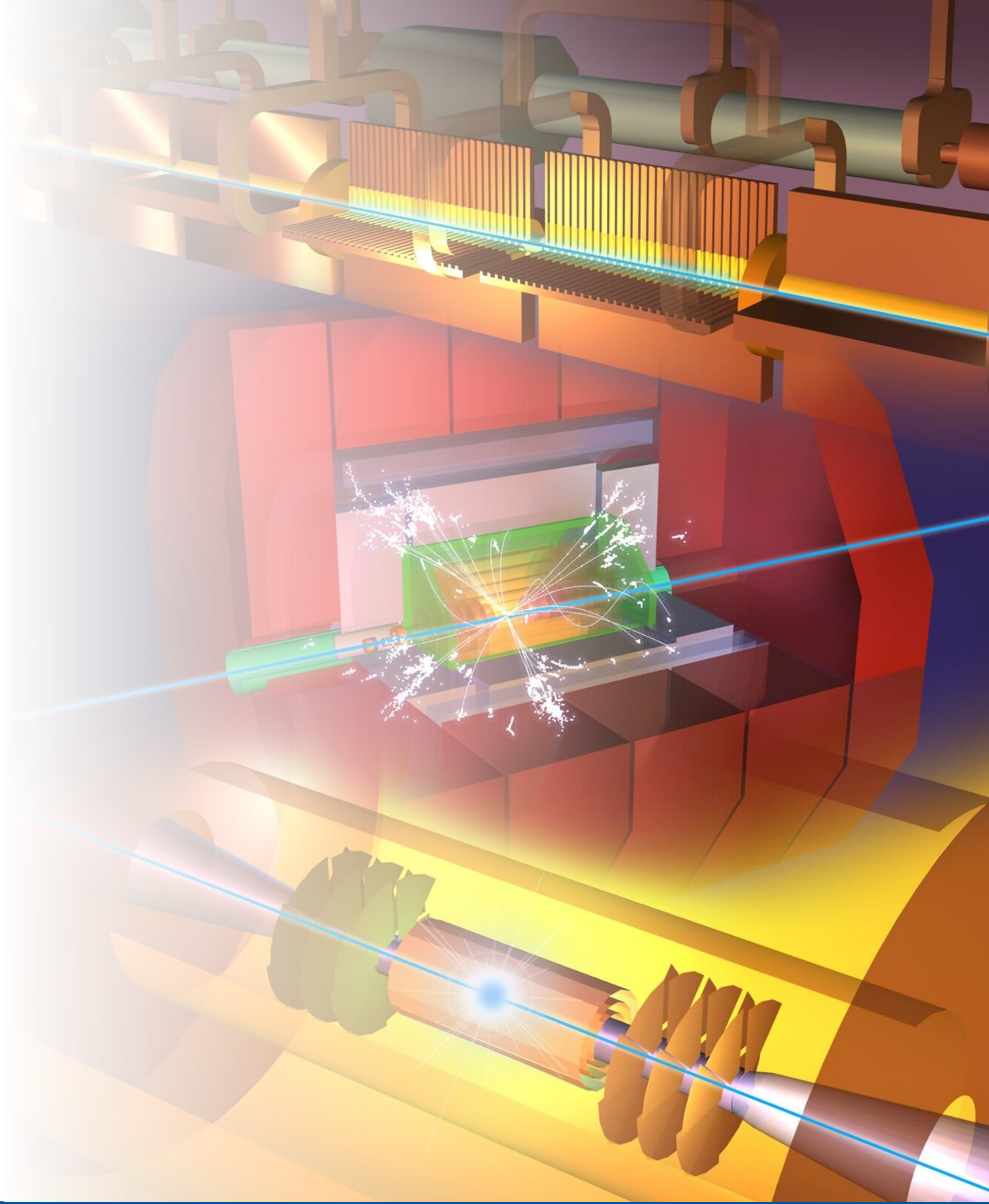
Andrea Latina (CERN)
on behalf of CLIC

The Compact Linear Collider (CLIC)

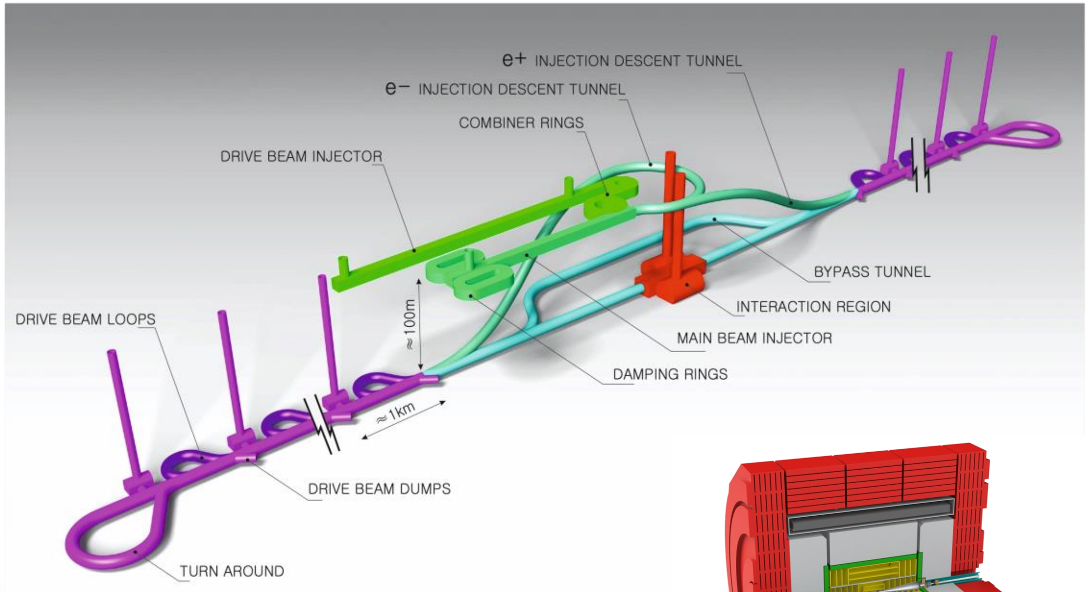


Outline

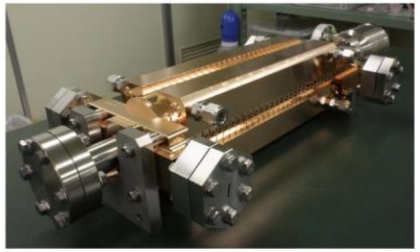
- CLIC project overview
- CLIC at 380 GeV
- Optimisation studies
- Applications
- Summary

IAS HKUST
14-16 Feb 2023

The Compact Linear Collider (CLIC)



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



- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 structures 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 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

- **Cost:** 5.9 BCHF for 380 GeV (stable wrt 2012)
- **Power:** 168 MW at 380 GeV (reduced wrt 2012), corresponding to 60% of CERN's energy consumption today

- Comprehensive **Detector and Physics** studies

Collaborations

CLIC accelerator

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

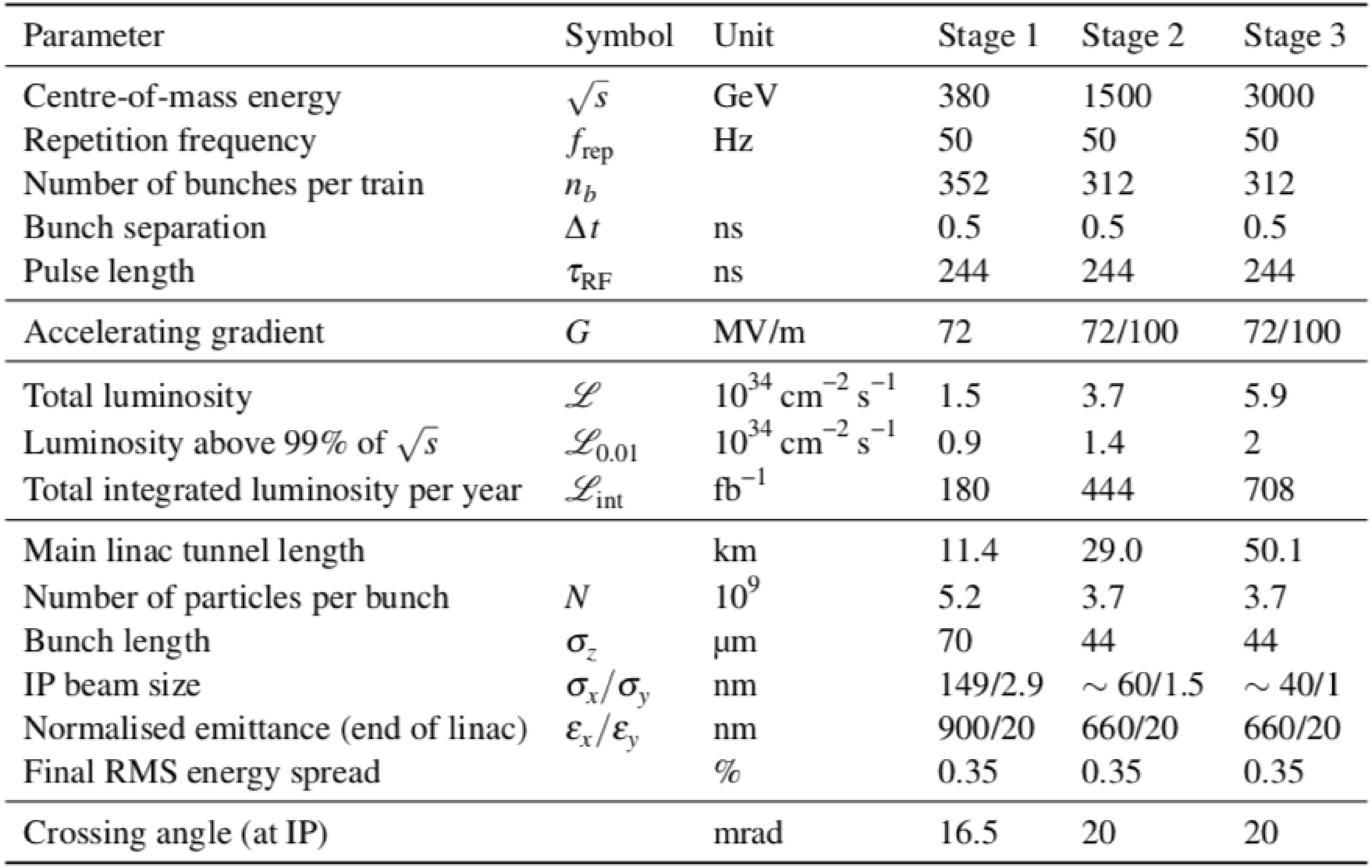
CLIC detector and physics (CLICdp)

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

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

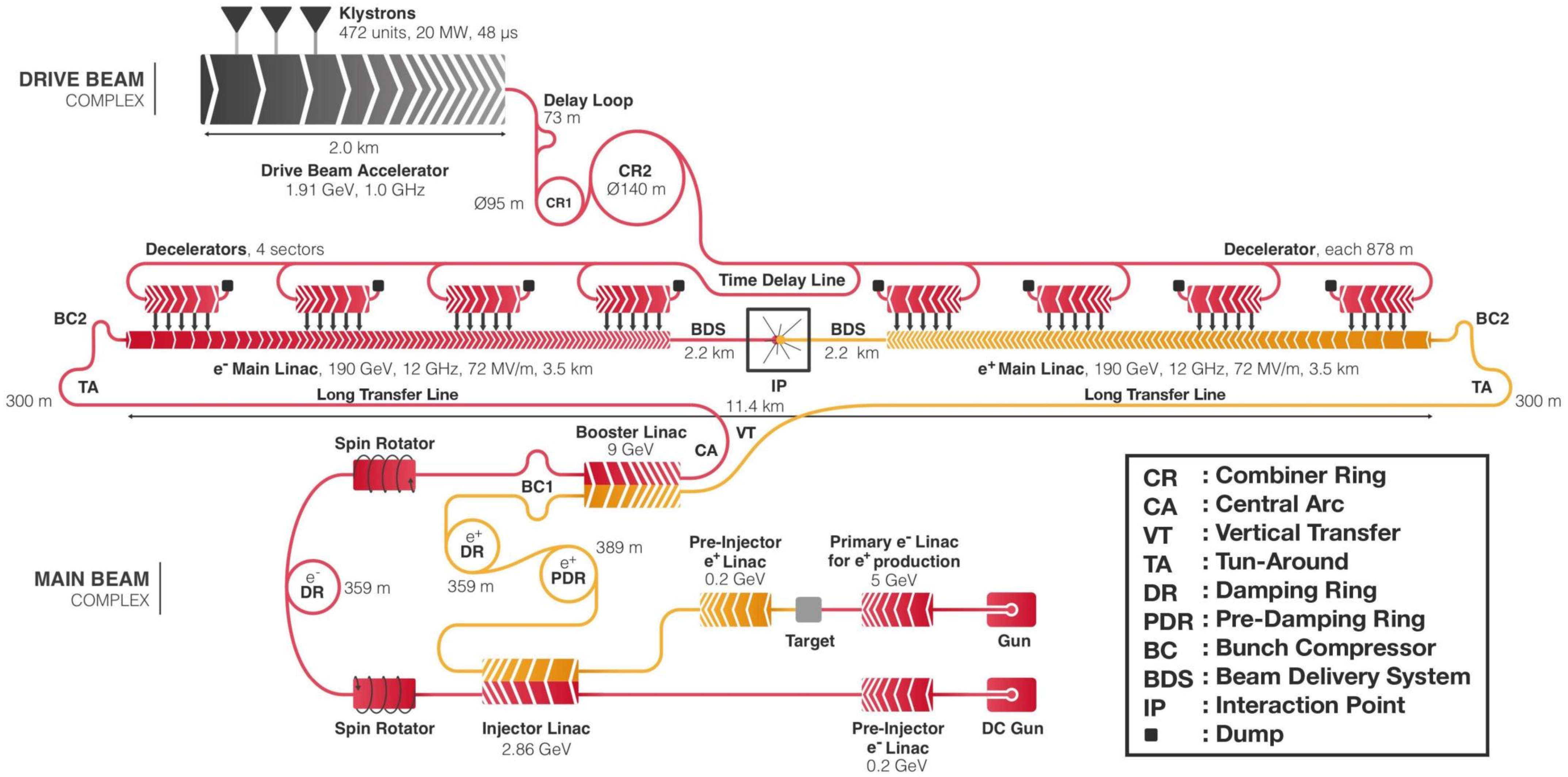
*Canada missing on map

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

CLIC Layout 380 GeV



CR : Combiner Ring
CA : Central Arc
VT : Vertical Transfer
TA : Tun-Around
DR : Damping Ring
PDR : Pre-Damping Ring
BC : Bunch Compressor
BDS : Beam Delivery System
IP : Interaction Point
■ : Dump

CLIC Luminosity Performance

Luminosity Targets

- The luminosity that can be achieved with a perfect machine is:

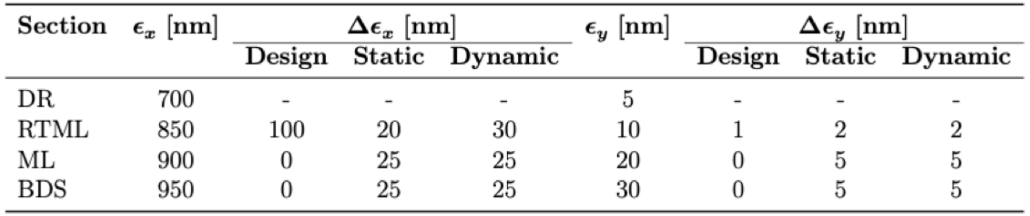
$$\mathscr{L} = 4.3 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- Luminosity predictions including static and dynamic imperfections can be made by simulating a larger emittance through a perfect machine.
  - With static imperfections (ε_X = 770 nm, ε_Y = 17 nm from DR):

$$\mathscr{L} = 2.3 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

  - With static and dynamic imperfections (ε_X = 860 nm, ε_Y = 29 nm from DR):

$$\mathscr{L} = 1.55 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$



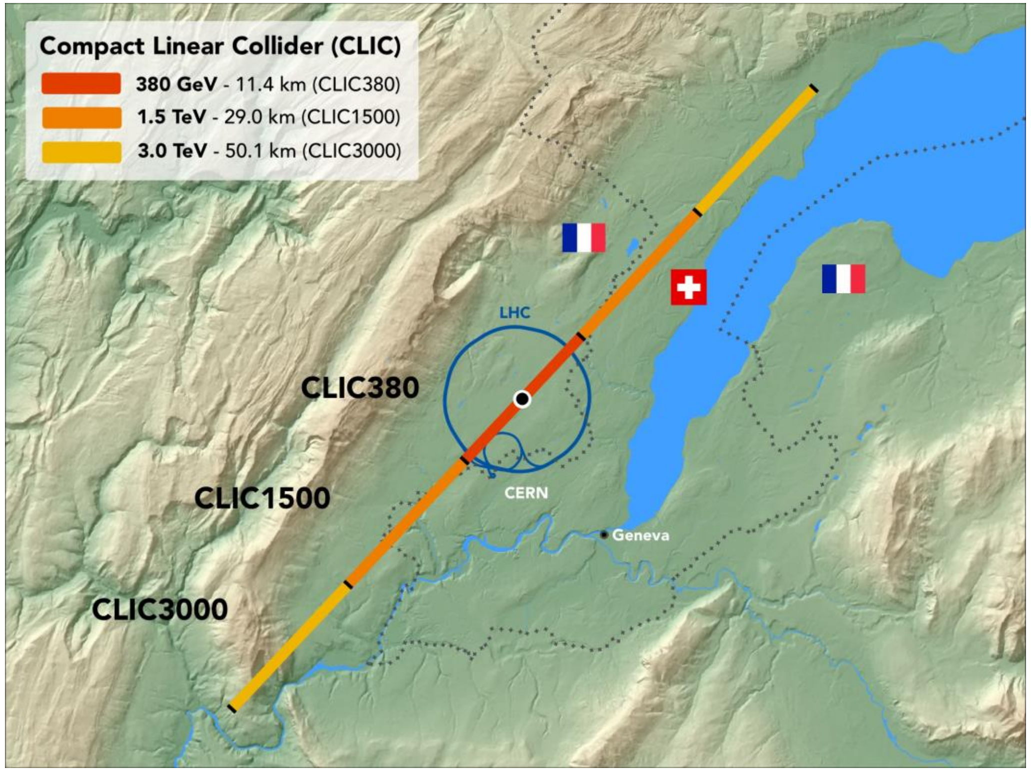
Section	ϵ_x [nm]	$\Delta\epsilon_x$ [nm]			ϵ_y [nm]	$\Delta\epsilon_y$ [nm]		
		Design	**Static**	**Dynamic**		**Design**	**Static**	**Dynamic**
DR	700	-	-	-	5	-	-	-
RTML	850	100	20	30	10	1	2	2
ML	900	0	25	25	20	0	5	5
BDS	950	0	25	25	30	0	5	5

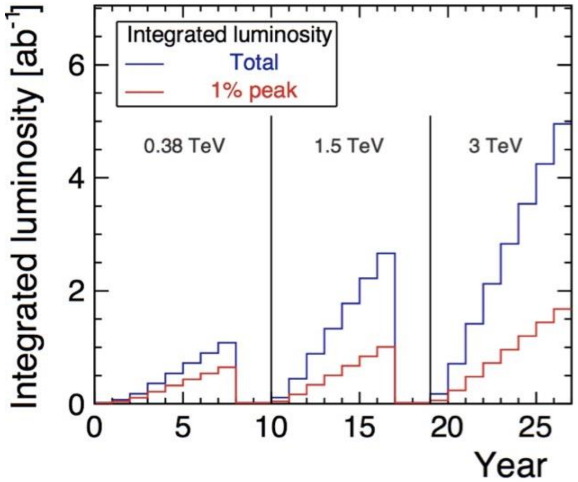
Table 3.1: Targeted horizontal and vertical emittance at the end of each section and the horizontal and vertical emittance growth budgets ($\Delta\epsilon_x$ and $\Delta\epsilon_y$ respectively): design values and contributions from static and dynamic imperfections.

