Overview of accelerator technologies and challenges

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Setting the scene

Particle accelerators are a major enabling technology.

When it comes to the next collider: as a community, we're not short on ideas.

- Recently >100 papers were submitted to the *Accelerator Frontier* of the US particle physics decadal community planning exercise known as *Snowmass'2021*.
- 160 contributions were received for the most recent European Strategy for Particle Physics.

This talk will cover various future colliders. Not all options are covered and all aspects of each collider design cannot be covered.

For a lot more detail, see references on final slides.

Who am I?

- Lecturer at University of Liverpool / Cockcroft Institute.
- Worked at CERN on FCC-ee.
- During my PhD, I worked on a compact FEL using CLIC technology.

I've tried to summarise some of the remaining technical challenges. It's impossible to be completely compressive and no doubt there are areas I've missed.

Acknowledgements: material drawn from:

- S. Gourlay, T. Raubenheimer, and V. Shitslev, "Challenges of Future Accelerators for Particle Physics Research" Front. Phys., 2022 https://doi.org/10.3389/fphy.2022.920520
- Laurie Nevay's talk at ECR Forum on Future Colliders in April 2022.
- Many CDRs and TDRs

Next collider options

Considerations for the next collider:

- **Technical feasibility**

Important to note: **new challenges create new opportunities.** R&D development feeds into other accelerator applications.

- **Cost**

(See later slides)

- **AC power consumption**

(See later slides)

- **CoM energy reach & physics potential**

Collider	Species	Nominal c.m. Energy (Range), TeV 10^{34} $cm^{-2}s^{-1}$	Luminosity per IP at Nominal c.m.e
FCCee	e^+e^-	0.24 (0.09–0.37)	8.5 (28.9)
CEPC	e^+e^-	0.24 (0.09–0.24)	8.3 (16.6)
ILC	e^+e^-	0.25 (0.09–3)	1.4
CCC	e^+e^-	0.25 (0.25–0.55)	1.3
CLIC	e^+e^-	0.38 (0.09–3)	1.5
CERC	e^+e^-	0.24 (0.09–0.6)	78
MC-Higgs	$\mu^+\mu^-$	0.13	0.01
LHeC	e^-p	1.3	1
High-Energy ILC	e^+e^-	3 (1–3)	6.1
High-Energy CCC	e^+e^-	3 (1–3)	6.0
High-Energy CLIC	e^+e^-	3 (1–3)	5.9
Muon Collider	$\mu^+\mu^-$	10 (3–14)	20
FCChh	pp	100	30
SPPC	pp	75 (75–150)	10
Laser-Driven WFA-LC	e^+e^-	3 (1–15)	10
Beam-Driven WFA-LC	e^+e^-	3 (1–14)	6
Structure WFA-LC	e^+e^-	3 (1–15)	5.9

Front. Phys., 2022, Sec. Radiation Detectors and Imaging
https://doi.org/10.3389/fphy.2022.920520

Next collider options

CIRCULAR VS LINEAR

Circular
- Multi-pass
- Synchrotron radiation
- High luminosity, multiple detectors
- Ideal for hadrons
- Limited by:
  - Maximum magnetic field
  - SR power loss

Linear
- Single-pass
- No synchrotron radiation
- Ideal for leptons
- Limited by:
  - Accelerating gradient
  - Stabilisation / feedback
  - Emittance preservation

FCC-ee, FCC-hh, CEPC, SppC

EIC, LHeC, muon collider

ILC, CLIC, AWAKE, C^3

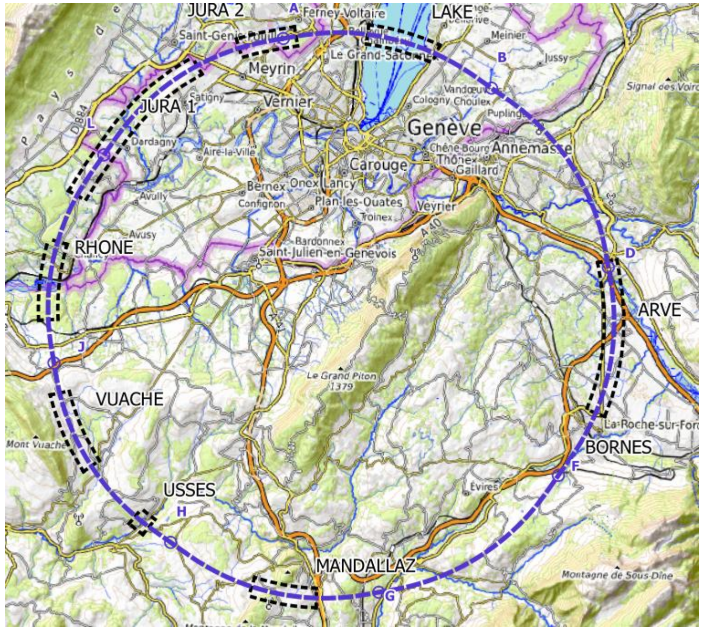
The Integrated FCC Programme

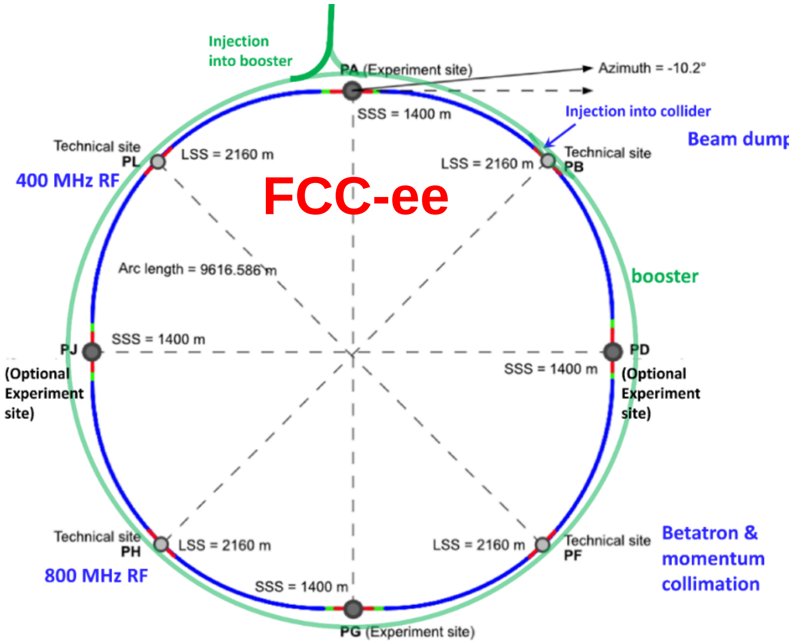
Comprehensive long-term program maximizing physics opportunities.

