CLIC power and energy studies

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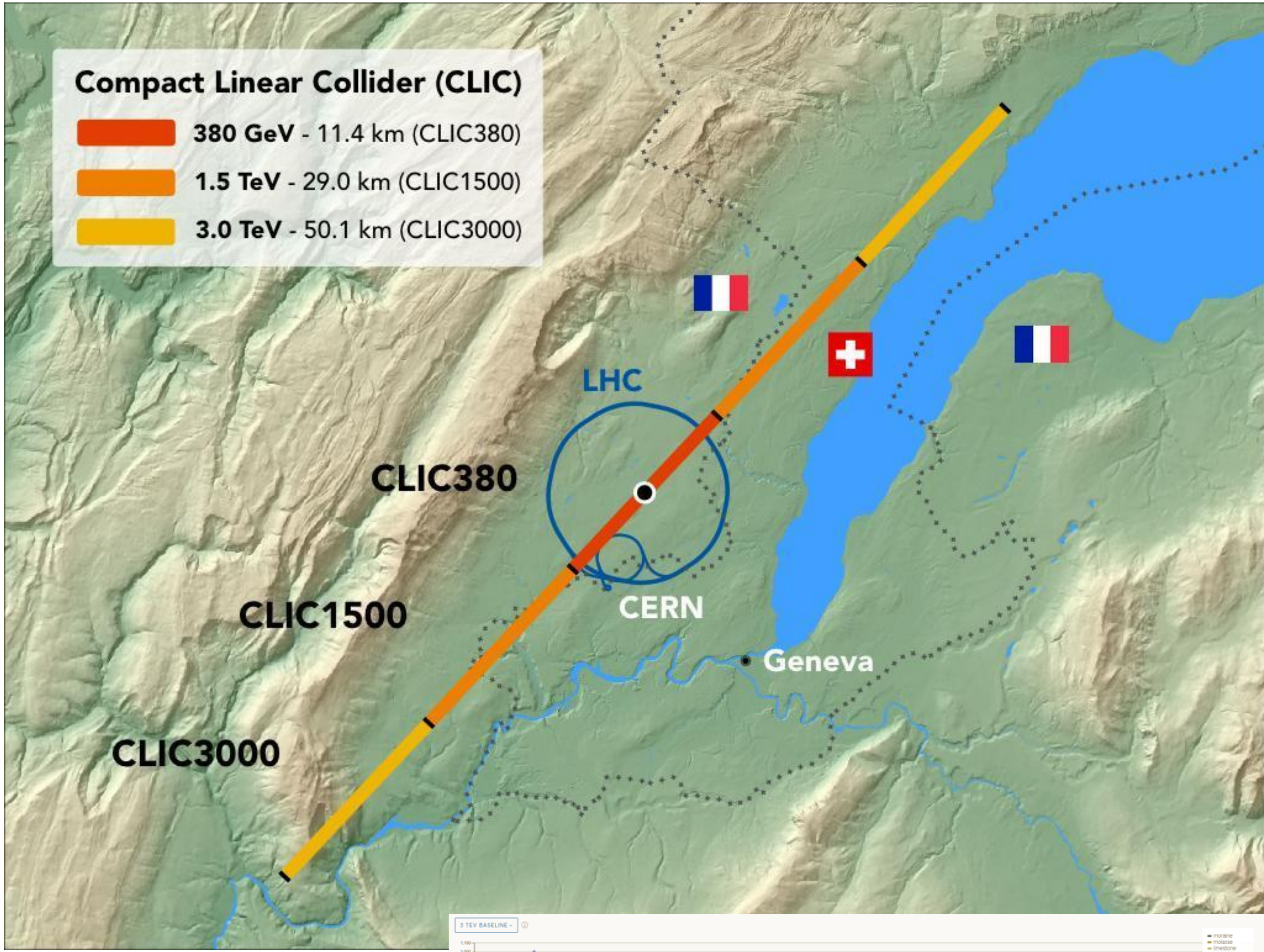
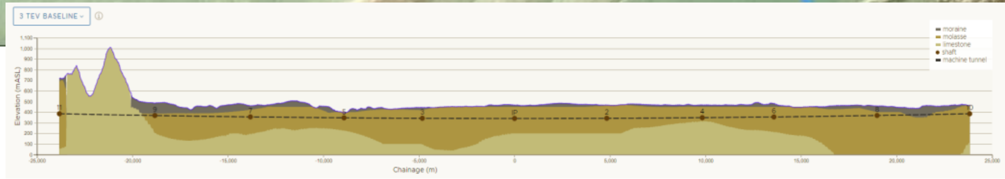
New power estimate for CLIC – focus on 380 GeV, design and technical developments (RF, magnets, infrastructure)

