Karlsruhe Institute of Technology

Institute for Beam Physics and Technology

Particle Accelerator Physics

Anke-Susanne Müller, Axel Bernhard, Bastian Härer, Bennet Krasch, Nathan Ray

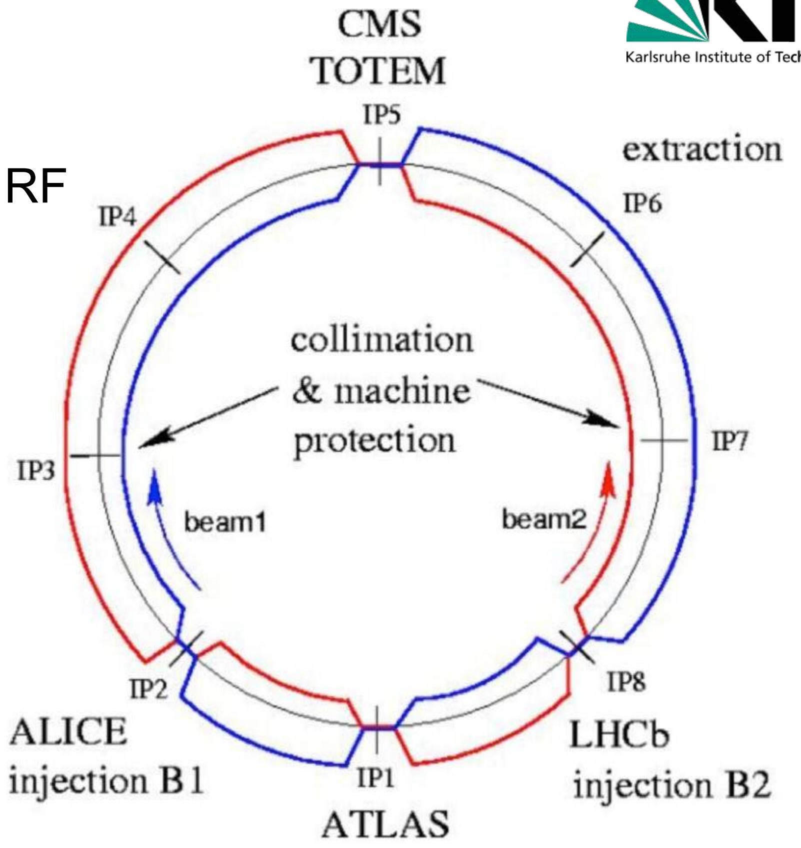
VIII - Current & future projects

- Concrete examples of current and future projects
  - LHC and HL-LHC
  - Linear colliders: CLIC & ILC
  - European XFEL
  - FCC
  - Muon Collider
  - (FFAGs)

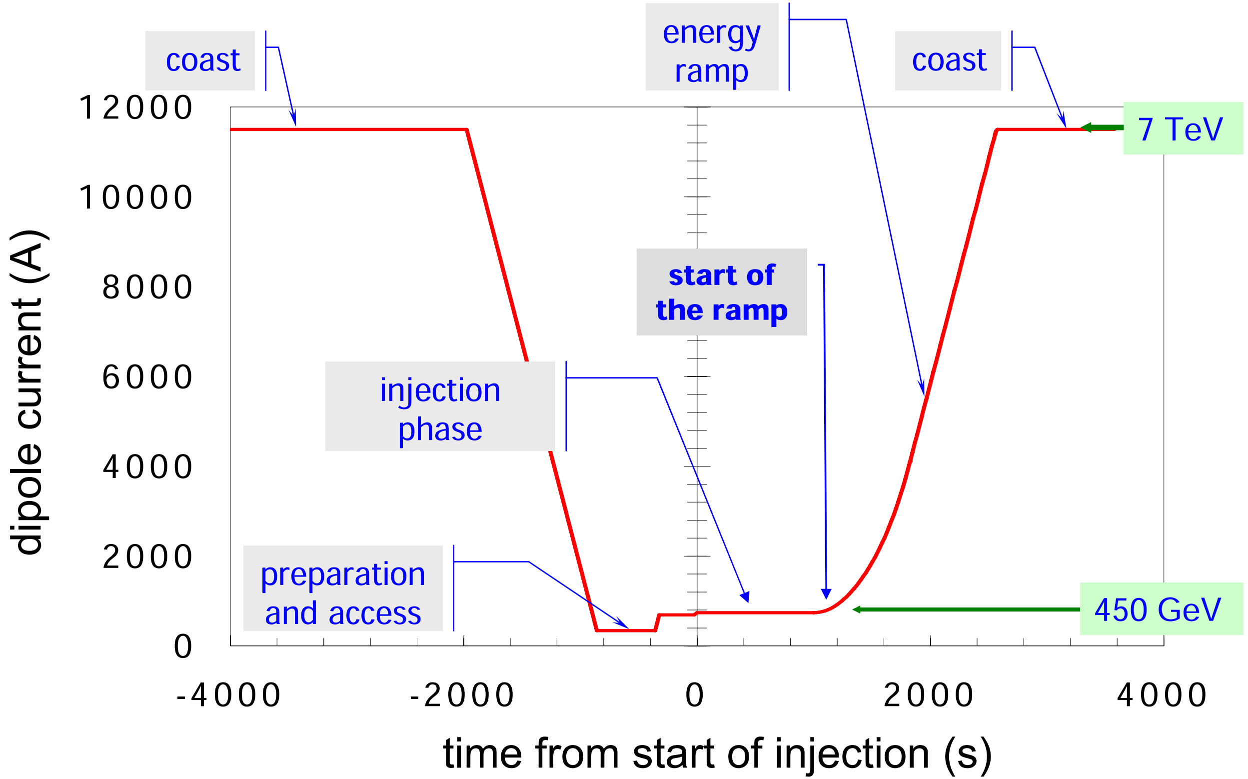
- New technologies
  - Plasma-based acceleration
  - Dielectric accelerators

The Large Hadron Collider

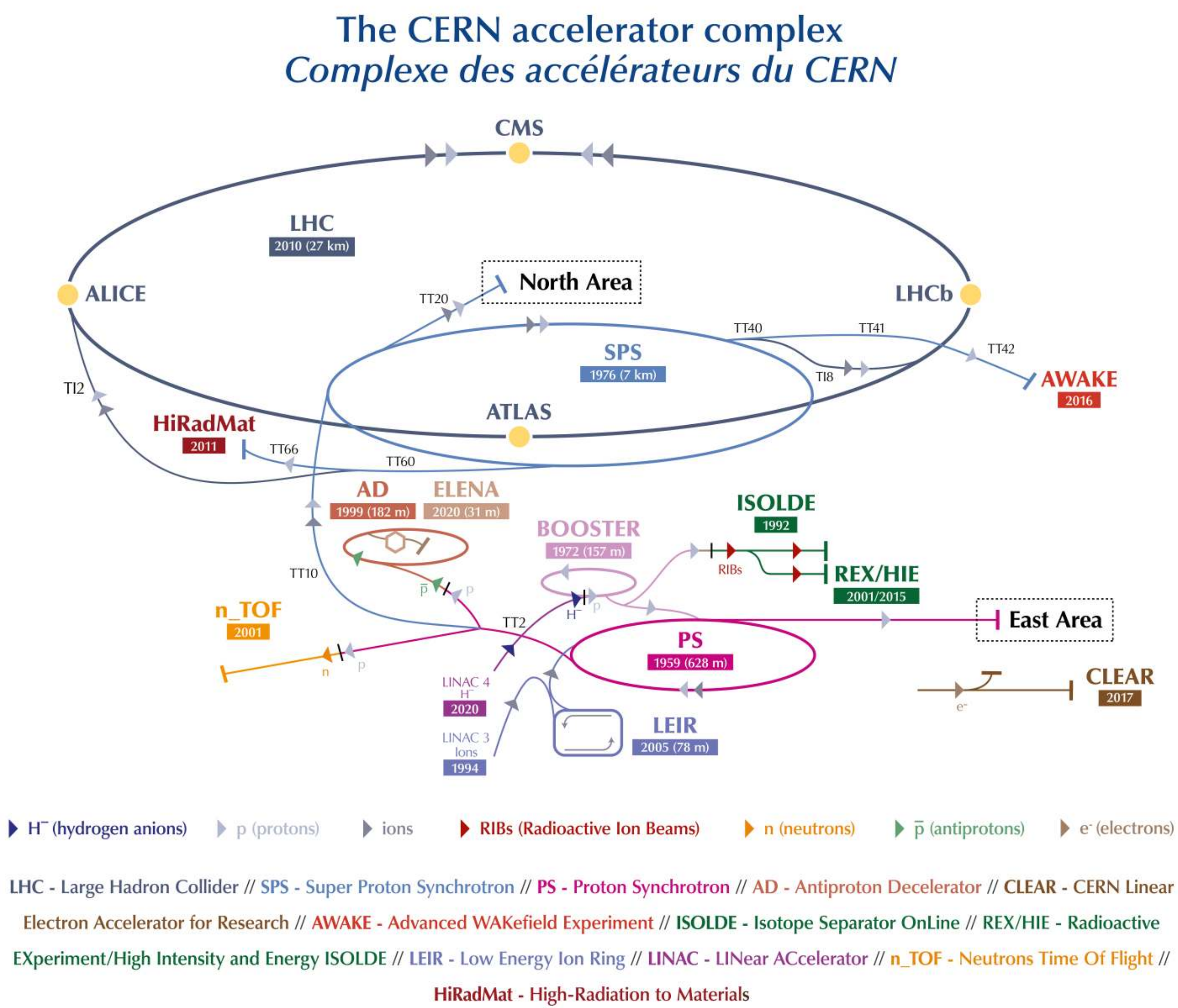
- Superconducting RF
- SC magnets (8.33 T at 1.9 K)
- FODO lattice
- 1232 15 m long dipoles
- “Two-in-one” magnets
- Field quality, resonances, ...
- Protons emitting synchrotron radiation
- Electron cloud effect
- 2808 bunches à 10^{11} protons
- Luminosity $\approx 10^{34}$ $cm^{-2}s^{-1}$
- Beam energy: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



Standard operation



L. Bottura, CERN

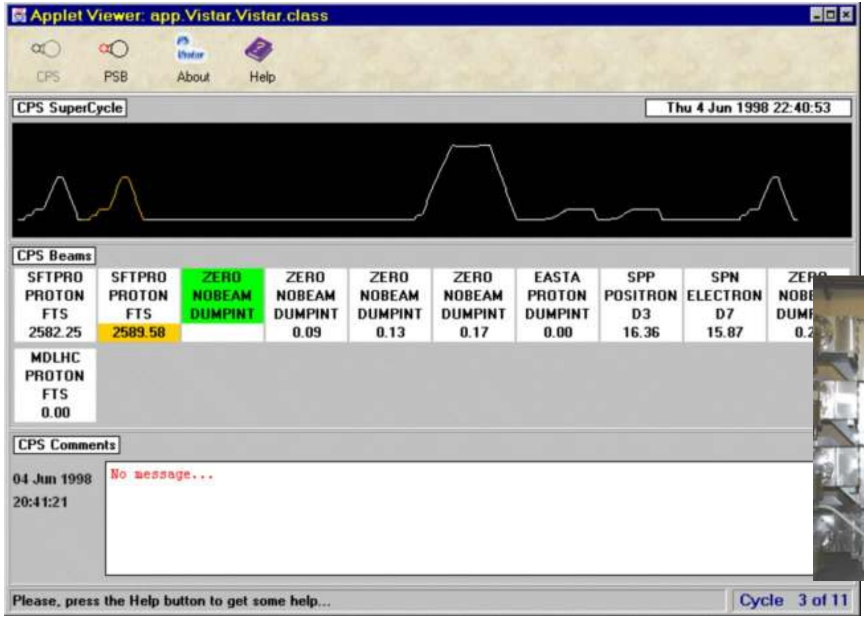


- Linac 4: 160 MeV
- Booster: 1.4 GeV
- PS: 25 GeV
- SPS: 450 GeV
- LHC: 7 TeV

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

Multi-cycling in the PS ("Proton Synchrotron")

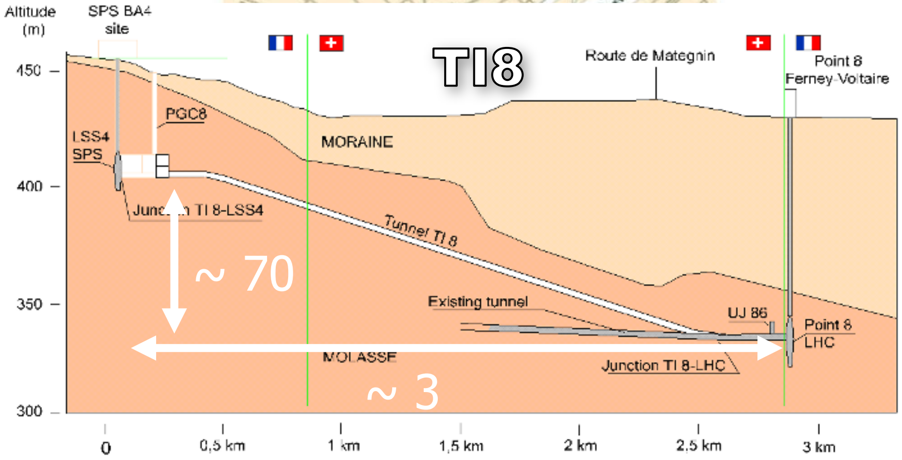
- The CERN Proton Synchrotron is a so-called multi-cycling machine:



- Different types of particles are accelerated one after the other in the same accelerator but with different cycles.

- This poses particular challenges for, among other things, beam diagnostics and timing.

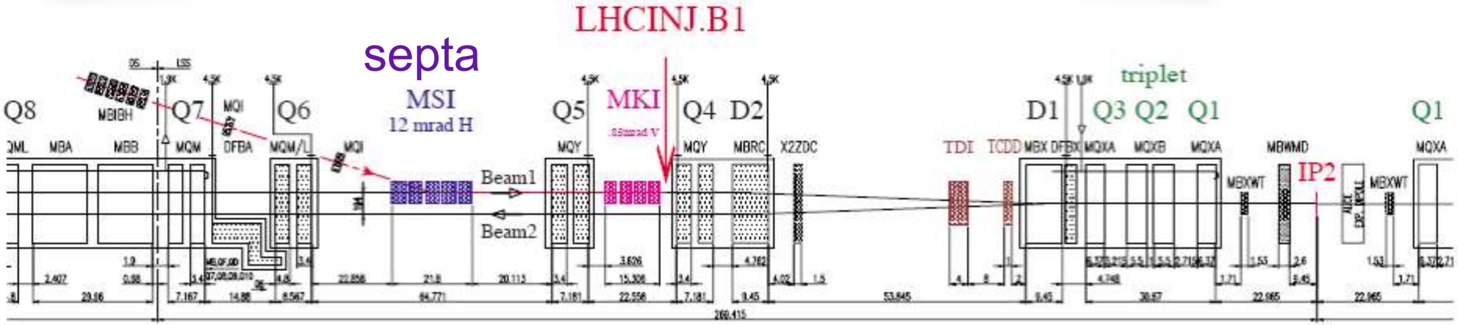
Beam transport: transfer line 8



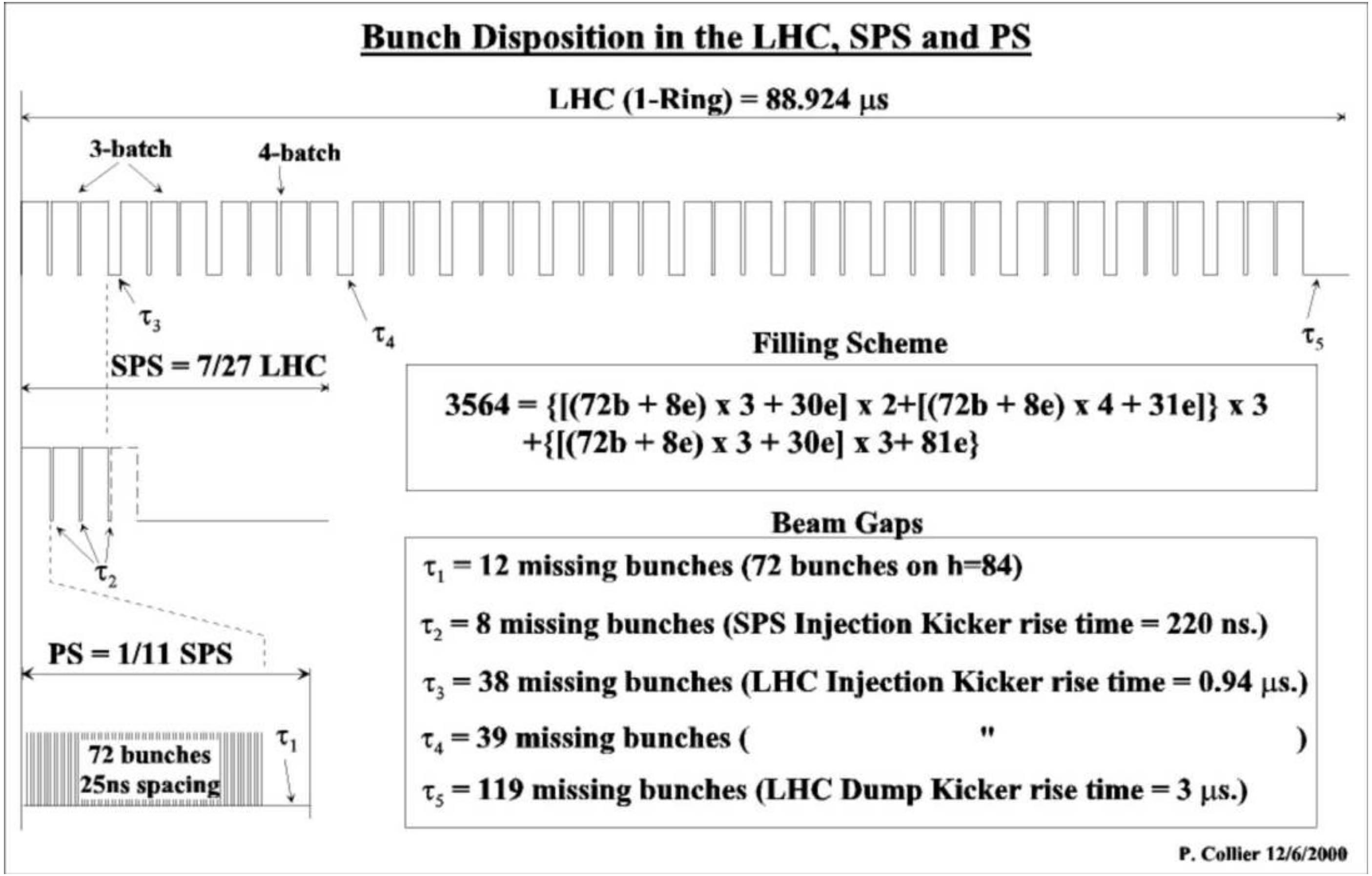
LHC

helium transport line

transfer line
(normal conducting)



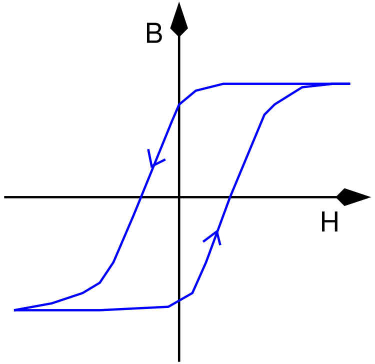
injection kickers



"filling pattern"

Why SC magnets?