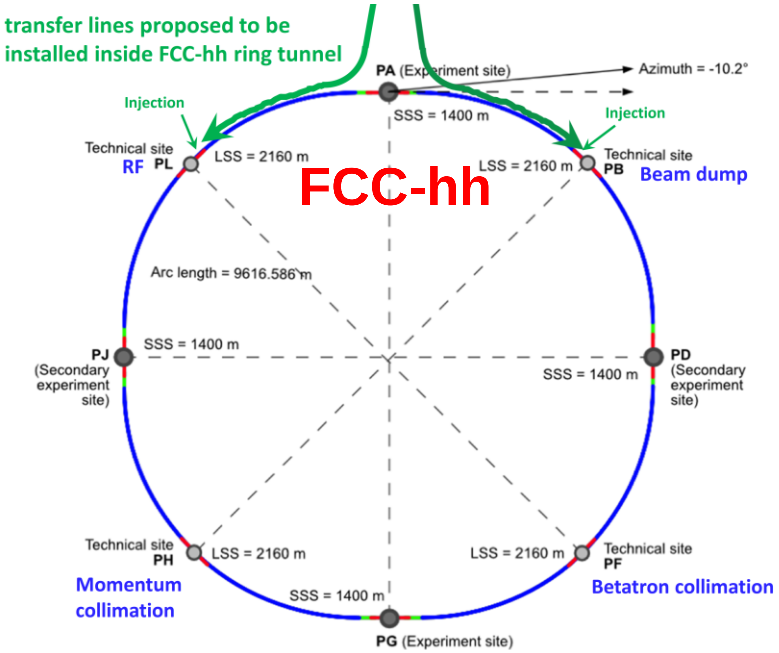
- **stage 1:** FCC-ee (Z, W, H, tt) as Higgs factory, electroweak & top factory at highest luminosities
- **stage 2:** FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options

Goal: demonstrate FCC feasibility by 2025/26

Infrastructure will support a **century of physics.**



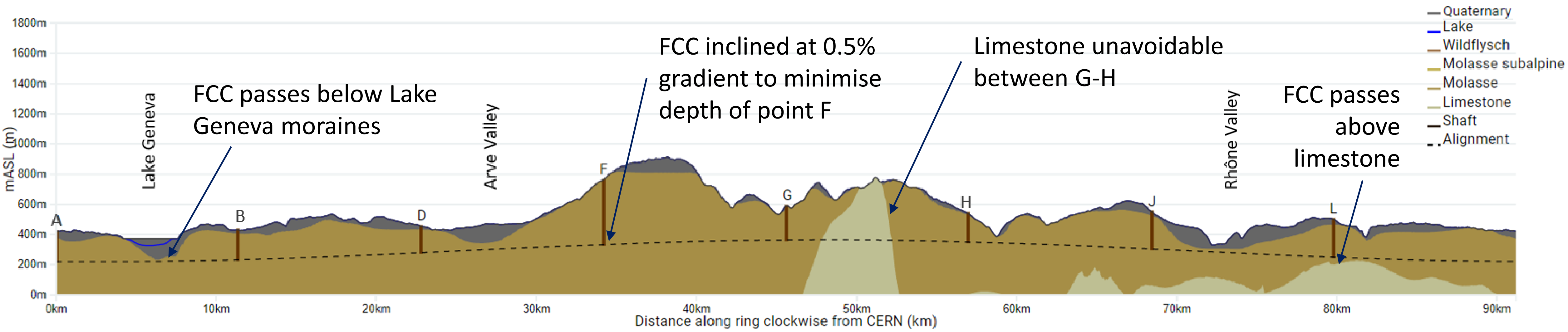




2020 - 2040 | **2045 - 2060** | **2065 - 2090**

FCC tunnel

John Osborne

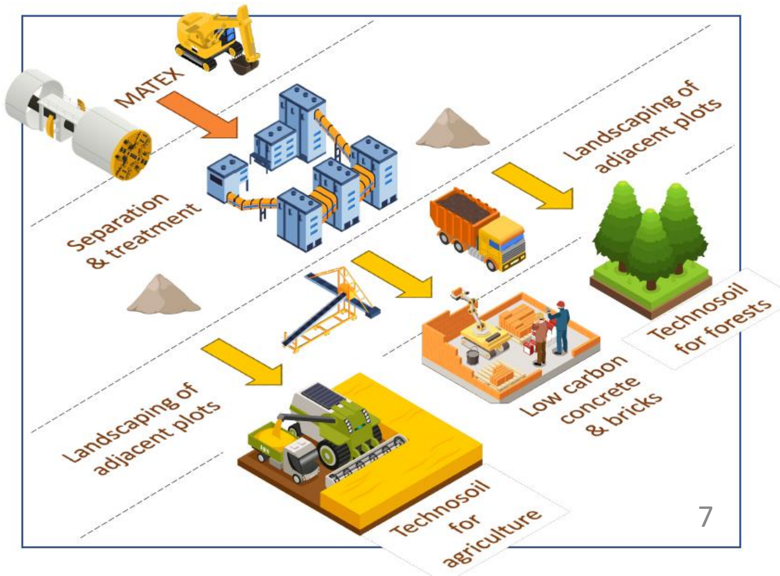


A: 202 m B: 200 m D: 177 m F: 399 m G: 228 m H: 139 m J: 251 m L: 253 m

Site investigations planned for 2024 – 2025:
~40-50 drillings, some 100 km of seismic lines

'Mining the Future' international competition
https://indico.cern.ch/event/1001465/

Winner: BG Ingineurs "Molasse is the new ore"
To overcome the challenge of the undefined petrographic composition of molasse, the consortium led by BG Ingineurs proposes to use online flow analysis, already used in cement plants, to immediately identify the excavated materials for further processing.



FCC-ee – e+/e- Future Circular Collider

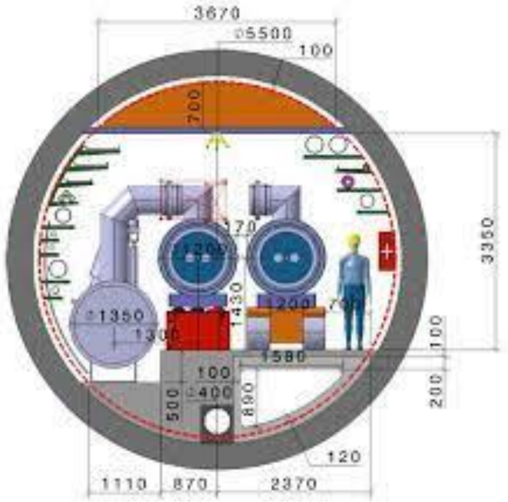
- **High luminosity precision study of Z, W, H, and $t\bar{t}$**
- Main technologies for the are well-developed and proven
- **Detailed multi-domain feasibility study underway** for 2026 ESPPU
- Although a lot of SR power, the E_c and W/m are only 10-20 % more than LEP.
  - Tapering of magnets around the ring account for the ~9 GeV / turn maximum energy loss
- Beam lifetime dominated by beamstrhlung
- **Remaining technical challenges**:
  - Obtaining the required diagnostic precision and emittance tuning
  - Size and number of components
  - Further improving electrical efficiency

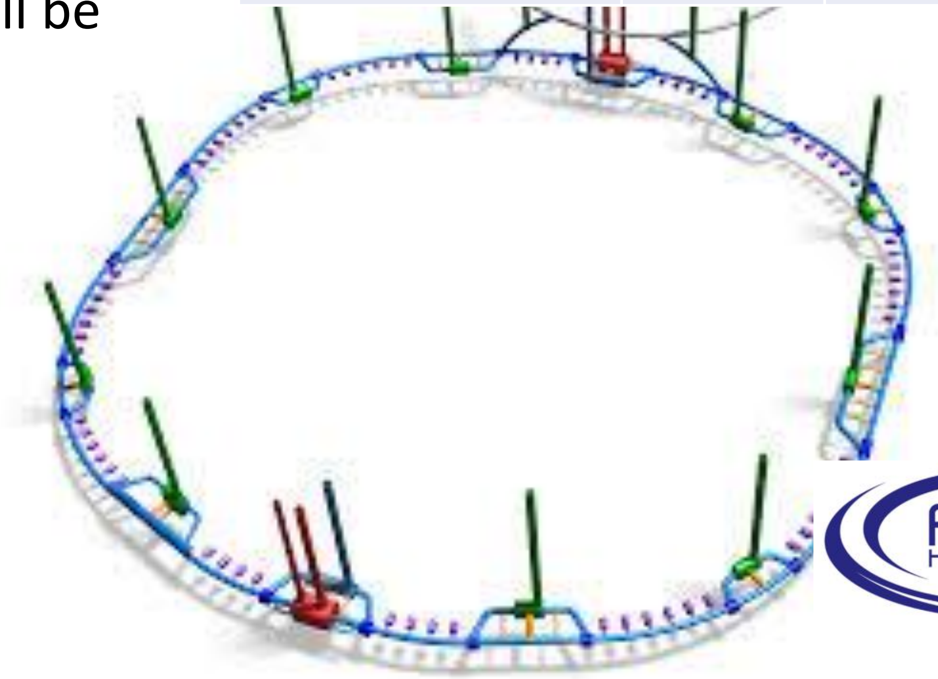
Parameter	Z	WW	H (ZH)	ttbar
Beam energy [GeV]	45	80	120	182.5
Bunches / beam	10000	880	248	36
SR power / beam [MW]	50			
Vertical beta* [mm]	0.8	1	1	1.6
$\mathcal{L}$ per IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.3	1.33

