Future High-Energy Collider Projects

Part 2

Roderik Bruce

Outline

First lecture

- Introduction
  - Considerations for collider design: particle type, energy, circular/linear…
  - Limitations for future colliders
  - European strategy for particle physics
- ILC (International Linear Collider)
- CLIC (Compact Linear Collider)

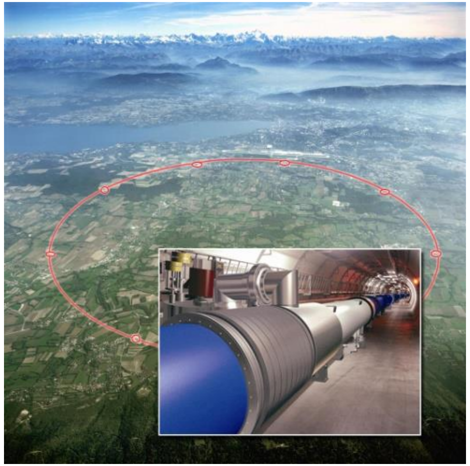
Second lecture

- HL-LHC (High-Luminosity Large Hadron Collider)
- FCC-hh (Future Circular collider, hadrons)
- FCC-ee (Future Circular collider, e+e-)
- CEPC/SppC (Chinese Electron-Positron Collider / Super proton-proton Collider)
- Muon collider

Linear

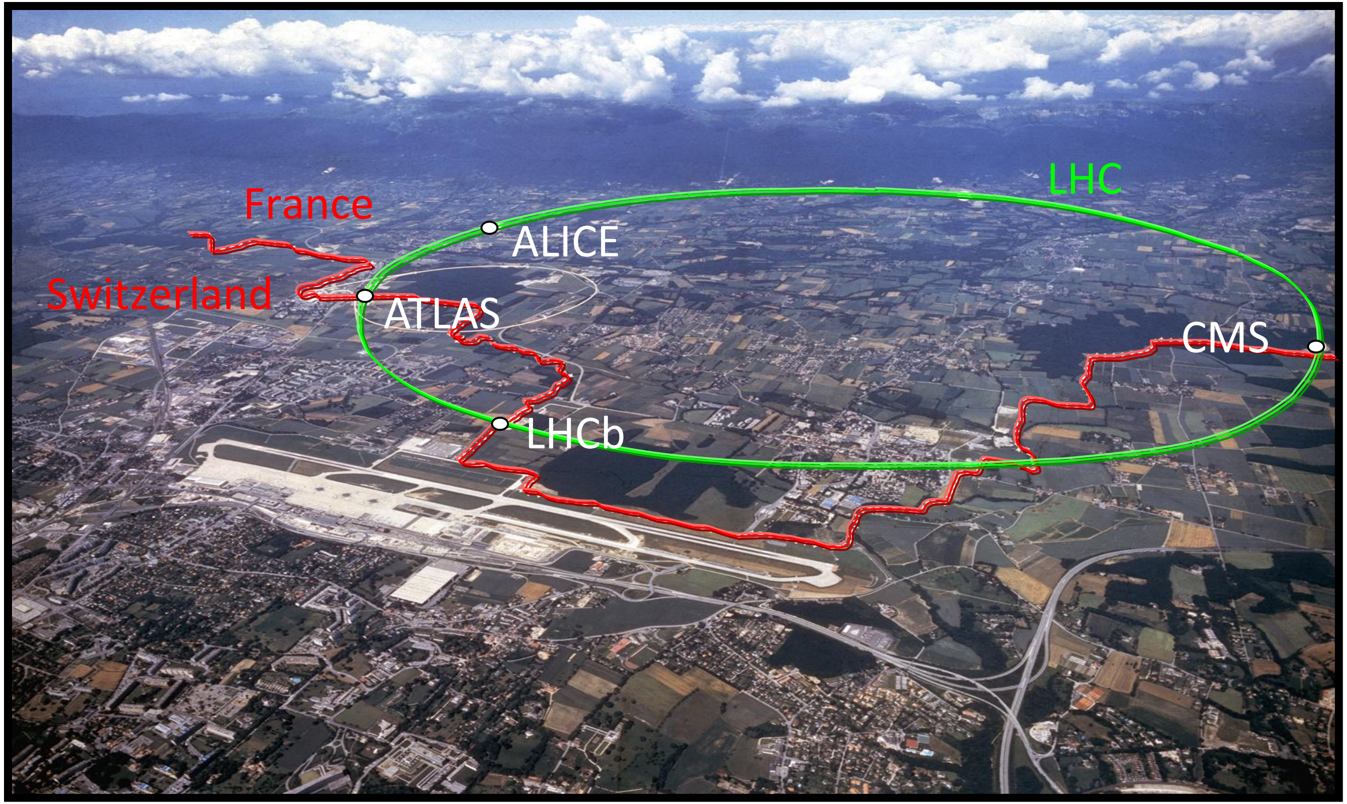
Circular

HL-LHC



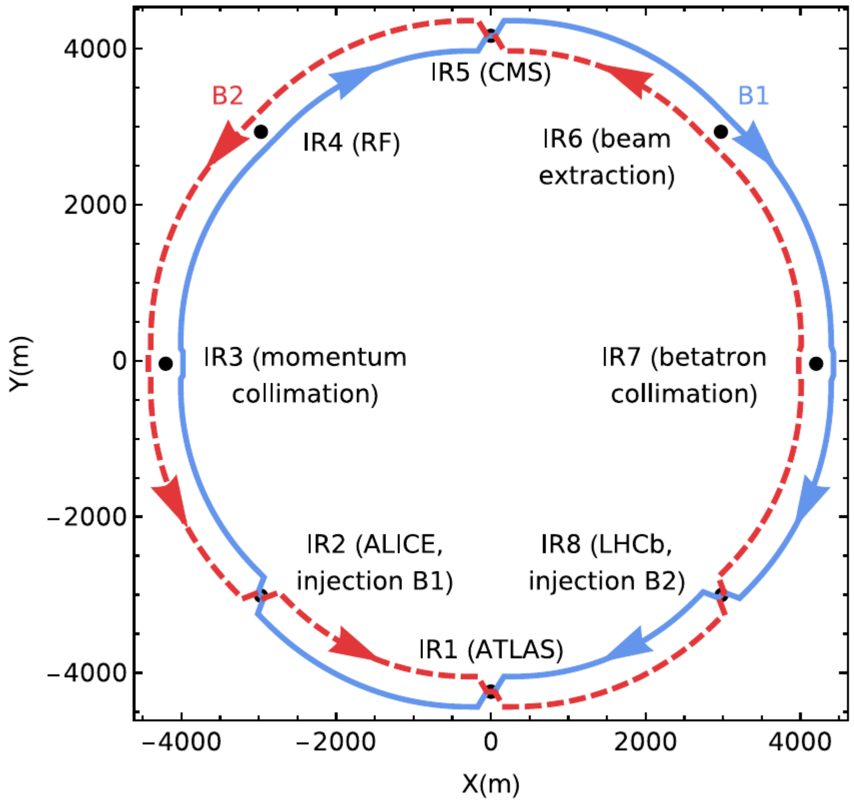
Reminder: LHC

- 27 km synchrotron, built to collide 7 TeV proton beams at 4 experiments
  - Largest collider and highest energy to date
- About 1 month per year: heavy-ion collisions
- About 1200 superconducting dipole magnets (NbTi) with 8.3 T field, operating at 1.9 K
  - In total, more than 9000 magnetic elements



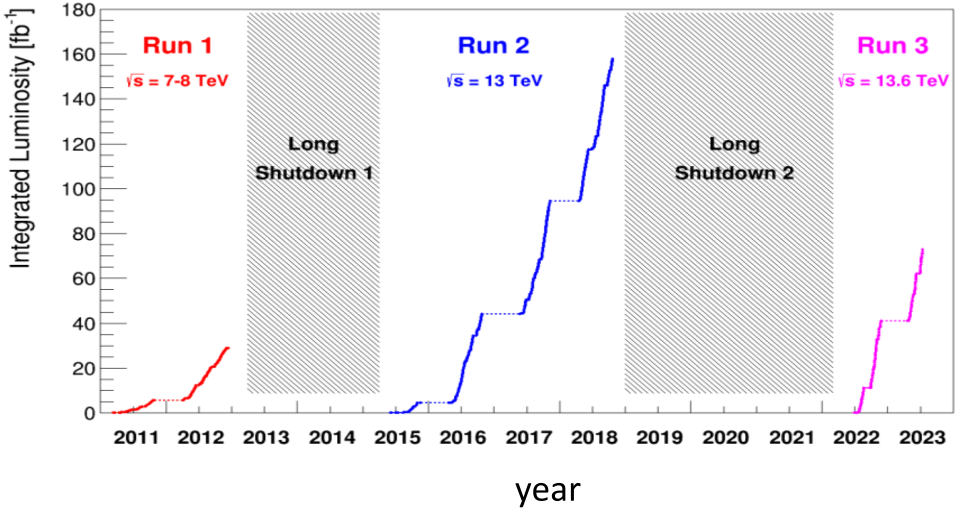
LHC layout

- 8 bent sections, arcs, and 8 straight sections, “insertion regions (IRs)”
- 4 experiments where beams collide (ATLAS – IR1, ALICE – IR2, CMS – IR5, LHCb – IR8)
- 2 IRs for beam cleaning (collimation), one for RF, one for beam extraction



LHC main parameters

Parameter	2024	Design
Energy [TeV]	**6.8**	7.0
No. of bunches	**2352**	2808
p/bunch (typical value) [10^{11}]	**1.6**	1.15
Max. stored energy per beam (MJ)	**410**	362
β* [cm]	**30**	55
Typical normalized **emittance** [μm]	**~1.8**	3.75
Peak **luminosity** [10^{34} cm^{-2}s^{-1}]	**2.1 (lev.)**	1.0



$$\frac{dR}{dt} = L \times \sigma_p \qquad L = \frac{kN^2 f\gamma}{4\pi\beta^*\varepsilon} \cdot F$$

Tot. no. events $$R_{tot} = \int L\,dt \times \sigma_p$$

- Design luminosity of 1×10^{34} cm^{-2}s^{-1} surpassed by more than a factor 2
- Collected in total more than 300 fb^{-1} of integrated luminosity at the high-luminosity experiments (ATLAS, CMS)

HL-LHC

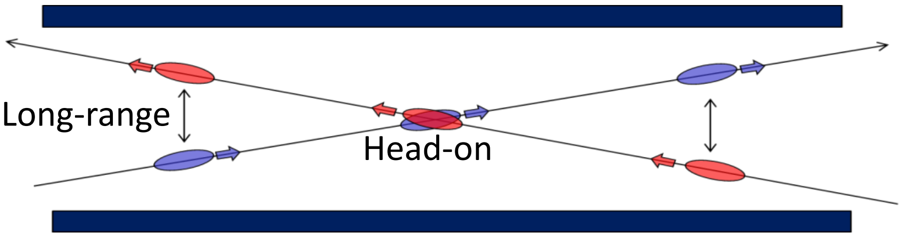
- High-luminosity LHC: Major upgrade of the LHC
- Main goals:
  - achieve a total integrated luminosity of 3000 fb^{-1}, a factor ~10 higher than what has been achieved so far since the start of the LHC
  - Target an integrated luminosity of ~250 fb^{-1} per year
  - Prepare machine for operation from 2029 and into 2040's

$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} \cdot F$$

	LHC 2024	HL-LHC
Protons per bunch	1.6×10^{11}	2.2×10^{11}
Number of bunches	2352	2750
Normalized emittance	1.8 micron	2.5 micron
Beta*	30 cm	15 cm
Full crossing angle	320 microrad	500 microrad
Geometric reduction factor F	0.6	0.35
"Virtual" luminosity	4.2×10^{34} $cm^{-2}s^{-1}$	2.4×10^{35} $cm^{-2}s^{-1}$
Levelled luminosity	2.1×10^{34} $cm^{-2}s^{-1}$	5×10^{34} $cm^{-2}s^{-1}$

