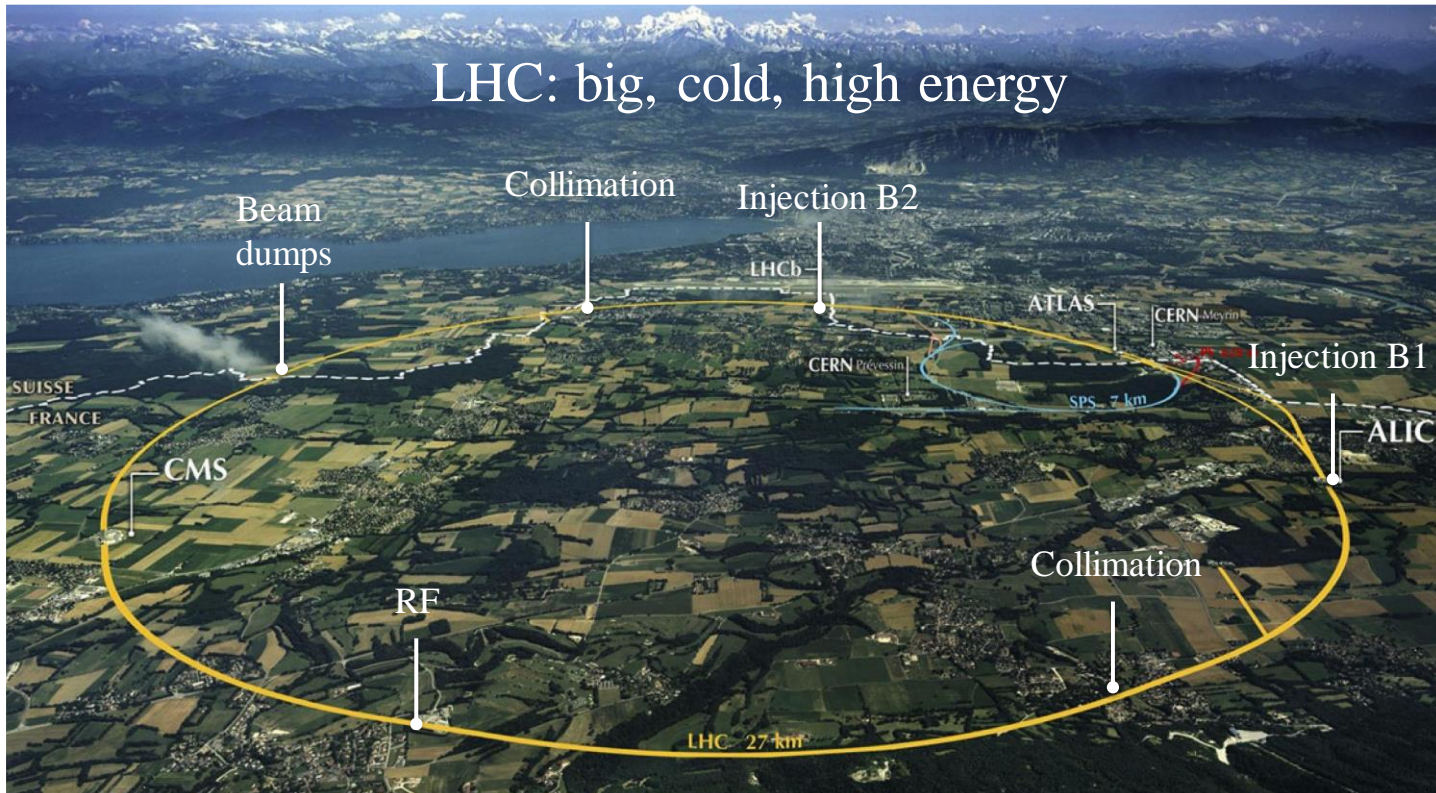


# The Large Hadron Collider : the LHC

The largest machine and scientific instrument ever built by mankind

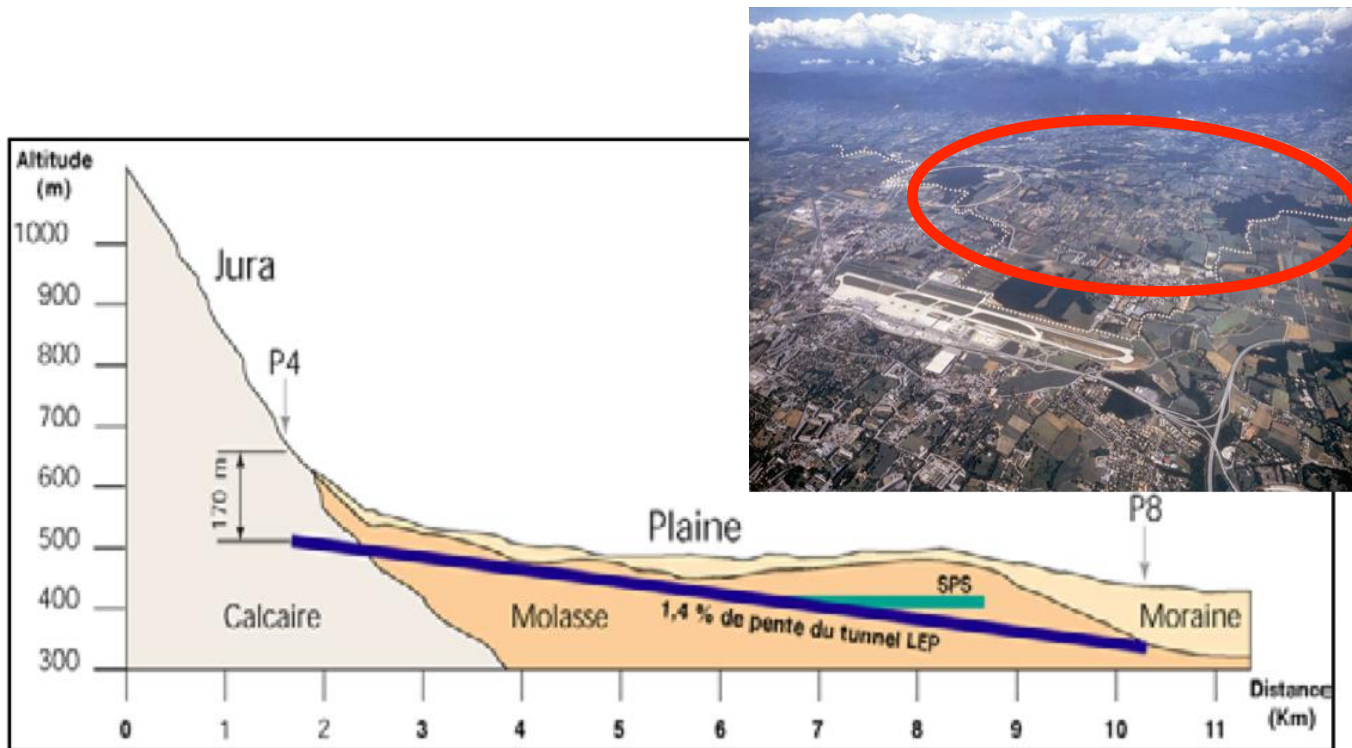
.... For the moment....

LHC: big, cold, high energy



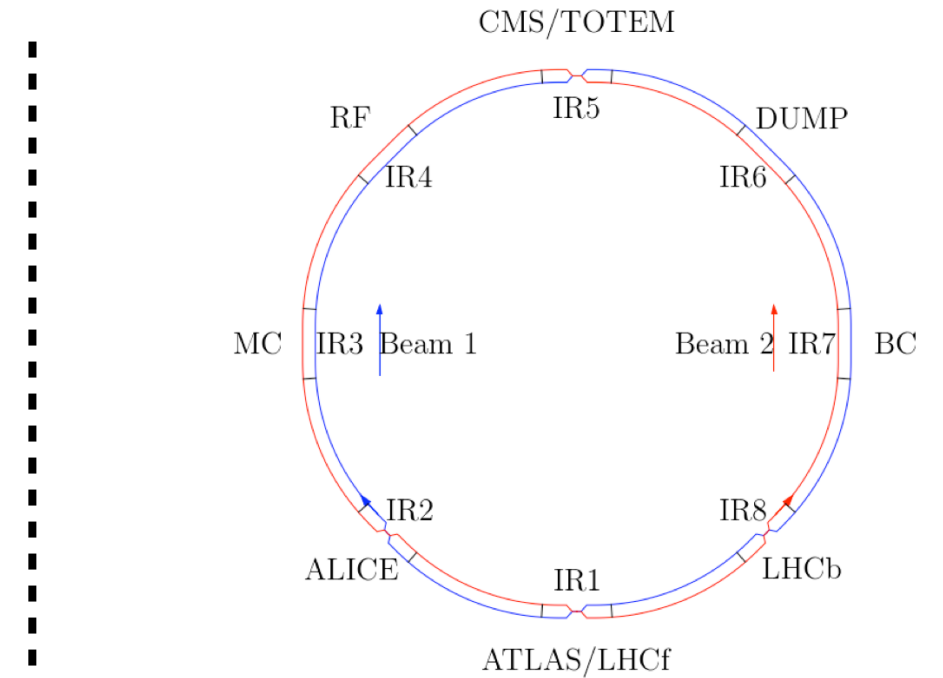
Quantity	Number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Nominal energy, protons	6.5 TeV (6.8 TeV)
Nominal energy, protons collisions	13 TeV (13.6 TeV)
No. of protons	Some $10^{14}$
Number of turns per second	11245
Number of collisions per second	1 billion

# LHC geometry: it is not flat... and it is not round



Tunnel build almost entirely on a geological layer called “Molasse”, easy to tunnel, but reach of water.