Result of detailed simulations

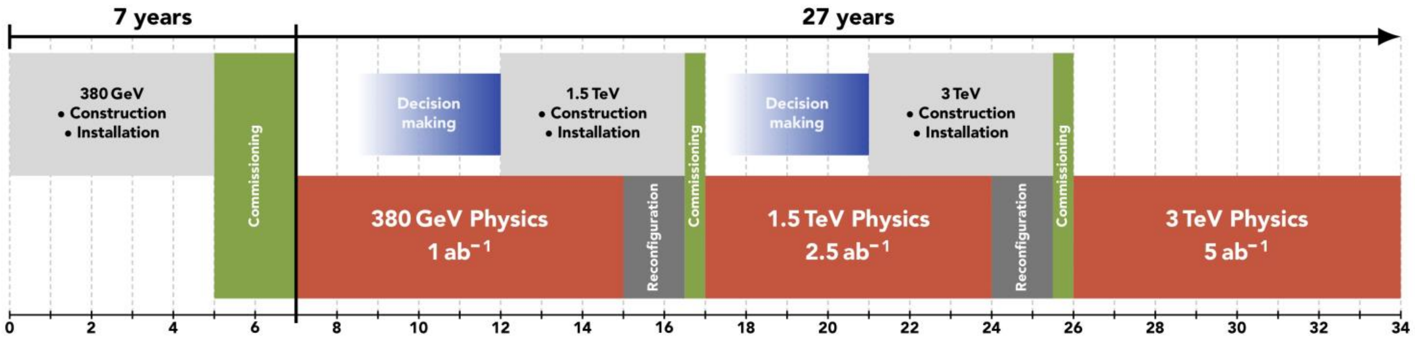
- Perfect machine luminosity is 4.3x10^{34} cm^{-2}s^{-1}.
- Average luminosity with static imperfections is 3.4x10^{34} cm^{-2}s^{-1}.
- 90% of machine achieved a luminosity above 2.7x10^{34} cm^{-2}s^{-1}.

CLIC timeline





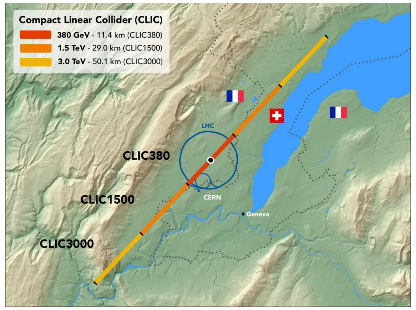
Ramp-up and up-time assumptions: arXiv:1810.13022, Bordry et al.

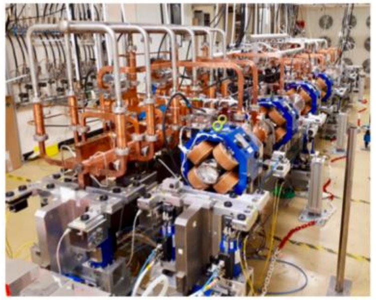


Technology Driven Schedule from start of construction shown above.

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

CLIC can easily be extended



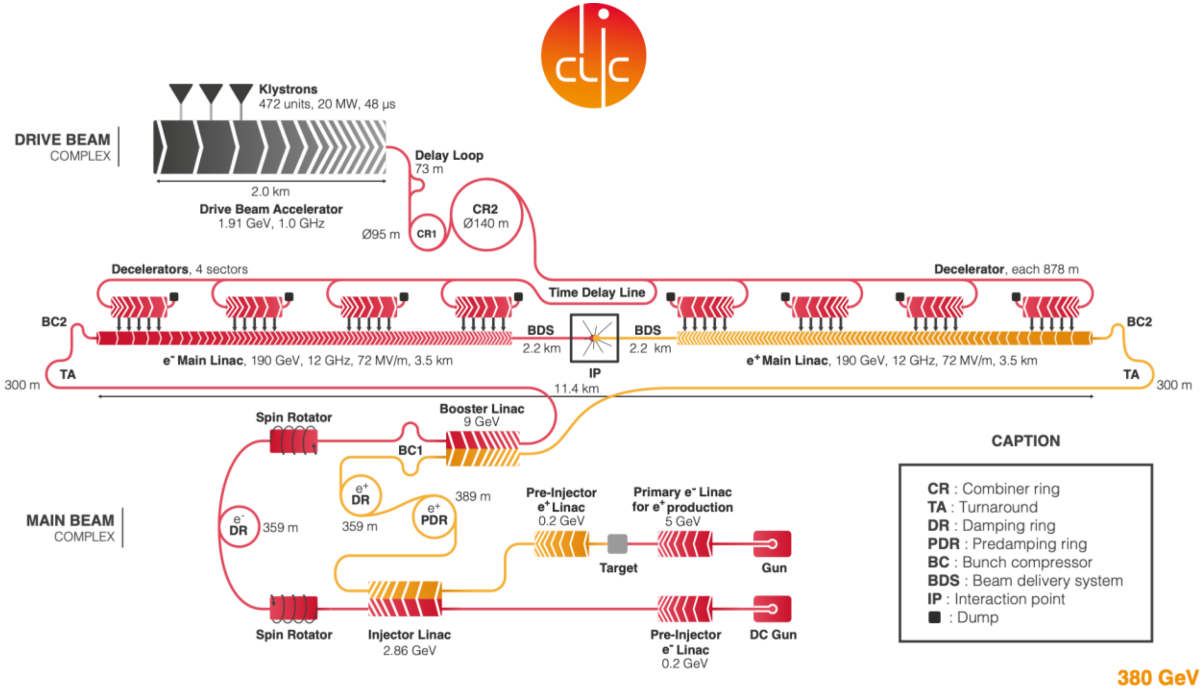


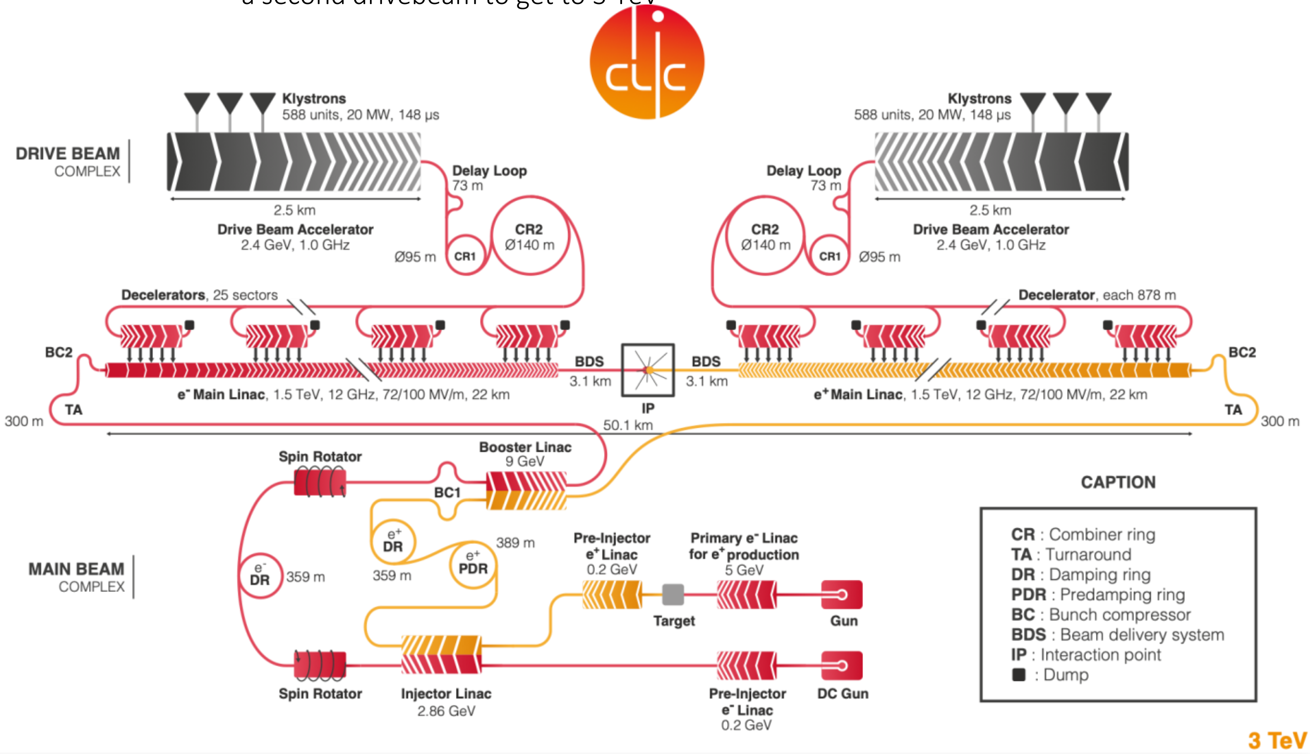
What are the critical elements:

- Physics
- Gradient and power efficiency
- Costs

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

Extend by extending main linacs, increase drivebeam pulse-length and power, and a second drivebeam to get to 3 TeV





CLIC - Scheme of the Compact Linear Collider (CLIC)

Resources

Available at:
clic.cern/european-strategy

3-volume CDR 2012


A MULTI-TEV LINEAR COLLIDER BASED ON CLIC TECHNOLOGY
CLIC CONCEPTUAL DESIGN REPORT

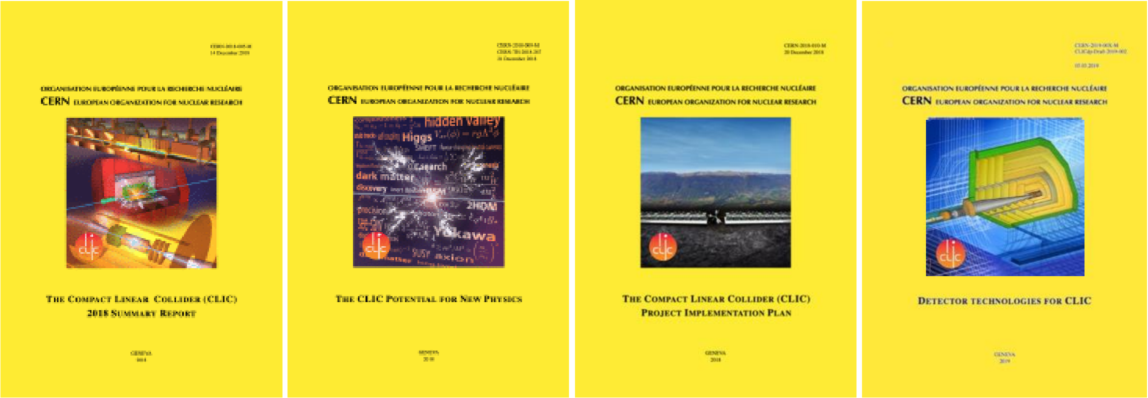
PHYSICS AND DETECTORS AT CLIC
CLIC CONCEPTUAL DESIGN REPORT

THE CLIC PROGRAMME: TOWARDS A STAGED e^+e^- LINEAR COLLIDER EXPLORING THE TERASCALE
CLIC CONCEPTUAL DESIGN REPORT

Updated Staging Baseline 2016


UPDATED BASELINE FOR A STAGED COMPACT LINEAR COLLIDER

4 CERN Yellow Reports 2018


THE COMPACT LINEAR COLLIDER (CLIC) 2018 SUMMARY REPORT

THE CLIC POTENTIAL FOR NEW PHYSICS

THE COMPACT LINEAR COLLIDER (CLIC) PROJECT IMPLEMENTATION PLAN

DETECTOR TECHNOLOGIES FOR CLIC

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

Two formal submissions to the ESPPU 2018


The Compact Linear e^+e^- Collider (CLIC): Accelerator and Detector
Input to the European Particle Physics Strategy Update on behalf of the CLIC and CLICdp Collaborations
18 December 2018

The Compact Linear e^+e^- Collider (CLIC): Physics Potential
Input to the European Particle Physics Strategy Update on behalf of the CLIC and CLICdp Collaborations
18 December 2018

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

CLIC is a mature design/study

The CLIC accelerator studies are mature:

Optimised design for cost and power

Many tests in CTF3, FELs, lightsources and test-stands

Technical developments of “all” key elements

Recent updates

- After the European Strategy for Particle Physics Update (ESPPU)
  - Immediate study of luminosity performance margins, gamma-gamma and Z-pole operation
  - Timeline for further studies changed (slower implementation)

Accelerator

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

Physics and Detector:

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

CLIC acc. studies – luminosities

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

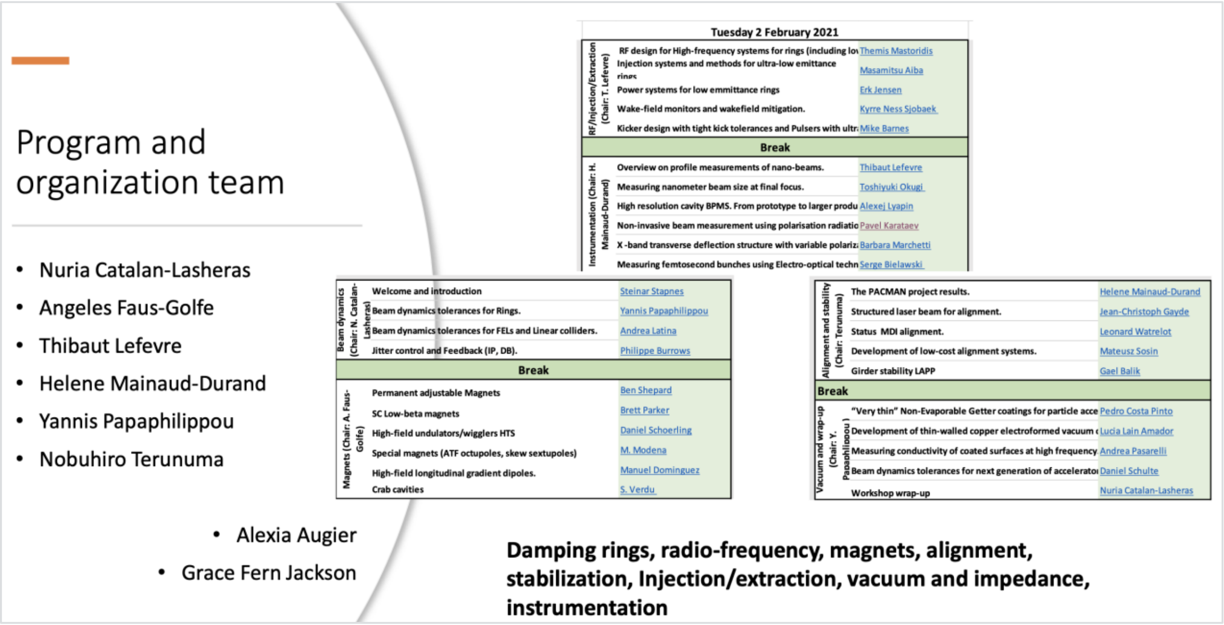
Luminosity margins and increases:

- Z pole performance, $2.3\text{x}10^{32} – 0.4\text{x}10^{34}$ cm^{-2} s^{-1}
- The latter number when accelerator configured for Z running (e.g., early or end of first stage)

- Baseline includes estimates static and dynamic degradations from damping ring to IP: $1.5 \text{ x } 10^{34}$ cm^{-2} s^{-1}, a "perfect" machine will give : $4.3 \text{ x } 10^{34}$ 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 and paper about all these studies



Program and organization team

- Nuria Catalan-Lasheras
- Angeles Faus-Golfe
- Thibaut Lefevre
- Helene Mainaud-Durand
- Yannis Papaphilippou
- Nobuhiro Terunuma