Compensation of geometric reduction factor

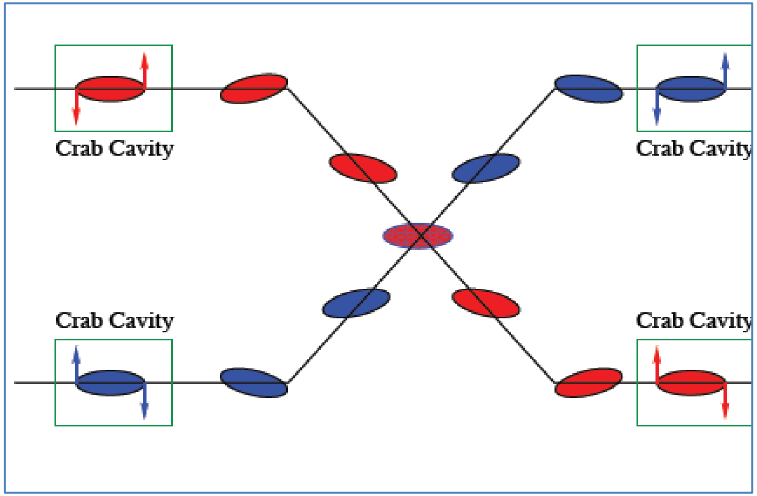
- Bunches experience electromagnetic force from the opposing beam at the collision point (head-on beam-beam) or nearby in common beam pipe (long-range beam-beam)
  - Need crossing angle, not only to avoid parasitic collisions



- Crossing angle at HL-LHC must be larger than at LHC, due to higher intensity
  - Would cause very large loss in luminosity: F≈0.35

$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} \cdot F$$

- To compensate: use "crab cavities" that tilt the bunches longitudinally and ensure overlap at the collision point



Crab cavities

- Create a oscillating transverse electric field
- Kick head and tail of the bunch in opposite directions

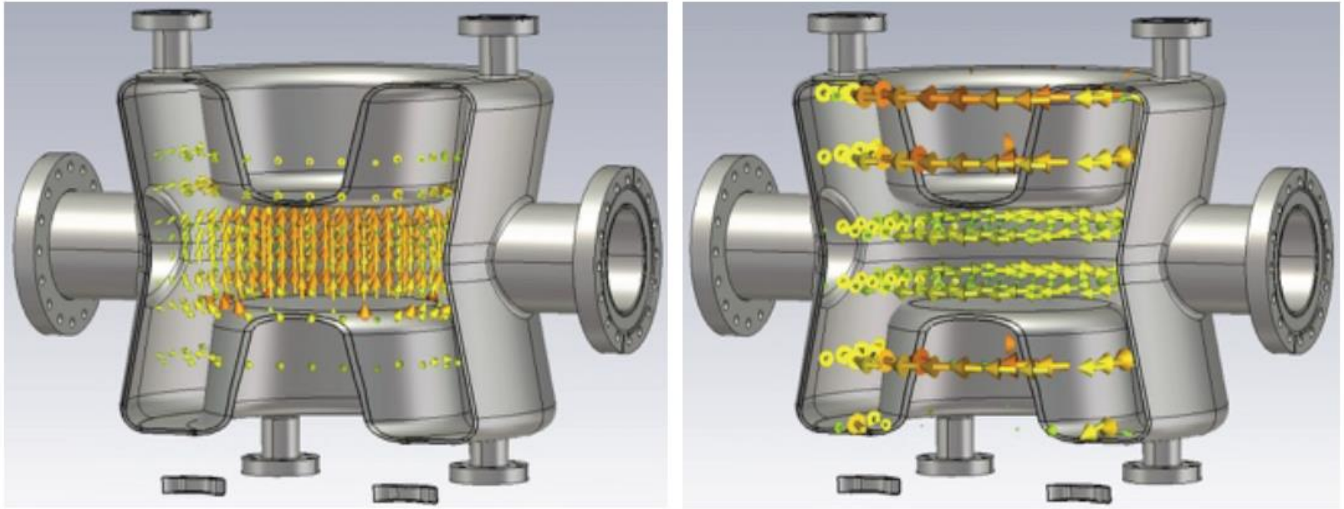
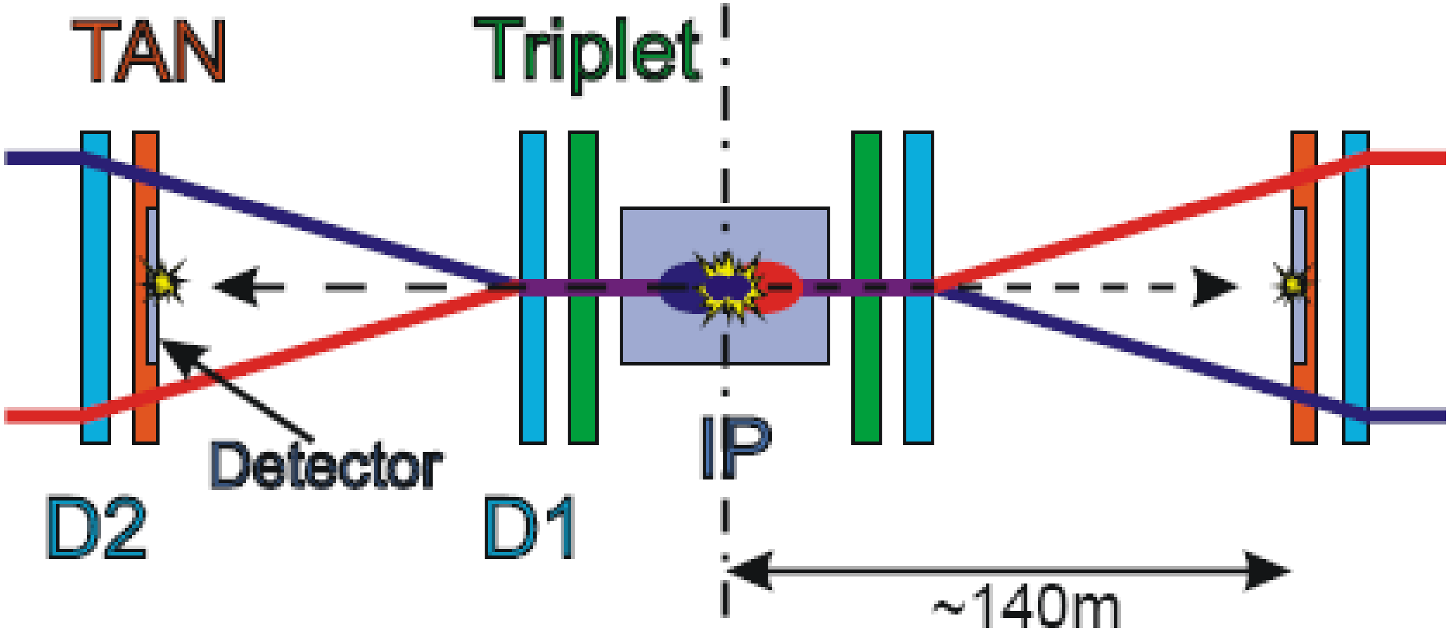


Figure 4. Electric (left) and magnetic (right) field distributions inside the DQWCC.

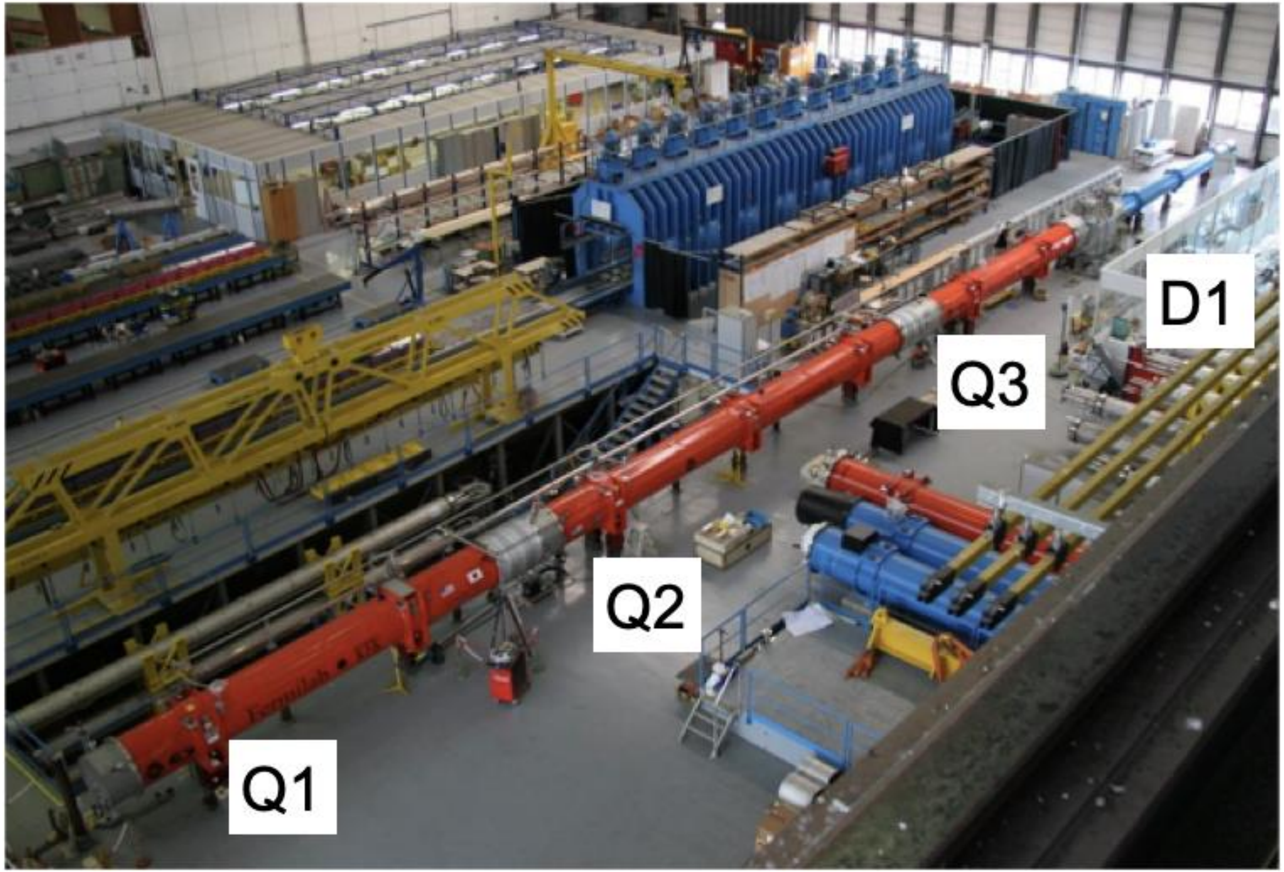
HL-LHC interaction region

For smaller β*: need new triplet

All magnets and other equipment in IR1 and IR5 to be completely exchanged for HL-LHC