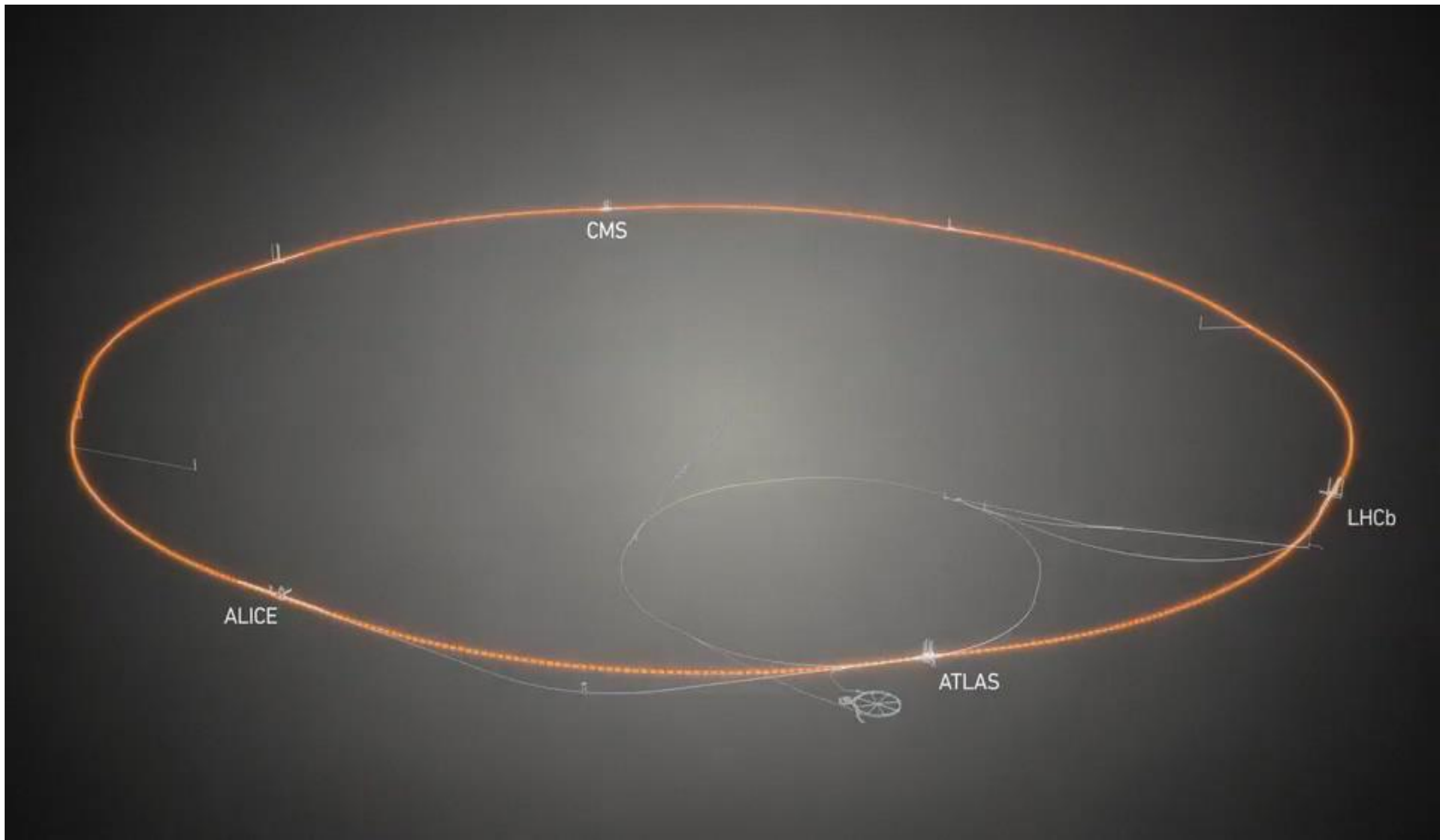
**Slope is 1.4%**



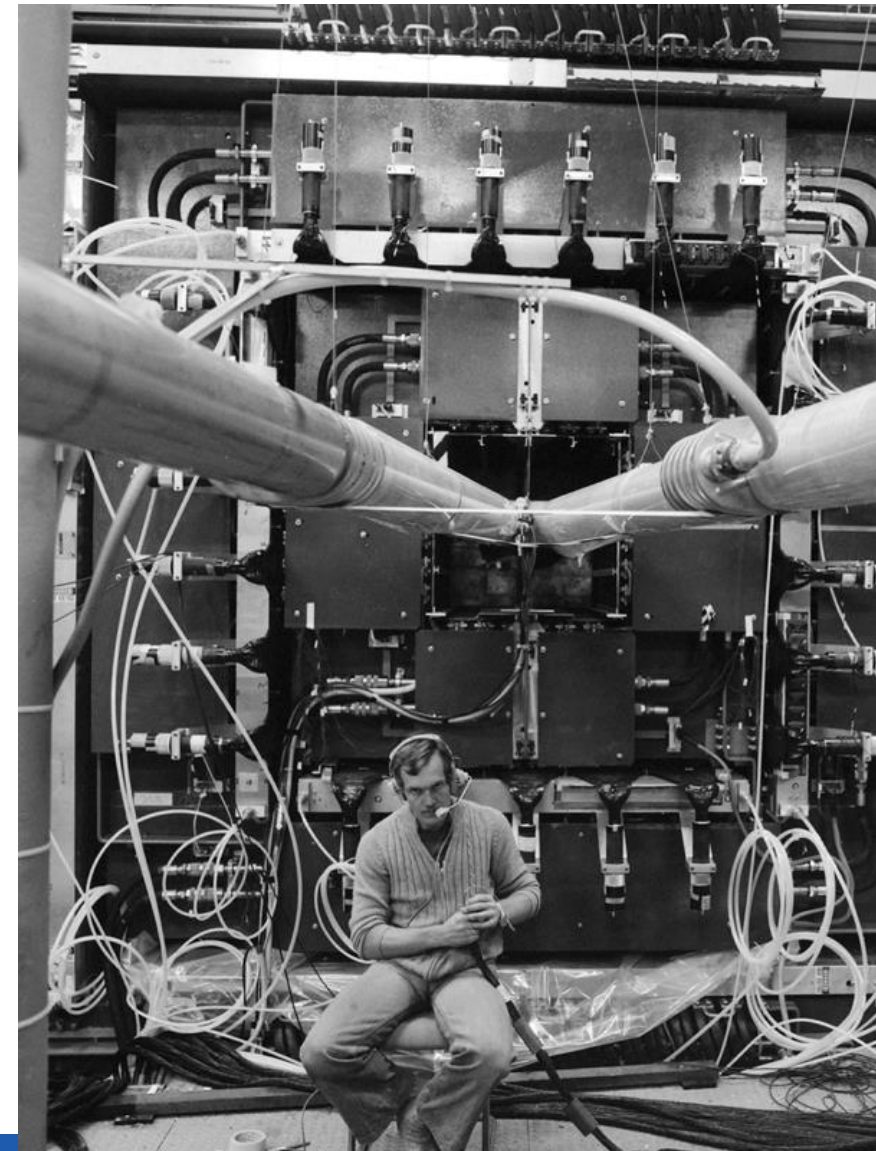
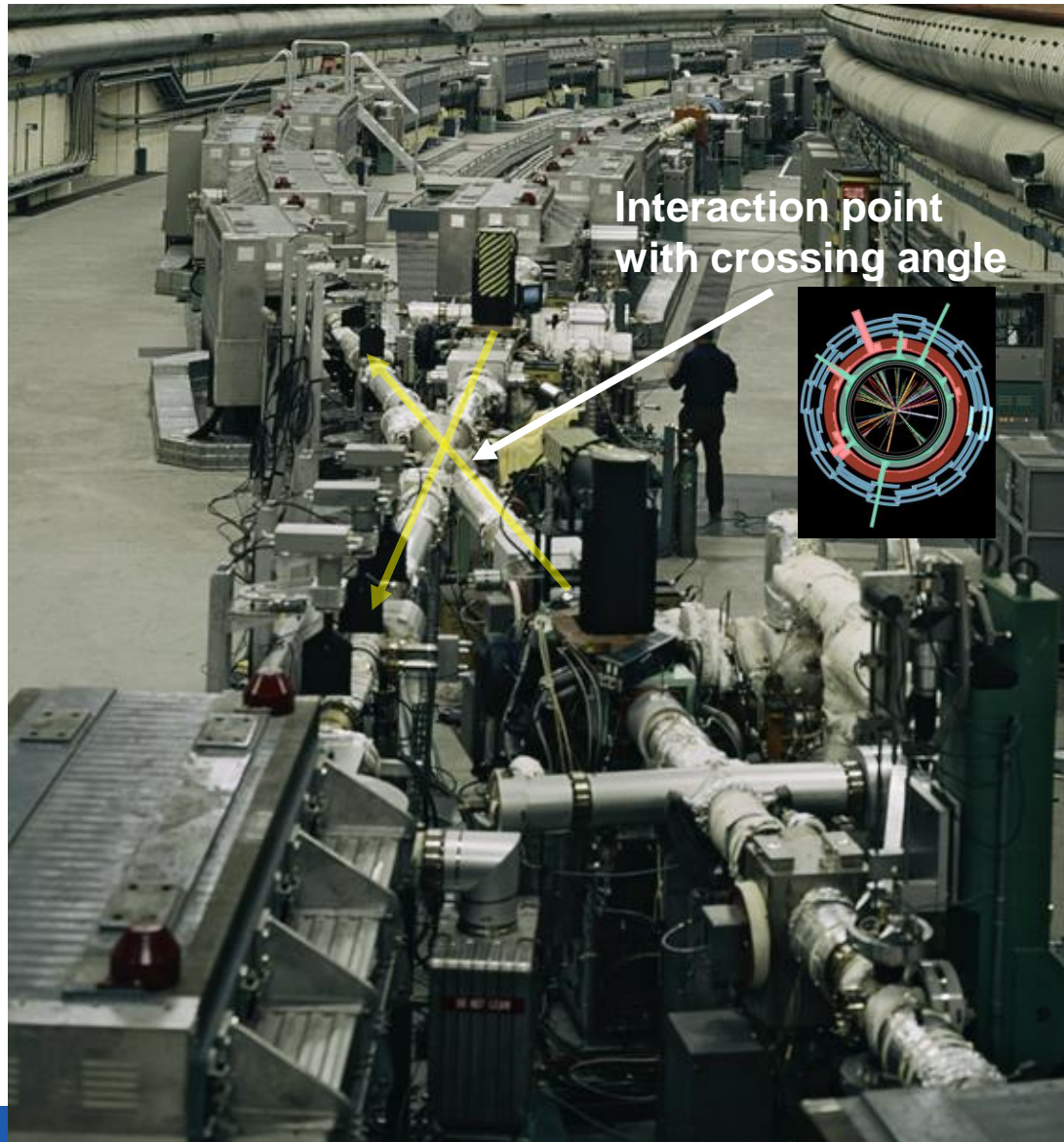
**LHC: 8 independent sectors**

