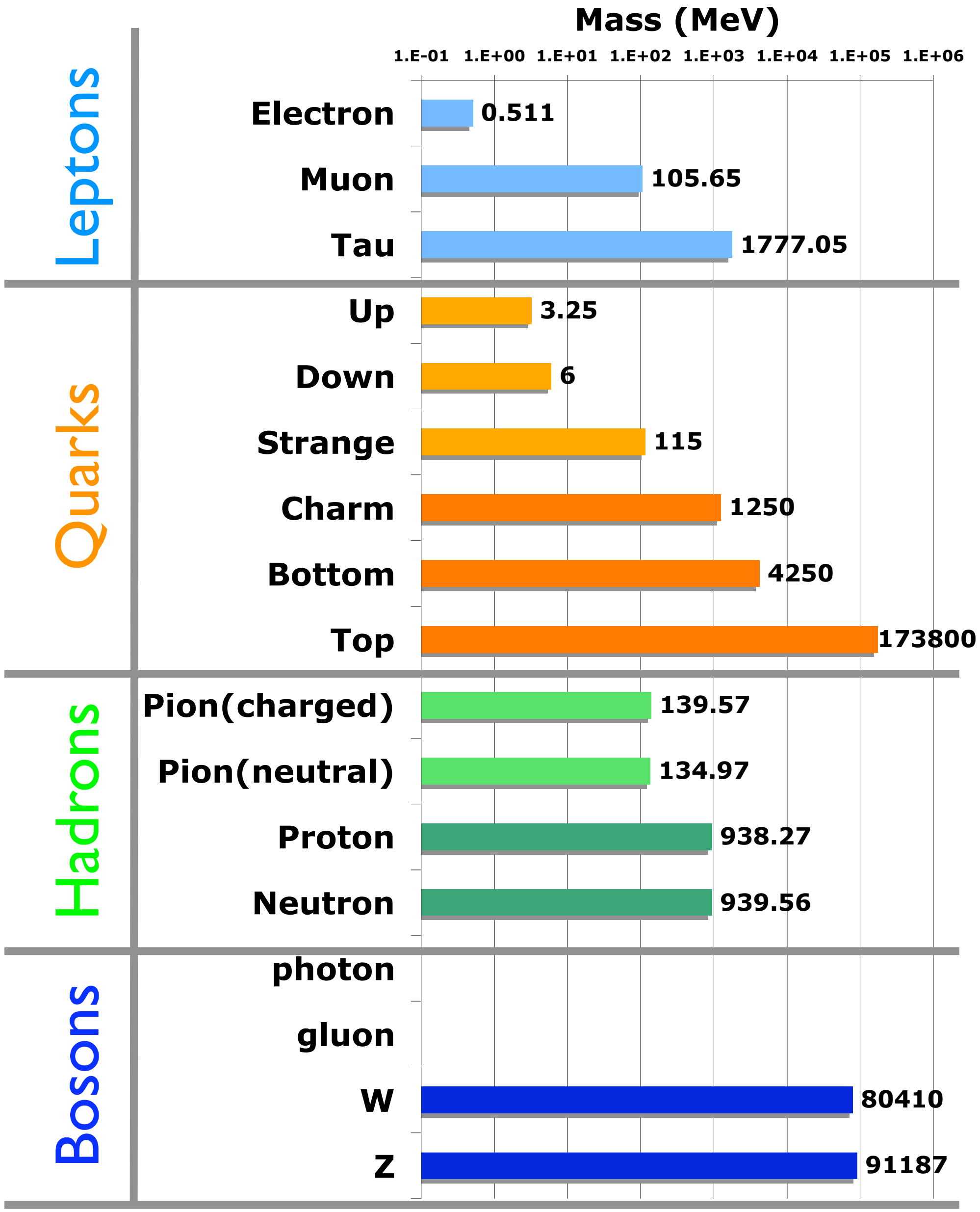
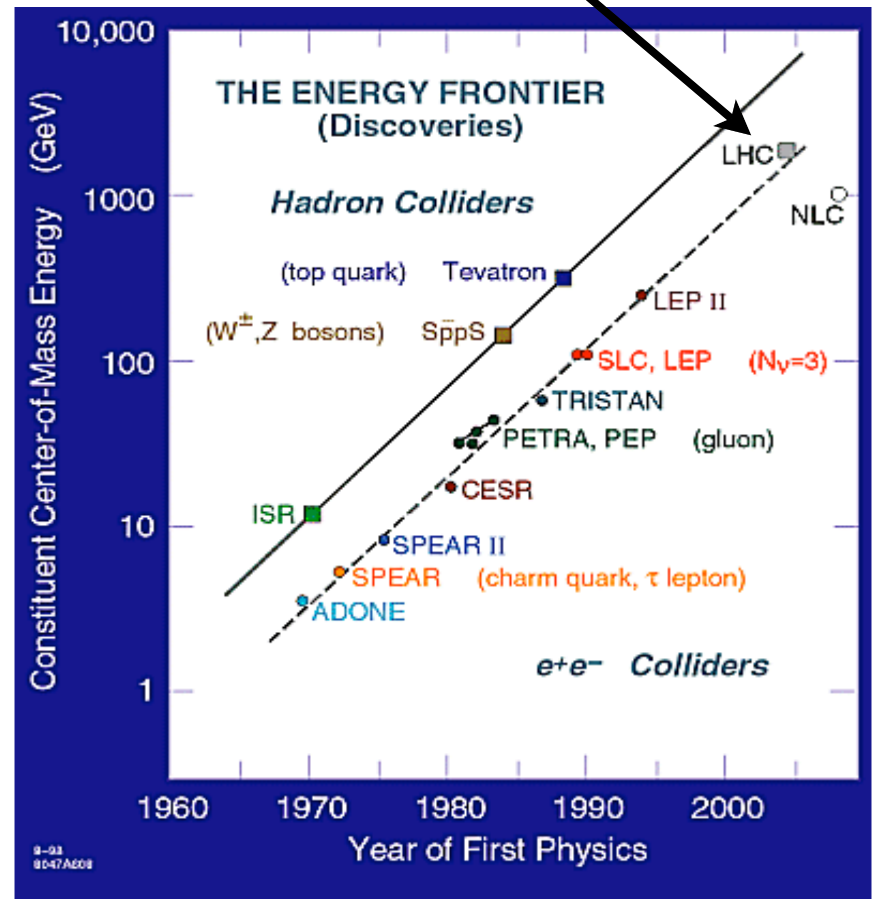
History/Energy line vs discovery



Higgs and super-symmetry ?
Or something else maybe

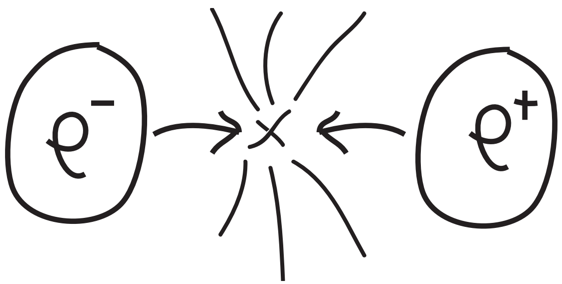


Behind the history plot is hidden the technological development required for each step

Obs: you can notice different particle species used in the different colliders electron-positrons and hadron colliders (either p-$\bar{p}$ as Tevratron, p-p as LHC)

The proper particle for the proper scope

Electrons (and positrons) are (so far) point like particles: no internal structure



The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision

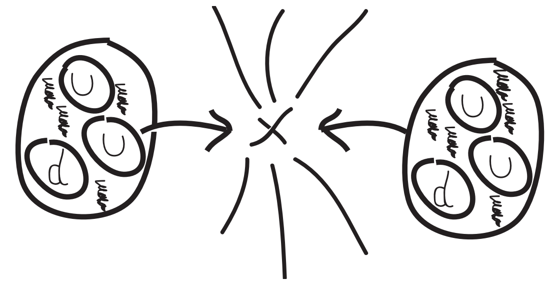
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

Pros: the energy can be precisely tuned to scan for example, a mass region.

Precision measurement (LEP)

Cons: above a certain energy is no more possible to use electrons because of too high synchrotron radiation (last lecture)

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons



The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent

Ecoll < 2Eb

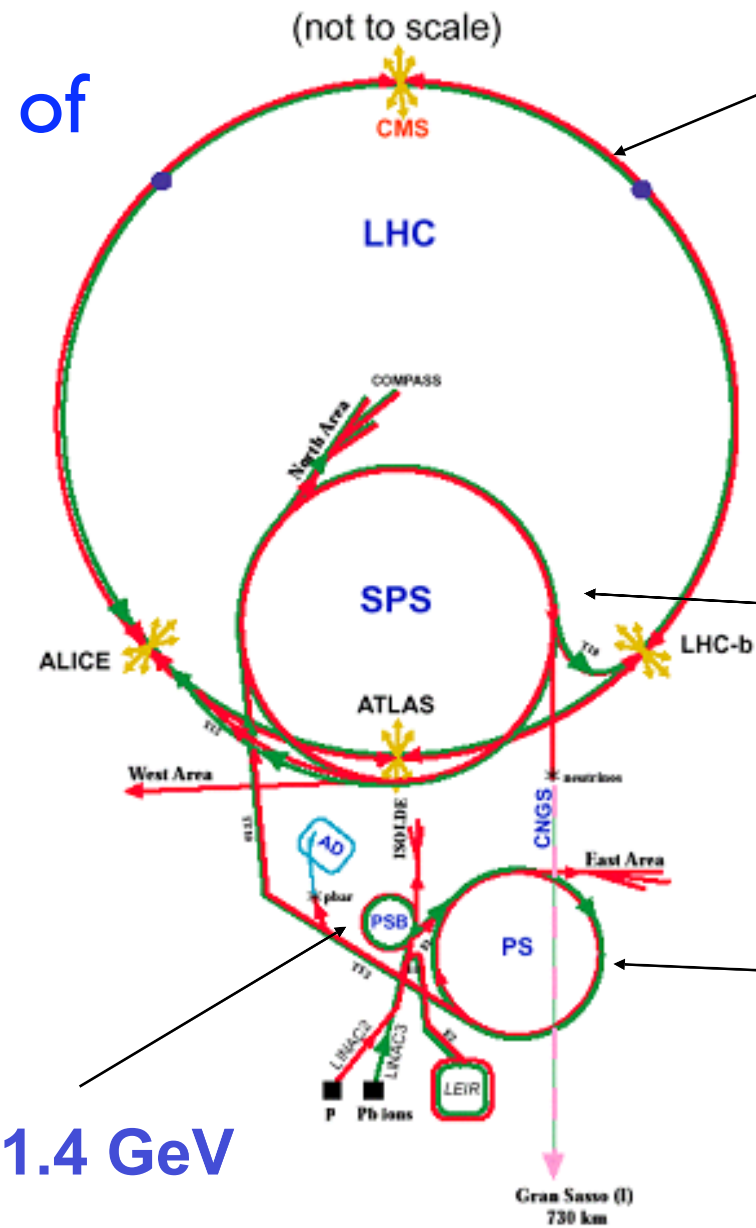
Pros: with a single energy possible to scan different processes at different energies.

Discovery machine (LHC)

Cons: the energy available for the collision is lower than the accelerator energy

CERN accelerator complex overview

Chain/sequence of accelerators



450 GeV /c – 7 TeV /c

26 - 450 GeV/c

1.4 GeV – 26 GeV/c

50 MeV – 1.4 GeV

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

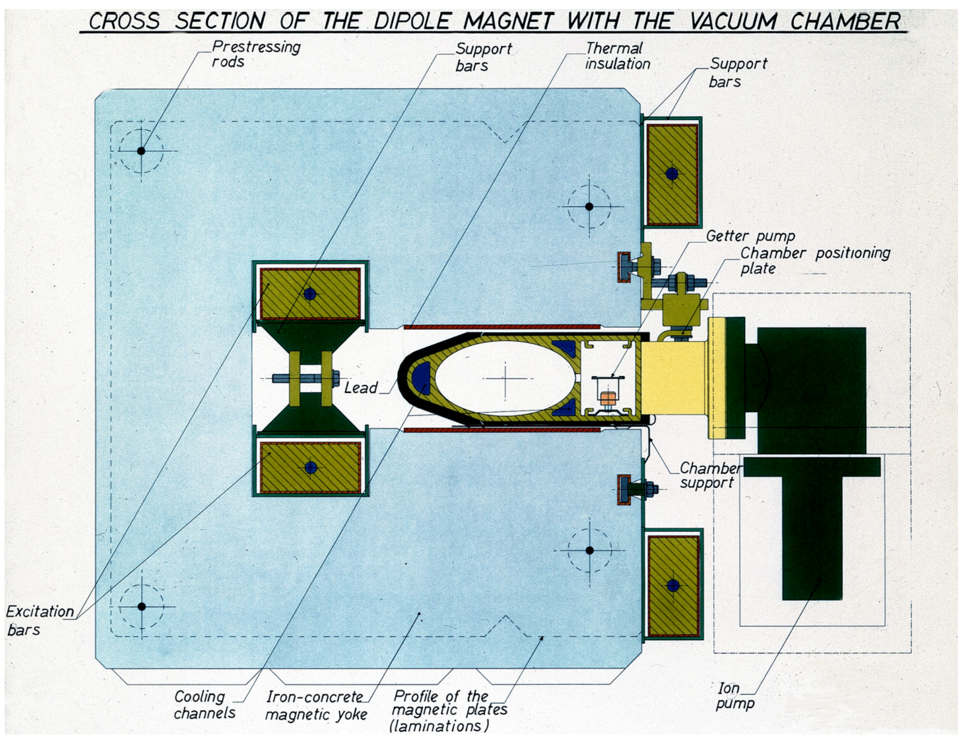
LEP vs LHC: Magnets, a change in technology

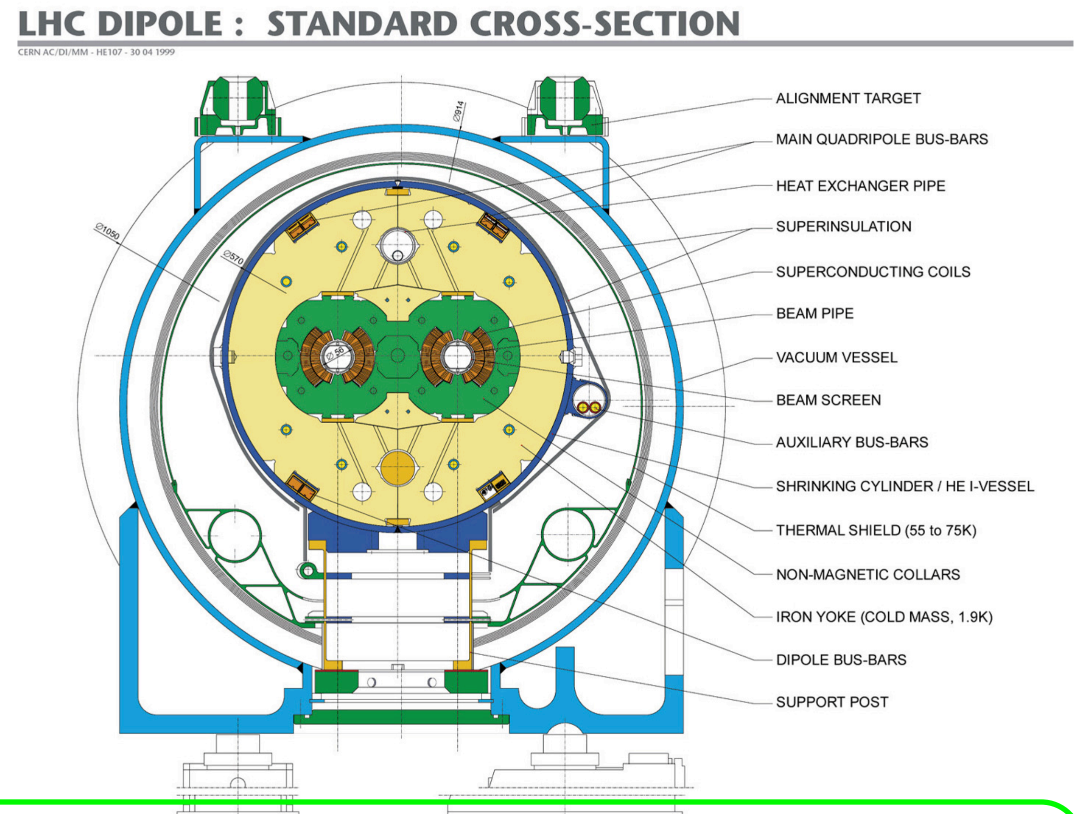
Bending Field → $p(TeV) = 0.3\ B(T)\ R(Km)$

(earth magnetic field is between 24,000 nT and 66,000 nT)

Tunnel R ≈ 4.3 Km LHC 7 TeV → B ≈ 8.3 T → ***Superconducting coils***

LEP 0.1 TeV → B ≈ 0.1 T → ***Room temperature coils***





Protons can go up in energy more than electrons because they ***emit less synchrotron radiation.*** Bending (dipoles) and focusing (quadrupoles) strengths require high magnetic fields generated by superconductors

Synchrotron radiation

Radiation emitted by charged particles accelerated longitudinally and/or transversally

Power radiated per particle goes like:

4th power of the energy
(2nd power)$^{-1}$ of the bending radius
(4th power)$^{-1}$ of the particle mass

$$P = \frac{2c \times E^4 \times r_0}{3\rho^2 \left(m_0 \times c^2\right)^3}$$

$r_0 = \frac{q^2}{4\pi\varepsilon_0 m_0 c^2}$ particle classical radius

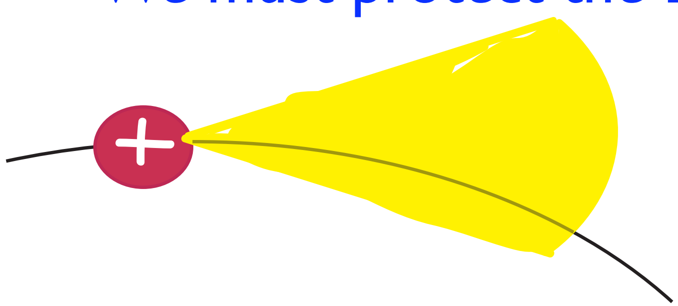
ρ particle bending radius

Energy lost per turn per particle due to synchrotron radiation:

e- W(MeV) = 8.85 x 10^{-5} x E^4(GeV)/ρ^2(km) ≈ 2 GeV (LEP)

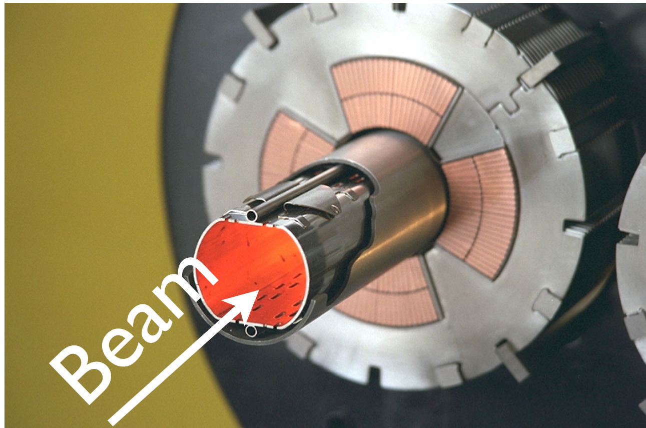
p W(keV) = 7.8 x 10^{-3} x E^4(TeV)/ρ^2(km) ≈ 6 keV (LHC)

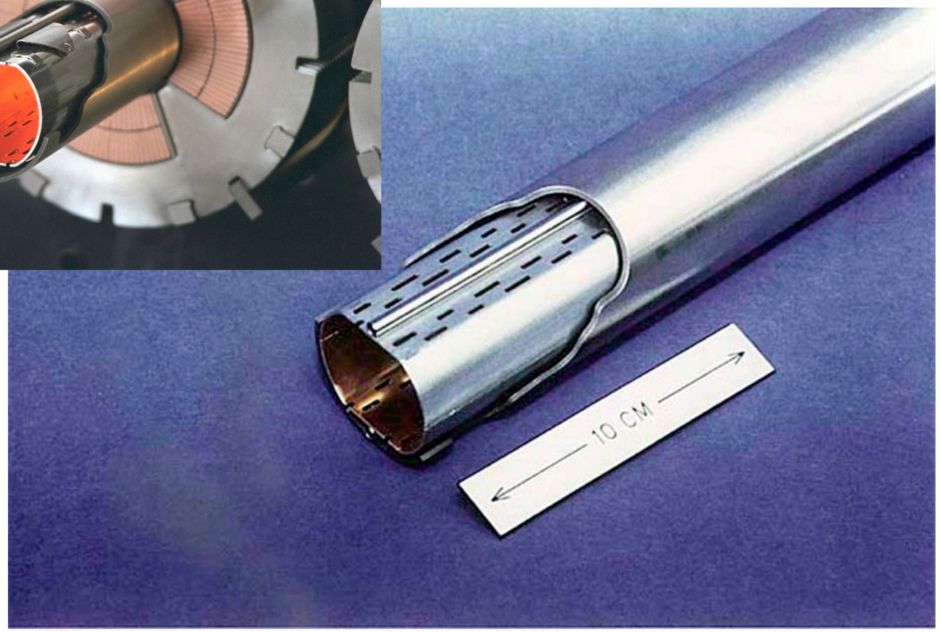
We must protect the LHC coils even if energy per turn is so low



Power lost per m in dipole: 0.206 W
Total radiated power per ring: 3.6 kW

LHC beam screen with cooling pipes





Beam screen to protect Superconducting magnets from Synchrotron radiation.

