CLIC accelerator developments

Philip Burrows

Oxford University

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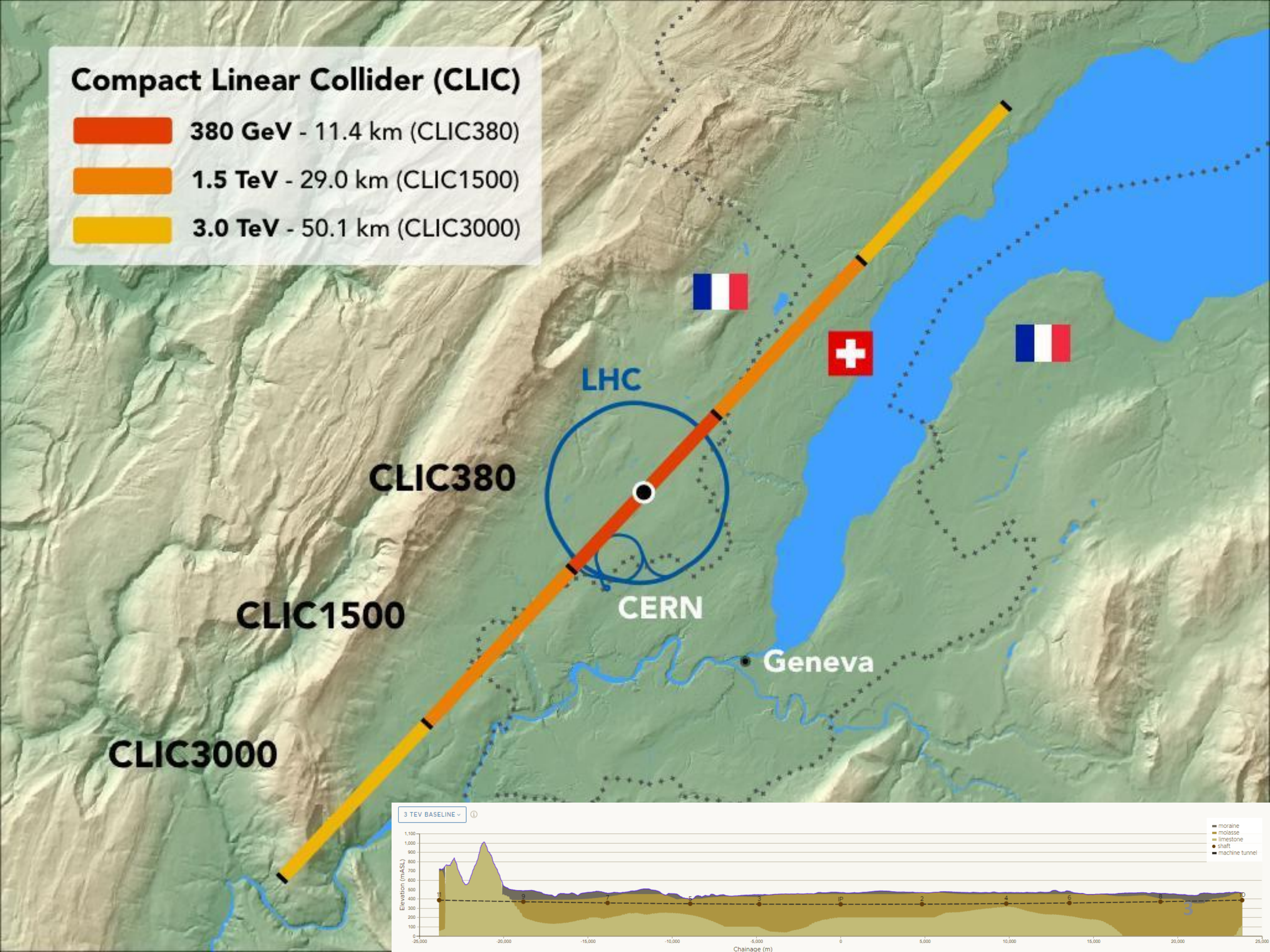
On behalf of the CLIC team

https://clic.cern

CLIC overview

- **Timeline:** e+e- linear collider at CERN for the era beyond HL-LHC
- **Compact:** novel and unique two-beam accelerating technique based on high-gradient room-temperature X-band RF cavities:

  first stage: 380 GeV, ~11km long, 20,500 cavities
- **Expandable:** staged collision energies from 380 GeV (Higgs/top) up to 3 TeV


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)

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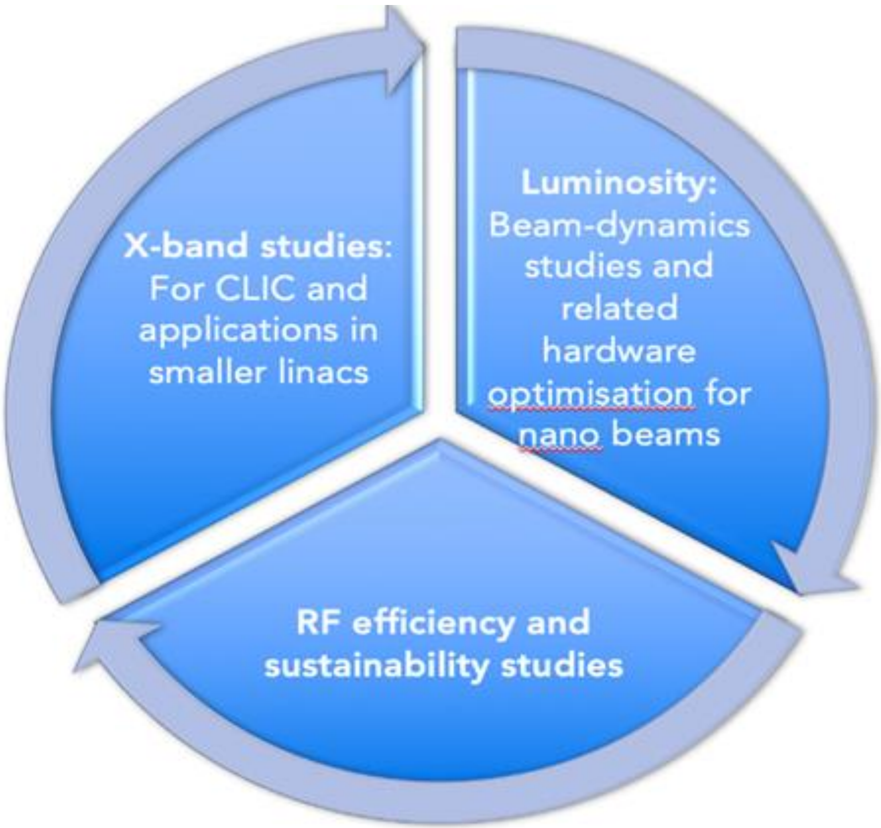
- Conceptual Design Report published in 2012
- Project Implementation Plan released in 2018: Cost: 5.9 BCHF for 380 GeV
- Status report: Snowmass 'white paper' 2022: https://arxiv.org/abs/2203.0918
- Comprehensive Detector and Physics studies – see other sessions
- Preparing CLIC Readiness Report for 2026 European Strategy Update

CLIC project readiness → 2025/26



CLIC Readiness Report as a step toward a TDR – for next European Strategy Update

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**

Plans for CLIC Readiness Report

- 380 GeV + 2 TeV (single drive beam); consider also 250 GeV @ 100Hz
- Luminosity performance update, including beam dynamics, nanobeam studies, and positron production (all energies)
- Energy, power, sustainability …
- Sustainability issues: running/energy models, CO2-eq Life Cycle Assessment (LCA): construction + operation + decommissioning
- X-band progress: CLIC, smaller facilities, industry
- RF design optimization/development – including injectors, R&D for higher gradients - links to wakefield acceleration where relevant
- Cost update w.r.t. to 2018, including impacts of more sustainable design
- Physics performance update including 'diversity' experiments eg. LDM
- Low cost/power klystron version (with fewer klystrons) @ 250 GeV

