The CLIC Accelerator Project: status and plans

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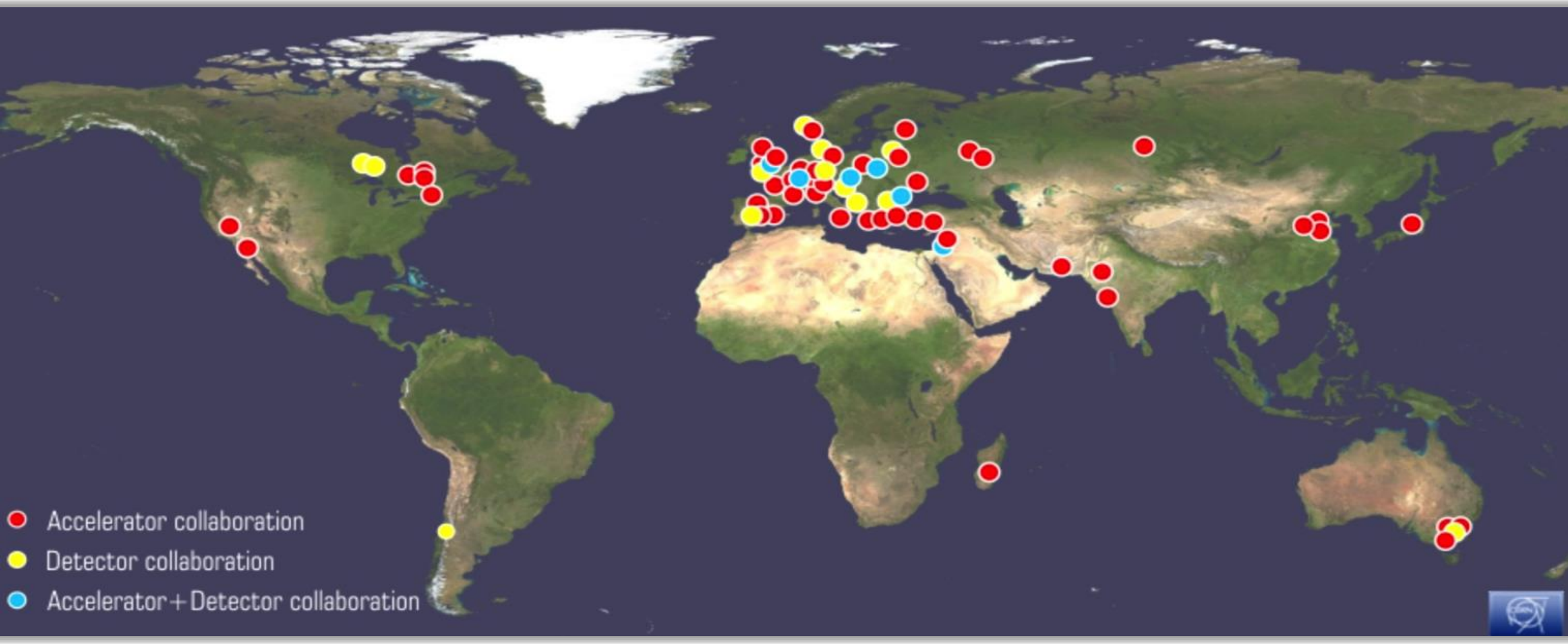
On behalf of the CLIC Collaborations

CLIC Collaborations

https://clic.cern

CLIC accelerator collaboration
50 institutes from 28 countries

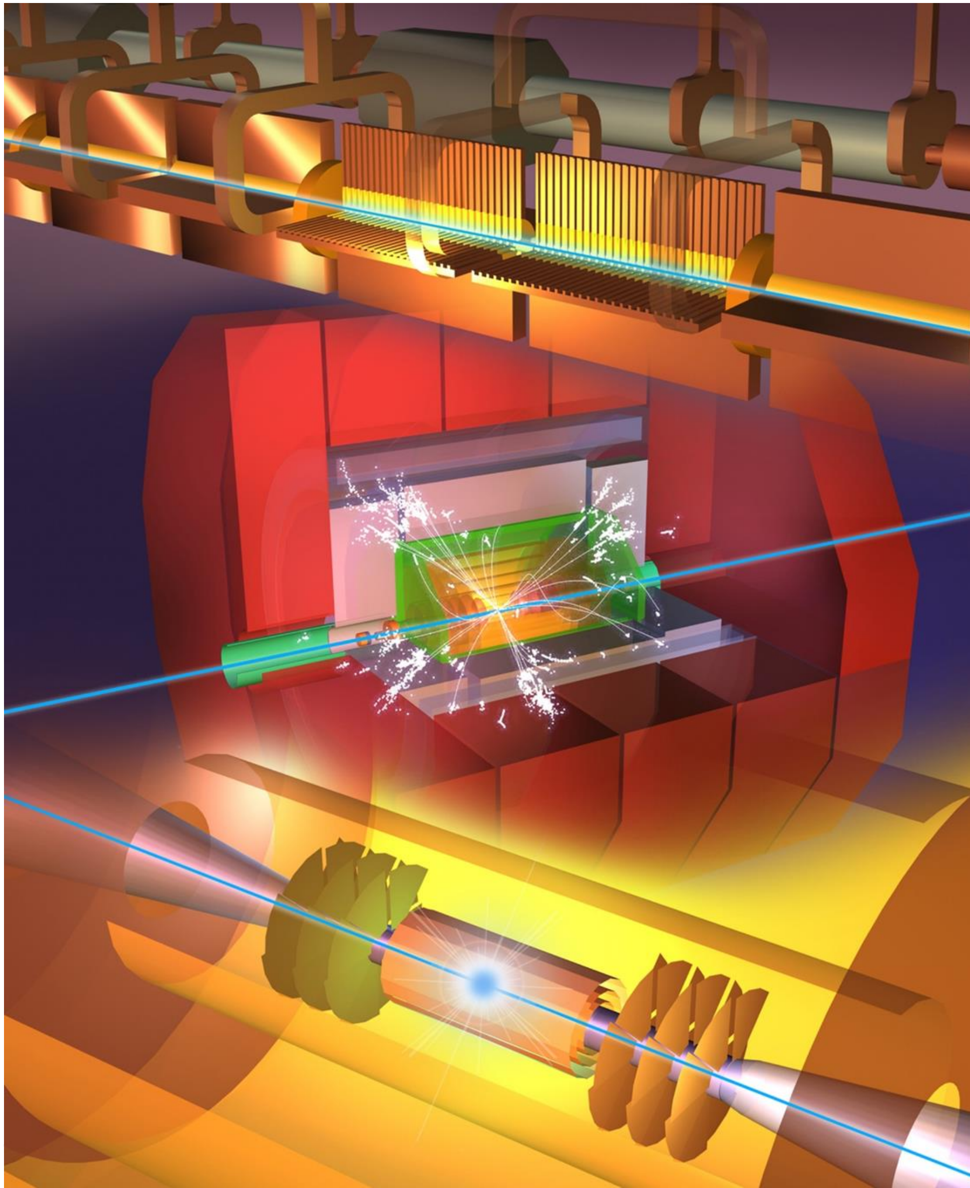
CLIC detector and physics (CLICdp)
30 institutes from 18 countries



CLIC Collaborations

Outline

- CLIC project overview
- Technical maturity
- Implementation
- Plans 2020-25
- Summary



Project overview

- **Timely:** e+e- linear collider at CERN for the post-LHC era
- **Compact:** novel and unique two-beam accelerating technique based on high-gradient room temperature RF cavities: ~11km first stage
- **Expandable:** staged collision energies from 380 GeV (Higgs/top) up to 3 TeV

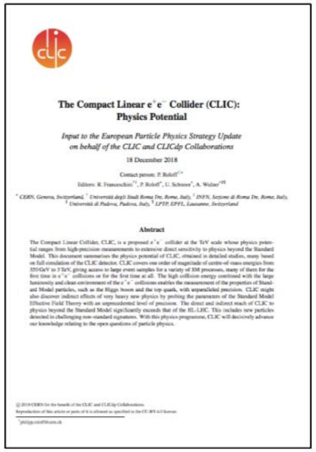
- **Cost:** 5.9 BChF for 380 GeV
- **Power:** 168 MW at 380 GeV

- **Conceptual Design Report published in 2012**
- **Energy-staging baseline 2016**
- **Project Implementation Plan released 2018**