FCC-hh

- **Same 100 km-scale tunnel as FCC-ee**
- LHC to be re-used as 3 TeV injector
- **Challenges**:
  - 16 T magnets required to reach the target energy of 100 TeV
  - Size and number of components
  - Crab cavity system (although experience will be gained from HL-LHC)

Parameter	FCC-hh	HL-LHC	LHC
CoM energy [TeV]	100	14	14
Dipole field [T]	~17	8.33	8.33
SR power / beam [kW]	32.1	0.33	0.17
beta* [mm]	1.1	0.15	0.55
Peak $\mathcal{L}$ [10^{34} $cm^{-2}s^{-1}$]	5-30	5	1
Stored energy	7.8	0.7	0.36

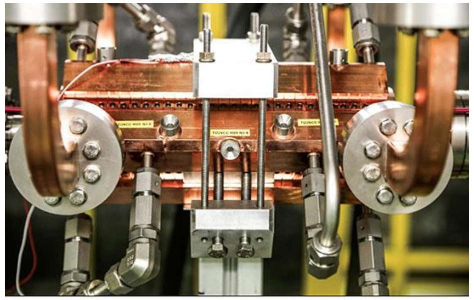


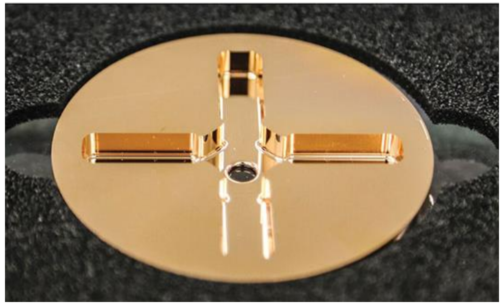


CLIC – Compact Linear Collider

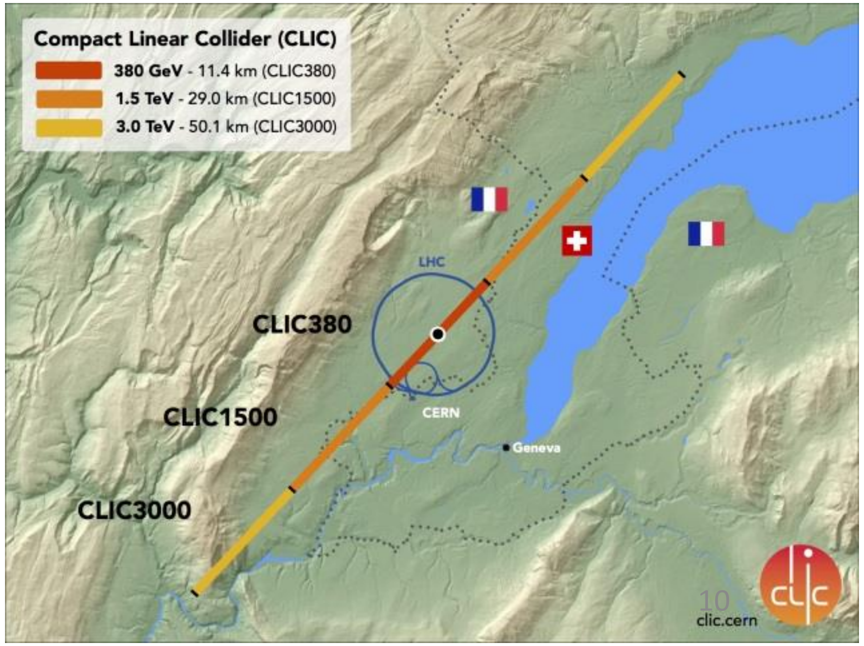
- Staged approach with CoM energies of 380 GeV, 1.5 TeV and 3 TeV (up to ~50km)
- Novel two-beam acceleration technique
  - NC accel. structures with gradients up to 100 MV/m
  - demonstrated at CLIC Test Facility at CERN
- CDR published in 2012
- An updated project description will be submitted for the next European Strategy Update 2026-27
- **Remaining technical challenges:**
  - Reduce power consumption (like most collider projects)
  - Nanometer-scale spot size and stability at the IP
  - 0.5 ns bunch spacing challenging for detectors

Parameter	Value
Beam energy [GeV]	140 – 3000
Accelerating gradient [MV/m]	100
beta* [mm]	1.1
Peak $\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	2
Power usage	Est. 580 MW





Single cell of 12 GHz accelerating structure

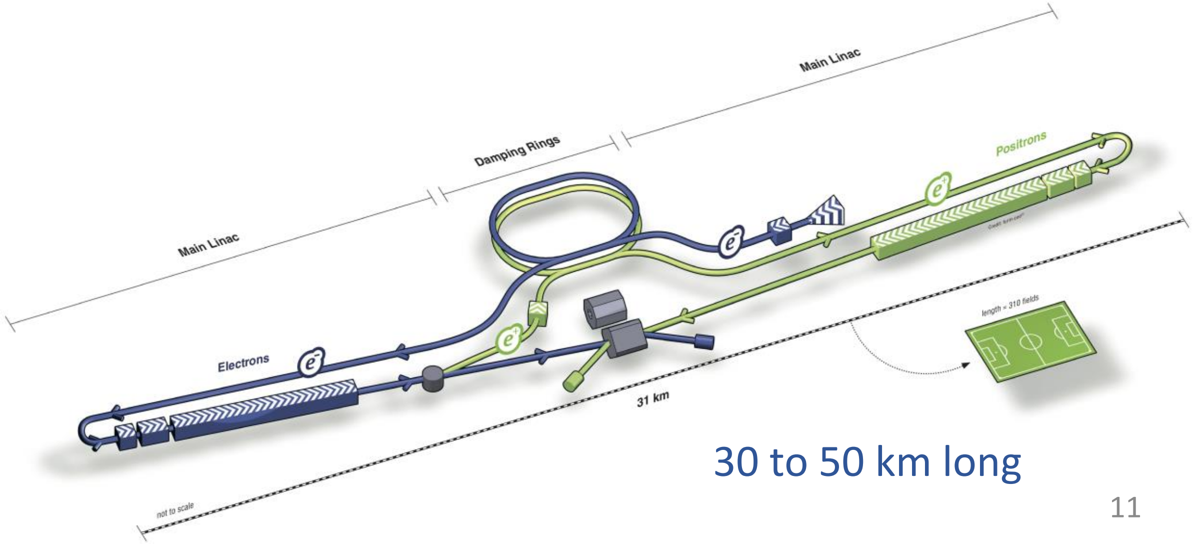


ILC - International Linear Collider

- Superconducting RF (SRF) cavities at 31.5 MV/m gradient
  - European XFEL at DESY is a 10%-scale demonstration ILC acceleration systems
- 'Shovel ready' design – TDR published in June 2013
- **Remaining technical challenges**:
  - improvement of the positron source,
  - achieving the nanometer-scale spot size and stability at the IP
  - optimizing the damping ring injection and extraction systems