**8 straight sections**

**8 arcs**



# ISR: first proton-proton collider

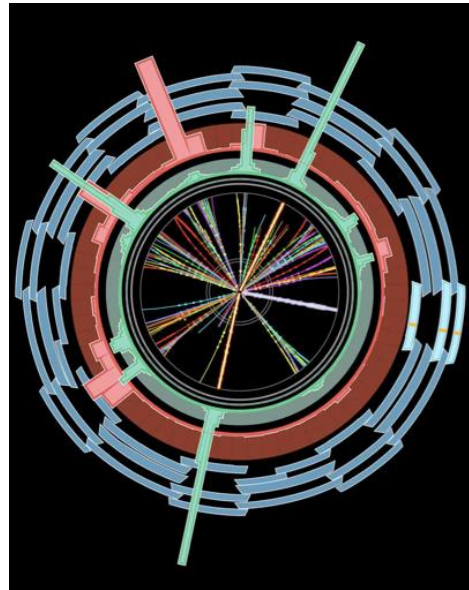


# Luminosity of a collider

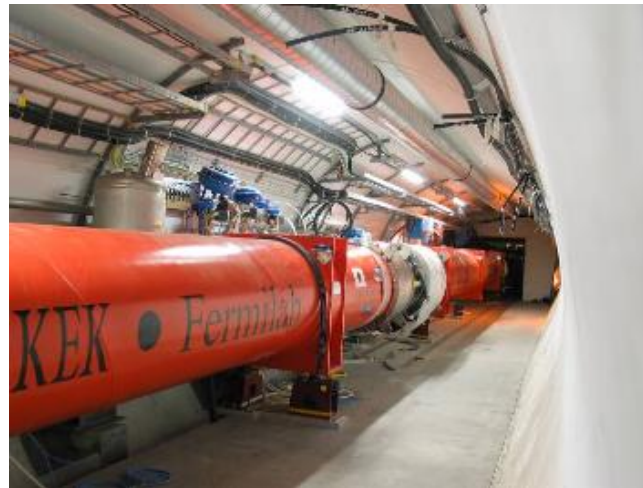
Given by Nature: what we want to study

$$N_{event} = L\sigma_{event}$$

What we can measure

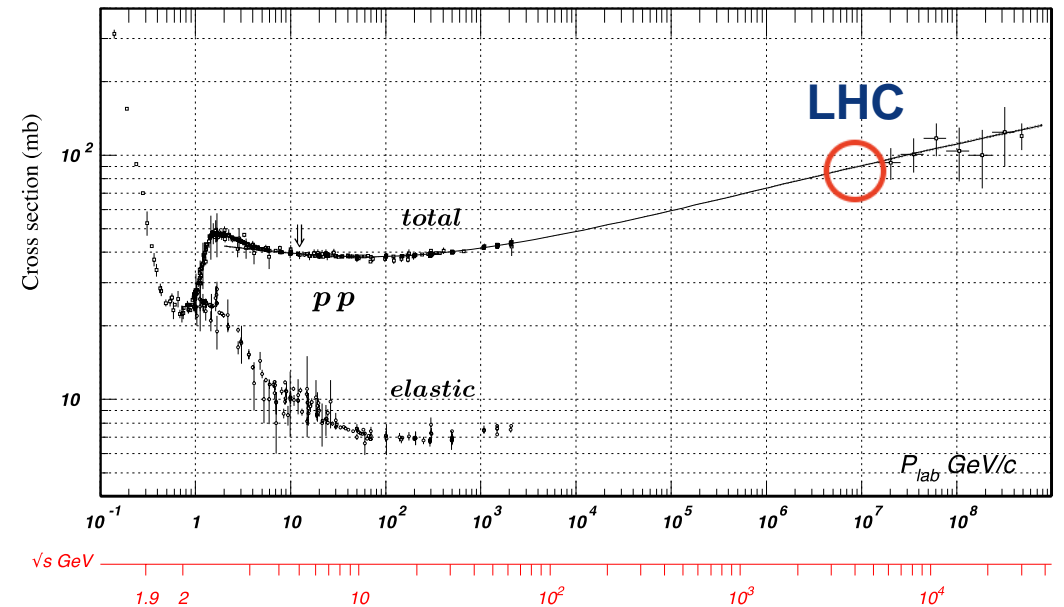


## Accelerator Technology



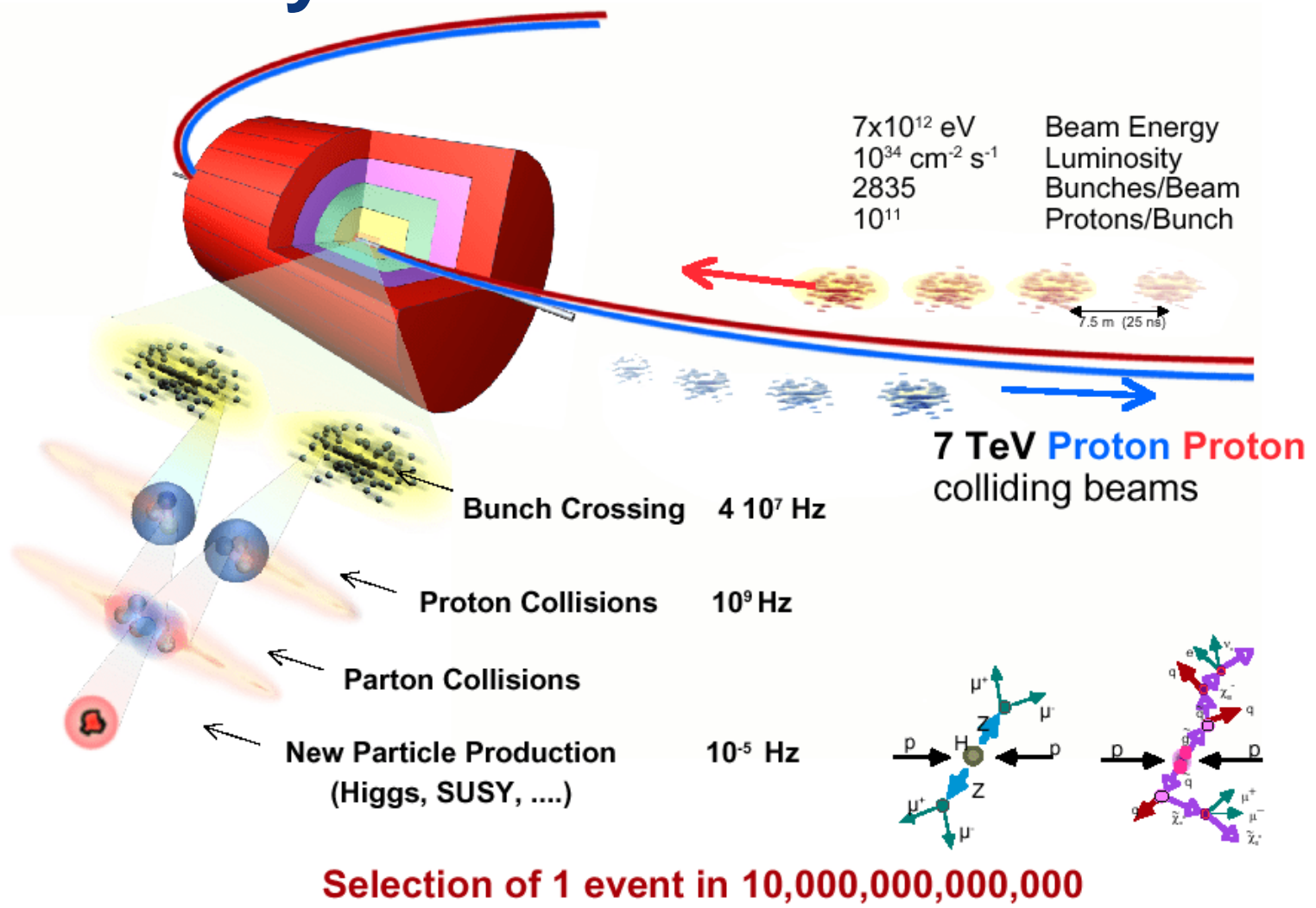
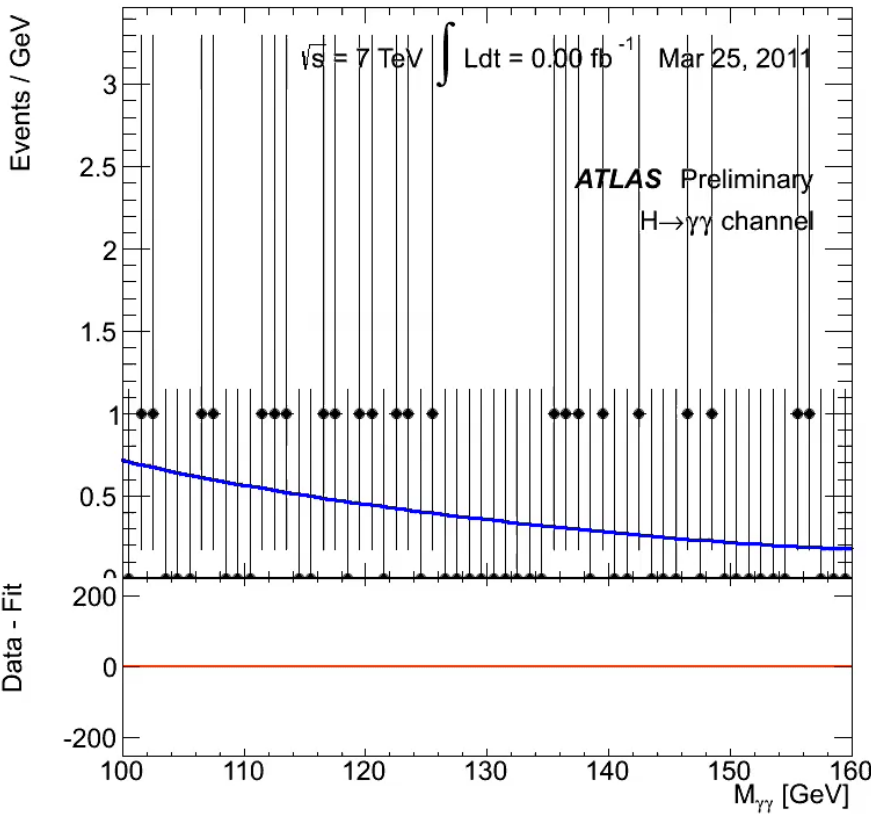
Cross section