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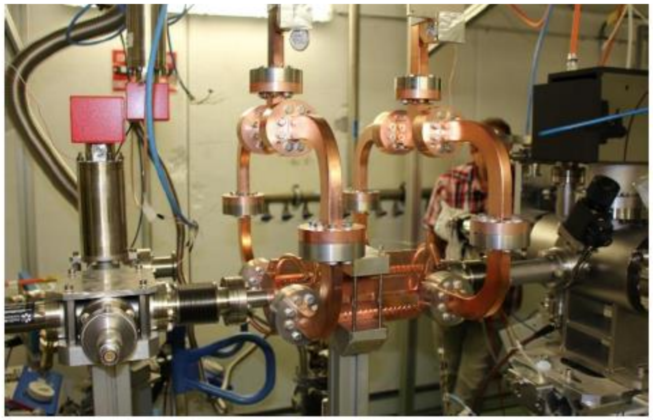
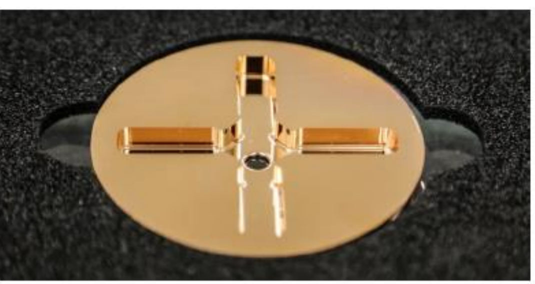
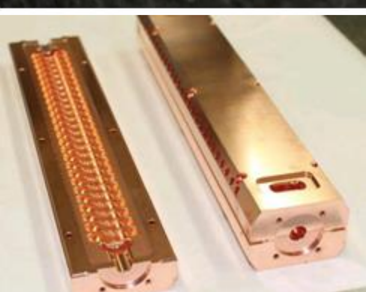
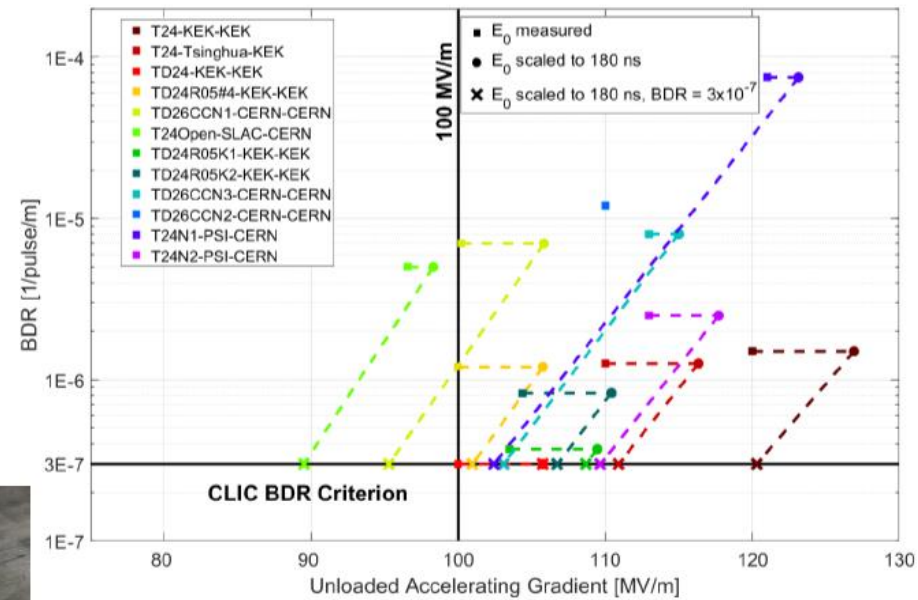
CLIC X-band structure development



Test structure





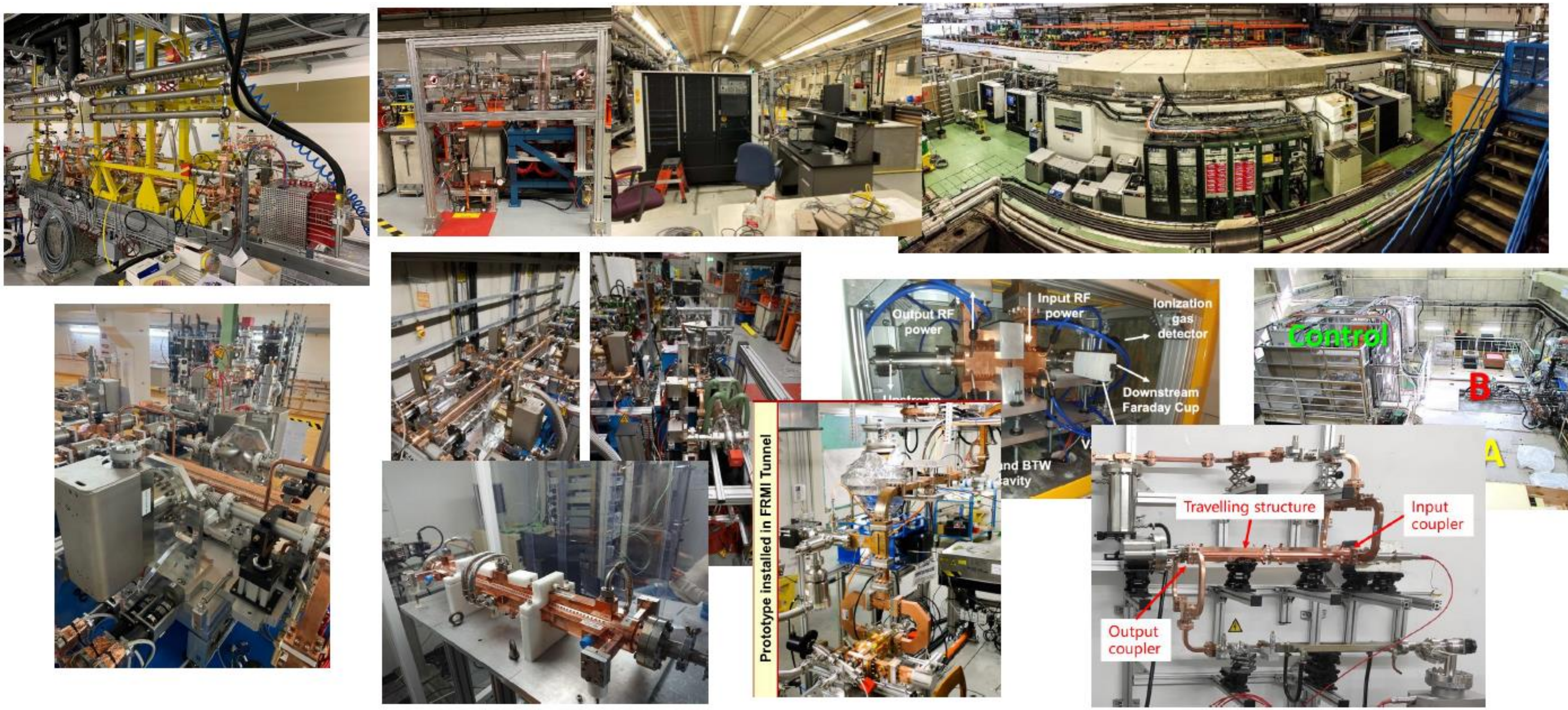


Achieved accelerating gradients in tests

→ **Emphasis on industrialising processes via collaboration with manufacturers**

→ **Collaboration with C**3**

Global X-band deployment



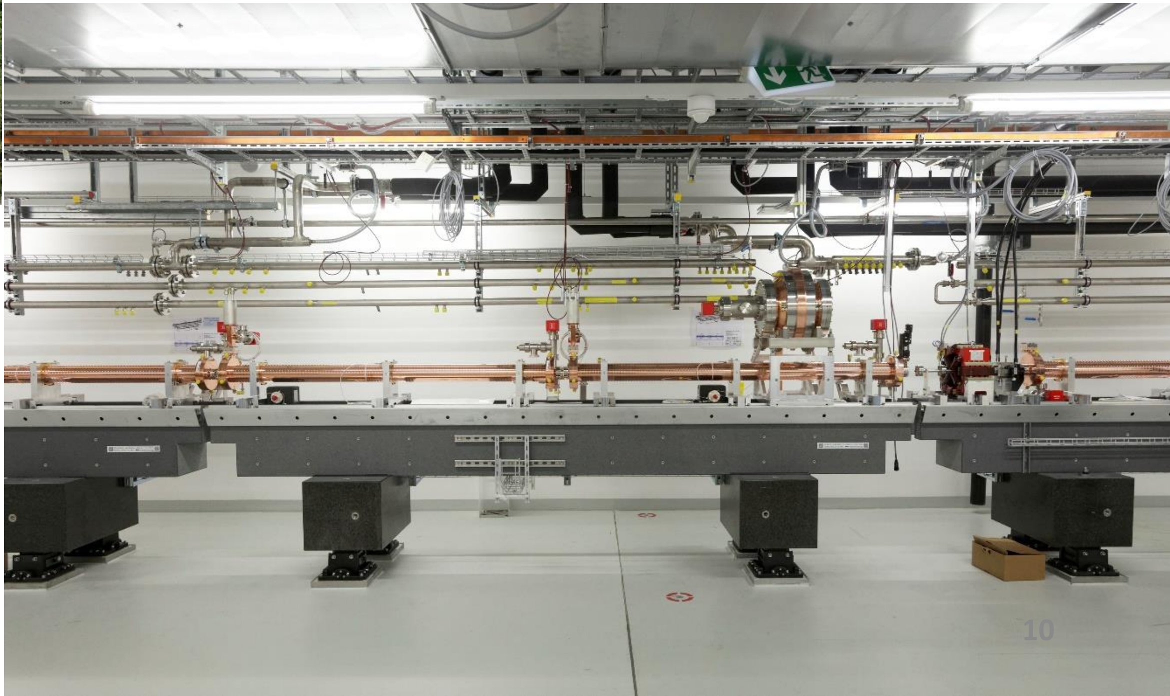
- Trieste, FERMI: Linearizer
- SwissFEL: Linearizer and PolariX deflector
- SARI: Linearizer, deflectors
- CERN: XBox-1 with CLEAR, accelerator
- DESY: FLASHForward and FLASH2, PolariX deflectors
- SLAC: NLCTA, XTA
- Argonne: AWA

- 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

- 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

SwissFEL

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



Industry X-band power sources

CPI:
50 MW: 15 tubes operating
59 MW high-efficiency
10 MW

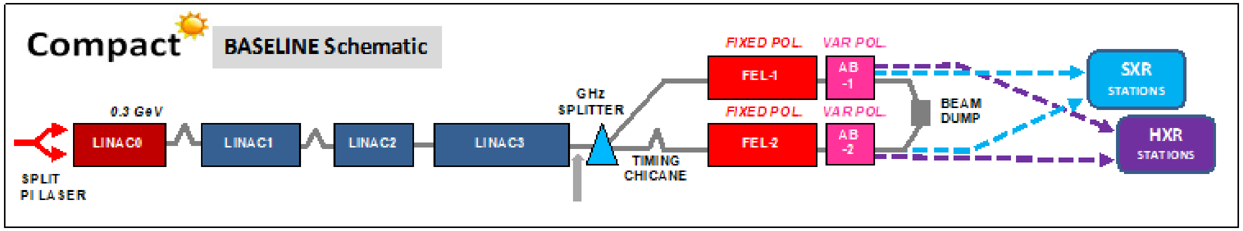
Canon:
6 MW (~10 tubes)
8-10 MW high-efficiency
20 MW

