

Particle Accelerators

KSETA topical course — 20 & 21 October 2025
Bastian Härer & Matthias Fuchs (IBPT)



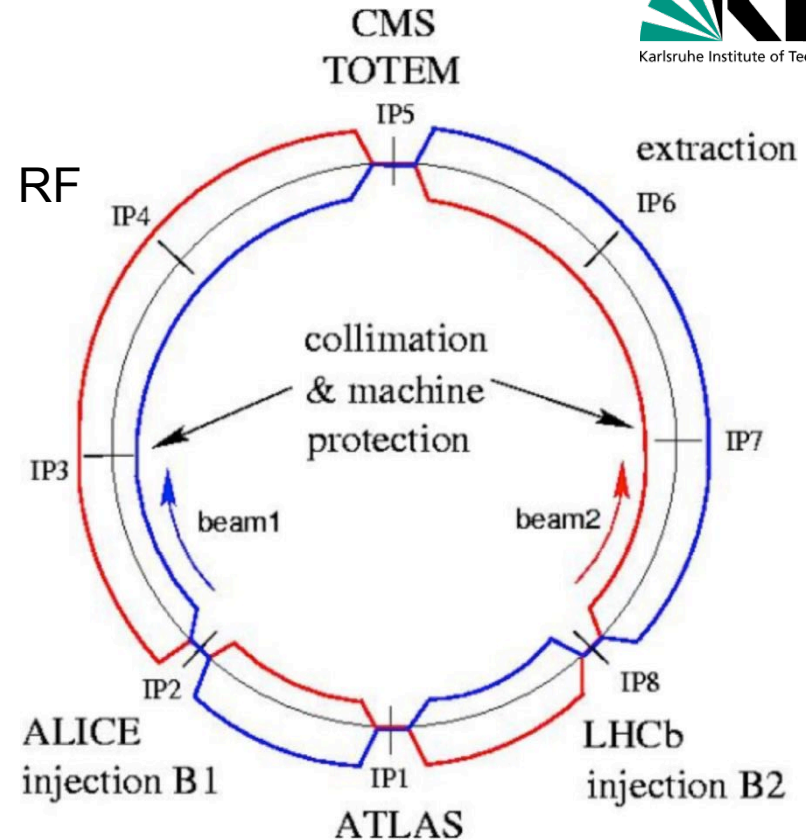
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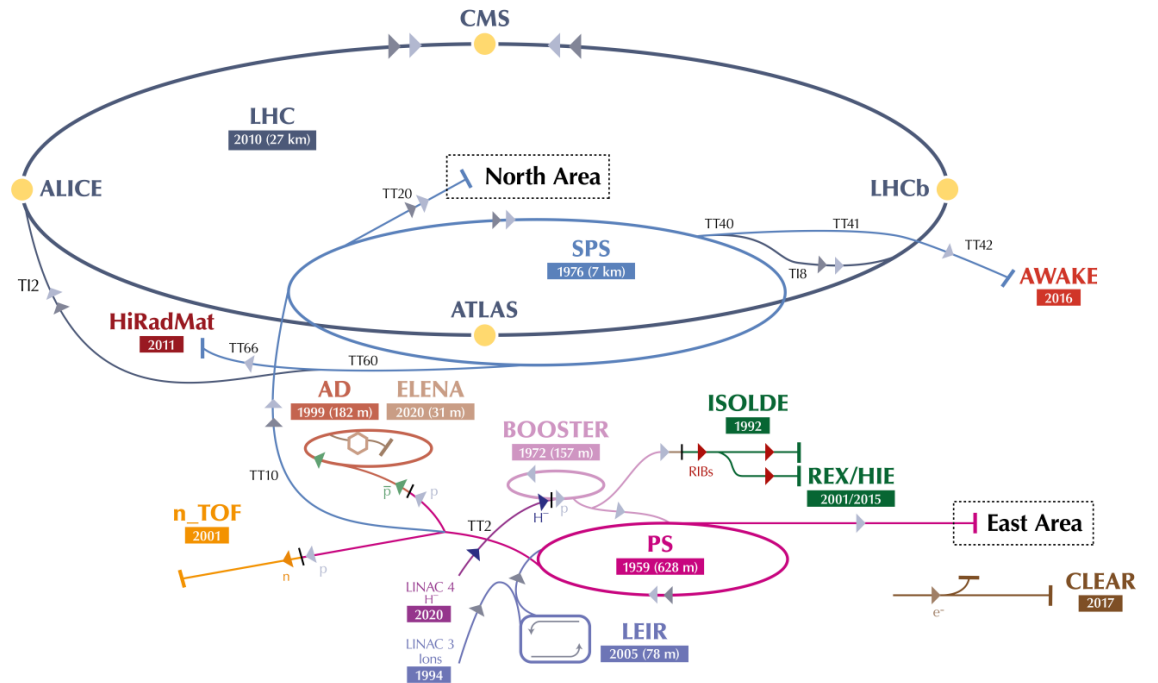
The Large Hadron Collider

- Superconducting RF
- SC magnets (8.33 T at 1.9 K)
- FODO lattice
- 1232 15 m long dipoles
- “Two-in-one” magnets
- Field quality, resonances, ...
- Protons emitting synchrotron radiation
- 2808 bunches à 10^{11} protons
- Luminosity $\approx 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Beam energy: 0.45 - 7 TeV



The CERN accelerator complex

Complexe des accélérateurs du CERN

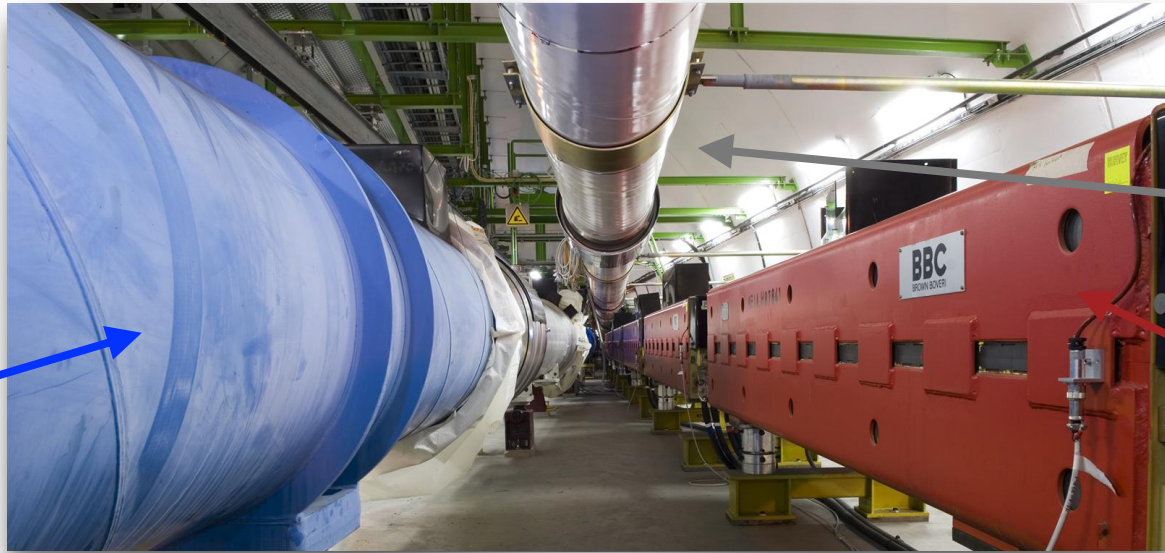


Linac 4:	160 MeV
Booster:	1.4 GeV
PS:	25 GeV
SPS:	450 GeV
LHC:	7 TeV

▶ H^- (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ $\bar{p}$ (antiprotons) ▶ e^- (electrons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKEfield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive Experiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

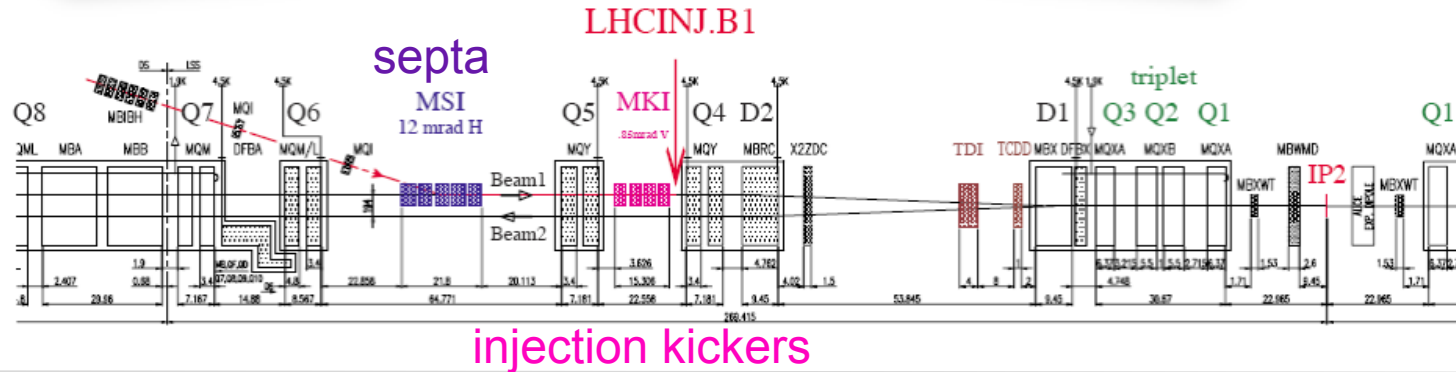
Reference: CERN Document Server,
<https://cds.cern.ch/record/2813716>



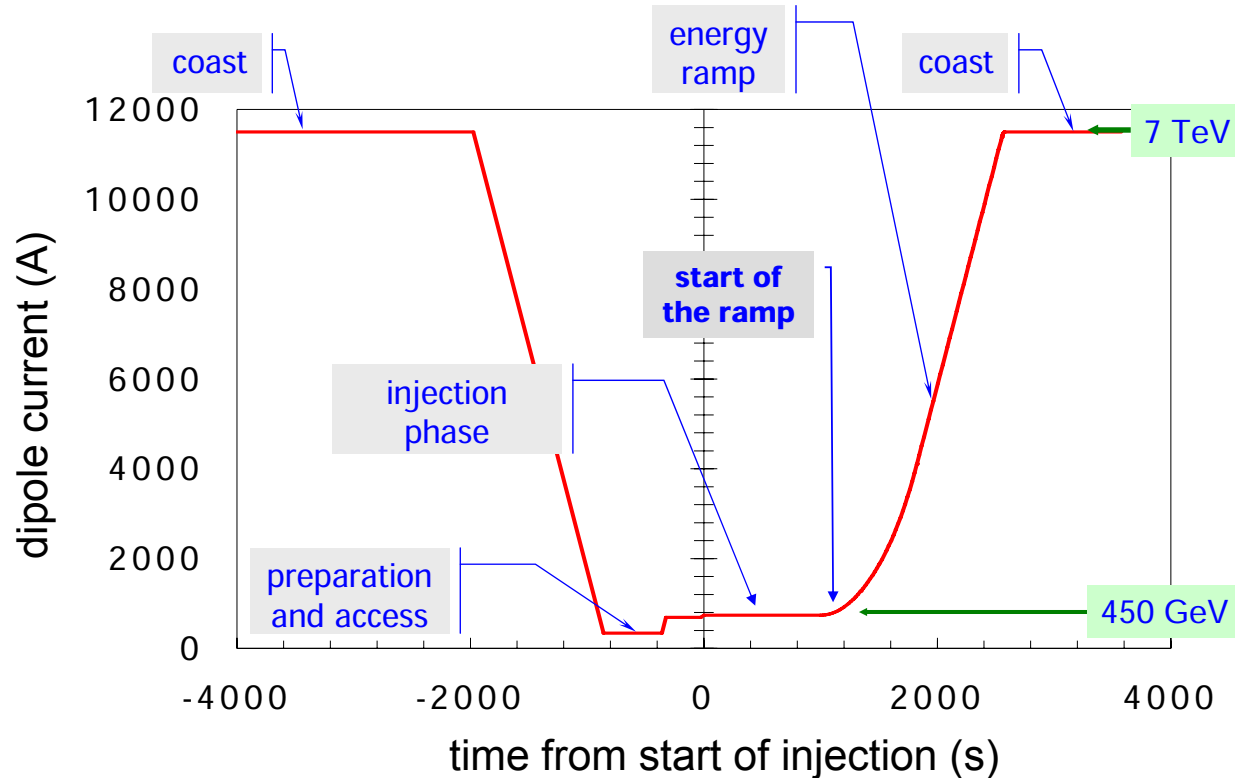
LHC

helium transport line

transfer line
(normal conducting)