Holes for vacuum pumping

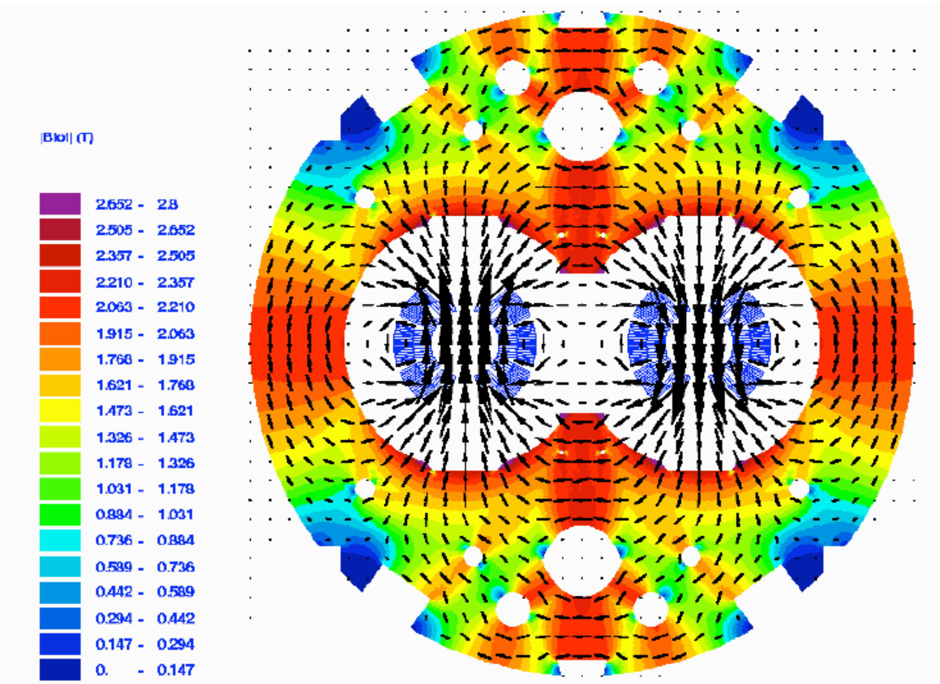
Atmosphere pressure = 750 Torr
Moon atmospheric pressure = 5 10^{-13} Torr

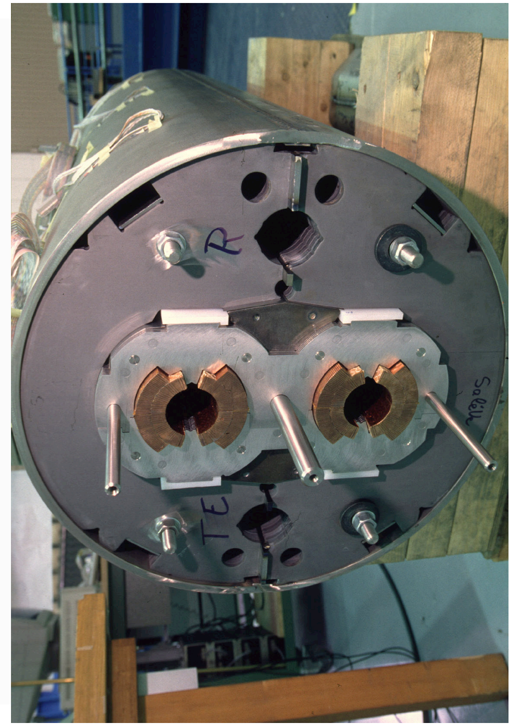
Vacuum required to avoid unwanted collision far from the experiments and decrease the Luminosity

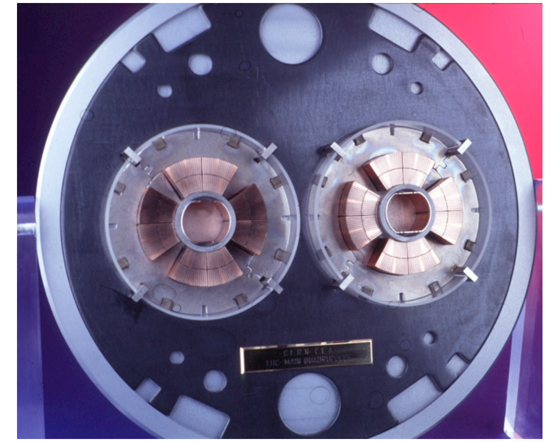
Typical vacuum: 10^{-13} Torr

There is ~6500 m^3 of total pumped volume in the LHC, like pumping down a cathedral.

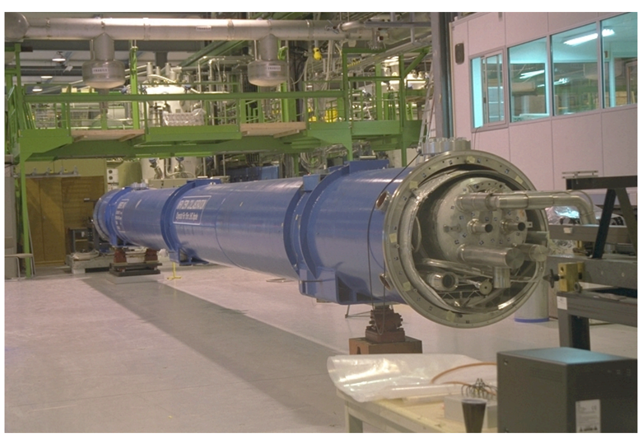
Two-in-one magnet design

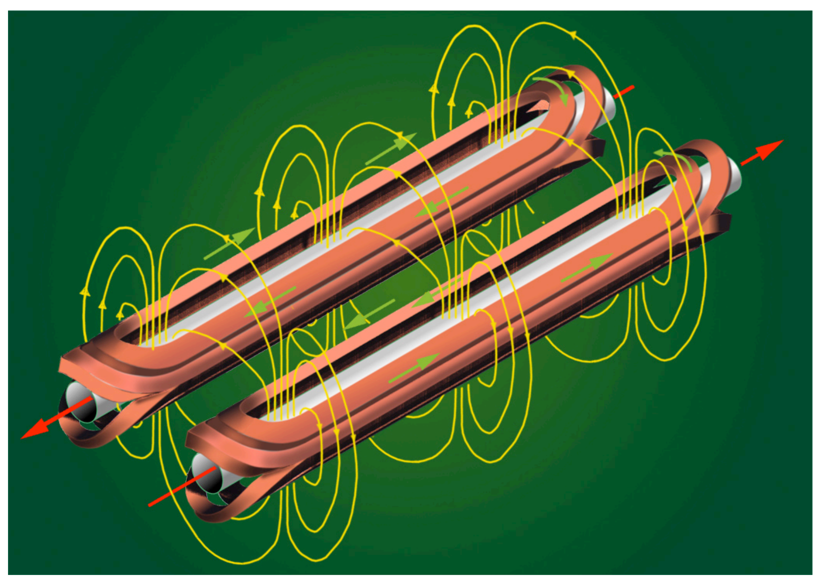




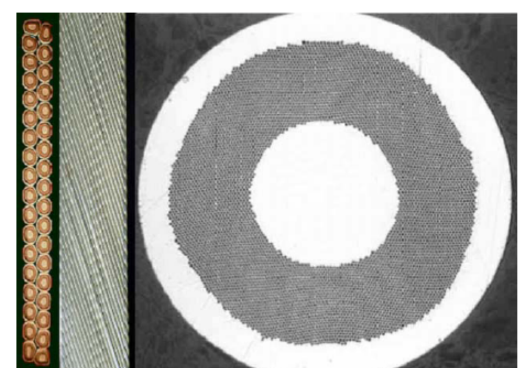


The LHC is <u>one ring</u> where <u>two accelerators</u> are coupled by the magnetic elements.

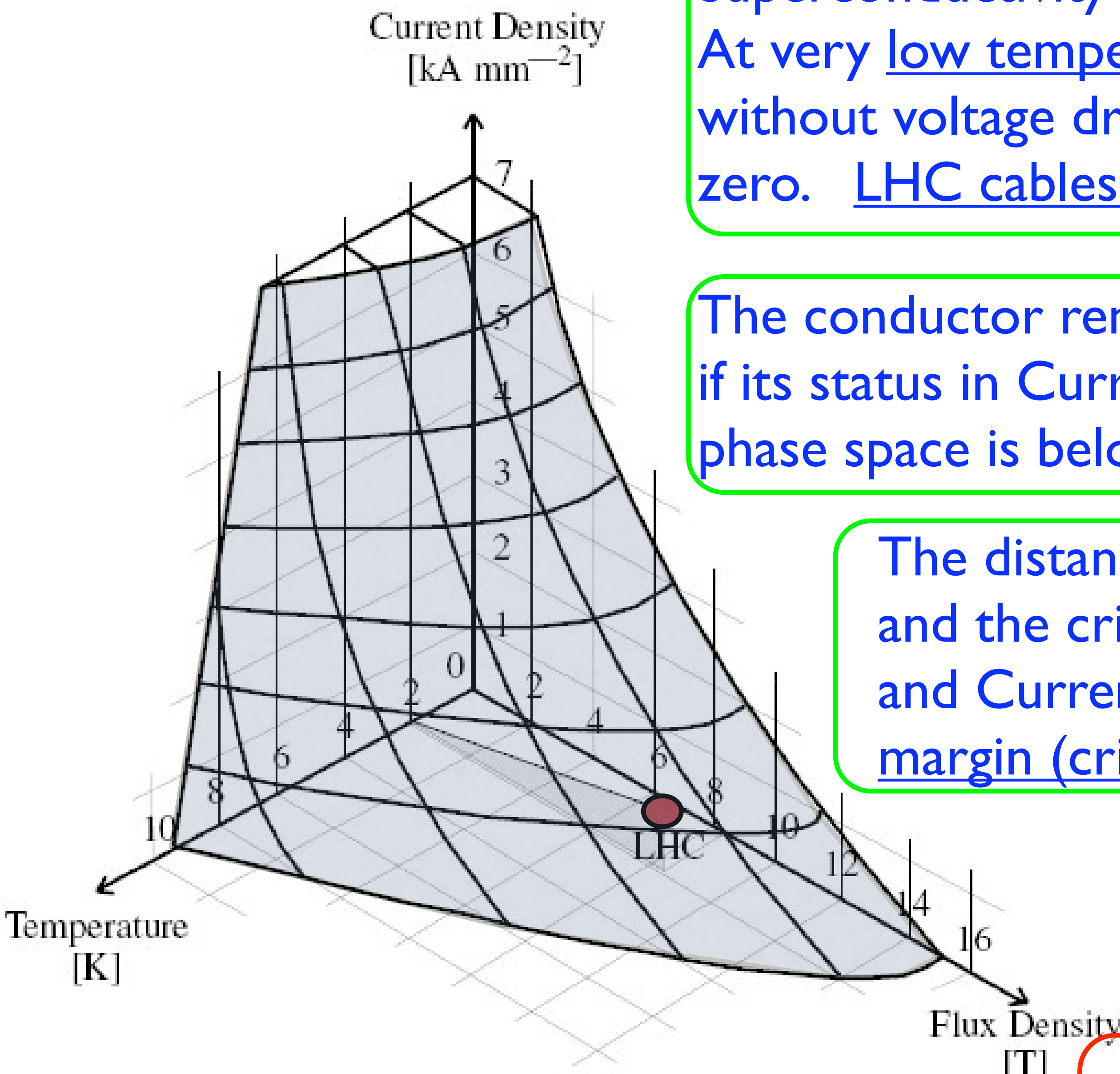




Nb -Ti superconducting cable in a Cu matrix



Very, very short introduction to Superconductivity for accelerators



See lecture of E. Todesco

Superconductivity is a property of some materials. At very <u>low temperature</u> they can carry currents without voltage drop, i.e. their resistivity goes to zero. <u>LHC cables: Nb-Ti working at 1.9 K</u>

The conductor remains Superconductor if its status in Current Density, Temperature, B field phase space is below the <u>Critical Surface</u>

The distance between the working point and the critical surface for a fixed B field and Current Density is the <u>temperature margin (critical temperature)</u>

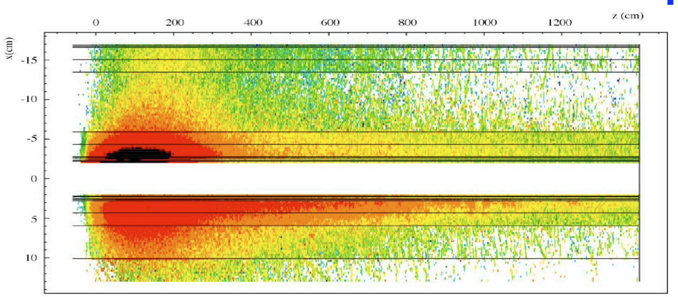
Transition to a normal conducting state is called <u>magnet quench</u>

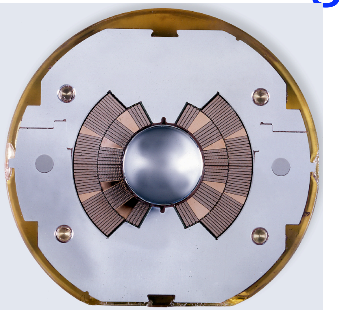
What can increase the temperature in a magnet ?

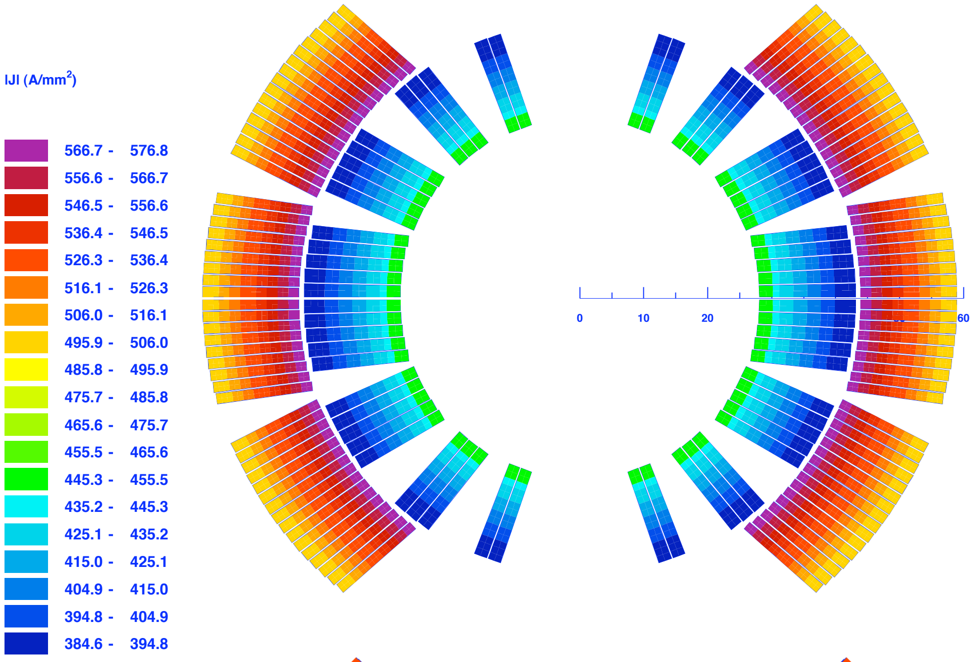
V. V. S. Introduction to Superconductivity II

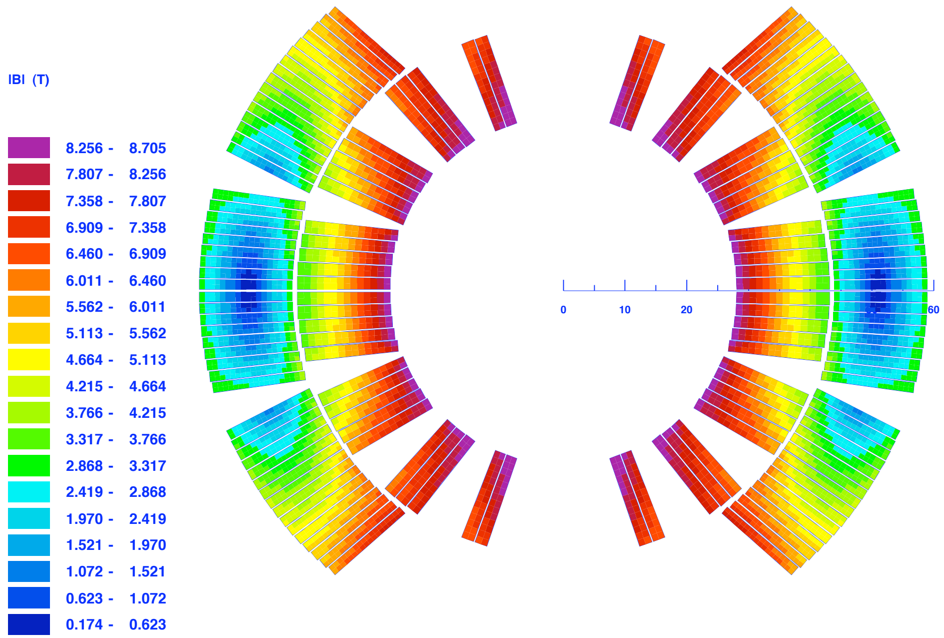
Beam losses can eat the temperature margin because of energy deposition

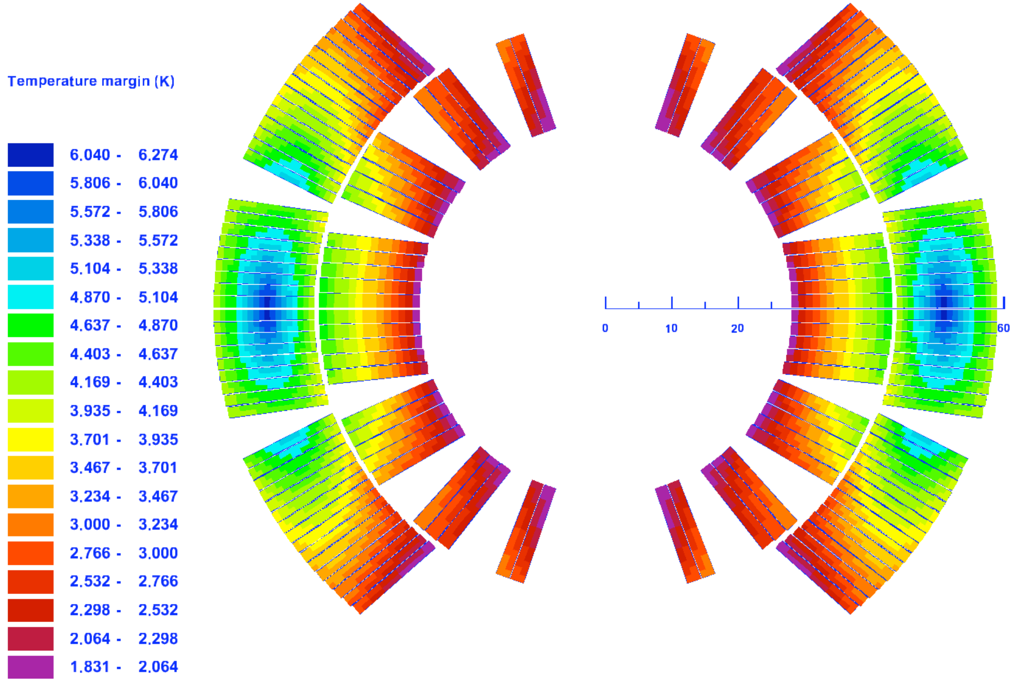
Limit of accepted losses: ~ <u>10 mW/cm^3</u> to avoid $\Delta T > 2$ K, the temperature margin











Courtesy of Stephan Russenschuck

How much is 10 mW/cm^3 ?