BVERI: 50 MW (2 tubes)
Hitachi: MgB2 solenoid

→ Emphasis on higher efficiency

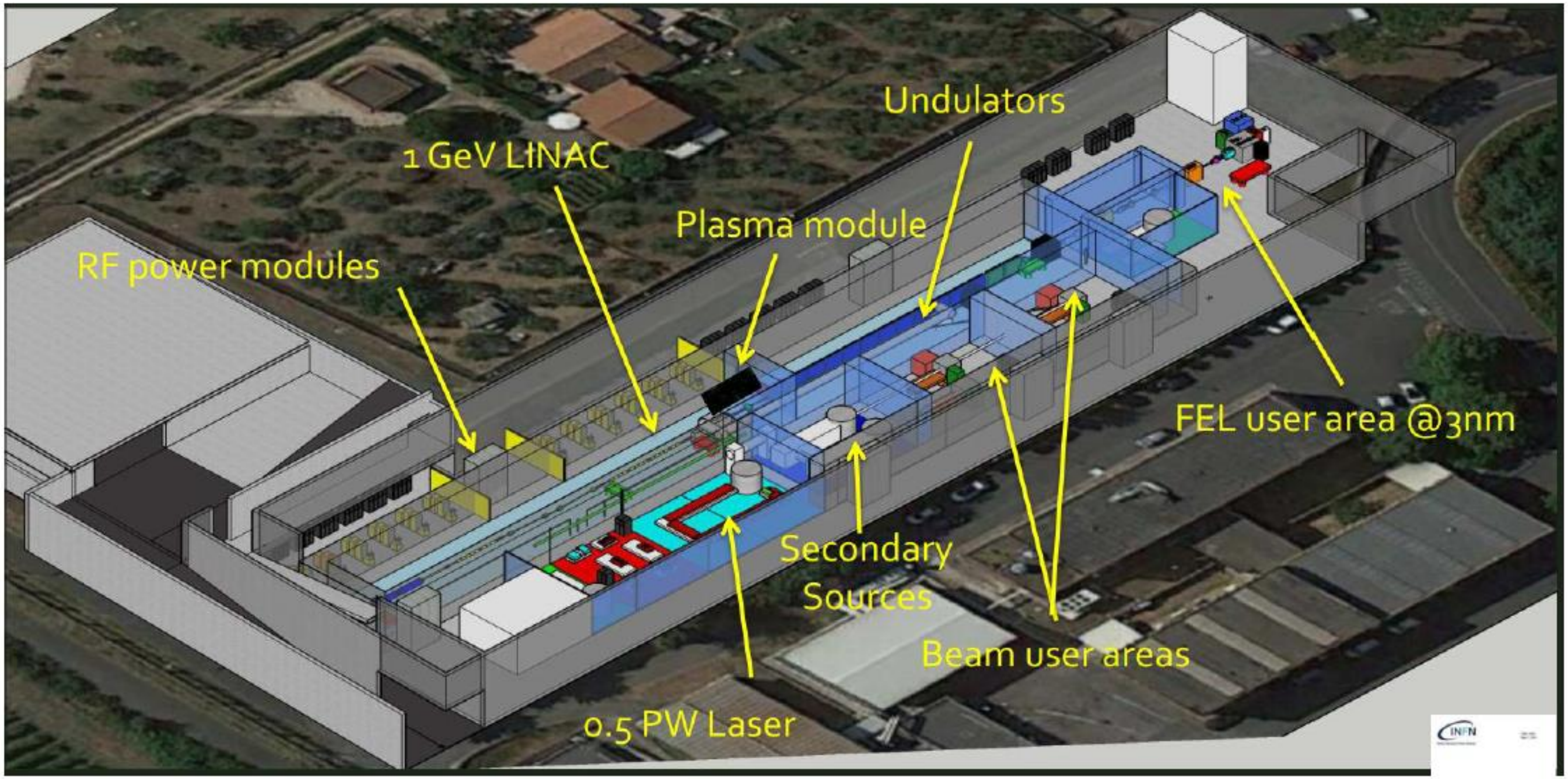
X-band technology applications

Compact XFEL (CompactLight)



EuPraxia@SPARC_LAB

Combining 1 GeV x-band linac with beam driven plasma wake field acceleration



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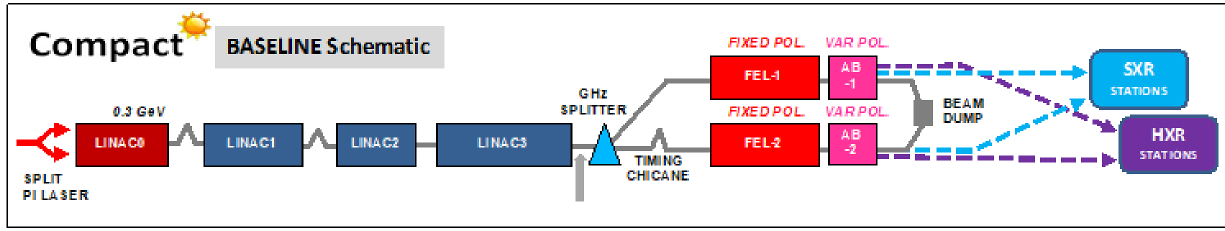
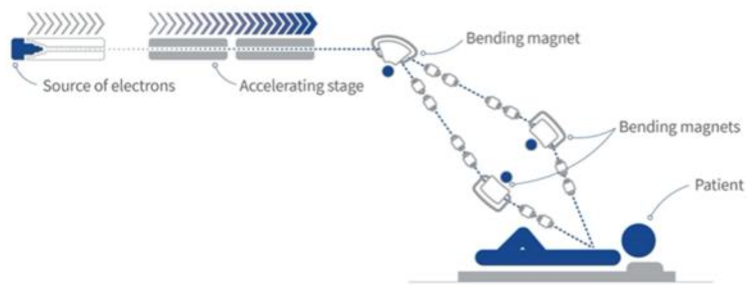


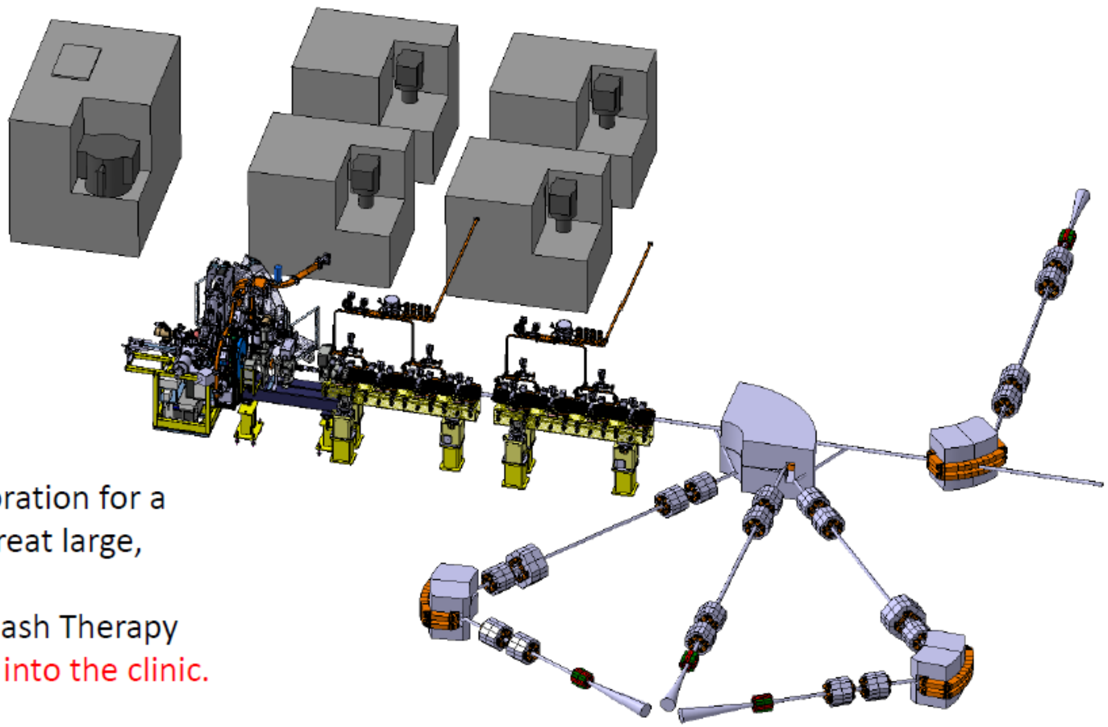
VHEE FLASH therapy (DEFT @ CHUV)




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

The DEFT concept



S-band photo injector
CLIC type accelerating modules

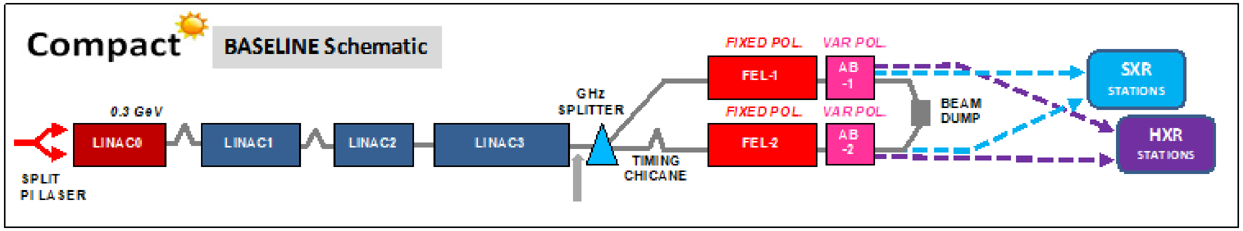
CHUV and CERN collaboration for a VHEE FLASH facility to treat large, deep-seated tumors.
DEFT – Deep Electron Flash Therapy
Taking VHEE *and* FLASH into the clinic.

