Future accelerators

Roderik Bruce

Outline

- 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)
- 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)
- Other future accelerator projects (briefly)

Linear (ILC, CLIC)

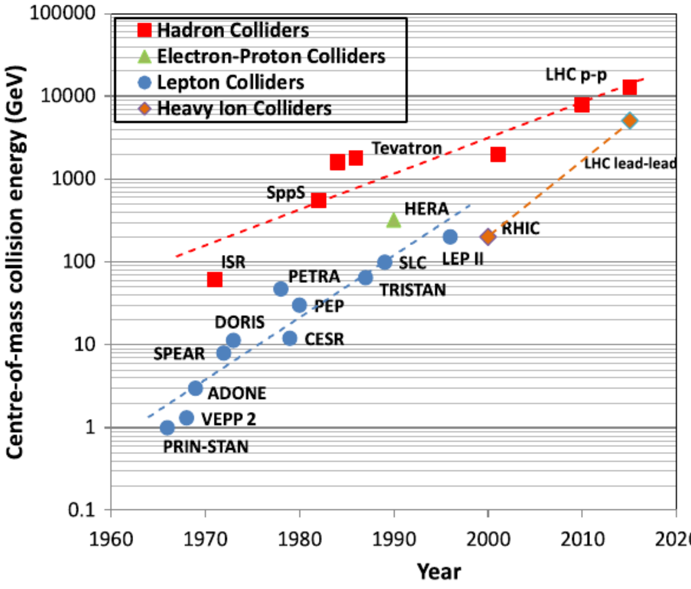
Circular (HL-LHC, FCC-hh, FCC-ee, CEPC/SppC)

Particle colliders

- Particle colliders have been instrumental for scientific discoveries in high energy physics for more than half a century
  - Key for establishing the standard model in particle physics

- Technological innovation made it possible to increase energy at a much faster pace than the costs

- LHC has the highest energy among colliders built so far
  - Circular collider, designed to collide 7 TeV protons and heavy ions

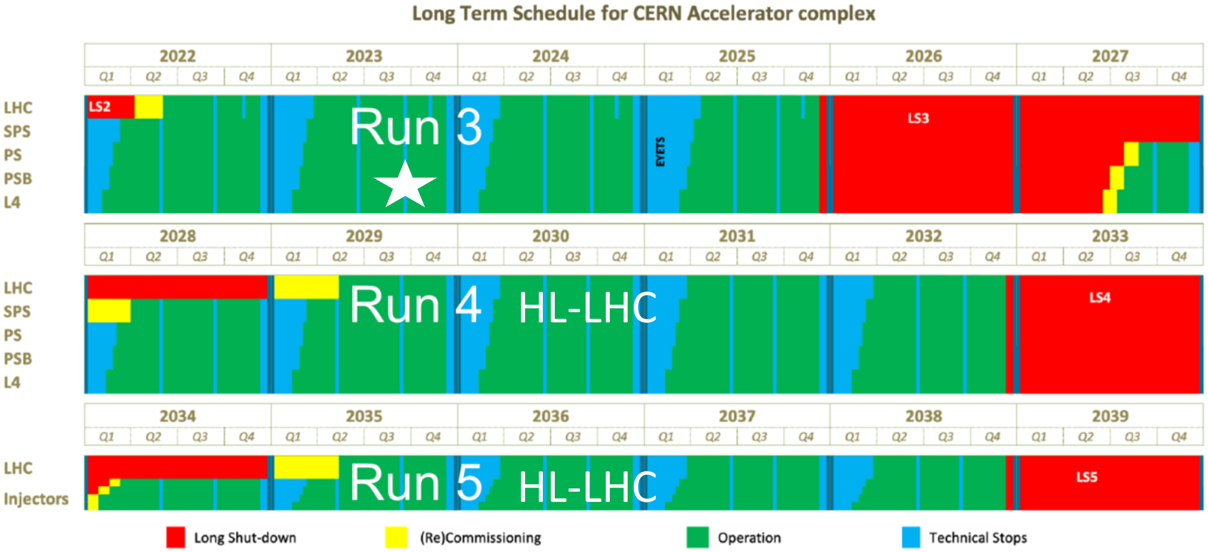


“Livingstone plot” of collider energy vs time (source)

LHC timeline

- Present LHC will operate for a few more years
- High-Luminosity LHC (HL-LHC) upgrades foreseen for next long shutdown (LS3) for Run 4
- HL-LHC planned to operate at least until ~2038, likely into the 2040s
- What happens next?
  - Nobody knows, but there are many ideas on the table
- It took ~25 years to design and build the LHC, so need to start thinking now about future options

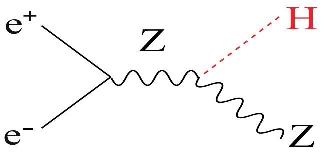
Tentative schedule, ***could well change***



3 main complementary ways to search for (and study) new physics at accelerators

Direct — production of a given (new or known) particle

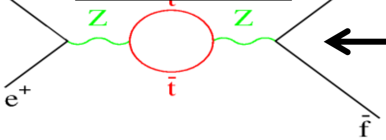
e.g.: Higgs production at future e^+e^- linear/circular colliders at $\sqrt{s}$ ~ 250 GeV through the HZ process
→ **need high E and high L**



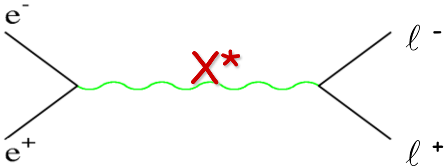
Indirect — precise measurements of known processes

→ look for (tiny) deviations from SM expectation from quantum effects (loops, virtual particles)
→ sensitivities to E-scales $\Lambda \gg \sqrt{s}$ → **need high E and high L**

$\sqrt{s}$ ~ 90 GeV



E.g. top mass predicted by LEP1 and SLC in 1993: m_{top} = 177 ± 10 GeV; first direct evidence at Tevatron in 1994: m_{top} = 174 ± 16 GeV

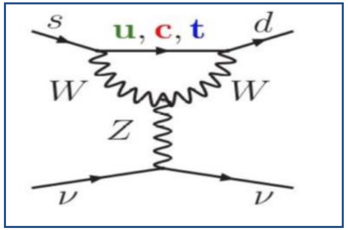


Main focus

Rare processes — suppressed in SM → could be enhanced by New Physics

e.g. neutrino interactions, rare decay modes → **need intense beams and/or ultra-sensitive (massive) detectors ("intensity frontier")**

E.g. $K^+ \to \pi^+\nu\nu$ decay (NA62 experiment)
Proceeds via loops → suppressed in the SM : BR~ 10^{-10}
Can be enhanced by new particles running in the loop.
Theoretically very clean.



Slide from F. Gianotti

Considerations for new colliders

- So, we want high energy and high luminosity
  - When we say high luminosity, we implicitly mean high event rate
  - Reminder: The luminosity directly determines the event rate

- How do we get there? Several choices to be made:
  - What to collide: lepton vs hadron
  - How to collide:
    - fixed target or colliding beams
    - linear vs circular collider
  - Acceleration technology
    - DC, RF, wakefield…
  - Magnet technology
    - Superconducting (what conductor?), normal conducting
  - Acceptable cost of construction, power consumption, site

- Think about various limitations to energy and luminosity and how to overcome them

$$\frac{dR}{dt} = L \times \sigma_p$$

Event rate

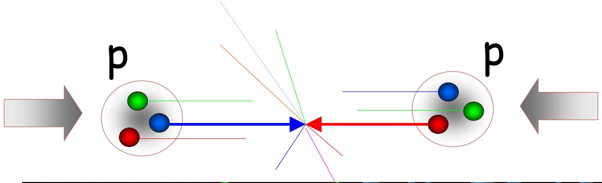
Luminosity (determined by and collider design: can be influenced)

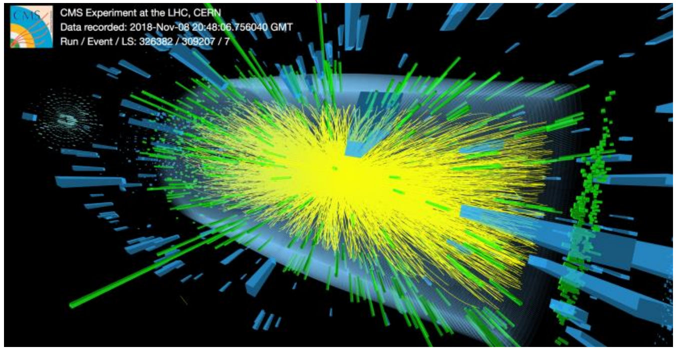
Cross section (given by physics, cannot be influenced)

Leptons vs hadrons

Hadrons (protons or ions)

- Mix of quarks, anti-quarks and gluons:
  - variety of processes
  - not all nucleon energy available in collision
  - Energy spread between partons – spread in collision energy
  - huge QCD background
- Can typically achieve highest collision energy
- Good for discoveries at the frontier of new physics

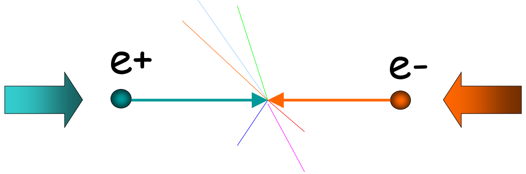




LHC Pb-Pb collision, CMS

Leptons (electrons, positrons, maybe muons)

- Elementary particles colliding - very well defined centre-of-mass energy
- Low background
- Good for high-precision measurements
- Higher energy loss from synchrotron radiation influences accelerator design → see next slides

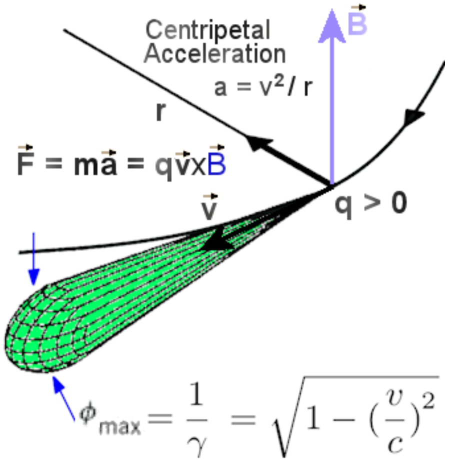


LEP II e+e- collision, DELPHI

Synchrotron radiation

- Classical electrodynamics: an accelerating charge radiates
  - Radiation carries off energy, which is taken away from the kinetic energy
  - Radiated energy needs to be replenished by accelerating RF cavities => could lead to very high power consumption
  - Radiated photons impact on vacuum chamber => causes heating, maybe even damage for high power loads

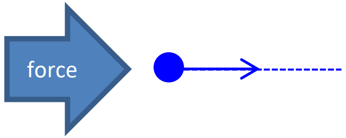
Imposes limitations on collider design



- Radiation also leads to shrinking emittance (and beam size) – lost momentum replenished only in longitudinal direction: “radiation damping”

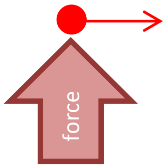
- Radiation in *longitudinal acceleration* negligible

Longitudinal acceleration



- Radiation loss for *transverse acceleration* (bending) can be large: depends on particle mass, energy, and bending radius:

Transverse acceleration

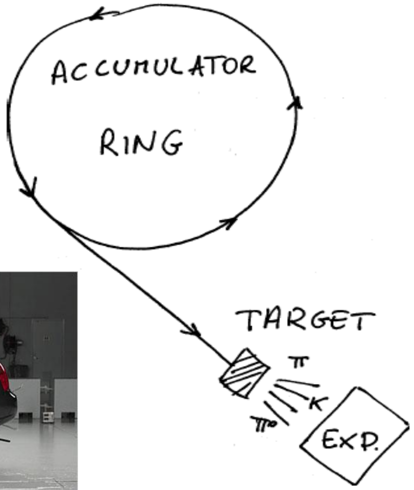


$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

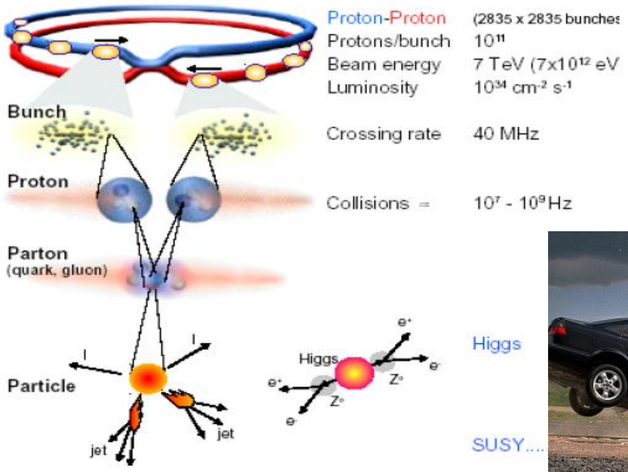
- Much stronger effect for leptons!

Collider vs fixed target experiments

- Fixed Target
- Collider



$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)}$$



<< $$E_{CM} = 2\left(E_{beam} + mc^2\right)$$

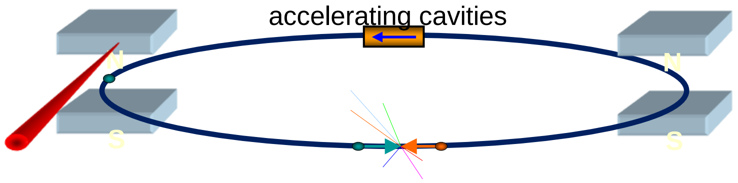
To achieve the highest possible centre-of-mass energy, need a collider

Circular vs linear collider

Circular Collider

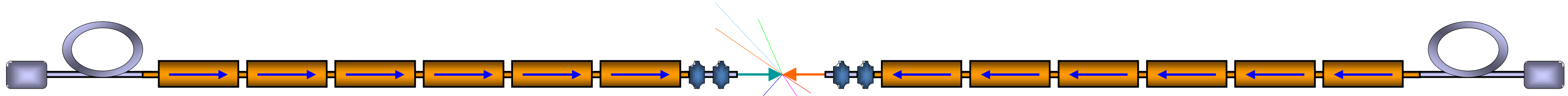
- multi-pass => Accelerate beam over many turns, let beam collide many times
- many magnets, few accelerating cavities
- Bending of beam trajectory => synchrotron radiation losses

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



Linear Collider

- single pass => need to be very efficient
- few magnets, many accelerating cavities
- Not limited by synchrotron radiation – promising choice for reaching highest lepton energies



Increasing beam energy

Circular Collider

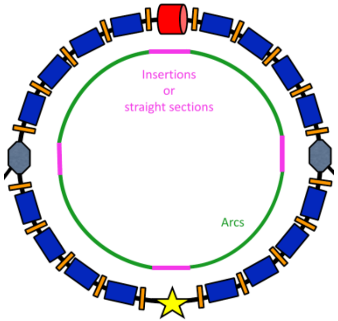
- Hadron beams: energy limited by ability of to keep particle on circular orbit
  - Maximum achievable dipole field (superconductor technology)
  - Radius of ring (cost, site)

- Lepton beams: radiation losses
  - RF power consumption
  - Disposal of radiated power
  - Radius of ring (cost, site)

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

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

$B\,\rho$ = **Beam rigidity**

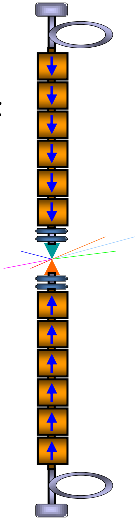


For protons:

$$E_{beam}[TeV] \approx 0.3 \times B[T] \times R[km]$$

Linear Collider

- Energy depends on
  - Accelerating gradient (RF technology)
    - Plasma wakefield acceleration promises large advancement, but not yet mature to produce required beam quality
  - Length (cost, site)



$$E_{cm} \approx L_{linac} G_{acc}$$

To push energy boundary: improve technology (B-fields, RF gradient) or build a larger machine

Increasing luminosity

Reminder: luminosity depends on beams and optics

Expression for round beams:

$$\frac{dR}{dt} = L \times \sigma_p$$

Higher intensity

Increase number of bunches

Increase bunch intensity

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

Increase F: shorter bunches, smaller crossing angle

$$\frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2}\right)^2}}$$

Smaller β*

Smaller emittance

Smaller beam size

In addition:

- Potential limitations on luminosity from losses and showers from the collisions

Considerations for future collider choices

D. Schulte

Physics potential	The collider energy The collider luminosity Particle type
Feasibility	The technical maturity The risk The schedule
Affordability	The collider cost The collider power consumption Availability of site

European strategy for particle physics

- Common strategy worked out in Europe to guide future decision-making in field: "European strategy for particle physics"
  - endorsed by the CERN council
- Based on bottom-up approach:
  - physics community is invited to submit proposals for near-term, mid-term and longer-term projects → community discussion in open symposium, Physics briefing book
  - Based on this input, the European Strategy Group formulates the strategy
    - consists of scientific delegates from CERN Member States, Associate Member States, directors of major European laboratories, representatives of various European organizations, some invitees from outside the European Community
- Initiated in 2006, updated in 2013 and 2020, next update foreseen in 2026/2027

2020 update: Key takeaway messages

Some recommendations in European strategy

Some points relevant to future high-energy colliders - see full document here

- [about LHC] "The successful completion of the high-luminosity upgrade …. should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC …. should be exploited. "

- "An electron-positron Higgs factory is the highest-priority next collider"

- "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. "

- "The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors"

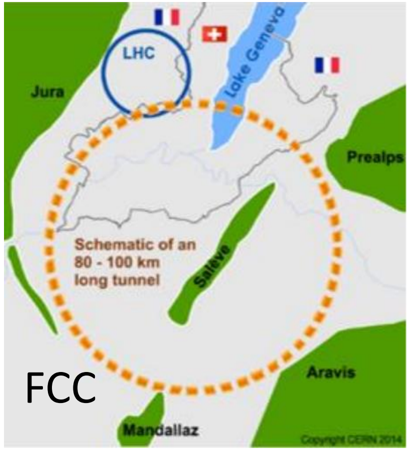
Future high-energy colliders studied at CERN

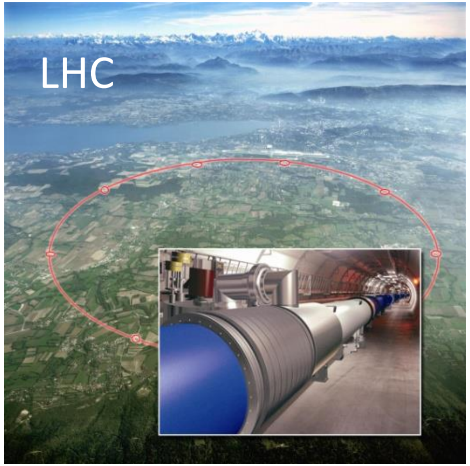
- **HL-LHC**: luminosity upgrade of the LHC.
  - Approved and financed - production and installation of upgrades already in full swing
  - 14TeV pp CMS and heavy ions as in LHC, 27 km