→ probability that something occurs in p-p collisions



# The events we want to study are rare

$$N_{event} = L\sigma_{event}$$



# We want to have the maximum Luminosity

**Proton Intensity per bunch**  
This comes from the injectors  
10 years of development  
Being done now

**Revolution frequency**  
This is fixed by the LHC circumference

**Number of bunches**  
This is more or less fixed

**How the bunches collides**  
This can be changed

$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

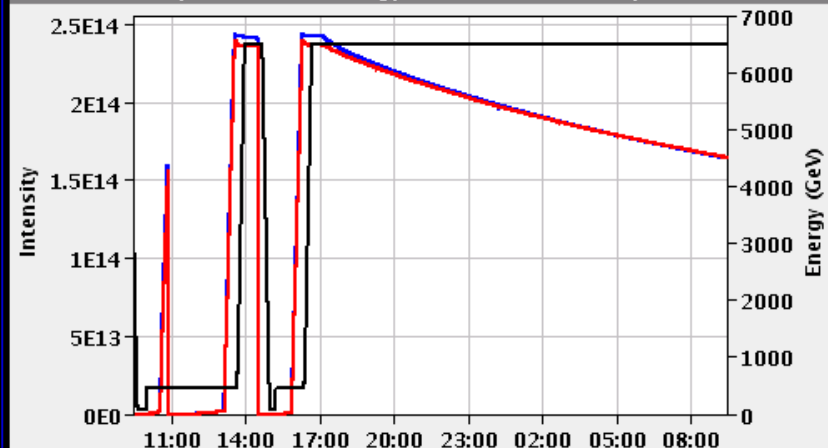
**Beam Spot size at collision point**  
This can be minimised by building new magnets → LS3 → post 2029  
Technology development 10-15 years long

# PROTON PHYSICS: STABLE BEAMS

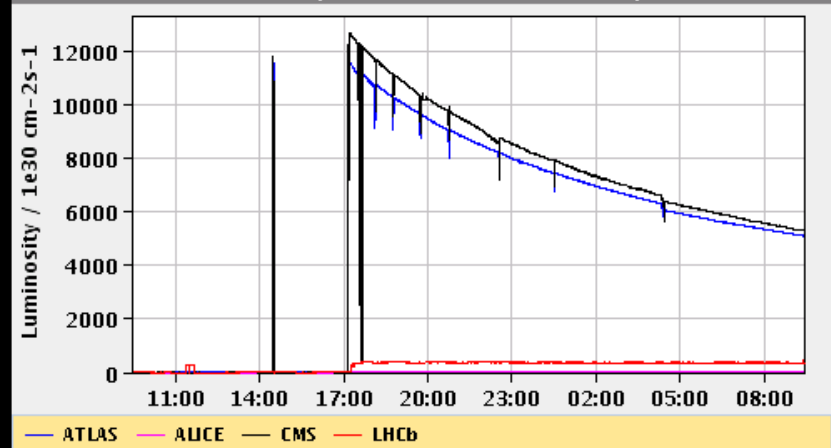
Energy: 6499 GeV    I(B1): 1.63e+14    I(B2): 1.68e+14

Inst. Lumi [(ub.s)<sup>-1</sup>]    IP1: 5097.01    IP2: 5.17    IP5: 5290.36    IP8: 369.43

FBCT Intensity and Beam Energy    Updated: 09:25:43



Instantaneous Luminosity    Updated: 09:25:44



Comments (07-Sep-2016 08:56:28)

fill for physics 2220 bunches  
Programmed dump at 9:30am  
Access: CMS and ALFA

BIS status and SMP flags

B1    B2

Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 25ns\_2220b\_2208\_1940\_2036\_96bpi\_24inj

PM Status B1    **ENABLED**    PM Status B2    **ENABLED**





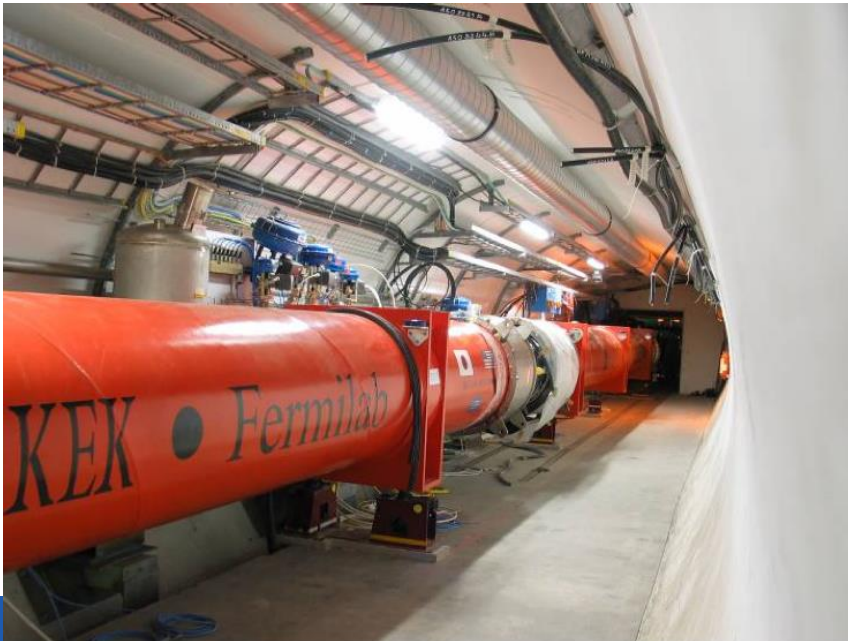
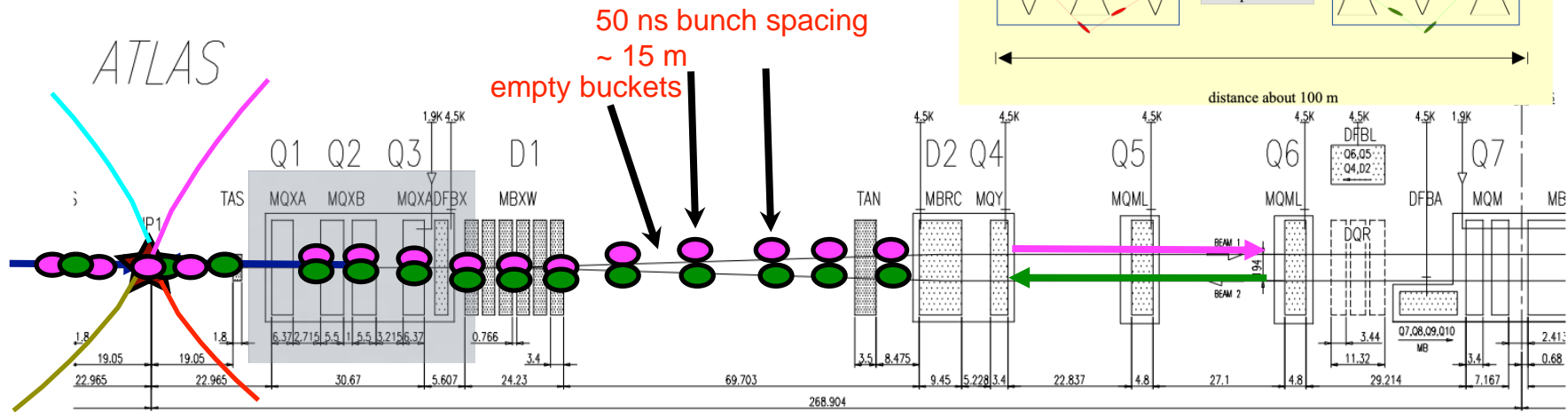
# Magnets for the LHC, every magnet has a role in the optics design