Parameter	Value
Beam energy [GeV]	125 – 500
Accelerating gradient [MV/m]	31
Horizontal beta* [mm]	20
Vertical beta* [mm]	0.4
Peak $\mathcal{L}$ [10^{34} $cm^{-2}s^{-1}$]	0.75 - 3
Power usage [MW]	Est. 164 - 300

9-cell Niobium SC cavity



30 to 50 km long

ILC - International Linear Collider

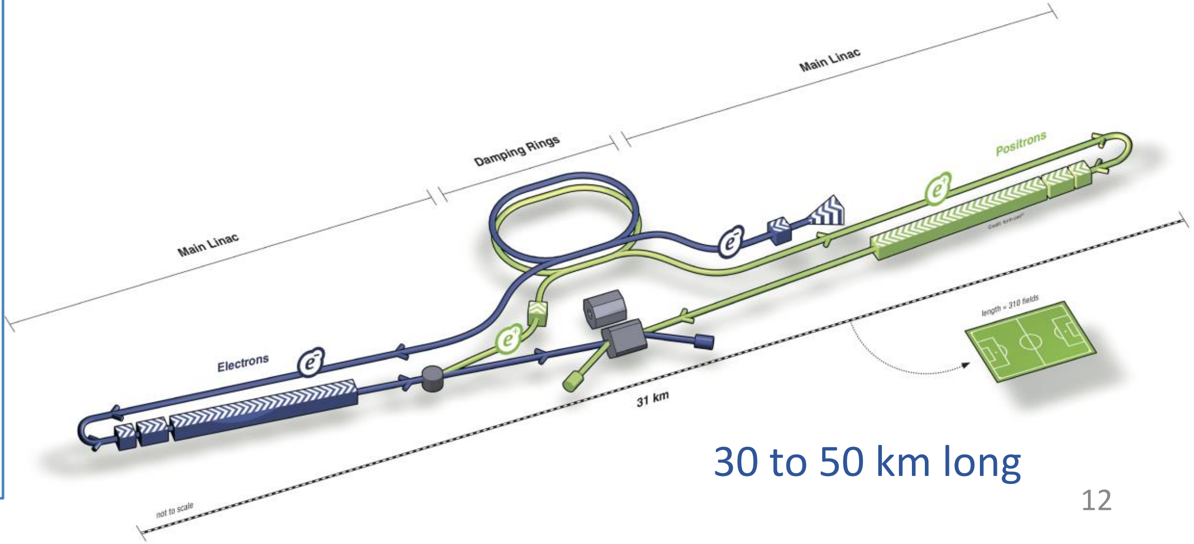
The **Ministry of Education, Culture, Sports, Science and Technology (MEXT)** in Japan assembled an experts panel in **July 2021** to review the latest ILC International Development Team proposal.

While recognizing the *“academic significance of particle physics and the importance of the research activities, including that of a Higgs factory”*, the panel says it is still *“premature”* to give the ILC pre-lab phase the go-ahead as they say this would be *“coupled with an expression of interest to host the ILC by Japan”.*

The panel also made reference to the *“increasing strain in the financial situation”* of some countries that may provide support for the ILC, with the recommendation to *“re-examine the approach towards a Higgs factory in a global manner”.*

https://www.kek.jp/en/topics-en/202202251335/

Parameter	Value
Beam energy [GeV]	125 – 500
Accelerating gradient [MV/m]	31
Horizontal beta* [mm]	20
Vertical beta* [mm]	0.4
Peak $\mathcal{L}$ [10^{34} $cm^{-2}s^{-1}$]	0.75 - 3
Power usage [MW]	Est. 164 - 300

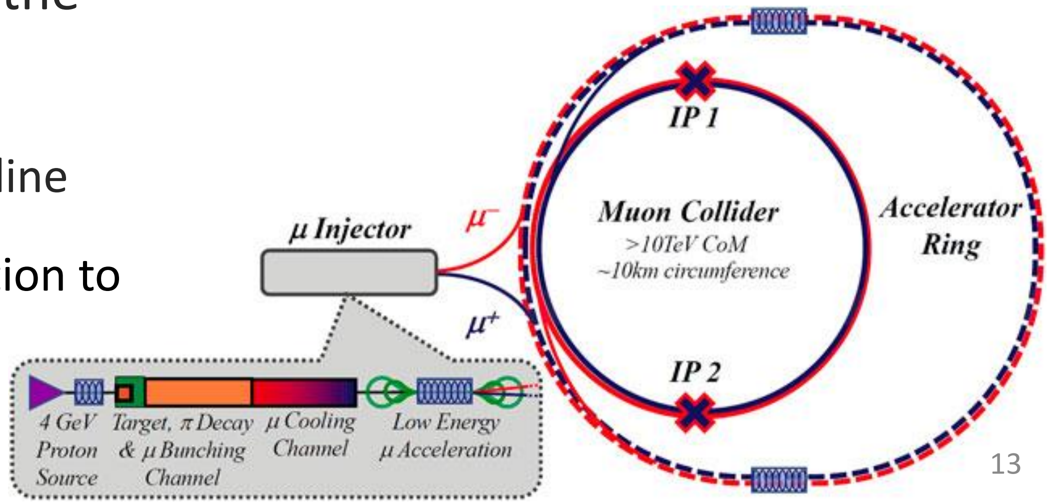


30 to 50 km long

Muon Collider

- Lepton collider with less SR power.
- Rapid acceleration -> collect and cool quickly
  - lifetime short: 2.2 μs
  - A lifetime of 105 ms in the lab. reference frame is reached at 5 TeV
- Muon decay dissipates the beam => SC dipole magnets capable of providing 10-15 T fields are required to minimise collider ring size to reduce losses
- Cooling system is essential.
  - Ionization-cooling technique has been demonstrated by MICE
- International Muon Collider Collaboration (IMCC) was formed based on a recommendation in the update of the European Strategy for Particle Physics
- **Technical challenges:**
  - Robust R&D programme needed to bring development inline with ILC and CLIC.
  - Intense neutrino flux from muon decays needs consideration to minimize the environmental impact

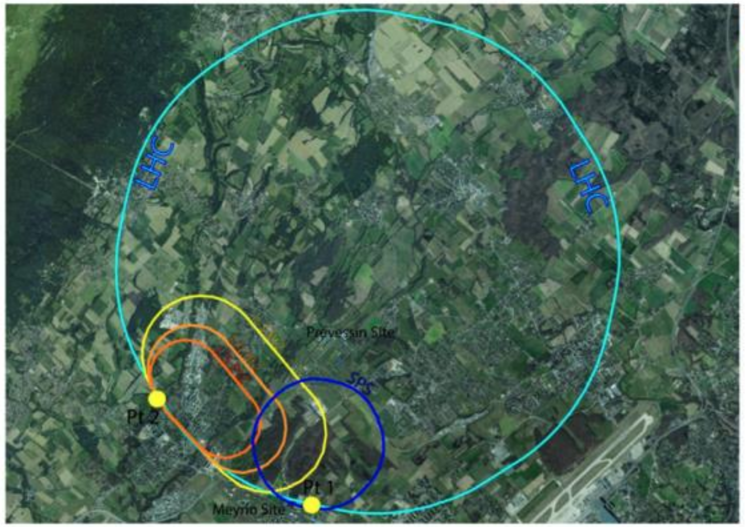
Parameter	Value
Beam energy [TeV]	1.5 - 7
Peak B [T]	16
Peak $\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	10
Power usage [MW]	Est. 580

