

Next-Generation Particle Accelerators: Overview and Outlook

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Österreichische Physikalische Gesellschaft

EPS Condensed Matter Division

Outline

- Motivation
- Next-Generation Colliders
- Towards the Next Flagship Collider: The European Strategy for Particle Physics

Accelerator Zoo



Today: ~ **30'000 accelerators** are operational world-wide*

The **large majority** is used in **industry** and **medicine**

- Industrial applications: ~ 20'000*
- Medical applications: ~ 10'000*

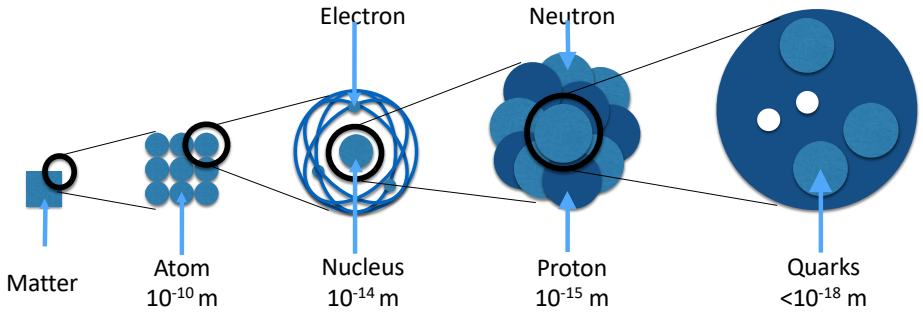
Less than a fraction of a percent is used for **research and discovery science**

- Cyclotrons
- Synchrotron light sources (electrons)
- Lin. & Circ. accelerators/colliders

*Source: World Scientific Reviews of Accelerator Science and Technology
A.W. Chao

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 !

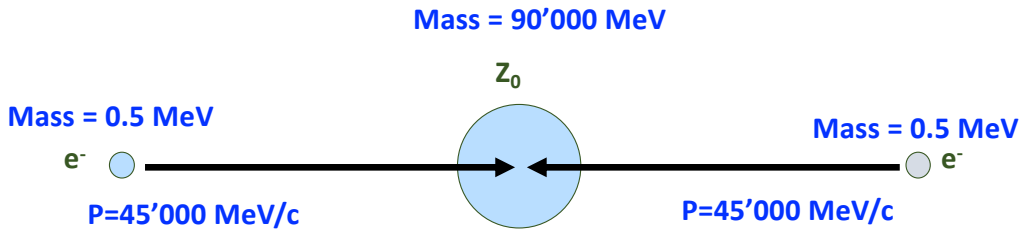
Why Do We Need Particles at even Higher Energies?

➔ To produce massive particles (e.g. W, Z, top, Higgs) that are either unknown or predicted by theories.

- The production of new massive particles is connected with the study of the smallest building blocks of matter done with high energy particle colliders.

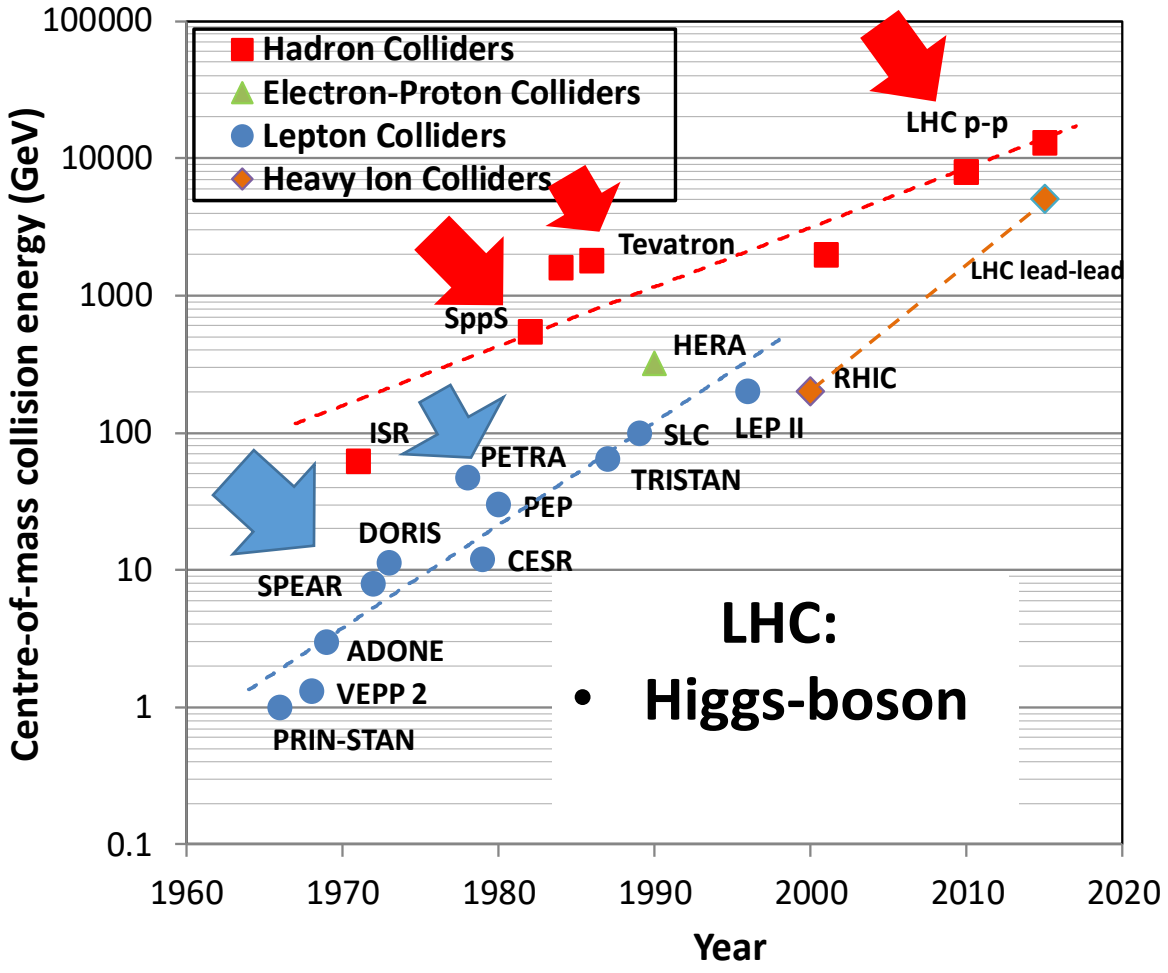


$$E = mc^2$$

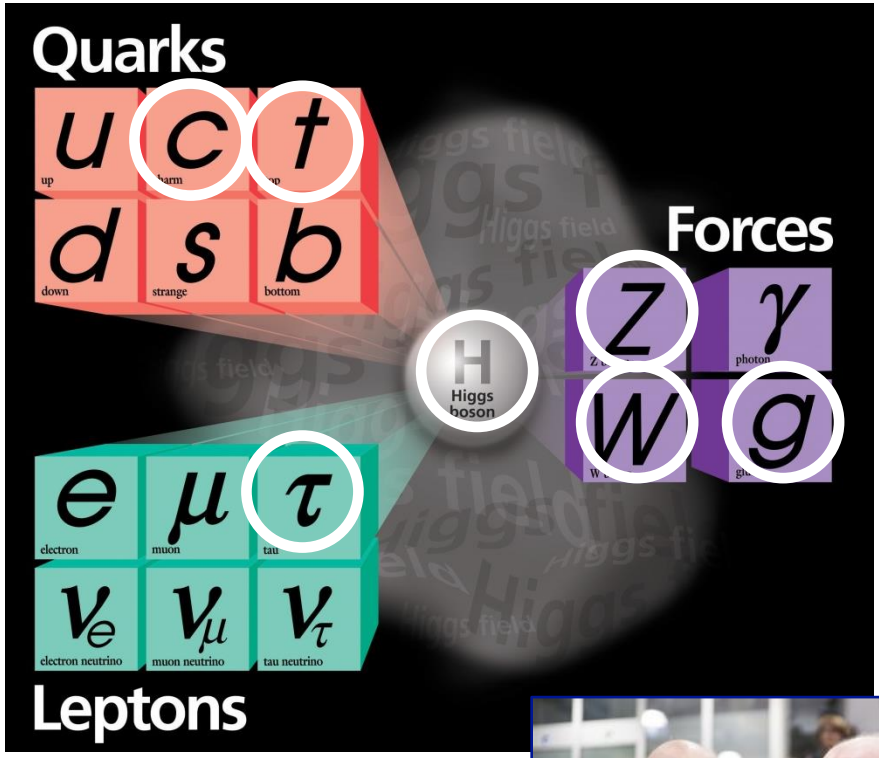


➔ Accelerators are powerful tools for particle discoveries and precision measurements!

Discoveries with Colliders



Standard Model
Particles and forces



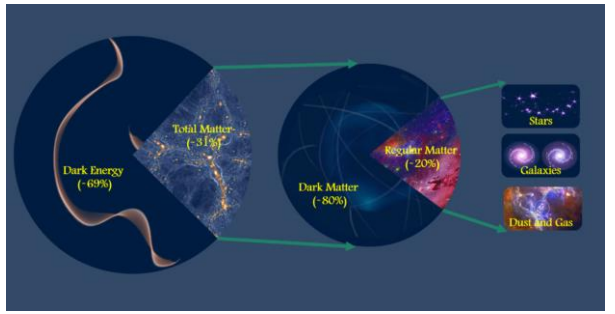


LHC: Discovery in 2012,
Nobel Prize in 2013

Open Questions

Despite of impressive progress and discoveries in the past decades several fundamental question remain open:

- Is there only a single type of **Higgs** boson and does it behave exactly as predicted?
- Why is the universe only of matter: Where has the **antimatter** gone that was produced simultaneously in the Big Bang?
- Today 80% of the mass of Universe is unknown. **What is the Universe made of?**



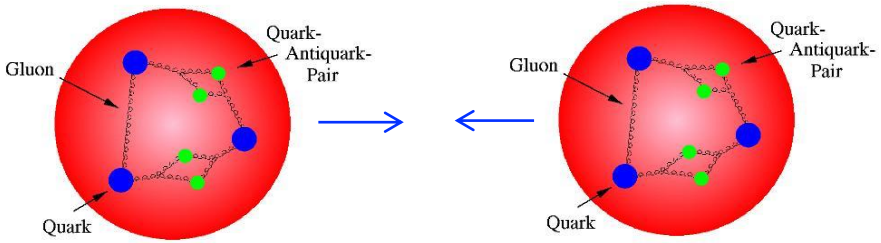
- Why is the **gravitation** so much small than the other forces? How to reconcile gravitation with quantum mechanics?

Collider Design Considerations

Colliders: Which Particle Types to Accelerate

Need stable charged partices

- Hadrons (protons, ions):
  - Compound particles (mix of quarks, anti-quarks and gluons)
  - Parton energy spread, energy available < E_{cm}
  - QCD processes produce large background



- Leptons (e-, e+, muons):
  - Elementary particles → all energy available
  - Well defined initial state
  - Background from other physics limited
  - Polarization
  - Muons: lifetime of only 2.2 µs



- Photons
  - e+/e- colliders can be turned to gamma-gamma by inverse compton scattering using lasers



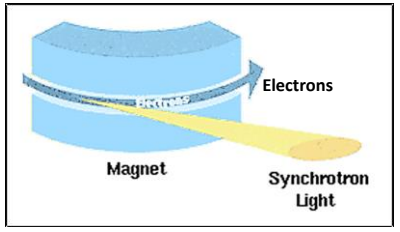
Which Accelerator Type: Circular versus Linear

Circular colliders:

Allows to re-collide bunches for hours.

Limitations:

- Hadron colliders: Limitation is magnet strength.
- Electron-positron colliders: Circular machines are limited by synchrotron radiation.
- Electrons/positrons are 2000 times lighter than protons → 10^{13} greater radiation losses = energy losses.



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

FCC-ee: energy loss of 10 GeV/turn at 182.5 GeV.

Linear colliders:

Favorable for acceleration of low mass particles to high energies.

Almost no synchrotron radiation in a linac.

Limitations:

- Beams must reach the final energy in a single pass. The limitation is the accelerating gradient.
- Must achieve luminosity in a single beam collisions.

Performance of a Collider: Luminosity

Luminosity measures the ability of a particle accelerator to produe the required number of useful interactions.

→ Proportionality factor between the number of events per second dR/dt and the cross-sections σ_p : $dR/dt = L \cdot \sigma_p$

Luminosity is given by:

$$L \propto \frac{k N_b^{\,2} f}{4\pi \sigma_x^* \sigma_y^*} F$$

- k = number of colliding bunch pairs
- N_b = bunch population
- f = repetition rate (revolution frequency for circular colliders)
- F = factor including several collision effects
- $\sigma^*_{x,y}$ = beam size at IP

Circular Collider:

LHC ring: f_{rep} = 11 kHz

$\sigma_x \sigma_y \approx (17) \times (17)\ \mu m^2$

Linear Collider:

LC: f_{rep} = few – 100 Hz

→ Factor 100-1000 in L already lost for LC

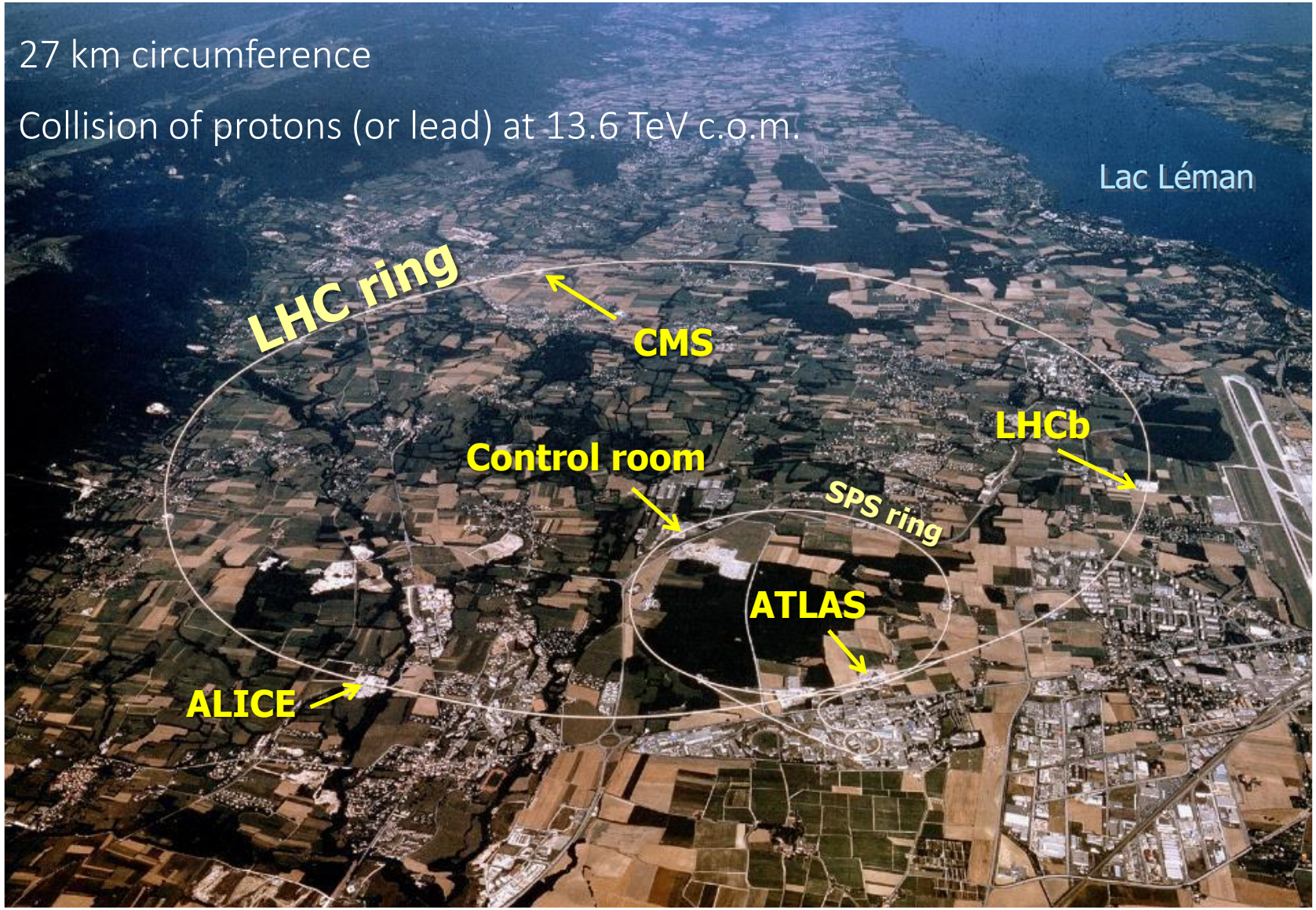
➔ Must push hard on beam cross-section at collision

$\sigma_x \sigma_y \approx (60\text{-}550) \times (1\text{-}5)\ nm^2$

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The Large Hadron Collider – High Luminosity Upgrade



High Luminosity LHC

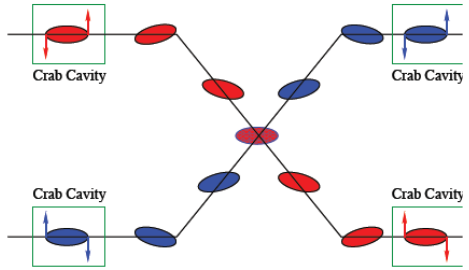
High Luminosity Upgrade in 2026 – 2030: **increase the integrated luminosity by a factor 10**

The LHC was built to accumulate about an integrated luminosity of **300 fb^{-1}** of proton–proton collisions at $E_{c.o.m.}$ = 14 TeV.

