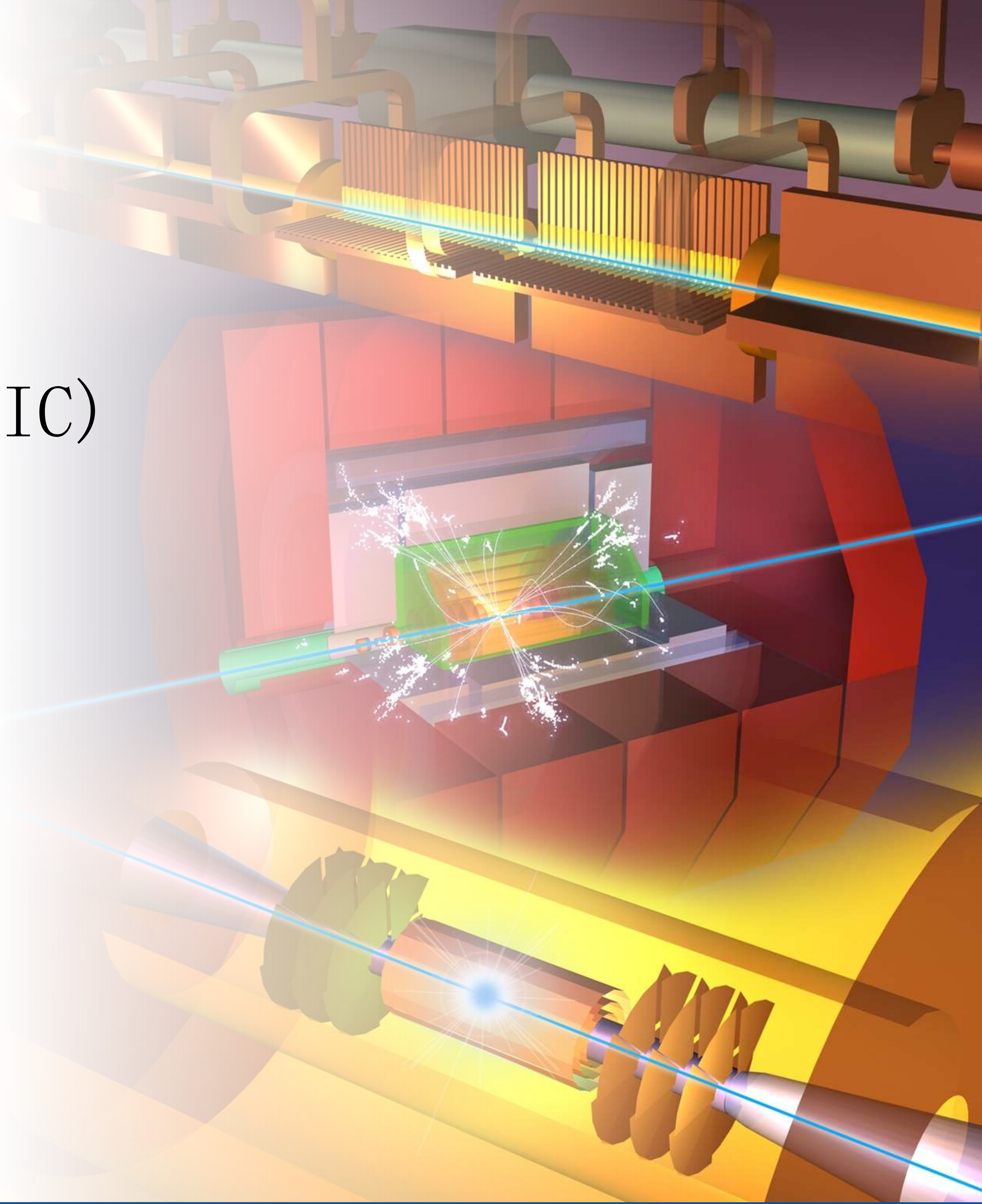
Steinar Stapnes
on behalf of CLIC

The Compact Linear Collider (CLIC)

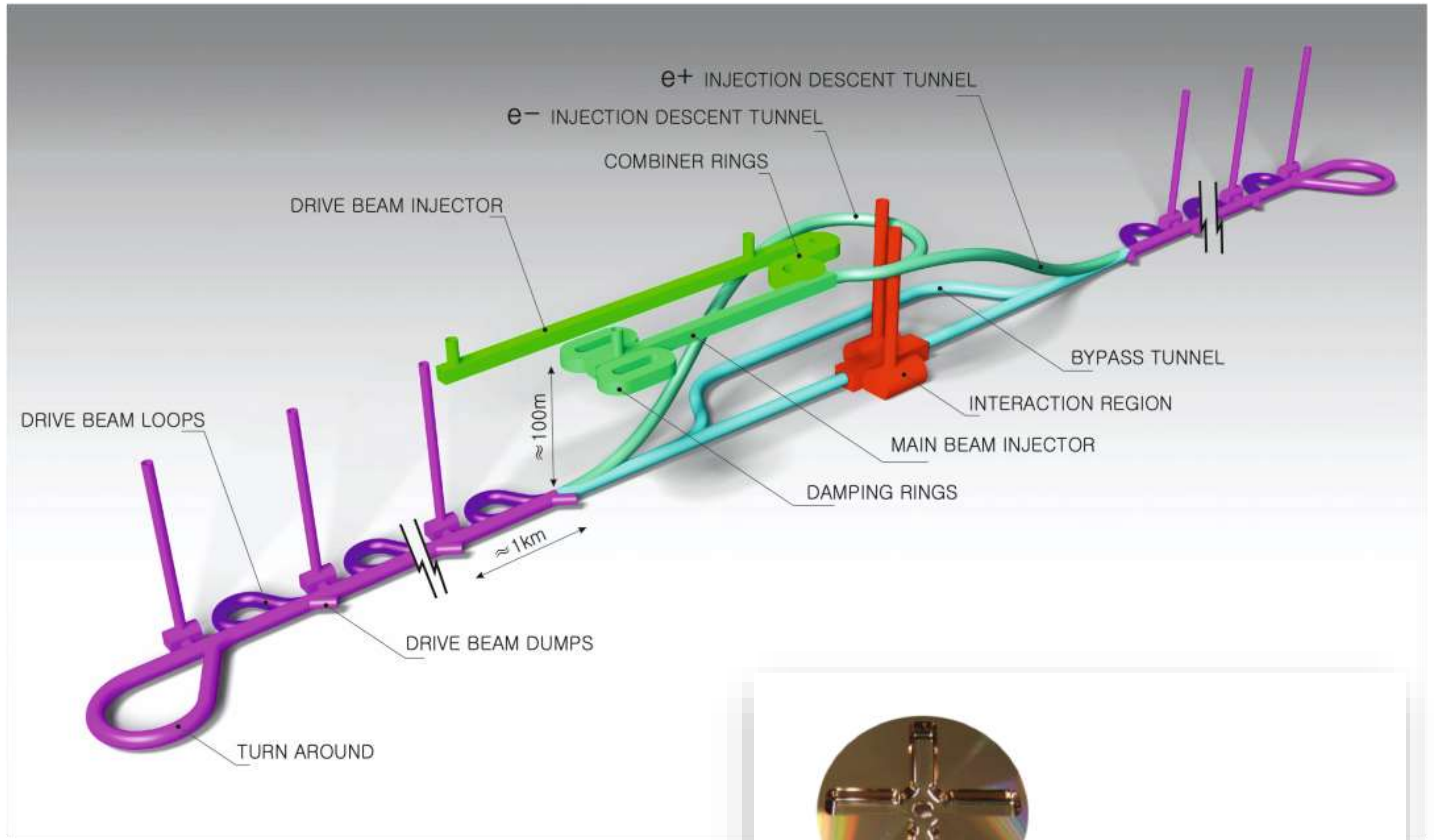
Outline

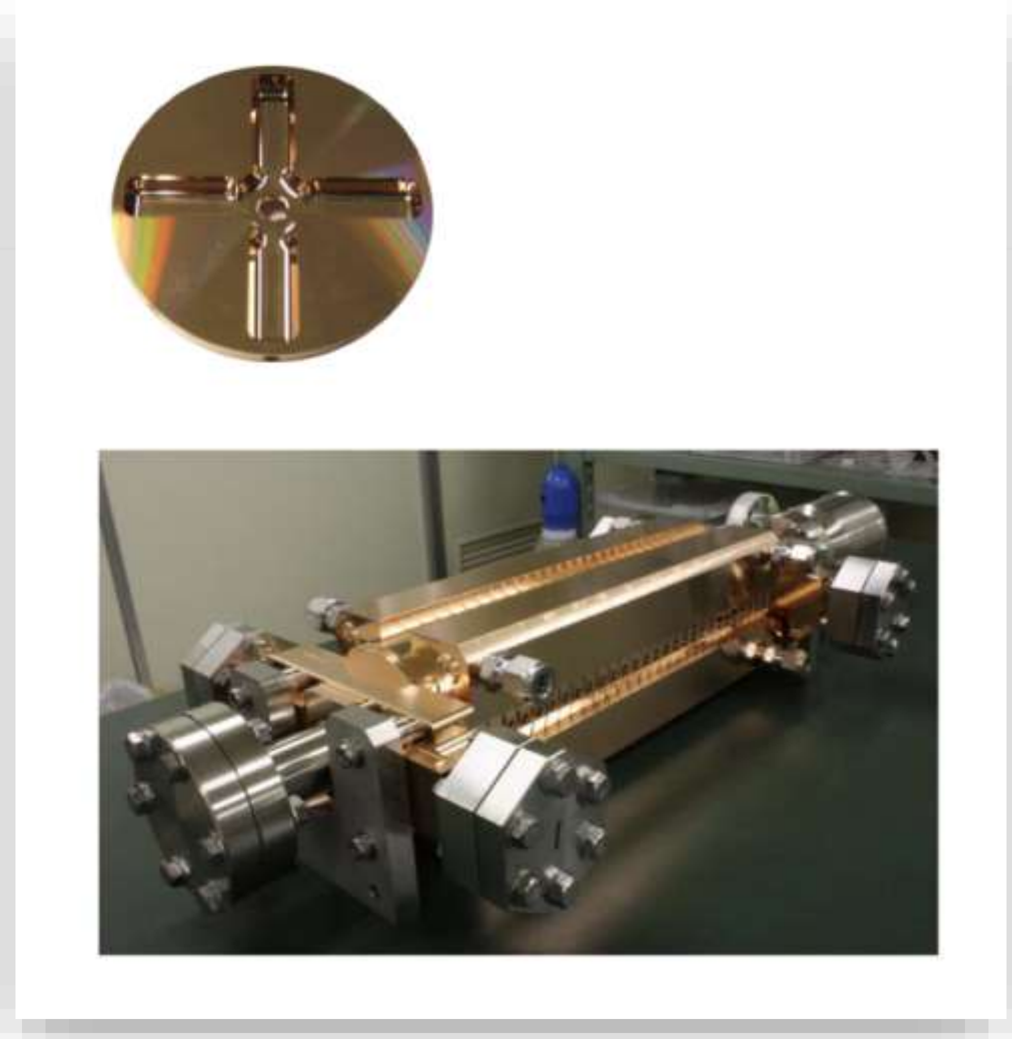
- Project overview, 380 GeV and 3 TeV
- Technical status – some examples
- Implementation
- Plans 2021-25
- Summary



CEPC international workshop
Oct 26th, 2020

Proposed e^+e^- linear colliders – CLIC





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

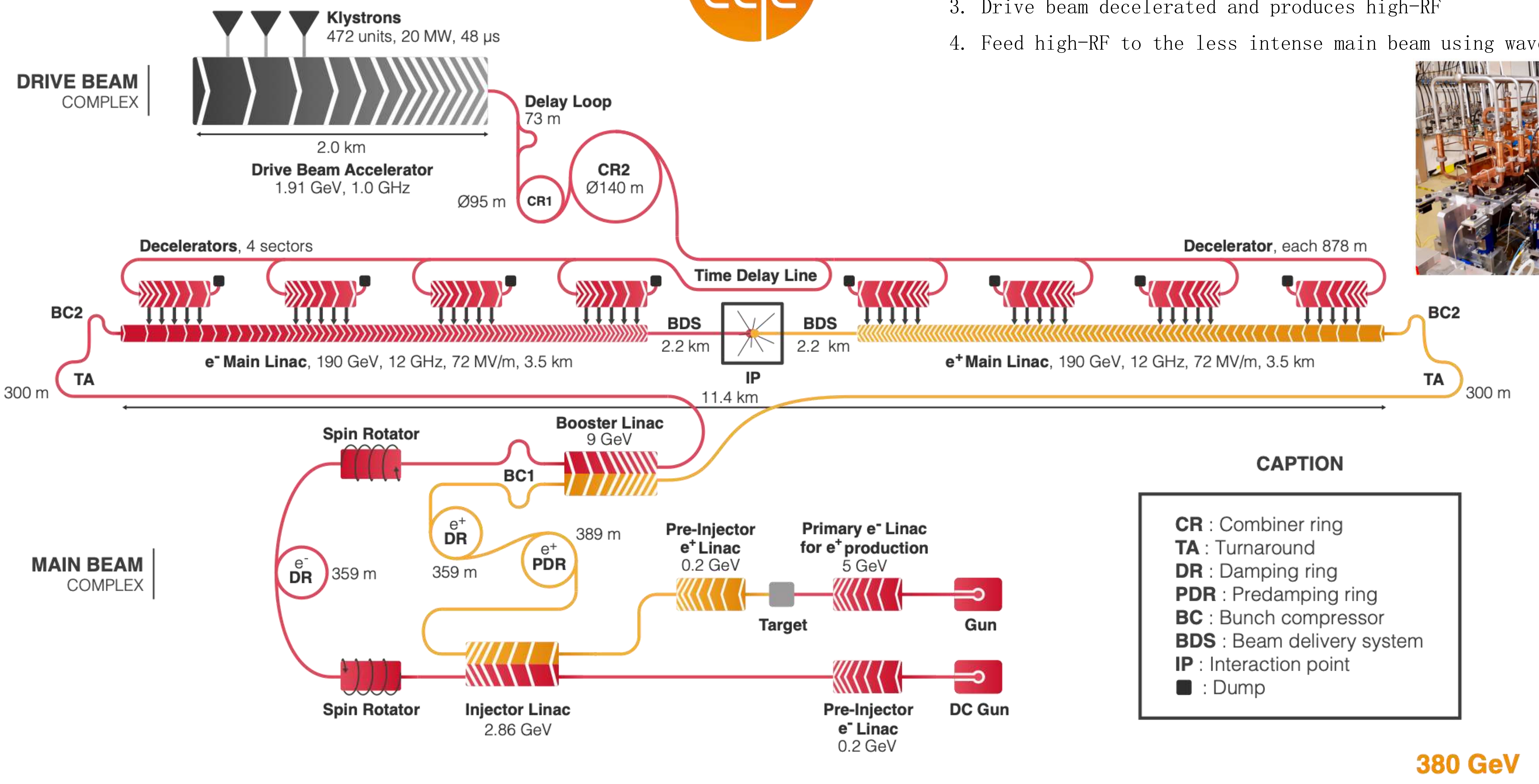
The Compact Linear Collider (CLIC)