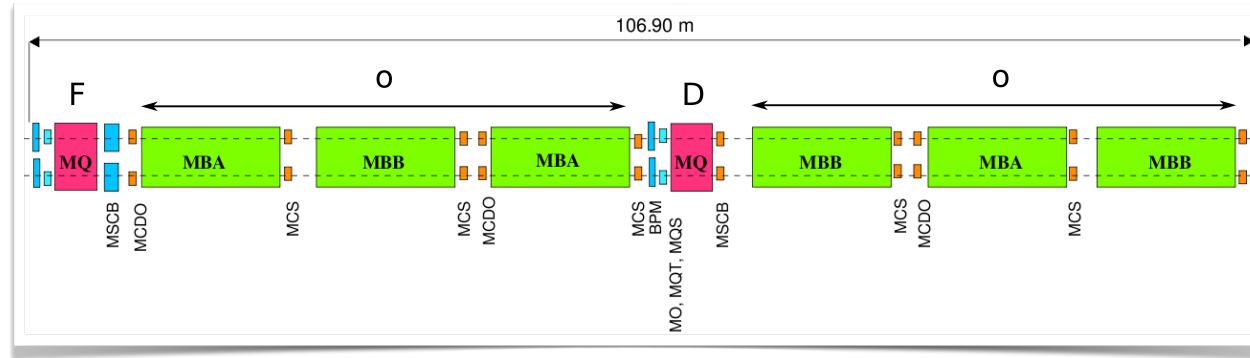


Standard operation



L. Bottura, CERN

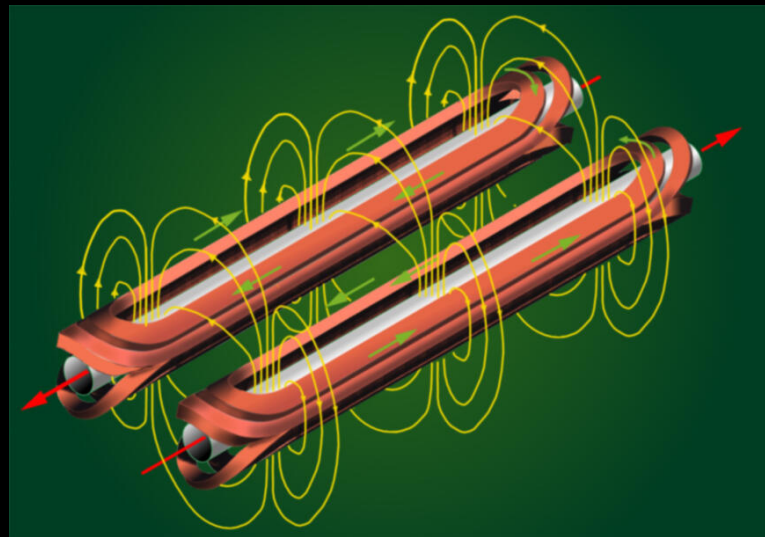
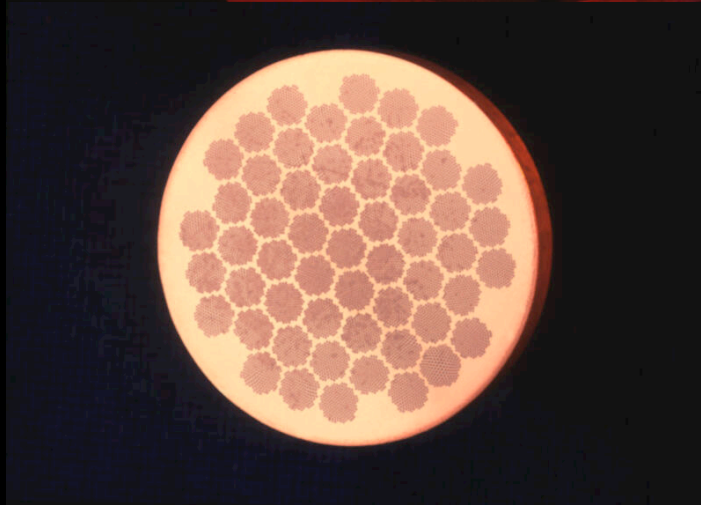
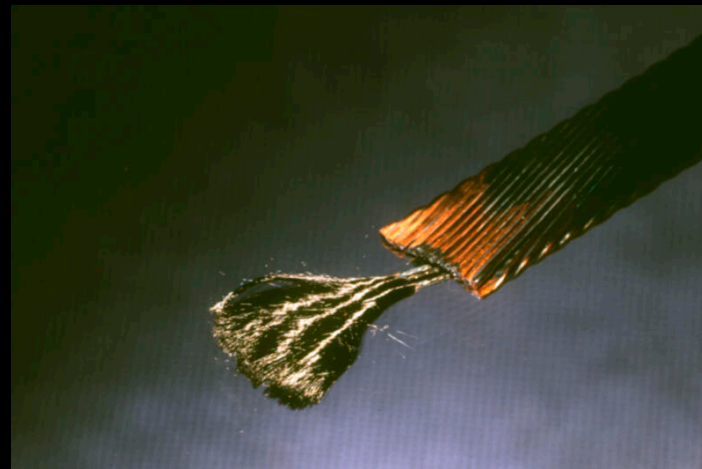
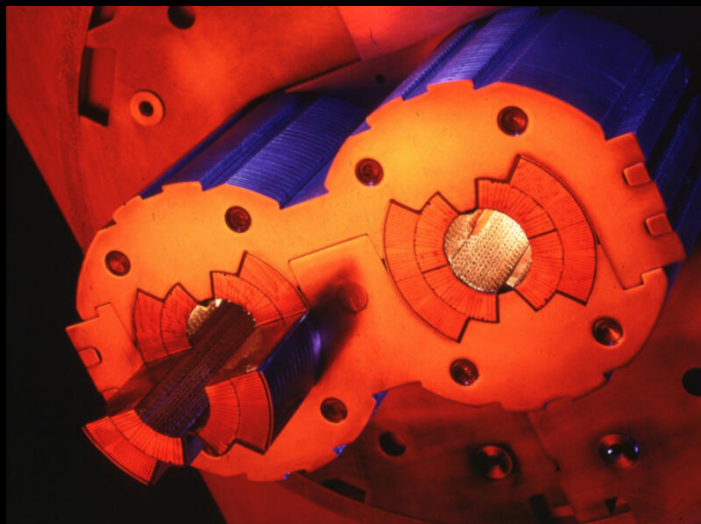
The LHC lattice



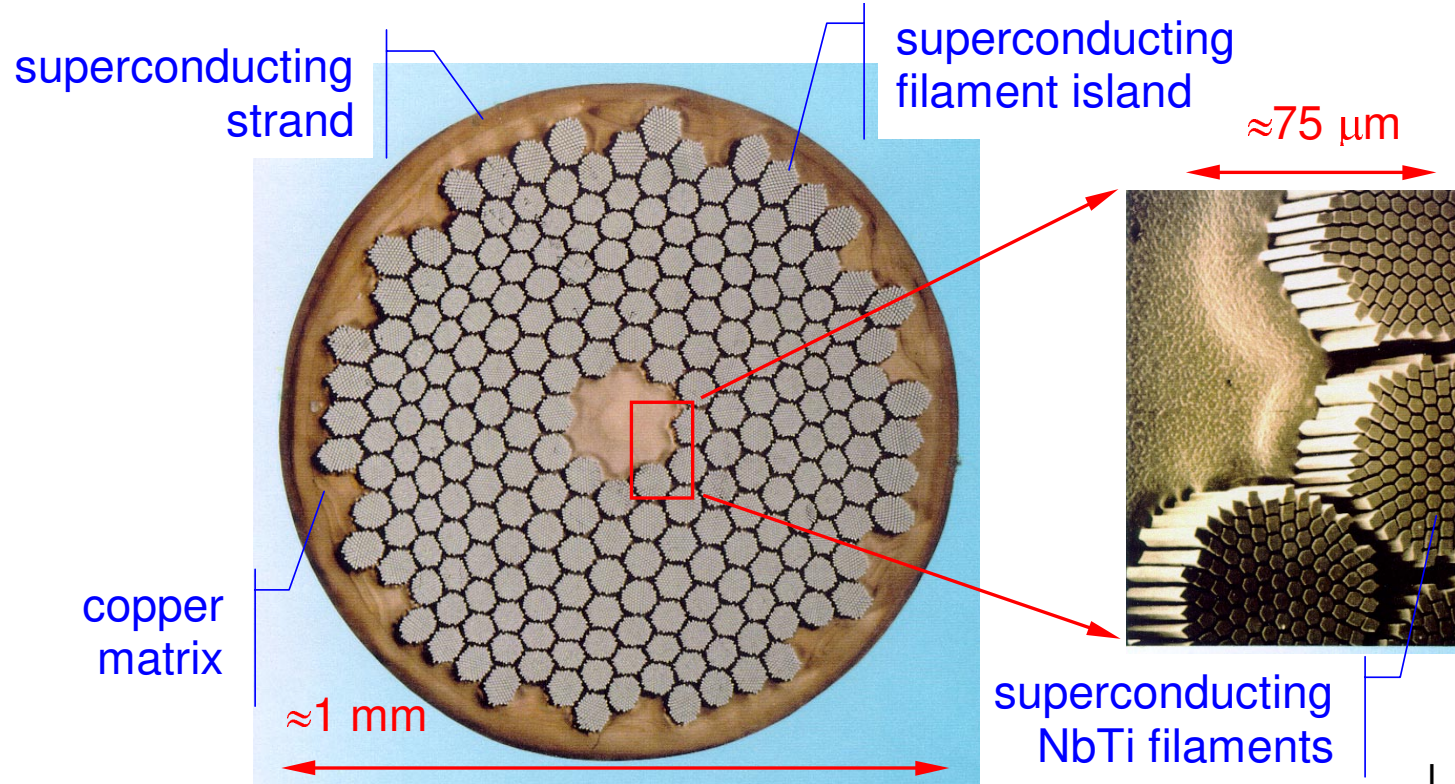
- For highest beam energies $\oint B ds$ must be maximized.
- Because of technical limitations of the magnetic field of the dipoles (quenches), the field must be distributed $\rightarrow$ large number of dipoles, high dipole filling factor
- Adequate lattice choice: FODO structure in the arc sections
- 23 FODO cells per arc (107 m length)
- Since the dipoles are very long (14.3 m), the magnets must be curved (about 2 cm sagitta)

The LHC under construction





Superconductor filaments

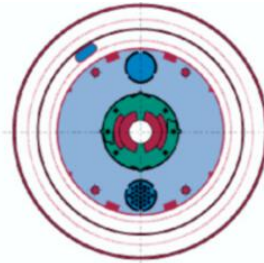


L. Bottura (CERN)

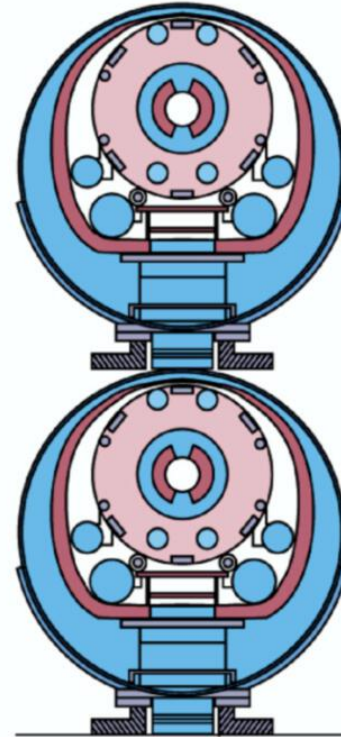
SC magnets in comparison



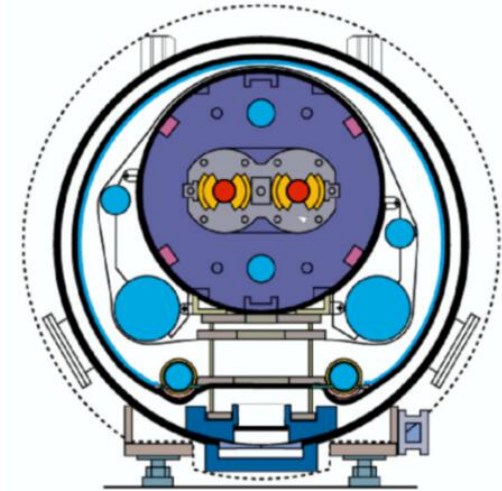
TEVATRON
 $B = 4 \text{ T}$
Bore : 76 mm