- **Comprehensive Detector and Physics studies (see other talks)**

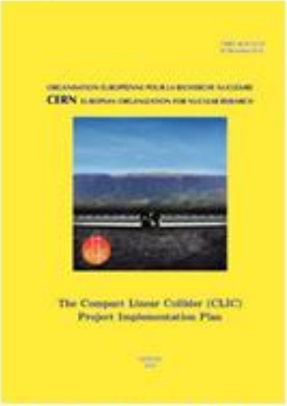
CLIC European Strategy Inputs

http://clic.cern/european-strategy

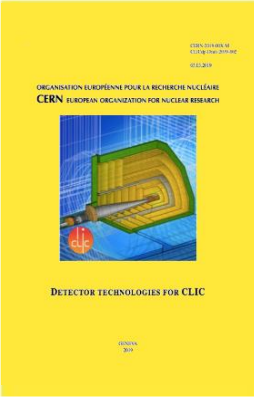


CERN-2018-005-M

CERN-2018-009-M

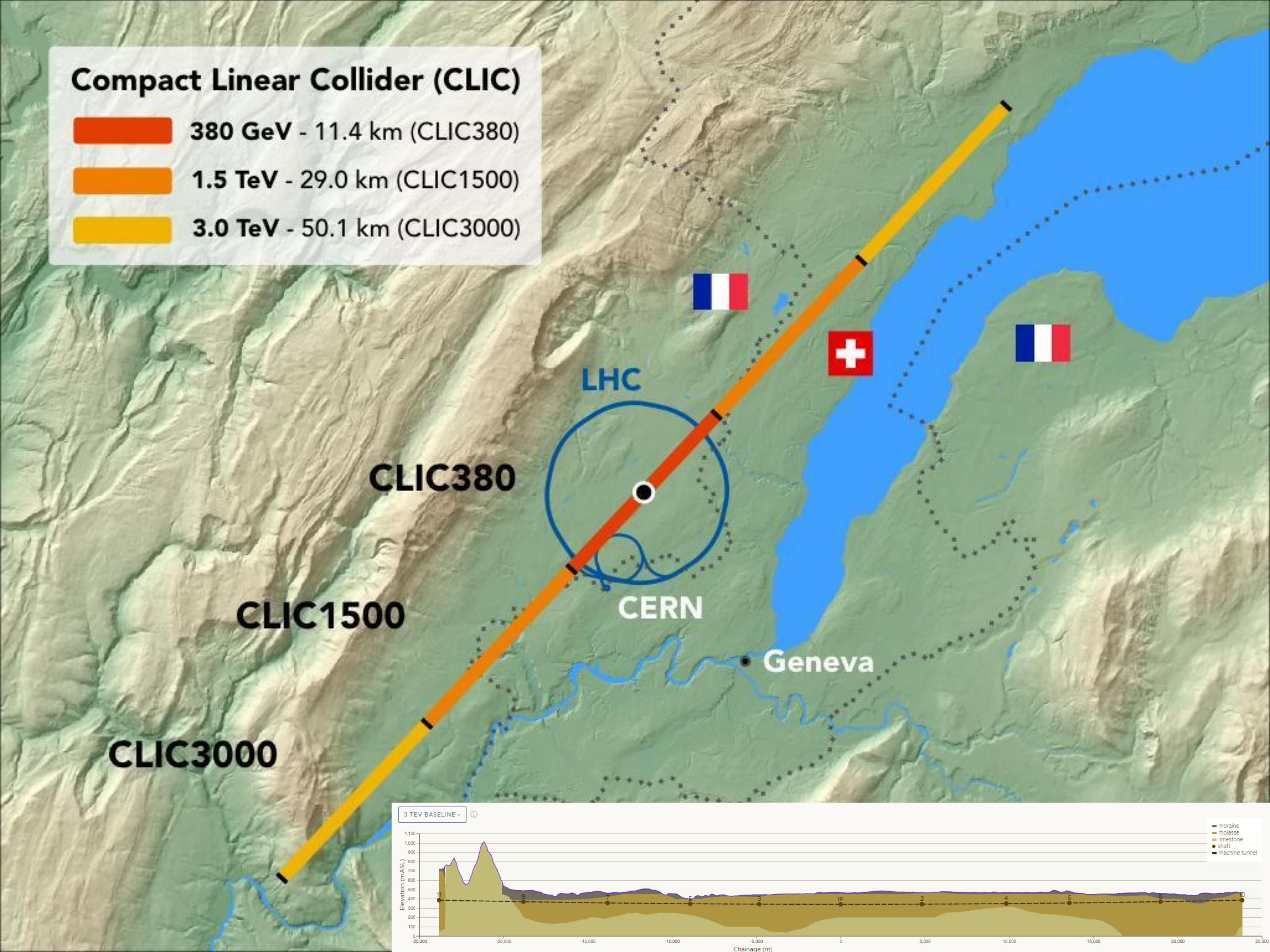


CERN-2018-010-M

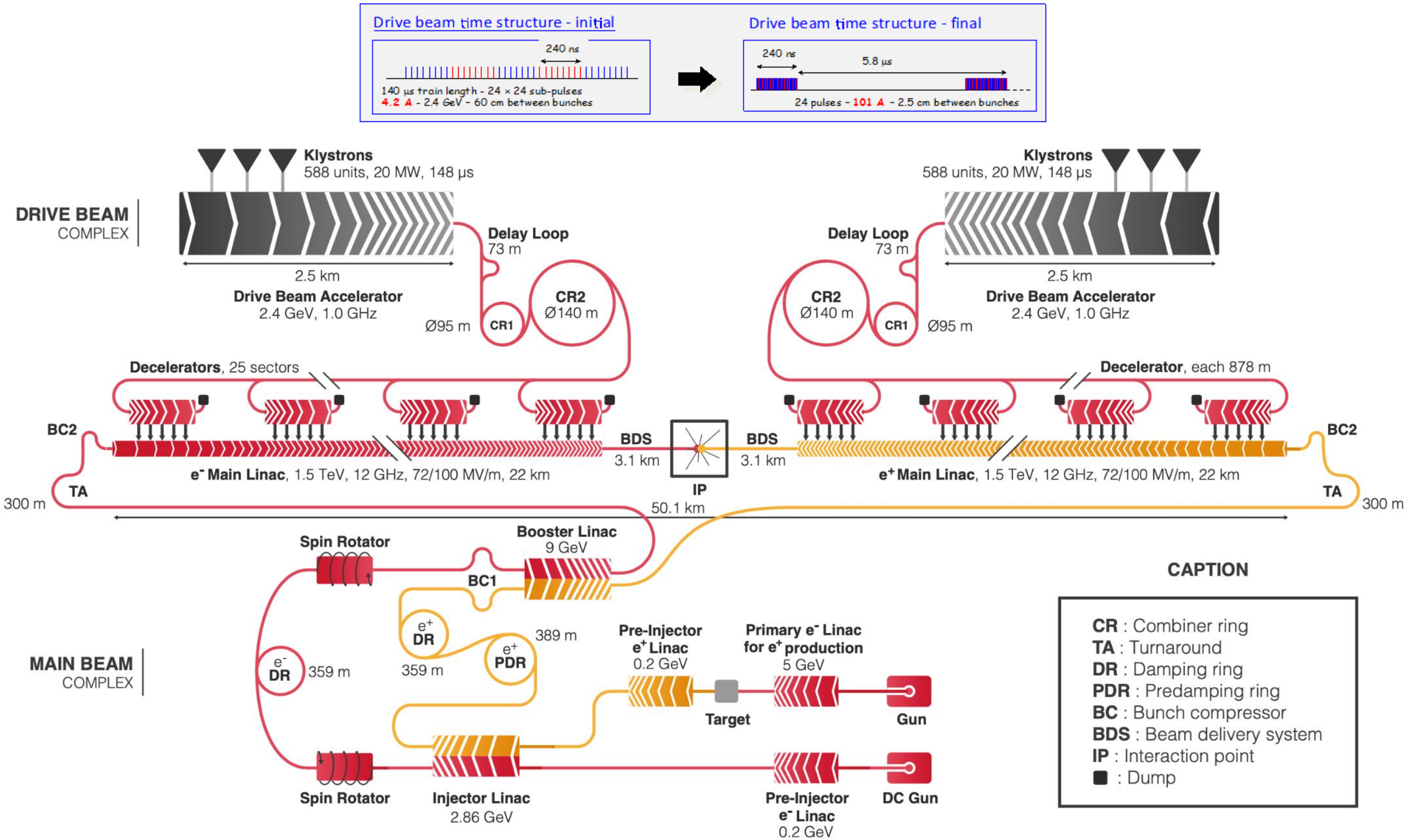


CERN-2019-001

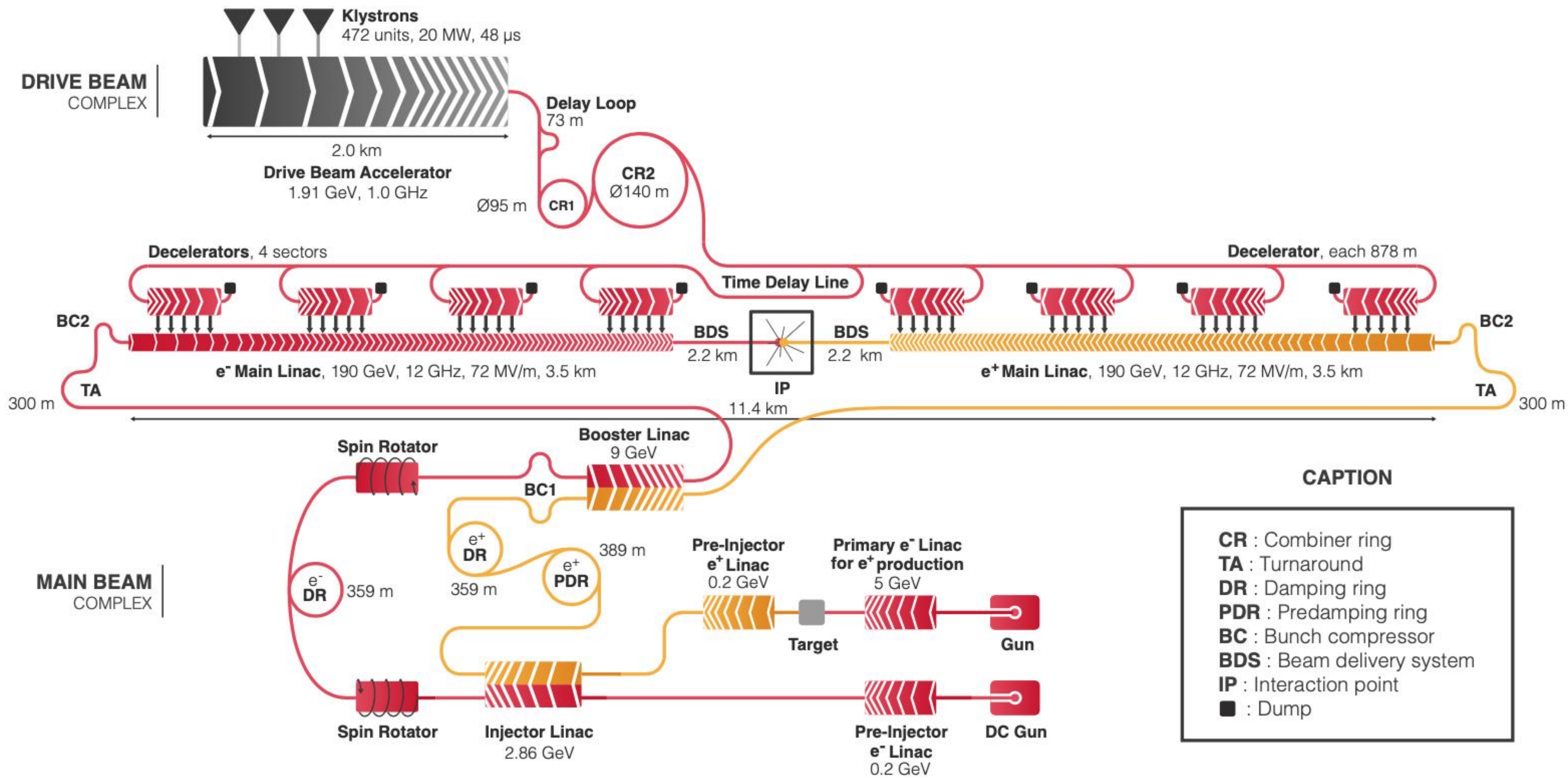
Letters of interest in preparation for Snowmass process


Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva
3 TEV BASELINE
moraine
molasse
limestone
shaft
machine tunnel
Elevation (mASL)
Chainage (m)

CLIC 3 TeV layout



CLIC 380 GeV layout

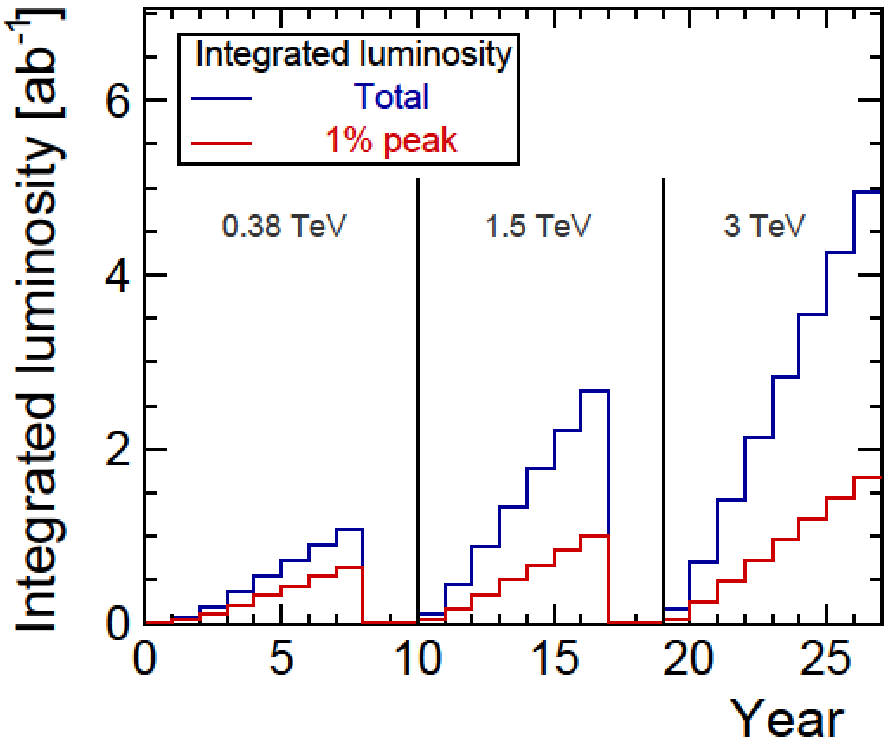


Baseline electron polarisation ±80%

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	$\mathscr{L}$	$10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\mathrm{int}}$	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

Luminosity staging baseline



Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

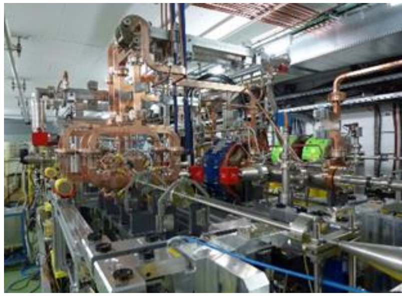
Baseline polarisation scenario adopted:
electron beam (–80%, +80%) polarised in ratio (50:50) at √s=380GeV ; (80:20) at √s=1.5 and 3TeV

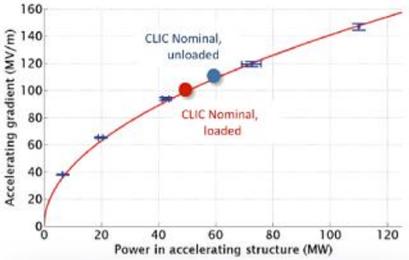
Staging and live-time assumptions following guidelines consistent with other future projects:
Machine Parameters and Projected Luminosity Performance of Proposed Future Colliders at CERN
arXiv:1810.13022, Bordry et al.

