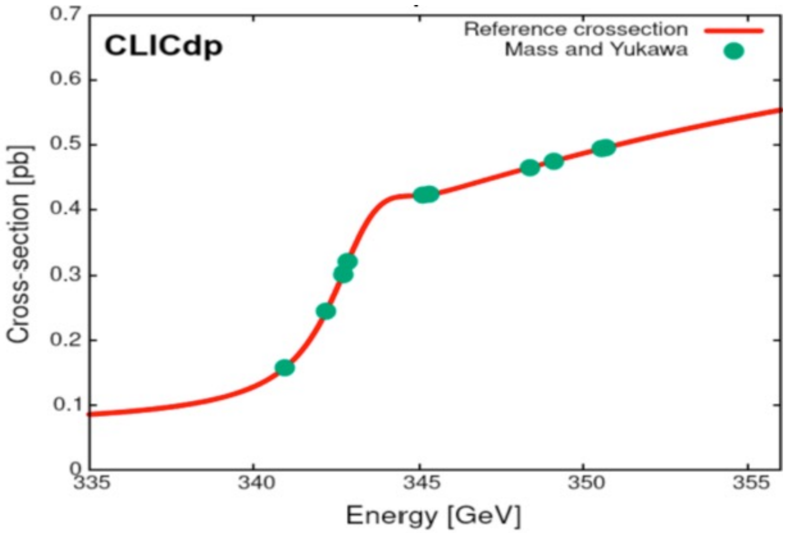
- Sensitivities under different integrated luminosity scenarios to complement accelerator luminosity studies

Increased integrated luminosity at 380 GeV ($4ab^{-1}$)

Baseline: 380 GeV ($1ab^{-1}$) + 1.5 TeV

	Benchmark	HL-LHC	HL-LHC + CLIC 380 ($4\,ab^{-1}$)	380 ($1\,ab^{-1}$) + 1500 ($2.5\,ab^{-1}$)	HL-LHC + FCC-ee 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

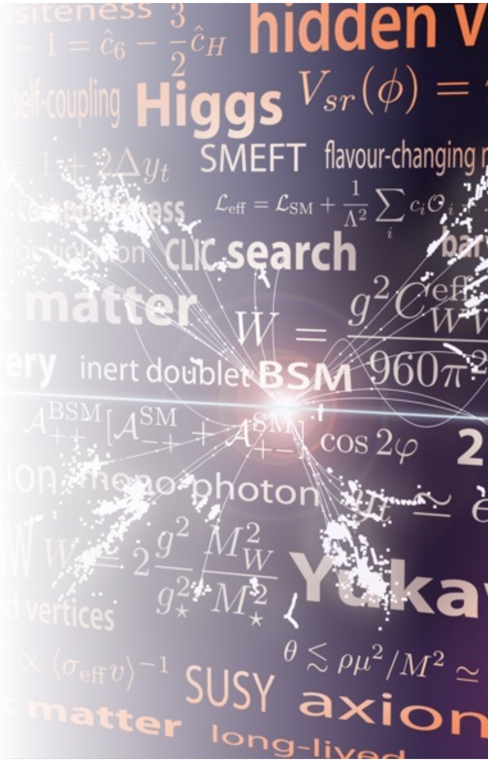
https://arxiv.org/abs/2001.05278
other sensitivities from Briefing Book https://arxiv.org/abs/1910.11775



Top-quark threshold scan

- Optimisation of scan points including beam spectrum; here optimising on mass and Yukawa coupling.
- Expected top-quark mass precision of 25MeV can be improved by 25% without losing precision on width or Yukawa.

https://arxiv.org/abs/2103.00522

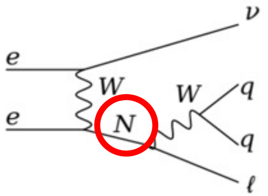


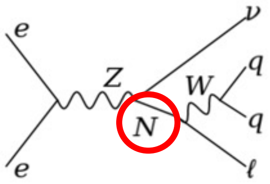
Physics Potential recent highlights 2: Multi-TeV stages

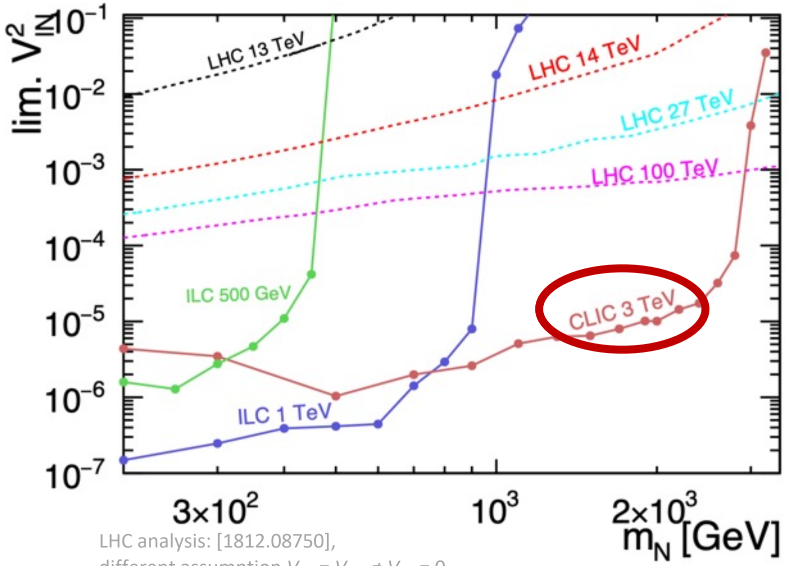
- Ongoing studies on new physics searches

Search for heavy neutrinos

- e+e- -> Nν -> qqlν signature allows full reconstruction of N
- BDT separates signal from SM; beam backgrounds included.
- cross-section limits converted to mass (m_N) coupling (V_{lN}) plane







LHC analysis: [1812.08750], different assumption $V_{eN} = V_{mN} \neq V_{\tau N} = 0$

Dark matter using mono-photon signature at 3TeV, e+e- -> XXγ

- New study using ratio of electron beam polarisations to reduce systematics
- Exclusions for simplified model with mediator Y and DM particle X
- For benchmark mediator of 3.5TeV, photon energy spectrum discriminates different DM mediators & allows 1TeV DM particle mass measurement to ~1% https://arxiv.org/abs/2103.06006