HERA
 $B = 4.5 - 6 \text{ T}$
BORE : 75 mm



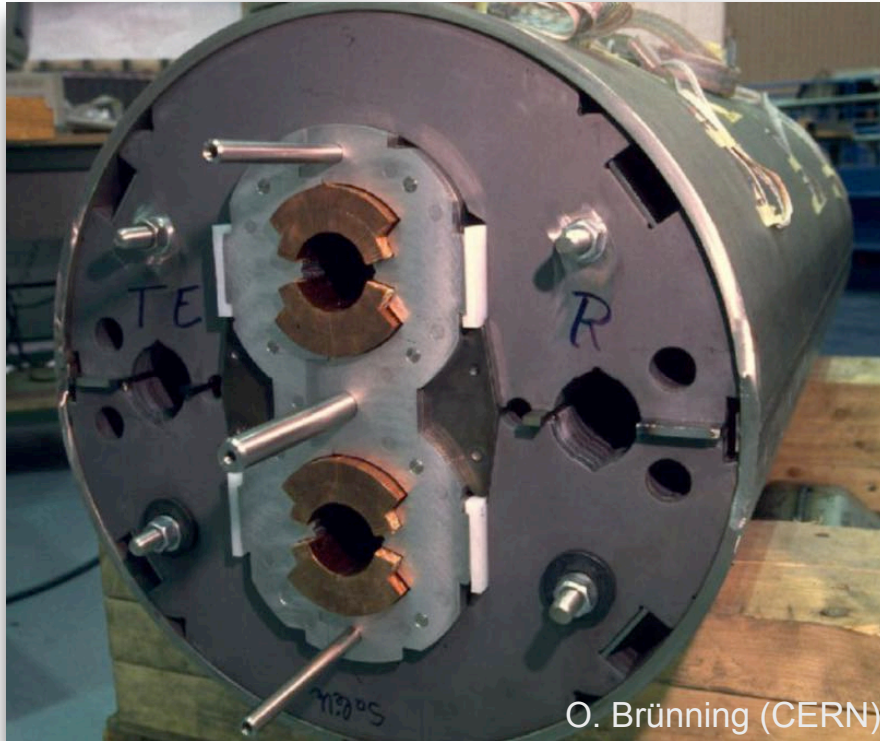
SSC
 $B = 6.6 \text{ T}$
Bore : 50 mm



LHC
 $B = 8.65 \text{ T}$
Bore : 56 mm

O. Brünning (CERN)

Mechanical stability



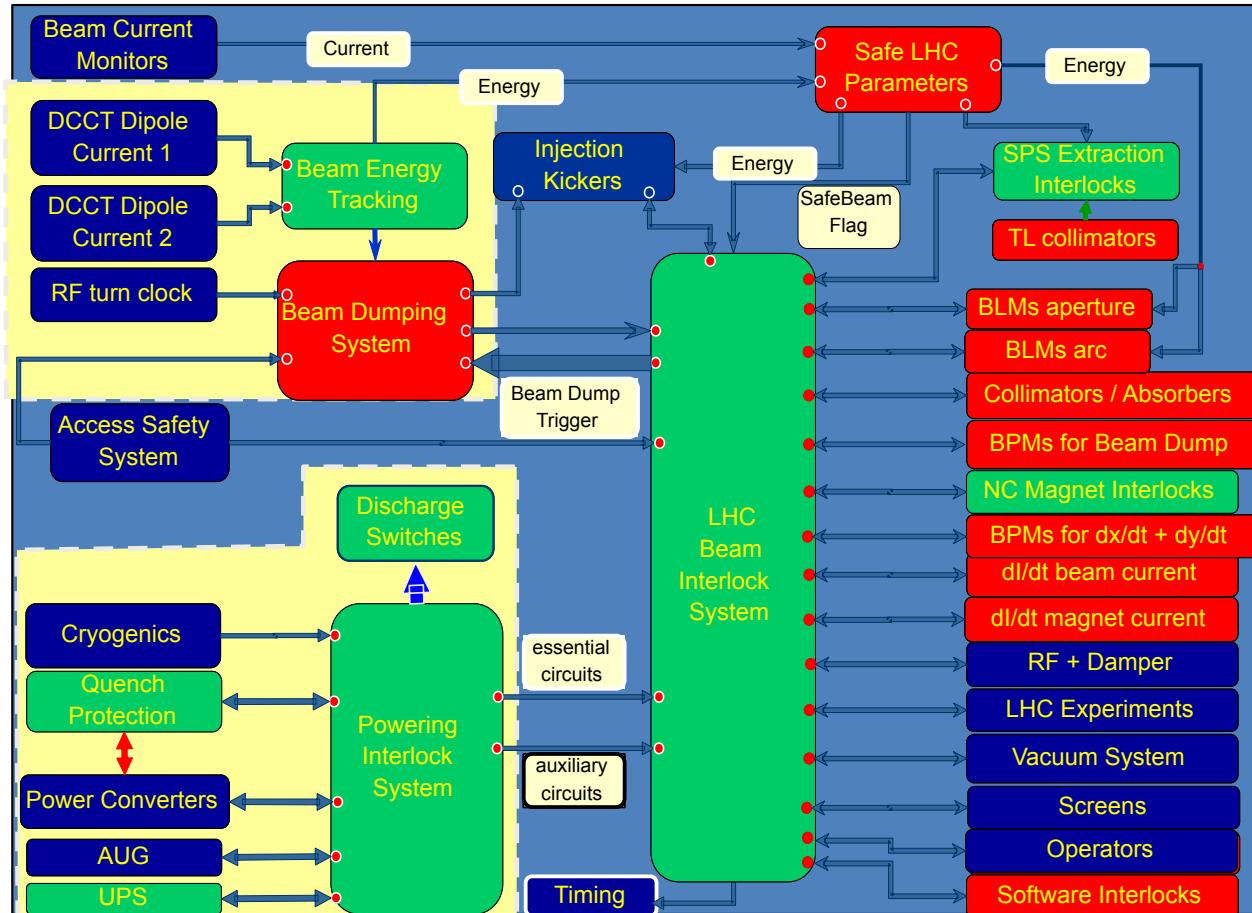
- With a field of $B = 8.4 \text{ T}$ and a current per winding of $I = 11 \text{ kA}$, a force of $F = 92400 \text{ N/m}$ acts on each of the 30 windings.
- This corresponds to 5 cars/m/winding.
- For all 30 inner windings the magnet must therefore withstand the equivalent of 150 cars/m without deforming.
- High demands on the mechanical stability of the design.

The LHC beam

	LEP2	LHC
Momentum at flat-top (TeV/c)	0.1	7
Dipole field at flat-top (T)	0.11	8.44
Luminosity ($10^{32} \text{ cm}^{-2}\text{s}^{-1}$)	1	100
Number of bunches	8	2808
Bunch population (10^{11})	4.2	1.15
Beam size (arc section)	1800/140 μm (h/v)	200-300 μm
Beam size (IP)	200/3 μm (h/v)	16 μm

- Energy in the magnet system: 10 GJ (Airbus A380 at 700 km/h)
- Energy per beam: 362 MJ (120 kg TNT or 20 kg Swiss cheese)
- In comparison: 0.7 MJ melt 1 kg copper
- Energy in the LEP2 beam: 0.03 MJ

⇒ **Active beam protection required (beamloss monitors, interlocks, & beam collimation)**

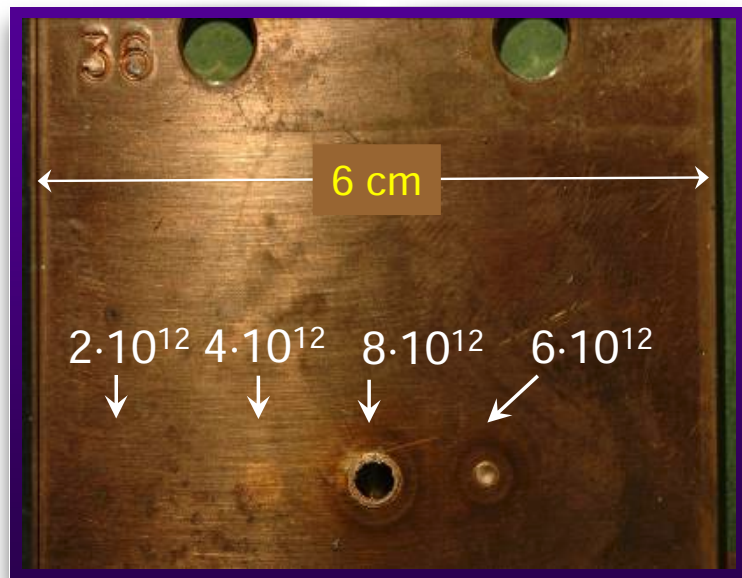


■ LHC machine protection & safety

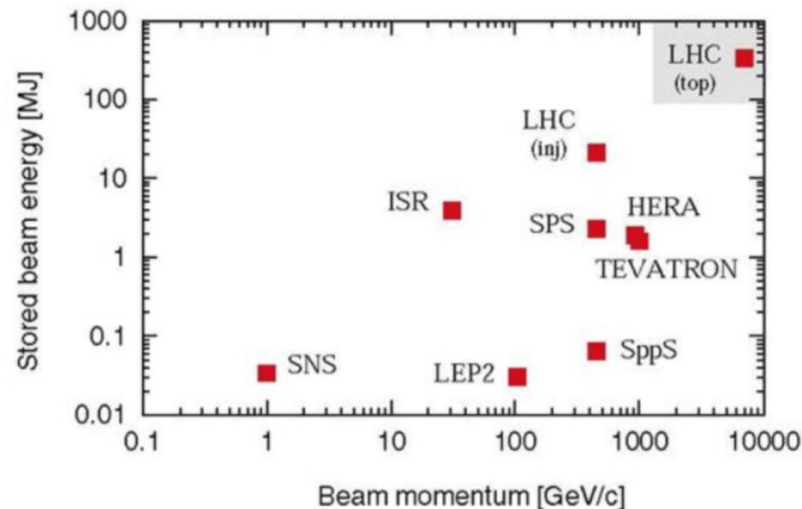
■ no comment...

Damages by the beam

- **LHC:** 100 times higher stored energy and smaller beams
→ 3 orders of magnitude higher energy density!

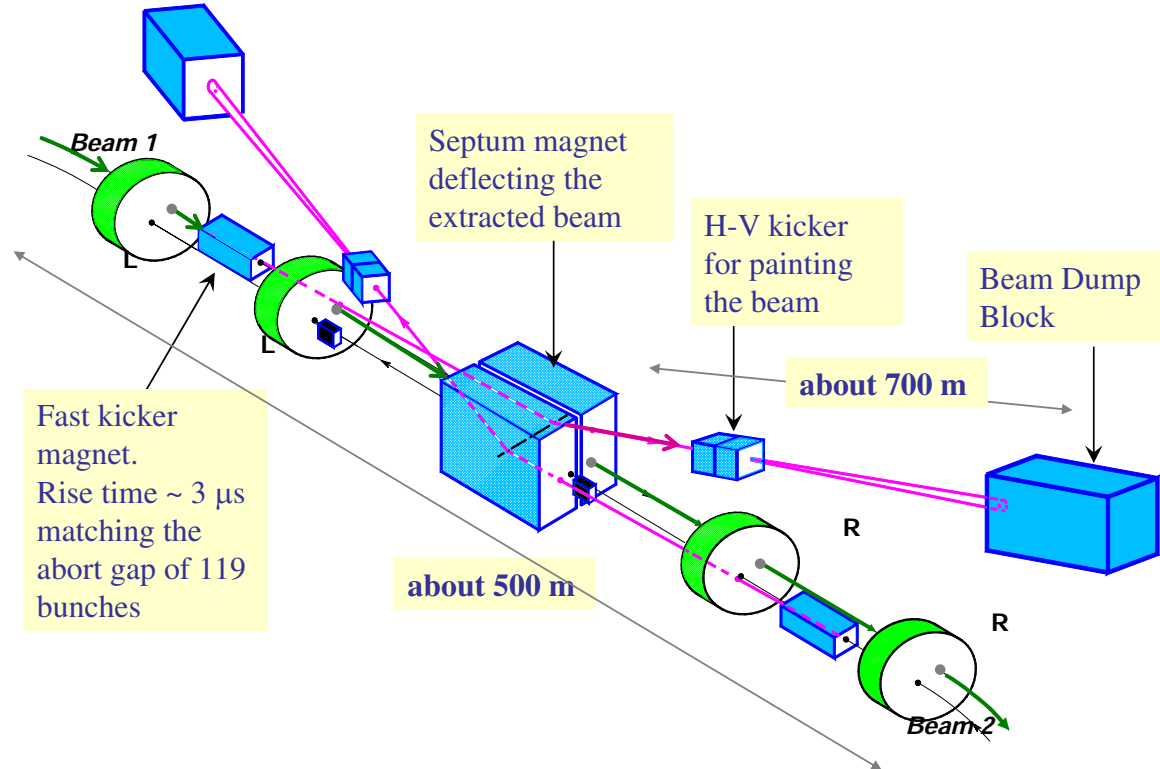


V. Kain, H. Burkhardt, CERN

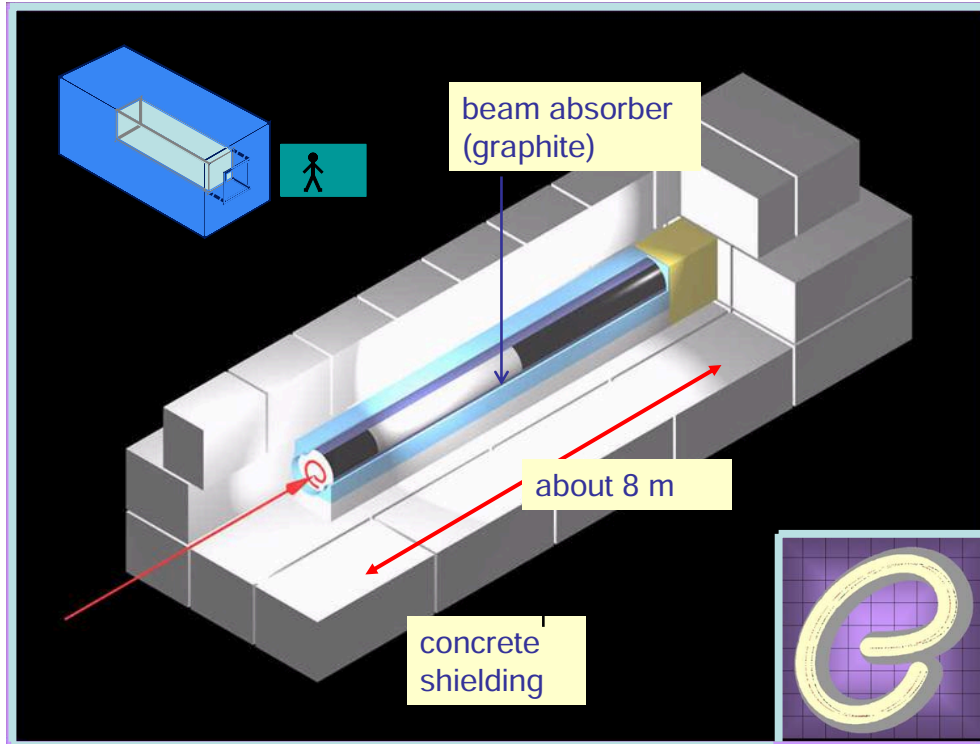


- Controlled experiment with SPS beam:
 - Beam energy: $E_0 = 450$ GeV
 - Beam size: $\sigma_{x/y} = 1.1/0.6$ mm
 - Visible damages starting from 4×10^{12} protons
 - No problem for less than 2×10^{12} protons
- **Special beam dump required!**