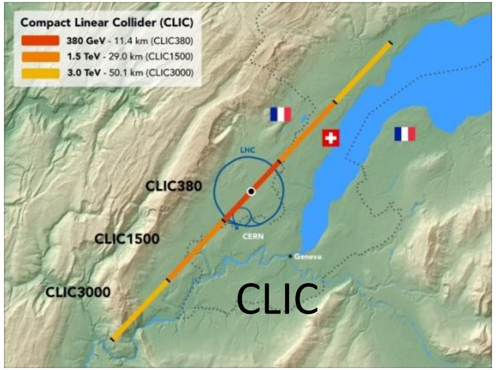
- **Future Circular Collider (FCC)** in different stages
  - Conceptual design report released
  - Circular e+e- collider in 100 km tunnel, up to 365 GeV CMS: FCC-ee
  - Re-use tunnel for 100 km hadron collider, 100 TeV pp CMS: FCC-hh
  - 2-step approach inspired by successful LEP – LHC programs at CERN
  - Alternative approaches:
    - energy upgrade of the LHC using stronger magnets: High-Energy LHC (HE-LHC)
    - Hadron-electron collisions at the FCC: FCC-he
    - Lower-field version of FCC-hh

- **Compact Linear Collider (CLIC)**
  - Linear e+e- collider, conceptual design report released
  - Up to ~50 km and 3 TeV CMS energy

- Other projects that are being studied
  - Muon collider
  - LHeC (hadron-electron collisions at the LHC)

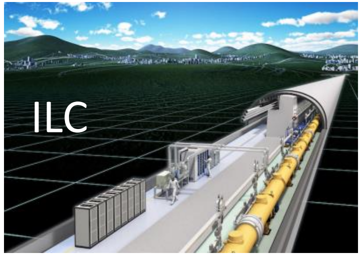




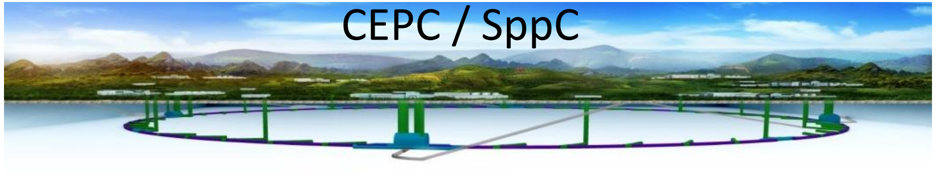


Initiatives in the rest of the world

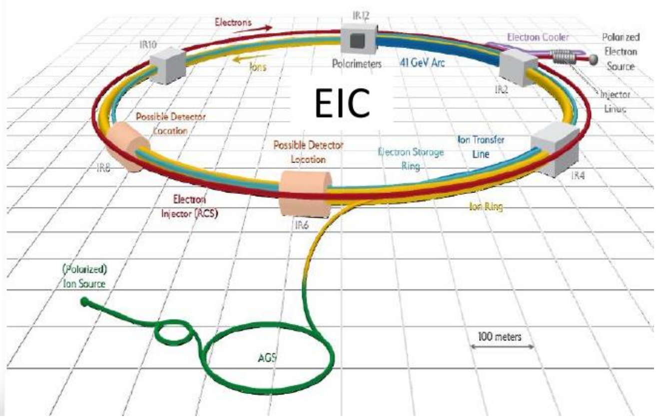
- **International Linear Collider (ILC)**
  - Linear e+e- collider, technical design report released – mature design
  - up to 500 GeV CMS, 31 km
  - Potentially hosted by Japan – waiting for political decisions



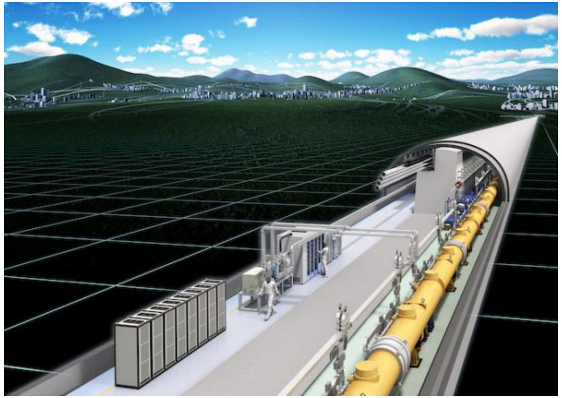
- **Chinese initiative for circular collider**
  - First: e+e- collider (CEPC), up to 240 GeV CMS energy, 100 km ring
  - followed by a 100 km hadron collider (SppC), 75 TeV CMS energy (proposals for extensions to ~150 TeV)



- **Electron-Ion Collider (EIC)** to be built at Brookhaven, US
  - Circular, up to 140 GeV CMS energy, ~3.4 km
  - Range of ions: p-U
  - Use existing RHIC with some upgrades for ions
  - New electron storage ring and injector
  - Project approved, announced timeline to completion of ~10-15 years

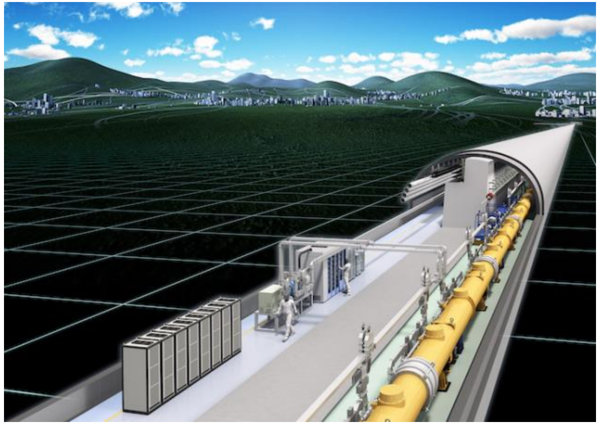


ILC



ILC basics

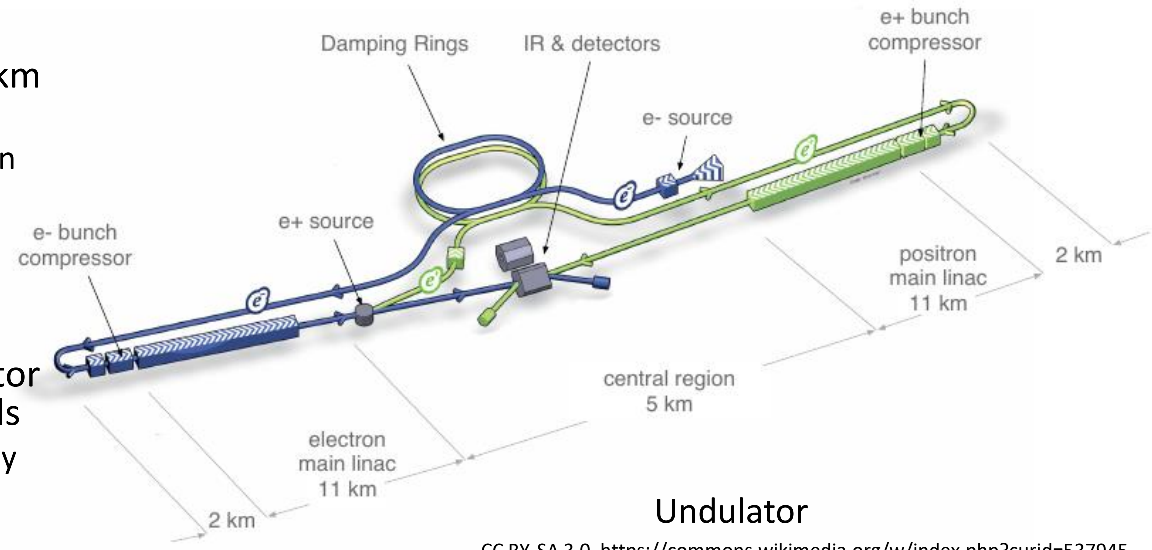
- International Linear Collider: e+e- collider, aiming at 100-250 GeV beam energy (up to 500 GeV centre of mass)
  - Extendable to 1 TeV (requires doubling the length)
- Foreseen length at 500 GeV CMS energy of 31 km
- Possibly to be built in Japan – waiting for political decisions and agreements on funding



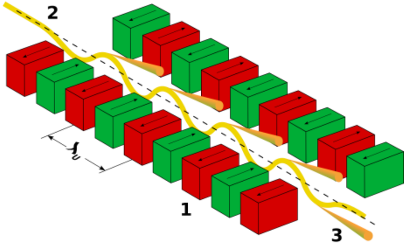
ILC layout and concept

- First, create e- (photocathode DC gun)
- Accelerate, send to circulate in 3.2 km damping ring
  - Shrinking emittance under radiation damping
- e- sent to main linac, accelerate
- To create e+: Electrons pass undulator – magnets with many periodic bends
  - Radiated photons impact on Ti-alloy target, creating e+e- pairs.
  - Capture e+, accelerate, send to damping ring
- Send e+ to main linac, accelerate
- Collide e+e- inside detector

From ILC design report



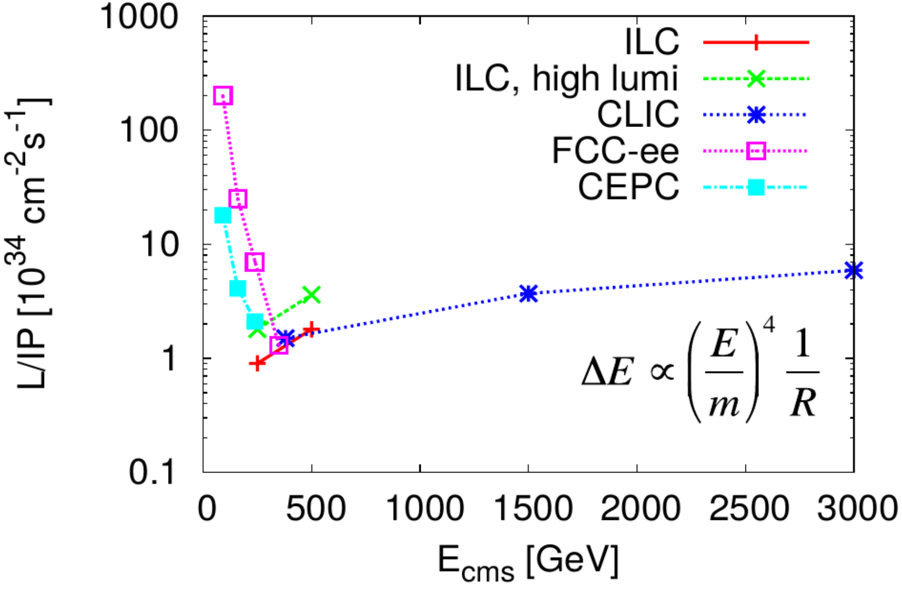
Undulator



Luminosity comparison

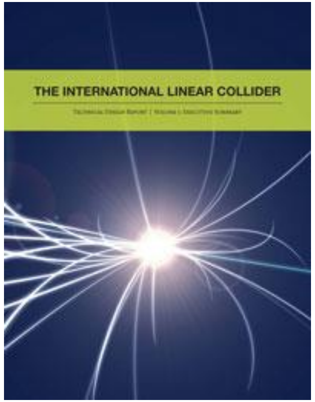
- Comparing luminosity between different future lepton colliders
  - Circular and linear

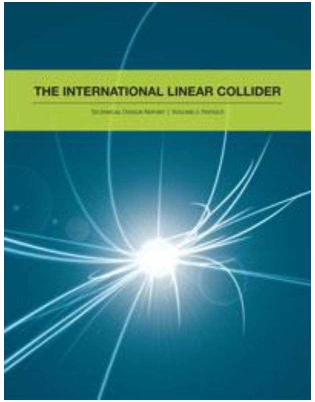
- At high energies, linear lepton colliders can achieve higher luminosity than circular ones
  - Intensity in circular colliders limited by synchrotron raditaion

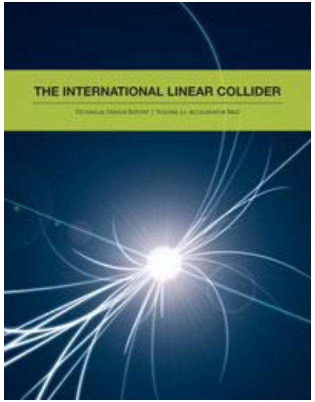


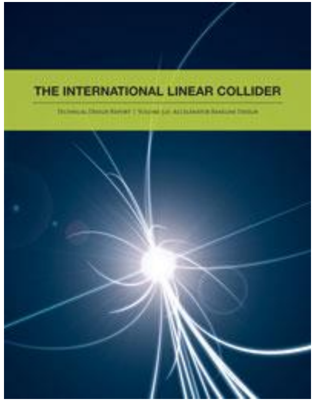
Further documentation

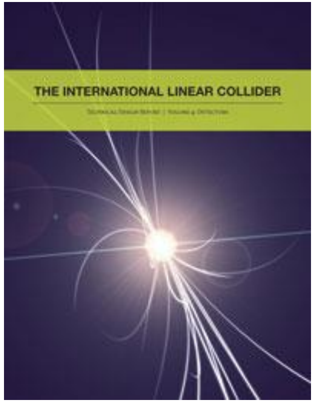
- ILC technical design report



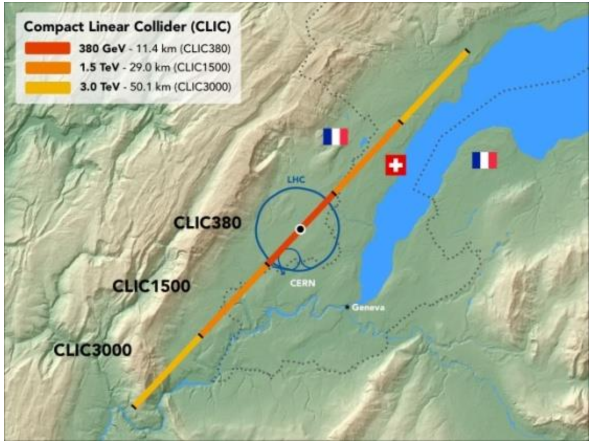








CLIC



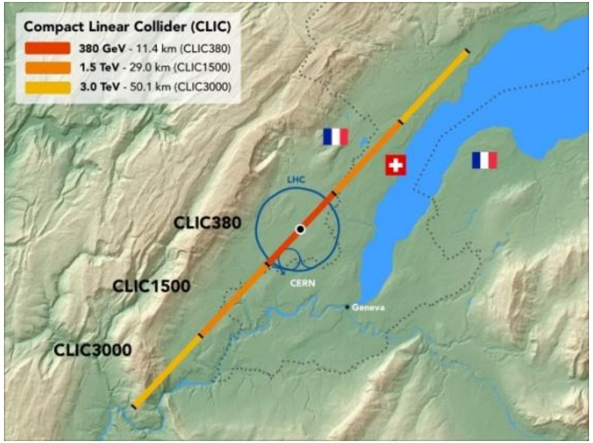
Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
CLIC380
CLIC1500
CLIC3000
LHC
CERN
Geneva

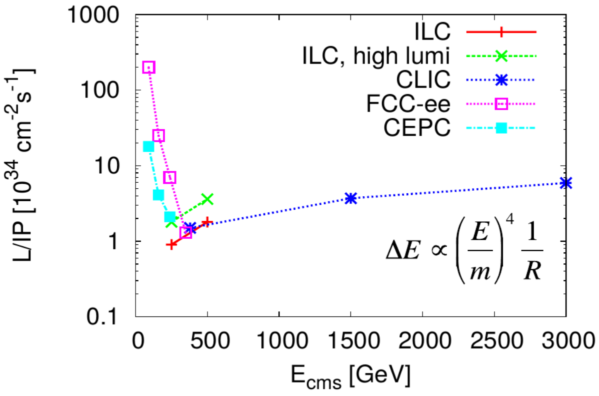
CLIC basics

- Linear e+e- collider, to be built in stages of increasing centre-of-mass energy:
  - 3 stages: 380 GeV – 3 TeV
  - Length between ~11 km and ~50 km

- Aiming at highest lepton energies

- 30 MW of beam power at 3TeV



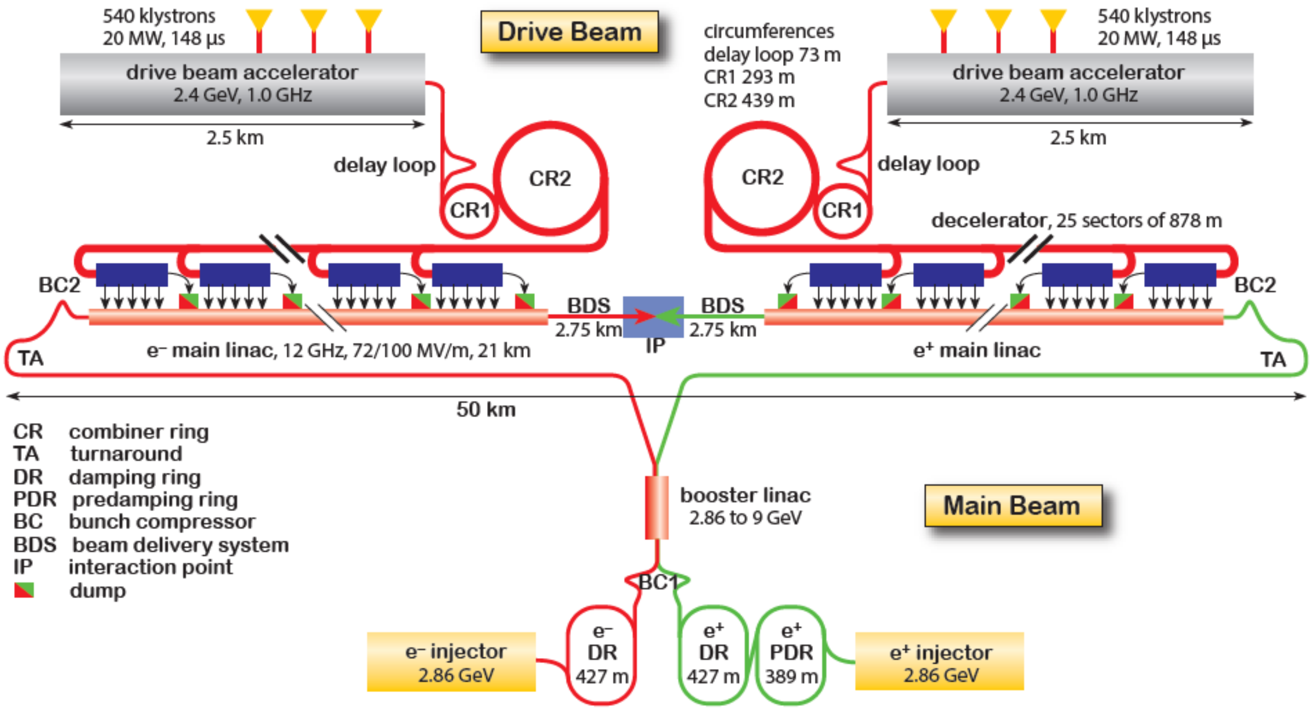


CLIC layout

- Concept:
  beam generation
  → pre-acceleration
  → damping rings
  → booster linac
  → main linacs
  →collisions