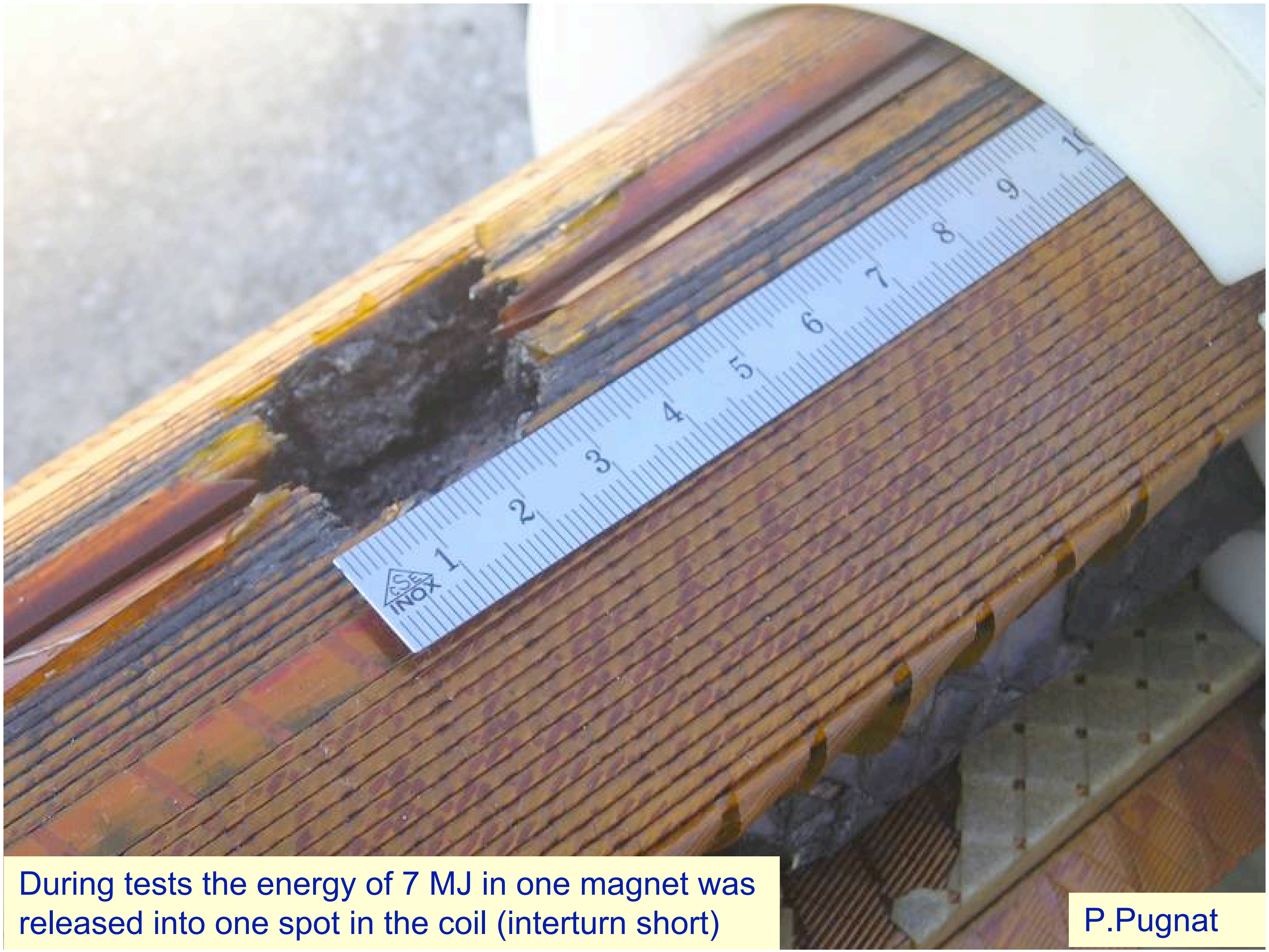
A fluorescente (known as neon) tube can be typically 1.2 m long with a diameter of 26 mm, with an input power of 36 W.

This makes a power density of about 56 mW/cm^3.

The power of a neon tube can quench about 5 LHC dipoles at collision energy.... because one does not need 10 mW/cm^3 for the entire volume of a magnet, but for about 1 cm^3.

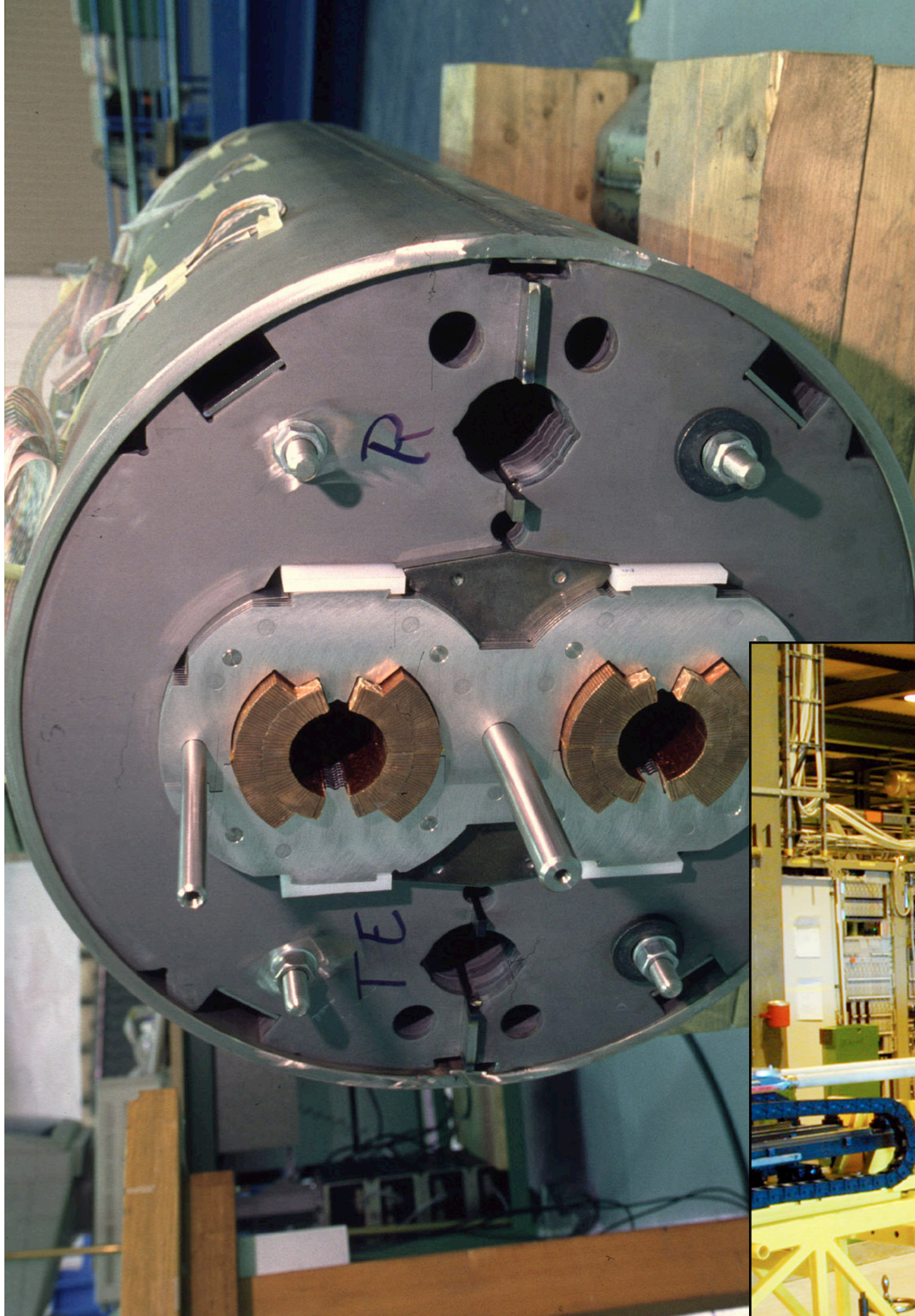
If you do the same basic computation with a normal 100 W resistive bulbs is even worst

When something goes wrong.... bad quench...



During tests the energy of 7 MJ in one magnet was
released into one spot in the coil (interturn short)

P.Pugnat

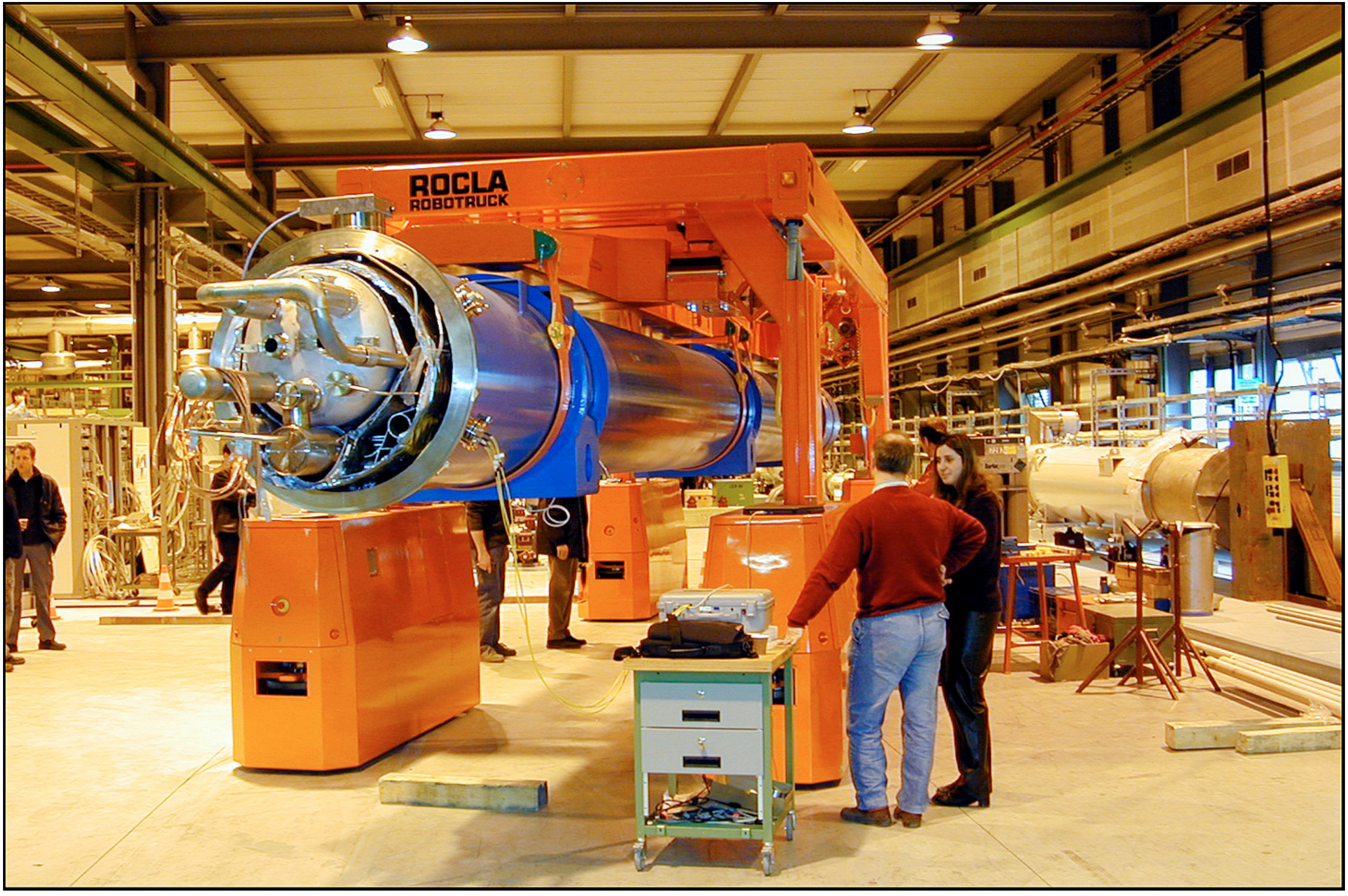


At 7 TeV:

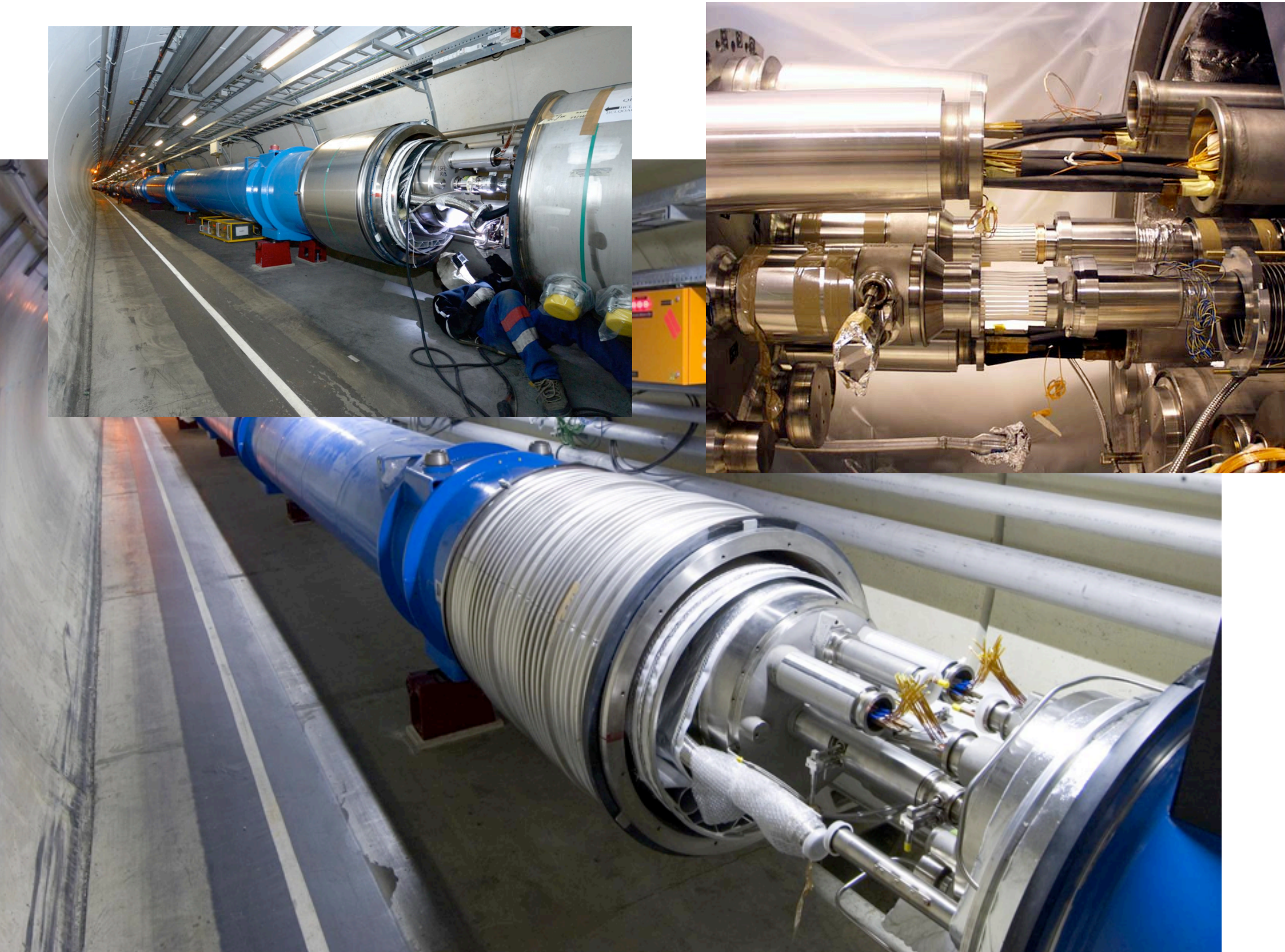
I_{max} = 11850 A Field=8.33 T
Stored energy= 6.93 MJ
Weight = 27.5 Tons
Length =15.18 m at room temp.
Length (1.9 K)=15 m - ~10 cm