Technology transfer to industry

Treatment from three directions in < 0.1 s

X-band technology applications

Compact XFEL (CompactLight)



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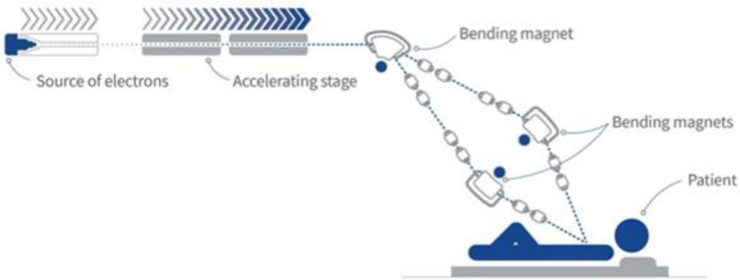

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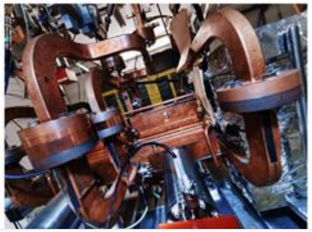
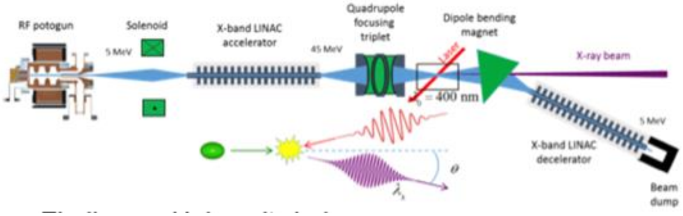
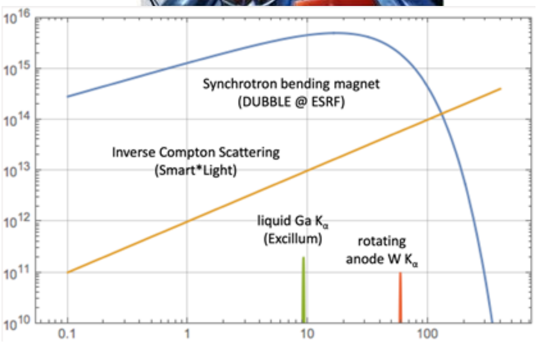


Inverse Compton Scattering source (Smart*Light)

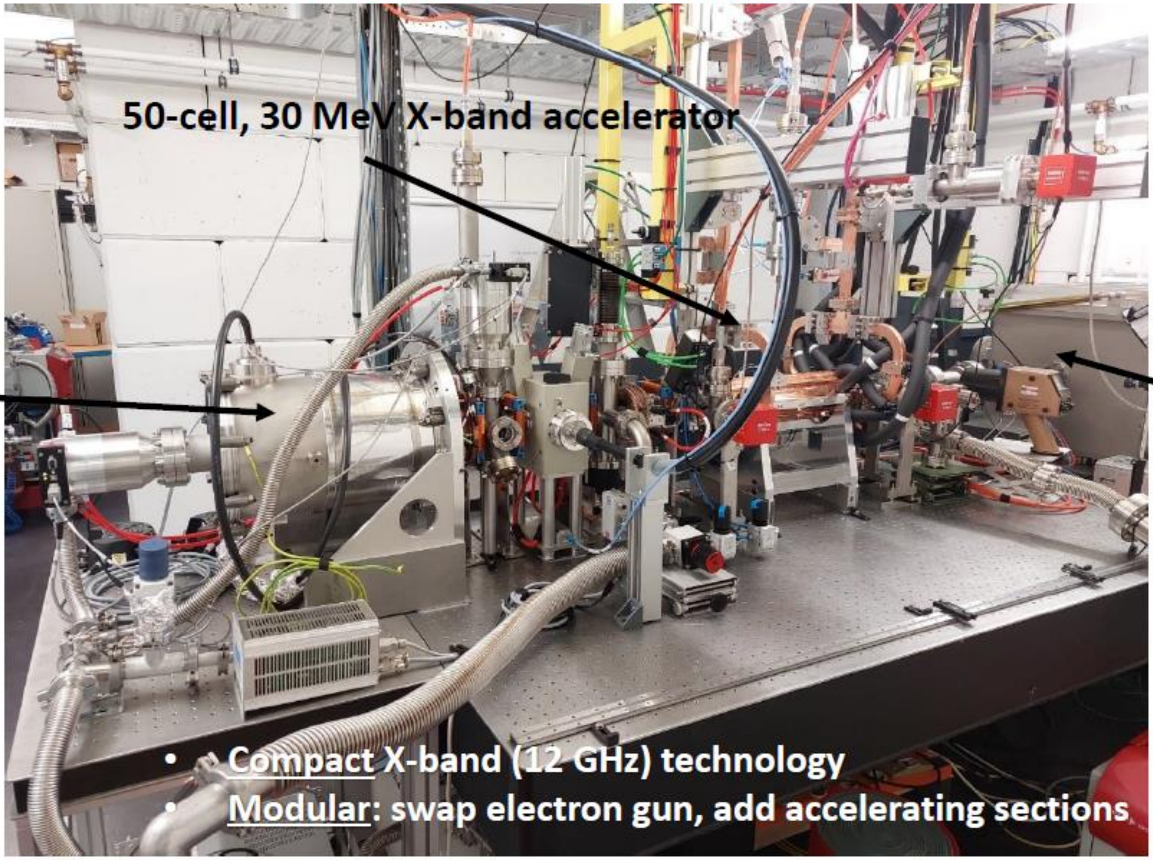




Smart*Light: a linear-accelerator-based ICS source

a real tabletop instrument

100 keV DC
electron gun



Under
commissioning

Interaction
chamber

X-band technology applications

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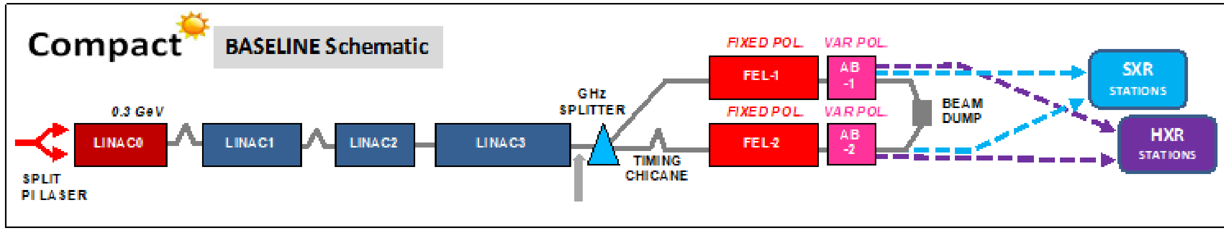

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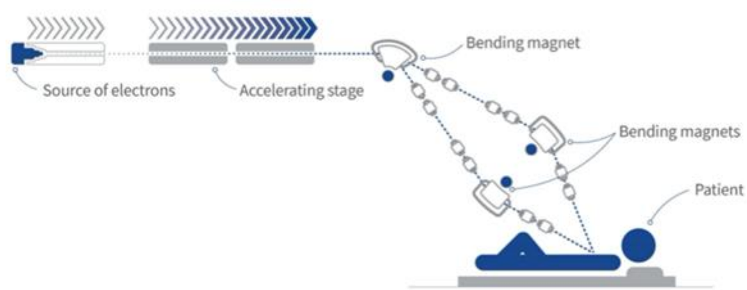

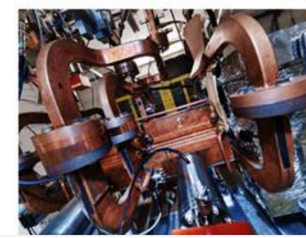
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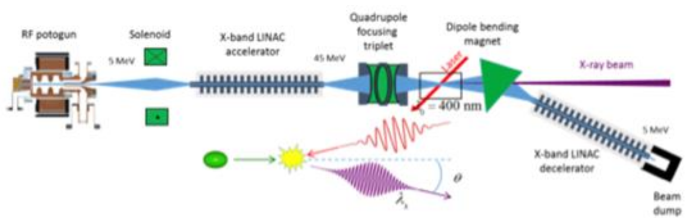
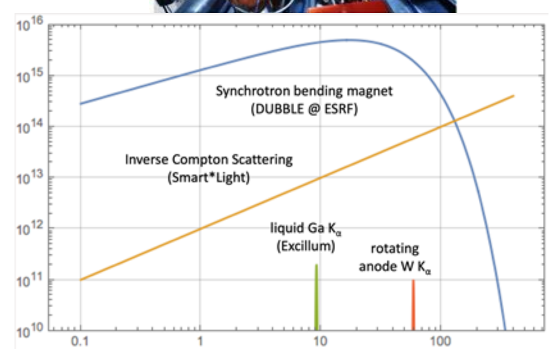
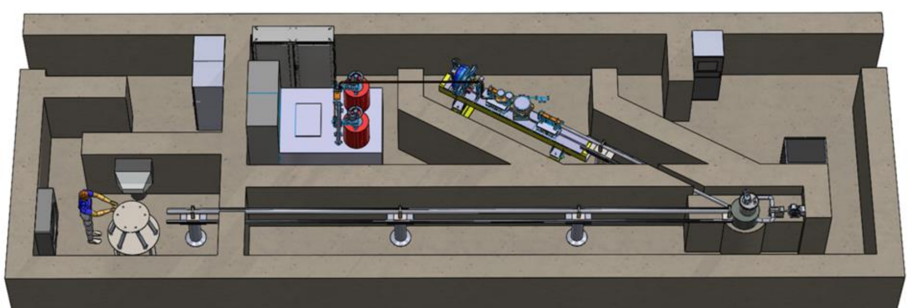