- Alexia Augier
- Grace Fern Jackson

Tuesday 2 February 2021

RF/Injection/Extraction (Chair: T. Lefevre)	RF design for High-frequency systems for rings (including lov	Themis Mastoridis
	Injection systems and methods for ultra-low emittance rings	Masamitsu Aiba
	Power systems for low emmittance rings	Erk Jensen
	Wake-field monitors and wakefield mitigation.	Kyrre Ness Sjobaek
	Kicker design with tight kick tolerances and Pulsers with ultr	Mike Barnes
Break		
Instrumentation (Chair: H. Mainaud-Durand)	Overview on profile measurements of nano-beams.	Thibaut Lefevre
	Measuring nanometer beam size at final focus.	Toshiyuki Okugi
	High resolution cavity BPMS. From prototype to larger produ	Alexej Lyapin
	Non-invasive beam measurement using polarisation radiatio	Pavel Karataev
	X -band transverse deflection structure with variable polariz	Barbara Marchetti
	Measuring femtosecond bunches using Electro-optical techn	Serge Bielawski

Beam dynamics (Chair: N. Catalan-Lasheras)	Welcome and introduction	Steinar Stapnes
	Beam dynamics tolerances for Rings.	Yannis Papaphilippou
	Beam dynamics tolerances for FELs and Linear colliders.	Andrea Latina
	Jitter control and Feedback (IP, DB).	Philippe Burrows
Break		
Magnets (Chair: A. Faus-Golfe)	Permanent adjustable Magnets	Ben Shepard
	SC Low-beta magnets	Brett Parker
	High-field undulators/wigglers HTS	Daniel Schoerling
	Special magnets (ATF octupoles, skew sextupoles)	M. Modena
	High-field longitudinal gradient dipoles.	Manuel Dominguez
	Crab cavities	S. Verdu

Alignment and stability (Chair: Terunuma)	The PACMAN project results.	Helene Mainaud-Durand
	Structured laser beam for alignment.	Jean-Christoph Gayde
	Status MDI alignment.	Leonard Watrelot
	Development of low-cost alignment systems.	Mateusz Sosin
	Girder stability LAPP	Gael Balik
Break		
Vacuum and wrap-up (Chair: Y. Papaphilippou)	"Very thin" Non-Evaporable Getter coatings for particle acce	Pedro Costa Pinto
	Development of thin-walled copper electroformed vacuum c	Lucia Lain Amador
	Measuring conductivity of coated surfaces at high frequency.	Andrea Pasarelli
	Beam dynamics tolerances for next generation of accelerato	Daniel Schulte
	Workshop wrap-up	Nuria Catalan-Lasheras

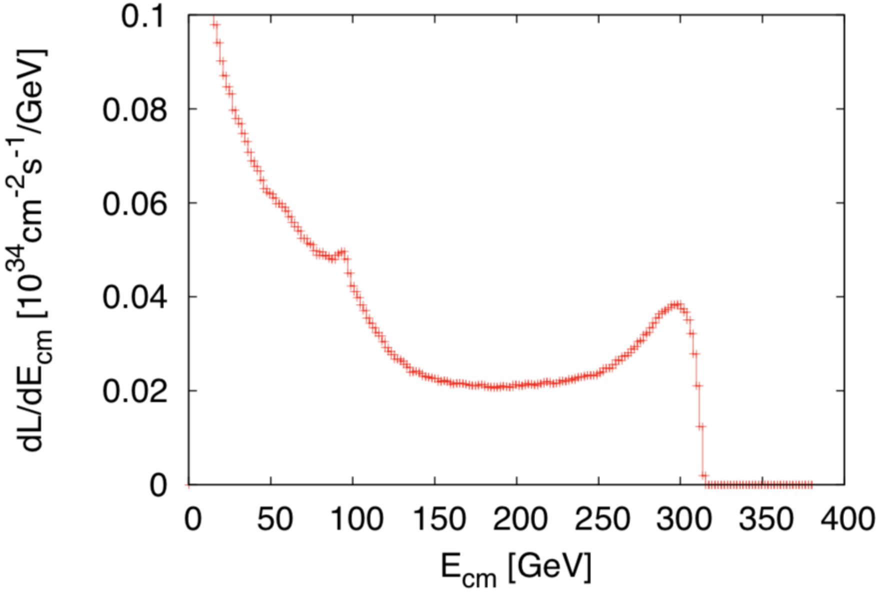
Damping rings, radio-frequency, magnets, alignment, stabilization, Injection/extraction, vacuum and impedance, instrumentation

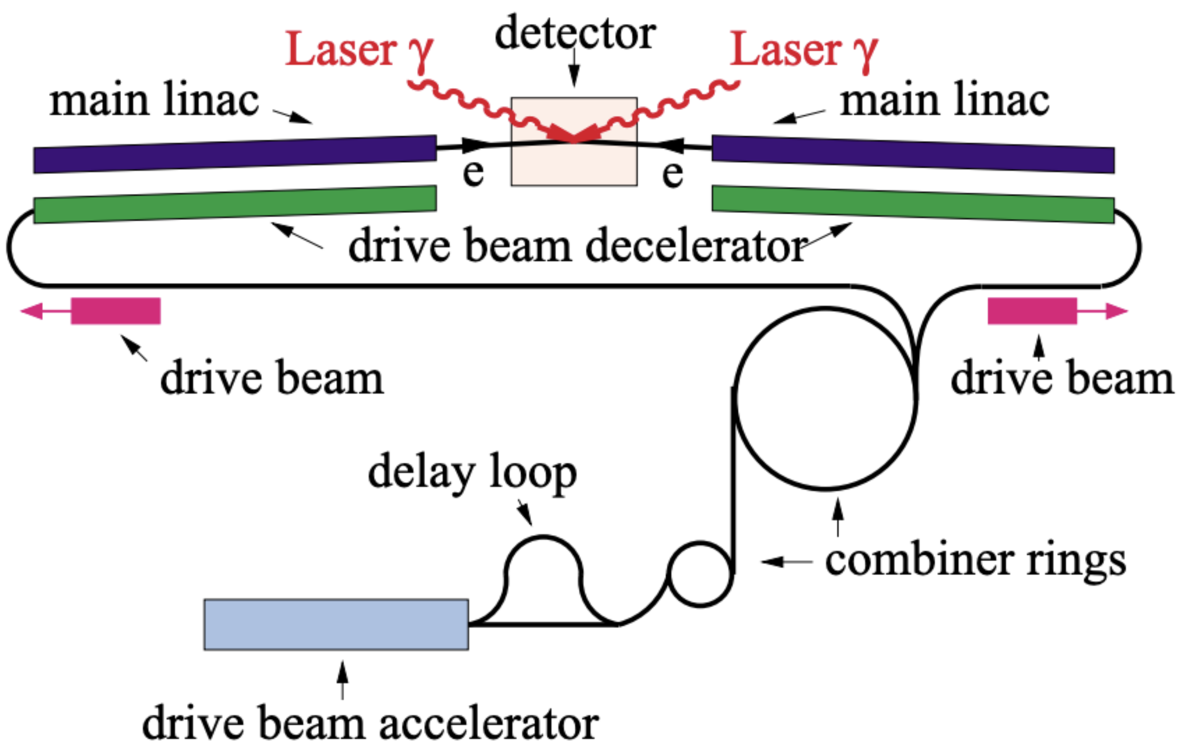
Nanobeam workshop (summary by Nuria Catalan): LINK

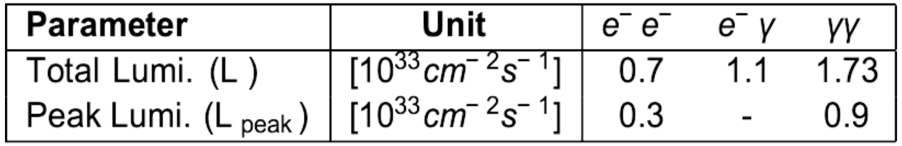
CLIC acc. studies – luminosities

Further work on luminosity performance, possible improvements and margins, gamma-gamma collider

- Gamma – Gamma spectrum (example)







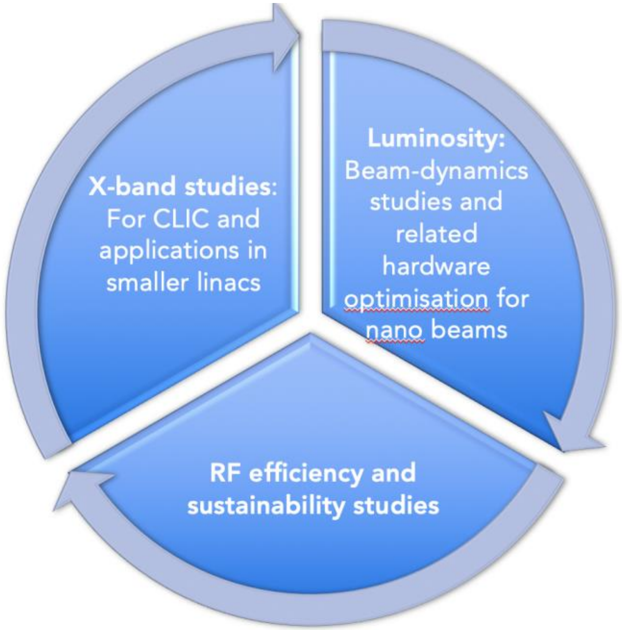
Parameter	Unit	e^-e^-	$e^-\gamma$	$\gamma\gamma$
Total Lumi. (L)	[$10^{33}cm^{-2}s^{-1}$]	0.7	1.1	1.73
Peak Lumi. (L_{peak})	[$10^{33}cm^{-2}s^{-1}$]	0.3	-	0.9

CLIC Project Readiness 2025-26

Project Readiness Report as a step toward a TDR – for next ESPP
Assuming ESPP in 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

Focusing on:

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



X-band studies: For CLIC and applications in smaller linacs

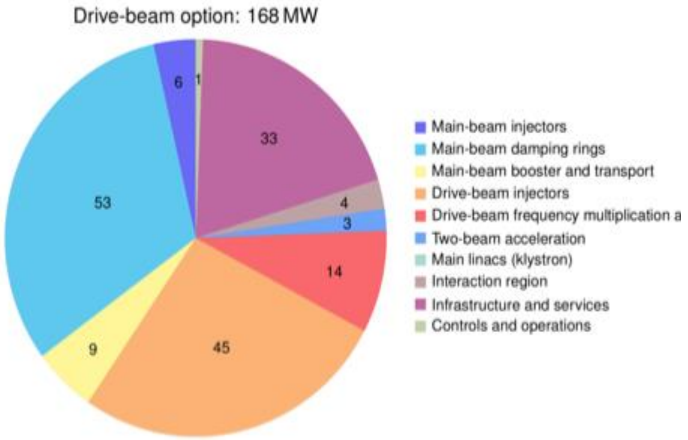
Luminosity: Beam-dynamics studies and related hardware optimisation for nano beams

RF efficiency and sustainability studies

Goals for these studies by ~2025:

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

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 optimized, etc

Further savings possible, main target damping ring RF significantly reduced, L-band klystrons (target 110-130 MW)

Energy consumption ~0.8 TWh yearly (target 0.6)
CERN is currently (when) running at 1.2 TWh (~90% in accelerators)

Design Optimisation:

The designs of CLIC, including key performance parameters as accelerating gradients, pulse lengths, bunch-charges and luminosities, have been optimised for cost but also increasingly focussing on reducing power consumption.

Technical Developments:

Technical developments targeting reduced power consumptions at system level high efficiency klystrons, and super conducting and permanents magnets for damping rings and linacs.

Running when energy is cheap:

CLIC is normal conduction, single pass, can change off-on-off quickly, at low power when not pulsed. Specify state-change (off-standby-on) times and power uses for each – see if clever scheduling using low-cost periods, can reduce the energy bill

Renewable energy (carbon footprint):

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

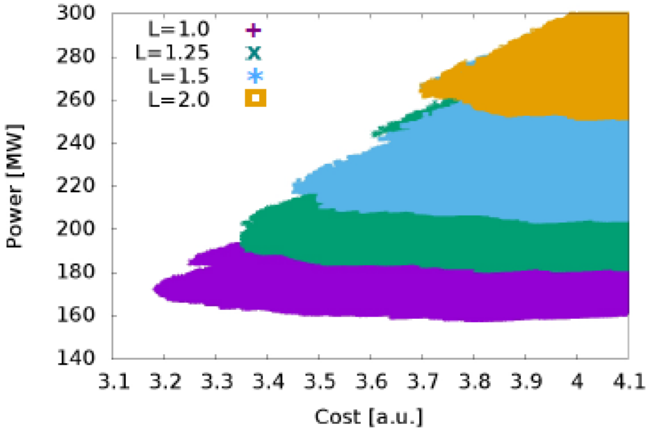
Optimisations – examples

Design Optimisation:
All projects aim to optimize – most often energy reach, luminosities and cost. Examples from all Higgs factories mentioned above.
Power is becoming at least as important, maybe even compromising ultimate performance for power saving.

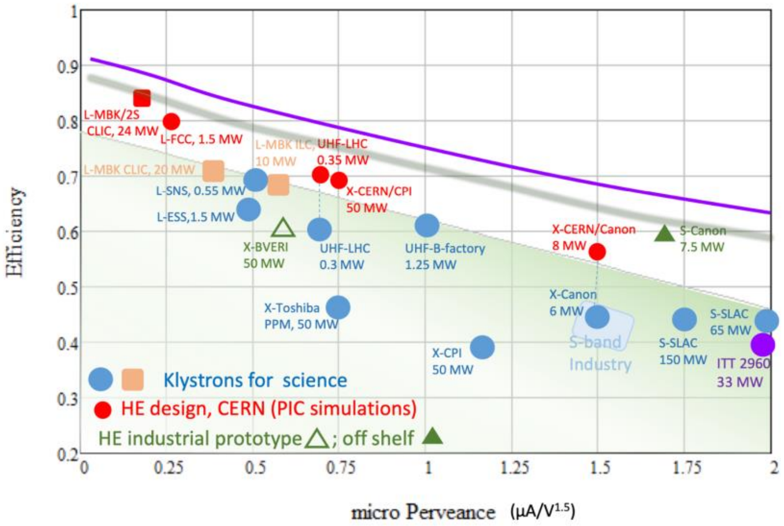
Technical Developments:
Technical developments targeting reduced power consumptions at system level high efficiency klystrons and RF systems generally, and super conducting (traditional SC, and HTS in particular) including cryo, and permanents magnets.

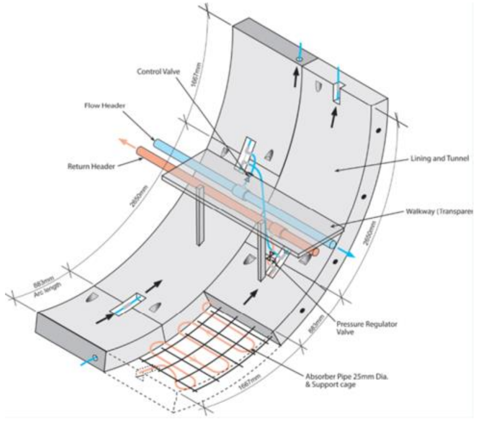
Heat recovery:
Already implemented in point 8 for LHC

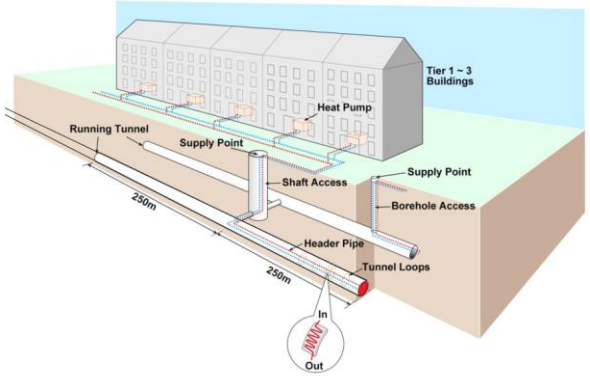
Tunnel heat recovery study by ARUP in 2022



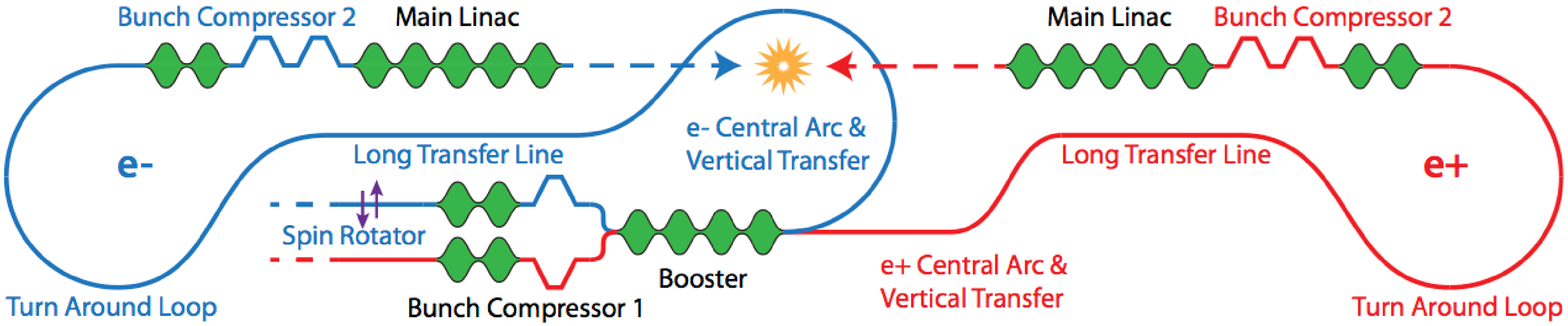
The designs of CLIC, including key performance parameters as accelerating gradients, pulse lengths, bunch-charges and luminosities, have been optimised for cost and power