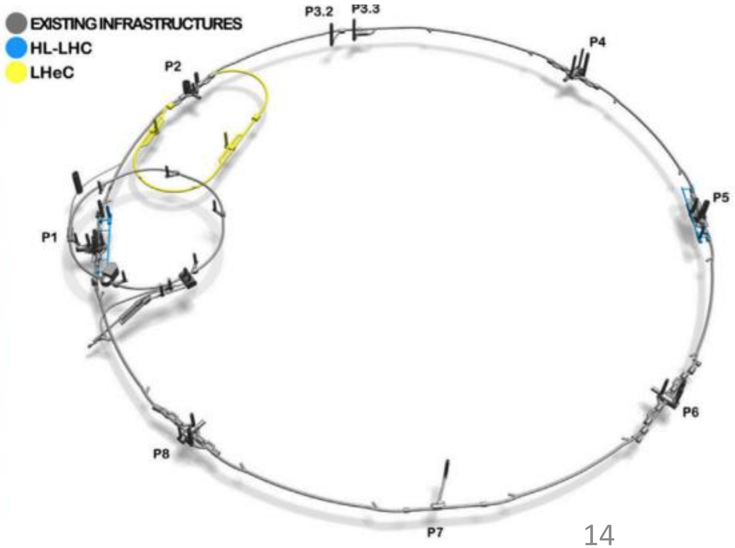


LHeC

- e- p collider operating ‘parasitically’ to the nominal LHC physics program
- Uses energy recovery linac (ERL) technology
- Maximises the use of existing LHC infrastructure
- PERLE test facility to demonstrate technology
- **Technical challenges:**
  - Synchrotron radiation originating from the bending of the electron beam onto the LHC hadron beam trajectories
  - Demonstration of multi-turn ERL operation with high beam current.

Parameter	Value
Beam energy [GeV]	50 (e-)
Peak $\mathcal{L}$ [10^{34} $cm^{-2}s^{-1}$]	1.2 – 2.4
Efficiency [%]	Up to 60
SR power loss [MW]	45 (e-)
Power usage [MW]	Est. 164 - 300





What else?

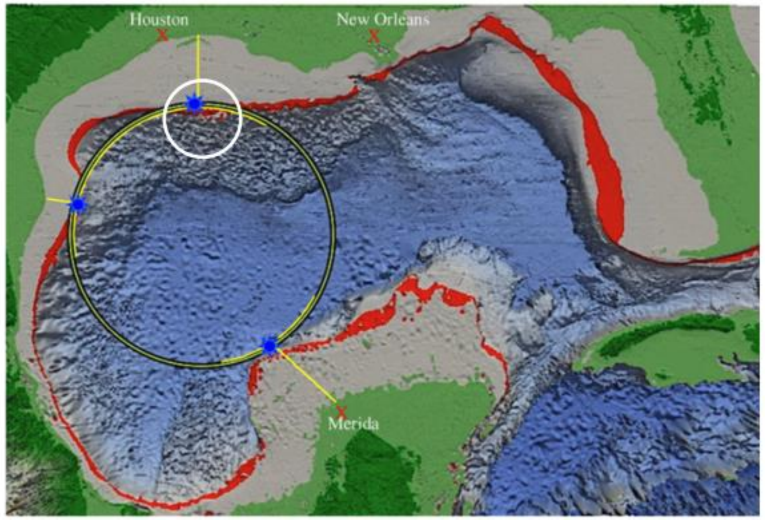
Circular Collider on the Moon (CCM)

- ~11000 km in circumference
- pp c.o.m collision energy of 14 PeV - *a Planck-scale collider*
- Luminosity ~6×10^{39} cm^{-2} s^{-1}
- Assumes a dipole magnetic field of 20 T
- *“CCM could be the (next-to-) next-to-next-generation discovery machine for high-energy particle physics and a natural successor to next-generation machines”.*
- Fortunately, in the excellent vacuum on the Moon no beam pipe would be needed.

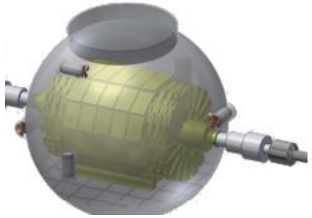
3 potential Earth-based sites for a circular collider approximately the same size as CCM

Collider in the Sea (CitS) floating in the Gulf of Mexico

- pp c.o.m collision energy of 100 – 500 TeV
- 100 – 1900 km in circumference
- Floating at a depth of ~100 m
- Luminosity ~$5\text{x}10^{35}$ cm^{-2} s^{-1}
- Hermetically sealed half-cells would be lowered to the water by a line of cranes and then taken to 100 m depth.
- *“No human being will ever be required to go below the sea surface for any operation in the installation, operation, or maintenance of the Collider in the Sea.”*



Potential site for the CitS in the Gulf of Mexico



Double-hull bathysphere containing the CMS detector.

(Mostly) common challenges

Reaching the advertised performance (inc. high-field magnet strengths)

Maintaining societal support

Energy Efficiency

Cost

Cost

Particularly difficult to accurately cost long-term projects in the current financial climate.

Typically:

- accelerator components (NC or/and SC magnets and RF systems) account for 50 ± 10% of the total cost,
- civil construction takes 35 ± 15%, and
- power production, delivery and distribution technology adds the remaining 15 ± 10%

V Shiltsev "A phenomenological cost model for high energy particle accelerators", 2014 J. of Instrumentation, vol. 9

Machine	Approximate Cost To Build
FCC-hh if ee built first	17 GCHF
FCC-hh on its own	24 GCHF
FCC-ee	10.5 GCHF
ILC	7.8 G$ (2012 USD)
CLIC	7-9 GCHF @500 GeV
LHeC	1-1.4 GCHF @50 GeV e-
Muon Collider	4.5 +- 1.5 GCHF @LHC tunnel

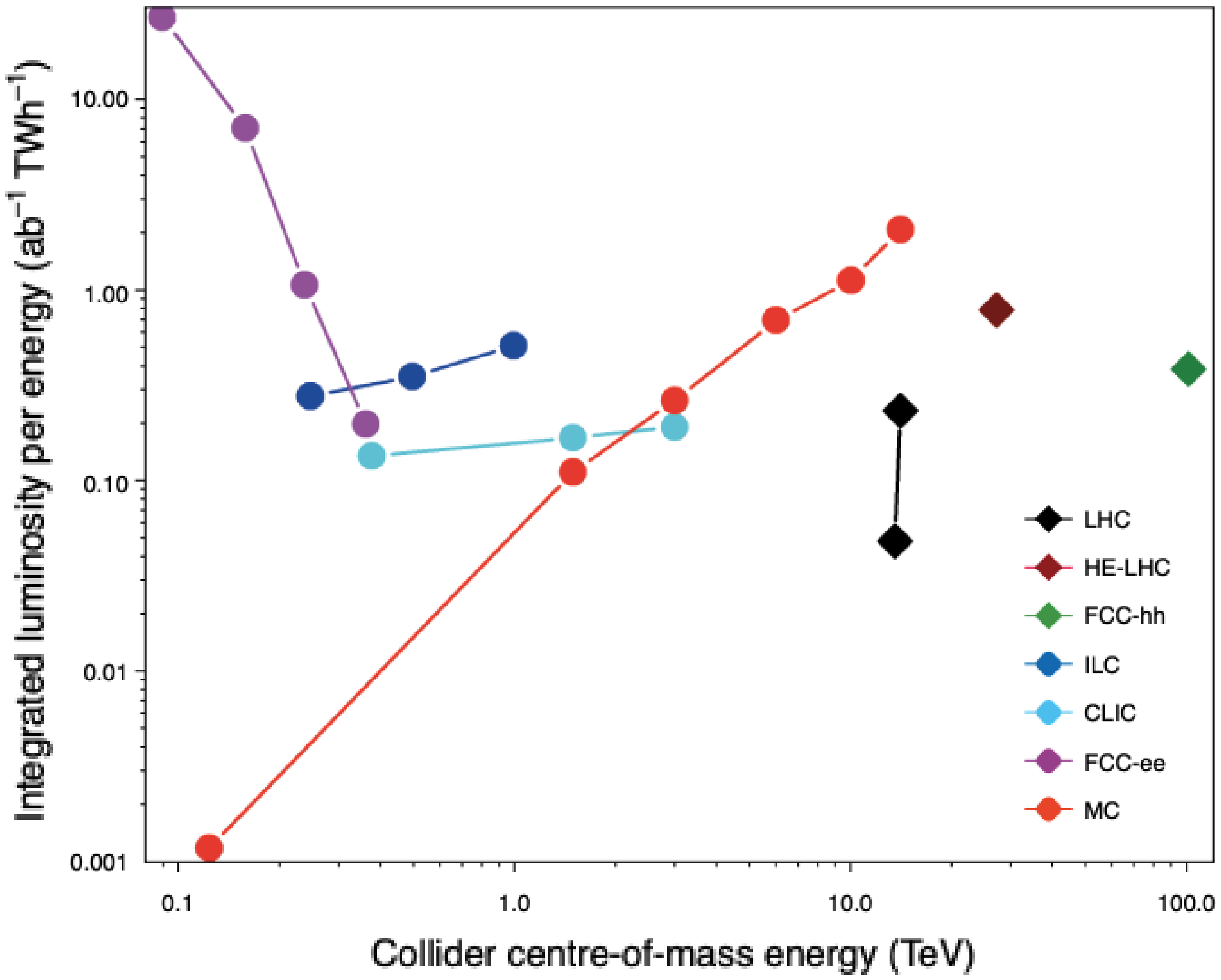
Not to be taken absolutely!

