Road towards Energy Efficient (and Sustainable) Accelerators

Steinar Stapnes

Corfu 24.04.2023

Outline

- Introduction
- Key projects, main challenges
- Design changes and ideas
- Technical developments
- Energy efficient and also sustainable
- A last slide and thanks

Today: Snapshot early 2023

ESPP update 2018-19:

Higgs factory next – project studies
FCC feasibility study
R&D on technologies and projects

Report of the Snowmass'21
Collider Implementation Task Force

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Abstract

The Snowmass'21 Implementation Task Force has been established to evaluate the proposed future accelerator projects for performance, technology readiness, schedule, cost, and environmental impact. Corresponding metrics has been developed for uniform comparison of the proposals ranging from Higgs/EW factories to multi-TeV lepton, hadron and *ep* collider facilities, based on traditional and advanced acceleration technologies. This report documents the metrics and processes, and presents evaluations of future colliders performed by Implementation Task Force.

Interesting Implementation Task Force Report:
https://arxiv.org/pdf/2208.06030.pdf

Snowmass provided(s) an opportunity for formulating new ideas, intermediate reports, overviews – for the US and worldwide

ESPP update 2025-26-27:

… to be done …

An increasing focus on power reduction, energy consumption and also carbon emission and other sustainability issues. This talks covers some examples of past, ongoing and future studies.

Initial considerations

Resource optimization as traditionally done for accelerators:

- Length/complexity -> construction cost
- Power/energy consumption -> operating costs

Traditionally we optimize for energy reach and luminosity wrt to cost and power

Sustainability in a wider sense adds new construction and operation optimization criteria:

- Energy use not only costs but also CO_2, embedded CO_2 in construction materials and components, rare earth usage, responsible sourcing in general for all parts, landscaping, integration in local communities, life cycle assessments including decommission and many more issues

Approaches to increase sustainability

Overall system design

- Compact accelerator -> high gradients, high field magnets
- Energy efficient -> low losses (wall-plug to beam)
- Effective -> small beam sizes to maximize luminosities
- Energy recovery concepts
- Civil engineering including landscaping and “community” integration

Subsystem and component design, e.g.

- High-efficiency cavities and klystrons
- Permanent magnets, HTS magnets
- Heat-recovery. e.g. in tunnel linings, possibly other components
- Responsible sourcing and material choices for all parts

Sustainable operation concepts

- Renewables
- Adapt to power availability
- Exploit energy buffering potential
- Recover energy

Good progress on the red points (was also part of the our radiational approach), initial progress/focus on the yellow/black ones

Let us look at some collider examples to identify critical design and systems wrt power and energy efficiency, and more general sustainability issues

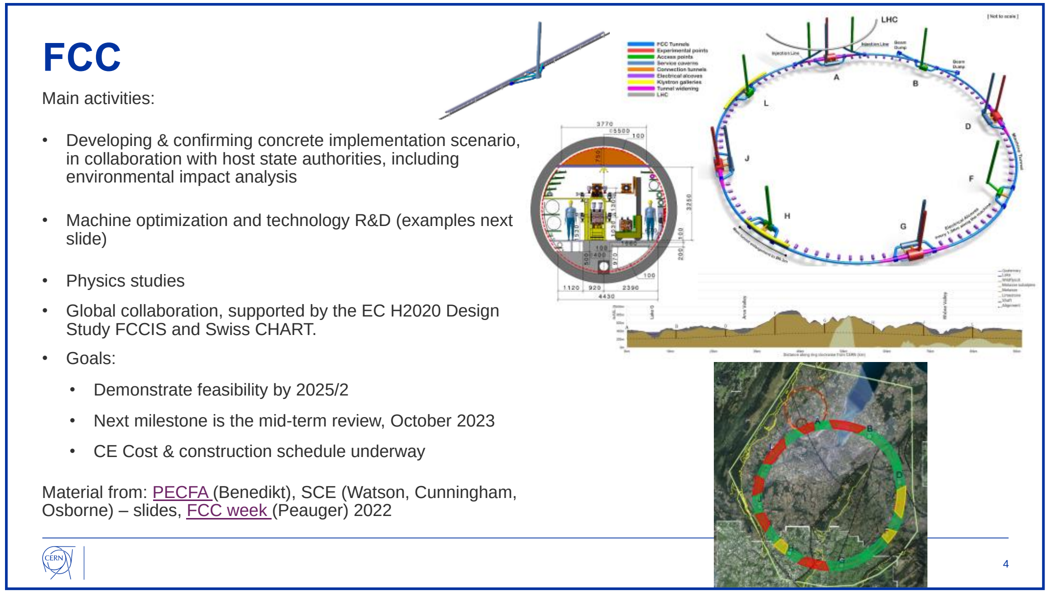
Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II					1
CEPC-0.24	II					1
ILC-0.25	I					1
CCC-0.25	III					2
CLIC-0.38	II					1
CERC-0.24	III					2
ReLiC-0.24	V					2
ERLC-0.24	V					2
XCC-0.125	IV					2
MC-0.13	III					3
ILC-3	IV					2
CCC-3	IV					2
CLIC-3	II					1
ReLiC-3	IV					3
MC-3	III					3
LWFA-LC 1-3	IV					4
PWFA-LC 1-3	IV					4
SWFA-LC 1-3	IV					4
MC 10-14	IV					3
LWFA-LC-15	V					4
PWFA-LC-15	V					4
SWFA-LC-15	V					4
FCChh-100	II					3
SPPC-125	III					3
Coll.Sea-500	V					4

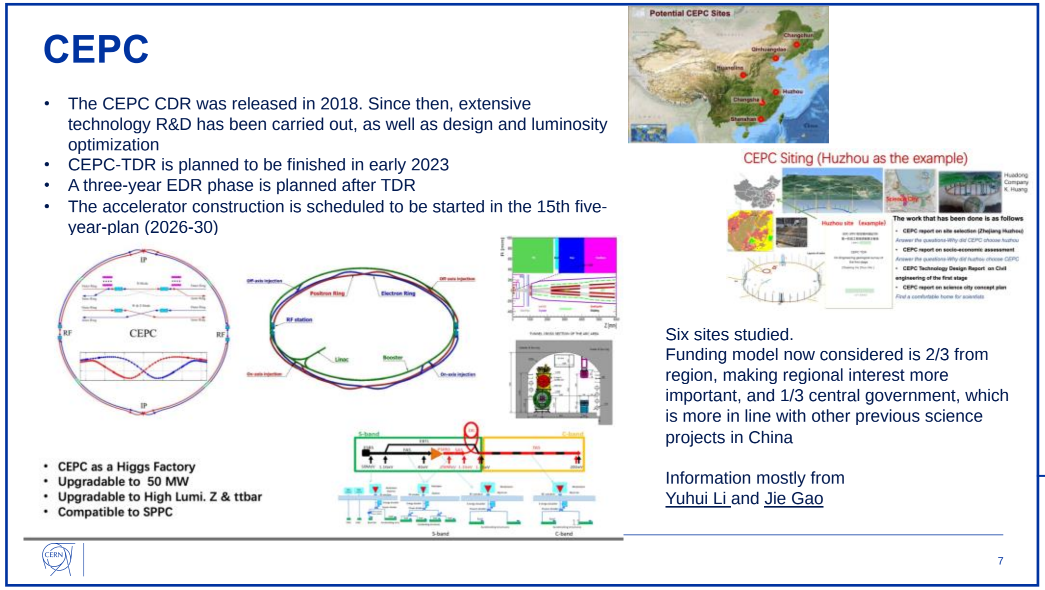
A catalogue of collider studies:

- Circular and linear collider Higgs factories (FCC-ee, CEPC, CLIC, ILC, C3, HALHV)
- Upgrades of these to LCs with multi-TeV energies,or becoming hadron colliders (FCChh, SPPC)
- Muon colliders
- Energy recovery concepts for circular and linear colliders (CERC, ReLiC, ERLC)
- Plasma based accelerator concepts

Light colour is good. Performance Achievability contentious/subjective.

Circular machines, e+e- and then hadrons





For the e+e- machines:

Synchrotron radiation makes them very large (high embedded carbon in tunnel CE and many active components) and requiring very high RF power (~150 MW) to compensate for losses.

-> Efficient RF systems, luminosities optimisation (luminosity for a given beam power) with combination of design optimisation and interaction point optimisation

For the hadron machines:

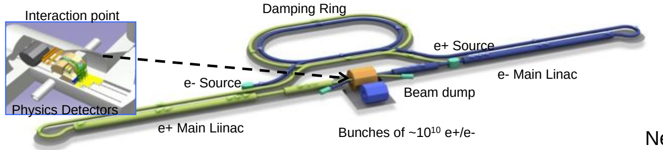
Embedded carbon in many heavy elements

High Field magnets very demanding, beyond performance and cost concerns also the power consumption is very high (including then cryo-system)

-> HFM research, e.g. HTS to operate at higher temperatures

Linear Colliders, for Higgs, top and later 1-3 TeV

The ILC250 accelerator facility

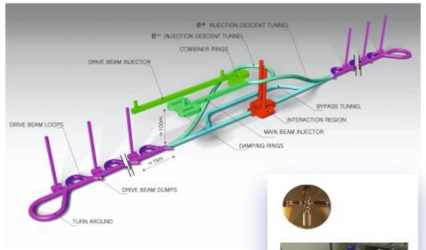


New funding for technology development, involving most European labs

- Creating particles — Sources
  - polarized elections/positrons
- High quality beam — Damping ring
  - low emittance beams
- Acceleration — Main linac
  - superconducting radio frequency (SRF)
- Collide them — Final focus
  - nano-meter beams
- Go to — Beam dumps

Recent talks (with more references): eeFACT-I1 and eeFACTI2 6

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.

Recent talks (with more references): eeFACT1 and eeFACT2

The CLIC accelerator studies are mature:
- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of "all" key elements

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For the e+e- linear colliders:

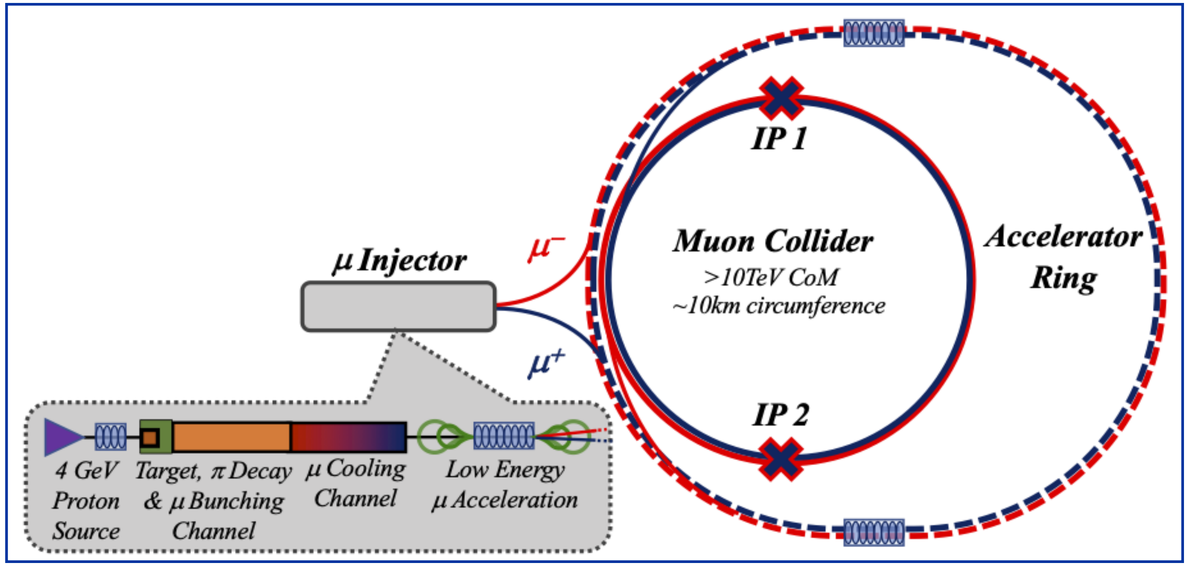
RF efficiency important, from wall plug to beam, becoming increasingly important as the operation energy increases

Nanobeams to maximise luminosity / beam-power, also increasingly difficult as energy increases (the beam are becoming smaller)

Embedded carbon ~proportional to facility length

-> Efficient RF systems, luminosities optimisation (luminosity for a given beam power) by stability, alignment, instrumentation etc for nano-beams, embedded carbon addressed by reducing length of installation and tunnel diameter

Muon Collider



For a muon collider:

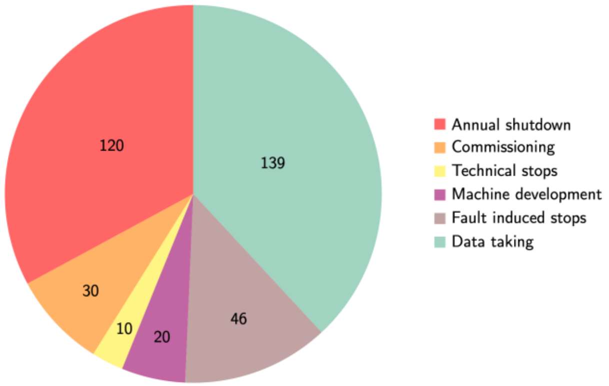
Concept build around reaching multi-TeV (~10 TeV) collision energies with improved L/P wrt e+e-, and in a much more compact facility than a ~100 TeV hadron collider.

Key challenges are muon cooling, fast acceleration and fast ramping and high field magnets – and other issues less directly related to power consumption or facility size

-> High field solenoids and dipoles – strong focus on HTS, high gradient SC and NC accelerator structures and power efficient RF sources

Power and energy

Proposal	CEPC		FCC-ee		CLIC	ILC‡	C³
Beam energy [GeV]	120	180	120	182.5	190	125	125
Average beam current [mA]	16.7	5.5	26.7	5	0.015	0.04	0.016
Total SR power [MW]	60	100	100	100	2.87	7.1	0
Collider cryo [MW]	12.74	20.5	17	50	–	18.7	60
Collider RF [MW]	103.8	173.0	146	146	26.2	42.8	20
Collider magnets [MW]	52.58	119.1	39	89	19.5	9.5	20
Cooling & ventil. [MW]	39.13	60.3	36	40	18.5	15.7	15
General services [MW]	19.84	19.8	36	36	5.3	8.6	20
Injector cryo [MW]	0.64	0.6	1	1	0	2.8	6
Injector RF [MW]	1.44	1.4	2	2	14.5	17.1	5
Injector magnets [MW]	7.45	16.8	2	4	6.2	10.1	4
Pre-injector [MW]	17.685	17.7	10	10	–	–	–
Detector [MW]	4	4.0	8	8	2	5.7	NE
Data center [MW]	NI	NI	4	4	NI	2.7	NE
Total power [MW]	259.3	433.3	301	390	107	138	150
Lum./IP [10^{34} $cm^{-2}s^{-1}$]	5.0	0.8	7.7	1.3	2.3	2.7	1.3
Number of IPs	2	2	4 (2)	4 (2)	1	1	1
Tot. integr. lum./yr [1/fb/yr]	1300	217.1	4000 (2300)	670 (340)	276	430	210
Eff. physics time / yr [10^7 s]	1.3	1.3	1.24	1.24	1.2	1.6	1.6
Energy cons./yr [TWh]	0.9	1.6	1.51	1.95	0.6	0.82	0.67



Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	290	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	20.5 km	I	I
CLIC (0.38 TeV)	110	11.4 km	II	I
CCC (0.25 TeV)	150	3.7 km	I	I
ILC (3 TeV)	~400	59 km	II	II
CLIC (3 TeV)	~550	50.2 km	III	II
CCC (3 TeV)	~700	26.8 km	II	II
MC (3 TeV)	~230	10-20 km	II	III
MC (14 TeV)	~300	27 km	III	III
FCC-hh (100 TeV)	~560	91 km	II	III
SPPC (125 TeV)	~400	100 km	II	III

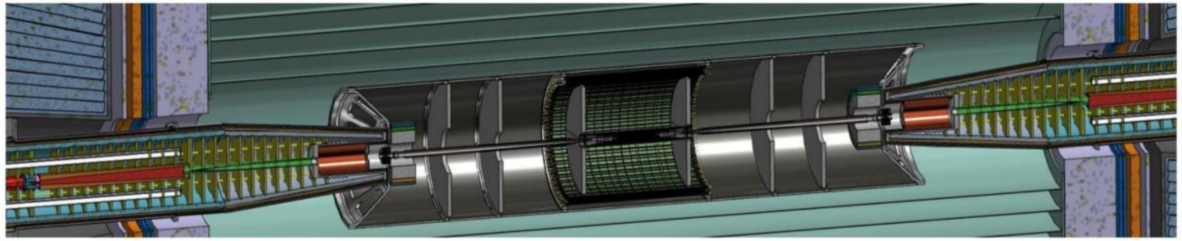
100 MW corresponds to ~0.6 TWh with the running scenario on the left

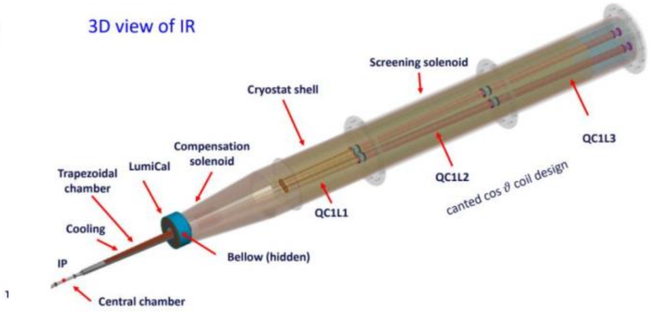
Some examples of design optimisation studies for lower power, improved luminosity/power ratios and more compact facilities

In many cases coupled to technology improvements (see examples later)

Improvements of L/P (from FCC-ee)

Novel outer support tube for central beam pipe and vertex detector

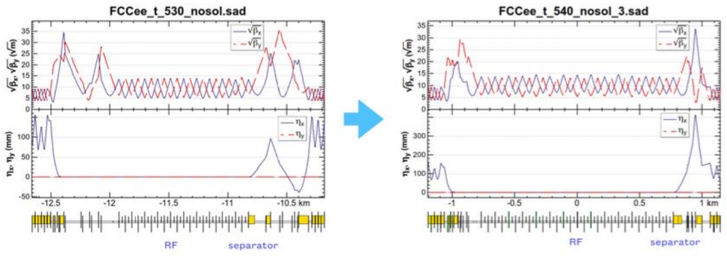




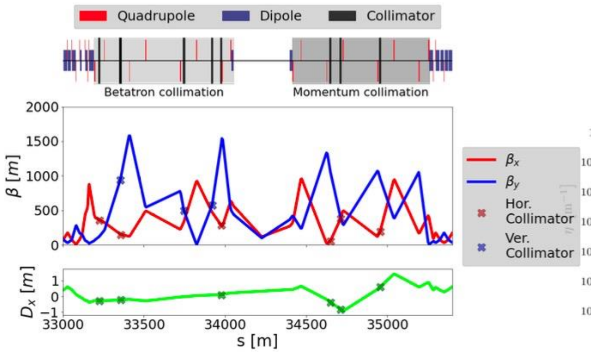
FCC-ee MDI examples, also studies of ID heat load distribution and beamstrahlung dump

Beam optics developments (examples)

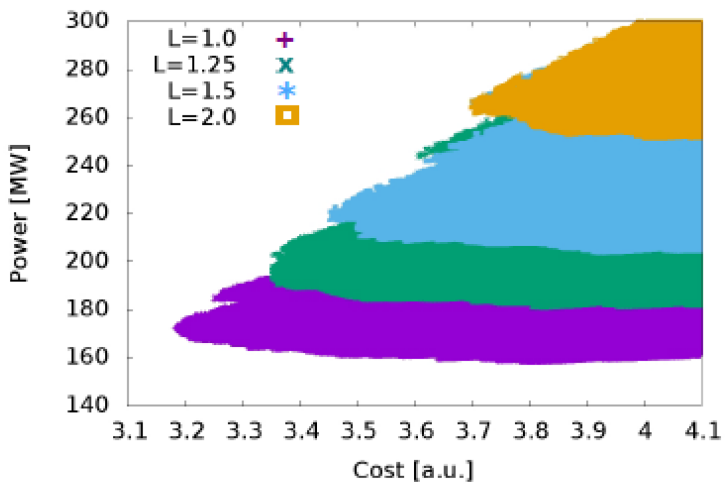
Points B, F, H & L (RF and other technical straights)