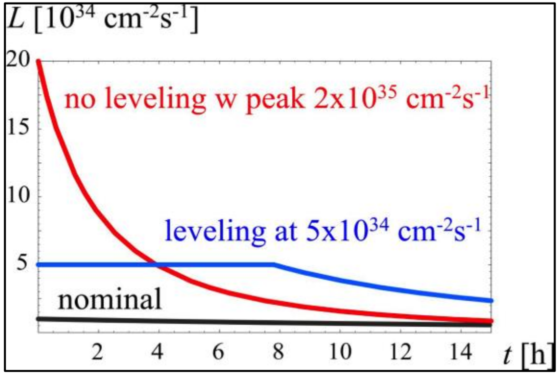


Comparison: LHC triplets



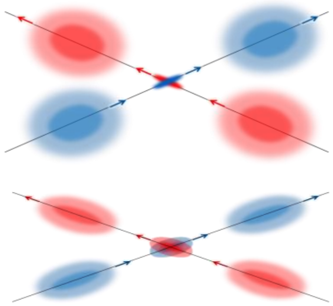
Luminosity leveling

- Experiments can only cope with a certain maximum event rate before saturating
- In LHC and HL-LHC, the achievable peak luminosity gives a significantly higher rate
- Solution: artificially reduce luminosity to stay within limit of experiments – **”leveling”**
  - Can be done by changing offset between beams, β* (beam size – chosen option in HL-LHC) or crossing angle



Separation leveling

β*-leveling



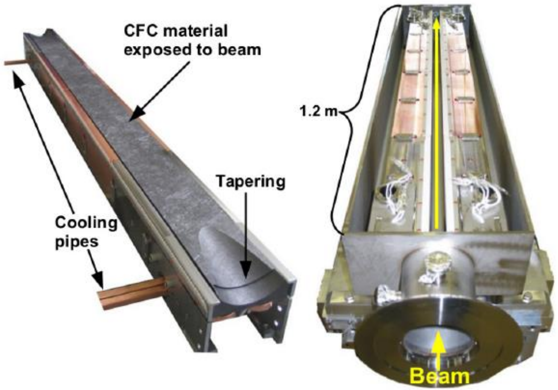
Collimation and machine protection

- Losses from the beam are inevitable, and could cause magnet quenches or even damage

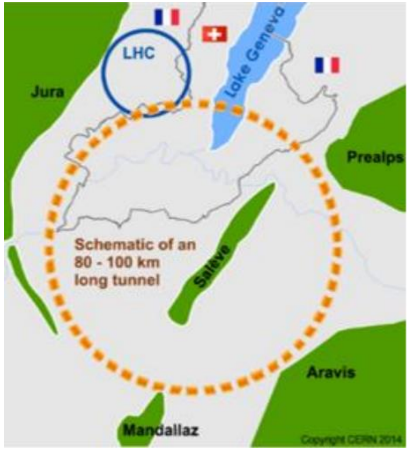
- With higher intensity in the HL-LHC, need to enforce machine protection

- New collimators to be installed to better protect the machine

680 MJ =
Total energy in one HL-LHC beam =
kinetic energy of TGV train at 215 km/h



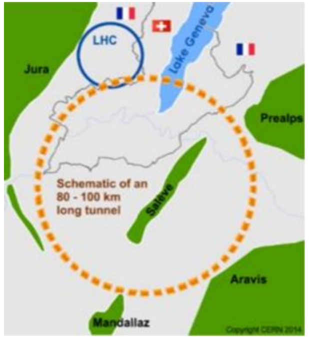
FCC-hh

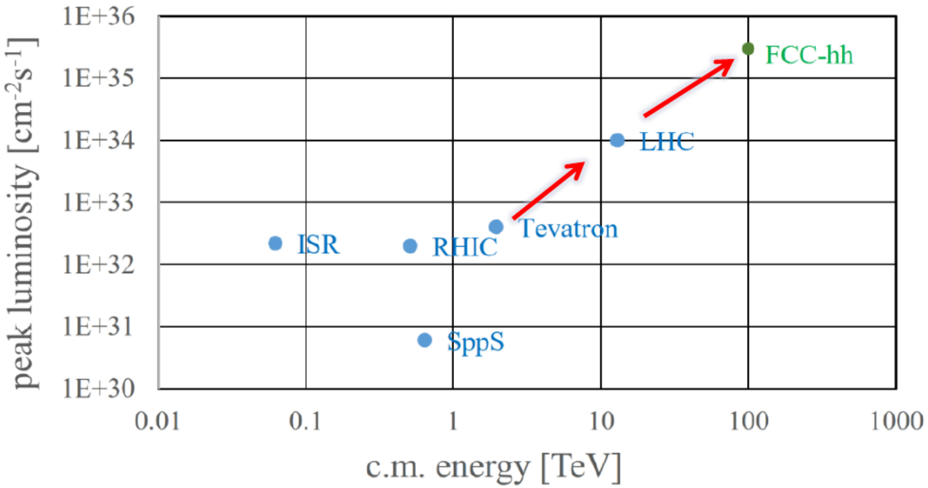


LHC
Lake Geneva
Jura
Prealps
Schematic of an
80 - 100 km
long tunnel
Salève
Aravis
Mandallaz
Copyright CERN 2014

FCC-hh general goals

- European strategy: “Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. “
- FCC-hh: collide 42-60 TeV protons (or heavy ions of equivalent magnetic rigidity) in tunnel of ~90 km
  - Factor ~6-8.5 higher energy than LHC, factor ~3 longer tunnel
  - International FCC collaboration (CERN as host lab)
- More than an order of magnitude higher peak luminosity than LHC; factor 6 higher than HL-LHC
- Goal: Achieve integrated luminosity of **20 000 fb^{-1} per experiment collected over 25 years** of operation (vs 3000 fb^{-1} for HL-LHC)





FCC-hh parameter comparison

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	84 - 120	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]	1100 - 4570	7.3	3.6
SR power / length [W/m/ap.]	14 - 58	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]	6.3 – 9.2	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

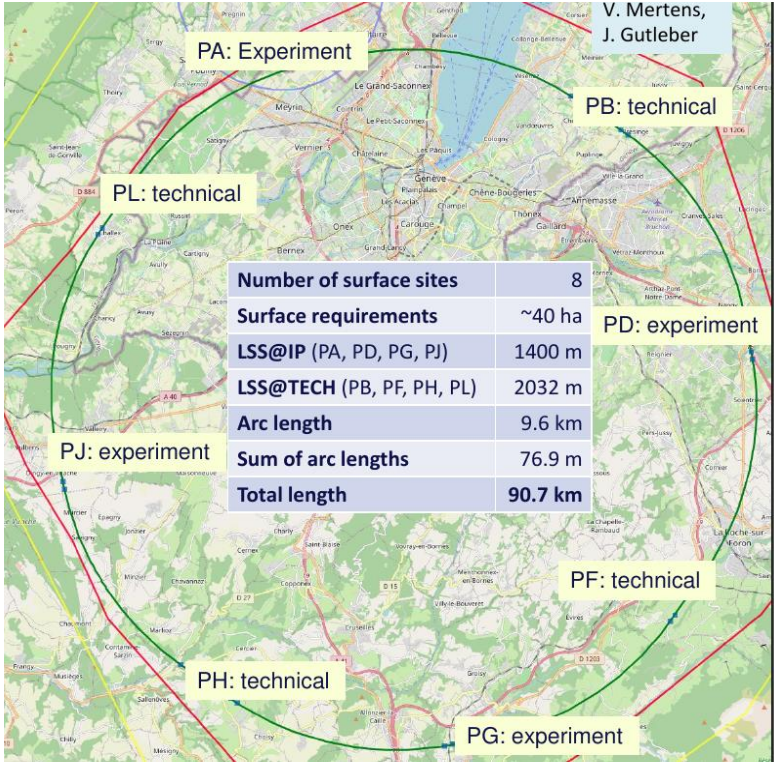
$$\frac{p}{q} = B\,\rho$$

$B\,\rho$ = Beam rigidity

Current working hypothesis on FCC placement

- Overall layout and placement optimisation process: Many options being studied

- Current baseline position based on:
  - lowest risk for construction, fastest and cheapest construction
  - feasible positions for large span caverns (most challenging structures)
  - Total length is 90.7 km
  - 8 surface sites with few ha area each



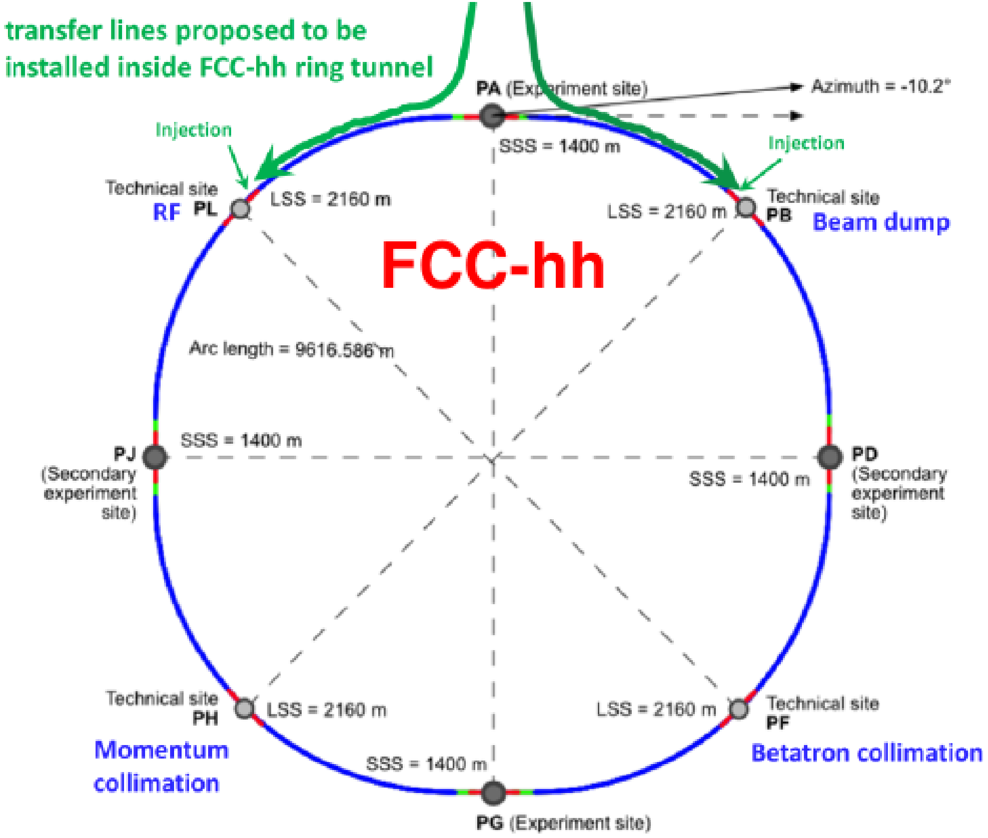
Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

FCC-hh layout

- Insertions in FCC-hh
  - Two high-luminosity experiments (A and G)
  - Two other experiments (D and J)
  - Two collimation insertions (F and H)
  - One extraction insertion (B)
  - One RF insertion (H)