- The highest possible beam energy requires a high integrated magnetic field: $E \propto \oint ds B(s)$
- With known dimensions of the tunnel and $p = 7\,\mathrm{TeV}$ the required bending field can be estimated: $B[\mathrm{T}] = \frac{1}{0.2998} \frac{p[\mathrm{GeV/c}]}{\rho[\mathrm{m}]}$ (ρ is the bending field of the dipoles)
- Of the 27 km circumference only 22.2 km are arc sections, which corresponds to a bending radius of 3.5 km. However, only about 80 % of the arc sections are actually dipole magnets, so the bending radius is $\rho = 2.784\,\mathrm{km} \rightarrow B \approx 8\,\mathrm{T} \rightarrow$ superconducting magnets!



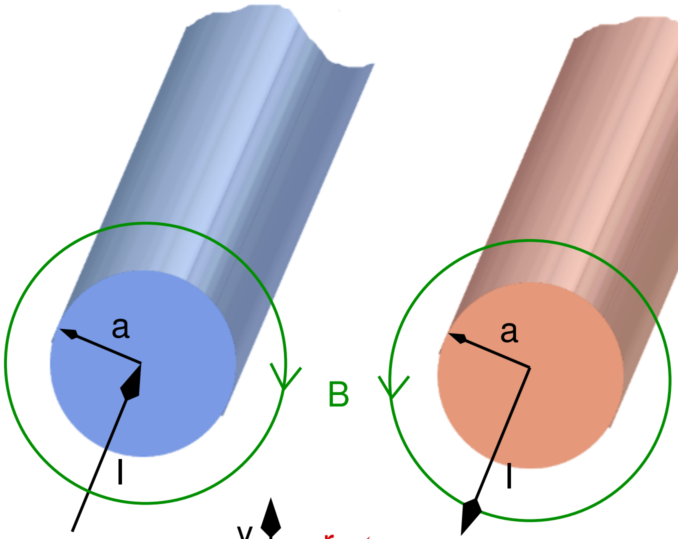
- Because of saturation, the field of Fe dominated magnets cannot reach fields beyond $2\,\mathrm{T}$.
- The field is realized by a special cable winding that enables the required current distribution.
- Highest precision and stability of the coils are required to create an adequate magnetic field.

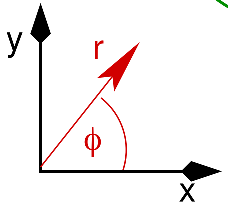
Field distribution

- Magnetic field outside and inside of the conductor:

$$r > a : \qquad \vec{B} = \frac{\mu_0 \, I}{2 \, \pi \, r} \begin{pmatrix} -\sin\phi \\ \cos\phi \\ 0 \end{pmatrix}$$

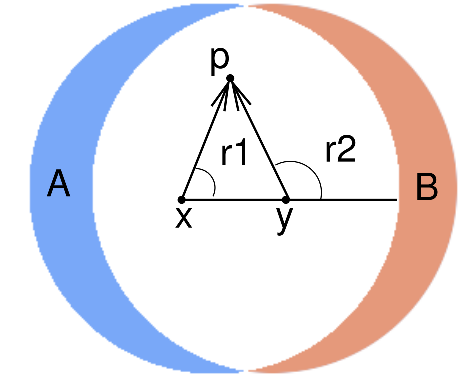
$$r < a : \qquad \vec{B} = \frac{\mu_0 \, j \, r}{2} \begin{pmatrix} -\sin\phi \\ \cos\phi \\ 0 \end{pmatrix}$$



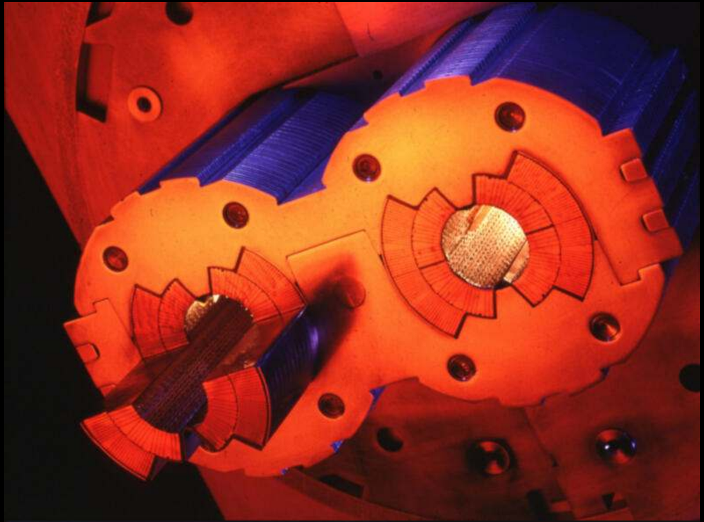
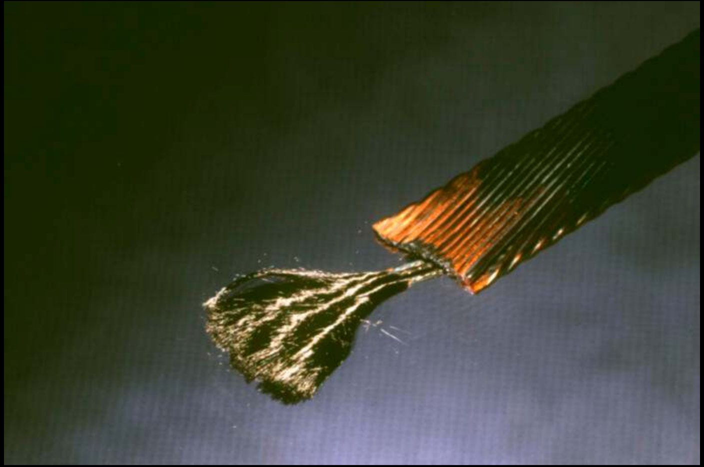
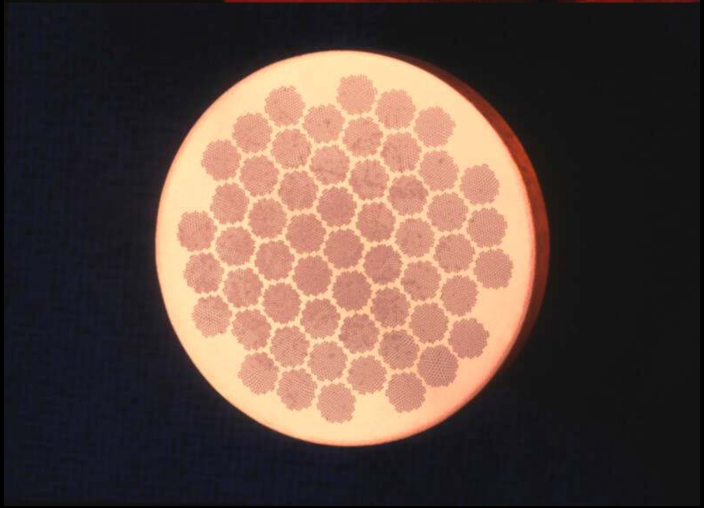
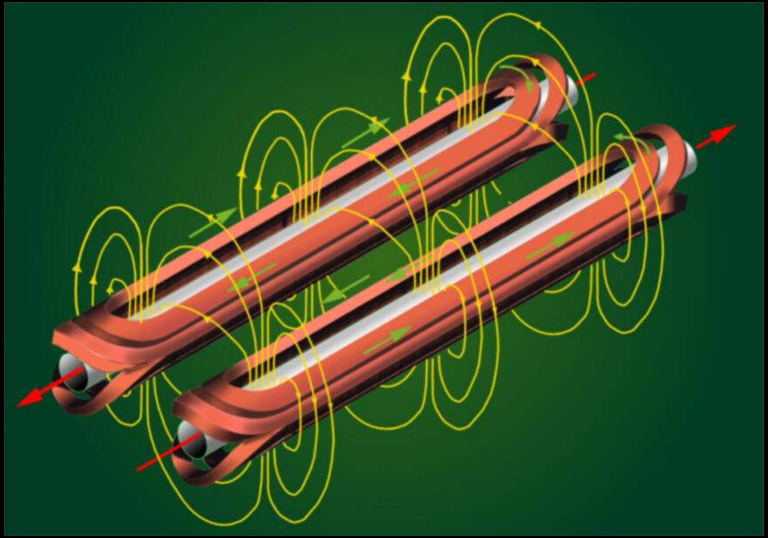


- Overlap of the cylinders provides

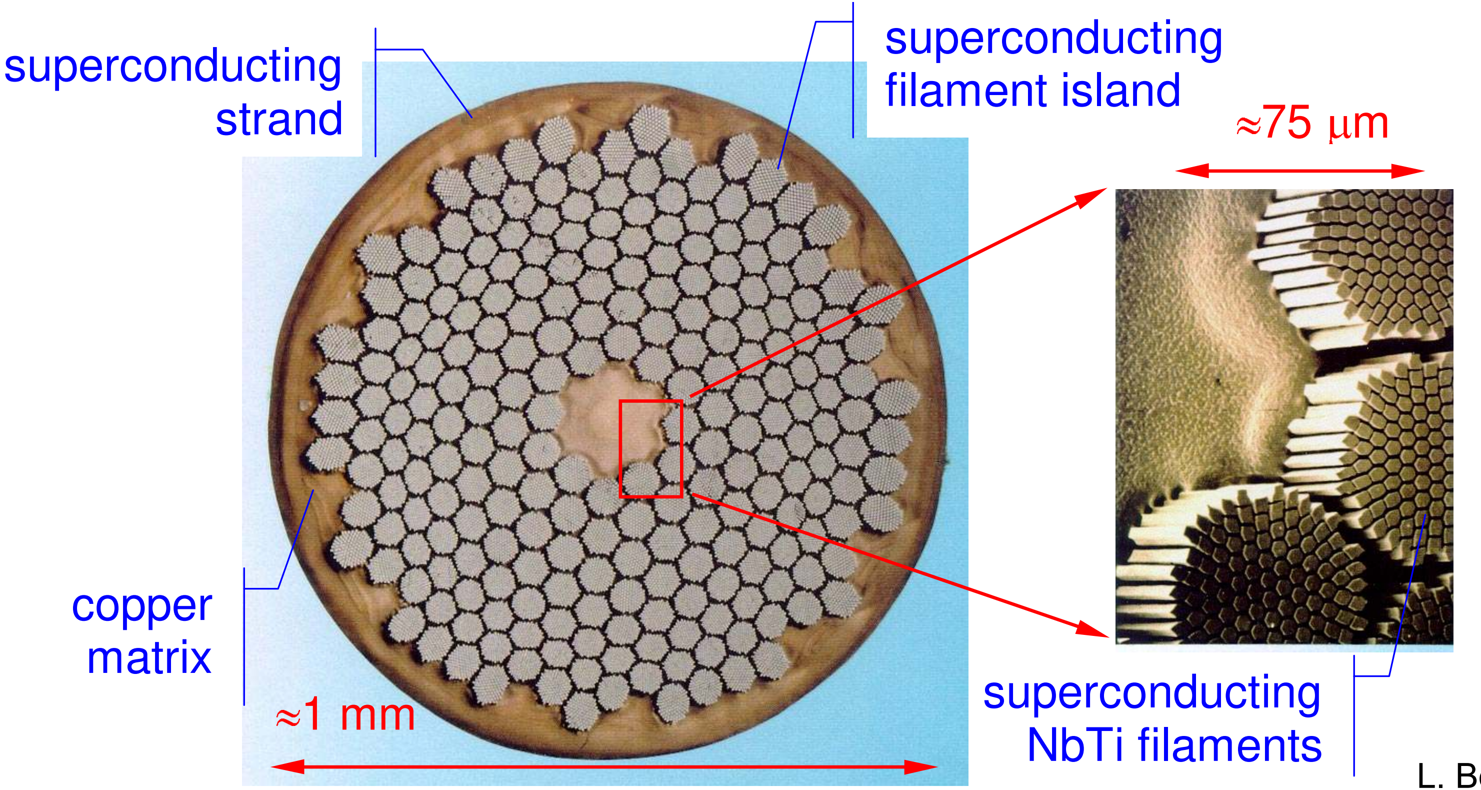
$$r_1 \sin\phi_1 - r_2 \sin\phi_2 = 0$$
$$r_1 \cos\phi_1 - r_2 \cos\phi_2 = d$$



- Within the overlap area applies: $j = 0, \; B_x = 0$ and $B_y = \text{const}$.
- Since the current mainly flows on the surface of the superconductor, the surface must be maximised → Many superconductor filaments!

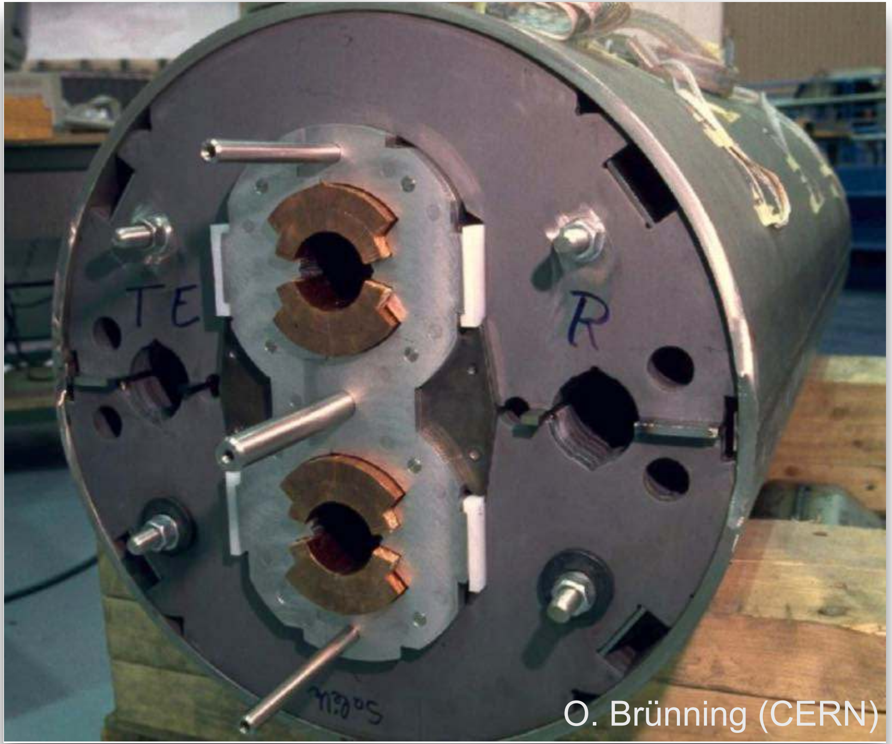





Superconductor filaments



L. Bottura (CERN)

Mechanical stability



- With a field of $B = 8.4\,\mathrm{T}$ and a current per winding of $I = 11\,\mathrm{kA}$, a force of $F = 92400\,\mathrm{N/m}$ 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.