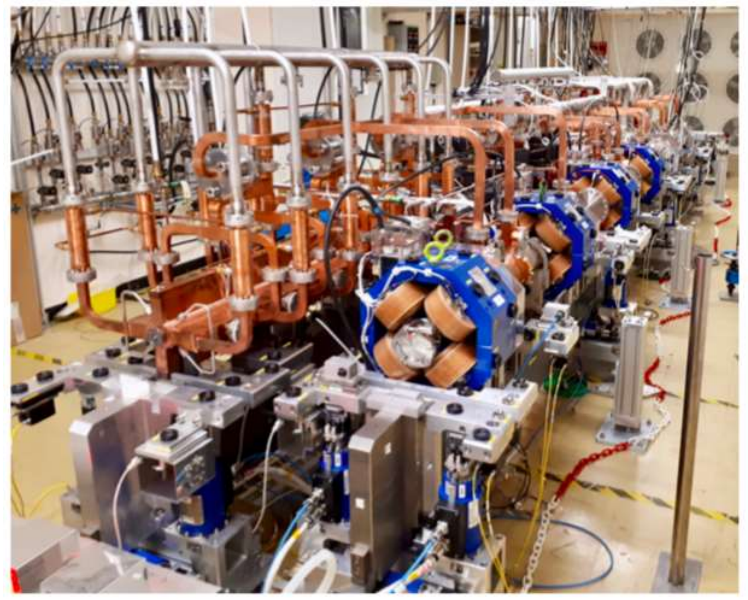
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC (~2035 Technical Schedule)
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20' 500 cavities at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged 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

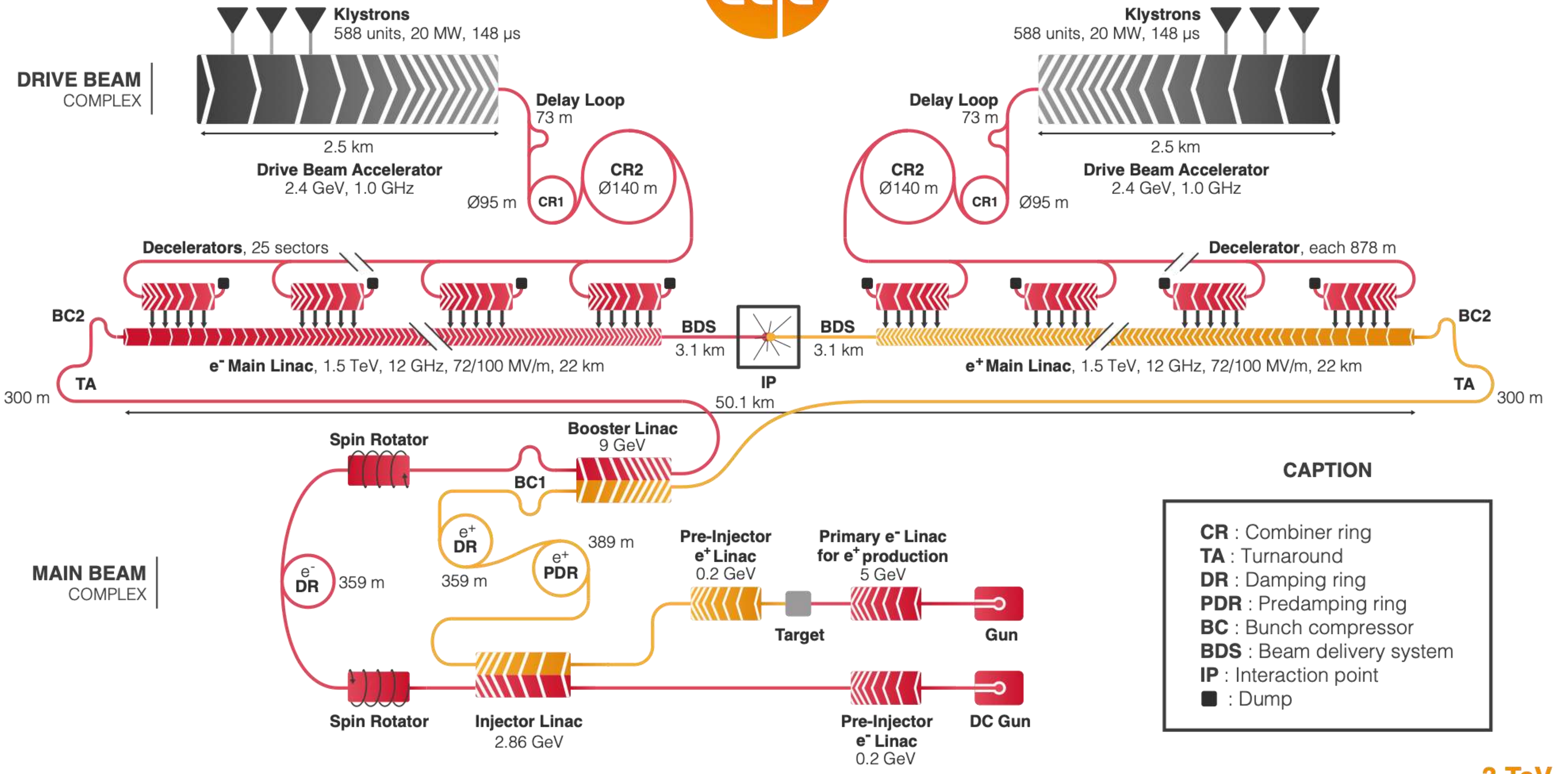
1. Drive beam accelerated to ~2 GeV using conventional klystrons
2. Intensity increased using a series of delay loops and combiner rings
3. Drive beam decelerated and produces high-RF
4. Feed high-RF to the less intense main beam using waveguides





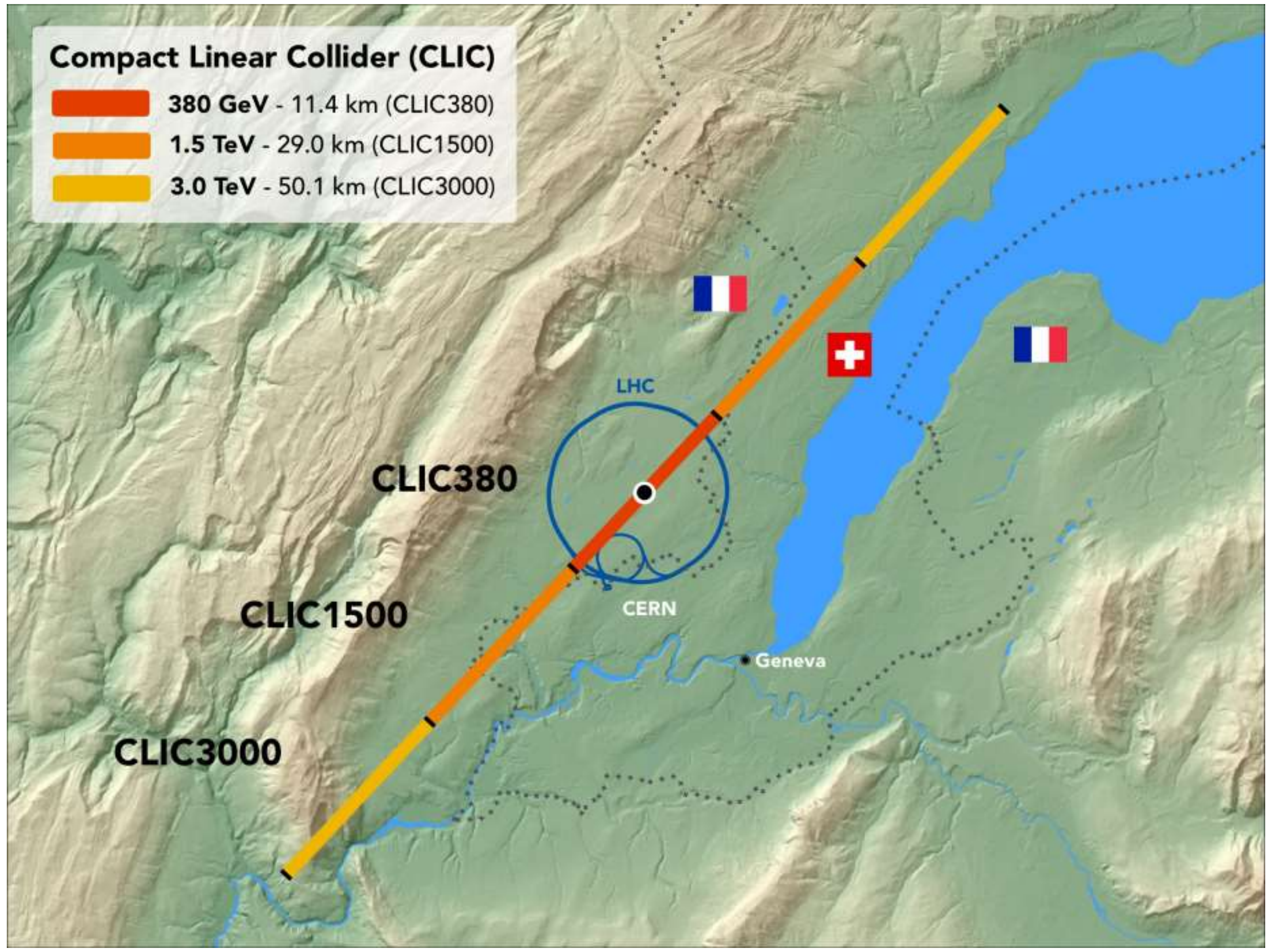
CLIC parameters

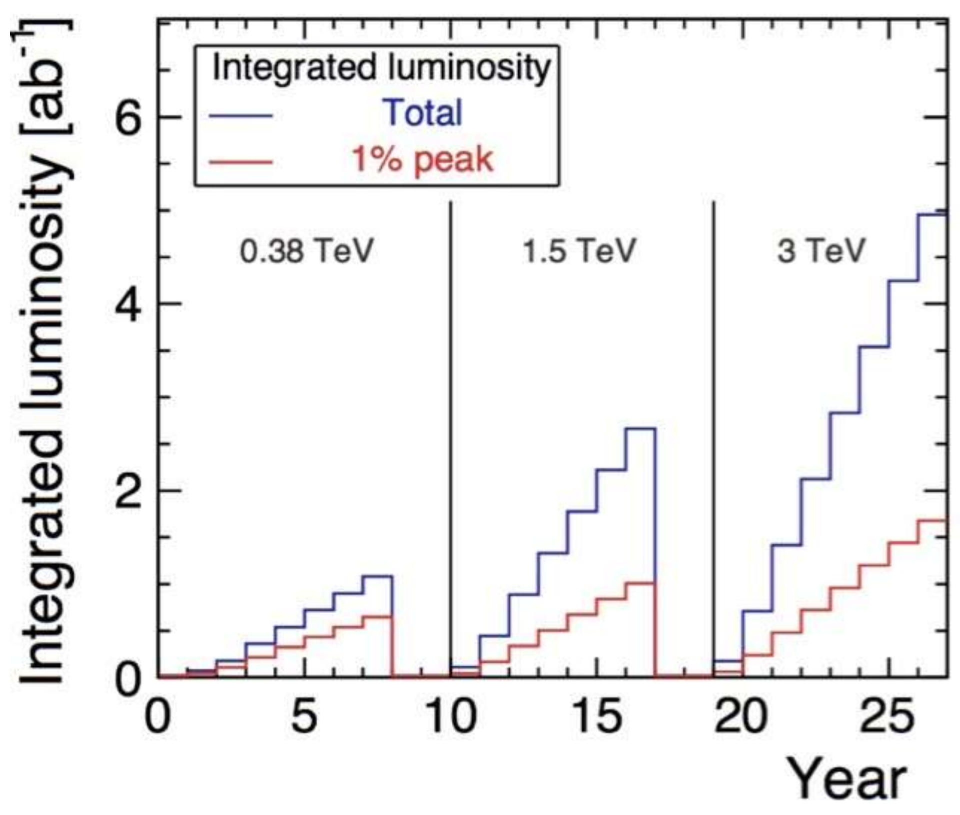
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	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 - Scheme of the Compact Linear Collider (CLIC)

CLIC timeline

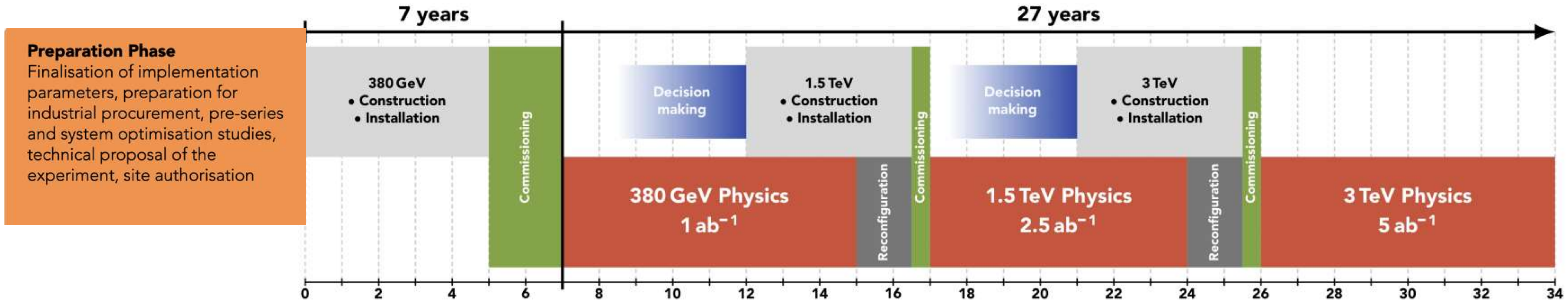




Ramp-up and up-time assumptions: arXiv:1810.13022, Bordry et al.

