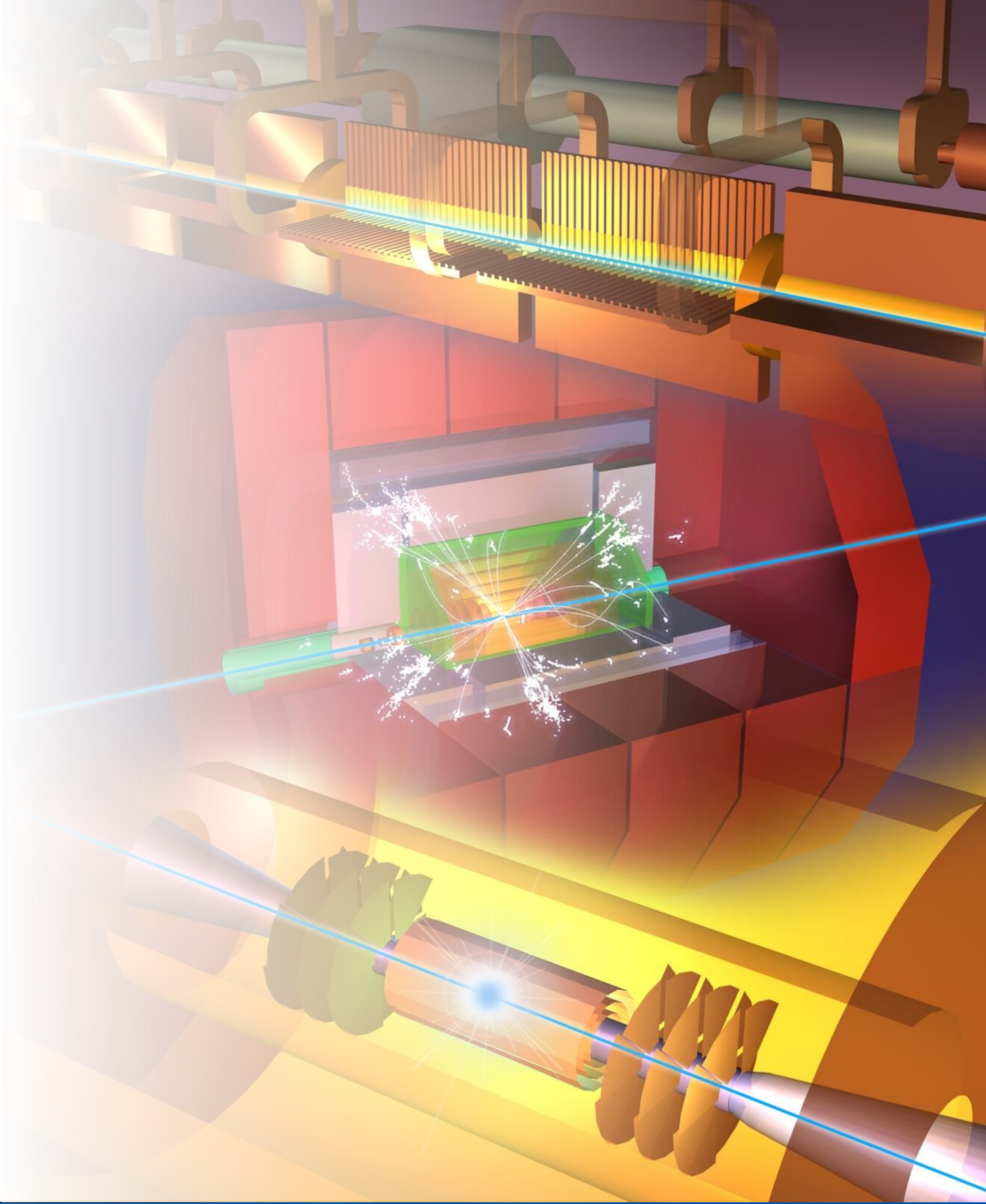
Steinar Stapnes
on behalf of CLIC

The Compact Linear Collider (CLIC)

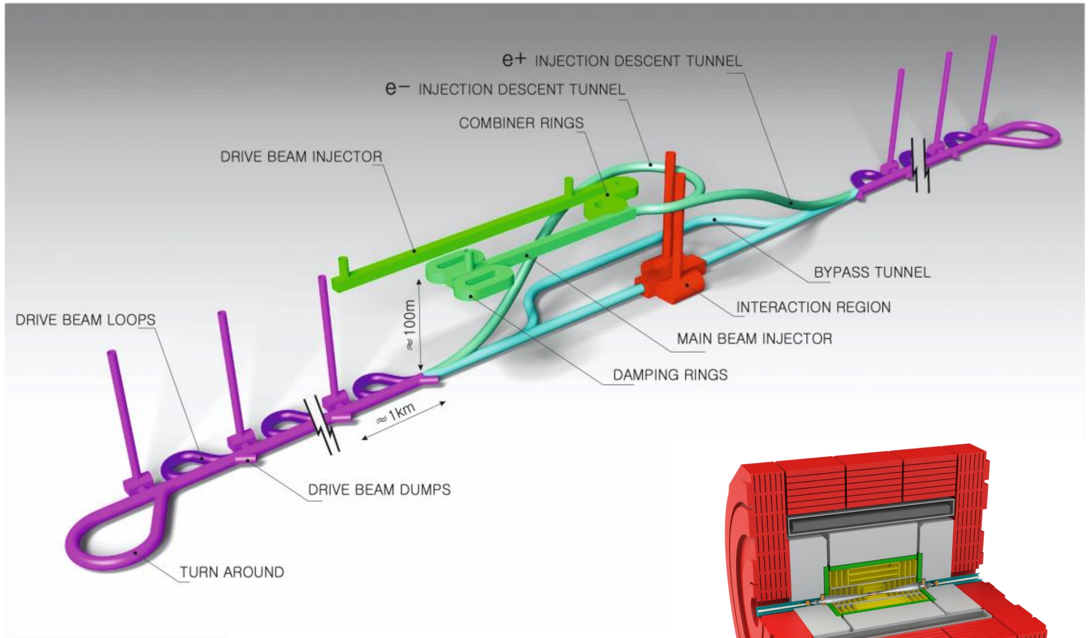


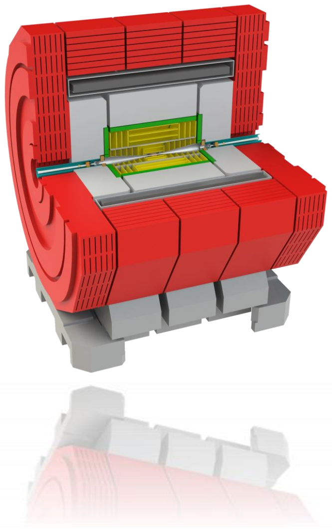
Outline

- A CLIC project overview
- CLIC at 380 GeV
- Multi-TeV studies
- Summary

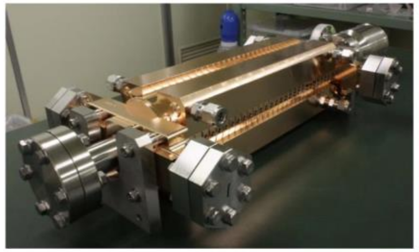
Plenary ECFA
Nov. 19th, 2021

Proposed e⁺e⁻ linear colliders – CLIC





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



The Compact Linear Collider (CLIC)

- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC (~2035 Technical Schedule)
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 cavities 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. Updated project overview documents in 2018 (Project Implementation Plan). See resource slide.