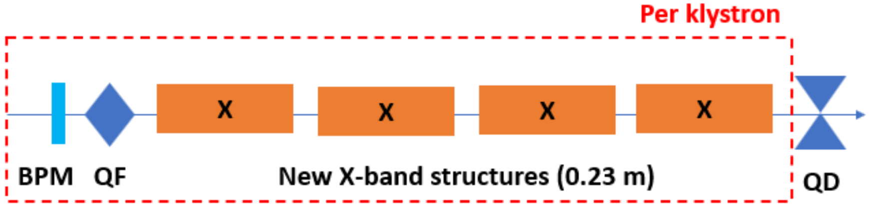


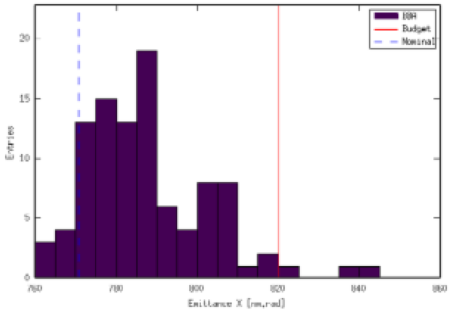


Rings to Main Linac optimisation

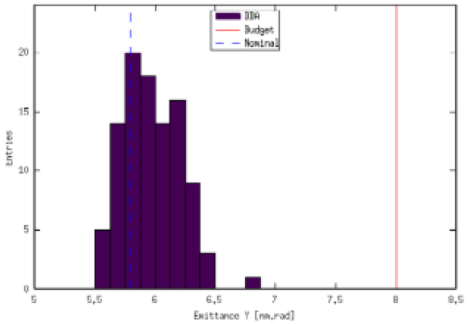


BC2 RF new optimisation for cost and power consumption





ε_X



ε_Y

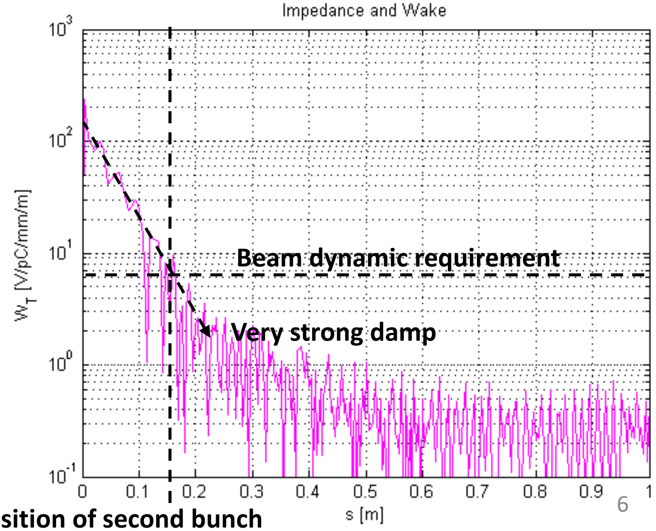
Beam parameter	Symbol	Unit	RTML entrance		RTML exit	
Collision energy	E_cm		**380 GeV**	**3 TeV**	**380 GeV**	**3 TeV**
Beam energy	E	GeV	2.86	2.86	9	9
Bunch charge	q	nC	0.832	0.592	0.832	0.592
No. of particles per bunch	N_p	10^9	5.2	3.7	5.2	3.7
No. of bunches per pulse	N_b		352	312	352	312
Bunch length (rms)	σ_z	µm	1800	1800	~70	~42
Energy spread (rms)	σ_E	%	~0.12	~0.12	< 1.7	< 1.7
Normalised emittances	ε_n_x	nm	700	700	< 800	< 800
(w/o imperfections)	ε_n_y	nm	5	5	< 6	< 6

	Initial	Final emittance(⋆)		
		by Design	with Static Imperfections	with Dynamic Imperfections
ϵ_x [nm]	700	< 800	< 820	< 850
ϵ_y [nm]	5	< 6	< 8	< 10

(⋆) 90th percentile.

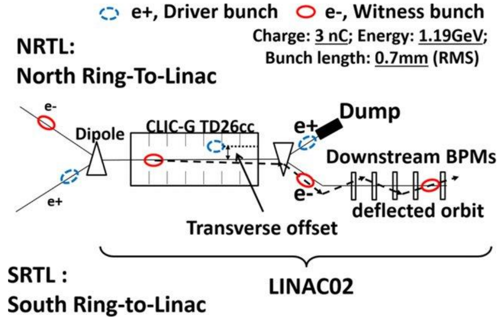
Main Linac

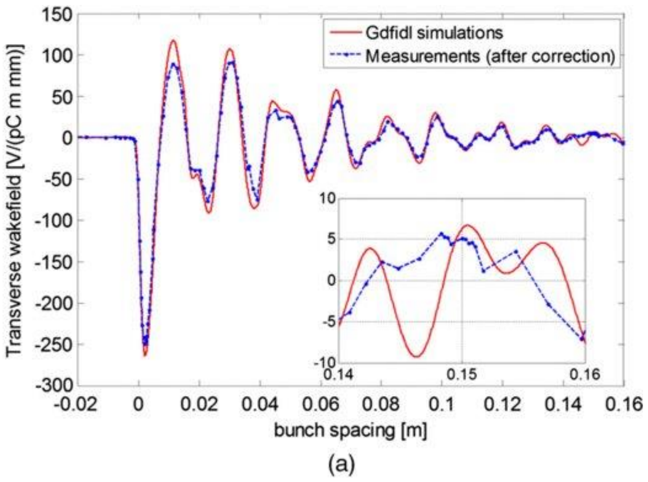
Long-range wakefields suppression



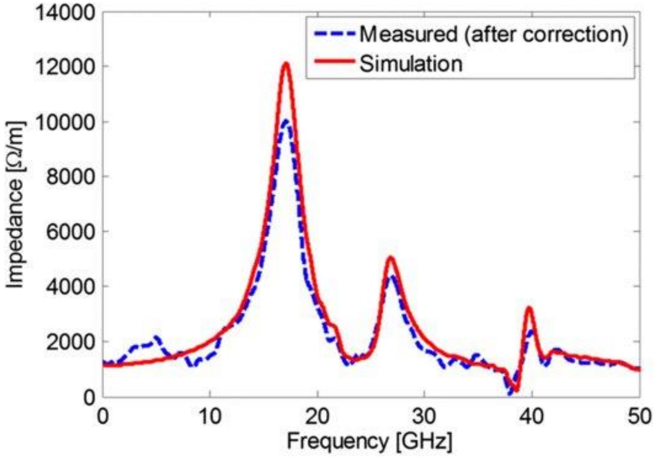
Position of second bunch

Experiment at FACET (SLAC)





(a)

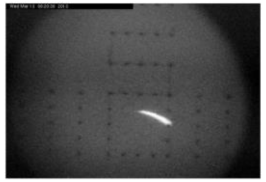


(b)

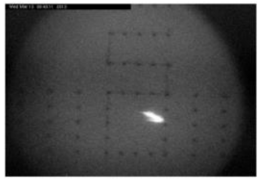
Full Tuning Procedure

- Each section was tuned in order:
  - RTML:
    - 121, DFS, Sextupole tuning (simplex).
    - Minimises emittance.
  - The corresponding beams at the end of the RTML were used to tune the ML:
    - 121, DFS, RF realignment.
    - Minimises emittance.
  - Beams at the end of the ML were used to tune the BDS collimation section:
    - 121, DFS, Sextupole tuning (simplex).
    - Minimises emittance.
  - Beams at the end of the collimation section were used to tune the FFS:
    - 121, DFS, Sextupole tuning (random walk and knobs).
    - Maximises luminosity.

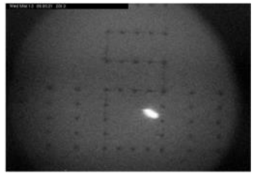
Tests of Beam-based orbit correction at FACET



Before correction



After 1 iteration



After 3 iterations

Running on renewables and when electricity is cheap

  - Two studies in 2017:
- 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.
  - Study done for 200 MW, in reality only ~110 MW are needed
- Self-sufficiency during all times can not be reached but 54% of the time CLIC could run independently from public electricity supply with the portfolio simulated.
  - Can one run an accelerator as CLIC in a mode where one turn “on” and “off” depending prices (fluctuating with weather, demand, etc) ?
  - Specify transition times (relatively fast for a LC) and the annual luminosity goal
  - Significant savings – but the largest saving is the obvious one, not running in the winter.
  - Flexibility to adjust the power demand is expected to become increasingly important and in demand by energy companies.
- More information (link)

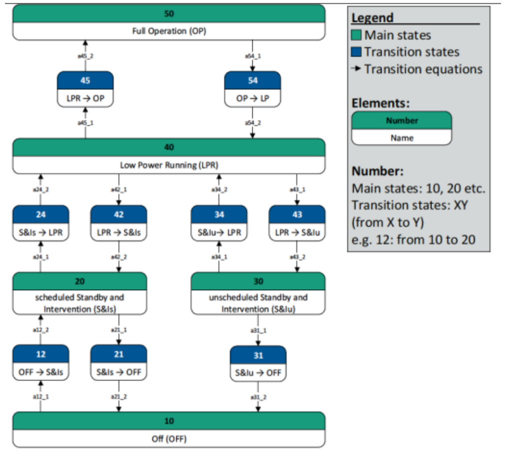
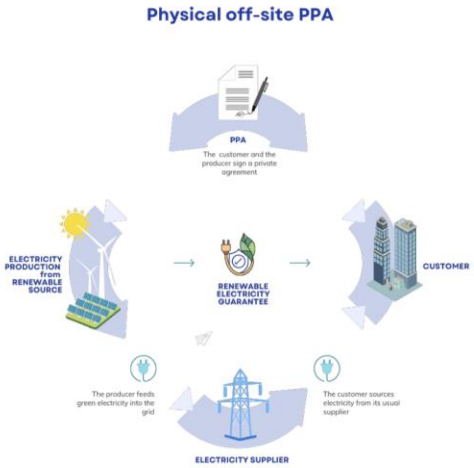


Figure 1-1: Schematic representation of the finite state machine

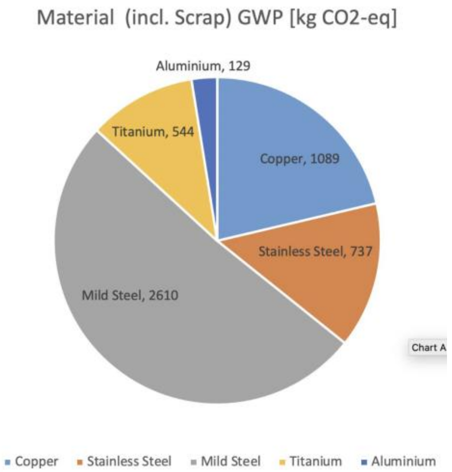


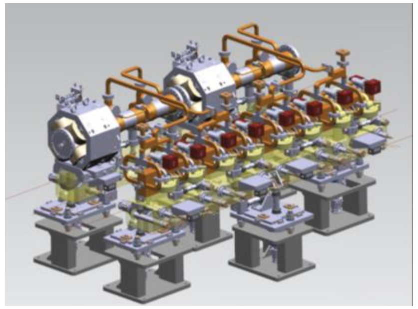
A real implementation:
A physical power purchase agreement (PPA) is a long-term contract for the supply of electricity at a defined, fixed price at the start and then indexed every year, negotiated between a producer of renewable electricity and a consumer for a defined period (generally 15 to 20 years).
Being considered for CERN initially at limited scale.
Advantages: price, price stability, green, renewable.

Nuclear energy remains very important, on the timescale of a future CERN facility: SMEs

Must be a goal to run future accelerator at CERN primarily on green and more renewable energy with very low carbon footprint. However, energy costs will remain a concern

Sustainable Construction – some elements



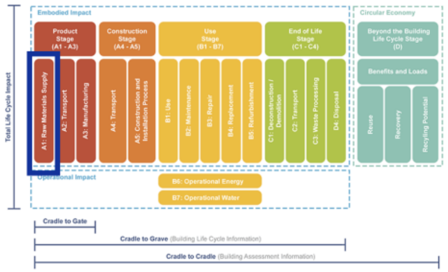


Talk by B.List (link)

Tunnel GWP (CO2 Impact) from Materials

Quantity	DB	Klys.
Inner Diameter [m]	5.6	10
Tunnel Cross Section [m^2]	25	79
Lining / Grouting [cm]	30 / 10	45 / 15
Concrete Area [m^2]	12.4	44.8
Lining&Floor Area [m^2]	8.2	19.7
Concrete per m [t/m]	31	129
Steel per m [t/m]	0.95	2.3
Concrete GWP [t CO2-eq/m]	3.1	12.9
Steel GWP [t CO2-eq/m]	1.6	3.8
Material GWP [t CO2-eq/m]	**5**	**17**
Total GWP (25% overhead)	**6**	**21**

Lifecycle stages according to EN 15978



Only A1 considered here!

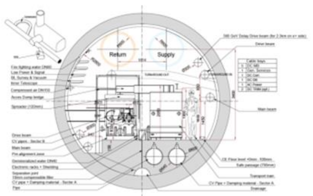
Similar CO2 estimates made for the FCC tunnel in the framework of Snowmass.

Assume a small tunnel (~5.6m diameter) and that the equipment in the tunnel has the same carbon footprint as the tunnel itself, 20km acc. incl. tunnel corresponds to 240 kton. This is equivalent to 50-60 TWh of nuclear power.

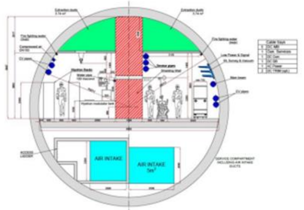
Goal and Scope

- Goal: Reduce embodied and construction environmental impacts
- LCA for 3 tunnel options (tunnels, caverns & access shafts)
- System boundaries: Embodied and construction.
  Excluding operation, use and end of life.

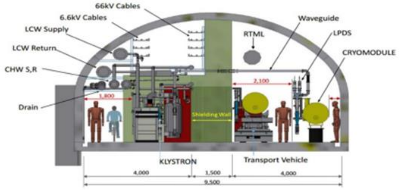
1. CLIC Drive Beam tunnel, 5.6m internal diameter



2. CLIC Klystron tunnel, 10m internal diameter



3. ILC Japan tunnel, arched 9.5m span



Carbon Cost/Life Cycle Assessment LCA study 2023

Two final comments:

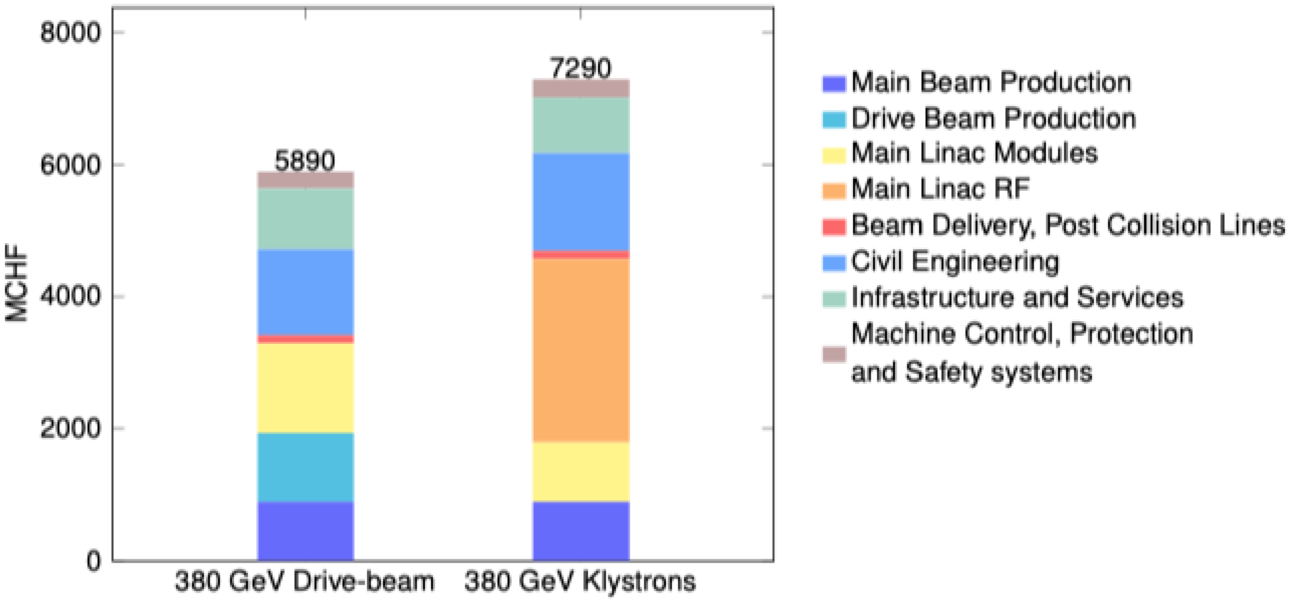
- The work on-going for the FCC to "integrate" into the areas near CERN, including getting rid of spoil, is obviously also a crucial element on the way to a environmentally integrated collider.