Thanks to L. Nevay who collated data

Efficiency

The 2020 update of the European Strategy for Particle Physics added **environmental impact** as an important requirement:

“A detailed plan for the minimisation of environmental impact and for the saving and re-use of energy should be part of the approval process for any major project.”



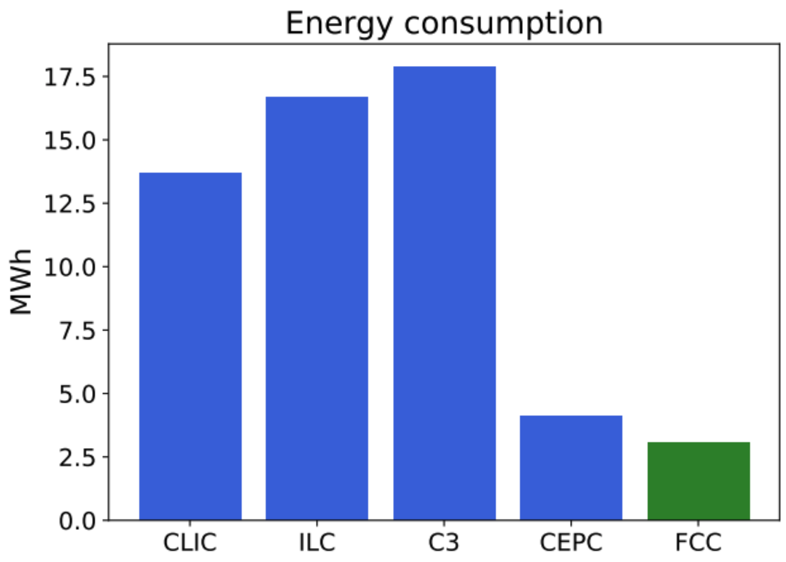
S. Gourlay, T. Raubenheimer, and V. Shitslev, “Challenges of Future Accelerators for Particle Physics Research” Front. Phys., 2022 https://doi.org/10.3389/fphy.2022.920520

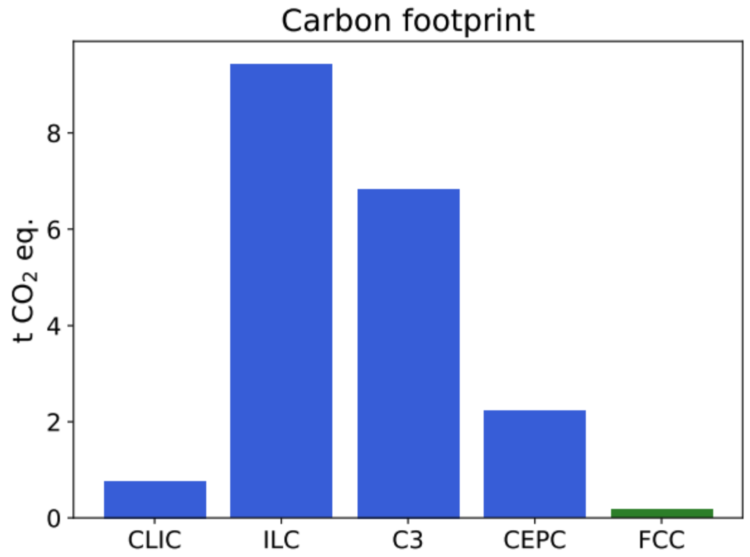
Efficiency – sustainability and carbon footprint studies

On a 'per Higgs' basis:

From the authors: These "'predictions' must be read relative to each other and with some caution."

P. Janot, A. Blondel "The carbon footprint of proposed e+e− Higgs factories" 2022, https://arxiv.org/abs/2208.10466





Higgs factory ->	CLIC	ILC	C^3	FCC-ee	CEPC
CoM energy [GeV]	110	250	250	240	240
Instantaneous wall-plug power [MW]	110	140	150	290	340
Annual energy consumption (TWh)	0.4	0.7	0.8	1.0	1.6

Also needing consideration:

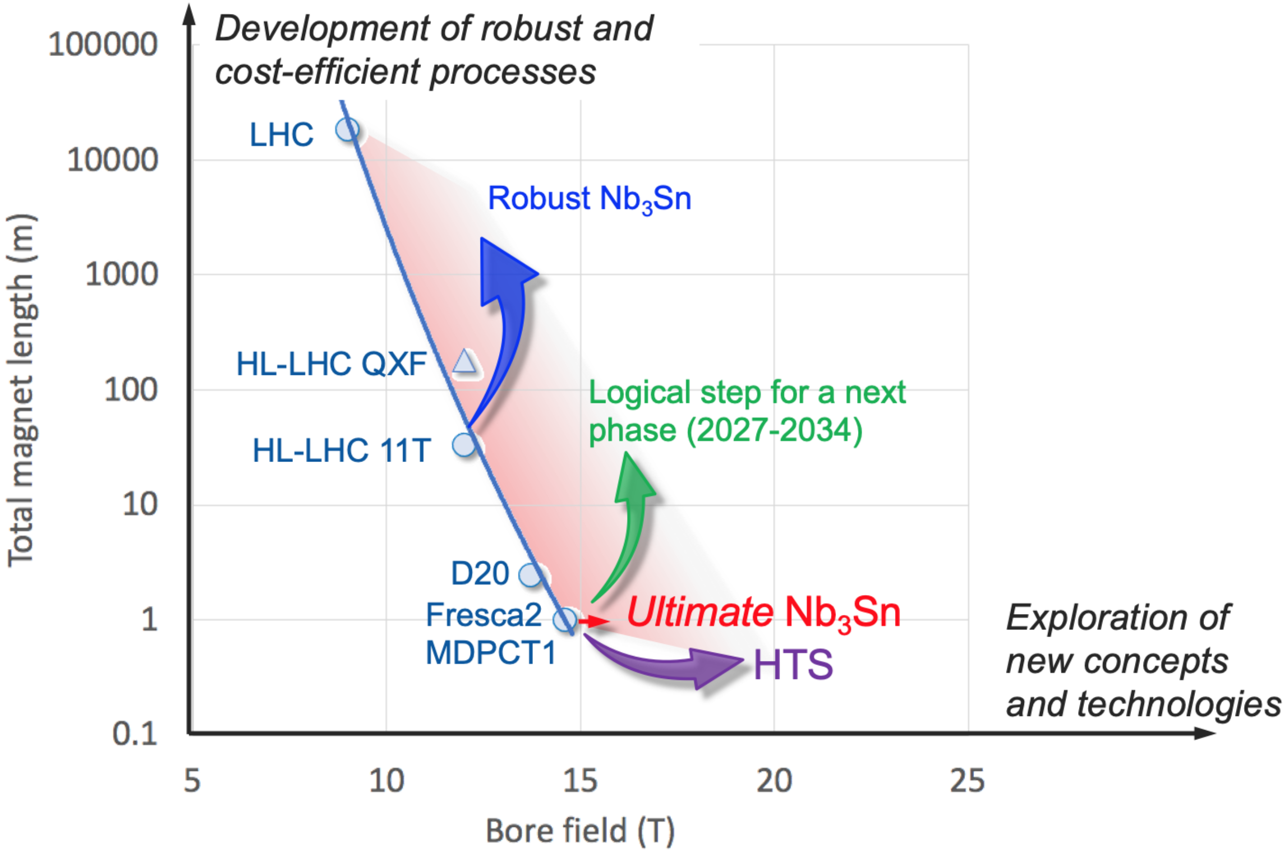
- Energy consumption related to data analysis and simulations and data storage.

