Future Collider Concepts to Reach the High Energy Frontier

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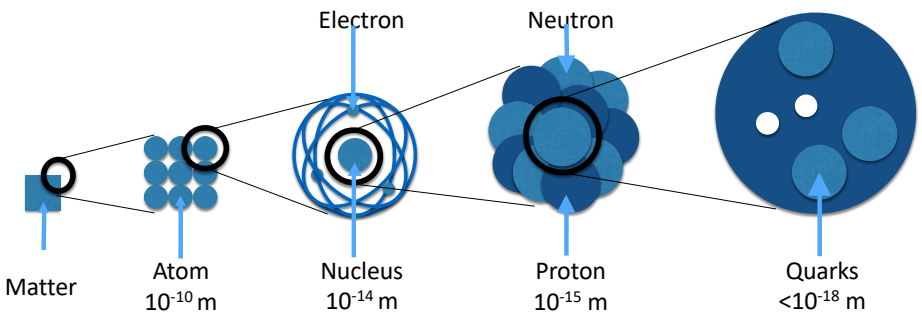
Why Do We Need Particles at even Higher Energies?

- **To study the smallest building blocks of matter**



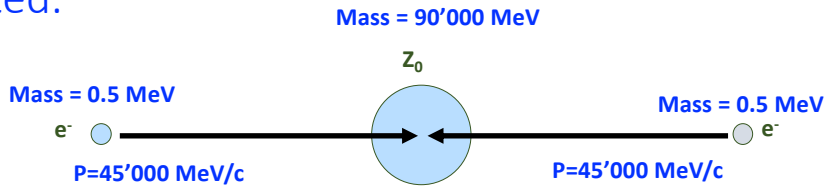
Optical Microscope:	10^{-6} m
Radioactive Source:	10^{-14} m
LHC:	$<10^{-21}$ m

Higher particle energy → smaller wavelength → smaller structures

→ Accelerators are Super-Microscopes !

- **To produce massive particles (e.g. W, Z, top, Higgs) that are either unknown or predicted by theories.**
  - The study of the smallest building blocks of matter with high energy particle colliders and the production of new massive particles is connected.

$$E = mc^2$$

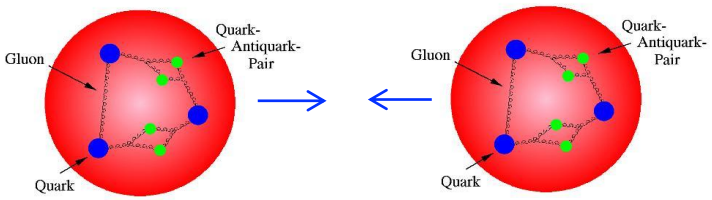


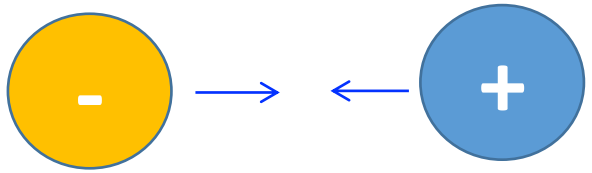
→ Accelerators are powerful tools for particle discoveries and precision measurements!

Which Particle Types to Accelerate?

- **Need stable charged partices:** protons, electrons, (muons), ions → most used: electrons and protons

- **Proton** collisions:
  - Mix of quarks, anti-quarks and gluns: variety of processes
  - Parton energy spread
  - QCD process large background sources
- **Electron/positron** collisions: elementary particles
  - Collision process known
  - Well defined energy
  - Background from other physics limited
- **Photon** collider:
  - e+/e- colliders can be turned to gamma-gamma by inverse compton scattering using lasers
- **Muons**: elementary particle, but lifetime only 2.2 µs





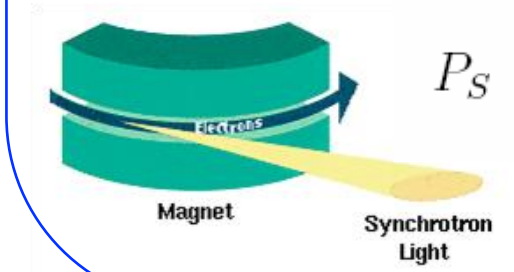
Which Accelerator Type: Circular versus Linear

Circular colliders:

Allows to re-collide bunches for hours.

Limitations:

- For hadron colliders: The limitation is magnet strength.
- For electron-positron colliders: Circular machines are limited by synchrotron radiation.



$$P_S = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

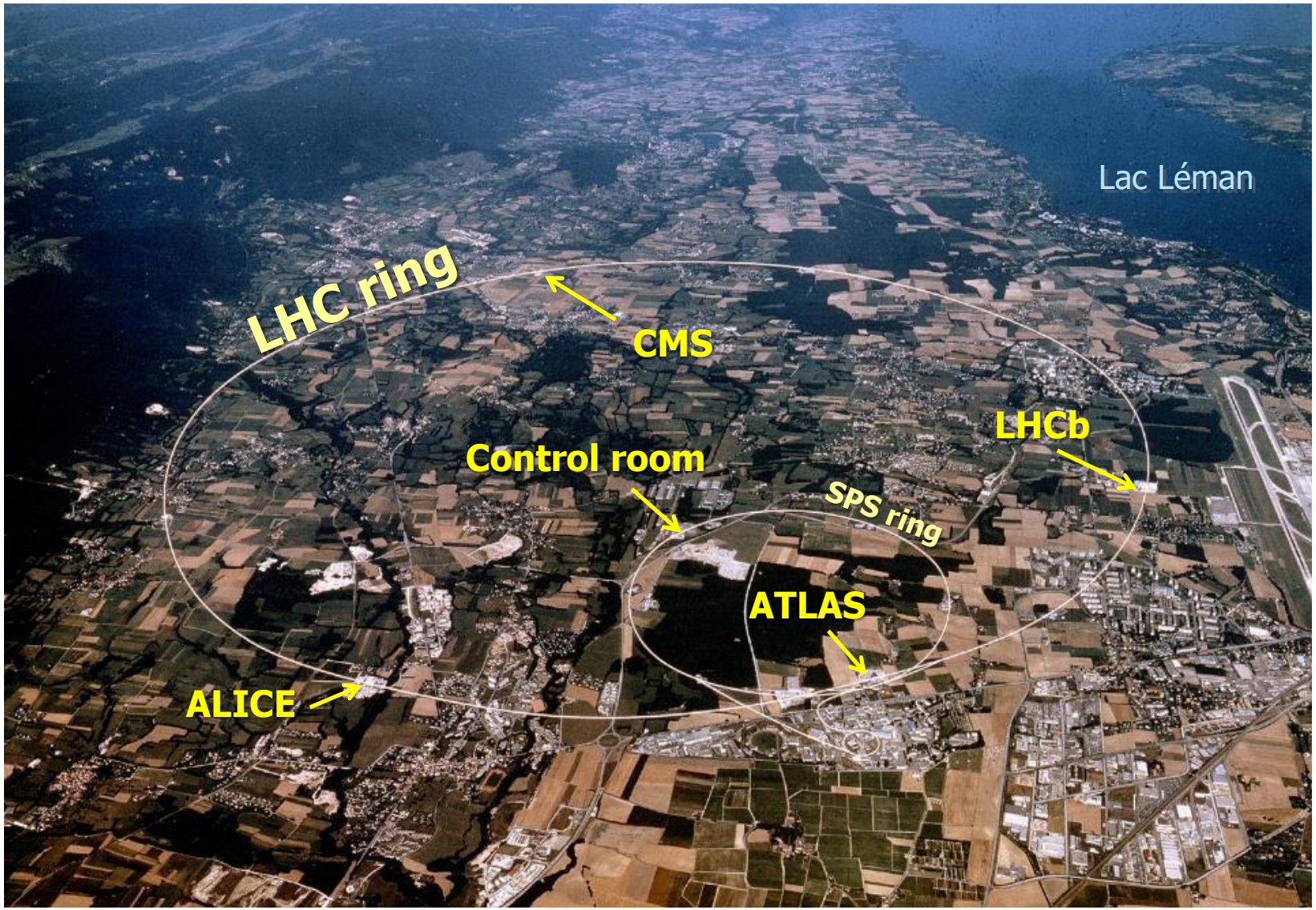
Linear colliders:

Favorable for acceleration of low mass particles to high energies.

Limitations:

- Linear machines accelerate particles in a single pass. The amount of acceleration achieved in a given distance is the *accelerating gradient*. This number is limited to 100 MeV/m for conventional copper cavities.

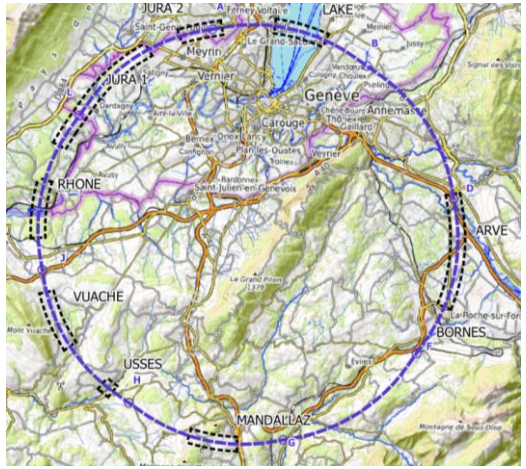
The Large Hadron Collider



- 27 km circumference
- Collision of protons (or lead) at 13.6 TeV c.o.m.
- High Luminosity upgrade in 2026-2028 to increase the integrated luminosity by a factor of 10
- Operating until 2042

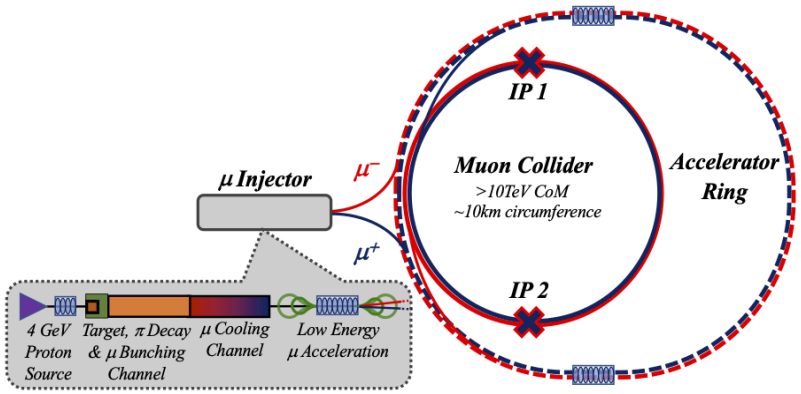
Future Colliders

Circular colliders



FCC at CERN
91 km, 380 GeV (e+e-), 100 TeV (pp)

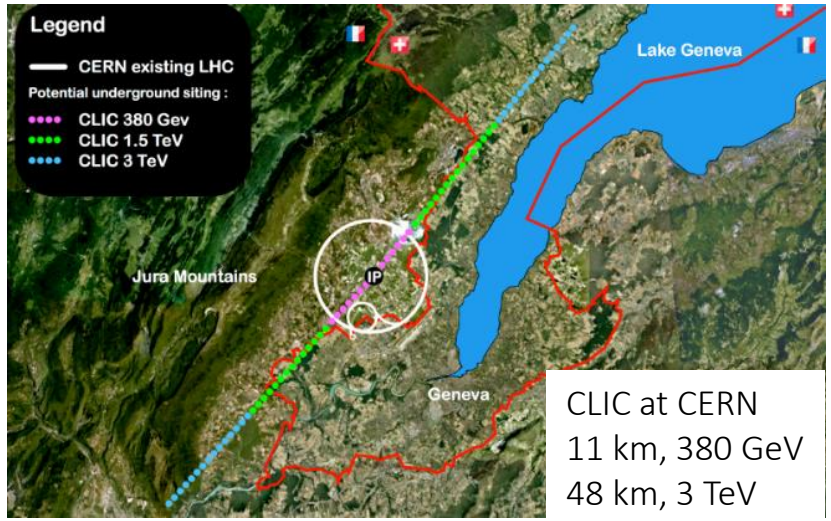
CEPC-SppC in China
100 km, 240 GeV (e+e-), 75-100+TeV (pp)



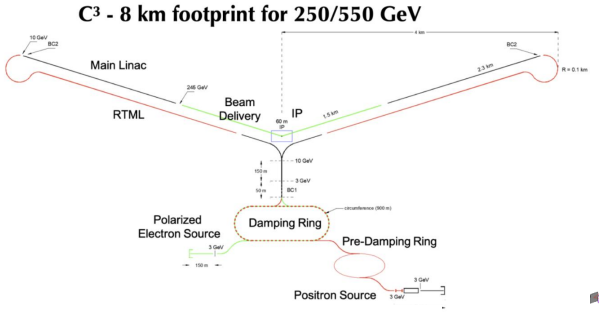
Muon Collider, 10 km, 10 TeV (μ+μ-)