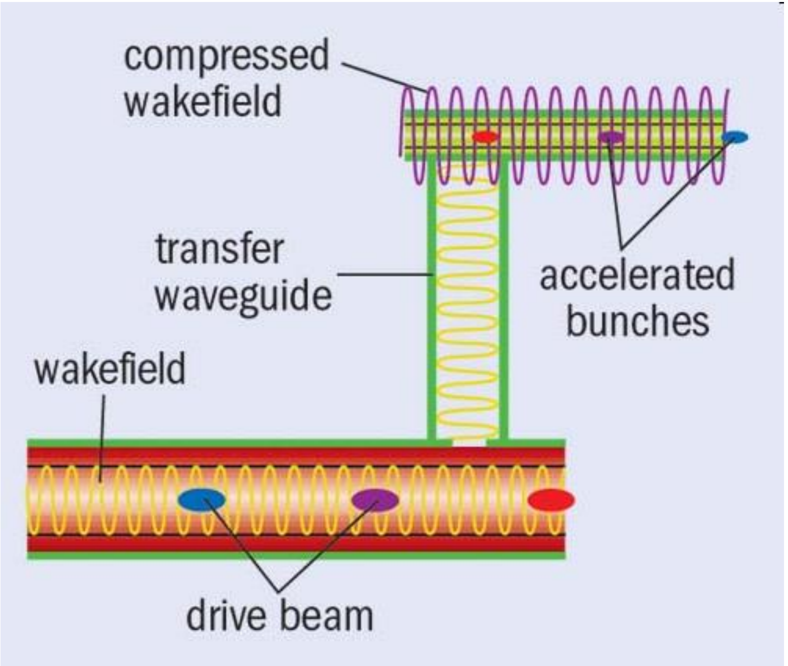
- CLIC aims at gradients of 100 MV/m, 20 times higher than the LHC
  - Compare 30 MV/m at ILC

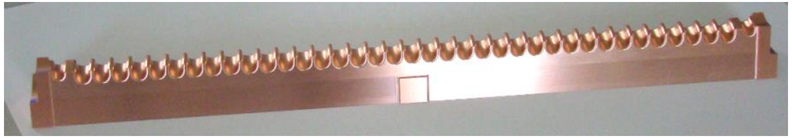
- Different acceleration concept in main LINAC from ILC :
  - drive-beam acceleration, with RF power taken from another e- beam



Two-beam acceleration scheme

- The high-current drive beam is decelerated in special power extraction structures (PETS)
- Generated EM field can be transferred in RF waveguides to the other beam => power is used to accelerate the main beam

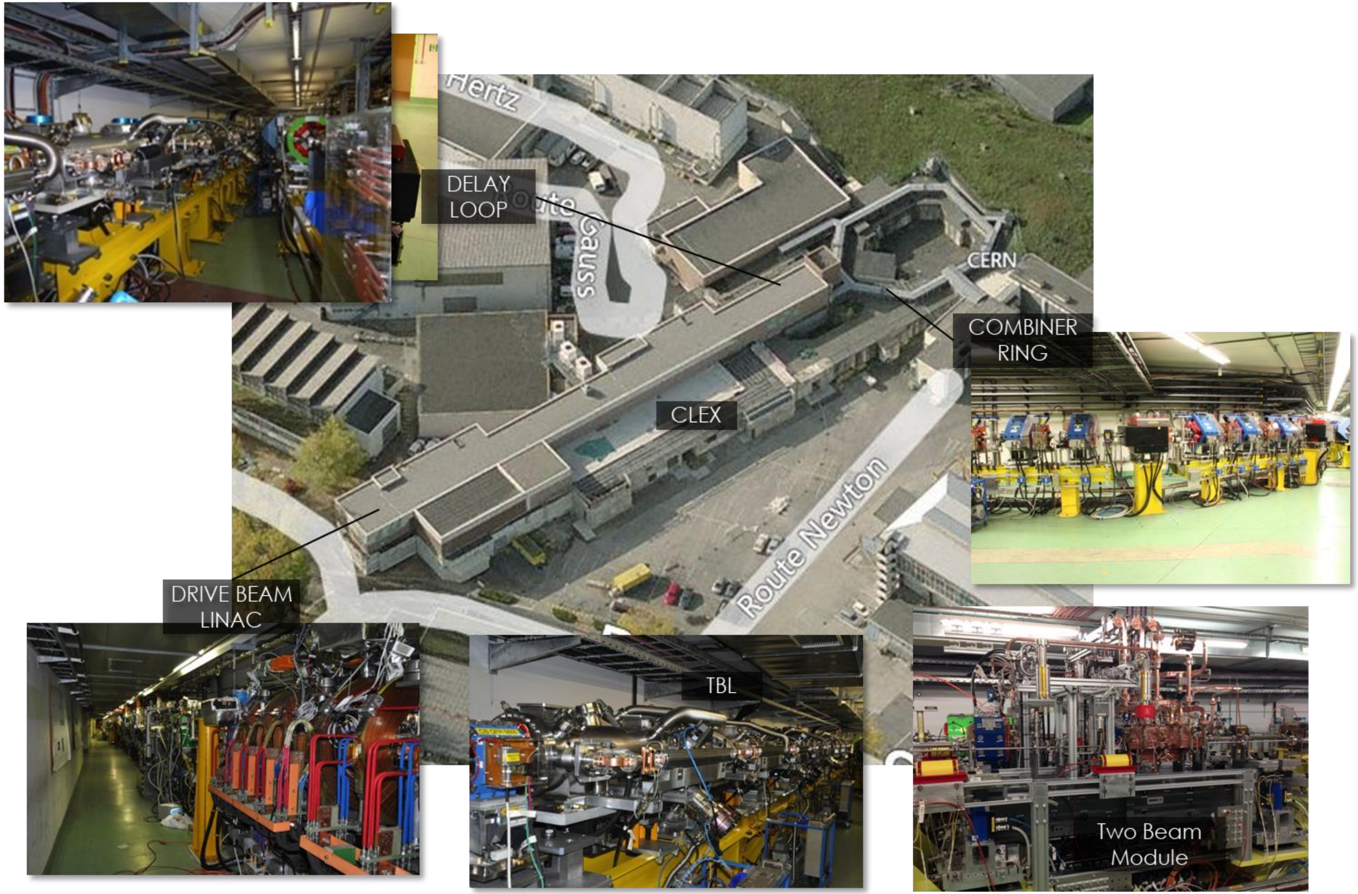




CLIC Test Facility (CTF3)

- Experimental tests carried out in test facility at CERN to demonstrate drive beam concept

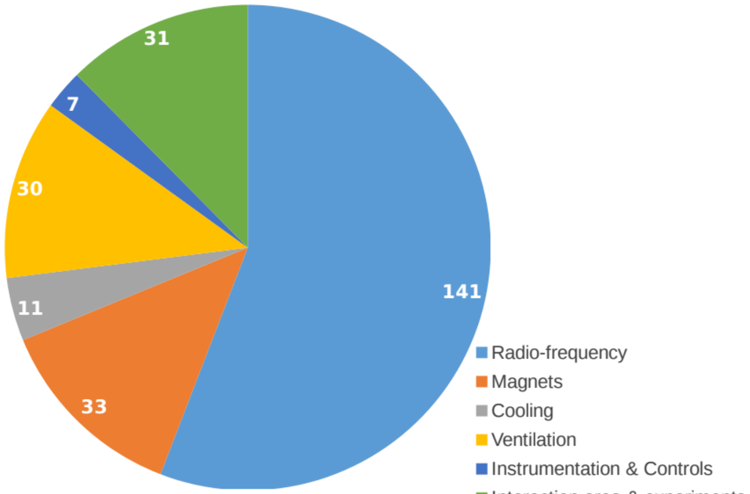
- Accelerating gradient of >100 MV/m achieved



CLIC power consumption

- Power and energy consumption at 380 GeV is well within the existing parameters and installations at CERN
- At 1.5 TeV: power will surpass the current CERN usage (2017) by ~30%
- At 3 TeV the energy consumption will be a factor two of the current CERN usage (2017)
- Development work ongoing to further improve energy efficiency

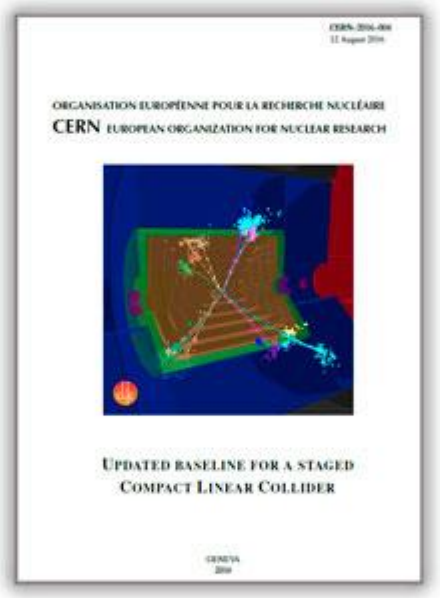
Estimated power consumption of CLIC in MW at 380 GeV (total: 252 MW)



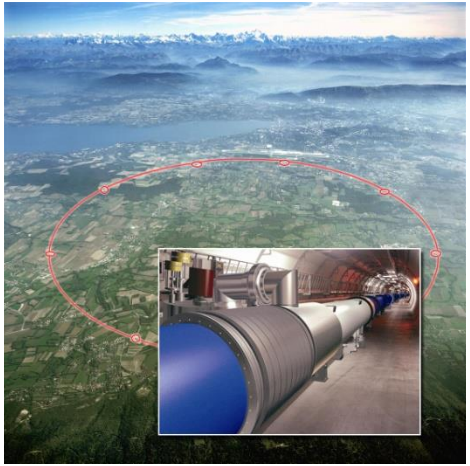
https://clic.cern

CLIC reference documents

- More information:
  - Conceptual design report (2012)
  - Updated CLIC baseline document (2016)

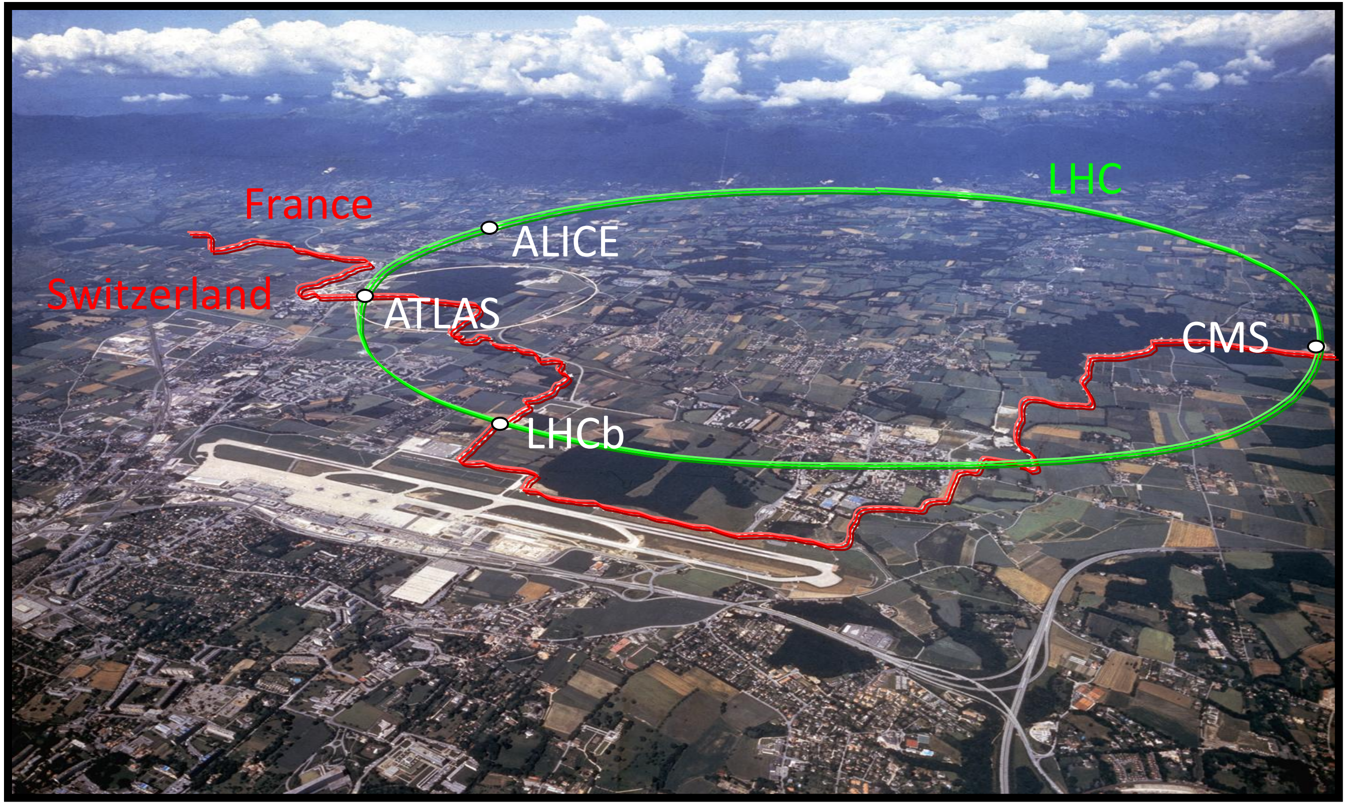


HL-LHC



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
- So far collected in total about 230 fb^{-1} of integrated luminosity at the high-luminosity experiments (ATLAS, CMS)



HL-LHC

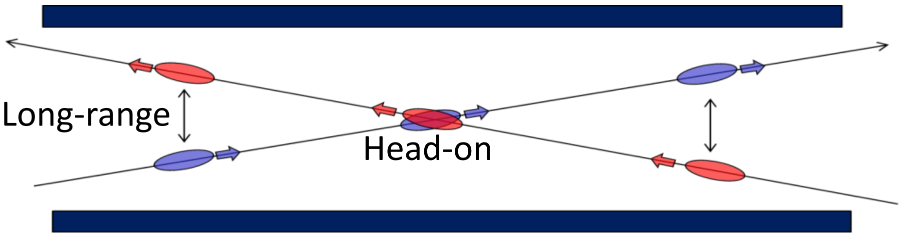
- High-luminosity LHC: Major upgrade of the LHC
- Main goals:
  - Target an integrated luminosity of at least ~250 fb^{-1} per year
  - Achieve a total integrated luminosity of 3000 fb^{-1} over the project lifetime, a factor ~15 higher than what has been achieved so far at LHC
  - Prepare machine for operation from 2029 and at least up to ~2038

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

	LHC 2018	HL-LHC
Protons per bunch	1.1×10^{11}	2.2×10^{11}
Number of bunches	2556	2750
Normalized emittance	1.8 micron	2.5 micron
Beta*	25-30 cm	15 cm
Full crossing angle	320 microrad	500 microrad
Geometric reduction factor F	0.6	0.35
"Virtual" luminosity		2.4×10^{35} $cm^{-2}s^{-1}$
Levelled luminosity	2.1×10^{35} $cm^{-2}s^{-1}$	5×10^{34} $cm^{-2}s^{-1}$

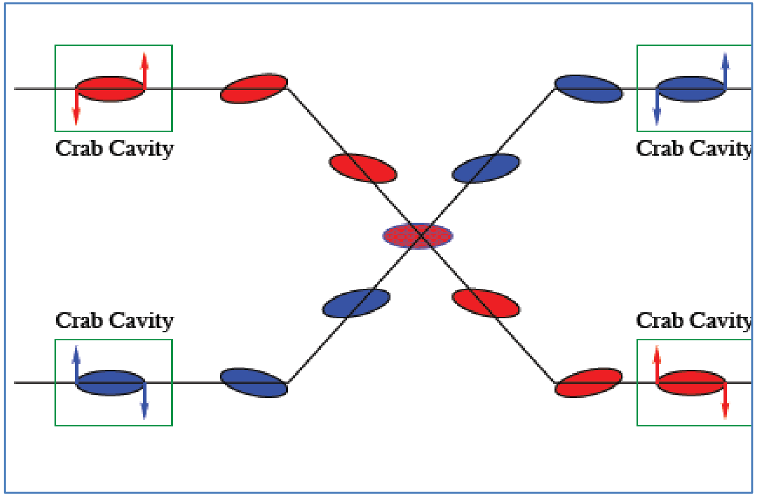
Compensation of geometric reduction factor

- 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

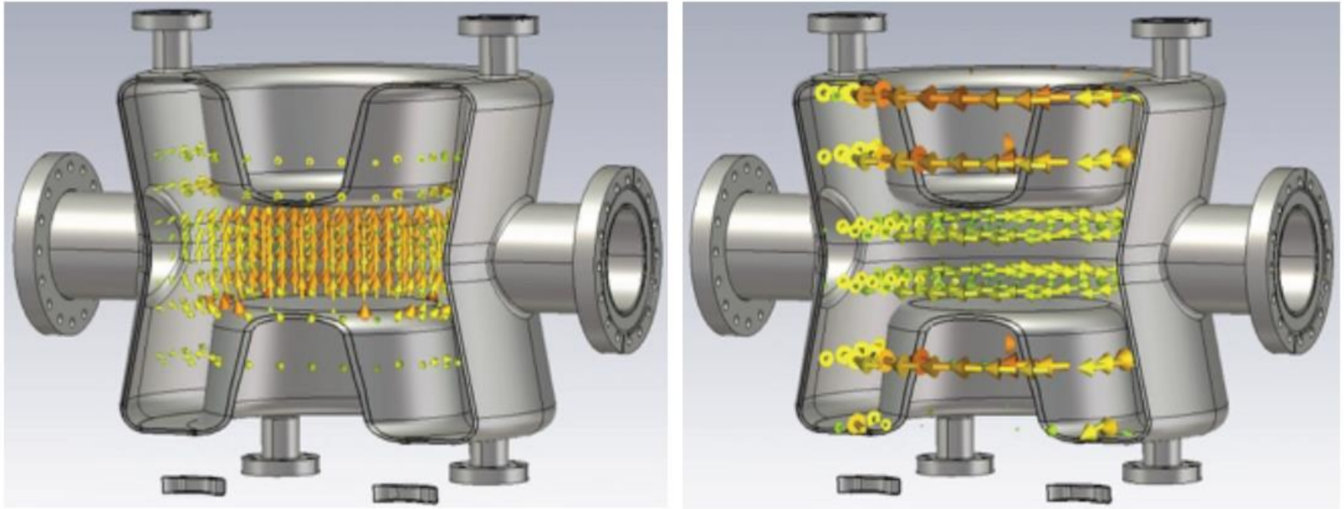
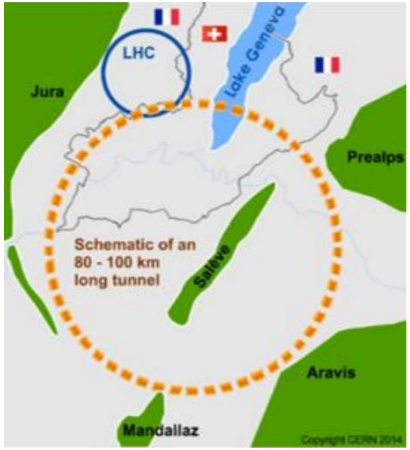


Figure 4. Electric (left) and magnetic (right) field distributions inside the DQWCC.