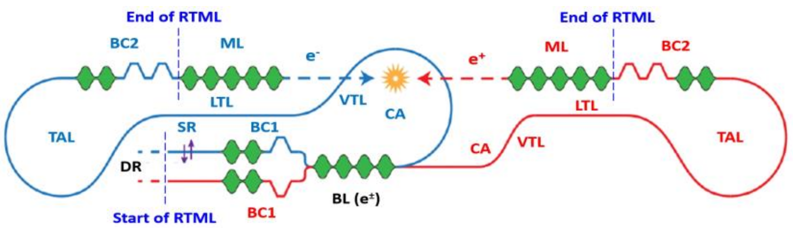
Neutron source (VULCAN)



Beam Dynamics: Injector improvements

Positron production:

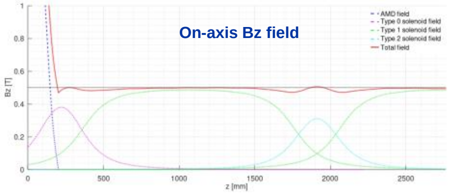
- Re-optimised using **realistic start-to-end simulation** reaches **positron yield: ~2**

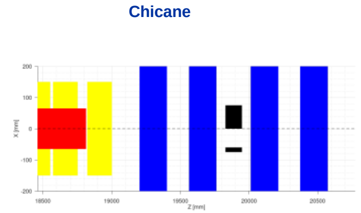


Rings-to-main-linac, RTML:

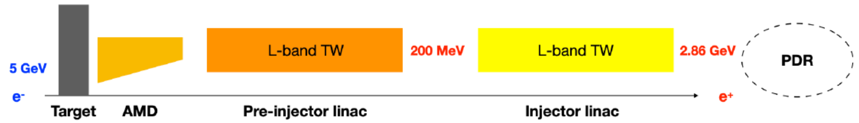
- Complete redesign of **Bunch compressor 2's X-band RF powering** and beam dynamics optimisation
  - Significant **power consumption reduction ~50%**

Beam Delivery System: studies at **7 TeV c.o.m**





- Schematic layout (**new baseline**) of the CLIC positron source



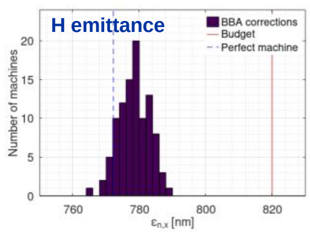
Accepted e⁺ yield: $\eta = \frac{N_{e^+}^{\mathrm{PDR}}}{N_{e^-}^{\mathrm{Primary}}} = 2$

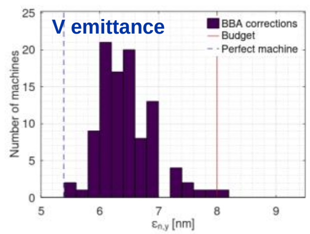
Y. Zhao, Wednesday, 2pm (Beam Dynamics) and 4pm (Sources); E. Manosperti, Wednesday 2:40pm, 4:45pm

Beam Dynamics: tuning performance boost

- **Advanced tuning procedures for smaller emittance growth even with realistic imperfections:**
  - **In the linac,** new emittance tuning knobs achieve < 1 nm (or even 0.5 nm!) emittance growth
  - **In the RTML,** emittance budgets are met with nearly 100% CL for both static and dynamic imperfections

RTML performance:
99% machines meet the emittance budgets



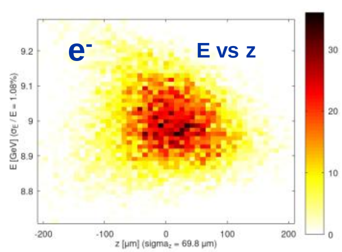


e^-

Parameter	Symbol	Unit	Value
Bunch length	σ_z	μm	70.4
Energy spread	σ_E/E	%	1.07
Horizontal normalised emittance	$\epsilon_{n,x}$	nm	773.8
Vertical normalised emittance	$\epsilon_{n,y}$	nm	5.40

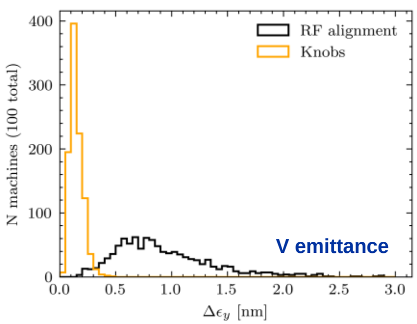
e^+

Parameter	Symbol	Unit	Value
Bunch length	σ_z	μm	68.6
Energy spread	σ_E/E	%	1.08
Horizontal normalised emittance	$\epsilon_{n,x}$	nm	763.1
Vertical normalised emittance	$\epsilon_{n,y}$	nm	5.08



Linac tuning:

- With a set of emittance tuning knobs it is possible to reduce the emittance growth down to < 0.5 nm

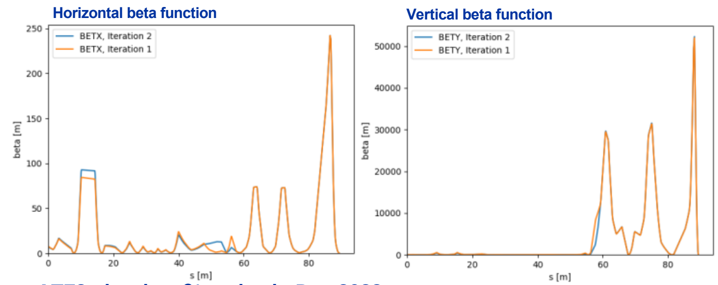


- Emittance tuning knobs provide additional margin for the emittance budget.
- Another set of the emittance tuning knobs can be used to assist the RF alignment.

Y. Zhao, Wednesday, 2pm

A. Pastushenko, Wednesday, 2:20pm

CLIC contributions to ATF2

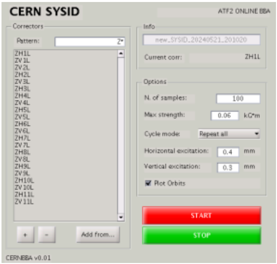


ATF2 ultra-low β* optics in Dec 2023

First measurements after COVID in Dec 2023:

Ultra-low β* studies

- Reviving the tuning procedures
- Including octupole knobs

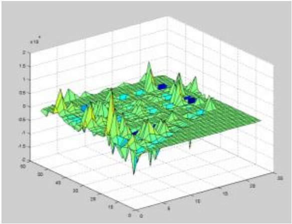


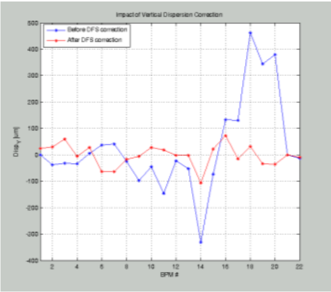
Automatic steering

Automatic Beam-Based Alignment and Flight Simulator

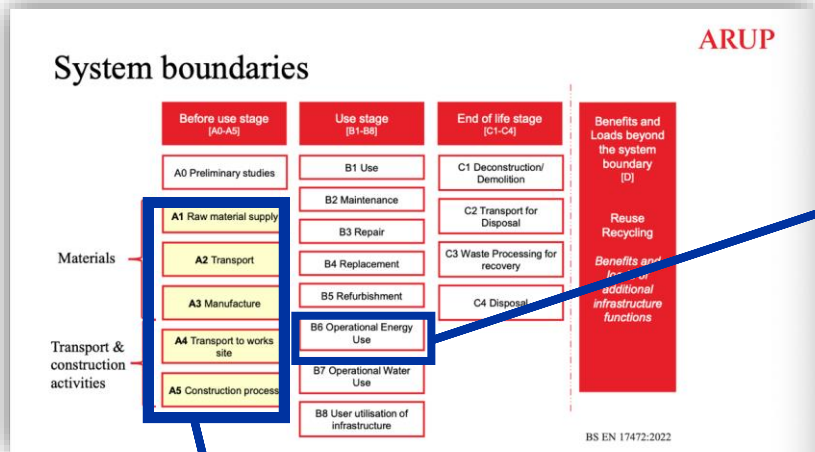
- Reviving EXT line correction
- BBA extended to **Linac**
- Plan to extend to **Damping Ring**
- New **Flight Simulato**r development started in Python