Linear colliders

ILC in Japan
20 km, 250 GeV
50 km, 1 TeV

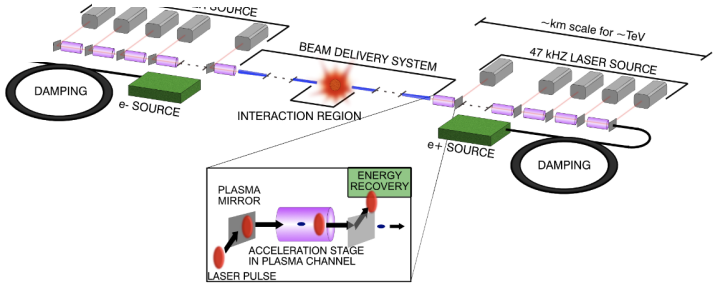


CLIC at CERN
11 km, 380 GeV
48 km, 3 TeV



Cool Copper Collider, C^3
8 km, 250/550 GeV

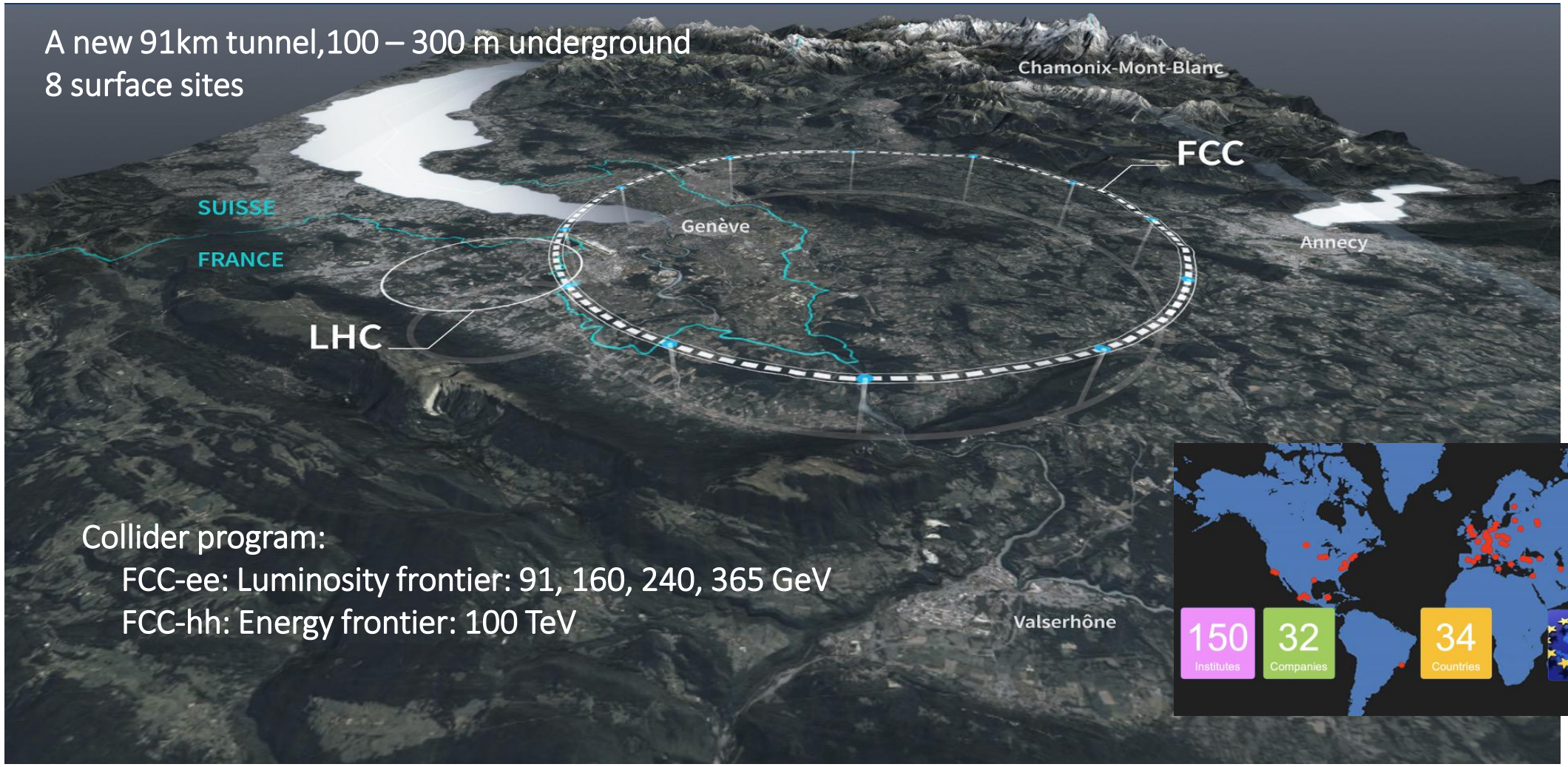
Colliders based on plasma wakefield
~4.5km, 1 TeV



Future Circular Collider

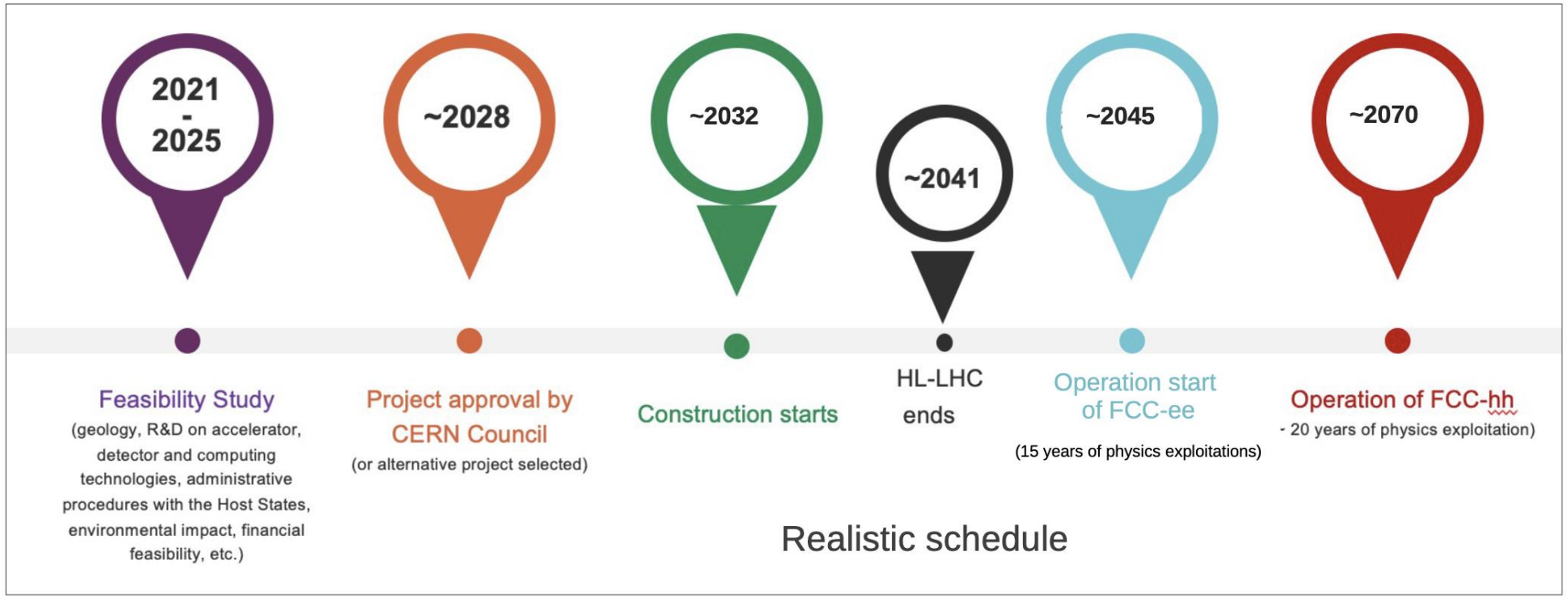
Future Circular Collider, FCC

Inspired by successful LEP – LHC program at CERN
Comprehensive long-term program maximizing physics opportunities



Collider program:
- FCC-ee: Luminosity frontier: 91, 160, 240, 365 GeV
- FCC-hh: Energy frontier: 100 TeV

FCC Timeline



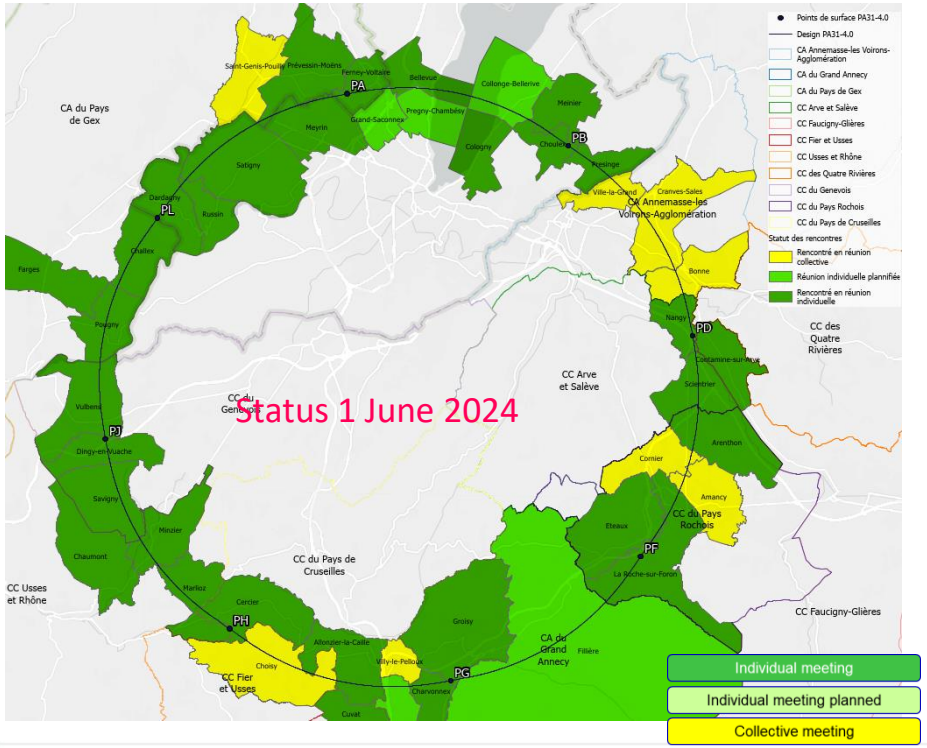
Feasibility Study by March 2025 as input for the ESPP update

→ demonstrate geological, technical, environmental and administrative feasiblity of the tunnel and surface areas and optimization of placement and layout of the ring

→ Optimise design of the colliders, injector chains, detectors and physics concept.

→ Develop consolidated cost estimate and funding and organisational models based on discussions with Council.

FCC Challenge: Optimized Placement and Layout

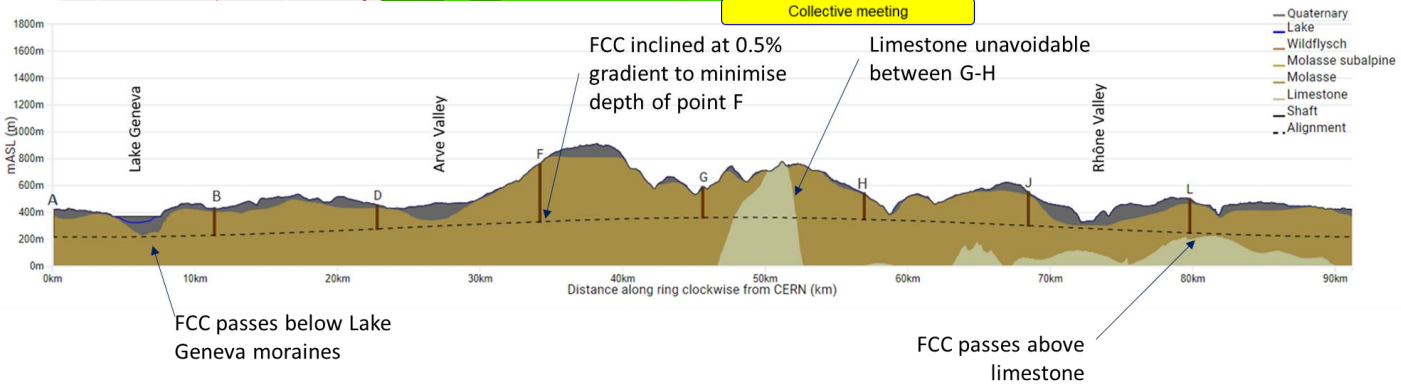


8 surface sites <40 ha total land use
Possibility for 4 experiment sites
All sites close to road infrastructures (< 5 km of new road)
Vicinity of several sites to 400 kV grid lines

Drilling work on the lake

- Regional implementation development:
  - Meetings with municipalities in F(31) and CH (10)
- Site investigations to identify location of geological interfaces
  - Molasse layer vs moraines/limestone
- Excavation material strategy

Sondage A89 (2007) incliné de 45° de 125 ml (surface plateforme estimée : 12 x 12 m soit environ 150 m²)



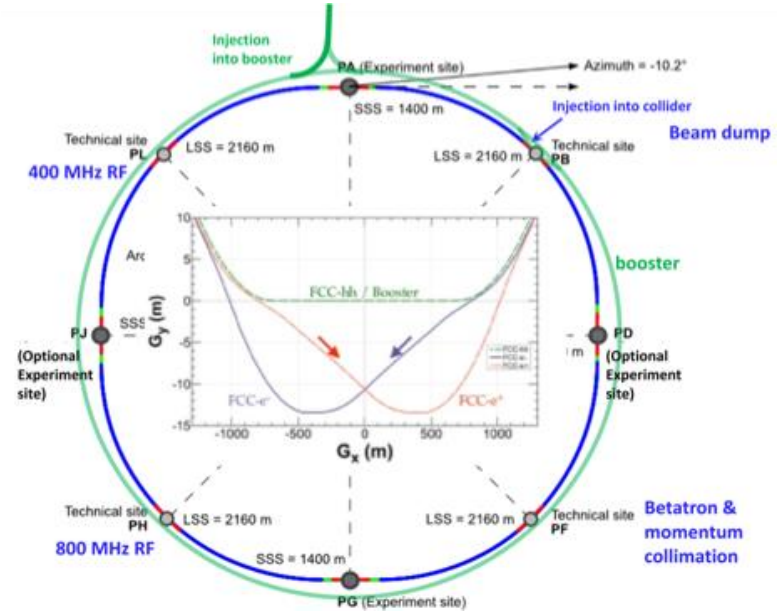
2023: "OpenSky Laboratory" project: Objective: Develop and test an innovative process to transform sterile "molasse" into fertile soil for agricultural use and afforestation. Near LHC P5. Duration: (2024-2027)

Shaft depth:

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

Stage 1: FCC-ee

- Double ring e^+e^- collider ~90 km.
- Follows footprint of FCC-hh, except around Ips.
- Asymmetric IR layout & optics to limit synchrotron radiation towards the detector.
- Synchrotron radiation power 50 MW/beam at all beam energies.
- Top-up injection (0.1 Hz at all energies) requires booster synchrotron in collider tunnel.