Field components and field errors

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- The fields of the individual LHC dipoles are measured in a warm and partly in a cold state before installation.
- The magnetic field can be broken down into its components:

$$\vec{B} = B_y + iB_x = \sum_{n=1}^{\infty} (\mathscr{B}_n + i\mathscr{A}_n) z^{n-1}$$

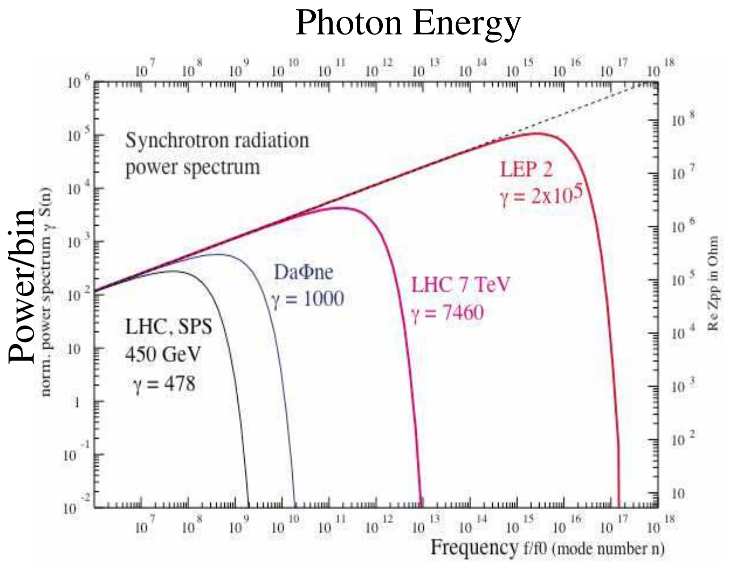
with $z = x + iy$

- Coefficients:
  - $\mathscr{B}_n$: normal coefficient, $\mathscr{A}_n$: skew coefficient
  - $n = 1$ is a dipole field, $n = 2$ is a quadrupole field, etc.
- In the LHC, the dipoles are installed in such a way that their field errors compensate each other as far as possible.

CDS: CERN-AC-0904053-06

Synchrotron radiation

- **LEP**
  - Energy loss per turn: $U_0 = 3\,\mathrm{GeV}$
  - Critical energy: $E_c = 730\,\mathrm{keV}$
  - Radiation power (at $I = 6\,\mathrm{mA}$): $18\,\mathrm{MW}$
- **LHC**
  - Energy loss per turn: $U_0 = 6.7\,\mathrm{keV}$
  - Critical energy: $E_c = 44\,\mathrm{keV}$
  - Radiation power (at $I = 1\,\mathrm{A}$): $7.2\,\mathrm{kW}$



$$E_c = \frac{3\,\hbar\,c\,\gamma^3}{2\,\rho}$$

Synchrotron radiation

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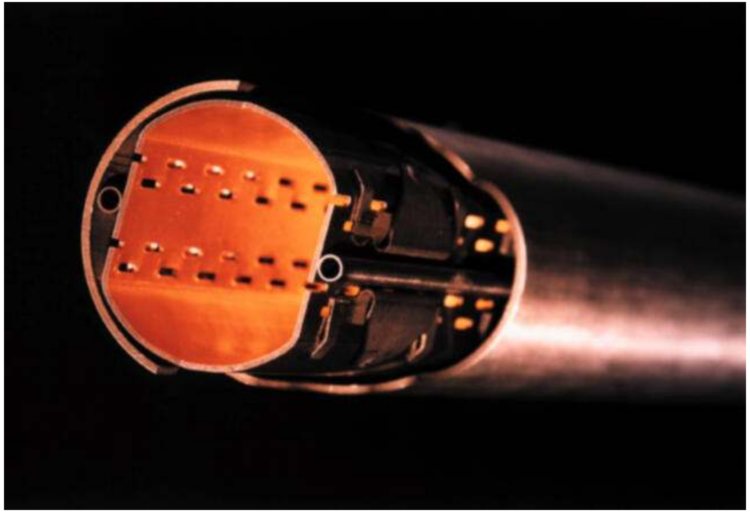
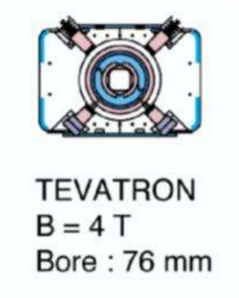
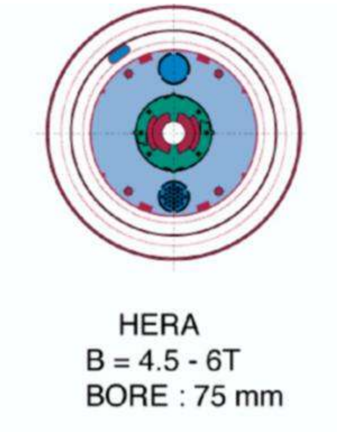
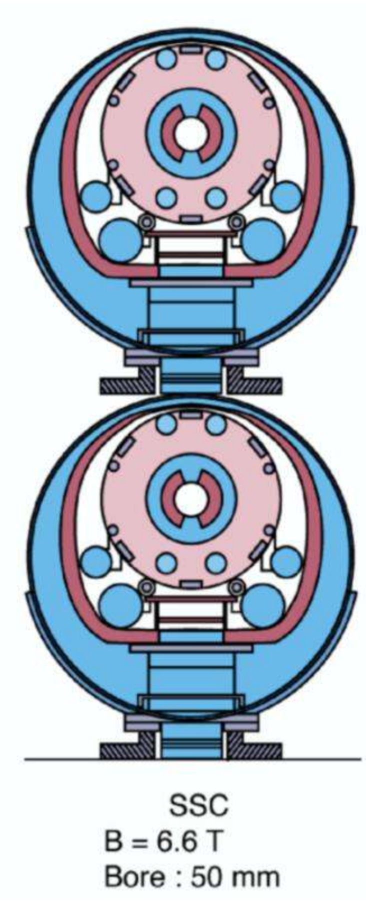


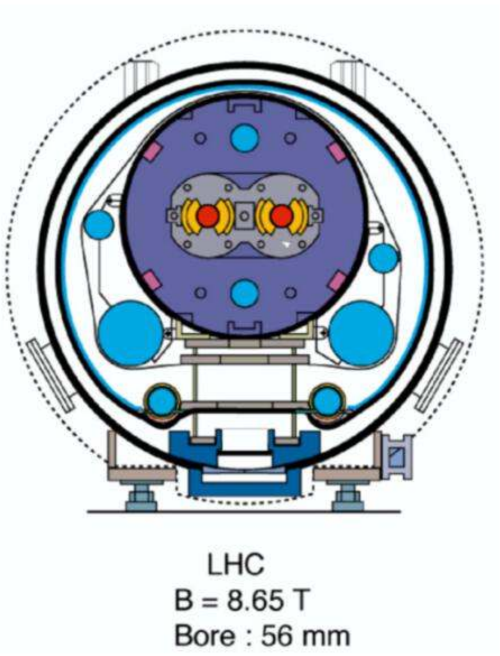
beam screen to protect superconductor from SR

SC magnets in comparison



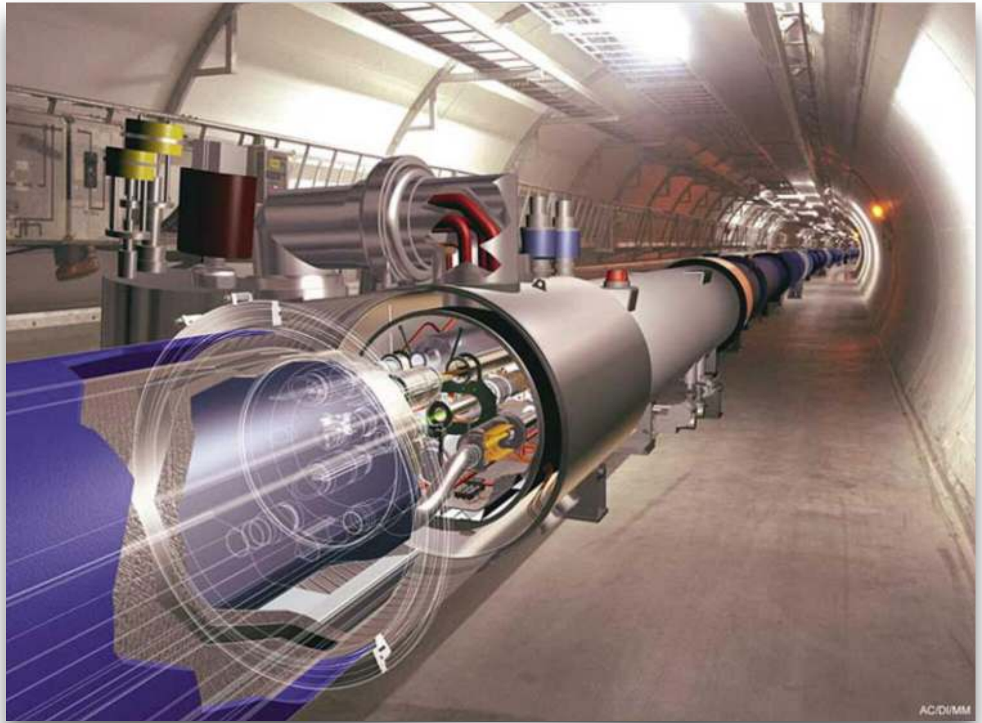






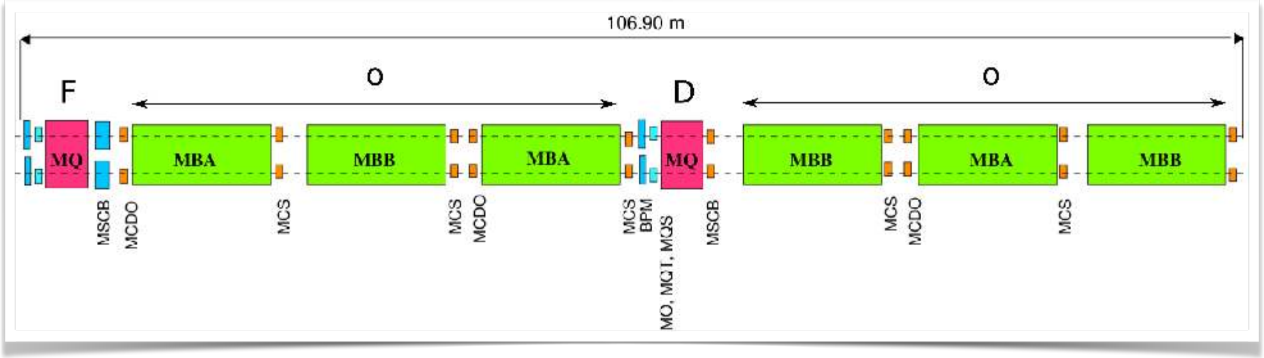
O. Brünning (CERN)

Cryomodule in the tunnel



The LHC under construction

The LHC lattice



- For highest beam energies $\oint B\,\mathrm{d}s$ must be maximized.
- Because of technical limitations of the magnetic field of the dipoles (quenches), the field must be distributed → 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 beam

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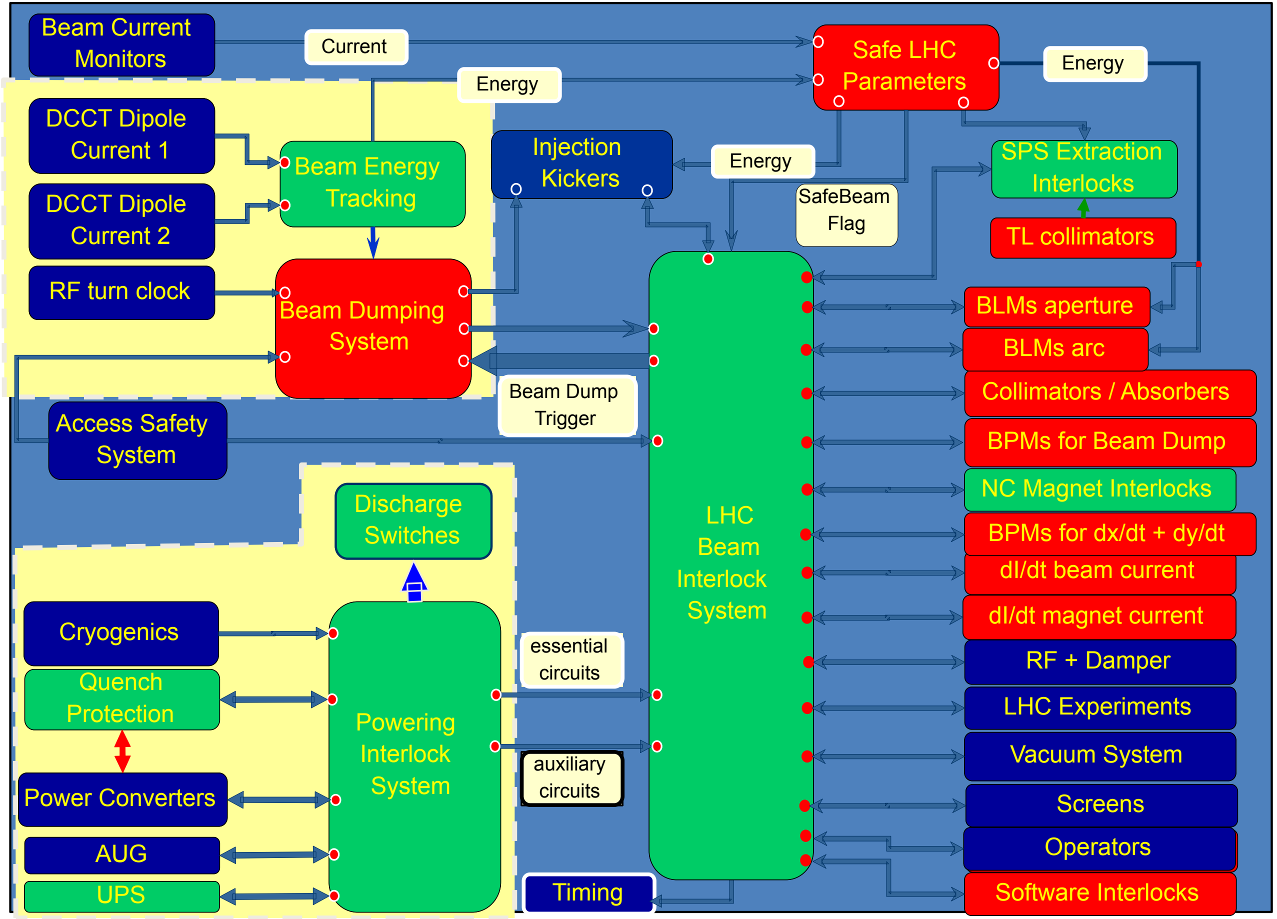
	LEP2	LHC
Momentum at flat-top (TeV/c)	0.1	7
Dipole field at flat-top (T)	0.11	8.44
Luminosity (10^{32} cm^{-2}s^{-1})	1	100
Number of bunches	8	2808
Bunch population (10^{11})	4.2	1.15
Beam size (arc section)	1800/140 µm (h/v)	200-300 µm
Beam size (IP)	200/3 µm (h/v)	16 µm

single vs. double ring!

flat vs. round beam

- 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

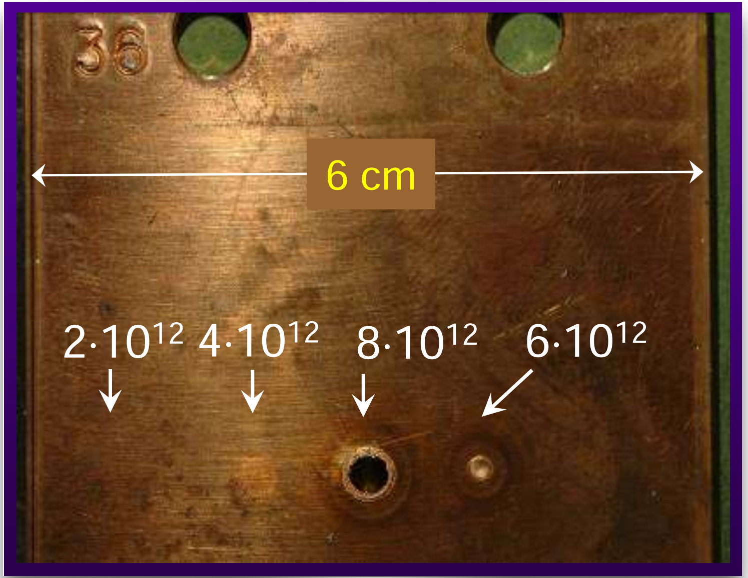
⇒ **Active beam protection required (beamloss monitors, interlocks, & beam collimation)**