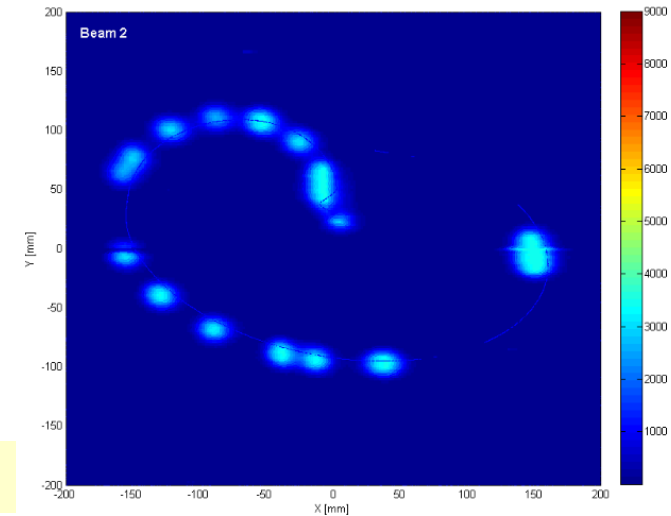
The LHC beam dump



The beam dump block



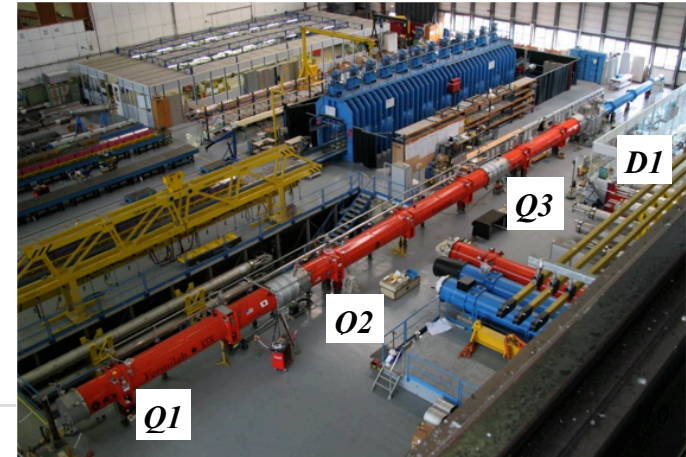
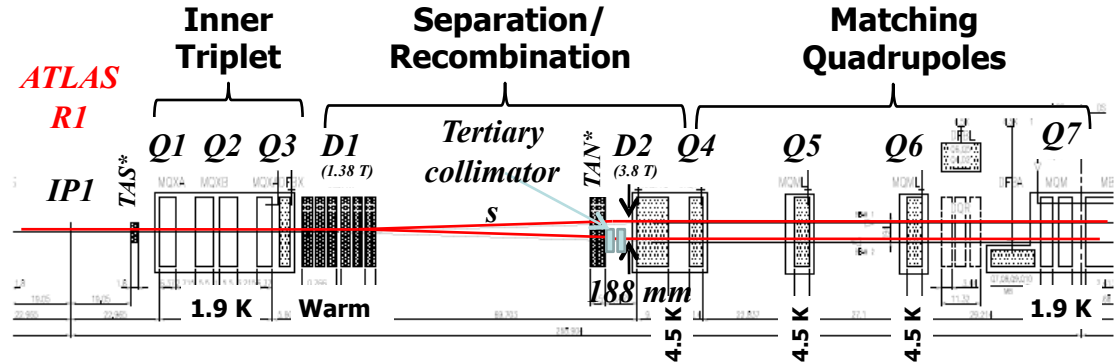
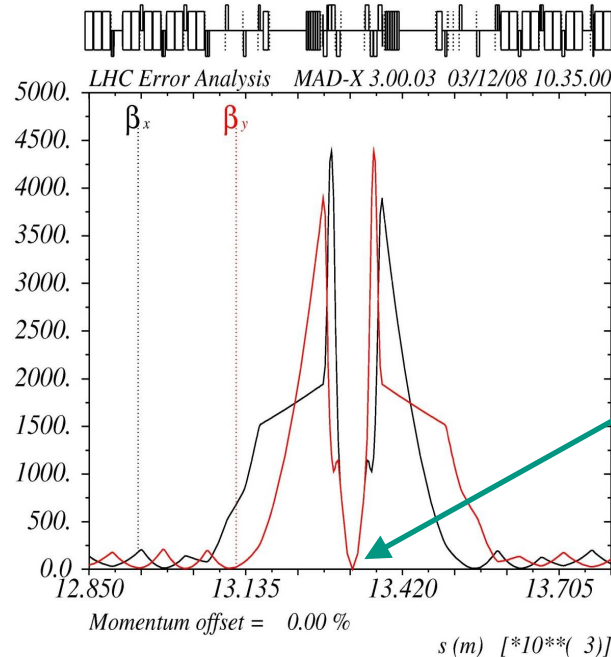
Test dump of 16 bunches



in $< 90 \mu\text{s}!!!$

The LHC interaction region

mini-beta optics



LHC Injectors Upgrade

Parameter	LHC	HL-LHC
Beam energy in collision [TeV]	7	7
Particles per bunch, N [10^{11}]	1.15	2.2
Number of bunches per beam, n_b	2808	2748
Number of collisions (IP1, IP5)	2808	2736
Crossing angle (IP1, IP5) [μrad]	285	590
Minimum β^* [m]	0.55	0.15
Normalized emittance ϵ_n [μm]	3.75	2.50
RMS energy spread [10^{-4}]	1.13	1.13 ¹
RMS bunch length [cm]	7.55	7.55 ²
Piwinski parameter, ϕ	0.65	3.14
Total loss factor without CC, R_0	0.836	0.305
Total loss factor with CC, R_1	–	0.829
Pile up without CCs and leveling ³	27	198
Pile up with CCs and leveling	–	138
Peak luminosity without CCs [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	1.00	7.18
Virtual luminosity with CCs [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$] ⁴	–	19.54
Levelled luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	1.5	5

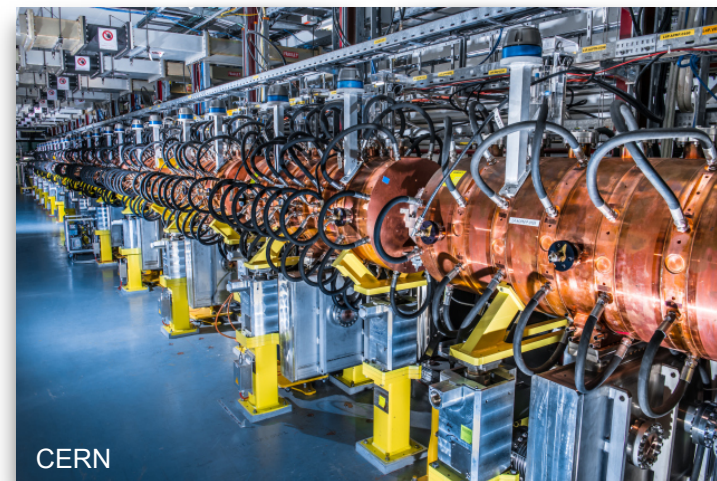
¹ Changed to 1.08×10^{-4} for V6.1.0 of the HL-LHC parameters (Oct. 2016).

² Changed to 8.1 cm for V6.1.0 of the HL-LHC parameters (Oct. 2016).

³ Calculated with an inelastic cross-section of 85 mb.

⁴ $\mathcal{L}_{peak} R_1/R_0$, with no limit in the event pile-up.

Remember: ϵ defined by quality of injectors



Quelle: <https://cds.cern.ch/record/2260707>

Pile up

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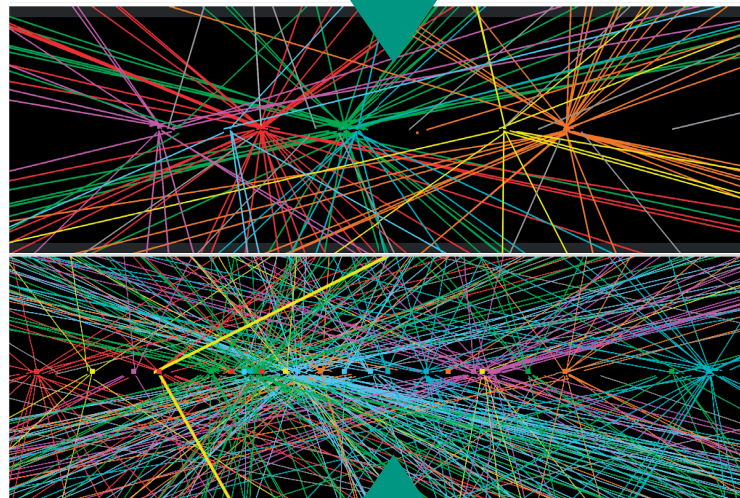
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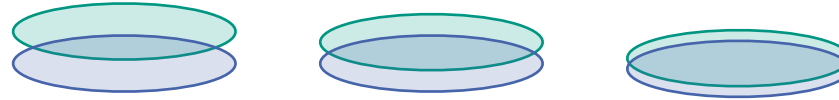
Collision event with 7 vertices



Collision event with 25 vertices

Luminosity levelling

■ Bunch overlap



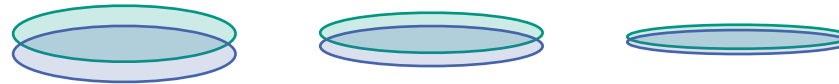
■ β^* squeeze



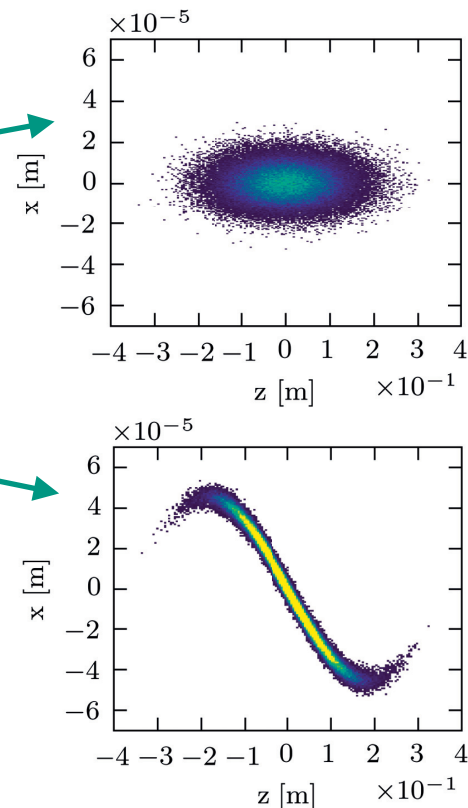
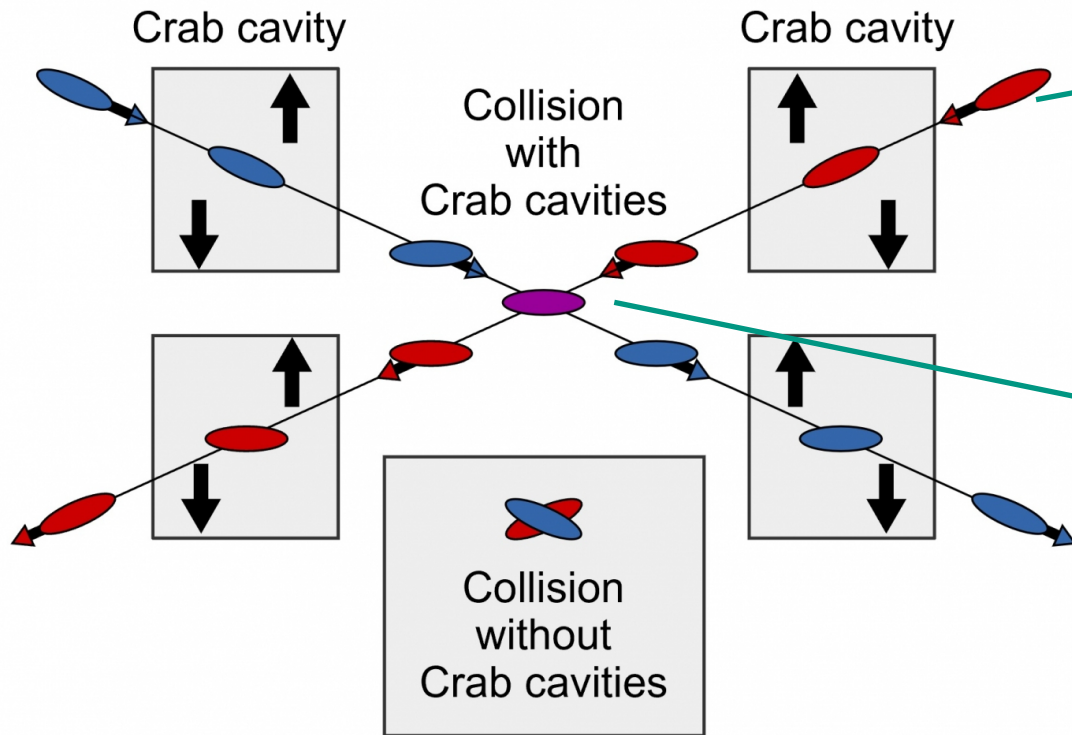
■ Crab cavities