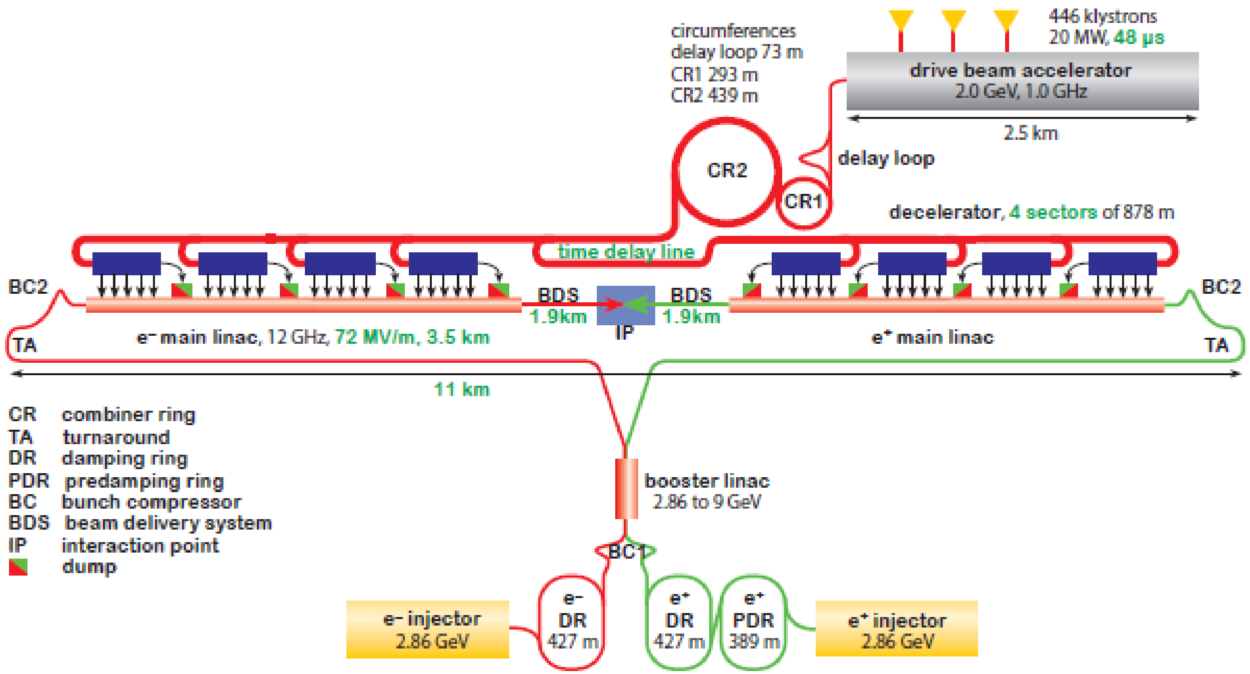
Energy use, cost studies and energy sources

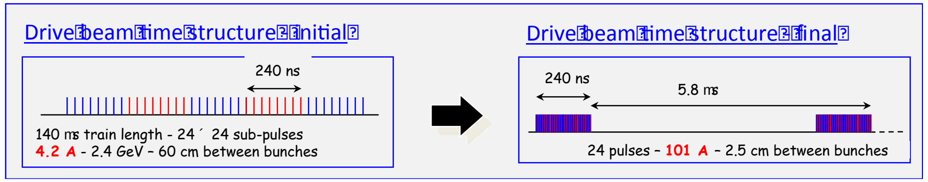


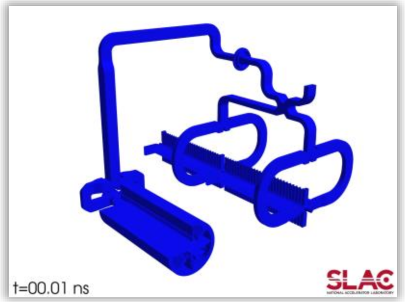


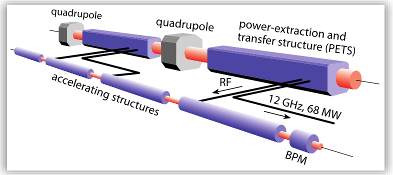
CLIC layout, power generation

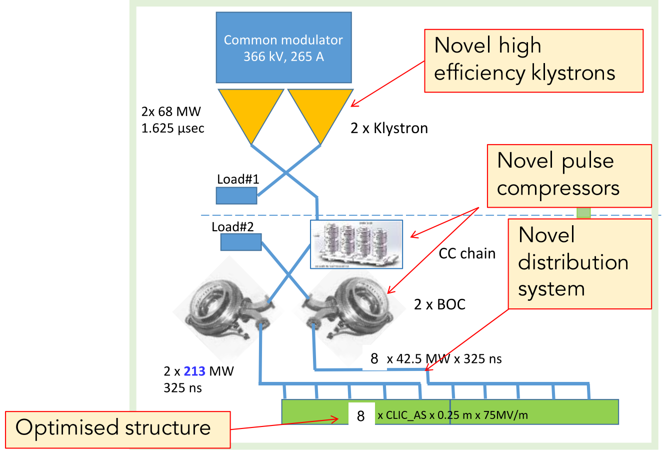
Drive-beam (low energy, high intensity, long pulses) created by klystrons



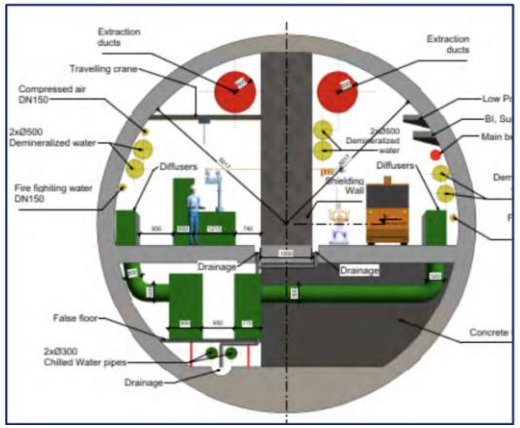








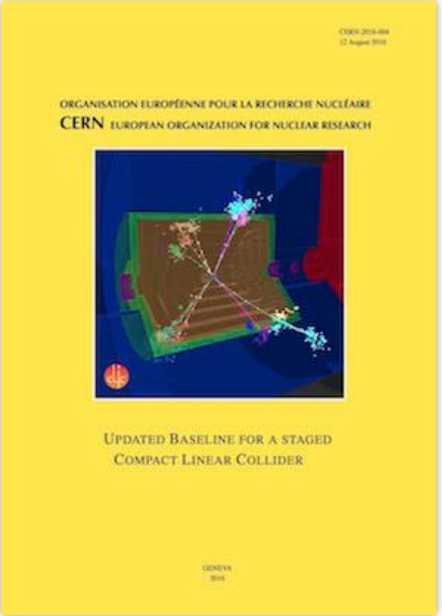
Note: We also study a klystron driven 380 GeV version – replacing the drive-beam complex on the surface with modulators, klystrons in the tunnel