Accelerator challenges

1. High-current drive beam bunched at 12 GHz
2. Power transfer and main-beam acceleration
3. Towards 100 MV/m gradient in main-beam cavities
4. Alignment and stability ('nano-beams')

- CTF3 (CLIC Test Facility) addressed drive-beam production issues
- X-band technology developed and verified with prototyping, test-stands, and smaller-scale systems
- Two C-band XFELS (SACLA and SwissFEL) now operational: large-scale demonstrations of normal-conducting, high-frequency, low-emittance linacs
- Other critical technical systems (alignment, damping rings, beam delivery, etc.) addressed via design and/or test-facility demonstrations

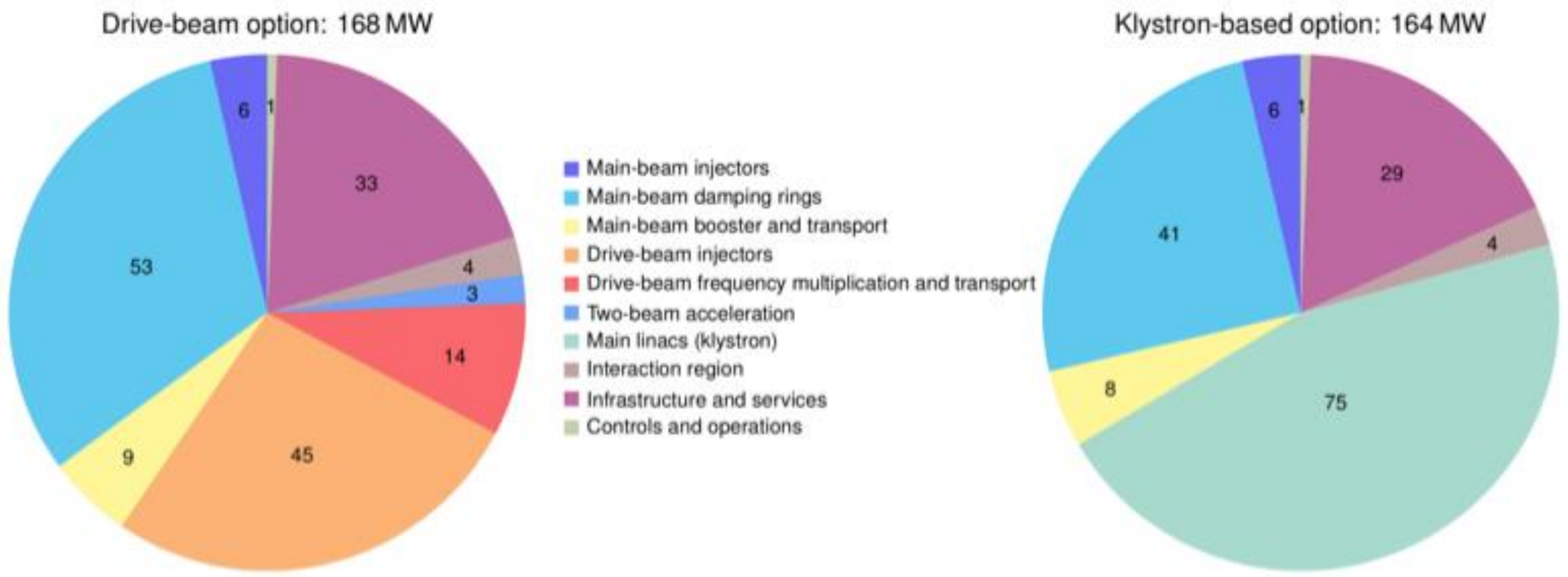




Power (380 GeV)

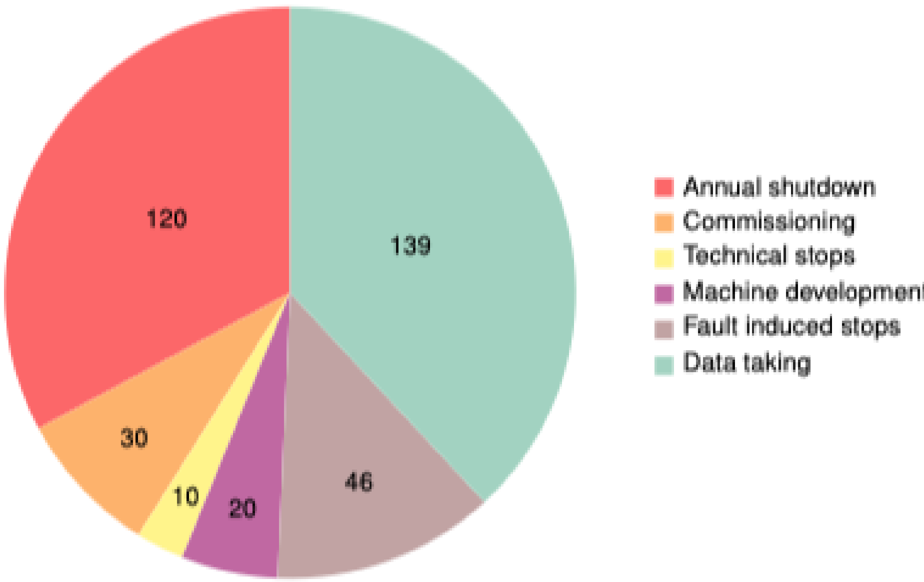
Power estimate bottom-up (concentrating on 380 GeV systems)

- **Very large reductions since CDR, better estimates of nominal settings, much more optimised drive-beam complex and more efficient klystrons, injectors etc.**

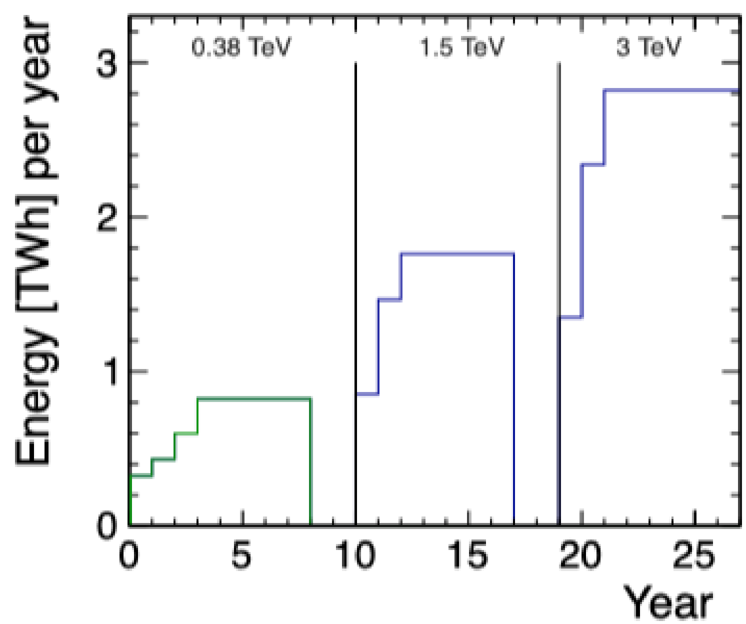


Further savings possible: damping ring RF, high-efficiency klystrons, permanent magnets …
Will look also more closely at 1.5 and 3 TeV numbers

Energy consumption



Collision Energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	168	25	9
1500	364	38	13
3000	589	46	17



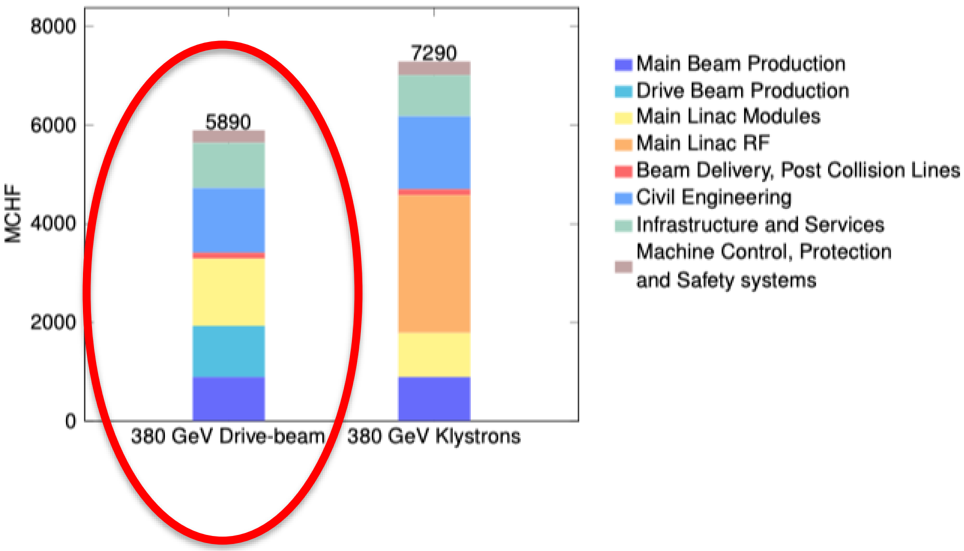
From running model and power estimates in the various operational states – the energy consumption can be estimated

CERN is currently consuming ~1.2 TWh yearly (~90% in accelerators)

Cost (380 GeV)

Accelerator re-costed bottom-up

- **Methods and costings validated at review 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:

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

Operation:

- **116 MChF consumables + spares (see below)**
- **Energy costs**

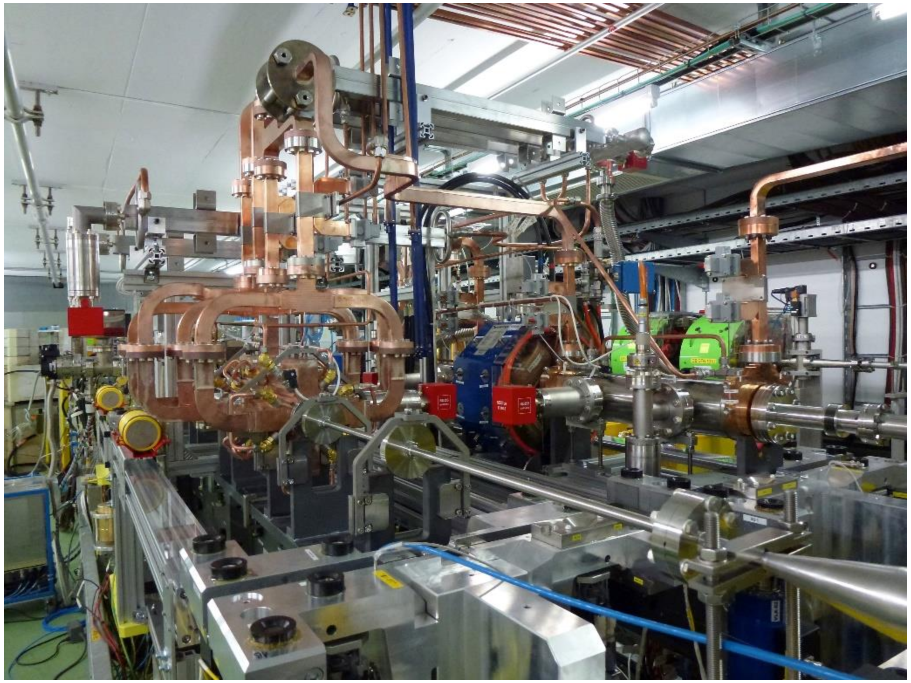
– 1% for accelerator hardware parts (e.g. modules).
– 3% for the RF systems, taking the limited lifetime of these parts into account.
– 5% for cooling, ventilation and electrical infrastructures etc. (includes contract labour and consumables)