FCC-hh



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

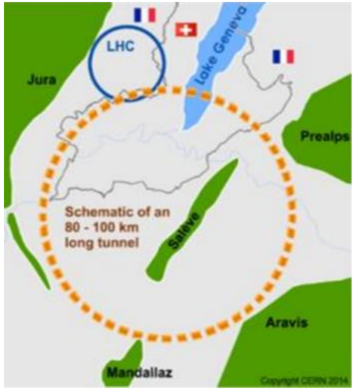
FCC-hh general goals

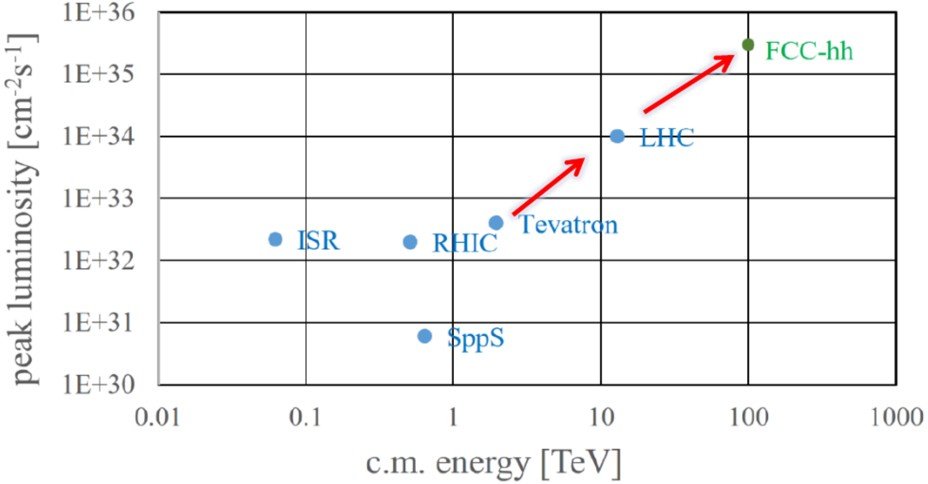
- European strategy: "Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. "

- FCC-hh: collide 50 TeV protons (or heavy ions of equivalent magnetic rigidity) in tunnel of 90.7 km
  - Factor 7 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)



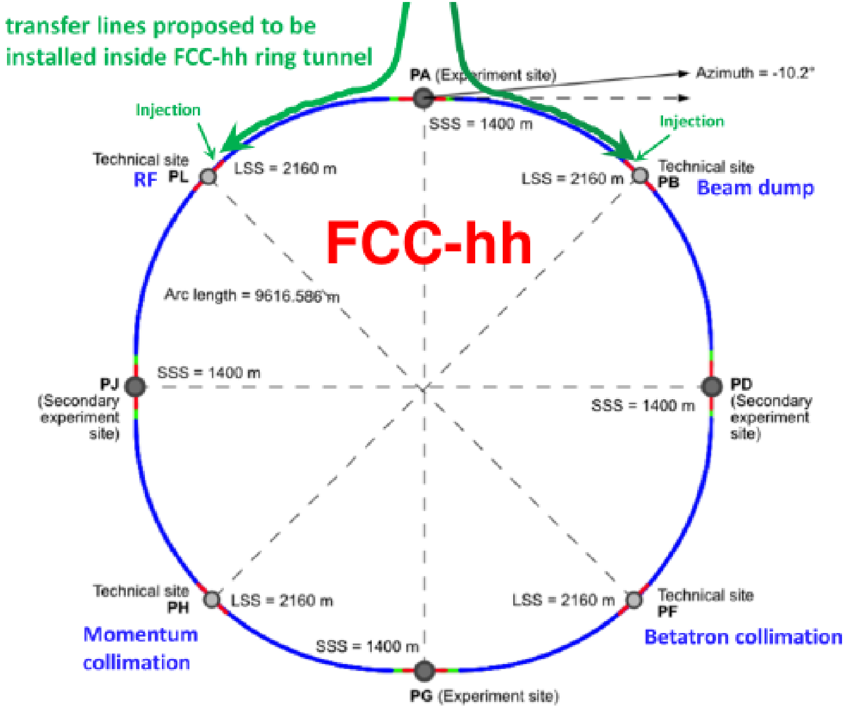


FCC-hh layout

- 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 (L)

- Insertions are 1.4-2.16 km long

- Compatible with LHC or SPS as injector

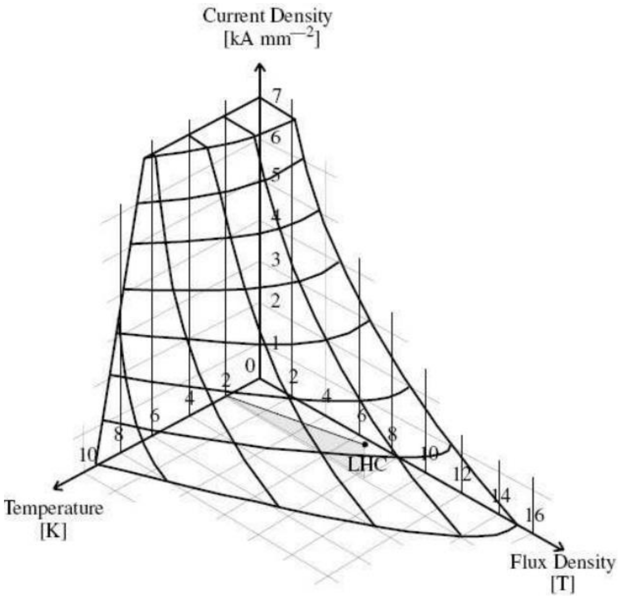


FCC-hh magnets

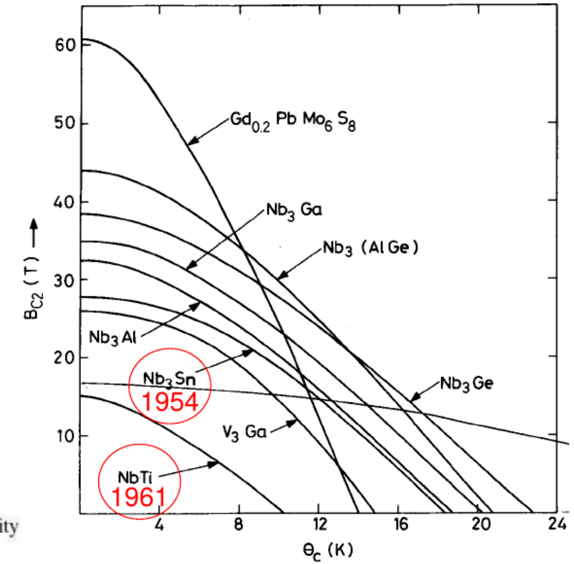
- Need 16 T dipole magnets – not feasible with today's technology → big challenge for technological development!
  - In LHC, 8.3 T, with NbTi superconductors
  - Cannot reach 16 T with NbTi: to be superconducting, need working point below "critical surface" in space spanned by temperature, current density and magnetic field

- For 16 T, rely on future developments of Nb3Sn superconductor technology
  - Alternatively, bet on high-temperature superconductors – significant technology development and cost reduction needed

- Advanced research program on high-field magnets going on!

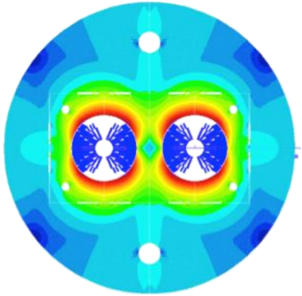


Critical surface for NbTi



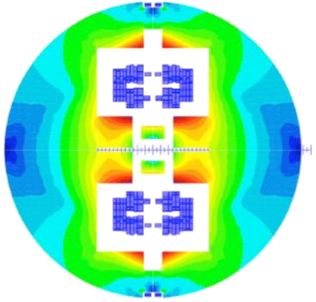
Research program on 16T Nb3Sn magnets

INFN
Cos-theta

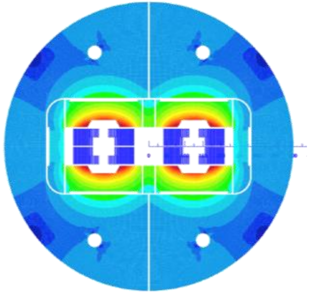


EuroCirCol
A key to New Physics

CIEMAT
Common coils



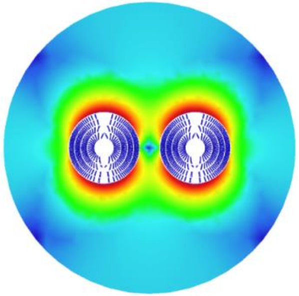
CEA
Blocks



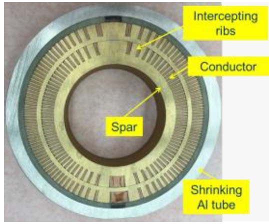
Swiss contribution

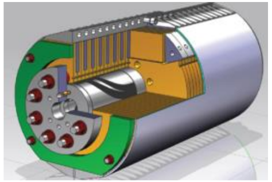
PSI

Canted Cos-theta



LBNL





FNAL

Short model magnets (1.5 m lengths) will be built until ~2025

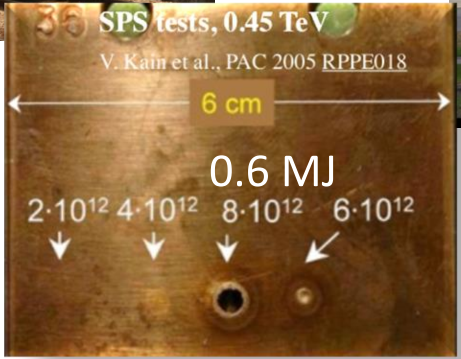
Next challenge: FCC-hh machine protection

HL-LHC: 680 MJ - kinetic energy of

TGV train cruising at 215 km/h

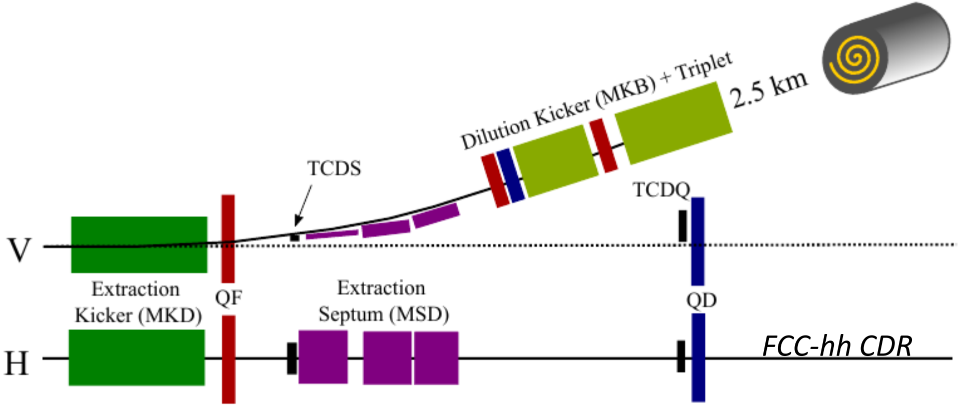
FCC-hh: 8.3 GJ – kinetic energy of

Airbus A380 (empty) cruising at 880 km/h



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

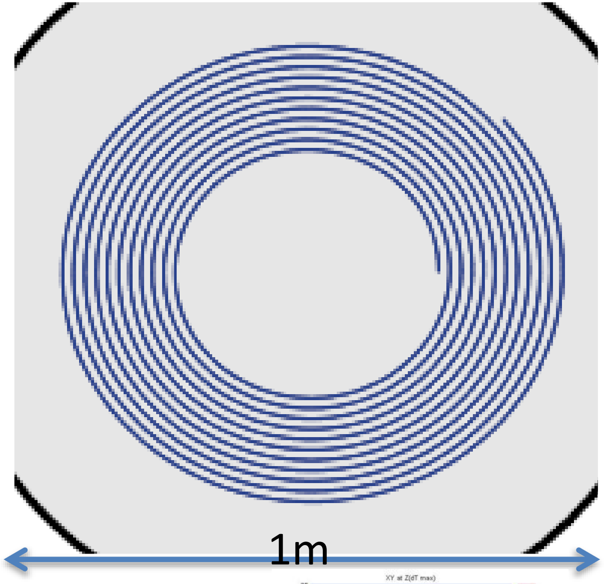


- Need to dispose of 8.3 GJ!
  - Enough to drill 300m long hole in copper

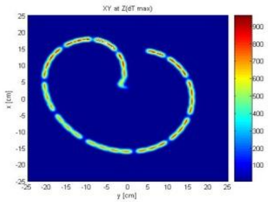
Beam dump

- Solution: as for LHC, distribute ("paint") beam transversely, but over much larger surface than in LHC
  - Beam-dump made of low-density graphite sheets, should not exceed 1500 deg C

D. Schulte, W. Bartmann



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

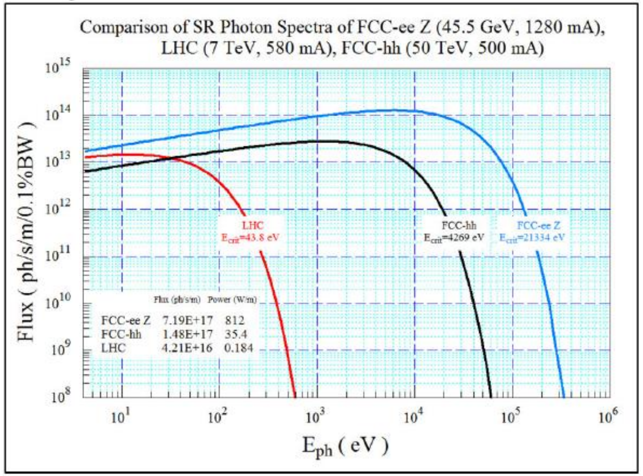
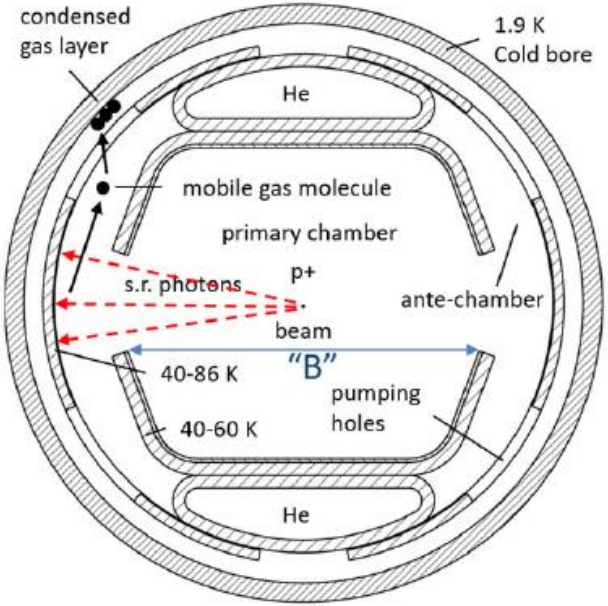
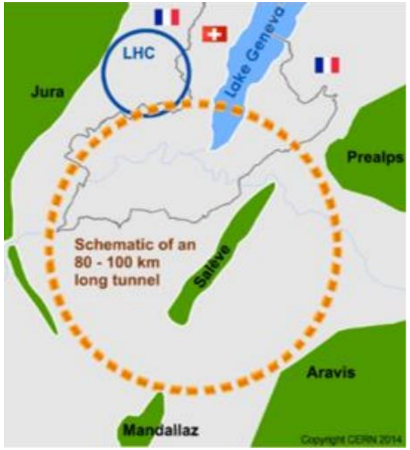


Figure 6.5: Synchrotron Radiation photon flux spectra for LHC, FCC-ee (Z-pole) and FCC-hh beams.