- Responsible purchasing – and understanding the impact on our supply chain, costs and potential for changes – will be essentials for future projects (information from E.Cennini)

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	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**

$$\text{CLIC 380 GeV Drive-Beam based:} \quad 5890^{+1470}_{-1270}\,\text{MCHF};$$

$$\text{CLIC 380 GeV Klystron based:} \quad 7290^{+1800}_{-1540}\,\text{MCHF}.$$

Cost - II

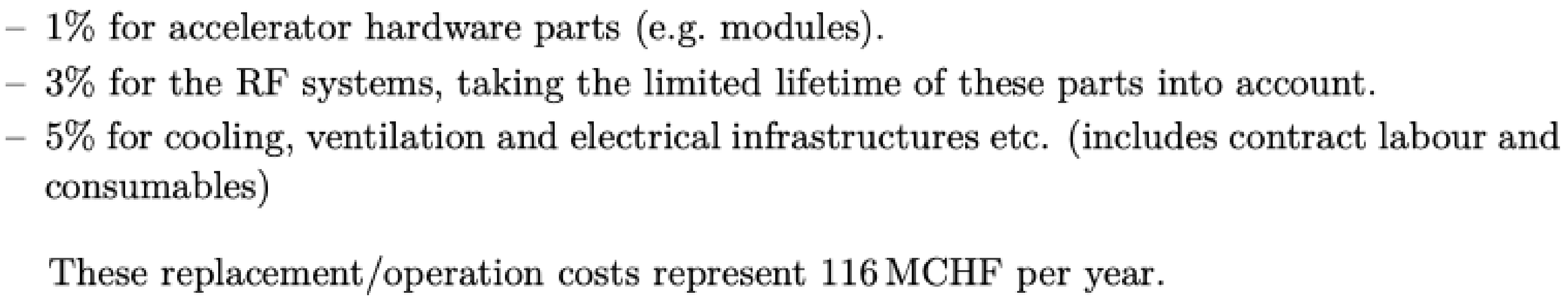
Other cost estimates:

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

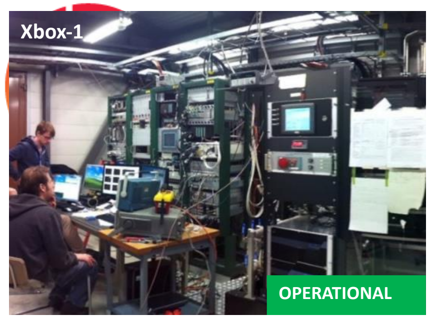


- 1% for accelerator hardware parts (e.g. modules).
- 3% for the RF systems, taking the limited lifetime of these parts into account.
- 5% for cooling, ventilation and electrical infrastructures etc. (includes contract labour and consumables)

These replacement/operation costs represent 116 MCHF per year.

N. Catalan

X-band tests



CPI 50MW 1.5us klystron
Scandinova Modulator
Rep Rate 50Hz
Beam test capabilities

Ongoing test:
CPI2 repair validation and interferometry tests

CPI 50MW 1.5us klystron
Scandinova Modulator
Rep Rate 50Hz

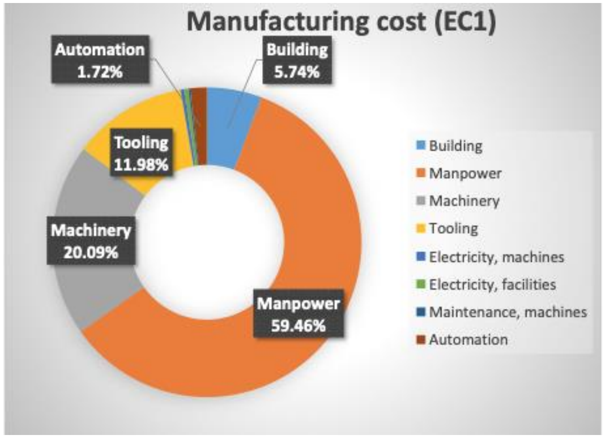
Ongoing test:
CLIC TD26 CLEX SuperStructure

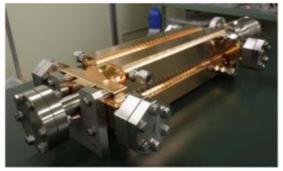
2x Toshiba 6MW 5us klystron
2x Scandinova Modulators
Rep Rate 400Hz

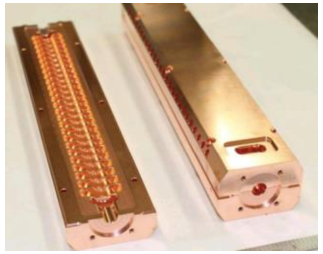
Ongoing test:
SARI X-band deflector
High power window

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

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







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

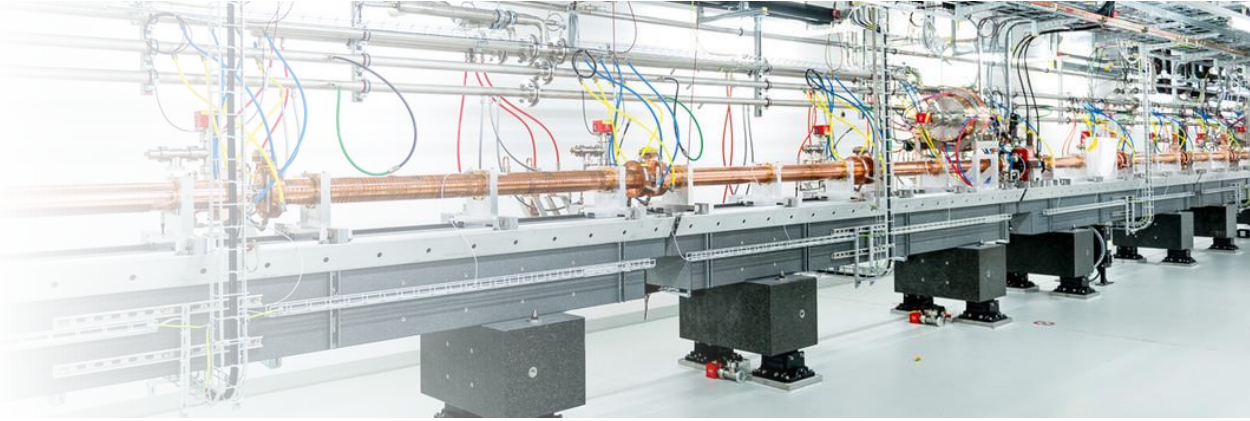
EU projects: ARIES, I-FAST, new TNA

Use in smaller linacs (C- and X-band)

SwissFEL: C-band linac

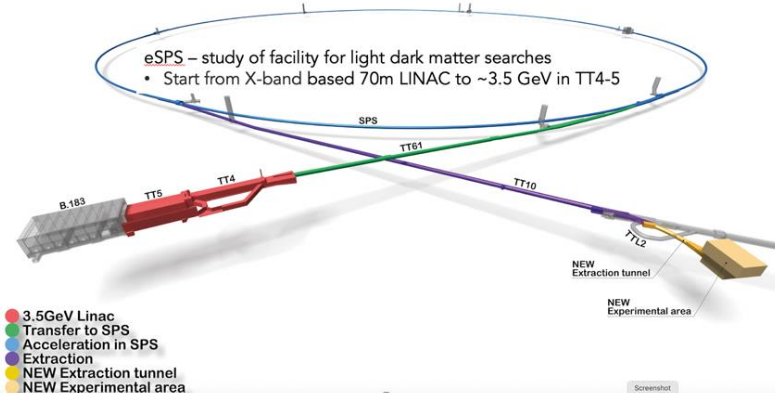
- 104 x 2 m-long C-band (5.7 GHz) structures (beam up to 6 GeV at 100 Hz)
- Similar µm-level tolerance
- Length ~ 800 CLIC structures
- Being commissioned
- X-band structures from PSI perform well

Photo: SwissFEL/PSI



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

CompactLight Design Study 2018-21 ([link]())
Compact FEL based on X-band technologies



eSPS – study of facility for light dark matter searches

- Start from X-band based 70m LINAC to ~3.5 GeV in TT4-5

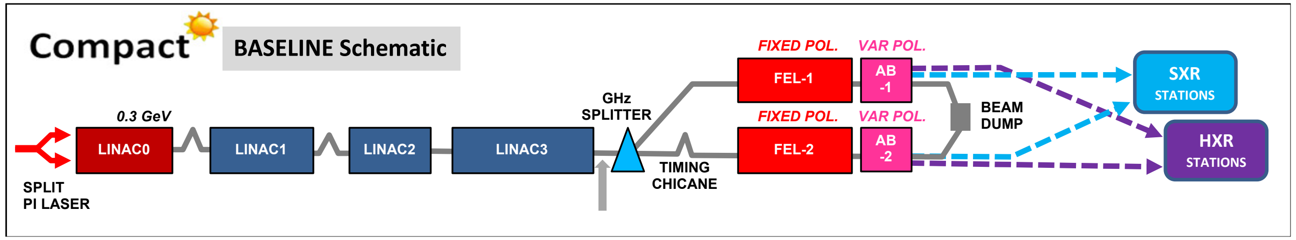
🟥 3.5GeV Linac
🟩 Transfer to SPS
🟦 Acceleration in SPS
🟪 Extraction
🟨 NEW Extraction tunnel
🟧 NEW Experimental area

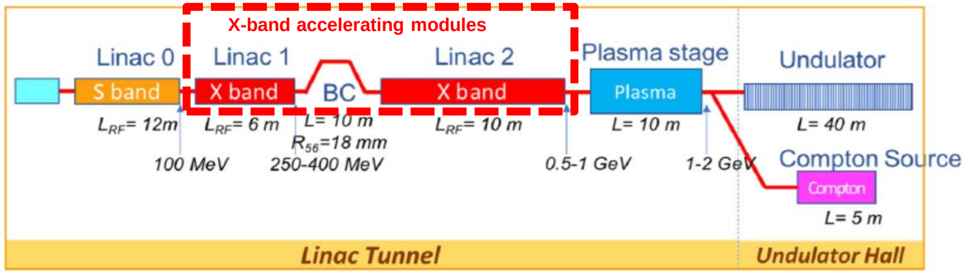
CERN: eSPS study (3.5 GeV X-band linac)

Applications – injector, X-band modules, RF

- CompactLight Design Studies 2018-21 (right)
- INFN 1 GeV linac
- Flash RT, at CHUV
- “Design Studies” for ICS
- AERES, IFAST and TNA project

Overview at [LINK]()

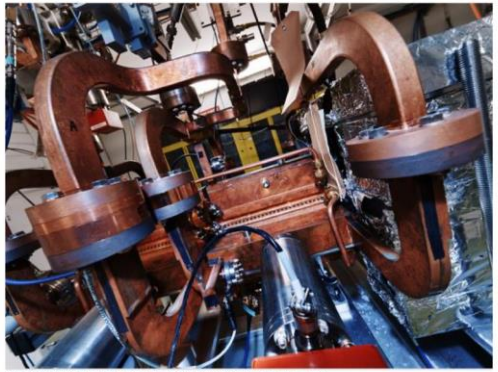




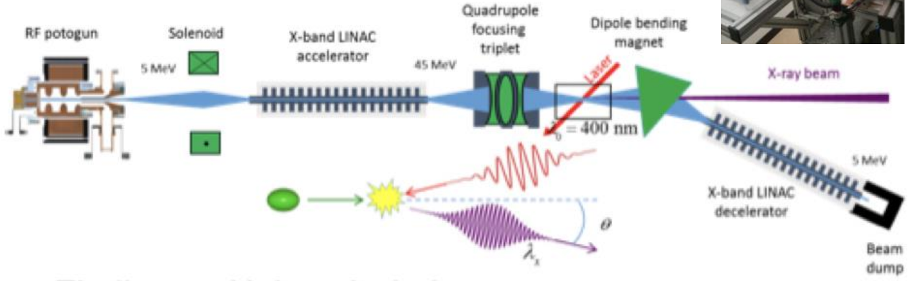
CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

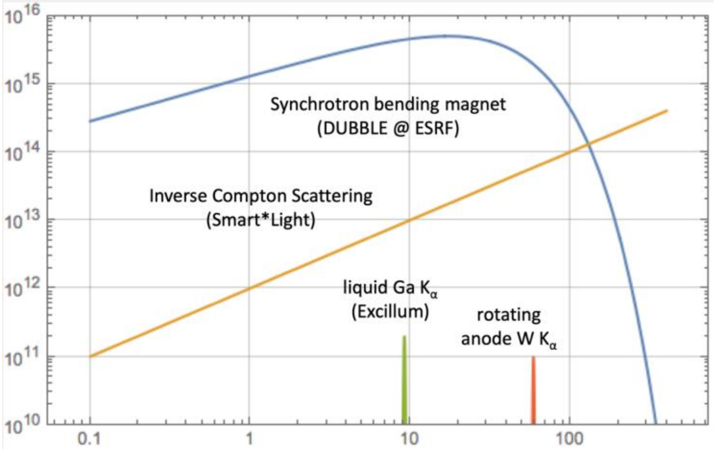
CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment

15 SEPTEMBER, 2020



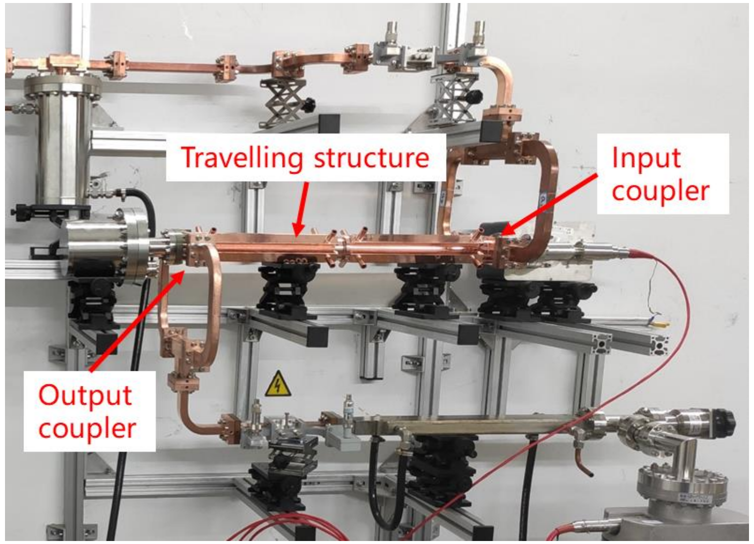
Close-up of the Compact Linear Collider prototype, on which the electron FLASH design is based (Image: CERN)



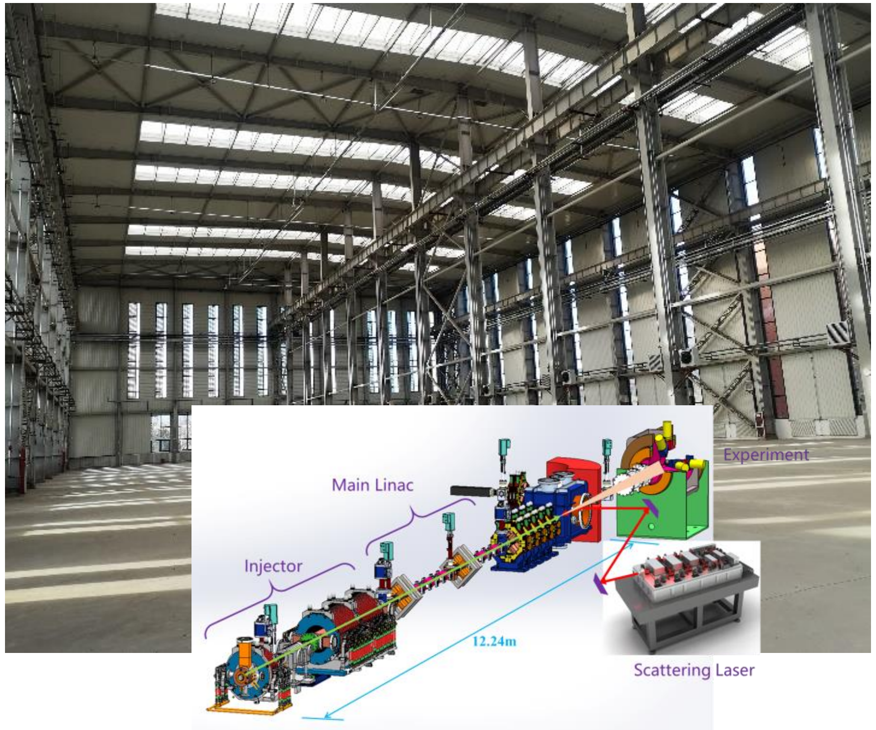


Beam Facilities using X-band technology

- 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

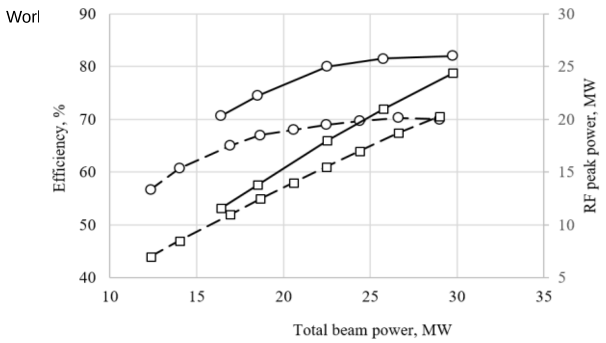


VIGAS



High Eff. Klystrons

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



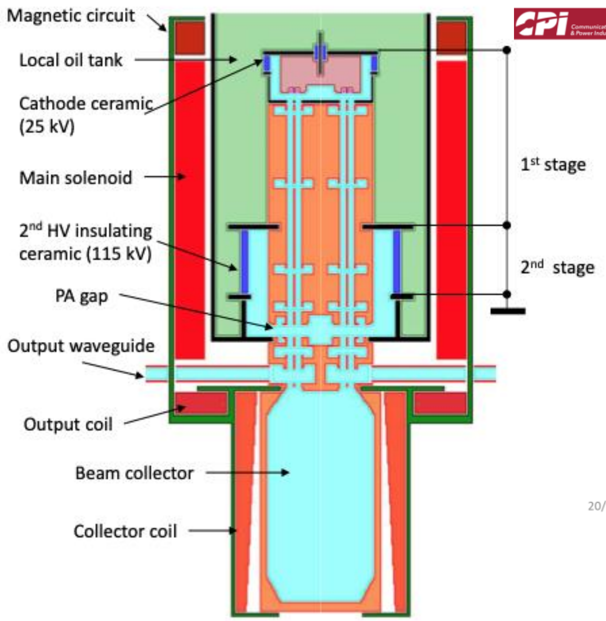
Location: CERN Bldg: 112

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

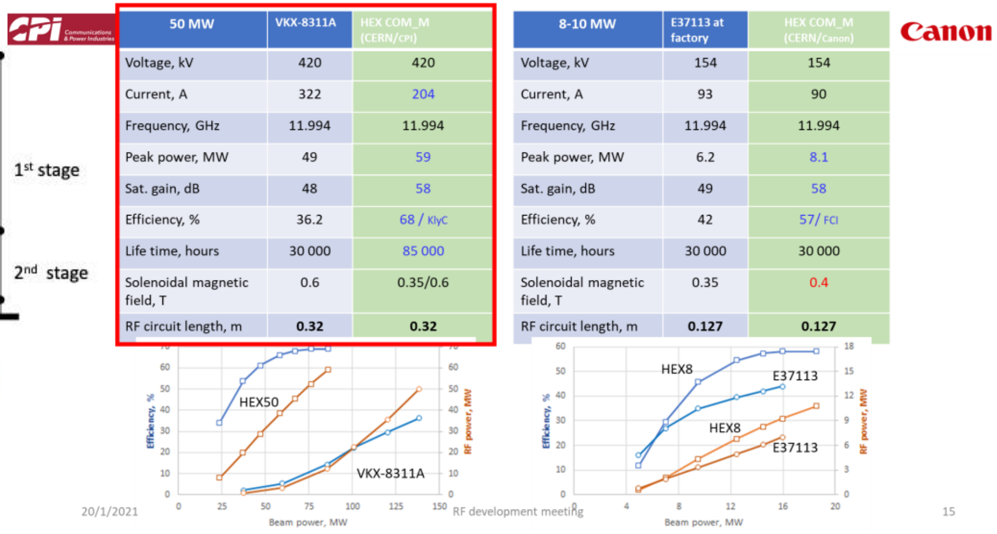
High Efficiency implementations:

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

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



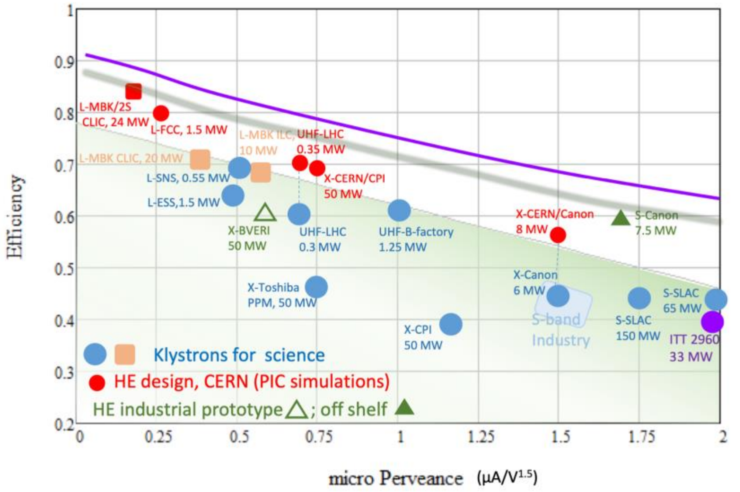
High Efficiency X-band klystrons retrofit upgrades (in collaboration with CPI and Canon).