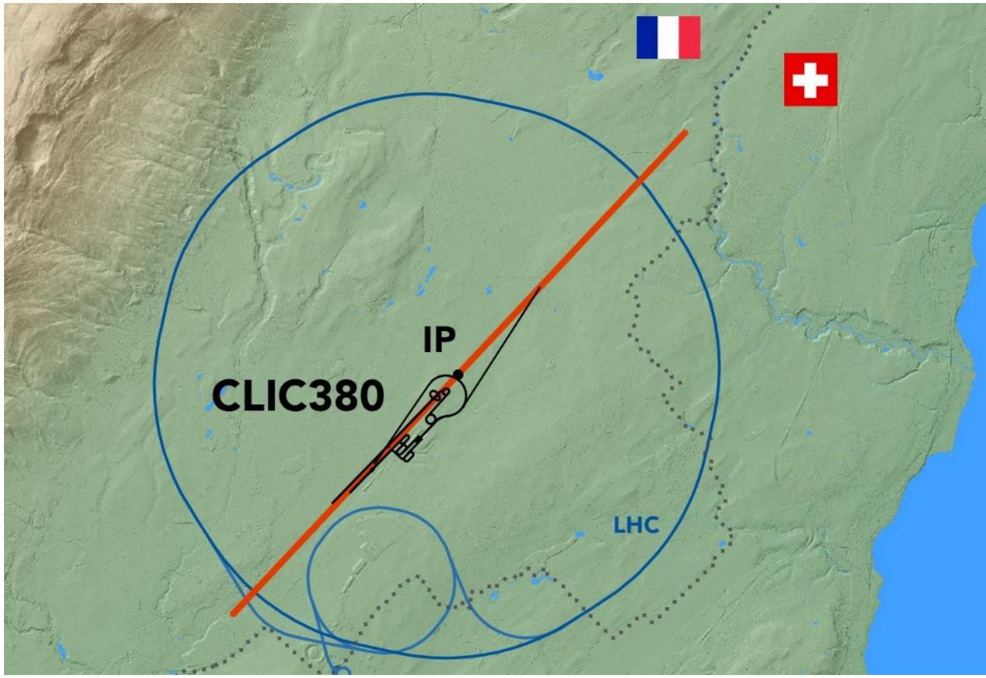
These replacement/operation costs represent 116 MCHF per year.

CLIC status summary

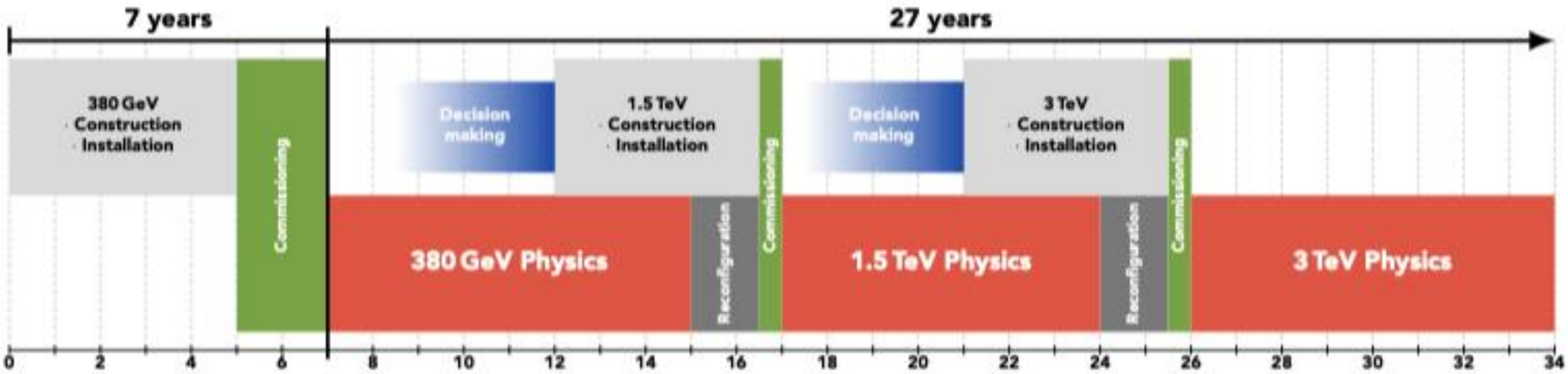
Key technologies have been demonstrated

CLIC is a mature project ready to move towards implementation of 380 GeV Higgs/top factory first stage





Technical schedule



Construction + installation:	**5 years**
Commissioning:	**2 years**
380 GeV physics programme:	**8 years**
Additional energy stages:	**…**

European Strategy Update

The vision is **to prepare a Higgs factory**, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges …

3. High-priority future initiatives **a) An electron-positron Higgs factory is the highest-priority next collider.** For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy ...

b) **Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders.** It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other **high-gradient accelerating structures**, bright muon beams, energy recovery linacs. The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. …

Deliberation document

The design, technology, and implementation aspects of CLIC indicate that the first stage (a Higgs factory) could be realised on a timescale of 15 years and could be extended to higher energies subsequently.

Reduction in energy consumption is an important consideration in accelerator design. Substantial progress has been achieved in the development of superconducting and **normal-conducting high-gradient accelerating structures**. This technology, which is needed for the e+e– colliders, is also driven by light source facilities all over the world.

Deliberation document

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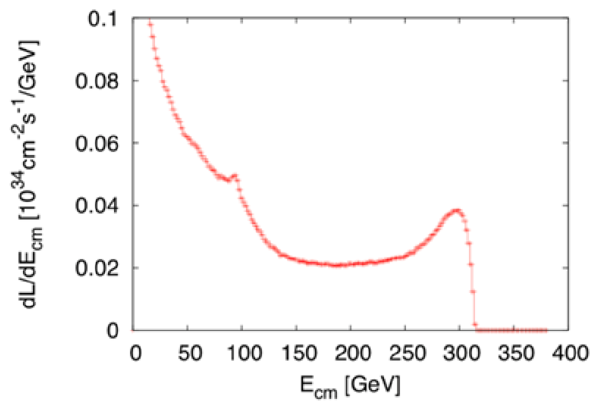
CLIC R&D and design work is fully consistent and aligned with this strategy and will continue

Recent studies I

- **Z-pole performance (first stage):**

  L (default) 2.3 x 10^{32} → 0.4 x 10^{34} cm^{-2} s^{-1} with accel. configured for Z running

- **Gamma-gamma collisions luminosity (example):**



- **Luminosity margins:**

  baseline 380 GeV design L = 1.5 x 10^{34} cm^{-2} s^{-1}
  'perfect' machine > DR L = 4.3 x 10^{34} cm^{-2} s^{-1}

  → significant margin for improvement

- **Luminosity upgrades:**

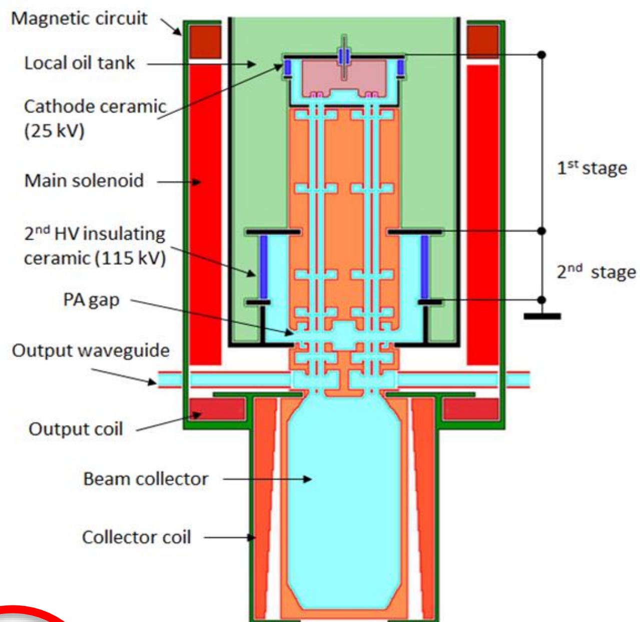
  doubling frequency (50 Hz → 100 Hz)

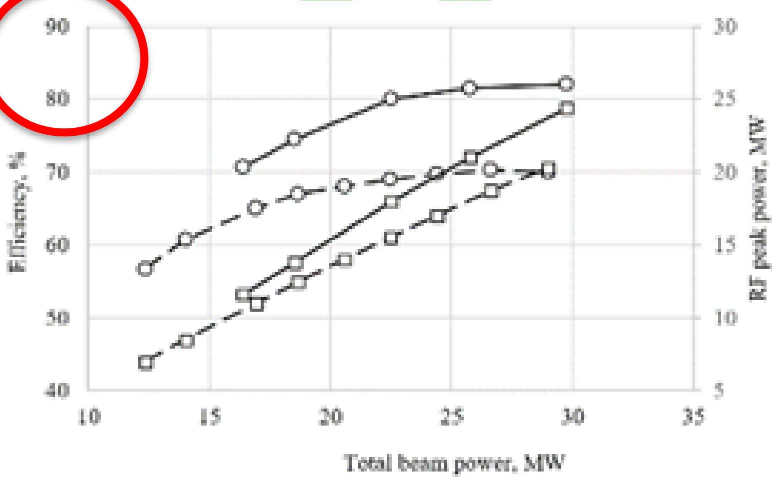
  → double the luminosity, with power +50 MW and cost ~5% increases

CLIC note: http://cds.cern.ch/record/2687090 (paper in preparation)

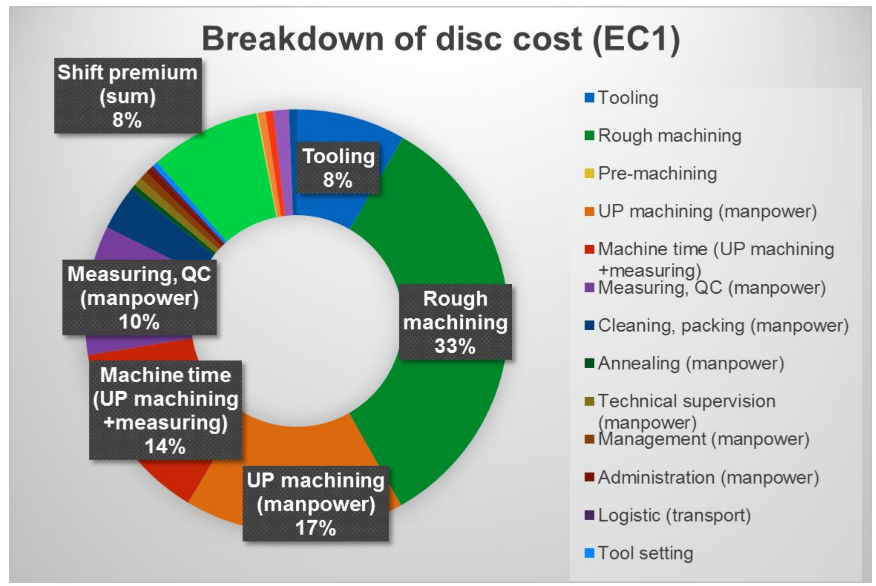
Recent studies II

High-efficiency klystron design





Industry survey for CLIC disk production



Industrial questionnaire:

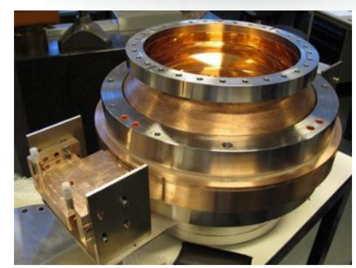
Capacity clearly available.
Preparation phase to mass production ~ five years.