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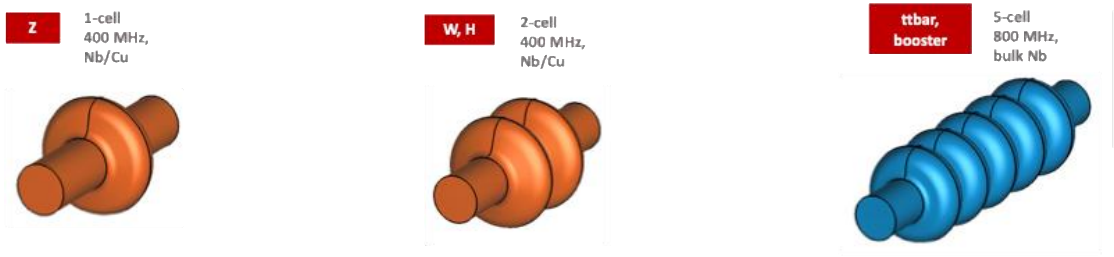
91, 160, 240, 365 GeV:
high-intensity electron positron collider for detailed study of the Z(10^6), W (10^6), Higgs boson (10^6), top quark (10^6).
➔ **Indirect sensitivity to new physics up to ~70 TeV (> 10 times LHC)**

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	≥5.0	1.25
total integrated luminosity/IP/year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

FCC-ee Challenges

50 MW synchrotron radiation/beam → Optimized RF system to increase energy efficiency



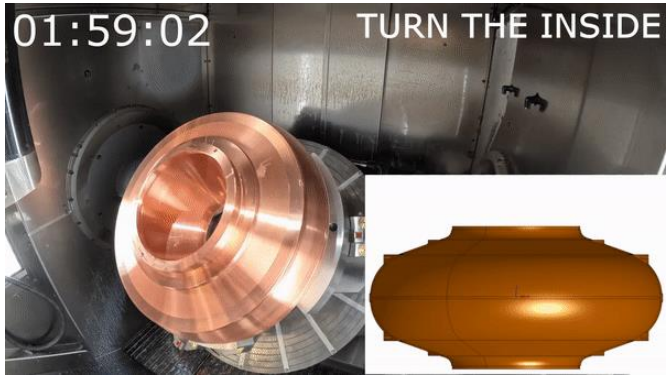
366 cryomodules and 1464 cavities, of which a quarter are based on Nb/Cu technology and the rest on bulk niobium.

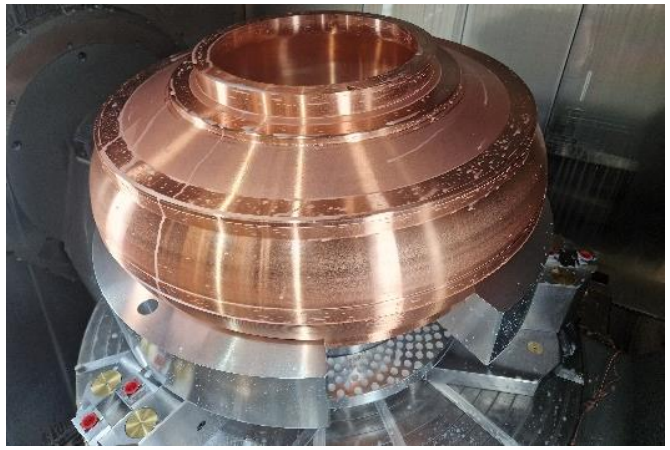
→ **Nb on Cu 400 MHz cavities** (KEK as R&D partner), seamless cavity production, coating techniques.

→ **Bulk Nb 800 MHz cavities,** surface treatment techniques.

→ **RF power source** R&D in synergy with HL-LHC. → boosting the efficiency of commercially available klystrons (TRL9) above 80% .

400 MHz
monoblock prototype





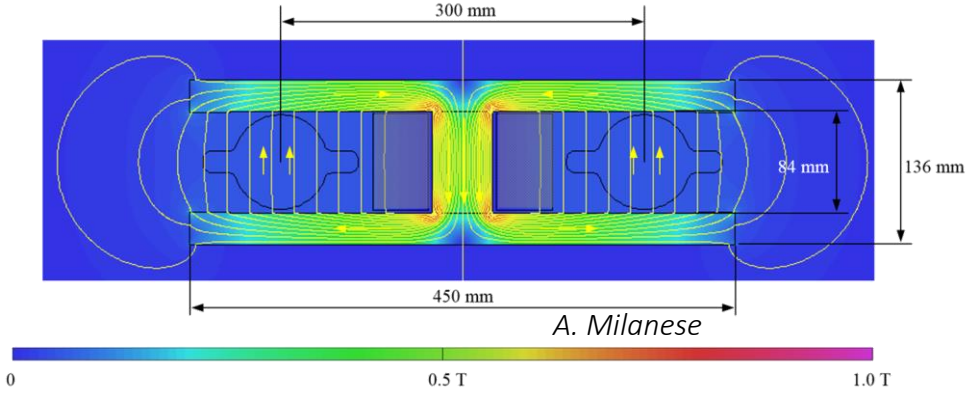
5-cell 800 MHz cavity development
collaboration with JLAB

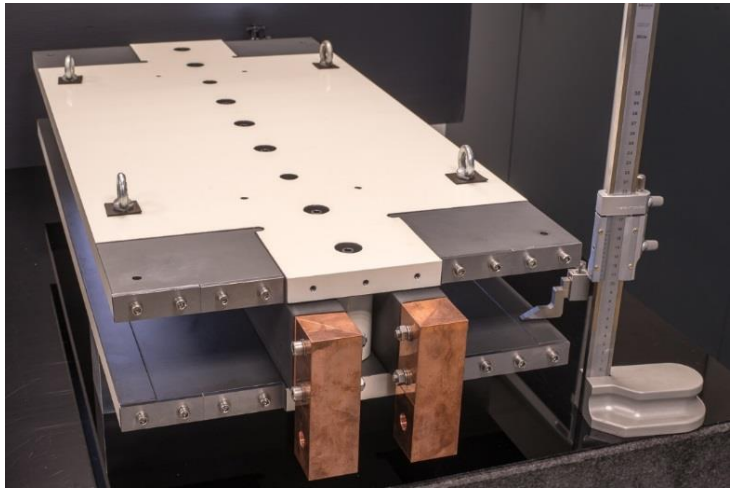
➔ Development also important for Energy Recovery Linacs!

FCC-ee Key Technologies

Prototypes of FCCee low power magnets

Energy efficient twin aperture arc dipoles:
16 MW (at 175GeV), with Al busbars

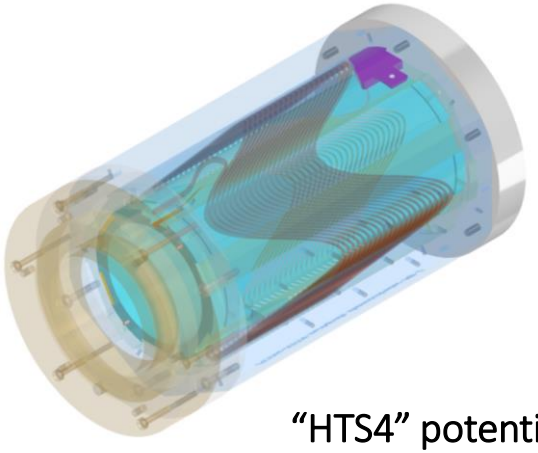


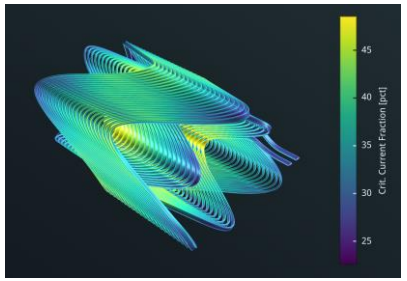


HTS option for FCCee arc quads and sextupoles:

"HTS4" project within CHART collaboration

- Nested SC sextupole and quadrupole.
- HTS conductors operating at around 40K.
- Cryo-cooler supplied cryostat.
- Produce a ~1m prototype by 2026.





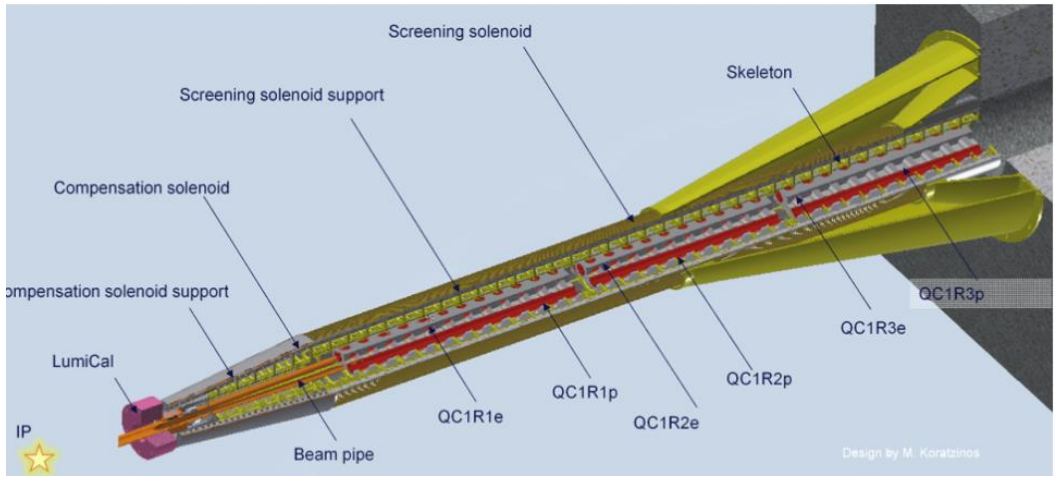
"HTS4" potential

- Power saving
- Reduced length
- Optics flexibility

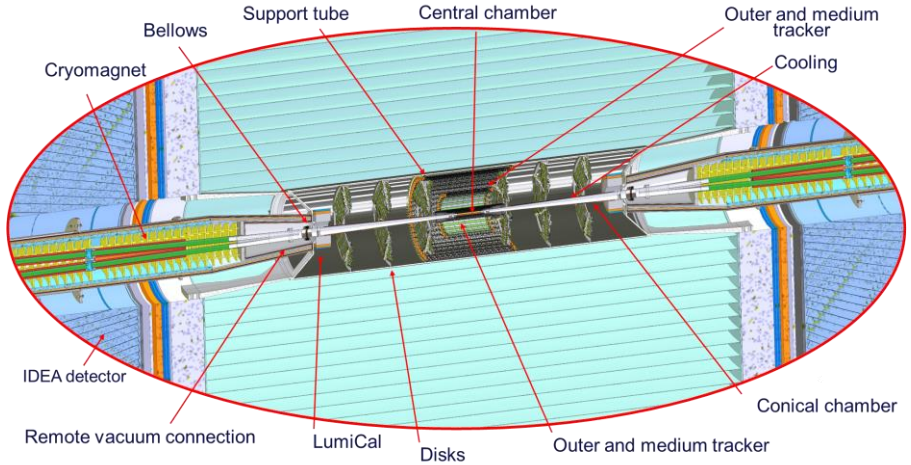
Even more efficient alternative magnet designs are being explored.

FCC-ee Machine Detector Interface

Challenge: L* is only 2.2 m ➔ Final focusing magnets (SC!) are deep inside the FCC-ee detectors.



Machine		FCCee	CEPC	ILC	SuperKEKB
Crossing-angle	mrad	30	33	14	83
L*	m	2.2	1.9	3.5	0.935
Vertical β_y* at IP	mm	0.7-1.6	0.9-2.7	0.4	0.3
Detector soln field	T	2/3	3	3.5/5	1.5
Detector stay clear	mrad	100	118/141	90	350/436
Two beam ΔX at L*	mm	66	62.7	49	77.6
He temperature	K	1.9	4.2	4.5	4.5

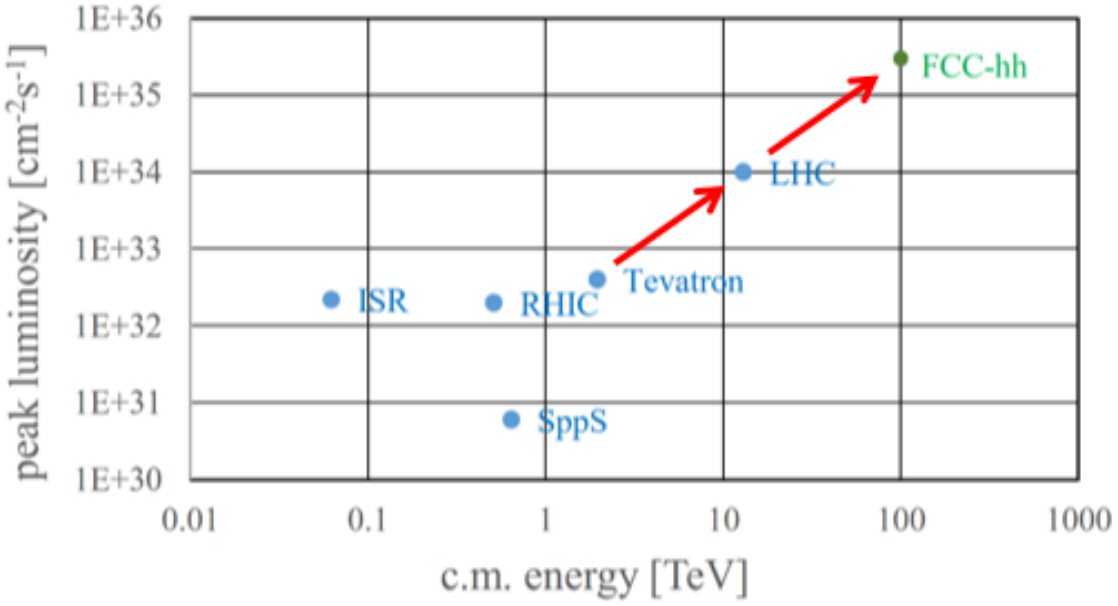


Event-rate (max 100kHz at Z) and radiation are minor problems at FCC-ee.

Technology developed for low-radiation environment like heavy-ion experiments are highly relevant for FCC-ee.