Test bench for magnetic measurements at 1.9 K

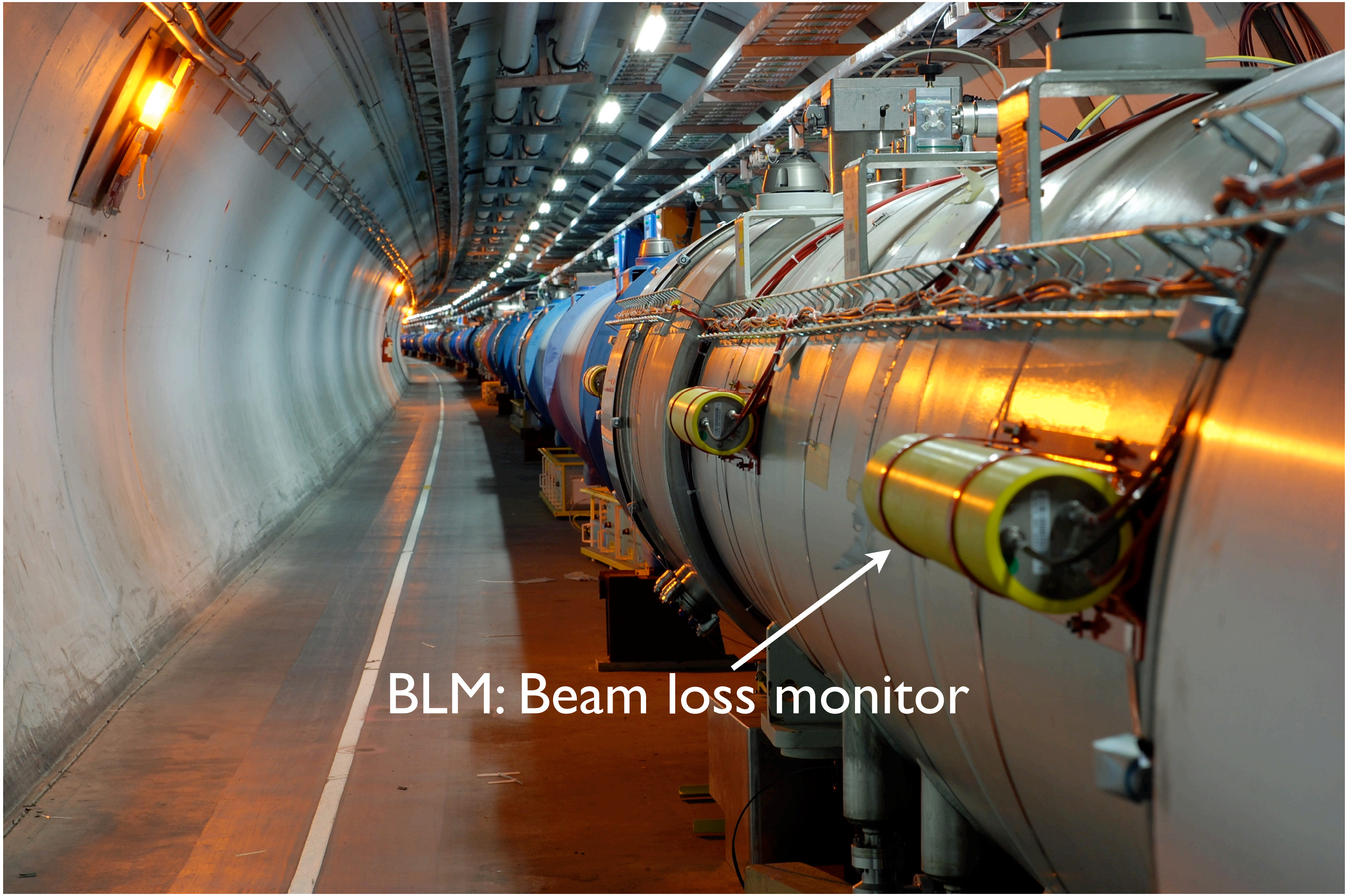
PS: they are not straight, small bending of 5.1 mrad


ROCLA
ROBOTRUCK

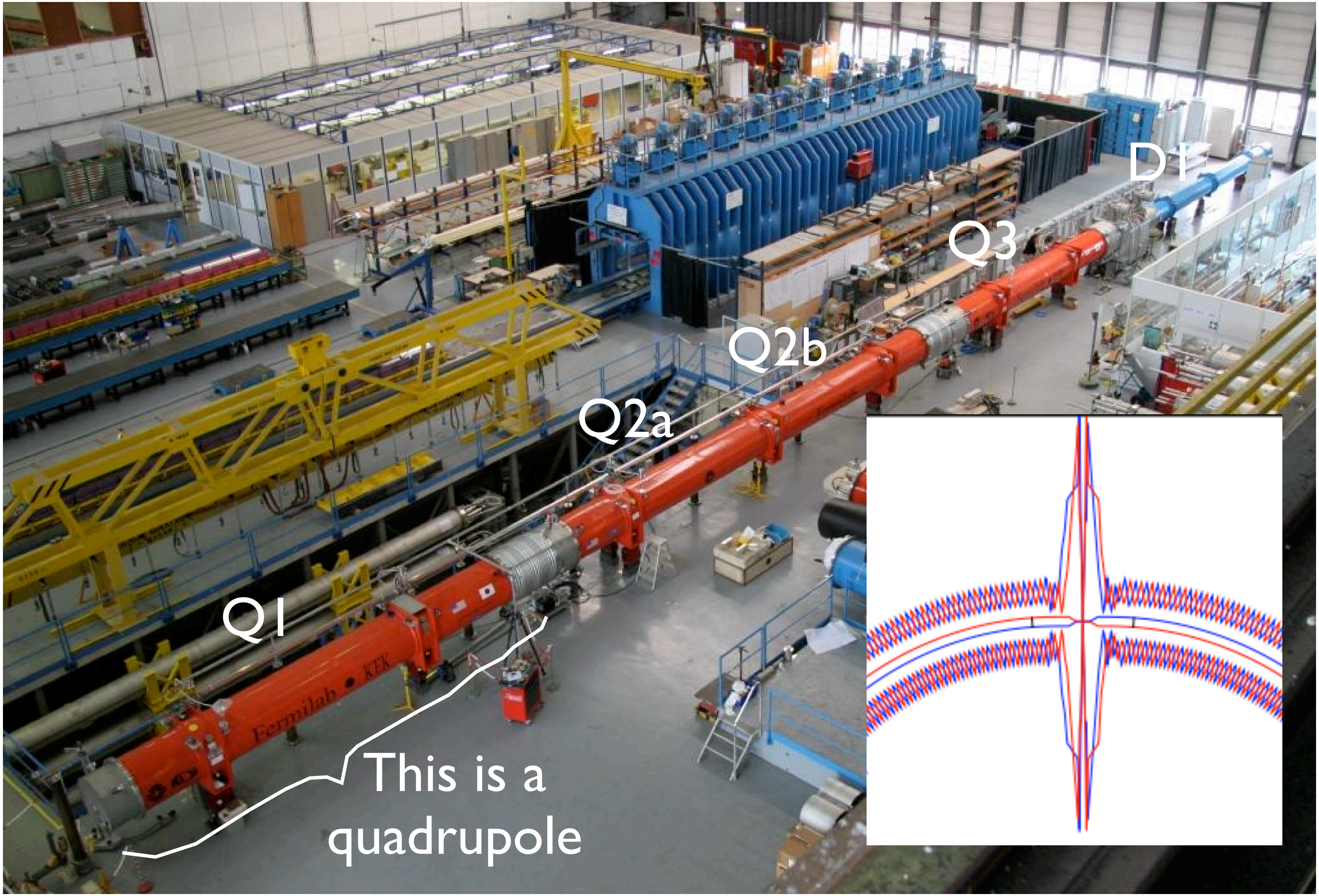
LHC during installation



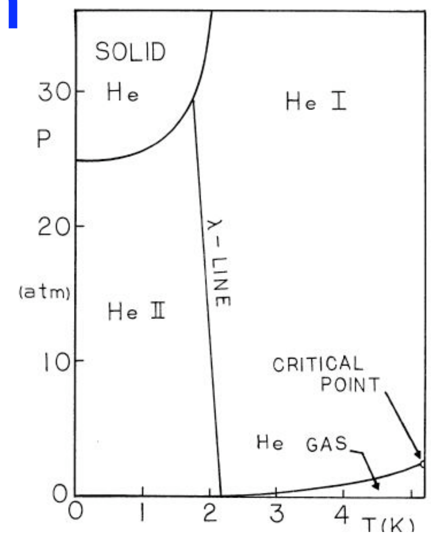
How to detect losses: BLMs installed in the tunnel



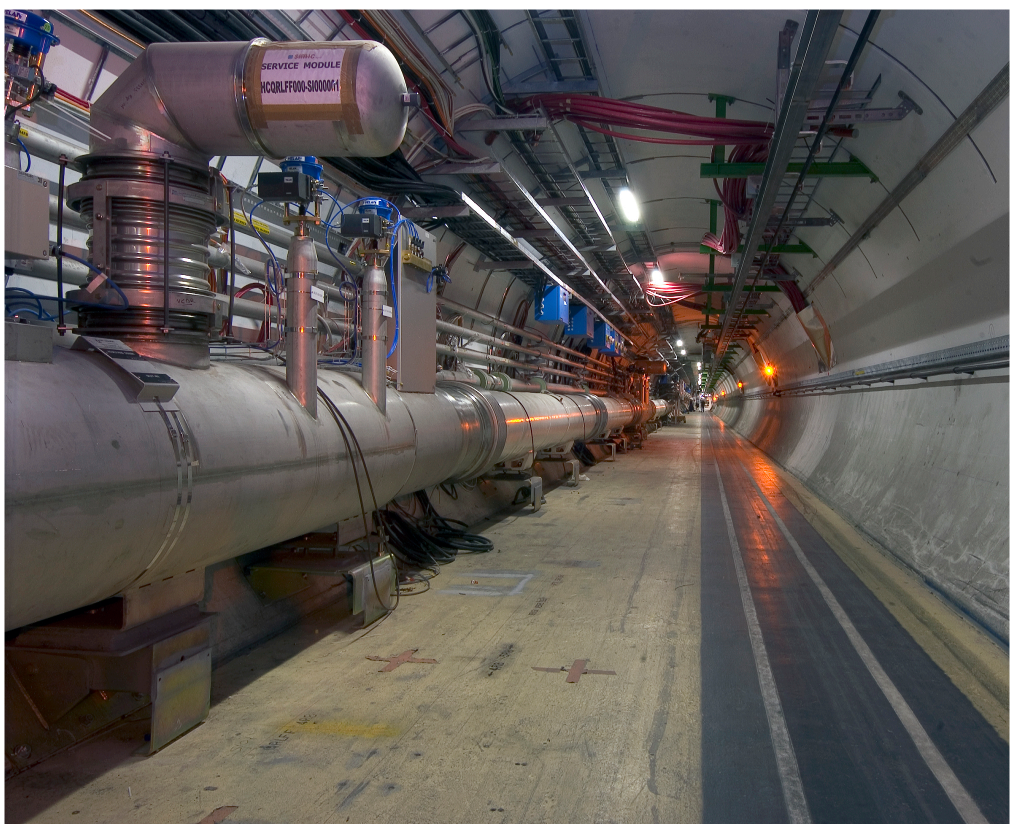
Triplets before lowering in the tunnel

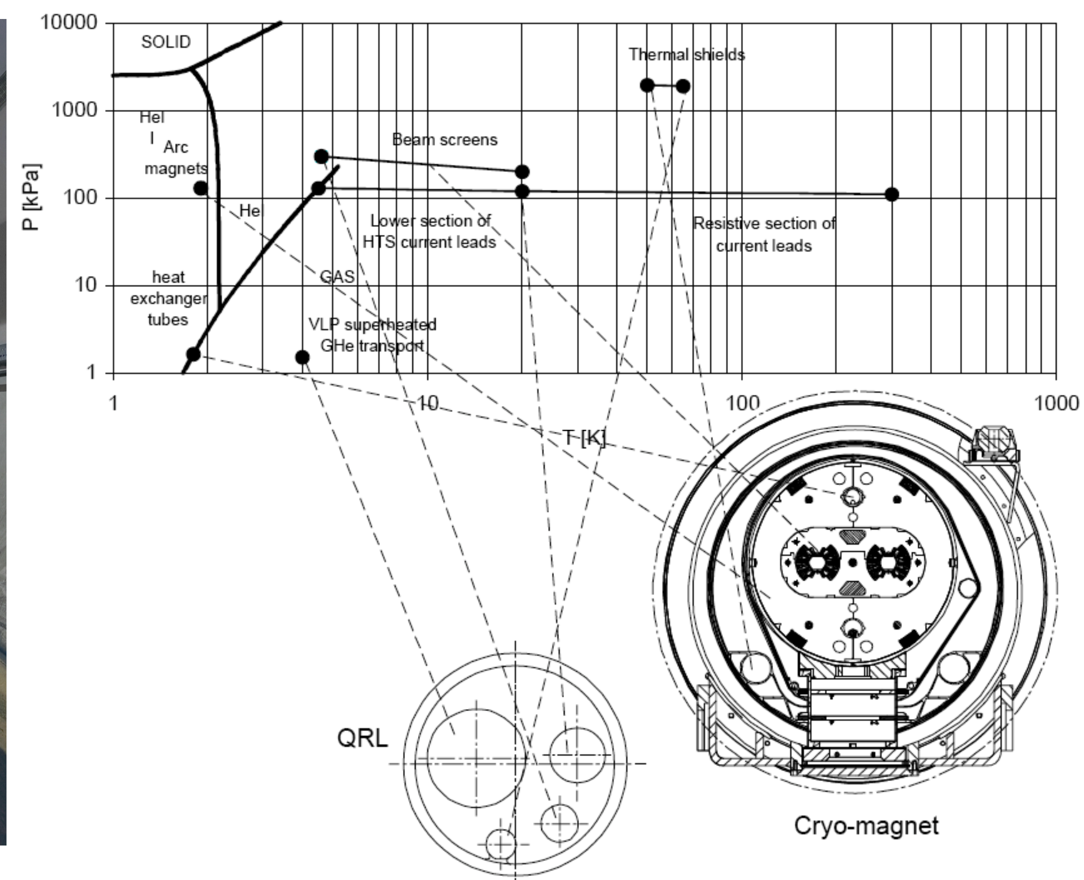


Which coolant ? Liquid superfluid helium



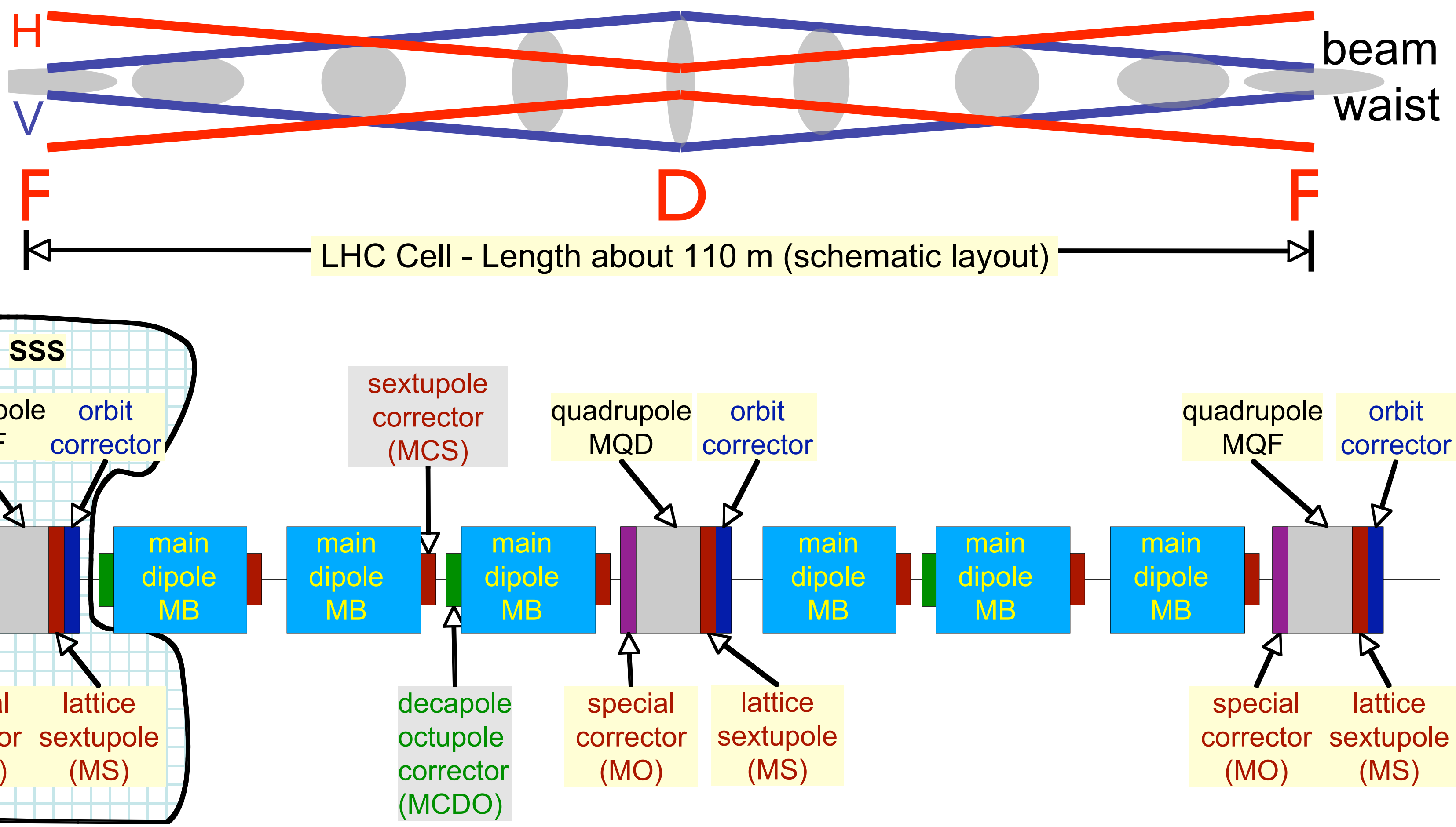
LHC cryogenics will need 40,000 leak-tight pipe junctions.
12 million litres of liquid nitrogen will be vaporised during the initial cooldown of 31,000 tons of material and the total inventory of liquid helium will be 700,000 l (about 100 tonnes)





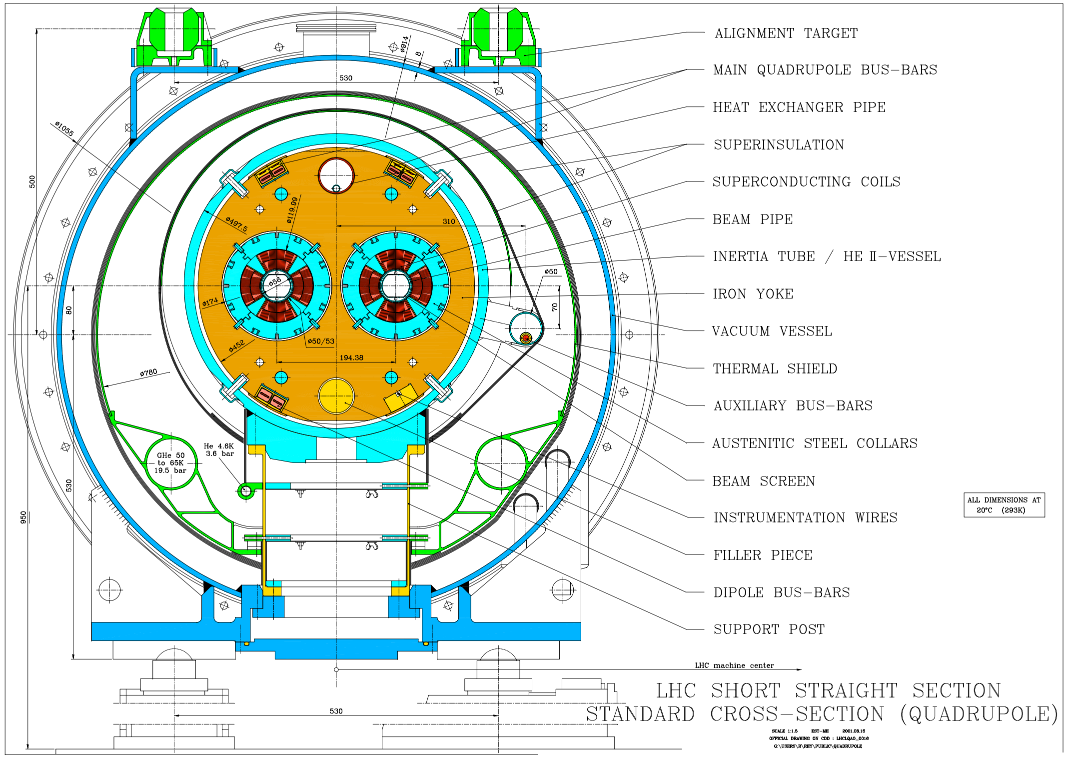
LHC optics, ARC lattice

Classical FODO cell with about 90^0 phase advance per cell
(F=focusing, O=drift, D=defocusing)



2-in-1 design true also for the optics:
a quadrupole F for beam 1 (circulating clockwise) is D for beam 2 circulating anticlockwise