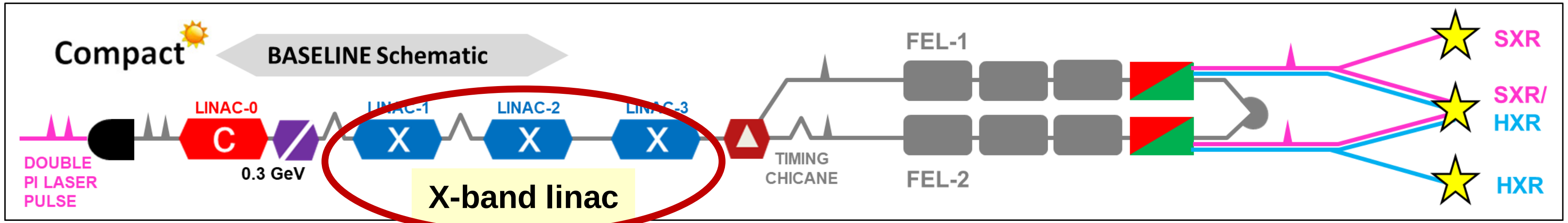
50 MW	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	58
Efficiency, %	36.2	68 / KlyC
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.35/0.6
RF circuit length, m	**0.32**	**0.32**

8-10 MW	E37113 at factory	HEX COM_M (CERN/Canon)
Voltage, kV	154	154
Current, A	93	90
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	58
Efficiency, %	42	57/ FCI
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.4
RF circuit length, m	**0.127**	**0.127**

20/1/2021 RF development meeting 15



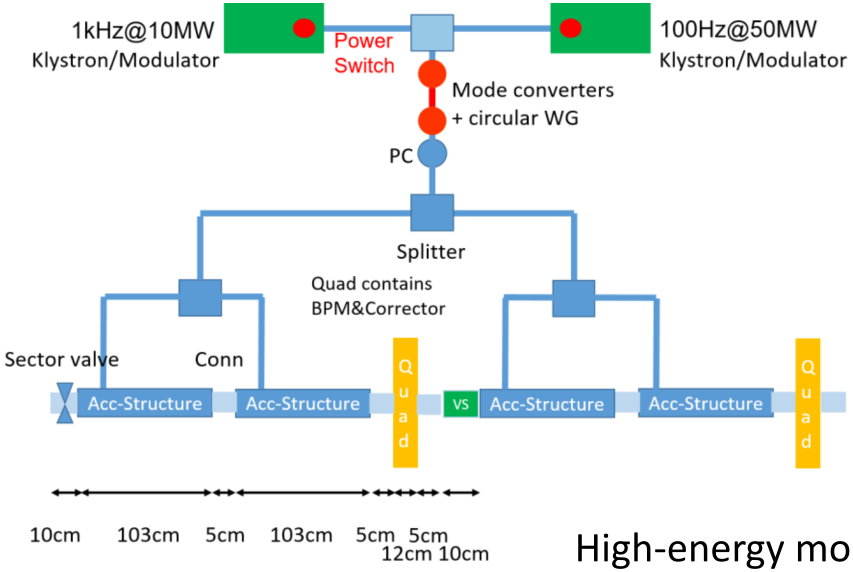
I-FAST – CompactLight Structure



10 MW, 1.5 µs @1 KHz

50 MW, 1.5 µs @100 Hz

Parameter	Unit	Dual mode		Dual source	
Operating Mode		B		U1, U2	
Repetition rate	kHz	0.1	0.25	0.1	1
Linac active length	m	94			
Number of structures		104			
Number of modules		26			
Number of klystrons		26		26 + 26	
Peak acc. gradient	MV/m	65	32	65	30.4
Energy gain per module	MeV	234	115	234	109
Max. energy gain	MeV	6084	2990	6084	2834



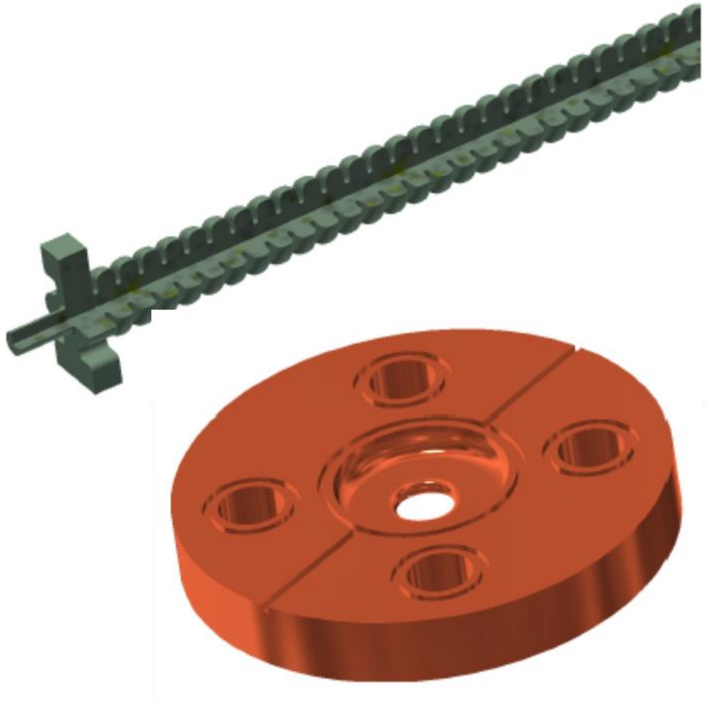
High-energy module

Task 7.5 Partners:

ELETTRA-ST **CERN** **INFN** **VDL-ETG** **COMEB** **TMD**

Accelerating structure RF operating parameters

Parameter	**Units**	**Value**		
Frequency	GHz	11.994		
Peak klystron power (100 - 250 Hz)	MW	50		
Peak klystron power (1000 Hz)	MW	10		
RF pulse length (250 Hz)	µs	1.5 (0.15)		
Waveguide power attenuation	%	≈ 10		
Average iris radius a	mm	3.5		
Iris radius a	mm	4.3-2.7		
Iris thickness t	mm	2.0-2.24		
Structure length L_s	m	0.9		
Unloaded SLED Q-factor Q_0		180000		
External SLED Q-factor Q_E		23300		
Shunt impedance R	MΩ/m	85-111		
Peak modified Poynting vector	W/µm^2	3.4		
Group velocity v_g/c	%	4.7-0.9		
Filling time t_f	ns	146		
Repetition rate	Hz	100	250	1000
SLED		ON	OFF	ON
Required klystron power	MW	44	44	9
Average accelerating gradient	MV/m	65	30	30

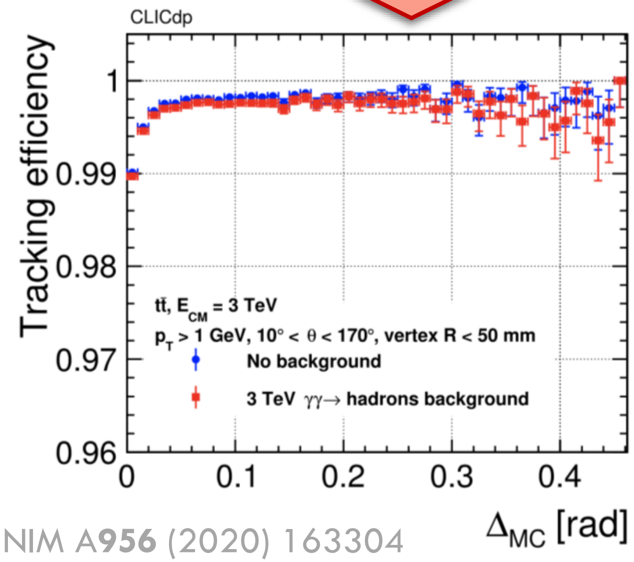


Two structures being manufactured

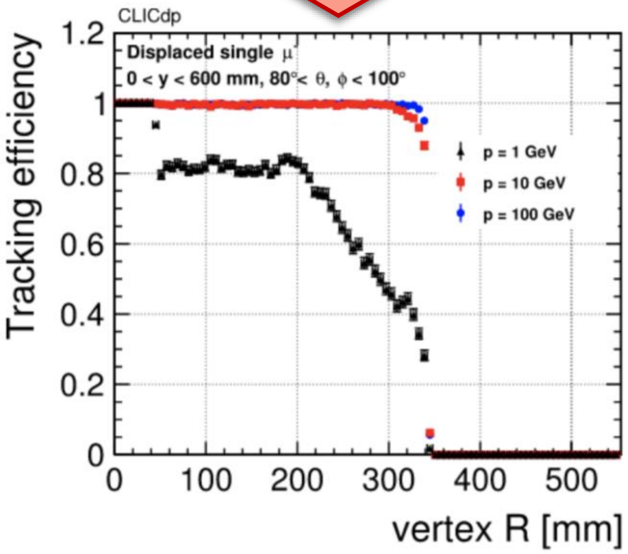
CLIC Detector

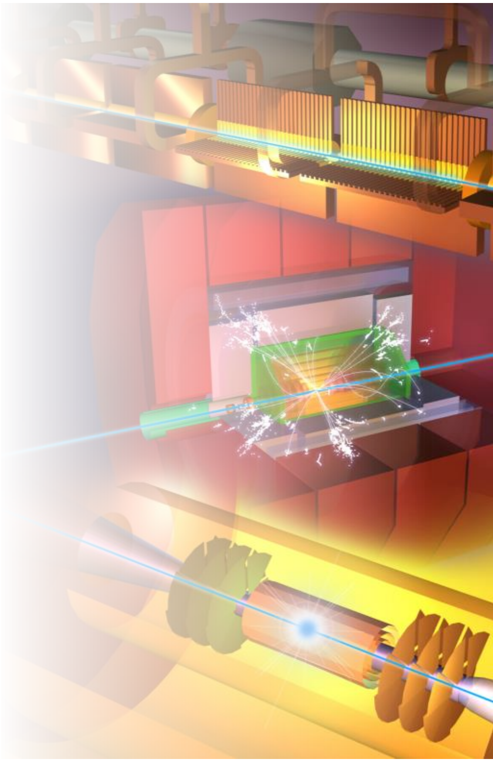
CLICdet:

- ◆ High-performing detector optimized for CLIC beam environment
- ◆ Full GEANT-based simulation, including beam-induced backgrounds, available for optimization and physics studies
- ◆ Mature reconstruction chain allows detailed performance characterisation
  – e.g. for tracking: effect of busy environment; displaced track reconstruction



NIM A**956** (2020) 163304

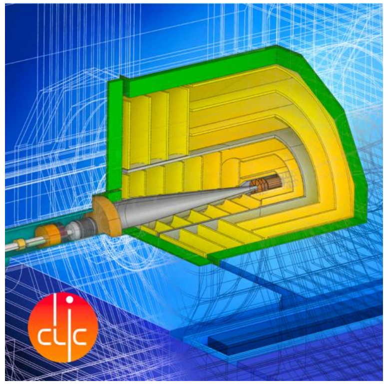




Software framework:

◆ Originally in iLCSoft, the simulation/reconstruction is now fully embedded in the **Key4HEP** ecosystem –> a common target for all future collider options
– existing reconstruction algorithms "wrappered" for the new framework

Detector R&D for CLICdet



Calorimeter R&D => within CALICE and FCAL

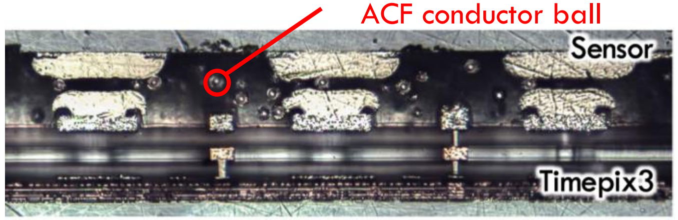
Silicon vertex/tracker R&D:

- Working Group within CLICdp and strong collaboration with DESY + AIDAinnova
- Now integrated in the CERN EP detector R&D programme

A few examples:

Hybrid assemblies:

◆ Development of **bump bonding** process for **CLICpix2** hybrid assemblies with 25 µm pitch https://cds.cern.ch/record/2766510



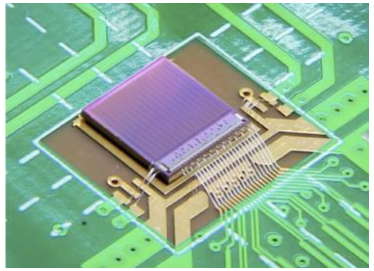
◆ Successful sensor+ASIC bonding using **Anisotropic Conductive Film (ACF)**, e.g., with CLICpix2, Timepix3 ASICs. ACF now also used for module integration with monolithic sensors. https://agenda.linearcollider.org/event/9211/contributions/49469/

Monolithic sensors:

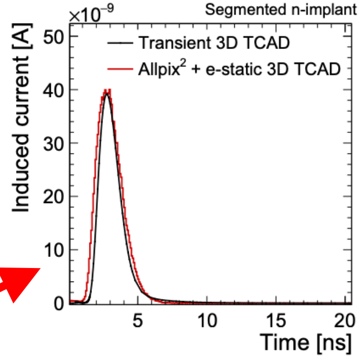
◆ Exploring sub-nanosecond pixel timing with **ATTRACT FASTPIX** demonstrator in 180 nm monolithic CMOS https://agenda.linearcollider.org/event/9211/contributions/49445/

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

CLICTD monolithic tracking sensor:

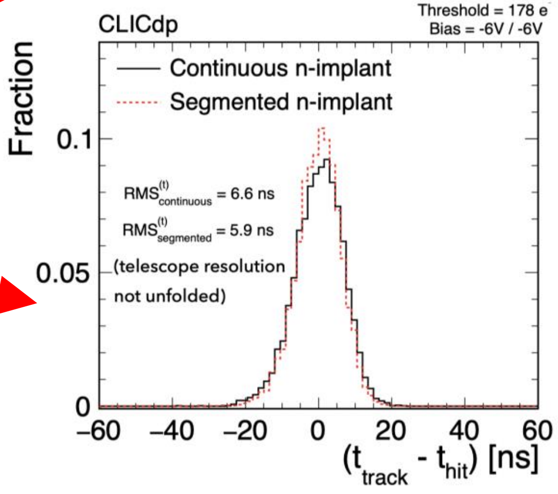


Detailed simulations, Allpix^2 transient Monte Carlo combined with electrostatic 3D TCAD.