Parameter	LHC (Run 3)	HL-LHC (target)
Peak luminosity	1×10^{34} $cm^{-2}s^{-1}$	5×10^{34} $cm^{-2}s^{-1}$ (levelled)
Integrated luminosity	~300–400 fb^{-1}	3000 fb^{-1} (4000 ultimate)
Pileup ⟨μ⟩	30–60	up to 140
β* at IP1 / IP5	30–55 cm	15 cm
Bunches / beam	2760	2760–2808
Bunch spacing	25 ns	25 ns

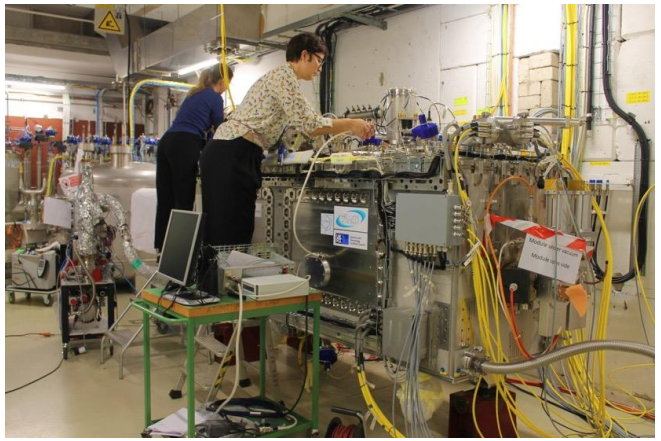


High-Luminosity LHC



Increase crossing angle Factor

Large beam separation at unwanted collision points → large crossing angle at Interaction Point



Increase bunch population

Injector Upgrade

from 1.15×10^{11} p to 2.2×10^{11} p;

Linac4 injects H^- at 160 MeV (vs 50 MeV Linac2).

$$\mathcal{L} = \frac{N^2 f_{rev} k_c}{4\pi\beta^*\varepsilon} \times F$$



Smaller β^*

Reduced emittance

Smaller beam size at IP → new focusing magnets

LHC triplet magnets: new magnet technology, larger aperture.

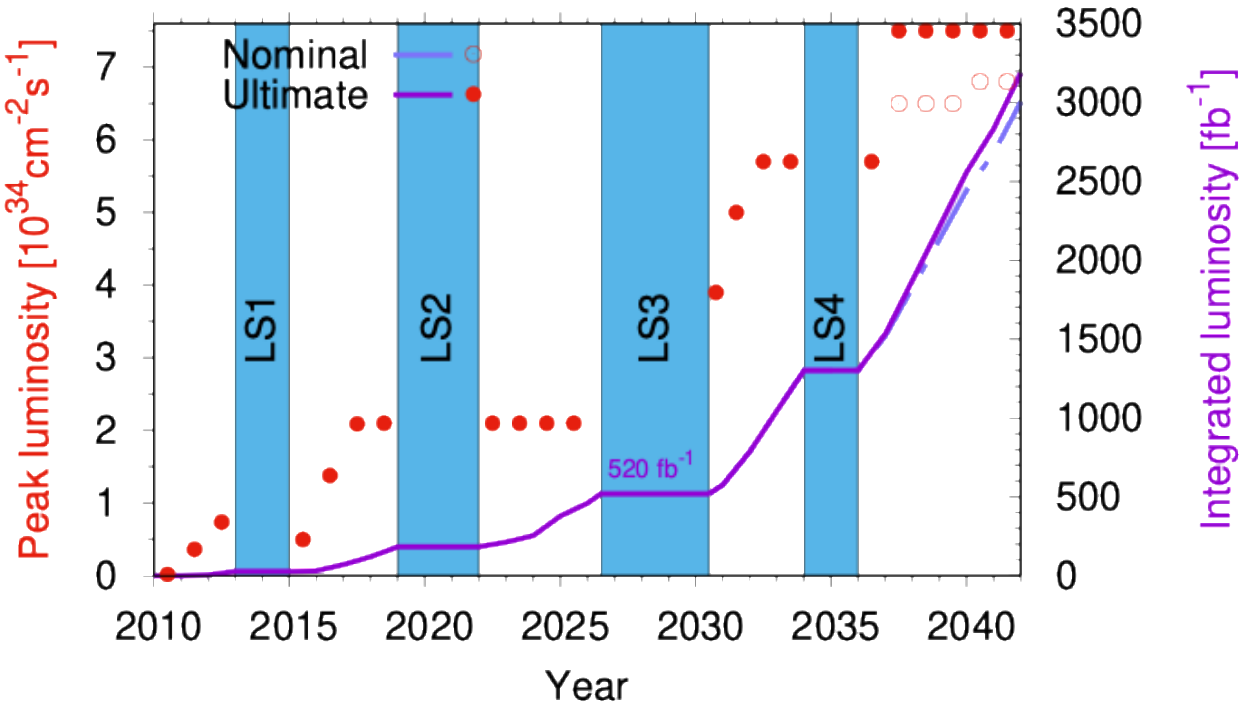
Nb_3Sn quadrupoles reach 12 T peak field (vs 8 T NbTi), 150 mm aperture (vs 70 mm), 7.2 m magnetic length

→ squeezing β* from ~35 cm to 15 cm.

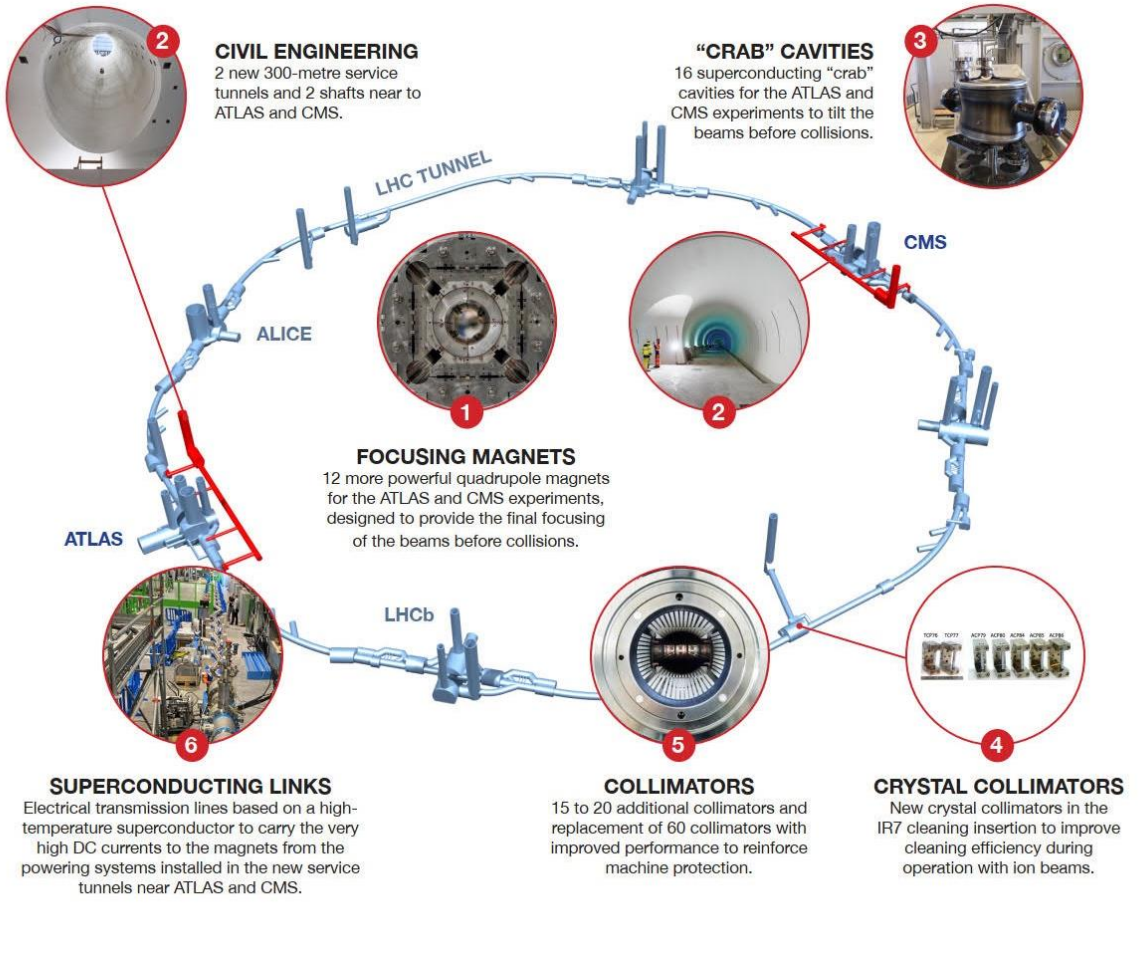
N: protons/bunch, f_{rev}: revolution frequency, kc: colliding bunch pairs, β: focusing at the IP, ε: emittance, F: crossing-angle factor*

High-Luminosity LHC

Reached and expected performance

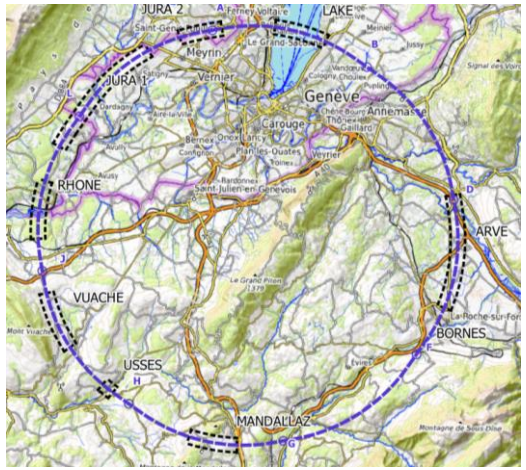


→ Keep LHC at forefront well into the next decade



Future Colliders

Circular colliders



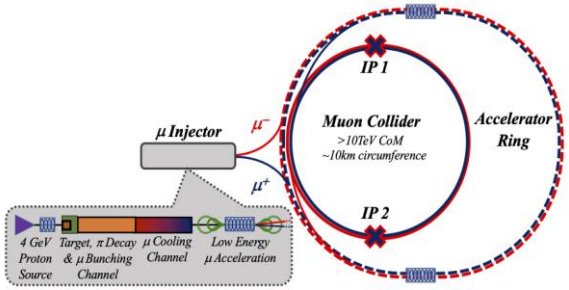
FCC at CERN
91 km, 380 GeV (e+e-), 100 TeV (pp)



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



LEP3 (e+e-, 91-230GeV)

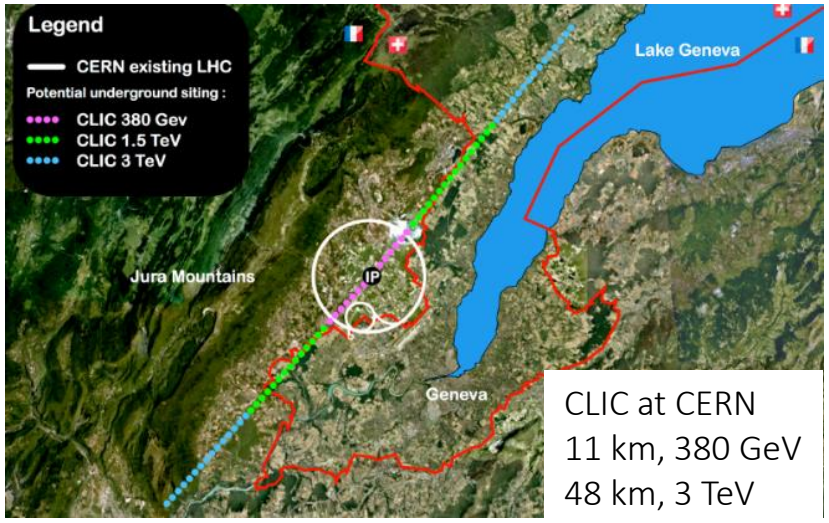


Muon Collider, 10 km, 10 TeV (μ+μ-)

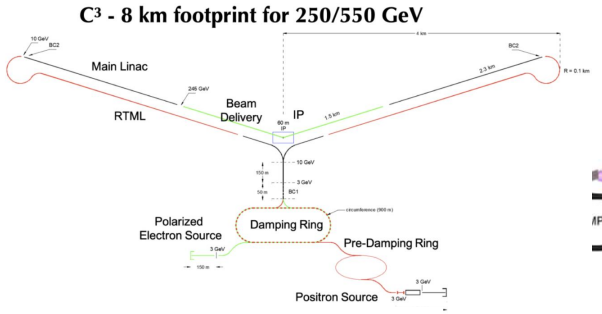
Linear colliders



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

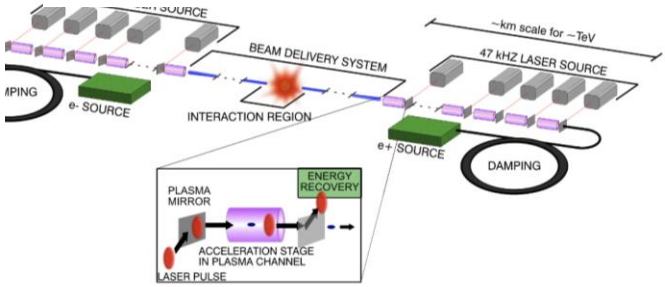


CLIC at CERN
11 km, 380 GeV
48 km, 3 TeV



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

Colliders based on plasma wakefield
~4.5km, 1 TeV



Motivation for Electron-Positron Collider

- Standard Model is complete, but not tested at loop level.
  - m_H = 125 GeV fixed last free SM parameter, but many electroweak observables still only known at few percent precision → leaves room for undetected quantum corrections.