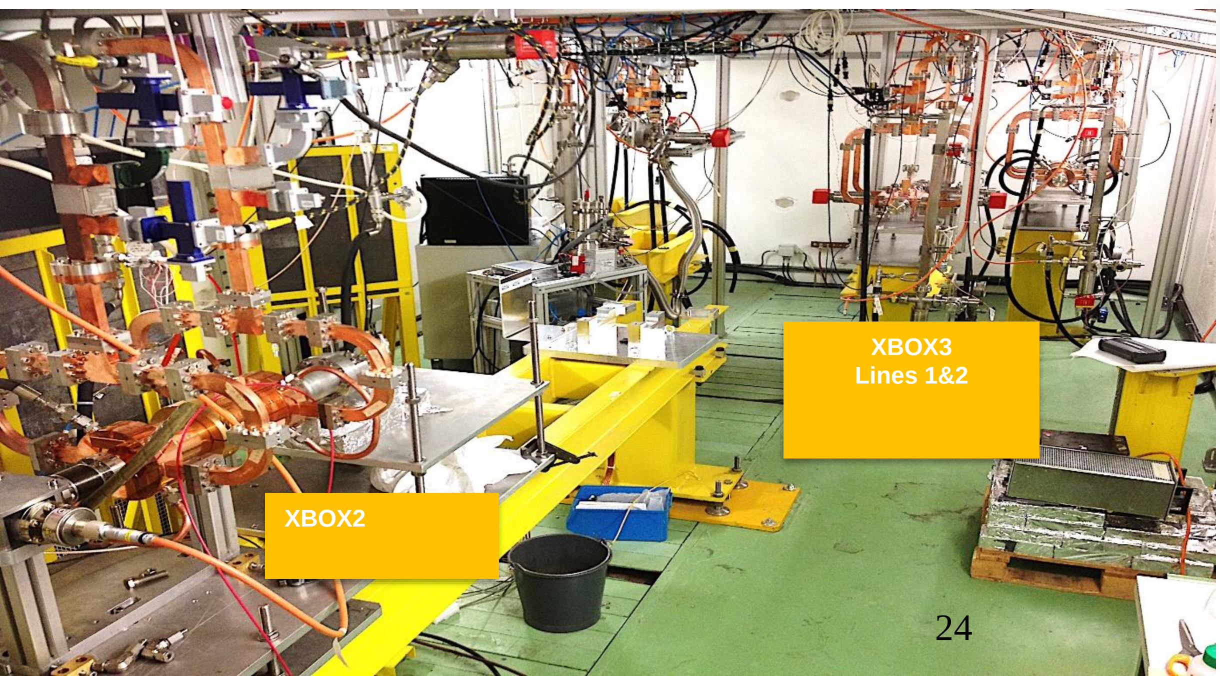
Drive-beam klystron: The klystron efficiency (circles) and the peak RF power (squares) simulated for the CLIC TS MBK (solid lines) and measured for the Canon MBK E37503 (dashed lines) vs total beam power. Publication: https://ieeexplore.ieee.org/document/9115885

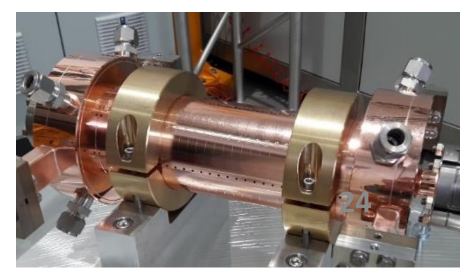
CLIC studies 2020-25

X-band technology:

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



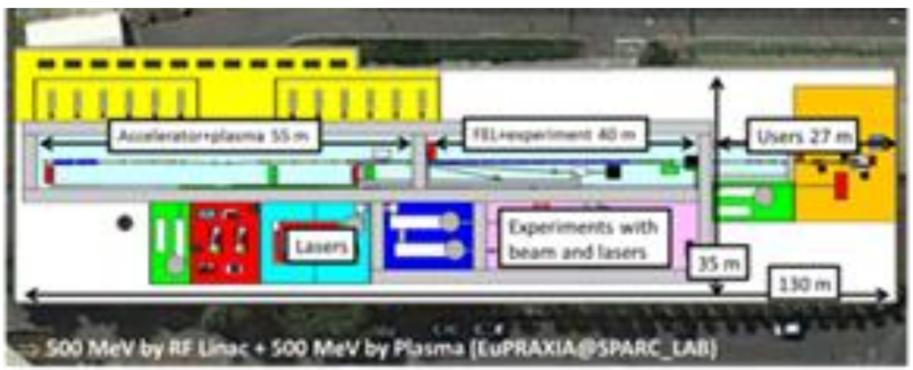




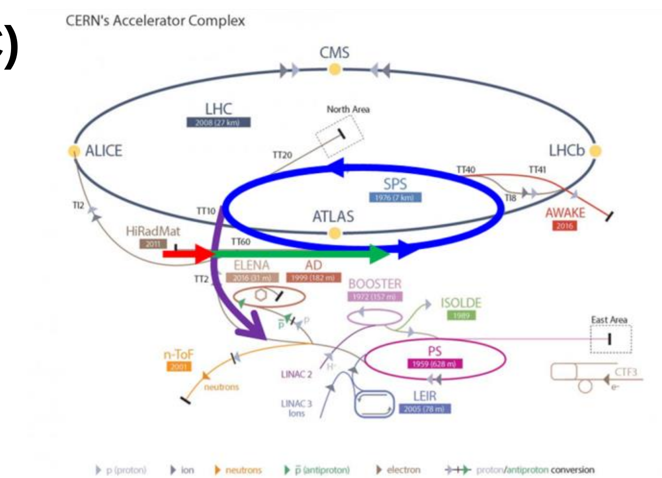
CLIC studies 2020-25

Applications of X-band technology:

- A compact FEL (CompactLight: EU Design Study 2018-21)
- Compact medical linacs (proton and electrons)
- Inverse Compton Scattering Source (SmartLight)
- Linearizers and deflectors in FELs (PSI, DESY, more)
- 1 GeV X-band linac at LNF
- eSPS for light dark matter searches (PBC)



⇒ 1 GeV by high gradient RF Linac only (EuSPARC)

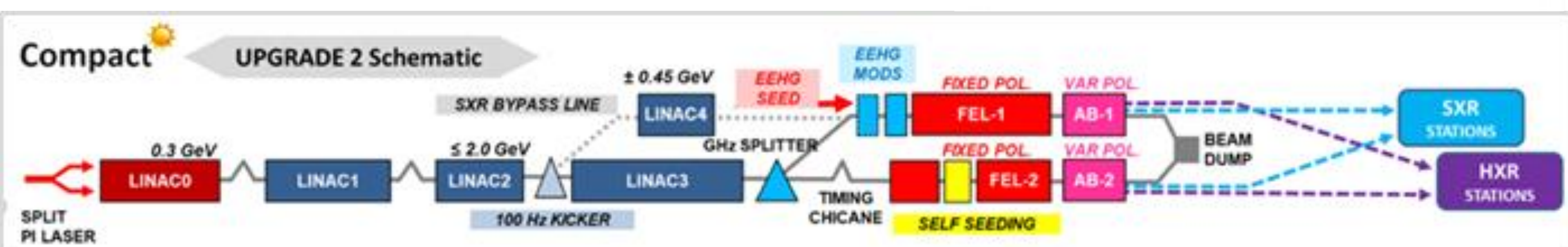


3.5GeV Linac

Transfer to SPS

Acceleration to in SPS

Extraction



CLIC studies 2020-25

Technical and experimental studies:

- **Injector studies suitable for X-band linacs (coll. with Frascati)**
- **Module studies (CLIC + other applications as just described)**
- **Beam dynamics and parameters: Nanobeams (focus on beam-delivery), pushing multi TeV region (parameters and beam structure vs energy efficiency)**
- **Tests in CLEAR (wakefields, instrumentation) and other facilities (e.g. ATF2)**
- **High efficiency klystrons …**

Summary

- CLIC is a mature project, 380 GeV initial stage ready for implementation
- The physics case is broad and profound, and being further developed
- The cost and implementation time are similar to LHC
- The detector concept and detector technologies R&D are advanced
- The full project status has been presented in a series of Yellow Reports and other publications: http://clic.cern/european-strategy
- CLIC offers a staged, flexible approach towards the energy frontier; keeps open other options (eg. circular colliders, muon collider) + provides a path to very high energies as accelerating technology advances: 3 TeV (100 MV/m X-band Cu structures)
  > 10 TeV (wakefield acceleration - ALEGRO)

Thanks to all CLIC collaborators for outstanding support

LINEAR COLLIDER COLLABORATION

Extra material

Energy studies - I

(Fraunhofer)

Topic 1:

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

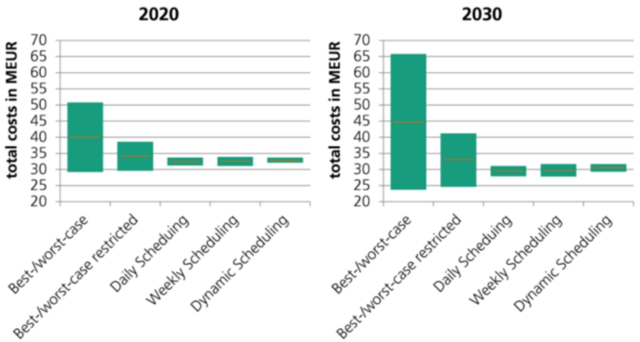


Figure 7.13: Relative energy cost by no scheduling, avoiding the winter months (restricted), daily, weekly and dynamic scheduling. As explained in the text the central values of the ranges shown should be considered the best estimates. The absolute cost scale will depend on prices, contracts and detailed assumption about running times, but the relative cost differences indicate that significant cost-reductions could be achieved by optimising the running schedule of CLIC to avoid high energy cost periods, also outside the winter shut-down periods. (image credit: Fraunhofer)

Energy studies - II

(Fraunhofer)

Topic 2:

- It is 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)
- However, self-sufficiency during all times can not be reached and only 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.
- Additional, the renewables are most efficient in summer, when prices are low anyway

Topic 3:

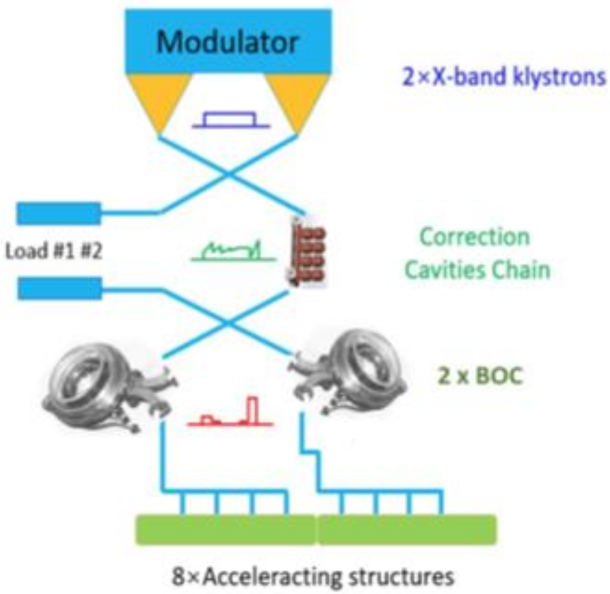
- The use of waste heat to generate electricity is technically difficult due to the low temperature of the waste heat. The heat would have to be raised to a significantly higher level and more electricity would be consumed than can be generated again in the later process.
- A reasonable option is to use the waste heat to provide space heating. Also for this option, the temperature must be raised via a heat pump and thus additional electricity must be used.
- Another possibility would be the research of further innovative concepts for the use of waste heat with very low temperature (for example very low temperature ORCs, thermoelectric generators or the storage of heat in zeolites).
- The fact that the maximum energy need locally is during the winter, when it is favourable of energy cost reasons to not run the accelerator, also makes is more difficult today to envisage efficient large scale energy recovery strategies.