Beam tests at DESY, e.g. 5.8 ns CLICTD time resolution achieved

https://agenda.linearcollider.org/event/9211/contributions/49443/



Physics Potential recent highlights 1:

Initial energy stage

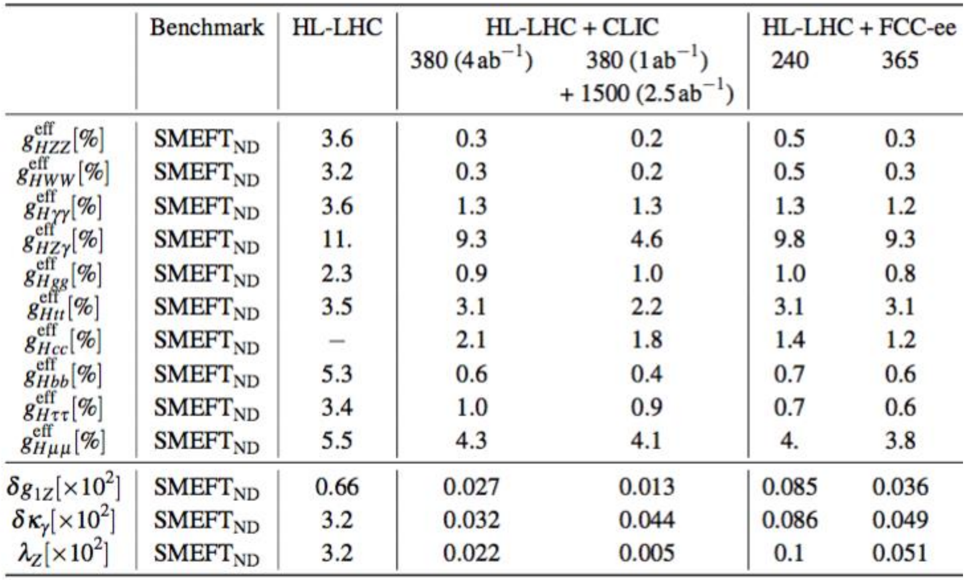
◆ **Ongoing studies on Higgs and top-quark precision physics potential**

Higgs coupling sensitivity:

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

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

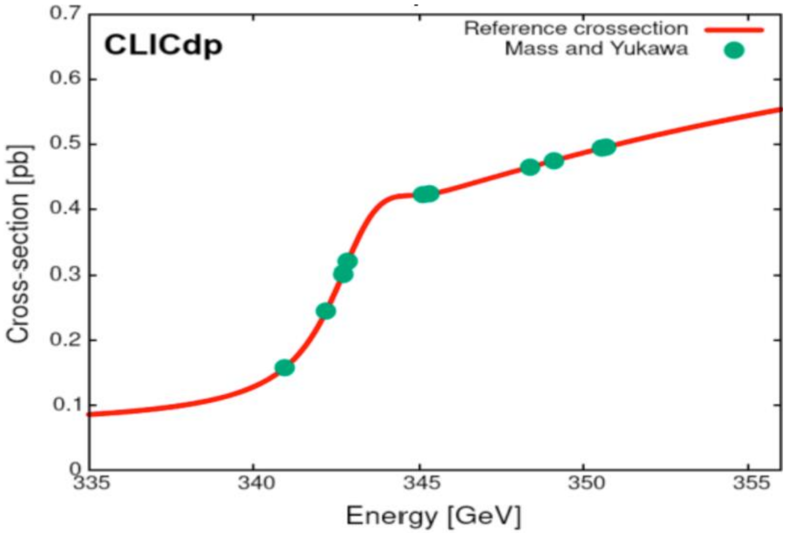
Baseline: 380 GeV ($1ab^{-1}$) + 1.5 TeV



	Benchmark	HL-LHC	HL-LHC + CLIC 380 ($4\,ab^{-1}$)	 380 ($1\,ab^{-1}$) + 1500 ($2.5\,ab^{-1}$)	HL-LHC + FCC-ee 240	 365
$g^{\mathrm{eff}}_{HZZ}[\%]$	$\mathrm{SMEFT_{ND}}$	3.6	0.3	0.2	0.5	0.3
$g^{\mathrm{eff}}_{HWW}[\%]$	$\mathrm{SMEFT_{ND}}$	3.2	0.3	0.2	0.5	0.3
$g^{\mathrm{eff}}_{H\gamma\gamma}[\%]$	$\mathrm{SMEFT_{ND}}$	3.6	1.3	1.3	1.3	1.2
$g^{\mathrm{eff}}_{HZ\gamma}[\%]$	$\mathrm{SMEFT_{ND}}$	11.	9.3	4.6	9.8	9.3
$g^{\mathrm{eff}}_{Hgg}[\%]$	$\mathrm{SMEFT_{ND}}$	2.3	0.9	1.0	1.0	0.8
$g^{\mathrm{eff}}_{Htt}[\%]$	$\mathrm{SMEFT_{ND}}$	3.5	3.1	2.2	3.1	3.1
$g^{\mathrm{eff}}_{Hcc}[\%]$	$\mathrm{SMEFT_{ND}}$	–	2.1	1.8	1.4	1.2
$g^{\mathrm{eff}}_{Hbb}[\%]$	$\mathrm{SMEFT_{ND}}$	5.3	0.6	0.4	0.7	0.6
$g^{\mathrm{eff}}_{H\tau\tau}[\%]$	$\mathrm{SMEFT_{ND}}$	3.4	1.0	0.9	0.7	0.6
$g^{\mathrm{eff}}_{H\mu\mu}[\%]$	$\mathrm{SMEFT_{ND}}$	5.5	4.3	4.1	4.	3.8
$\delta g_{1Z}[\times 10^2]$	$\mathrm{SMEFT_{ND}}$	0.66	0.027	0.013	0.085	0.036
$\delta\kappa_{\gamma}[\times 10^2]$	$\mathrm{SMEFT_{ND}}$	3.2	0.032	0.044	0.086	0.049
$\lambda_Z[\times 10^2]$	$\mathrm{SMEFT_{ND}}$	3.2	0.022	0.005	0.1	0.051

https://arxiv.org/abs/2001.05278

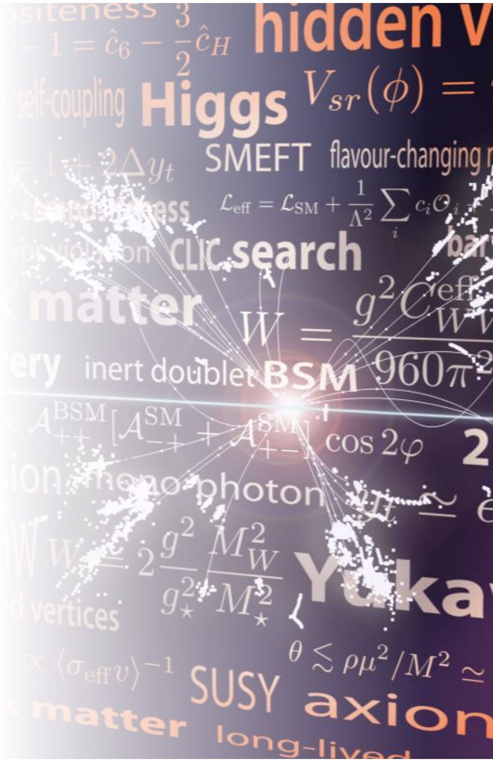
other sensitivities from Briefing Book https://arxiv.org/abs/1910.11775



Top-quark threshold scan

◆ Optimisation of scan points including beam spectrum; here optimising on mass and Yukawa coupling.

◆ Expected top-quark mass precision of 25MeV can be improved by 25% without losing precision on width or Yukawa.
https://arxiv.org/abs/2103.00522

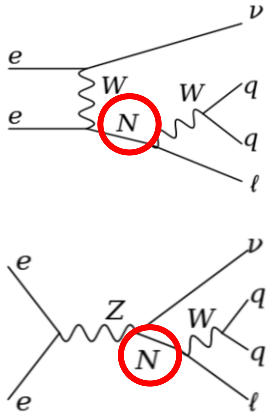


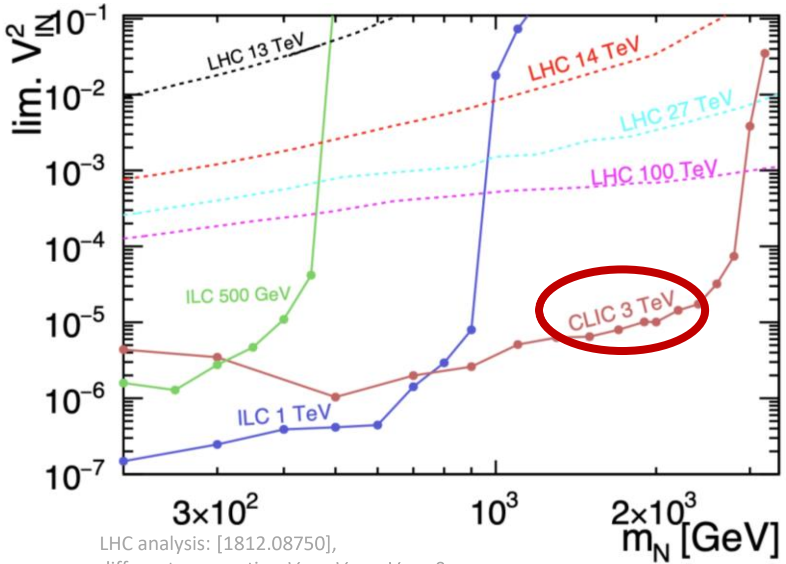
Physics Potential recent highlights 2:
Multi-TeV stages

- **Ongoing studies on new physics searches**

Search for heavy neutrinos

- e+e- -> Nν -> qqlν signature allows full reconstruction of N
- BDT separates signal from SM; beam backgrounds included.
- cross-section limits converted to mass (m_N) coupling (V_{lN}) plane



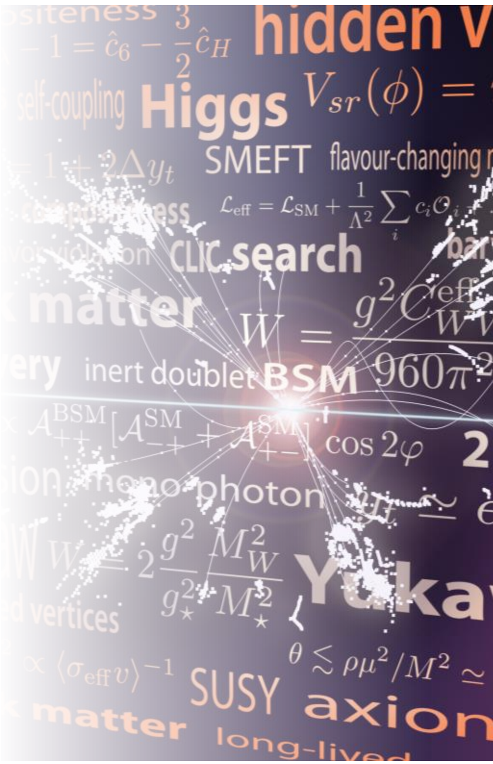


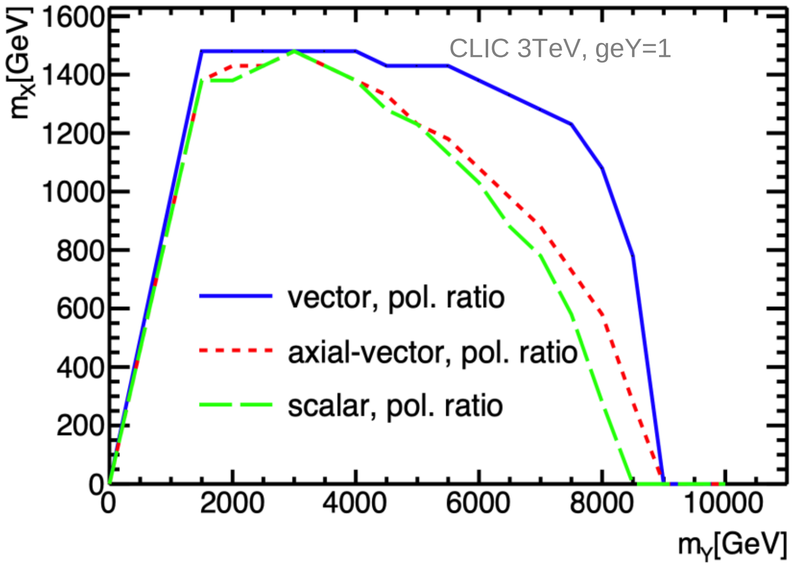
LHC analysis: [1812.08750], different assumption $V_{eN} = V_{mN} \neq V_{\tau N} = 0$

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

- New study using ratio of electron beam polarisations to reduce systematics
- Exclusions for simplified model with mediator Y and DM particle X
- For benchmark mediator of 3.5TeV, photon energy spectrum discriminates different DM mediators & allows 1TeV DM particle mass measurement to ~1%

https://arxiv.org/abs/2103.06006



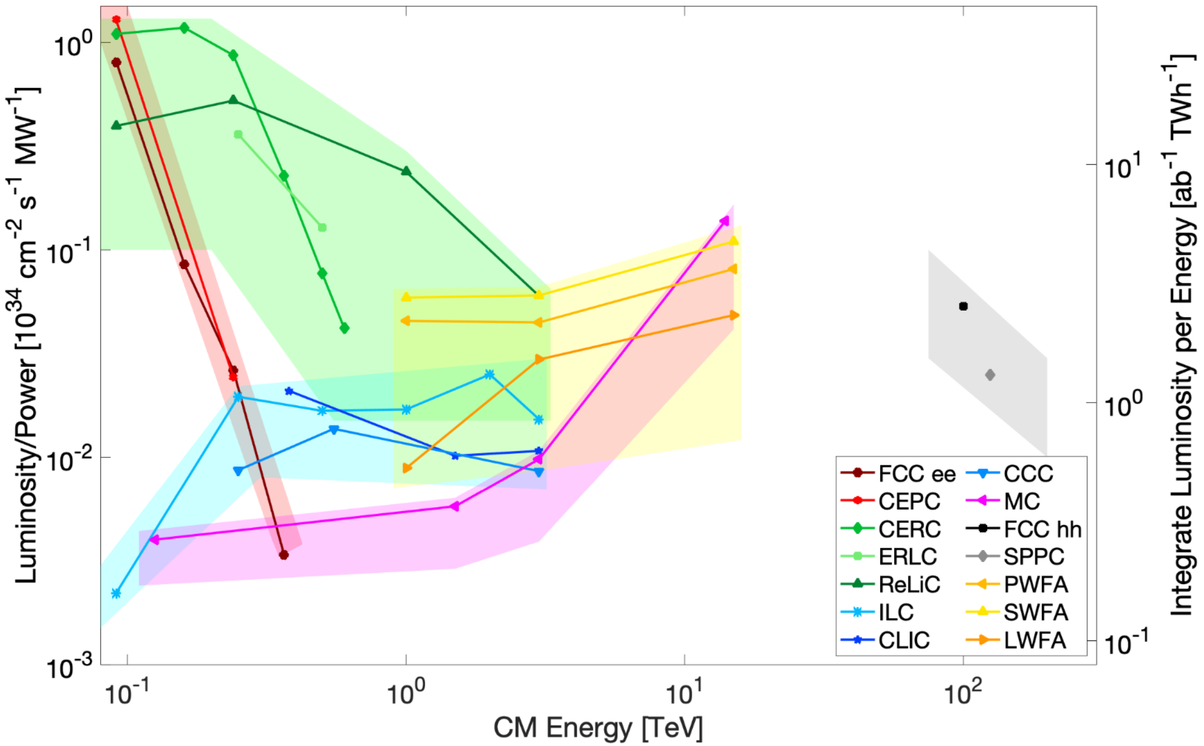


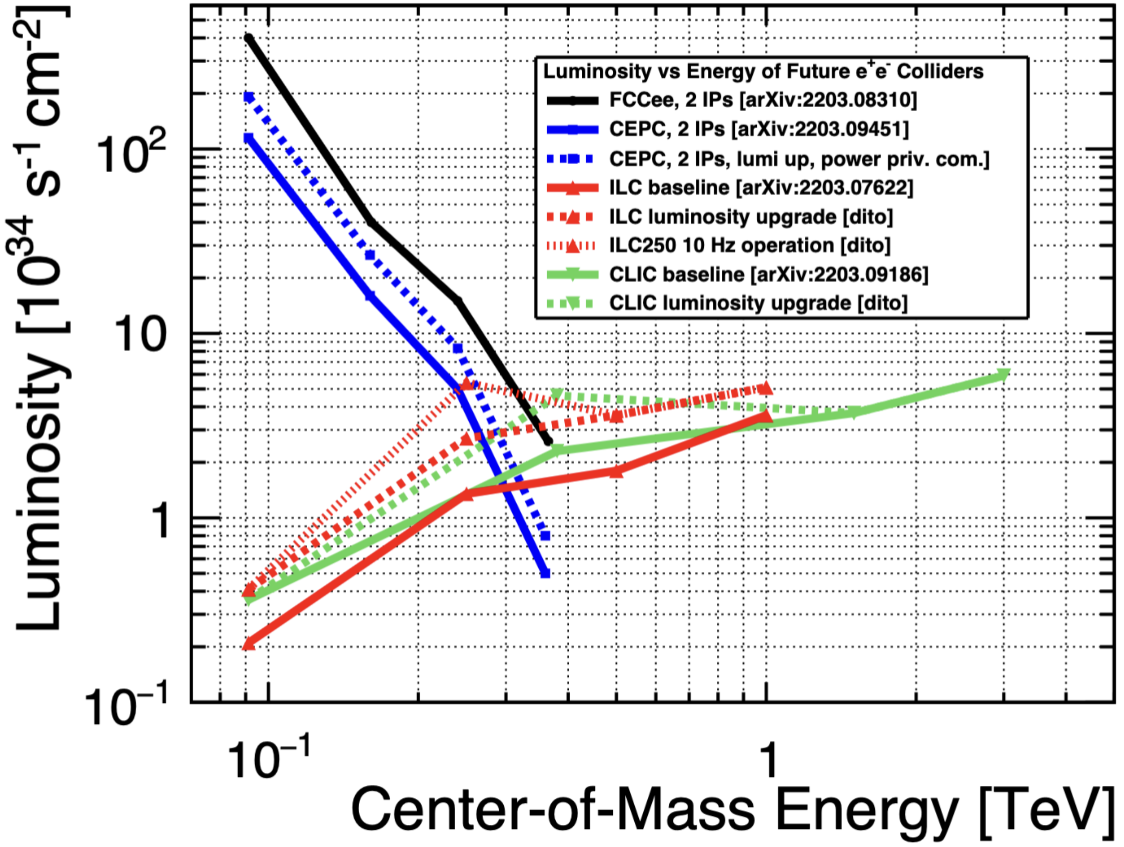
Summary and thanks

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

- Thanks to Steinar Stapnes and to many CLIC accelerator colleagues for slides and inputs, and to Aidan Robson for the CLICdp slides

Luminosity of future colliders





Personnel estimate and cost – and Higgs factories

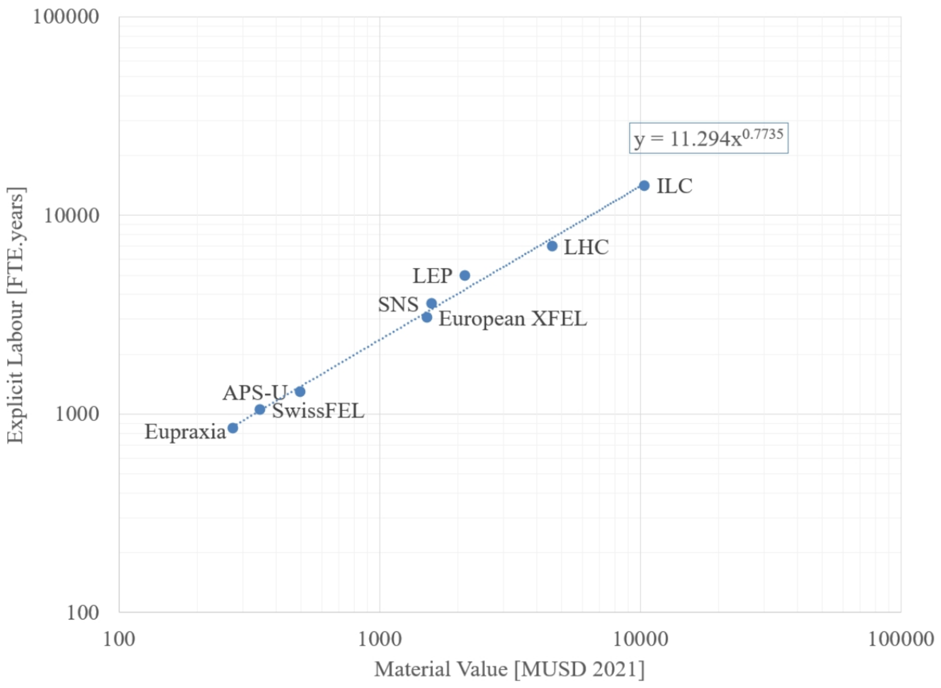


Figure 5: Explicit labor for several large accelerator projects vs. project value.