- **Cost:** 5.9 BCHF for 380 GeV (stable wrt 2012)
- **Power:** 168 MW at 380 GeV (reduced wrt 2012), some further reductions possible

- 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

CLIC parameters

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2} s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2} s^{-1}	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{int}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

CLIC is a mature design/study

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” items

Resources

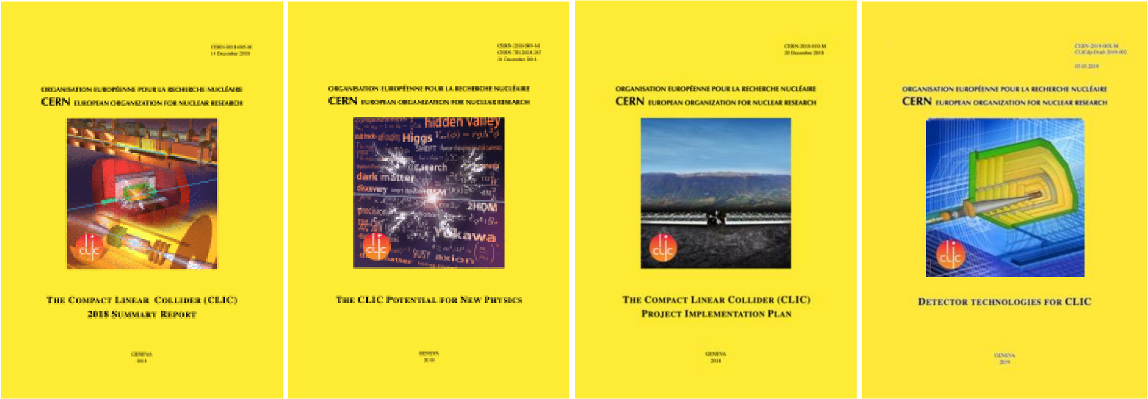
Available at:
clic.cern/european-strategy

3-volume CDR 2012

Updated Staging Baseline 2016

Two formal submissions to the ESPPU 2018

4 CERN Yellow Reports 2018



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

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

Updates since 2019

- After ESU
  - Immediate study of luminosity performance margins, gamma-gamma and Z-pole operation
  - Timeline for further studies changed (slower implementation)

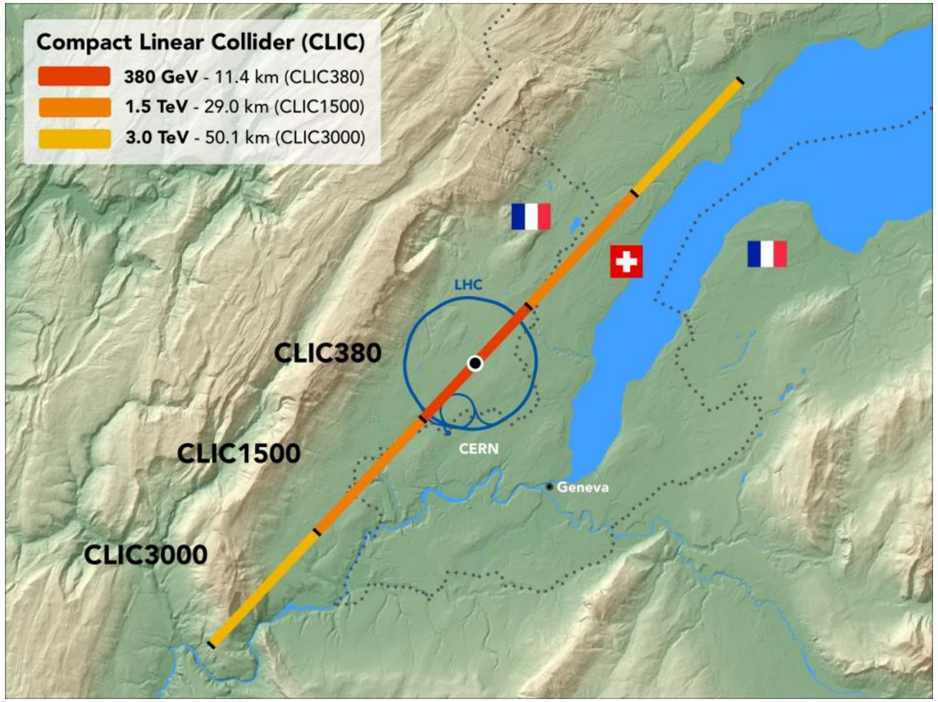
Accelerator

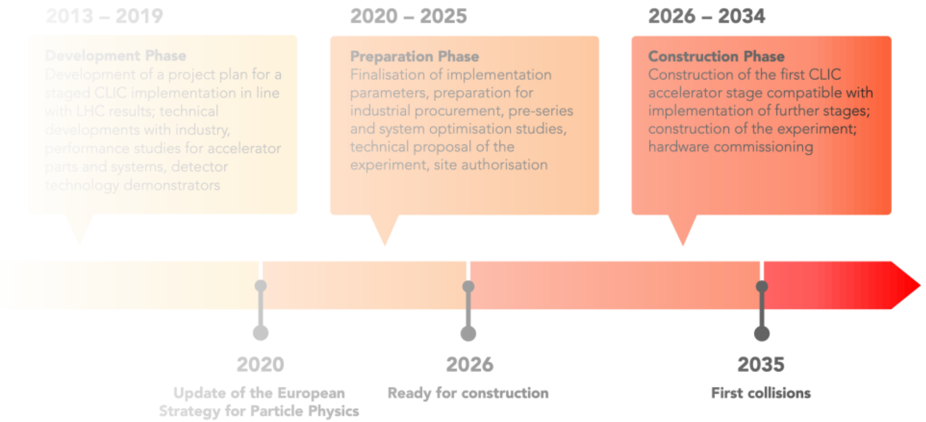
- Resources too limited to move into TDR “proper”
- External projects using X-band technology very important and much increased
- Prioritise R&D type of studies and development of core technologies (will show later)

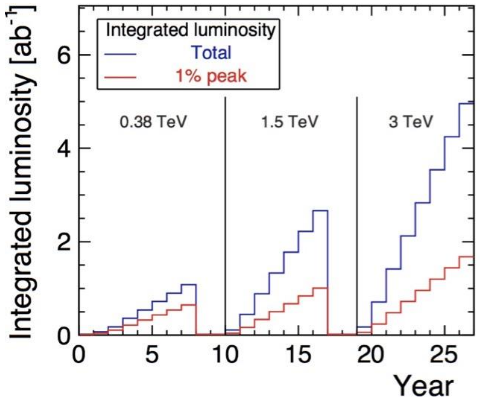
Physics and Detector:

- Less resources for dedicated CLIC studies, more “Higgs-factory” approach (i.e. CLIC, ILC, FCC-ee, CEPC) and continue linking to detector R&D collaborations

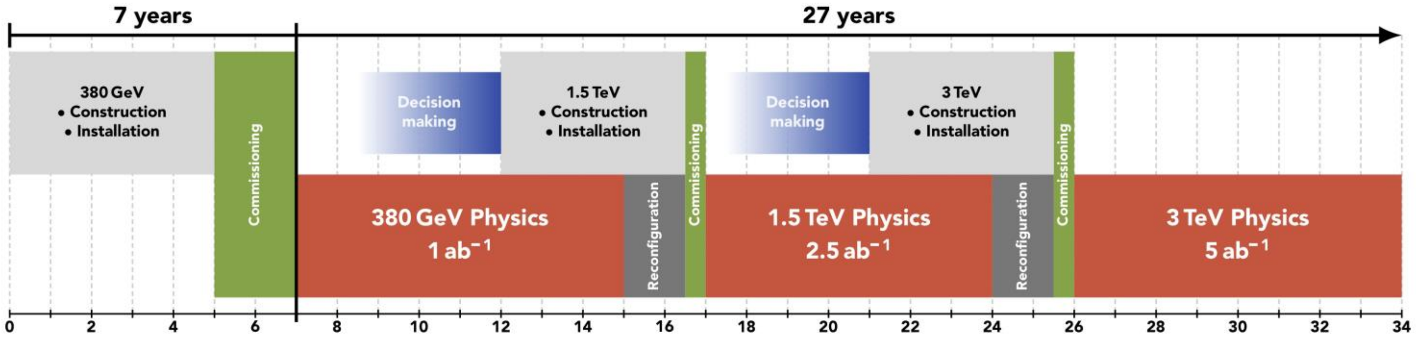
CLIC timeline







Ramp-up and up-time assumptions:
arXiv:1810.13022, Bordry et al.



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)

CLIC Project Readiness Report (PRR)

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.