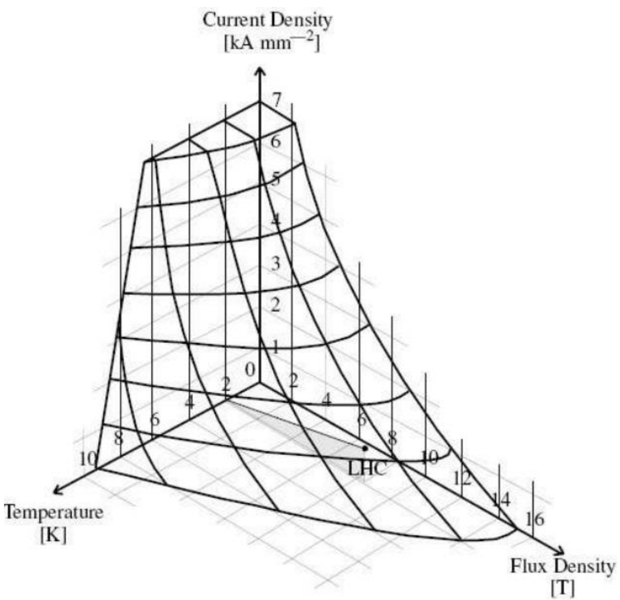
- Insertions are 1.4/2.2 km long

- Use LHC or SPS as injector

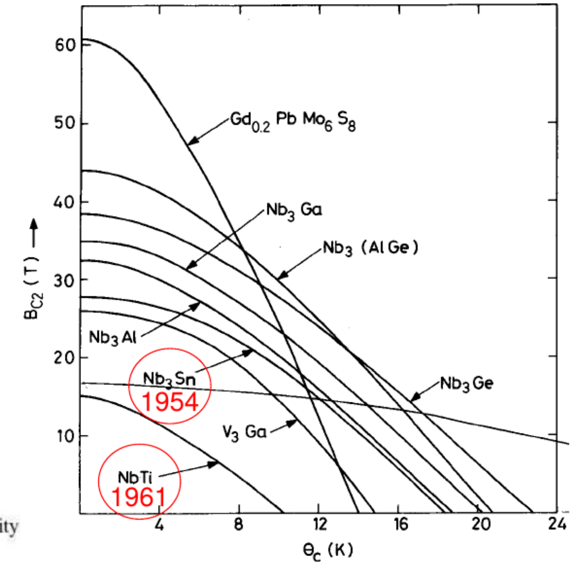


FCC-hh magnets

- Need 14-20 T dipole magnets – not feasible with today's technology → big challenge for technological development!
  - In LHC, 8.3 T, with NbTi superconductors
  - Cannot much higher with NbTi: to be superconducting, need working point below "critical surface" in space spanned by temperature, current density and magnetic field
- Rely on future developments of Nb3Sn superconductor technology
- Alternative: high-temperature superconductors
  - significant technology development and cost reduction needed



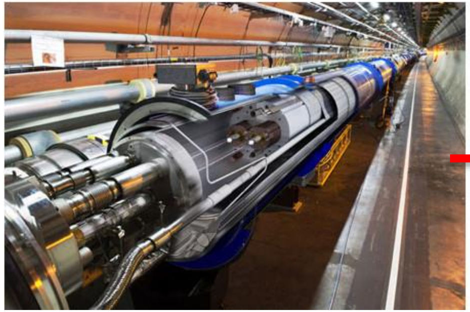
Critical surface for NbTi



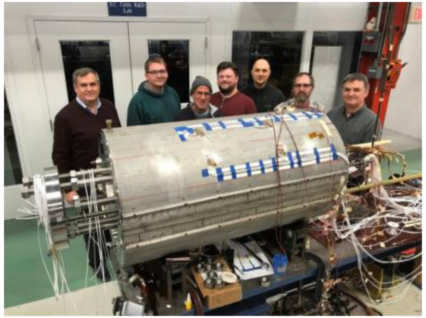
Road to high-field magnets

- For HL-LHC:
  - Three full-scale Nb3Sn quadrupoles for HL-LHC built and successfully tested (US)
  - Four 11T Nb3Sn dipoles initially scheduled for installation in LS2 (2019-2022) postponed due to performance issues
- Small demonstrator for 14.5 T Nb3Sn dipole at Fermilab, but still a long way to go for operational magnets and industrial production

from
LHC technology
8.3 T Nb-Ti



via
HL-LHC technology

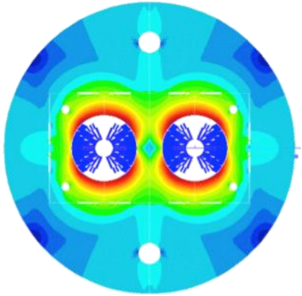


FNAL
demonstrator
14.5 T Nb_3Sn

Research program on Nb3Sn magnets

INFN

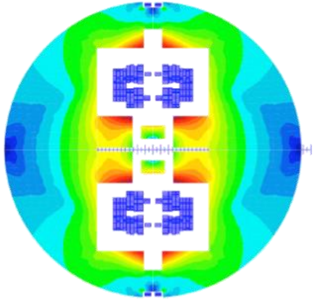
Cos-theta



EuroCirCol
A key to New Physics

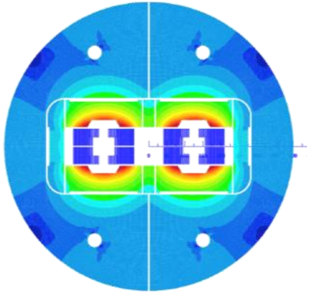
CIEMAT

Common coils



CEA

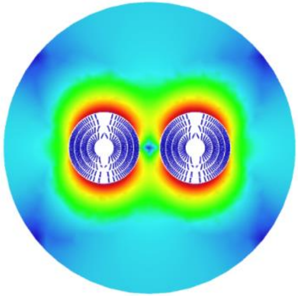
Blocks



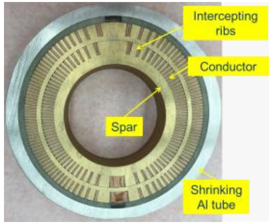
Swiss contribution

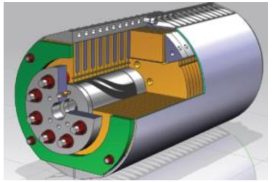
PSI

Canted Cos-theta



LBNL





FNAL

Next challenge: FCC-hh machine protection

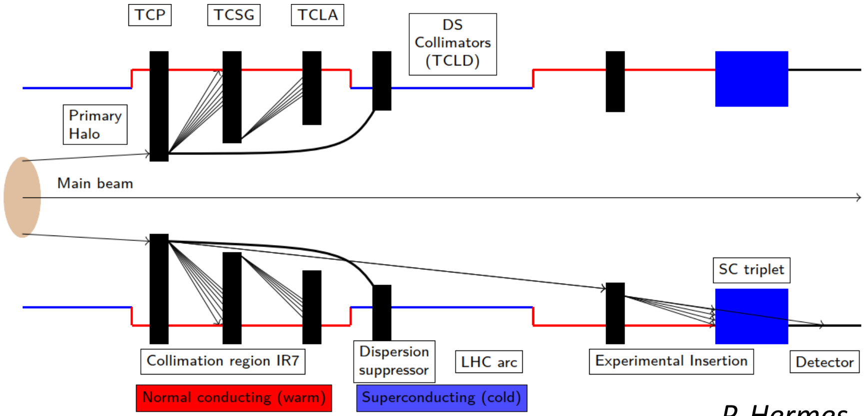
HL-LHC: total stored energy of beam = 680 MJ = kinetic energy of TGV train cruising at 215 km/h

FCC-hh: : total stored energy of beam = 8.3 GJ = kinetic energy of Airbus A380 (empty) cruising at 880 km/h

FCC-hh collimation

- The loss of even a tiny fraction of the beam could cause a magnet quench or even damage
- To safely intercept any losses and protect the machine: use collimation system
  - Should be the smallest aperture limitation in the ring
- 500 kW of continuous losses from collisions, downstream of experiments
- Design requirement: safely handle beam lifetime of 12-minute during ~10 s from instabilities, operational mistakes, orbit jitters….
  - Corresponds to power load of about 11.6 MW from the beam losses
  - Collimators must digest these losses without breaking, while protecting the superconducting magnets

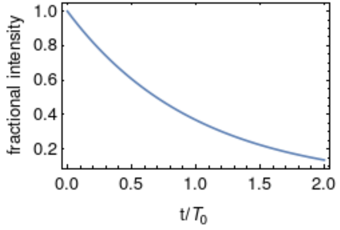
Deploying multi-stage collimation system inspired by LHC



P. Hermes

Beam lifetime:
usually defined as time needed for reduction of intensity by factor 1/e assuming losses proportional to intensity (often true, but not always)

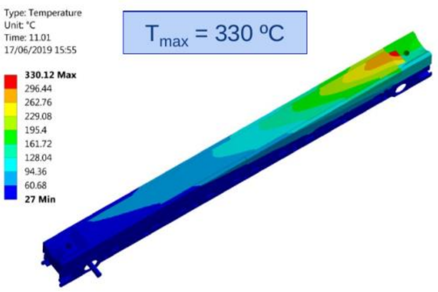
$$-\frac{dN}{dt} \propto N(t) \Rightarrow N(t) = N_0 e^{-t/T_0}$$

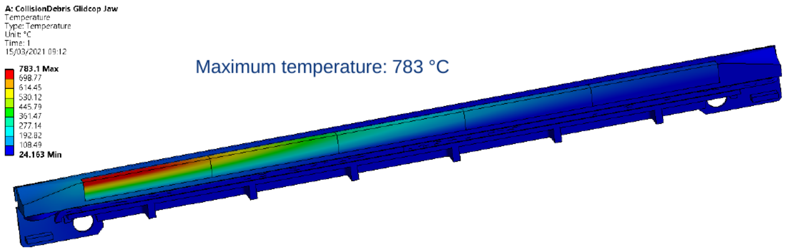


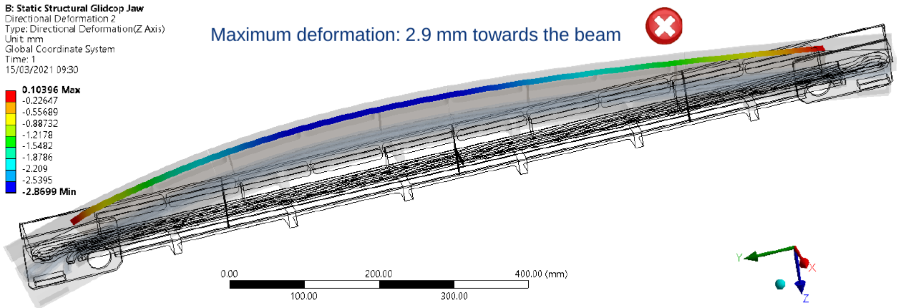
Beam lifetime:

Robustness studies

- Use carbon-based materials for highest robustness, with hardware design based on LHC but developed further
- Very important to study material response to the high loads
- Typically 3-stage simulations:
  - Generation of impact coordinates of lost particles
  - Energy deposition studies
  - Thermo-mechanical study using e.g. ANSYS of dynamic material response
    - Study peak temperatures, deformations, melting, detachment of material
- Very challenging engineering task to design these collimators



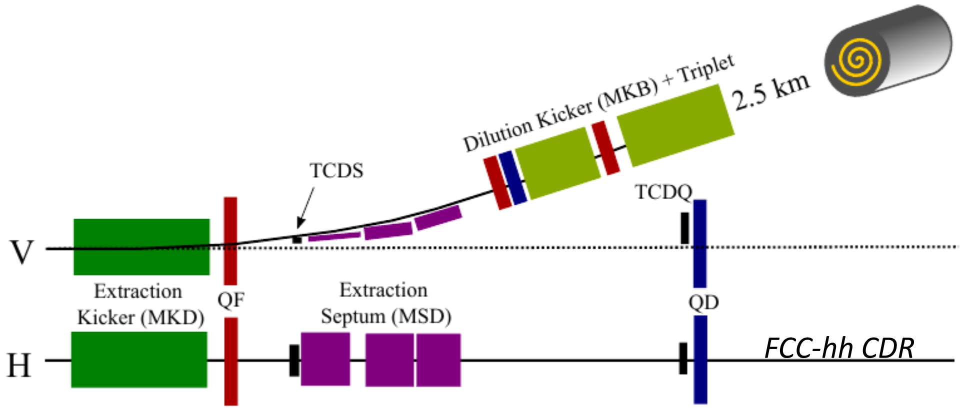




Beam dump

- Need beam dump to safely extract and dispose of beam in case of any failure, or the remaining beam a the end of luminosity production
  - Extract beam in separate dump channel using very fast dipole magnets