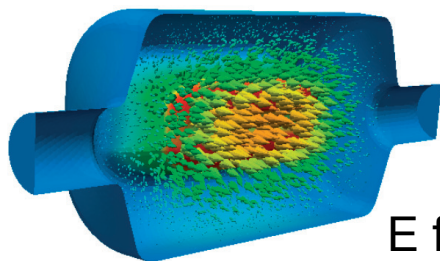
■ Combinations



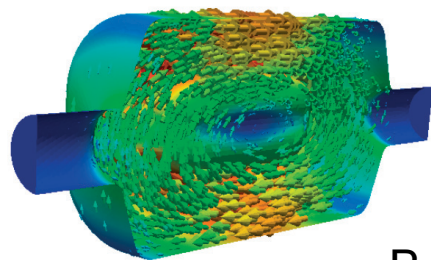
Crab cavities



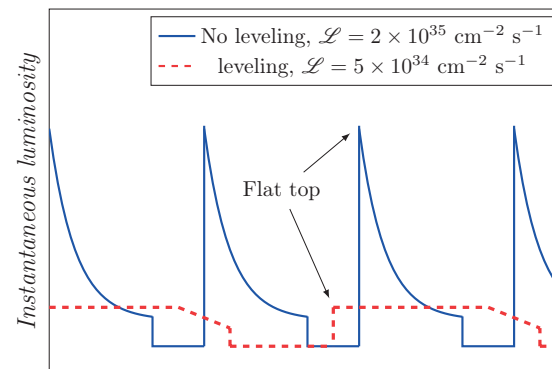
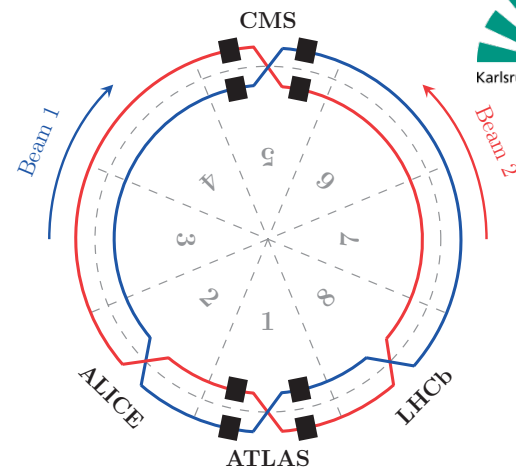
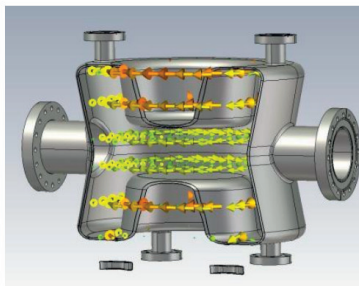
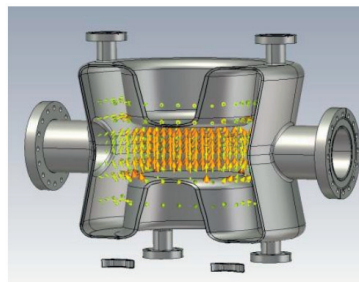
Crab cavities II



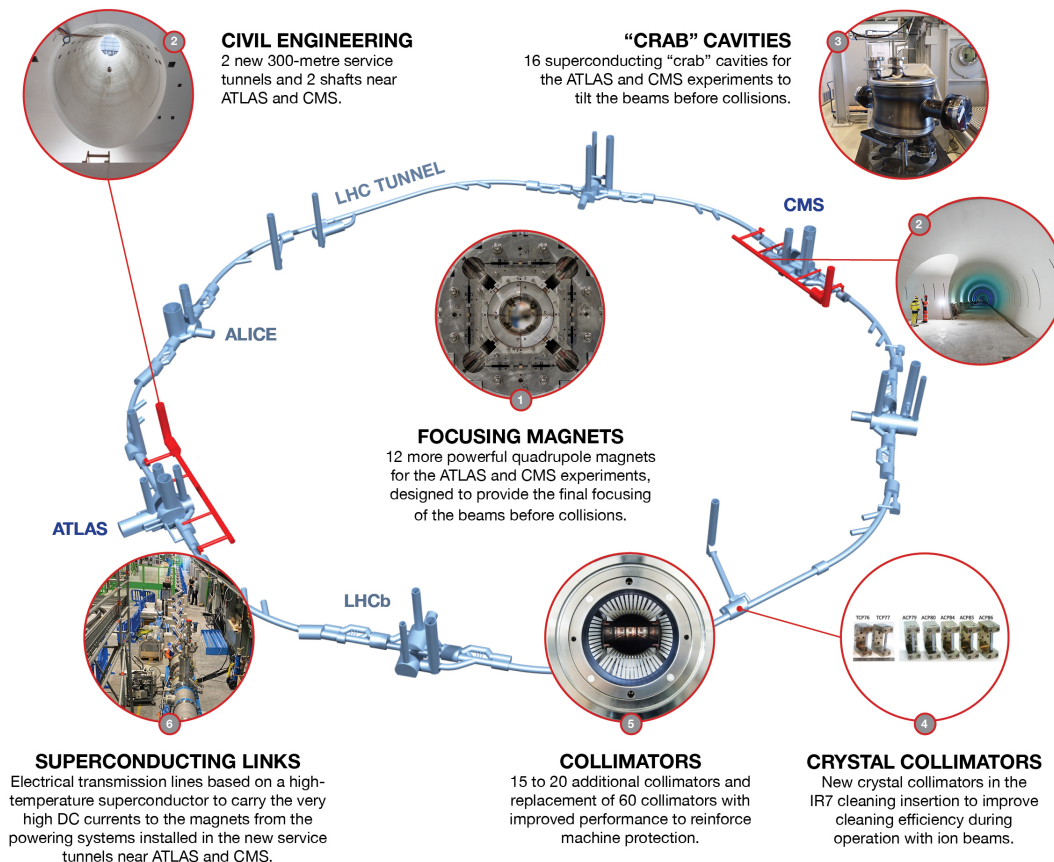
E field



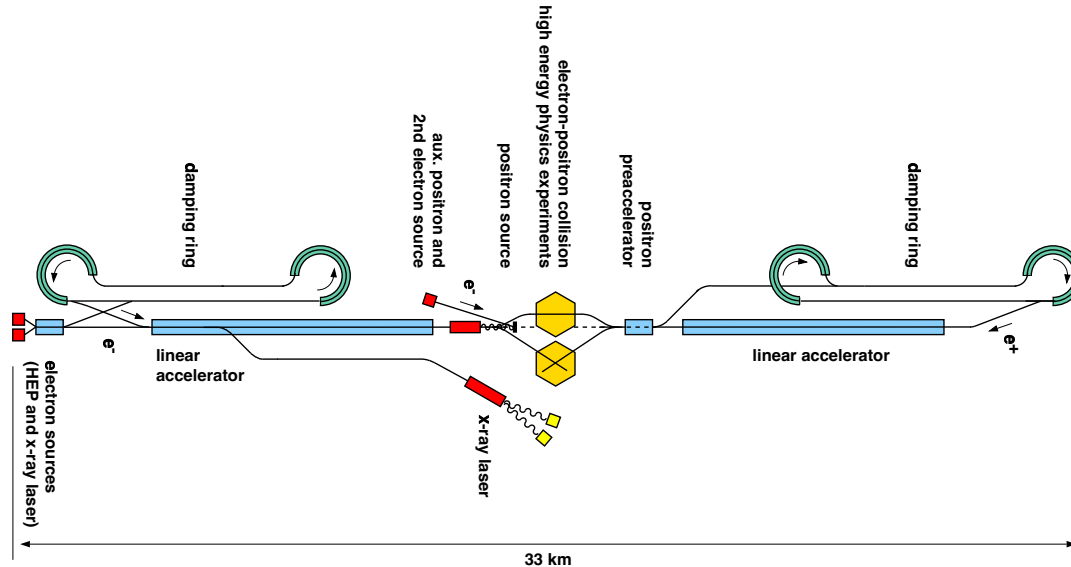
B field



Quelle: A. Santamaria Garcia, PhD thesis

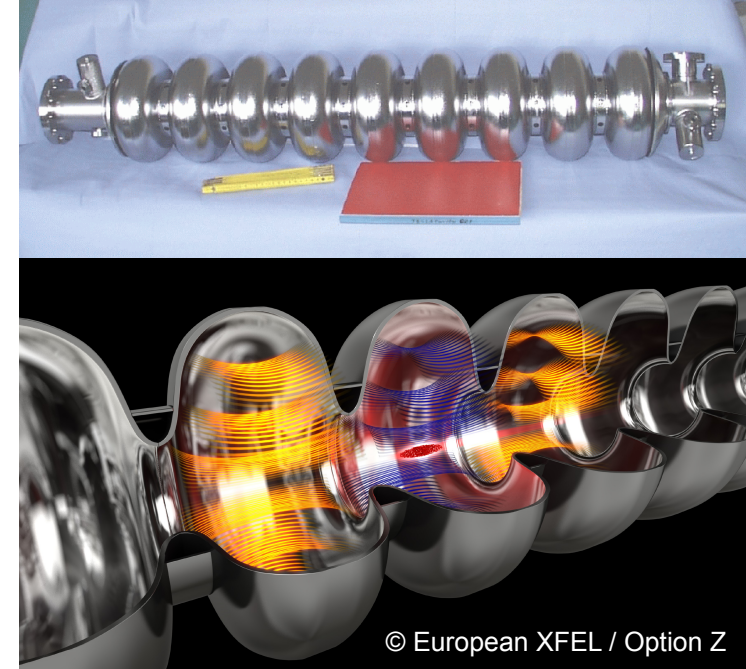


TESLA, X-FEL and ILC



- “1 TeV energy superconducting linear accelerator”
- 500 GeV beam energy

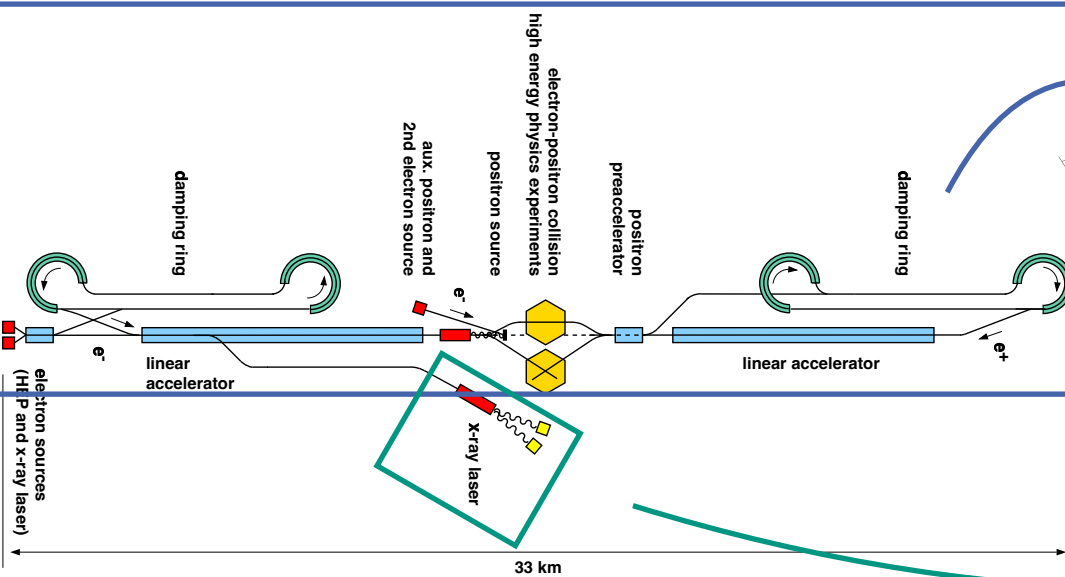
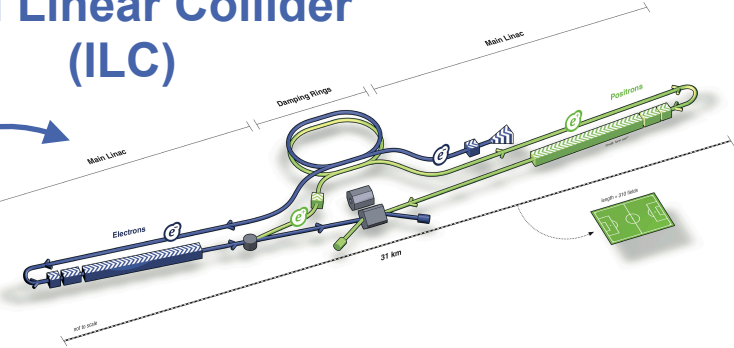
Quelle: TESLA Technical Design Report