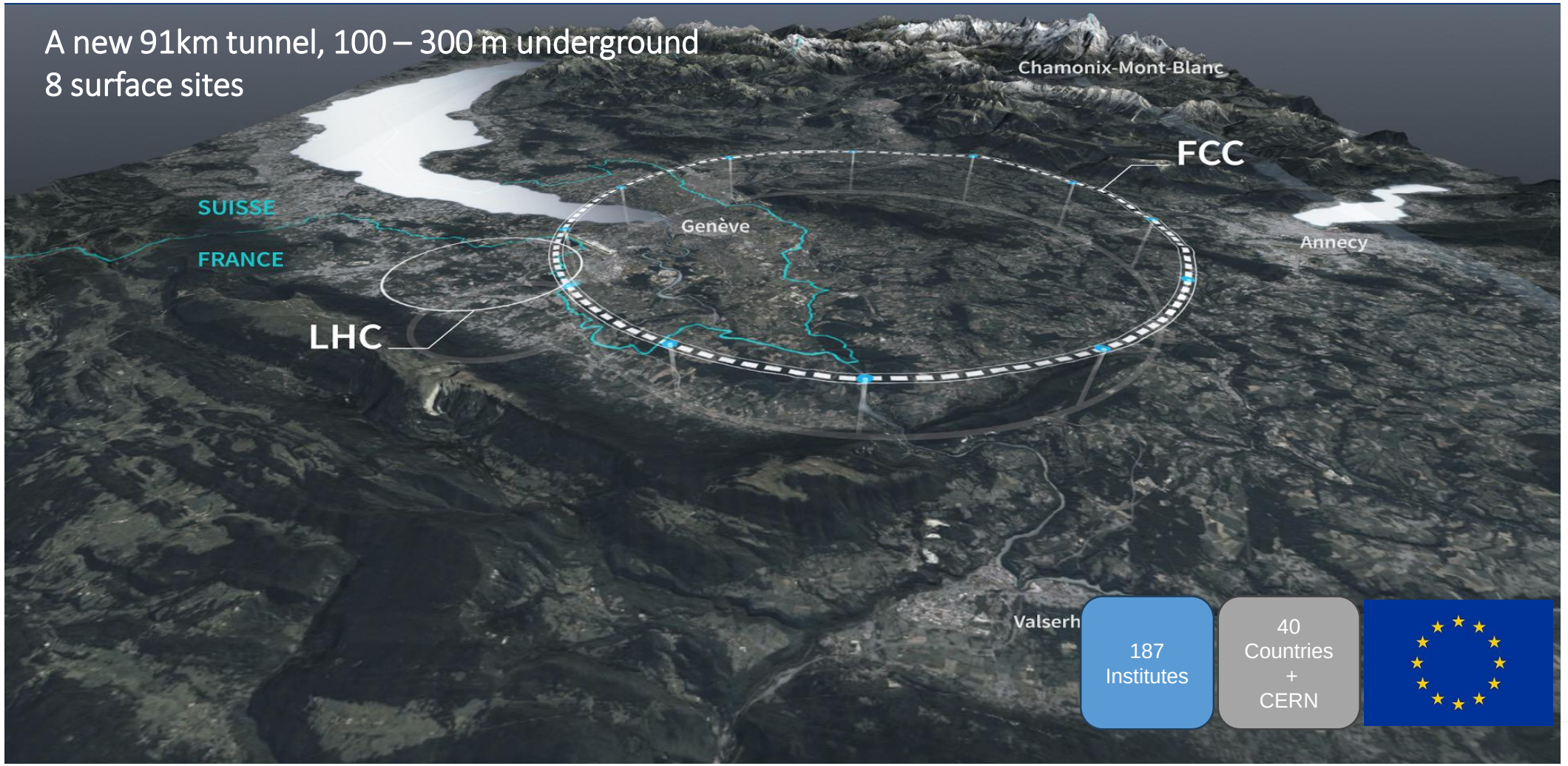
- Precision observables magnify new physics.
  - m_W, m_Z, Γ_Z, $\sin^2\theta_{eff}$, Higgs coupling: per mille measurements are sensitive to virtual effects of particles too heavy to produce directly, up to O (10 TeV).

- e+e- gives access, which no hadron collider has.
  - With known, tunable c.o.m. energy and clean leptonic initial state no QCD background and pileup (as is limiting in LHC).

Future Circular Collider

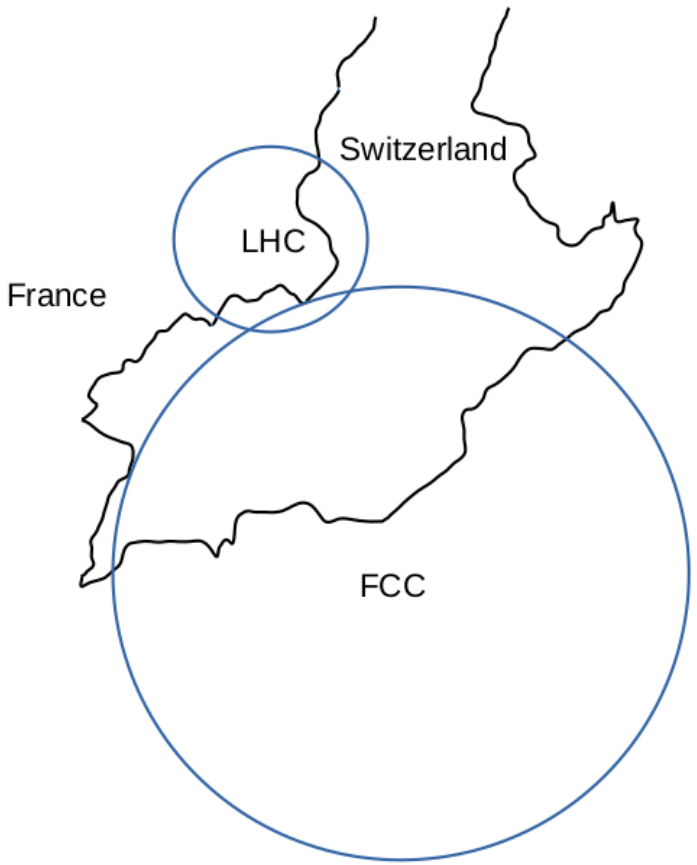
Future Circular Collider, FCC

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



Future Circular Collider

Re-using CERN infrastructure

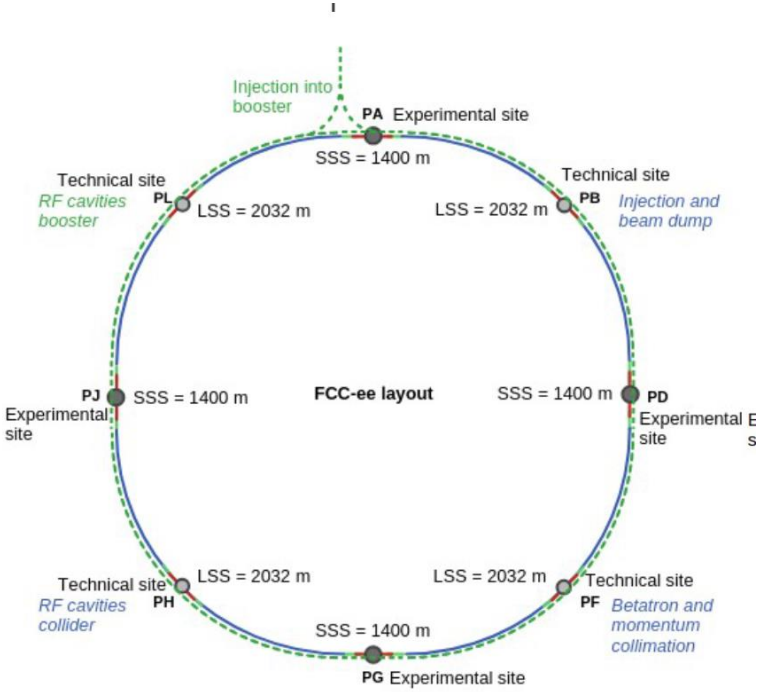


2020 - 2045

FCC-ee
Electron Positron Collider

91, 160, 240, 365 GeV: detailed study of the Z, W, Higgs boson, top quark.

➔ **Indirect** sensitivity to new physics up to ~70 TeV (> 10 x LHC)

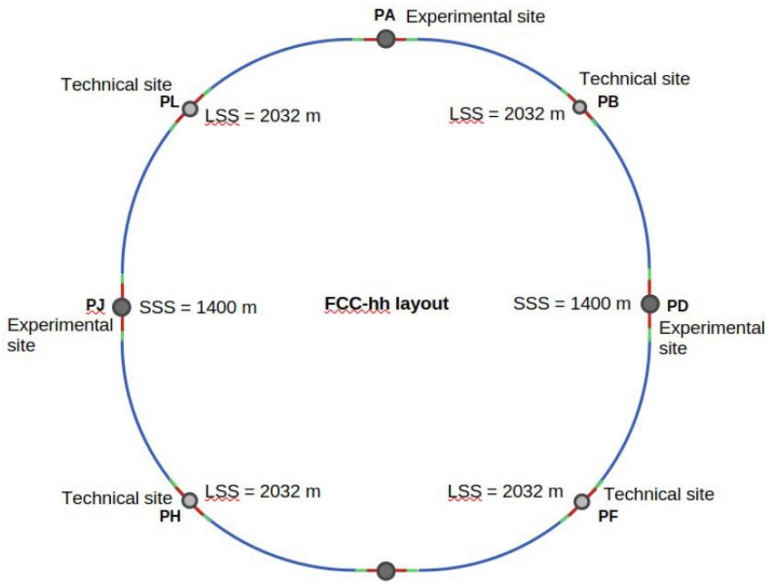


2048 - 2062

FCC-hh
Proton Proton Collider

85 TeV (vs 14 TeV for LHC), heavy-ion (Pb) collider at 39 TeV.

➔ **Direct** discovery potential for new physics up to ~40 TeV (~10 x LHC)



~2075 ?

Future Circular Collider, FCC-ee

FCC-ee design is dominated by the choice to allow for ~50 MW synchrotron radiation power per beam.

	Z	WW	ZH	ttbar
Beam energy [GeV]	45.6	80	120	182.5
SR power/beam [MW]		50		
SR losses/turn [GeV]	**0.0394**	**0.374**	**1.89**	**10.42**
Beam current [mA]	1270	137	26.7	4.9
Bunches/beam [-]	11200	1780	440	60
Bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
RF voltage 400/800MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Horizontal β-function at IP [mm]	110	200	240	1000
Vertical β-function at IP [mm]	0.7	1.0	1.0	1.6
Horizontal emittance [nm]	0.71	2.17	0.71	1.59
Vertical emittance [pm]	1.9	2.2	1.4	1.6
Luminosity/IP [$10^{34}cm^{-2}s^{-1}$]	141	20	5	1.25
Integrated luminosity/IP/year [ab^{-1}]	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

Energy loss due to synchrotron radiation is proportional to $n \times E^4/\rho$.

→ Number of particles n is defined at a given energy E and a radius ρ

→ Beam requirements and collider design are **very tight**:

- Ultra-small vertical emittance
- Continuously high bunch intensity for high luminosity
- Tight alignment tolerances
- Continuous beam injection

Challenges for the FCC Program

FCC-ee:
~50MW synchrotron radiation/beam
→ Optimized RF system to increase efficiency

FCC-ee/hh:
91 km long tunnel
→civil engineering

FCC-hh:
Upgrade to 100 TeV
→ high-field superconducting magnets, 14 – 20 T

FCC-ee: RF System

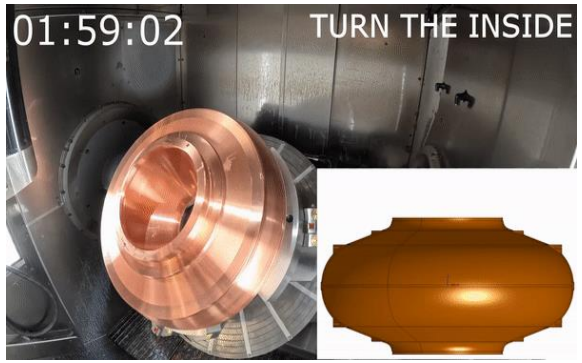
Example: with ~91 km circumference at 182.5 GeV: ~10 GeV of beam energy is lost per turn!

→Needs to be given back by RF system!

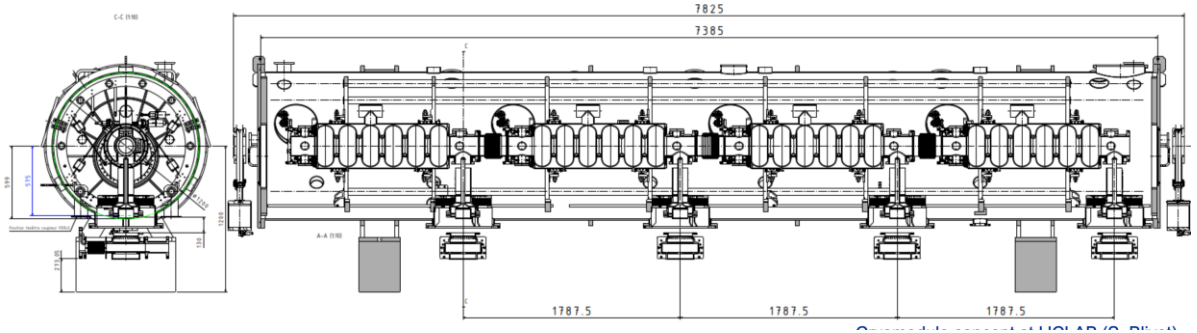
→Highly efficient RF system is essential for high energy lepton colliders.

- **R&D Activities:**
  - Tristron RF power source: Increase efficiency: reach 90% efficiency (vs 55% today)
  - Cavities: Improve surface resistance and gradient
    - 400 MHz cavities: Nb on Cu 400 MHz cavities: seamless cavity production, coating techniques
    - Bulk Nb 800 MHz cavities: surface treatment techniques
  - Cryogenic refrigeration plants with increased energy efficiency.

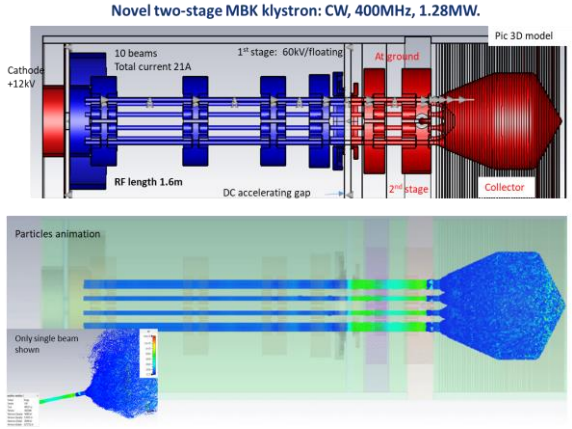
400 MHz
monoblock prototype



800 MHz Cryomodule concept (IJCLAB)



High-efficiency klystron R&D
in collaborations with THALES & CANON

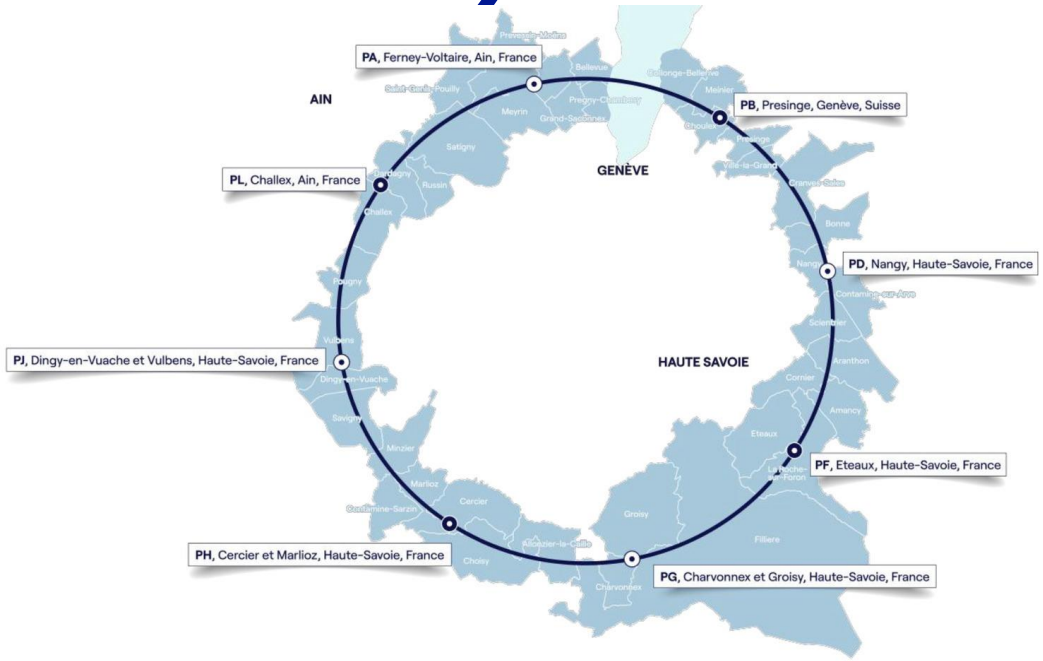


FCC-ee: Optimized Placement and Layout

- Site investigation:
  - Boreholes (27) and seismic survey (>80km) confirm tunnel stays in favourable molasse rock.
  - Develop excavated material disposal/reuse strategy (e.g. transform to fertile soil).
  - Plan tunnel-boring strategy.