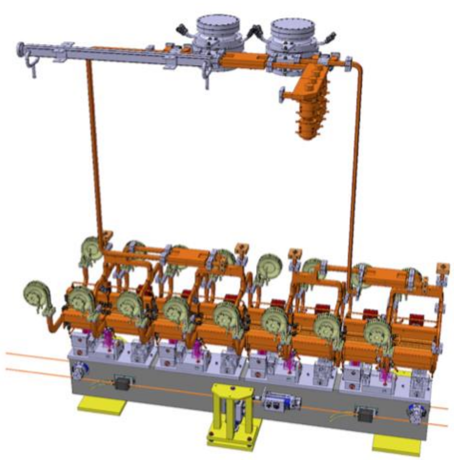
More in chapter 7.4.3 of the CLIC project plan (link)

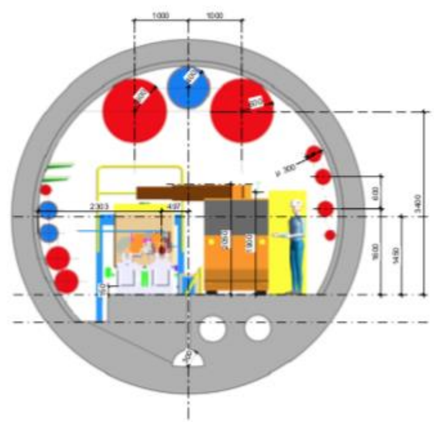
380 GeV klystron option

Replace drive-beam complex by local X-band RF power in tunnel

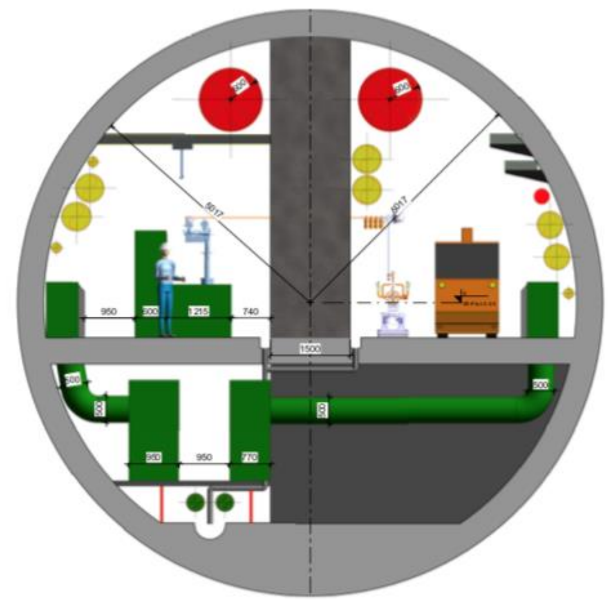
Simpler module, larger tunnel







(a)

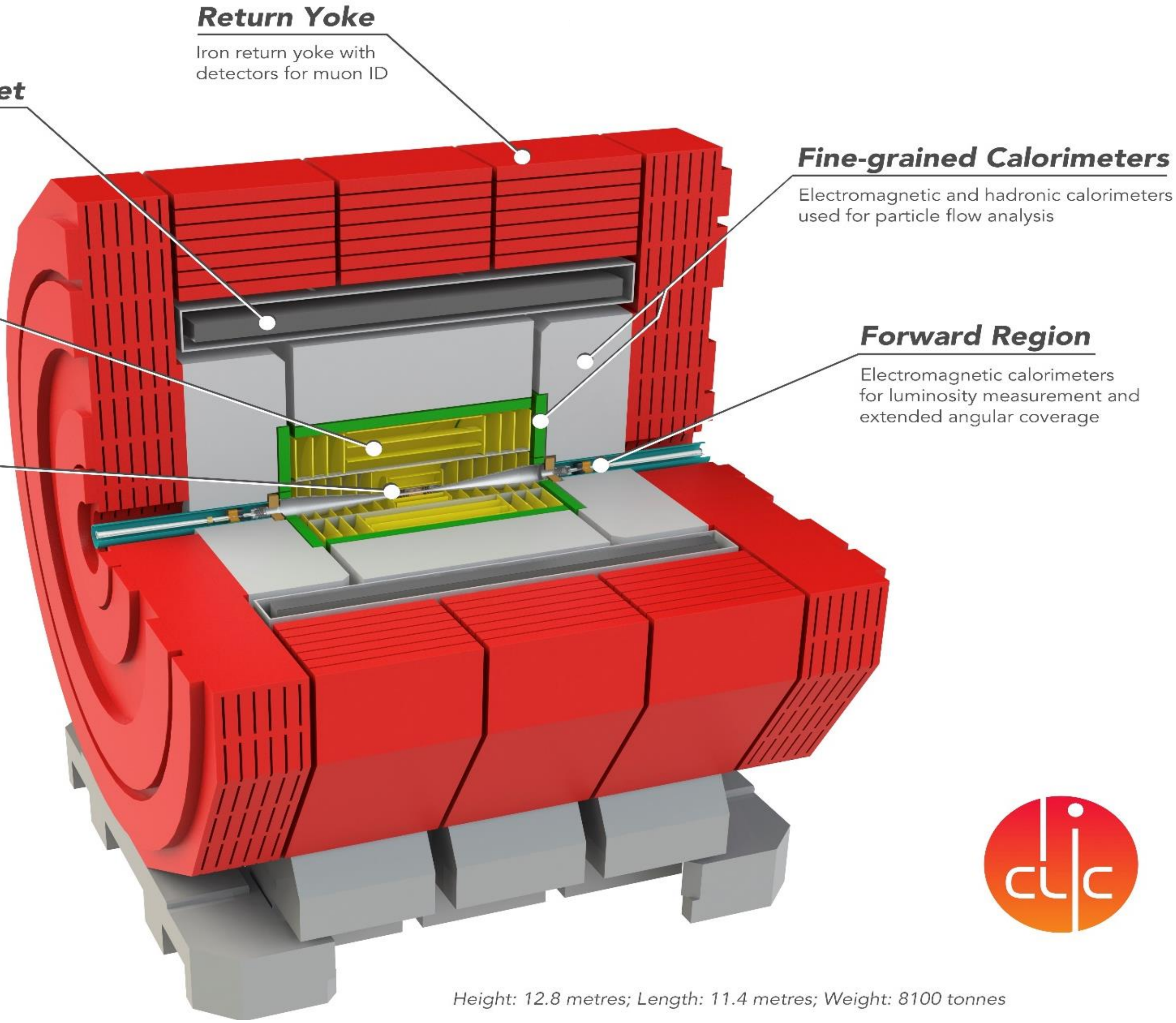


(b)

LINEAR COLLIDER COLLABORATION

CLIC detector

Mature CLICdet detector model; performance extensively validated:



Tracking detector
Material: 1–2% X_0 / layer
Single-point resolution: 7 micrometres

Vertex detector
25 micrometre pixels
Material: 0.2% X_0 / layer
Single-point resolution: 3 micrometres
Forced air-flow cooling

Electromagnetic calorimeter
40 layers (silicon sensors, tungsten plates)
Material: 22 X_0 + 1 λ_I

Hadronic calorimeter
60 layers (plastic scintillators, steel plates)
Material: 7.5 λ_I

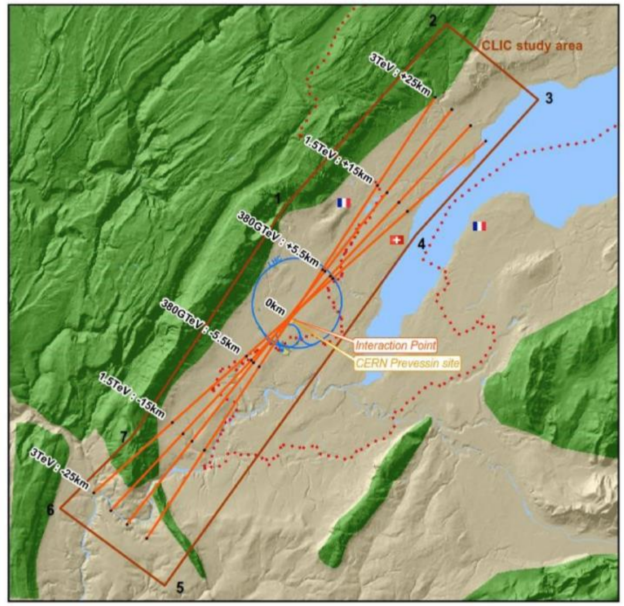
Learn more about the CLIC detector at clic.cern

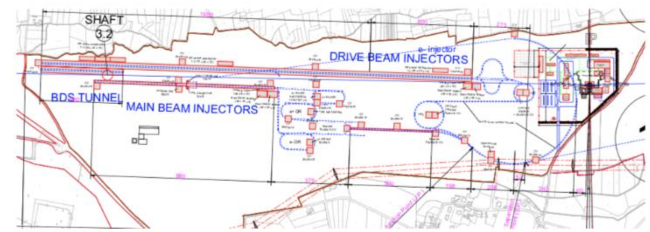
Civil Engineering and Infrastructure Studies

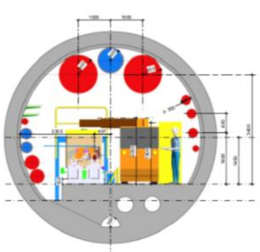
Important effort within:

- **Civil engineering**
- **Electrical systems**
- **Cooling and ventilation**
- **Transport, logistics and installation**
- **Safety, access and radiation protection systems**

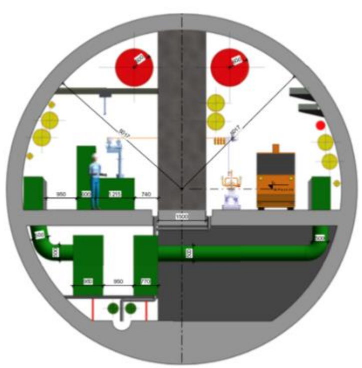
Crucial for cost/power/schedule



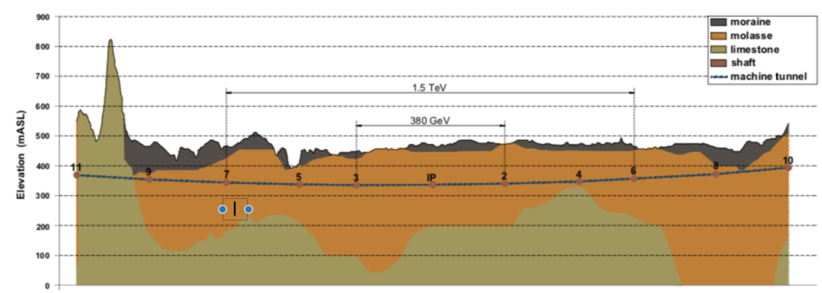




(a)