New collimation optics for 4 IPs



Examples of LC system optimizations



Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum

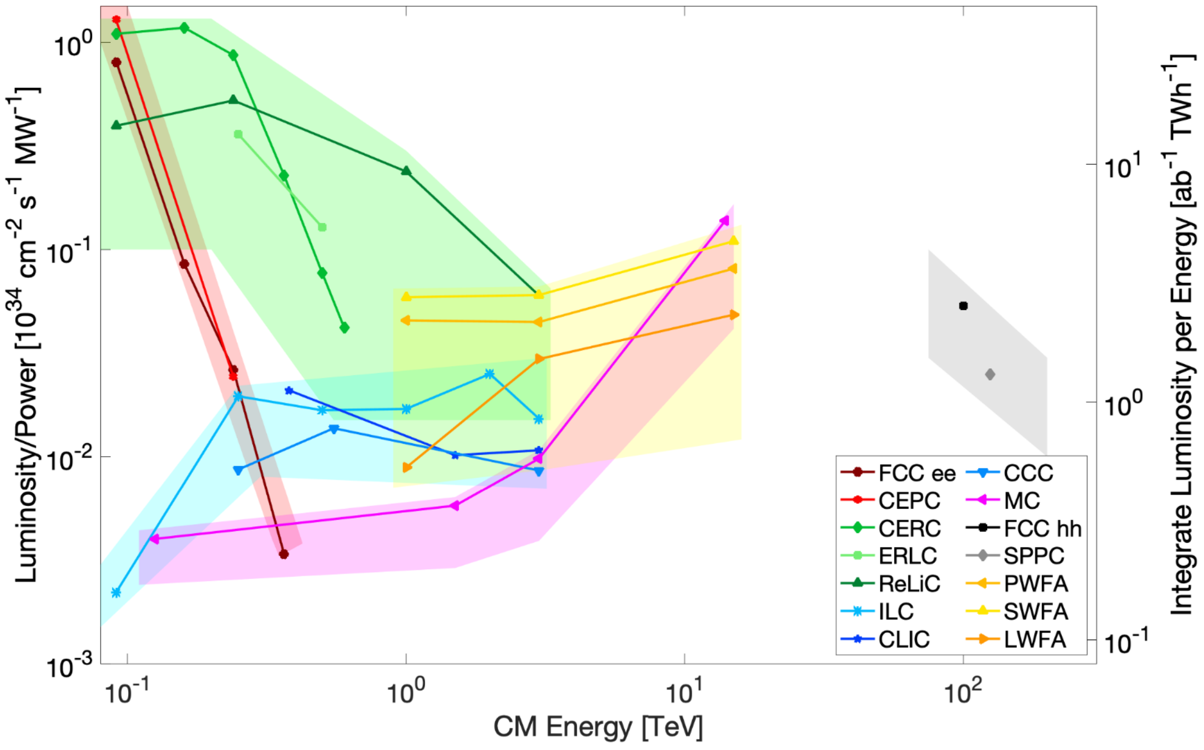
Design Optimisation for CLIC

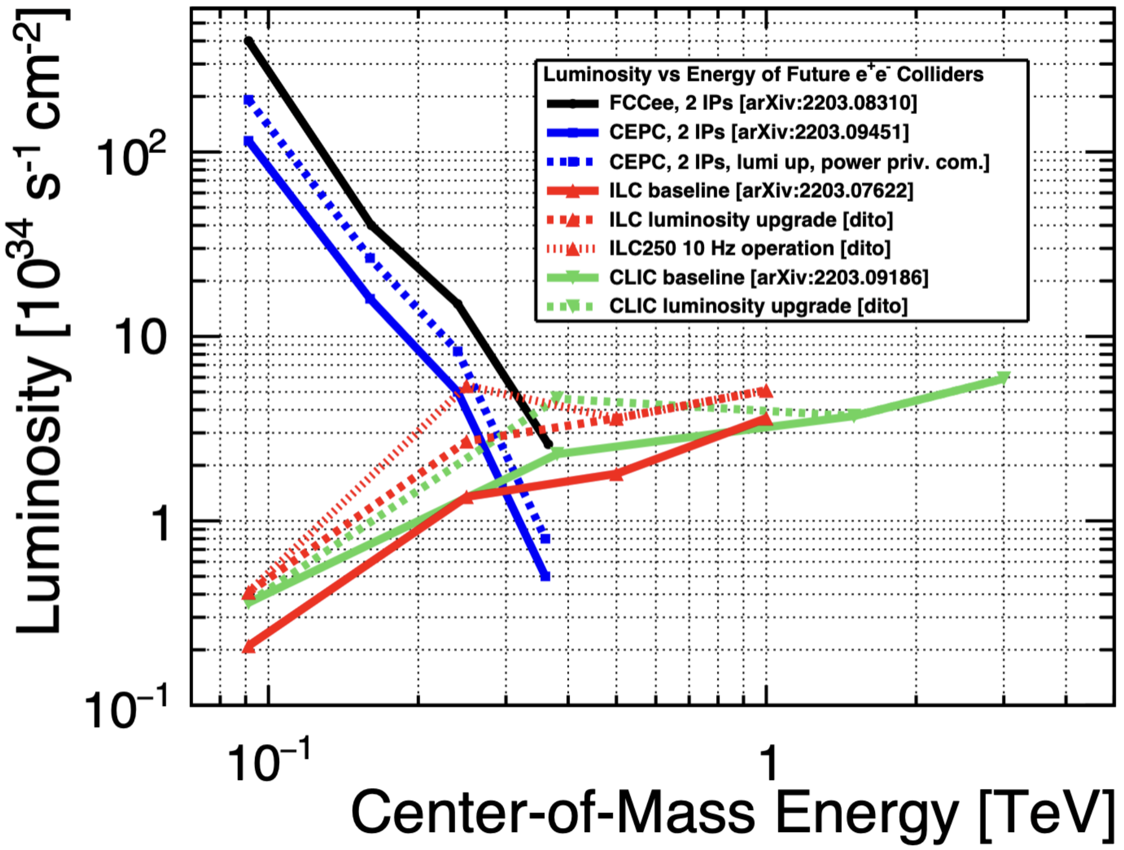
- The designs of CLIC, including key performance parameters as accelerating gradients, pulse lengths, bunch-charges and luminosities, have been optimised for cost but also increasingly focussing on reducing power consumption.
- This was done in 2015 optimising the 380 GeV machine (selected to cover top and Higgs)
- In parallel: Re-design and optimisation of RF systems (e.g. damping rings and drivebeam)

For ILC design optimisations have been and are being done, also focussing on parameters choices, for example repetition rates, pulse-lengths, cryo and RF systems for various luminosity choices

In both cases it would be interesting to repeat these studies now, focussing more strongly on power consumption (and including a lot of progress in technical developments).

Luminosities versus power for Higgs factories





Per IP, from Snowmass

Higgs factories

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Energy cons./yr [TWh]	0.9	1.6	1.51	1.95	0.6	0.82	0.67

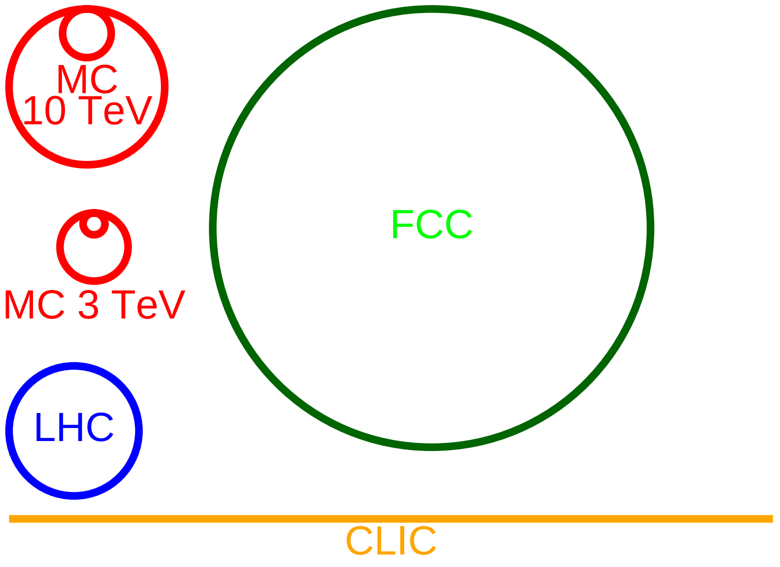
Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150

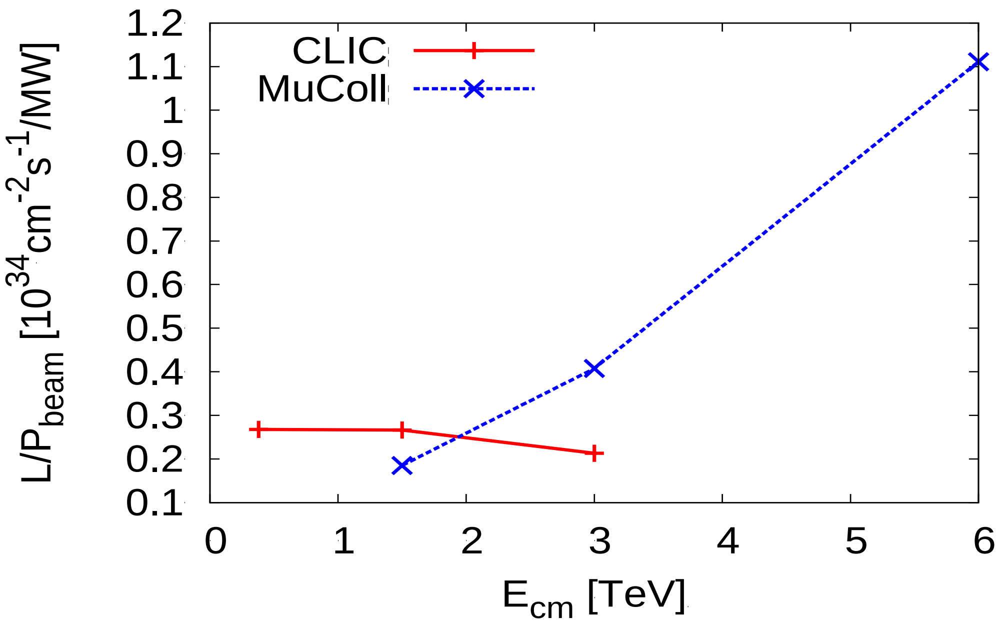
Table 1: Main parameters of the submitted Higgs factory proposals. The cost range is for the single listed energy. The superscripts next to the name of the proposal in the first column indicate (1) Facility is optimized for 2 IPs. Total peak luminosity for multiple IPs is given in parenthesis; (2) Energy calibration possible to 100 keV accuracy for M_Z and 300 keV for M_W; (3) Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes

Abstract

A special session at eeFACT'22 reviewed the electrical power budgets and luminosity risks for eight proposed future Higgs and electroweak factories (C^3, CEPC, CERC, CLIC, FCC-ee, HELEN, ILC, and RELIC) and, in comparison, for a lepton-hadron collider (EIC) presently under construction. We report highlights of presentations and discussions.

Addressing size, lumi, cost, power - a Muon Collider



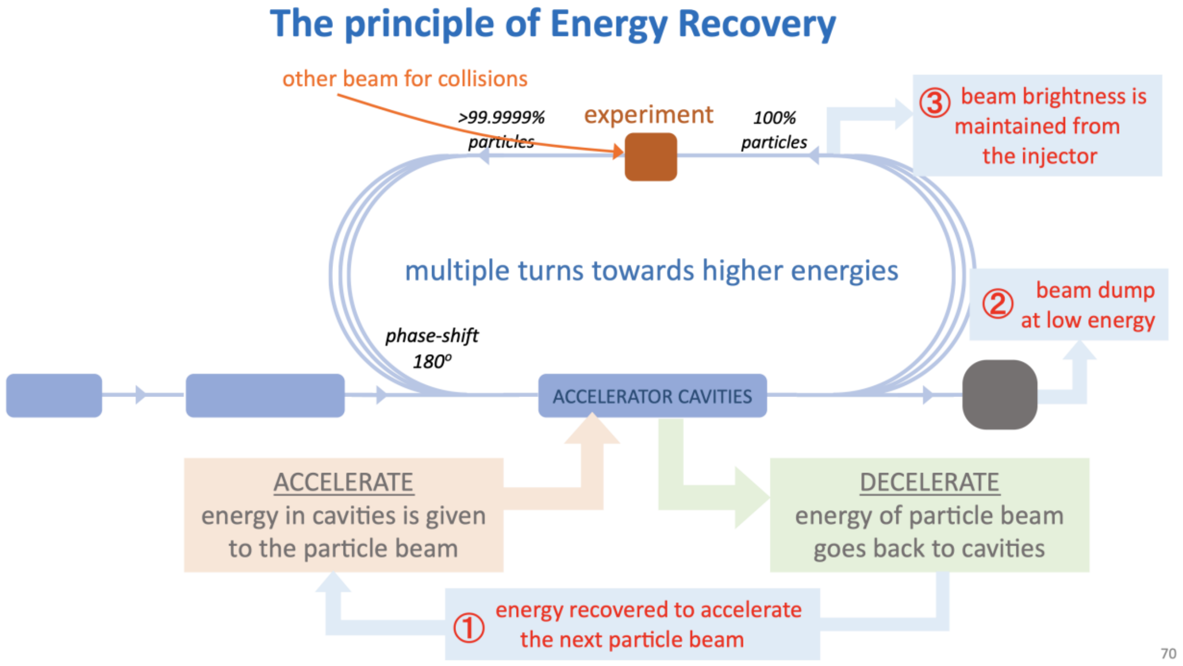


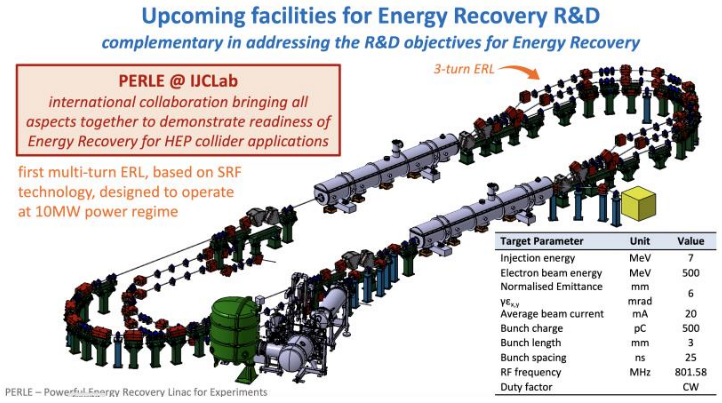
Muon Collider goals (10 TeV):

- Much more luminosity than CLIC at 3 TeV ($L=20\times10^{34}$, CLIC: $L=6\times10^{34}$)
- Lower power consumption than CLIC at 3 TeV ($P_{beam,MC}=0.5P_{beam,CLIC}$)
- Lower cost

Keep in mind:
Compact and low energy energy consumption, cheaper construction and operation, lower carbon embedded and in operation

Energy Recovery principle and machine concepts





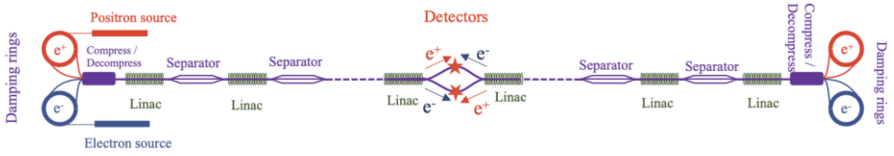


Figure 3-8. *Conceptual layout of ReLiC.*

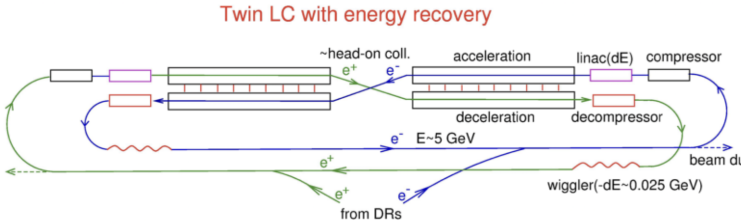
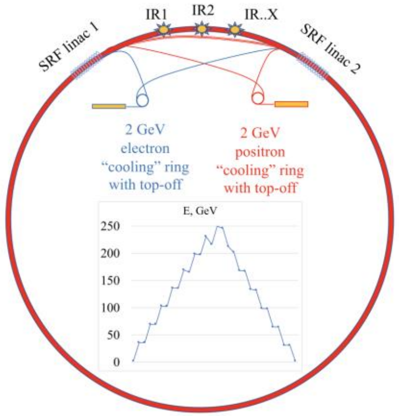


Figure 3-10. *Conceptual layout of the ERLC.*

Can reduce power, but can also be used to reach higher luminosities by providing more wall-plug to beam power efficiency.

Several e+e- concepts presented for Snowmass (circular and linear concepts).

Also for LHeC



A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration

B. Foster,[1,*] R. D'Arcy,[2] and C. A. Lindstrøm[3]

[1] *John Adams Institute for Accelerator Science at University of Oxford, Oxford, UK*
[2] *Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*
[3] *Department of Physics, University of Oslo, Oslo, Norway*

(Dated: March 17, 2023)

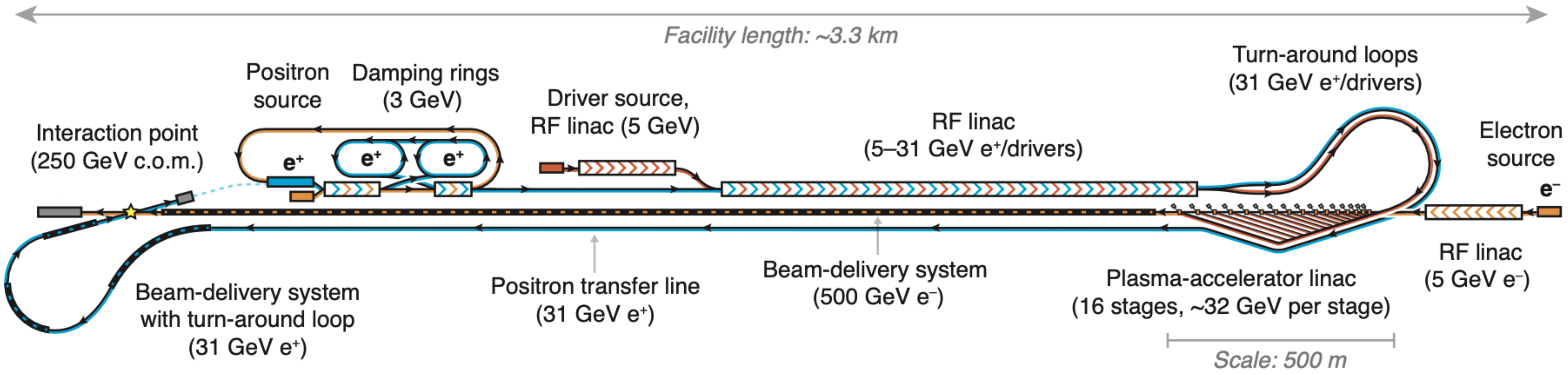
The construction of an electron–positron collider "Higgs factory" has been stalled for a decade, not because of feasibility but because of the cost of conventional radio-frequency (RF) acceleration. Plasma-wakefield acceleration promises to alleviate this problem via significant cost reduction based on its orders-of-magnitude higher accelerating gradients. However, plasma-based acceleration of positrons is much more difficult than for electrons. We propose a collider scheme that avoids positron acceleration in plasma, using a mixture of beam-driven plasma-wakefield acceleration to high energy for the electrons and conventional RF acceleration to low energy for the positrons. We emphasise the benefits of asymmetric energies, asymmetric bunch charges and asymmetric transverse emittances. The implications for luminosity and experimentation at such an asymmetric facility are explored and found to be comparable to conventional facilities; the cost is found to be much lower.

HALHF

https://arxiv.org/abs/2303.10150

Certainly very compact so embedded CO_2, likely very reduced costs compared to other Higgs-factories, not clear of power is different to any other LC.

Technically still uncertain.