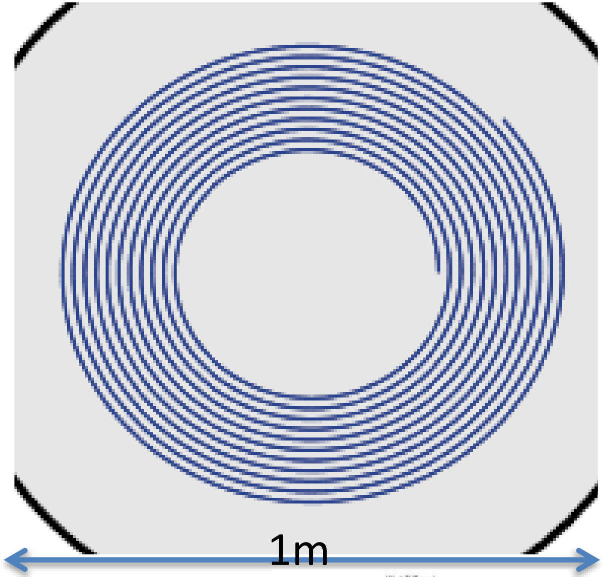
- Need to dispose of 8.3 GJ!
  - Enough to drill 300m long hole in copper



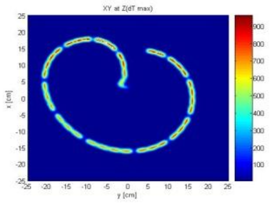
Beam dump

D. Schulte, W. Bartmann

- Solution: as for LHC, distribute (“paint”) beam transversely, but over much larger surface than in LHC
  - Dynamically changing magnetic field while beam is passing
  - Beam-dump made of low-density graphite sheets, should not exceed 1500 deg C



LHC pattern (same scale)



Synchrotron radiation in FCC-hh

- FCC-hh first hadron collider where synchrotron radiation power has potentially limiting effects
  - About 5 MW power loss per beam, lost continuously around the ring!
- Need about 12 MW of RF power per beam to replenish lost energy
- Need to cool away the 5MW heating power of lost photons around the ring - need much more cooling power than 5 MW (Carnot process – look back at thermodynamics)
  - If beamscreen kept at 2K : 3500 MW
  - If beamscreen kept at 50 K: 100 MW → choose this option!
  - Special beam screen design to intercept photons in a slit

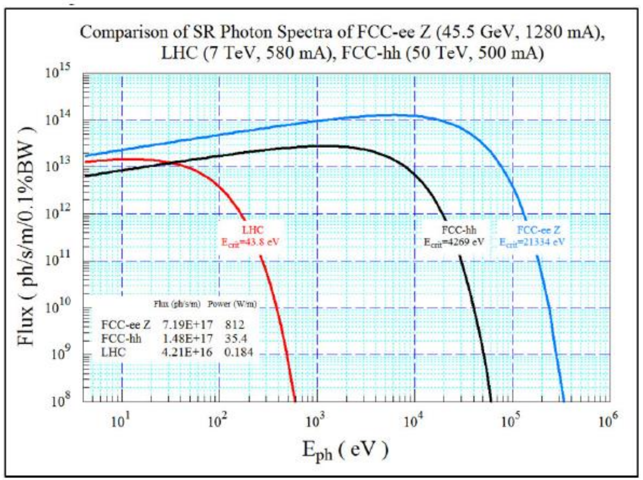
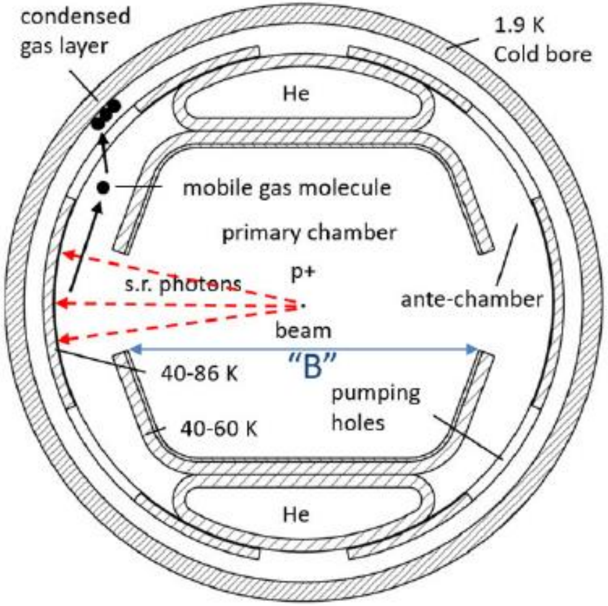


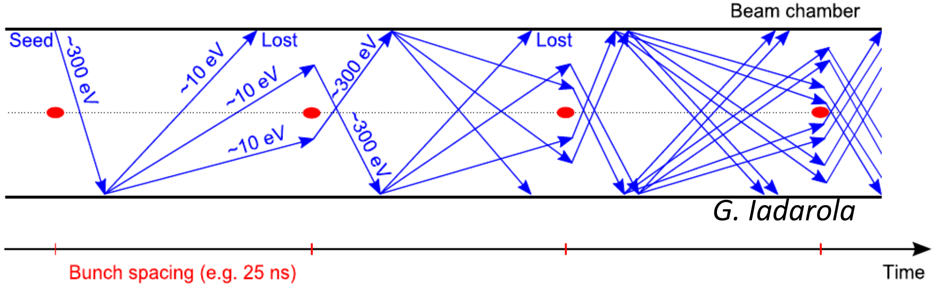
Figure 6.5: Synchrotron Radiation photon flux spectra for LHC, FCC-ee (Z-pole) and FCC-hh beams.

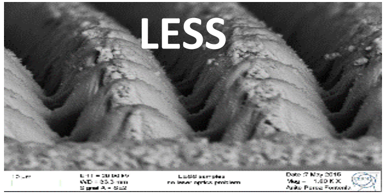


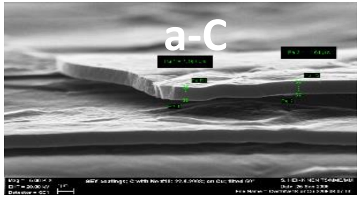
FCC-hh conceptual design report

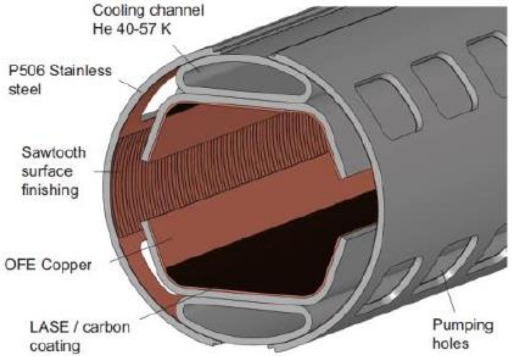
Electron cloud effects

- Electrons inside vacuum chamber accelerated by field from passing bunch
- Electrons hit inside of vacuum chamber, releasing more electrons, in turn accelerated => ever increasing cascasde of electrons
- Causes heating, potential beam instabilities, worse vacuum...
- Big challenge for LHC, even more for FCC-hh
- Mitigations:
  - Beam screen design, surface treatment, coatings
  - If nothing else helps: increase spacing between bunches

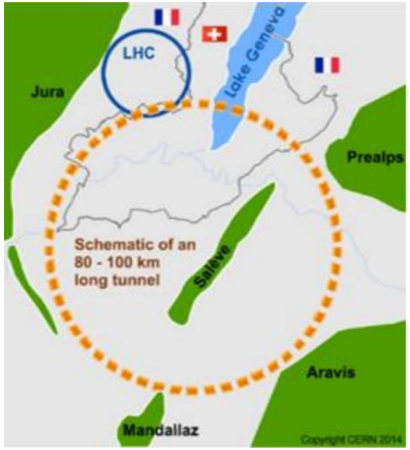








FCC-ee


LHC
Lake Geneva
Jura
Prealps
Schematic of an
80 - 100 km
long tunnel
Salève
Aravis
Mandallaz
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FCC-ee

- European strategy: "An electron-positron Higgs factory is the highest-priority next collider"
- FCC-ee is a high-luminosity, high-precision e+e- circular collider
- Several different operational energies are foreseen to perform precision measurements of **Z**, **W** and **H** bosons and the **top quark**

FCC-ee parameter table

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
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	$\geq$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

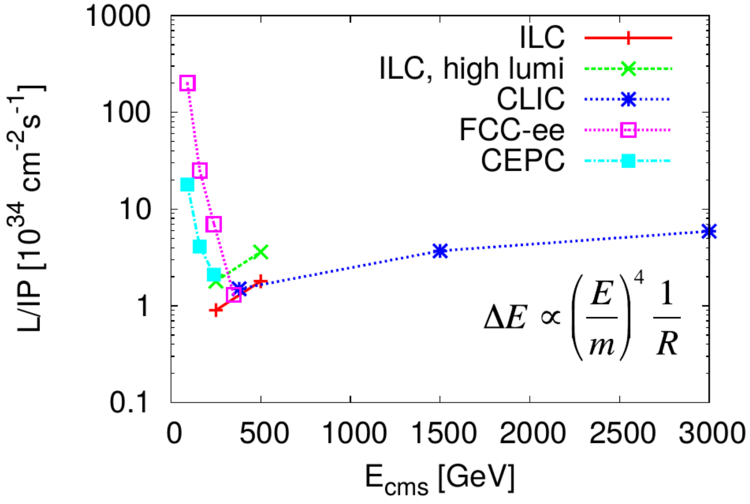
3 years
2 x 10^6 H

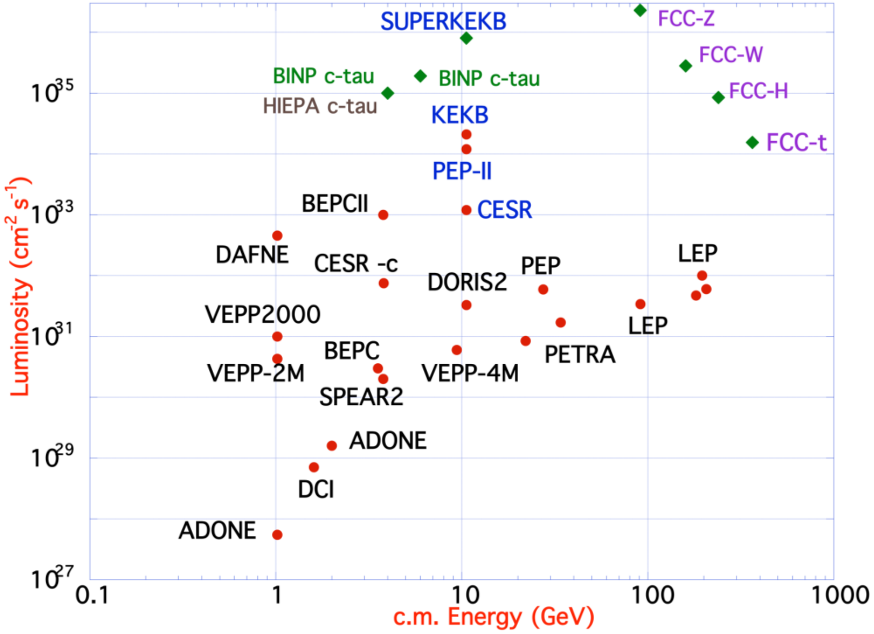
5 years
2 x 10^6 tt pairs

Luminosity comparison

- To reach the physics goals, need to significantly increase luminosity w.r.t. previous lepton colliders

- Can reach higher luminosity than linear colliders at lower energy
  - The higher the energy, the more severe limitations from synchrotron radiation