- Territorial implementation:
  - Work with France and Switzerland to identify and legally secure the land and underground volumes needed.
  - Develop a joint cross-border environmental impact assessment framework.

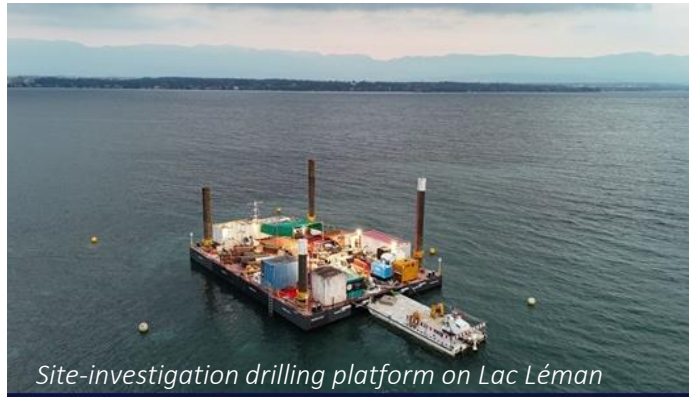
- Public participation: > 20 events
  - French and Swiss law require public to be consulted before any approval.
  - > 20 events, workshops, site visits, environment &socio-economic impact.



8 surface sites, 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


Site-investigation drilling platform on Lac Léman

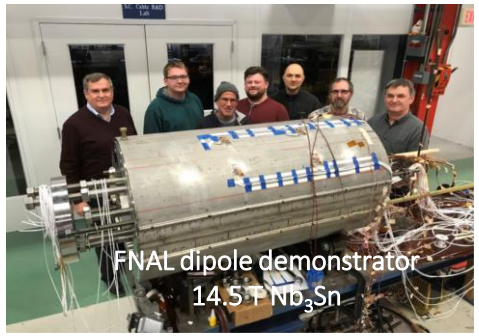
Key Challenges of FCC-hh: Magnets

- FCC-hh: Baseline: 85 TeV c.o.m. collision energy, 14 T dipole magnets, start ~2075.

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

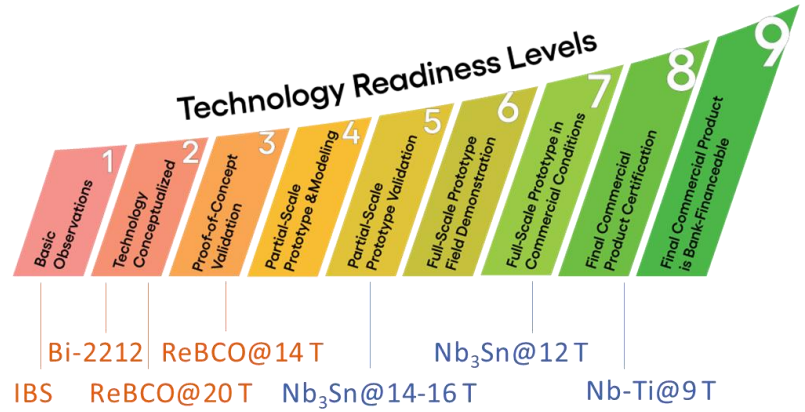




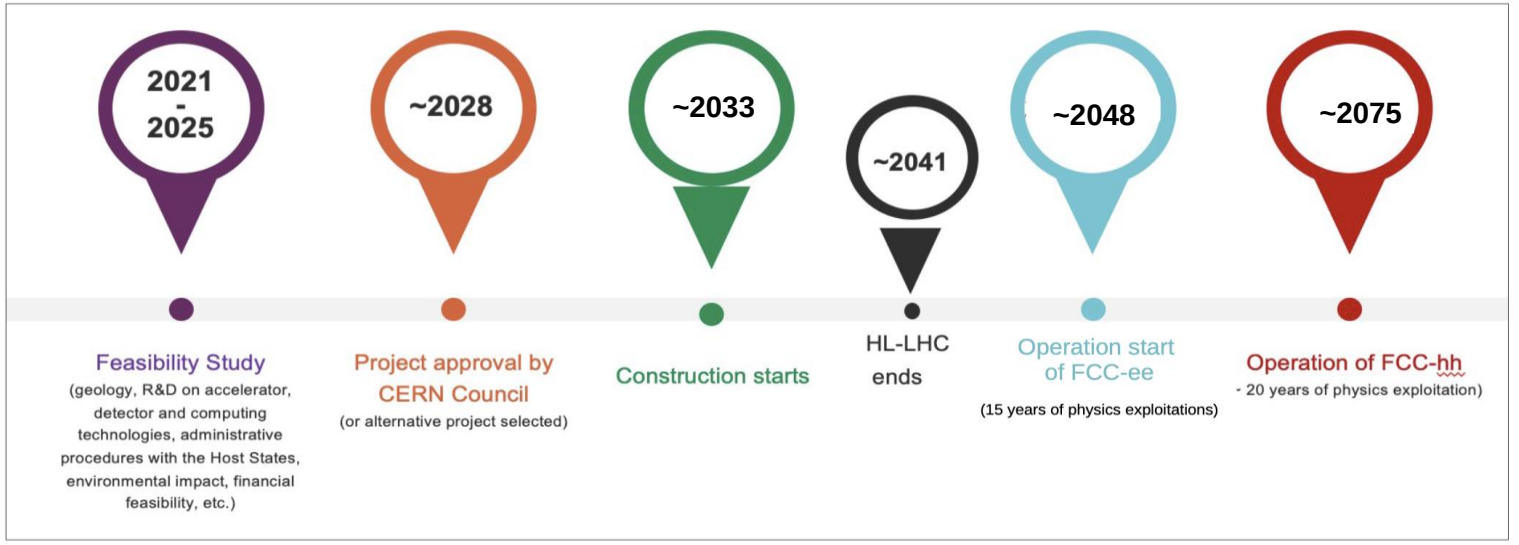


Main R&D activities:

- Materials:
  - ~14 T for Nb3Sn
  - at least ~20 T for HTS inserts
- Magnet technology: engineering, robustness, insulating materials, field quality
- Production of models and prototypes
- Infrastructure and test stations: for tests up to ~20 T and 20-50 kA



FCC-ee Timeline



- 2025/26: **Positive assessment** of the Feasibility Study and Council approving the continuation
  → **FCC moves towards technical design**
- 2026 – 2028: **Reference Design Phase:**
  - Integrated technical baseline
  - Resource-loaded project master schedule
  - Updated cost estimate with uncertainty
  - Project-wide risk register
  - Procurement strategy (incl. in-kind contribution opportunities).

→Aiming for project decision by CERN Council after the Reference Design Phase

- 2029 – 2032 Technical Design Phase

LEP3

LEP3

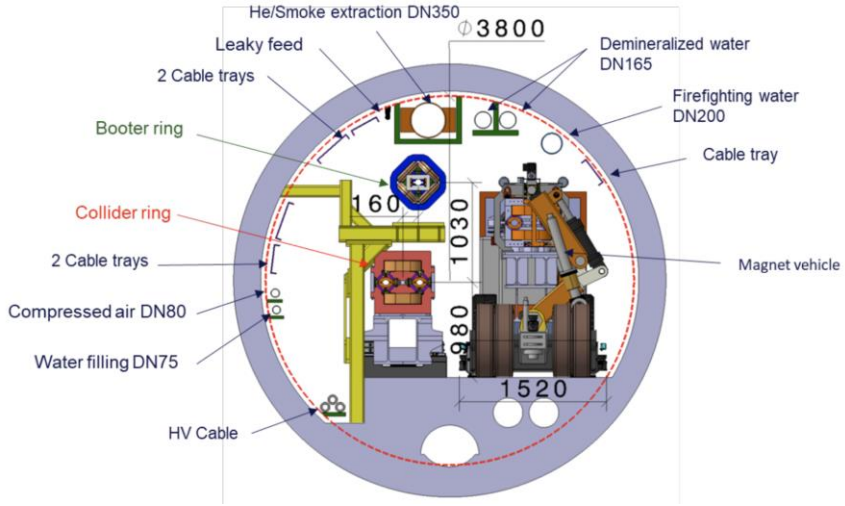
➔ A high luminosity electron-positron Higgs boson factory in the LHC tunnel

Strategy:

- re-use as much as possible the existing infrastructure of CERN.
- Utilise maximally the R&D already carried out, strong synergy with FCC-ee.
- Keep the required financing within the envelope of the current budget of CERN.

Parameter	Value
Number of Experiments	2
Energies c.o.m	91 GeV (Z), 160 GeV (WW), 230 GeV (ZH)
Instantaneous luminosity	50 (Z), 10 (WWW), 3 (ZH) x 10^{34} cm^{-2} s^{-1}
Crossing angle	30 mrad
Max. SR power loss	Fix at ~50 GeV @ H mode
Max SR energy loss/turn	~5.15 GeV @ H mode
Total RF voltage	5.7 GV (800MGz, 22.5MV/m, SCRF cavities

Continuous top-up injection using a separate full-energy booster



Compared to the linear e+e- colliders proposed, LEP3 provides similar luminosity for ZH production, higher luminosity at lower energies, and options for multiple experiments.

Muon Collider

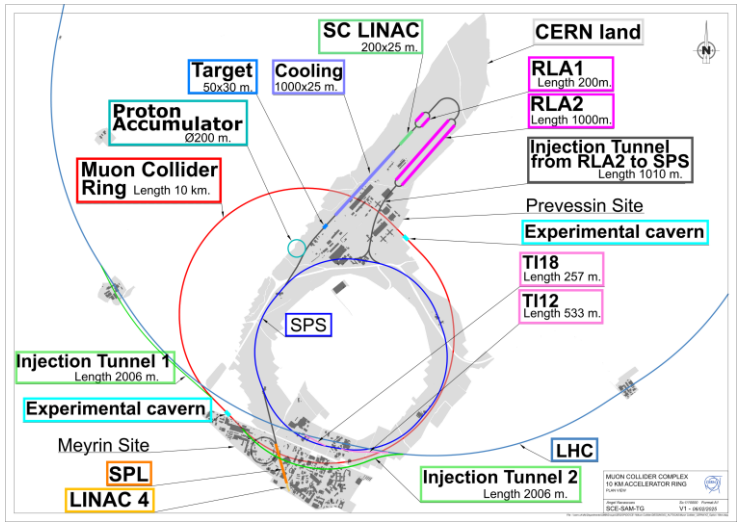
Muon Collider



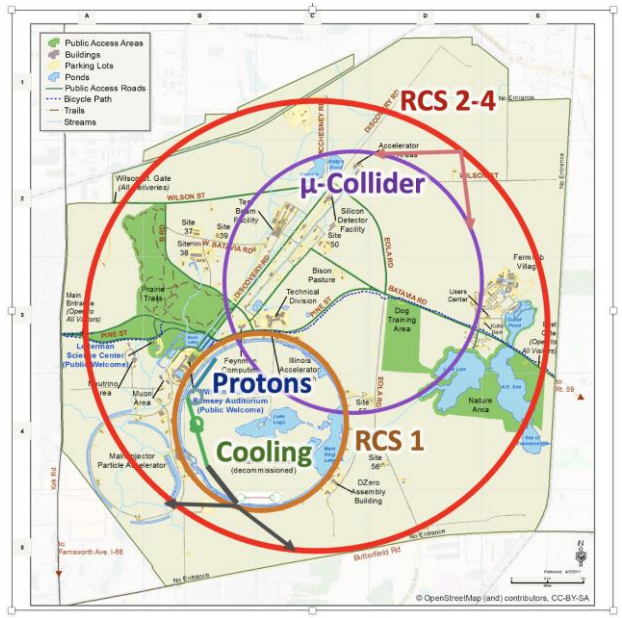
- Muons radiate far less synchrotron radiation than electrons (mass is 207 x higher).
- Combines the physics advantages of an e+e- and a hh collider, with a much smaller size.
- A 10-TeV muon collider would have similar discovery reach as a 100-TeV proton collider.
- Technology and design has advanced in the past years: no unsurmountable obstacles, but still in the **R&D phase**.

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

Staged approach

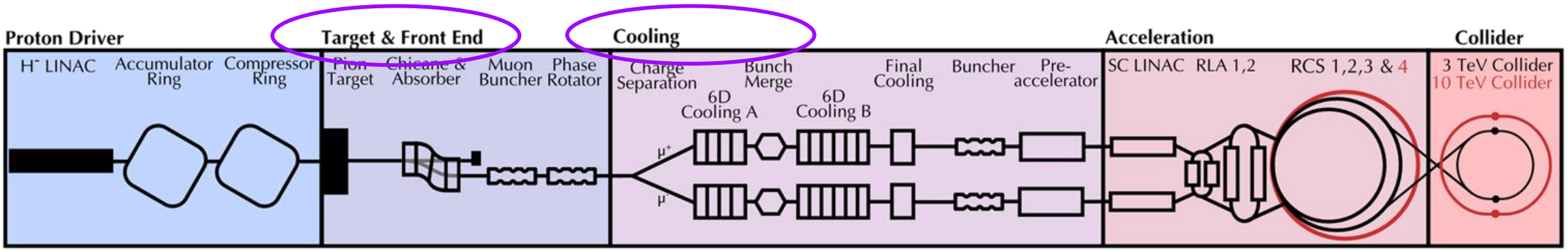


Muon collider proposal at **CERN**



Muon collider proposal at **Fermilab**

Muon Collider



Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muon 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.