A. Pastushenko, Tuesday, 11:45am


Linac response matrix

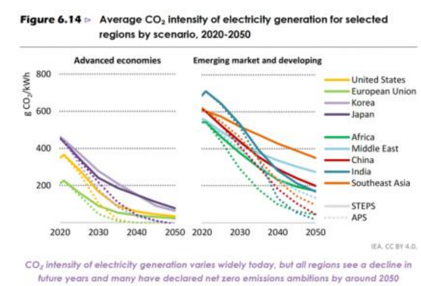

Dispersion correction in the linac

Sustainability: towards a Life Cycle Assessment (LCA) for LCs



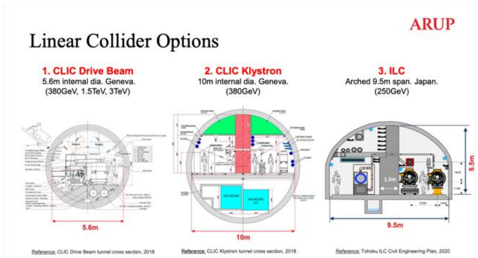
What is the carbon intensity of energy in ~2050 (operation):

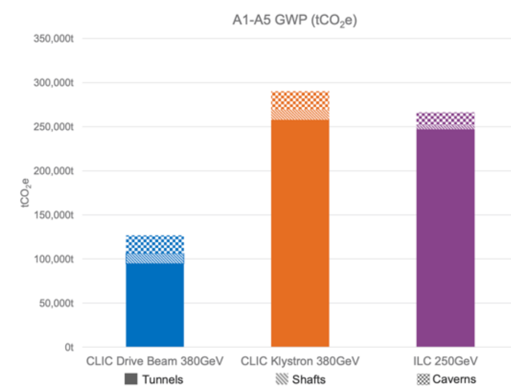
- 50% nuclear and 50% renewable give ~10-15g/kWh
- France summer-months are today ~40g/kWh
- ILC has a green implementation concept including compensation and contracting renewable energy
- Reductions predicted (LINK)



LCA report for Civil Engineering: LINK

Addressing the Civil Engineering impact





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

Steinar Stapnes

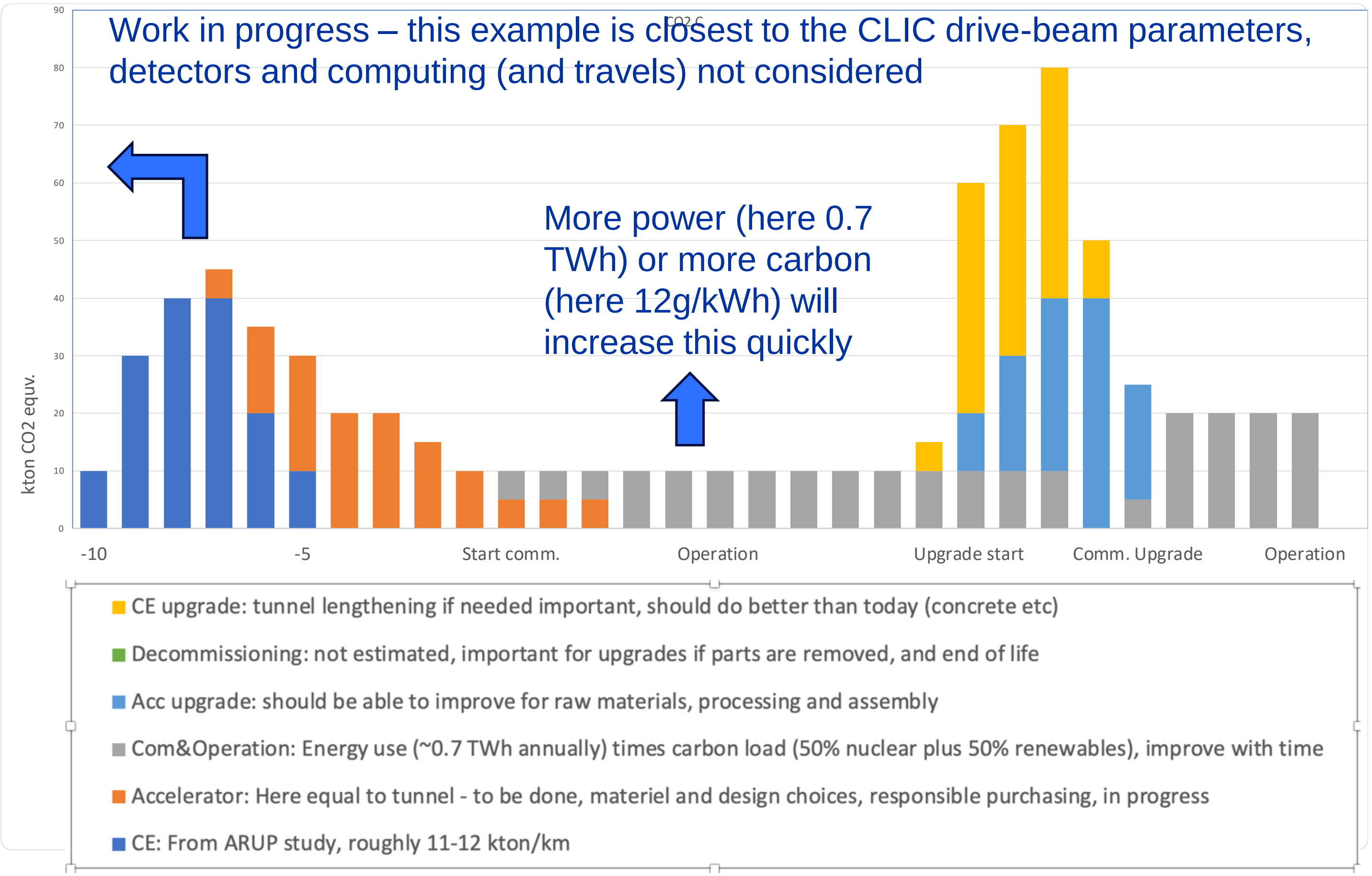
Towards Carbon Accounting with LCA

Work in progress – this example is closest to the CLIC drive-beam parameters, detectors and computing (and travels) not considered

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

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

More power (here 0.7 TWh) or more carbon (here 12g/kWh) will increase this quickly



Steinar Stapnes

Summary

CLIC technology is being advanced via application projects:

FELs, Inverse Compton Scattering, medical, neutron source …

Beam dynamics developments are improving performance:

Positron sources, RTMLs, linac tuning, nanobeams @ ATF2

Life-Cycle Assessment studies are making progress:

Civil engineering → accelerator components + operations

Preparing CLIC Readiness Report for European Strategy Update 2026

Thanks to CLIC colleagues

Steffen Doebert, Angeles Faus-Golfe, Andrea Latina, Vlad Musat, Steinar Stapnes, Laurence Wroe

CLIC Collaborations

https://clic.cern

CLIC accelerator:

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

CLIC detector and physics (CLICdp):

- **30 institutes from 18 countries**
- **Physics prospects & simulation studies**
- **Detector optimisation + R&D for CLIC**

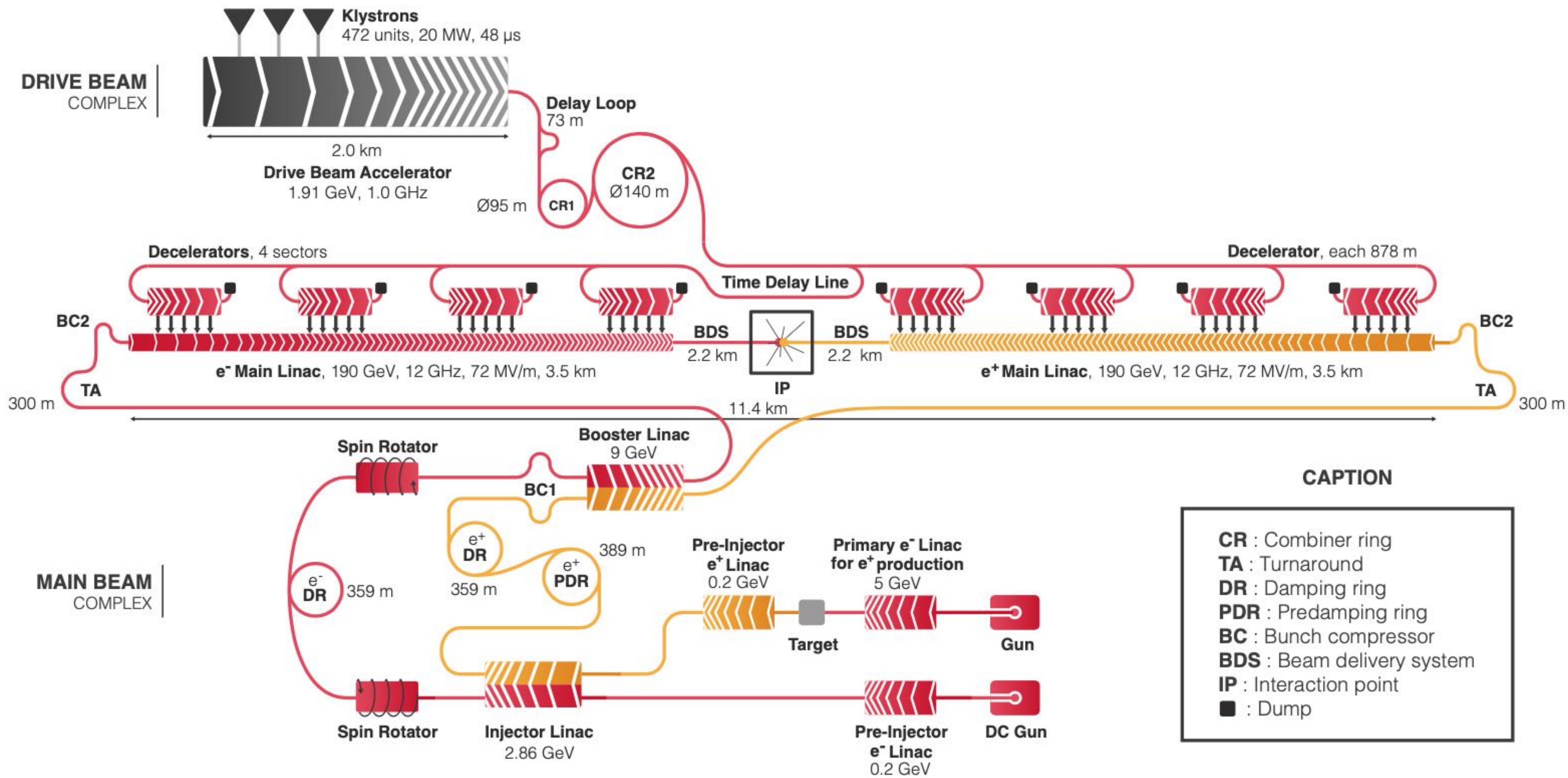
+ strong participation in the CALICE and FCAL Collaborations and in AIDA-2020/AIDAinnova