One FTEy estimated to 200kUS$

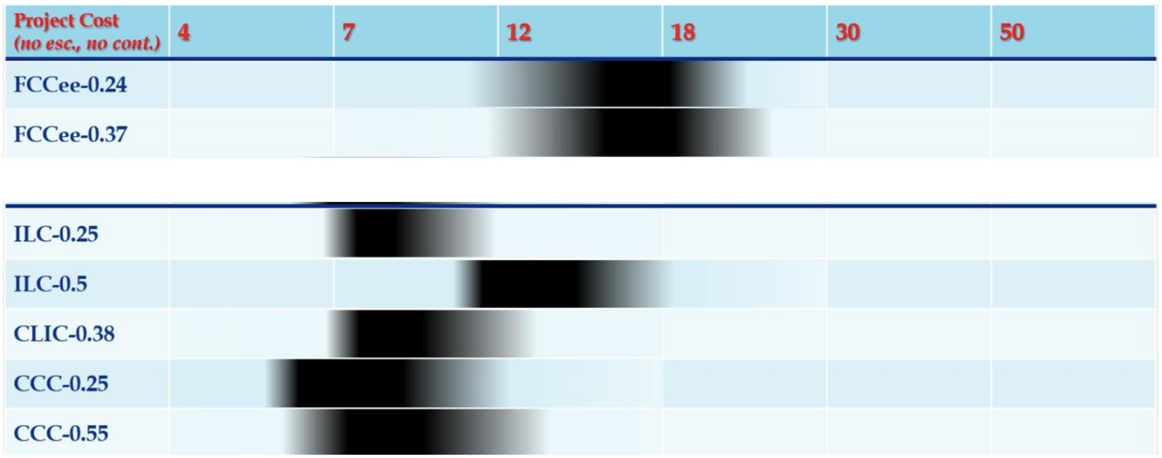
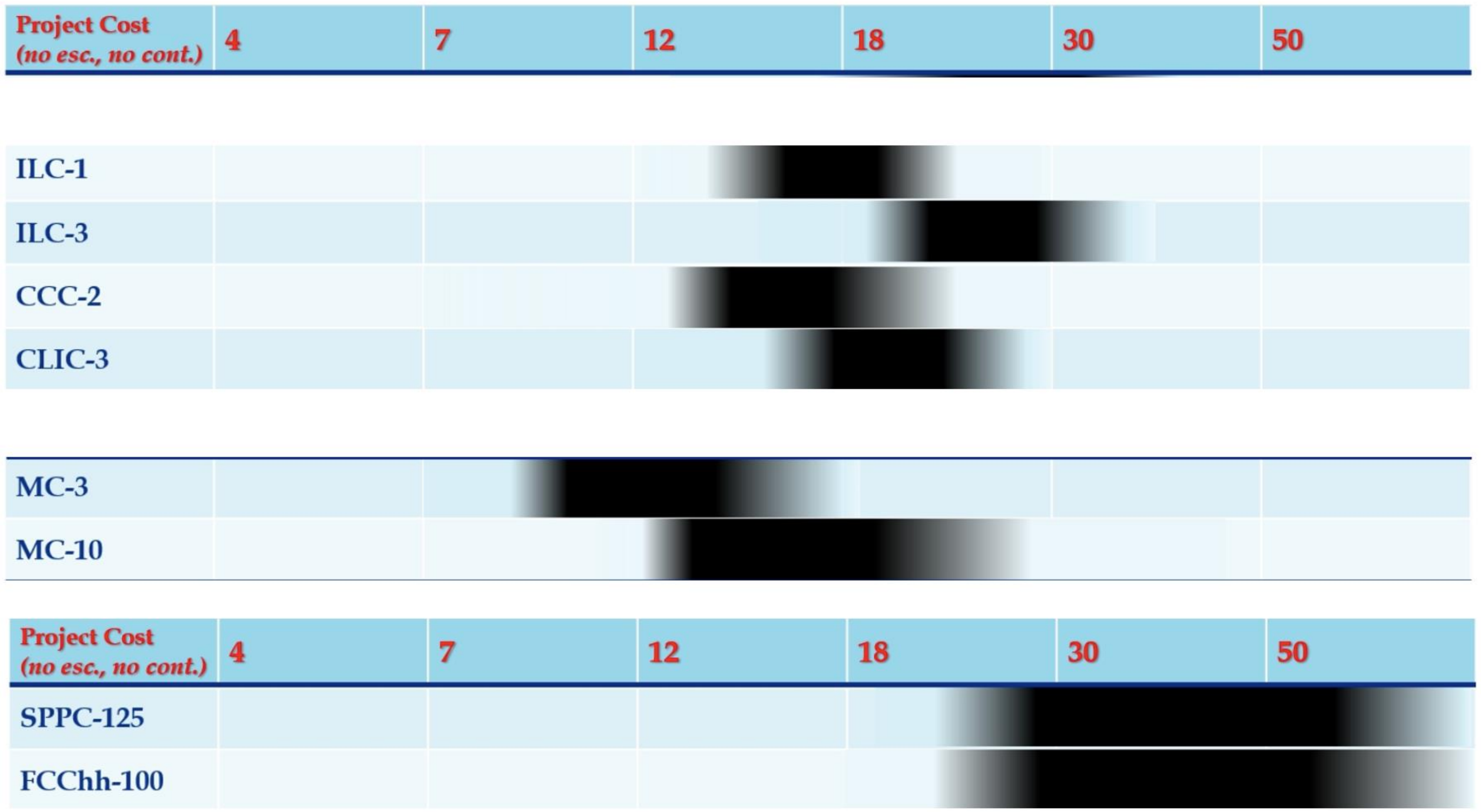
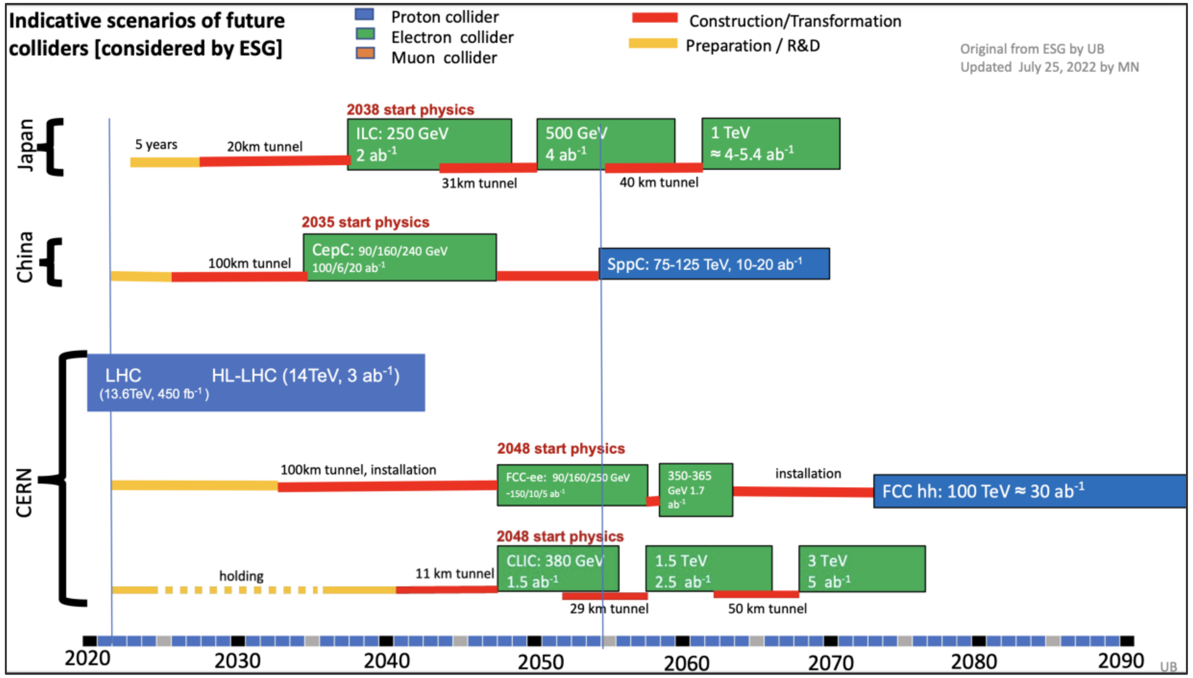


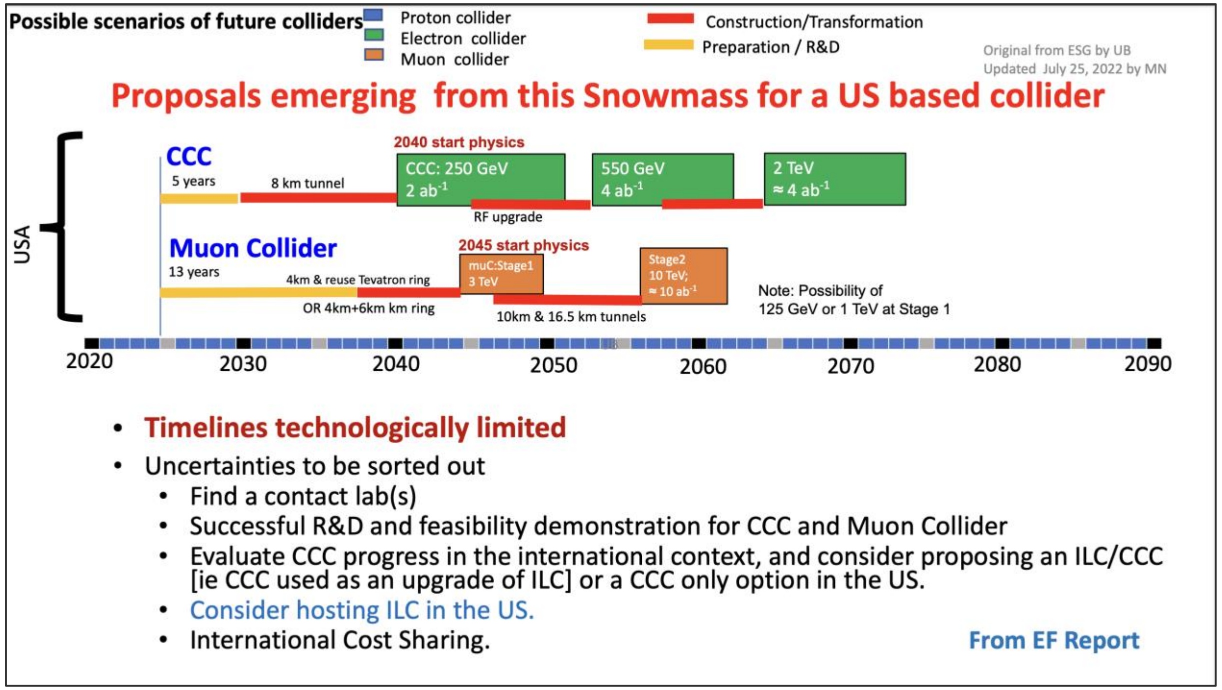
Figure 8: The ITF cost model for the EW/Higgs factory proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

Higher energy projects – and costs



Timelines in Snowmass Energy Frontier summary





- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - Consider hosting ILC in the US.
  - International Cost Sharing.

From EF Report

Comments:

- Timelines are technologically limited – except the CERN projects that are linked to completion of the HL-LHC
- CEPC and ILC schedules are mature, but the projects need to pass approval processes in the near future to maintain these schedules
- CCC and MC are less well defined but R&D and project development on the shown timescales is reasonable, CCC can also upgrade ILC
- A clear wish to develop options for future US-sited EF colliders
- US put emphasis on “fast” access to a Higgs factory
- From Meenakshi Narain EF summary Snowmass

Pushing the acc. technology – R&D

CLIC core studies:

Normal conducting accelerating structures are limited in gradient by three main effects (setting aside input power):

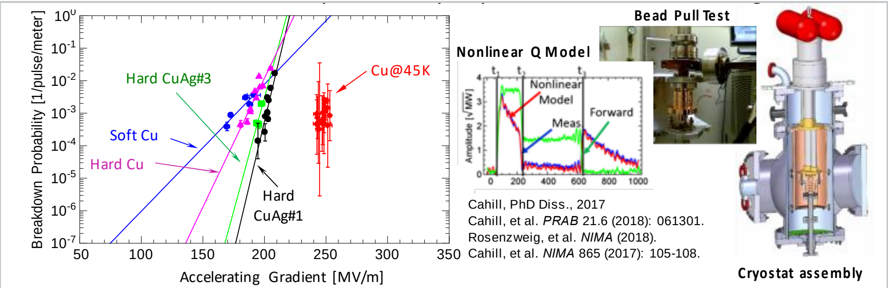
- Field emission
- Vacuum arcing (breakdown)
- Fatigue due to pulsed surface heating

Studying these processes gives important input into:

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

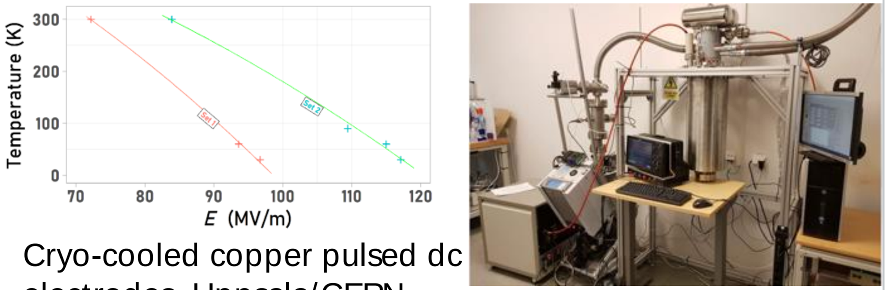
Designs for CLIC steadily improving, but also RFQ, Muon collider, XFEL, ICS, etc
Important experimental support

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

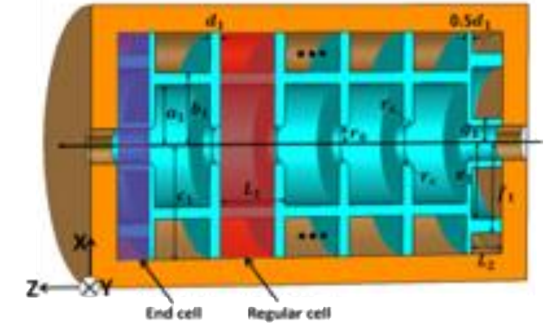


Cahill, PhD Diss., 2017
Cahill, et al. *PRAB* 21.6 (2018): 061301.
Rosenzweig, et al. *NIMA* (2018).
Cahill, et al. *NIMA* 865 (2017): 105-108.

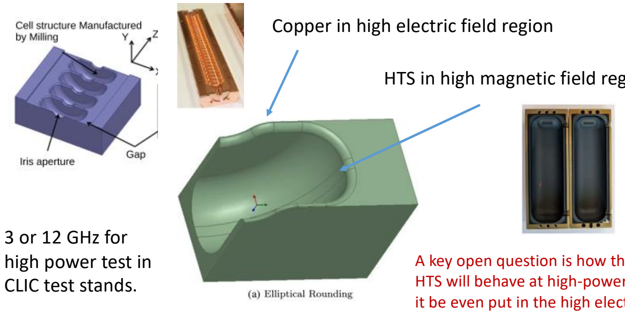
Cryo-cooled copper cavity, SLAC



Cryo-cooled copper pulsed dc electrodes, Uppsala/CERN



Implementation



Copper in high electric field region

HTS in high magnetic field region

3 or 12 GHz for high power test in CLIC test stands.

A key open question is how the HTS will behave at high-power. Can it be even put in the high electric field region?

Cryogenic systems extended: Combining high-gradients in cryo-copper and high-temperature superconductors for high-efficiency and reduced peak RF power requirements.