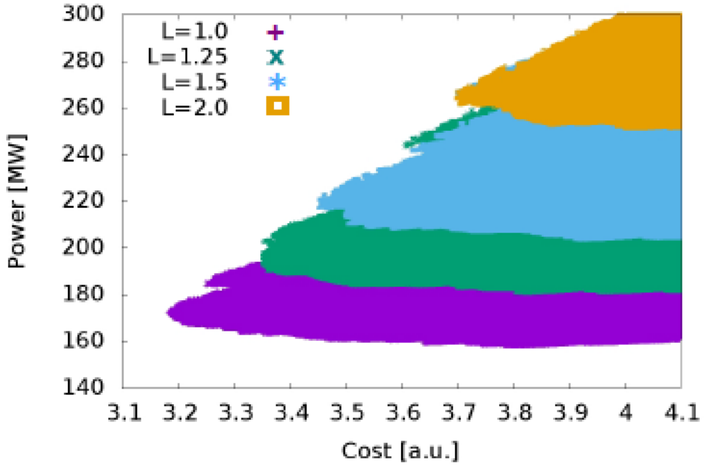
CLIC cost and power optimisation

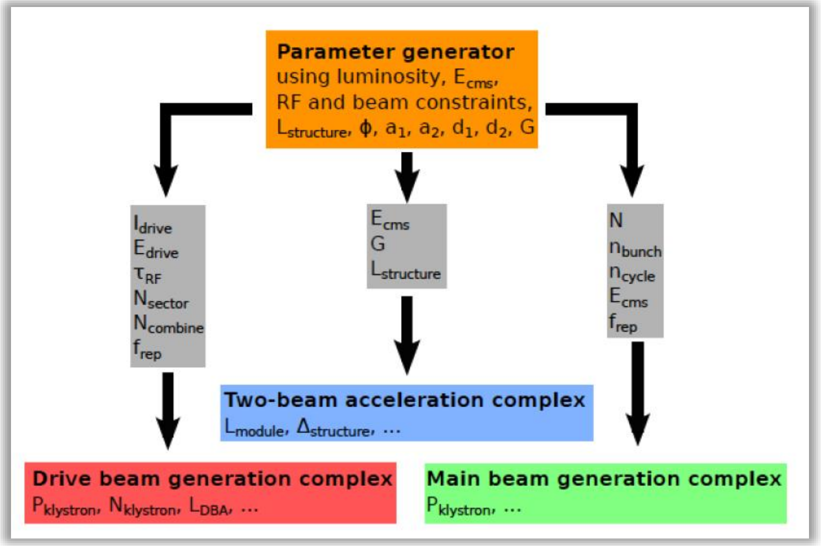
- CDR 2012: Cost and power estimated (bottom up, PBS based, focus 3 TeV machine but also 500 GeV estimated – less precise/partly based on scaling from higher energies)

- 2016: Cost and power update for 380 GeV drivebeam based machine made
- Still a very limited exercise:
  - Optimize accelerator structures, beam-parameters and RF system -> defines machine layout for 380 GeV
  - Remove pre-damping ring for electrons, scale DB better, some other minor changes
  - Largely scaling from 500 GeV



Yellow report: New reference plots for power, costs, luminosities, physics, etc





CLIC parameters

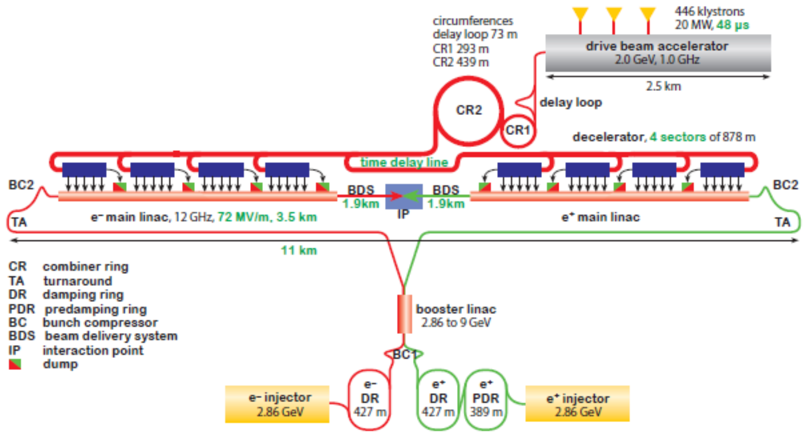
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total 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)	$\varepsilon_x/\varepsilon_y$	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

During 2017-18

- Project breakdown structure (**PBS**) of the **costing tool** has been used both for the Drive Beam and Klystron –based options in order to insure the consistency of the power and the cost estimate
- **Operating** (not the specification) **values** have been used as much as possible for the RF power sources and magnet power supplies

- Key design and technical changes:
  - Injector optimized
  - CV, EL and other infrastructure re-evaluated
  - Development of high efficiency klystrons (see talk of Steffen Doebert)
  - Special consideration for X-band klystrons (see later in this talk)
  - Drive beam energy is reduced from 2.4 to 1.9 GeV, more optimized RF system
  - Different design of the BDS at 380 GeV
  - Magnet development (see later)
  - Instrumentation, alignment and stabilization systems checked
  - etc

- First real bottom up estimate at 380 GeV



Reducing the power for the klystron based version

A Prototype of Superconducting Solenoid for 50 MW X –band Klystron

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W. Wuench, I. Syratchev, G. Mcmonagle, N. Catalan-Lasheras, S. Calatroni, and S. Stapnes (CERN)
H. Watanabe, H. Tanaka, Y. Koga, S. Kido, T. Koga, and K. Takeuchi et al., (Hitachi)
in cooperation with SLAC and CPI

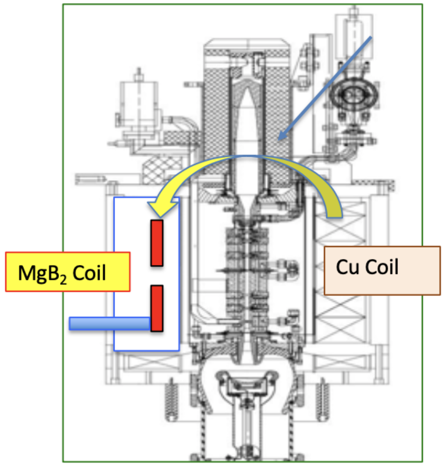
High-efficiency RF Workshop, Uppsala Univ., 18 June., 2019