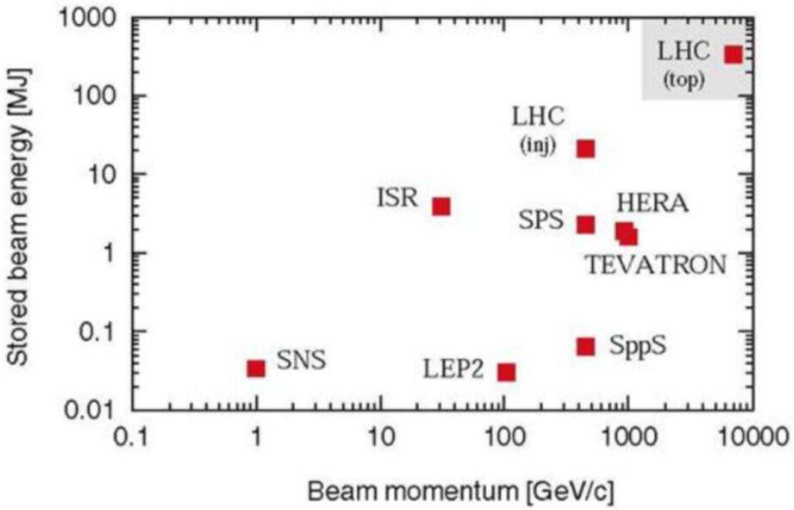
- LHC machine protection & safety
- no comment…

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

Hydrodynamic tunneling experiment at HiRadMat

F. Burkart, PhD thesis

- 15 copper cylinders exposed to SPS beam
- L=10 cm, 4 cm radius

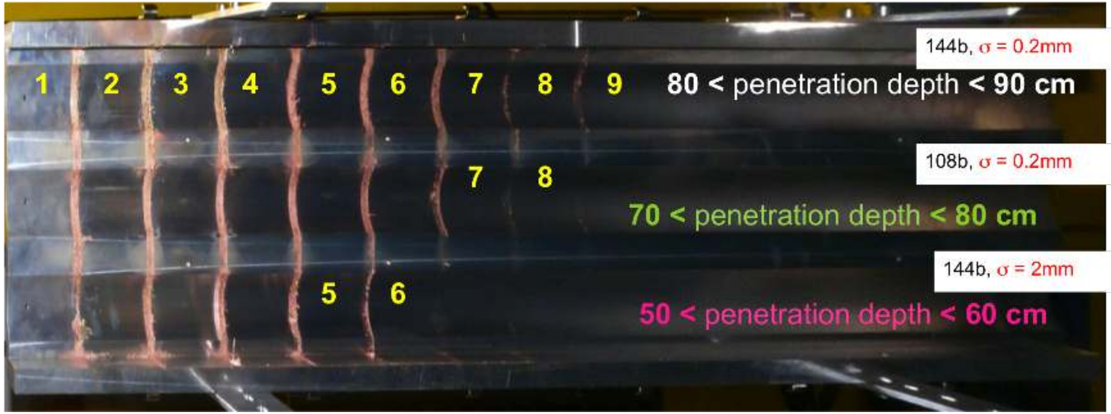
Experimental results I

- Beam energy: 440 GeV
- Bunch intensity: 1.5×10^{11} protons,
- Bunch length 0.5 ns, bunch separation 50 ns

target 3

target 2

target 1



top cover of the experimental setup after irradiation with traces of melted copper

F. Burkart, PhD thesis

Experimental results: target 3

front back

Target 3: first cylinder

front back

Target 3: second cylinder

F. Burkart, PhD thesis

Hydrodynamic tunneling

- Heated material undergoes phase transition
  - liquefaction
  - evaporation
  - weakly ionised plasma
- High temperature creates high pressures
  - launches radially outgoing shock wave
  - substantial density depletion along axis
- Subsequent bunches penetrate much deeper into the target.

F. Burkart, PhD thesis

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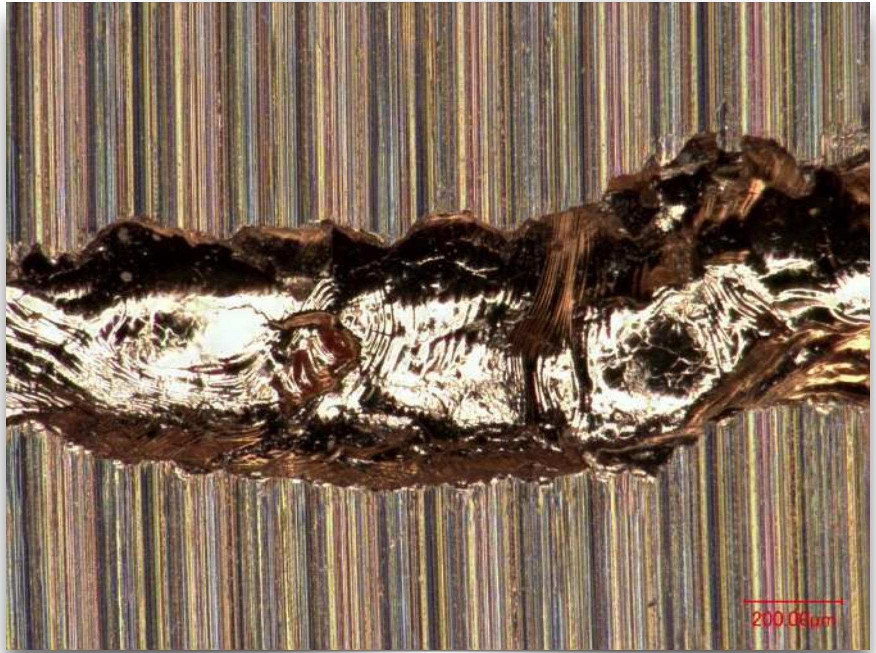
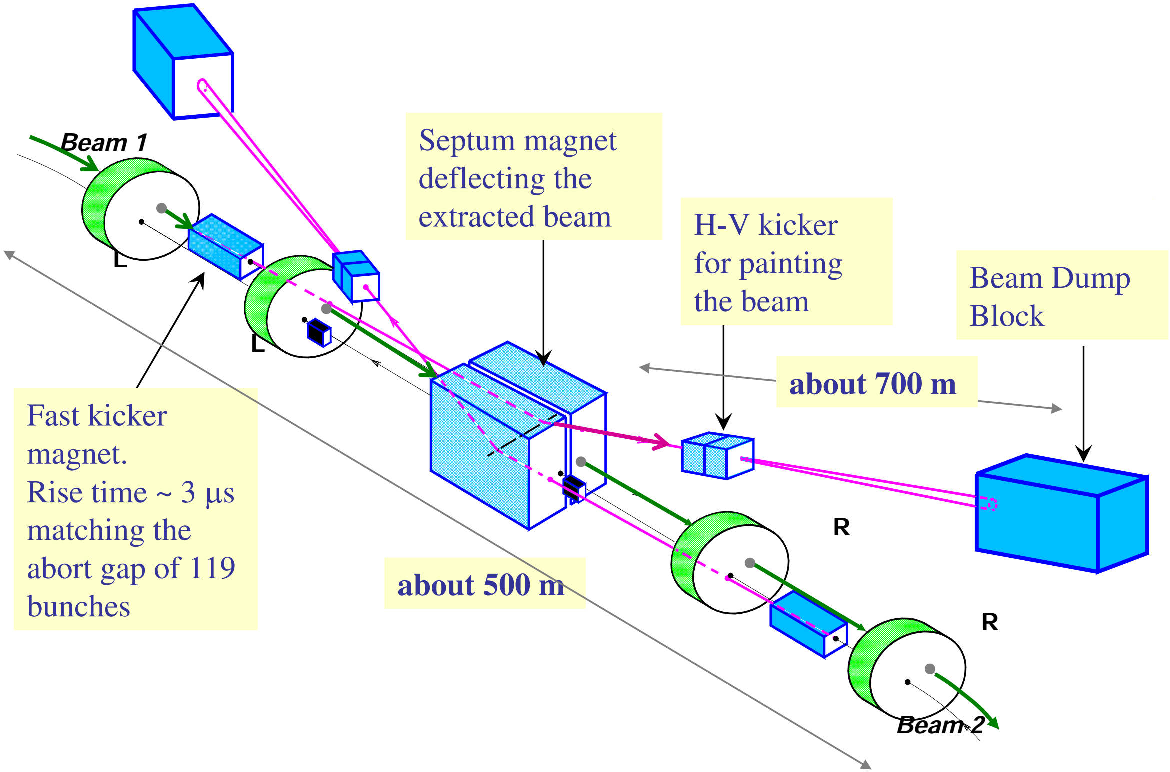
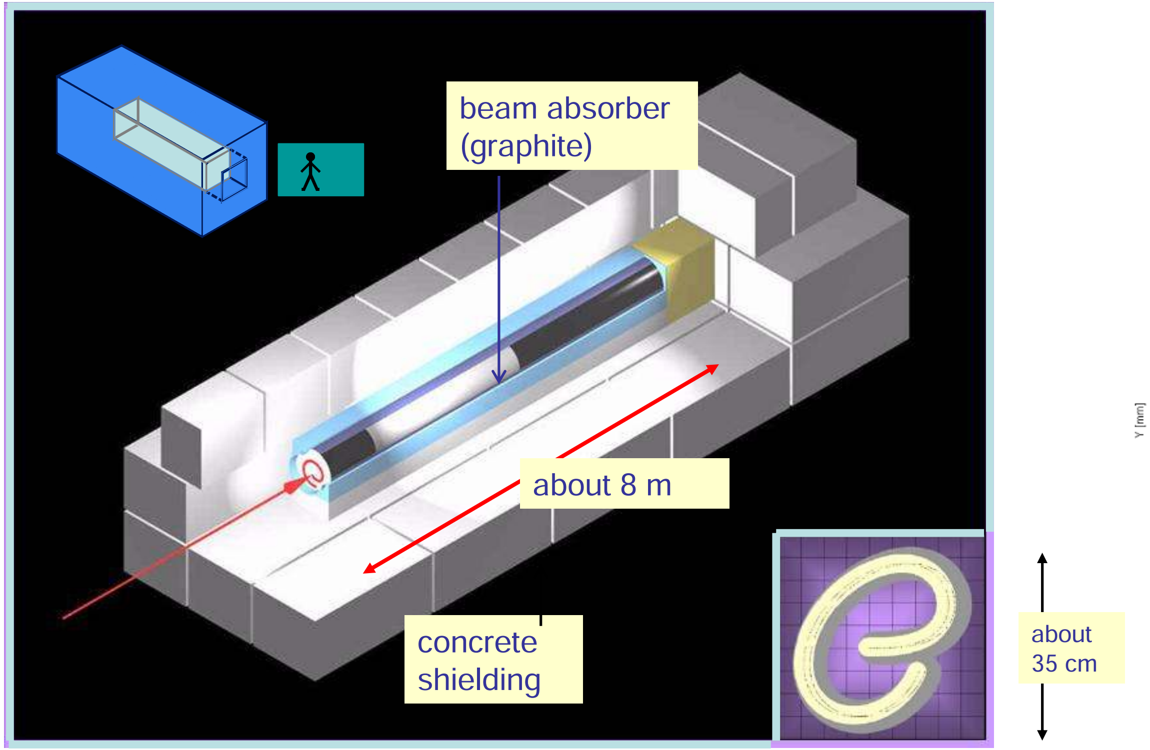


F. Burkart, PhD thesis

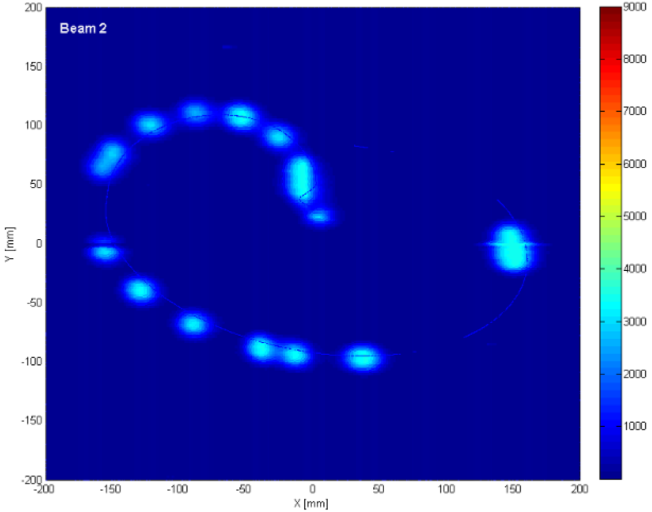
The LHC beam dump



The beam dump block



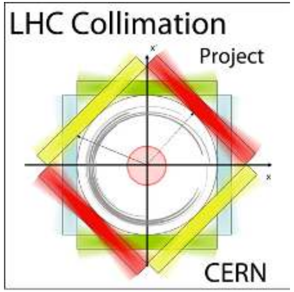
Test dump of 16 bunches

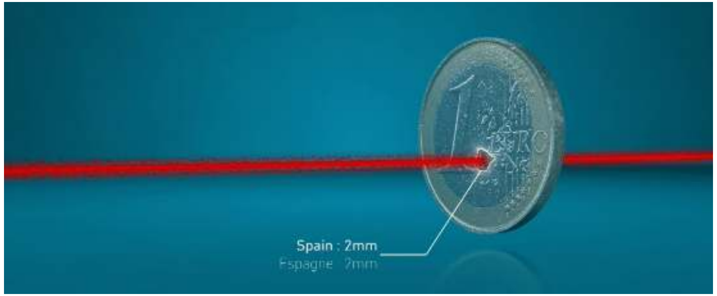


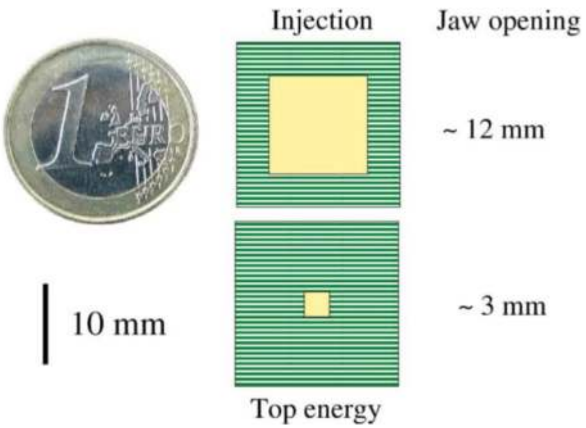
in < 90 µs!!!

Beam loss in superconducting environment

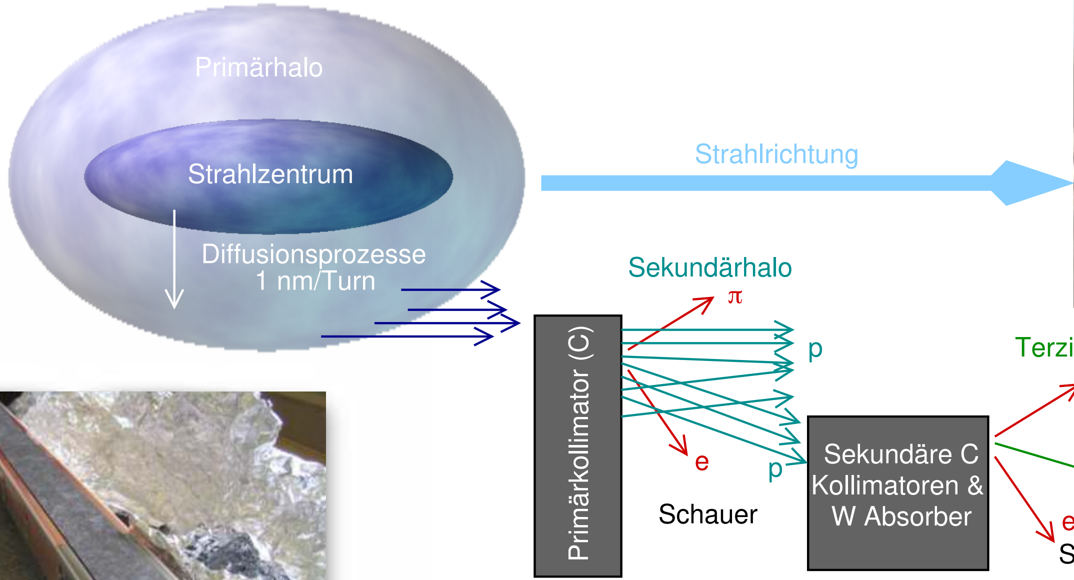
- During a sudden beam loss 2 MJ/mm are being deposited in the magnet within 200 ns.
  → quench of the superconducting magnet!
- This energy corresponds to 0.5 kg TNT.
- An LHC dipole quenches at 8.5 W/m.
- Maximum beam loss: at 7 TeV: 1% in 10 s corresponding to 500 kW
- A sophisticated system of multi-stage collimators prevents energy deposition and thus quenching.

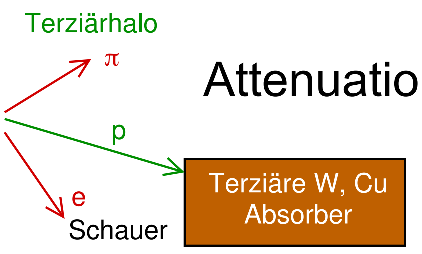


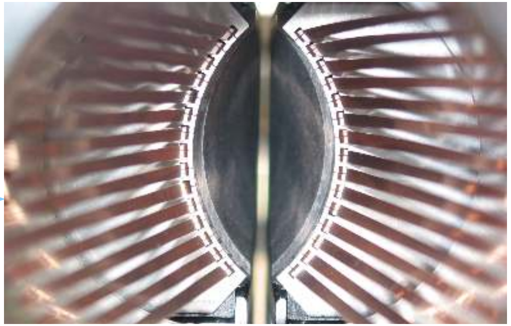




Collimation







Attenuation of > 10^5

- 122 collimators of 8 types in total
- Problem: C is radiation hard, but has a high impedance!