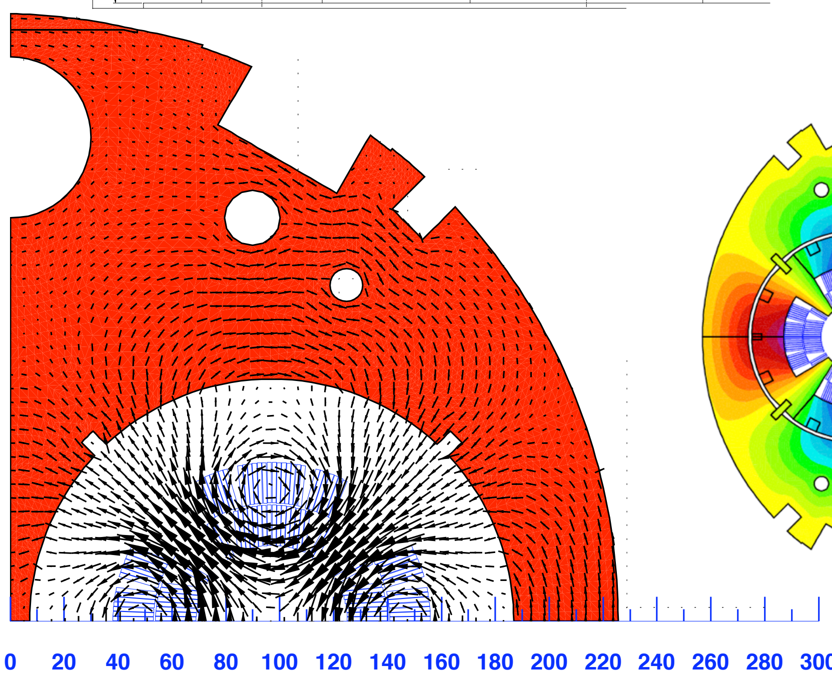
Quadrupoles are also two-in one

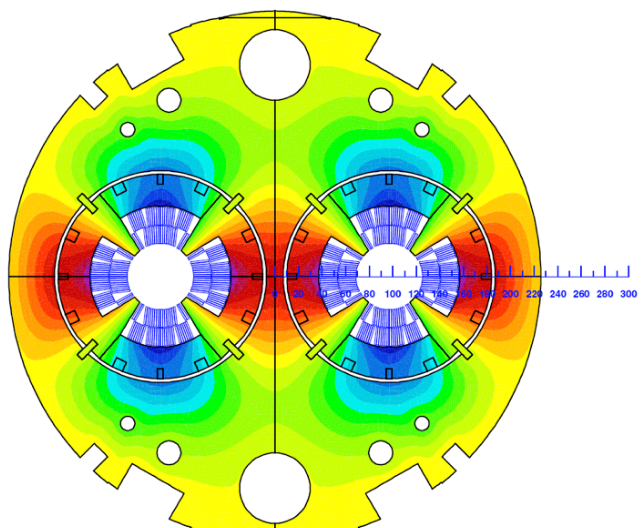


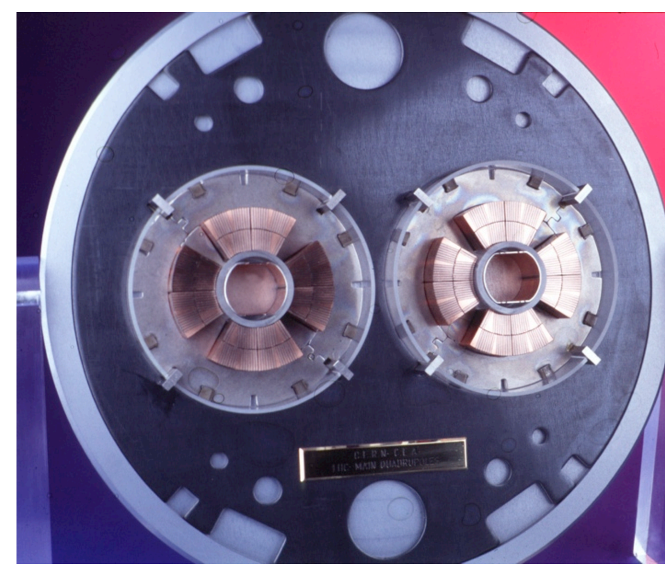
At 7 TeV:

I_{max} = 11850 A
Field=225 T/m

Weight = 6.5 Tons
Length =3.1 m





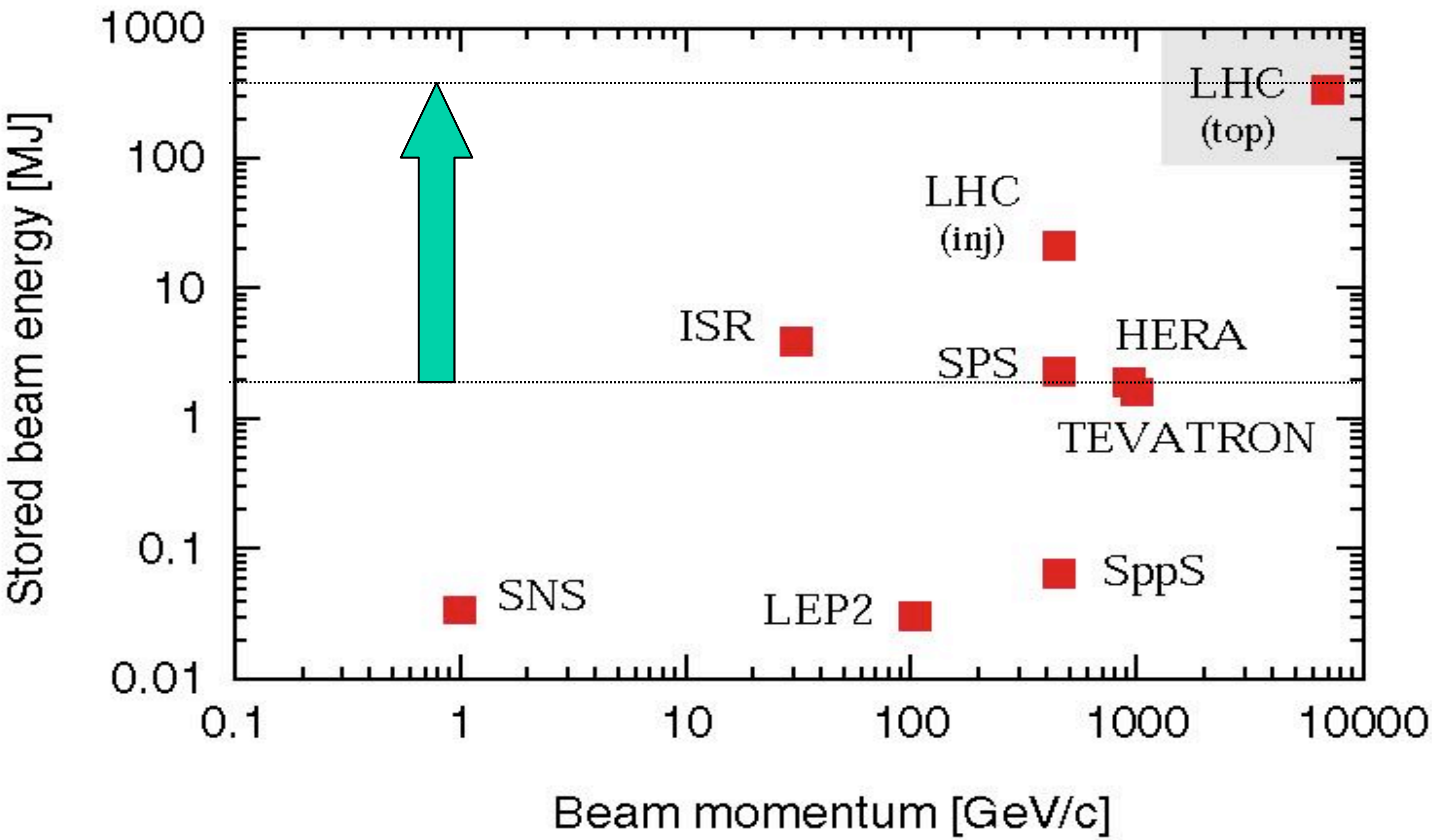


Magnets for the LHC, total budget, every magnet has a role in the optics design

Name	Quantity	Purpose
MB	1232	Main dipoles
MQ	400	Main lattice quadrupoles
MSCB	376	Combined chromaticity/ closed orbit correctors
MCS	2464	Dipole spool sextupole for persistent currents at injection
MCDO	1232	Dipole spool octupole/decapole for persistent currents
MO	336	Landau octupole for instability control
MQT	256	Trim quad for lattice correction
MCB	266	Orbit correction dipoles
MQM	100	Dispersion suppressor quadrupoles
MQY	20	Enlarged aperture quadrupoles

In total 6628 cold magnets ...

LHC: the issue of stored beam energy



Why do we have to protect the machine ?

Why do we have to protect the machine ?

Total stored beam energy at top energy (7 TeV), nominal beam, 334 MJ (or 120 kg TNT)
Nominal LHC parameters: 1.15 10^{11} protons per bunch
2808 bunches
0.5 A beam current

British aircraft carrier:
HMS Illustrious and Invincible weigh 20,000 tons all-up and fighting which is 2 x 10^7 kg.
Or the USS Harry S. Truman (Nimitz-class) - 88,000 tons.

Energy of nominal LHC beam = 334 MJ or 3.34 x 10^8 J

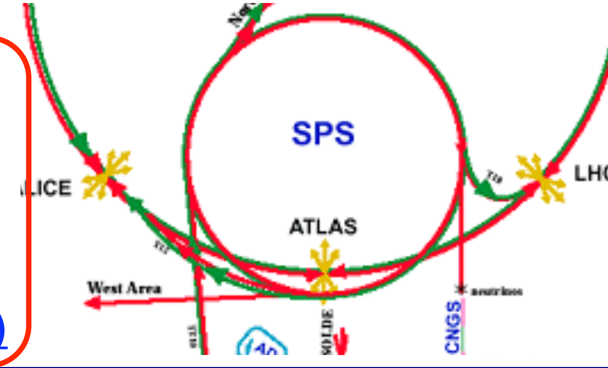
which corresponds to the aircraft carrier navigating
at v=5.8 m/s or 11.2 knots (or around 5.3 knots if you're an American aircraft carrier)

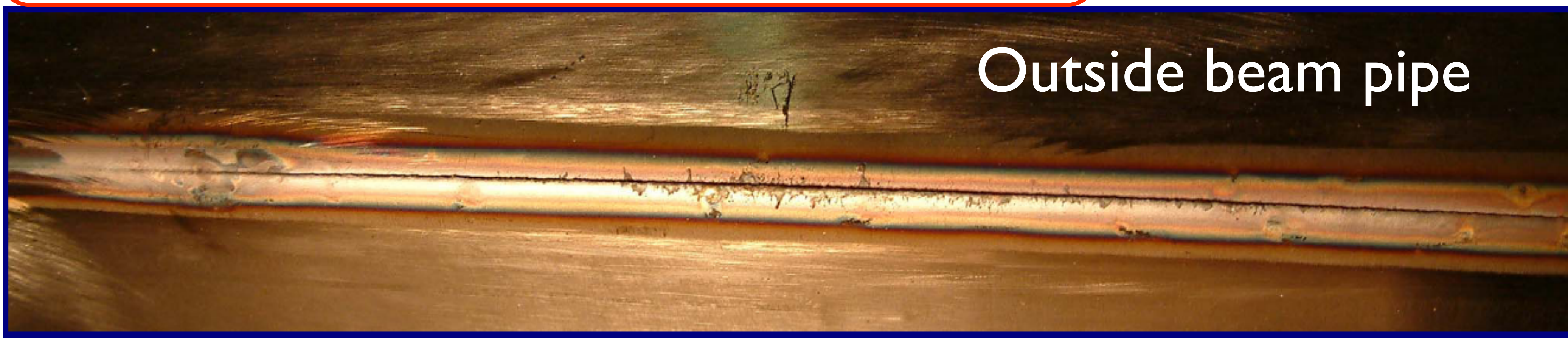
So, what if something goes wrong?

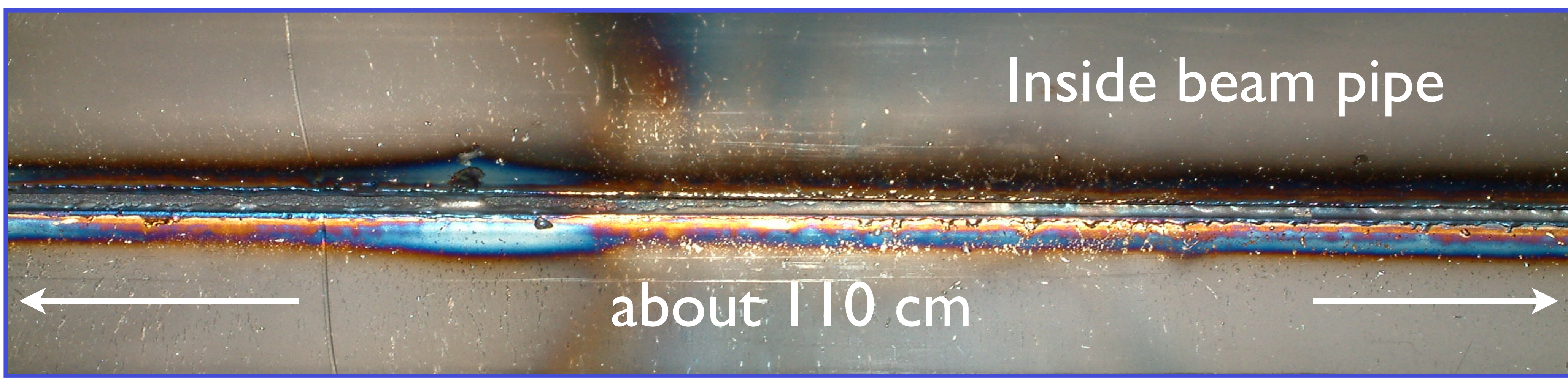
What is needed to intercept particles at large transverse amplitude or with the wrong energy to avoid quenching a magnet?

3 years ago something went wrong during a test ...

LHC extraction from the SPS
450 GeV/c, 288 bunches
Transverse beam size 0.7 mm (1 σ)
1.15×10^{11} p+ per bunch, for total intensity of 3.3×10^{13} p+
Total beam energy is 2.4 MJ, lost in extraction test (LHC 334 MJ)





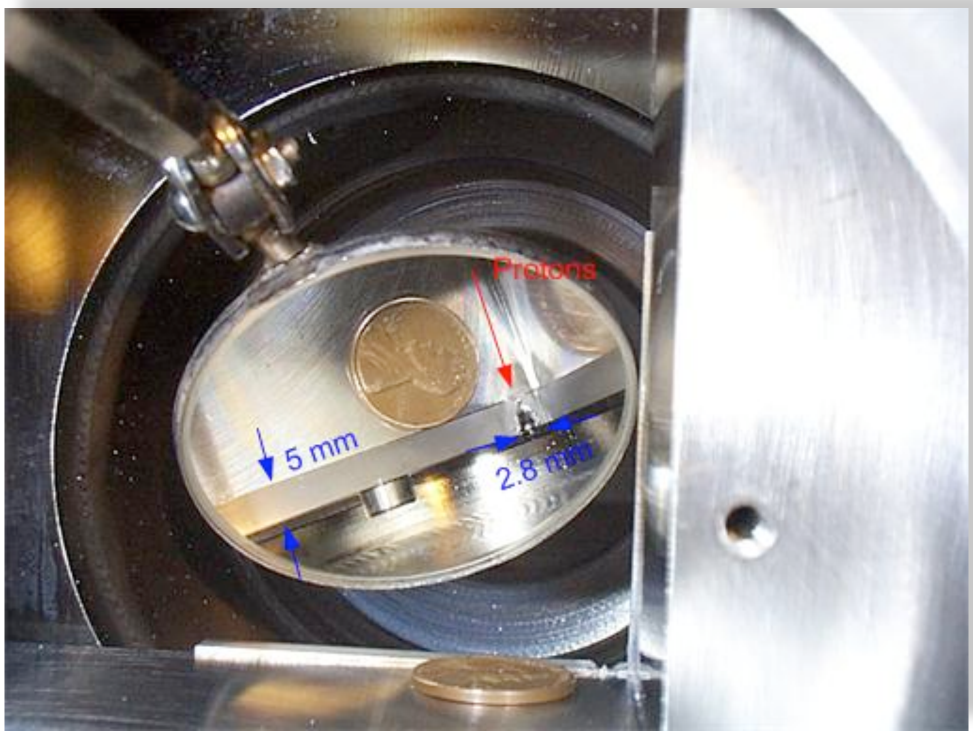


B.Goddard CERN AB/BT

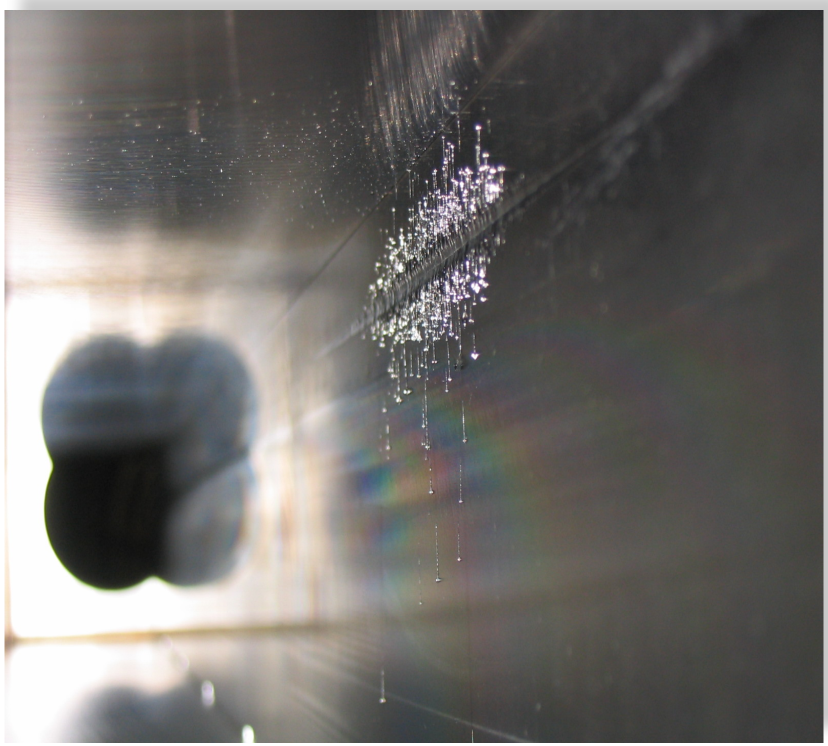
Tevatron accident in 2003 (courtesy of N. Mokhov)

Accident caused by uncontrolled movement of beam detectors (Roman Pots) which caused a secondary particle shower
magnet quench → no beam dump → damage on approximatively 550 turns

Tungsten collimator. Tmelting = 3400 °C



1.5 m long stainless steel collimator



Collimation system for machine protection

Two sections in LHC dedicated to beam cleaning:

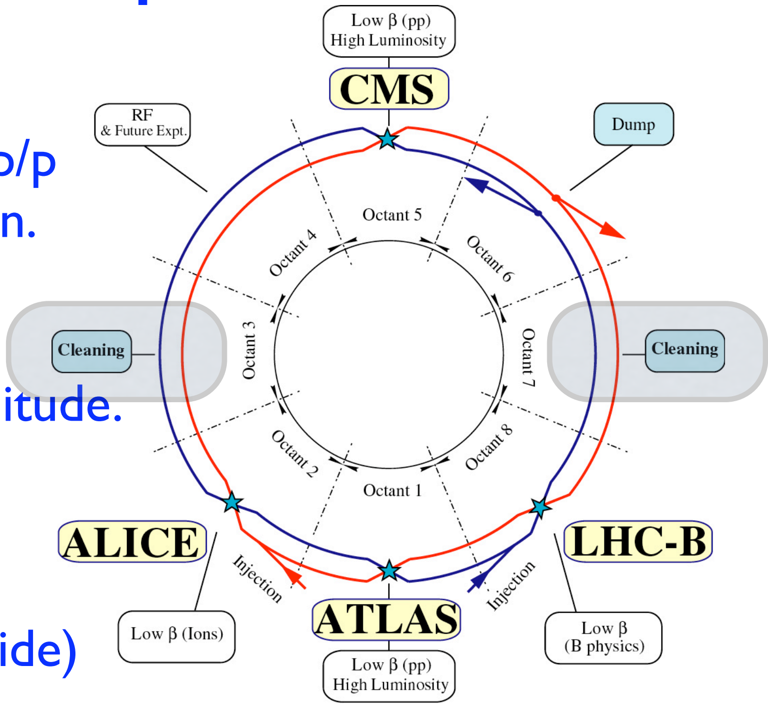
IR3 momentum cleaning → remove particles with too large dp/p ($> \pm 10^{-3}$) thanks to large dispersion.

$$\Delta x = D\frac{\Delta p}{p}$$

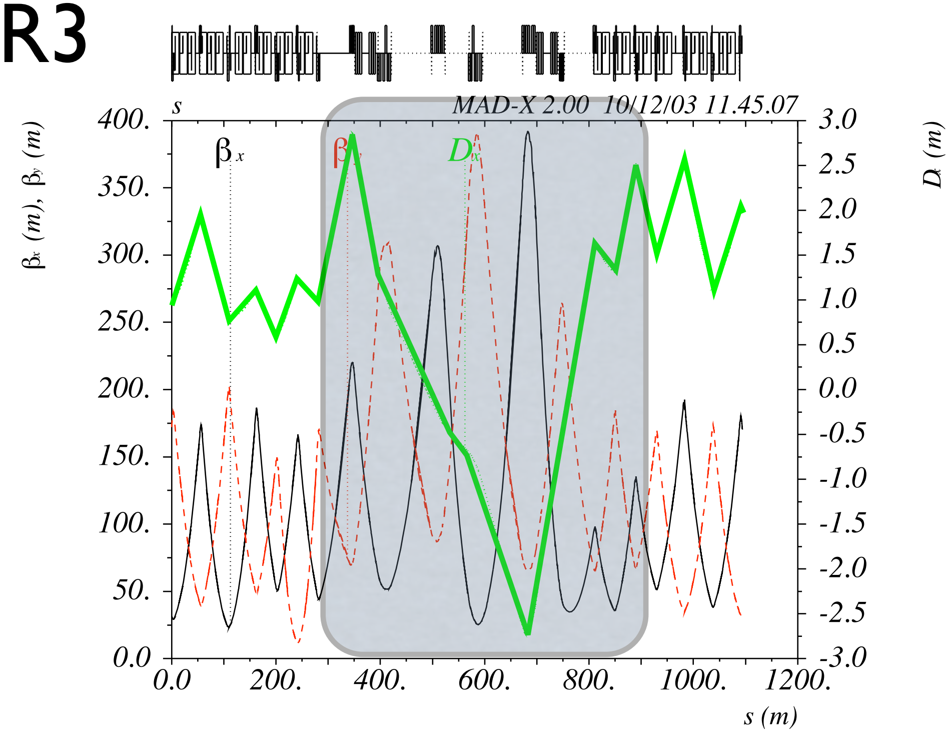
IR7 betatron cleaning → remove particles at too large amplitude. Dispersion as small as possible.

$$x_{max} = \sqrt{\varepsilon\beta}$$

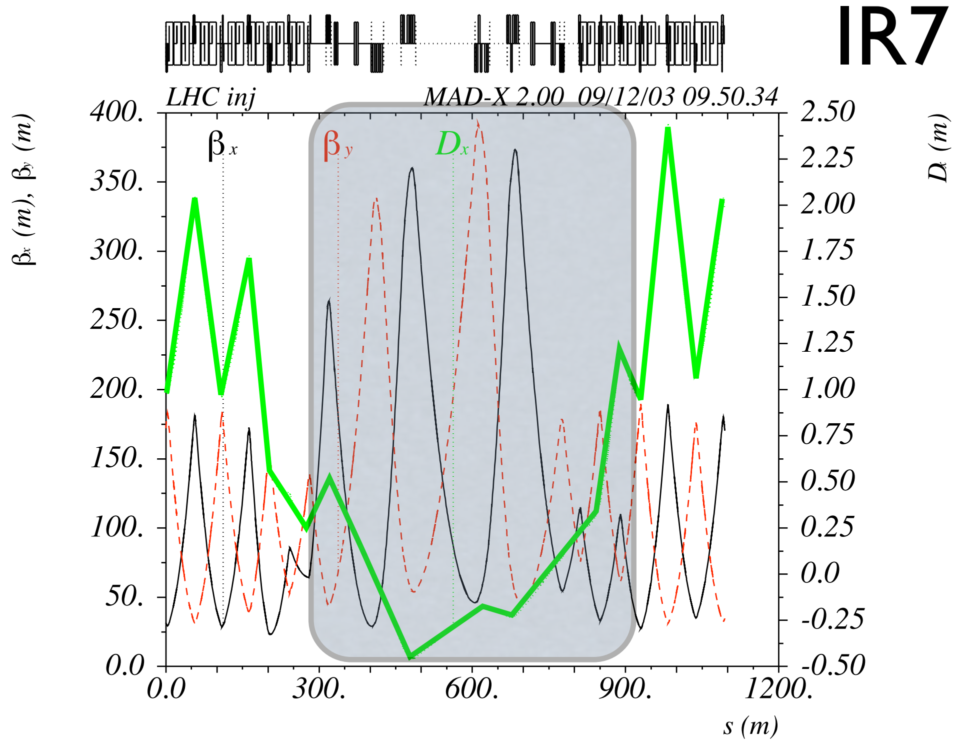
Done by intercepting particle with 2 stage collimation (next slide)



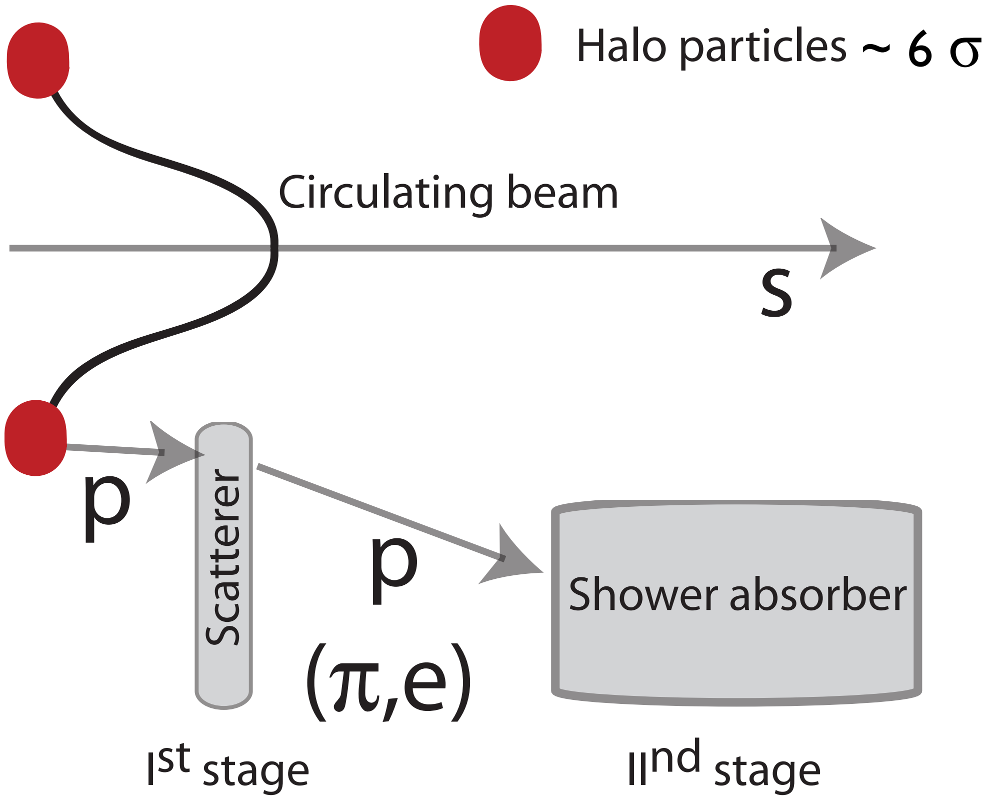
IR3

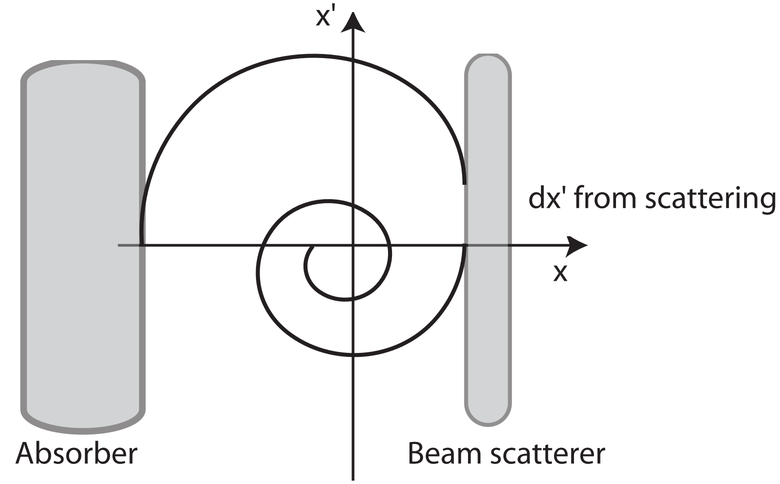


IR7



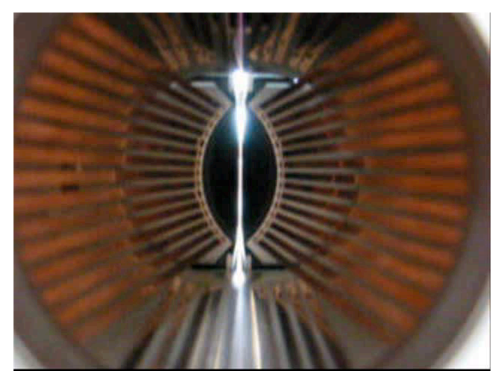
2 stage collimation

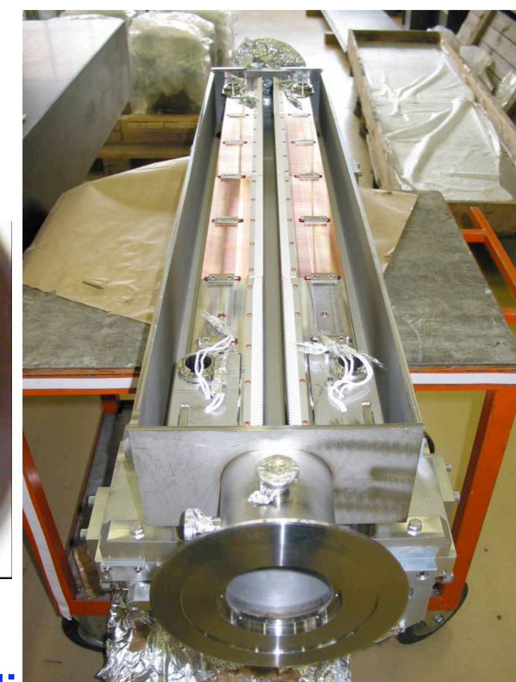




Materials chosen:
Metals where possible
or C-C fibers

Robustness required,
listen to 10^{13} p on a
C-C Jaw

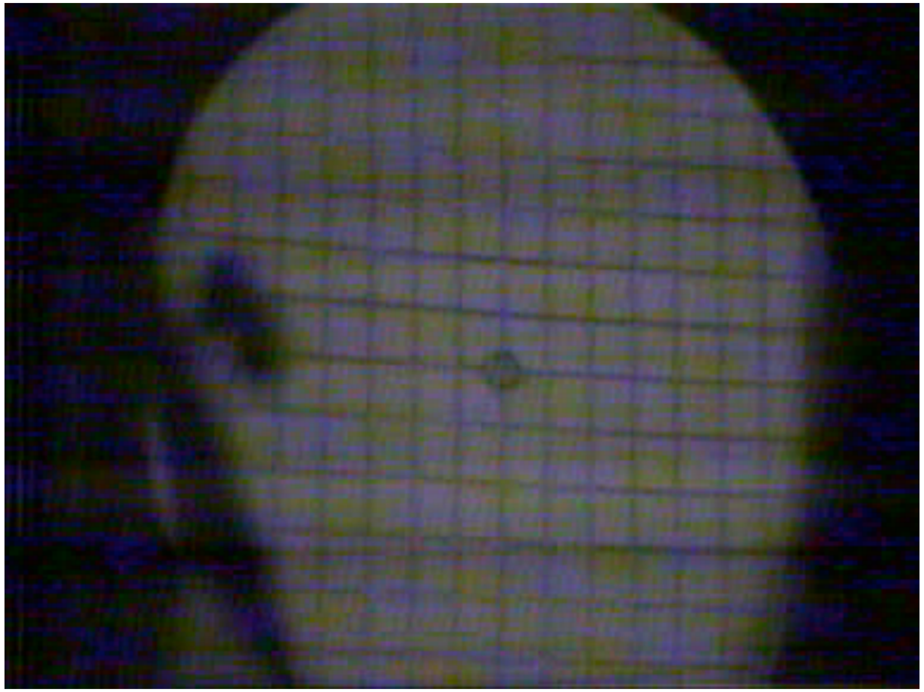


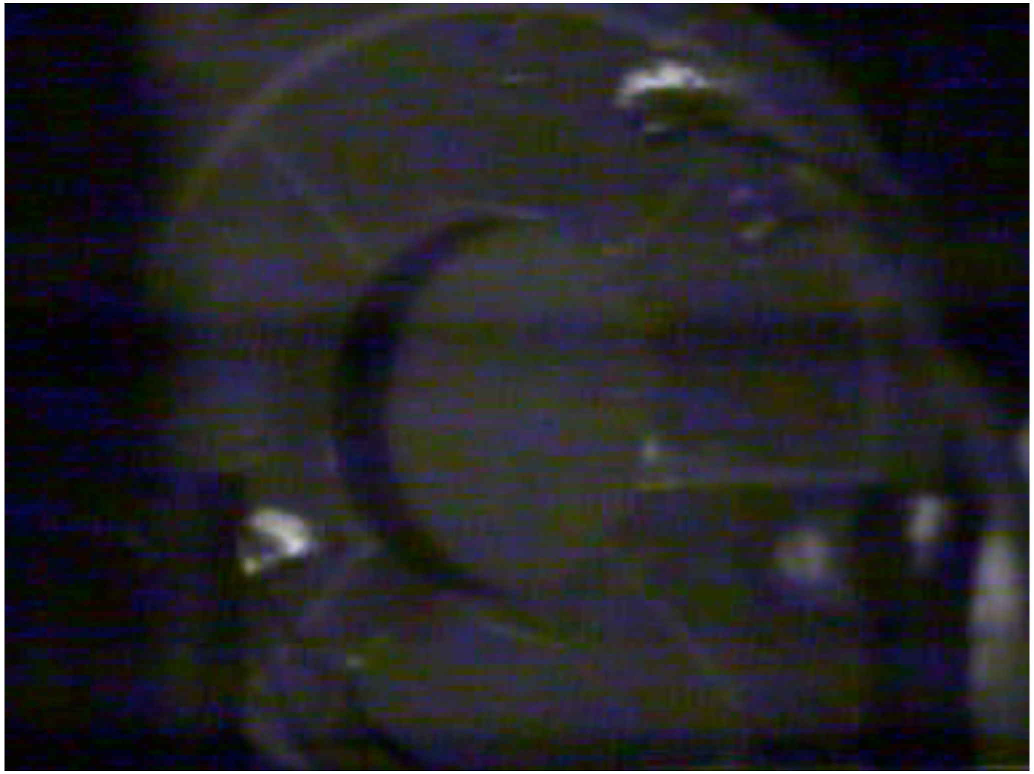


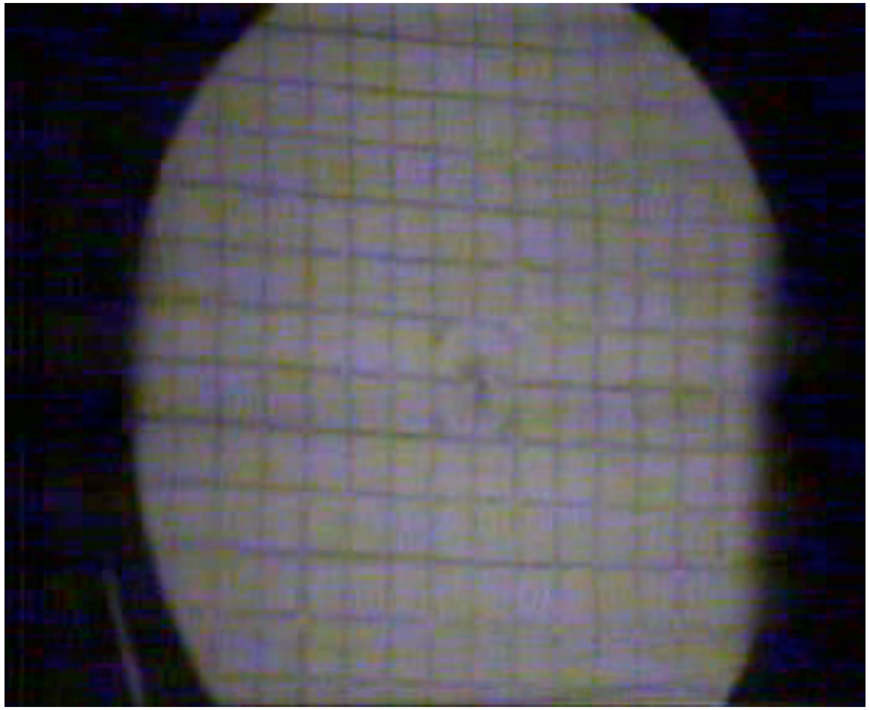
Courtesy of S. Redaelli

Collimator in the tunnel during installation

Beam Hitting detector screens

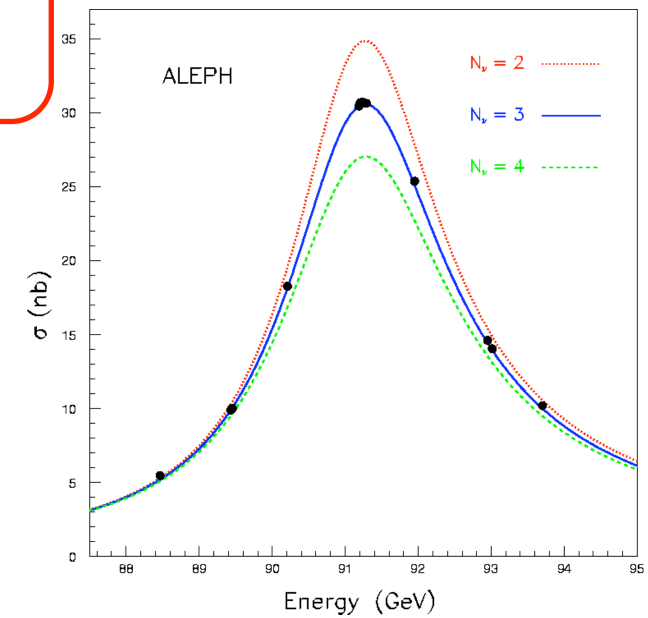






What can influence an accelerator?

The physics case:
the Z mass at LEP has been measured with an error of 2 MeV.
Energy of the accelerator has to be know better than 20 ppm.