Background and Objectives

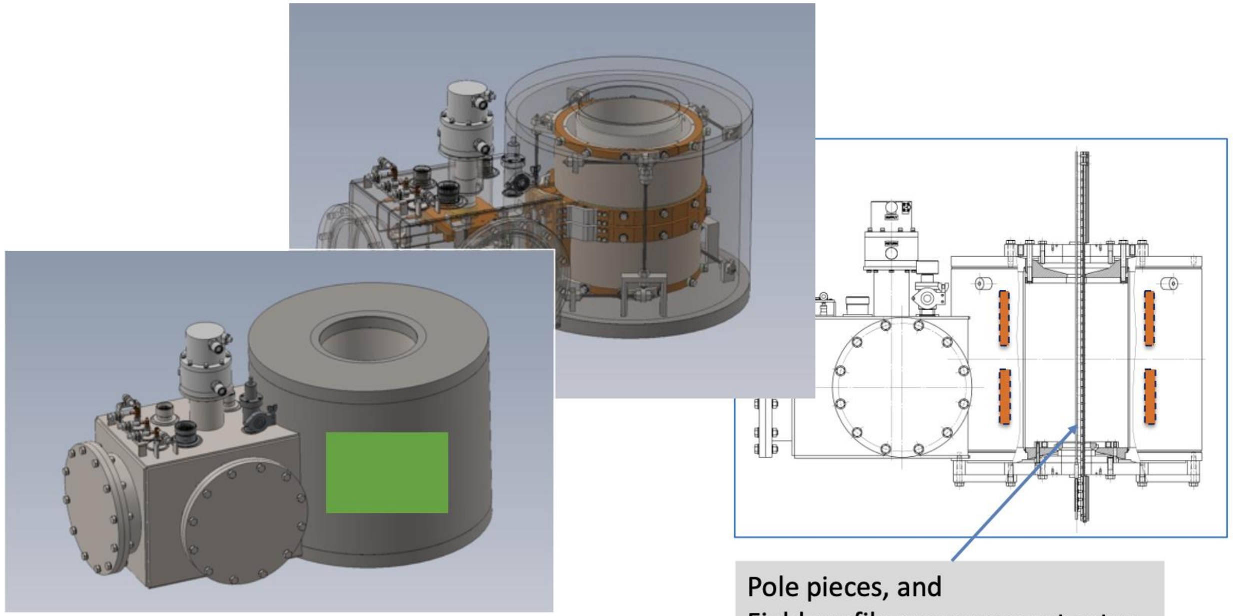
- The CLIC-380 staging scenario being studied at CERN,
- X-band (12 GHz) klystron-based accelerating scheme as a quick option.
- The X-band klystron requiring a beam-focusing solenoid and magnet field:
  - Bc = ~ 0.6 T in a warm bore-diameter of 0.24 m
- A Cu-based solenoid magnet, currently consuming
  - Power of ~20 kW/**Klystron**, corresponding to ~ 100 MW for ~ 5,000 Klystrons for CLIC-380.
- The superconducting magnet option may realize:
  - Power saving down to < 2 kW/Klystron (for , corresponding to ~ 10 MW, for Cryogenics. --> 90 % power saving

A SC Prototype Magnet proposed

Design Parameters	
Superconductor * (T-operation)	MgB_2 (@ 20 K)
Current	50A/57.1 A (62.8 A)
Central field	0.7 T/0.8 T (0.9 T)
Stored energy	~ 10 kJ
Cryo-cooler applied	6.7 W @ 20 K 13.5 W @ 80 K
AC Plug-Power	≤ 3 kW (< 1,5 kW/Klystron in case of a pair)



Prototype Coil Assembly with Cryostat functioning as Flux-rerun Iron Yoke and Cryo-cooler



Pole pieces, and
Field profile measurement setup

Progress in 2018/2019

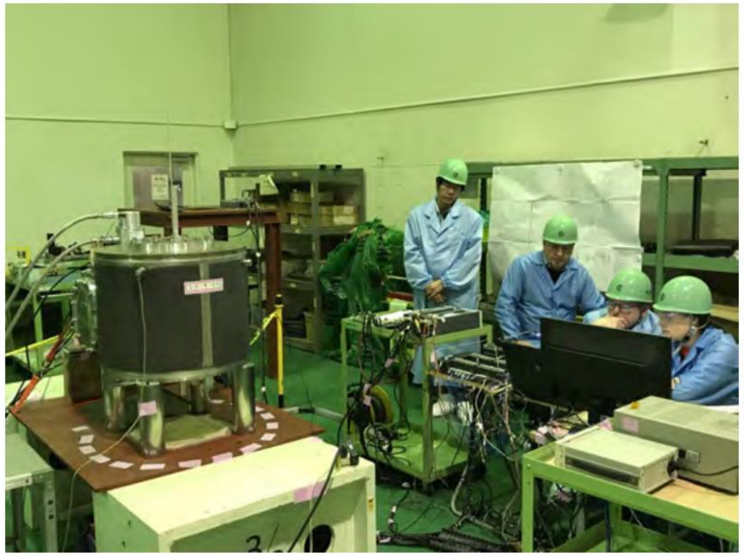
2018:

- **Jan:** MgB2 conductor fabrication started,
- **May:** A model magnet fabrication started,
- **Aug:** MgB2 conductor fabrication completed, including the performance test
  - Confirming $I_{op} \geq 50$ A, at 0.7 T, ≥ 20 K.
- **Sept:** Coil-winding started,
- **Oct:** Coil-winding and heat-treatment completed.
- **Nov:** Epoxy-resin impregnation
- Dec: Coil assembled with Cryostat and Cryocooler
- Dec: Magnet system complete, and Cool-down start

2019:

- Jan: Coil reached 16 K, and the 1st excitation reached Bc = 0.9 T, I = 62 A (max)
- Jan: Cryocooler failure and the investigation in progress.
- Feb: Acceptance tests including the full excitation up to Bc ≥ 0.9 T, field profile measurement, a quench-test at Tc ≥ 28 K, and emergency-safety test, with CERN participation.