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 ...**

# Inner triplet: final focusing

⇒ how to make the beam small at the IP



# Triplets before lowering in the tunnel



# ..... what we wanted...

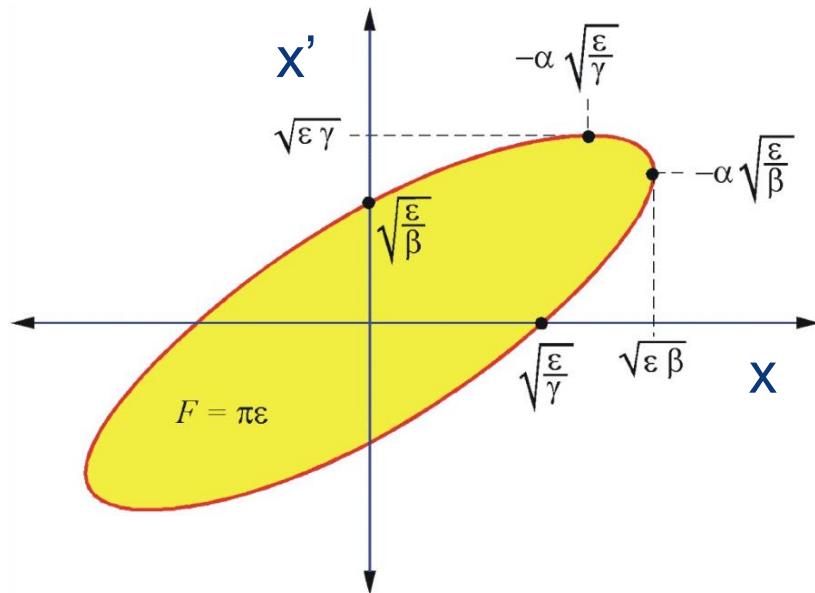
*oh surprise...*

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \epsilon$$

**Learned:**

a) definition of Twiss parameters comes from the equation of motion and beta function

b) The dynamics is really on/within an ellipse

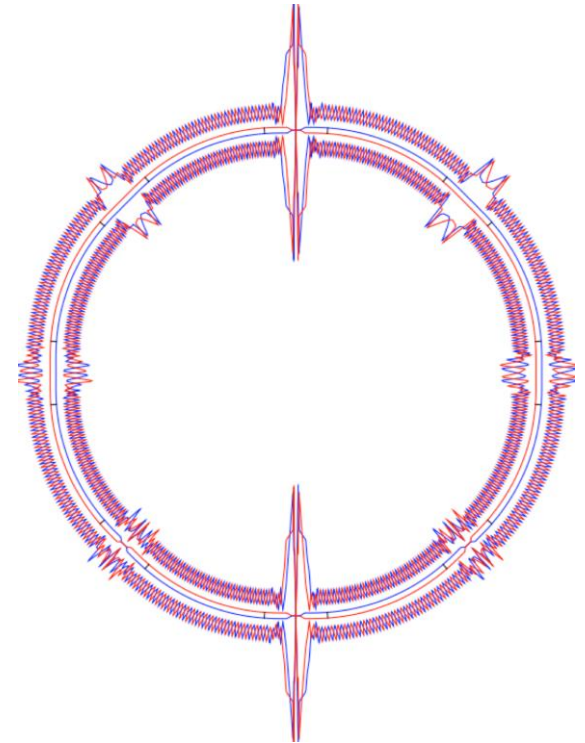


**Twiss parameters:**

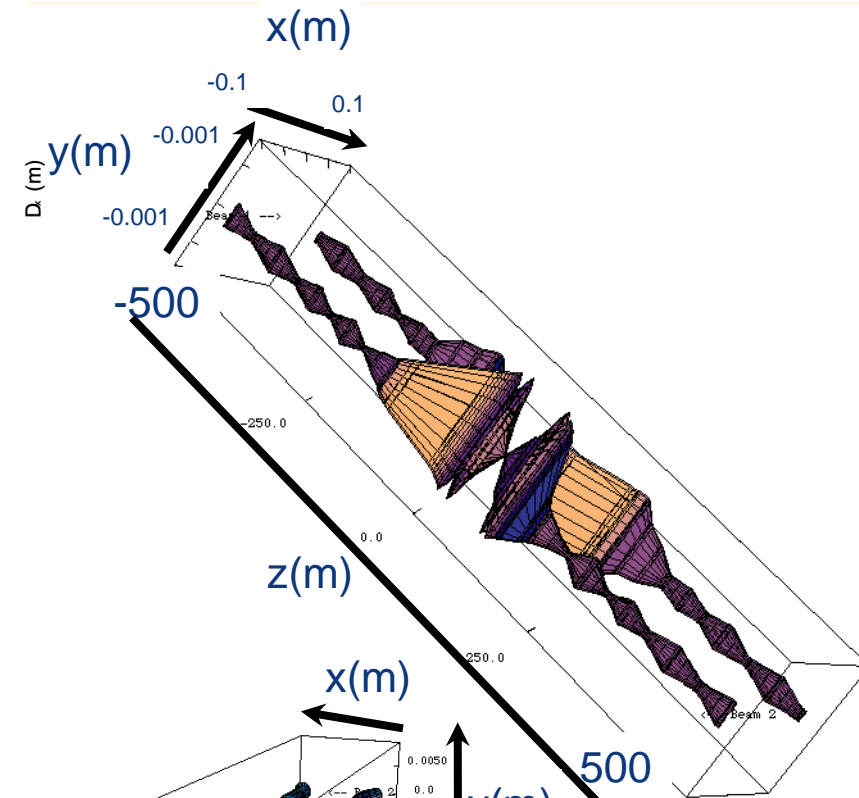
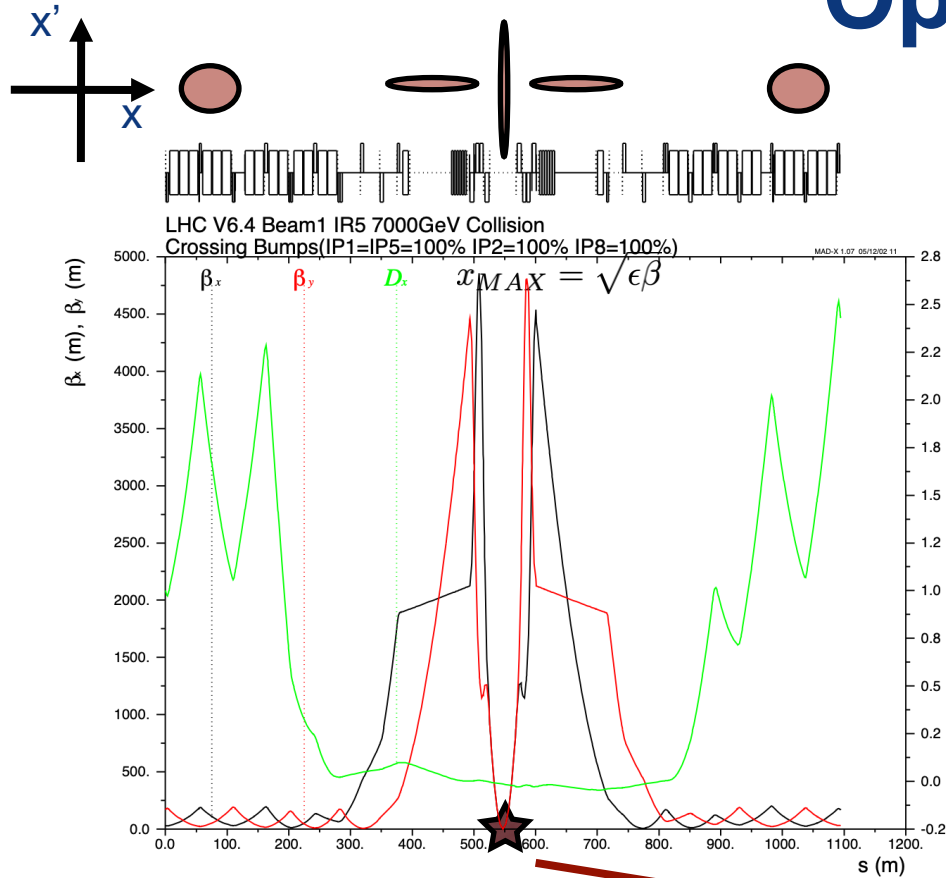
$$\alpha(s) := -\frac{\beta'(s)}{2}$$