Energy measurements obtained by during last years of LEP operation

Nominal (GeV)	E_{CM} (LEP) (GeV)
181	180.826 ± 0.050
182	181.708 ± 0.050
183	182.691 ± 0.050
184	183.801 ± 0.050
Combined	182.652 ± 0.050

What can influence the energy of a collider?

“Rappel”of strong focusing synchrotron optics

Stable orbit is bent by the main dipoles, centered in the quadrupoles, no field

Energy fixed by bending strength and cavity frequency

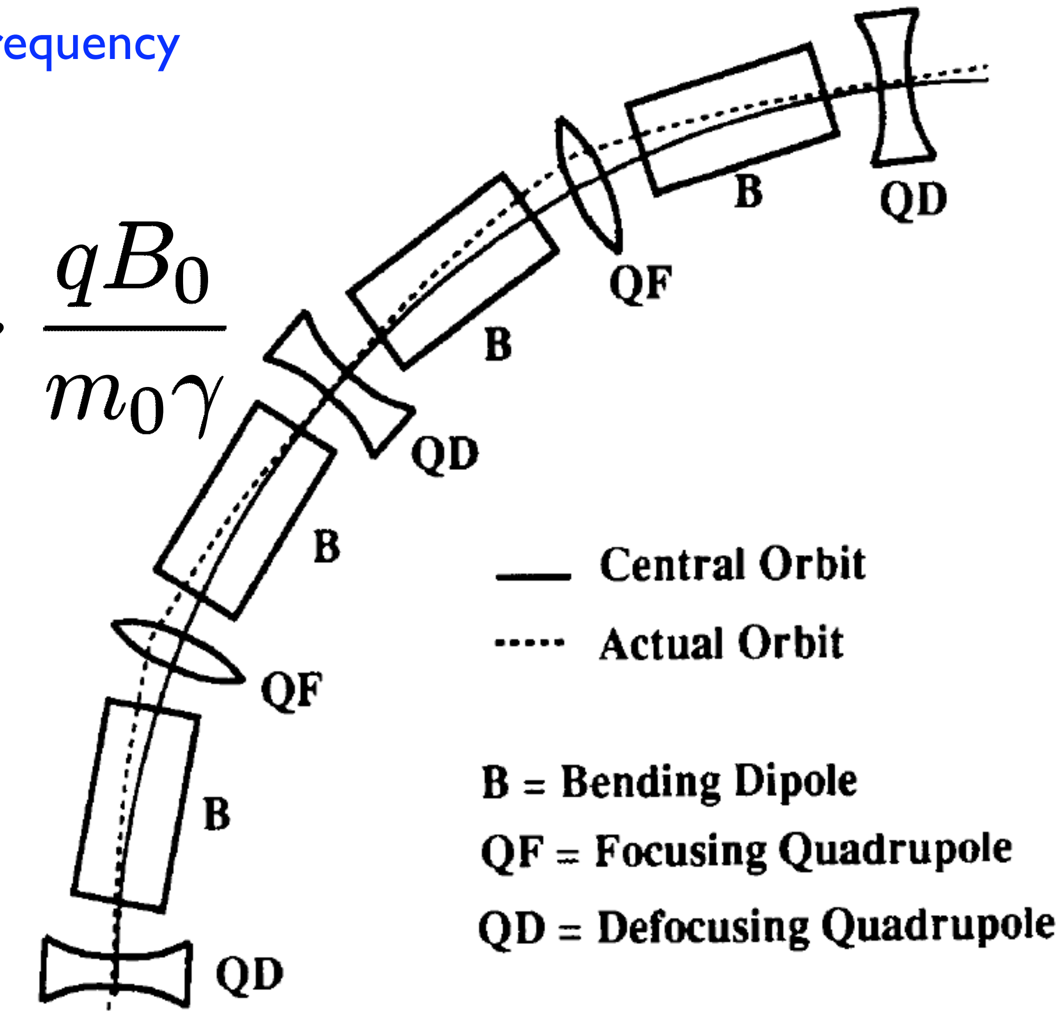
$$f_{RF} = h \cdot f_{rev}$$

$$f_{rev} = \frac{v}{C_c} = \frac{v}{2\pi\rho} = \frac{1}{2\pi} \cdot \frac{qB_0}{m_0\gamma}$$

A variation of the Circumference C induces changes in the energy proportional to α, the momentum compaction factor.

$$\frac{\Delta E(t)}{E_0} = -\frac{1}{\alpha}\frac{\Delta C(t)}{C_c}$$

In LEP $\alpha = 1.86\ 10^{-4}$ a small variation the circumference induces a large variation in energy



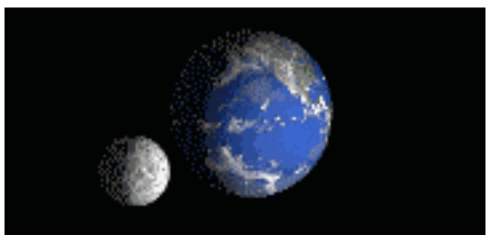
see trasp. Elias

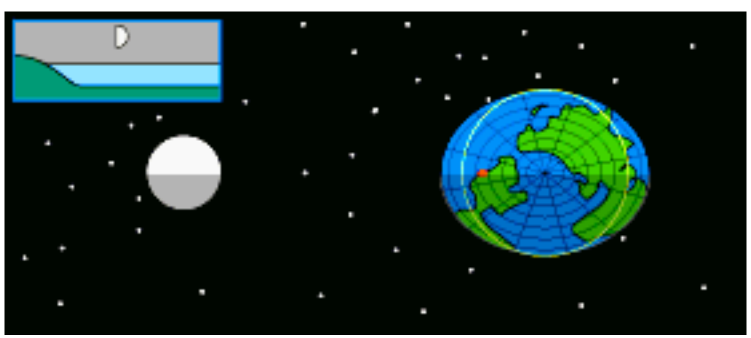
Moon tides can change earth geometry

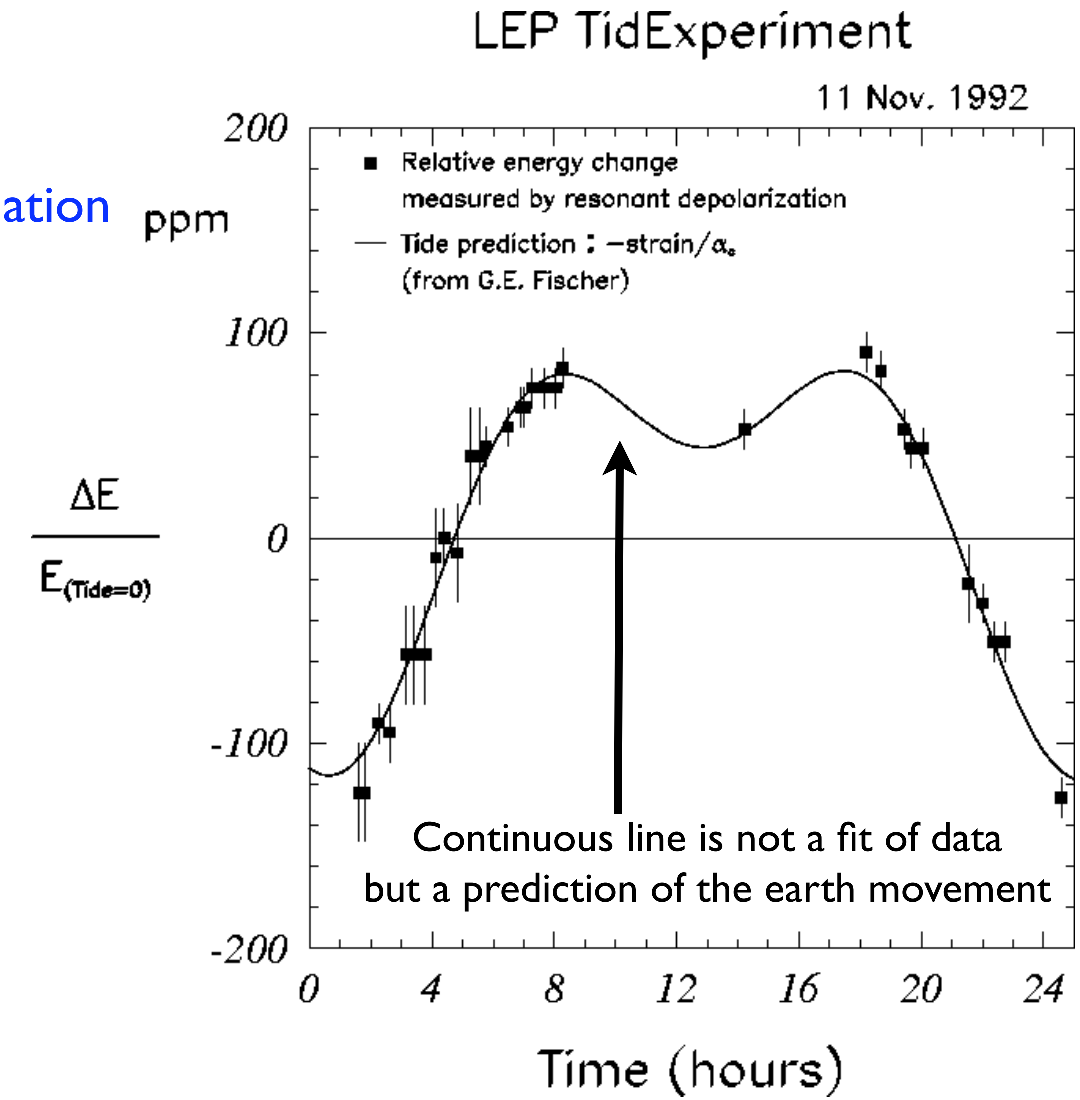
<u>Moon induces a earth deformation similar to water tide.</u>

Total deformation of the LEP about <u>4 mm</u>
Energy variation of 100 ppm

The 12 h cycle is due to the earth deformation



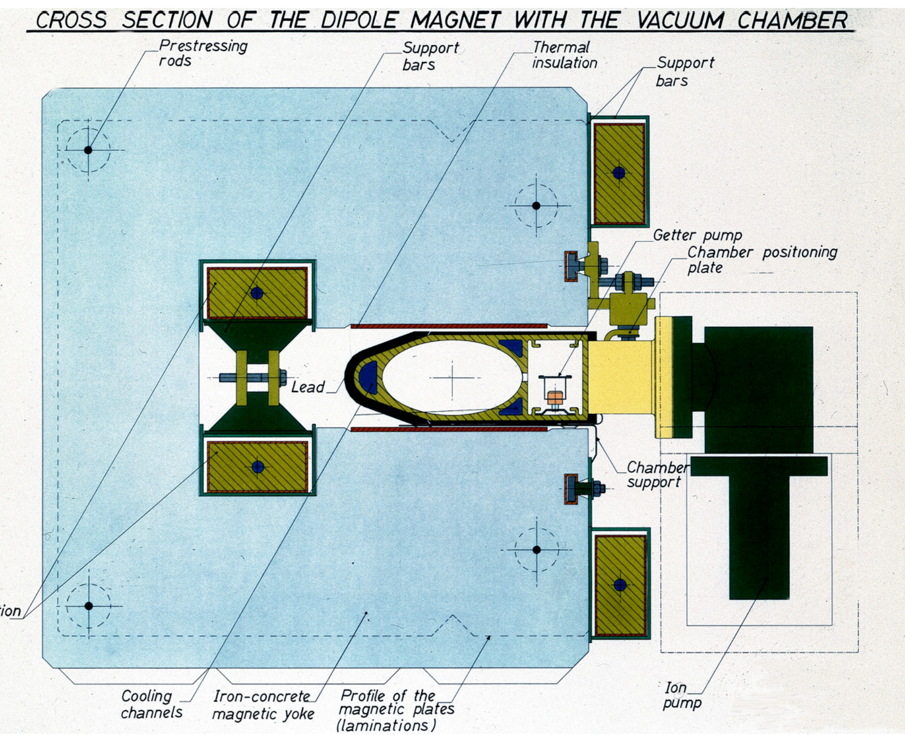


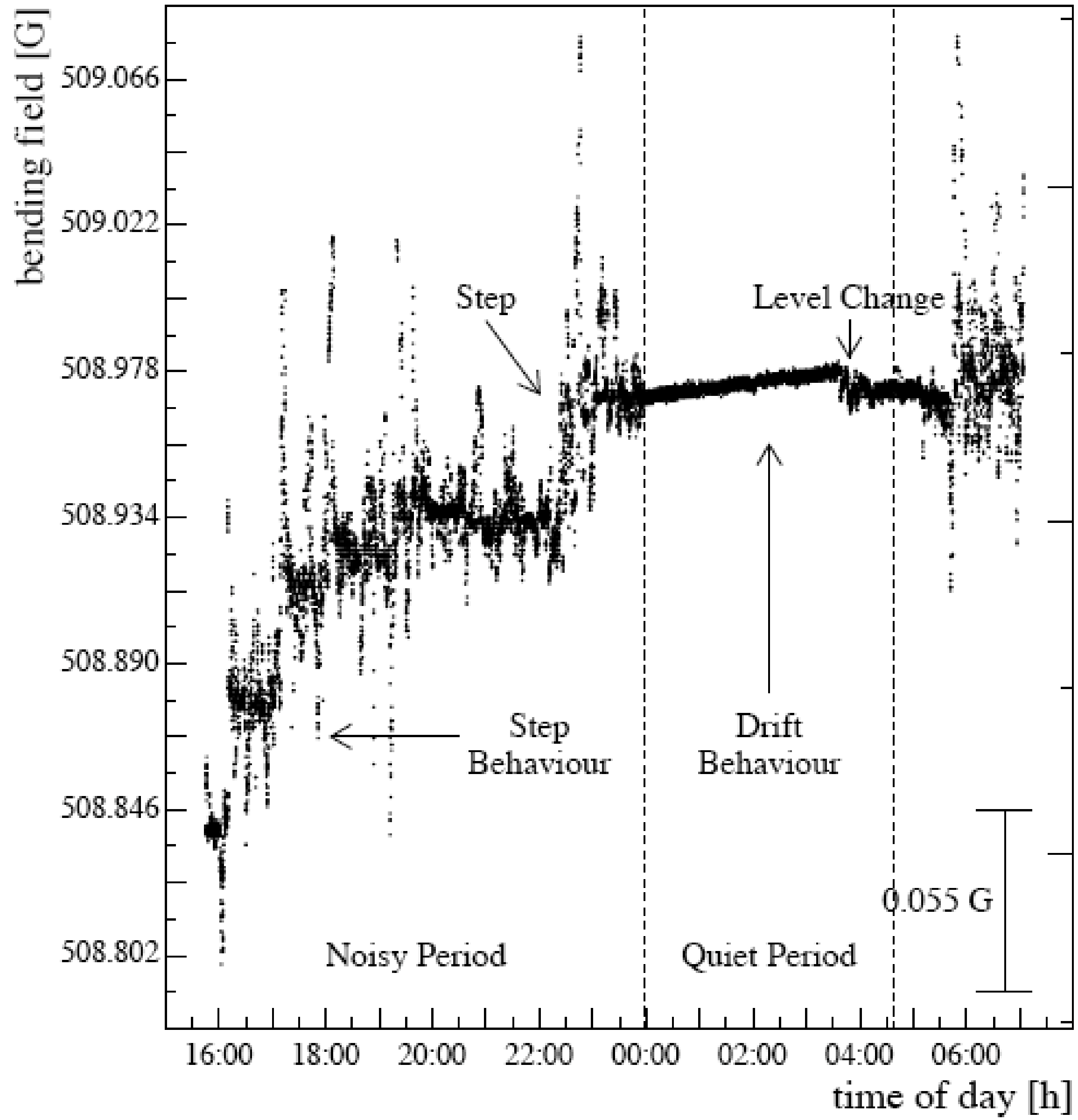


The effect is modulated by the different tide intensities and by the SUN tides

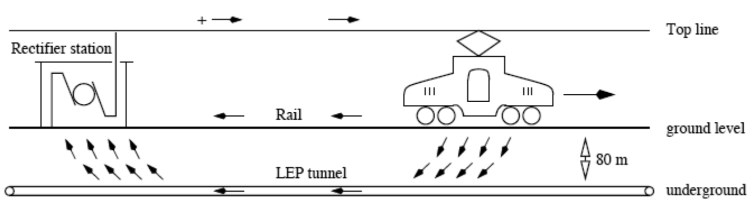
The problem: an accelerator is not in the middle of nothing

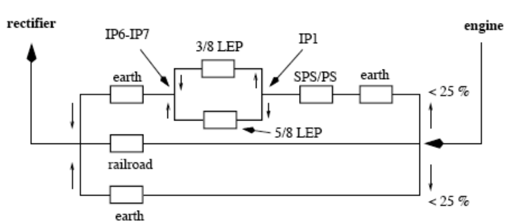
Observed variation of the bending strength of the LEP dipoles during the day