Superconducting Nb cavities:
9 cells, 1.3 GHz, 23.4 MV/m

TESLA, X-FEL and ILC

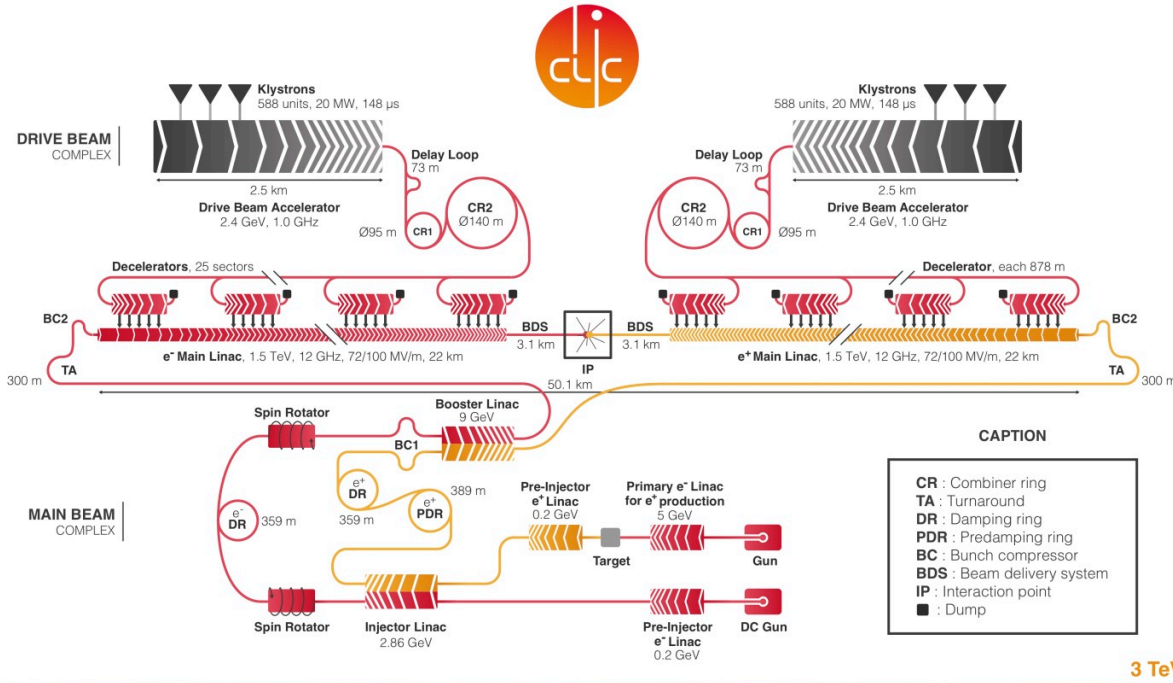
International Linear Collider (ILC)



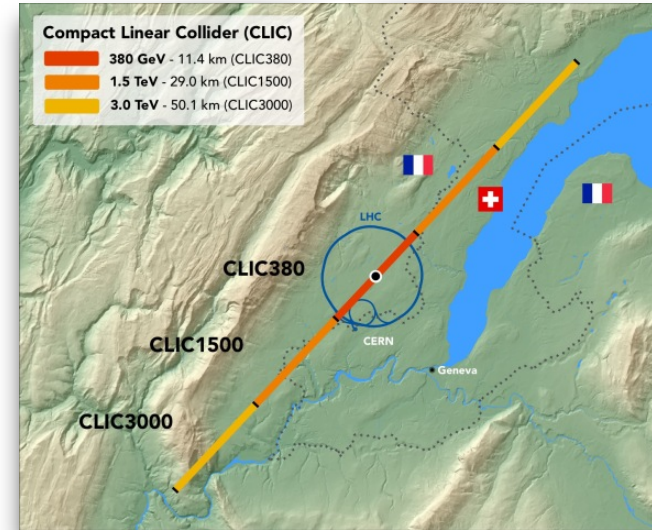
European X-FEL



CLIC — Compact Linear Collider



3 TeV



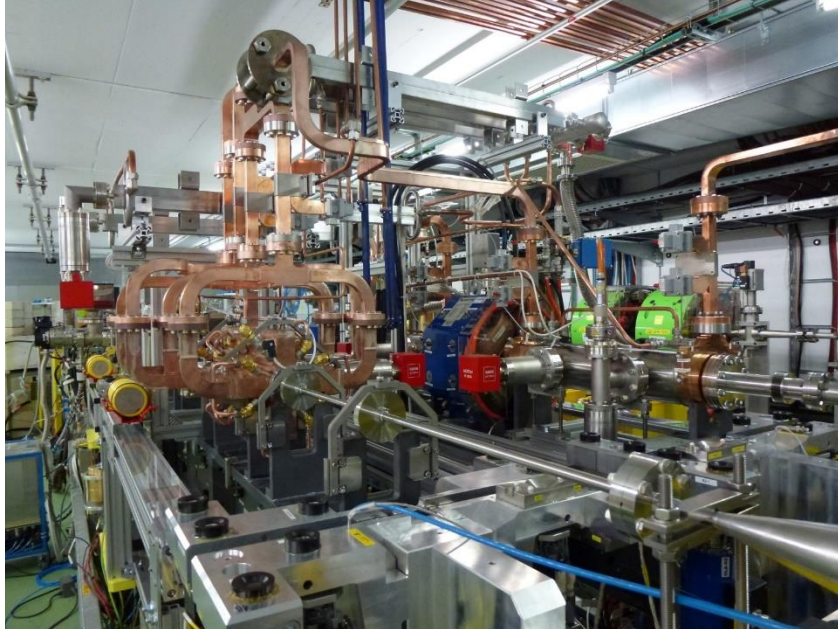
CERN - <https://cds.cern.ch/record/2297076>

CLIC - Scheme of the Compact Linear Collider (CLIC)

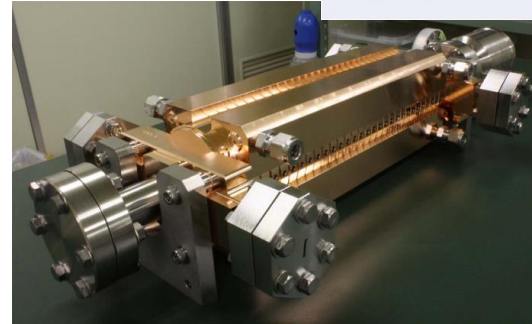
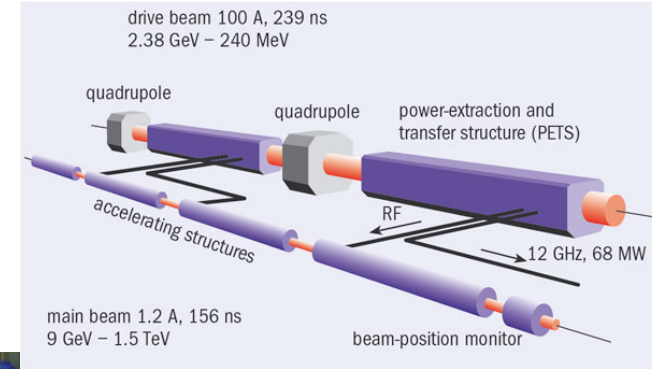
CERN - <https://cds.cern.ch/record/2655160?ln=en>



Two-beam acceleration



CLIC test facility



S. Staples — Future Collider CAS

100 MV/m accelerating gradient achieved!

Linear vs. circular collider

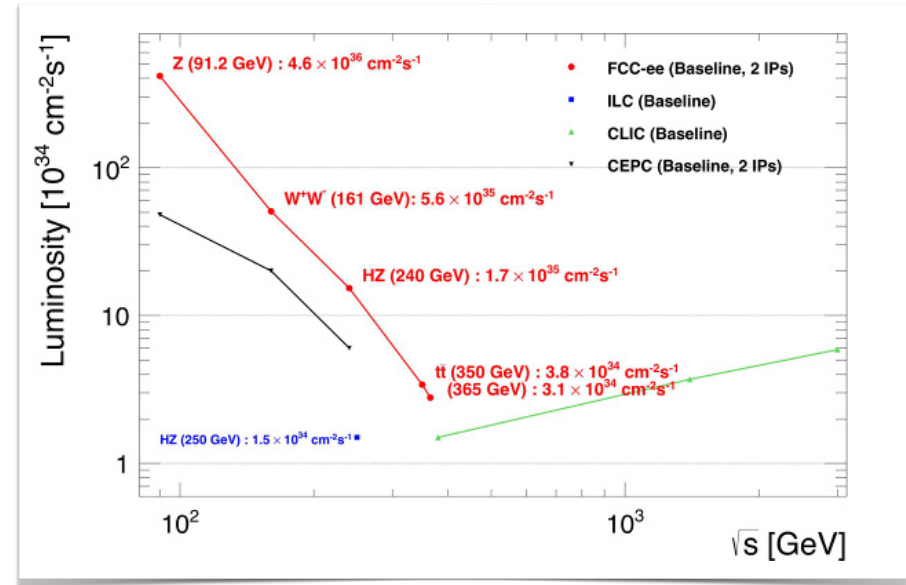
Linear collider

- no synchrotron radiation
- only one experiment at a time
- single use of particle bunches

Circular colliders

- multiple experiments
- bunches can be collided multiple times
- SR radiation power increases $P \propto \gamma^4$

Trade-off between SR power and luminosity



FCC-ee Design Report: Baseline luminosities expected to be delivered for different e^+e^- collider projects

Mont Blanc

Annemasse

Salève

Annecy

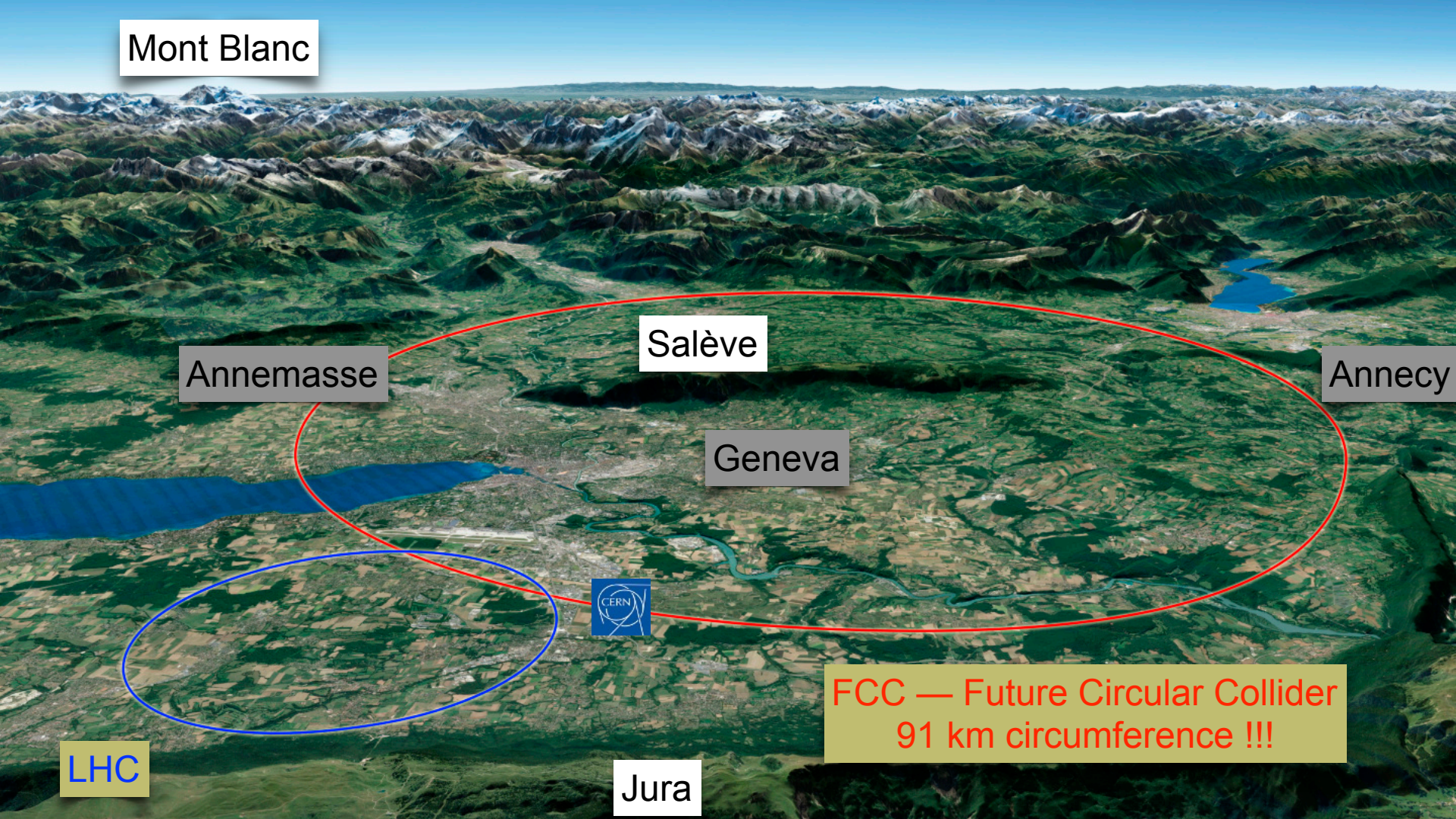
Geneva



LHC

Jura

FCC — Future Circular Collider
91 km circumference !!!