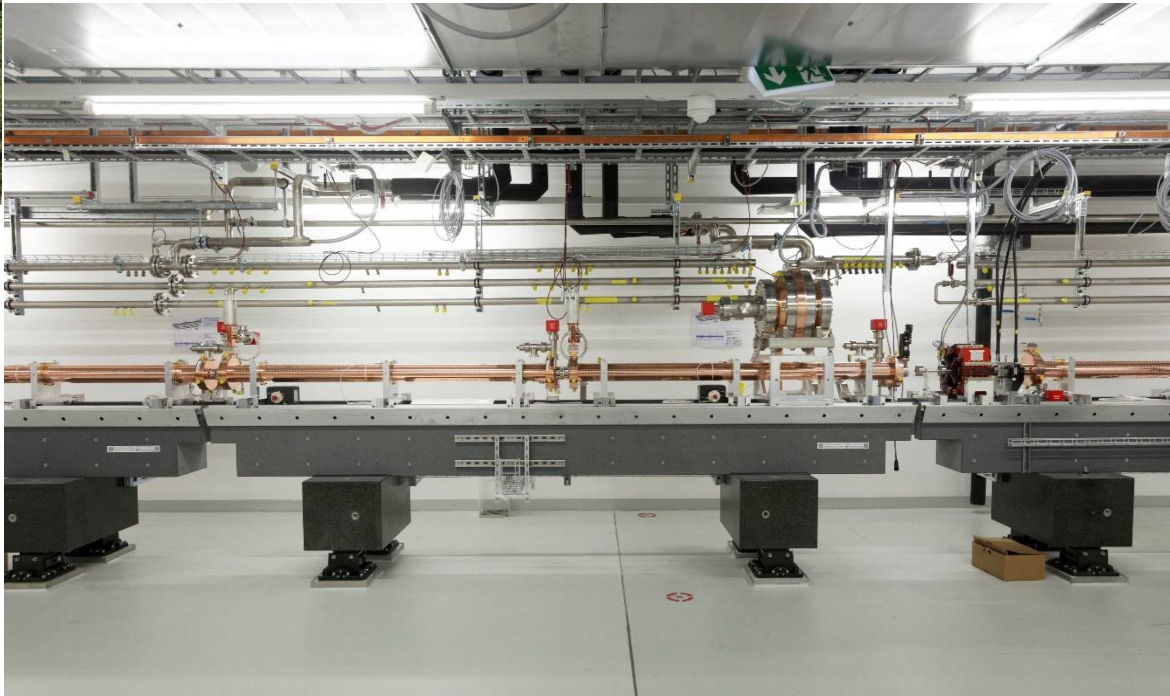


(b)

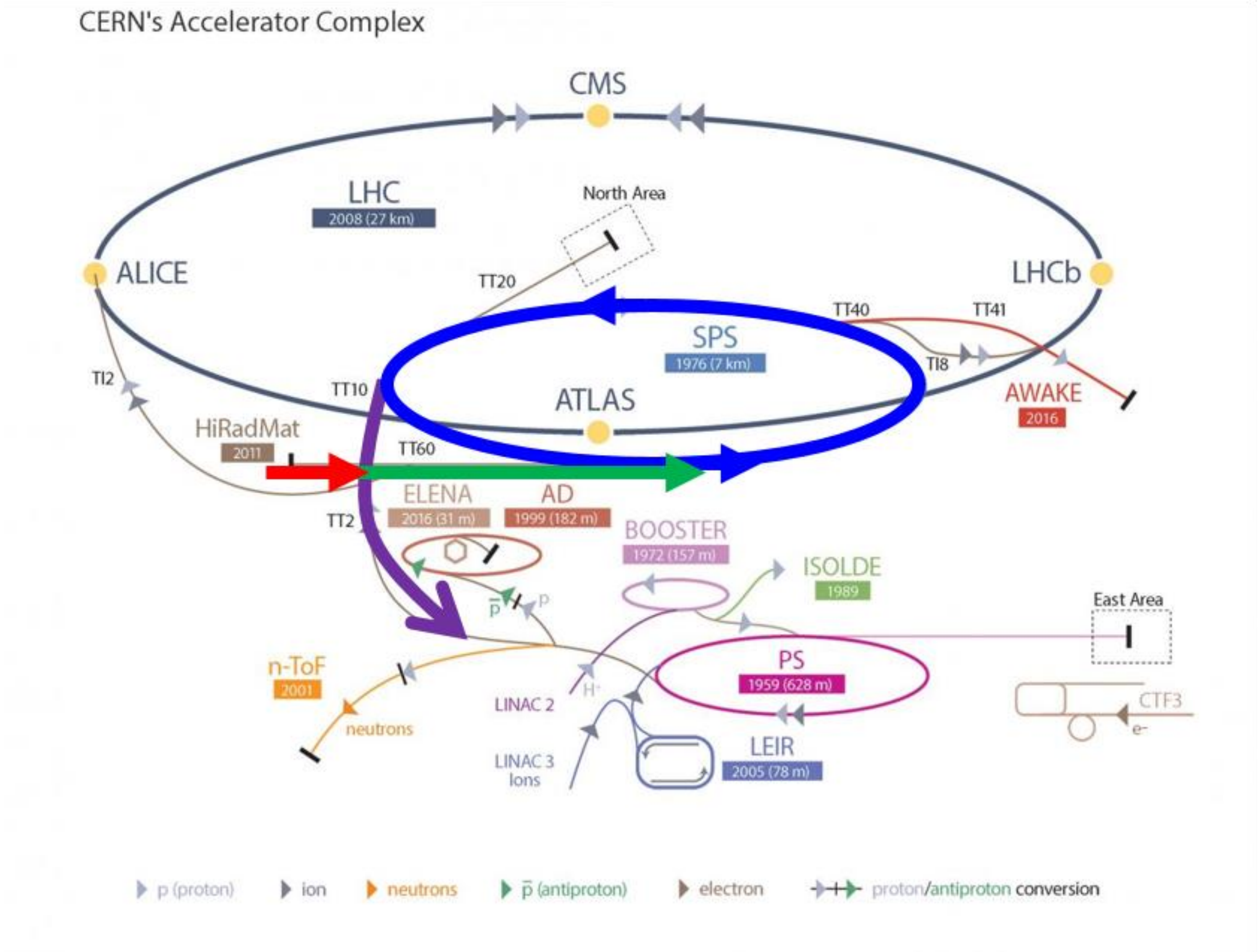


SwissFEL

- 104 x 2m-long C-band structures
  (beam → 6 GeV @ 100 Hz)
- Similar um-level tolerances
- Length ~ 800 CLIC structures



eSPS proposal



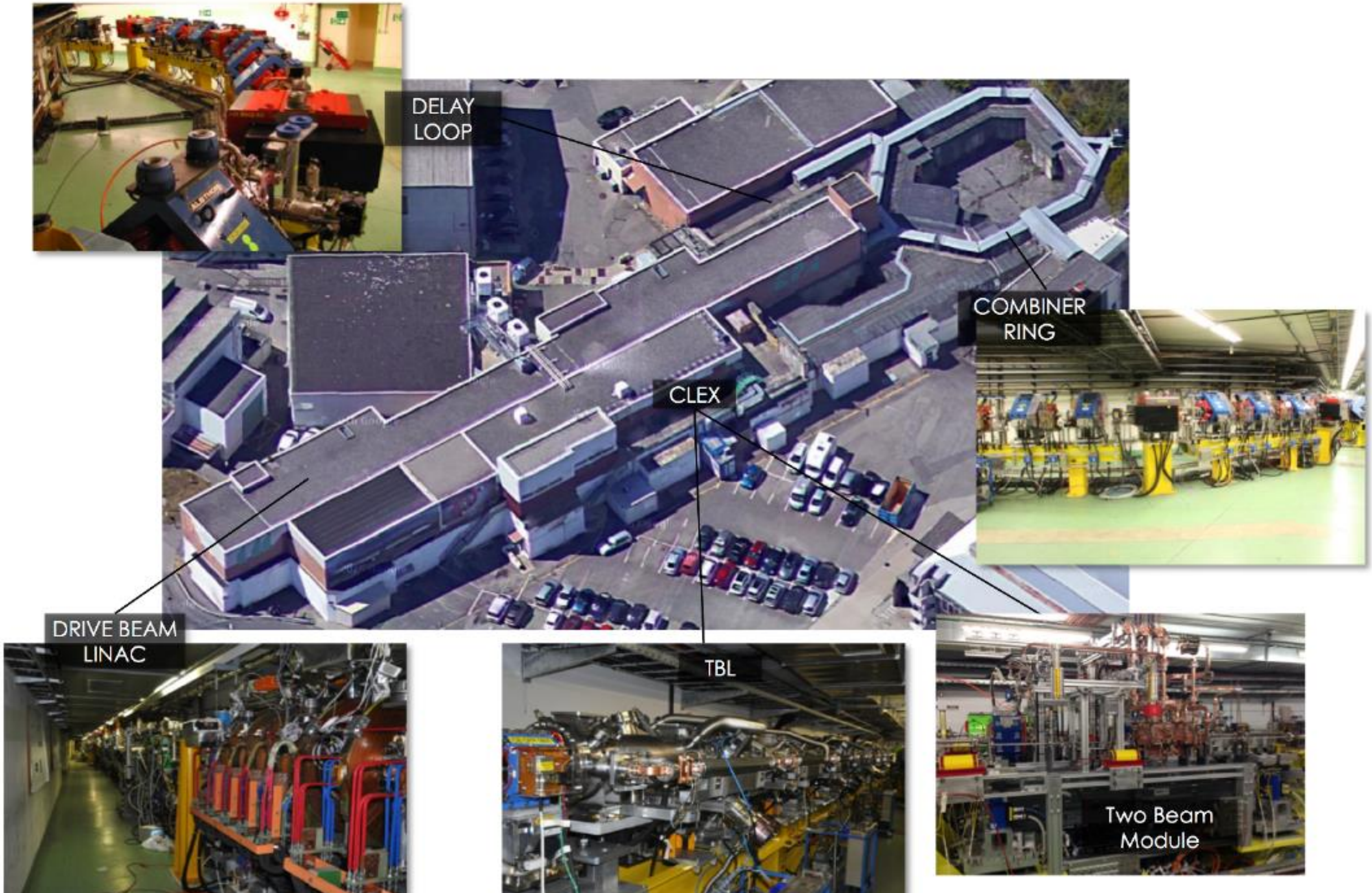
3.5GeV Linac

Transfer to SPS

Acceleration to in SPS

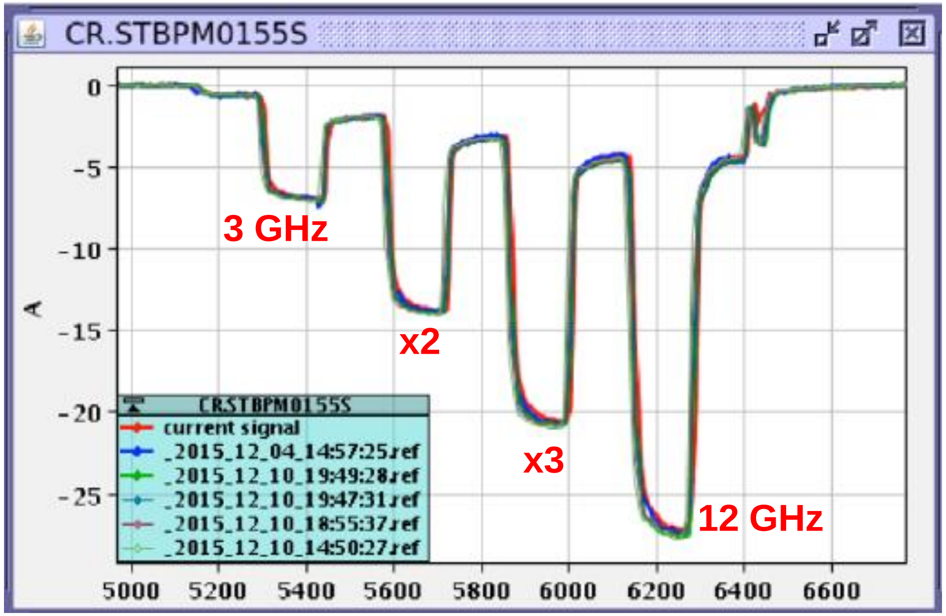
Extraction

CLIC Test Facility (CTF3)