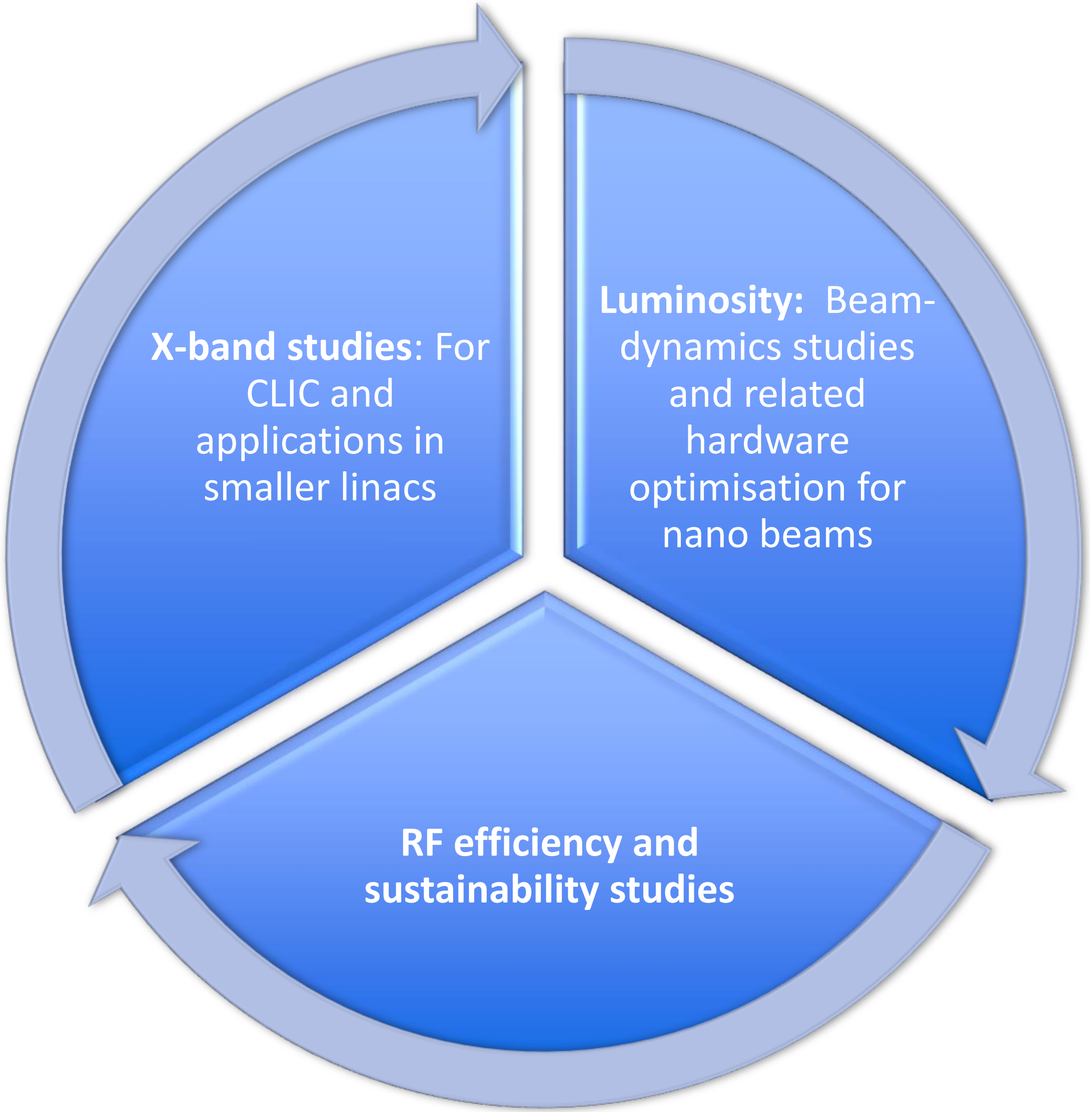
Focusing on:

- The X-band technology readiness for the 380 GeV CLIC initial phase
- Optimizing the luminosity at 380 GeV
- Improving the power efficiency for both the initial phase and at high energies

More details:

- X-band studies: Structure manufacturability and optimized conditioning, interfaces to all connecting systems for large scale production, designs for and support of use in applications, e.g. for FEL linacs, ICS and medical linacs, possible future improvements for power/cost
- Luminosity: beamdynamics studies and related hardware optimisation for nano beams from damping rings to final focus (mechanical and thermal stability, alignment, instrumentation, vacuum systems, stray field control, magnet stability, etc)
- Improving damping ring and drive beam RF efficiency, study parameters and potential hardware changes to reduce power, from 380 GeV to multi-TeV energies with high luminosities

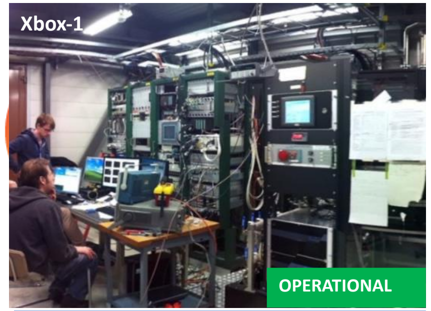
CLIC Project Readiness Report (PRR)



Goals for these studies:

- Improved 380 GeV parameters/performance/project plan
- Push multi-TeV options/parameters

X-band



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

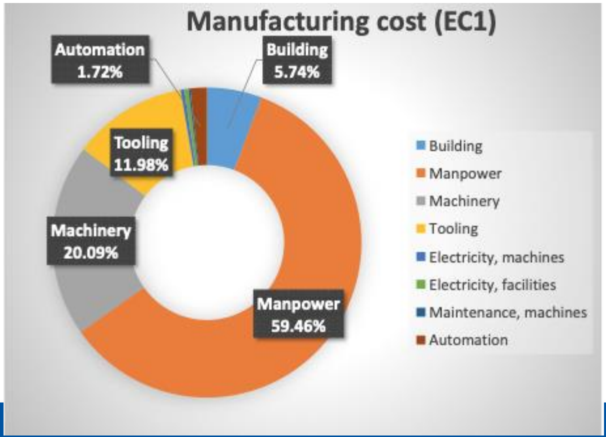
Ongoing test:
CLIC TD26 CLEX SuperStructure

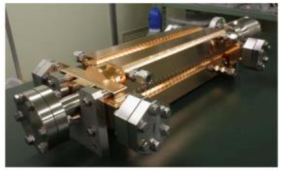
2x Toshiba 6MW 5us klystron
2x Scandinova Modulators
Rep Rate 400Hz

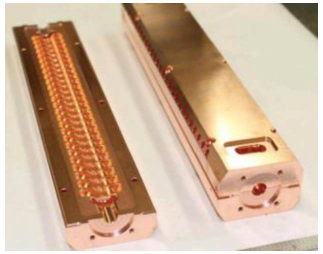
Ongoing test:
SARI X-band deflector
High power window

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

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







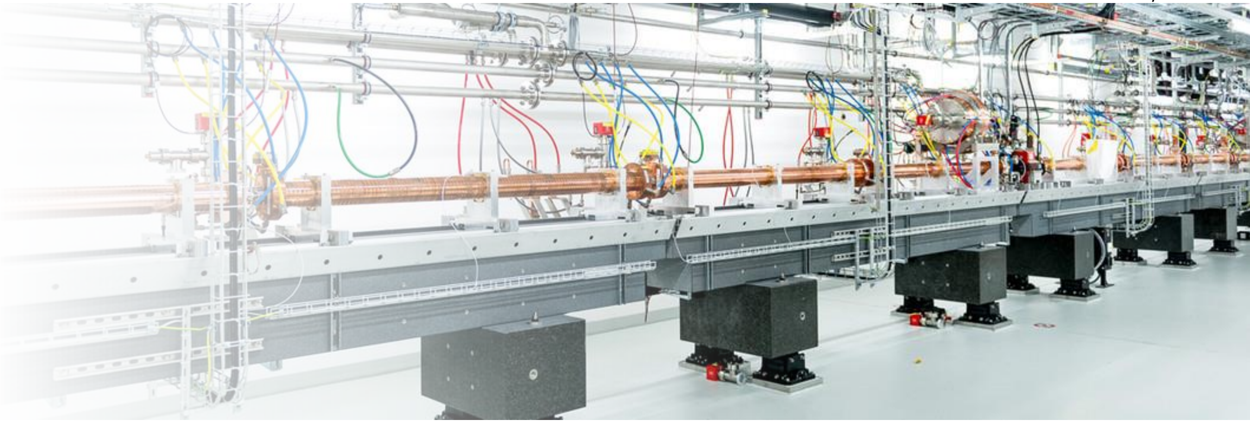
Structures and components production programme to study designs, operation/conditioning, manufacturing, industry qualification/experience

EU projects: ARIES, I-FAST, new TNA

Use in smaller linacs (C and X-band)