$$\gamma(s) := \frac{1 + \alpha^2(s)}{\beta(s)}$$

$$\beta(s)$$

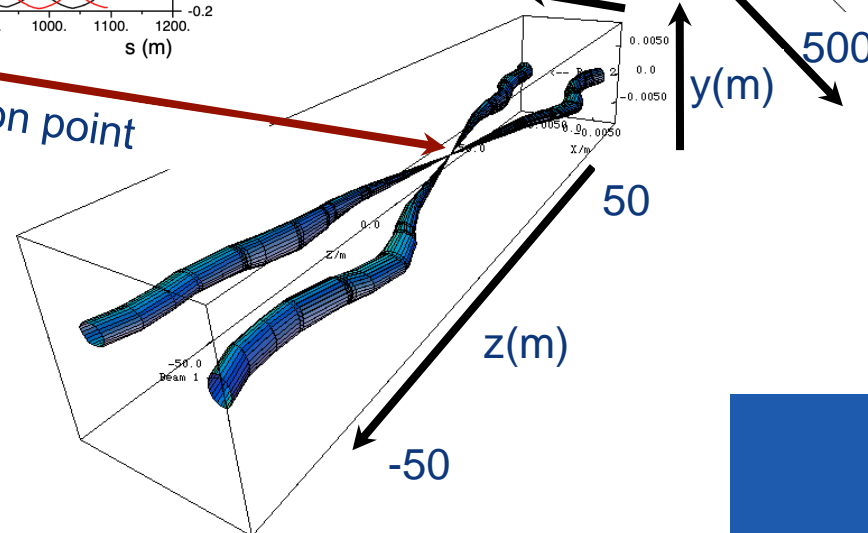


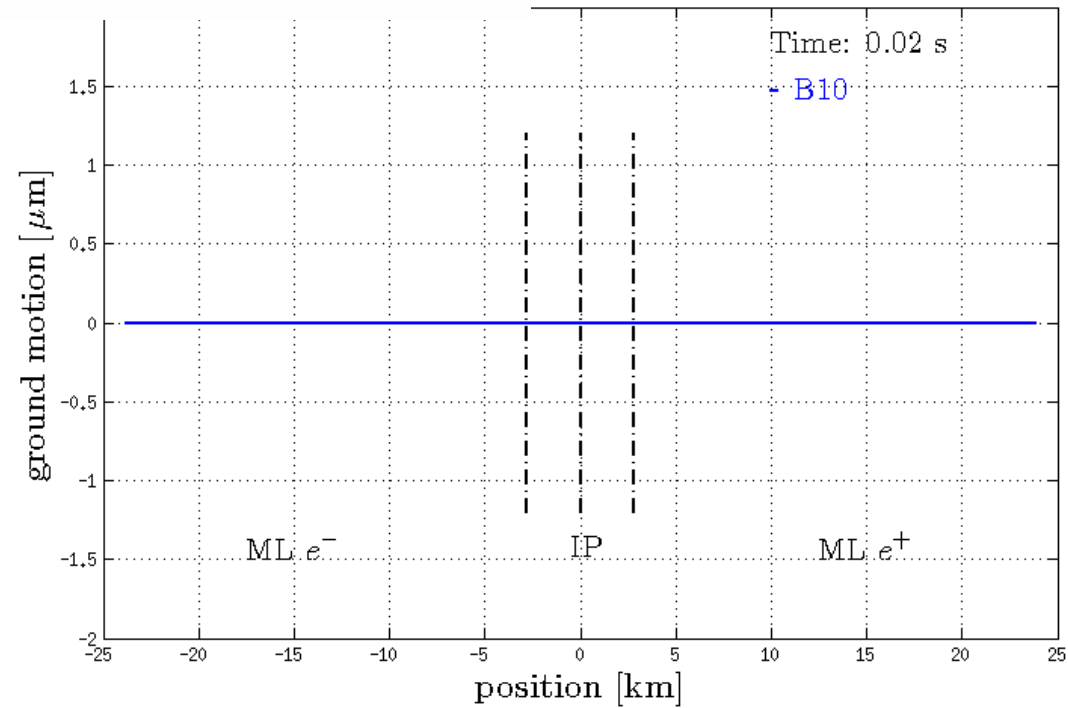
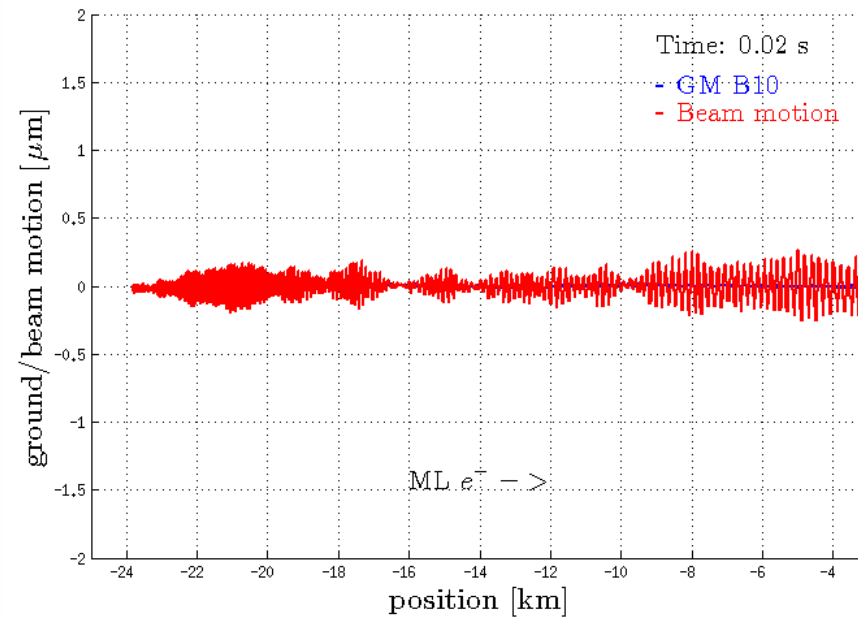
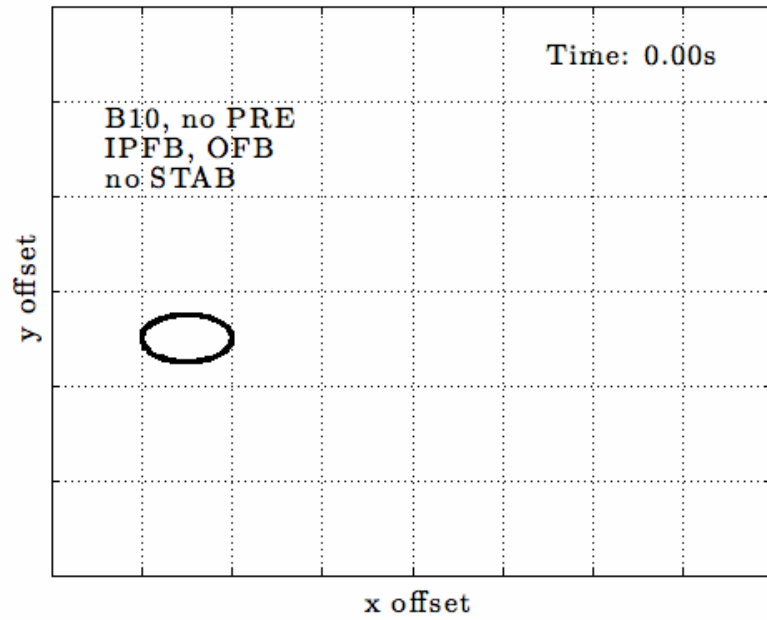
# Optics at collision IP5- CMS

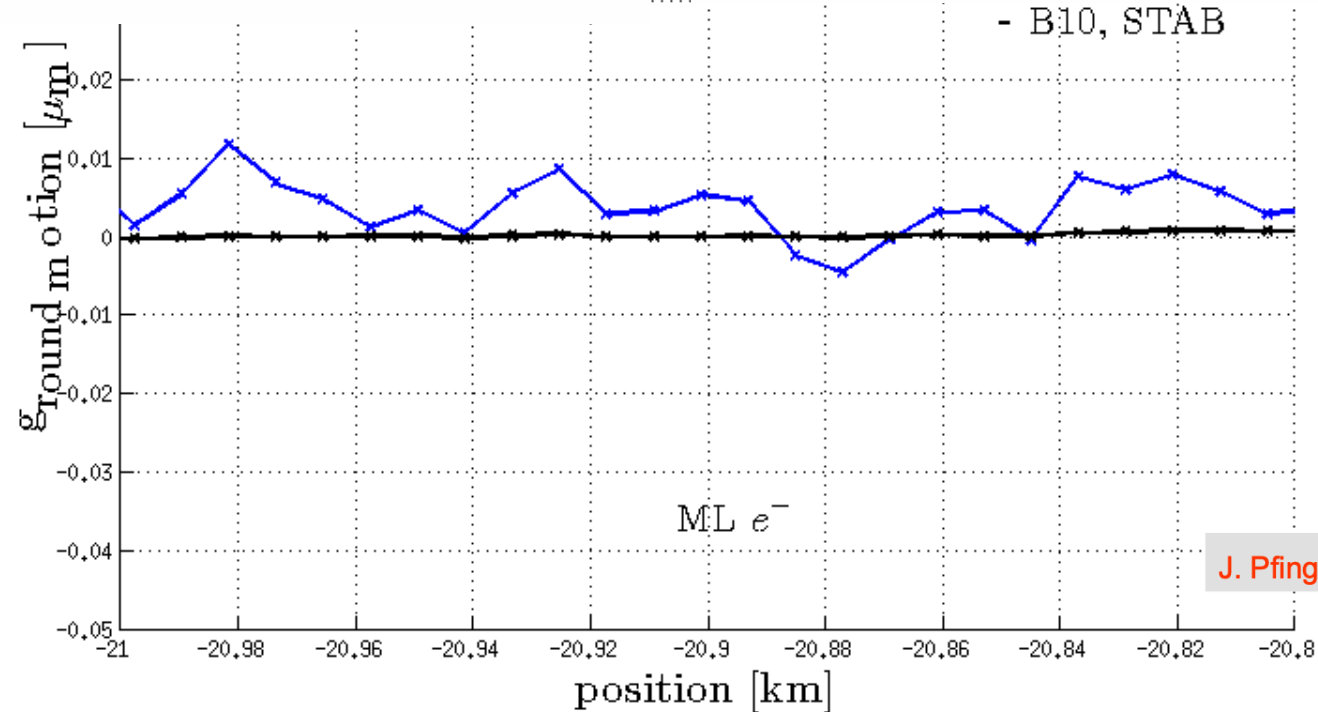
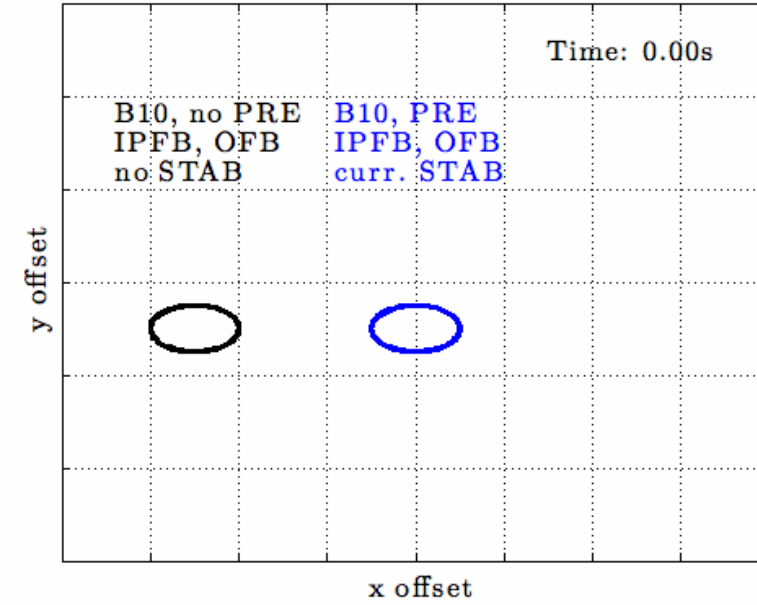
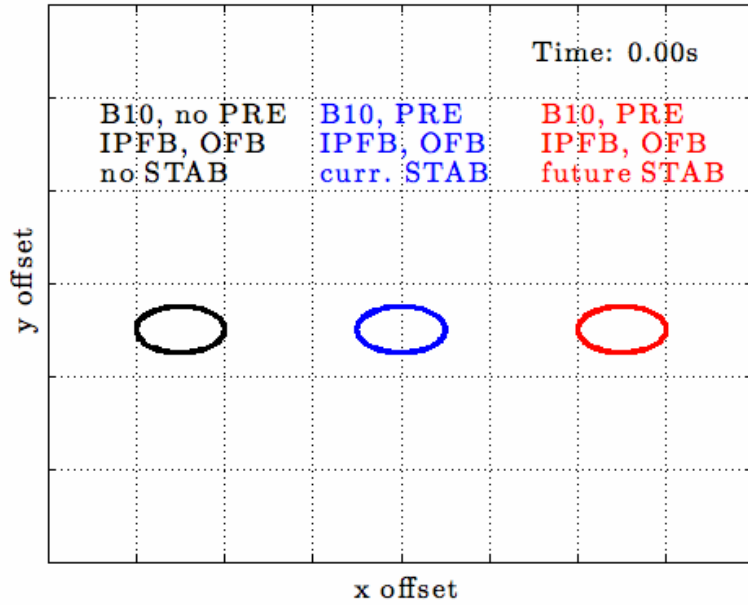