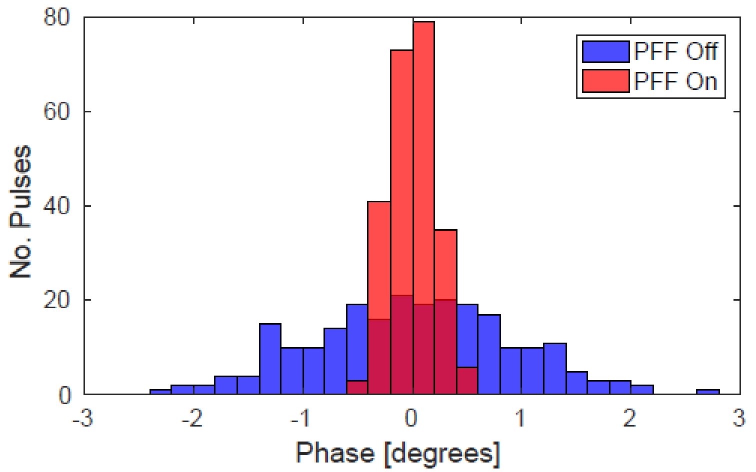
Status

- **Produced high-current drive beam bunched at 12 GHz**



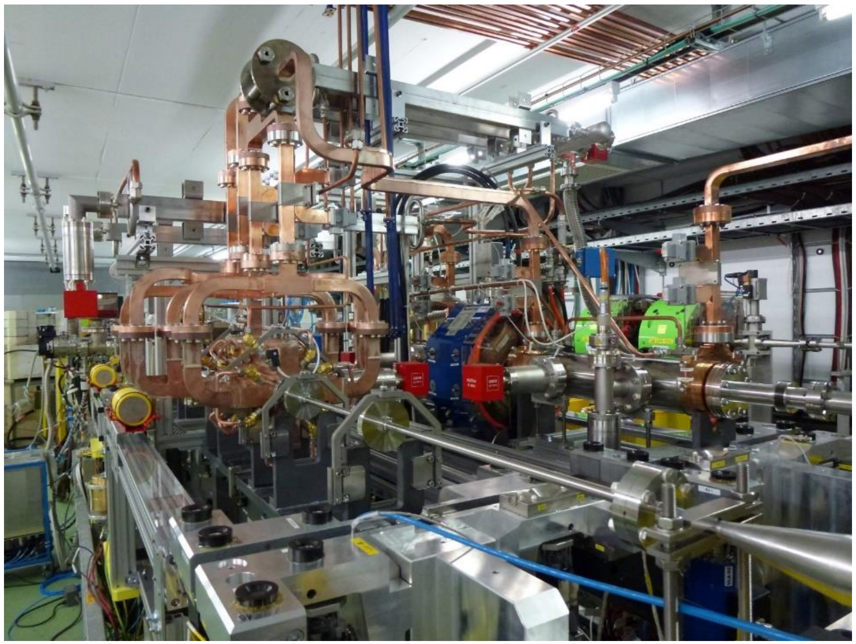
28A

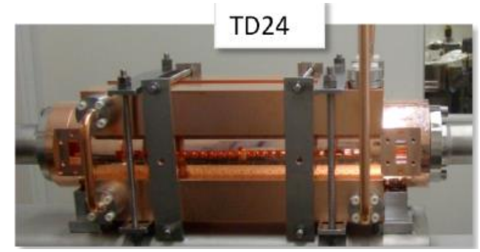
Arrival time stabilised to 50 fs



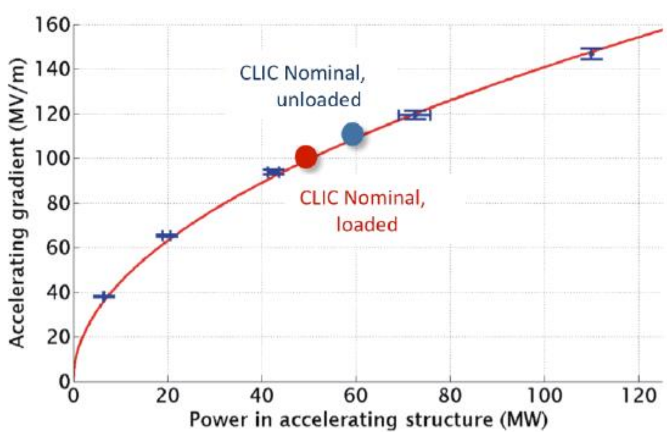
Status

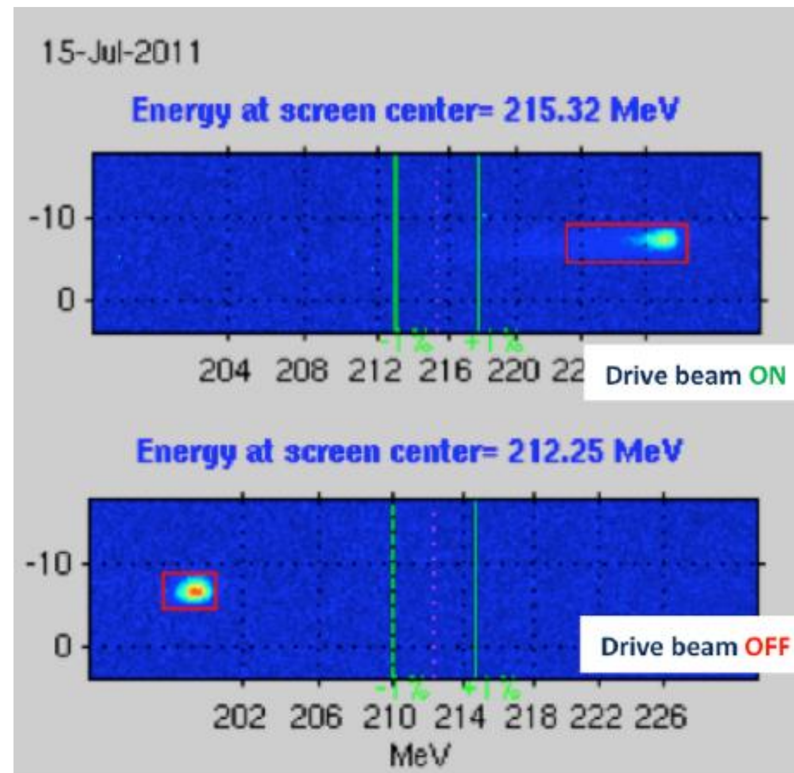
- **Demonstrated two-beam acceleration**





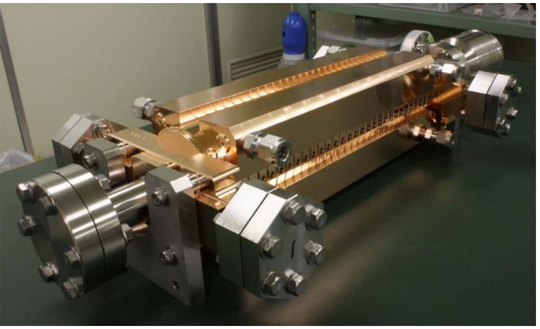
31 MeV = 145 MV/m

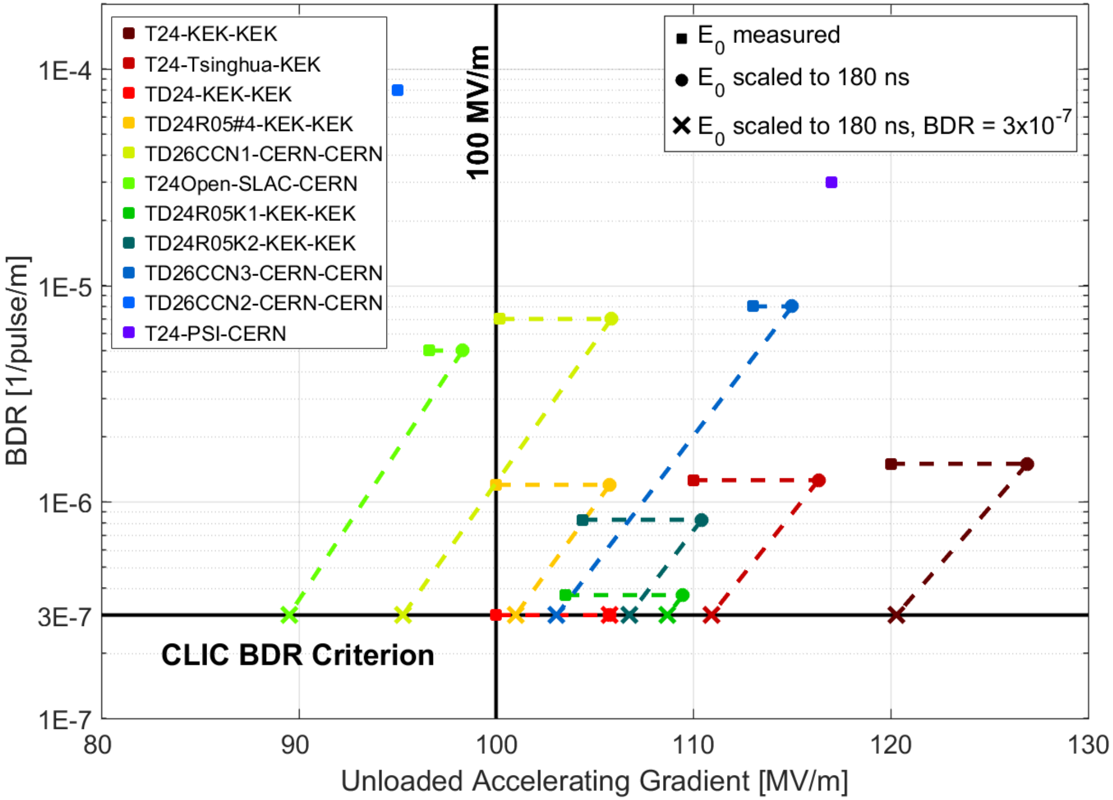


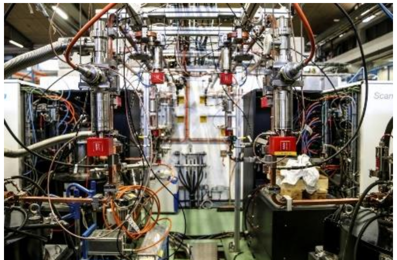


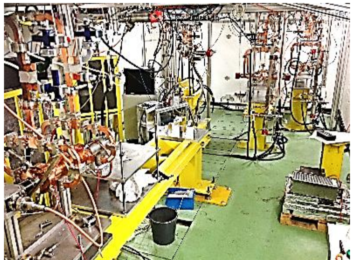
Status

- **Achieved 100 MV/m gradient in main-beam RF cavities**









Updated CLIC luminosity model

First-stage construction period ends with one year of beam commissioning with the whole machine before Lumi starts

Luminosity ramp-up:

380 GeV:	**10%, 30%, 60% then nominal L (same as ILC)**
1.5 TeV:	**25%, 75% then nominal L**
3 TeV:	**25%, 75% then nominal L**

Updated CLIC availability model

Task force study of LHC + modern light sources;

→ CLIC availability model common with FCCee

120 days	**winter shutdown (17 weeks)**
30 days	**commissioning**
20 days	**machine development**
10 days	**technical stops**
185 days	**physics @ 75% efficiency**
	→ 1.2 107 s (c.f. ILC 1.6 10**7 s)**

Full project schedule