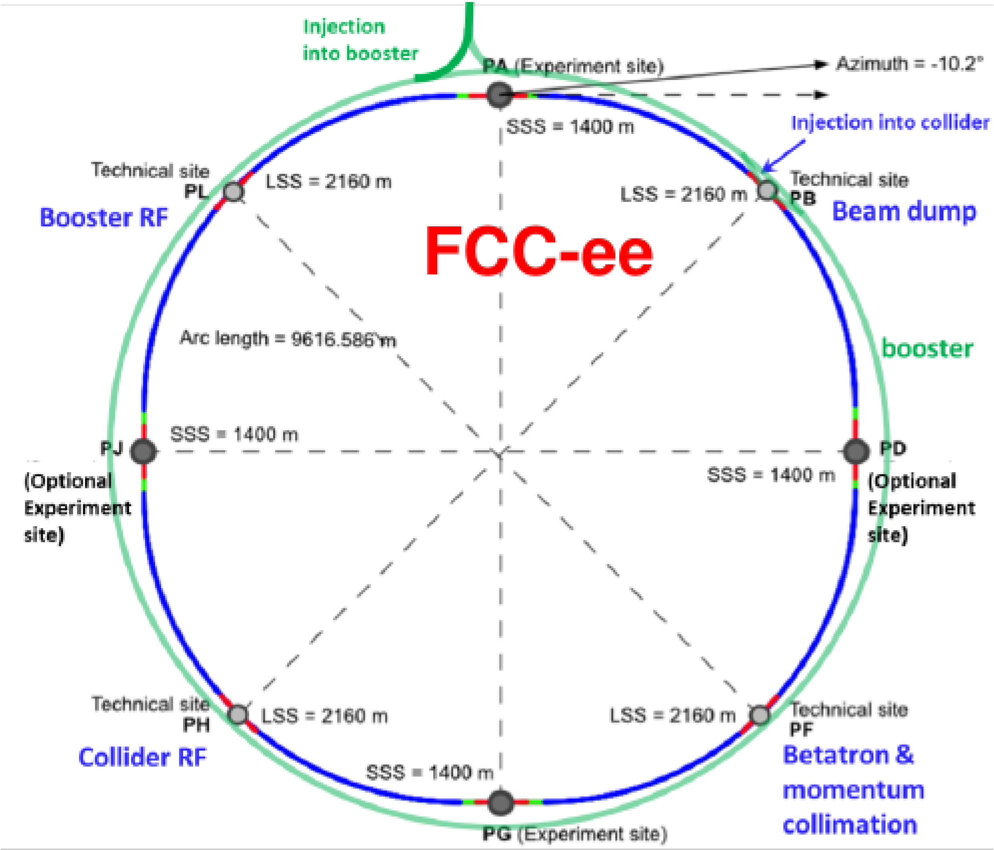




FCC-ee layout

- Two-ring layout with 4 collision points

- Same footprint as FCC-hh



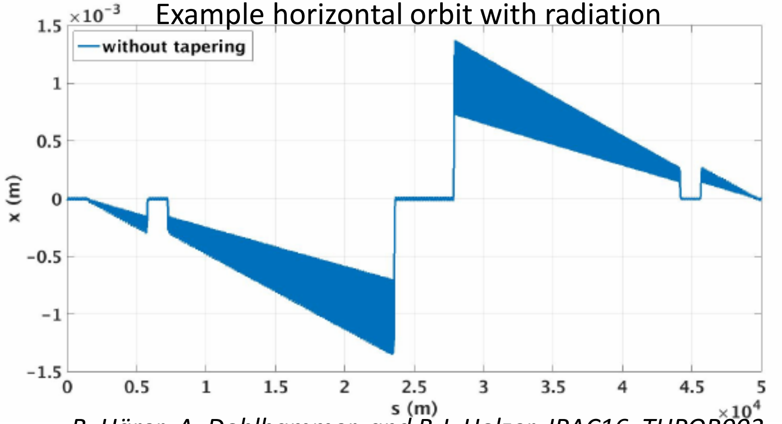
Synchrotron radiation in FCC-ee

- Design choice: limit radiation power to 50 MW per beam (still huge!)
  - RF cavities have a certain (in)efficiency → total RF power consumption for both beams up to about 160 MW
  - Lower intensity at higher energy => *lower luminosity*
  - Not critical for cooling – normal-conducting magnets

- At highest energy, 182.5 GeV, loss of 9 GeV or ~5% per turn
  - Also: particles that have lost energy are overbent by the dipoles => accumulate large transverse offsets, "saw tooth" orbit if nothing is done

$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Example horizontal orbit with radiation

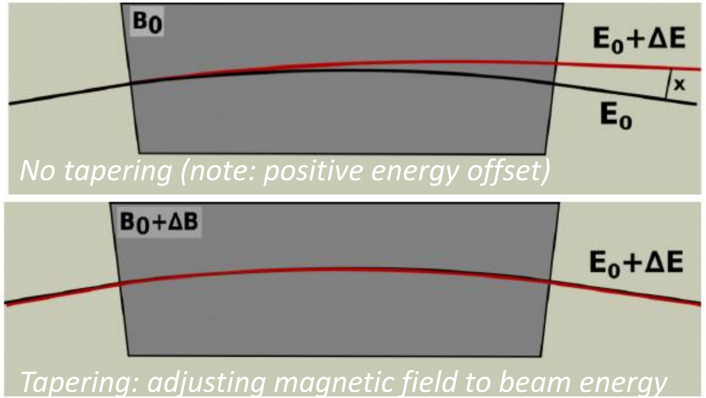


B. Härer, A. Doblhammer, and B.J. Holzer, IPAC16, THPOR003

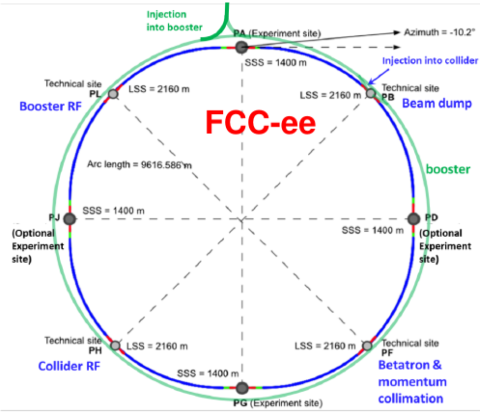
Tapering

- To avoid large transverse offsets due to over-bending: "Tapering scheme"

- Vary magnetic strengths along the ring, so that we always match the beam energy



B. Härer, A. Doblhammer, and B.J. Holzer, IPAC16, THPOR003

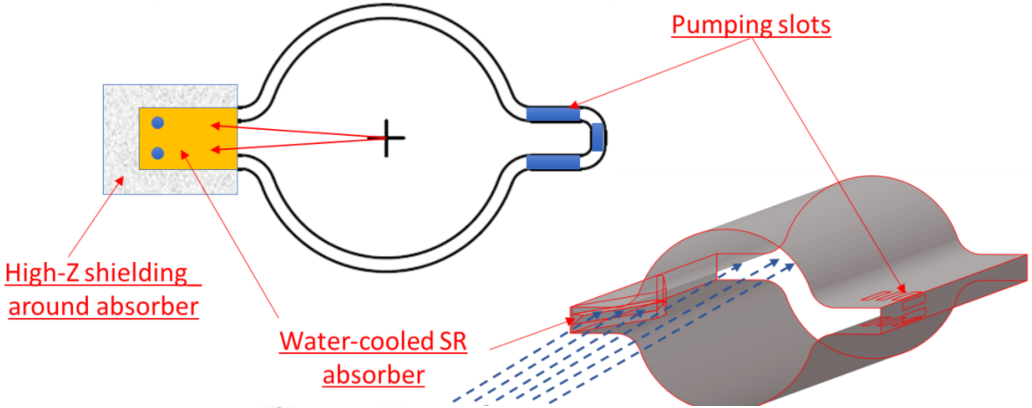


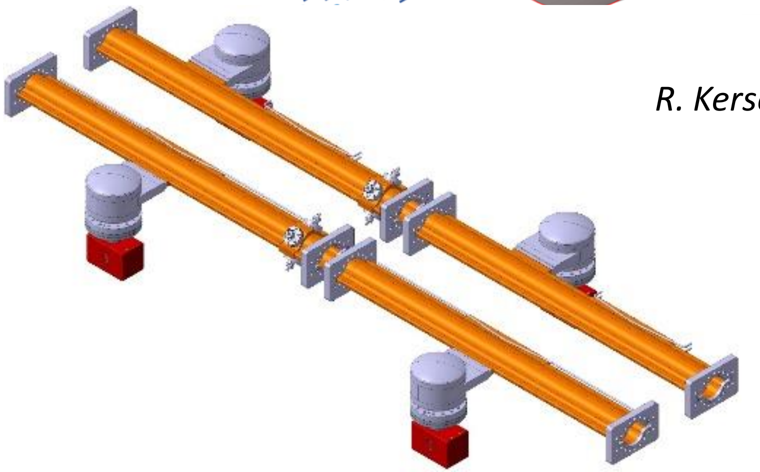
FCC-ee vacuum and beamscreen

- Need absorbers to intercept radiated photons (present design: ~6 m spacing)
  - ”winglets” in the plane of the orbit to capture photons

- Continuous impact of photons can cause heating, outgassing and bad vacuum

- Challenging beam screen design
  - Use NEG (Non Evaporable Getter) pumps next to photon absorbers – pump away emitted gas molecules



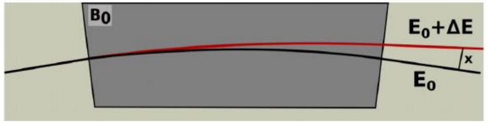


R. Kersevan

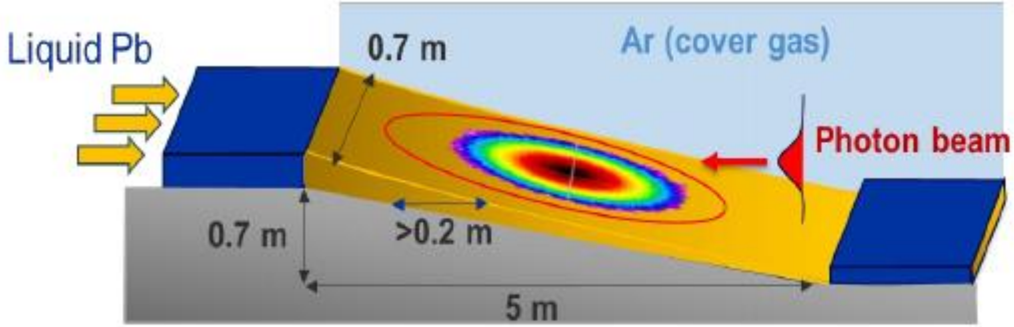
Beamstrahlung

- Particles radiate not only in magnets, but also due to electromagnetic field of opposing beam: “beamstrahlung”
- FCC-ee will be the first collider where beamstrahlung plays a significant role in beam dynamics
  - Collider must have sufficiently large momentum acceptance to hold a particle that loses its energy in a single photon emission due to beamstrahlung.
    - A particle with 2% momentum deviation must still stay within the beampipe without touching it
- Power of radiated photons reaches almost 400 kW – big engineering challenge!
  - Photons hit downstream vacuum chamber in localized spot – engineering challenge to dispose of heat without material damage
  - Different solutions under study: solid graphite absorber (might break), absorber with flowing liquid Pb

Bunch Energy [GeV]	Beamstrahlung Parameter Υ	Photons per particle n_γ	Average photon energy [MeV] $< E_\gamma >$	Total photon beam power [kW]
45.6	$1{,}81 \times 10^{-4}$	0,148	2	390
182.5	$9{,}12 \times 10^{-4}$	0,242	67	88

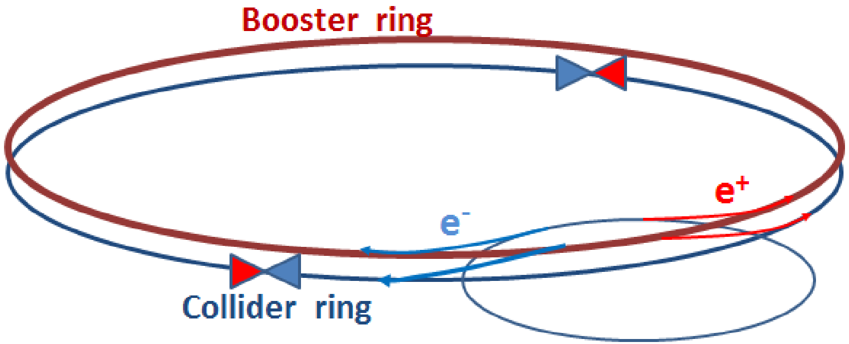


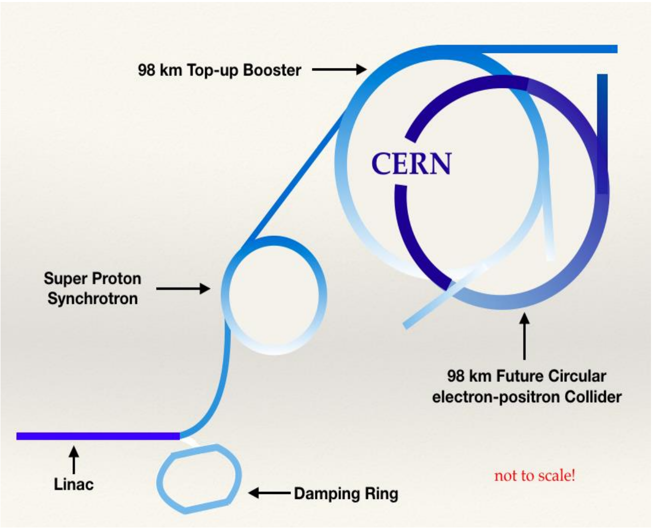
M. Calviani et al.