FCC-hh conceptual design report

FCC-ee


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

FCC-ee

- European strategy: "An electron-positron Higgs factory is the highest-priority next collider"

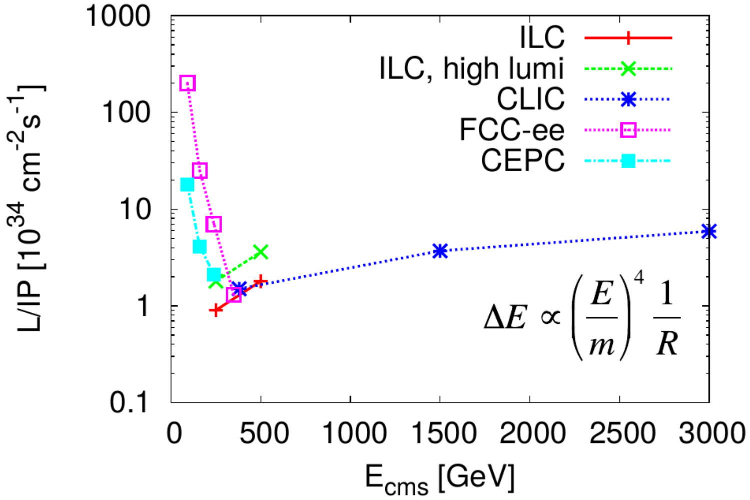
- FCC-ee is a high-luminosity, high-precision e+e- circular collider

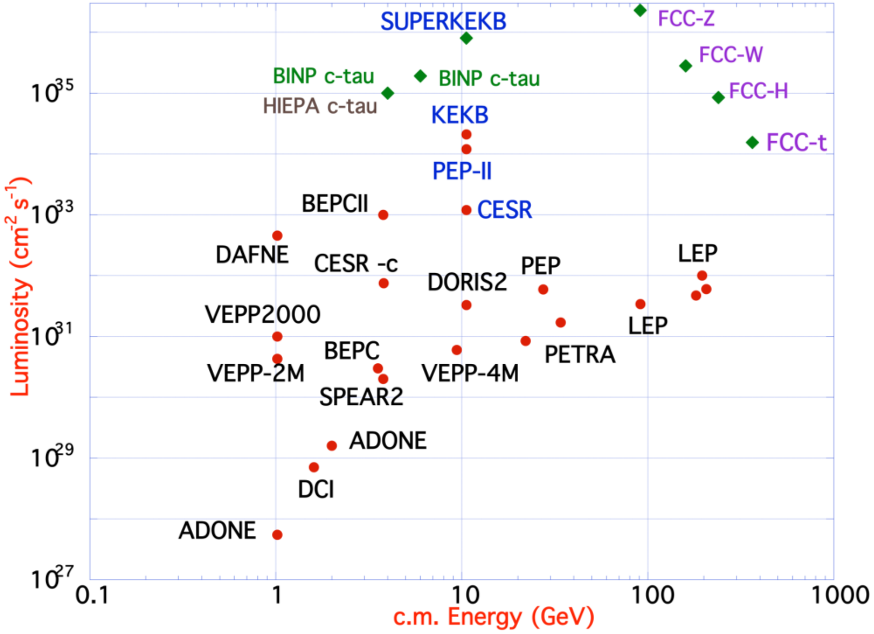
- Several different operational energies are foreseen to perform precision measurements of **Z**, **W** and **H** bosons and the **top quark**
  - Goal: provide samples of 5×10^{12} Z bosons, 10^{8} W pairs, 10^{6} Higgs bosons and 10^{6} top quark pairs.

- Beam energy: 45-182 GeV

Luminosity comparison

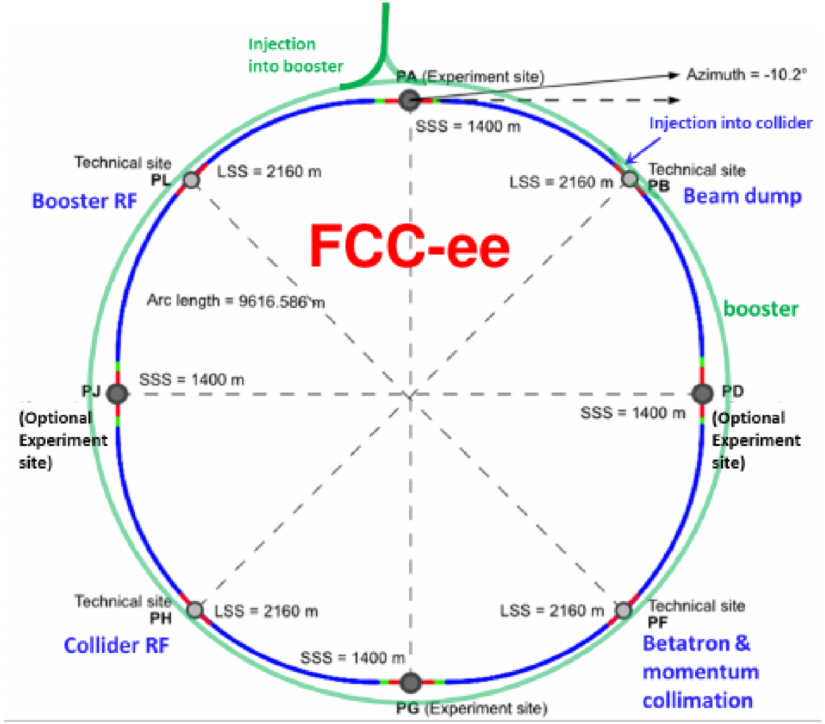
- To reach the physics goals, need to significantly increase luminosity w.r.t. previous lepton colliders
- Can reach higher luminosity than linear colliders at lower energy
  - The higher the energy, the more severe limitations from synchrotron radiation





FCC-ee layout

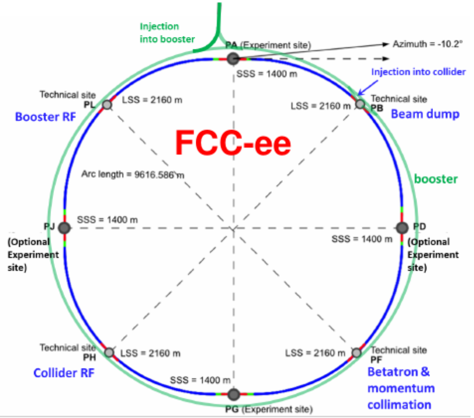
- Two-ring layout with two or four collision points and two RF insertions
- Follows footprint of FCC-hh, except around interaction points (IPs)
  - Need a crossing angle at IP - cannot bend beams close to IP - this would generate photons/background
  - Special layout with last bend far from IP



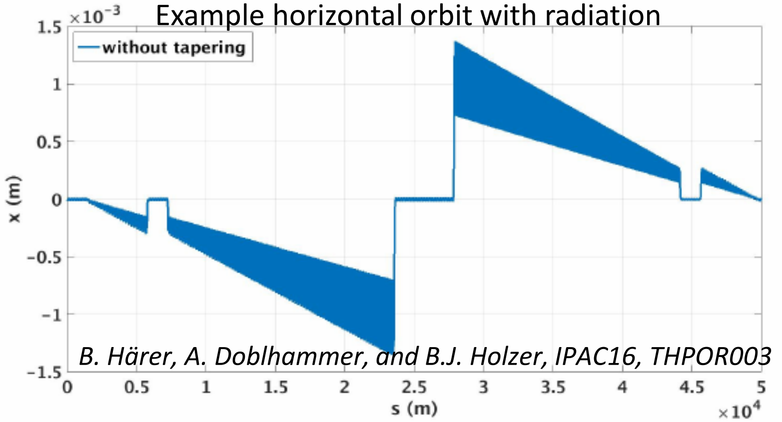
Synchrotron radiation in FCC-ee

- 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

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



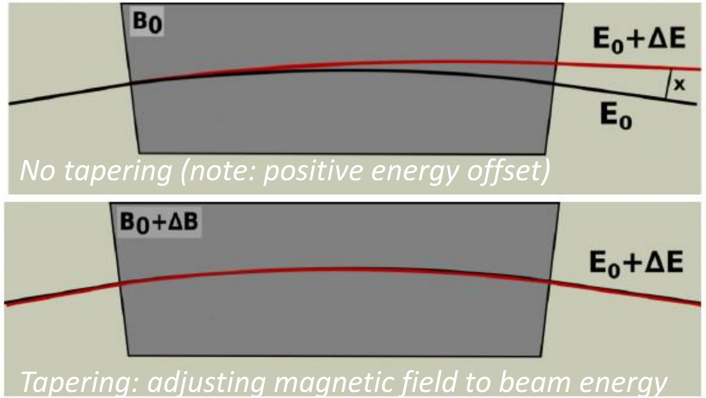
- At highest energy, 182.5 GeV, loss of 9 GeV or ~5% per turn
  - May not be enough to replenish energy once per turn → maybe use two RF insertions to control energy in collisions at both Ips
  - Also: particles that have lost energy are overbent by the dipoles => accumulate large transverse offsets, "saw tooth" orbit if nothing is done



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

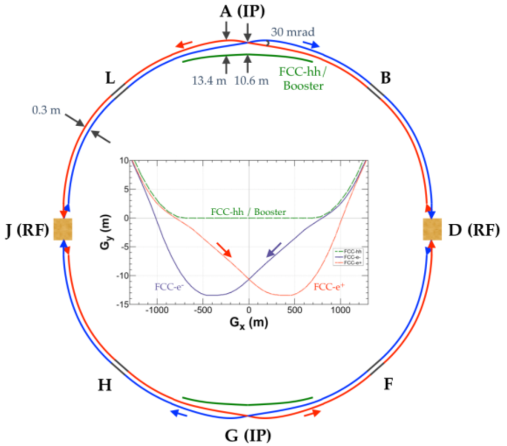
Tapering

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



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

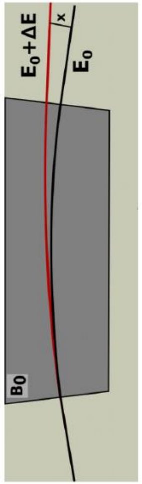
- Vary magnetic strengths along the ring, so that we always match the beam energy

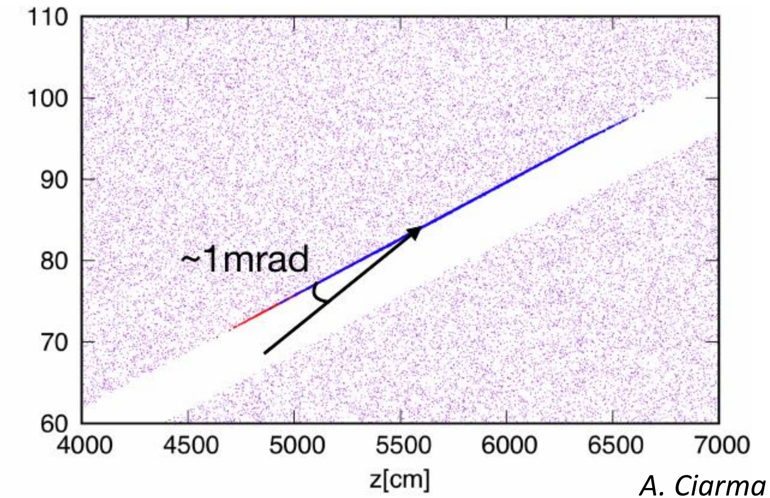


Beamstrahlung

- 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!
  - Photons hit downstream vacuum chamber in localized spot – engineering challenge to dispose of heat without material damage

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 x 10^{-4}	0,148	2	390
182.5	9,12 x 10^{-4}	0,242	67	88





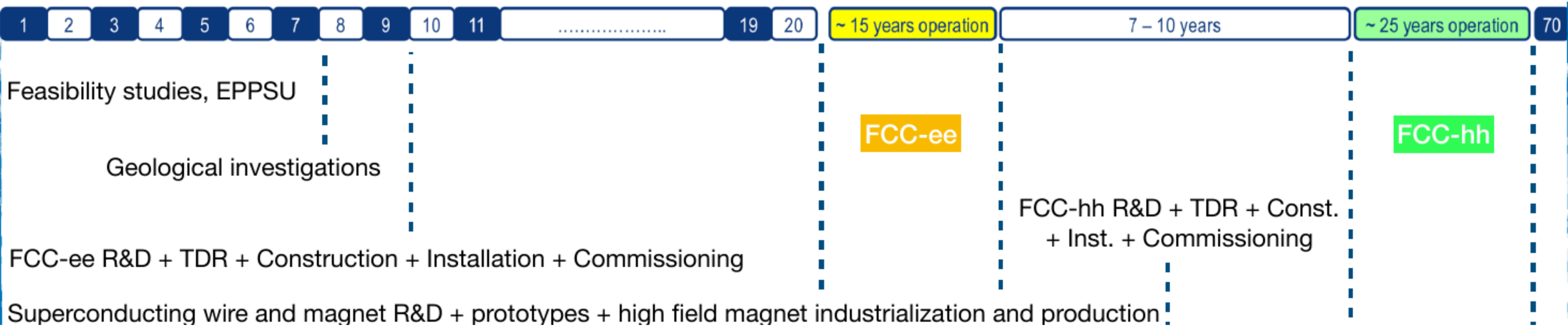
A. Ciarma

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



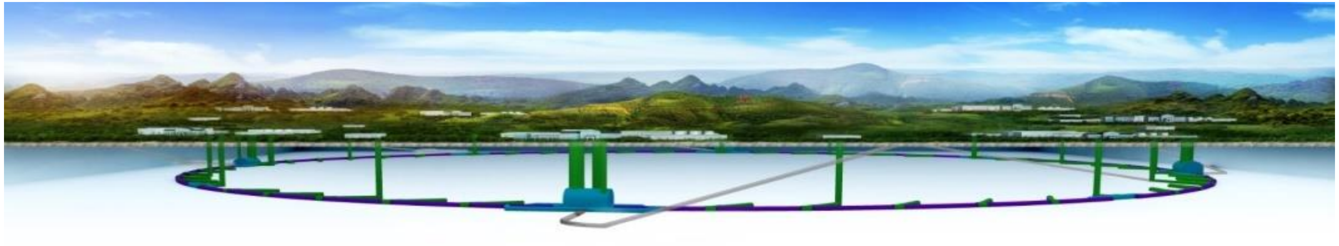
FCC design report

- **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/

CEPC / SppC



CEPC (Circular Electron Positron Collider)

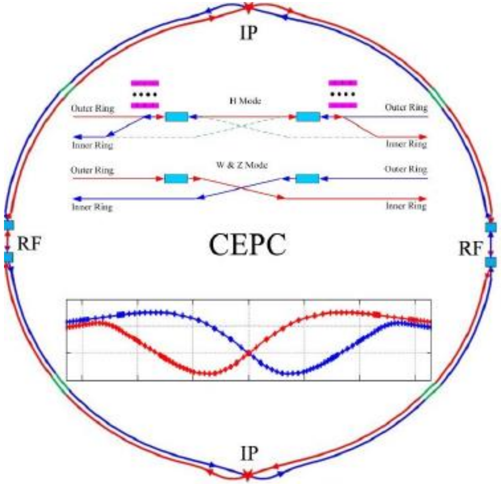
- Chinese proposal for e^+e^- collider 90-240 GeV, 100 km ring
- Focus on Higgs production
- Two collision points, two RF insertions
- Limit synchrotron radiation power to 30 MW per ring
- More info: conceptual design report

Table 3.1: CEPC 10-year operation plan

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 particles
H	240	3	0.8	7	5.6	1×10^6
Z	91	32 (*)	8	2	16	7×10^{11}
W^+W^-	160	10	2.6	1	2.6	1.5×10^7

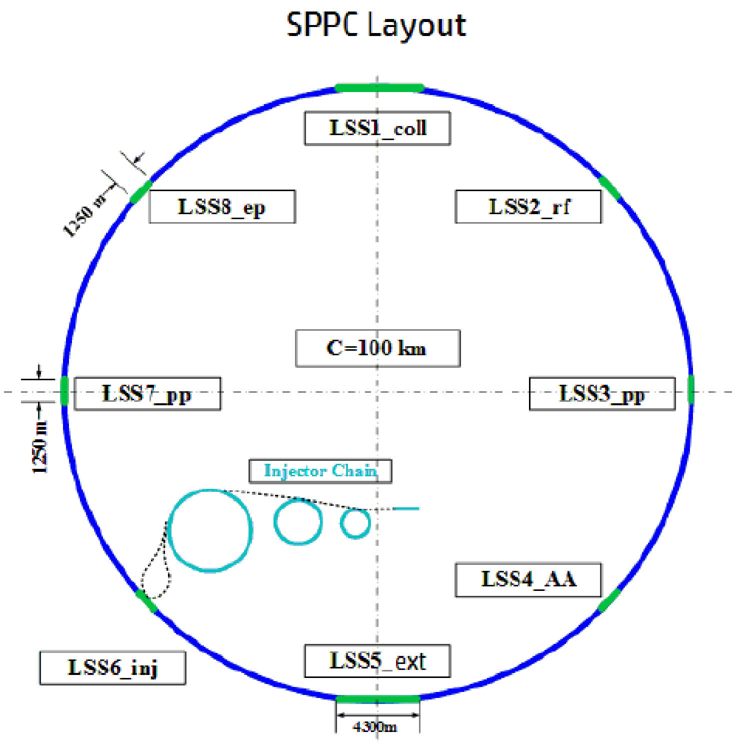
(*) Assuming detector solenoid field of 2 Tesla during Z operation

CEPC design report

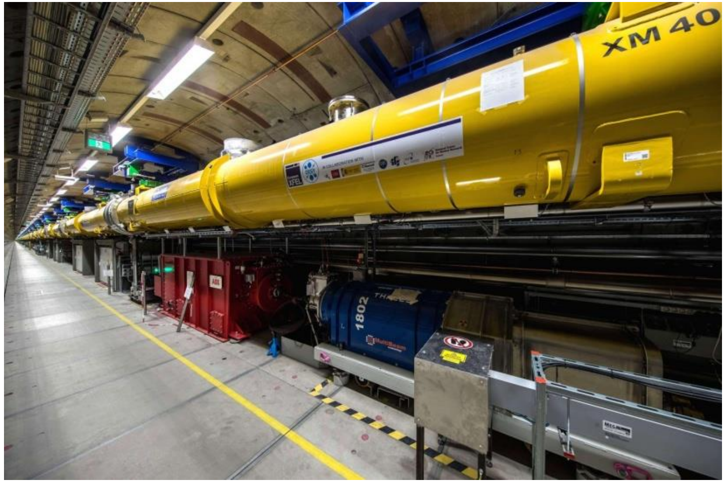


SppC (Super proton-proton Collider)

- 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
- More info in [conceptual design report]



Other Accelerator Studies



Physics beyond colliders

Physics Beyond Colliders study group set up in 2016 to explore the opportunities offered by the CERN accelerator complex and other scientific infrastructure to get new insight into some of today's outstanding questions in particle physics through projects complementary to high-energy colliders (i.e. projects requiring different types of beams and experiments) and other initiatives in the world. Projects should exploit the uniqueness of CERN accelerator complex and infrastructure.