HiLumi HL-LHC PROJECT

LHC Injectors Upgrade

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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} cm^{-2} s^{-1}]	1.00	7.18
Virtual luminosity with CCs [10^{34} cm^{-2} s^{-1}][4]	–	19.54
Levelled luminosity [10^{34} cm^{-2} 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] $\mathscr{L}_{peak}\ R_1/R_0$, 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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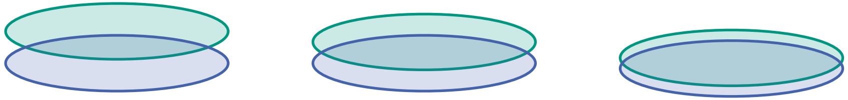
Collision event with 7 vertices

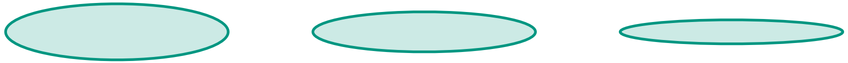
Collision event with 25 vertices

Luminosity levelling

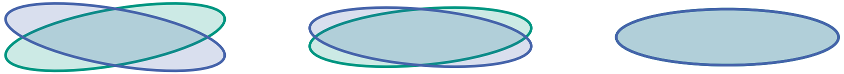
- Bunch overlap



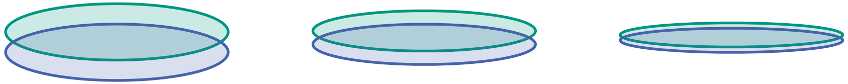
- β^* squeeze



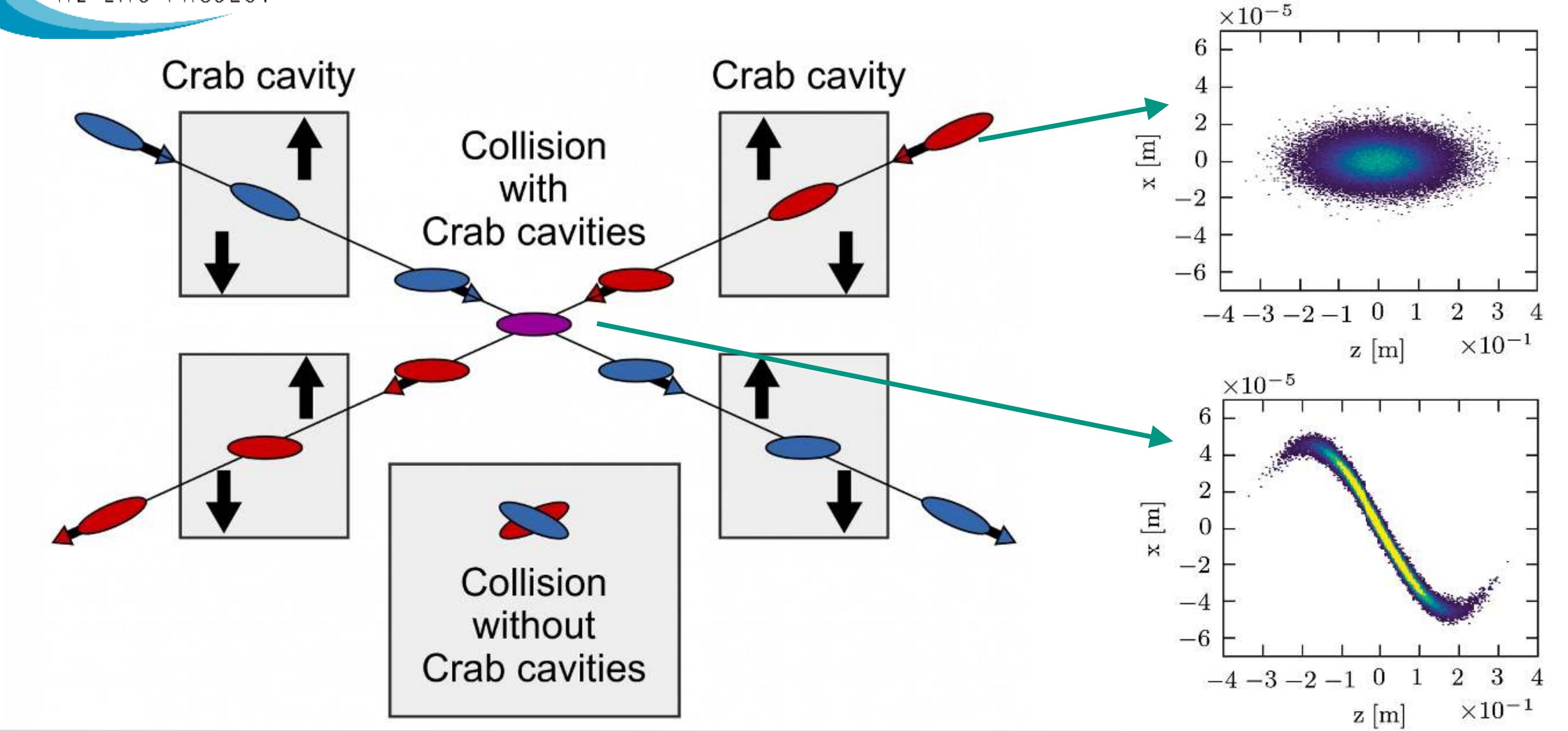
- Crab cavities



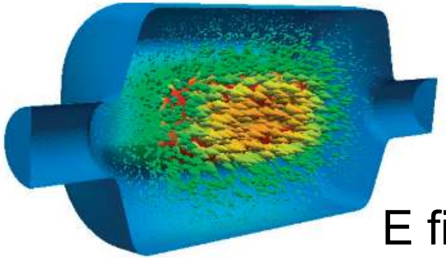
- Combinations

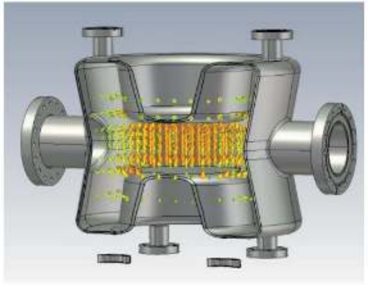


Crab cavities

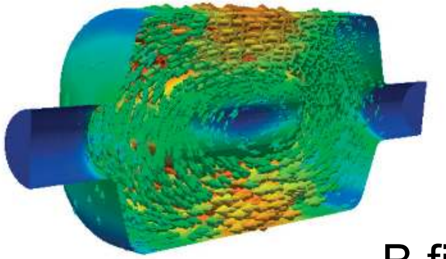


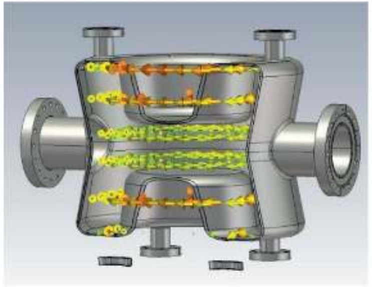
Crab cavities II



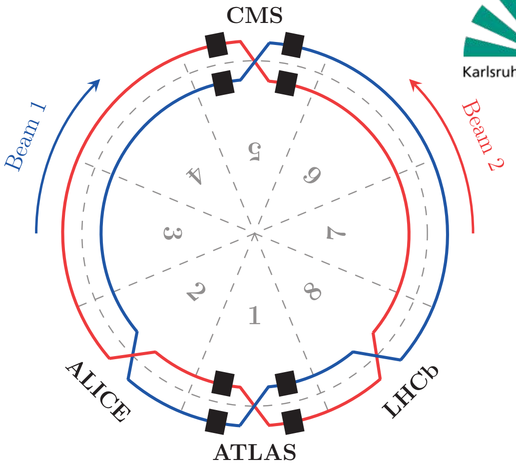


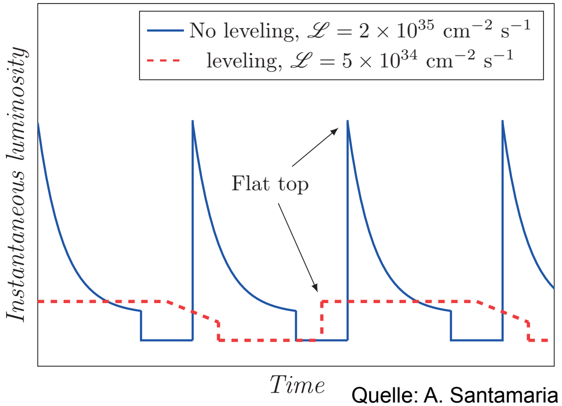
E field



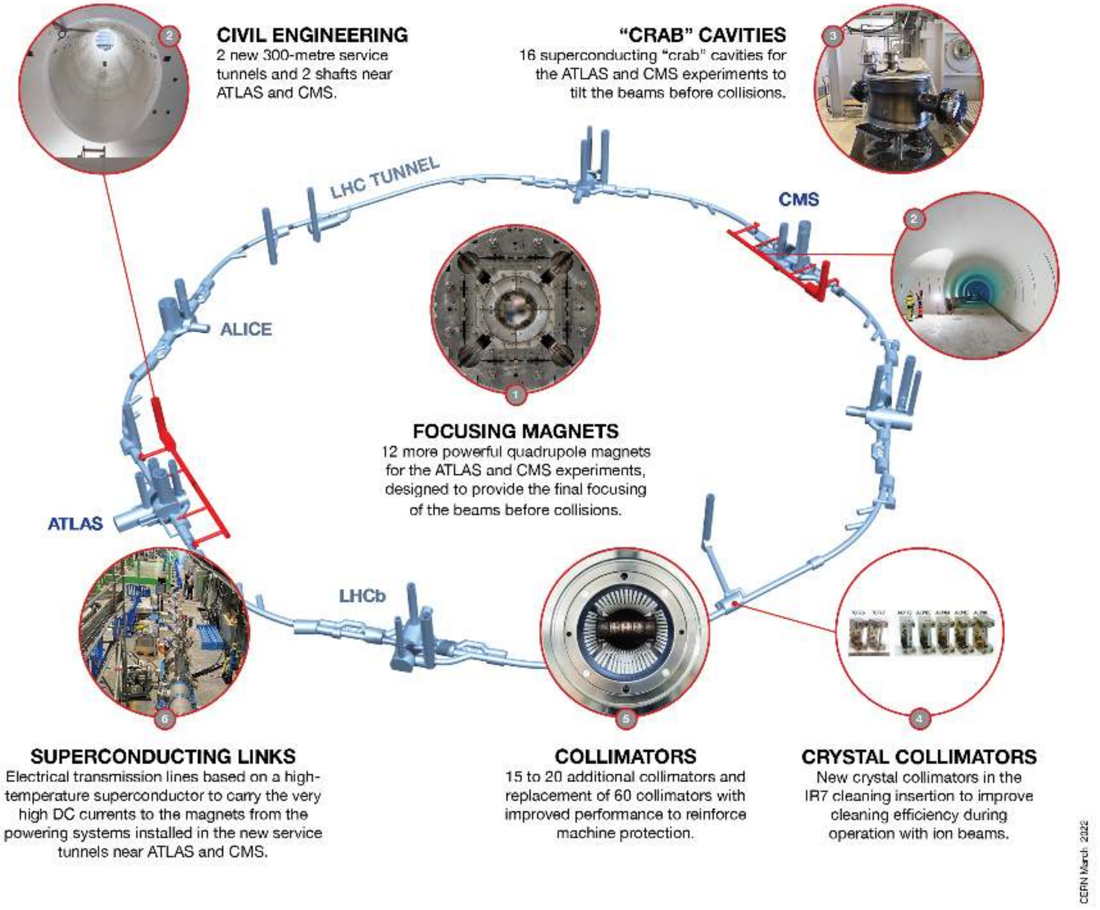


B field

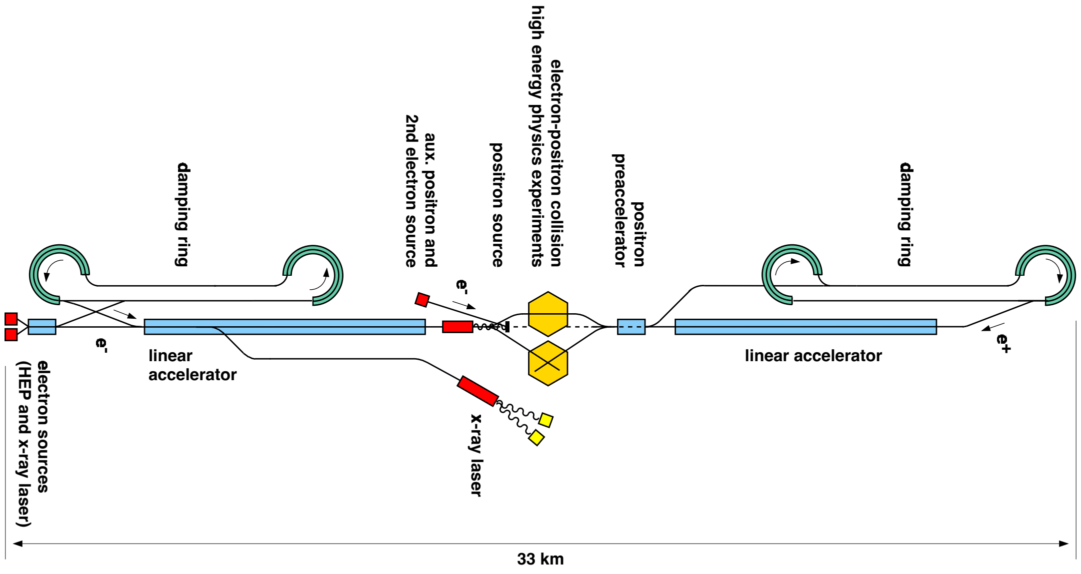


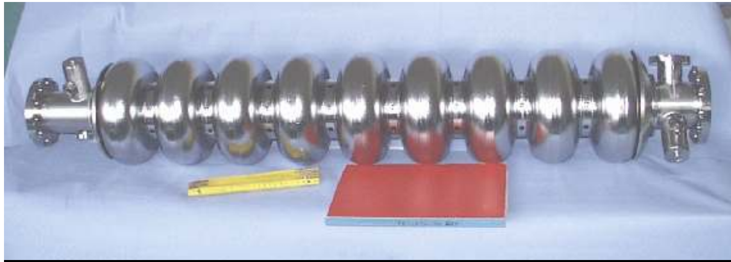


Quelle: A. Santamaria Garcia, PhD thesis


CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near ATLAS and CMS.
"CRAB" CAVITIES
16 superconducting "crab" cavities for the ATLAS and CMS experiments to tilt the beams before collisions.
LHC TUNNEL
CMS
ALICE
FOCUSING MAGNETS
12 more powerful quadrupole magnets for the ATLAS and CMS experiments, designed to provide the final focusing of the beams before collisions.
ATLAS
LHCb
SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry the very high DC currents to the magnets from the powering systems installed in the new service tunnels near ATLAS and CMS.
COLLIMATORS
15 to 20 additional collimators and replacement of 60 collimators with improved performance to reinforce machine protection.
CRYSTAL COLLIMATORS
New crystal collimators in the IR7 cleaning insertion to improve cleaning efficiency during operation with ion beams.
CERN March 2022

TESLA, X-FEL and ILC





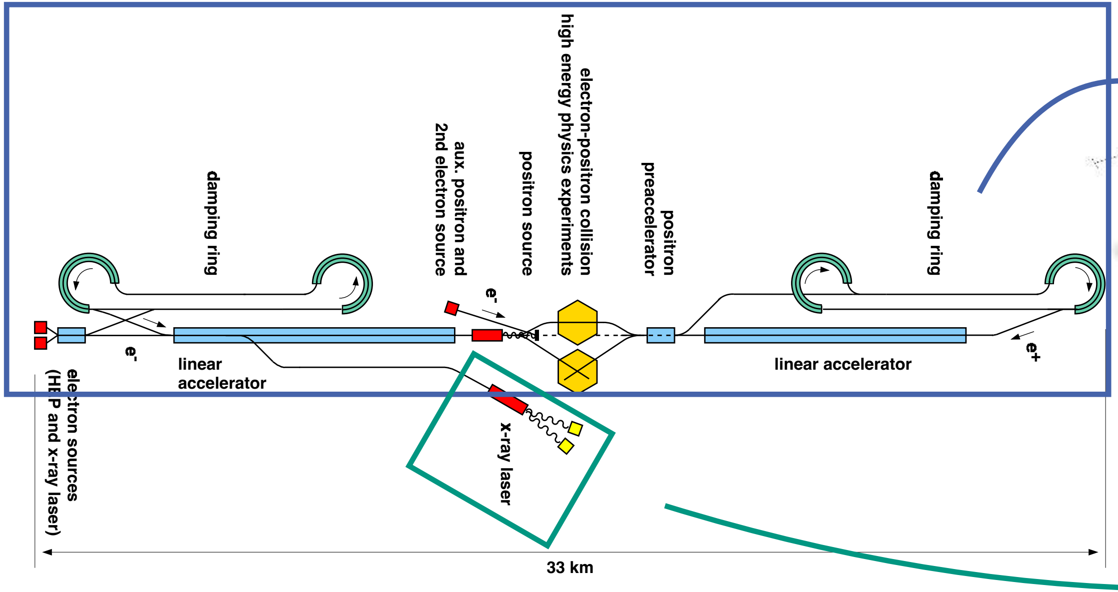
- "1 TeV energy superconducting linear accelerator"
- 500 GeV beam energy