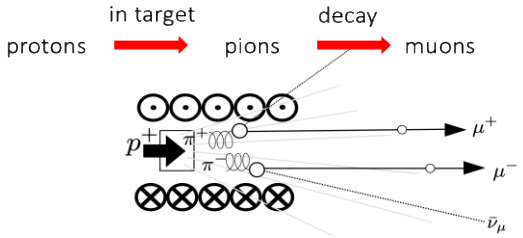
Muon Collider Challenges – Target

High power proton beam for muon production via pion decay

→ 5 GeV proton beam

→ 5×10^{14} protons/pulse

→ 5 Hz repetition rate

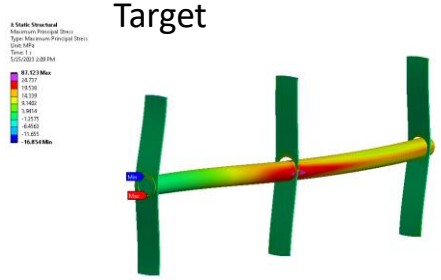


→ **2 MW target**, with high pion/muon yield

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

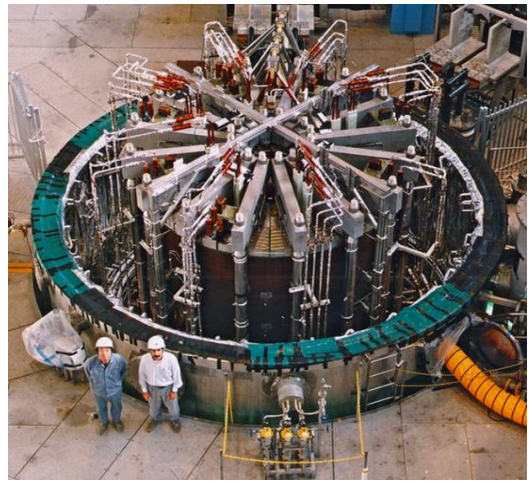


Target



Operation at 2000 °C to maximise stress resistance

Large bore, high field solenoid
Nb_3Sn or HTS

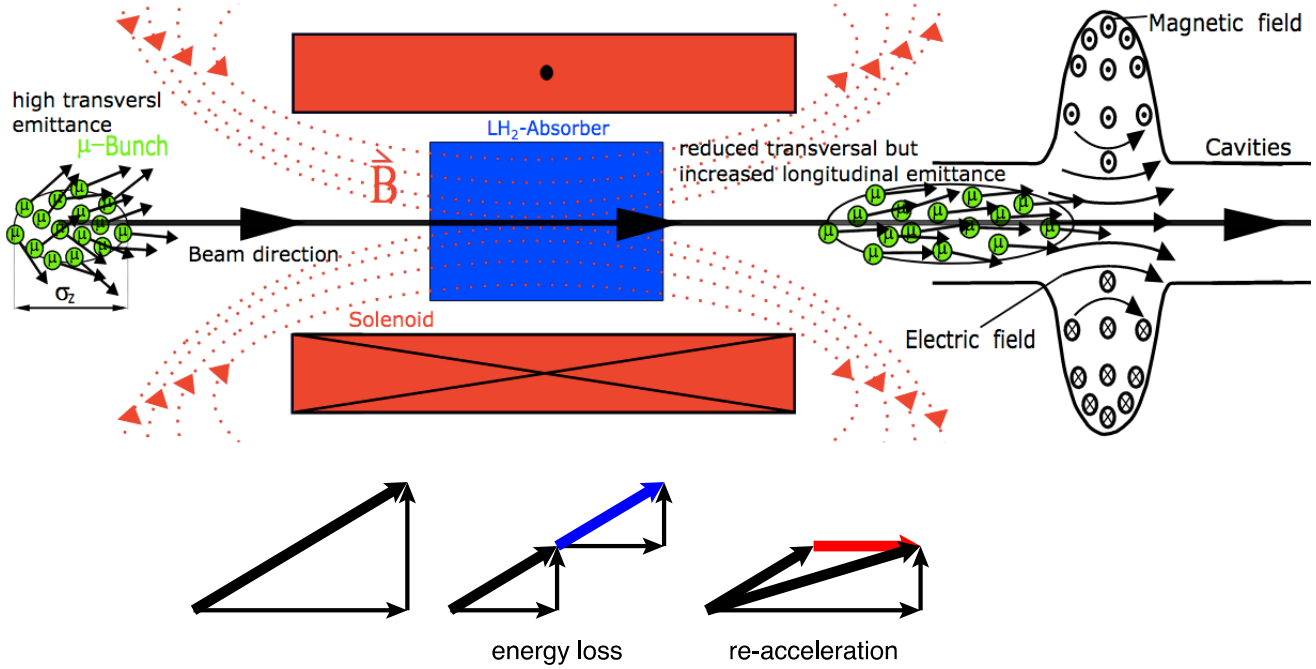


ITER Central Solenoid Model Coil
13 T in 1.7 m (LTS)

Muon Collider Challenges – Cooling

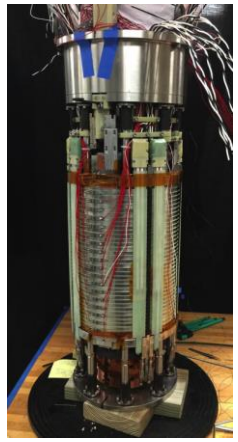
Generated muon bunch has too large emittance

- **4D cooling**: transverse emittance reducing on the cost of the longitudinal one.
- High field solenoids to minimize beta-function and reduce scattering.
- High RF gradients to quickly compensate for ionization energy loss.



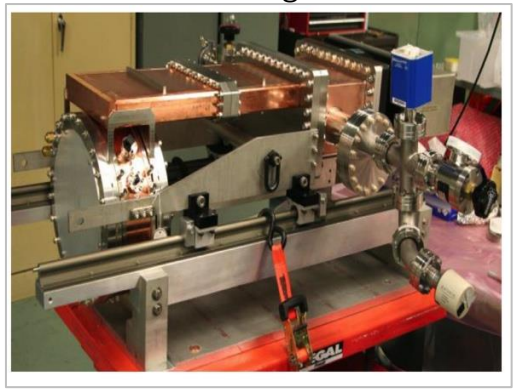
In MICE (UK) : principle demonstrated with no RF
Nature vol. 578, p. 53-59 (2020)

Highest field solenoids



32 T with low temperature HTS

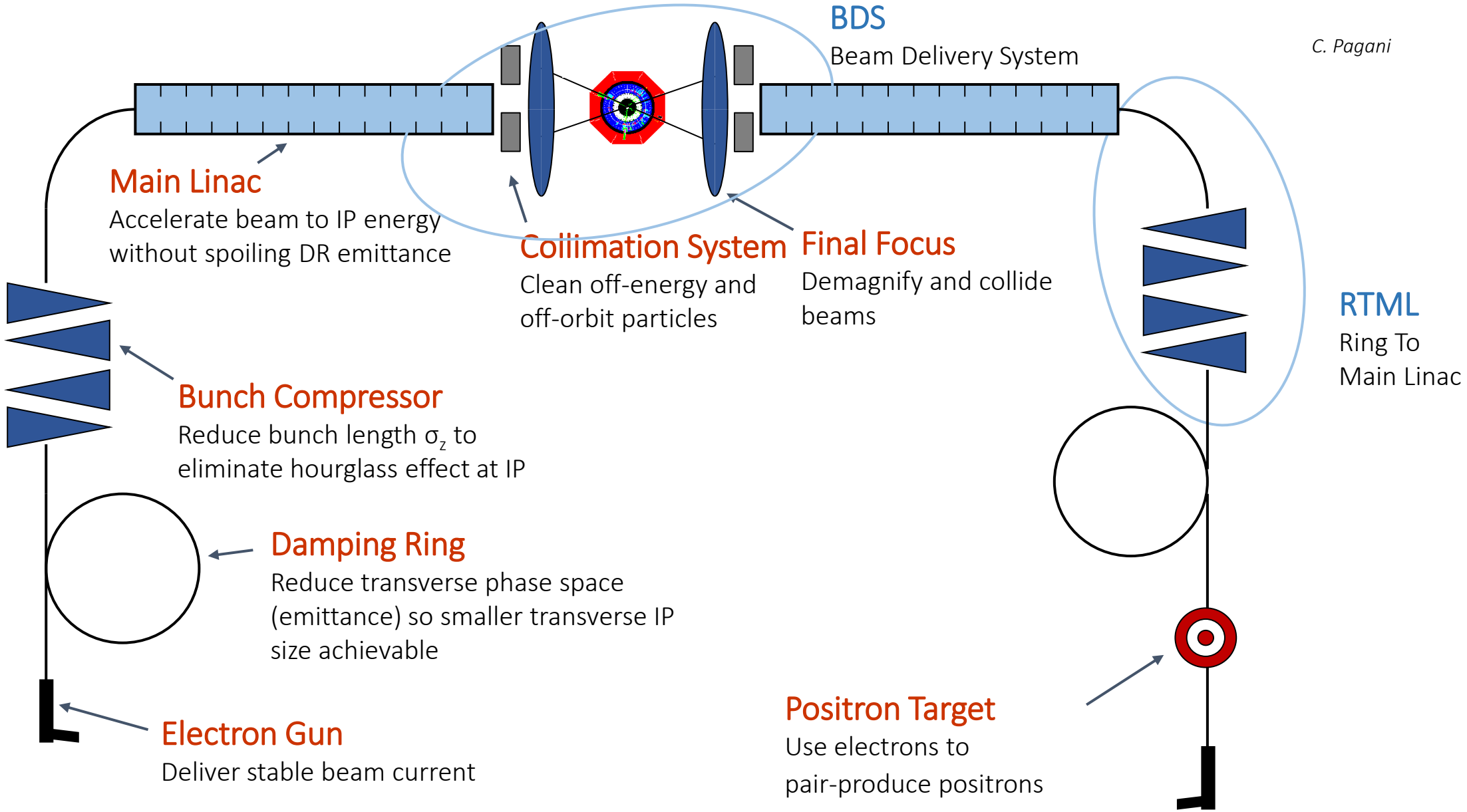
RF cavities in magnetic field



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

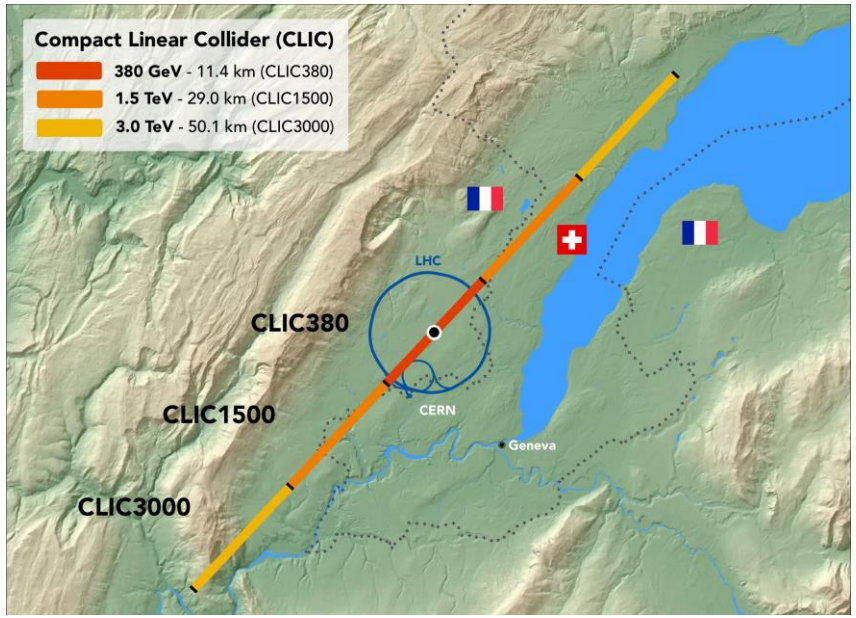
Linear Colliders

Generic Linear Collider



Linear Colliders

CERN: Compact Linear Collider, CLIC



12 GHz normal conducting cavities

100 MV/m accelerating gradient

CDR published in 2012, Project Implementation Plan in 2018

Two-beam accelerating technique

Initial stage: 380 GeV c.o.m.

Final stage: 3 TeV c.o.m.

Japan: International Linear Collider, ILC



1.3 GHz superconducting cavities

31.5 MV/m accelerating gradient

TDR published in 2013

250 GeV c.o.m.



ILC – Superconducting Accelerating Structures

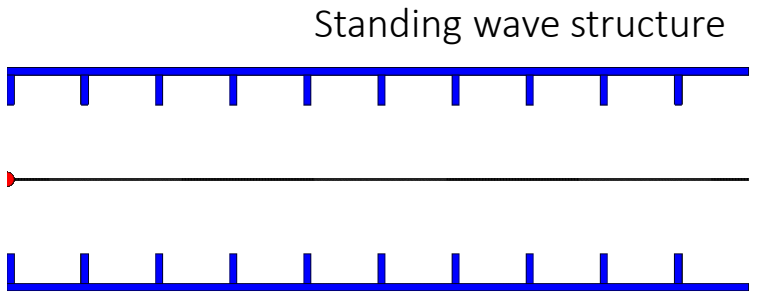
- Superconducting cavity (Ni at 2 K)
- RF frequency is 1.3 GHz, 23 cm wavelength
- Gradient is 31.5 MV/m
- Need about 16000 cavities to reach 250 GeV



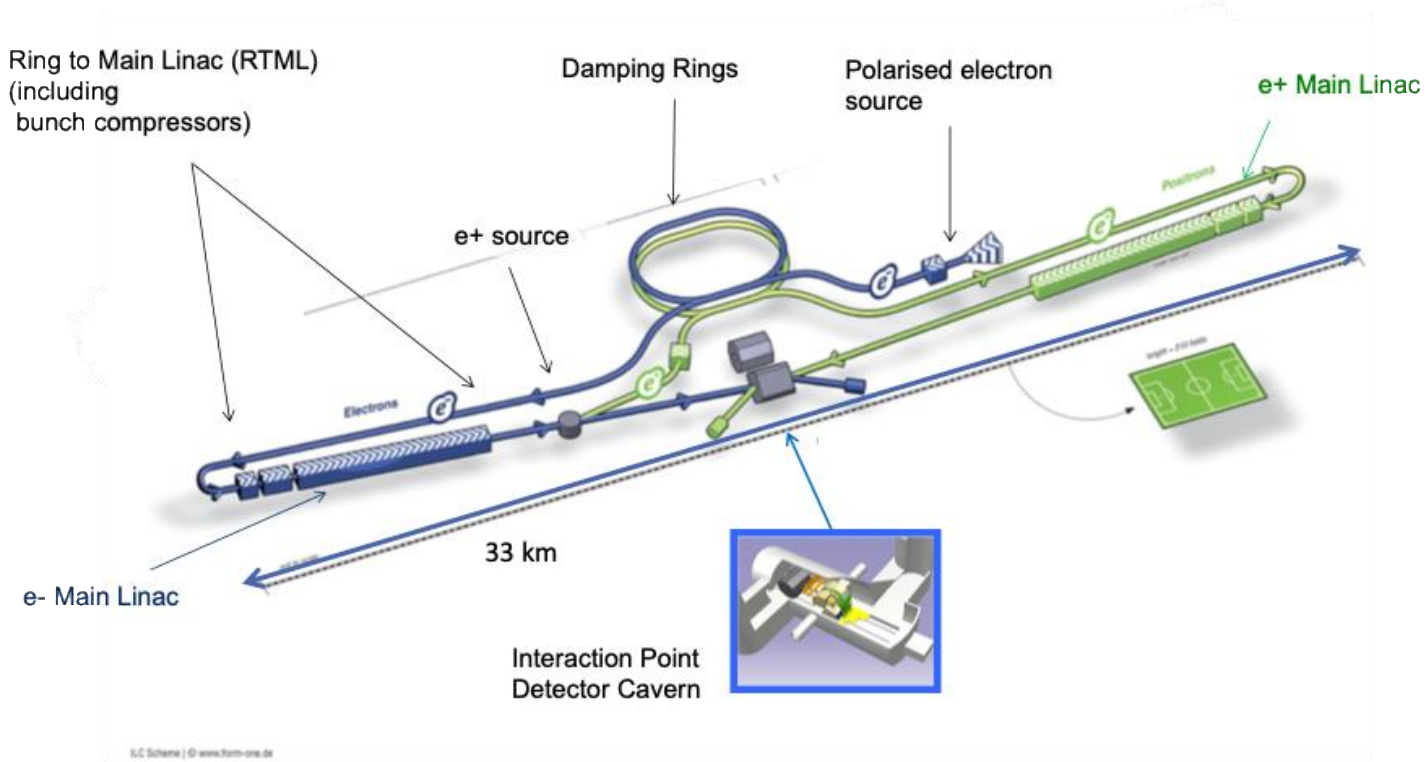
Mature technology and industrialisation:

- several FEL linac built and operated (EUXFEL, LCLS-II)
- Leading industries in Europe

High efficiency thanks to superconductivity.