Acceptance Test at Hitachi
14 – 15 Feb., 2019



Summary: Development of a Superconducting Solenoid for X-band Klystron beam-focusing

Objective

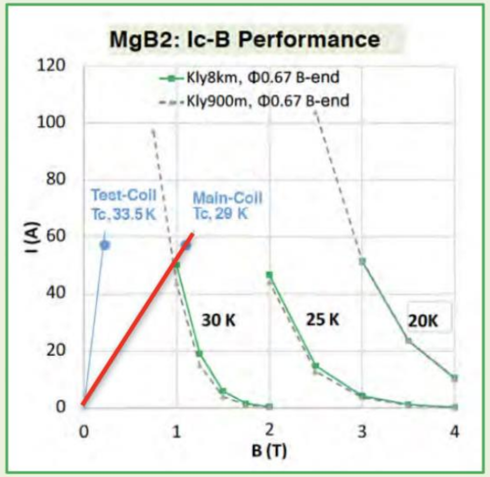
- SC-mag technology to be demonstrated for high-efficiency X-band Klystron for future applications

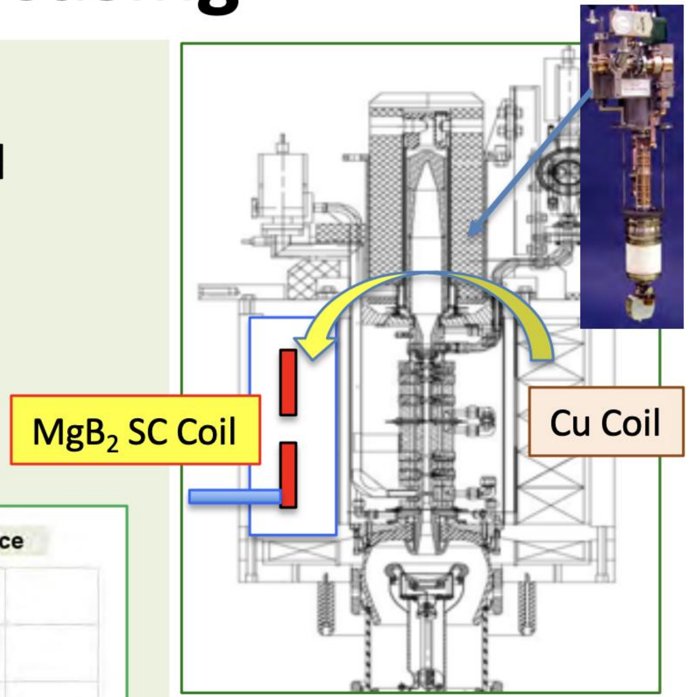
Prototype SC Magnet **Design:**

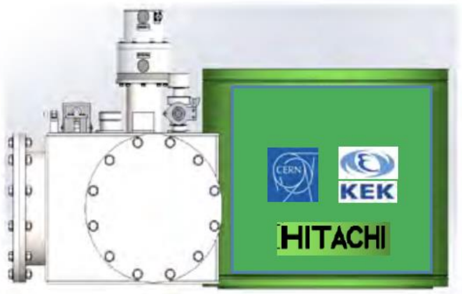
- Superconductor: **MgB_2**
- B_c: > **0.7 T** (at a warm bore aperture of ~ 0.24 m)
- T-operation: **20 K** or higher
- AC-plug power: < 3 kW

  → **< 1.5 KW / Klystron, by pairing**

  → **< 1/10 AC-power of Cu-Coil**



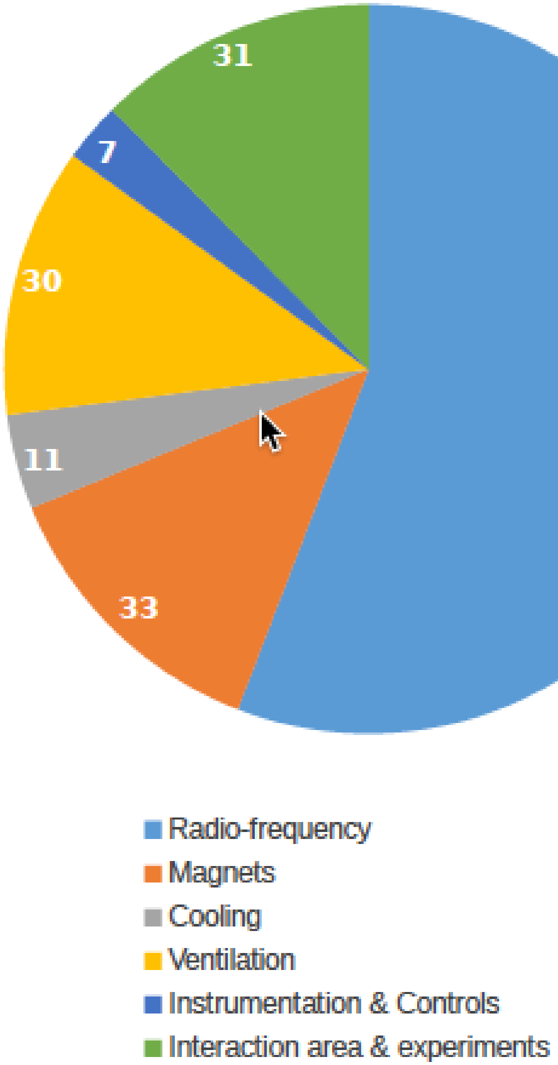




Progress and Further Plan:

- MgB_2 conductor performance confirmed,
- Magnet fabrication completed,
- Magnet Performance: **B_c = 0.9 T. at Tc =28 K, (AC-plug = 2.8 kW)**
- Performance to be evaluated, with Klystron, at CERN in 2019.