Technology Driven Schedule from start of construction on the right.

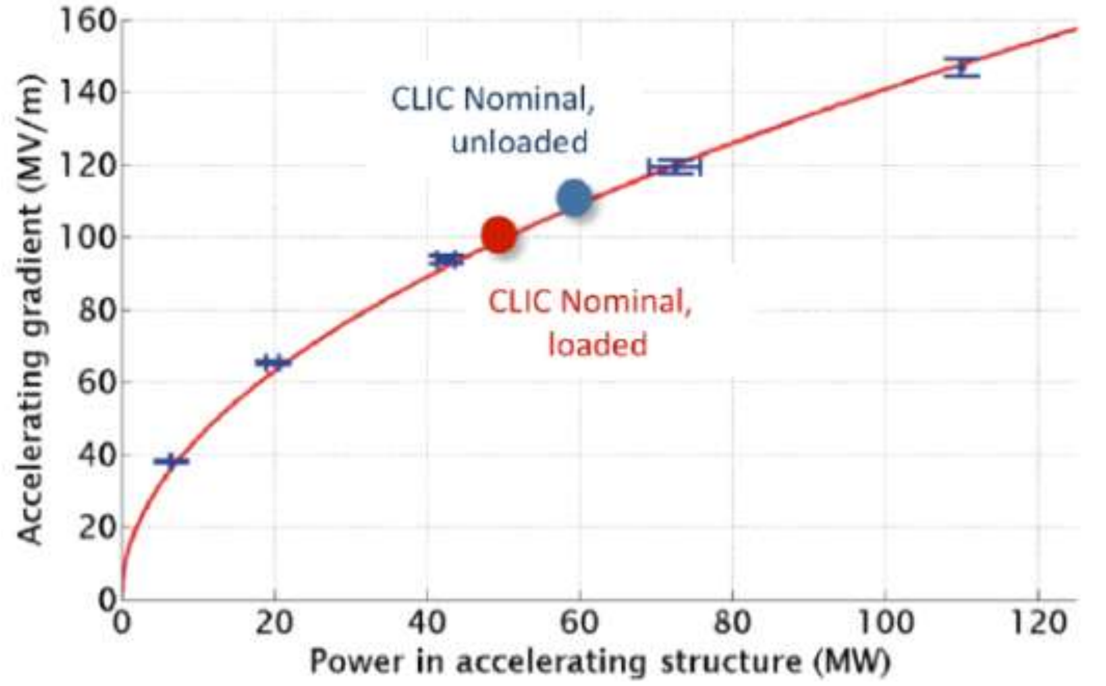
A preparation phase of ~5 years is needed before (estimated resource need for this phase is ~4% of overall project costs)



Accelerator challenges

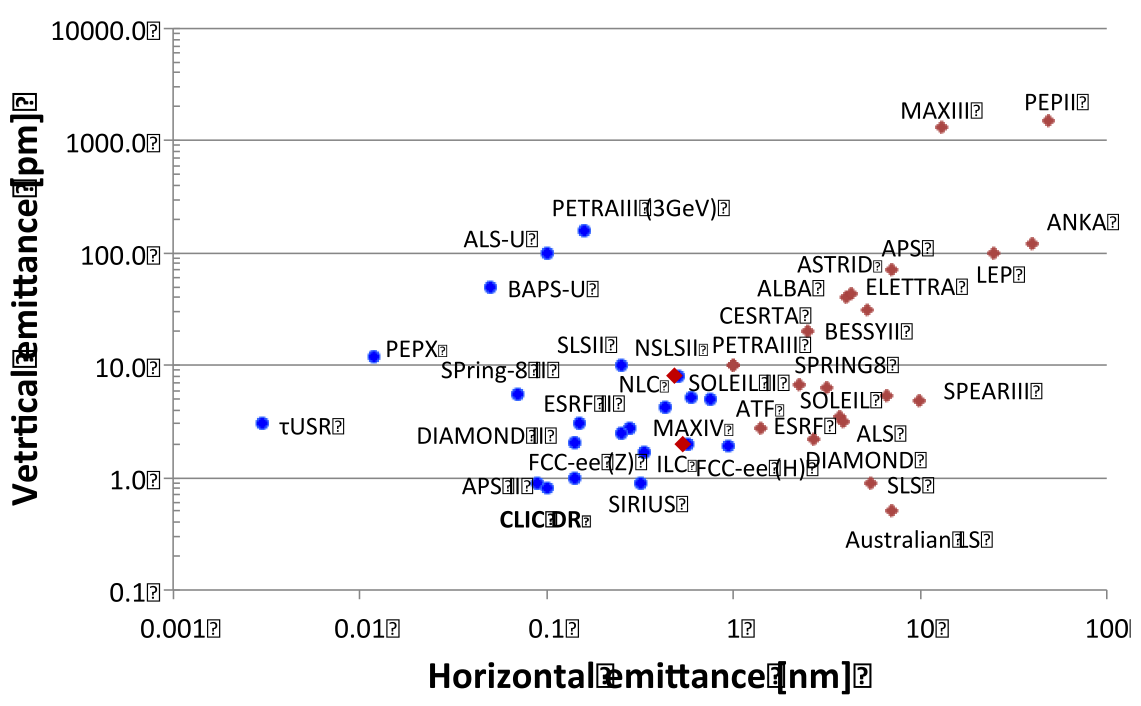
Details in PIP, DOI: http://dx.doi.org/10.23731/CYRM-2018-004

- 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
  3. Towards 100 MV/m gradient in main-beam 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
- Two C-band XFELS (SACLA and SwissFEL – the latter particularly relevant) now operational: large-scale demonstrations of normal-conducting, high-frequency, low-emittance linacs



Low emittance generation and preservation

Target and achieved emittance in existing and planned machines

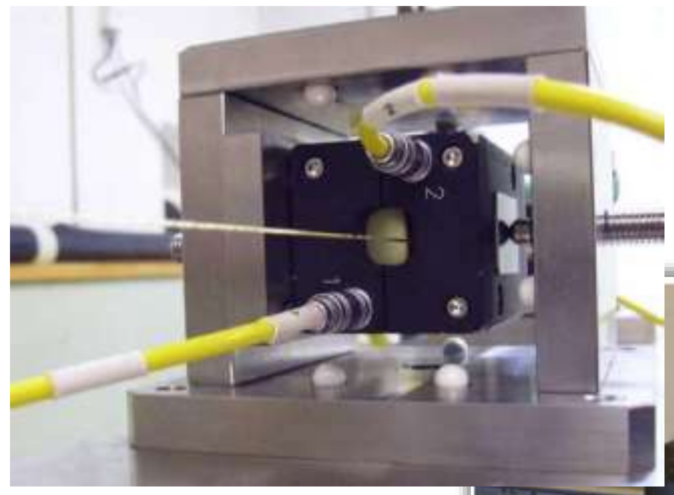


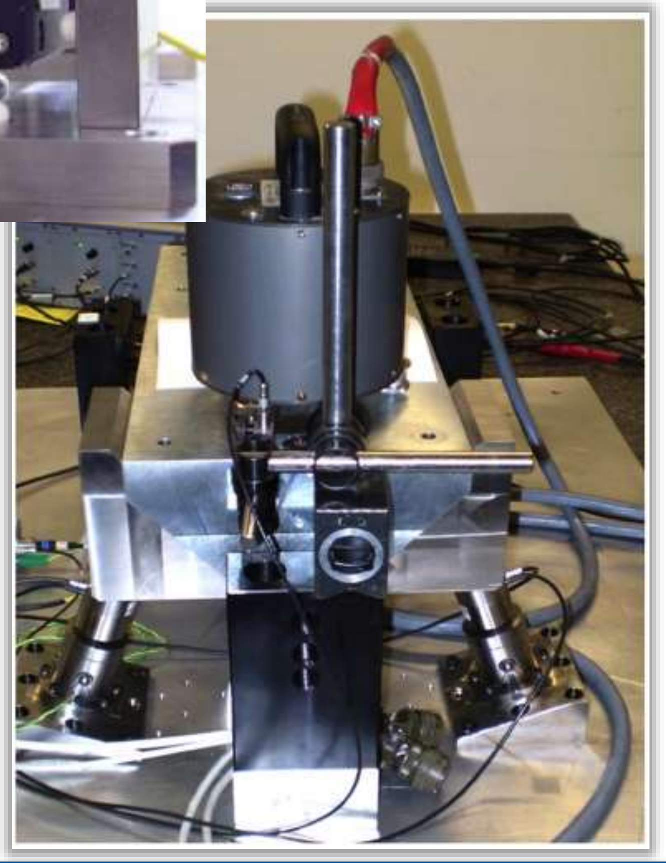
Low emittance damping rings

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)





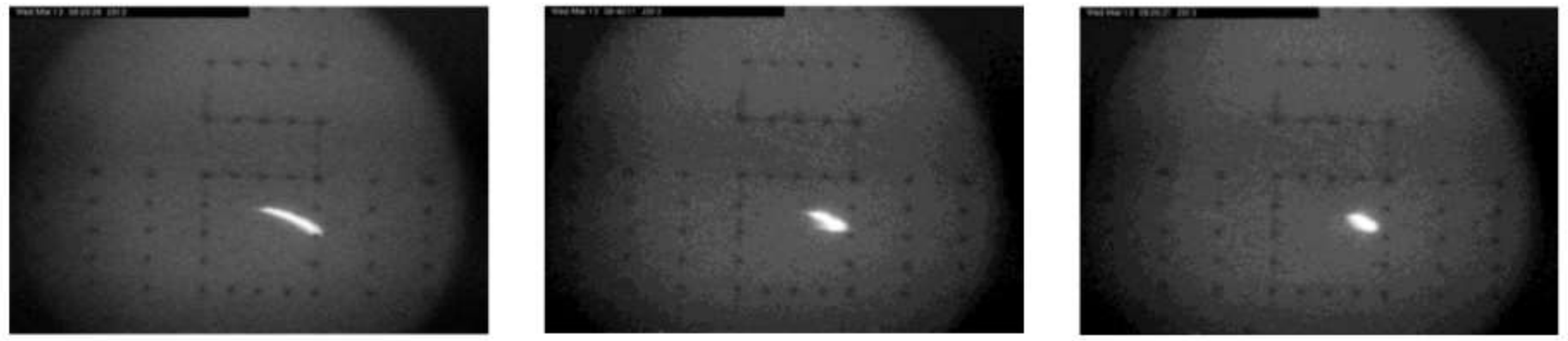
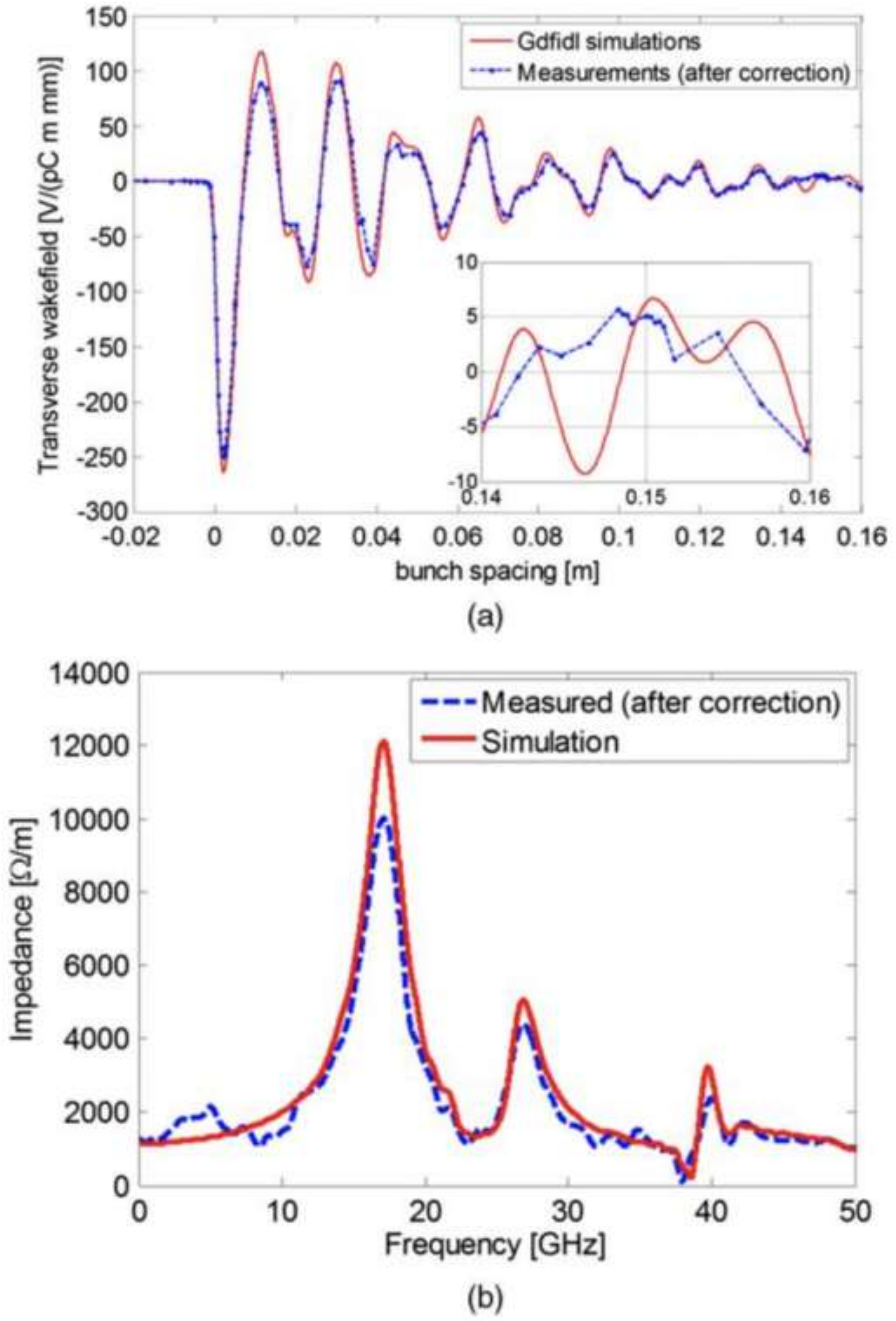