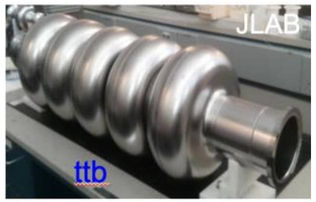
Examples of technical developments
RF improvements
Magnets
Nanobeam related HW

SC RF

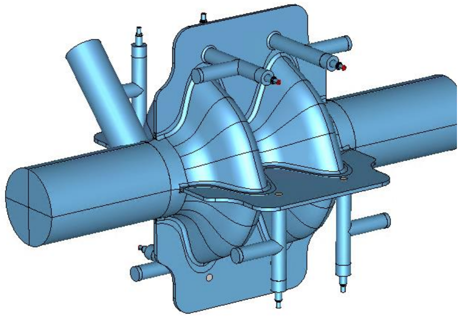
New

400 MHz 1-cell cavities
Nb/Cu

400 MHz 2-cell cavities
Nb/Cu
2-cell is better for W working point
(reduced RF power per cav., improved HOM damping)



800 MHz 5-cell cavities
Bulk Nb



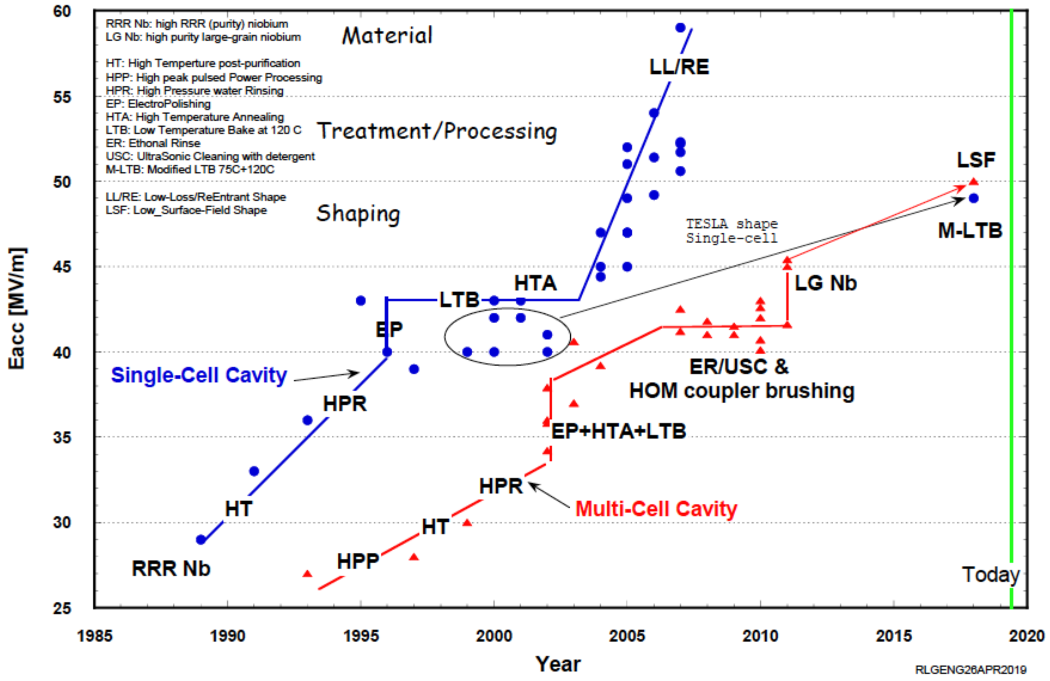
FCC-ee baseline left

Right: Swell 2-cell 600 MHz cavity for Z, W, H

Very interesting **alternative cavity** option which would cover three machines (no need to remove cryomodules after operation at Z)

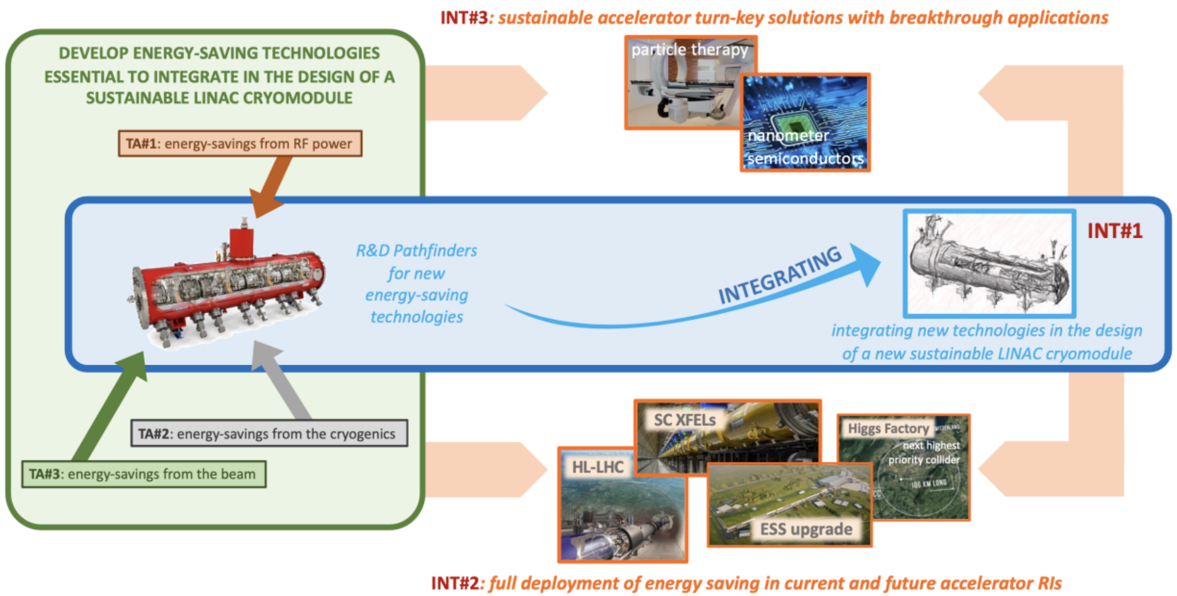
Highly damped RF cavity for transverse HOMs thanks to four waveguide slots and coaxial RF lines

Bulk niobium (1.3 GHz as ILC and FEL linacs), constantly improving gradient, Q, and processing steps (possibly reducing chemical use)

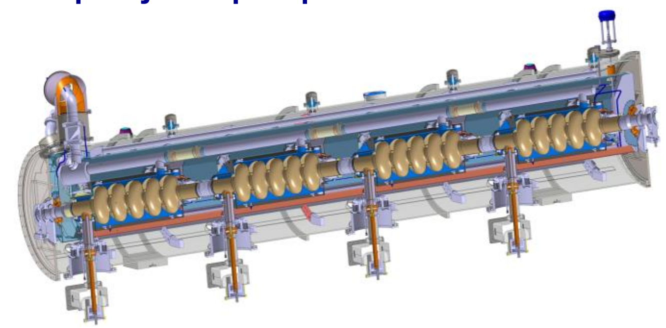


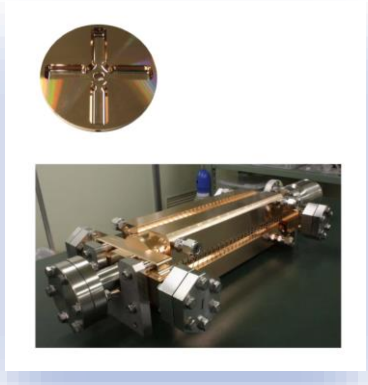
Improvements in gradients with for example travelling wave structures or Nb_3Sn coating are being pursued, power efficiency (Q) always integrated part of the studies

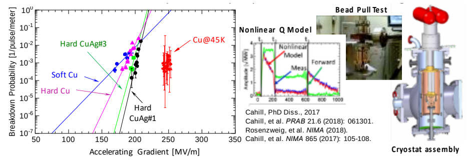
Energy recovery for SC RF, and NC RF



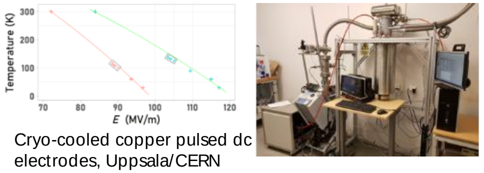
Innovate for Sustainable Accelerating Systems (iSAS)
EU project proposal



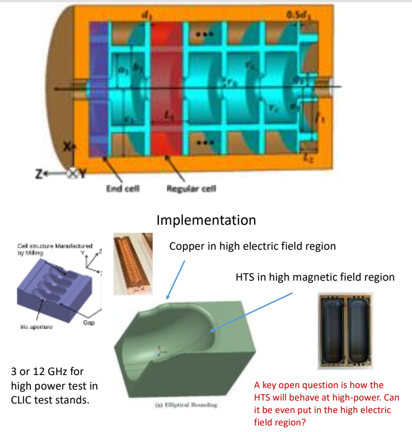




Cryo-cooled copper cavity, SLAC



Cryo-cooled copper pulsed dc electrodes, Uppsala/CERN



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

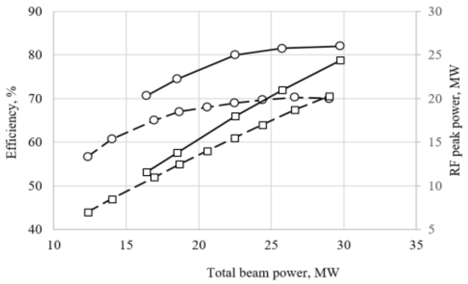
CLIC structures very optimised.

Can improve gradients running at ~50K (C3) but less clear if more power efficient

Coat with HTS to improve RF efficiency and lower peak power requirements (CLIC, C3, I.FAST)

High Eff. Klystrons

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

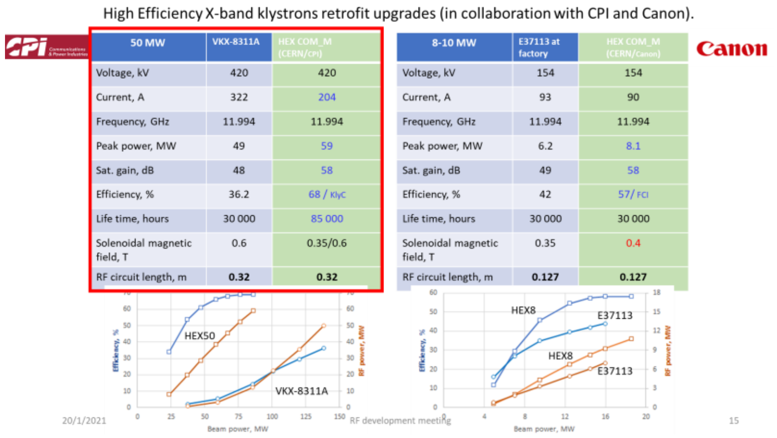


Location: CERN Bldg: 112

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. See more later.
Publication: https://ieeexplore.ieee.org/document/9115885

High Efficiency implementations:

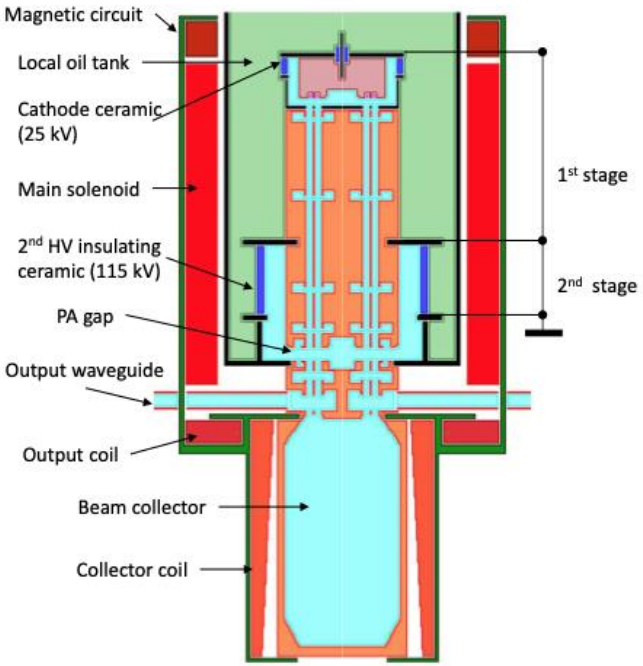
- New small X-band klystron – recent successful prototype
- Large X-band with CPI
- L-band two stage, design done, prototype desirable

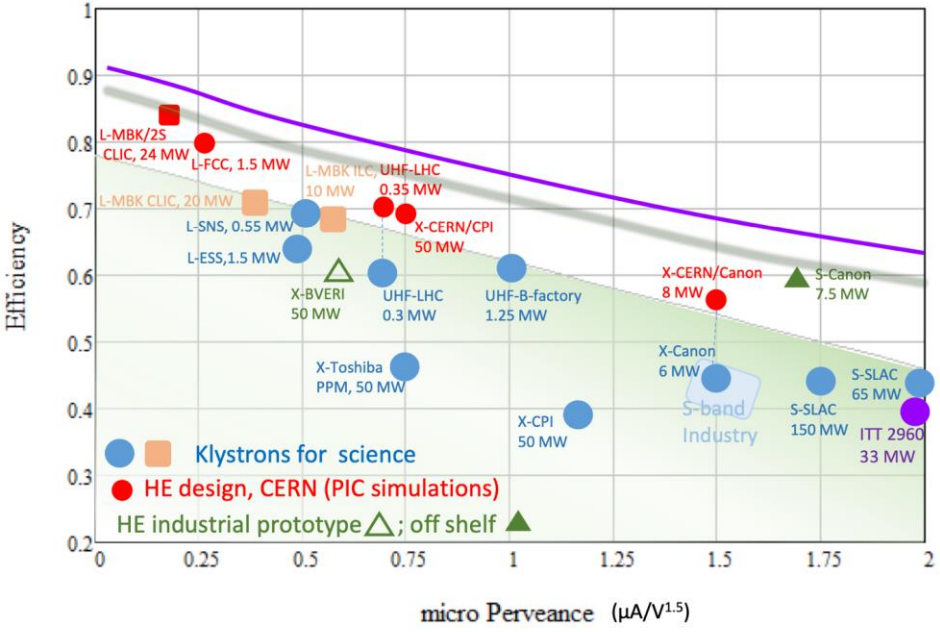


High Efficiency X-band klystrons retrofit upgrades (in collaboration with CPI and Canon).

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**





Magnets

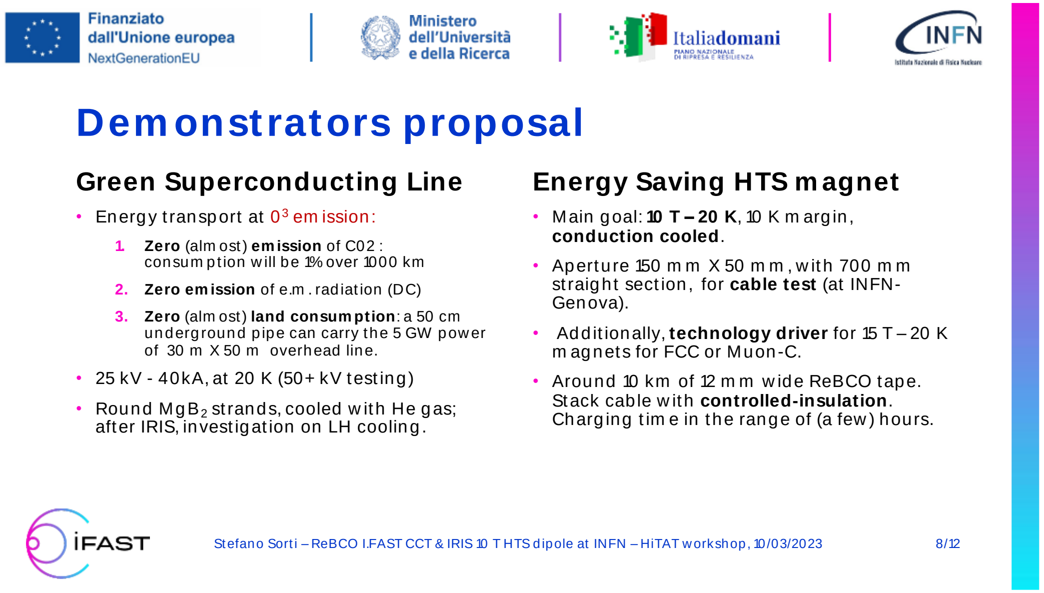
Primary goal of HFM is to open for high energy hadron colliders

Also important for muon collider (solenoid fields for cooling system probably ok, performance increases with achievable dipole fields in collider ring)

Increased interest for HTS not only for high field, but also for power reduction (i.e. for Higgs factories). In some cases permanent magnets can also be used.

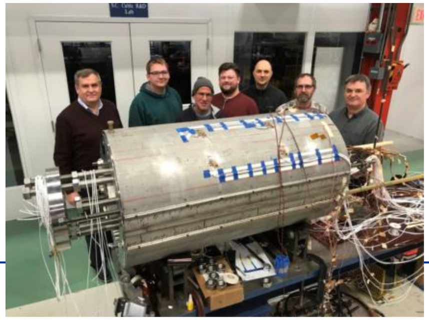
Three linked challenges of machines depending on HFM at very large scale as hadron colliders: fields, costs and power

- Even with cost targets a factor 2-3 lower than today (a much larger factor for HTS) the costs are very high (see later)
- FCC-hh estimated roughly at 560 MW and ~4TWh annually from CDR, for Nb_3Sn and at 1.9K. Do not have estimate for SPPC. Combined with increased energy price this is a “challenge”.
- A fourth challenge is the industrial interests for HF and long dipole magnets (and Nb_3Sn generally). Contrary to RF systems such magnets are generally not needed for small accelerators or industry.



12 T Nb_3Sn quadrupole

14.5 T Nb_3Sn



Magnets also important in Higgs factories

1.5 TeV CLIC power
Magnets second largest

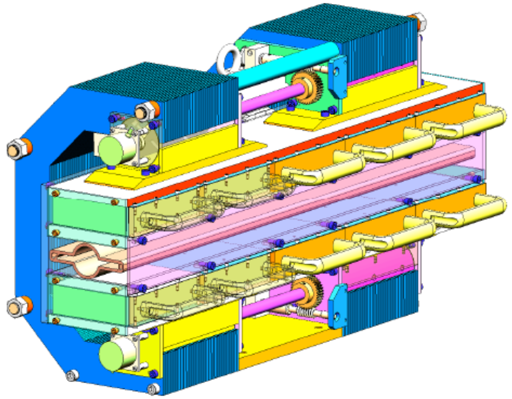
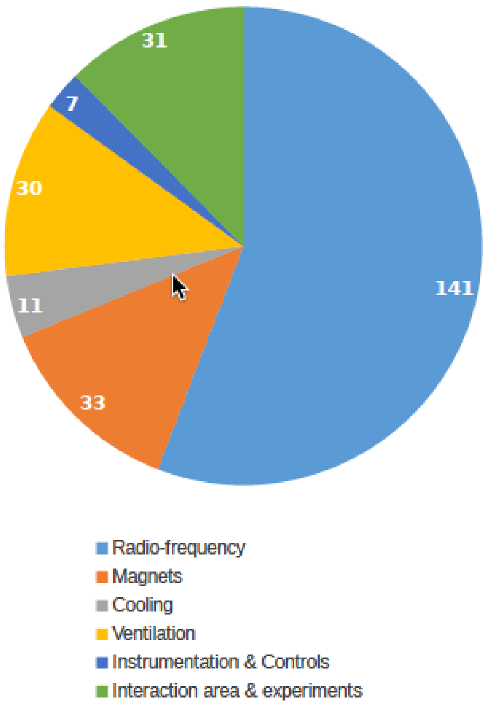


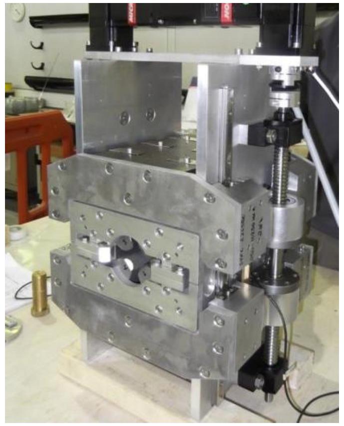
Figure 3: Overview of possible design of PM dipole for ILC damping ring.



HTS magnets might be of interests in all circular and linear Higgs factories to reduce 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.

For CLIC the dominant power is in the drive-beam quadrupoles, successfully prototyped and tested as permanent (two different strengths) magnets, and also dipoles (in drivebeam turn arounds)



Longitudinal gradient dipole magnet for the CLIC DR (CIEMAT)

doi:10.18429/JACoW-IPAC2018-MOPML048 CC-BY-3.0

Nanobeams

A very important part of increasing the energy efficiency of a collider is reducing the beamsizes at the collision point.

This involved optimisation of every part of the machine, from injectors to damping rings to main linacs/rings to beam-delivery/interaction point.

and covers in terms of design and technologies

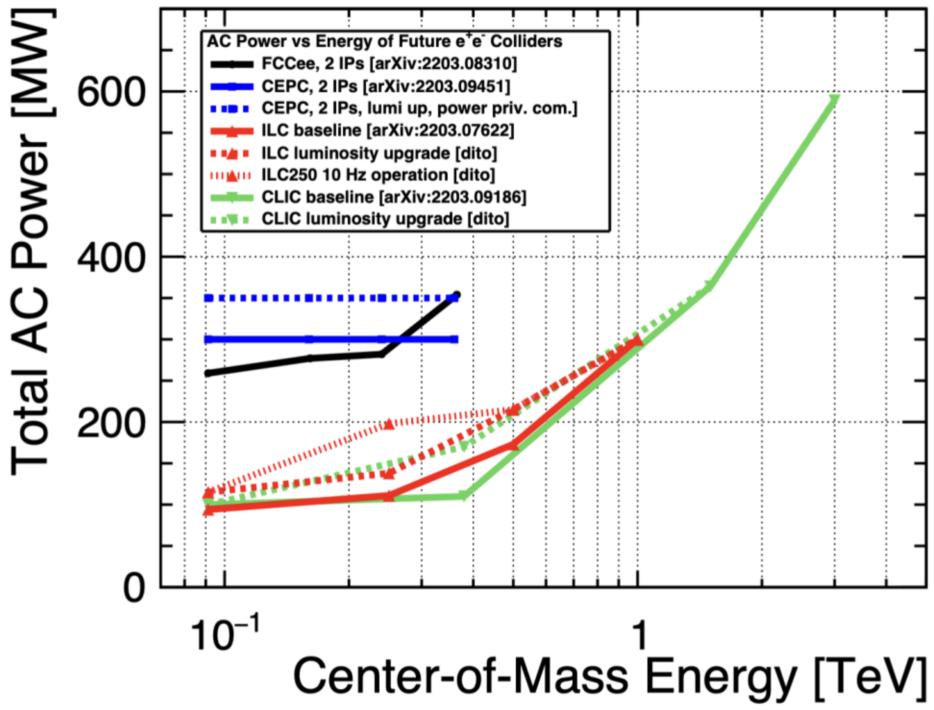
beam-dynamics, steering and feedback, precise instrumentation, alignment, stability (passive/active), injection, extraction, precise magnets, vacuum, studies of ground vibrations and stray-field, temperature control and more.

This has been extensively developed and prototyped in CLIC, ILC, FEL linacs, and as shown earlier are key studies in FCC-ee and CEPC.

Beyond studies and HW developments, test in beam facilities as ATF2, SuperKEKb, FACET, light sources and FEL linacs are essential.