SwissFEL: C-band linac

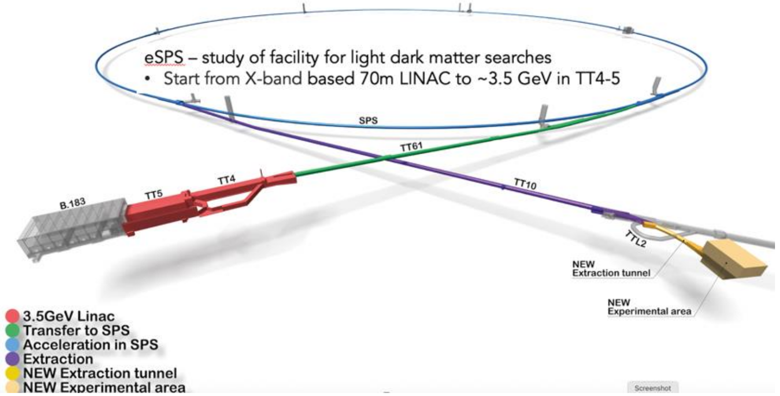
Photo: SwissFEL/PSI



- 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

26 academic and industrial partners: http://www.compactlight.eu/Main/HomePage

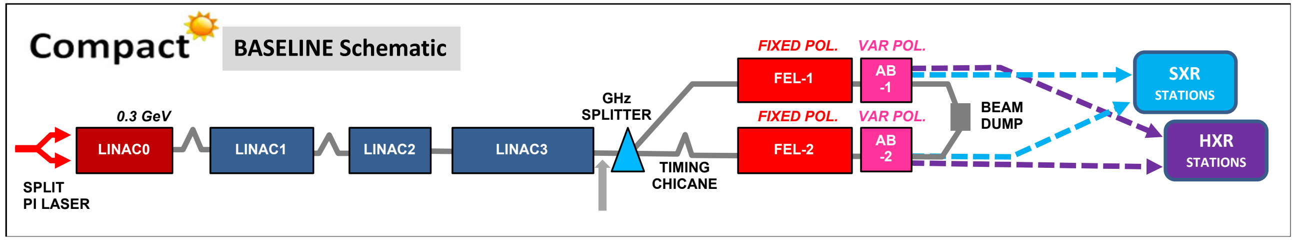
CompactLight Design Studies 2018-21 (link)
Compact FEL based on X-band technologies

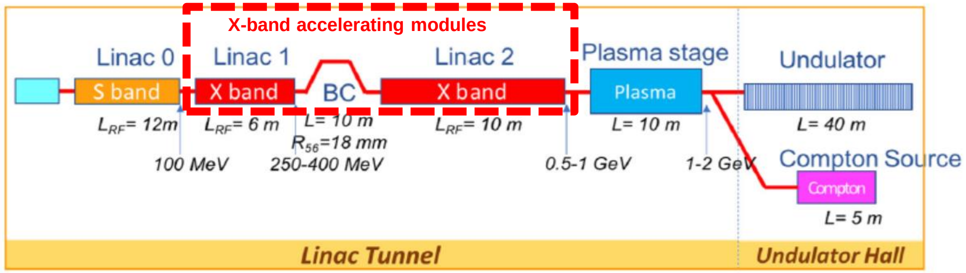


CERN: eSPS study (3.5 GeV X-band linac)

Applications – injector, X-band modules, RF

- CompactLight Design Studies 2018-21 (right)
- INFN 1 GeV linac
- Flash RT CDR, next build it at CHUV
- "Design Studies" for ICS
- AERES, IFAST and TNA project

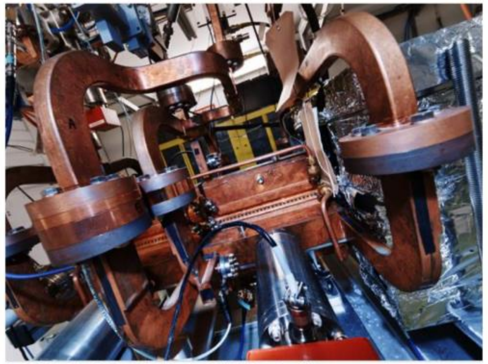




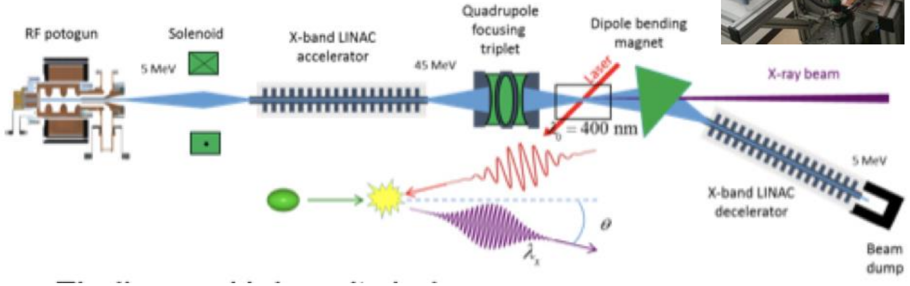
CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

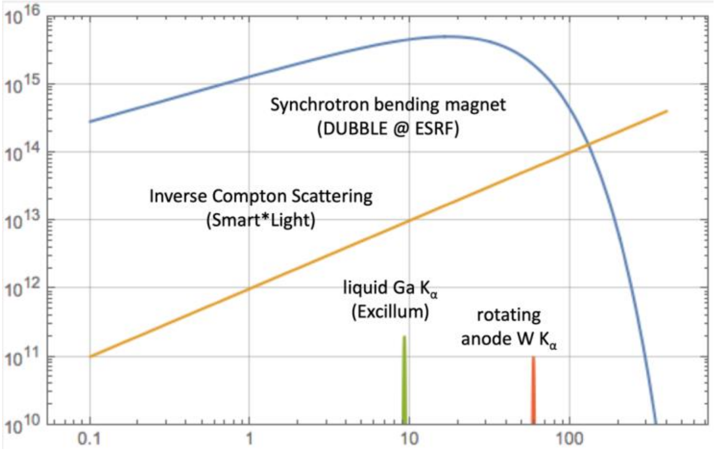
CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment

15 SEPTEMBER, 2020



Close-up of the Compact Linear Collider prototype, on which the electron FLASH design is based (Image: CERN)

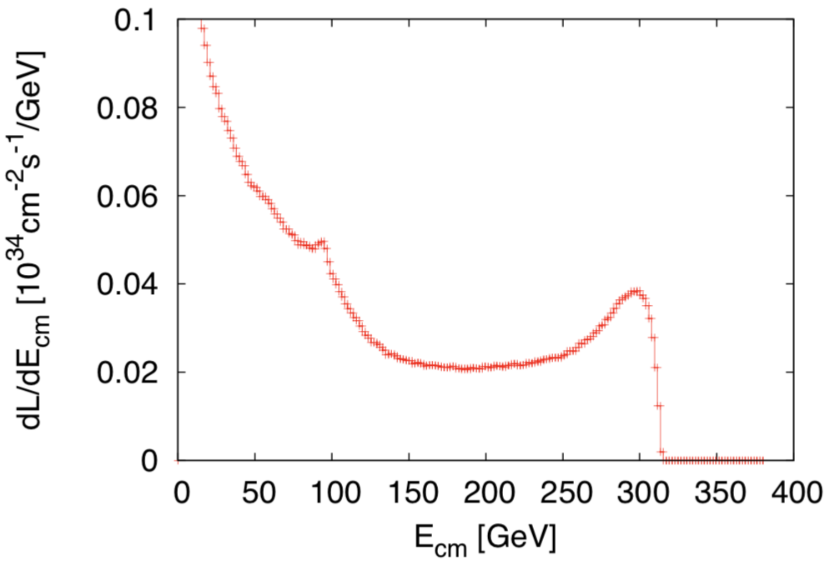




CLIC acc. studies – luminosities

Further work on luminosity performance, possible improvements and margins, operation at the Z-pole and gamma-gamma

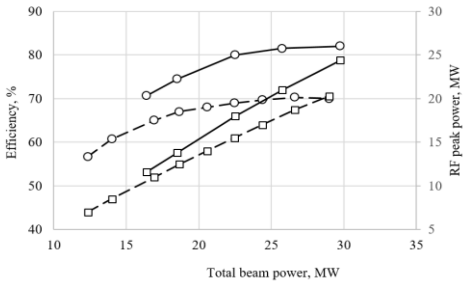
- Z pole performance, 2.3×10^{32} – 0.4×10^{34} cm^{-2} s^{-1}
    - The latter number when accelerator configured for Z running (e.g. early or end of first stage)
- Gamma – Gamma spectrum (example)
- Luminosity margins and increases
    - Baseline includes estimates static and dynamic degradations from damping ring to IP: 1.5×10^{34} cm^{-2} s^{-1}, a "perfect" machine will give : 4.3×10^{34} cm^{-2} s^{-1}, so significant upside
    - In addition: doubling the frequency (50 Hz to 100 Hz) would double the luminosity, at a cost of +50 MW and ~5% cost increase
    - **Studies cover from beam-dynamics to technical studies of the required performances of stability, alignment, instrumentation, magnets, BDS, final focus, injectors including positrons, damping rings – priority for next ESU**