Interaction point

At collision the beams are “squeezed” down to few microns at the interaction point



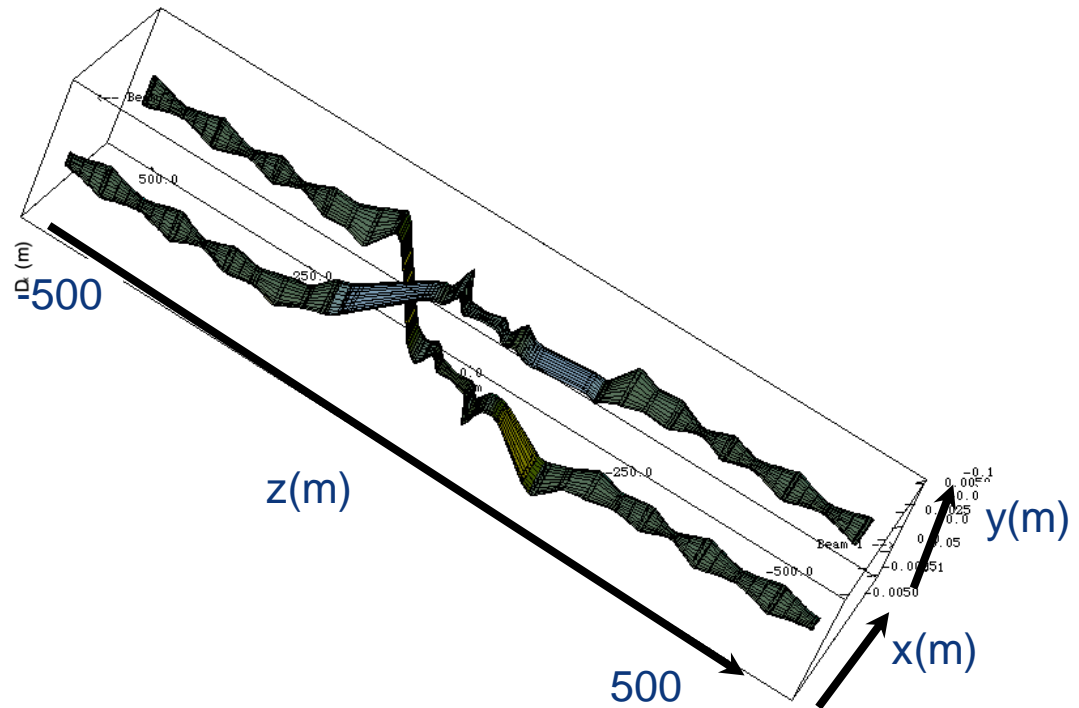
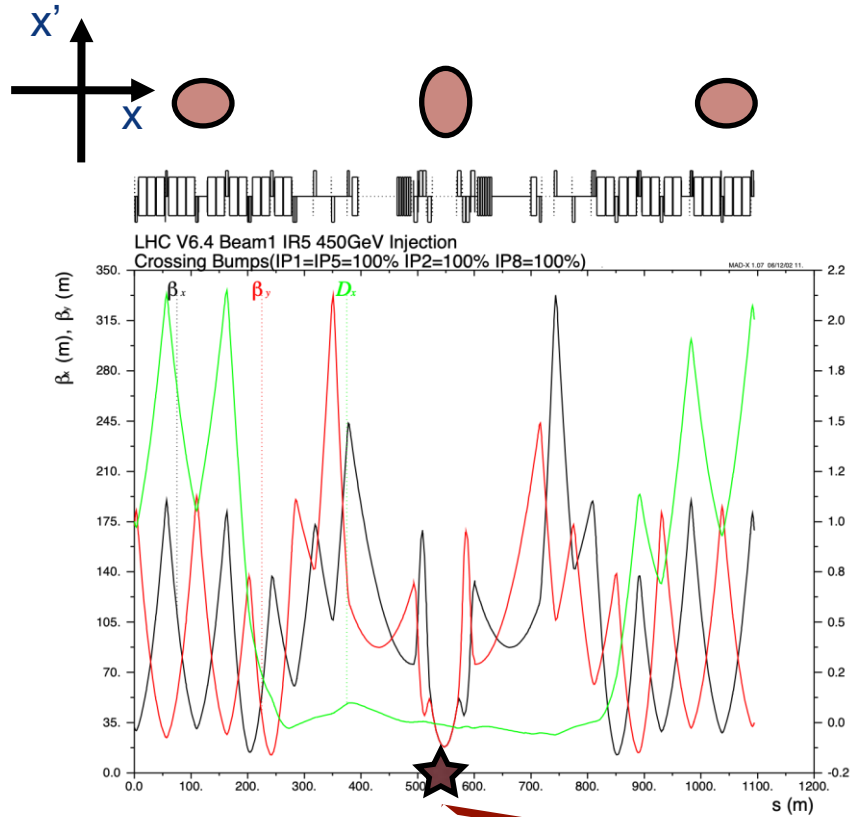