From Power and Energy towards addressing other sustainability meeting

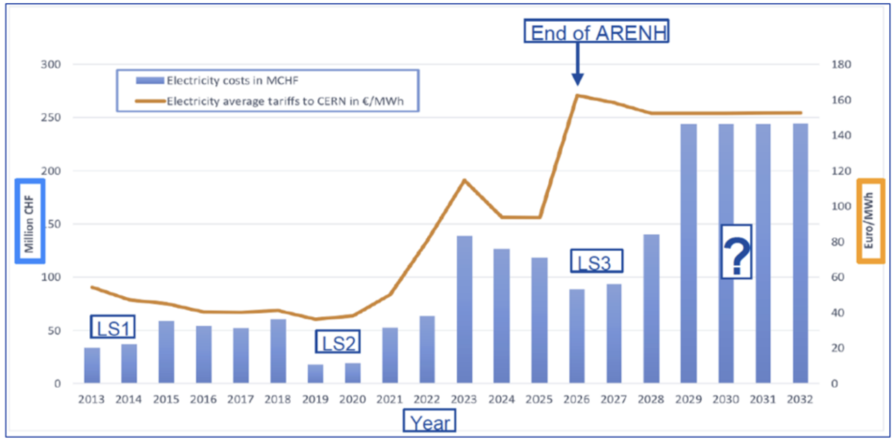
Power and energy



Typical power numbers for Higgs factories on the right – table also shown earlier

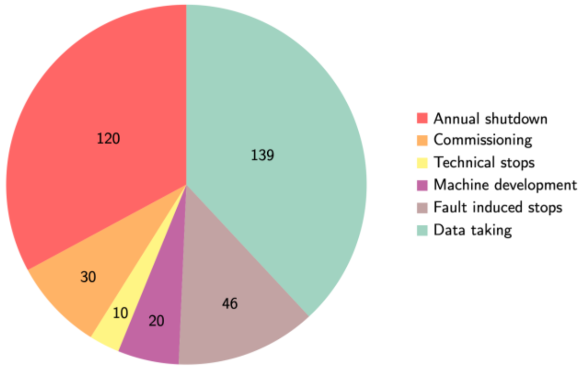
The CERN “standard” running scenario is shown below, used to convert to annual energy needs.

Extrapolating out to 2032 assuming: No ARENH and ”high” future electricity prices



Very uncertain but MTP assumes 140 MCHF/TWh beyond 2026.

With “standard” running scenario (on the right) every 100 MW corresponds to ~0.6 TWh annually, corresponding to ~85 MCHF annually.



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, availability 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)

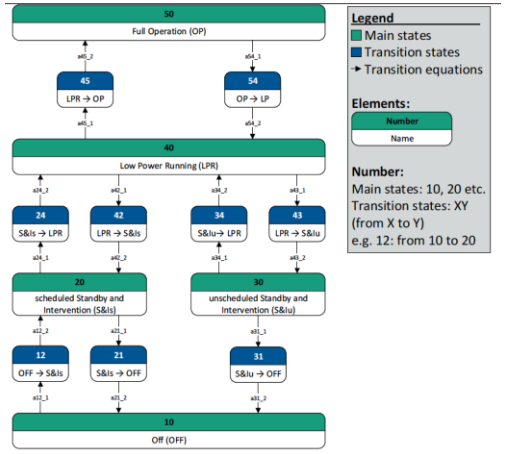
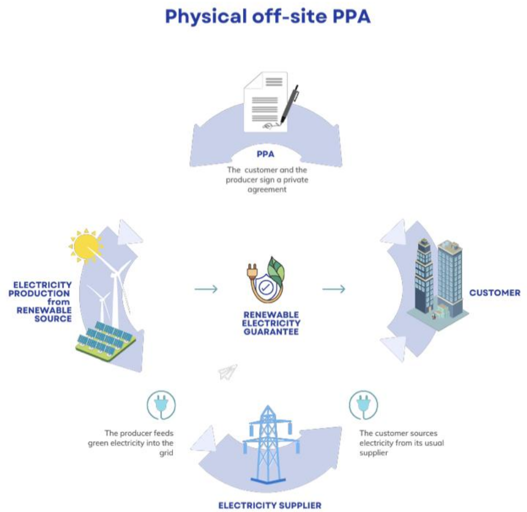


Figure 1-1: Schematic representation of the finite state machine



A real implementation of renewable energy supply:

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.

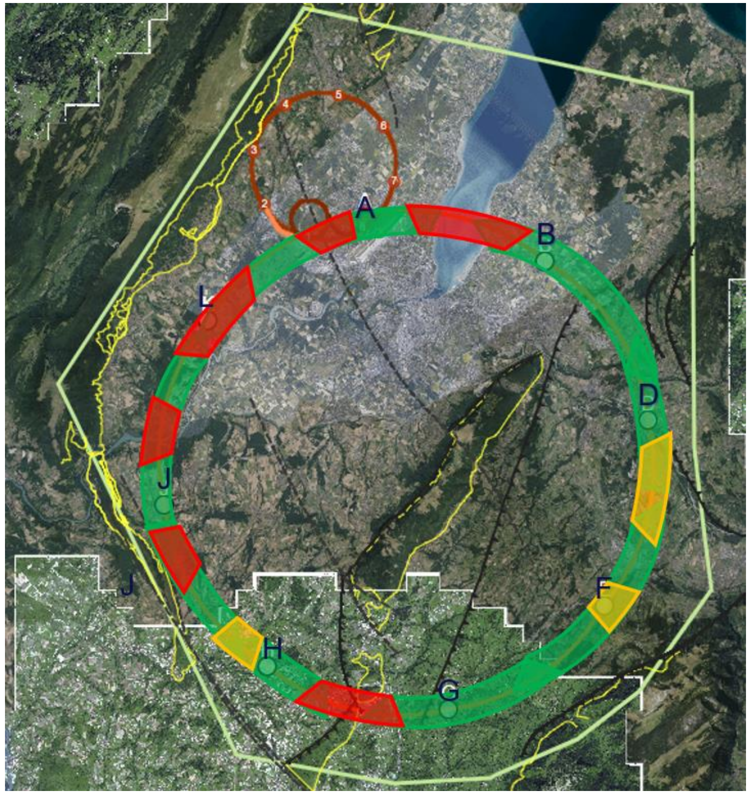
Nuclear energy remains very important, on the timescale of a future CERN facility maybe also: SMEs

— 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 (two slides back).

Integration in the area

FCC:

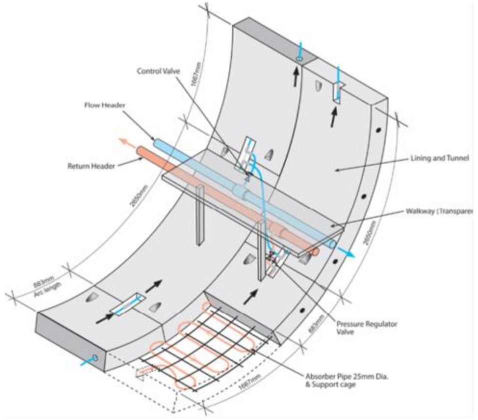
- Developing & confirming concrete implementation scenario, in collaboration with host state authorities, including environmental impact analysis

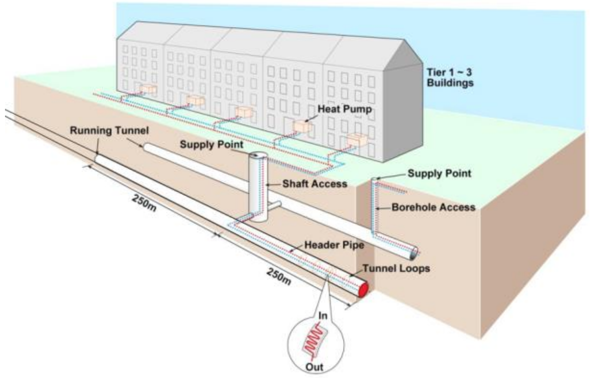


CERN generally:

Heat recovery: Already implemented in point 8 for LHC

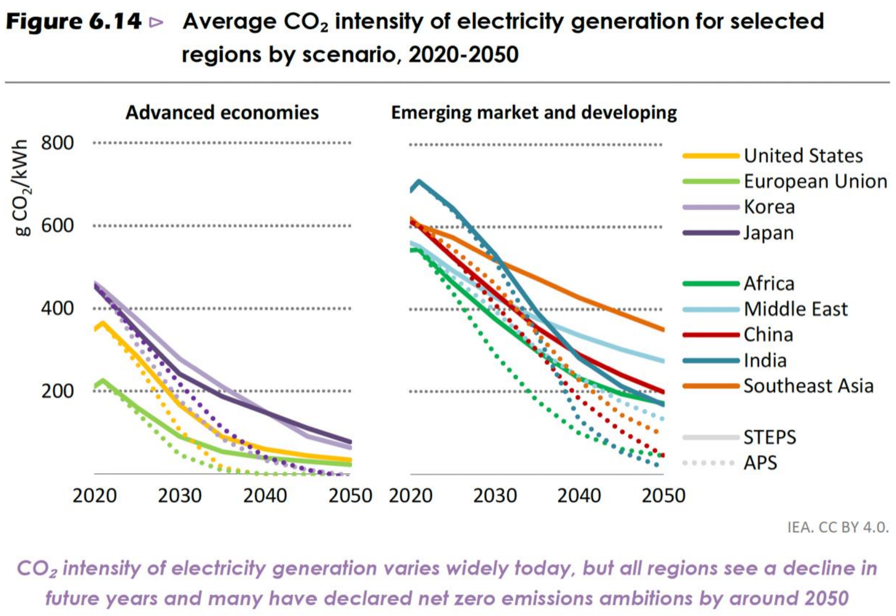
Tunnel heat recovery study by ARUP in 2022, results interesting but …

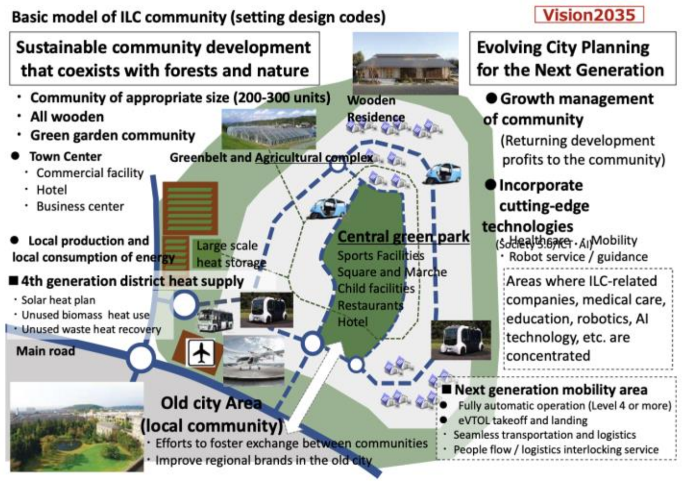




Sustainability during operation – proactivity

- Operation costs dominated by energy (and personnel, not discussed in the following)
- Reducing power use, and costs of power, will be crucial. Other consumables (gas, liquids, travels …) during operation need to be well justified. Align to future energy markets, green and more renewables, make sure we can be flexible customer and deal with grid stability/quality.
- Carbon footprint related to energy source, relatively low already for CERN (helped by nuclear power), expected to become significantly lower towards 2050 when future accelerators are foreseen to become operational (in Europe, US and Japan). Provided we can run on green mixtures (PPA example at CERN, also built fully into the green ILC concept) we can also contractually chose green options. LCs are very suited for this (variable power load).





For ILC: renewable energy available (Tohoku Electric Power) in local grid at ~23% level, need 0.5-1 % for ILC. Additionally considers increased CO2 absorption to be fully neutral.

A rough estimate, assuming ~50% nuclear and ~50% renewables (as wind/sun/hydro):

1 TWh annually equals ~12.5 ktons CO2 equiv. annually

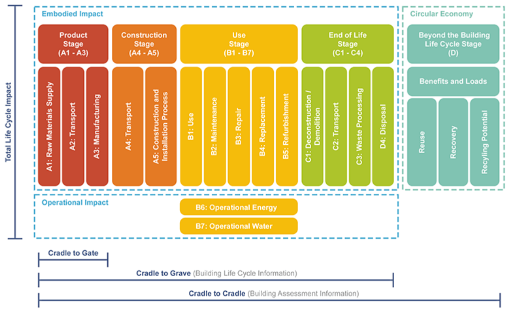
(note: this is factor four below the current French summer month average)

Sustainable Construction – Life Cycle Assessment

For carbon emission the construction impact will be much earlier and might be more significant (also rare earths and many other issues etc):

- Construction: CE, materials, processing and assembly – not easy to calculate
- Markets will push for reduced carbon, responsible purchasing crucial (see right) – construction costs likely to increase

Decommissioning – how do we estimate impacts ?



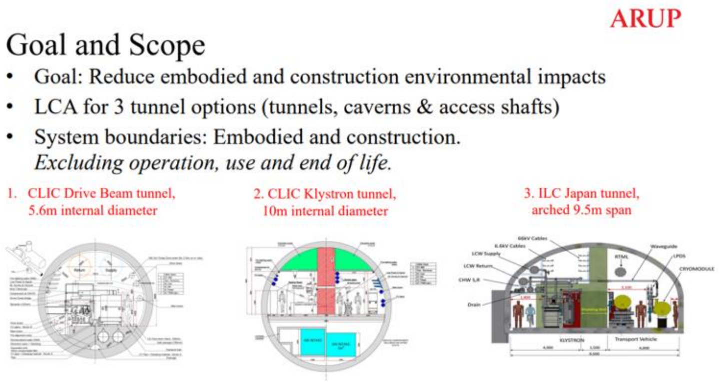
Assume a small tunnel (~5.6m diameter) **and** that the equipment in the tunnel has the same carbon footprint as the tunnel itself, a 20km accelerator (tunnel plus components) corresponds to 240 kton CO2 equiv.

Many caveats, this is only a very first indication of the scale:

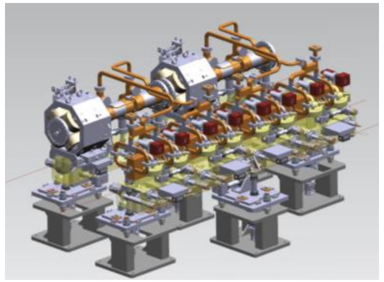
+ many more components in tunnel (also infrastructure), injectors, shafts, detectors, construction work, spoils, etc etc
+ upgrades and decommissioning, this is not only an initial important contribution
- improvement and optimisations (e.g. less and/or better concrete mixes, support structures, less steel in tunnels, responsible purchasing, etc etc)

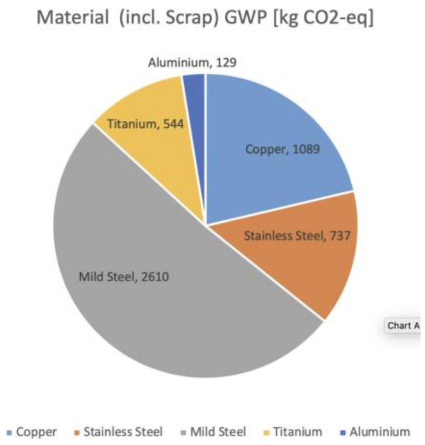
Responsible purchasing – and understanding the impact on our supply chain, costs and potential for changes – will be essentials for future projects (CERN implementation information from E.Cennini)

Carbon Cost/Life Cycle Assessment LCA study 2023



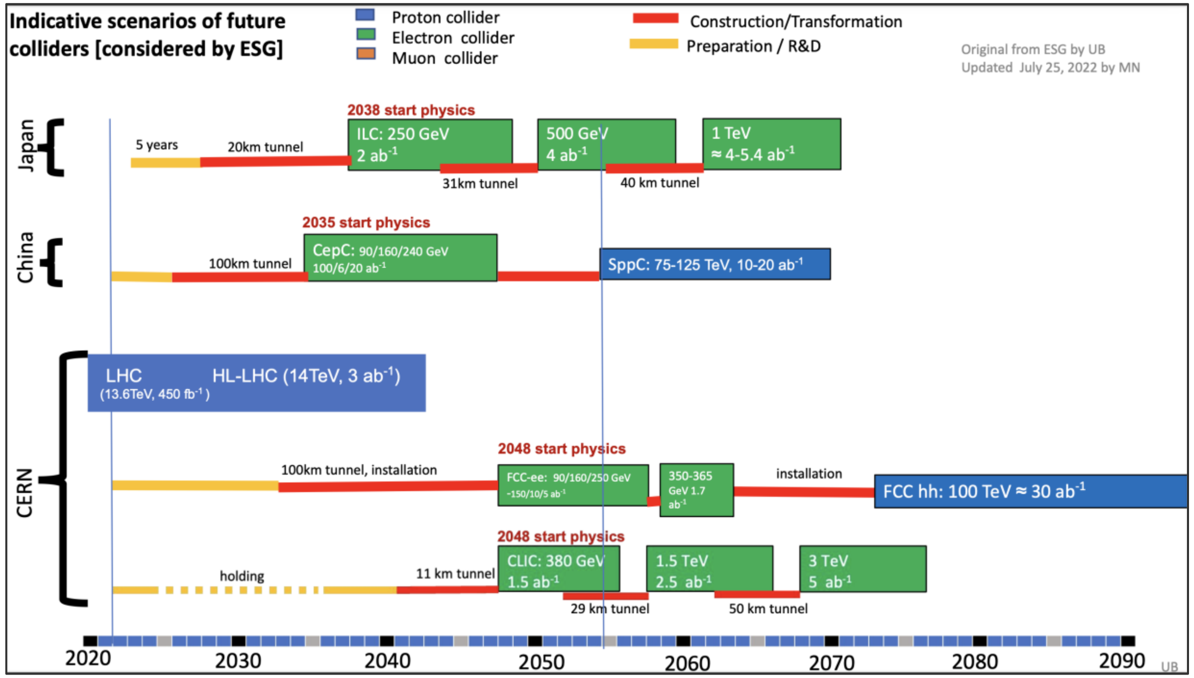
Quantity	DB	Klys.
Inner Diameter [m]	5.6	10
Tunnel Cross Section [m^2]	25	79
Lining / Grouting [cm]	30 / 10	45 / 15
Concrete Area [m^2]	12.4	44.8
Lining & Floor Area [m^2]	8.2	19.7
Concrete per m [t/m]	31	129
Steel per m [t/m]	0.95	2.3
Concrete GWP [t CO2-eq/m]	3.1	12.9
Steel GWP [t CO2-eq/m]	1.6	3.8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

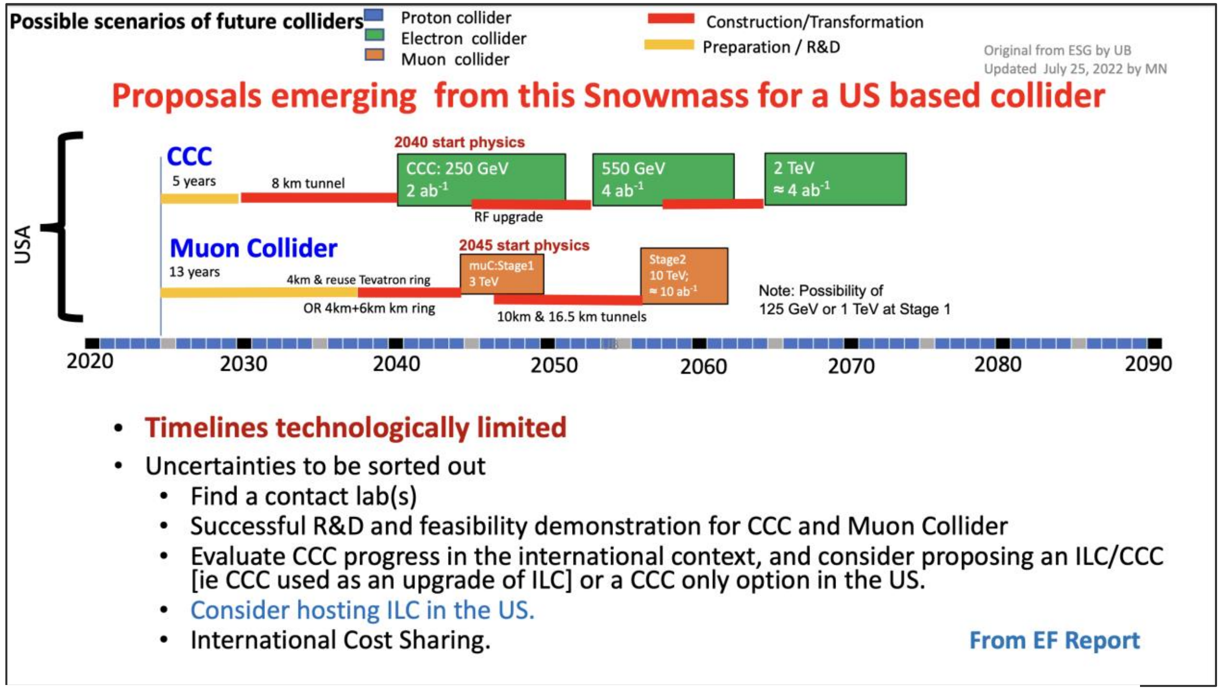




Talk by B.List (link)

Timelines in Snowmass Energy Frontier summary





Comments:

- Timelines are technologically limited – except for 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

Will not discuss the timelines here, but the construction comes a decade before operation, and it is also the area where the carbon emission is harder to reduce

Summary

Power efficiency, energy consumption and also carbon emission and other sustainability targets are today important drivers of accelerator development and R&D:

- Related to designs, new concepts and many technical developments
- Very large synergy across the entire field of accelerator science (small and large installations)
- Funding in many cases “encourages” this R&D

Important to be pro-active, anticipating the changes happening in the energy markets and society with respect to sustainability driven changes.
Important present our future projects are part of these changes and making use of these changes

- Power, energy efficiency at all levels
- Adapting to and using more renewables (increased availability of it, can be increased by contracts)
- Reducing carbon in construction from civil engineering to technical components
- Making use of materials, technologies and working with suppliers that are invested in these changes
- Integration in/with local areas, their infrastructure and development plans

There is a clear road towards more energy efficient and sustainable accelerators, some are more ambitious or easily adapted than others in this area, but all designs have and will continue to pursue this road.