Top-up injection

- Even with a 2-3% momentum acceptance, resulting beamstrahlung losses give ~18 minute beam lifetime at highest energy
  - Remember: Beam lifetime is time needed for reduction of intensity by factor 1/e
  - In addition, losses from radiative Bhaba scattering
- Very short beam lifetime => use "top-up injection"
  - Inject beams at collision energy, while colliding
    - Compare hadron machines: inject at low energy, then accelerate to top energy, then put beams in collision
  - Requires a booster ring – to be built in the same tunnel
- Injector chain: source, LINAC(s), positron target, damping ring, pre-booster, booster



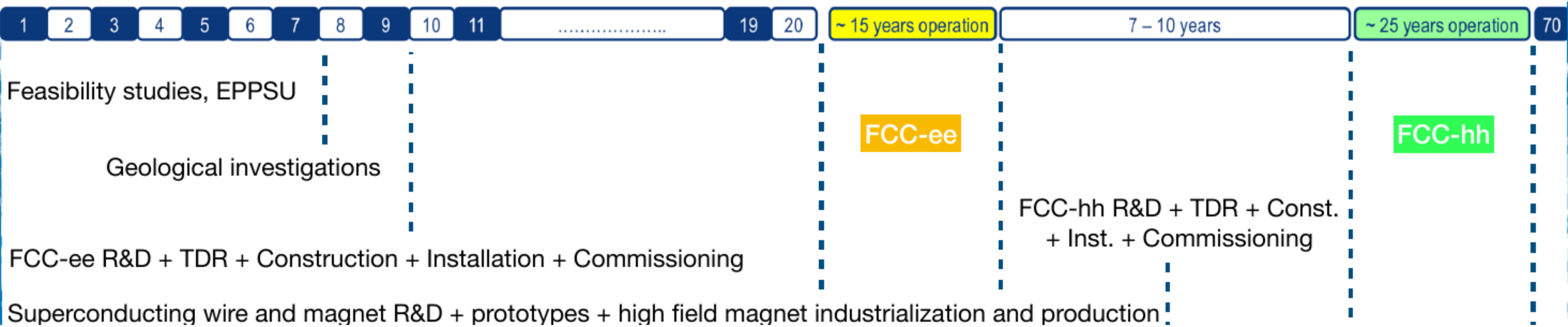


FCC-ee power consumption

Beam energy (GeV)	45.6 Z	80 W	120 ZH	182.5 ttbar
RF (SR = 100)	163	163	145	145
Collider cryo	1	9	14	46
Collider magnets	4	12	26	60
Booster RF & cryo	3	4	6	8
Booster magnets	0	1	2	5
Pre injector	10	10	10	10
Physics detector	8	8	8	8
Data center	4	4	4	4
Cooling & ventilation	30	31	31	37
General services	36	36	36	36
Total	259	278	282	359

Overall FCC timeline

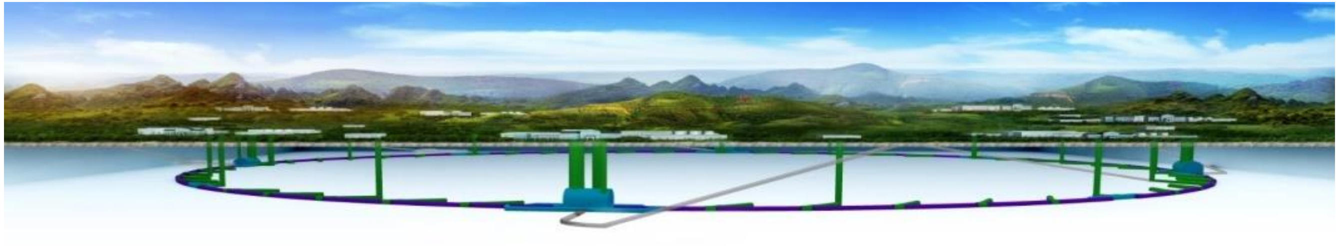
- Foreseen FCC timeline spans several decades
- Remember: it took ~25 years from the start of the LHC design to the start of operation



FCC documentation

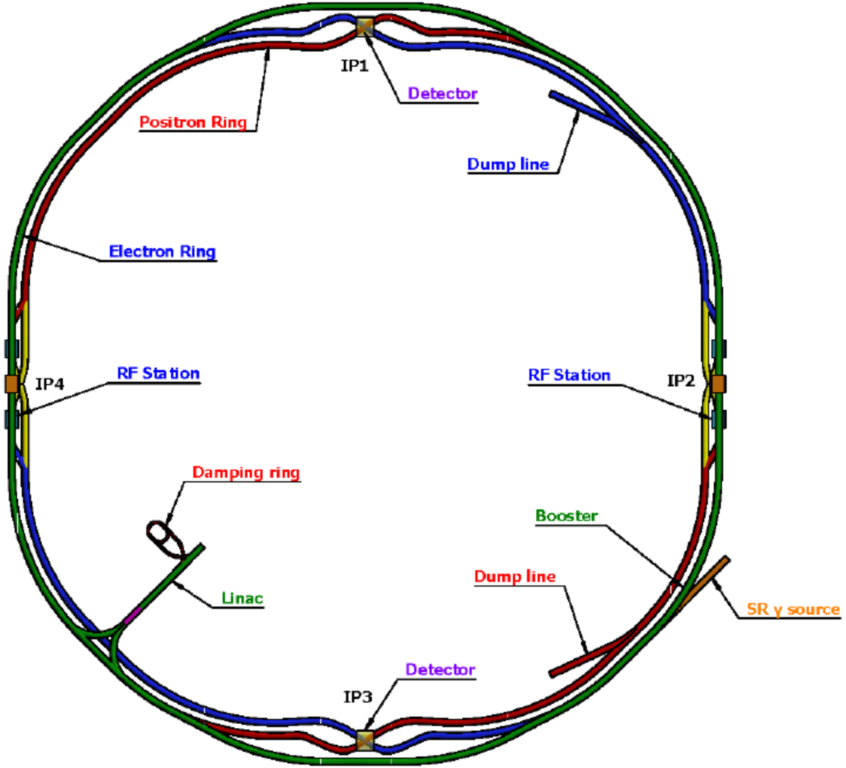
- **FCC-Conceptual Design Reports (completed in 2018):**
  - **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
  - CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**
  - EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 , EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382
- **Summary documents provided to EPPSU SG**
  - **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
  - Accessible on http://fcc-cdr.web.cern.ch/
- **Feasibility study report** being prepared for 2025

CEPC / SppC



CEPC (Circular Electron Positron Collider)

- Chinese proposal for e^+e^- collider 90-240 GeV, 100 km ring
- Four operation modes: H, Z, WW, ttbar
- Two collision points, two RF insertions
- Limit synchrotron radiation power to 30 MW per ring, option to go to 50 MW



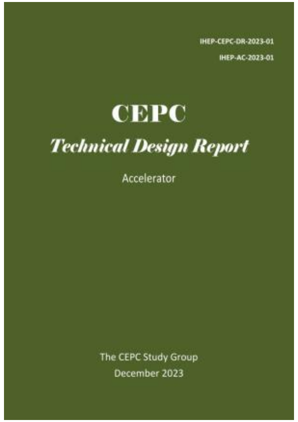
CEPC parameter table

	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	816/816/408	150/150/75	13.2/13.2/6.6
Piwinski angle	4.88	24.23	5.98	1.23
Bunch number	268	11934	1297	35
Bunch spacing (ns)	591 (53% gap)	23 (18% gap)	257	4524 (53% gap)
Bunch population (10^{11})	1.3	1.4	1.35	2.0
Beam current (mA)	16.7	803.5	84.1	3.3
Phase advance of arc FODO (°)	90	60	60	90
Momentum compaction (10^{-5})	0.71	1.43	1.43	0.71
Beta functions at IP β_x^*/β_y^* (m/mm)	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Betatron tune ν_x/ν_y	445/445	317/317	317/317	445/445
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Energy spread (natural/total) (%)	0.10/0.17	0.04/0.13	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) (%)	1.6/2.2	1.0/1.7	1.05/2.5	2.0/2.6
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF voltage (GV)	2.2	0.12	0.7	10
RF frequency (MHz)	650			
Longitudinal tune ν_s	0.049	0.035	0.062	0.078
Beam lifetime (Bhabha/beamstrahlung) (min)	40/40	90/2800	60/195	81/23
Beam lifetime requirement (min)	18	77	22	18
Hourglass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34} cm^{-2} s^{-1})	5.0	115	16	0.5

Table 3.1: CEPC operation plan (@ 30 MW)

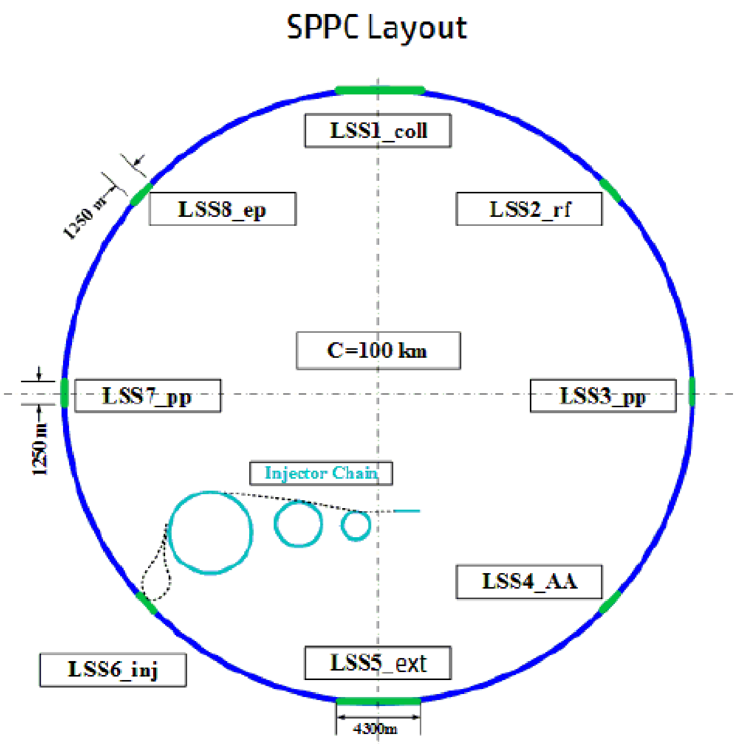
Particle	$E_{c.m.}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Integrated L per year (ab^{-1}, 2 IPs)	Years	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H	240	5	1.3	10	13	2.6×10^6
Z	91	115*	30	2	60	2.5×10^{12}
W	160	16	4,2	1	4.2	1.3×10^8
$t\bar{t}$**	360	0.5	0.13	5	0.65	0.4×10^6