Stage 2: FCC-hh

- **Order of magnitude** performance increase in both energy & luminosity
- **100 TeV** cm collision energy (vs 14 TeV for LHC), heavy-ion (Pb) collider at 39 TeV ➔ Direct discovery potential for new physics up to ~40 TeV (~10 times the LHC)
- **Integrated Luminosity of 20 ab^{-1}** per experiment collected over 25 years of operation (vs 3 ab^{-1} for HL-LHC)

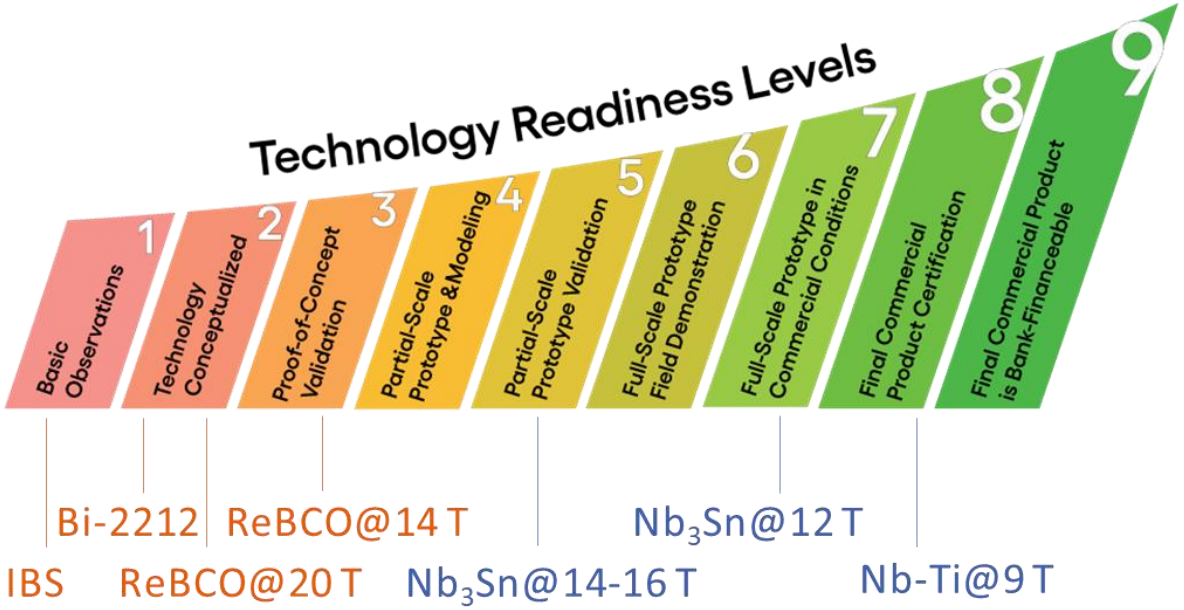


parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

FCC-hh Key Challenge – Magnets

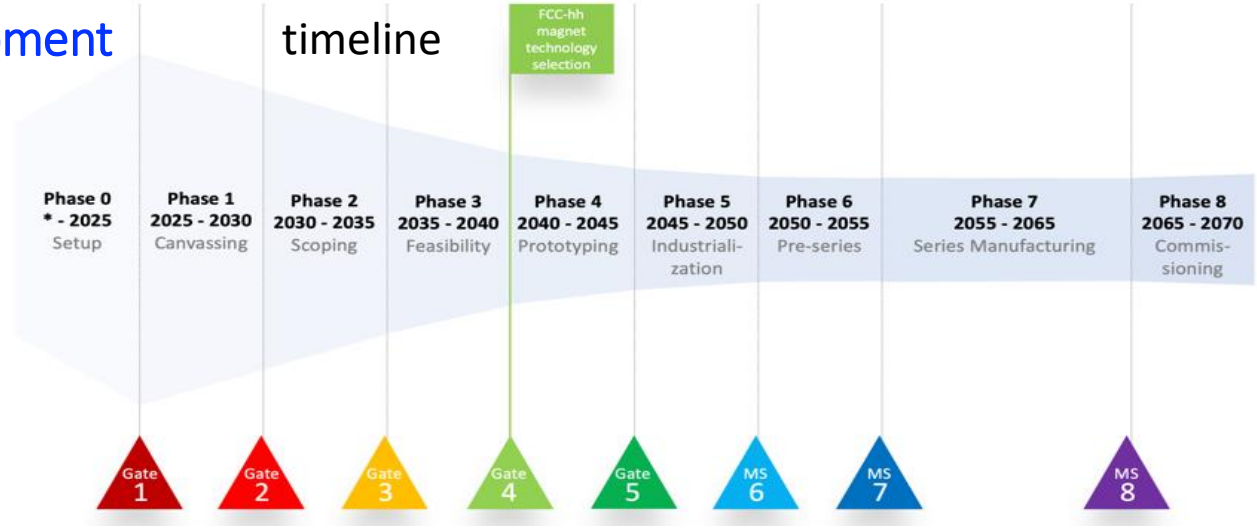
Magnet development is part of the ESPP accelerator R&D roadmap

- **FCC-hh magnets – main R&D activities:**
  - Materials: Goals:
    - **~16 T for Nb3Sn,**
    - **at least ~20 T for HTS inserts**
  - Magnet technology: engineering, mechanical robustness, insulating materials, field quality
  - Production of models and prototypes: demonstrate material, design, engineering choices, industrialisation, costs
  - Infrastructure and test stations: for tests up to ~20 T and 20-50 kA



FCC-hh Challenges

➔ FCC-hh magnet development timeline



With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

➔ Energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …
➔ Power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
➔ Stored beam energy: ~ 9 GJ → machine protection

➔ **Pile-up in the detectors: ~1000 events/Xing**

Muon Collider

Muon Collider

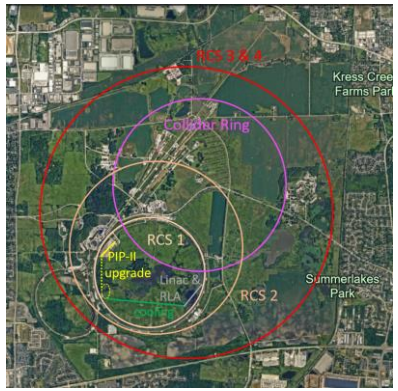
Motivation:

- Previous studies in the US, experimental program in the UK and alternatives studies by INFN
- New strong interest in high energy, high luminosity lepton collider
  - Combination of precision physics and discovery reach
- Muon colider promises sustainable approach to the energy frontier
  - Limited power consumption, cost and land use
- Technology and design has advanced in the past years
  - No unsurmountable obstacles

Goal:

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

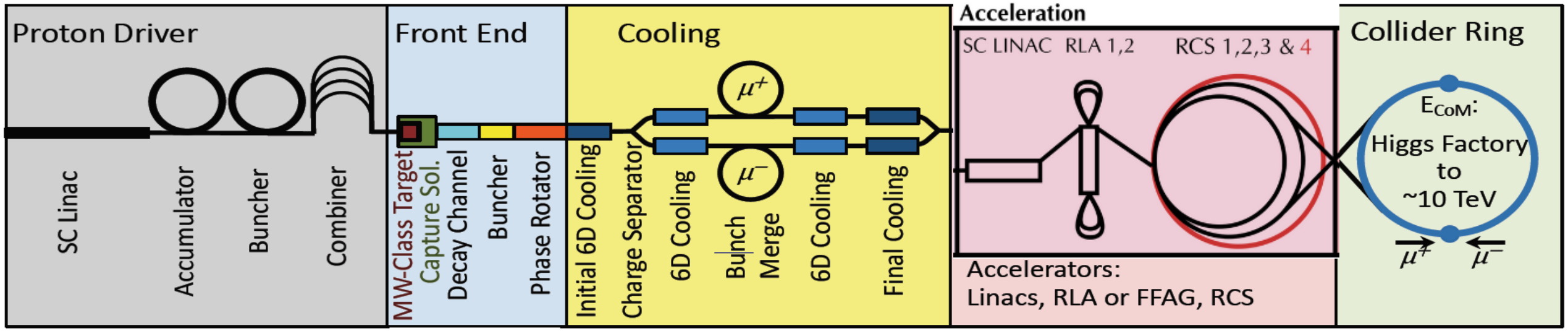
- Staged approach
- Collider operational in 2050



Organization:

- International Muon Collider Collaboration, IMCC
  - Support from the EU → MuCol
- Particle Physics Prioritisation Panel (P5) endorses muon collider R&D: **"this is our muon shot".**
  - recommend joining the IMCC
  - Consider FNAL as a host candidate
  - Addendum to CERN-DoE-NSF agreement is in preparation

Muon Collider



Short, intense proton bunch

Protons produce pions which decay into muons, muons are captured

Ionisation cooling of μ in matter

Acceleration to collision energy

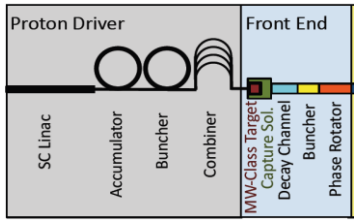
Collision

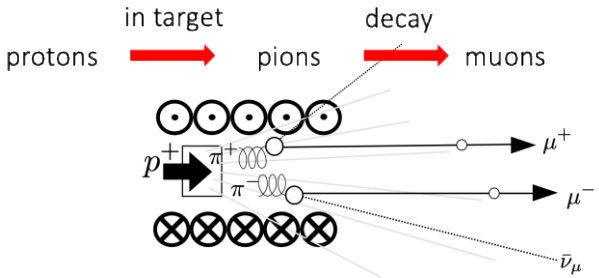
Parameter	Symbol	Value
Beam energy	E	$5000\ GeV$
Luminosity per IP	$\mathcal{L}$	$\sim 20 * 10^{34} cm^{-2}\ s^{-1}$
Bunch population	N_p	$1.8\ *\ 10^{12}$
Repetition rate	f_r	$5\ Hz$
Normalized transverse rms emittance	$\varepsilon_{nx} = \varepsilon_{ny}$	$25\ \mu m$
Geometric transverse rms emittance	$\varepsilon_{gx} = \varepsilon_{gy}$	$0.528\ nm$
Longitudinal geometric rms emittance	ε_L	$70\ mm$
Rms bunch length	σ_z	$1.5\ mm$
Relative rms energy spread	$\delta = \frac{\sigma_E}{E}$	$0.1\ \%$
Beta function at IP	$\beta_x^* = \beta_y^*$	$1.5\ mm$
Circumference	C	$\sim 10\ km$

➔ **Design is fully driven by short muon lifetime, 2.2 μs:** ionization cooling, fast acceleration, high RF gradients and high field magnets!

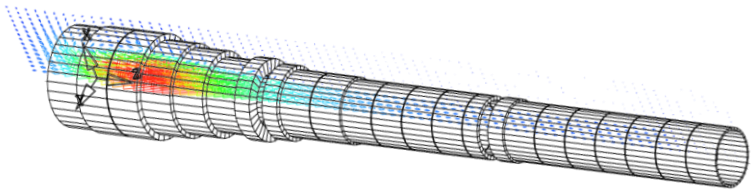
Muon Collider Challenges – Target

→ 5 GeV proton beam
→ 2 MW = 400 kJ x 5 Hz

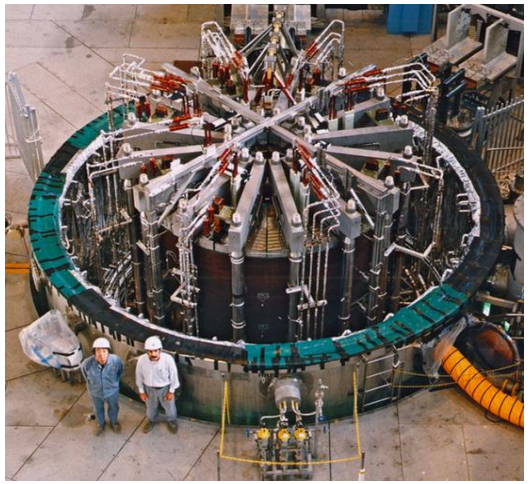




Target solenoid design ongoing
Either large bore 20 T HTS or 15 T LTS with 5 T insert

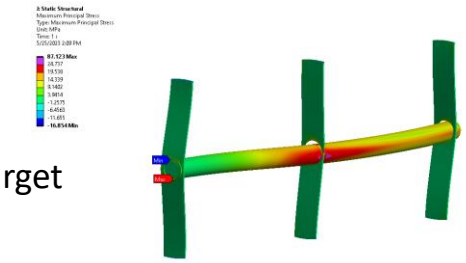


Large bore, high field solenoid
Nb_3Sn or HTS



ITER Central Solenoid Model Coil
13 T in 1.7 m (LTS)

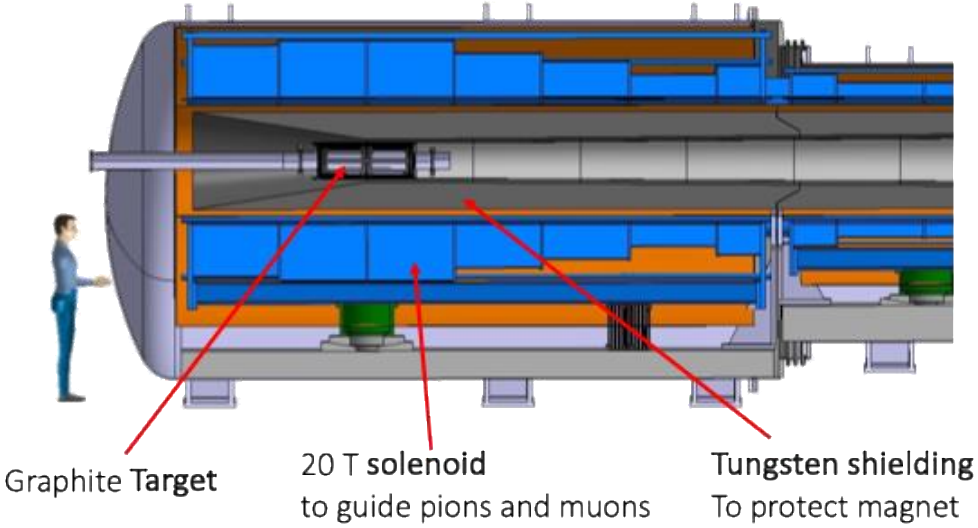
2 MW target, FLUKA studies:
stress in target, shielding, vessel is OK.
Cooling OK.
Look closer at window.