There are also concern that implementing some of the changes above will increase costs. However not implementing them might well increase costs more.

No conclusions but
thanks – most of the slides/information from:

The Snowmass Implementation Task Force (names on page 2, chair T.Roser)
The eeFACT summary team (F.Zimmermann et al. – linked to Snowmass AF3 WG)
M.Benedikt, F.Peauger
T.Watson, R.Cunningham and J.Osborne
S.Michizono, B.List
W.Wuensch, I.Syratchev, S.Calatroni
D.Schulte
E.Nanni
J.D'Hondt
L.Rossi
M.Giovannozzi
Y.Li, J.Gao
N.Bellegarde, E.Cennini
M.Narain
more
….

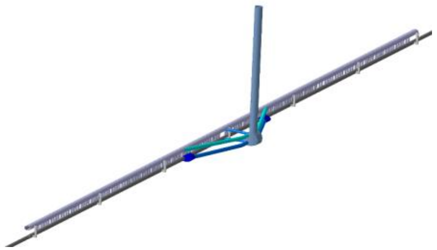
home.cern

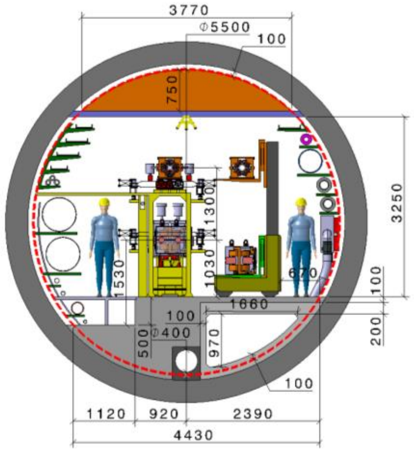
FCC

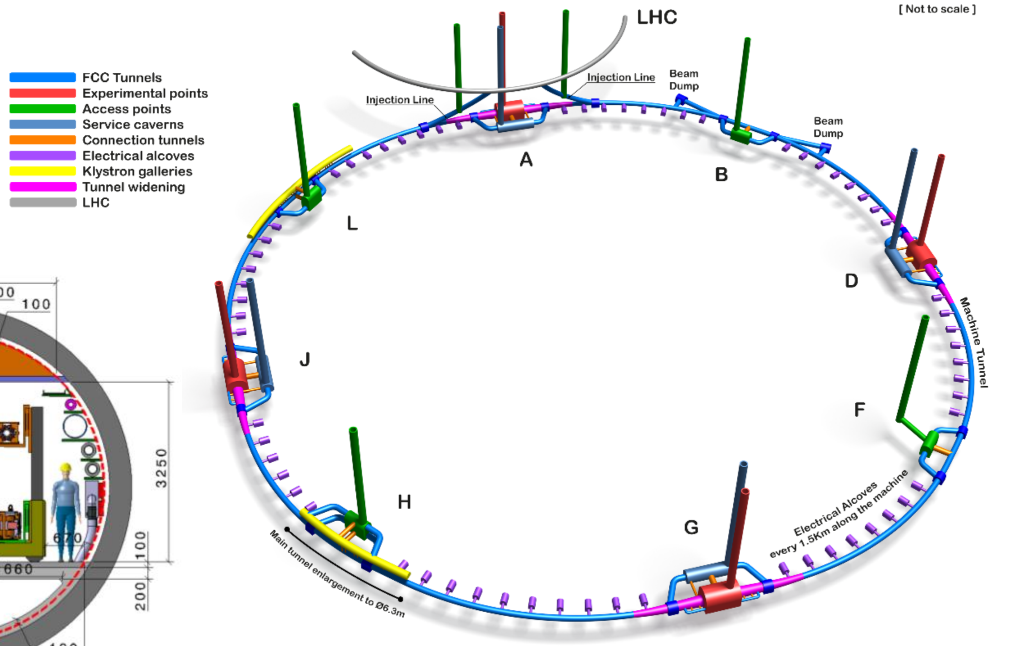
Main activities:

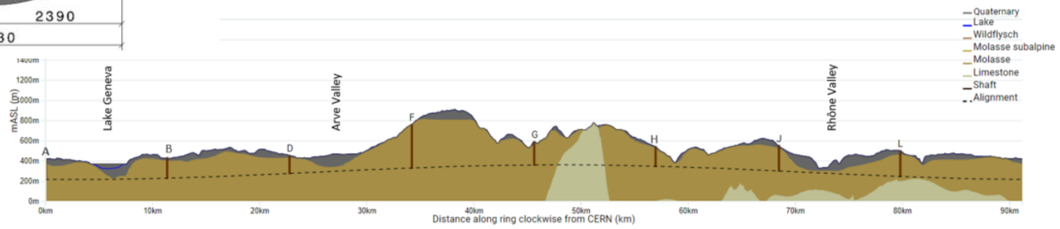
- Developing & confirming concrete implementation scenario, in collaboration with host state authorities, including environmental impact analysis
- Machine optimization and technology R&D (examples next slide)
- Physics studies
- Global collaboration, supported by the EC H2020 Design Study FCCIS and Swiss CHART.
- Goals:
  - Demonstrate feasibility by 2025/2
  - Next milestone is the mid-term review, October 2023
  - CE Cost & construction schedule underway

Material from: PECFA (Benedikt), SCE (Watson, Cunningham, Osborne) – slides, FCC week (Peauger) 2022









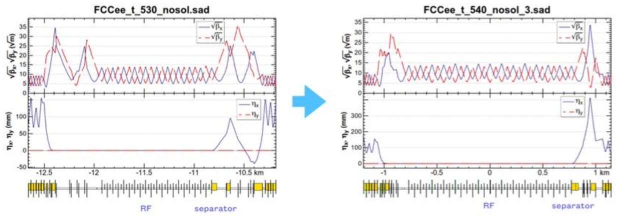
Progress on underground design

- 90.6km alignment, PA31-3.0
- Integration studies (klystrons, alcoves, caverns, beam dump)
- 8 point baseline design frozen
- Excavated materials study

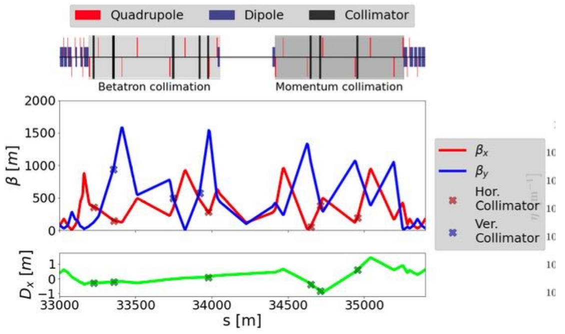
Some examples of design and technical studies

Beam optics developments (examples)

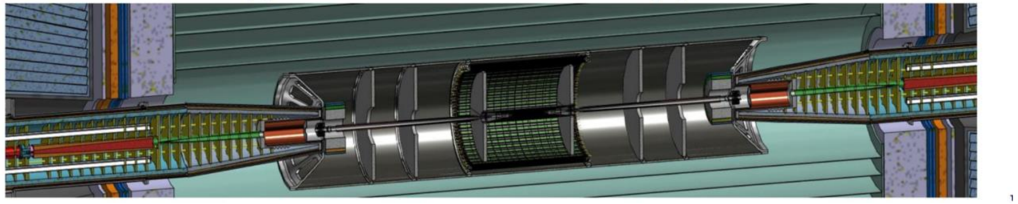
Points B, F, H & L (RF and other technical straights)

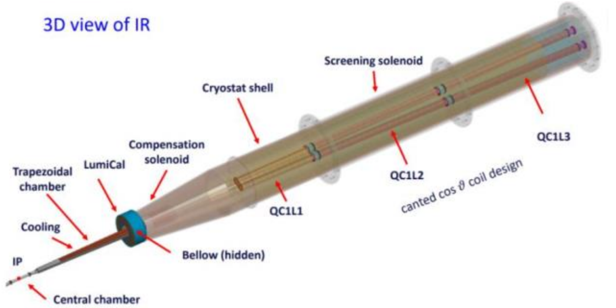


New collimation optics for 4 IPs



Novel outer support tube for central beam pipe and vertex detector

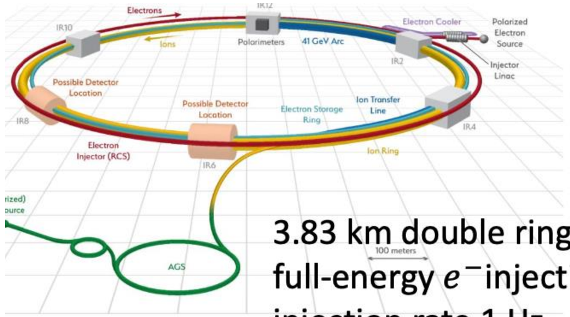




FCC-ee MDI examples, also studies of ID heat load distribution and beamstrahlung dump

US EIC Electron Storage Ring similar to FCC-ee with beam parameters almost identical, but twice the maximum electron beam current, or half the bunch spacing, and lower beam energy.

>10 areas of common interest identified by the FCC and EIC design teams, addressed through joint EIC-FCC working groups, still evolving.



3.83 km double ring, full-energy e^- injection, injection rate 1 Hz, every 2 min into same bucket

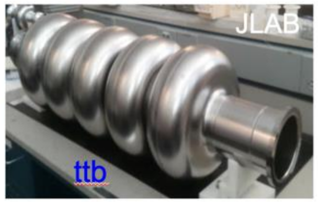
400 MHz 1-cell cavities

Nb/Cu

400 MHz 2-cell cavities

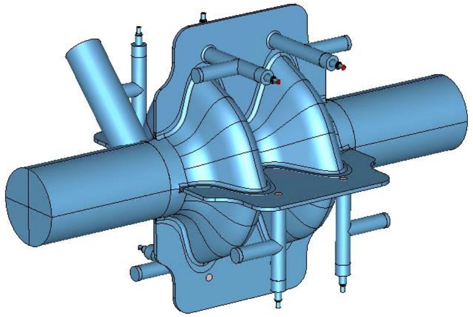
Nb/Cu

2-cell is better for W working point (reduced RF power per cav., improved HOM damping)



800 MHz 5-cell cavities

Bulk Nb



Baseline left

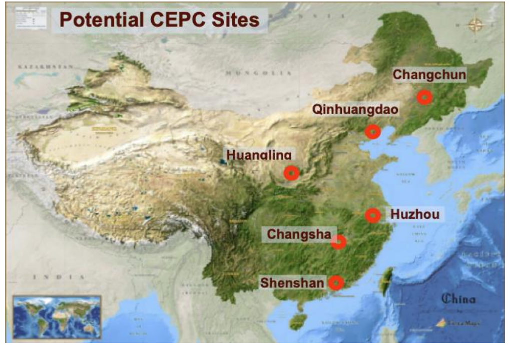
Right: Swell 2-cell 600 MHz cavity for Z, W, H

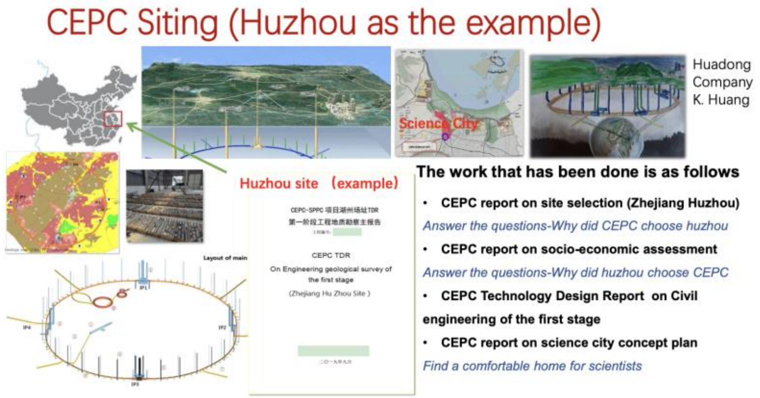
Very interesting **alternative cavity** option which would cover three machines (no need to remove cryomodules after operation at Z)

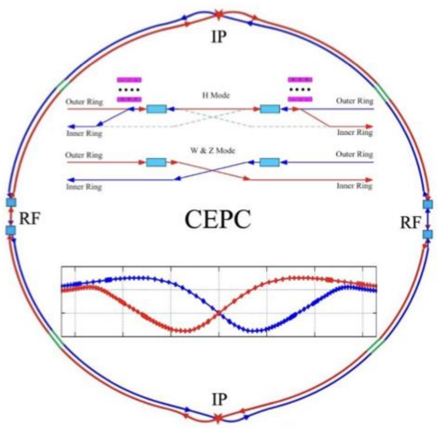
Highly damped RF cavity for transverse HOMs thanks to four waveguide slots and coaxial RF lines

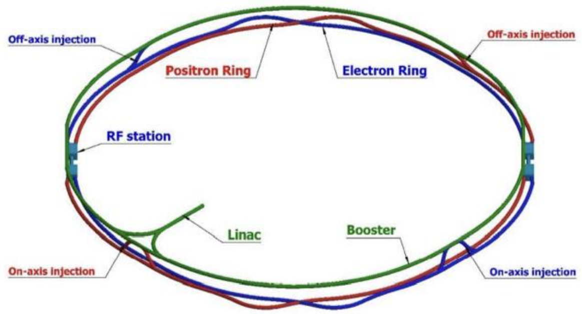
CEPC

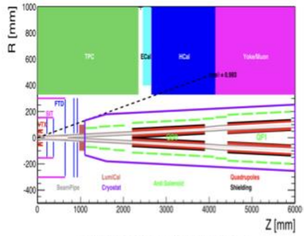
- The CEPC CDR was released in 2018. Since then, extensive technology R&D has been carried out, as well as design and luminosity optimization
- CEPC-TDR is planned to be finished in early 2023, review in June this year
- A three-year EDR phase is planned after TDR
- The accelerator construction is scheduled to be started in the 15th five-year-plan (2026-30)
- The CEPC aims to start operation in 2030s, as a Higgs (Z/W) factory

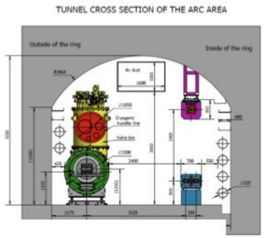


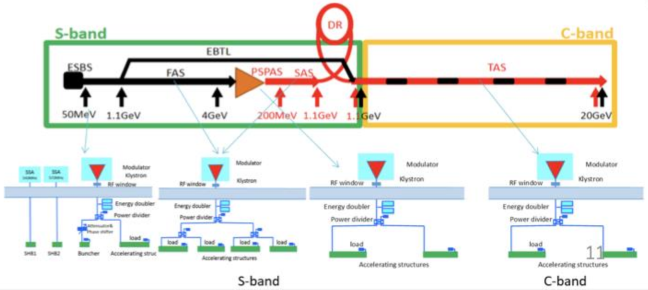












- **CEPC as a Higgs Factory**
- **Upgradable to 50 MW**
- **Upgradable to High Lumi. Z & ttbar**
- **Compatible to SPPC**

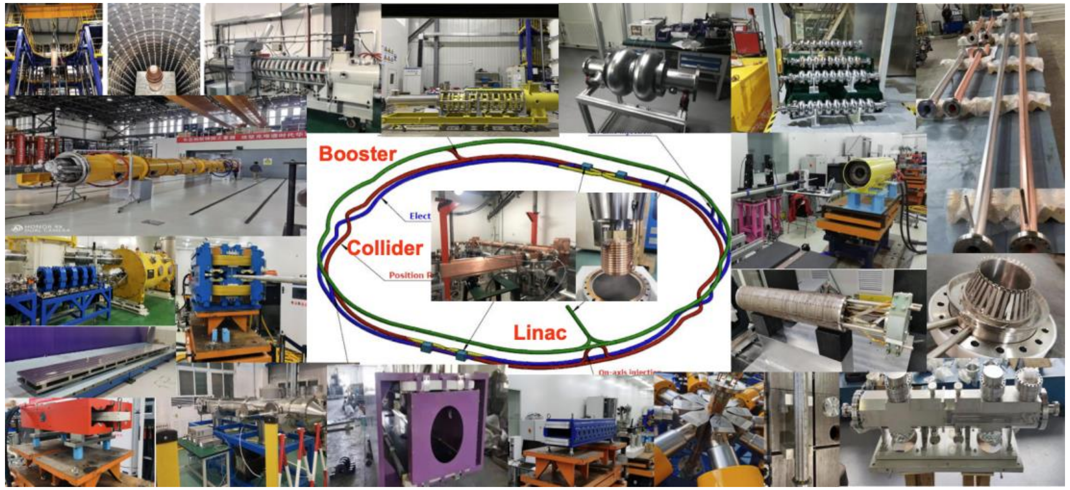
Six sites studied.
Funding model now considered is 2/3 from region, making regional interest more important, and 1/3 central government, which is more in line with other previous science projects in China

Information mostly from
Yuhui Li and Jie Gao

CEPC prototyping

CEPC key technology R&D

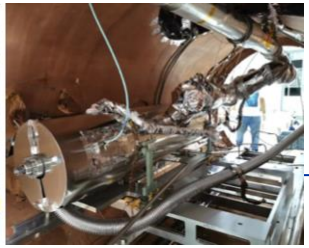
Technology	Category	Quantity	Specification	R&D Status
650MHz 1 cell SRF cavity	Collider	240	Q= 3E10 @ 39.3 MV/m	Q= 6.3E10 @ 31 MV/m
650MHz 2 cell SRF cavity	Collider	240	Q= 4E10 @ 22 MV/m	Q= 6E10 @ 22 MV/m
1.3GHz SRF cavity	Booster	96	Q=3E10 @ 24 MV/m	Q= 4.3E10 @ 31 MV/m
650MHz high efficiency Klystron	Collider	120	Efficiency:75%; Power:800kW	Efficiency: ~70%; Power: 600kW
Electrostatic deflector	Collider	32	Electro field: 2.0MV/m; stability: 5 x 10-4; good field range: 46mm x 11mm	Prototype fulfill the specification
C-band RF cavity	Linac	292	45MV/m	2-m prototype engineered, waiting for high power test
Cool Copper RF cavity (C-band)	Linac	/	120MV/m	Physical design finished, in the manufacture process
Positron source FLUX concentrator	Linac	1	Center field>6T	Center field: 6.2T
Dual aperture dipole	Collider	2384	Field strength: 140Gs~560Gs, aperture:70mm; length: 28.7m in 5 segments; harmonic component <5×10-4; fields difference <0.5%	All specifications are satisfied in the 1-m prototype; full length prototype in manufacture
Dual aperture qudrupole	Collider	2392	Field gradient: 3.2~12.8T/m; length: 2m, aperture: 76mm; harmonic component <5×10-4; field difference<0.5%。	Preliminary measurement in the prototype shows prominent results, more test in process
Weak field dipole	Booster	16320	Field error <1E-3@60Gs	Prototype fulfills the specifications
Visual alignment device	All	11	Pixel position accuracy 5μm+5μm/m; angular accuracy: (h) 1.8”, (v) 2.2”;	Prototype manufactured, in test
Superconducting high field dipole magnet	SPPC	/	20T	12T



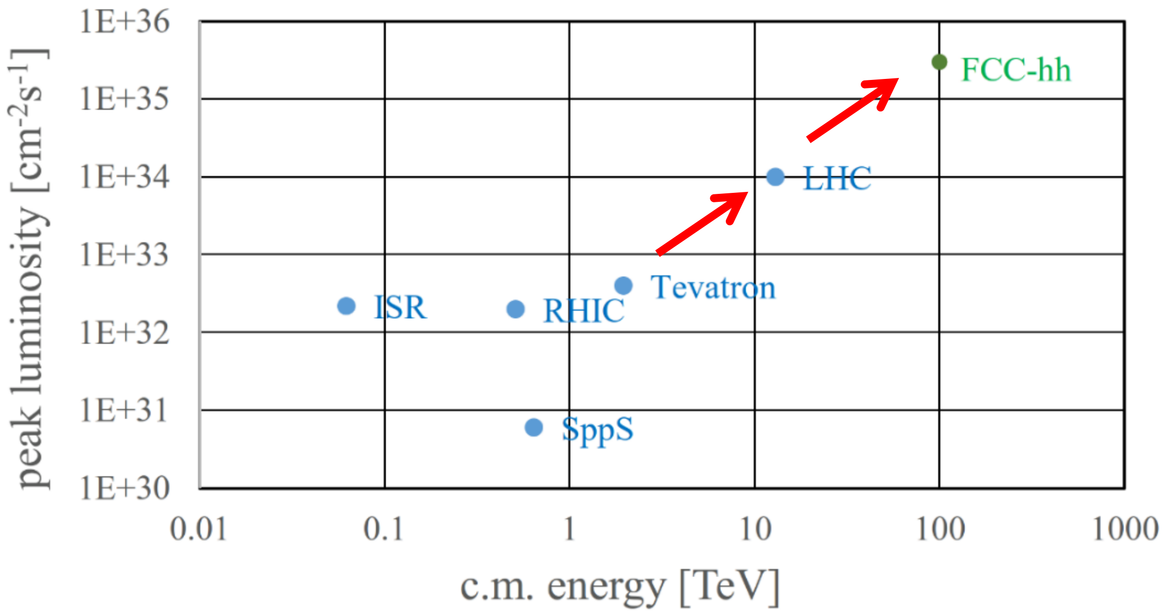
key technologies developed in other projects