Figure 8.10: Phosphorous beam profile monitor measurements at the end of the FACET linac, before the dispersion correction, after one iteration step, and after three iteration steps. Iteration zero is before the correction.

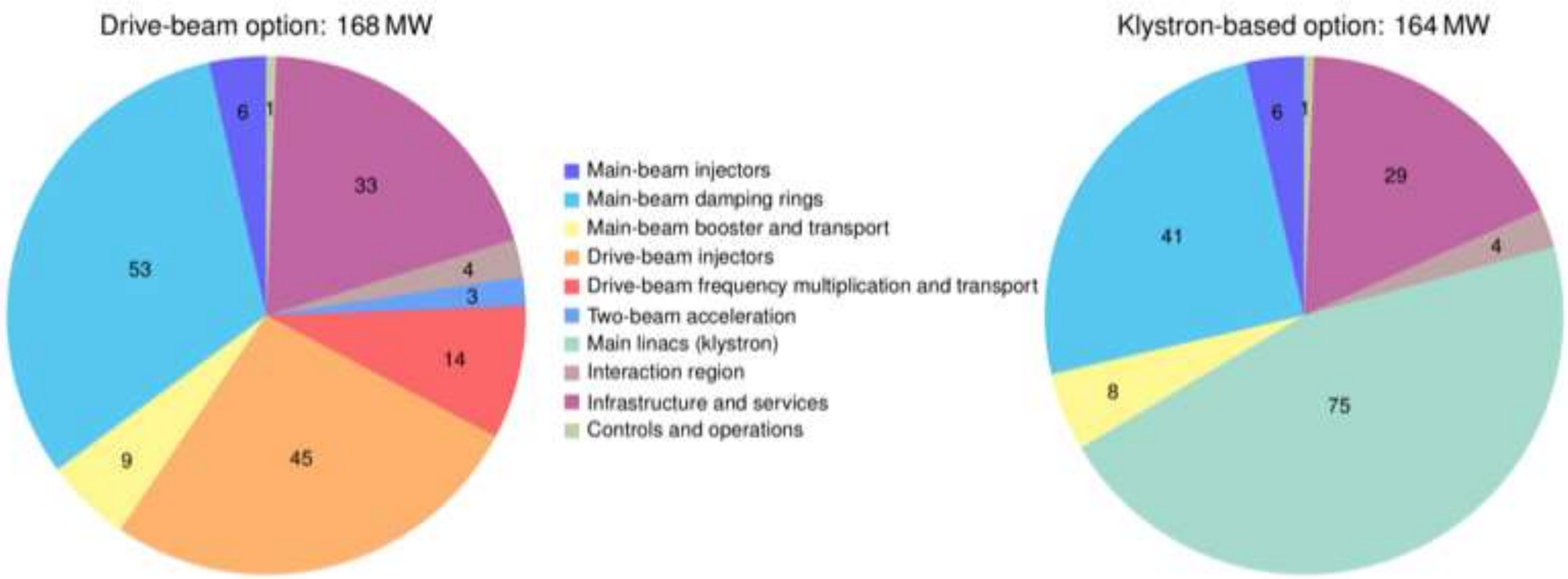


Wake-field measurements in FACET

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

Technical Developments

Power and energy

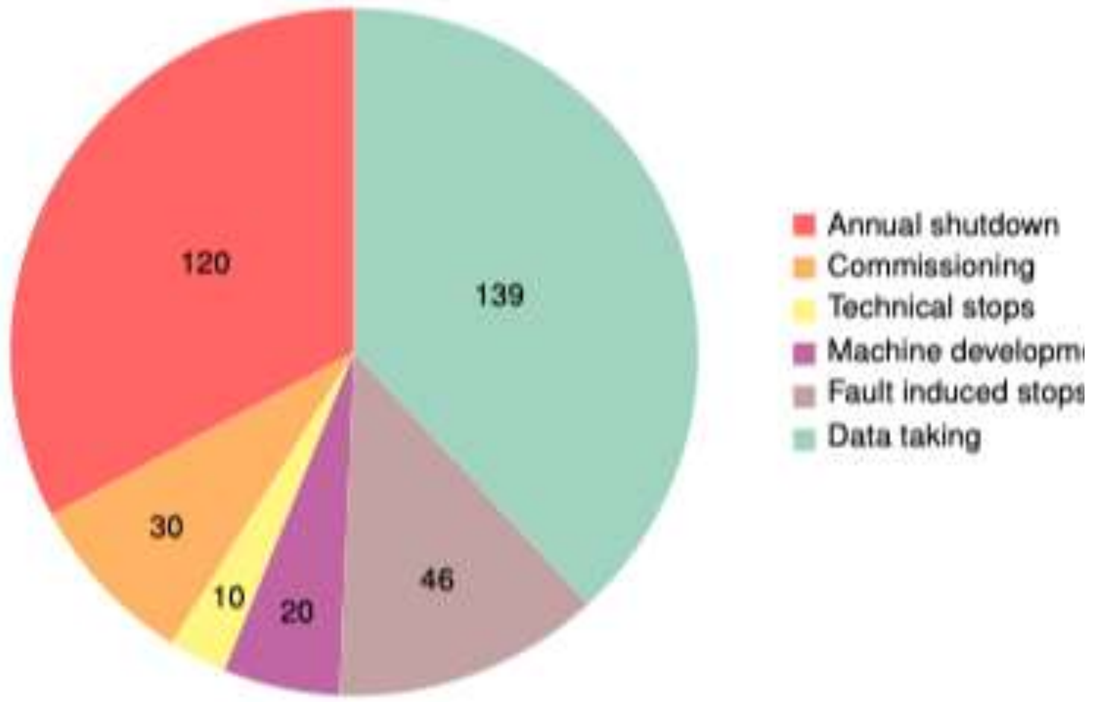


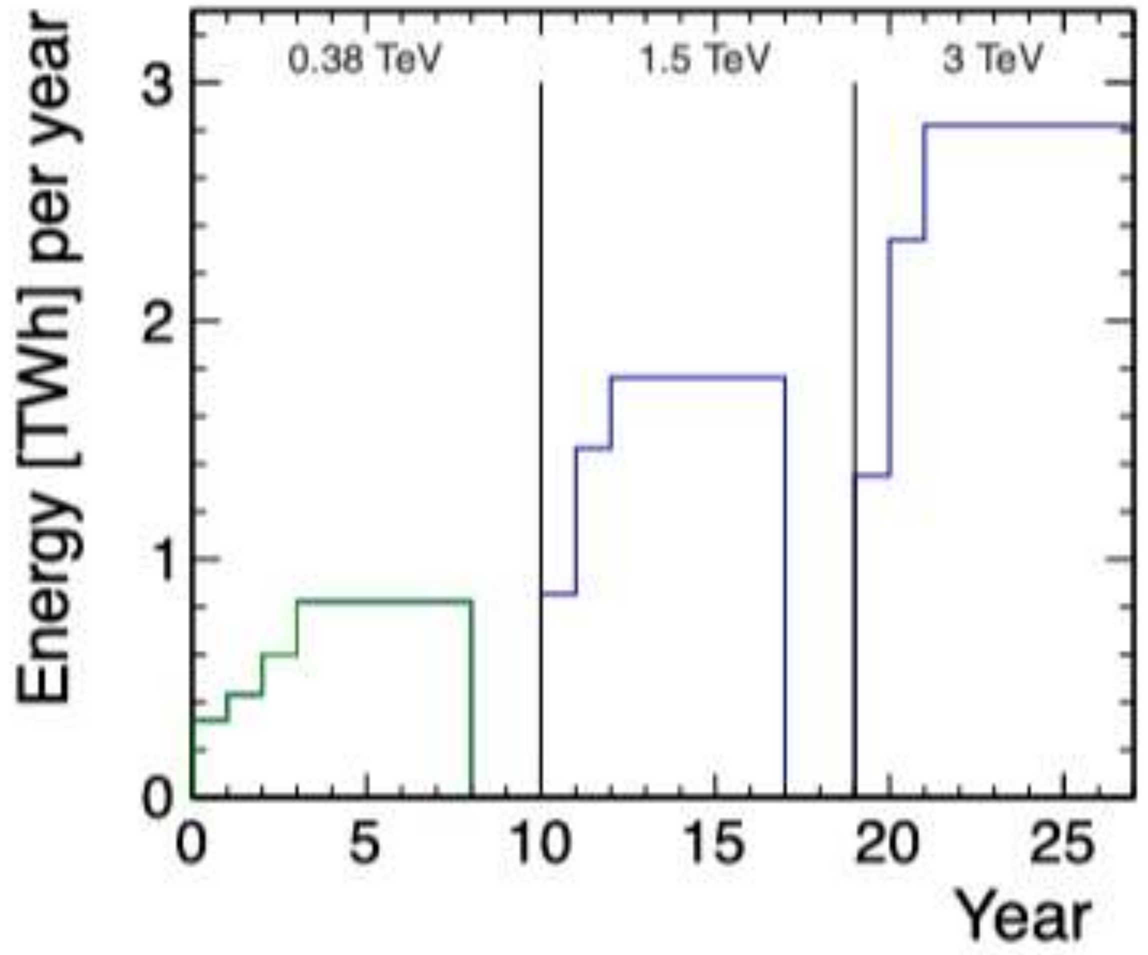
Power estimate bottom up (concentrating on 380 GeV systems)

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

Further savings possible, main target damping ring RF

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 at various states – the energy consumption can be estimated

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

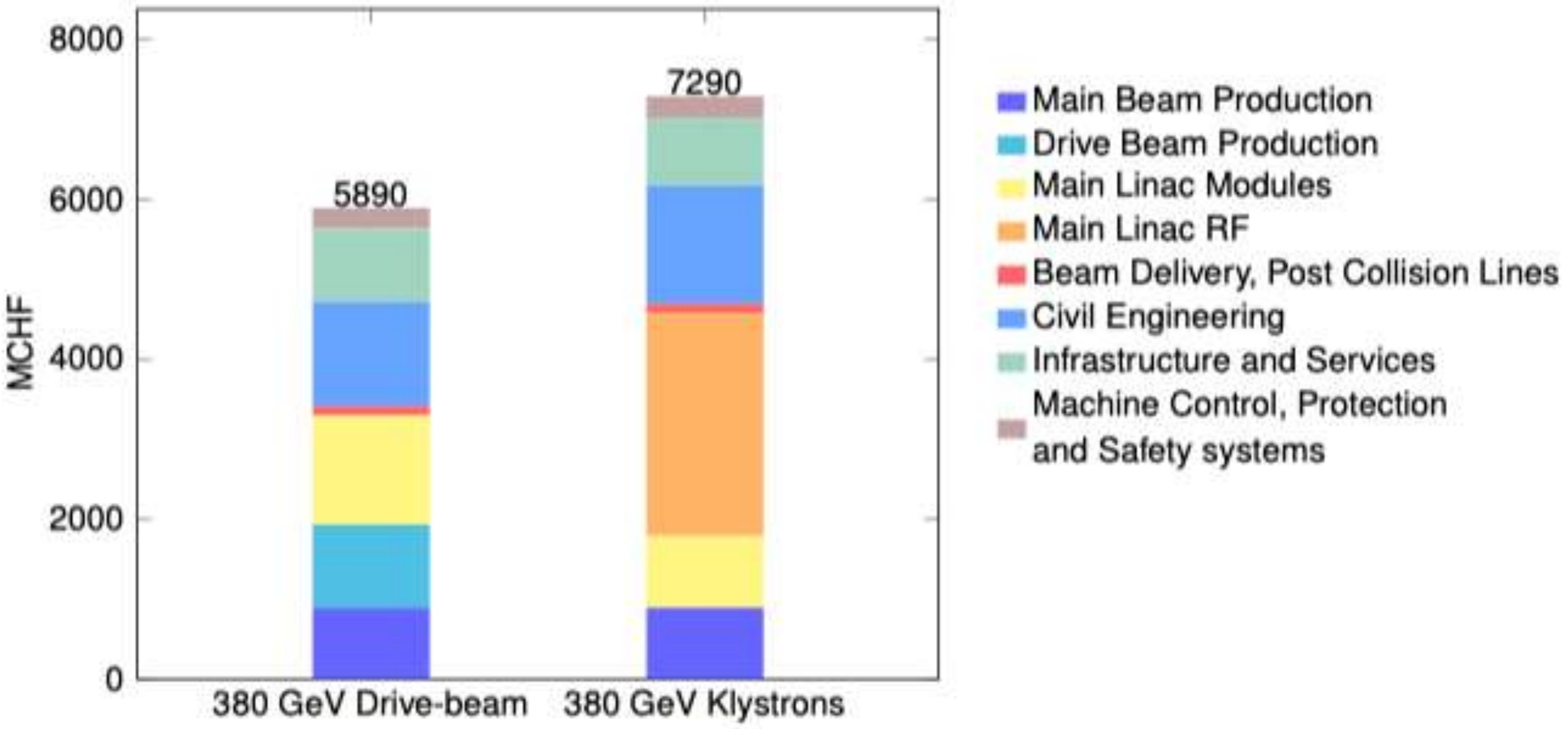
Will look also more closely at 1.5 and 3 TeV numbers next (in blue in figure to illustrate not optimized as for 380 GeV), Hi-Eff L-band klystrons development (see later), damping ring RF as mentioned, include reduction using permanent magnets