ILC



Quantity Name	Symbol	Unit LCF	Initial-250 250 LP	Upgrades 250 FP	 550 FP	Initial-550 550 LP	Upgrade 550 FP
Centre-of-mass energy	$\sqrt{s}$	GeV	250	250	550	550	550
Inst. luminosity	$\mathscr{L}$ $(10^{34}cm^{-2}s^{-1})$		2.7	5.4	7.7	3.9	7.7
Polarisation	$\lvert P(e^-)\rvert$/ $\lvert P(e^+)\rvert$ (%)		80 / 30	80 / 30	80 / 60	80 / 30	80 / 60
Repetition frequency	f_{rep}	Hz	10	10	10	10	10
Bunches per pulse	n_{bunch}	1	1312	2625	2625	1312	2625
Bunch population	N_e	10^{10}	2	2	2	2	2
Linac bunch interval	Δt_b	ns	554	366	366	554	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	8.8	5.8	8.8
Beam pulse duration	t_{pulse}	μs	727	897	897	727	897
Average beam power	P_{ave}	MW	10.5	21	46	23	46
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
RMS hor. beam size at IP	σ_x^*	nm	516	516	452	452	452
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7	5.6	5.6	5.6
Lumi frac. in top 1 %	$\mathscr{L}_{0.01}/\mathscr{L}$	%	73	73	58	58	58
Lumi in top 1 %	$\mathscr{L}_{0.01}$ $(10^{34}cm^{-2}s^{-1})$		2.0	4.0	4.5	2.2	4.5
Site AC power	P_{site}	MW	143	182	322	250	322
Annual energy consumption		TWh	0.8	1.0	1.8	1.4	1.8
Site length	L_{site}	km	33.5	33.5	33.5	33.5	33.5
Average gradient	g	MV/m	31.5	31.5	31.5	31.5	31.5
Quality factor	Q_0	10^{10}	2	2	2	2	2
Construction cost		BCHF	8.29	+0.77	+5.46	13.13	+1.40
Construction labour		kFTE y	10.12		+3.65	13.77	
Operation and maintenance		MCHF/y	156	182	322	273	322
Electricity		MCHF/y	66	77	142	115	142
Operating personnel		FTE	640	640	850	850	850

Table 1: Summary table of the LCF accelerator parameters in the initial 250 GeV configuration and possible upgrades, as well as in an initial 550 GeV configuration and its luminosity upgrade.

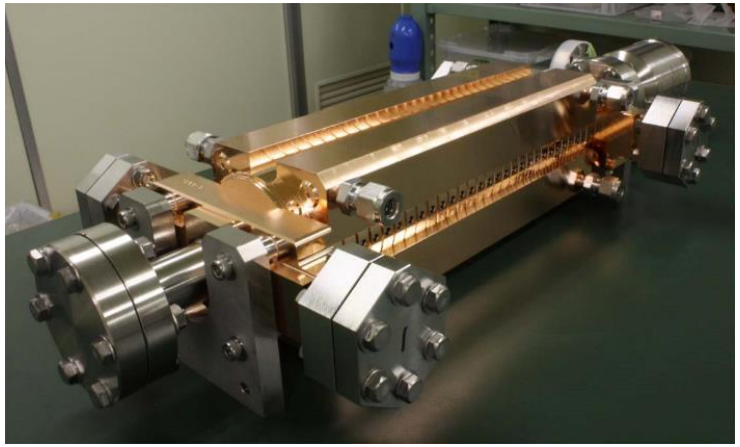
LCF, Linear Collider Facility

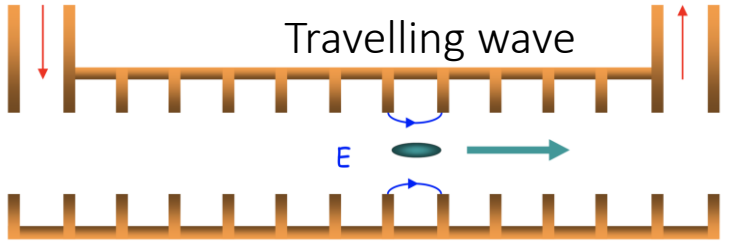
Studies to implement a SCRF based LC at CERN:

- Consider implementation of energies above 250 GeV (even initially), specifically 380 GeV and 550 GeV
- Increase luminosity wrt to parameters and share on **two IPs**
  - Key changes: Bunch trains 5 Hz to 10 Hz, double numbers of bunches per train
- **Combine with CLIC footprint/studies** as much as possible.

CLIC – High Gradient Accelerating Structures

- Normal conducting cavity
- RF frequency is 12 GHz (X-band), 25 mm wavelength
- Gradient is 100 MV/m
- Need about 140000 structures to reach 3 TeV

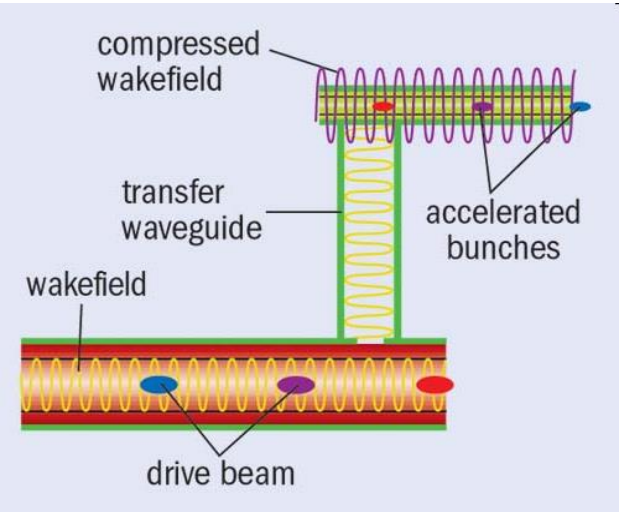




Particles "surf" the electromagnetic wave

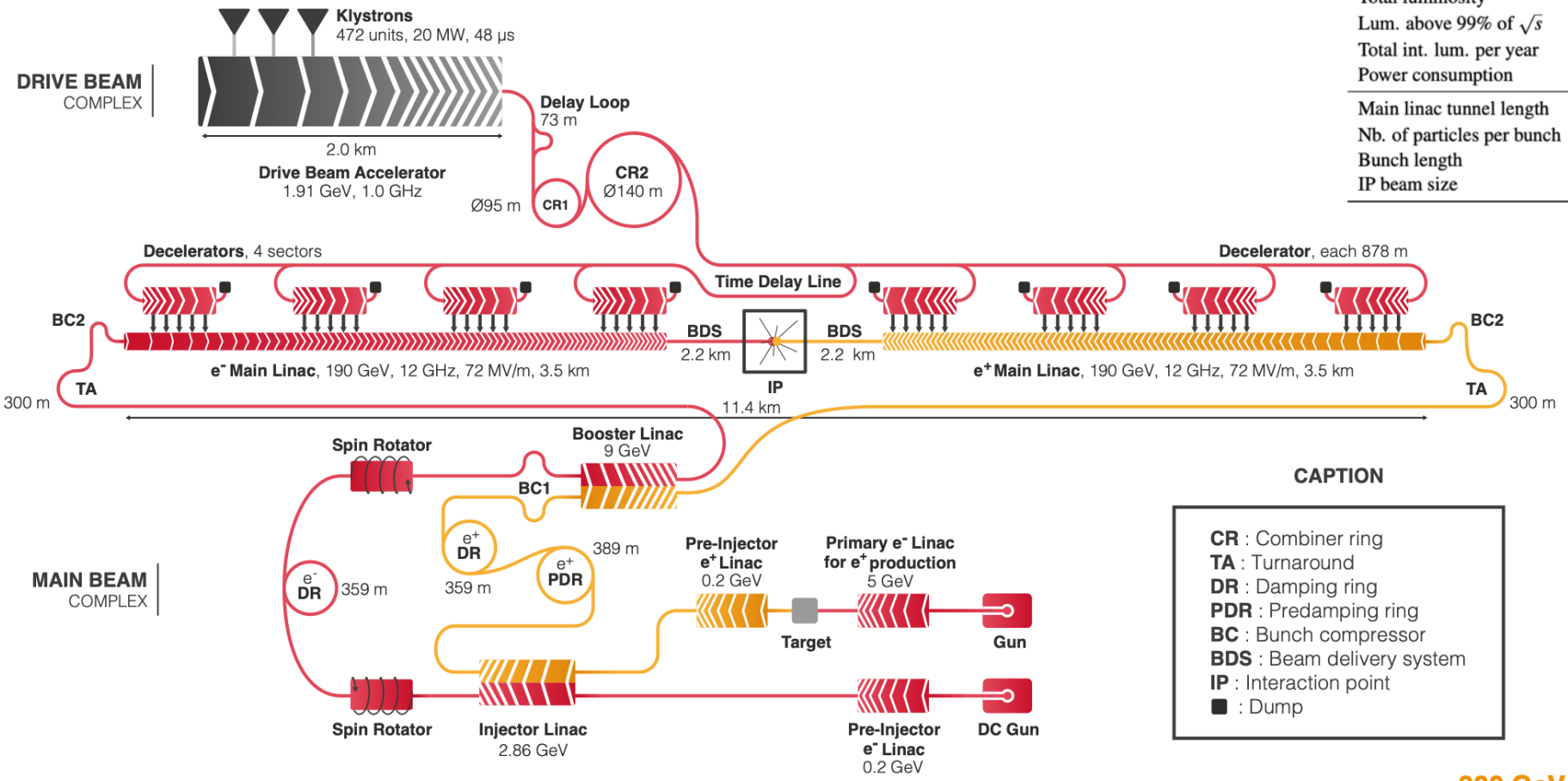
- BUT: powering system (modulators/klystrons) have low efficiency at high frequencies and short pulses

➔Solution: Two-beam scheme: use low frequency efficient modulators/klystrons units to accelerate high current long electron pulses (drive beam) and extract required high-frequency RF power from the drive beam to the main beam.



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

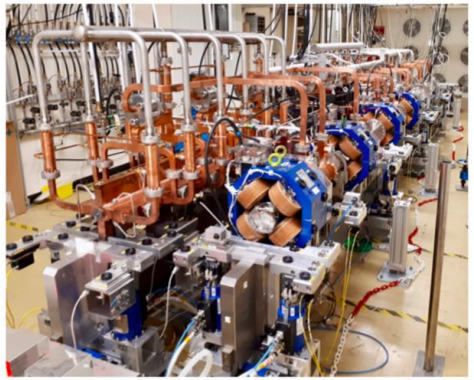


Parameter	Unit	380 GeV	1.5 TeV	250 GeV	550 GeV
Centre-of-mass energy	GeV	380	1500	250	550
Repetition frequency	Hz	100	50	100	100
Nb. of bunches per train		352	312	352	352
Bunch separation	ns	0.5	0.5	0.5	0.5
Pulse length	ns	244	244	244	244
Accelerating gradient	MV/m	72	72/100	72	72
Total luminosity	$10^{34}\,cm^{-2}s^{-1}$	4.5	3.7*	~3.0	~6.5
Lum. above 99% of $\sqrt{s}$	$10^{34}\,cm^{-2}s^{-1}$	2.7	1.4	~2.1	~3.2
Total int. lum. per year	fb^{-1}	540	444	~350	~780
Power consumption	MW	166	287	~130	~210
Main linac tunnel length	km	11.4	29.0	11.4	~15
Nb. of particles per bunch	10^9	5.2	3.7	5.2	5.2
Bunch length	μm	70	44	70	70
IP beam size	nm	149/2.0	60/1.5	~184/2.5	~124/1.7

CAPTION

CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

380 GeV



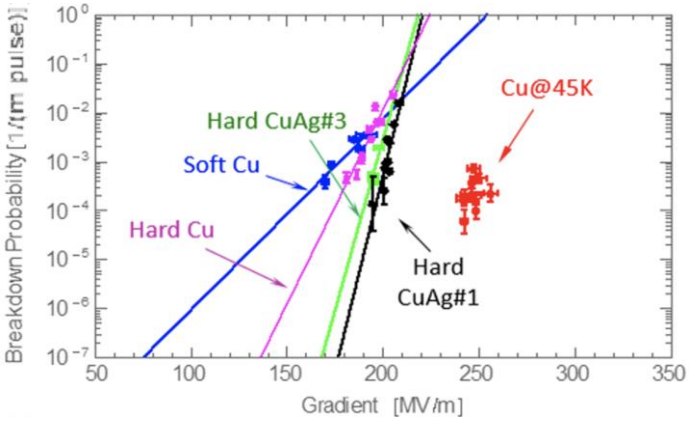
Two-beam scheme at CERN

Cool Copper Collider (C3)

Novel linac concept: C-band Cu RF cavities at 77 K (LN2)

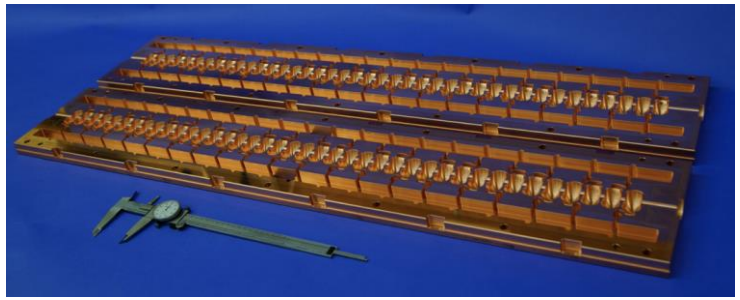
- High gradient comparable with CLIC but with a conventional RF system
- Compact footprint: ~8 km.
  - 250GeV (70MV/m structures), 550 GeV (120MV/m structures).
- Significant progress in last years, demonstrator needed.