Extra material

CLIC parameters

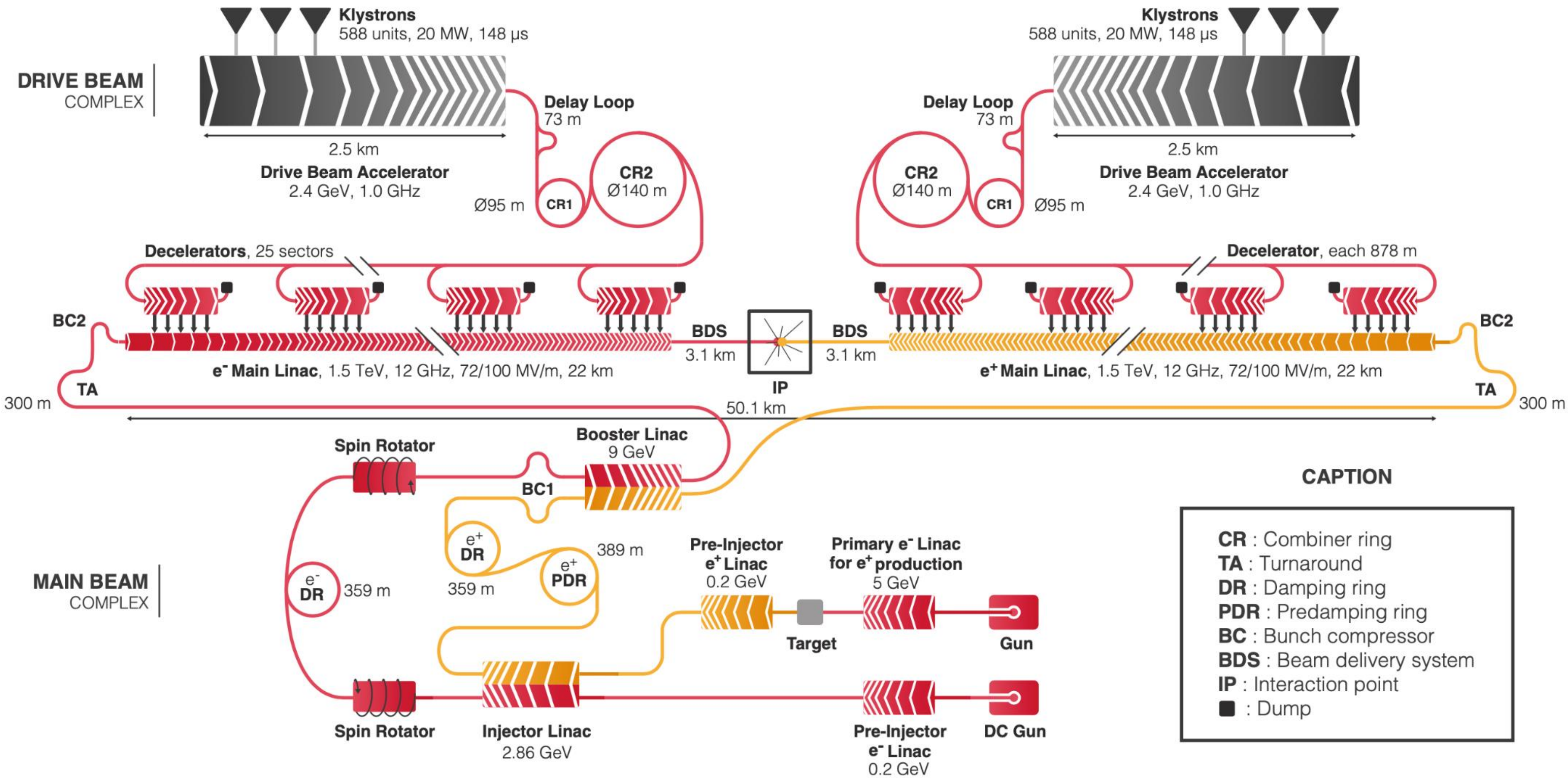
Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,cm^{-2}\,s^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,cm^{-2}\,s^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	µm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

CLIC 380 GeV layout



Baseline electron polarisation ±80%

CLIC 3 TeV layout



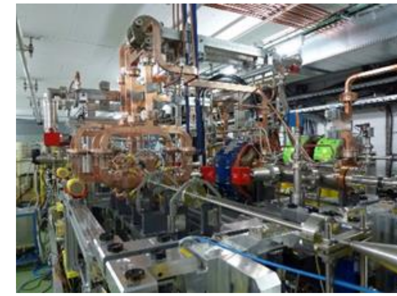
CAPTION

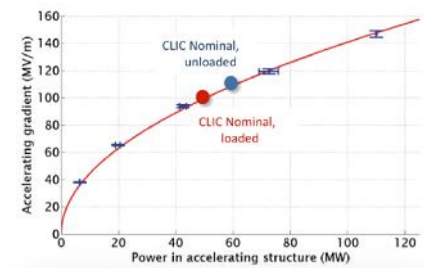
CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

Baseline electron polarisation ±80%

Accelerator challenges

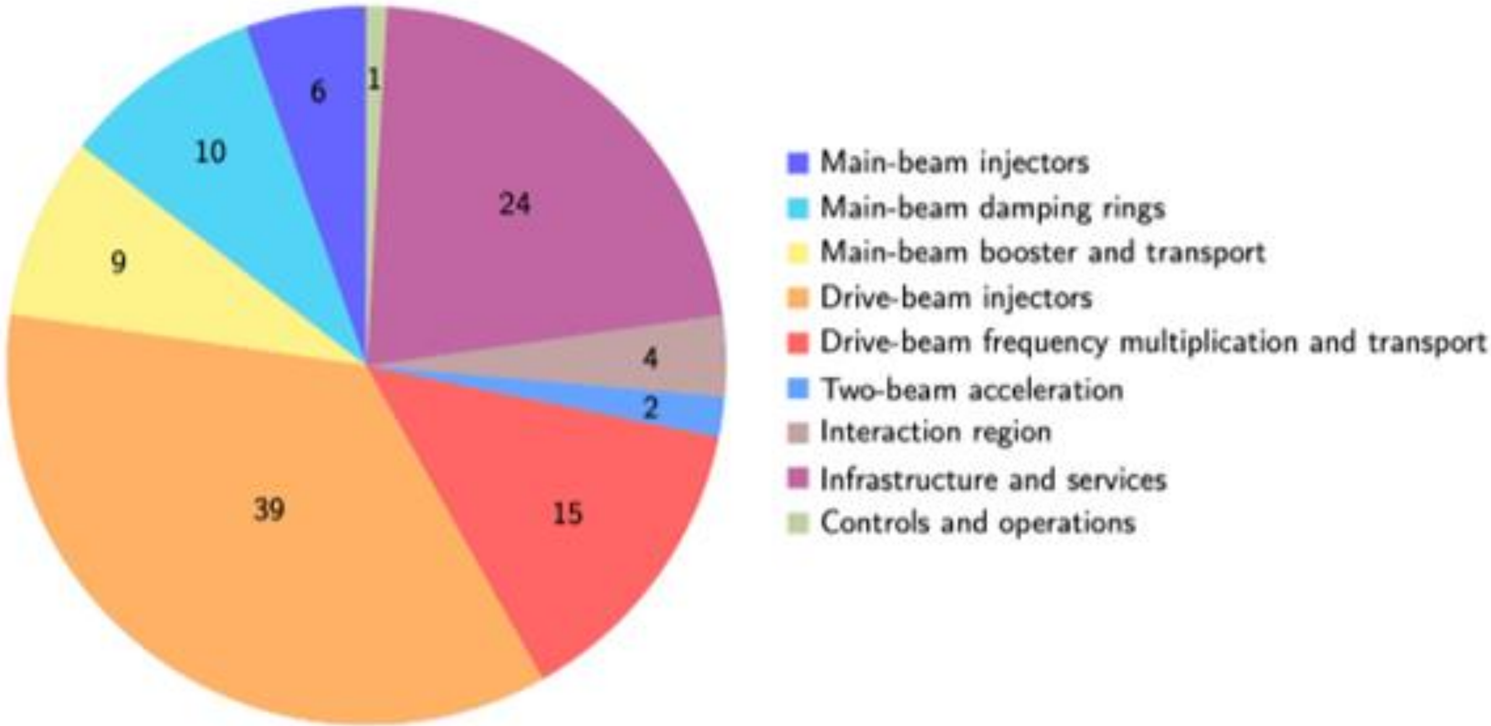
1. High-current drive beam bunched at 12 GHz
2. Power transfer and main-beam acceleration
3. Towards 100 MV/m gradient in main-beam cavities
4. Alignment and stability (‘nano-beams’)