More about energy & cost; using scheduling to lower costs and use of renewables (both well adapted to LCs) and energy recovery in spare slides

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

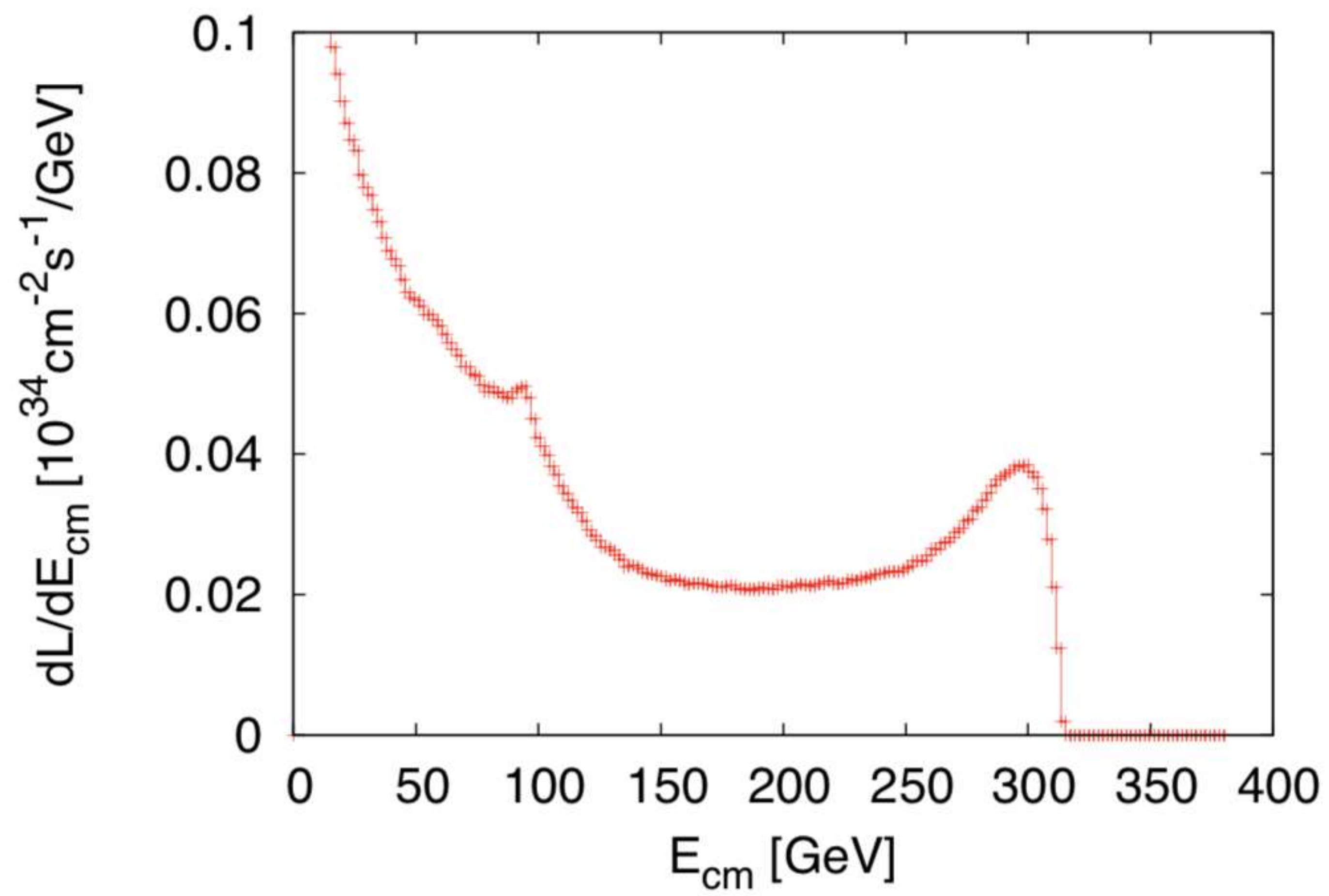
– 1% for accelerator hardware parts (e.g. modules).
– 3% for the RF systems, taking the limited lifetime of these parts into account.
– 5% for cooling, ventilation and electrical infrastructures etc. (includes contract labour and consumables)

These replacement/operation costs represent 116 MCHF per year.

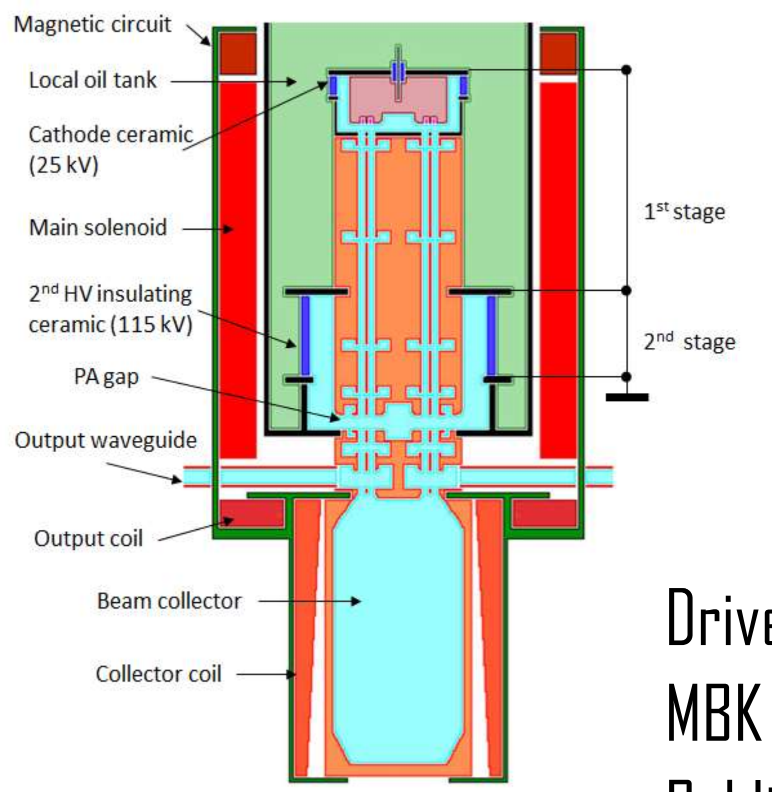
CLIC acc. studies 2019/20 – some examples

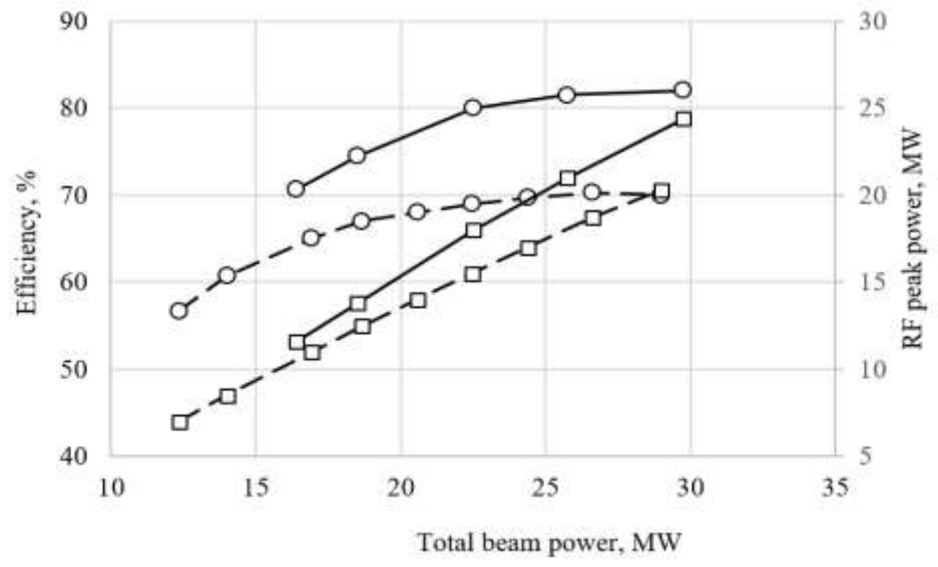
Further work on luminosity performance, possible improvements and margins, operation at the Z-pole and gamma-gamma

- 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
- CLIC note about these studies

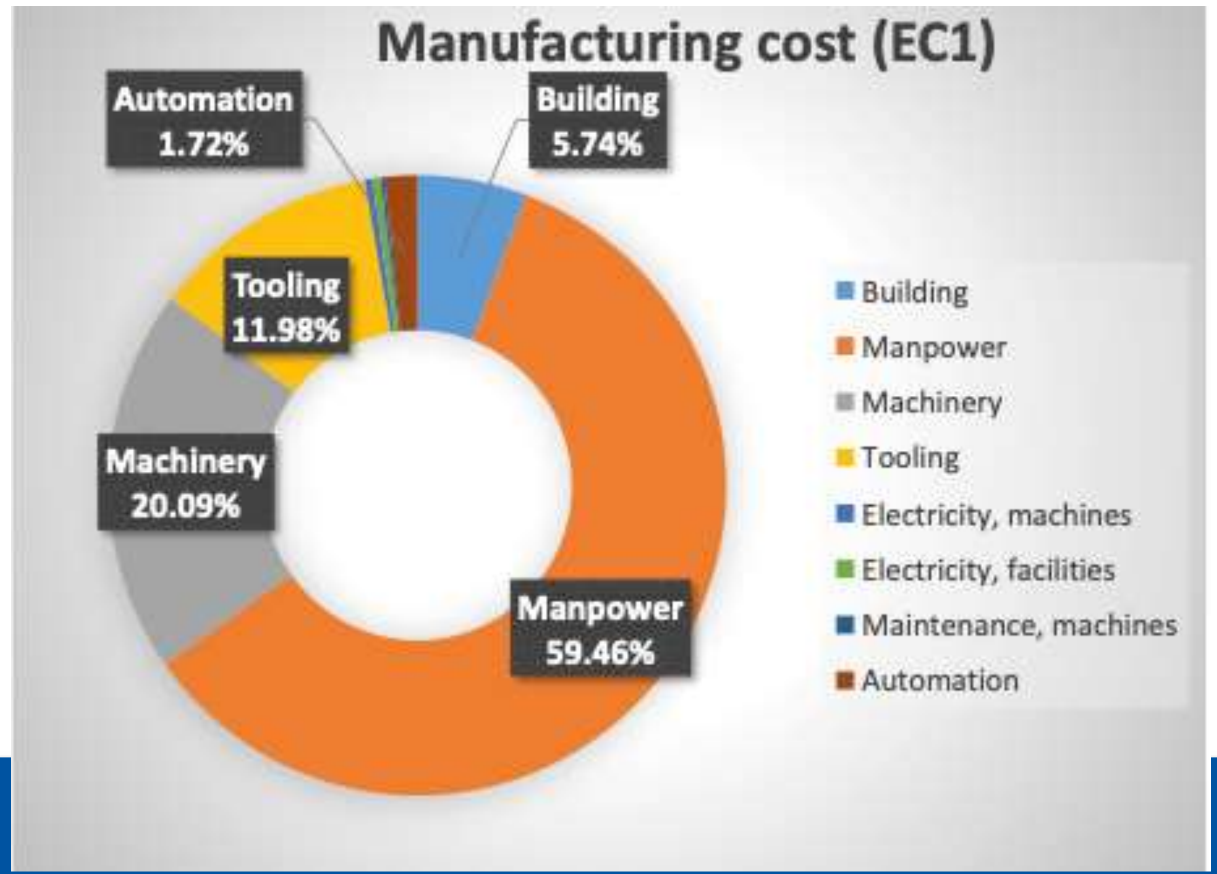


Industrial questionnaire:
Based on the companies feedback, the preparation phase to the mass production could take about five years. Capacity clearly available. Talk of of Anastasiya