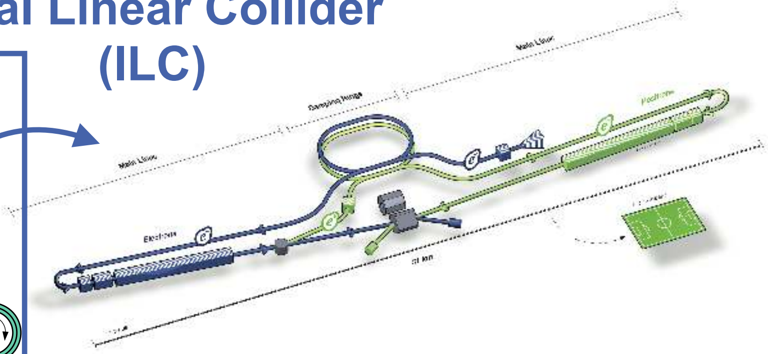
Quelle: TESLA Technical Design Report

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

TESLA, X-FEL and ILC

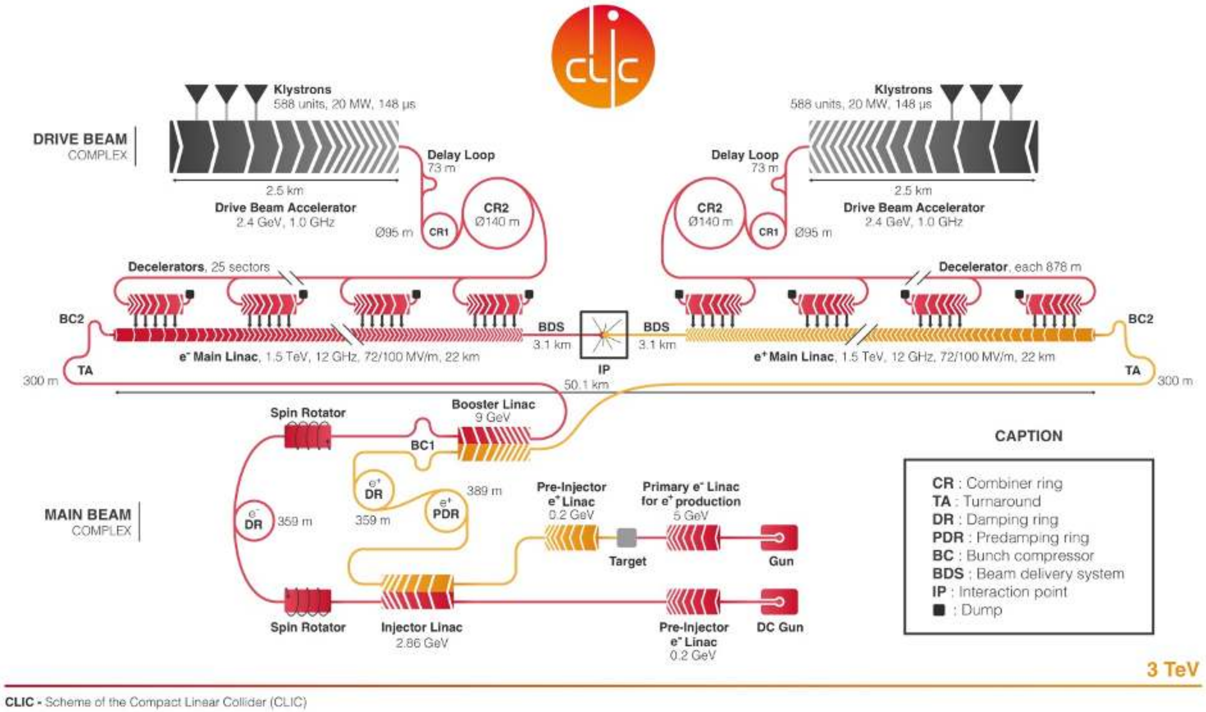
International Linear Collider (ILC)





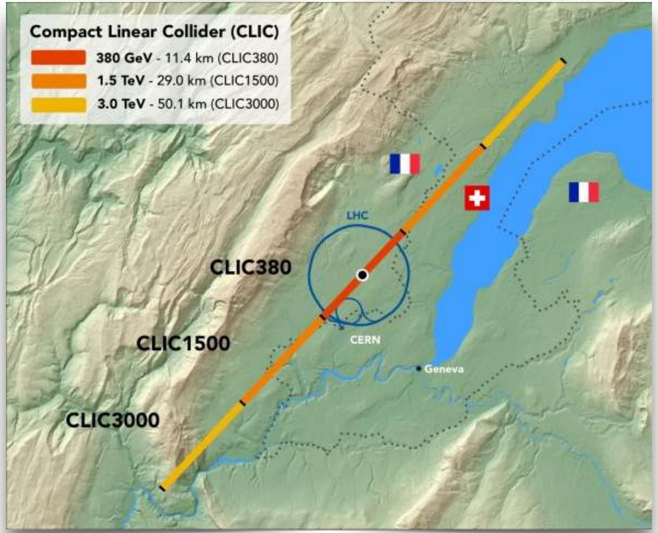
European X-FEL

CLIC — Compact Linear Collider



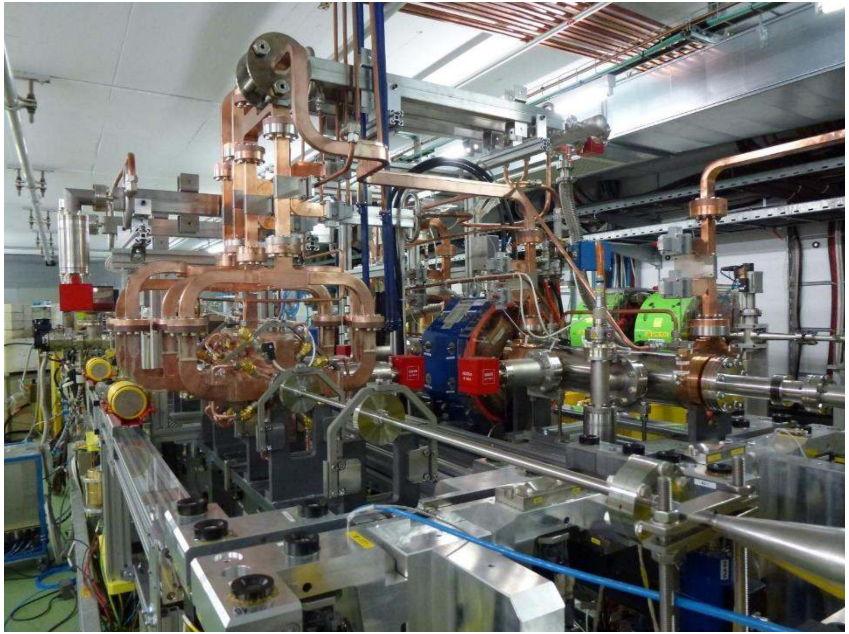
CLIC - Scheme of the Compact Linear Collider (CLIC)

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

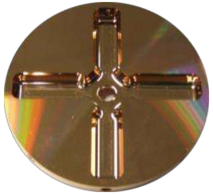


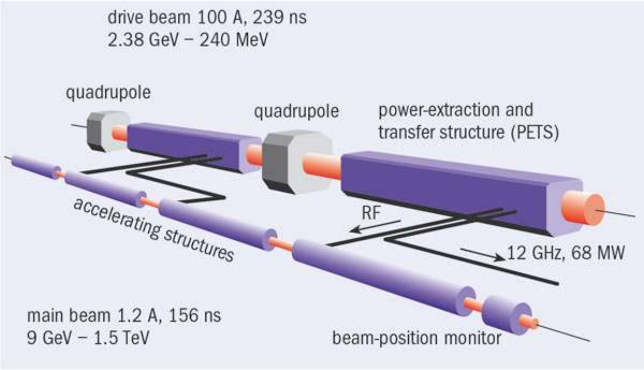
CERN - https://cds.cern.ch/record/2297076

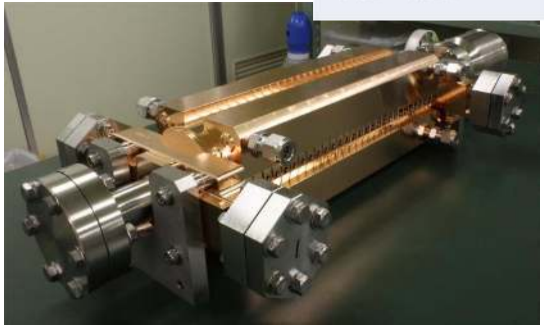
Two-beam acceleration



CLIC test facility







S. Staples — Future Collider CAS

100 MV/m accelerating gradient achieved!

Muon Collider

- Elementary particles
- High energy
- Low synchrotron radiation

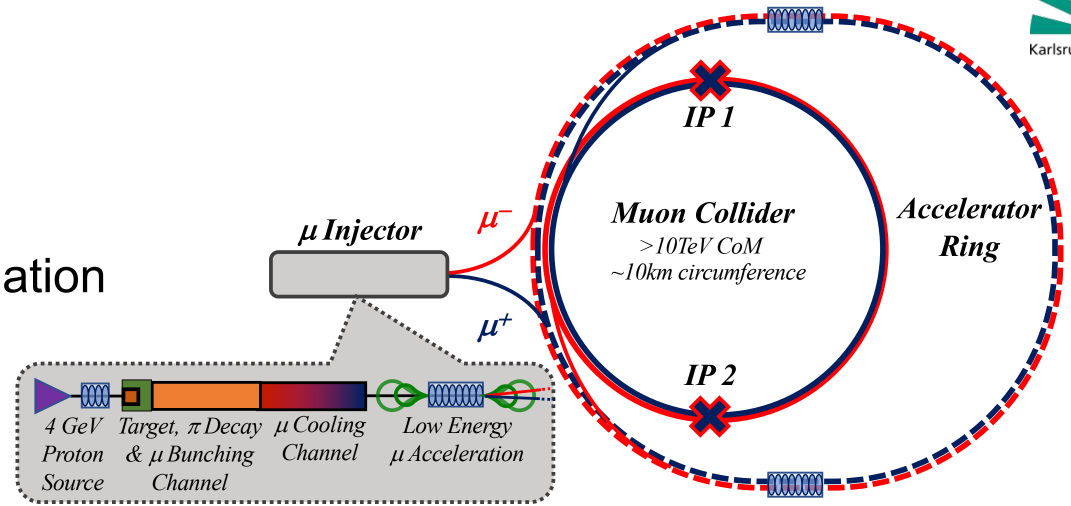
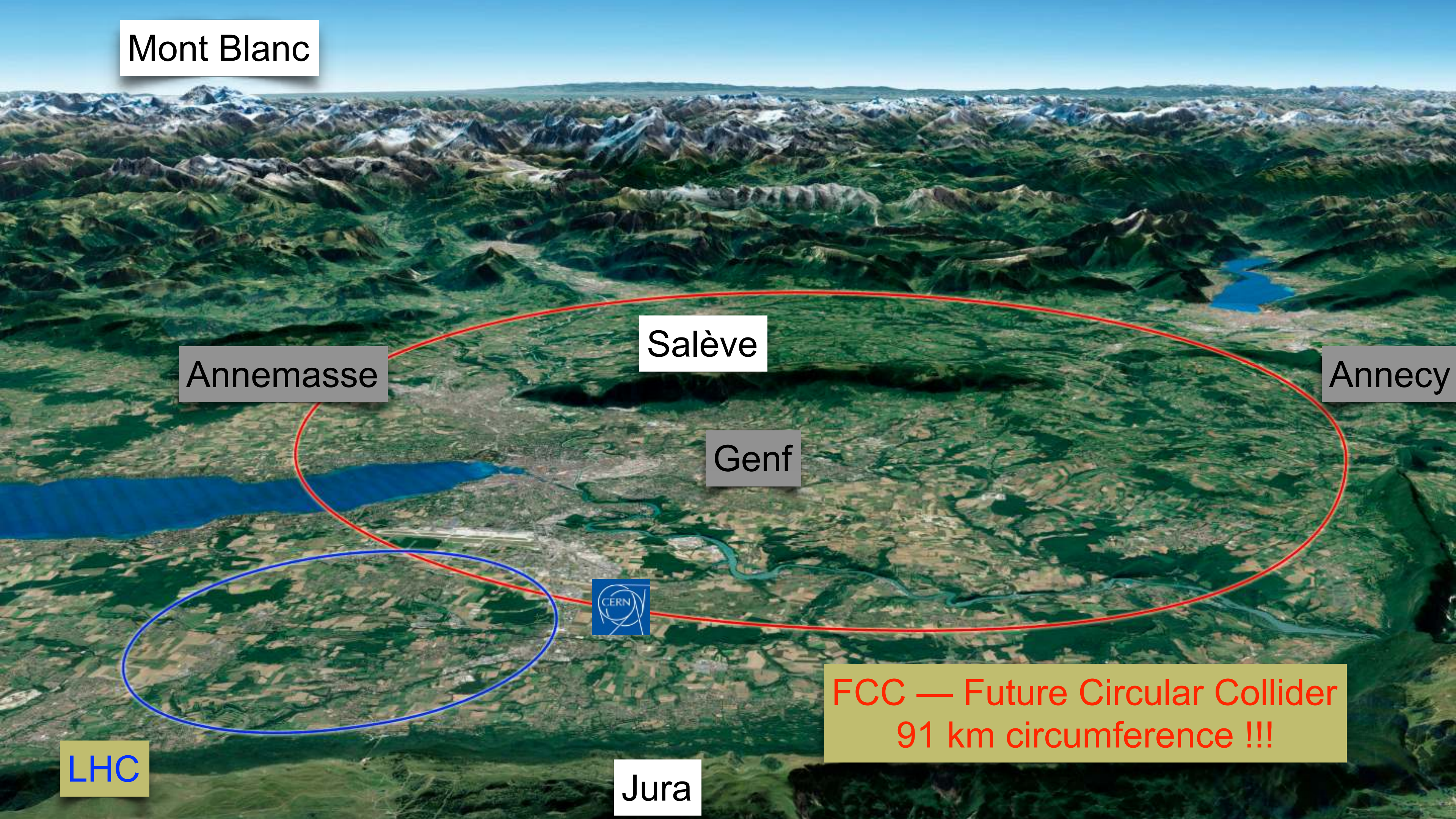


Fig. 1: A conceptual scheme for the Muon Collider

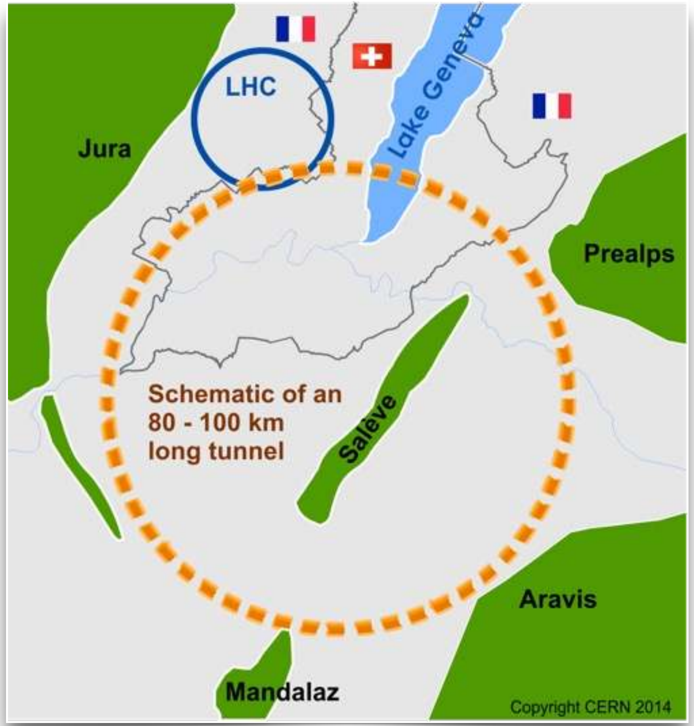
Design challenges

- 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


Mont Blanc
Salève
Annemasse
Annecy
Genf
CERN
FCC — Future Circular Collider
91 km circumference !!!
LHC
Jura