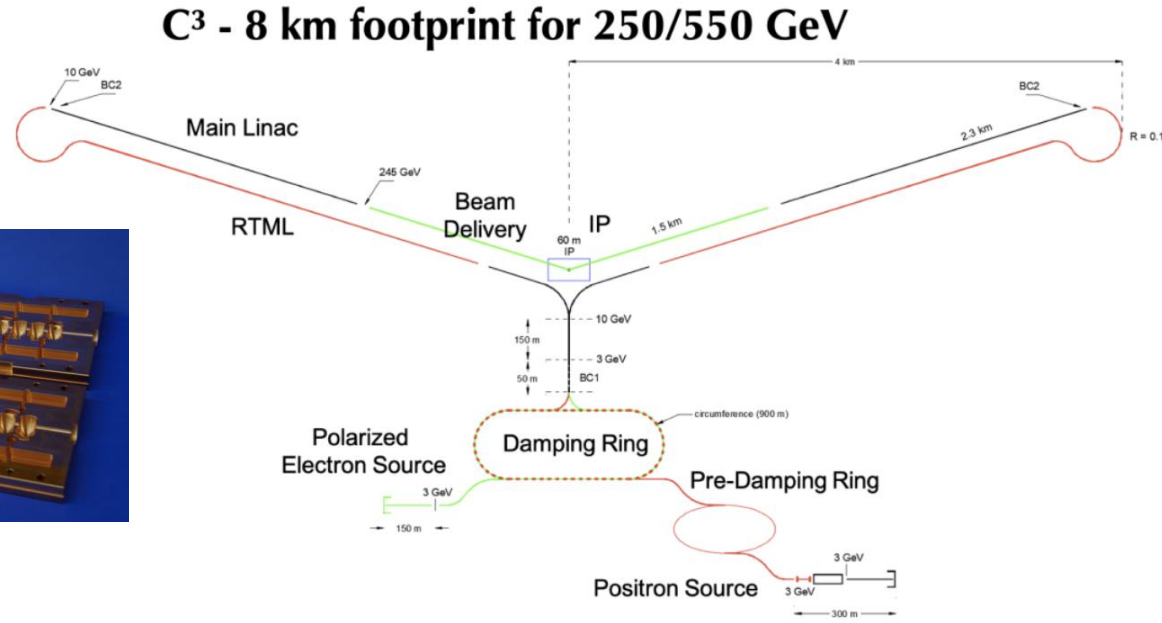
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Single Beam Power [MW]	2	2.45
Added Beam Power [kW/m]	1.1	1
Site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



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

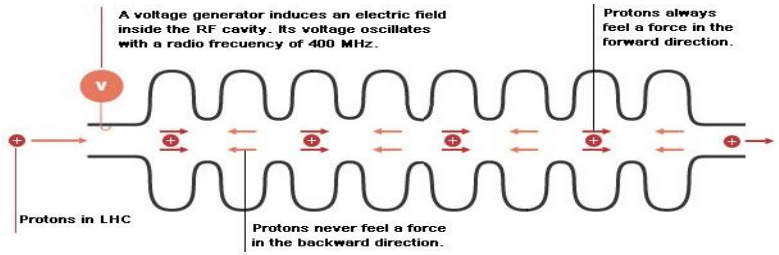
C3 prototype one meter structure



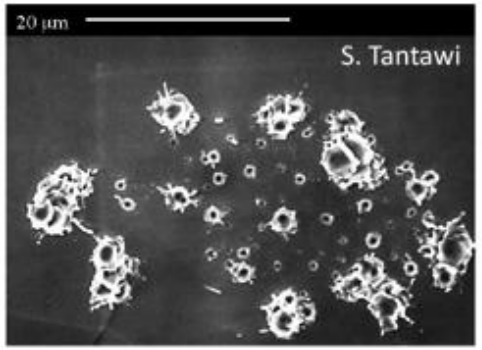


Accelerating Gradient

Conventional RF Cavities



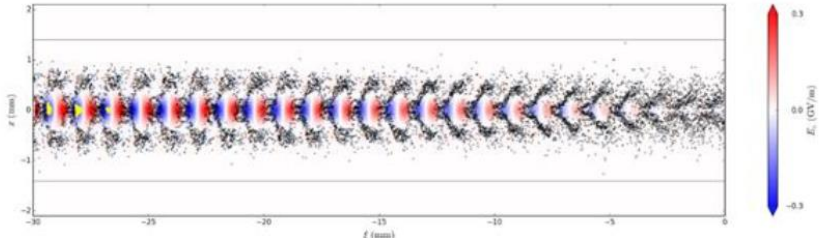
Surface of Copper Cell After Breakdown Events

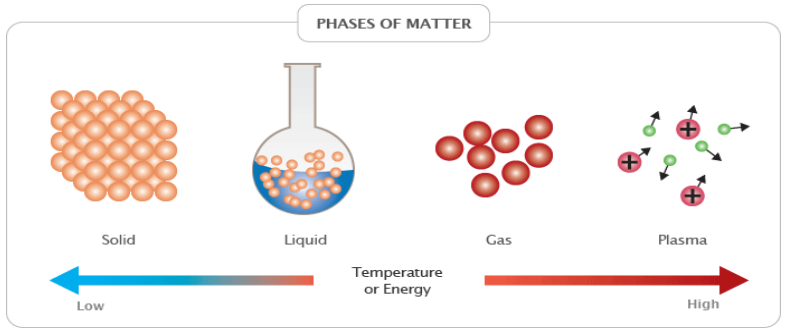


Typical gradients:
- LHC: 5 MV/m
- ILC: 35 MV/m
- CLIC: 100 MV/m

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

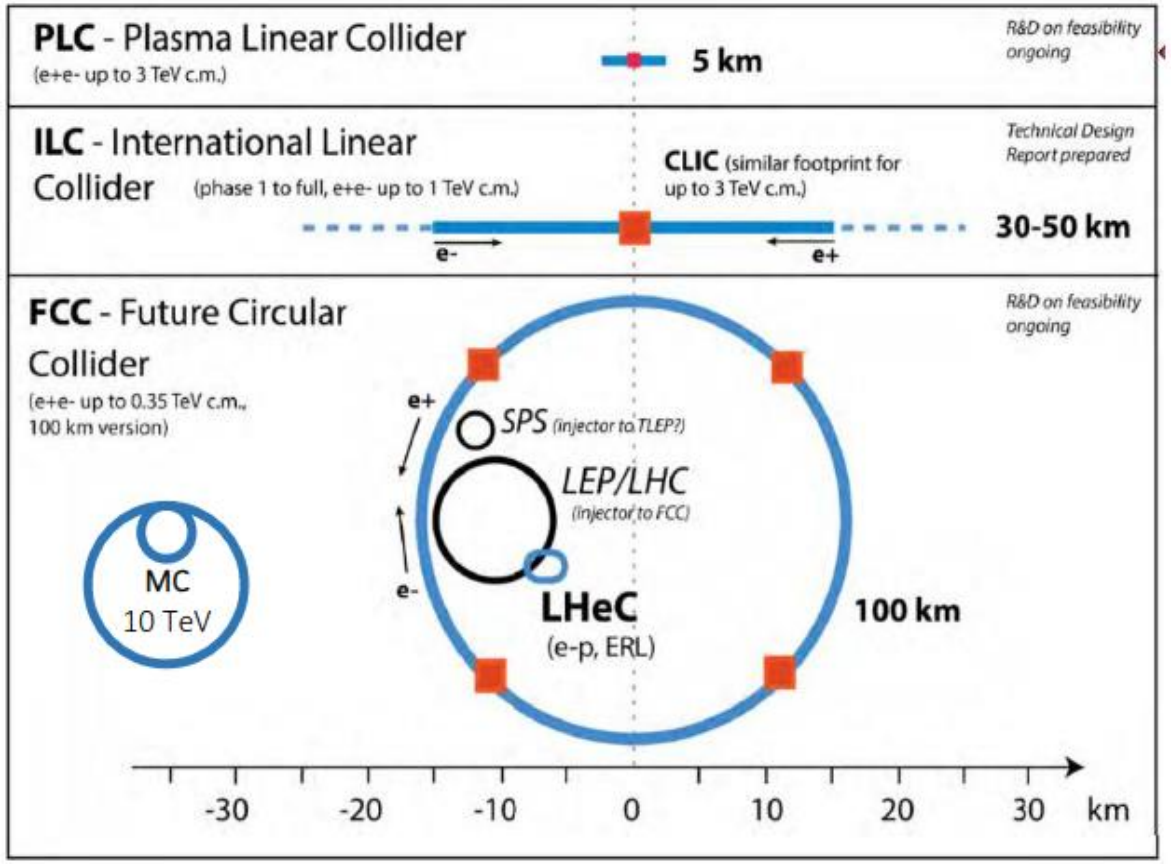
Colliders Based on Pasma Wakefield Acceleration

In linear colliders:

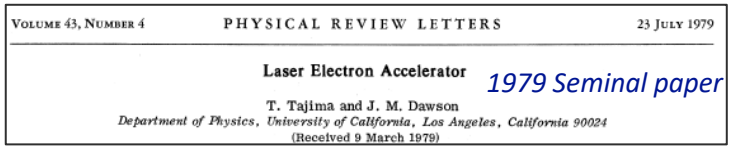
→Energy reach = length x gradient

With plasma wakefield acceleration:

→achieve same beam energy in much smaller facilities.



Plasma Wakefield Acceleration


VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, California 90024

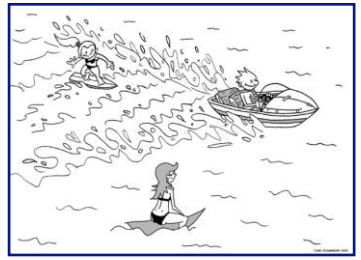
(Received 9 March 1979)

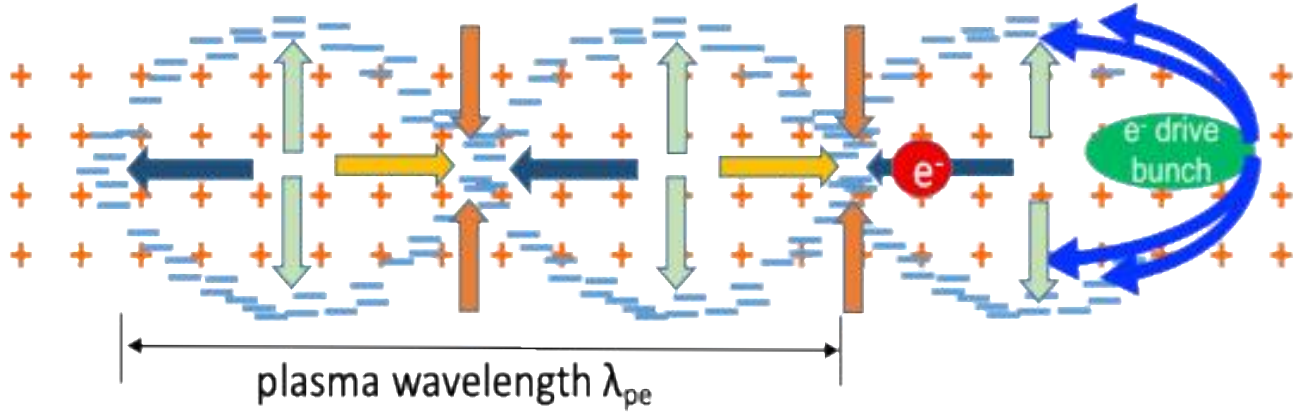
1979 Seminal paper

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} = 1x10^{18} cm^{-3} ➔ E_{WB} = ~100 GV/m ➔ λ_{pe} = ~30 µm

Energy Gain – State-of-the-Art

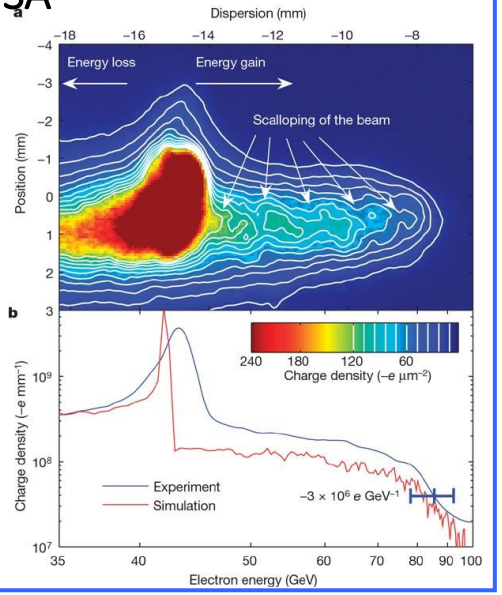
Electron Driven

42 GeV in 85 cm



FACET, SLAC, USA

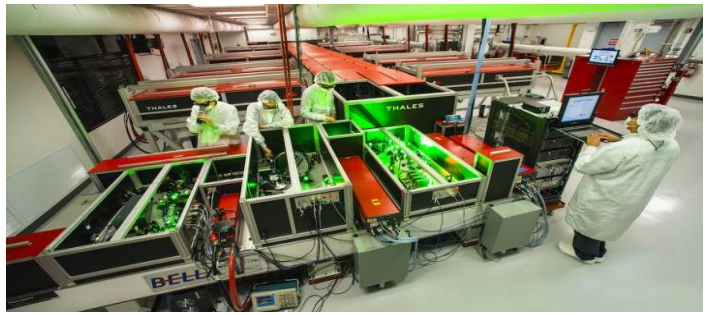
→ gradient of 52 GV/m



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

Laser Driven

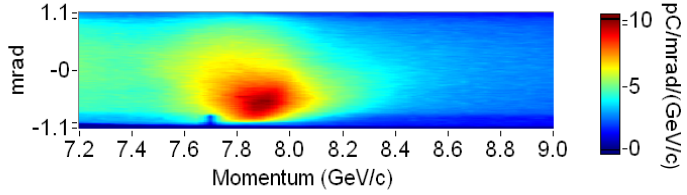
8 GeV in 20 cm



BELLA, Berkeley Lab, USA



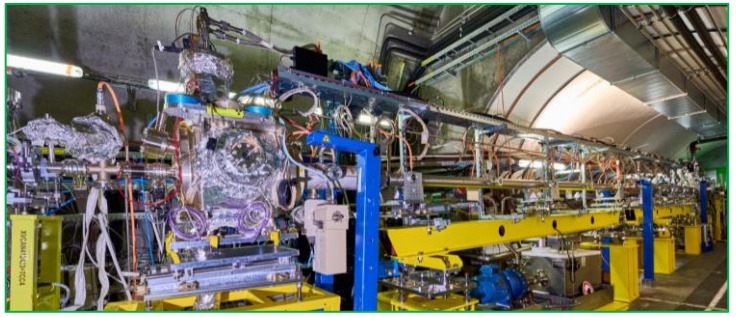
laser-heated capillary discharge waveguide, 20cm-scale plasma



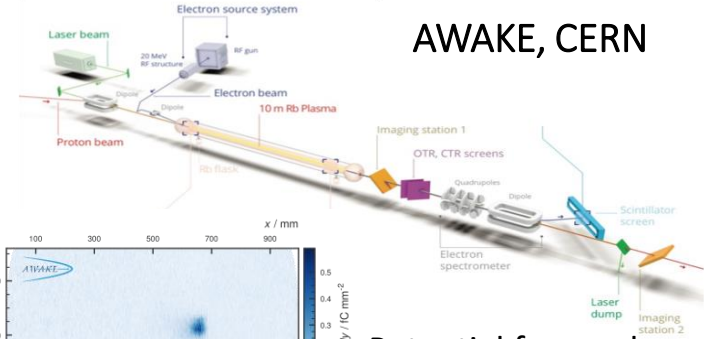
*A.J.Gonsalves et al., Phys.Rev.Lett. **122**, 084801 (2019)*

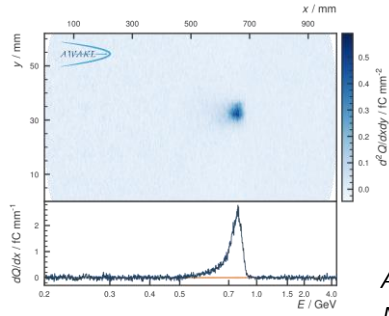
Proton Driven

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)

➔ Lots of progress on other key R&D challenges (stability, efficiency, beam-quality, etc.).
➔ international efforts to move from R&D towards designing accelerators.

Plasma Wakefield Acceleration Applications

Short-term (5-10 yrs)

First Applications

Light Sources, FEL
Medical applications
National security
Radiation generation

Mid-term (10-20 yrs)

Particle physics applications

Fixed target experiments
Injector for a synchrotron/collider
Collider components
Test beams

Long-term (> 20 yrs)

HEP colliders

Higgs factories
Energy frontier linear collider (10 TeV)

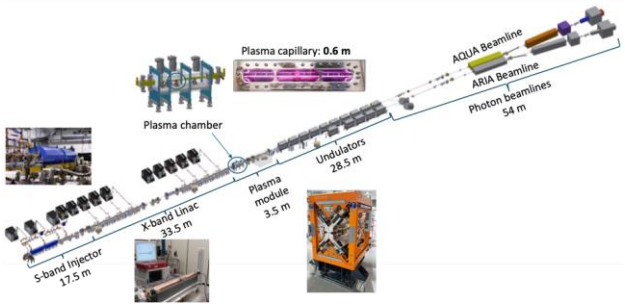
250 GeV

10 TeV

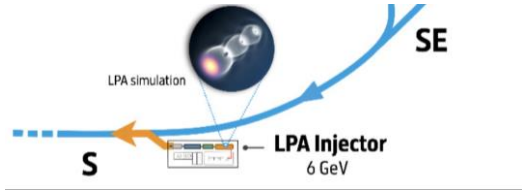
O (~10s GeV)

O (~5 GeV)

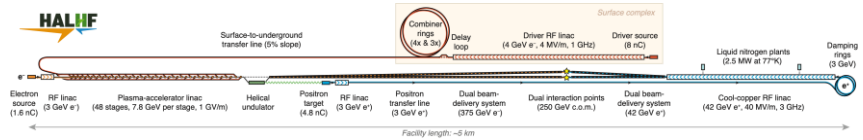
EuPRAXIA



Plasma injector into PETRA IV



HALHF: 250 GeV Higgs factory



Outline

- Motivation
- Next-Generation Colliders
- Towards the Next Flagship Collider: The European Strategy for Particle Physics

What is the European Strategy for Particle Physics?