- CLIC note and paper about these studies

High Eff. Klystrons

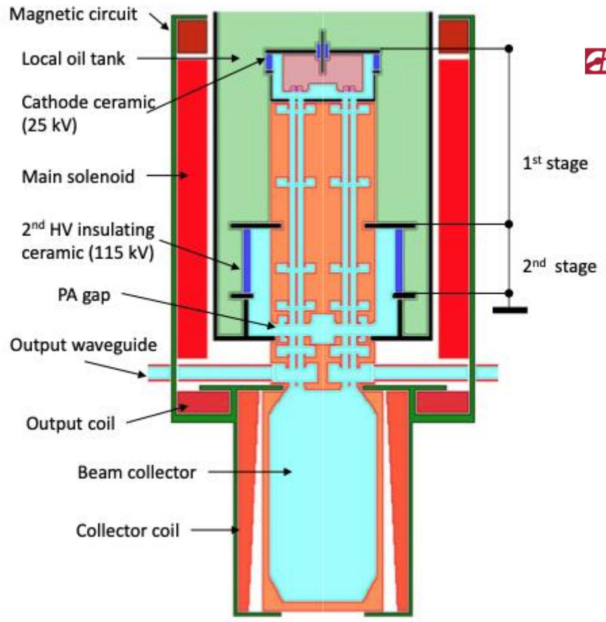
L-band, X-band (for applications/collaborators and test-stands



Location: CERN Bldg: 112

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).

CPI

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**

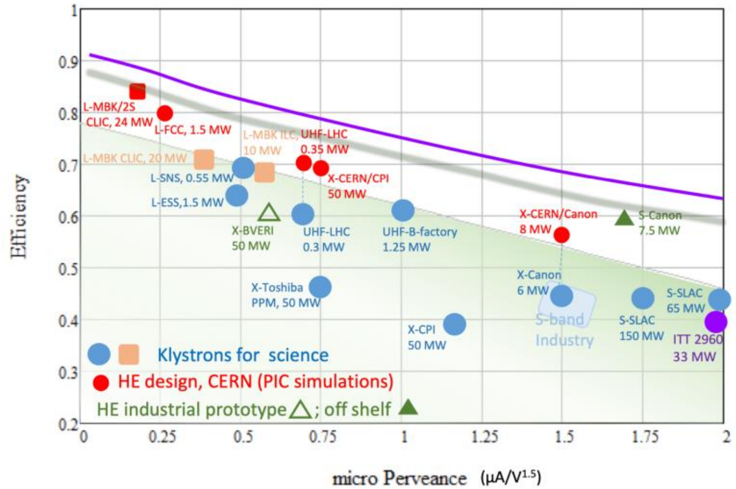
Canon

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**

High Efficiency implementations:

- New small X-band klystron, ordered
- Large with CPI, work with INFN
- L-band two stage, design done, prototyping for FCC

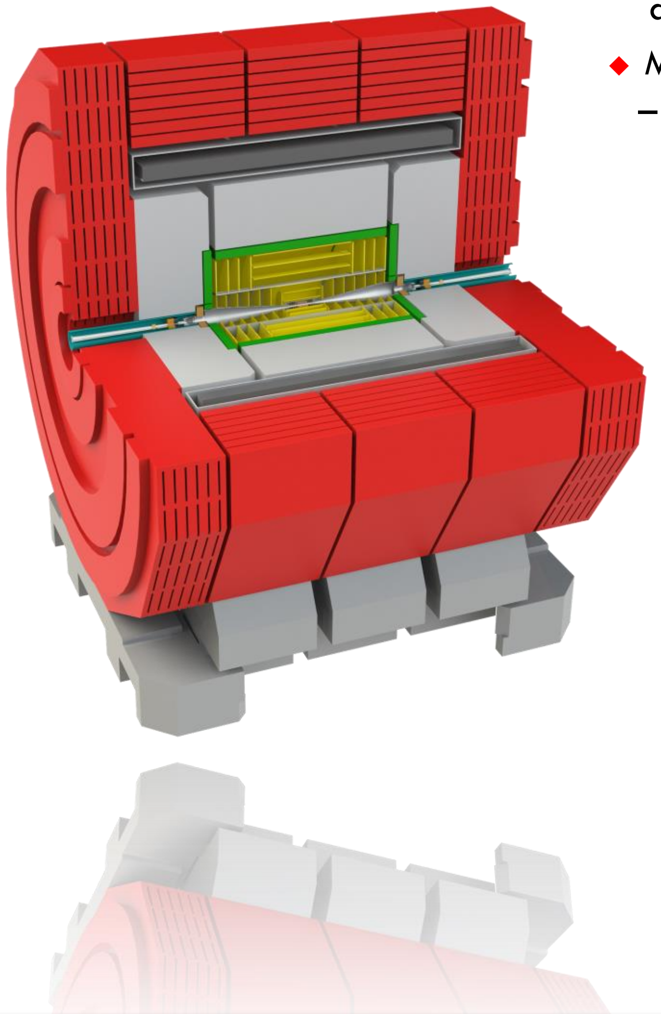
Also important, redesign of damping ring RF system (well underway) – no klystron development foreseen

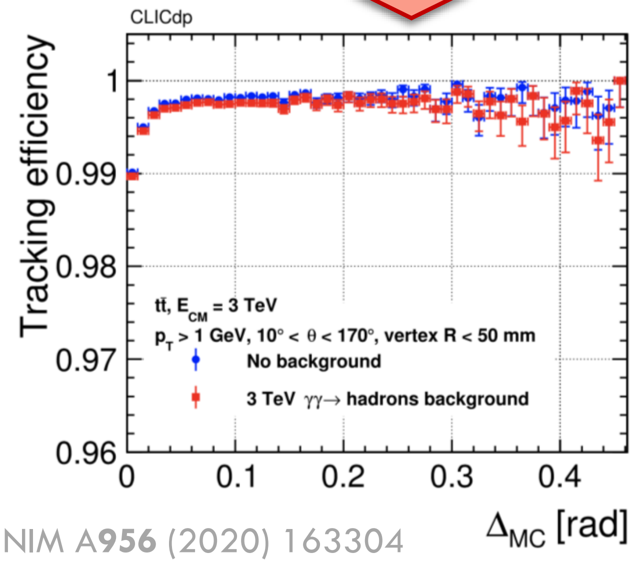


CLIC Detector

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





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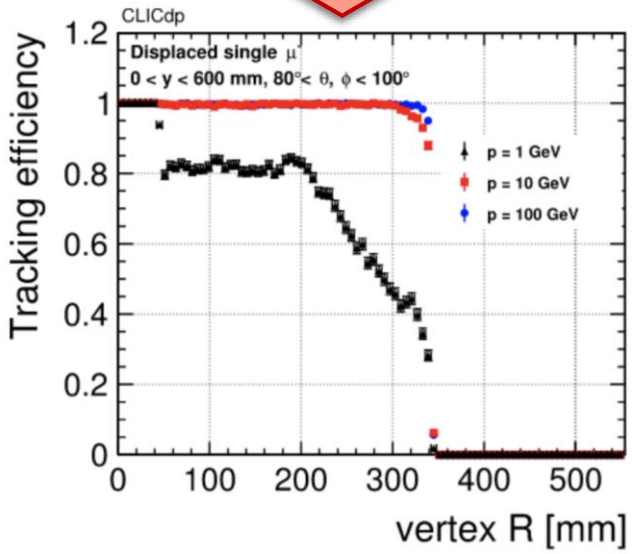
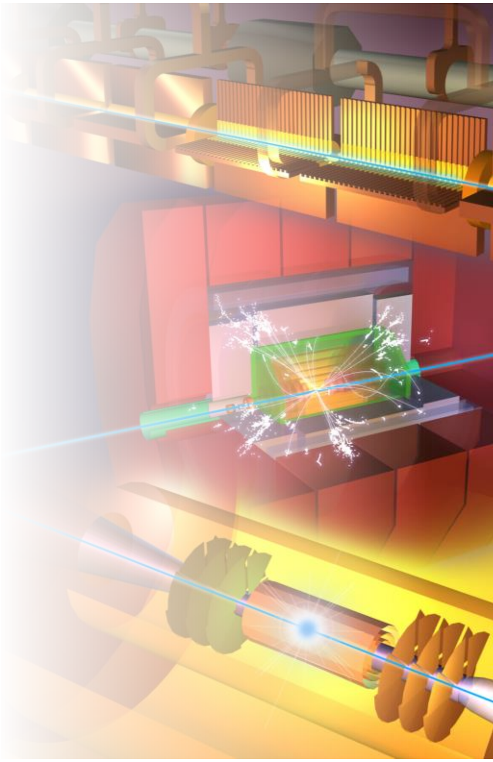
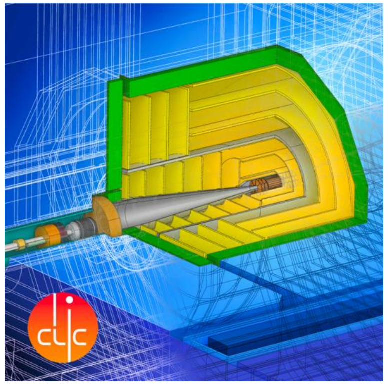