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



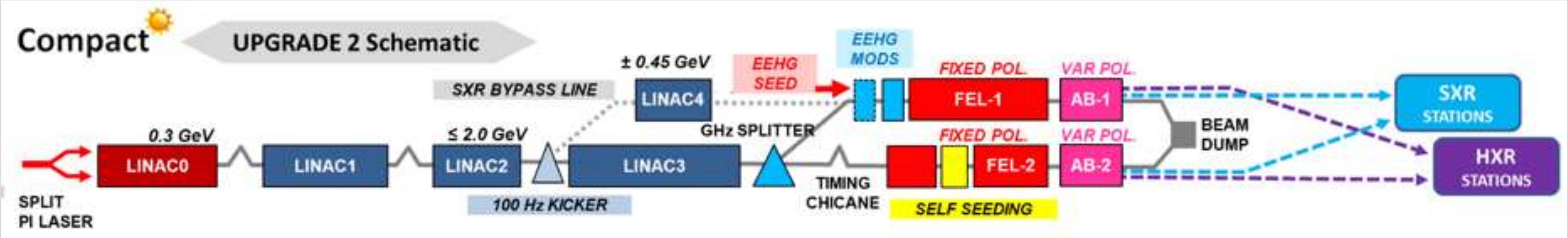
CLIC studies 2021-25

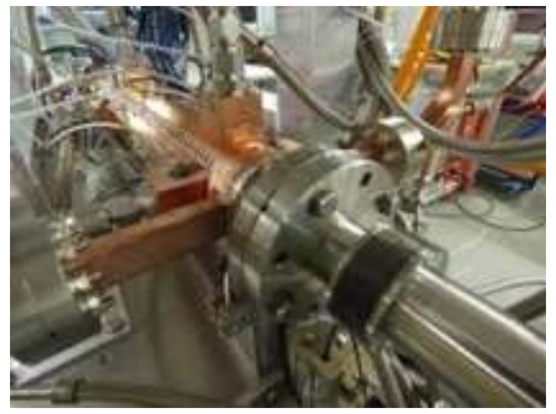
X-band technology:

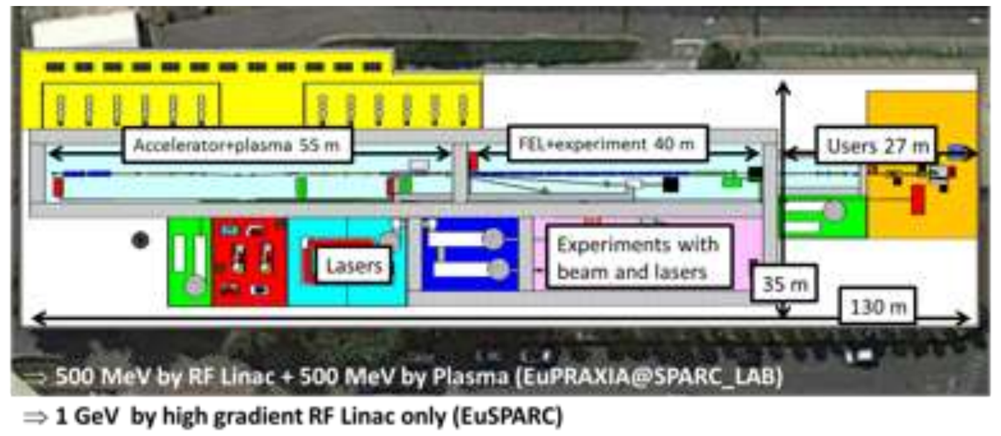
- Design and manufacturing of X-band structures and components
- Study structures breakdown limits and optimization, operation and conditioning
- Baseline verification and explore new ideas
- Assembly and industry qualification
- Structures for applications, FELs, medical, etc

Technical and experimental studies, design and parameters:

- Module studies (see some targets for development below)
- Beamdynamics 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
- Injector studies suitable for X-band linacs (coll. with Frascati)







Application of X-band technology (examples):

- 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 (within the PBC-project)

More information: CLIC mini week (1.10.2020)

Summary

- CLIC is a mature project, prepared for a 380 GeV initial stage
- There presents a consistent way forward with initial LC at "SM energies", keeping the options open for future upgrades and/or circular accelerators further on
- The cost and implementation time for CLIC 380 are similar to LHC
- The physics case is broad and profound, and being further developed
- 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 (+some more recent results in slides)

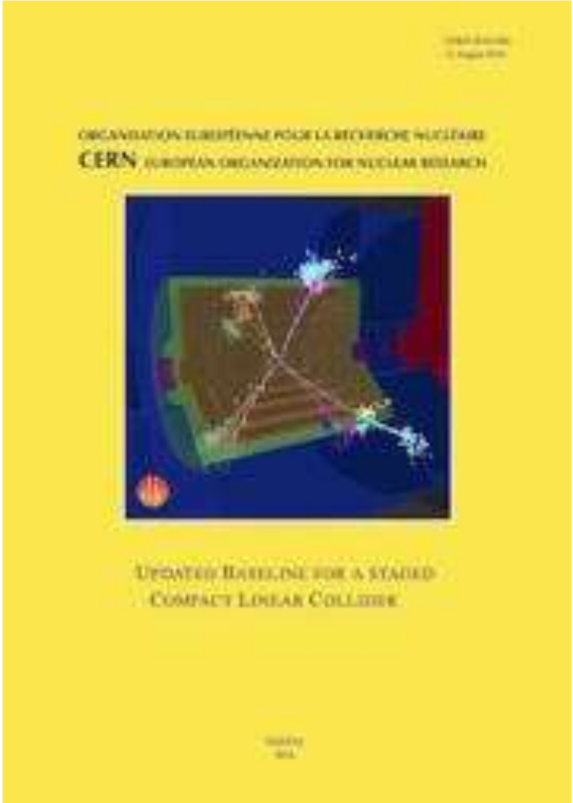
Picture from the CLIC week 2019, this year the week had to be arranged remotely

Collaboration maps on very last slide

Resources

3-volume CDR 2012

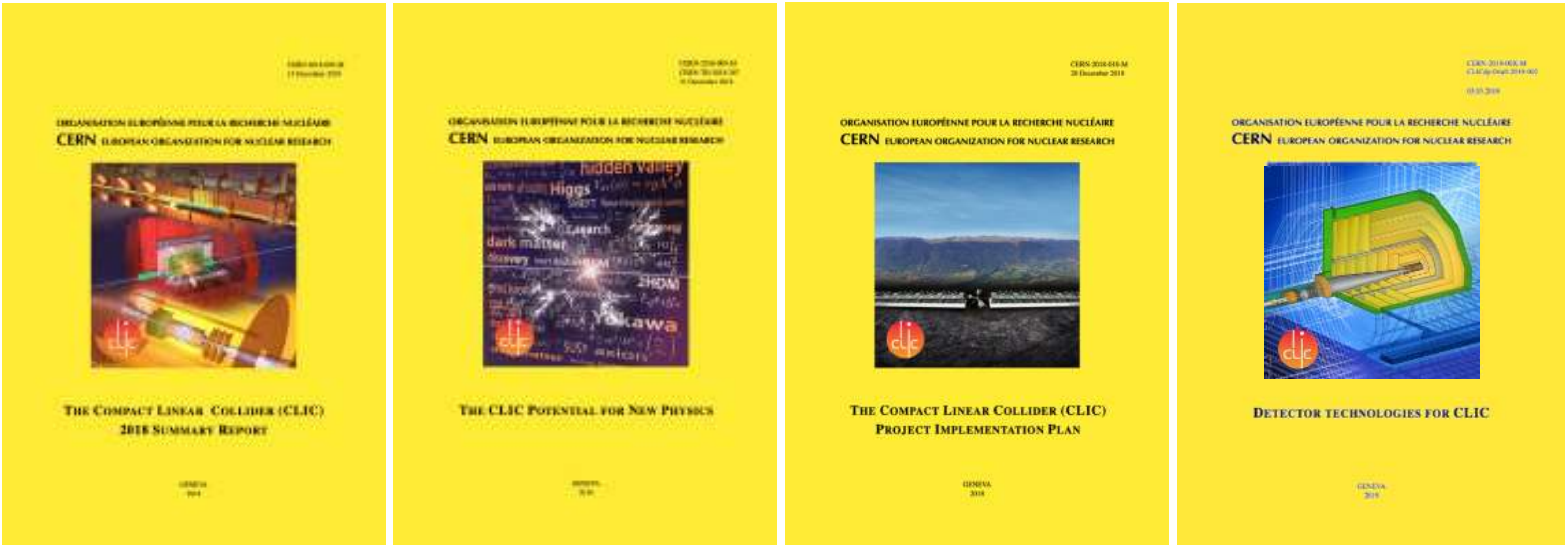
Updated Staging Baseline 2016



Two formal submissions to the ESPPU 2018

Available at: clic.cern/european-strategy

4 CERN Yellow Reports 2018



Details about the accelerator, detector R&D, physics studies for Higgs/top and BSM – see also slides 20-21 for more recent studies

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

Some more information
(referred to in earlier slides)

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

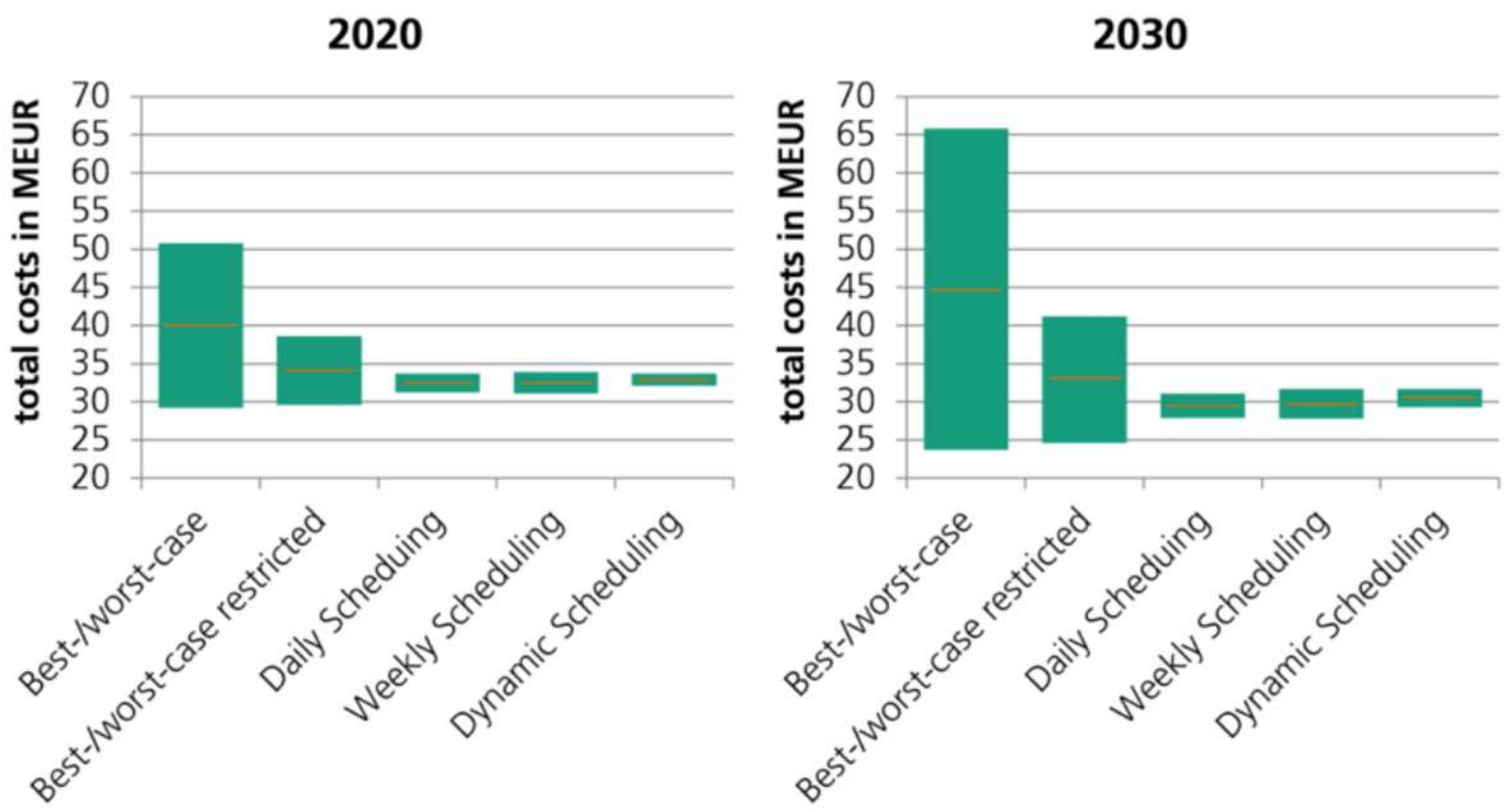


Figure 7.13: Relative energy cost by no scheduling, avoiding the winter months (restricted), daily, weekly and dynamic scheduling. As explained in the text the central values of the ranges shown should be considered the best estimates. The absolute cost scale will depend on prices, contracts and detailed 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