More details technical design report , 2023

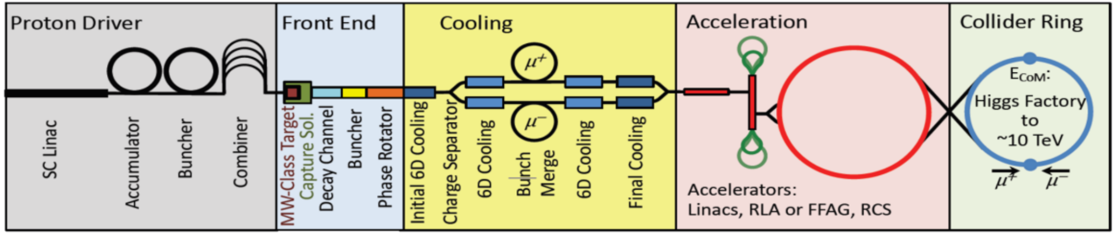


SppC (Super proton-proton Collider)

- 100 km hadron collider to later be installed in the same tunnel as CEPC
- Design report scenario:
  - use 12 T high-temperature iron-based superconductors for high field dipole magnets => centre of mass energy of 75 TeV
  - “ultimate” upgrade: 24T field, 150 TeV CMS energy
  - Operating at 4.2 K
  - Luminosity of 10^{35} cm^{-2} s^{-1}
- Baseline layout with 8 insertions for experiments, collimation, extraction, injection, RF
- , following conceptual design report in 2018



Muon collider



Muon collider study

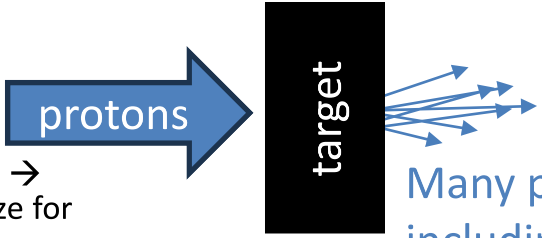
- Could use heavier leptons than e+e- to minimize synchrotron radiation in a circular lepton collider
  - Could reach much higher energy than with e+e- for the same radius, still with “cleaner” collisions than protons
  - Or reach similar energies with a much smaller machine → cost- and energy-efficient

$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

- Use muons?
  - mass = 106 MeV/c^2 = 207 m_e
  - Challenge 1: Unstable, 2.2 μs mean lifetime
    - Need to very quickly accelerate them to high energy – with time dilation, factor γ longer lifetime
  - Challenge 2: experimental backgrounds due to e+ and e- from muon decay
  - Challenge 3: abundant neutrinos from muon decay could reach surface and interact, causing radiation

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

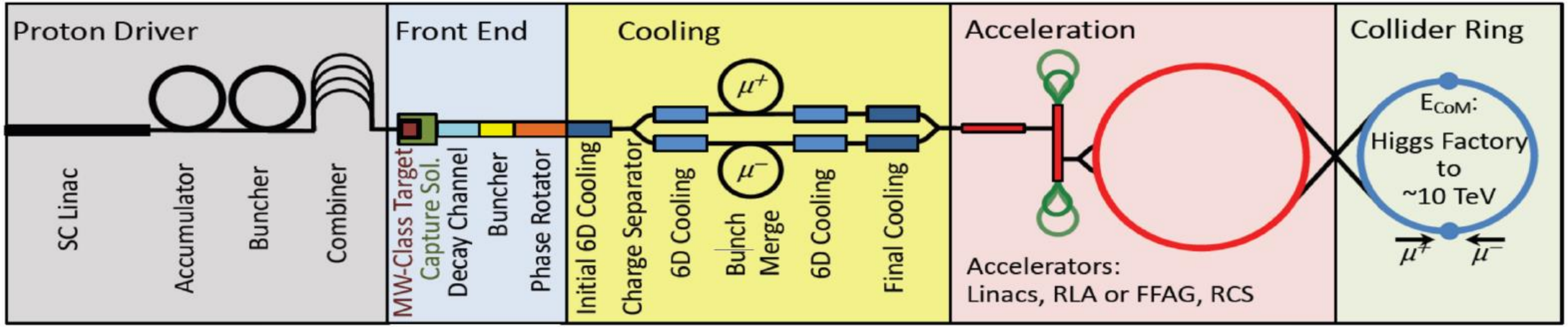
- Production of muons – presently considered option:
  - Let high-power proton beam hit a target
  - Pions are produced, which later decay into muons
  - Muons have relatively large transverse momentum spread → need to very quickly "cool" them to achieve small beam size for higher luminosity
    - Challenge 4: very fast cooling of muon beam



Many particles, including π+, π-

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

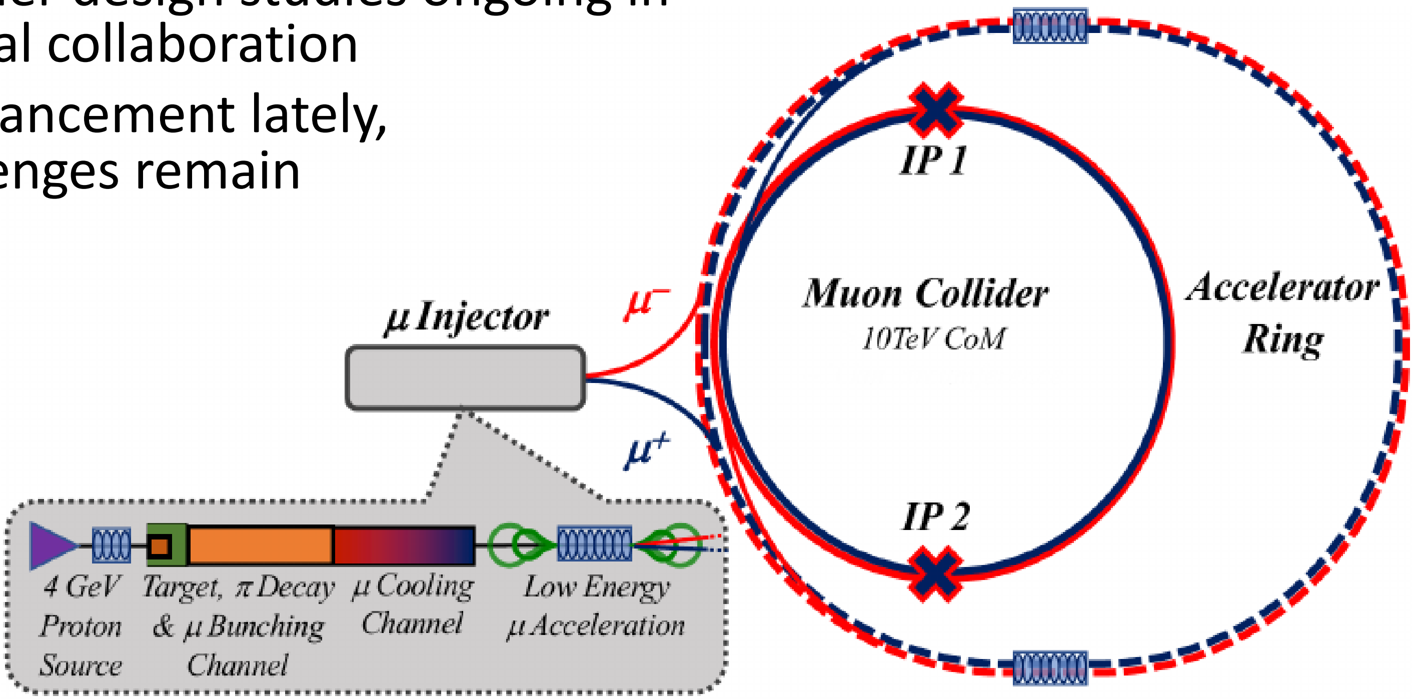
Muon collider – schematic design



- High power proton beam (short intense bunches) and low repetition rate on target.
- Target and capture channel, protons produce pions which decay into muons.
- Large energy spread µ beam split to sequence of bunches.
- Stages of muon ionisation cooling in matter.
- Merging of µ bunches into one bunch.
- Low energy acceleration with recirculating linacs.
- Acceleration to collision energy in a sequence of pulsed synchrotrons.
- Collider packed with high field magnets to minimise circumference and maximise luminosity.

Later design

- Muon collider design studies ongoing in international collaboration
- A lot of advancement lately, many challenges remain



Summary

- LHC will be upgraded to **HL-LHC**, and operate to ~2041
  - Future collider projects on the table, but no decision yet

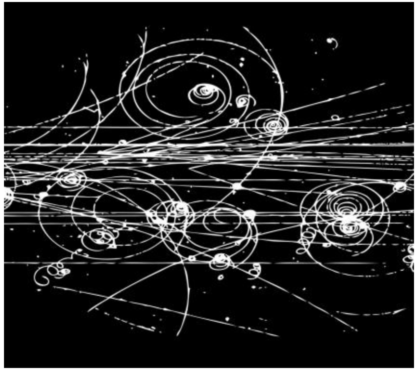
- Main projects studied at CERN
  - **FCC-ee**: circular e+e- collider
    - e+e- Higgs factory is highest priority it European strategy
    - conceptual design report exists; studies are ongoing to give more inputs to next European strategy
  - **FCC-hh**: circular pp collider with ion option
    - High priority by European strategy
    - conceptual design report exists; studies are ongoing to give more inputs to next European strategy
  - **CLIC**: Linear e+e- collider
    - Also fulfills priority on a Higgs factory in European strategy
    - Conceptual design report exists, technology and concept demonstrated
  - **Muon collider:** potential for high-energy circular lepton collider without radiation limitation, very challenging
  - All machines have many interesting beam physics aspects and difficult challenges – I could cover only a few!

- Initiatives in other parts of the world
  - **ILC**: Linear e+e- collider, possibly hosted by Japan
    - Mature design with technical design report; ready to be built. Awaiting political decisions
  - **CEPC / SppC**: circular e+e- collider followed by hadron collider, Chinese initiative
    - Technical design report exists. China will decide
  - **EIC**: circular electron-ion collider, to be built in the US
    - Approved project with conceptual design report

Future colliders?

Particle collisions 50 years ago

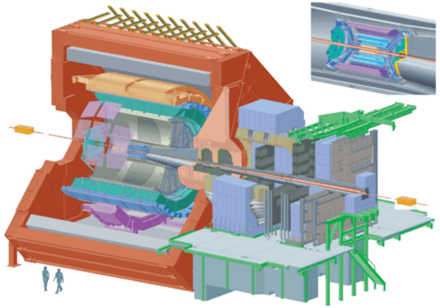
32 cm bubble chamber with liquid hydrogen, 16 GeV pion interacting with proton

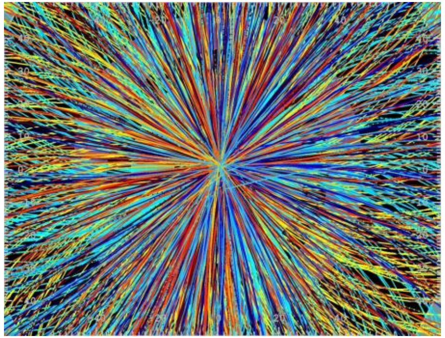


https://cds.cern.ch/record/39474

Particle collisions today

574 TeV Pb beams colliding at ALICE, LHC





Particle collisions in 50 years

We know only that we will need scientists and engineers to design, operate and optimize the machines, and to analyze the data