Software framework:

- 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



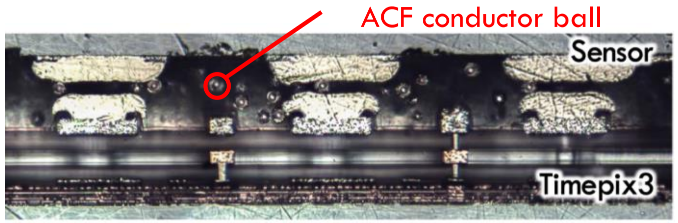
Calorimeter R&D => within CALICE and FCAL
Silicon vertex/tracker R&D:

- 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



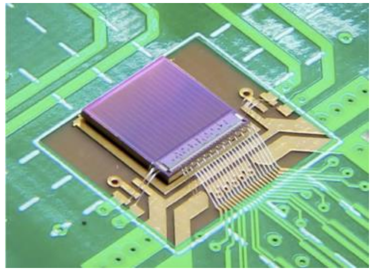
◆ Successful sensor+ASIC bonding using **Anisotropic Conductive Film (ACF)**, e.g. with CLICpix2, Timepix3 ASICs.
ACF now also used for module integration with monolithic sensors.
https://agenda.linearcollider.org/event/9211/contributions/49469/

Monolithic sensors:

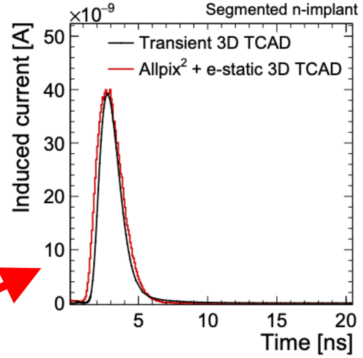
◆ Exploring sub-nanosecond pixel timing with **ATTRACT FASTPIX** demonstrator in 180 nm monolithic CMOS
https://agenda.linearcollider.org/event/9211/contributions/49445/

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

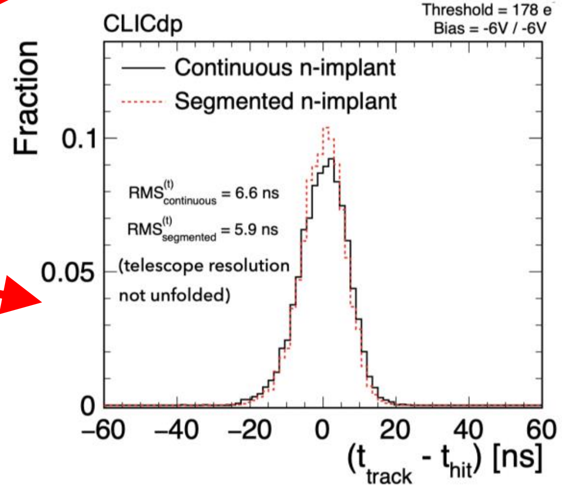
CLICTD monolithic tracking sensor:



Detailed simulations, Allpix^2 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:

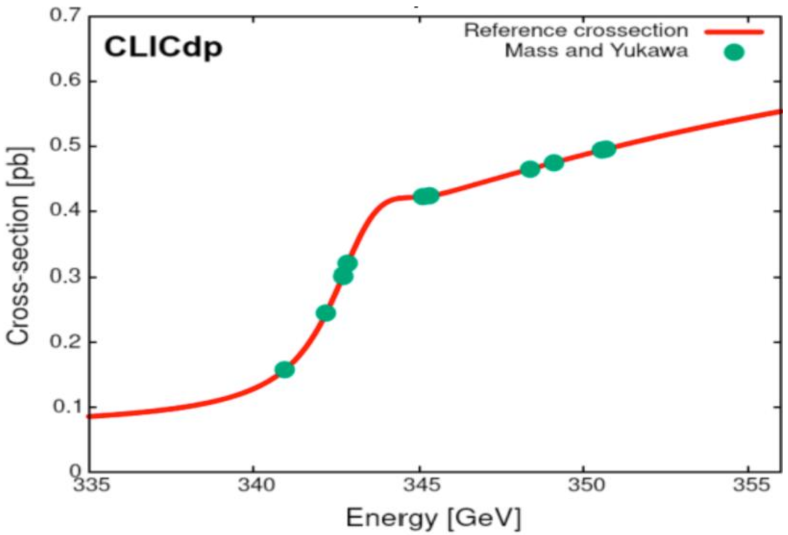
- Sensitivities under different integrated luminosity scenarios to complement accelerator luminosity studies

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

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

	Benchmark	HL-LHC	HL-LHC + CLIC		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

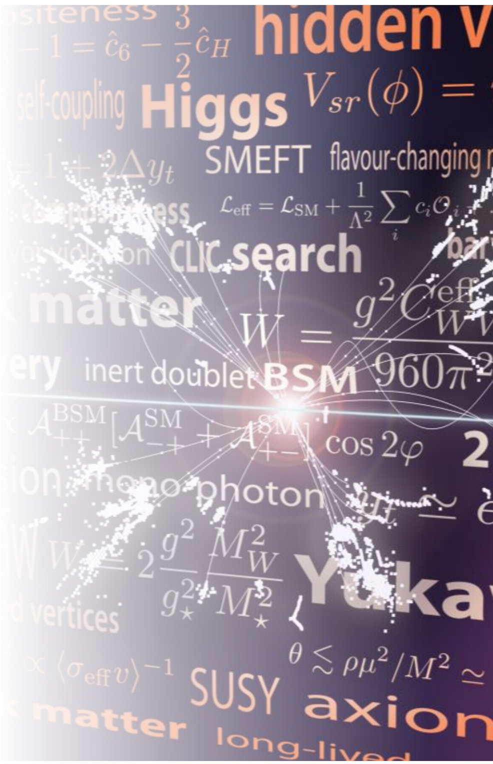
https://arxiv.org/abs/2001.05278
other sensitivities from Briefing Book https://arxiv.org/abs/1910.11775



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.

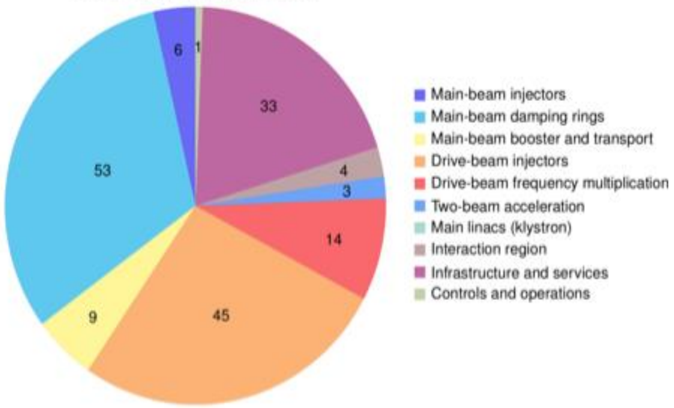
https://arxiv.org/abs/2103.00522



Power and Energy

(for cost see backup slides)

Drive-beam option: 168 MW



Klystron-based option: 164 MW

Power estimate bottom up (concentrating on 380 GeV systems)

- Very large reductions since CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimized, etc

Further savings possible, main target damping ring RF, L-band klystron (target 140-150 MW)

Energy consumption ~0.8 TWh yearly (target 0.7)
CERN is currently (when) running at 1.2 TWh (~90% in accelerators)

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.