QCD measurements
COMPASS++, DIRAC++
NA61++, NA60++
Fixed target (gas, bending crystals) in ALICE and LHCb

Hidden sector with "beam dump"
NA64++ (e,μ)
NA62++
Beam Dump Facility at North Area (SHiP)
LDMX@eSPS
AWAKE++

Rare decays and precise measurements
KLEVER ($K^0_L \rightarrow \pi^0 \nu\nu$)
TauFV@BDF: $\tau \rightarrow 3\mu$
REDTOP (η decays)
MUonE (hadronic vacuum polarization for $(g-2_\mu)$)
Proton EDM

Long-lived particles from LHC collisions
FASER, MATHUSLA, CODEX-b, milliQAN

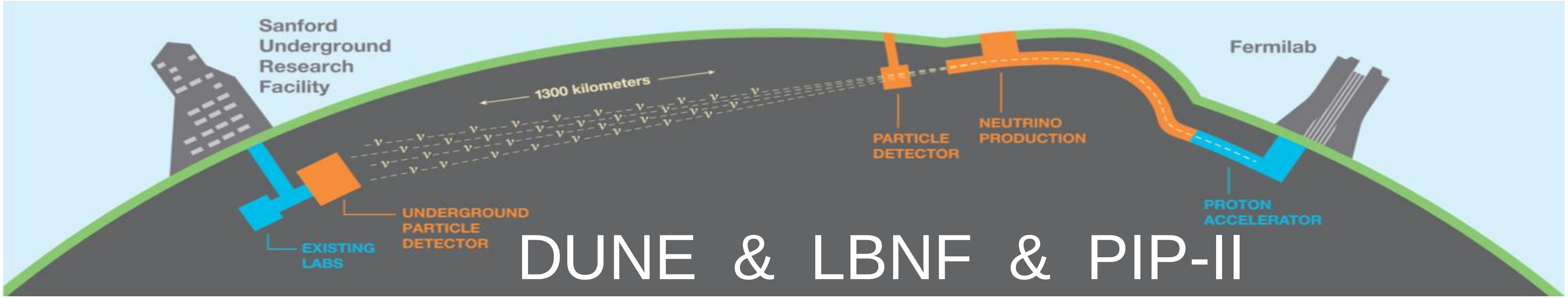
Other facilities:
γ-factory from Partially Stripped Ions; nuSTORM

Non-accelerator projects
Exploit CERN's technology (RF, vacuum, magnets, optics, cryogenics) for experiments possibly located in other labs.
E.g. axion searches: IAXO (helioscope), JURA (Light Shining through Wall)

→ Report submitted to the ESPP

LBNF/DUNE

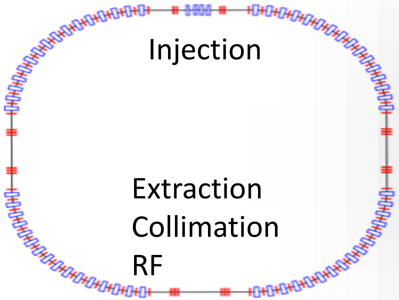
- American project, with proton accelerator at Fermilab, sending neutrinos through the Earth to a detector 1300 km away

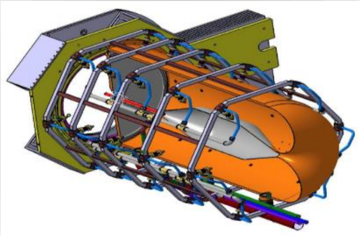


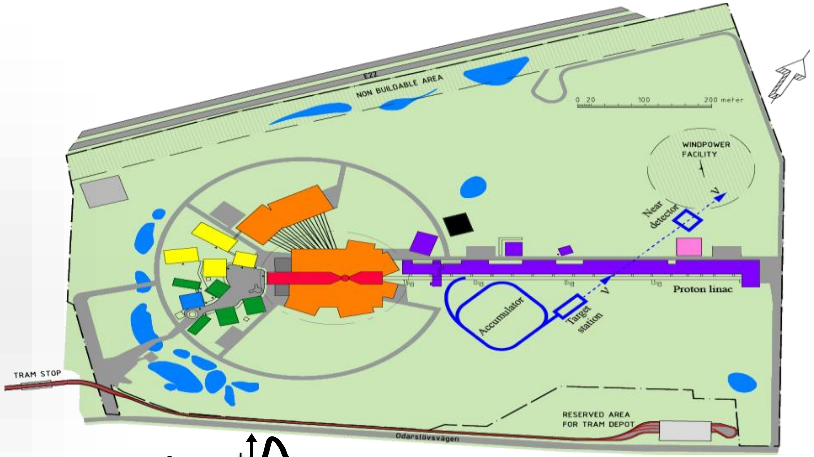
- Status:
  - **Far site:** Construction at started Nov 2018. Currently building or refurbishing ~100 year old rock handling systems at former gold mine to be able to move ~800k tons of excavated rock to surface
  - **Near Site**: site preparation construction contract awarded last month, design of facilities and neutrino beamline underway.
  - **DUNE**: two prototype detector models constructed and operating at CERN.

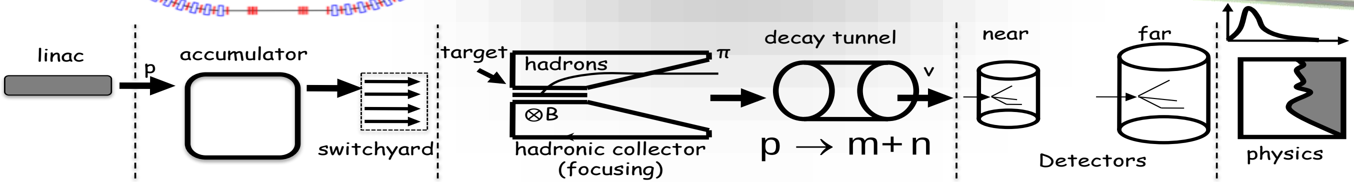
ESS Neutrino Super Beam (ESSnuSB)

- **Doubling the ESS beam power for a second target**
  - linac duty cycle doubling to 8 % (RF sources, cooling)
    - using new H^- source
  - accumulator ring (~400 m circ.) compress 2.86 ms beam pulse to few µs
    - multi-turn injection, stripping $H^- \rightarrow H^+$
  - 2nd target station with magnetic horn (350 kA)
    - to deliver ~300 MeV neutrinos









Summary (1)

- LHC will be upgraded to **HL-LHC**, and operate until 2035-2040
  - 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
  - Also: HE-LHC, FCC-eh, muon collider, LHeC
  - All these machines have many interesting beam physics aspects – 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
    - Conceptual design report exists. China will decide
  - **EIC**: circular electron-ion collider, to be built in the US
    - Approved project with conceptual design report

Summary (2)

From 2019 – with reservation for updates

Project	Type	Energy [TeV]	Int. Lumi. [ab^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU[1] + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

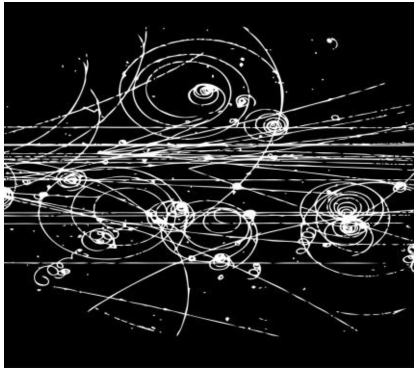
D. Schulte, 2019

[1]United States dollar as in January 2012

Future colliders?

Particle collisions 50 years ago

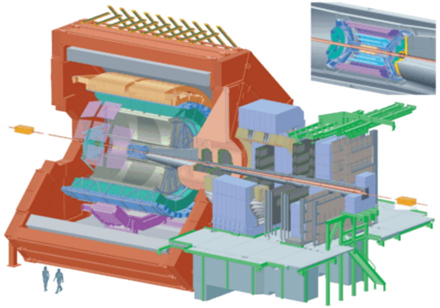
32 cm bubble chamber with liquid hydrogen, 16 GeV pion interacting with proton

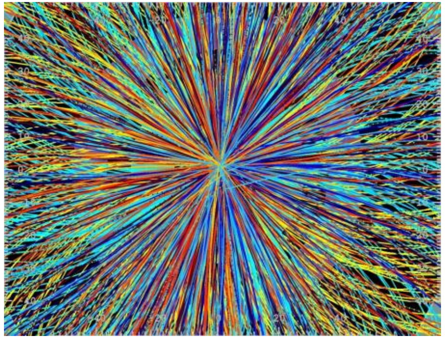


https://cds.cern.ch/record/39474

Particle collisions today

574 TeV Pb beams colliding at ALICE, LHC





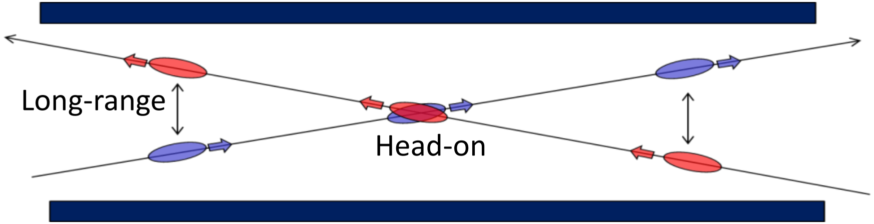
Particle collisions in 50 years

Backup

Some limitations on intensity and beam size

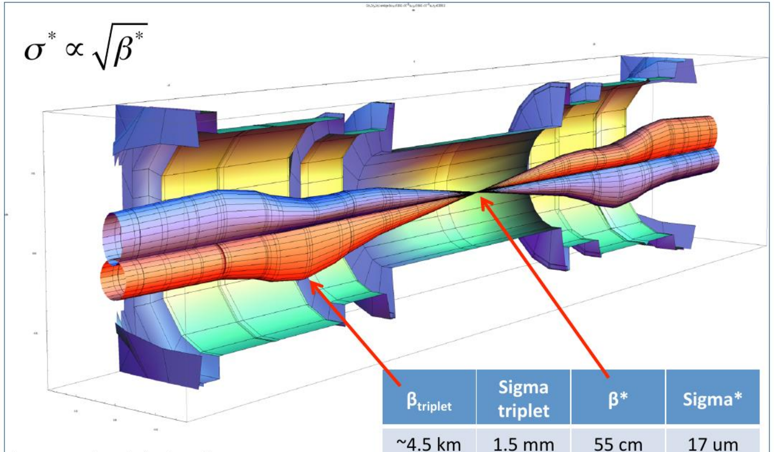
(not exhaustive list)

- Intensity
  - Limitations in beam production scheme
  - Collective effects and instabilities, e.g. space charge, impedance effects, beam-beam effects
  - Beam-beam effects (detrimental non-linear electromagnetic field acting on opposing beam)
  - In circular lepton machines, limitations on RF power (compensate synchrotron radiation losses)
  - Detrimental effects of beam losses



$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

- Beam size
  - β* limited by magnet focusing strength and aperture in final focus quadrupoles
  - Emittance: limitations in beam production, larger risk for instabilities, blowup (intra-beam scattering); not easy to reduce emittance of existing beam, need dedicated cooling etc
    - Lepton machines: equilibrium emittance determined by accelerator lattice
    - Can use damping rings to shrink emittance
  - Beam-beam effects



$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

Image courtesy John Jowett

Radiated power

- For full derivation, see e.g. Jackson, Classical electrodynamics, chapter 14

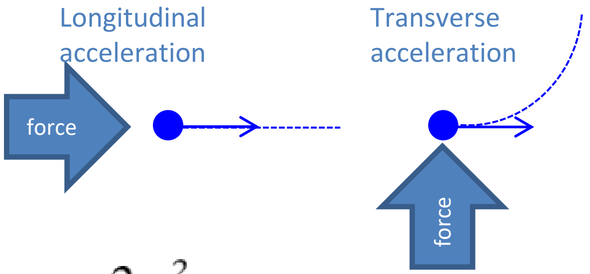
- *Very* short summary
  - Write down electric and magnetic fields of moving point charge (at relativistic speed)
  - Power radiated is given by integral of Poynting vector over closed surface around charge, let R→∞ (only 1/R terms in fields contribute)
  - Integrate …. don't be in a hurry

- Result:
  - Energy loss is negligible for longitudinal acceleration, except for extreme (unphysical) gradients
  - For transverse acceleration (as in circular colliders), energy loss could be significant - 4^{th} power dependence on energy and mass
  - Effect is much more limiting for light particles, such as electrons/positrons
    - Electrons are 2000 times lighter than protons!

$$\mathbf{B} = [\mathbf{n} \times \mathbf{E}]_{\text{ret}}$$

$$\mathbf{E}(\mathbf{x}, t) = e\left[\frac{\mathbf{n} - \boldsymbol{\beta}}{\gamma^2(1 - \boldsymbol{\beta}\cdot\mathbf{n})^3 R^2}\right]_{\text{ret}} + \frac{e}{c}\left[\frac{\mathbf{n} \times \{(\mathbf{n} - \boldsymbol{\beta}) \times \dot{\boldsymbol{\beta}}\}}{(1 - \boldsymbol{\beta}\cdot\mathbf{n})^3 R}\right]_{\text{ret}}$$

$$P(r) = \oint \mathbf{S}\cdot d\mathbf{a} = \frac{1}{\mu_0}\oint (\mathbf{E} \times \mathbf{B})\cdot d\mathbf{a}$$



$$P = \frac{2}{3}\frac{e^2 c}{\rho^2}\beta^4\gamma^4$$ … meaning… $$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Radiation damping

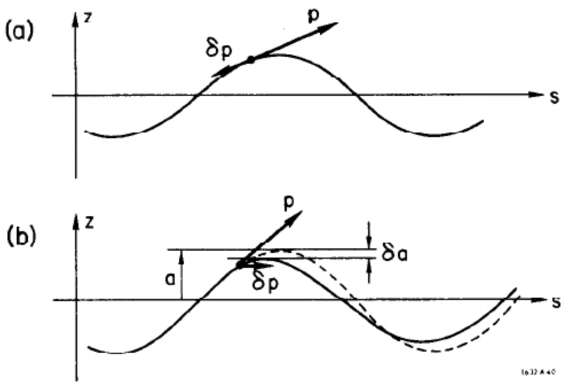
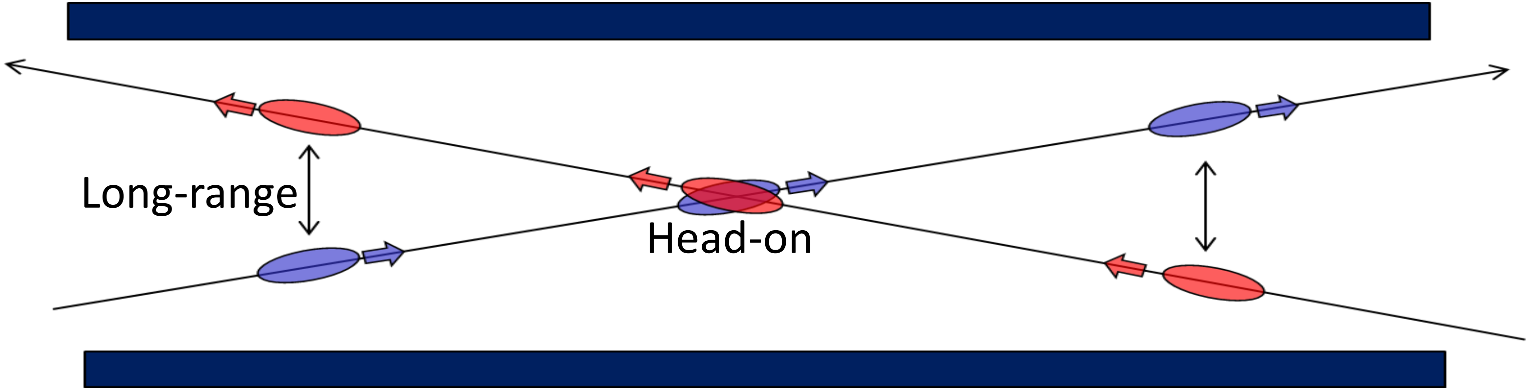


FIG. 40--Effect of an energy change on the vertical betatron oscillations: (a) for radiation loss, (b) for rf acceleration.

M. Sands, [SLAC-121 UC-28]

- Emitted photons along betatron trajectory – (almost) no change in angle of particle
- Energy losses compensated by RF, giving purely longitudinal momentum kick
  - Increases longitudinal momentum and not transverse => decrease in angle
  - Smaller betatron amplitudes => smaller emittance, "radiation damping"
    - Remember: emittance determines phase space area occupied by beam
- On the other hand: photon emission gives small random energy (and very small angle) change => blowup, "quantum excitation"
- Equilibrium between radiation damping and quantum excitation exists: equilibrium emittance
  - Time needed for the beam to reach the equilibrium emittance: "Damping time"
  - Equilibrium emittance is typically smaller in vertical than horizontal plane => "flat" lepton beams

Geometric reduction factor



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

$$\frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2}\right)^2}}$$

- Bunches must collide with an angle, "crossing angle" – otherwise we get unwanted collisions outside interaction point
  - Crossing angle need to be large enough so that bunches are not perturbed by electromagnetic field at parasitic encounters (long-range beam-beam effect)

- Fewer collisions when overlap is not perfect – geometric reduction factor
  - Depends on crossing angle, bunch length, and transverse size

ILC main parameters

From ILC design report

			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_y^*	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ_y^*	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}$ $cm^{-2}s^{-1}$	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

CLIC parameters

Parameter	Symbol [unit]	ILC 250	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	250	380	3000
Luminosity	L [$10^{34}cm^{-2}s^{-1}$]	1.35	1.5	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	1	0.9	2
Gradient	G [MV/m]	31.5	72	100
Particles per bunch	N [10^9]	20	5.2	3.72
Bunch length	σ_z [μm]	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	516/7.7	149/2.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	35	30	20*
Bunches per pulse	n_b	1312	352	312
Bunch distance	Δz [mm]	554	0.5	0.5
Repetition rate	f_r [Hz]	5	50	50

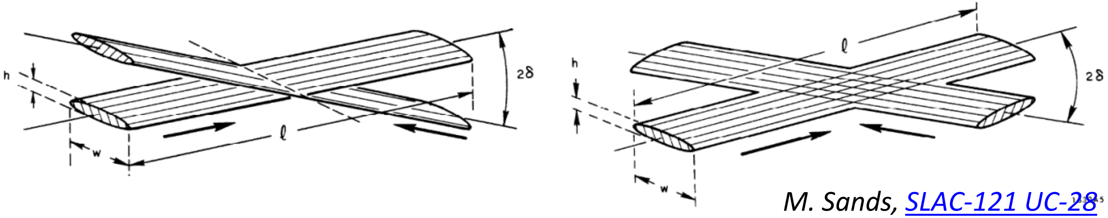
D. Schulte

Flat beams in lepton colliders

- Naturally smaller vertical beam size from radiation damping
  - Often true also for linear colliders due to horizontal bending in damping rings, transfer lines etc.