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



Future Circular Collider Study

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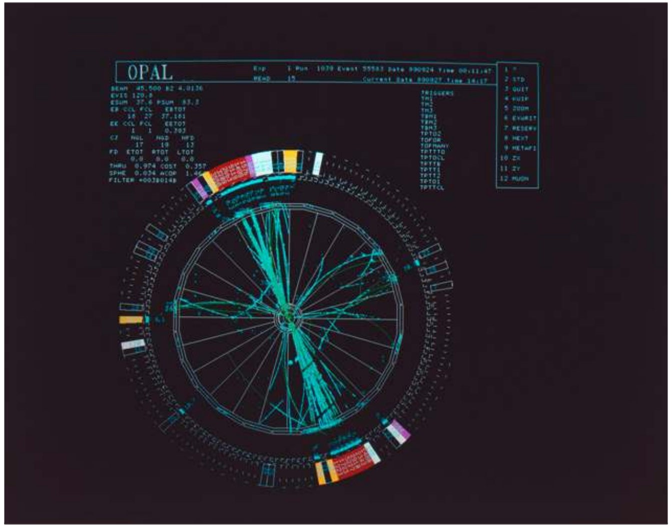
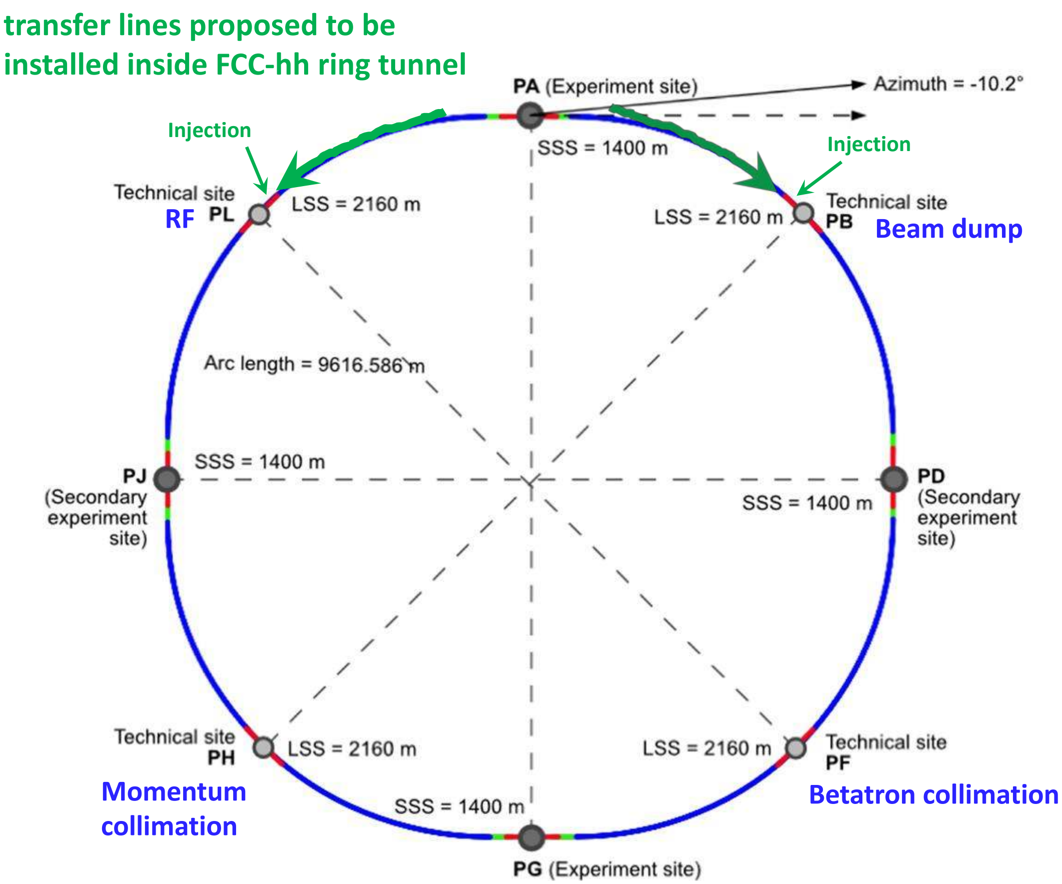


https://cds.cern.ch/record/2554156

FCC-hh

- 50 TeV beam energy
- 16 T Nb_3SN magnets
- $U_0 \approx 5$ MeV/turn

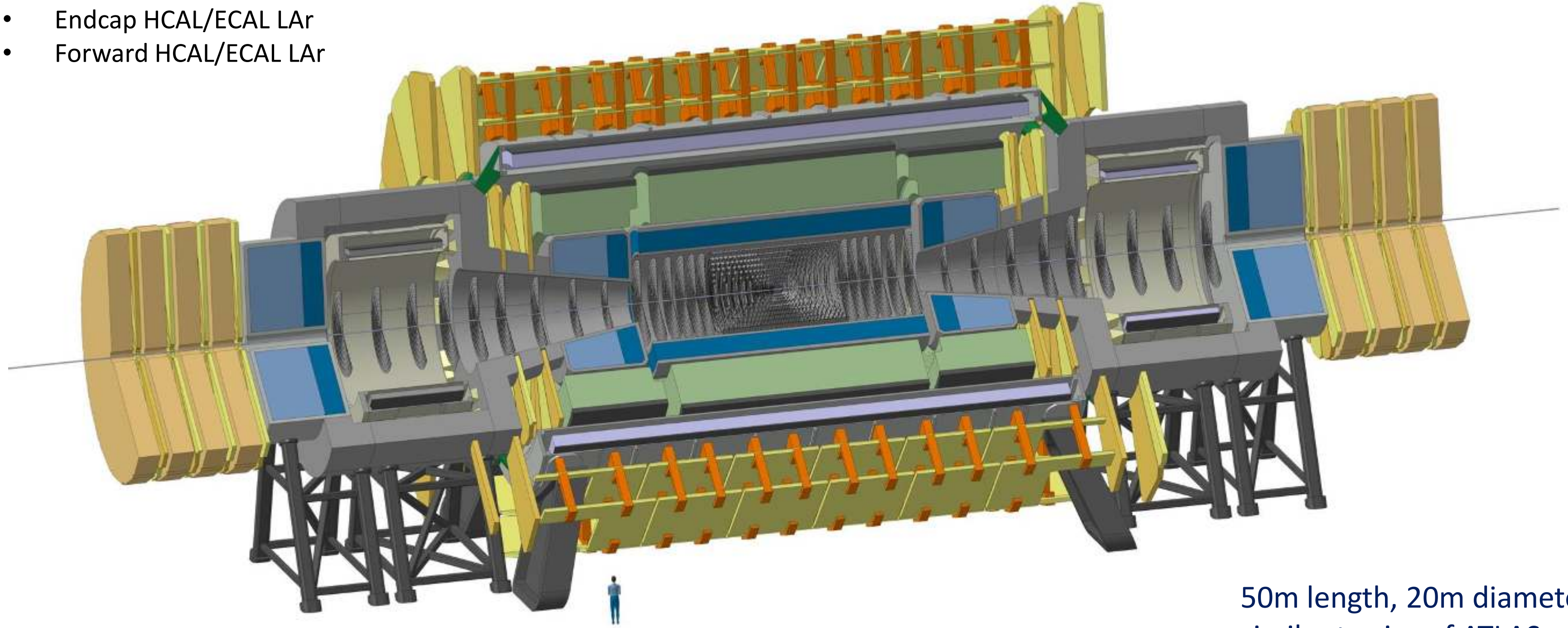


Vacuum tests of the beam screen prototype at KARA!!!

- 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

Karlsruhe Institute of Technology



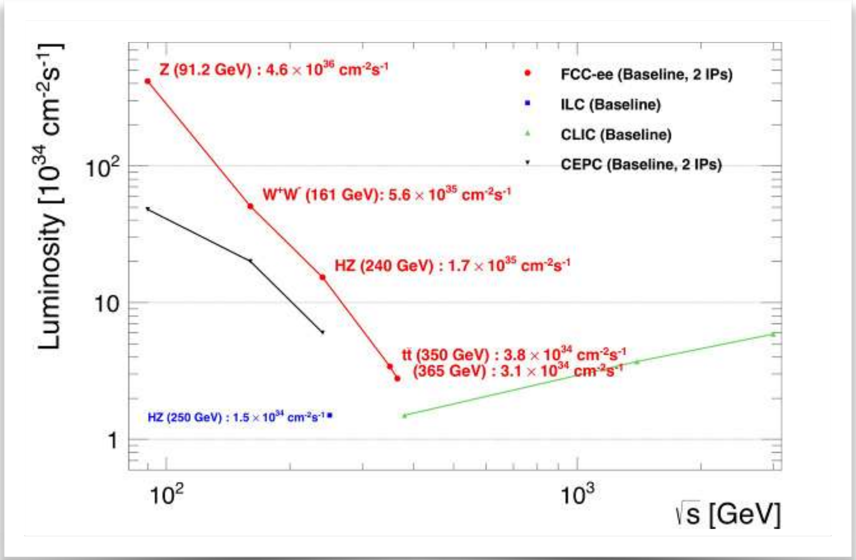
50m length, 20m diameter
similar to size of ATLAS

W. Riegler: FCC Week Brussels

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!**

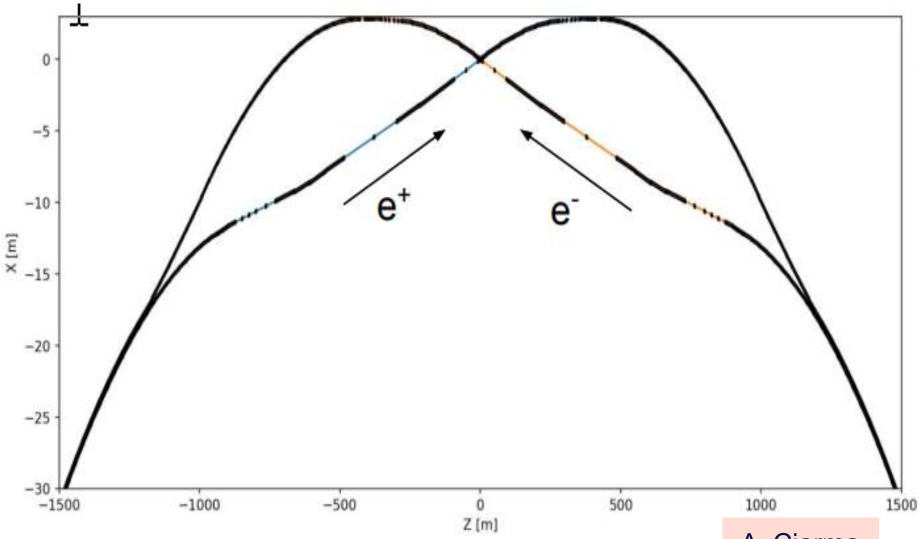
Energy (GeV)	# bunches	# particles per bunch (10^{11})	Luminosity (10^{34}/cm^{2}s)
45.6	16640	1.7	460
80.0	2000	1.5	56
120.0	328	1.8	17
182.5	48	2.3	3.1



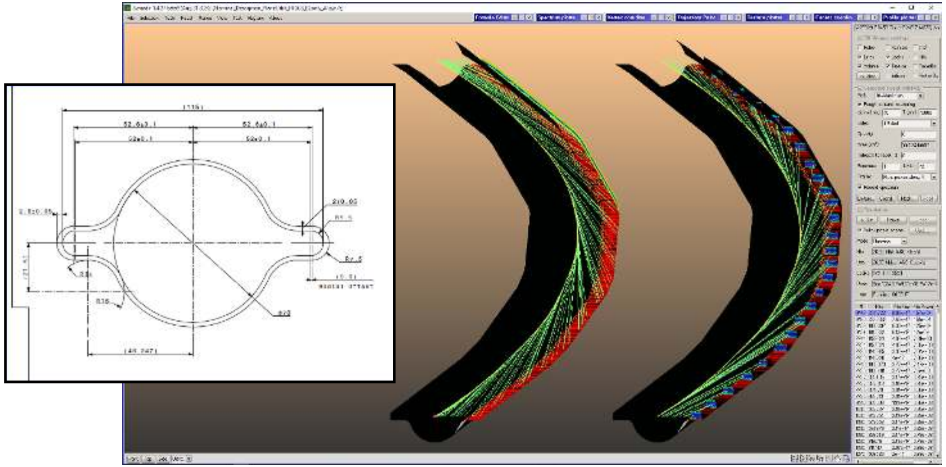
FCC-ee Design Report: Baseline luminosities expected to be delivered for different e^+e^- collider projects

A design dominated by synchrotron radiation

- Interaction region layout to avoid deflection in front of detector



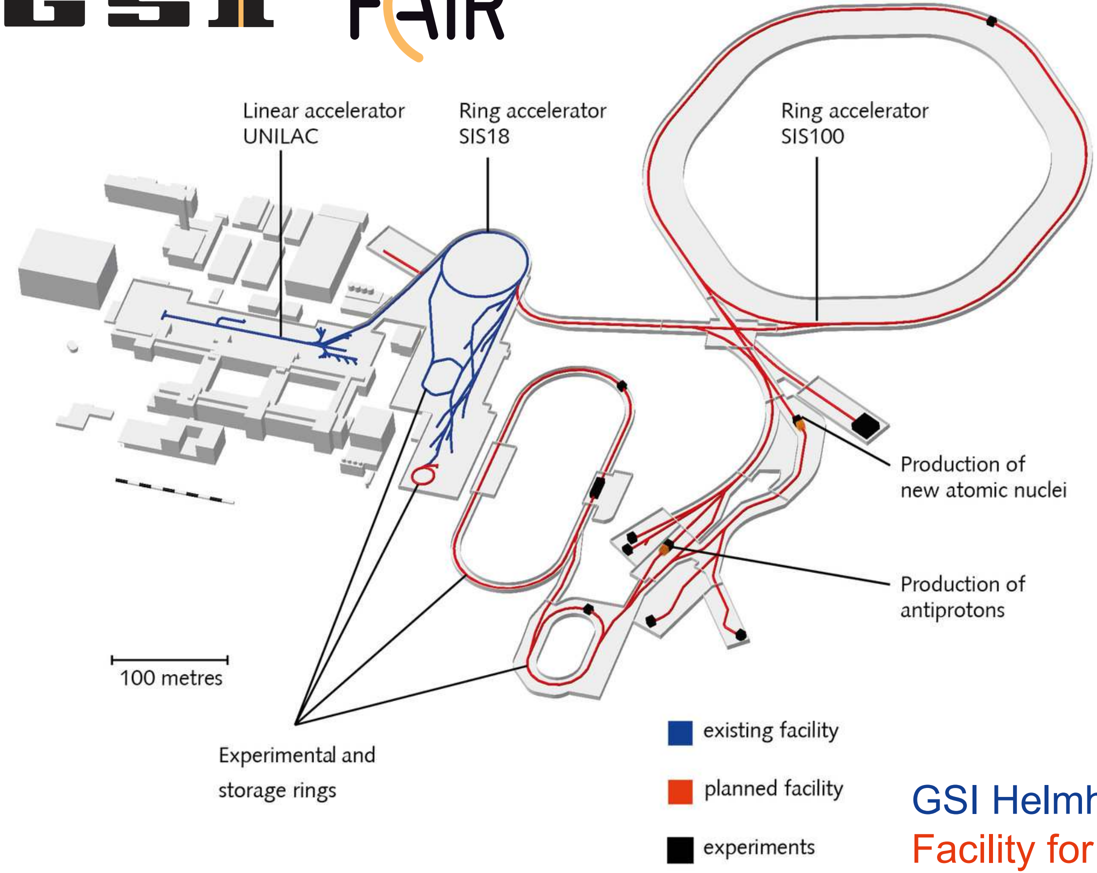
A. Ciarma



R. Kersevan

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


GSI
FAIR
© GSI/FAIR, Zeitrausch



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

construction site September 2024

construction site September 2024

magnet of the Super-FRS

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

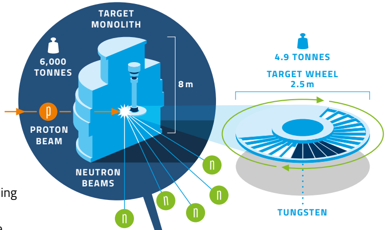
How does it work?

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.

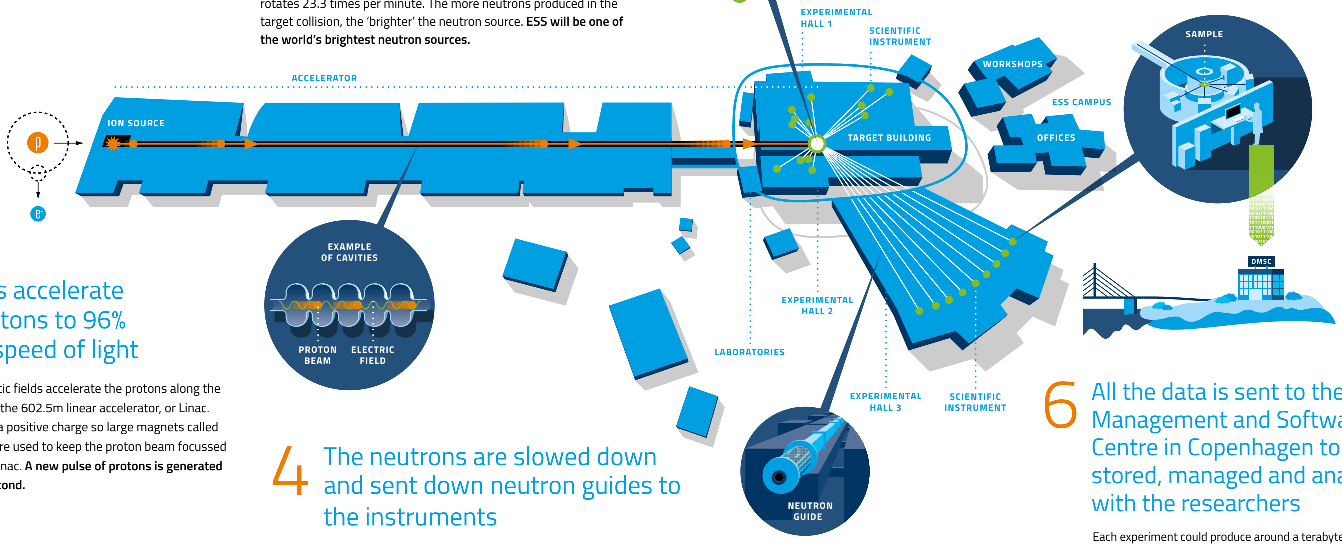
3 The protons strike the target and high-energy neutrons are released

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.**



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.