- The ESPP aims to **develop a common vision for the future of particle physics in Europe** within the international context.
  - It guides CERN and European countries in major decisions: facilities, investments, research directions



- **Why** is the Strategy needed?
  - HEP/PP projects are long-term (decades), expensive (billions), and multinational
  - Need coordination across countries and labs
  - Avoid duplication and align efforts toward common scientific goals

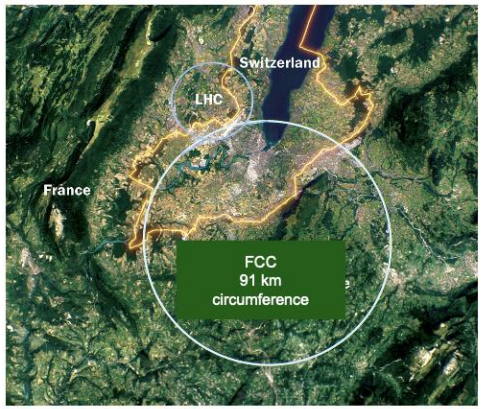
- **Every ~6-7 years**. First adopted in 2006, updated in 2013 and most recently in 2020
  - 2006: Original strategy: LHC; mooting of an LHC luminosity upgrade, accelerator-technology R&D, coordination with a potential ILC project
  - 2013: 1st update: High-Luminosity LHC; the need for a post-LHC programme
  - 2020: 2nd Update: FCC feasibility study
  - 2026: recommendation for the next large-scale accelerator project at CERN – reaching consensus on a preferred option and possible alternatives.

- 21 March 2024, the CERN Council formally launched this update of the European Strategy for Particle Physics. **Process concluded in June 2026.**
  - Two-year process involving the whole community

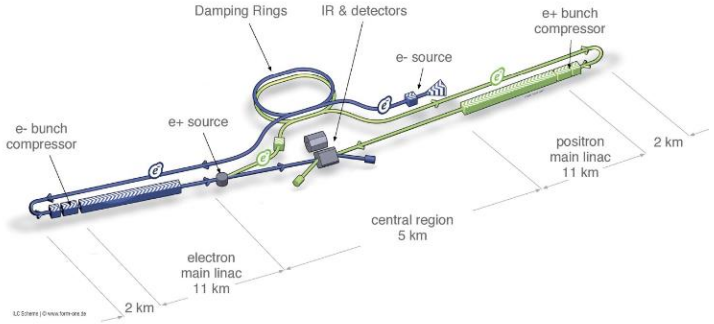
ESPP: Proposed Large Scale Projects at CERN

e^+e^- colliders
("Higgs, Electroweak, Top and Flavor Factories factories")

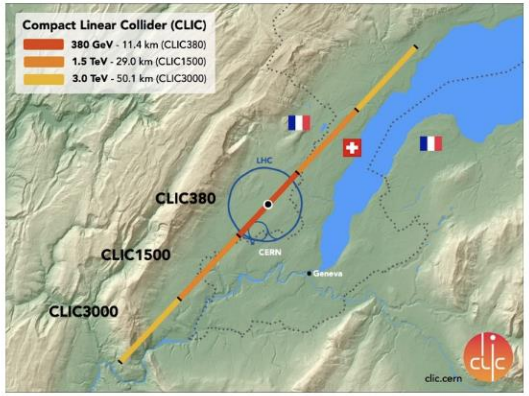
FCC-ee (e^+e^-, circular, 91 – 365 GeV)



LCF (e^+e^-, linear, 91 – 240, 550 GeV)



CLIC (e^+e^-, linear, 380 GeV, 1.5 TeV)



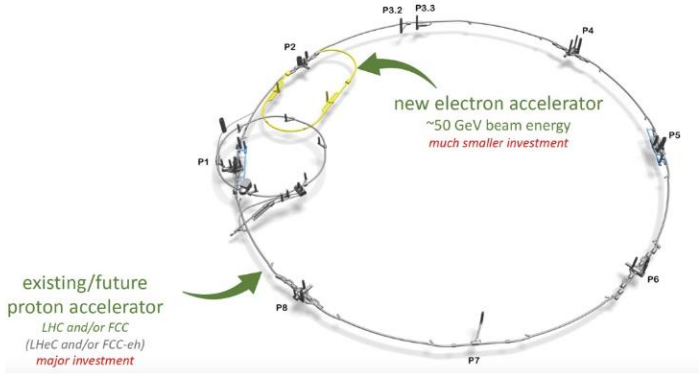
Intermediate projects

(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10++ TeV parton center-of-mass scale)

LEP3 (e^+e^-, circular, 91 – 230 GeV)

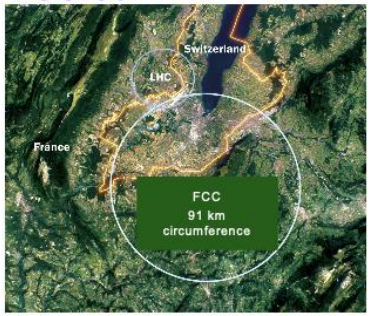


LHeC (ep, circular, electron ERL, 50 GeV e^-, > 1 TeV ep collisions)



The Vision: Collider Options for >10 TeV Parton-c.o.m. Energies

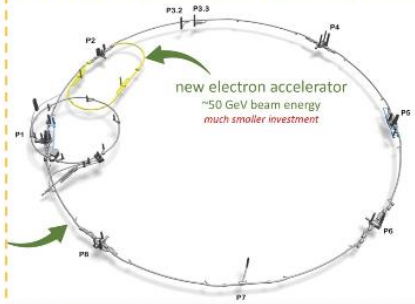
FCC-ee



LEP3

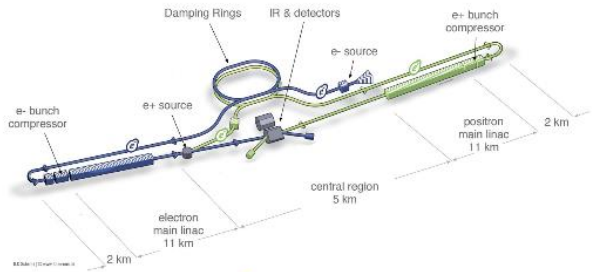


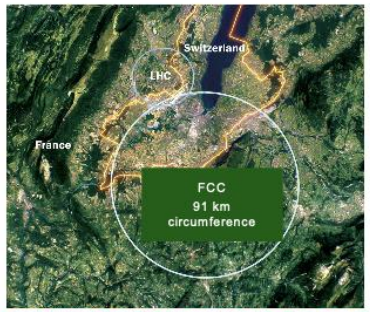
LHeC



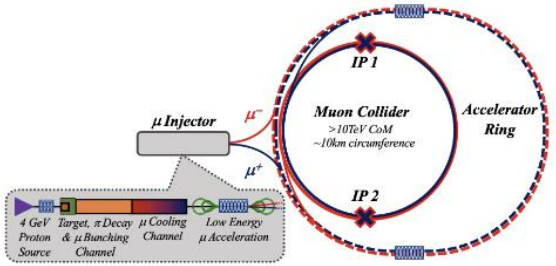
PERLE

LCF, CLIC





FCC-hh,
baseline 85 TeV (→ 120 TeV)
+ possibility for HI collisions



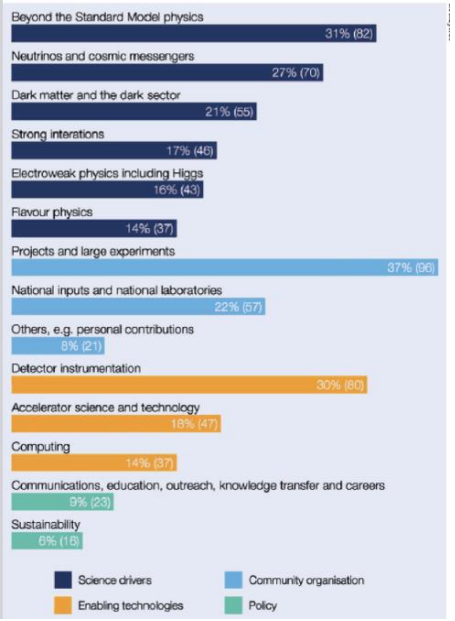
Muon Collider (3, 10 TeV)

R&D



e^+e^- with improved acceleration technologies
LCF, C^3 (→ 1 TeV), CLIC (1.5 TeV), HALHF, …
→ plasma acceleration for higher energies

Timeline for the Update of the European Strategy for Particle Physics



266 submissions received

- Major flagship projects
- Many projects in other physics areas
- Input from national HEP communities
- National labs
- Early career researchers
- …

Council appointment of the members of the **PPG** and decision on the venue for the **Open Symposium**

End September 2024

December 2024

Council decision on the venue for the **ESG Strategy Drafting Session**

Deadline for the submission of main input from the community

31 March 2025

26 May 2025

Deadline for the submission of additional national input in advance of the **Open Symposium**

Open Symposium

23-27 June 2025

End September 2025

Submission of the "Briefing Book" to the **ESG**

Deadline for the submission of final national input in advance of the **ESG Strategy Drafting Session**

14 November 2025

1-5 December 2025

ESG Strategy Drafting Session

Submission of the draft strategy document to the Council

End January 2026

March and June 2026

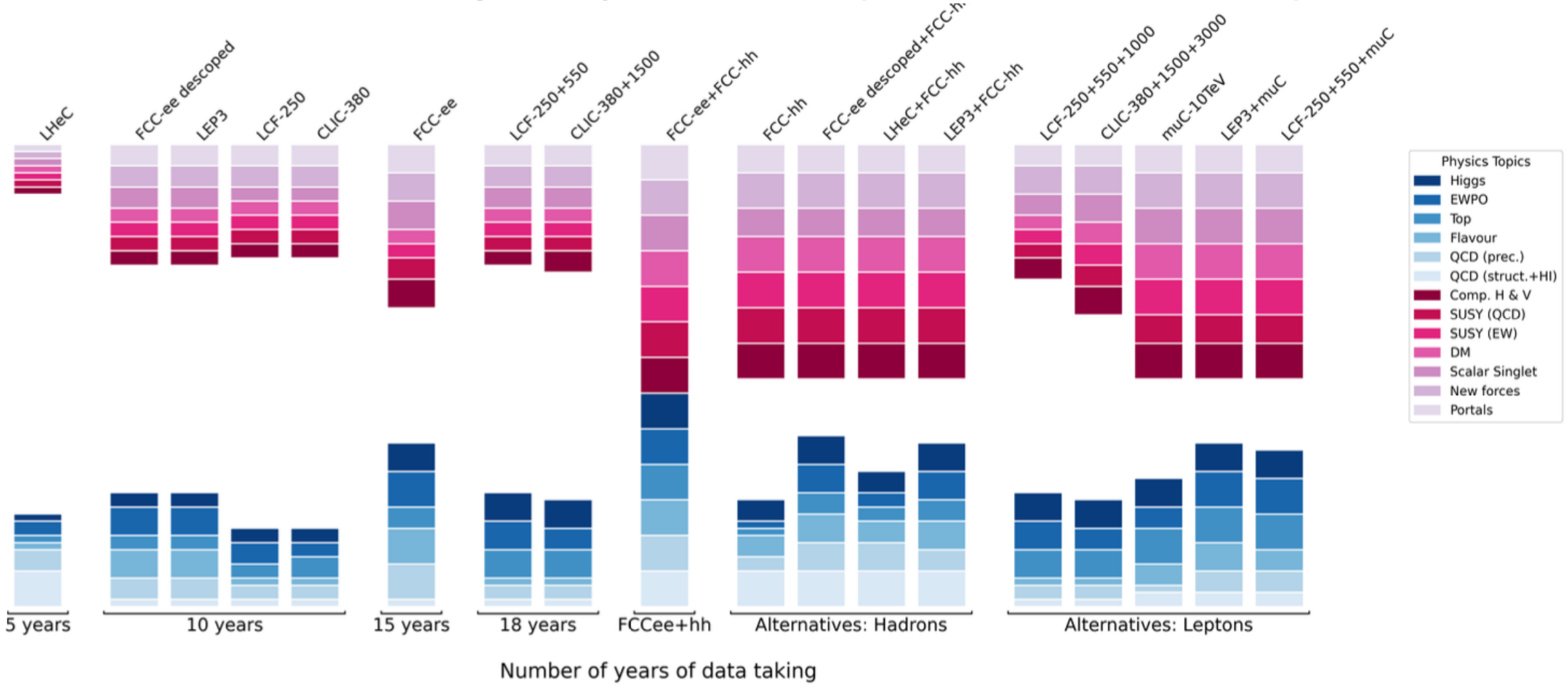
Discussion of the draft strategy document by the Council and **updating of the Strategy**

European Strategy Group Documents

- High-Level recommendations summarised in the Recommendation Document
  - Released on 12th Dec. 2025
- Deliberation Document
  - More detailed explanation to justify the recommendations.
- ESG Working Group Reports
  - Physics potential, Project assessment, final input from the National HEP communitites
- All reports available on the Strategy page: https://europeanstrategyupdate.web.cern.ch/



ESPP: Coverage of the Physics Landscape



Stacked ranking in each physics area (blue) and BSM model (red) as a function of the estimated total amount of time from the start of the data taking. Also shown combinations of the lower-energy projects with a high- energy option.

ESPP: Comparison of e+e- Colliders

Machine	Precision Physics	BSM physics	Physics vs CEPC	Technical readiness	Constr. cost (BCHF)	Time scale	Path to ≥10 TeV
FCC-ee	22	23			15.3	2046-2060	
Descoped FCC-ee	15	17			12.9	2046-2055	
LCF550	15	17			14.8	2045-2065	
CLIC1500	14	18			14.6	2045-2066	
LCF250	10	16			9.4	2045-2053	
CLIC380	10	16			7.5	2045-2054	
LEP3	15	17			4.1	2047-2062	
LHeC	8	7			2.1	2044-2051	

Physics: from WG2b: sum of precision/BSM physics

Phys vs CEPC: competitiveness, assuming CEPC is running in parallel

Tech readiness: from WG2a

Construction cost: from proponents + exp. (CERN part)

Strong preference for FCC-ee with respect to the other collider options considered is based on detailed scientific assessment of the ESG.

ESPP Recommendations

The full exploitation of the physics potential of the LHC and the HL-LHC and the completion of the high-luminosity upgrade remain the highest priorities of European particle physics. Every effort must be made to complete the HL-LHC upgrade within the current schedule.

A. The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.

B. A descoped FCC-ee is the preferred alternative option for the next flagship collider at CERN.

→ *All possible efforts should be made by the CERN Council and CERN management to explore if FCC-ee or a descoped FCC-ee can be realised over the next years.* ***Aim for a decision in 2028.***

Summary

- The particle physics field is entering an exciting new chapter of discovery.
  - The High Luminosity LHC will keep delivering forefront measurements and discovery potential for the next decade, building on decades of breakthroughs.

- A broad portfolio of collider concepts is under development for the next flagship machine.
  - FCC-ee/FCC-hh, LEP3, a muon collider, linear colliders (ILC, CLIC, C3) and plasma wakefield acceleration each offer a different route to higher energy and precision.

- Europe has a bold vision, backed by the community, for the future of particle physics.
  - The European Strategy for Particle Physics shows an ambitious path towards the next flagship collider, promising decades of exciting new physics beyond the LHC.

Thank You!