- Beam-beam effect
  - Focusing of e+e- beams due to each others' fields => higher luminosity
  - Bending of particles => synchrotron radiation, "beamstrahlung" => unwanted energy spread in collisions

- To avoid energy spread and keep luminosity high: collide "flat" beams, with much smaller beam size in one plane



M. Sands, SLAC-121 UC-28

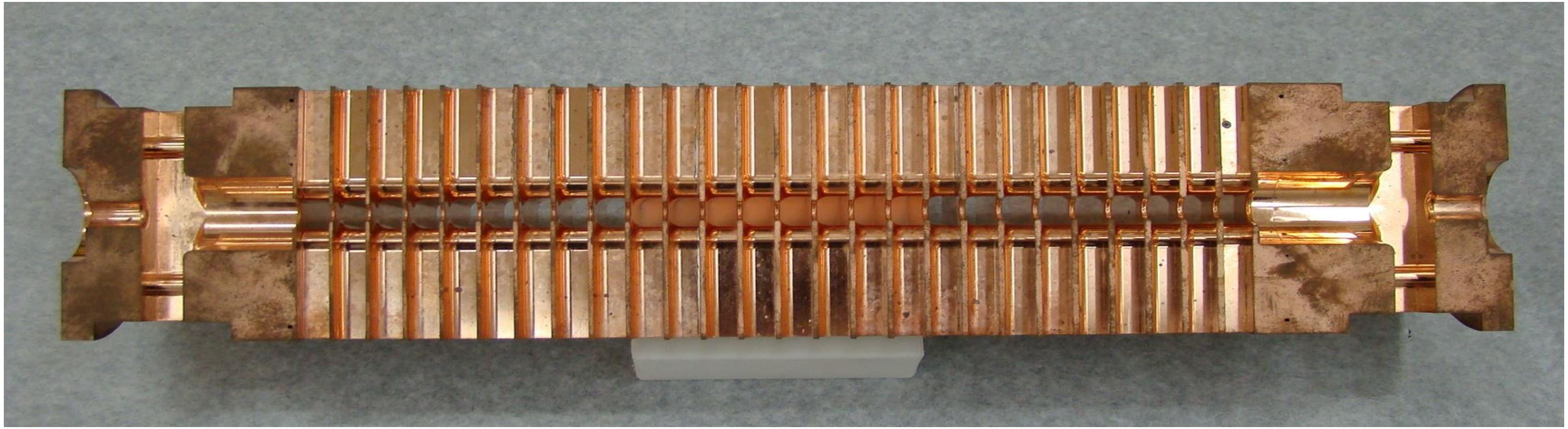
Luminosity depends on product of beam sizes: $$L \propto \frac{N^2}{\sigma_x^* \sigma_y^*}$$

average number of photons per collision depends on sum of beam sizes:

$$n_\gamma \approx \frac{12}{\pi^{3/2}} \frac{\alpha r_e N_b}{\sigma_x^* + \sigma_y^*} \approx \frac{12}{\pi^{3/2}} \frac{\alpha r_e N_b}{\sigma_x^*}$$

M.A. Valdivia García et al., doi:10.18429/JACoW-IPAC2019-MOPMP035

CLIC cavities



D. Schulte

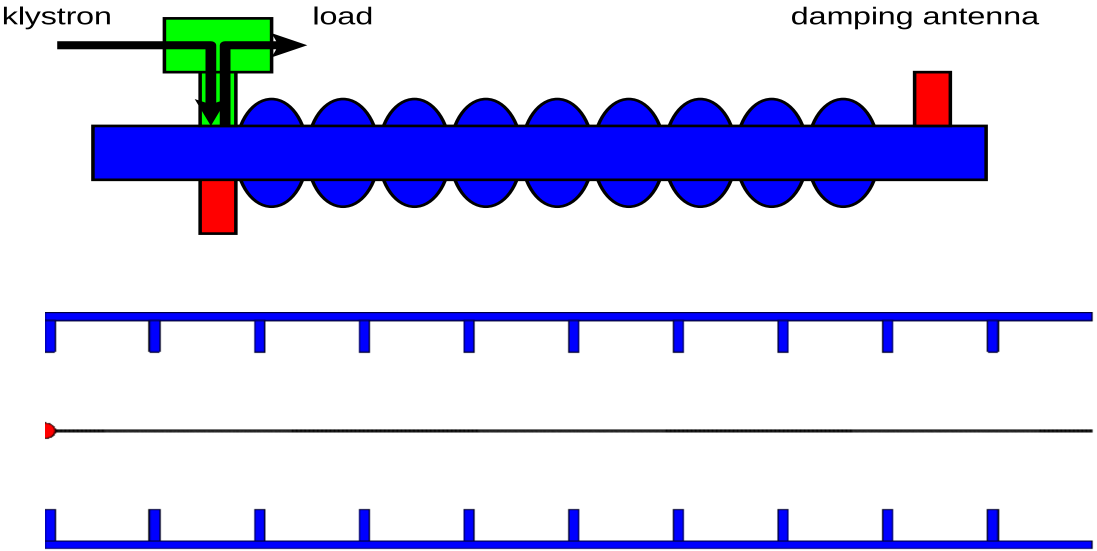
- To reach 100 MV/m: different type of cavity from ILC
- 12 GHz, 23 cm long, normal conducting
  - ⇒ Much worse conductor than SC, but allows reaching higher fields
  - ⇒ Problem: power is very rapidly lost in the walls
  - ⇒ Need to put in very intense and short RF pulses timed to the passage of the beam

Power flow
- 1/3 lost in cavity walls
- 1/3 in filling the structure and into load
- 1/3 into the beam

Average RF power about 3 kW/m
About 1 kW/m into beam

ILC Cavities

- Superconducting cavity (Ni at 2 K)
- RF frequency is 1.3 GHz, 23 cm wavelength
- Length is 9 cells = 4.5 wavelengths = 1 m



D. Schulte

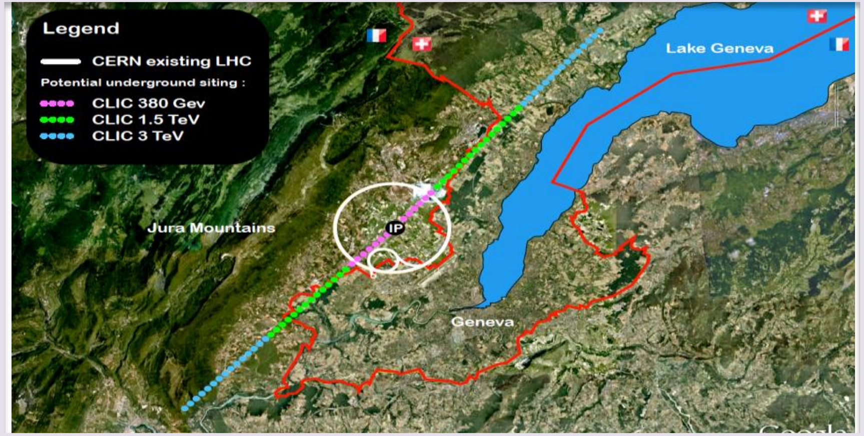
- Standing wave structure, achieving gradients of 31.5 MV/m
- Theoretical field limit around 50-60 MV/m
  - In reality, reaching about 30-40 MV/m with imperfections
- Need about 8000 cavities

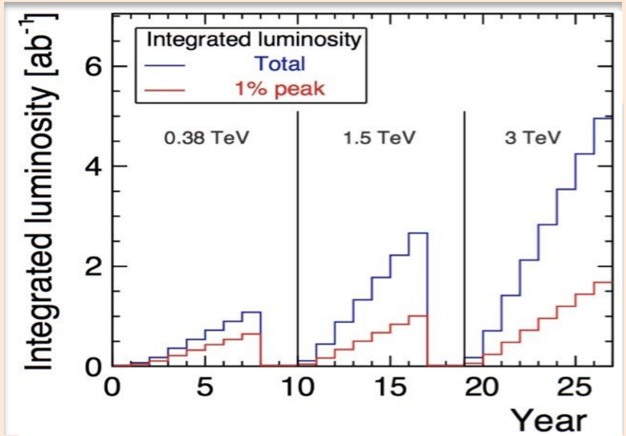
CLIC Staged Scenario

3 stages foreseen:

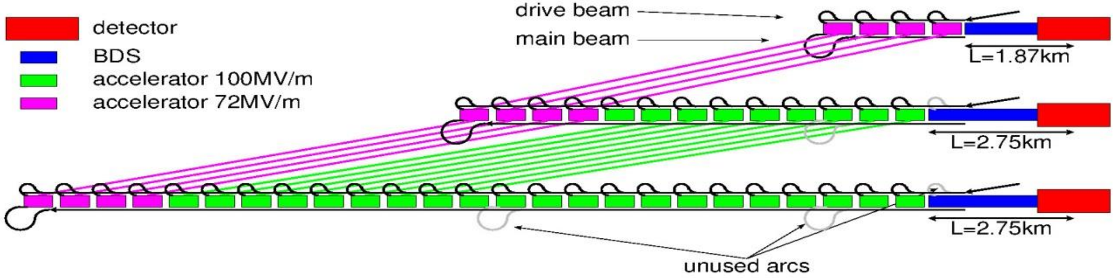
Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

Central complex on Prevessin site



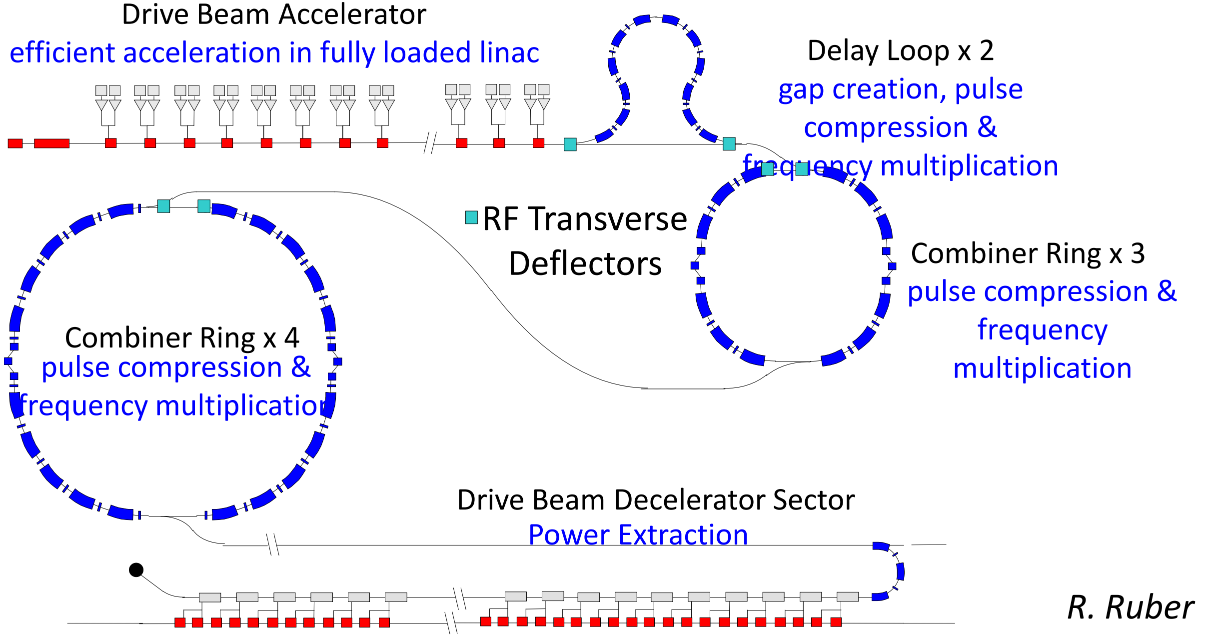


Luminosity evolution



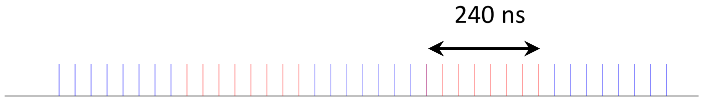
Drive beam acceleration

- To produce very rapid pulses: use two-beam acceleration scheme
- A very long beam pulse at 4A, 140 us produced in LINAC
- Use combiner rings to decrease bunch spacing of drive beam => produce very short and intense 100 A pulse
- Send to decelerating structure



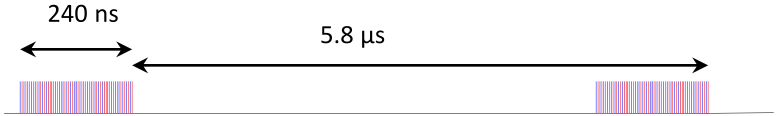
R. Ruber

Drive beam time structure - initial



140 µs train length - 24 x 24 sub-pulses - 4.2 A
2.4 GeV - 60 cm between bunches

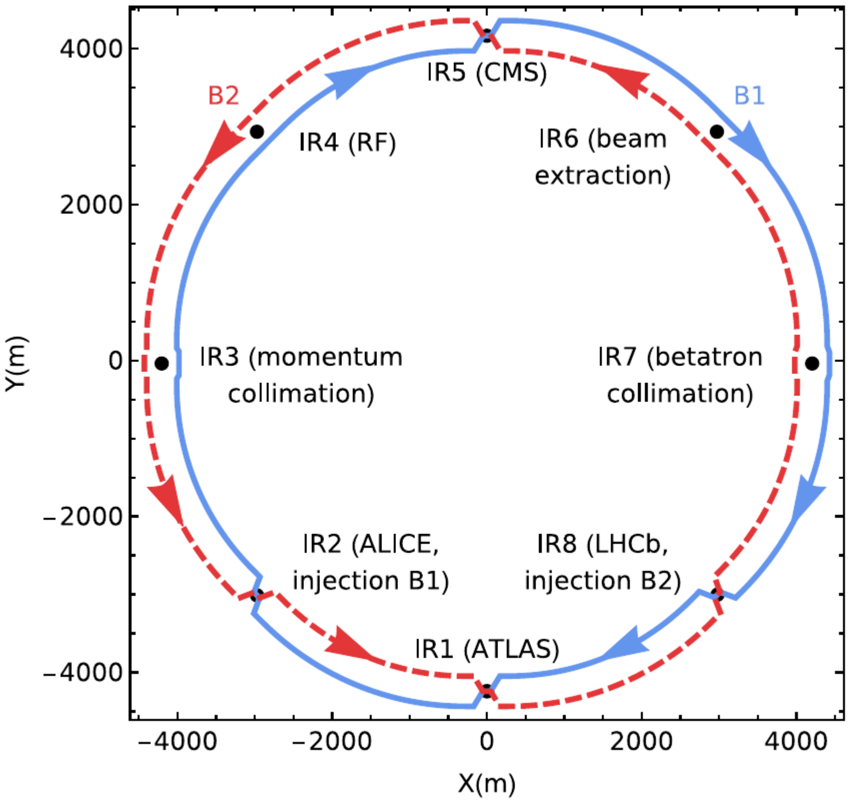
Drive beam time structure - final



24 pulses – 100 A – 2.5 cm between bunches

LHC layout

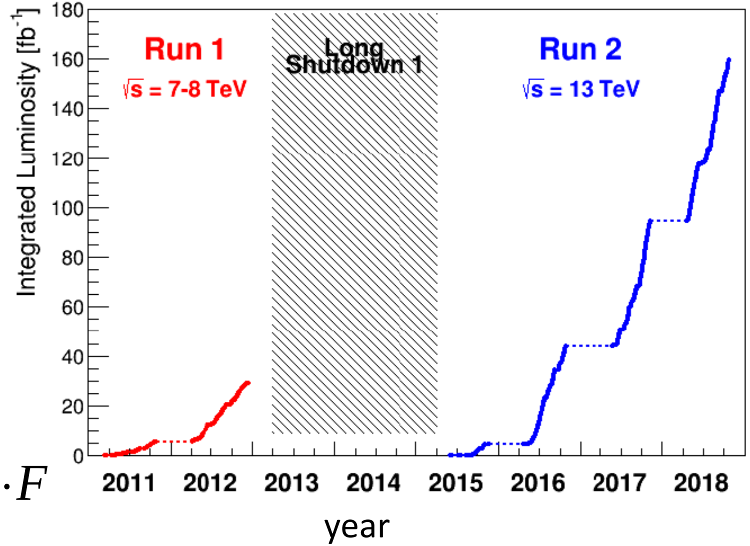
- 8 bent sections, arcs, and 8 straight sections, “insertion regions (IRs)”
- 4 experiments where beams collide (ATLAS – IR1, ALICE – IR2, CMS – IR5, LHCb – IR8)
- 2 IRs for beam cleaning (collimation), one for RF, one for beam extraction



LHC main parameters

Parameter	2018	Design
Energy [TeV]	**6.5**	7.0
No. of bunches	**2556**	2808
p/bunch (typical value) [10^{11}]	**1.1**	1.15
Max. stored energy per beam (MJ)	**312**	362
β* [cm]	**30→25**	55
Typical normalized **emittance** [μm]	**~1.8**	3.75
Peak **luminosity** [10^{34} cm^{-2}s^{-1}]	**2.1**	1.0

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

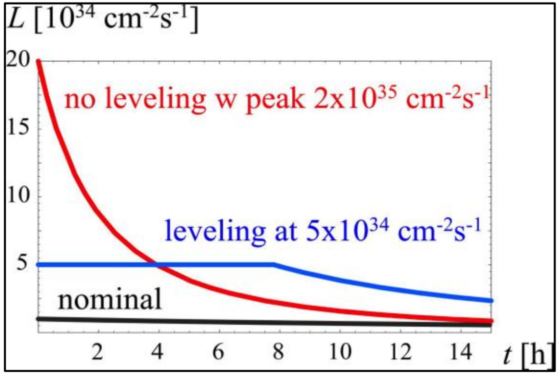


- Design luminosity of 1×10^{34} cm^{-2}s^{-1} surpassed by more than a factor 2

- Collected in total about 190 fb^{-1} of integrated luminosity at the high-luminosity experiments (ATLAS, CMS)

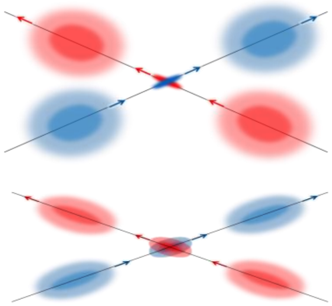
Luminosity leveling

- Experiments can only cope with a certain maximum event rate before saturating
- In 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



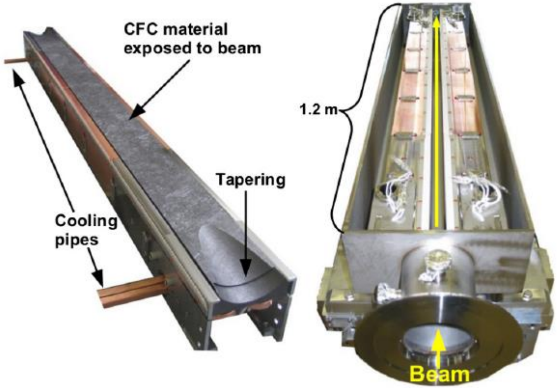
Collimation and machine protection

- 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

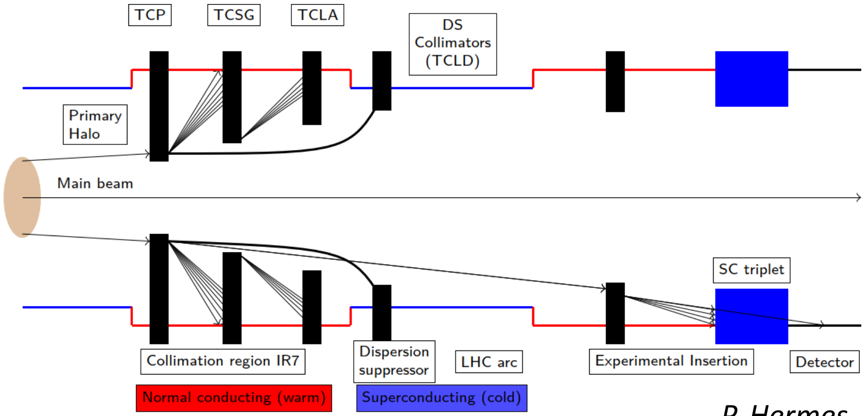
680 MJ =
Total energy in one HL-LHC beam =
kinetic energy of TGV train at 215 km/h