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

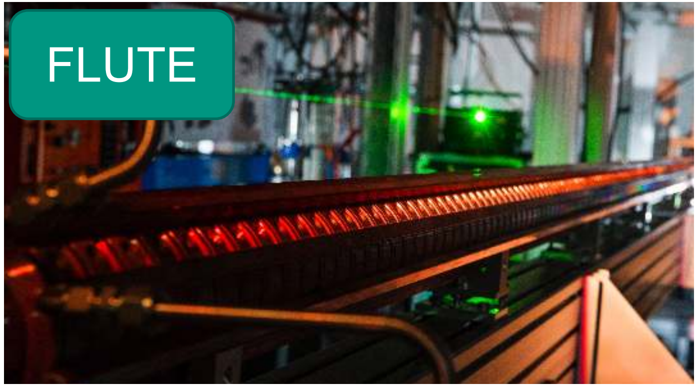
The guides are extremely stable, with highly reflective walls, so that as many neutrons as possible reach all the way to the end. **Some of these neutron guides are up to 160 m in length!**

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

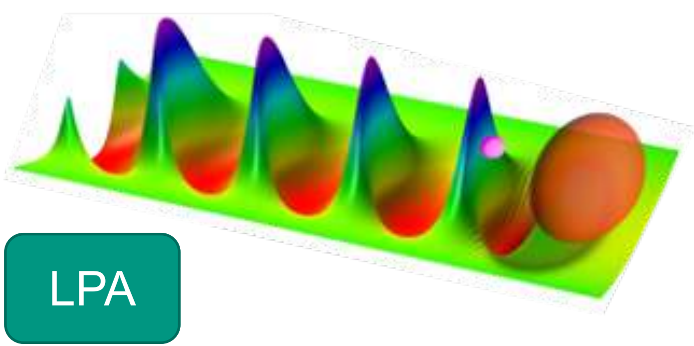
Each experiment could produce around a terabyte of data – **that is around 500 hours of movies!** Software and scientific computing experts help the researchers understand, visualise and interpret their results.

Karlsruhe Institute of Technology

Accelerator test facilities at IBPT/KIT



in operation

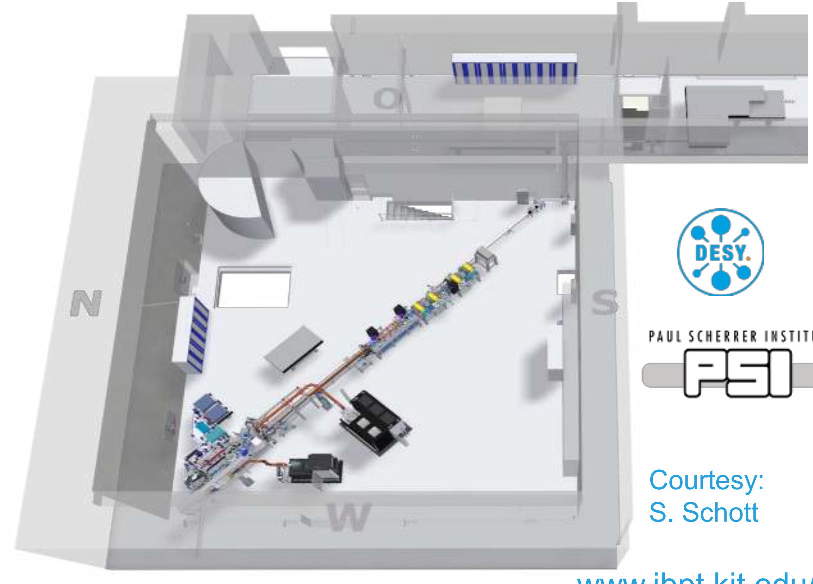


under construction

FLUTE: Accelerator Test Facility at KIT

- FLUTE (Ferninfrarot Linac- Und Test-Experiment)
  - Test facility for accelerator physics within ARD
  - Experiments with THz radiation

Final electron energy	~ 41	MeV
Electron bunch charge	0.001 - 1	nC
Electron bunch length	1 - 300	fs
Pulse repetition rate	5	Hz
THz E-Field strength	up to 1.2	GV/m



Courtesy:
S. Schott

www.ibpt.kit.edu/flute

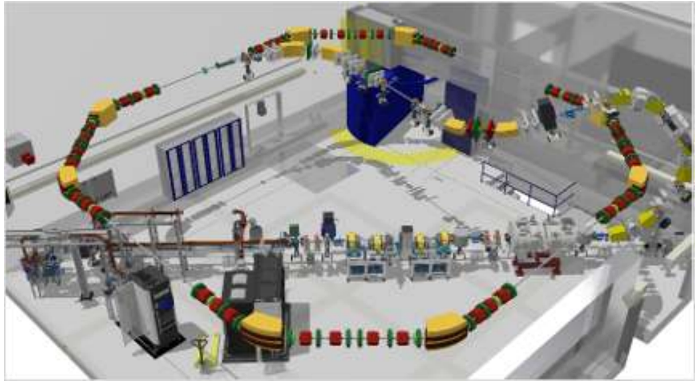
- R&D topics
  - Serve as a test bench for new beam diagnostic methods and tools
  - Systematic bunch compression and THz generation studies
  - Develop single shot fs diagnostics
  - Synchronization on a femtosecond level

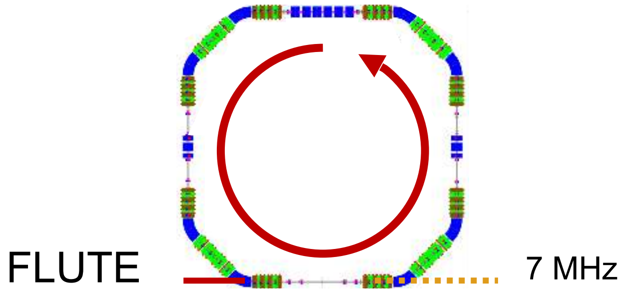
cSTART project at KIT

Karlsruhe Institute of Technology

*compact **St**orage Ring for **A**ccelerator **R**easearch and **T**echnology*

- Motivation: Storage of ultra-short (fs) electron bunches at high repetition rate
- Goal: **Injection & storage** of bunches produced by a laser plasma accelerator
- Unique design: lattice with high energy acceptance designed for bunches in **non-equilibrium state**





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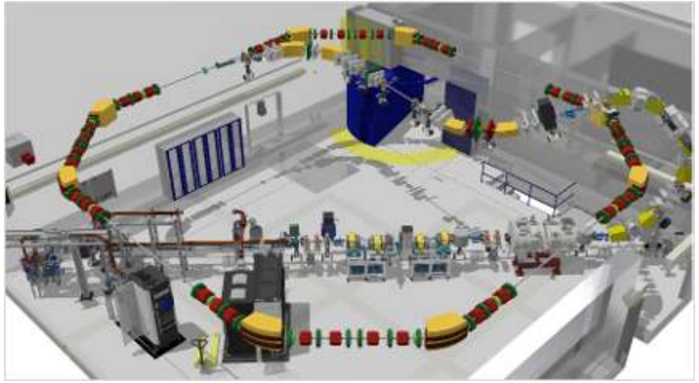
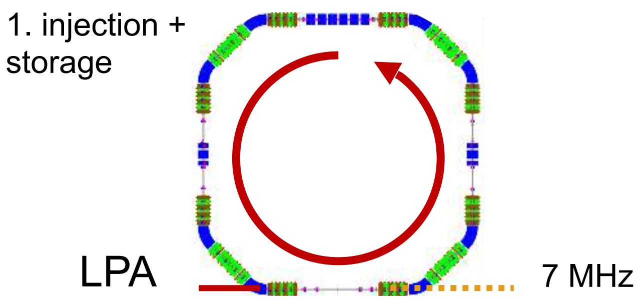
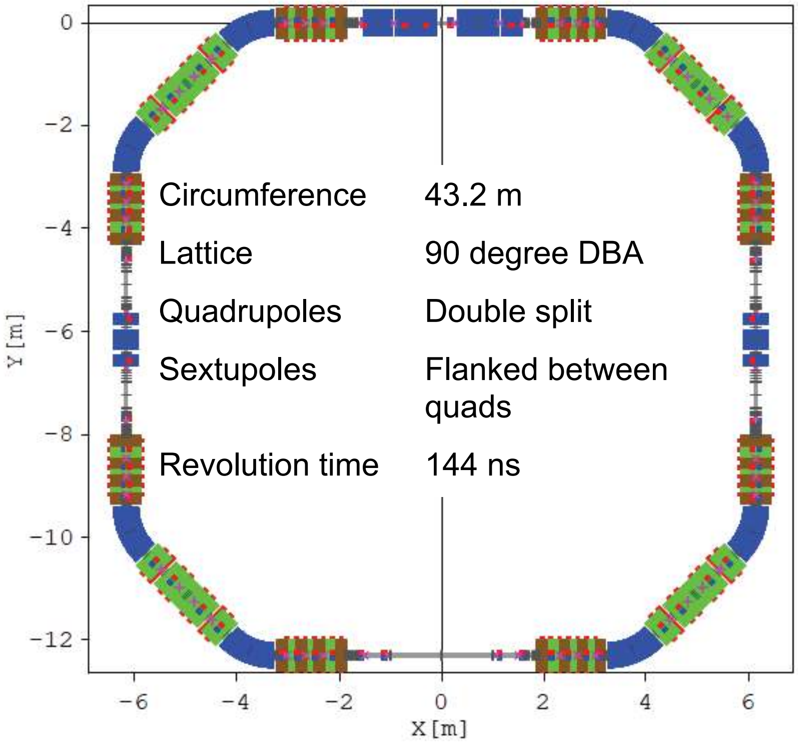




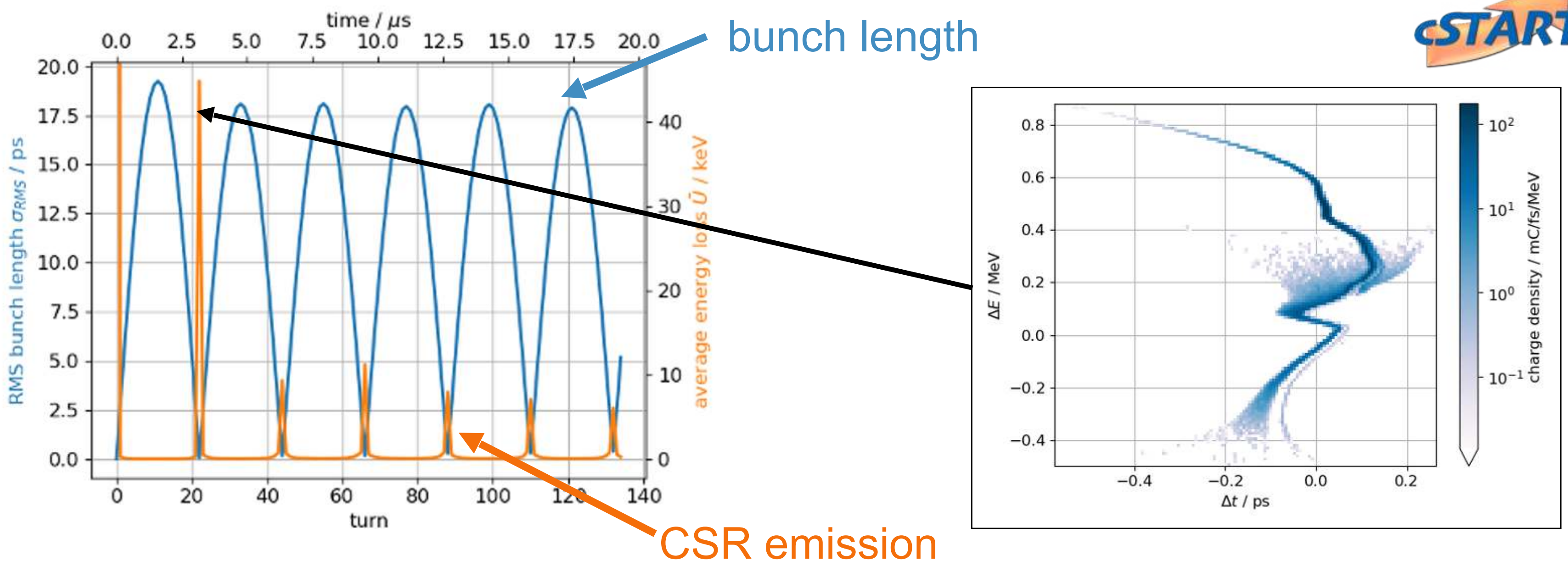
cSTART Project

- **Motivation:** Storage of ultra-short (fs) electron bunches with high repetition rate
- Compact storage ring with very large momentum acceptance and dynamic aperture
- Status:
  - Technical design and specification: finished
  - Injection line magnets: first magnets delivered, rest in production
  - Test diagnostics at KARA booster: ongoing



Circumference	43.2 m
Lattice	90 degree DBA
Quadrupoles	Double split
Sextupoles	Flanked between quads
Revolution time	144 ns

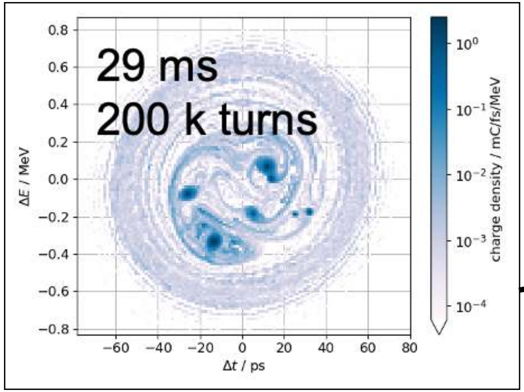
Short bunches in non-equilibrium at cSTART

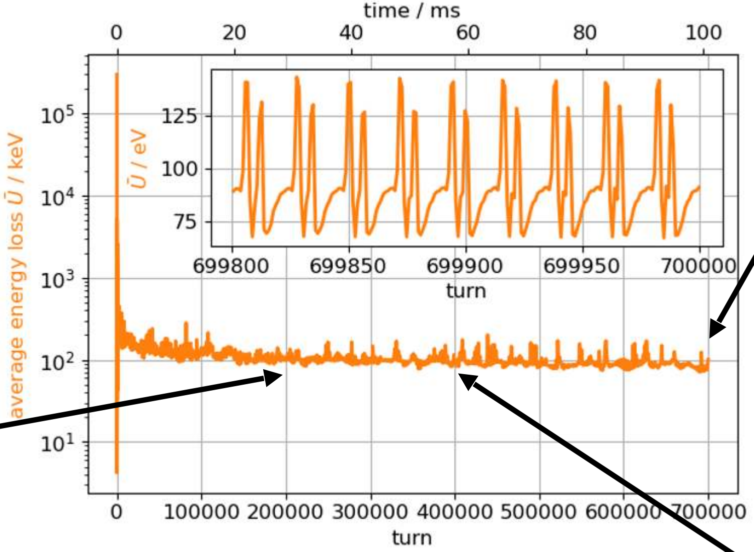


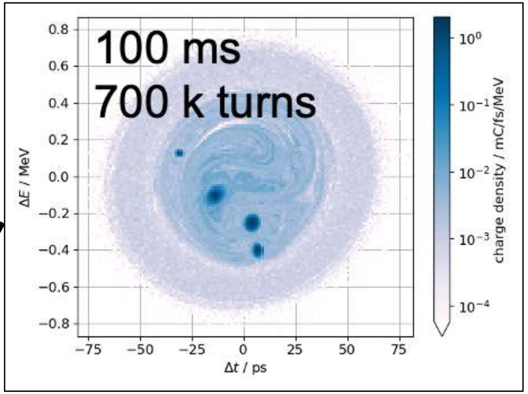
fs bunch length recovered every
~18 turns with strong THz emission

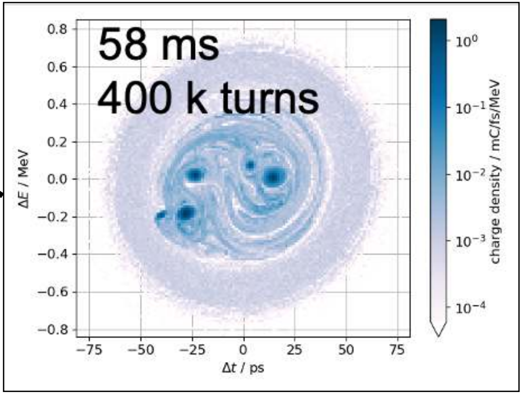
Courtesy M. Schwarz

Evolution over 100 ms









- Bunch remaining in non-equilibrium for 100 ms sustains micro-bunches
- 40 % of bunch charge in sub-ps short micro-bunches

Courtesy M. Schwarz

Laser plasma accelerator

Commercial Laser System
- For laser plasma accelerator (LPA) injector
- Parameters: > 1.5 J, < 25 fs, > 60 TW, 10 Hz
  - Commissioning ongoing

LPA design by KIT
- Led by Prof. Matthias Fuchs
- In cooperation with DESY