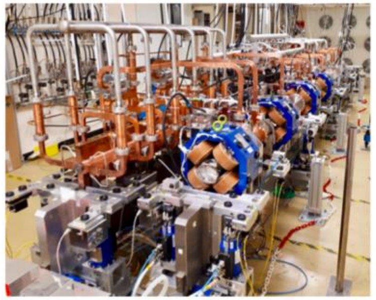
Running when energy is cheap:

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, can reduce the energy bill

Renewable energy (carbon footprint):

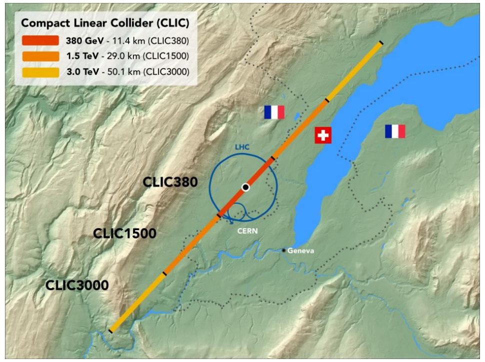
Is it possible to fully supply the annual electricity demand of the CLIC-380 by installing local wind and PV generators (this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators, at a cost of slightly more than 10% of the CLIC 380 GeV cost)

CLIC can easily be extended



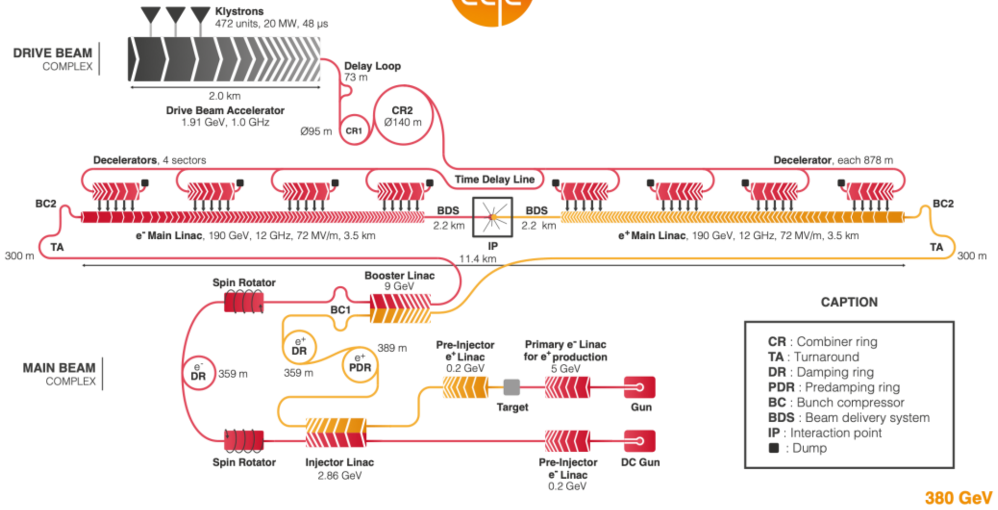
What are the critical elements:

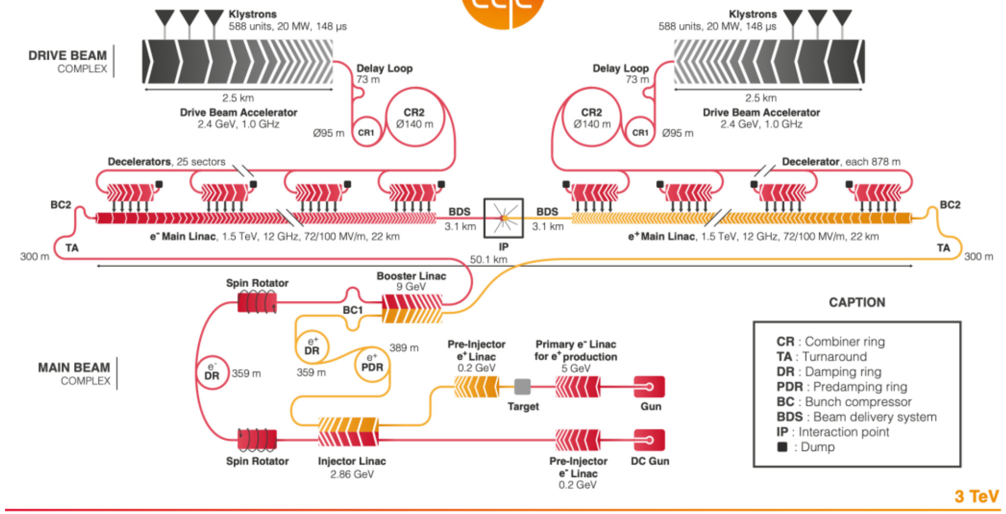
- Physics
- Gradient and power efficiency
- Costs



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)

Physics Potential recent highlights 2: Multi-TeV stages

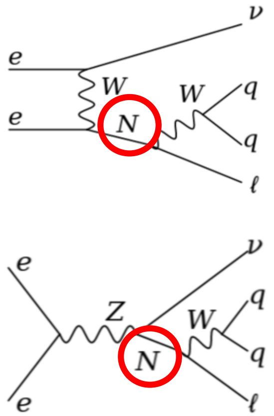
◆ Ongoing studies on new physics searches

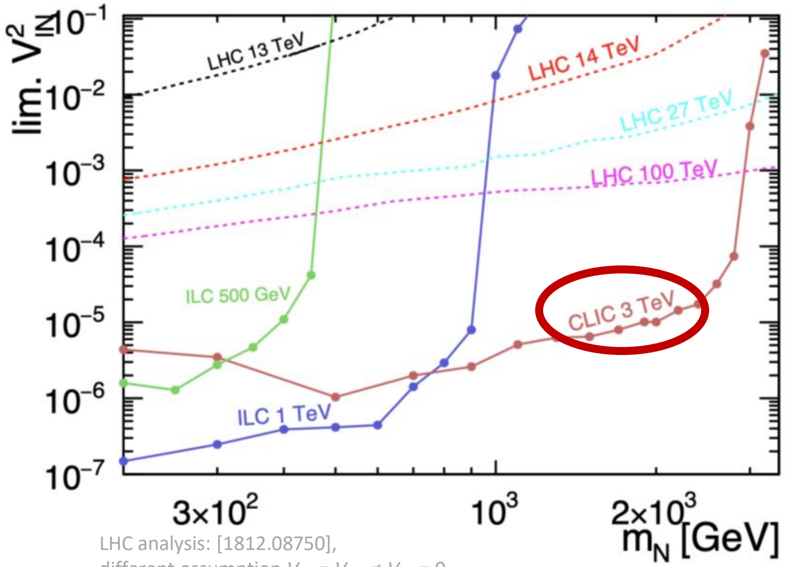
Search for heavy neutrinos

◆ 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 $V_{eN} = V_{mN} \neq V_{\tau N} = 0$

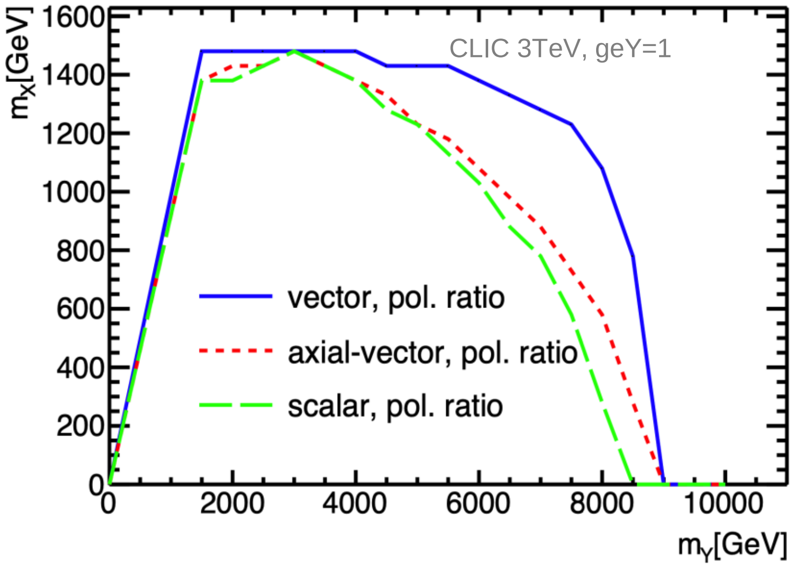
Dark matter using mono-photon signature at 3TeV, e+e- -> XXγ

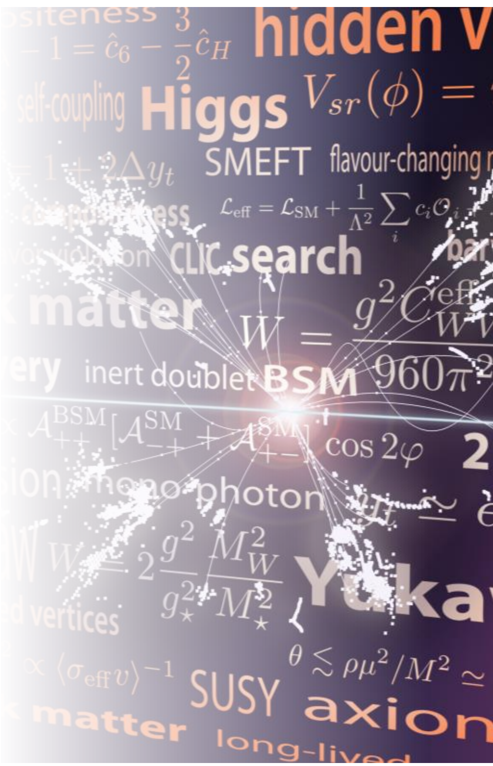
◆ New study using ratio of electron beam polarisations to reduce systematics