Magnets

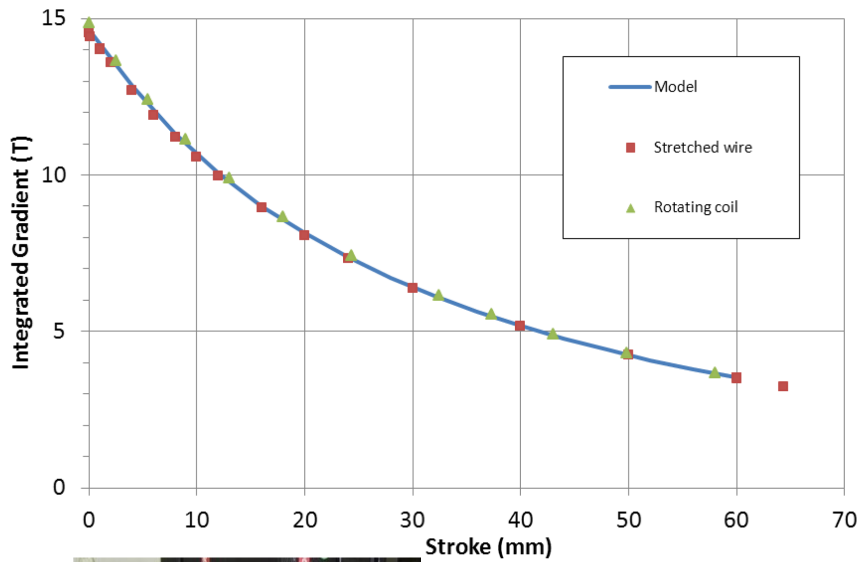


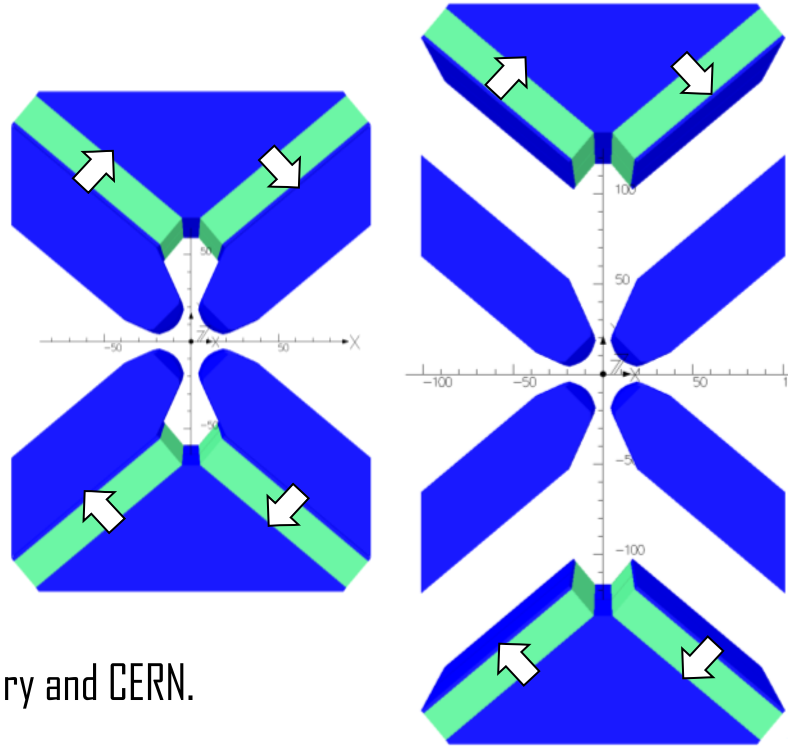
1.5 TeV power

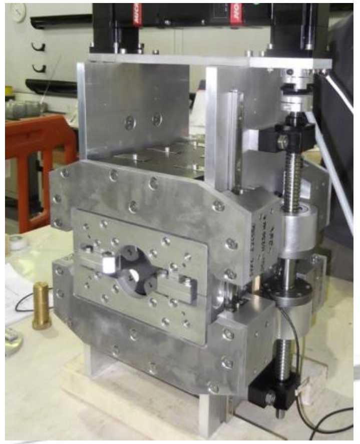
ZEPTO (Zero Power Tuneable Optics) project is a collaboration between CERN and STFC Daresbury Laboratory to save power and costs by switching from resistive electromagnets to permanent magnets.

High strength quadrupoles

High strength Drive Beam quadrupole (tunes 60.4 to 15.0 T/M). Uses 4 NdFeB blocks (18x100x230 mm) with Br=1.37, requires 64 mm motion range.







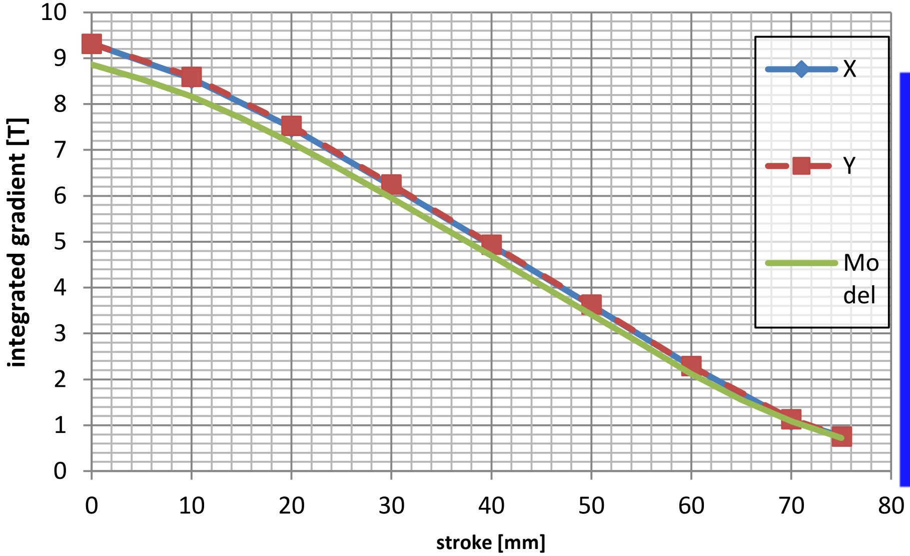
Built and tested at Daresbury and CERN.