- International travel (whilst not to the exclusion of our international colleagues).

High-field magnets

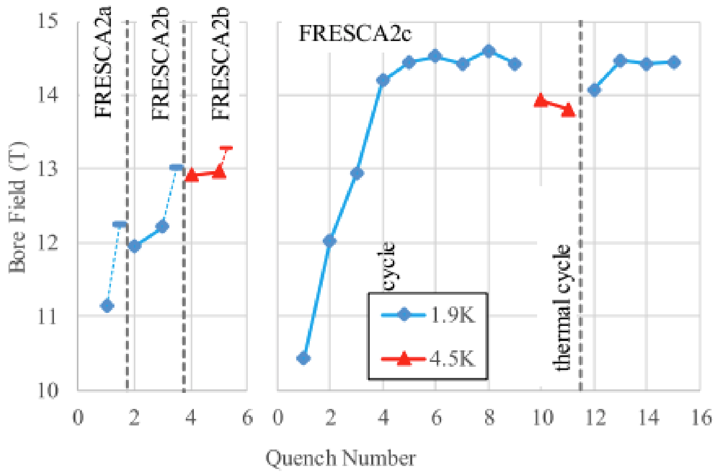
L. Bottura, F. Gianotti, A. Siemko

- High-field magnets are the key enabling technology for future hadron colliders.
- A number of collider projects (FCC-hh, HL-LHC, SppC, muon collider) are striving for very high B fields (≥ 16 T).
- CERN budget for high-field magnets doubled in 2020 Medium-Term Plan (~200 MCHF over ten years)
- Materials:
  - NbTi (LHC) - limited to max. fields of ~8 T
  - Nb3Sn (HL-LHC, FCC-hh) – could double field achievable to ~16 T. Goal: ~20 T for HTS inserts
  - HTS (SppS) – early stage R&D, could have significant cost savings over current HTS



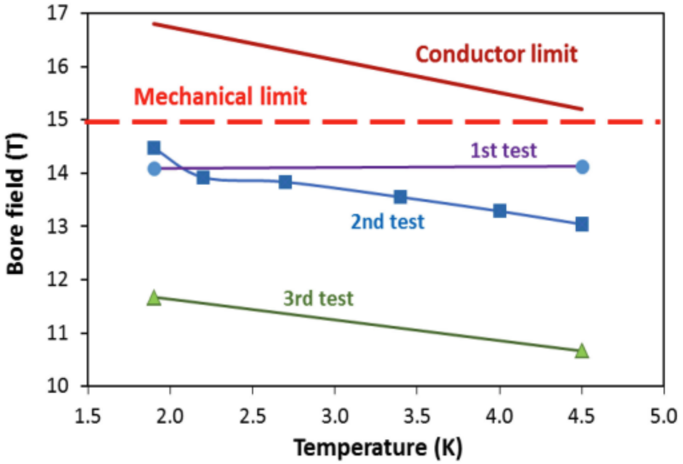
Recent achievements in this area

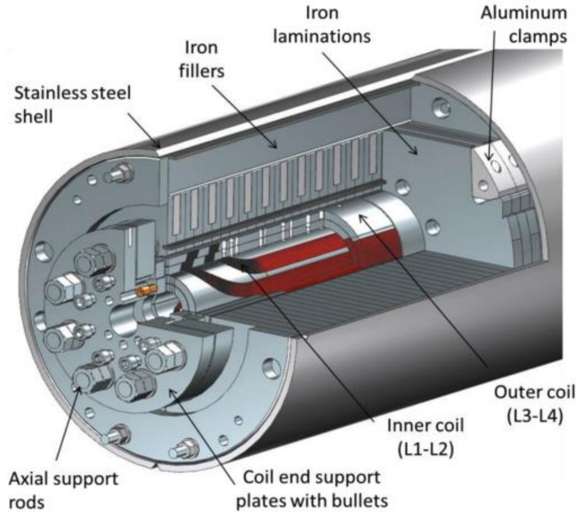
FRESCA2, with a 100 mm bore Nb_3Sn dipole, achieved a **world-record field** of **14.6 T** at 1.9 K.



G. Willering et al (2019) IEEE Transactions on Applied Superconductivity, PP(99):1-1

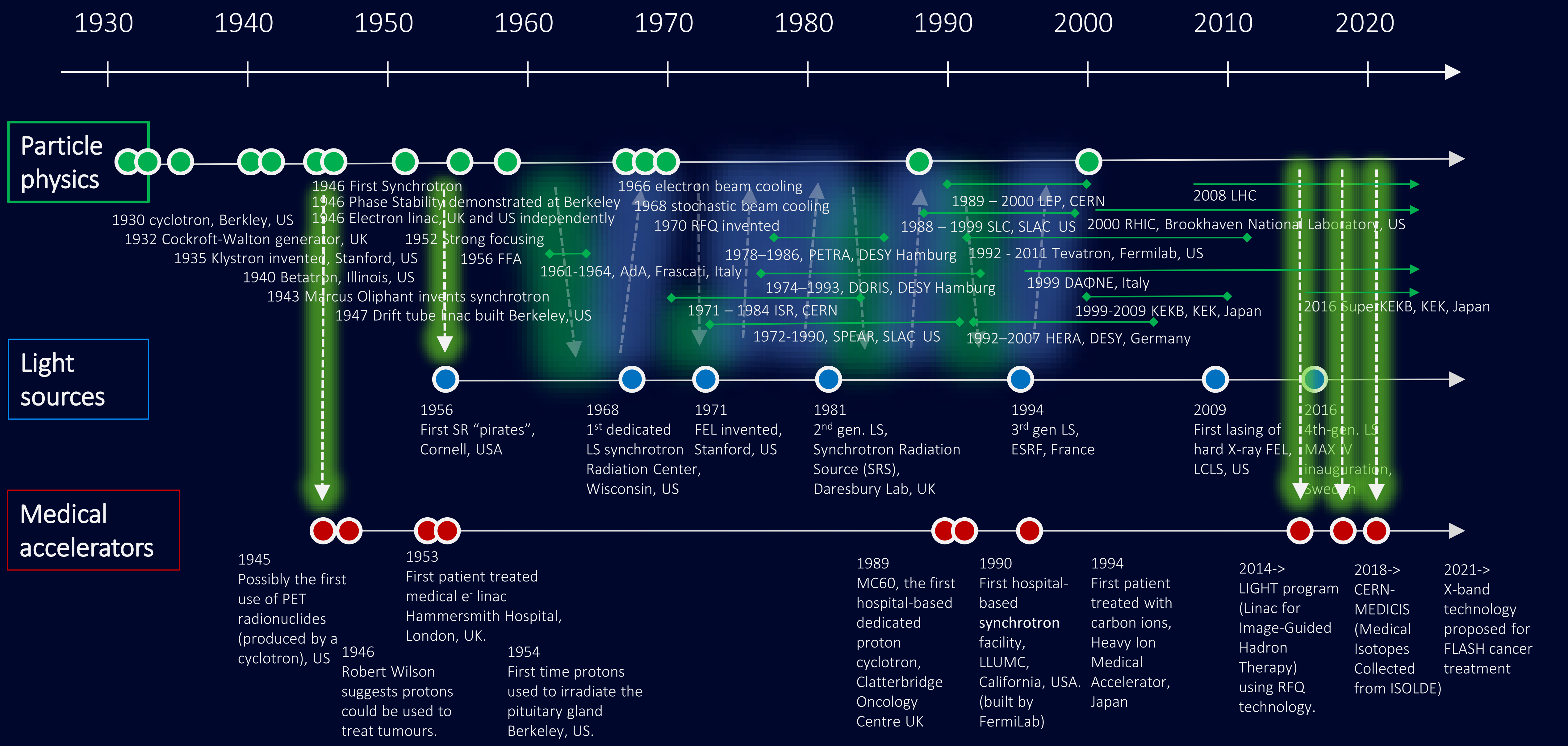
The US Magnet Development Program (MDP) tested a Nb_3Sn dipole demonstrator with 60 mm aperture, reached a similar field, of **14.5 T** at 1.9 K.