Technology	Category	Quantity	Specification	R&D Status
2860MHz klystron	Linac	35	Power: 80MW Efficiency: 55%	Power: 65MW Efficiency: 42%
Advanced S-band cavity	Linac	111	30MV/m	HEPS production fulfill CEPC specifications
Single aperture Mag	D(160)+Q(960)+S(1864)+Corr.(5808)	/	/	HEPS production fulfill CEPC specifications
BPM & electronics	All	~5000	Spatial resolution: 600nm response frequency:10Hz	Spatial resolution: 100nm response frequency:10Hz
Cryogenic machine	Collider/booster	4	18kW@4.5K	2.5kW@4.5K collaboration with CAS
kicker ceramic vacuum chamber and coating	transport line	/	75x56x5x1200mm	Prototype in manufacture
in-air delay-line dipole kicker & pulser	transport line	/	Trapezoid pulse width=440-2420ns,1kHz	Design completed
in-air delay-line nonlinear kicker & pulser	transport line	/	Trapezoid pulse width=440-2420ns,1kHz	Design completed
strip-line kicker & fast pulser	transport line	/	pulse width<10ns, 20kV into 50Ω	HEPS devices fulfill specifications
slotted-pipe kicker & fast pulser	transport line	/	Trapezoid pulse width≤250ns	HEPS devices fulfill specifications
in-air Lambertson septa	transport line	/	septum thickness≤3.5mm	HEPS devices fulfill specifications
in-vacuum Lambertson septa	transport line	/	septum thickness≤2mm	HEPS devices fulfill specifications
Electric source	All	9294	Stability: 100-1000ppm; accuracy: 0.1%	HEPS devices fulfill specifications
Vacuum chamber &NEG coating	collider	~200km	Length: 6000mm; aperture: D56mm vacuum: 3 × 10[illegible] Torr NEG film H_2 pumping speed: 0.5 L/s·cm²	Prototype fulfill specifications
Vacuum bellow	collider/booster	24000/12000	Force 125±25 g/finger;	HEPS devices fulfill specifications
Vacuum gate valves	All	1040	Leakage: 1×10[illegible] mbar·L/s @ 5000 times	Life time: 100



FCC-hh: highest collision energies



Order of magnitude performance increase in energy & luminosity

100 TeV cm collision energy (vs 14 TeV for LHC)

20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)

similar performance increase as from Tevatron to LHC

Key technology: high-field magnets

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [mm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

Detailed documentation from the ESPP: http://fcc-cdr.web.cern.ch, and more recent talk in the 2022 FCC week: LINK (Giovannozzi)

SPPC

SppC Collider Parameters in TDR

-Parameter list (updated Feb. 2022)

Jingyu Tang
Haocheng Xu

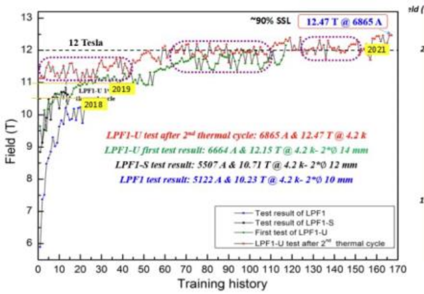
Main parameters		
Circumference	100	km
Beam energy	62.5	TeV
Lorentz gamma	66631	
Dipole field	20.00	T
Dipole curvature radius	10415.4	m
Arc filling factor	0.780	
Total dipole magnet length	65442.0	m
Arc length	83900	m
Total straight section length	16100	m
Energy gain factor in collider rings	19.53	
Injection energy	3.20	TeV
Number of IPs	2	
Revolution frequency	3.00	kHz
Revolution period	333.3	μs
Physics performance and beam parameters		
Initial luminosity per IP	4.3E+34	$cm^{-2}s^{-1}$
Beta function at initial collision	0.5	m
Circulating beam current	0.19	A
Nominal beam-beam tune shift limit pe	0.015	
Bunch separation	25	ns
Bunch filling factor	0.756	
Number of bunches	10080	
Bunch population	4.0E+10	
Accumulated particles per beam	4.0E+14	

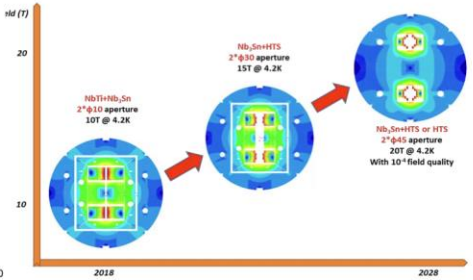
Normalized rms transverse emittance	1.2	μm
Beam life time due to burn-off	8.1	hour
Turnaround time	2.3	hour
Total cycle time	10.4	hour
Total / inelastic cross section	161	mbarn
Reduction factor in luminosity	0.81	
Full crossing angle	73	μrad
rms bunch length	60	mm
rms IP spot size	3.0	μm
Beta at the 1st parasitic encounter	28.625	m
rms spot size at the 1st parasitic encoun	22.7	μm
Stored energy per beam	4.0	GJ
SR power per ring	2.2	MW
SR heat load at arc per aperture	26.3	W/m
Critical photon energy	8.4	keV
Energy loss per turn	11.40	MeV
Damping partition number	1	
Damping partition number	1	
Damping partition number	2	
Transverse emittance damping time	0.51	hour
Longitudinal emittance damping time	0.25	hour

Ecm=125TeV with dipole field of 20T

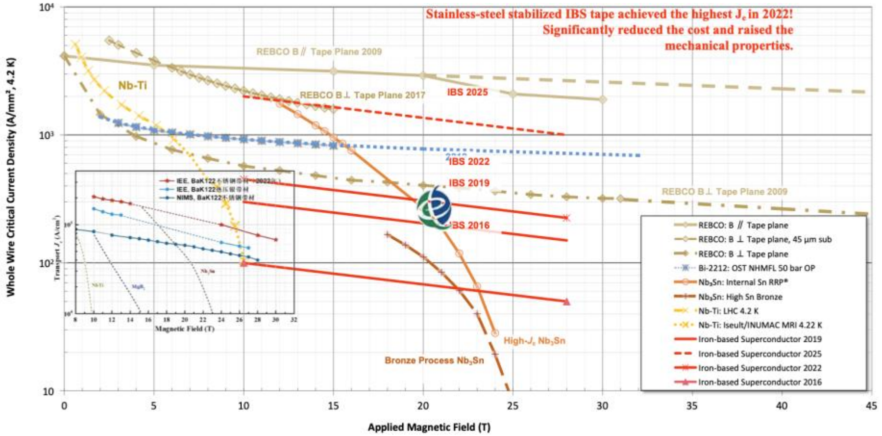
Recent focus on:
- Compatibility with CEPC
- Lattice design
- HFM developments

Picture of LPF1-U

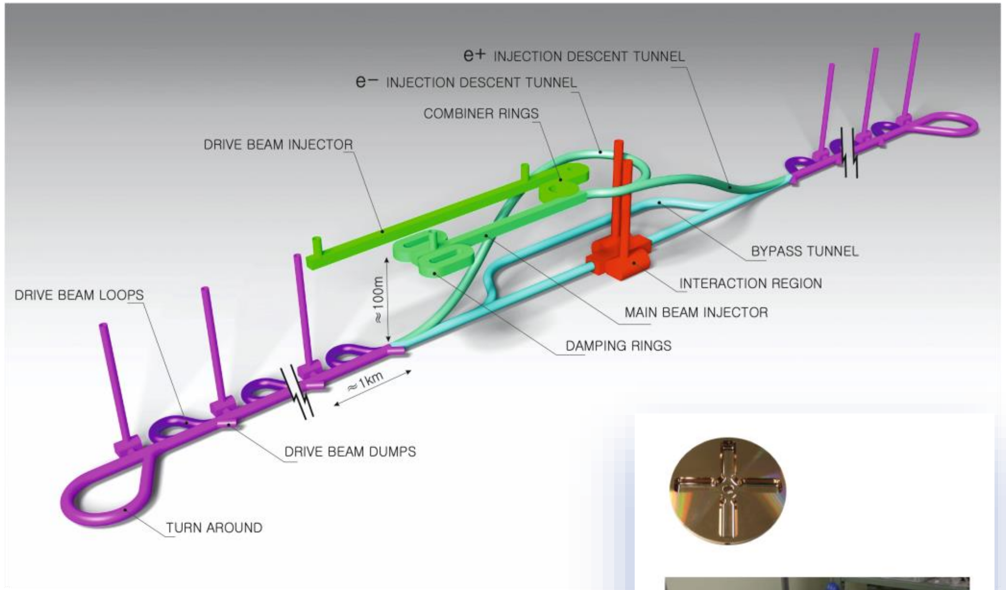


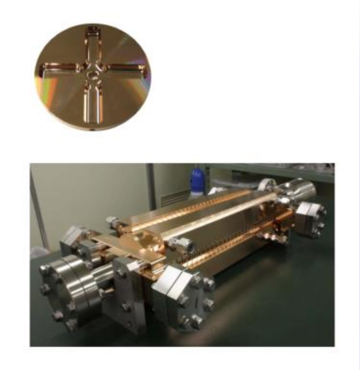


Dual aperture superconducting dipole achieves 12.47 T at 4.2 K
Entirely fabricated in China. The next step is reaching 16-19T field



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.

Recent talks (with more references): eeFACT1 and eeFACT2

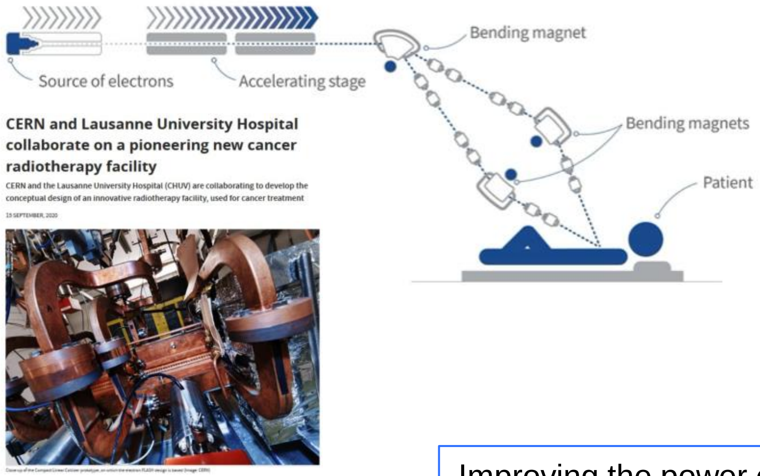
The CLIC accelerator studies are mature:

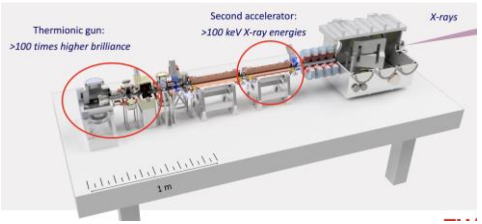
- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of "all" key elements

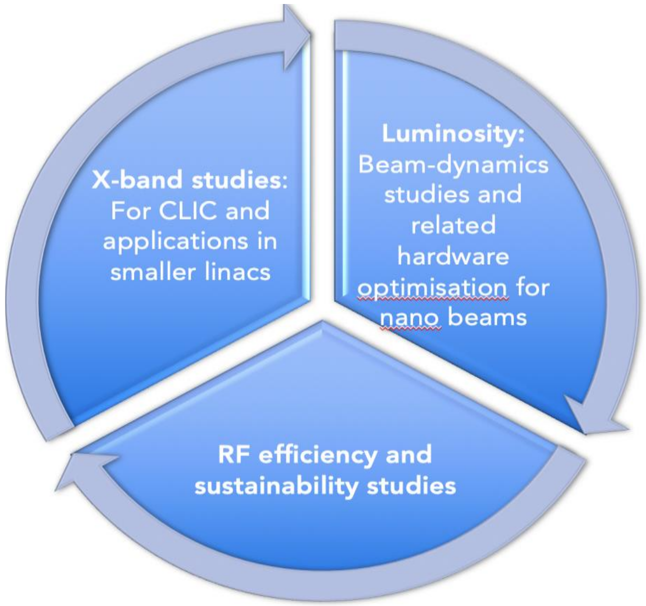
On-going CLIC studies towards next ESPP update

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

The X-band technology readiness for the 380 GeV CLIC initial phase - more and more driven by use in small compact accelerators







Optimizing the luminosity at 380 GeV – already implemented for Snowmass paper, further work to provide margins will continue.

Luminosity margins and increases:

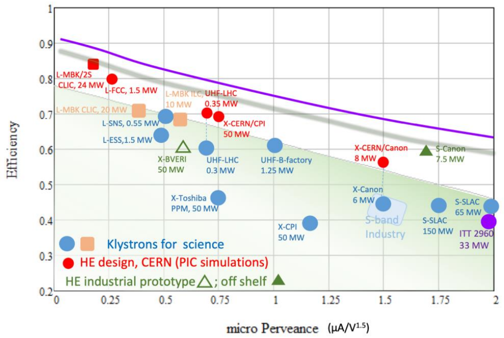
- Initial estimates of static and dynamic degradations from damping ring to IP gave: 1.5 x 10^{34} cm^{-2} s^{-1}
- Simulations taking into accord static and dynamic effects with corrective algorithms give 2.8 on average, and 90% of the machines above **2.3 x 10^{34} cm^{-2} s^{-1}** (this is the value currently used)

Improving the power efficiency for both the initial phase and at high energies, including more general sustainability studies

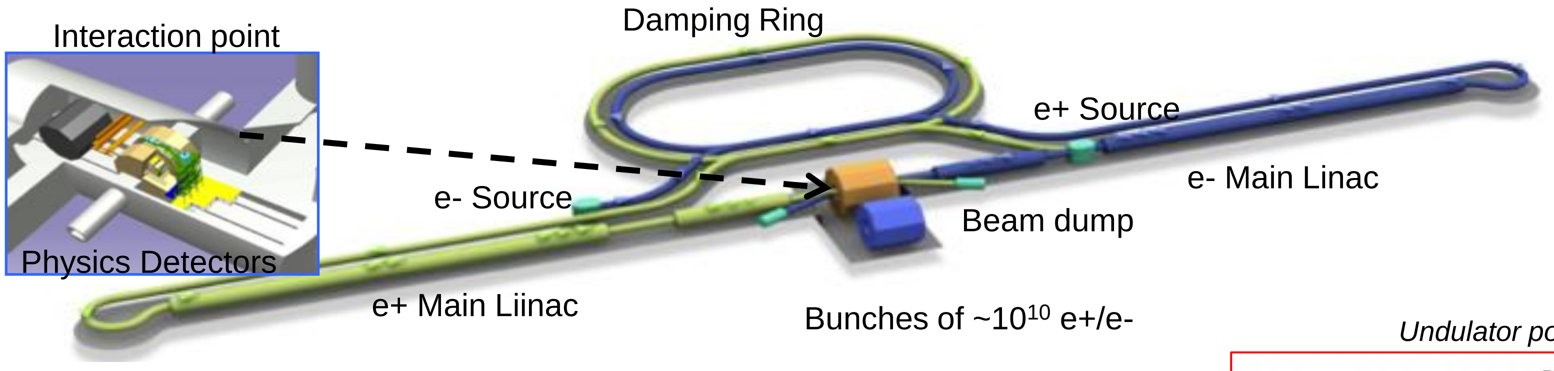
Power estimate bottom up (concentrating on 380 GeV systems)

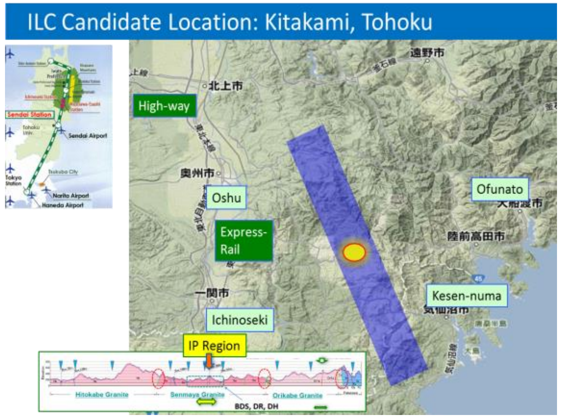
- Very large reductions since the CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimized, main target damping ring RF significantly reduced, recent L-band klystron studies

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

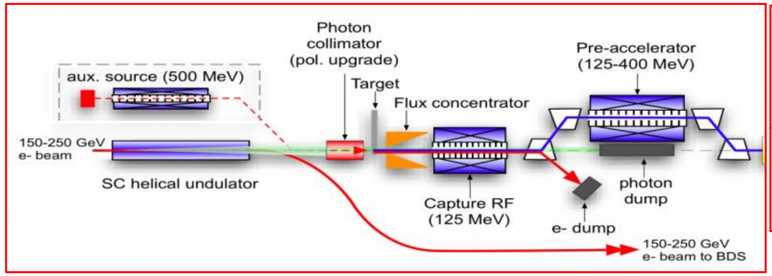


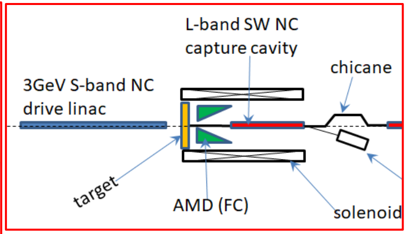
The ILC250 accelerator facility





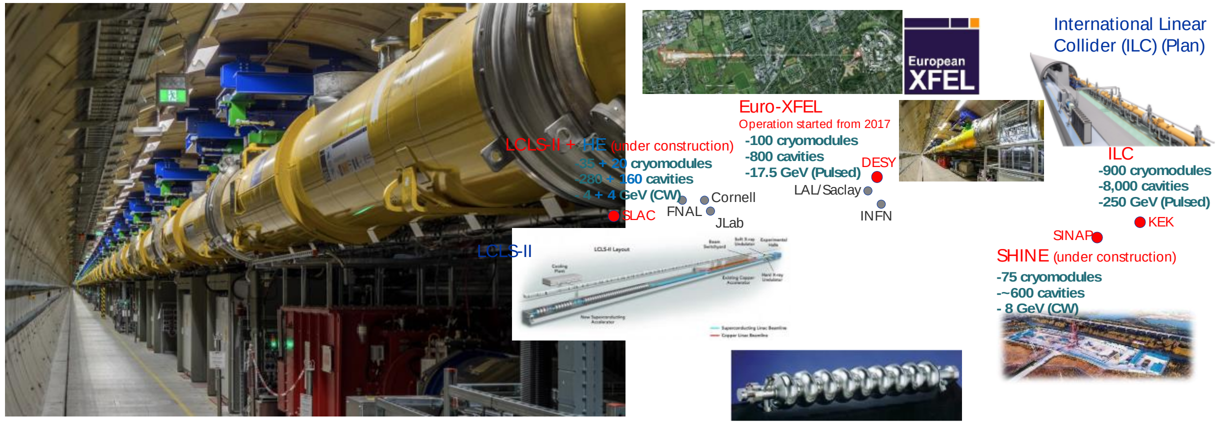
Undulator positron source





Electron driven positron source

- Creating particles — Sources
  - polarized elections/positrons
- High quality beam — Damping ring
  - low emittance beams
- Acceleration — Main linac
  - superconducting radio frequency (SRF)
- Collide them — Final focus
  - nano-meter beams
- Go to — Beam dumps



Recent talks (with more references): eeFACT-I1 and eeFACTI2

Technical work in progress – European focus

Recent progress:
A subset of the technical activities of the full ILC preparation phase programme have been identified as critical. Moving forward with these is being supported by the MEXT (ministry) providing increased funding.
European ILC studies, distributed on five main activity areas, is foreseen to concentrate (for the accelerator part) on these technical activities :

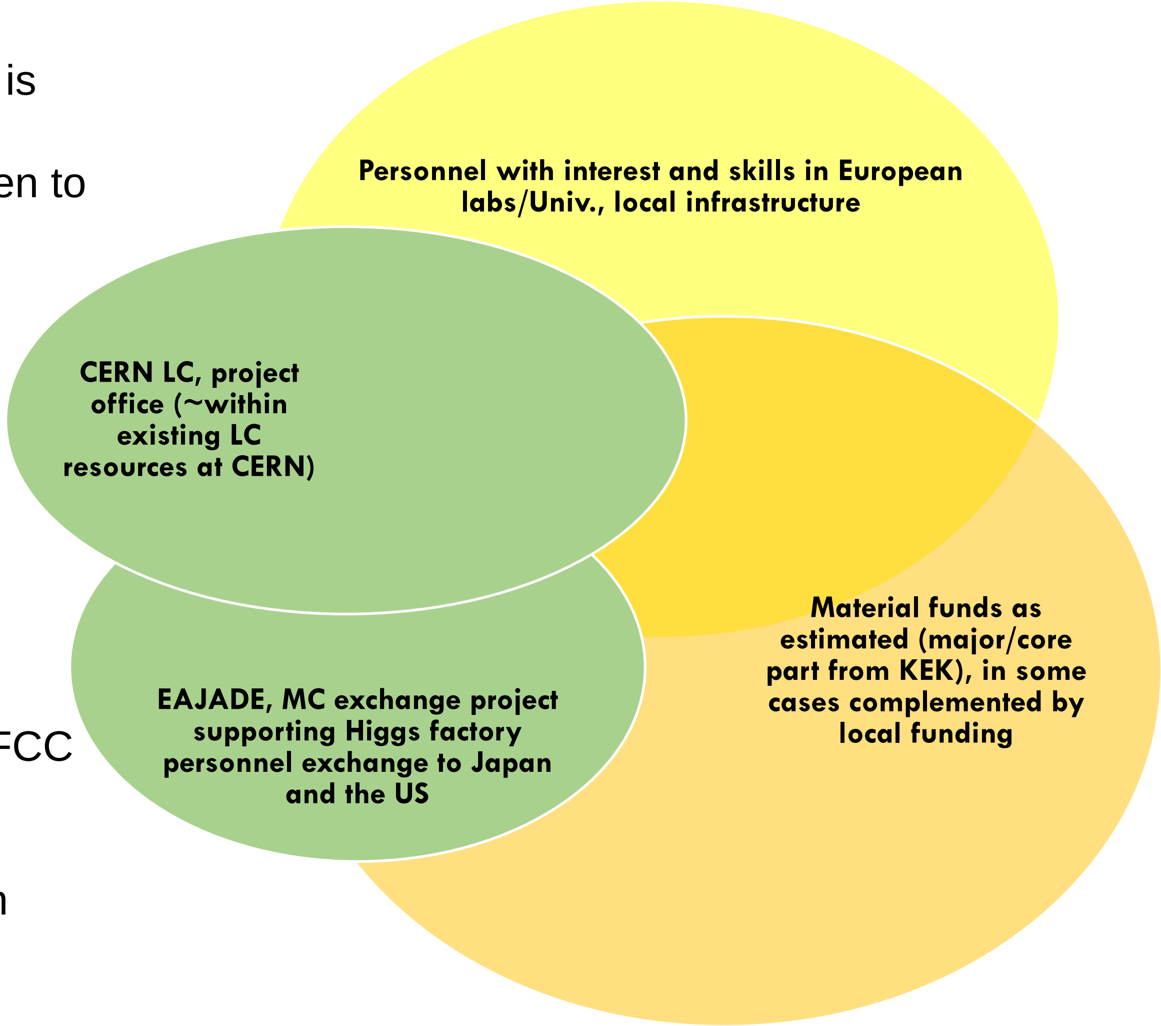
A1 with three SC RF related tasks
- SRF: Cavities, Module, Crab-cavities