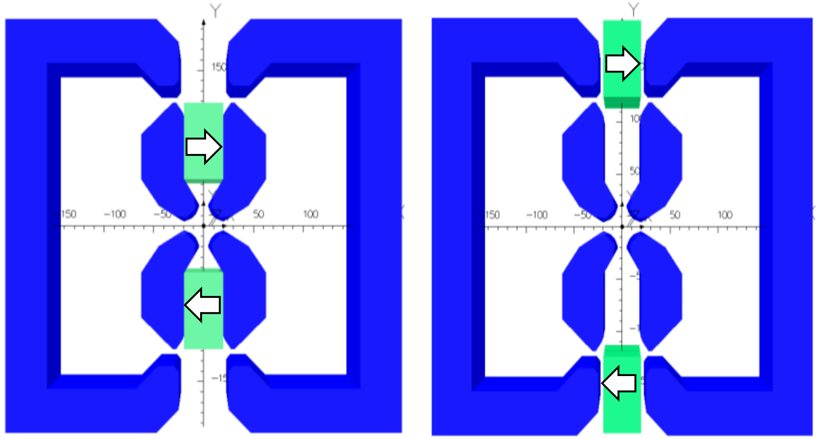
Meets to needs of CLIC DB

Science & Technology Facilities Council

Low strength quadrupoles

Low strength Drive Beam quadrupole (tunes 43.4 to 3.5 T/M). Uses 2 NdFeB blocks (37.2x70x190 mm) with Br=1.37, requires 75 mm motion range.





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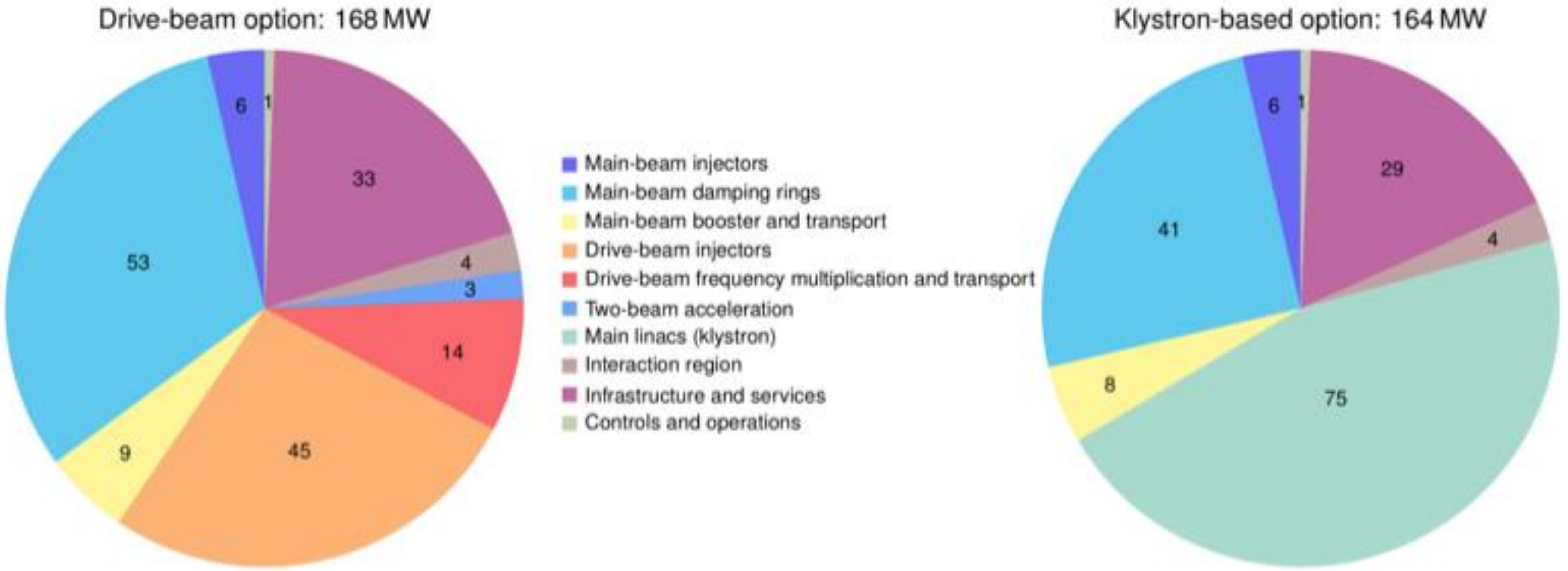
Power



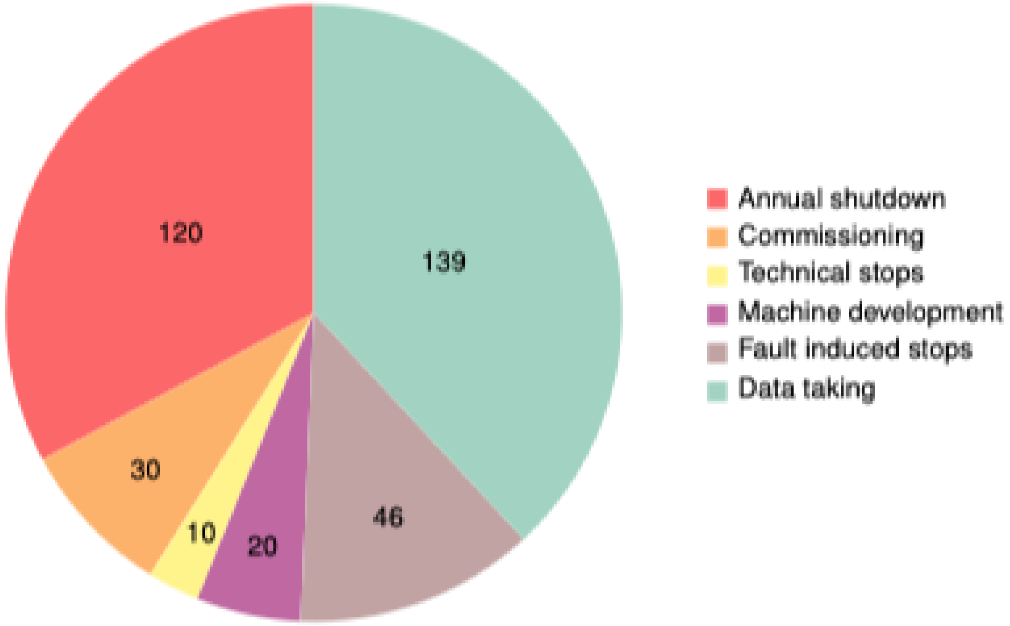
Power estimate bottom up (concentrating on 380 GeV systems)