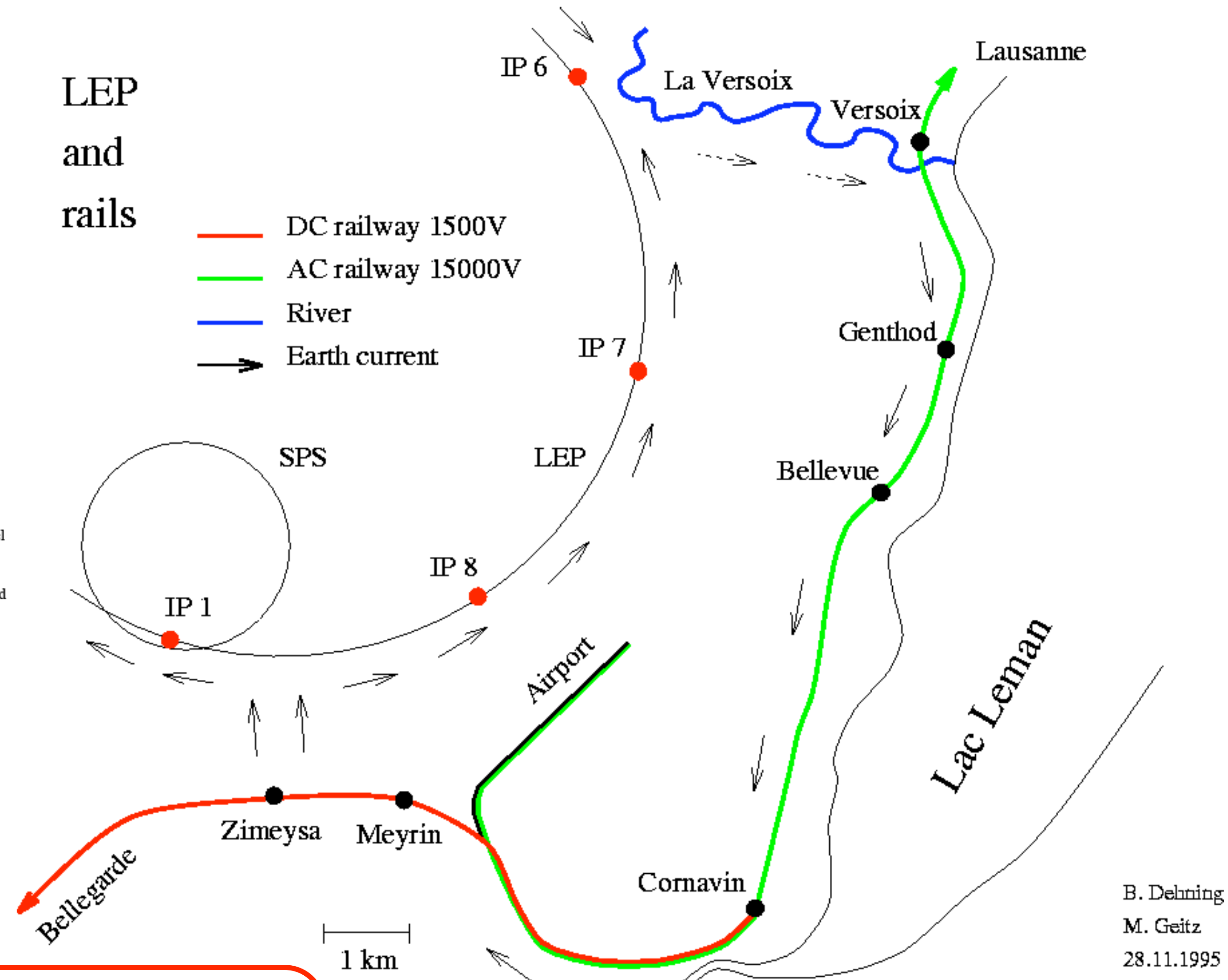




Influence of train leakage current

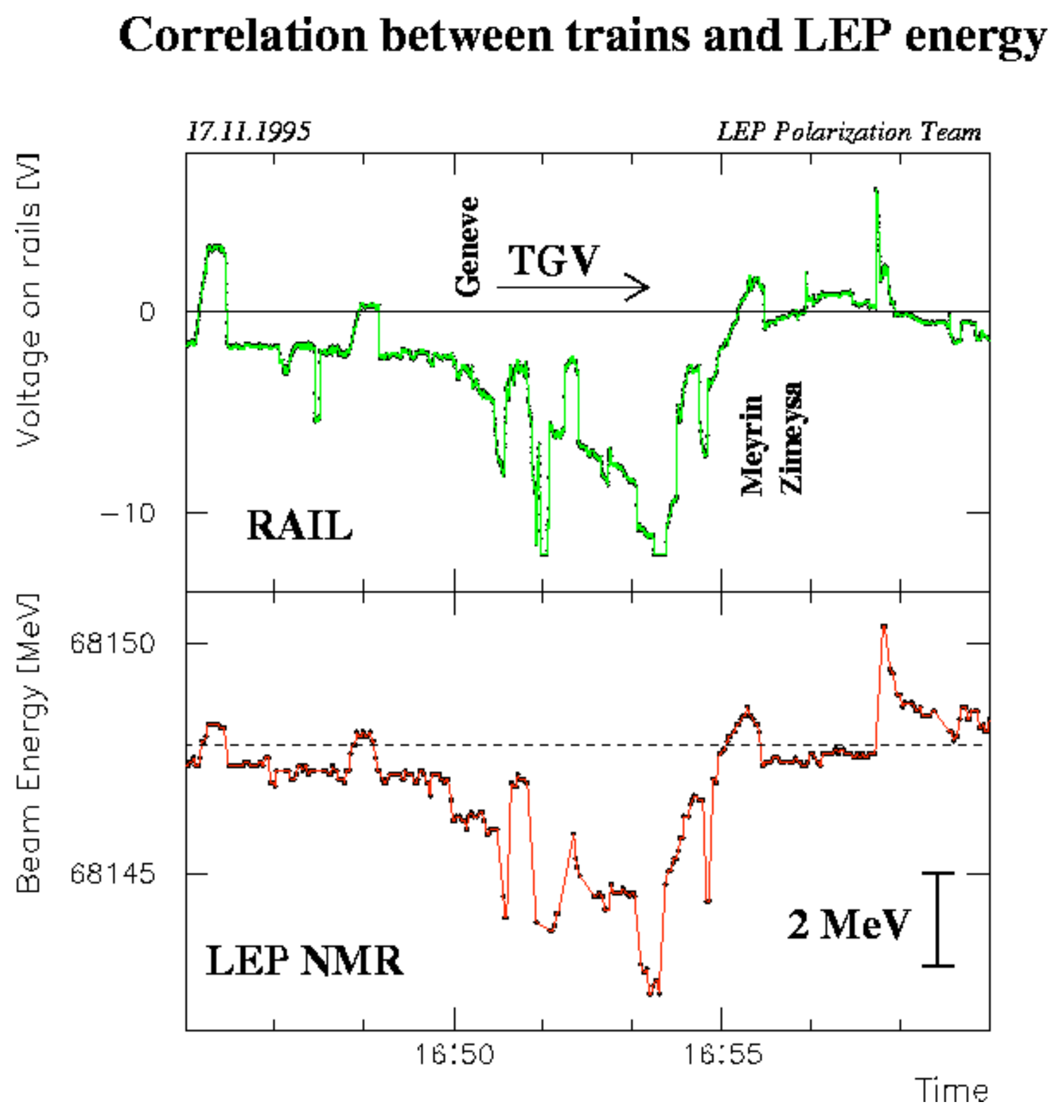






LEP beam pipe as ground for leakage current.
Variation of the dipole field due to the current .
Change in energy following the SNCF train table

The evidence, TGV to Paris at 16:50 ...

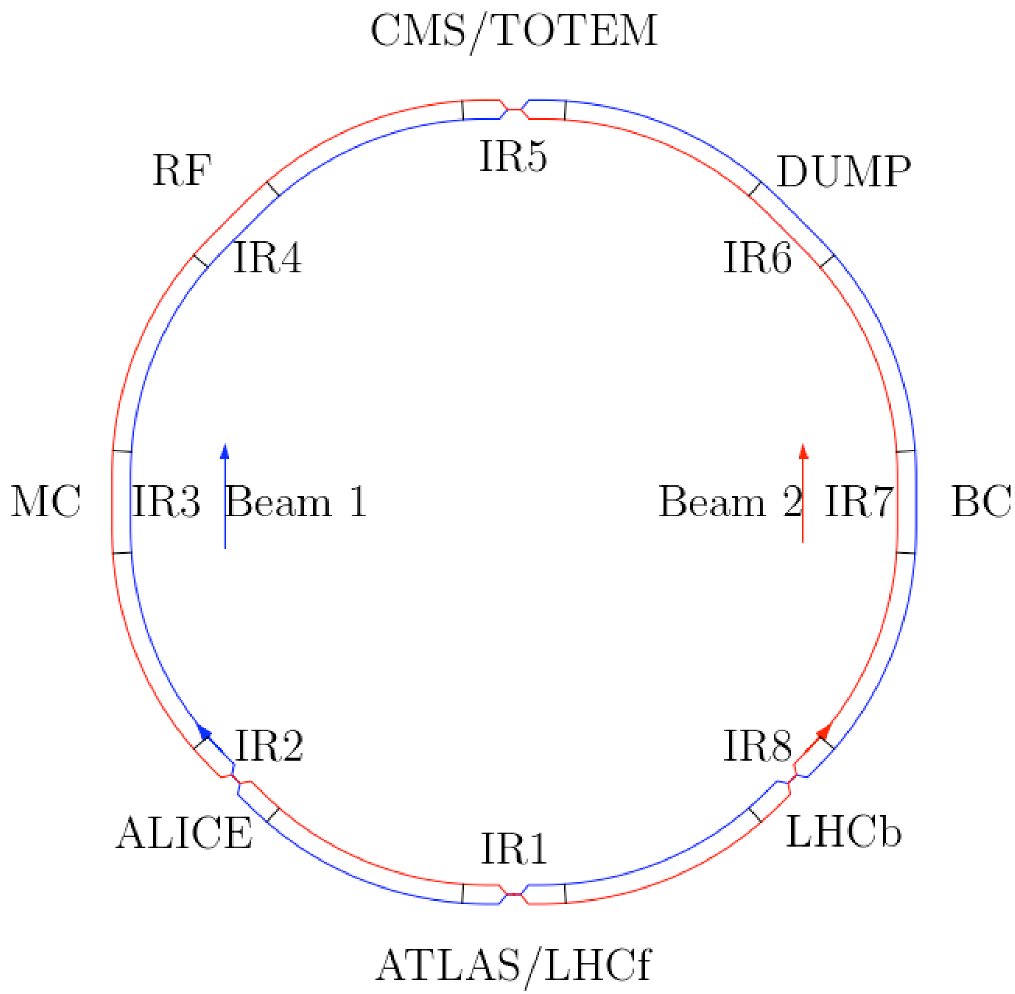


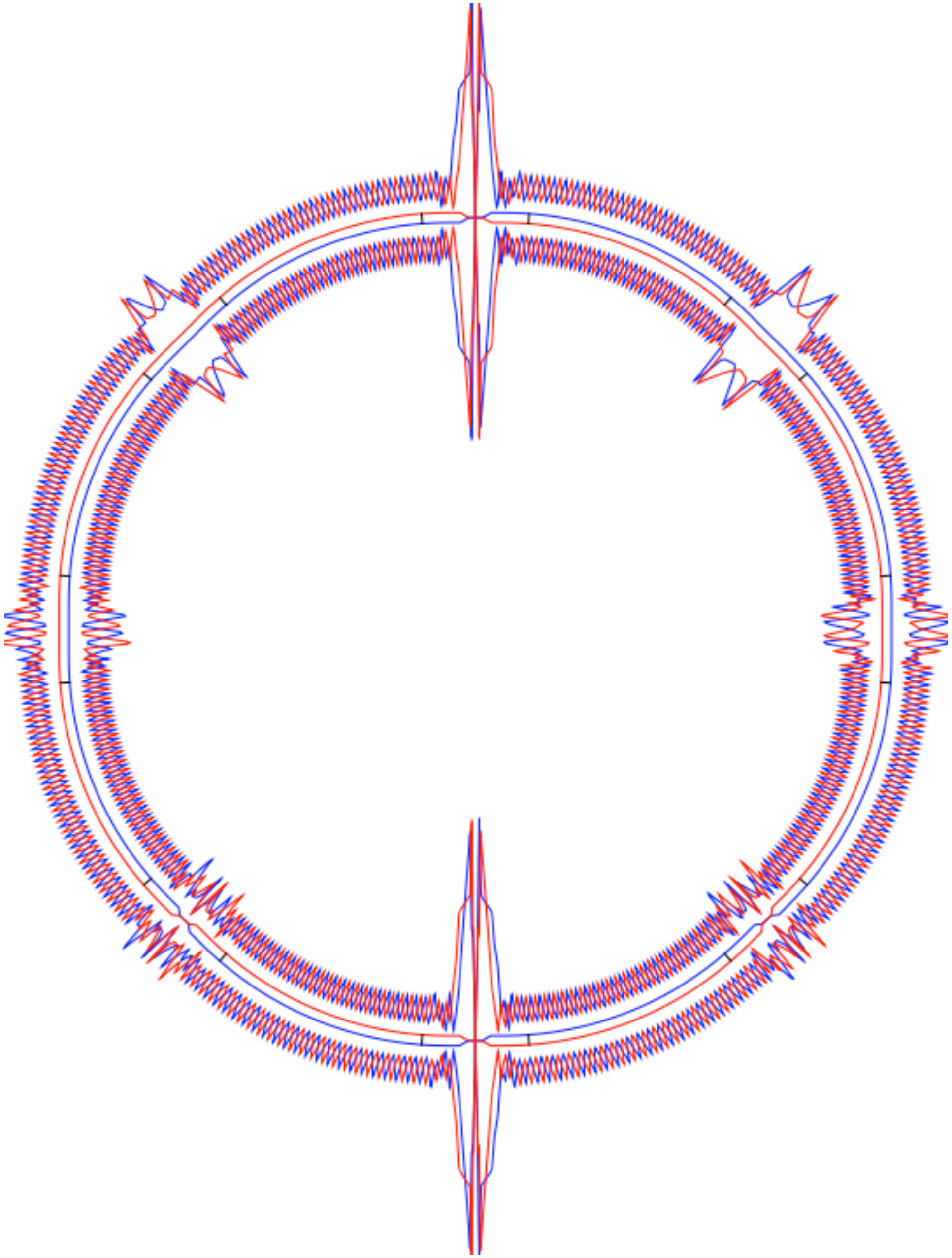
Conclusion/future..

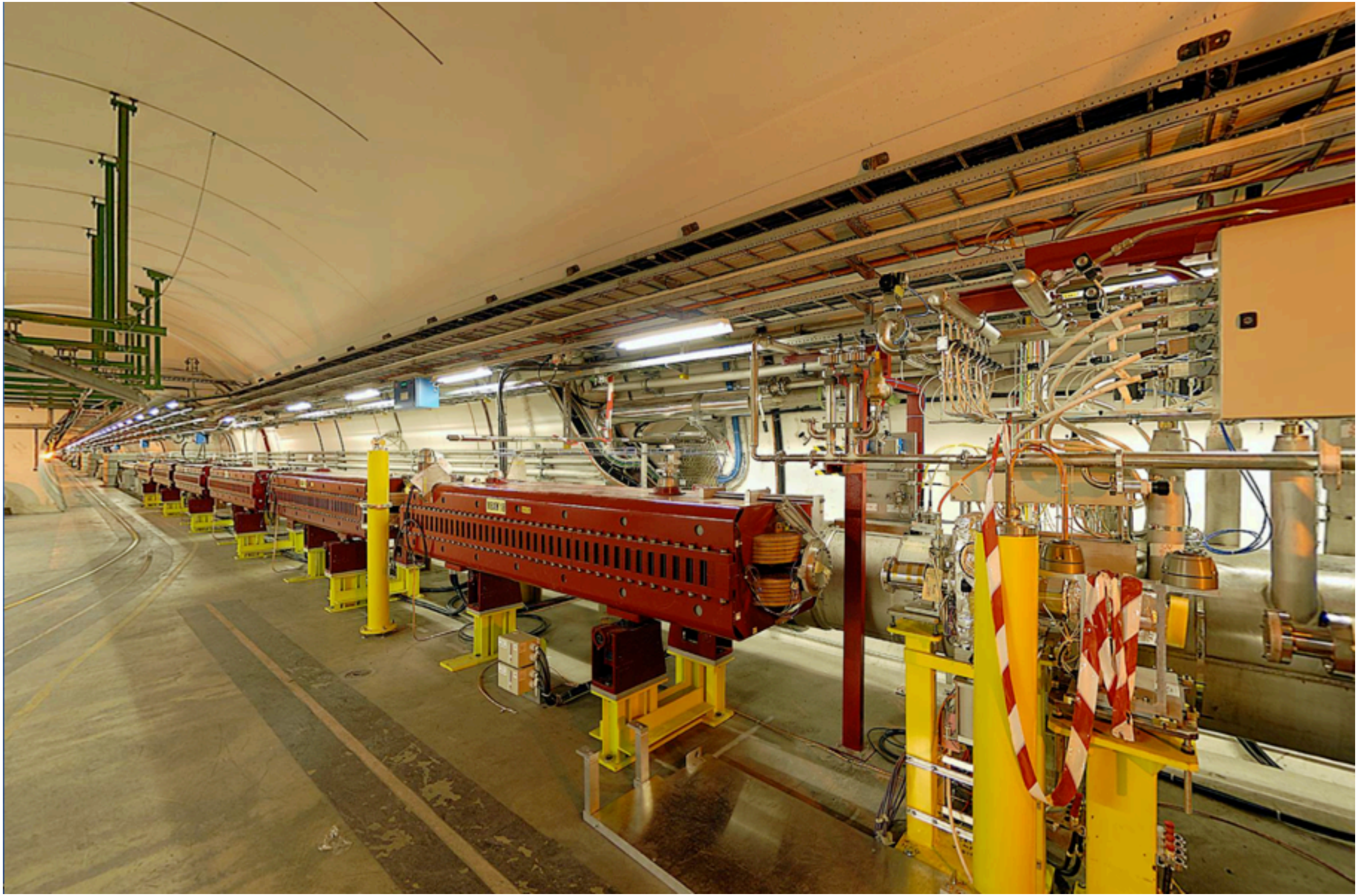
- As last transparency, what about the future.
- The "after LHC" is going to be a LINEAR COLLIDER with leptons:
  - Linear because of synchrotron radiation
  - with electrons (lepton) because of precision measurements

- Thanks for your attention.

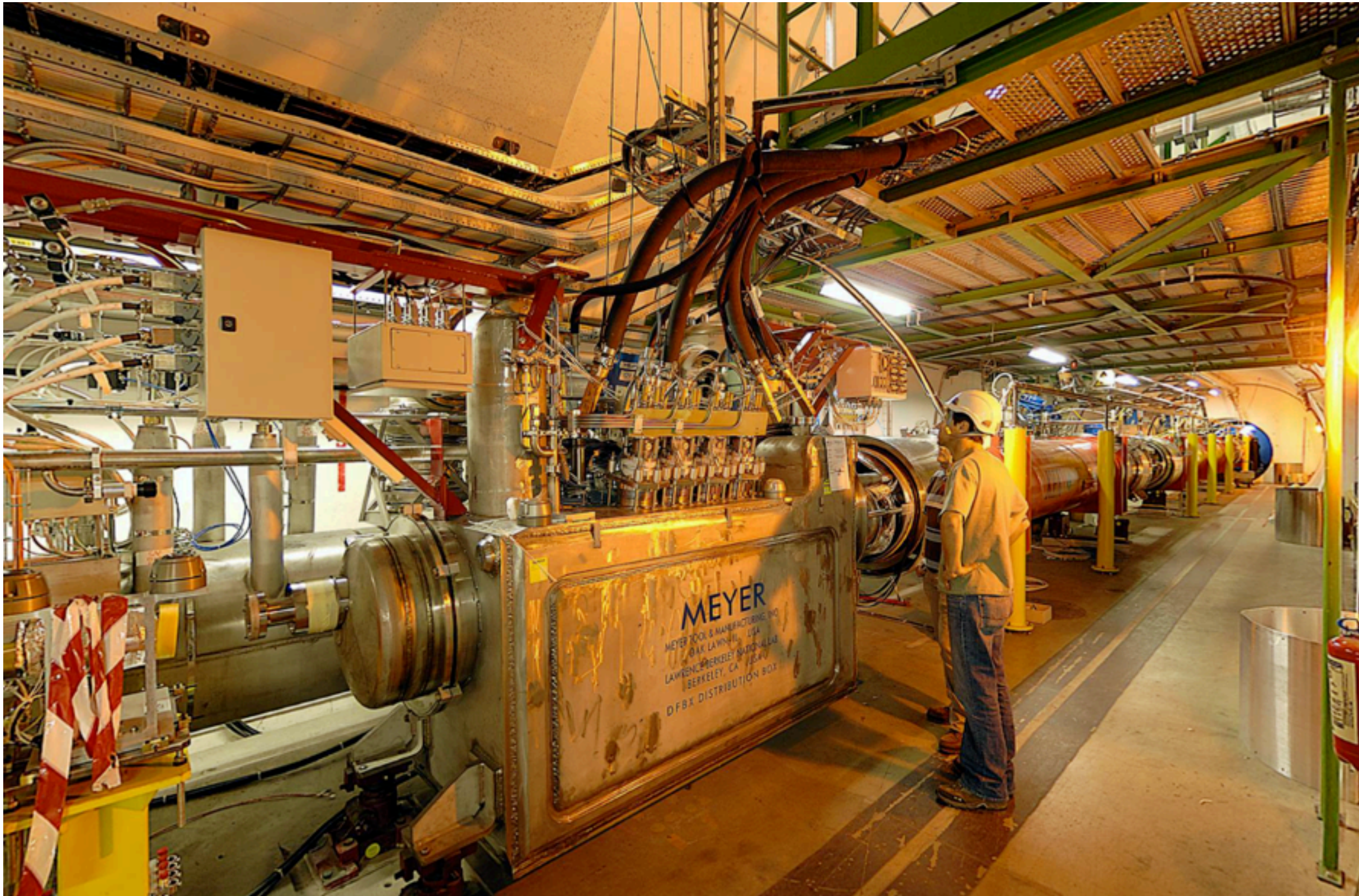
The LHC optics in one slide







Near the IPs



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Triplets before lowering in the tunnel