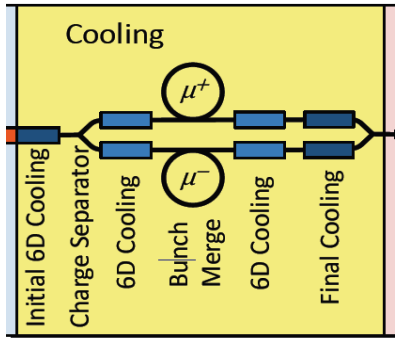
Target

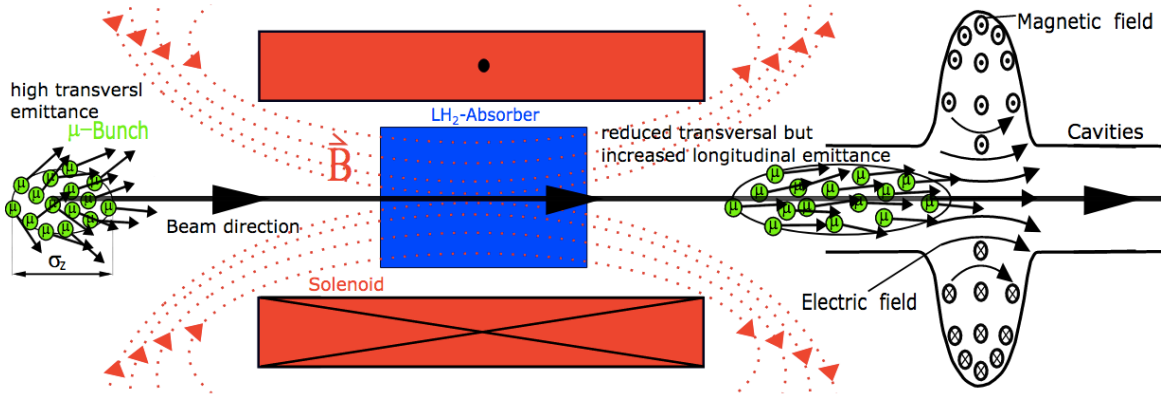
Operation at 2000 °C to maximise stress resistance

400 kJ protons to produce 5 x 10^{13} captured muon pairs

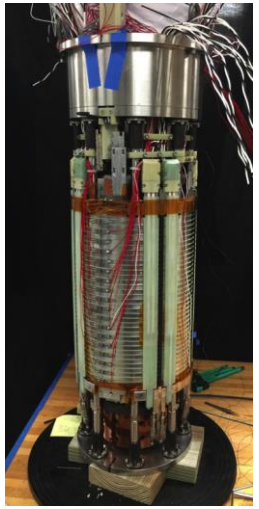


Muon Collider Challenges – Cooling

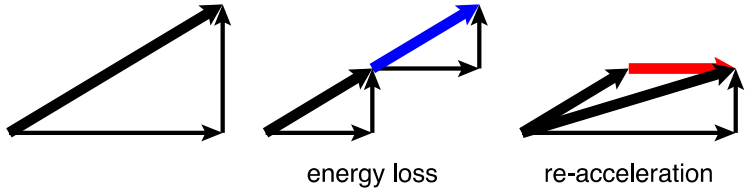




Highest field solenoids:

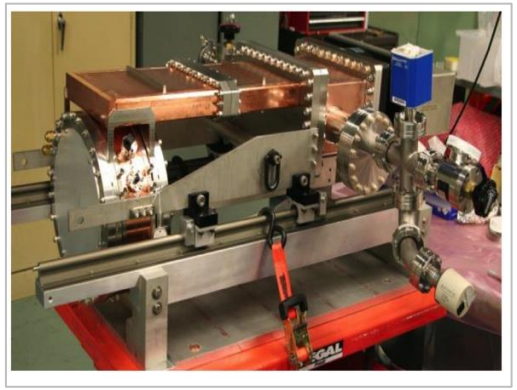


32 T with low temperature HTS



In MICE (UK) : principle demonstrated with no RF
Nature vol. 578, p. 53-59 (2020)

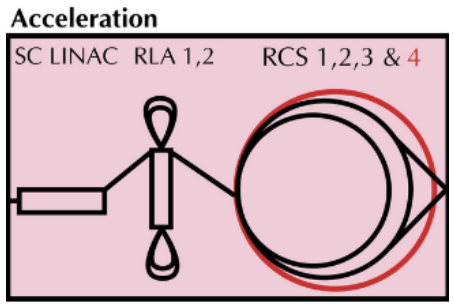
RF cavities in magnetic field



MuCool demonstrated >50 MV/m in 5 T, H2-filled copper, Be end caps

Muon Collider Challenges – Accelerators and Collider

Accelerators:

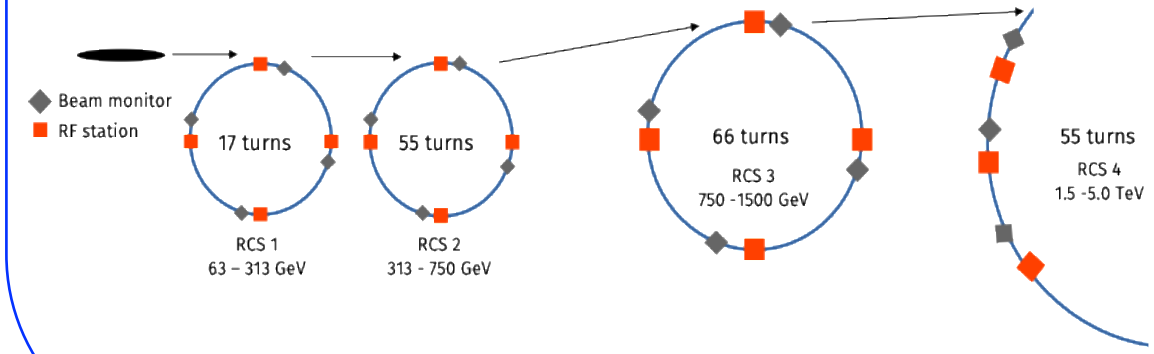


Acceleration time: 10 ms in the four accelerators

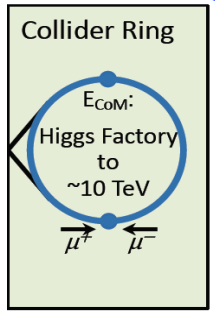
Recirculating linacs, dog-bone shape: MeV to 63 GeV

Racpid cycling synchrotron, RCS:

- Large RF voltage required: 5000 SC TESLA RF cavities
- Fast ramping magnets: e.g. 4200T/s in RCS 1
- RCS2,3 and 4 are hybrid RCS:
  - pulsed normal conducting and fixed field SC magnets.



Collider:



High performance 10 TeV challenges:

Very small beta-function at IP (1.5 mm)

Large energy spread (0.1%)

Maintain short bunches (1.5 mm)

Final focusing quadrupoles:

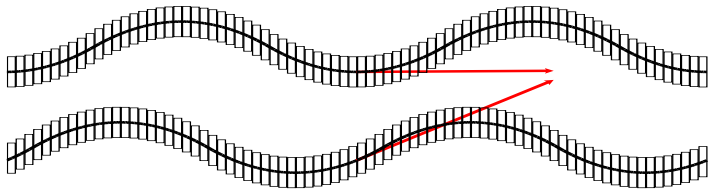
Significant aperture, very high magnetic field (HTS technology).

Minimize circumference and maximize luminosity.

- 10 km ring for 10 TeV : 16 T Nb_3Sn or HTS dipoles
- 20-40 mm tungsten shielding inside magnet to mitigate power loss of 500W/m due to muon decays

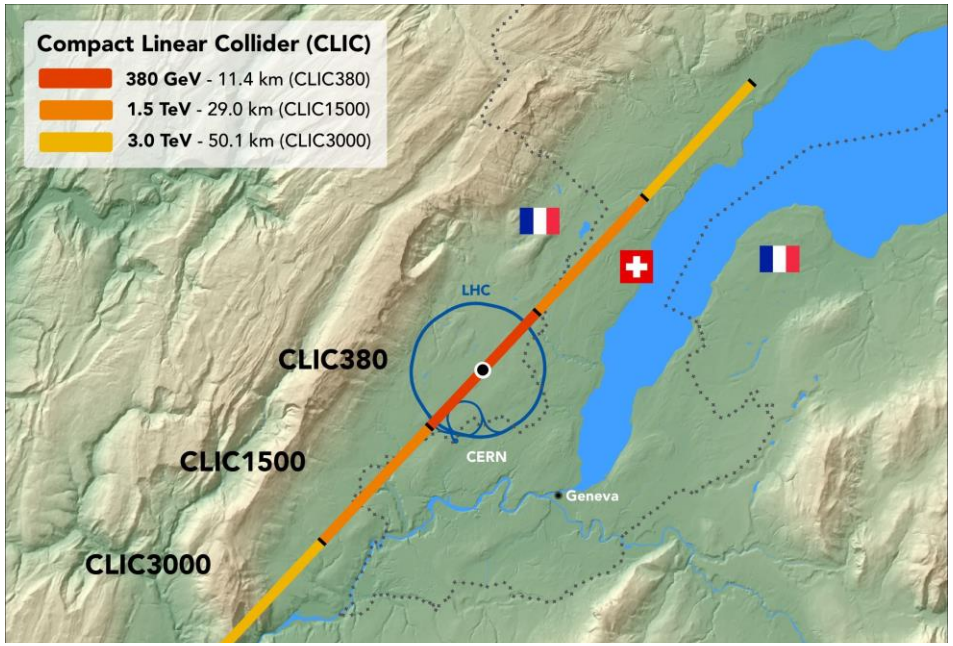
Neutrino flux:

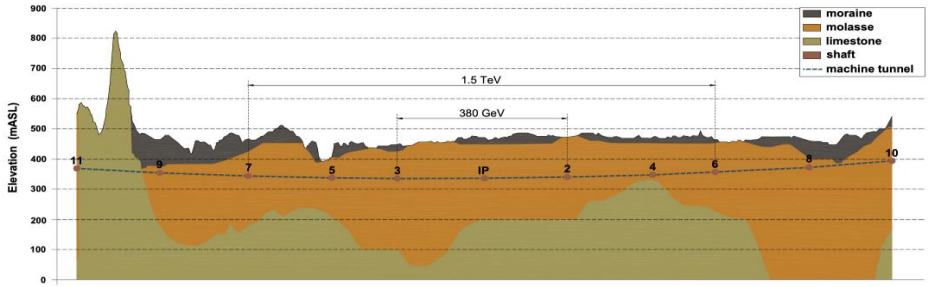
Fewest possible straight sections, mover system



Linear Collider

CLIC, e+e- Linear Collider





- 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, ~11km in its initial phase
- Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)
- Comprehensive Detector and Physics studies done
- 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.
- Project Readiness Report for 2026 ESPPU: 380 GeV + 2 TeV, also 250 GeV @ 100 Hz
    - Performance updates, sustainability aspects, cost update

CLIC

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

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
- **Event-rate similar to FCC-ee**

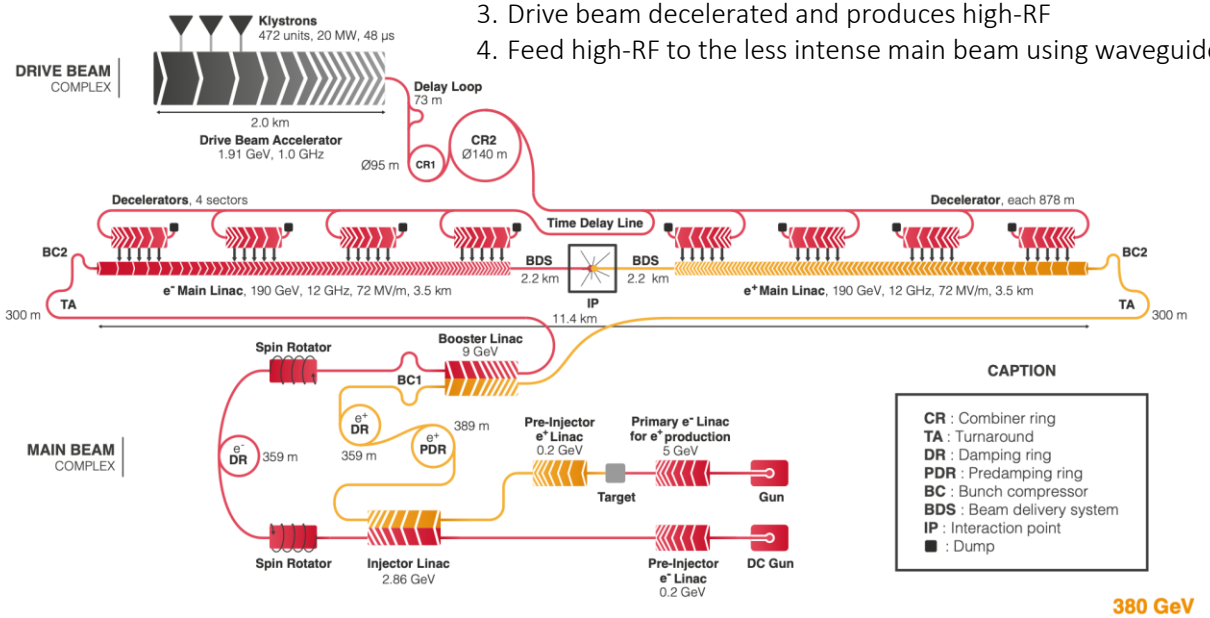
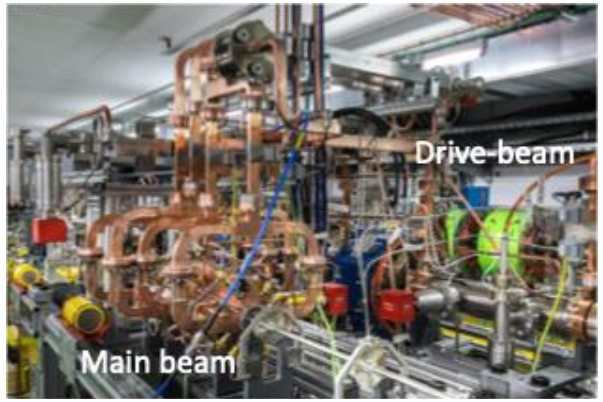


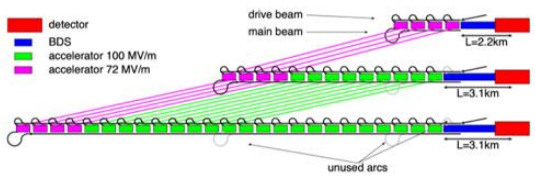
Table 1.1: Key parameters of the CLIC energy stages.

Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	μm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20



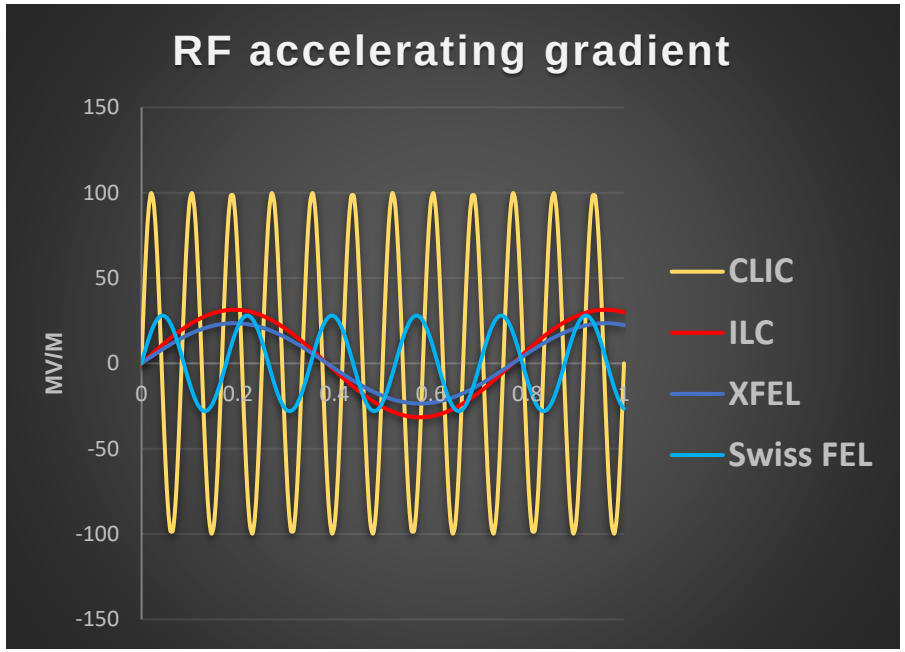
Energy from drive beam is extracted in the PETS in form of powerful RF waves → used to accelerate main beam.

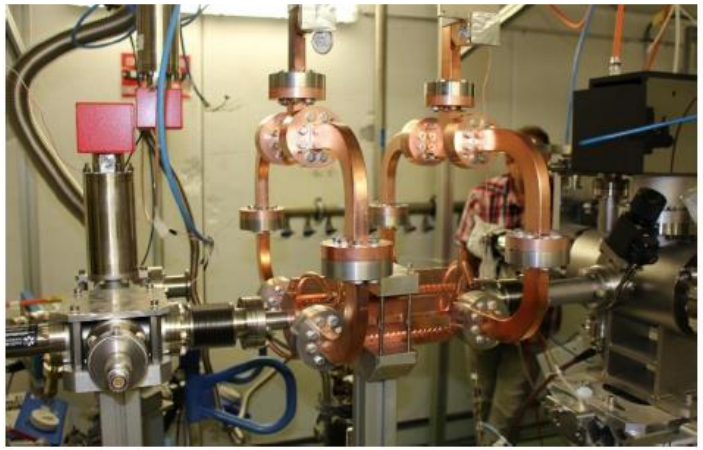
From 380 GeV to 3 TeV:

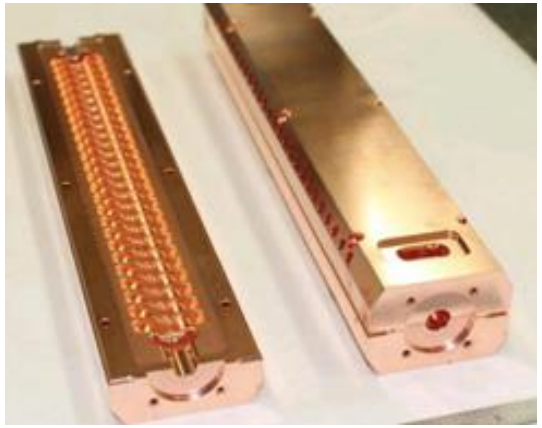


CLIC – High Gradient X-Band Technology

12 GHz → X-band







Test structure

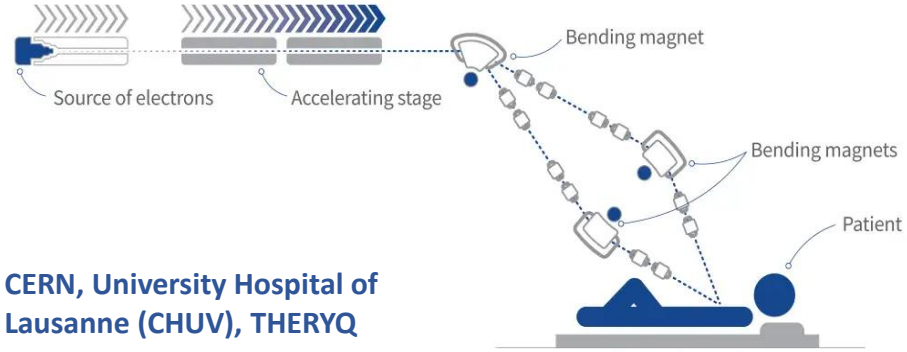
X-band technology readiness: manufacturability and developments driven by use in small compact accelerators for industrial experience.

Compact linacs have many users: research accelerators, medical or industrial linacs.

- Trieste, FERMI: Linearizer
- SwissFEL: Linearizer and PolariX deflector
- SARI: Linearizer, deflectors
- CERN: XBox-1 with CLEAR, accelerator
- DESY: FLASHForward and FLASH2, PolariX deflectors
- SLAC: NLCTA, XTA
- Argonne: AWA

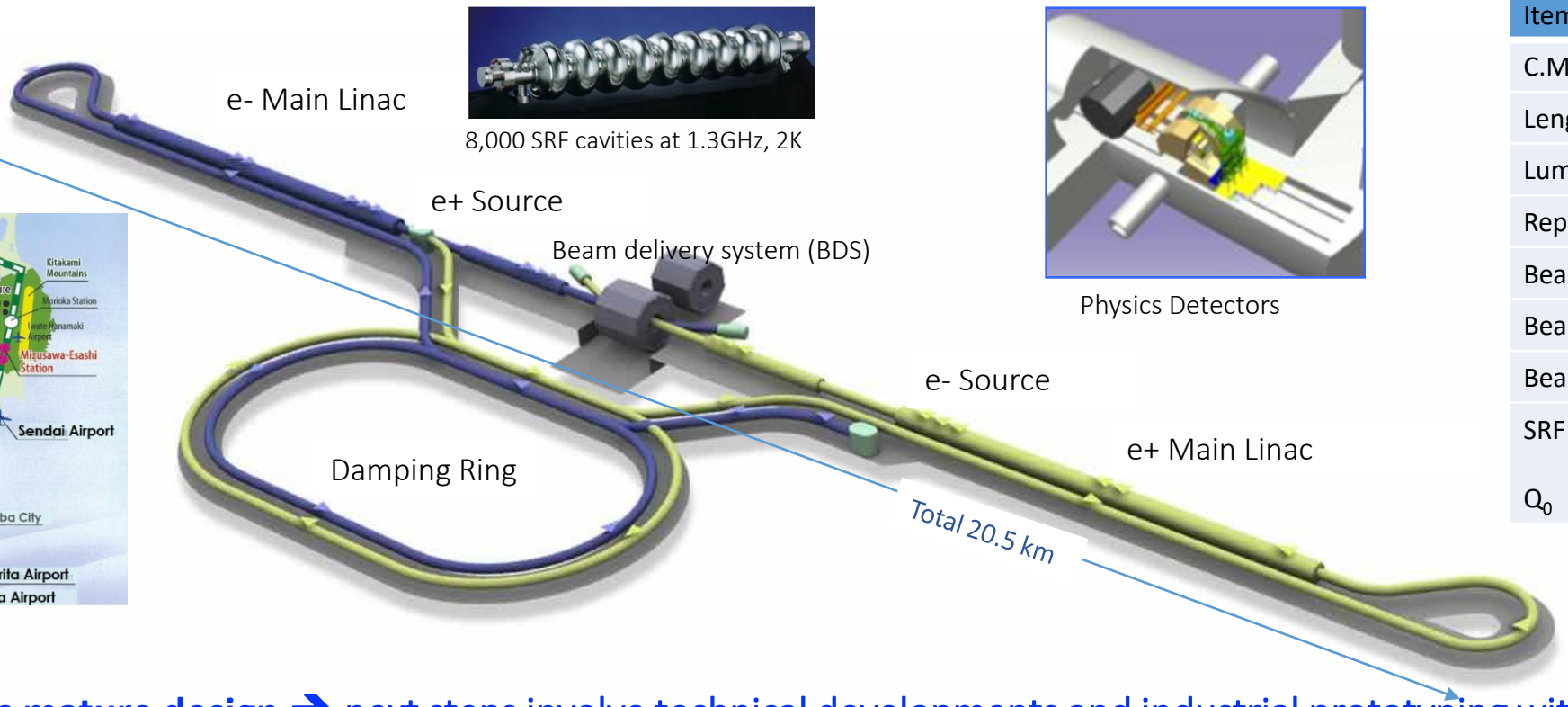
- TU Eindhoven: SMART*LIGHT, ICS
- Tsinghua: VIGAS, ICS
- CERN: AWAKE electron injector
- INFN Frascati: EuPRAXIA@SPARC_LAB, a
- DESY: SINBAD/ARES, deflector
- CHUV/CERN: DEFT, medical accelerator
- Daresbury: CLARA, linearizer
- Trieste: FERMI energy upgrade

- KEK: NEXTEF
- CERN: XBox-2,3 and SBox
- Tsinghua: TPot
- Valencia: IFIC VBox
- Trieste: FRMI S-Band
- SLAC: Cryo-systems
- LANL: CERF-NM
- INFN Frascati: TEX
- Melbourne: AusBox



CERN, University Hospital of Lausanne (CHUV), THERYQ

ILC 250 GeV Accelerator Facility



8,000 SRF cavities at 1.3GHz, 2K

Physics Detectors

Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35×10^{34} cm^{-2}s^{-1}
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) $Q_0 = 1 \times 10^{10}$

ILC has mature design ➔ next steps involve technical developments and industrial prototyping with final specs.

Key Challenge: SC RF systems:

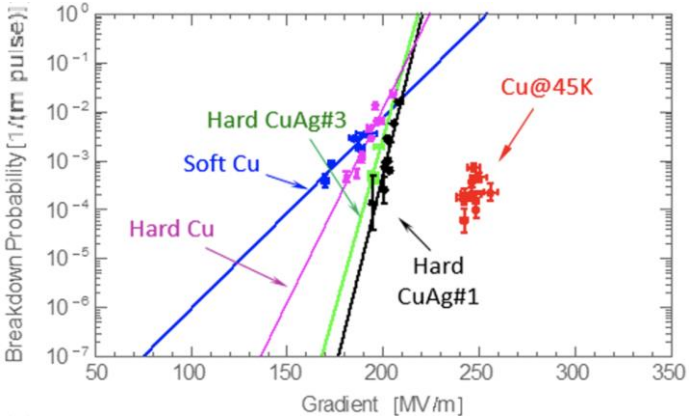
- Huge global interest: European XFEL (800 cavities!), LCLS-II, Shanghai XFEL…
- Nb cavity performance advancements made at many labs
- Improved fabrication techniques and surface treatments → prospects for higher gradient, Q, yield, reduction in cost, cryo power

ILC project status:

- April 2023: ILC budget at KEK increased, International Expert Panel: reviewed models for realising a large global project such as ILC, informal conversations involving funding agencies.
- Cost update in progress for input to ESPPU

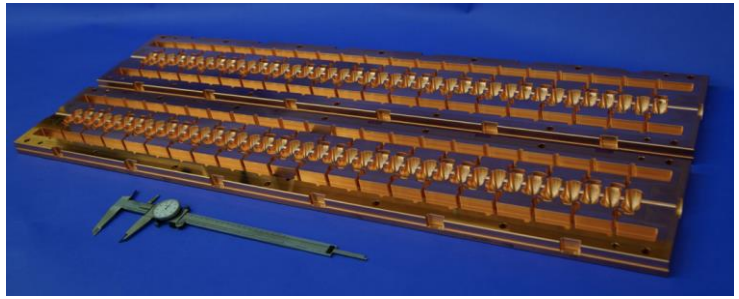
Cool Copper Collider (C3)

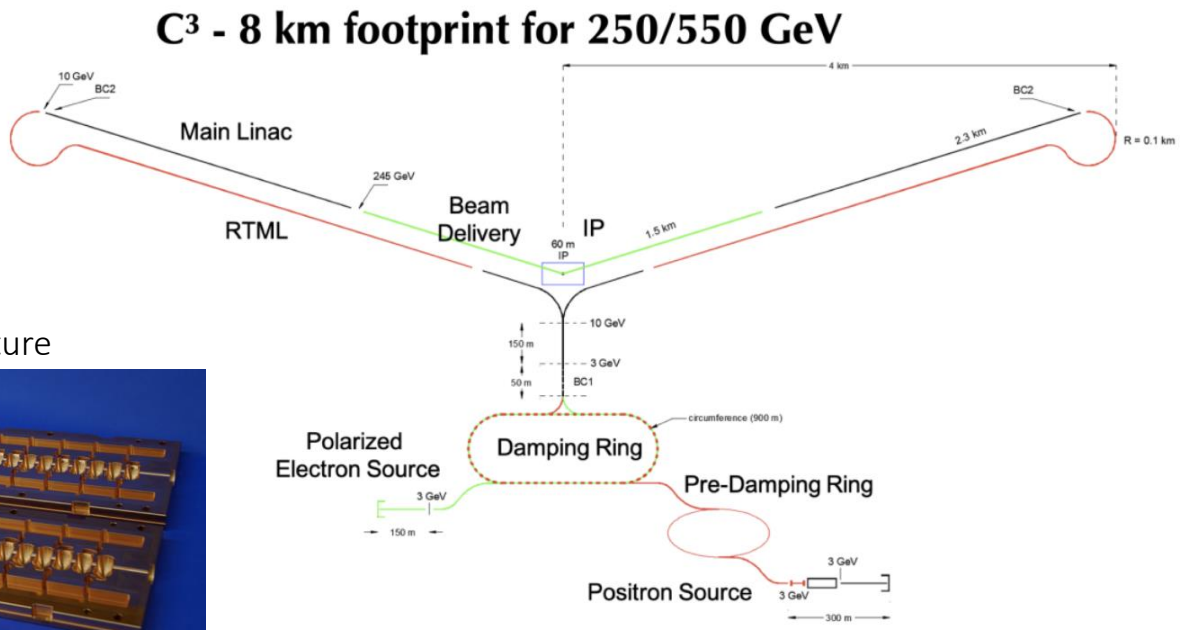
- **Novel linac concept: C-band Cu RF cavities at 77 K (LN2)**
  - High gradient comparable with CLIC but with a conventional RF system
  - Compact footprint**: ~8 km (250/550 GeV)**
  - Significant progress in last years, demonstrator needed



Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002

C3 prototype one meter structure



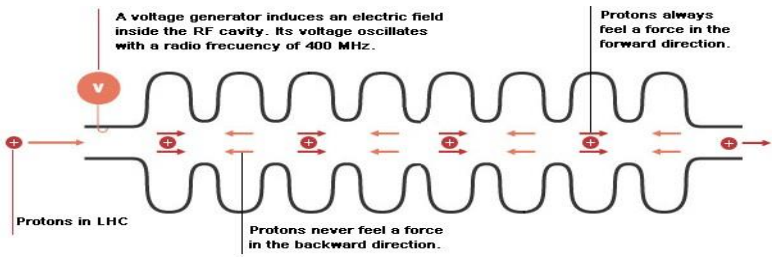


CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Single Beam Power [MW]	2	2.45
Added Beam Power [kW/m]	1.1	1
Site Power [MW]	~150	~175

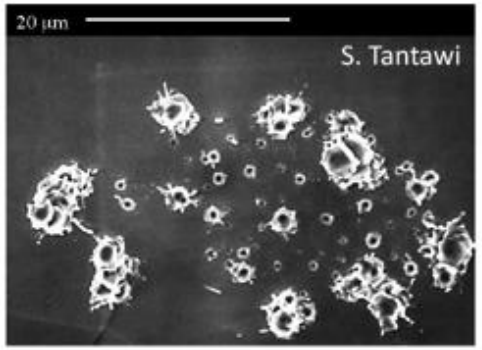
- Design aim:
  - **550 GeV c.o.m. energy with 120 MV/m structures**
  - **Start at 250 GeV with 70 MV/m structures**
- Beam parameters optimised for same integrated luminosity as ILC: 2 ab^{-1} in 10 years @ 250 GeV.
- Benefits from synergies with ILC and CLIC:
  - Beam delivery system and interaction region based on ILC
  - Damping rings and injectors based on CLIC

Accelerating Gradient

Conventional RF Cavities



Surface of Copper Cell After Breakdown Events

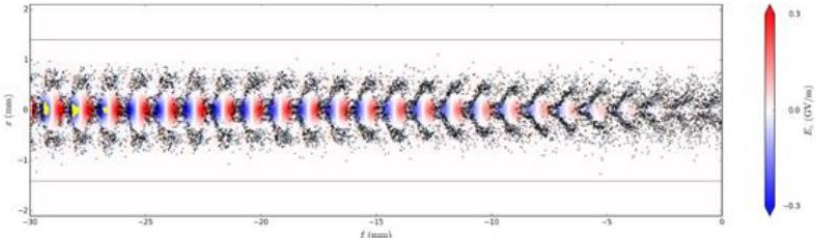


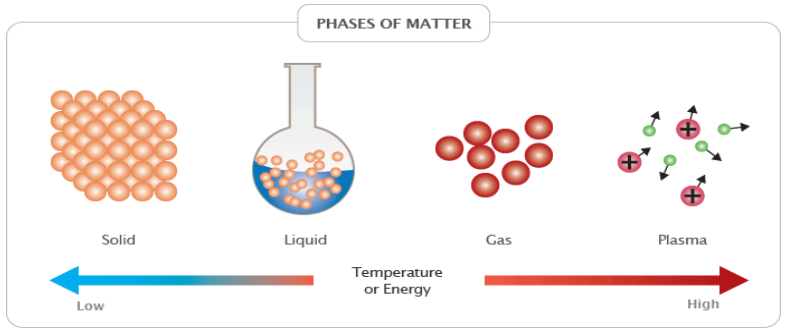
Typical gradients:

LHC: 5 MV/m
ILC: 35 MV/m
CLIC: 100 MV/m

Accelerating fields are **limited to ~120 MV/m**
In metallic structures, a too high field level leads to **break down** of surfaces, creating electric discharge. Fields cannot be sustained; structures might be damaged.

Plasma Acceleration





Plasma is already ionized or "broken-down" and can sustain **electric fields up to three orders of magnitude higher gradients**
→ order of 100 GV/m.
→ ~1000 factor stronger acceleration!

Colliders Based on Plasma Wakefield Acceleration

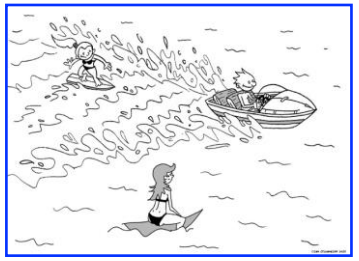
Plasma Wakefields

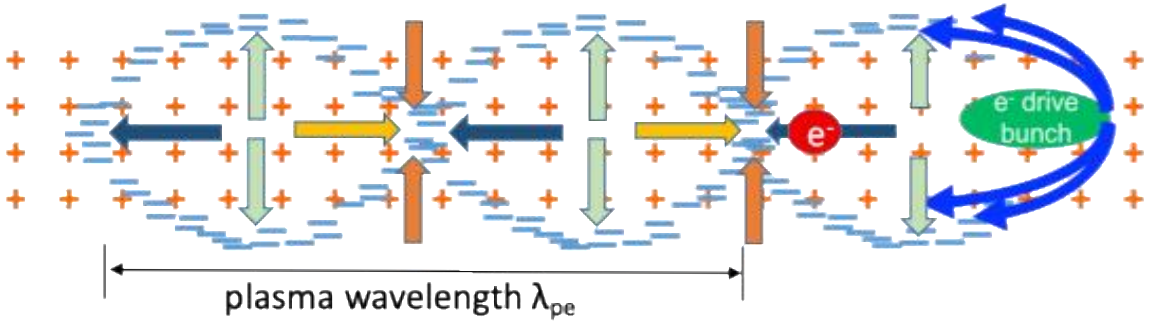
Idea: Using plasma to convert **the transverse electric field** of a drive bunch into a **longitudinal electric field in the plasma.**

Plasma: quasi-neutral, electrostatic interactions dominate, charge particles are dense enough to support collective behaviour.

Drive-bunch or pulse: relativistic charged particles bunches or laser pulse.

Witness-bunch: accelerated in the longitudinal electric field.





Accelerating for e-
Decelerating for e-
Focusing for e-
Defocusing for e-

$$\omega_{pe} = \sqrt{\frac{n_{pe} e^2}{m_e \varepsilon_0}}$$

$$\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}}$$

The maximum accelerating field (wave-breaking field) is: $E_0 \approx 0.96\sqrt{n(10^{14}\ \mathrm{cm}^{-3})}[\mathrm{GV/m}]$

Example: $n_{pe} = 7\times10^{17}\ \mathrm{cm}^{-3}$ ➔ $E_{WB} = 80$ GV/m
Example: $n_{pe} = 7\times10^{14}\ \mathrm{cm}^{-3}$ (AWAKE) ➔ $E_{WB} = 2.5$ GV/m

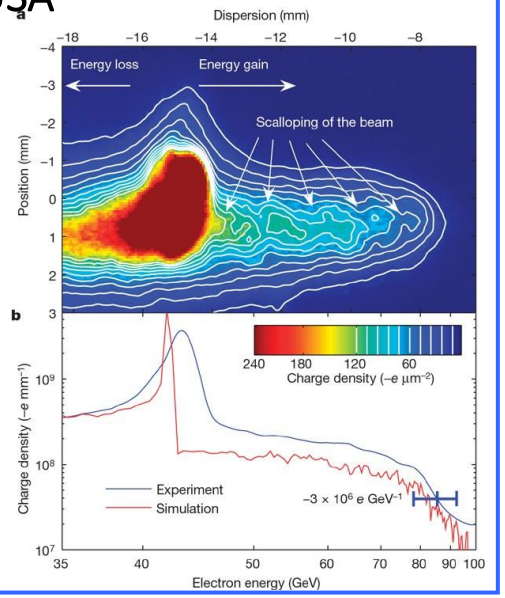
Energy Gain – State-of-the-Art

Electron Driven

42 GeV in 85 cm

FACET, SLAC, USA

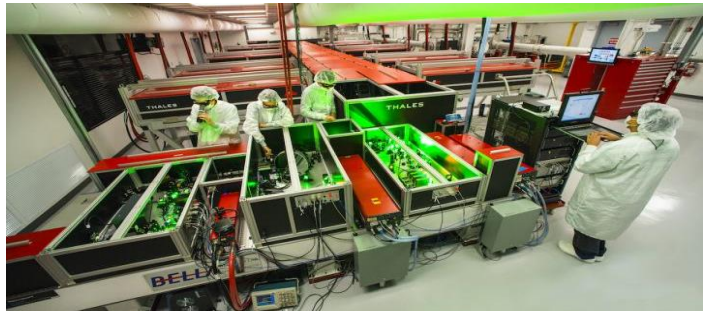
→ gradient of 52 GV/m



I. Blumenfeld et al, Nature 455, p 741 (2007)

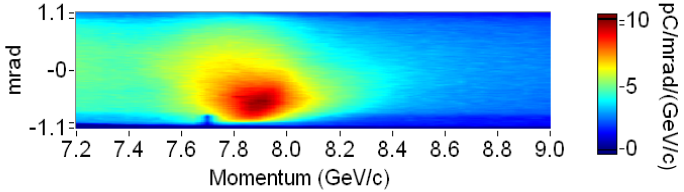
Laser Driven

8 GeV in 20 cm



BELLA, Berkeley Lab, USA

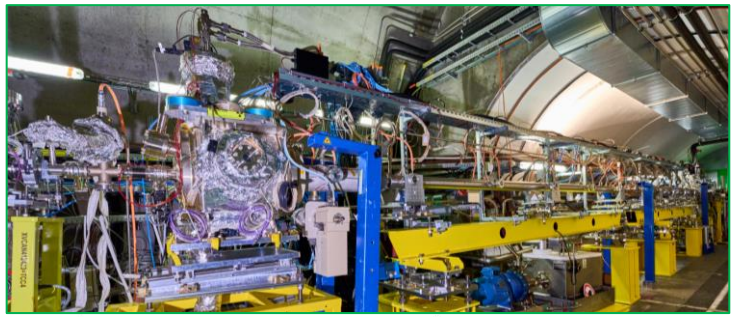
laser-heated capillary discharge waveguide, 20cm-scale plasma



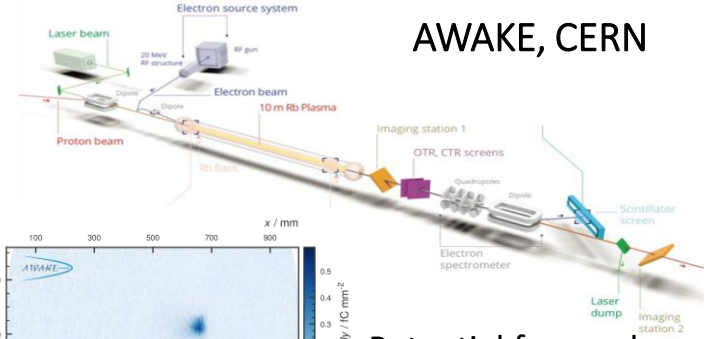
A.J.Gonsalves et al., Phys.Rev.Lett. ***122****, 084801 (2019)*

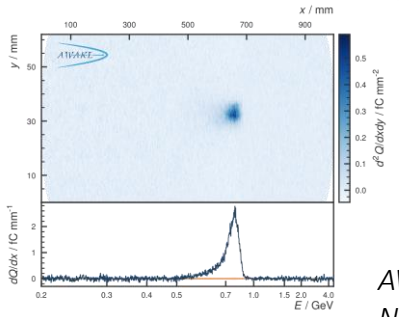
Proton Driven

Proof-of-concept 2 GeV in 10 m



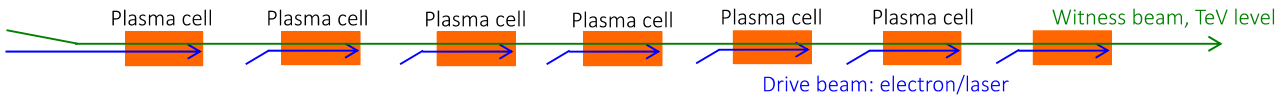
AWAKE, CERN





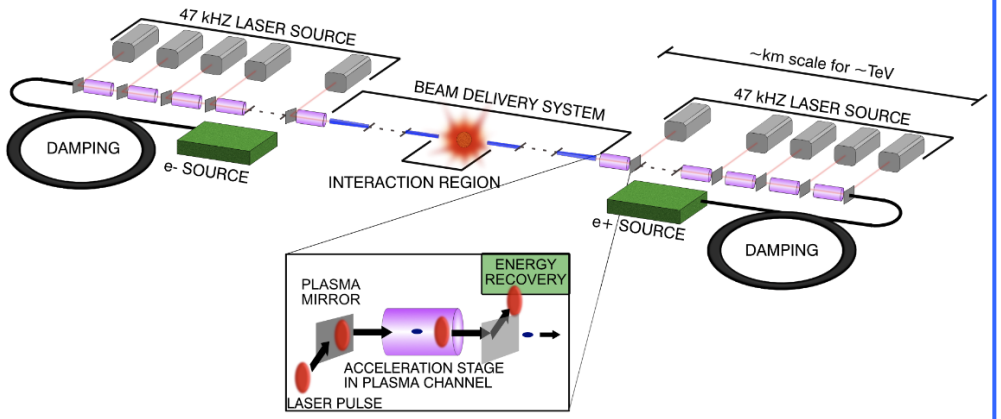
Potential for much larger energy gain in single plasma source

AWAKE Collaboration, Nature 561, 363–367 (2018)