A2 Sources
- Concentrate on undulator positron scheme – fast pulses magnet, consult on conventual one (used by CLIC and FCC-ee)

A3 Damping Ring including kickers
- Low Emittance Ring community, and also kicker work in CLIC and FCC

A4 ATF activities for final focus and nanobeams
- Many European groups active in ATF, more support for its operation expected using the fresh funding

A5 Implementation including Project Office
- Dump, CE, Cryo, Sustainability, MDI, others (many of these are continuations of on-going collaborative activities)



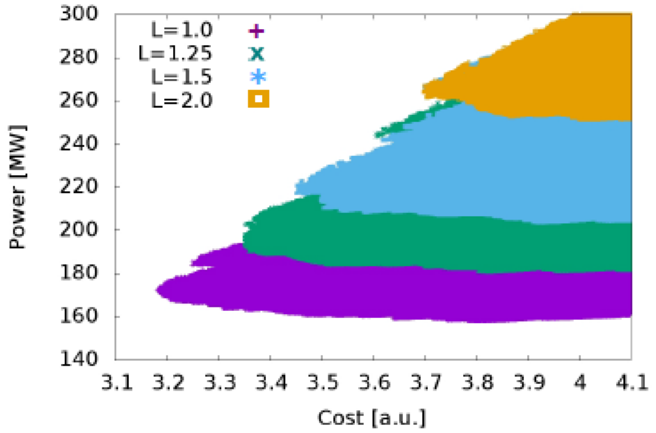
EAJADE: Information at [LINK]

Power optimization – examples

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

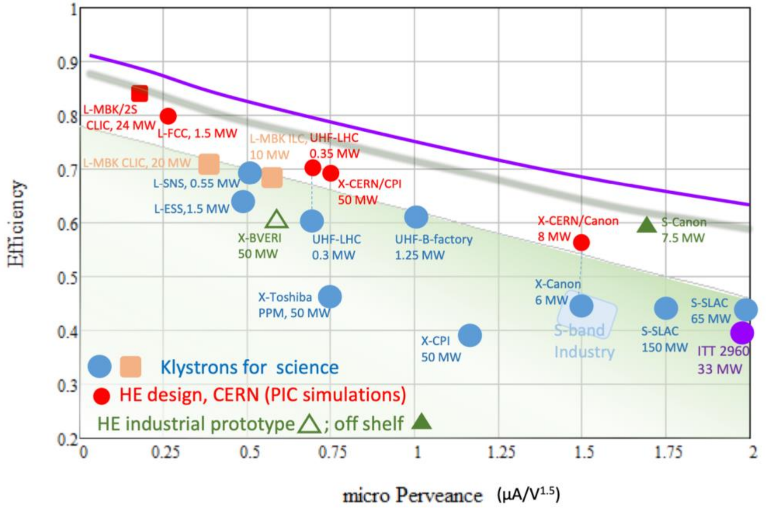
Technical Developments:
Technical developments targeting reduced power consumptions at system level high efficiency klystrons and RF systems generally, RF cavity design and optimisation, magnets (traditional SC and HTS including cryo, and also permanents magnets).

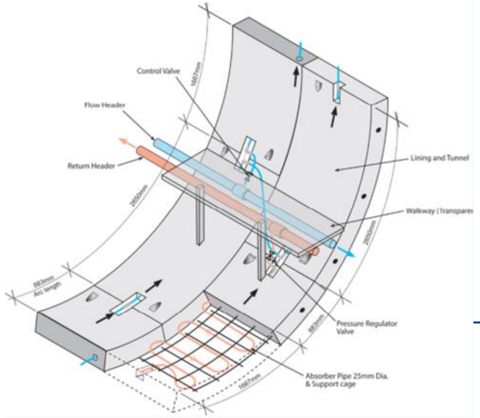
Heat recovery:
Already implemented in point 8 for LHC
Tunnel heat recovery study by ARUP in 2022, results interesting but …

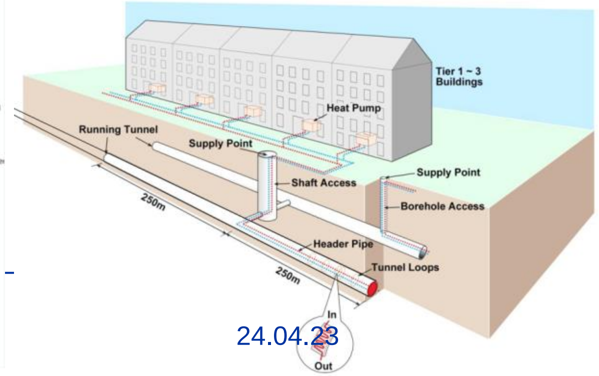


Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum

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







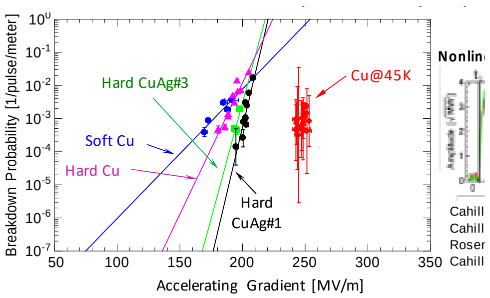
C3 Accelerator Complex

8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

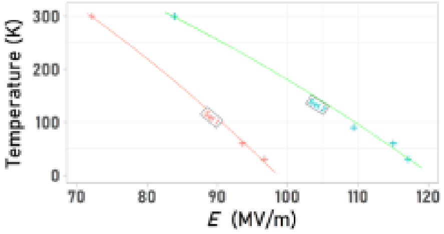
- 7 km footprint at 155 MeV/m for 550 GeV CoM – present Fermilab site

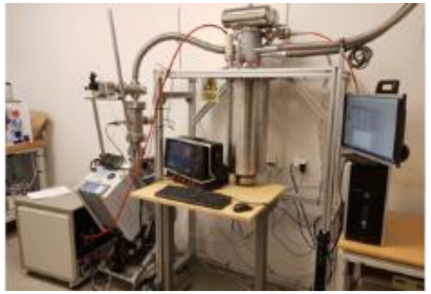
Large portions of accelerator complex are compatible between LC technologies

- Beam delivery and IP modified from ILC (1.5 km for 550 GeV CoM)
- Damping rings and injectors to be optimized with CLIC as baseline
- Reliant on work done by CLIC and ILC to make progress

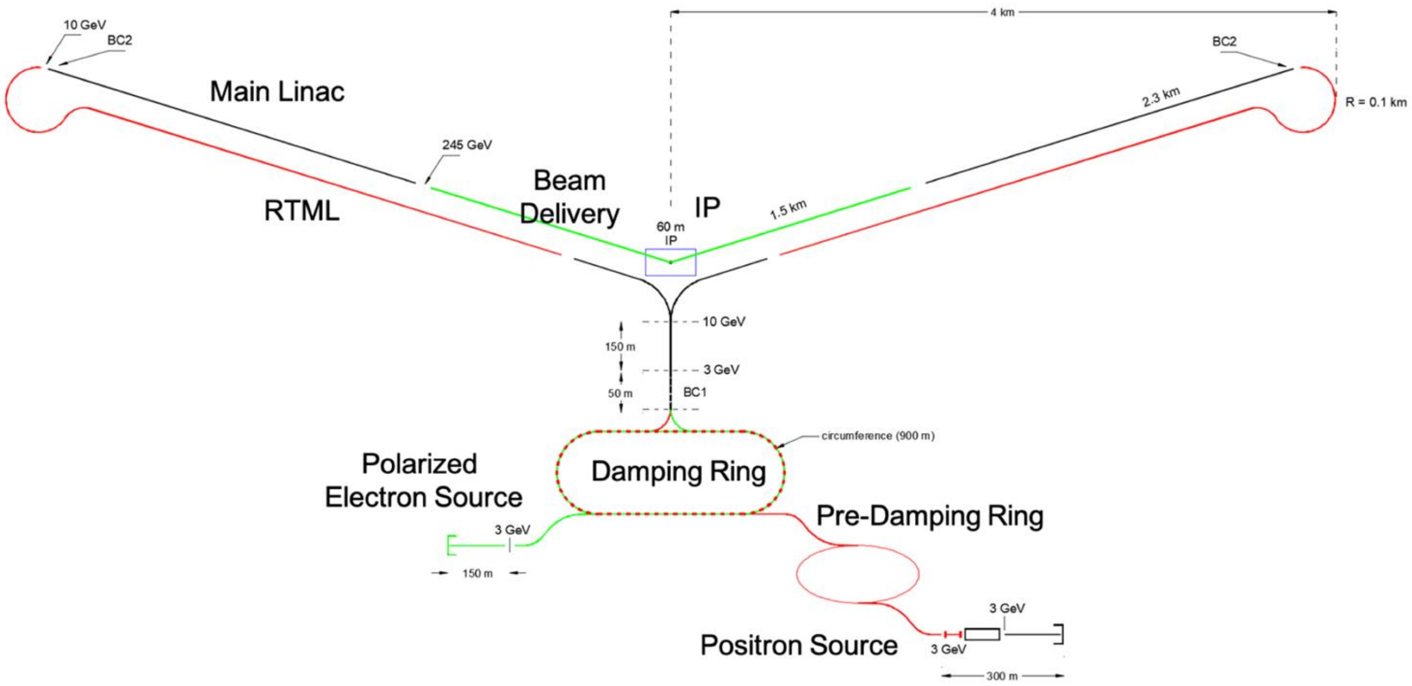


Cryo-cooled copper cavity, SLAC



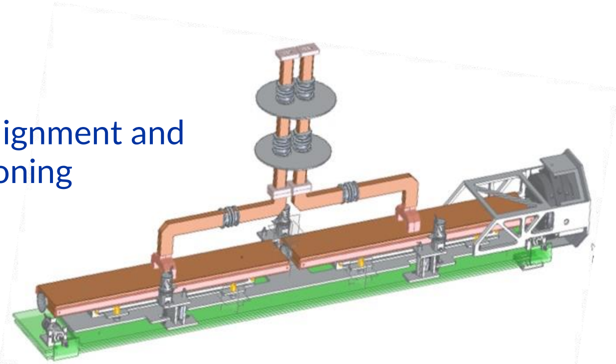


Cryo-cooled copper pulsed dc electrodes, Uppsala/CERN

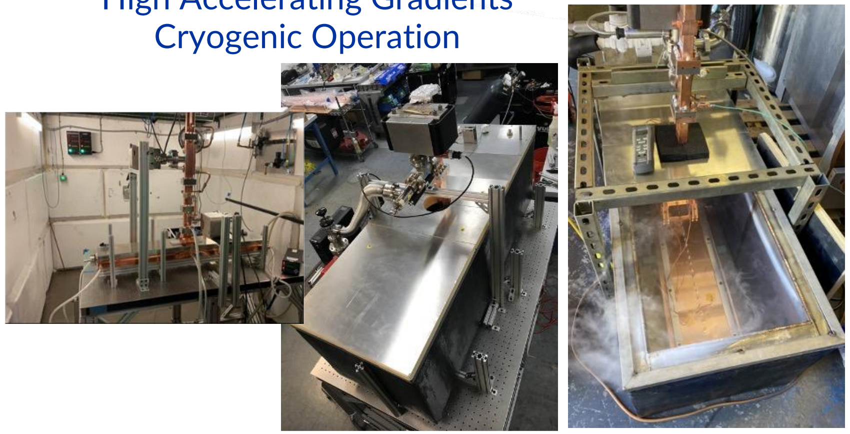


Ongoing Technological Development

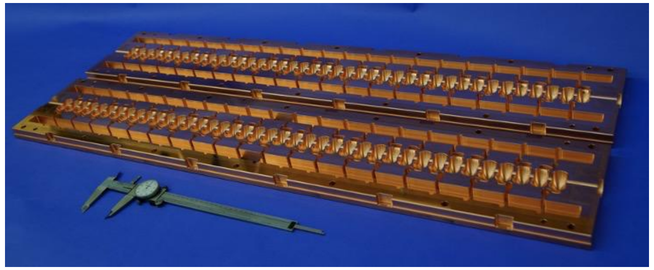
Preliminary Alignment and
Positioning



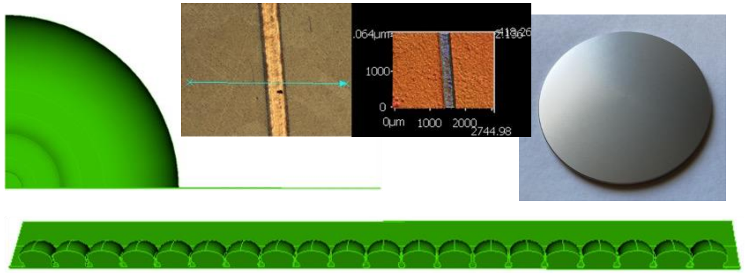
High Accelerating Gradients
Cryogenic Operation

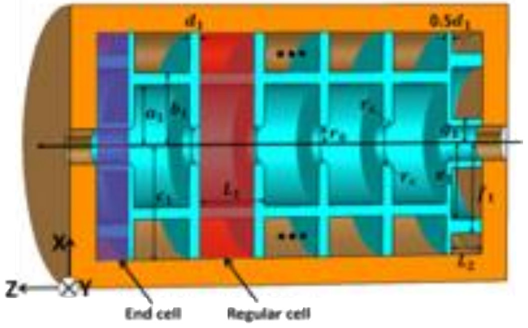


Modern Manufacturing
Prototype One Meter Structure



Integrated Damping
Slot Damping with NiChrome Coating

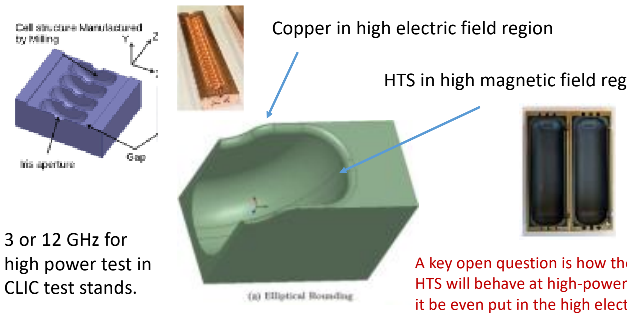




Implementation

Copper in high electric field region

HTS in high magnetic field region



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

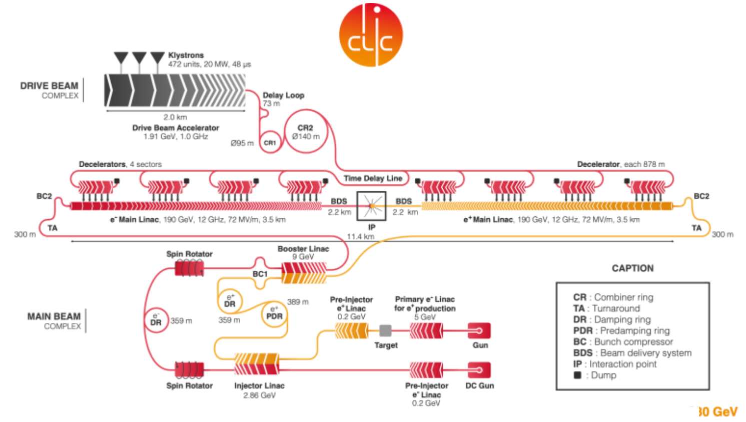
A key open question is how the HTS will behave at high-power. Can it be even put in the high electric field region?

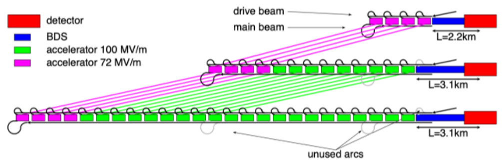
Cryogenic systems extended: Combining high-gradients in cryo-copper and high-temperature superconductors for high-efficiency and reduced peak RF power requirements.

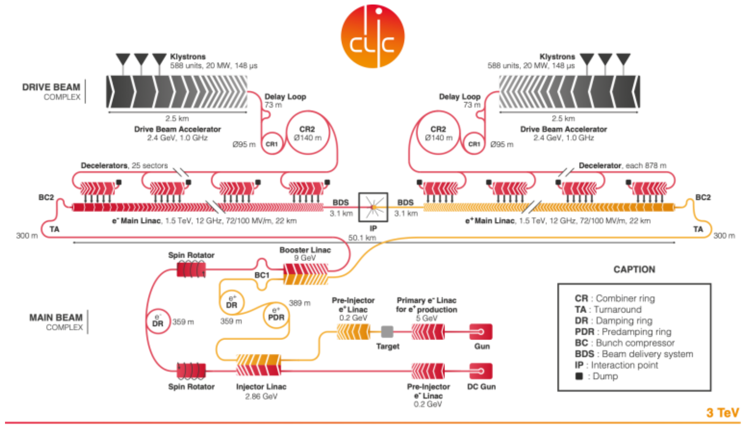
Slides/figures from Nanni and Calatroni/Wuensch

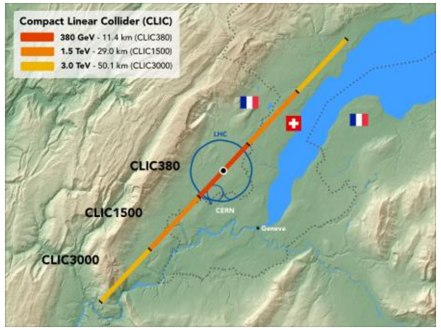
CLIC, ILC, C3 energy upgrades

CLIC can easily be extended into the multi-TeV region (3 TeV studied in detail)









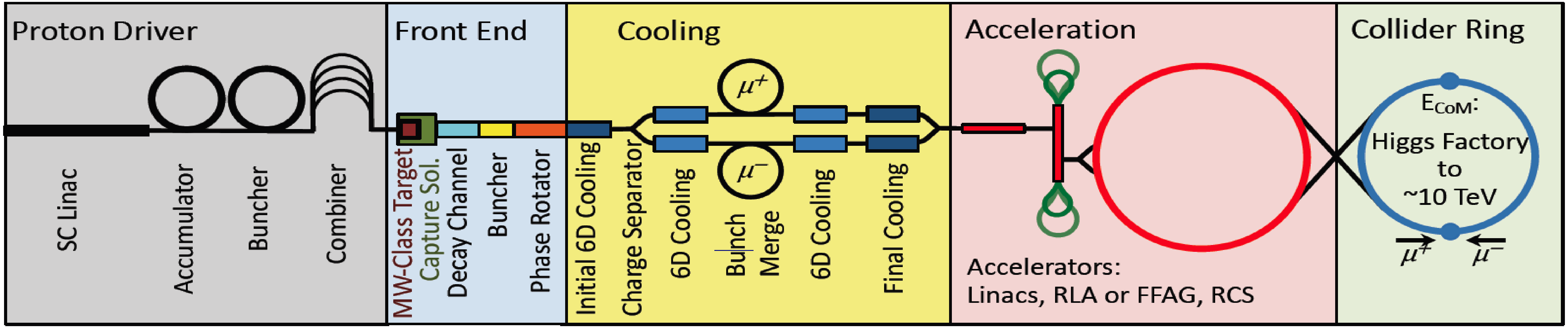
Extend by extending main linacs, increase drivebeam pulse-length and power, and a second drivebeam to get to 3 TeV

ILC has foreseen extensions to ~ 1TeV with existing or modestly improved SCRF technology.
However, improvements in gradients with for example travelling wave structures or Nb_3Sn coating have motivated ideas of reaching ~3 TeV in 50km (gradients well above 50 MeV/m needed)

C3 is similar to CLIC in gradient and a 3 TeV C3 concept have been formulated.
C3 would also fit into an ILC tunnel with its suitable klystron gallery, as a potential upgrade.