A. V. Zlobin et al (2021) Transactions on Applied Superconductivity, Vol. 31, No. 5

A scattered history of particle accelerators



Summary

- Long term goal: world-leading HEP infrastructure for 21st century to push particle-physics precision and energy frontiers far beyond present limits
- We are not short on ideas, with a variety of accelerator options exist for a variety of particles.
- As with any long-term project, it can be difficult to predict what the future holds.
- I hope we continue this theme of curiosity-driven science leading to unexpected outcomes. Accelerators are one bridge from fundamental exploratory science to applied research and high-impact societal benefit.

Slide by Michael Benedikt

Electron Ion Collider (EIC)

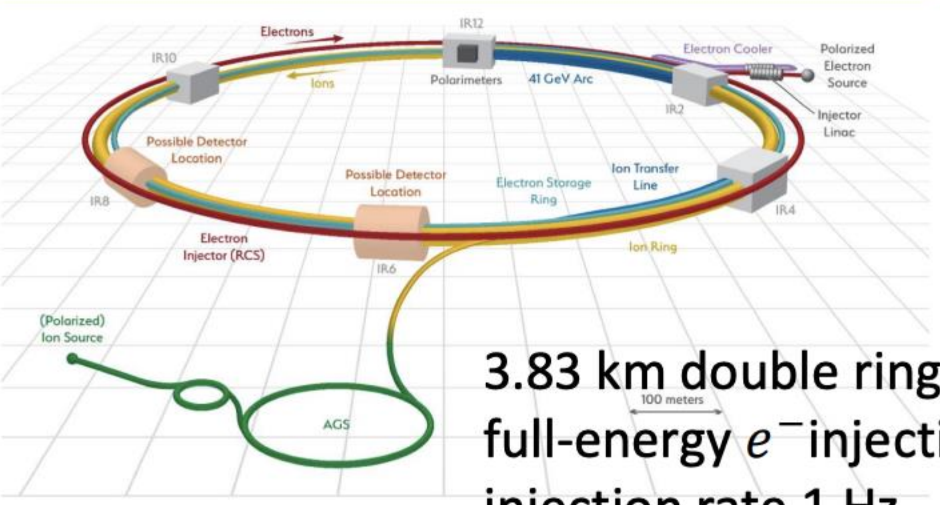
US EIC Electron Storage Ring similar to, but more challenging than, FCC-ee

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.

EIC will start beam operation about a decade prior to FCC-ee

The EIC will provide another invaluable opportunity to train the next generation of accelerator physicists on an operating collider, to test hardware prototypes, beam control schemes, etc.



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

	EIC	FCC-ee-Z
Beam energy [GeV]	10 (18)	45.6 (80)
Bunch population [10^{11}]	1.7	1.7
Bunch spacing [ns]	10	15, 17.5 or 20
Beam current [A]	2.5 (0.27)	1.39
SR power / beam /meter [W/m]	7000	600
Critical photon energy [keV]	9 (54)	19 (100)

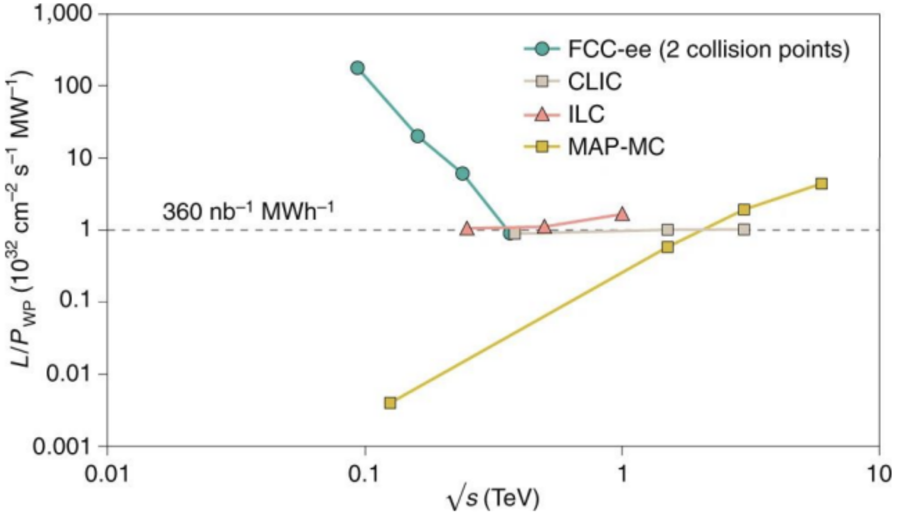
Slide by Michael Benedikt

sustainability and carbon footprint studies

FUTURE CIRCULAR COLLIDER

highly sustainable Higgs factory

luminosity vs. electricity consumption



Thanks to twin-aperture magnets, thin-film SRF, efficient RF power sources, top-up injection

optimum usage of excavation material

int'l competition "mining the future®"

https://indico.cern.ch/event/1001465/

FCC-ee annual energy consumption ~ LHC/HL-LHC

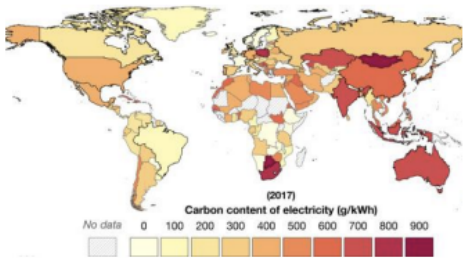
120 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	293					1005644	MWh
Downtime operation	42	1008	109					110266	MWh
Hardware, Beam commissioning	30	720		139				100079	MWh
MD	20	480			177			85196	MWh
technical stop	10	240				87		20985	MWh
Shutdown	120	2880					69	199872	MWh
Energy consumption / year	365	8760						1.52	TWh
Average power								174	MW

J.-P. Burnet, FCC Week 2022

incl. CERN site & SPS

CERN Meyrin, SPS, FCC	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Energy consumption (TWh/y)	1.82	1.92	2.09	2.54

powered by mix of renewable & other C-free sources



https://www.carbonbrief.org/

France & Switzerland: already ~ lowest electricity C content in the world (90% C-free)