◆ 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





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):

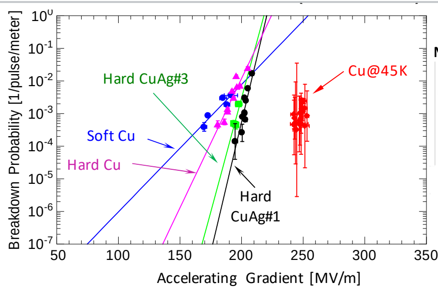
- Field emission
- Vacuum arcing (breakdown)
- Fatigue due to pulsed surface heating

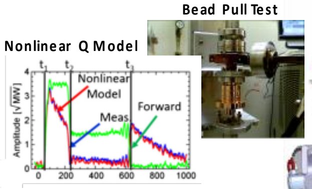
Studying these processes gives important input into:

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

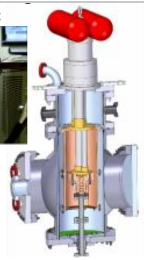
Designs for CLIC steadily improving, but also RFQ, Muon collider, XFEL, ICS, etc
Important experimental support

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



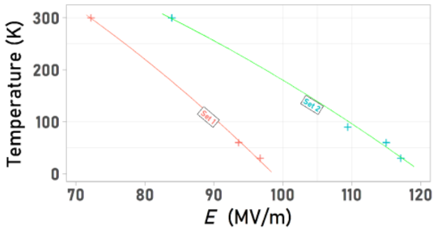


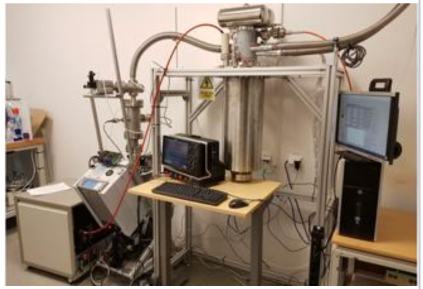
Cahill, PhD Diss., 2017
Cahill, et al. *PRAB* 21.6 (2018): 061301.
Rosenzweig, et al. *NIMA* (2018).
Cahill, et al. *NIMA* 865 (2017): 105-108.



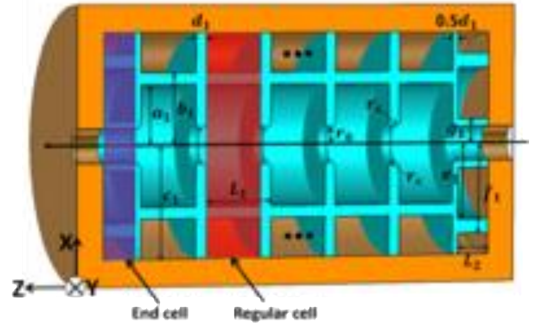
Cryostat assembly

Cryo-cooled copper cavity, SLAC

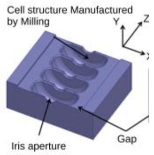




Cryo-cooled copper pulsed dc electrodes, Uppsala/CERN

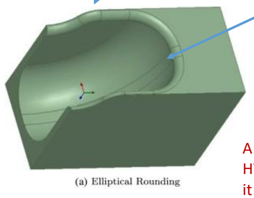


Implementation



Copper in high electric field region

HTS in high magnetic field region



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.

Connecting - the collaborative cloud

The LC studies at CERN also contains work for ILC, and common working groups have been active for many years. Many collaborating institutes work on both.

The physics and detector community, including software, also in many cases do common studies or work on both

Good participation in ECFA H/t/etc working groups and Detector Roadmap processes

LDG report covers both NCRF and SFR cavities and a lot of common interest on gradient/efficiency challenges and work on RF sources. Compact and efficient RF in general very nicely pushed forward by a variety of smaller machines, in many cases outside HEP

CLIC in particular, with a drivebeam, very high alignment/stability requirements and multi-TeV studies also connect into novel RF technology studies as plasma (and a general focus on compact linacs for "applications")

Links also to muon cooling RF challenges

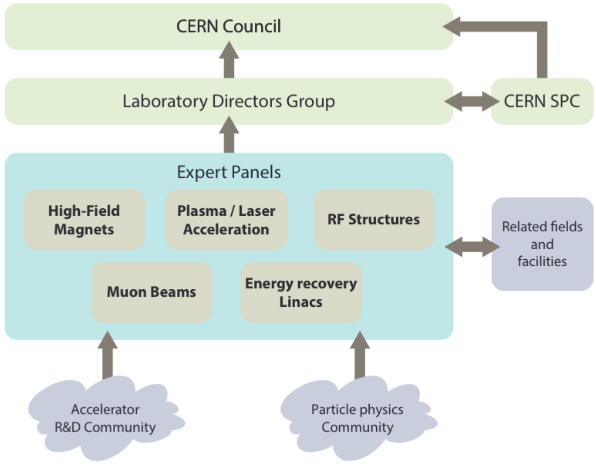


Fig. 1.1: Roadmap panel structure.

Summary and thanks

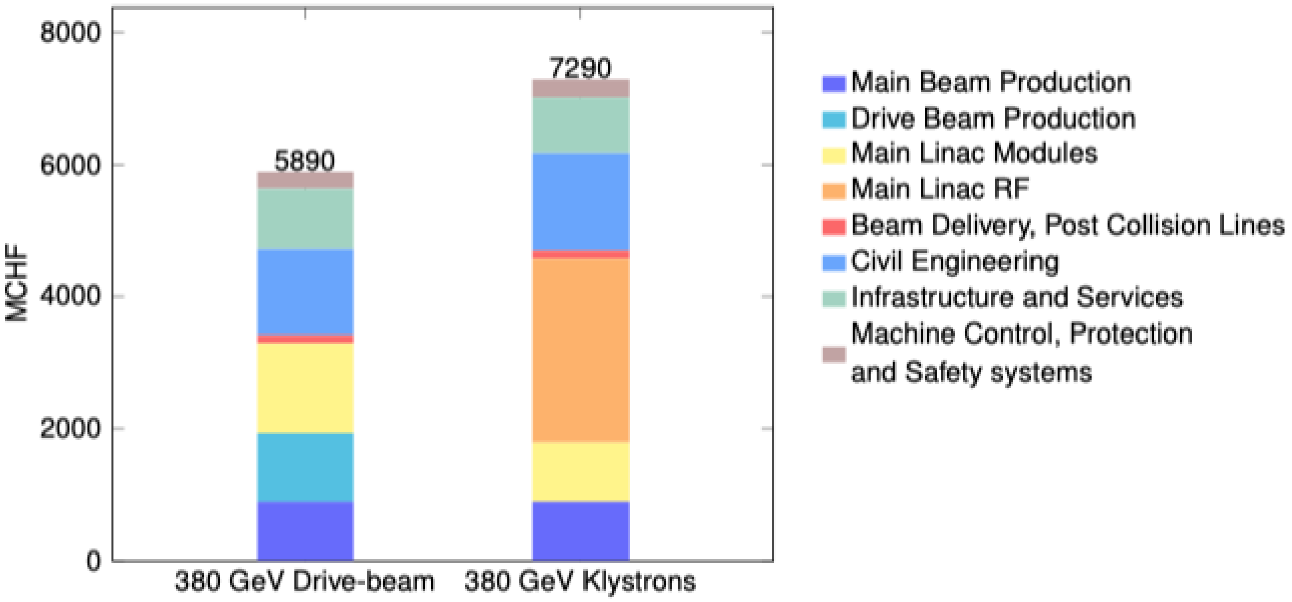
- CLIC studies focused on core technologies, X-band and nanobeam, for next ESU, well underway.
- Keep focus on both 380 GeV and multi-TeV performance and R&D
- Greatly helped by studies of smaller linacs and systems using X-band technology
- Detector and physics studies continue at lower pace, also in many areas integrated or connected with "Higgs-factory" studies, and wider Detector R&D efforts

- Thanks to many CLIC accelerator colleagues for slides and input, and the CLICdp slides in particular compiled by Aidan Robson

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.