No convincing study of improving lum/P ratio for LCs at multi-TeV energies well above 3 TeV, even maintaining it is hard. Going beyond 3 TeV (with other RF methods) would require very small beams, extreme requirements for stability, improved wall-plug to beam efficiency, etc.
It is not only a question of gradient.

Key Challenges and possible solutions



Proton complex
- Compressing proton to few bunches

Target
- Target
- Solenoid

Cooling channel
- Channel design
- Solenoids
- RF in magnetic field
- Absorbers
- Integration

RCS
- Beam dynamics
- Ramping magnets
- Power converter
- RF system

Collider ring
- Optics
- Magnets
- Neutrino flux
- Detector background background

Solutions studied – linked to progress in many areas (not complete):
Progress on **high** power proton drivers and targets, cooling studies/demonstrations in MICE and RF in magnetic fields, progress in high field solenoids as needed for target and cooling channel, RCS technologies as RF (similar to ILC) and fast ramping magnets (normal or HTS), use of NbTi or HTS in collider ring, studies of mover system to reduce environmental neutrino flux and it results, detector background studies and experiences from HL-LHC detector studies … more information at link to EPP2024 (Schulte)

R&D for Improved SRF Performance & Sustainability

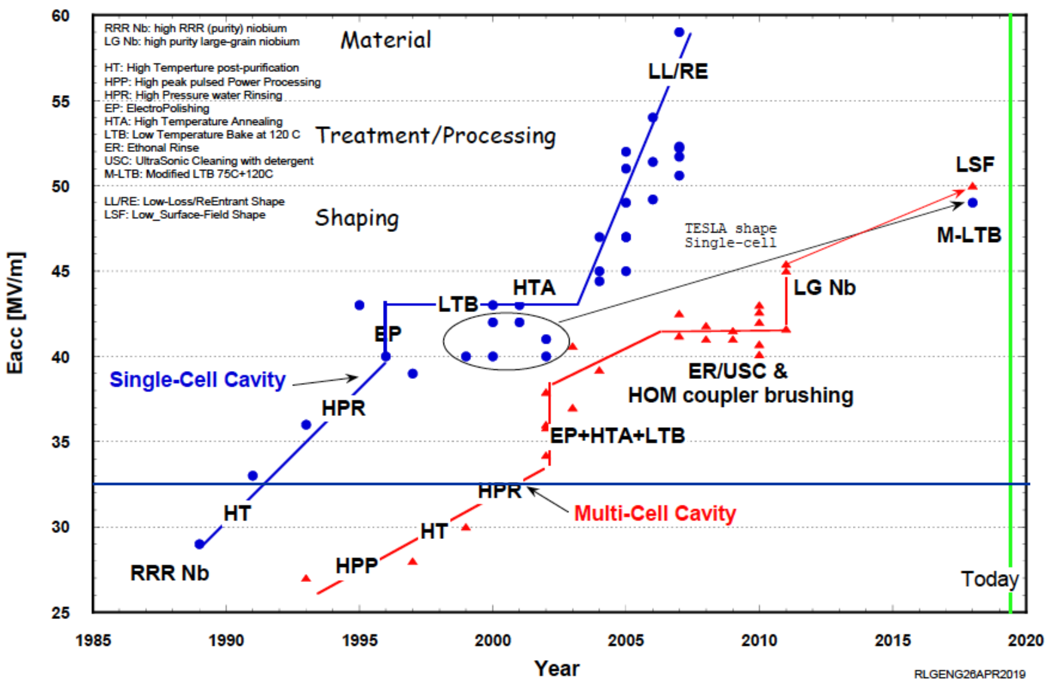
Better surface treatments and cavity shapes improve cavity performance. Lots of progress in last 10 years

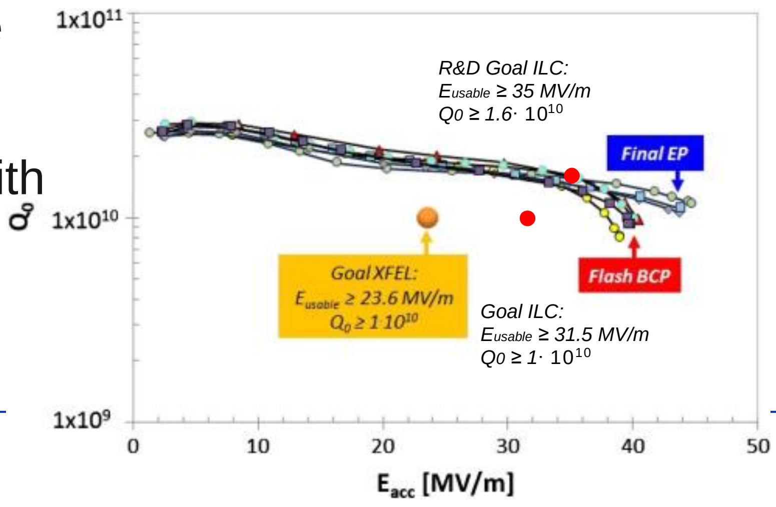
Raise gradient: fewer cavities for same beam energy
Short term goal: 31.5MV/m -> 35MV/m
Medium term goal: 45MV/m
Lab record: 59MV/m

Improve Q_0: reduce cryogenic losses
(1W @ 2K requires ~750W AC power!)
Short term goal: 1E10 -> 2E10

New treatments reduce / avoid need for electropolishing treatments (involving aggressive chemicals)

R&D into replacement of bulk niobium cavities with Nb or Nb_3Sn coated copper:
reduce niobium consumption,
increase performance (arXiv:2203.09718)





Cost

EPPS 2019:
- FCC-ee (~11-13 BCHF), FCC-hh (~+17-18 BCHF) – FCC-hh standalone (~24 BCHF)
- CLIC 380 and CEPC (both ~6 BCHF)
- ILC 250 (~5 BCHF)
- CLIC 3TeV (~+11 BCHF) if extended from 380 GeV, or standalone (~18 BCHF)
- ILC 1 TeV and luminosity increase (+ depends on SRF technology advances ..)
- Muons not estimated

Material costs (value) estimated in a traditional way (ala LHC), prices in 2018 CHF

Snowmass ("30 Parameter Cost Model”) – main elements in report (link on page 2 of this talk):
- 2021 US$
- Green field (in reality some machines will be extension of others)
- Add personnel estimate (see next slide)
- In most cases use estimates from recent machines (e.g. injectors, RF, CE, …)
- Use learning curves
- For HF magnets use “aspirational costing”, a factor ~2 lower than current Nb_3Sn pricing and a higher factor for HTS
- Special considerations made for Novel Technologies (will not show these estimates)

Personnel estimate and cost – and Higgs factories

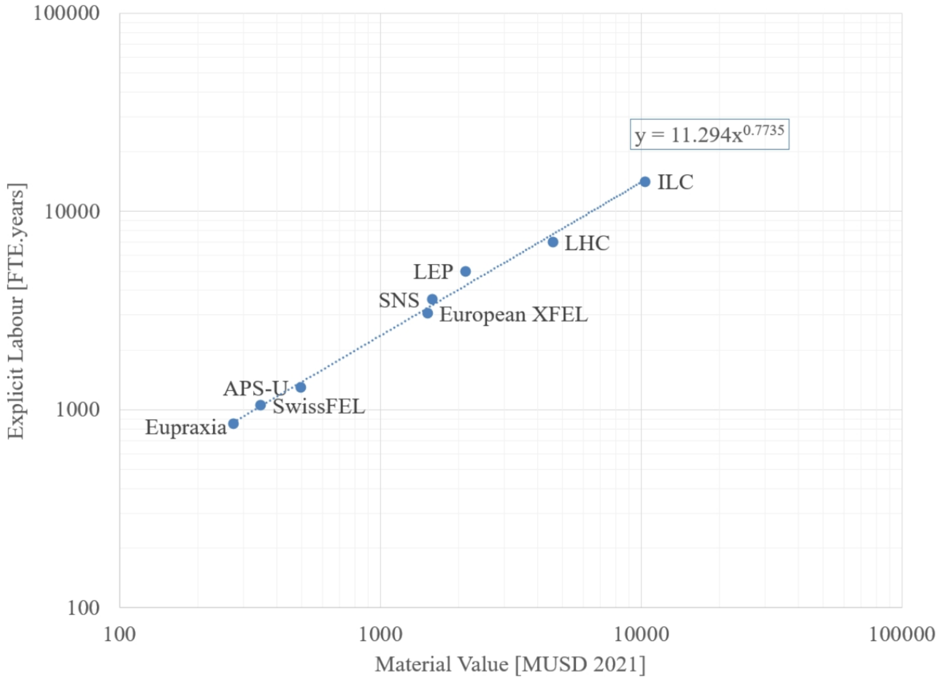


Figure 5: Explicit labor for several large accelerator projects vs. project value.

One FTEy estimated to 200kUS$

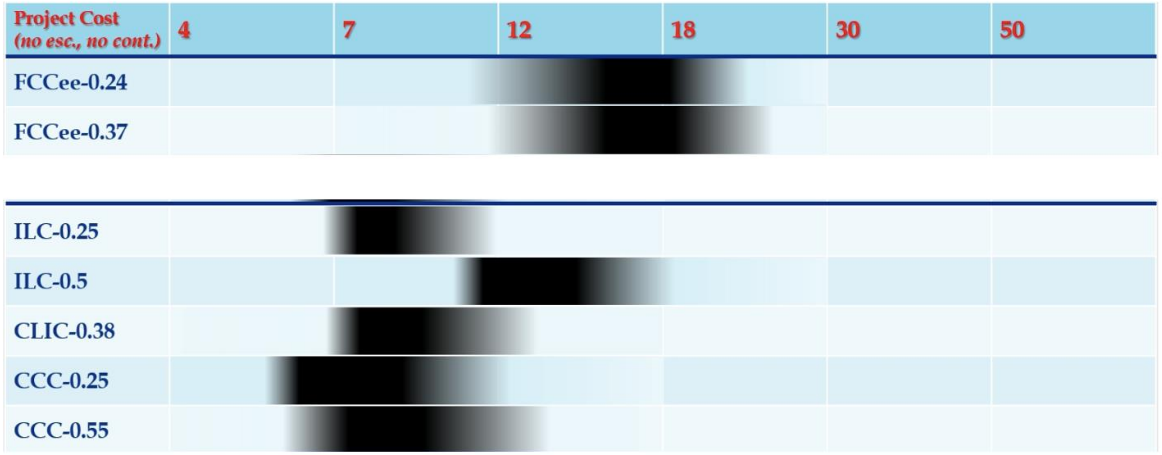
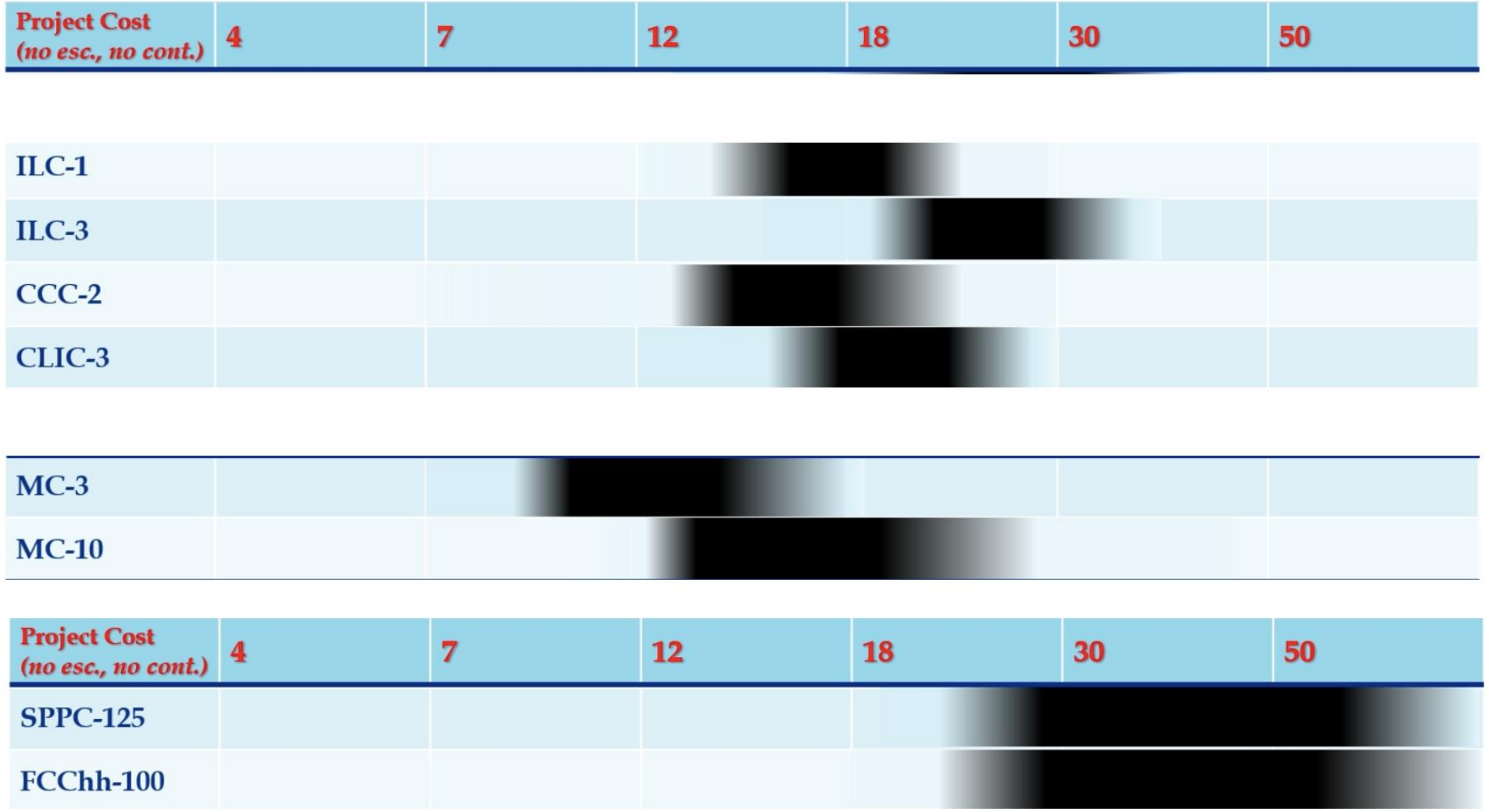


Figure 8: The ITF cost model for the EW/Higgs factory proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

Higher energy projects – and costs

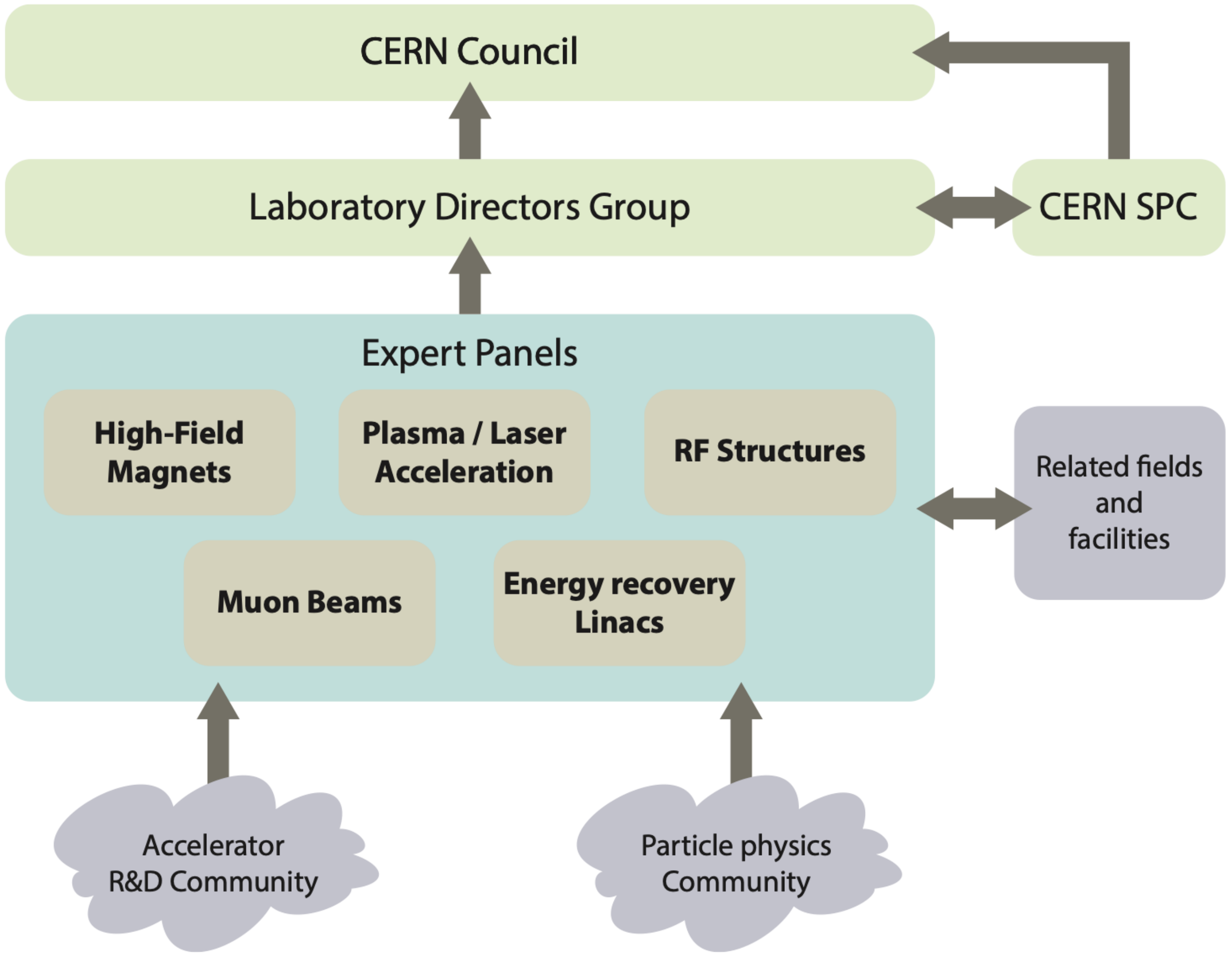


LDG accelerator R&D roadmap

The European Strategy contains clear recommendations on accelerator R&D:

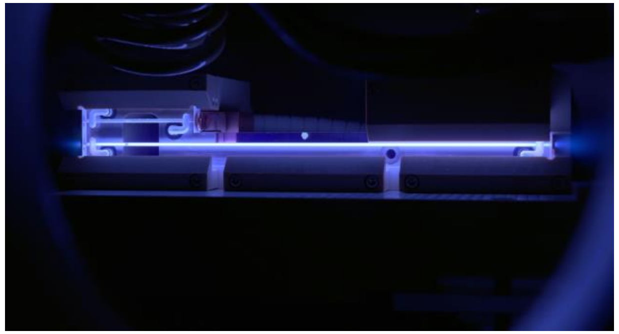
- The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies.
- The European particle physics community must intensify accelerator R&D and sustain it with adequate resources; a roadmap should prioritise the technology.
- Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.

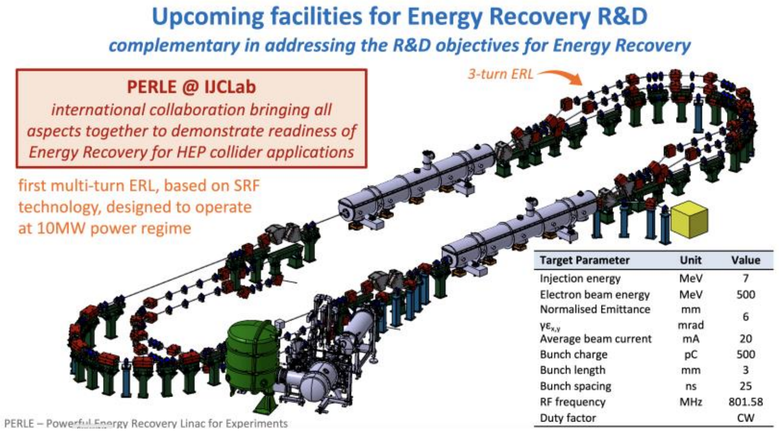
From Dave Newbold



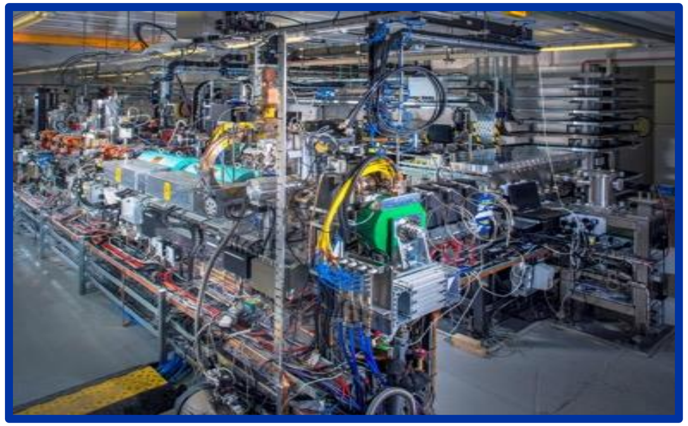
Energy recovery and Plasma

Project concepts exists and need to be further checked and developed. Practical work concentrated on smaller facilities (e.g. PEARL, bERLinPro, EUPRAXIA and many others (Flashforward, CLARA, AWAKE ……), use of plasma acc. for injectors, in many cases outside particle physics). LHeC still the most "worked through" collider concept making use of energy recovery ?





Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\epsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW



From PECFA reports on Plasma and Energy Recovery