- CTF3 (CLIC Test Facility) addressed 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 application in smaller-scale systems
- Two C-band XFELS (SACLA and SwissFEL) now operational: large-scale demonstrations of normal-conducting, high-frequency, low-emittance linacs

Power + energy: 380 GeV



Power = 110 MW

Annual energy consumption = 0.6 TWh (~ 50% of current CERN energy use)

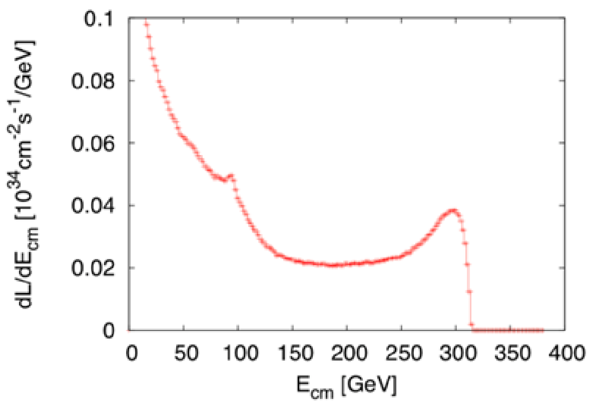
Further savings possible: high-efficiency klystrons, permanent magnets …
Looking also more closely at 1.5 and 3 TeV numbers

Luminosity studies

- **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)

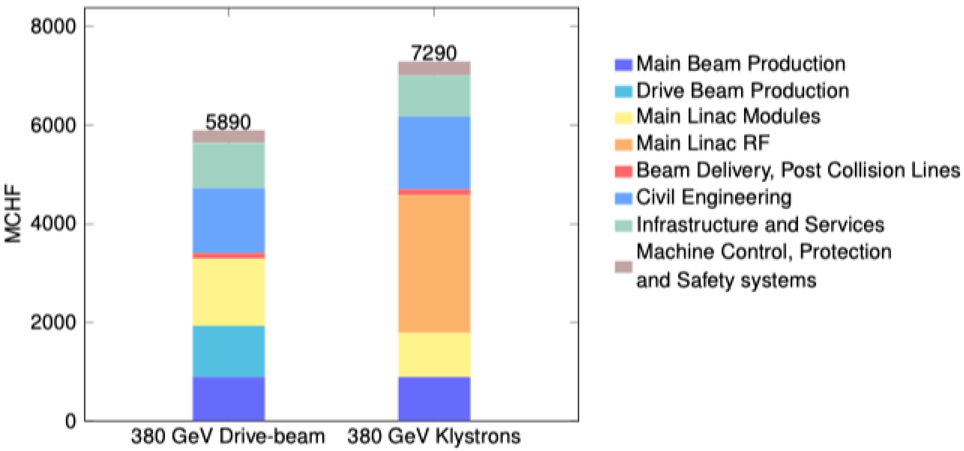
  → double the luminosity, with power +50 MW and cost ~5% increases

CLIC note: http://cds.cern.ch/record/2687090

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)**

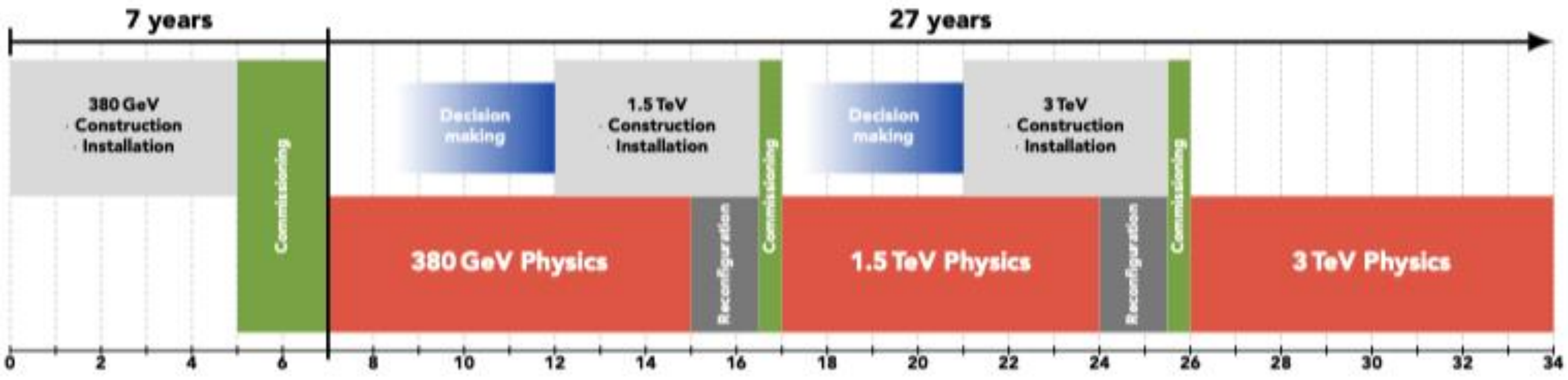
Operation:

- **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 timeline



Technology-driven schedule from start of construction shown above.

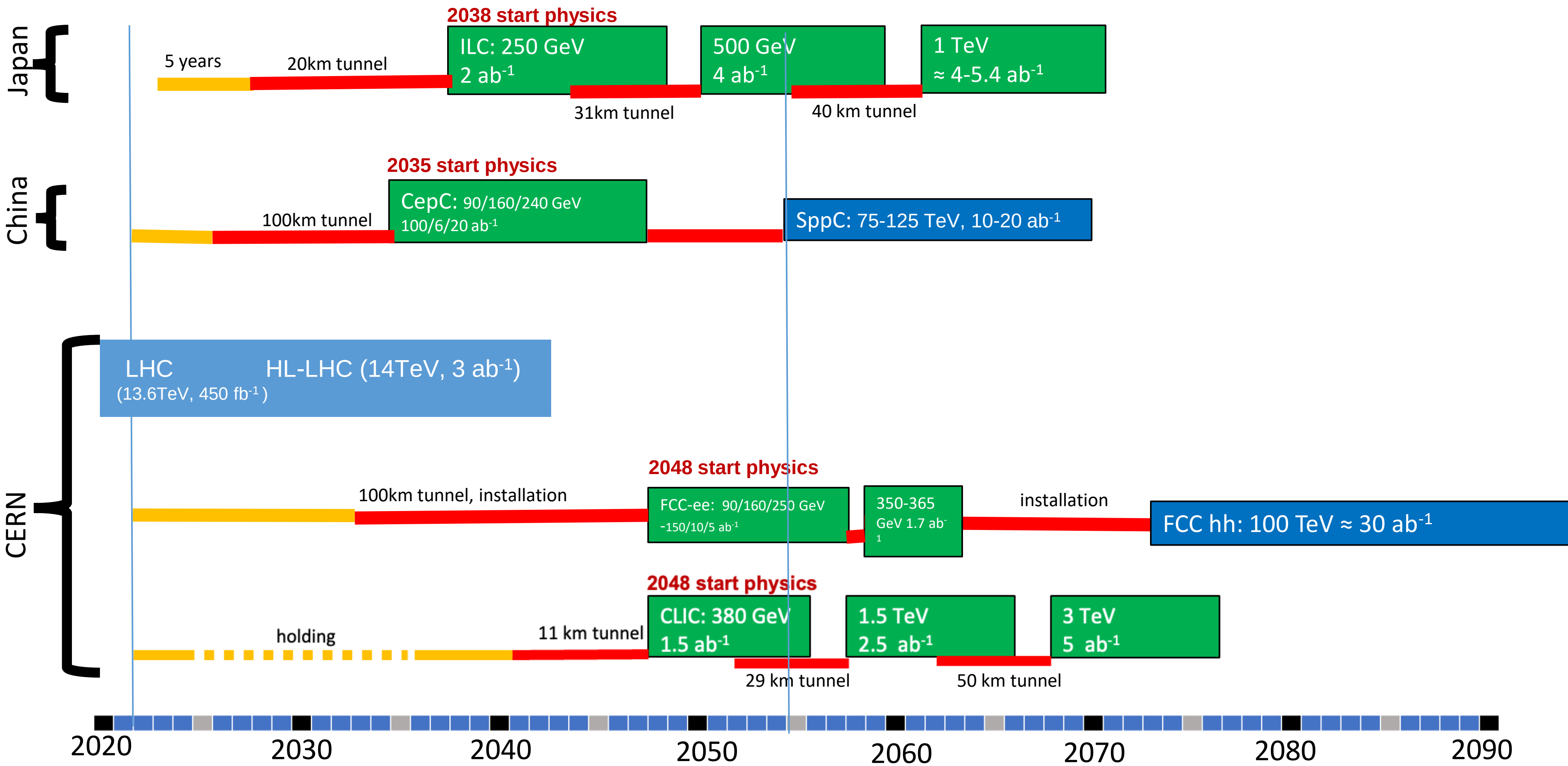
A preparation phase of ~5 years is needed beforehand
(estimated resource needed ~4% of overall project cost)

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)



CLIC detector