FCC-hh 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: must safely handle beam loss power of 11.6 MW
  - For beam lifetime of 12-minute during ~10 s from instabilities, operational mistakes, orbit jitters….
  - Collimators must digest these losses without breaking, while protecting the superconducting magnets

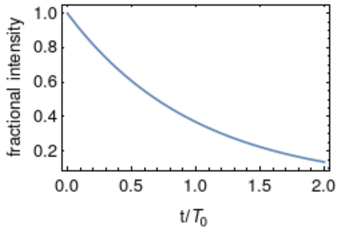
Deploying multi-stage collimation system inspired by LHC



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)

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

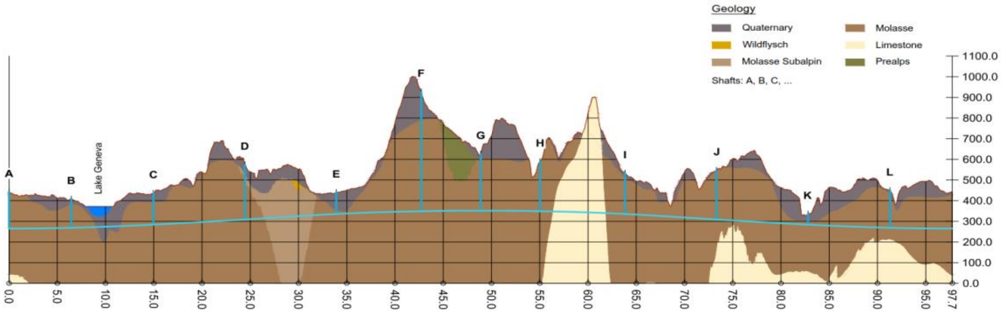


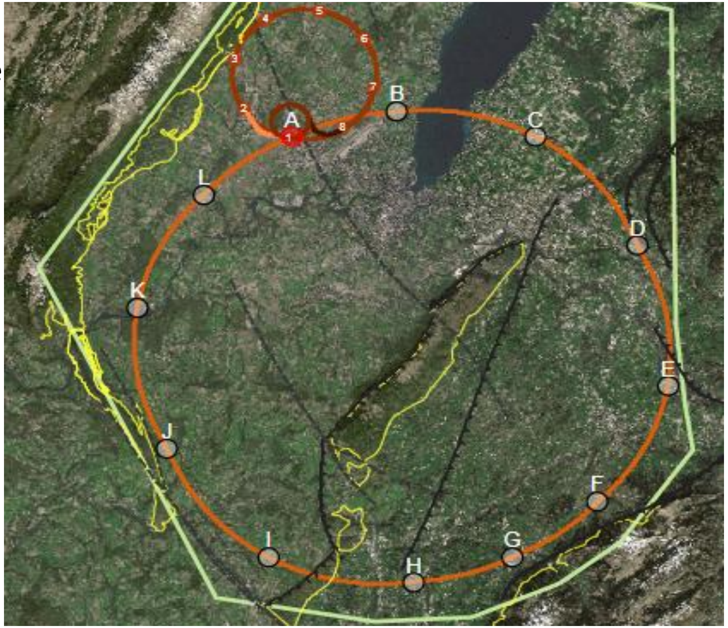
Beam lifetime:

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 structure
  - Total length is 97.75 km, 83 km for arcs
  - 12 surface sites with few ha area each





FCC-hh parameter comparison

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

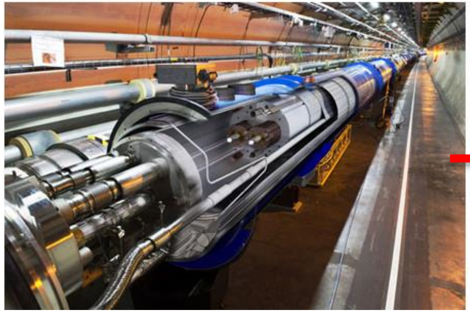
$$\frac{p}{q} = B\,\rho$$

$B\,\rho$ = Beam rigidity

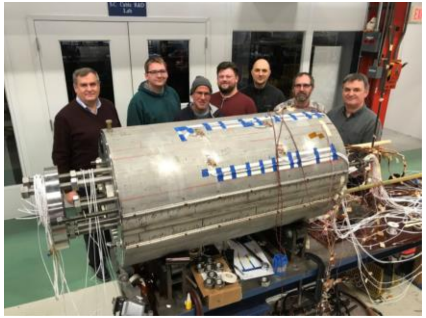
Road to 16 T magnets

- 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



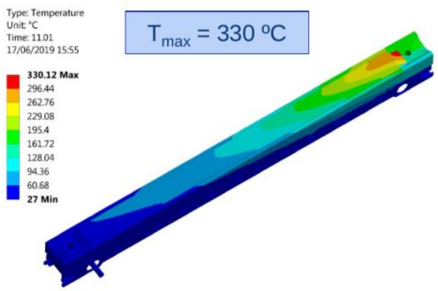
via
HL-LHC technology

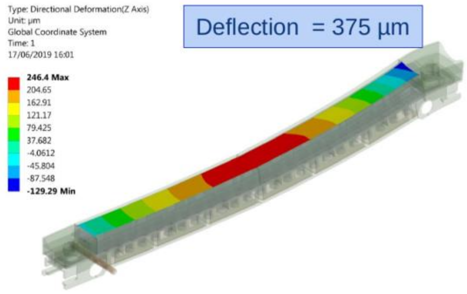


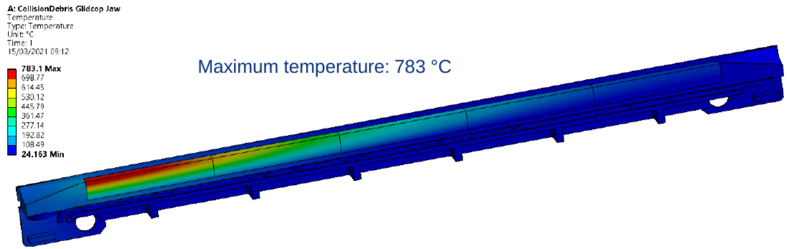
FNAL demonstrator
14.5 T Nb_3Sn

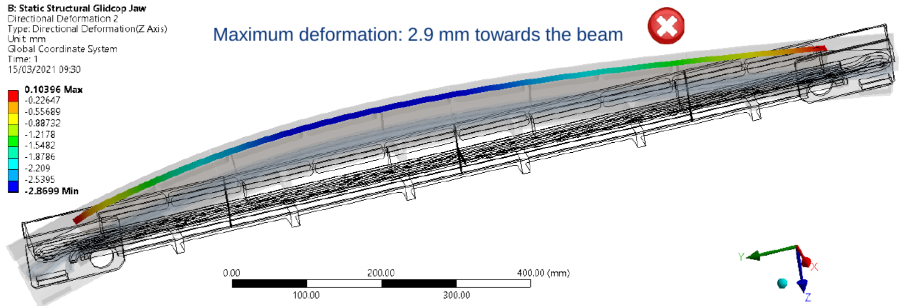
Robustness studies

- 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



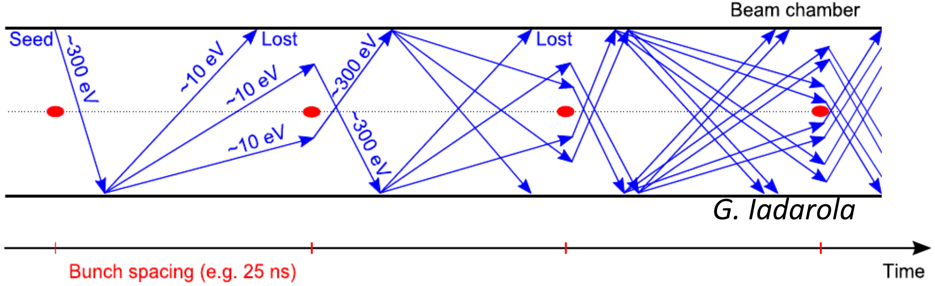


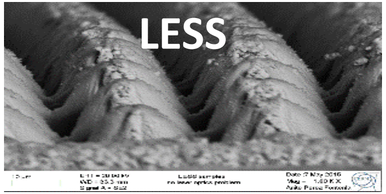


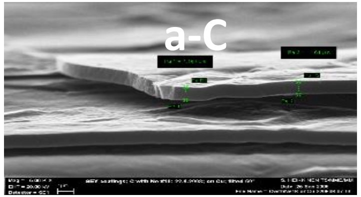


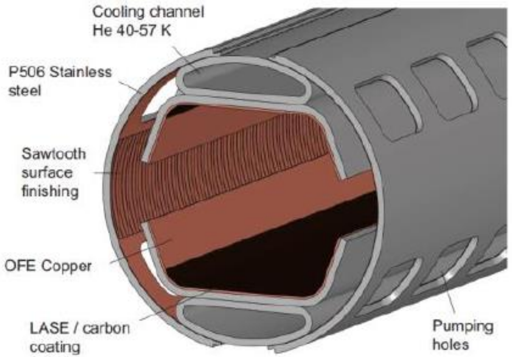
Electron cloud effects

- 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 baseline parameters

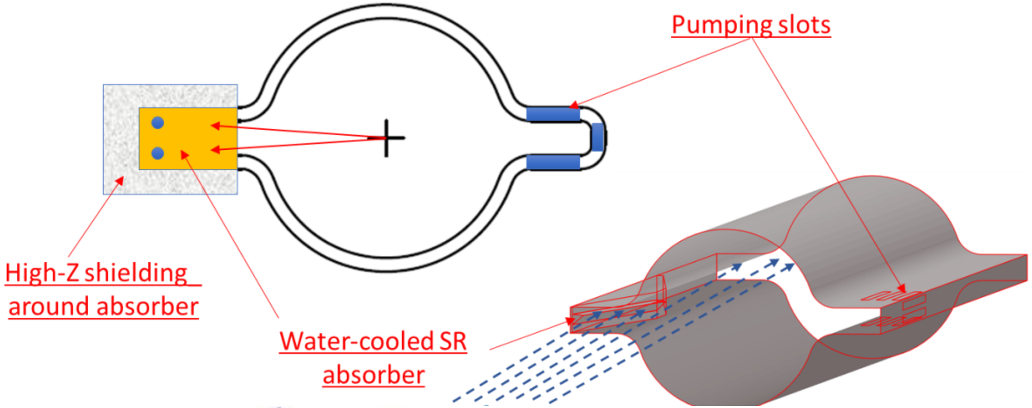


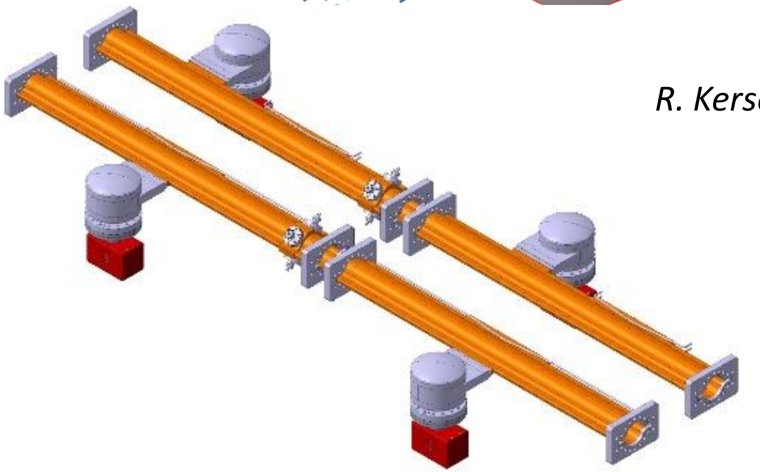

F. Zimmermann. M. Benedikt

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
Synchrotron radiation energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad. Bhabha / Beamstrahlung [min]	68 / >200	49 / >1000	38 / 18	40 / 18

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





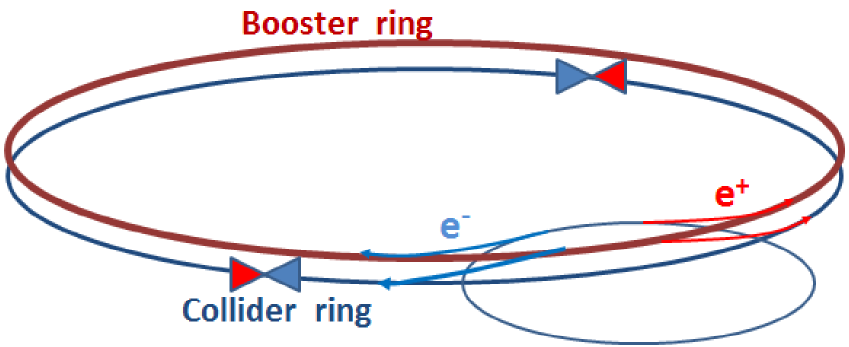
R. Kersevan

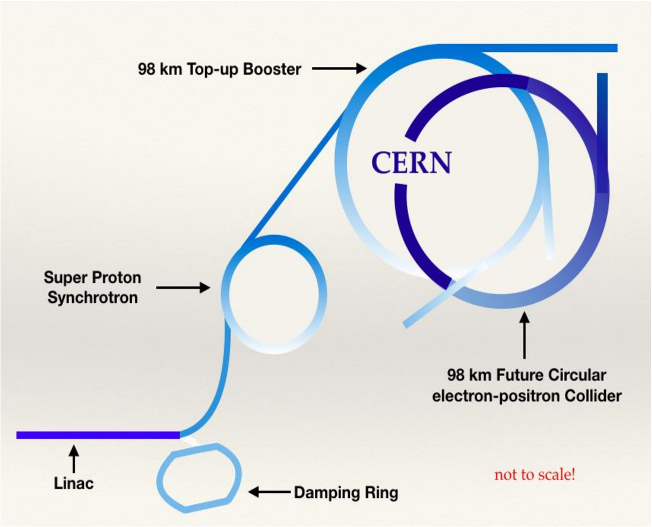
Top-up injection

- 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

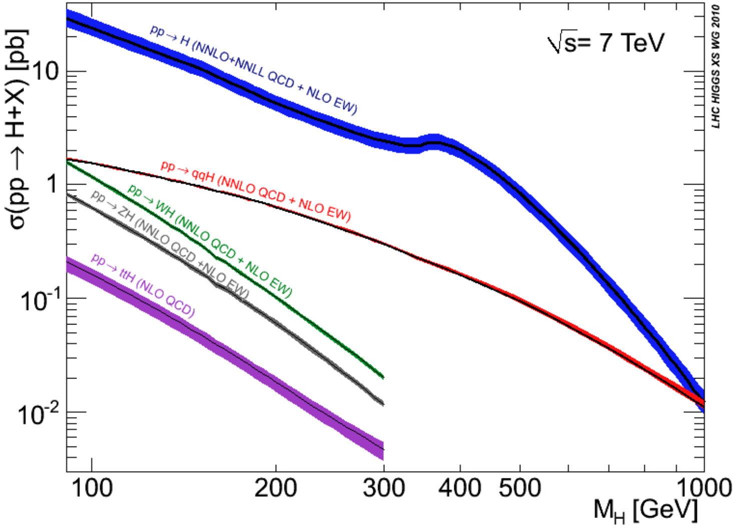
- Very short beam lifetime => use "top-up injection"
  - Inject beams at collision energy, while colliding
    - Compare hadron machines: inject at low energy, then accelerate to top energy, then put beams in collision
  - Requires a booster ring – to be built in the same tunnel

- Injector chain: source, LINAC(s), positron target, damping ring, pre-booster, booster



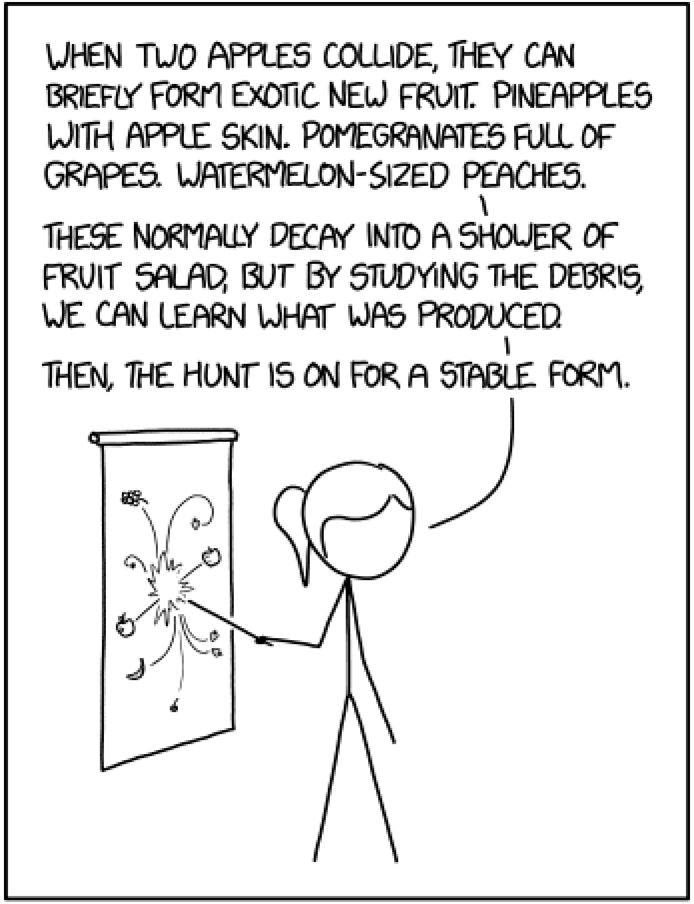


Higgs cross section:



$$\sigma_{react} \approx 1\,pb$$

Coffee break – some fruit?



HOW NEW TYPES OF FRUIT ARE DEVELOPED

Source: https://xkcd.com/1949/