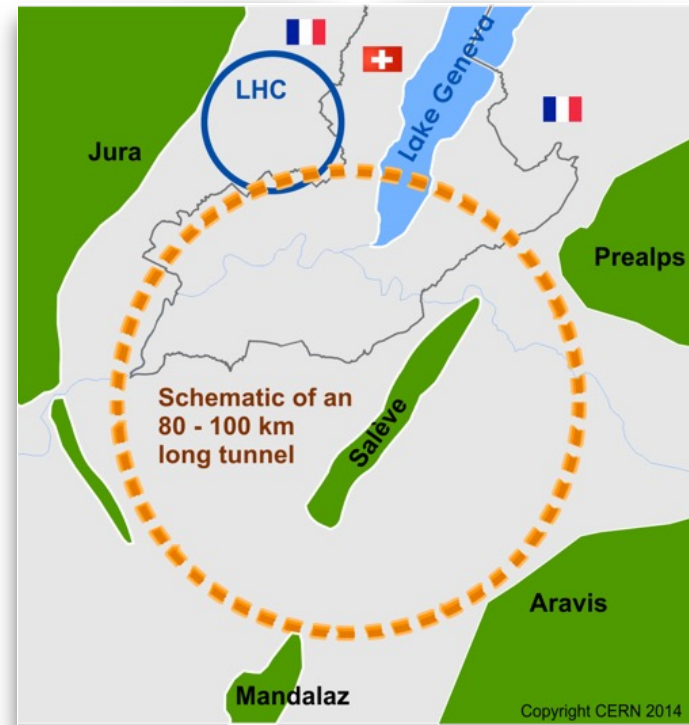
Future Circular Collider Study



- **FCC-hh** (hadron collider)
 - 100 TeV center-of-mass energy
 - discovery machine

- **FCC-ee** (electron positron collider)
 - precision measurements
 - Z, W and H boson, top quark
 - 91 GeV - 370 GeV cm energy

- **FCC-he** (electron proton collision option)
 - deep inelastic scattering



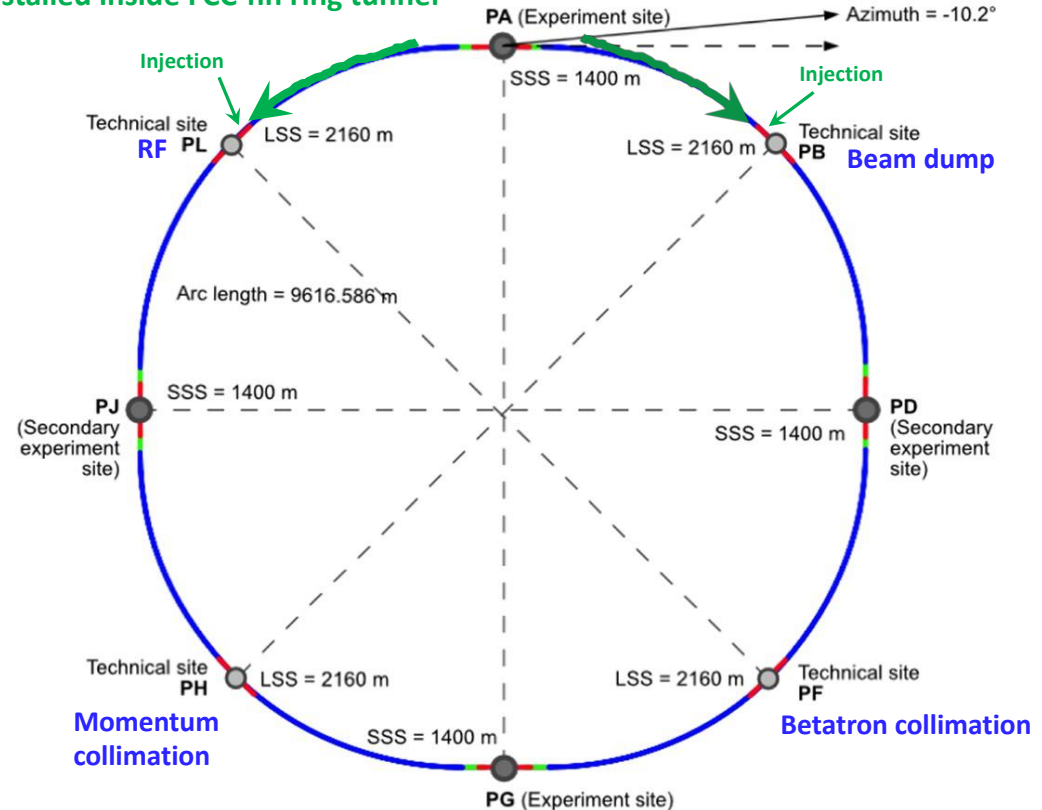
FCC-hh

- 50 TeV beam energy
- 16 T Nb₃SN magnets
- $U_0 \approx 5$ MeV/turn



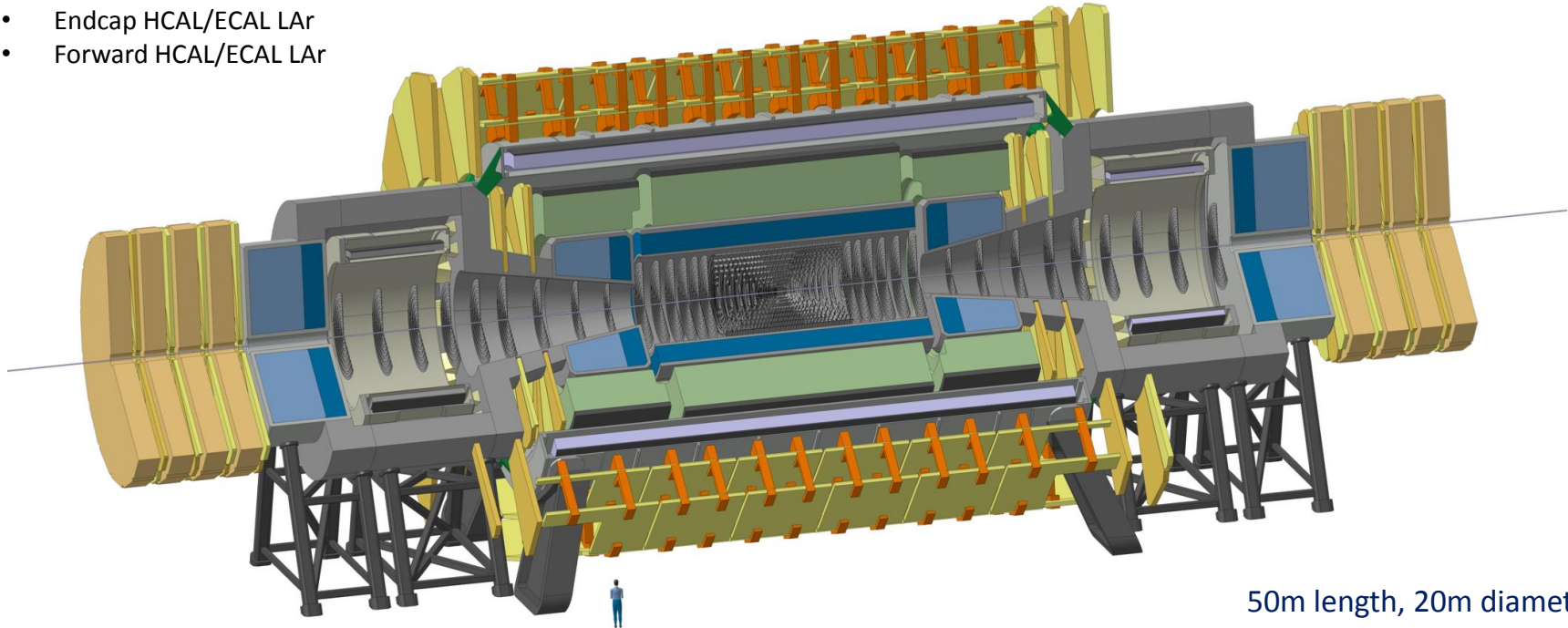
Vacuum tests of the beam screen prototype at KARA!!!

transfer lines proposed to be
installed inside FCC-hh ring tunnel



- 4T, 10m solenoid, unshielded
- Forward solenoids, unshielded
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

FCC-hh: Detector

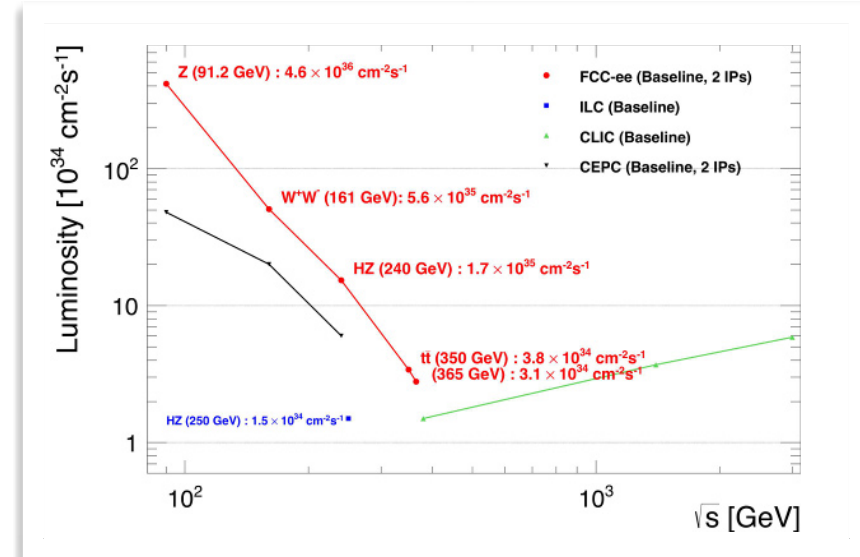


50m length, 20m diameter
similar to size of ATLAS

FCC-ee: Luminosity vs. radiation power

- Higher luminosity than linear colliders (below 400 GeV)
- Higher repetition rate & current
- Multiple experiments
- FCC-ee: SR power limited to 50 MW!**

Energy (GeV)	# bunches	# particles per bunch (10^{11})	Luminosity ($10^{34}/\text{cm}^2\text{s}$)
45.6	16640	1.7	460
80.0	2000	1.5	56
120.0	328	1.8	17
182.5	48	2.3	3.1



FCC-ee Design Report: Baseline luminosities expected to be delivered for different e⁺e⁻ collider projects

-

- Vacuum chamber with winglets to place SR absorbers with great distance to lower impedance.