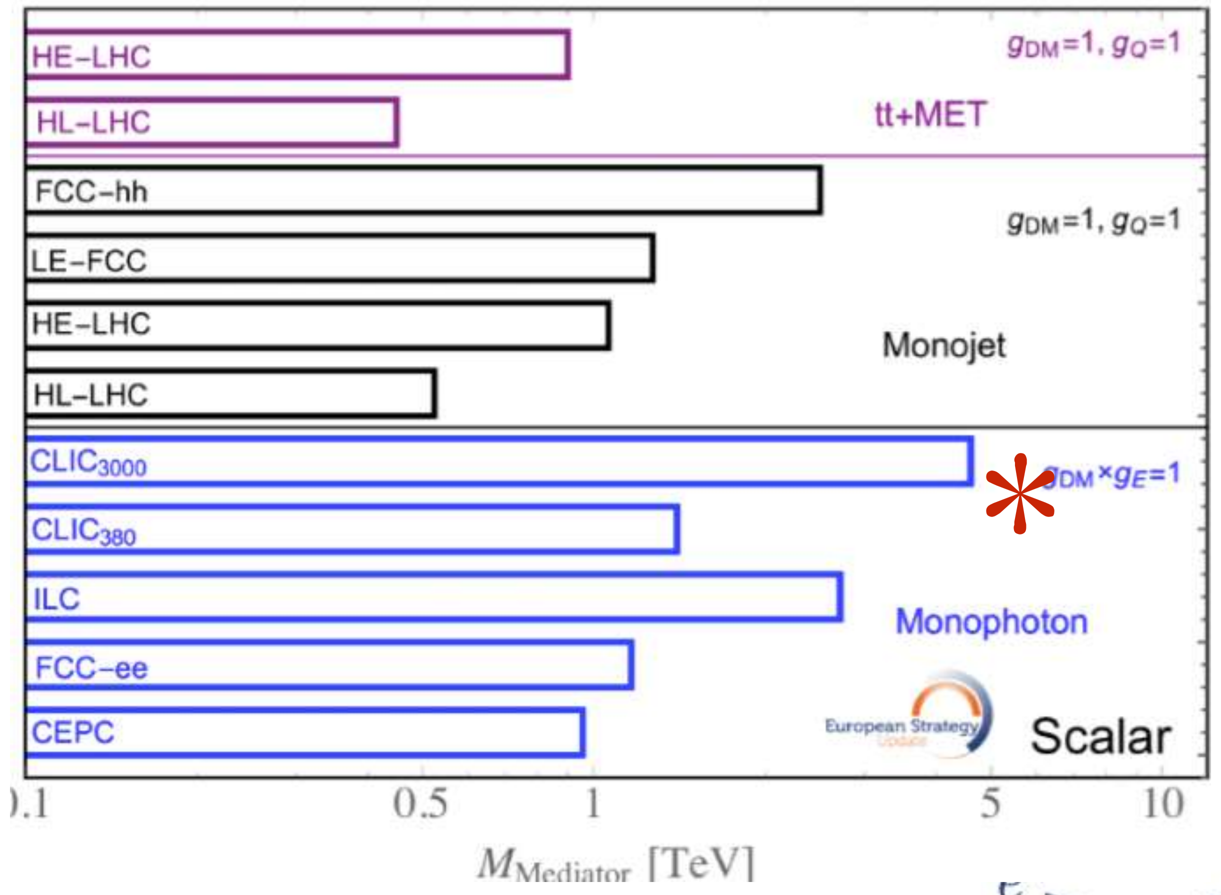
Topic 3:

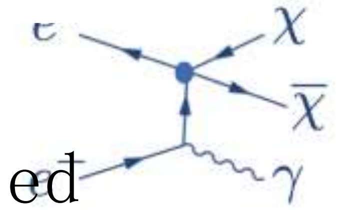
- The use of waste heat to generate electricity is technically difficult due to the low temperature of the waste heat. The heat would have to be raised to a significantly higher level and more electricity would be consumed than can be generated again in the later process.
- A reasonable option is to 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)

CLIC Physics Potential highlights 2019

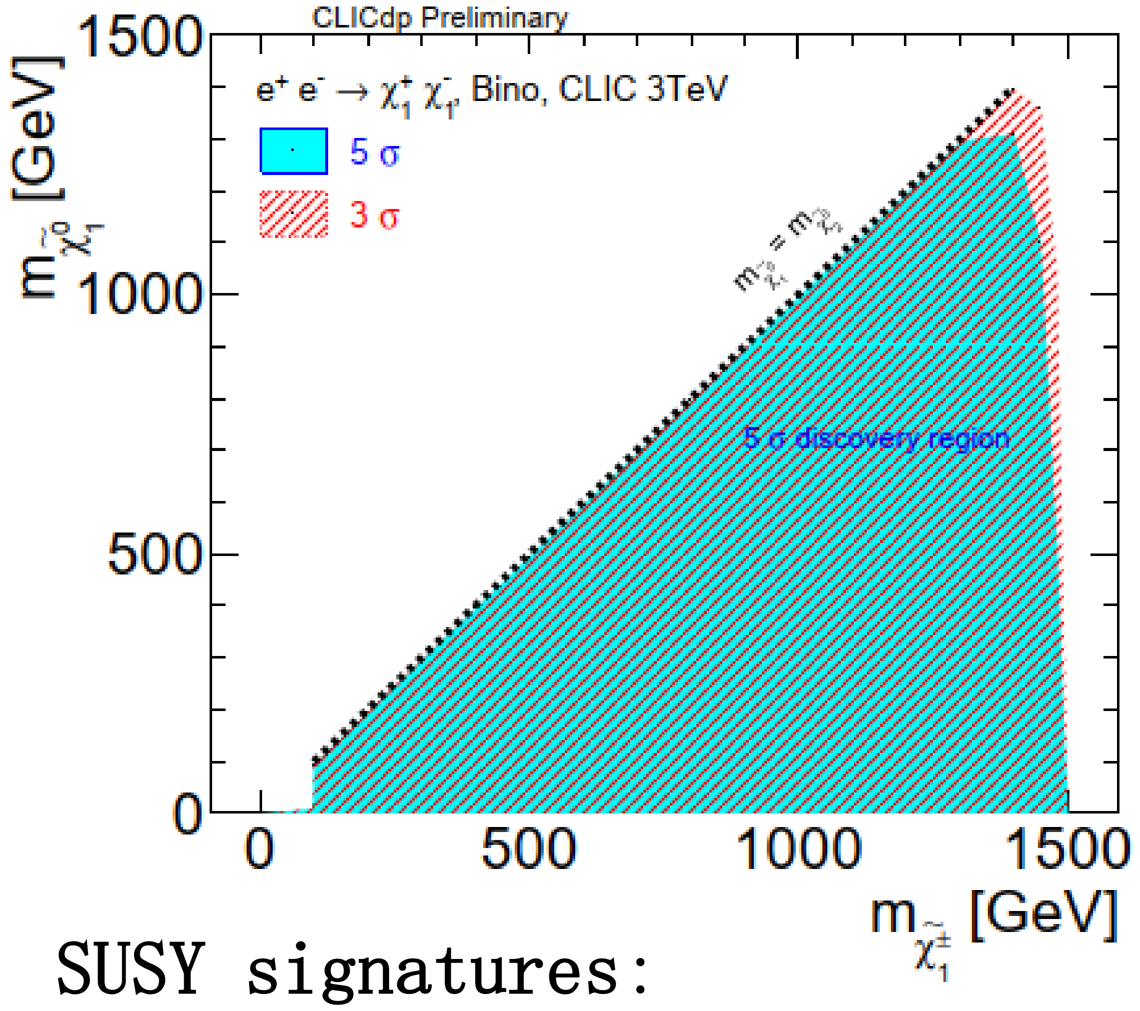
Approaching and after Granada, dedicated studies addressed extra questions raised, to allow direct comparisons with other proposals; and studies focusing on the high-energy potential are continuing





Dark matter:

- Searching for simplified model dark matter scalar mediator using mono-photon signature
- Higher mass reach



$e^+e^- \to \chi_1^+ \chi_1^-$ with $\chi_1^\pm \to \chi_1^0 W^\pm$ and $W^+W^- \to qqqq$ or $W^+W^- \to e^- \mu^+ \nu \nu$ or $e^+ \mu^- \nu \nu$

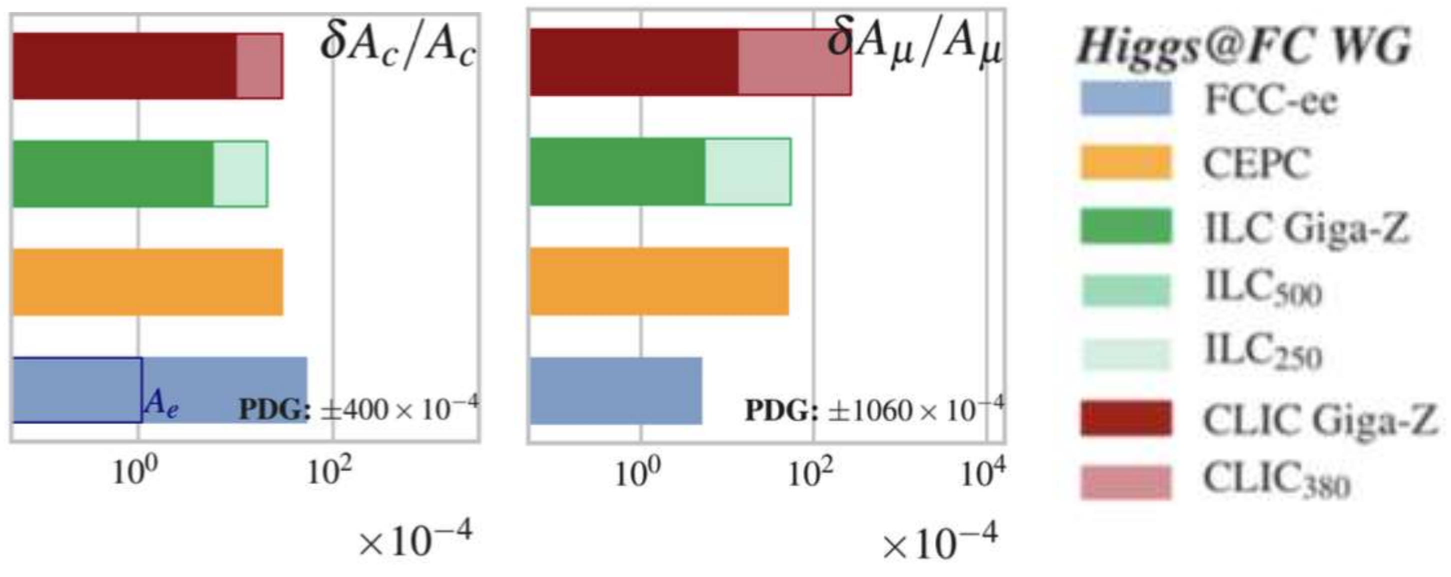
SUSY signatures:

- Scan of parameter space in R-parity conserving scenario
- Larger kinematic coverage; difficult to access at LHC

Electroweak precision at the Z:

- A dedicated CLIC run at the Z pole could produce ~100fb^{-1} over 2 years -> 4.5 billion Zs

  Also considered return-to-Z at 380 GeV
- Some significant improvement over current PDG; confirms that electron beam polarisation is equivalent to higher stats for several observables



Papers completed on:

- HZ at 3TeV in the all-hadronic mode https://arxiv.org/abs/1911.02523
- HH sensitivity https://arxiv.org/abs/1901.05897
- Track reconstruction https://arxiv.org/abs/1908.00256

Higgs coupling sensitivity:

- evaluated under longer first stage scenario https://arxiv.org/abs/2001.05278

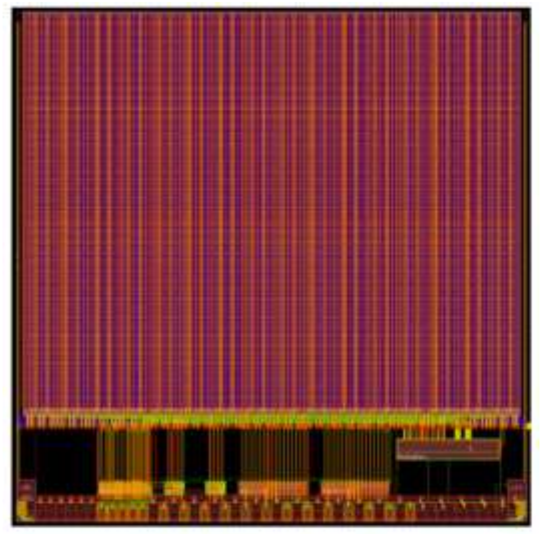
	Benchmark	HL-LHC	HL-LHC + CLIC 380 (4 ab^{-1}) (Longer first stage 380 GeV)	HL-LHC + CLIC 380 (1 ab^{-1}) + 1500 (2.5 ab^{-1}) (Baseline, 380 GeV + 1.5 TeV)	HL-LHC + FCC-ee 240	HL-LHC + FCC-ee 365
g_{HZZ}^{eff}[%]	SMEFT$_{ND}$	3.6	0.3	0.2	0.5	0.3
g_{HWW}^{eff}[%]	SMEFT$_{ND}$	3.2	0.3	0.2	0.5	0.3
$g_{H\gamma\gamma}^{eff}$[%]	SMEFT$_{ND}$	3.6	1.3	1.3	1.3	1.2
$g_{HZ\gamma}^{eff}$[%]	SMEFT$_{ND}$	11.	9.3	4.6	9.8	9.3
g_{Hgg}^{eff}[%]	SMEFT$_{ND}$	2.3	0.9	1.0	1.0	0.8
g_{Htt}^{eff}[%]	SMEFT$_{ND}$	3.5	3.1	2.2	3.1	3.1
g_{Hcc}^{eff}[%]	SMEFT$_{ND}$	–	2.1	1.8	1.4	1.2
g_{Hbb}^{eff}[%]	SMEFT$_{ND}$	5.3	0.6	0.4	0.7	0.6
$g_{H\tau\tau}^{eff}$[%]	SMEFT$_{ND}$	3.4	1.0	0.9	0.7	0.6
$g_{H\mu\mu}^{eff}$[%]	SMEFT$_{ND}$	5.5	4.3	4.1	4.	3.8
$\delta g_{1Z}[\times10^2]$	SMEFT$_{ND}$	0.66	0.027	0.013	0.085	0.036
$\delta \kappa_\gamma[\times10^2]$	SMEFT$_{ND}$	3.2	0.032	0.044	0.086	0.049
$\lambda_Z[\times10^2]$	SMEFT$_{ND}$	3.2	0.022	0.005	0.1	0.051

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

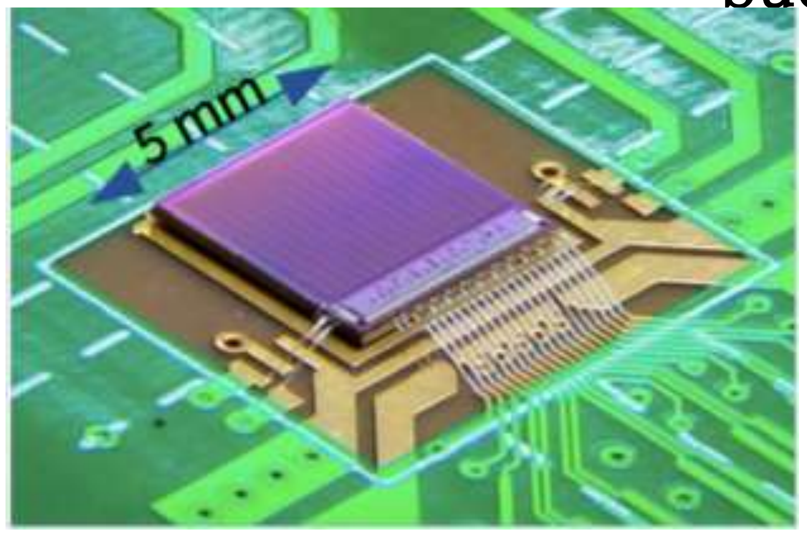
CLIC Detector Technologies R&D highlights 2019

Pursuing various technologies for CLIC vertex and tracking system,
to meet spatial and timing precision requirements, and material budget.