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

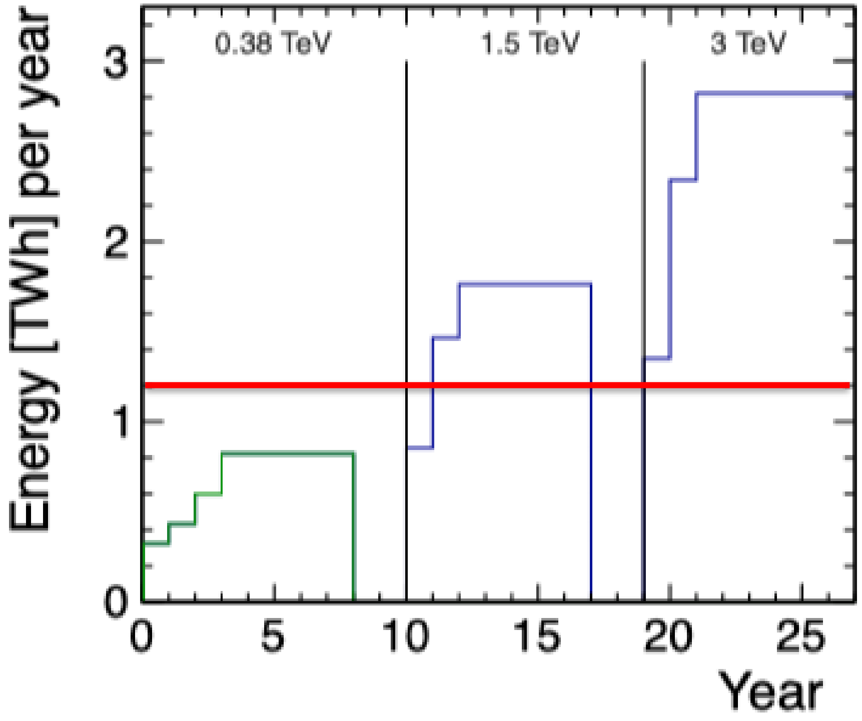
Further savings possible, main target damping ring RF

Did not revise 1.5 and 3 TeV numbers, some possible gains also there (10-15%) but were much better estimates already in 2012.

Energy



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



From running model (above) and power estimates at various states – the energy consumption can be estimated

CERN is currently consuming ~1.2 TWh yearly (~90% in accelerators), increasing to 1.4 for HL LHC

Ramp up:

- 10, 30, 60% lum at stage 1
- 25, 75% stages 2,3

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

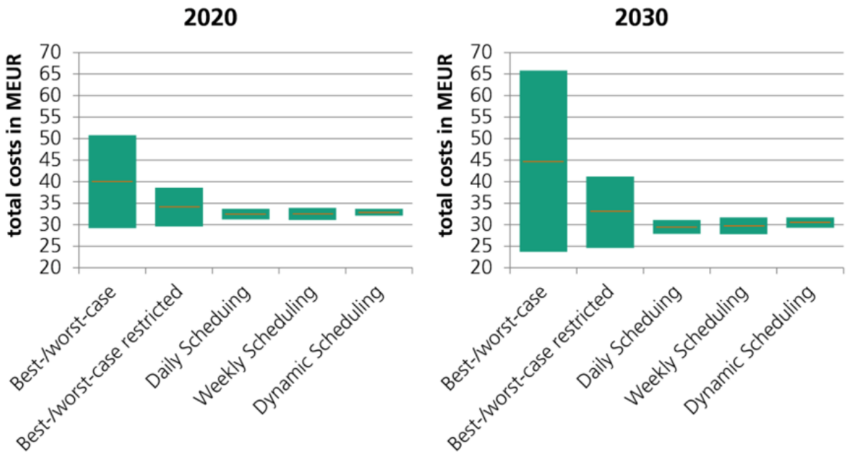


Figure 7.13: Relative energy cost by no scheduling, avoiding the winter months (restricted), daily, weekly and dynamic scheduling. As explained in the text the central values of the ranges shown should be considered the best estimates. The absolute cost scale will depend on prices, contracts and detailed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

Final words

The CLIC power and energy use are now quite optimized

- Further gains possible for DB RF

Most energy cost reduction are by not running in the winter

- Flexible scheduling to use excess power potentially interesting, in particular in view of push towards renewables where fluctuations are large
- Storage not yet mature on the level needed (can change with time)

Renewables interesting for future, clearly interesting to build future colliders at sunny and windy places – difficult to imagine in Geneva area (maybe better here)

A final comment:

- LC's have a reputation for being power hungry
- However, the CLIC average annual energy consumption (0.7 TWh) is less than 50% of FCC-ee (1.9 TWh)
- FCC-hh is 4.0 TWh/year
- So power and energy are general challenges

CERN

CLIC

CLIC Efficiency

Mains	
Modulators	
	0.89
Klystrons	
	0.7
Waveguide	
	0.985
DB RF structures	
	0.95
Drive beam	
Total wall plug to drive beam efficiency	0.58

Drive beam	
	0.97x0.9
PETS	
	0.98
Waveguides	
	0.92
RF structures	
	0.44x0.64
Main beam	
Total drive beam to main beam efficiency	0.22

Total 12.7%

Adding overheads etc: 11%