Muon Collider

- Elementary particles
- High energy
- Low synchrotron radiation

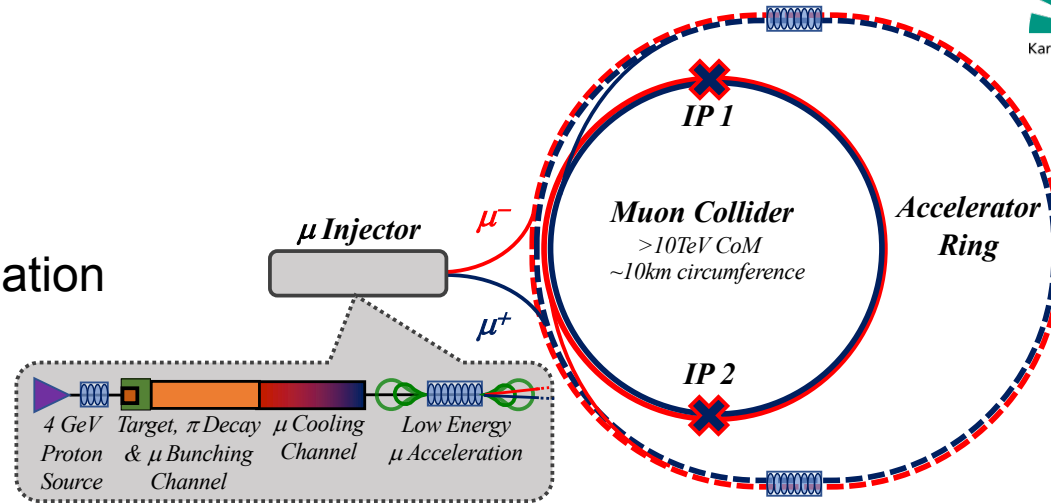
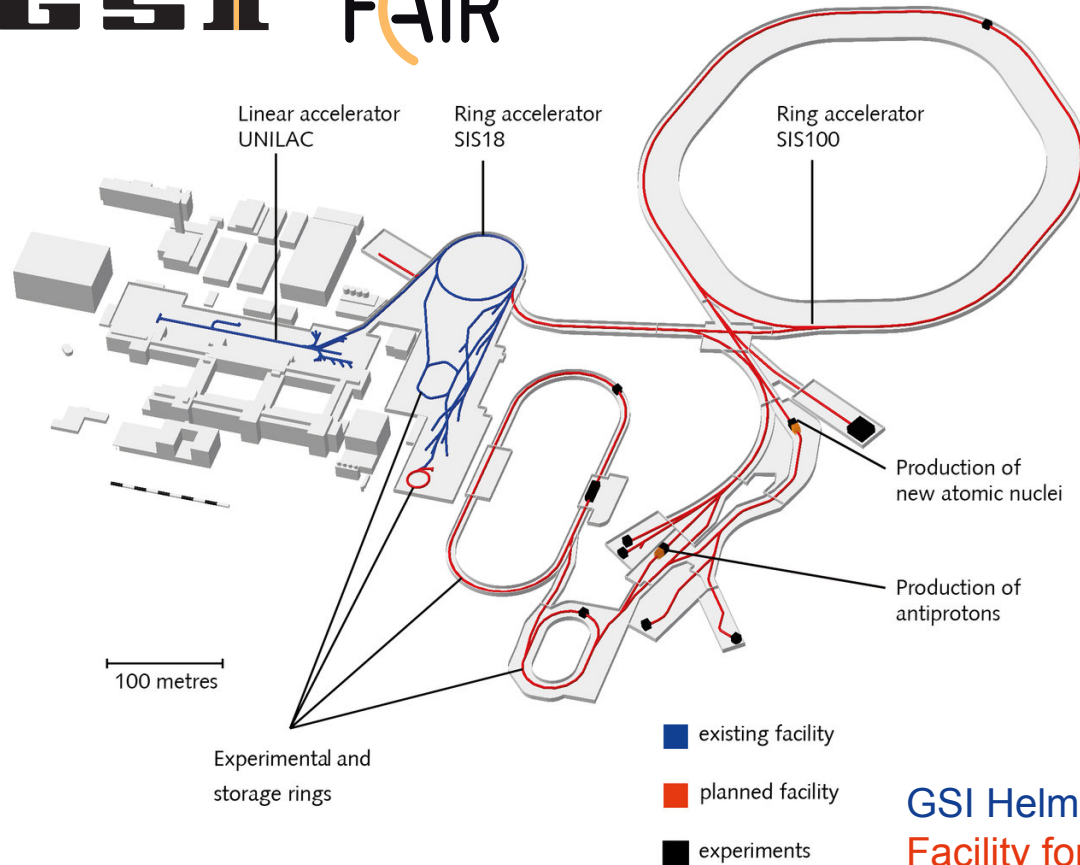


Fig. 1: A conceptual scheme for the Muon Collider

Design challenges

- Cooling of the muon beam
- Fast-ramping high-field magnets (T/ms), corresponding SRF system
- **Muon decay:** Dipoles must be robust to radiation, high neutrino flux, detector must distinguish between signal and beam-induced background





SIS100

- 1.1 km
- 30 GeV/nucleon
- Superconducting

Superconducting Fragment Separator

- Separator for radioactive nuclei
- Protons... Uranium

GSI Helmholtzzentrum für Schwerionenforschung
Facility for Antiproton and Ion Research



© GSI/FAIR, Zeitrausch

construction site September 2024



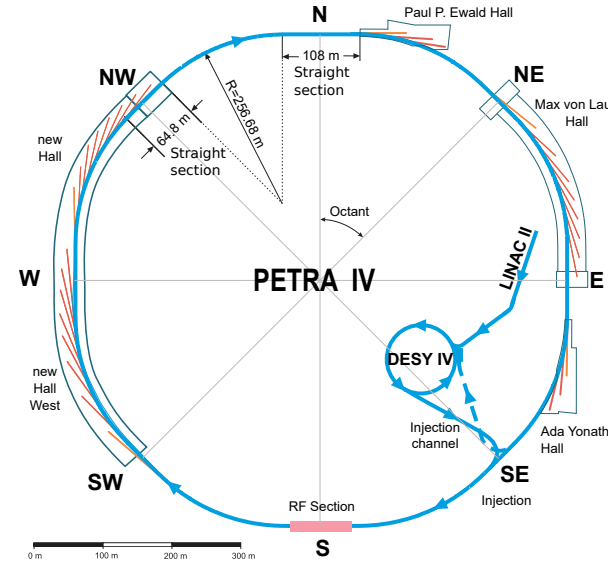
magnet of the Super-FRS

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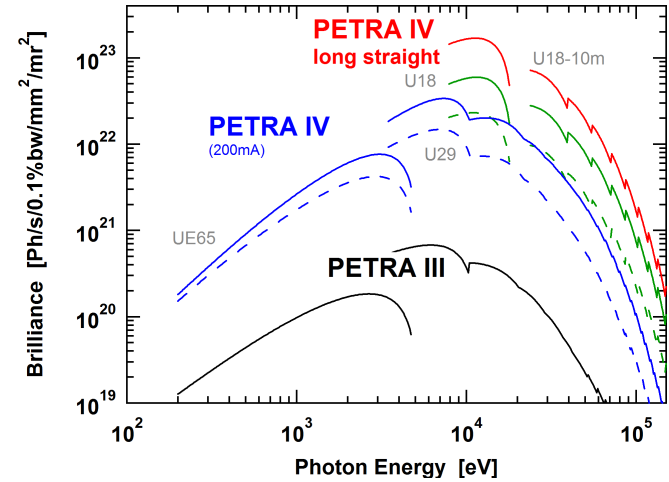
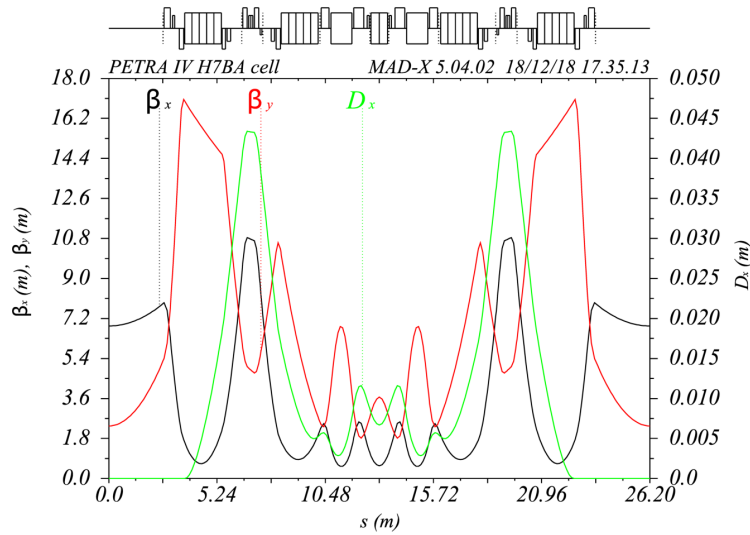


PETRA IV.

Upgrade of PETRA III to the Ultimate 3D X-ray Microscope
Conceptual Design Report



- Upgrade of PETRA III
- Energy $E = 6 \text{ GeV}$
- Circumference $C = 2304 \text{ m}$
- Emittance $\epsilon_x < 20 \text{ pm}$
- Diffraction-limited until photon energy of $\approx 10 \text{ keV}$



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First light foreseen in 2032

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ESS — European Spallation Source



Research with neutrons

- Neutrons are excellent for probing materials on a molecular level.

ESS

- Replacing reactor technology
- High brightness neutron beams
- Created by 2 GeV protons hitting a spinning tungsten target



How does it work?

1 Protons are generated in the ion source

Hydrogen is heated using microwaves, until it becomes a plasma. Then the electrons are stripped away and the protons are steered and focussed into the accelerator.

3 The protons strike the target and high-energy neutrons are released

The ESS target is a 2.5 metre diameter stainless steel disc containing bricks of tungsten – a heavy metal with many neutrons. The disc rotates 23.3 times per minute. The more neutrons produced in the target collision, the 'brighter' the neutron source. **ESS will be one of the world's brightest neutron sources.**

2 Cavities accelerate the protons to 96% of the speed of light

Electromagnetic fields accelerate the protons along the protons along the 602.5m linear accelerator, or Linac. Protons have a positive charge so large magnets called quadrupoles are used to keep the proton beam focussed all along the Linac. **A new pulse of protons is generated 14 times a second.**

4 The neutrons are slowed down and sent down neutron guides to the instruments

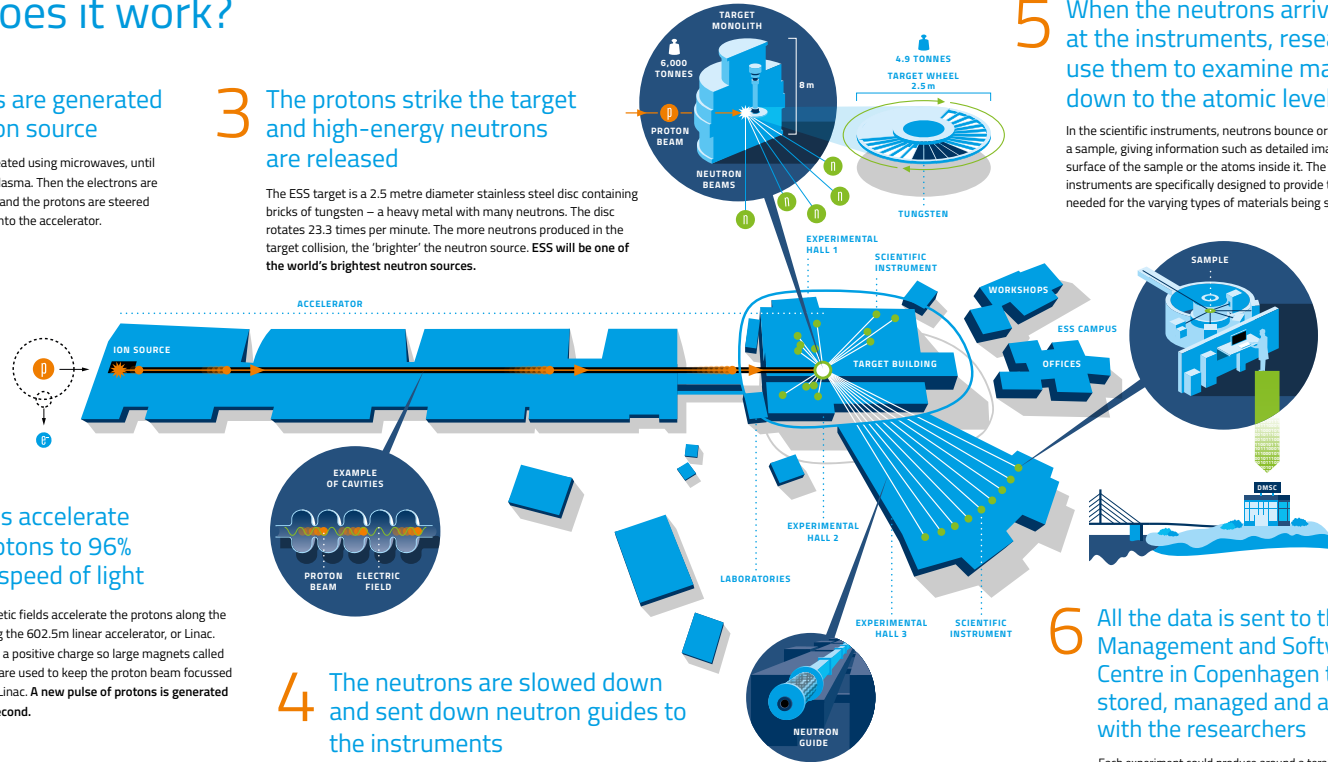
The guides are extremely stable, with highly reflective walls, so that as many neutrons as possible reach all the way to the end. **Some of these neutron guides are up to 160 m in length!**

5 When the neutrons arrive at the instruments, researchers use them to examine matter down to the atomic level

In the scientific instruments, neutrons bounce or scatter off a sample, giving information such as detailed images of the surface of the sample or the atoms inside it. The different instruments are specifically designed to provide the data needed for the varying types of materials being studied.

6 All the data is sent to the Data Management and Software Centre in Copenhagen to be stored, managed and analysed with the researchers

Each experiment could produce around a terabyte of data – **that is around 500 hours of movies!** Software and scientific computing experts help the researchers understand, visualise and interpret their results.



- Today's accelerator technology enables us to conduct exciting and diverse research.
- However, accelerators tend to reach enormous sizes.

■ What can we do to make them smaller and both construction and operation more cost effective?