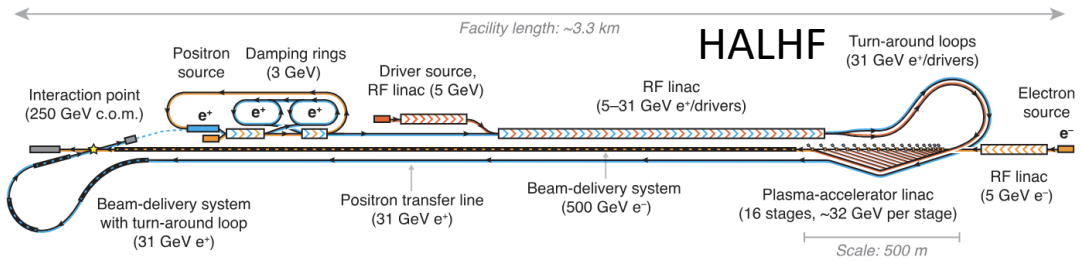
Collider Concepts Based on Plasma Wakefield

e+ e- collider, 1 TeV c.o.m., **laser driven**



C.B.Schroeder et al., 2023, JINST 18 T06001, arXiv:2203.08366

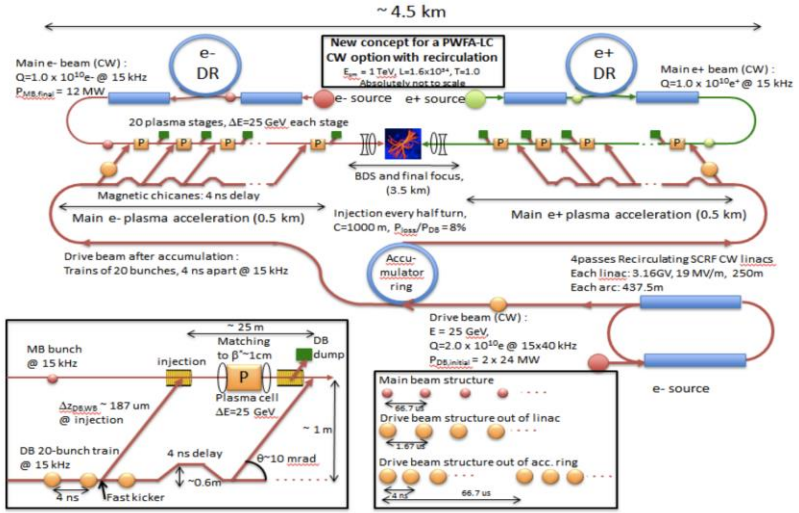
e+e- collider, e+ 31GeV (conventional), e- 500 GeV (**electron driven**)



B. Foster, R. D'Arcy, C. Lindstrom, 2023, New J.Phys. 25 093037 250 GeV c.o.m.

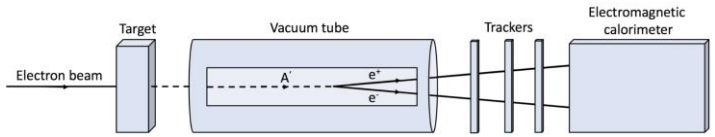
➔ **All designs thus far are straw-person concepts**

e+e- collider, 1 TeV c.o.m., **electron driven**



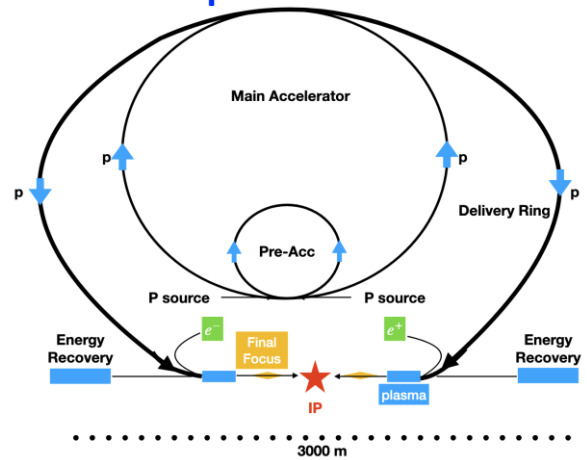
E. Adli et al., 2013, arXiv:1308.1145

Fixed target dark matter experiment.
50 GeV electrons, **proton-driven**



E. Gschwendtner et al. (AWAKE Collaboration), Symmetry 2022,14,1680

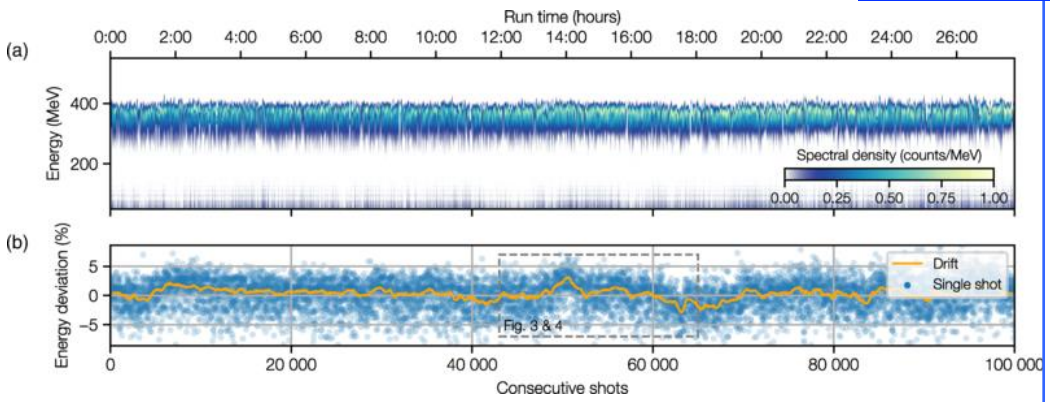
e+ e- collider, 250 GeV c.o.m.
proton driven



J. Farmer, A. Caldwell, A. Pukhov, 2024, arXiv:2401.14765

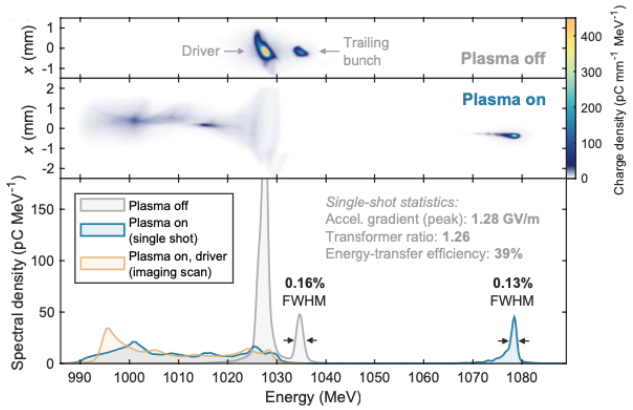
Plasma Wakefield Accelerator Challenges

Stable 24hr operation



A. Maier et al., Phys. Rev. X 10, 031039 (2020)

Transfer **efficiency 42+/-4%** with **0.2% energy spread**, up to **70%** when allowing energy spread increase



C.A. Lindstrøm et al., Phys.Rev.Lett. **126**, 014801 (**2021**)

Stability

Efficiency

Staging

Challenges

Beam quality after acceleration

High witness bunch charge

Reproducibility

High repetition rate

Efficient drivers

Positron acceleration

ESPP 2020: Plasma R&D Roadmap:

- Feasibility and pre-CDR study
- Technical demonstation

Exploring the Quantum Universe

US Snowmass and P5:

- End-to-end design concept of a 10 TeV parton-center-of-mass collider

➔ Requires international, multi-dimensional R&D efforts.

Summary

Figure-of-Merit

T. Roser et al., On the feasibility of future colliders: report of the Snowmass'21 Implementation Task Force, 2023, JINST 18 P05018

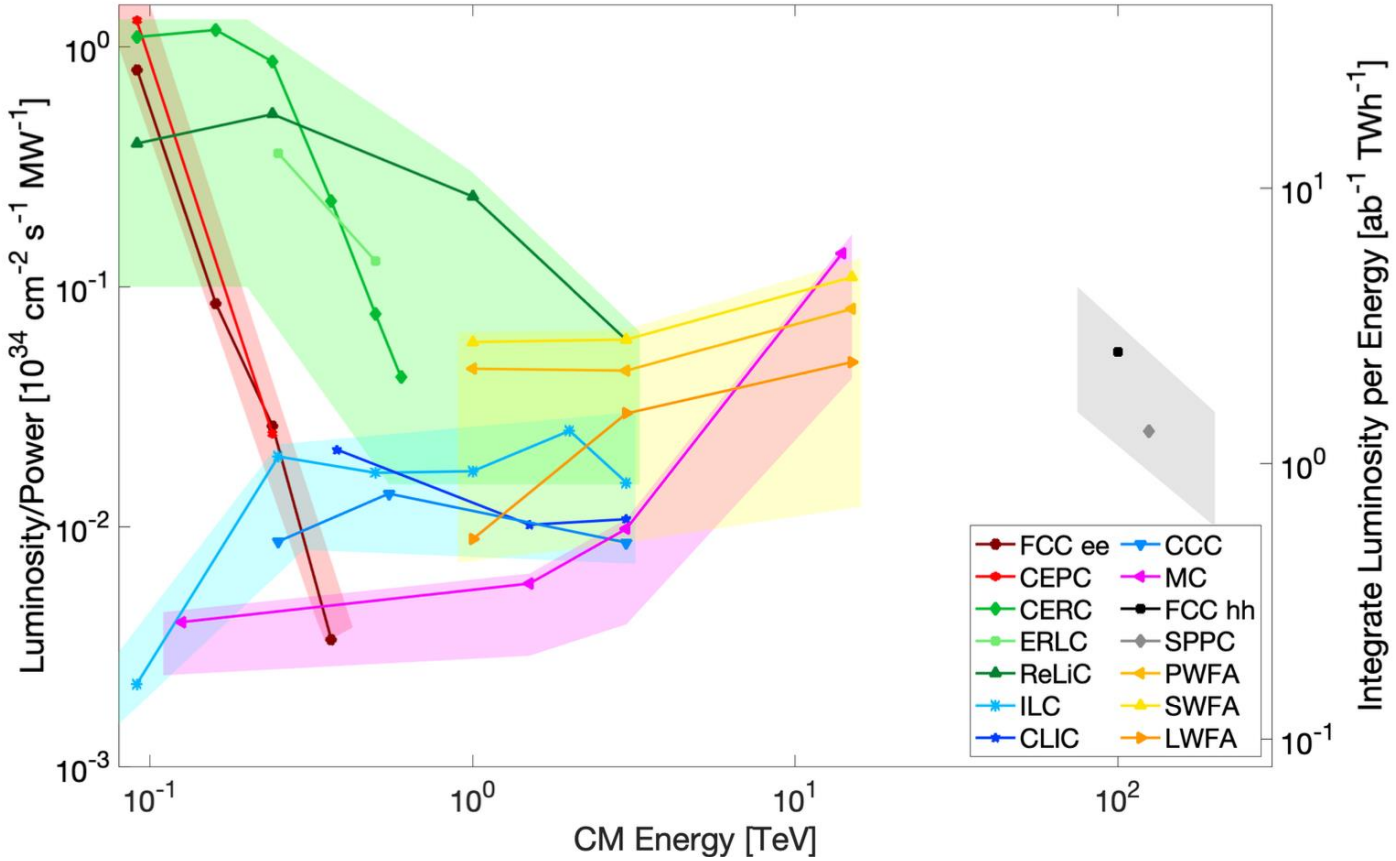


Figure 4. Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh. Integrated luminosity assumes 10^7 seconds per year. The luminosity is per IP. Data points are provided to the ITF by proponents of the respective machines. The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.

Lots of efforts to review the power consumption estimates for all future accelerators

Power Consumption

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
CERC (0.24 TeV)	90	91 km	II	I
ReLiC (0.24 TeV)	315	20 km	II	I
ERLC (0.24 TeV)	250	30 km	II	I
XCC (0.125 TeV)	90	1.4 km	II	I
MC (0.13 TeV)	200	0.3 km	I	II
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
ReLiC (3 TeV)	~ 780	360 km	III	I
MC (3 TeV)	~ 230	10-20 km	II	III
LWFA (3 TeV)	~ 340	1.3 km (linac)	II	I
PWFA (3 TeV)	~ 230	14 km	II	II
SWFA (3 TeV)	~ 170	18 km	II	II
MC (14 TeV)	~ 300	27 km	III	III
LWFA (15 TeV)	~ 1030	6.6 km	III	I
PWFA (15 TeV)	~ 620	14 km	III	II
SWFA (15 TeV)	~ 450	90 km	III	II
FCC-hh (100 TeV)	~ 560	91 km	II	III
SPPC (125 TeV)	~ 400	100 km	II	III

Table 11. Table summarizing the categories of power consumption, size, complexity and required radiation mitigation for the evaluated collider proposals. Color schemes and categories are explained in section 4.2 (power consumption), section 4.3 (size), 4.4 (complexity) and section 4.5 (radiation). For linear colliders, the size of the machine includes main linac and final focus, but excludes damping rings, except where otherwise noted.

T. Roser et al., On the feasibility of future colliders: report of the Snowmass'21 Implementation Task Force, 2023, JINST 18 P05018

Readiness

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

Table 9. Table summarizing the TRL categories, technology validation requirements, cost reduction impact and the judgement of performance achievability on technical components and subsystems for the evaluated collider proposals. Colors and categories are described above in section 3 and go from lighter/lower/easier to darker/higher/more challenging. The first column "Design Status" indicates current status of the design concepts: I — TDR complete, II — CDR complete, III — substantial documentation; IV — limited documentation and parameter table; V — parameter table. The last column indicates the overall risk tier category, ranging from Tier 1 (lower overall technical risk) to Tier 4 (multiple technologies that require further R&D).

T. Roser et al., On the feasibility of future colliders: report of the Snowmass'21 Implementation Task Force, 2023, JINST 18 P05018

Summary

➔**High energy accelerators are the key instruments** for the study of the fundamental constituents of matter and their interactions.

➔**There are several future collider concepts to reach the high energy frontier**:

- **High energy e+e- colliders** like the ILC, CLIC, FCC-ee, CEPC have indirect access to mass scales of 50-100TeV. The **RF technology** is one of the main challenges of these accelerators.
- **High energy proton colliders** like the FCC-hh or the SppC have direct access to the 50-100 TeV mass scale. These accelerators need to use **high field magnets**, which is one the main R&D focus.
- **A muon collider** could have similar reach, with **significant technological challenges** still to be solved.
- **Plasma wake field acceleration** can provide electric fields that are several orders of magnitude higher than the ones in conventional cavities. This concept still **needs further development** for a high luminosity application but could be already used in the mid-term future for fixed target experiments.

➔**The developments are done by international teams/collaborations**, usually led by a major lab with special interest in the project but with world-wide participation. Decision for the future:

➔Europe: European strategy upgrade of particle physics (ESPP)

➔USA: Particle Physics Project Priorization Panel (P5) and Snowmass Process

➔China: Five-year plan to decide on funding

➔Japan: Yearly budget plan

Many thanks for the valuable input from

Michael Benedikt, Phil Burrows, Spencer Gessner, Elias Metral, Daniel Schulte, Bernd Stechauner, Frank Zimmermann.