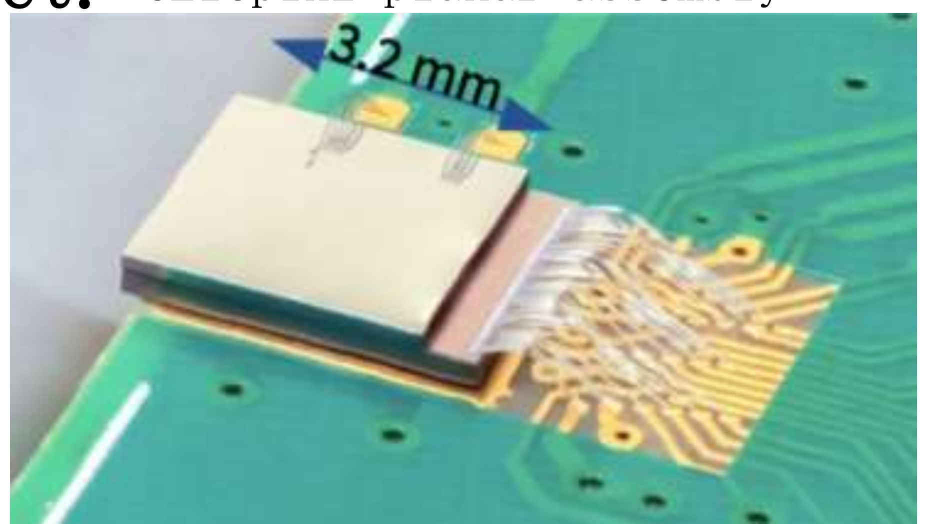
CLICTD chip



CLICTD on test board



CLICpix2 planar assembly



CLICTD: fully integrated small collection electrode HR-CMOS chip, new in 2019

- 30 x 37.5 μm^2 pixel size, 30 x 300 μm^2 readout channel size
- Using novel CMOS process modifications for faster charge collection
- Designed from detailed TCAD studies [JINST 14 (2019) no 5 C05013](#)
- Encouraging preliminary performance results from lab and first test beam (DESY)

CLICpix2: a readout chip from Timepix family for the CLIC tracker requirements

- 25 x 25 μm^2 pixel size, pixel matrix of 128 x 128
- Excellent timing performance
- 3μm target spatial resolution still challenging with thin sensors

Novel hybrid device assembly techniques: encouraging results from fine-pitch bump-bonding, and anisotropic conducting film

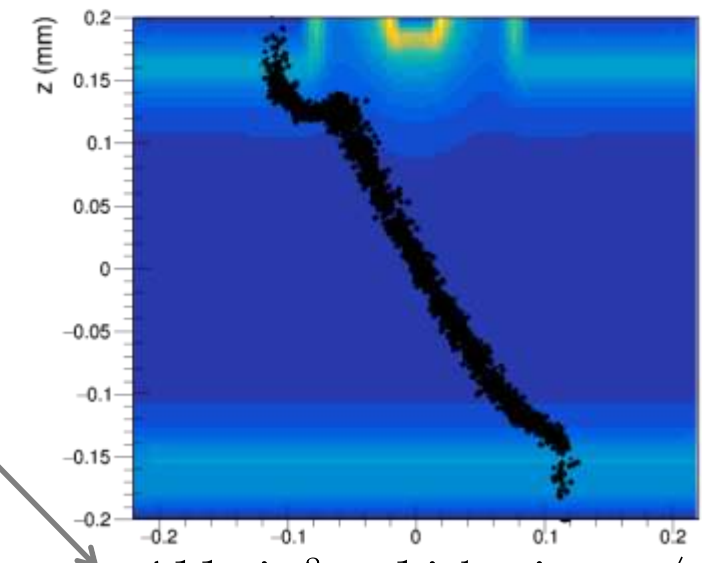
Common tools we have developed are being used increasingly widely:

Allpix² simulation framework

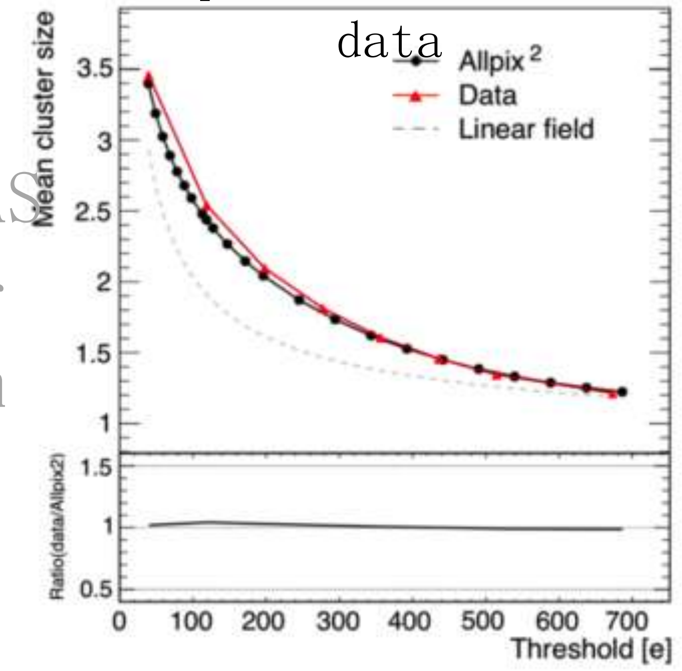
- Full Geant4 simulation of charge deposition
- Fast charge propagation (drift-diffusion model)
- Electric fields from TCAD can be imported

https://cern.ch/allpix-squared

Allpix² simulation



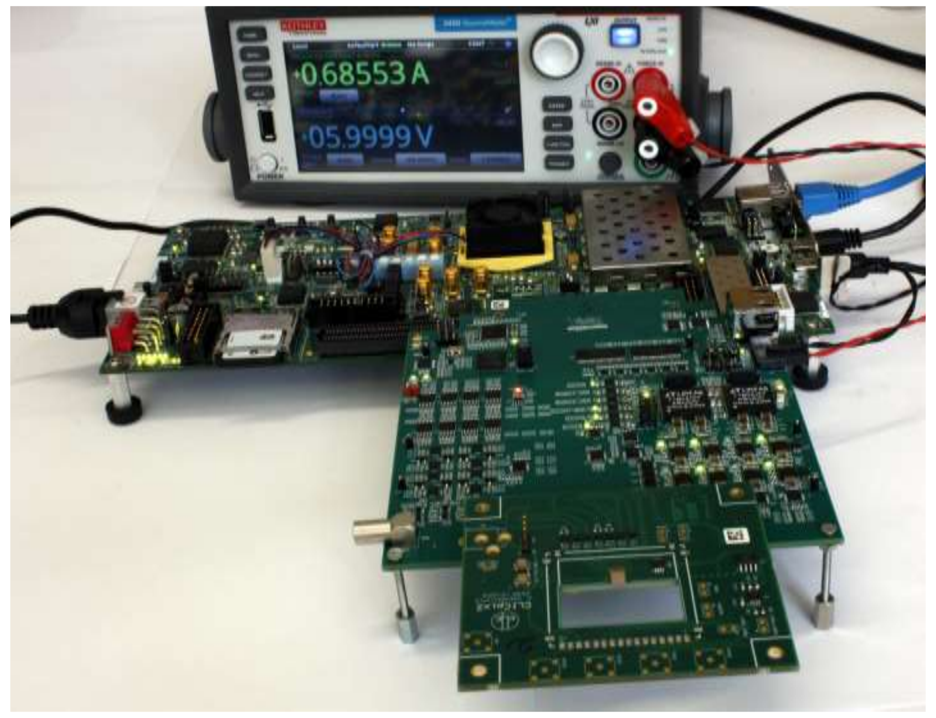
Allpix² validation w/ data



CaRIBOu readout

- Universal readout system developed w/ ATLAS
- System-on-chip architecture – crucial for new sensor development phase in lab & beam tests

CaRIBOu



Corryvreckan testbeam reconstruction

- Package for offline event building in complex data-taking environments, combining detectors with different readout architectures

https://cern.ch/corryvreckan

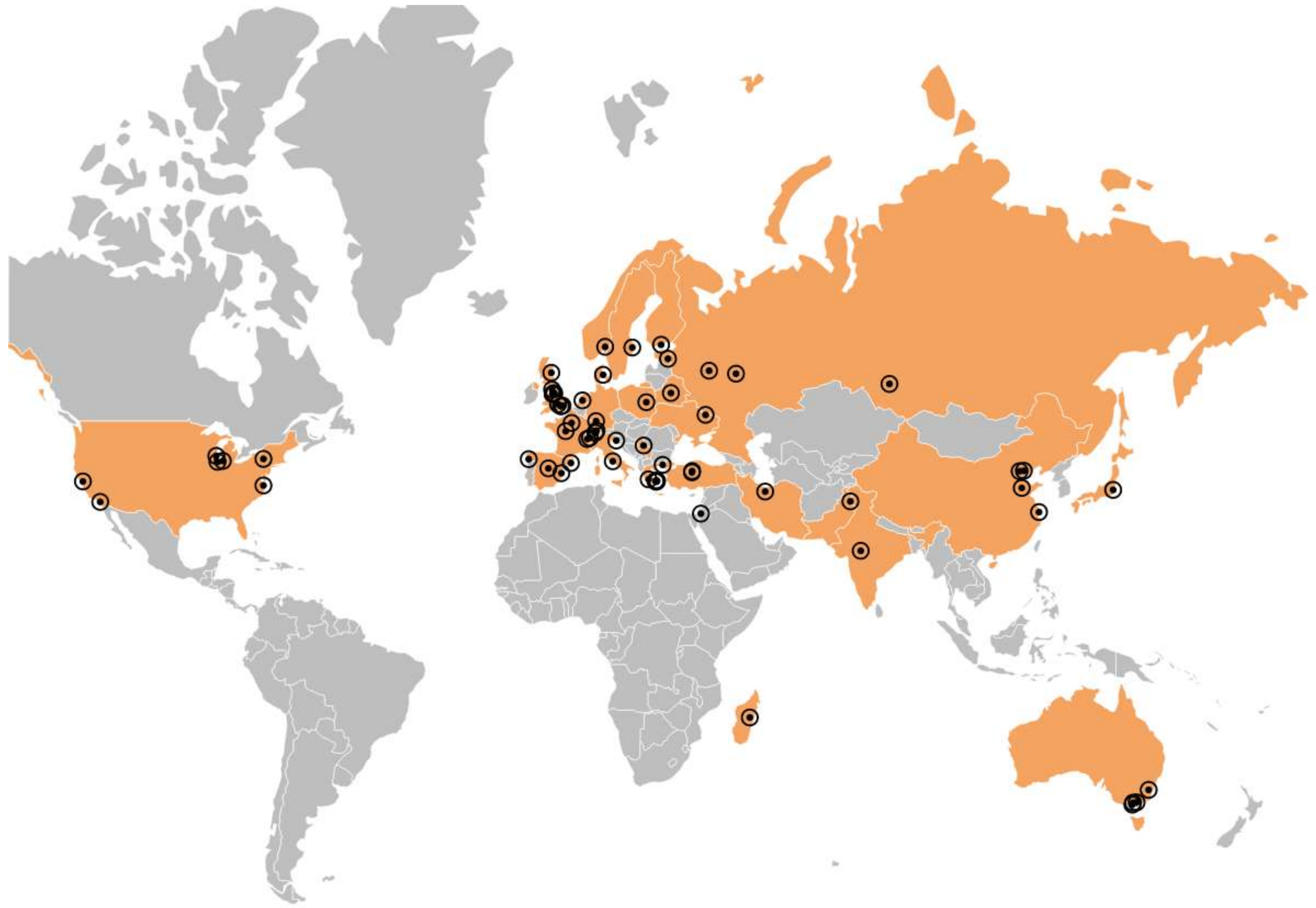
Collaborations

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