J. Pfungstner

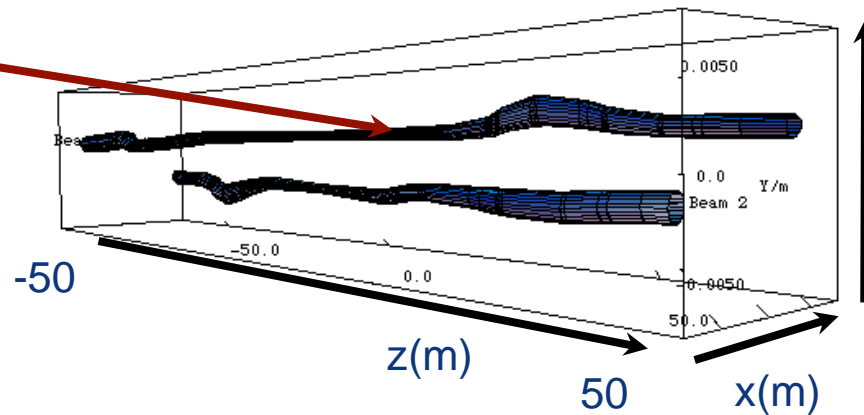


# Injection optics and during acceleration IP5- CMS



During acceleration the beams are separated and their dimensions is few mm

Interaction point



# We want to have the maximum Luminosity

**Proton Intensity per bunch**  
This comes from the injectors  
10 years of development

**Revolution frequency**  
This is fixed by the LHC circumference

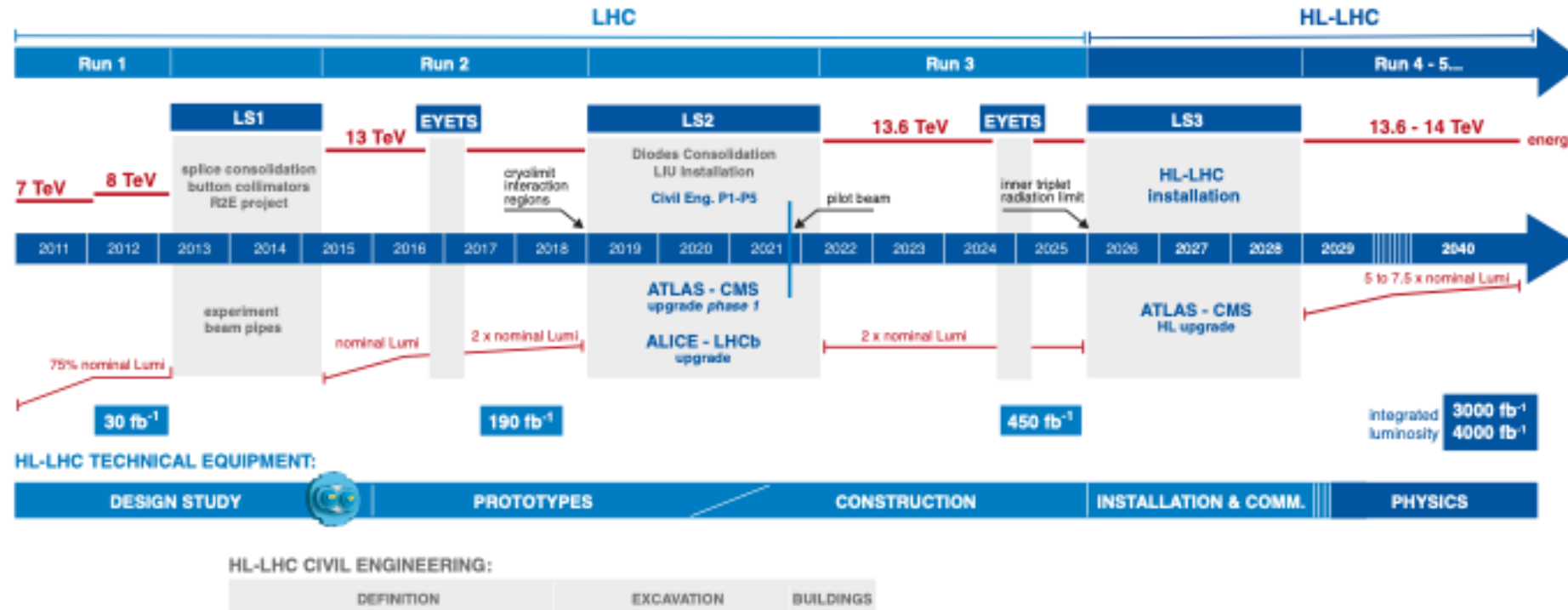
**Number of bunches**  
This is more or less fixed

**How the bunches collides**  
This can be changed

$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

**Beam Spot size at collision point**  
This can be minimised by building new magnets → LS3 → post 2029  
Technology development 10-15 years long





### Technical limitation on **integrated luminosity**:

1. **Collider** (radiation damage to the IT magnets – correctors and quadrupoles)
2. **Experiments** (radiation damage in the Inner Tracker)

### Technical limitation on the **instantaneous luminosity**:

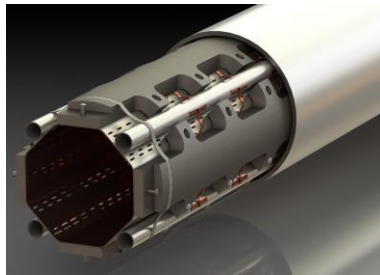
1. **Collider** (cryolimit in the triplet region) at  $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  twice the nominal design luminosity)
2. **Experiments** (pile up in the detectors). Designed for PU 40 they are actually dealing with 60 (average)

# HL-LHC: High Luminosity LHC in a nutshell



CERN May 2016

Technology landmarks



**CIVIL ENGINEERING**  
2 new caverns and two new 300-metre service galleries, two new large shafts; 10 new technical buildings on surface in P1 and P5 (ATLAS and CMS)



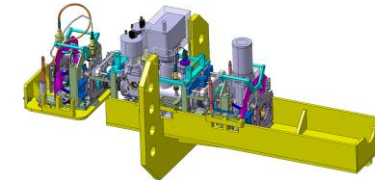
**"CRAB" CAVITIES**  
8 superconducting "crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.



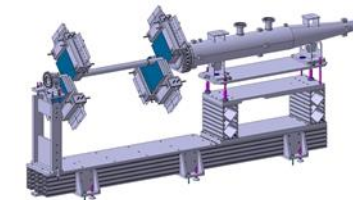
**BENDING MAGNETS**  
2 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.



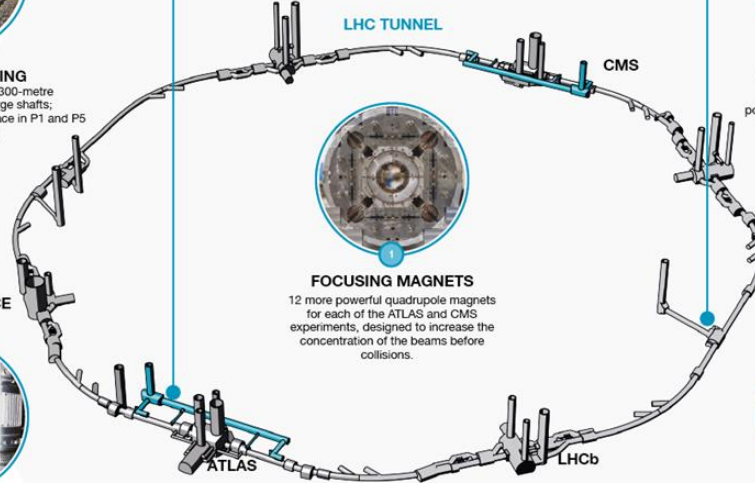
**FOCUSING MAGNETS**  
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.



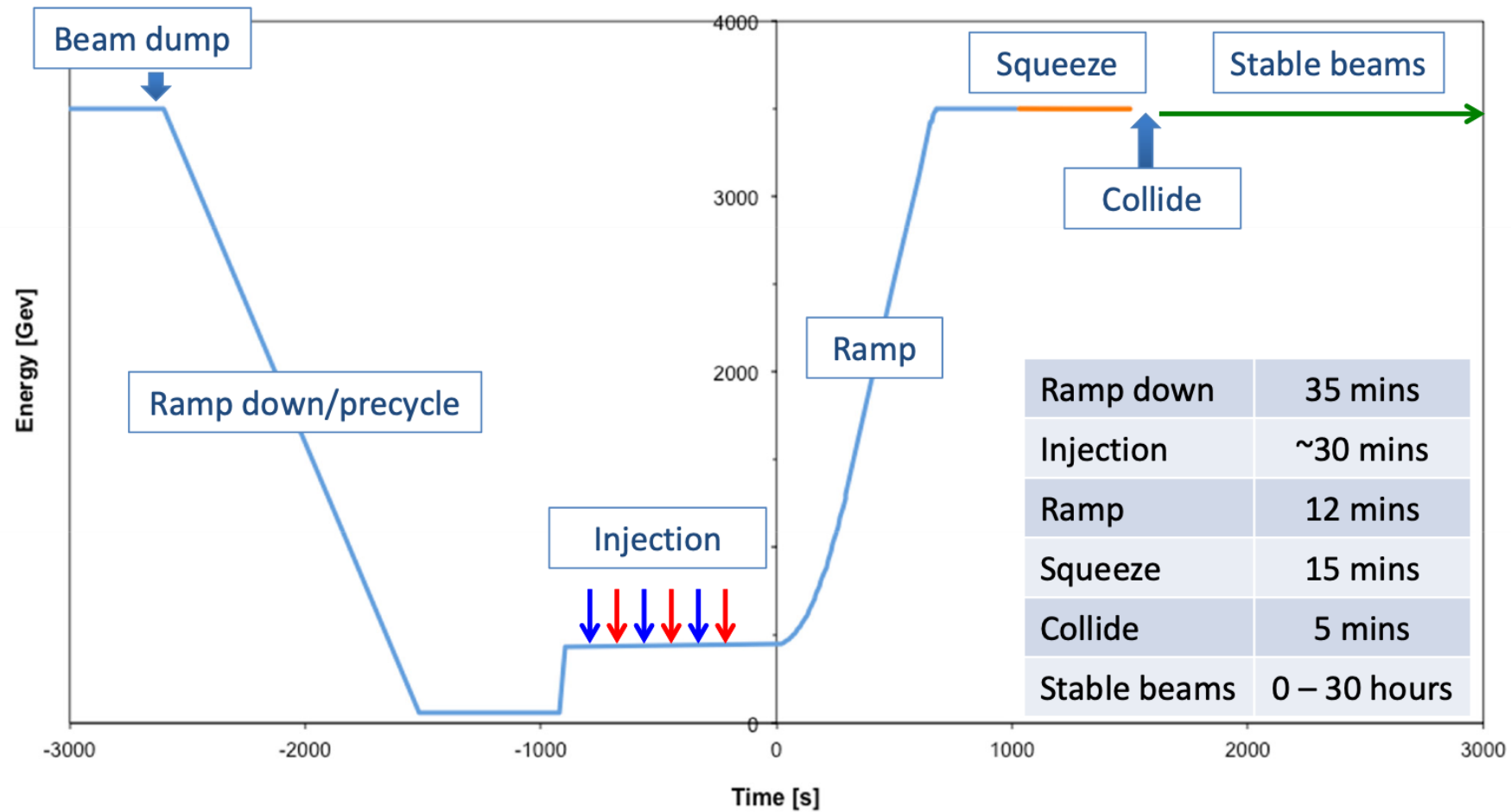
**COLLIMATORS**  
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.



**SUPERCONDUCTING LINKS**  
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service galleries to the LHC tunnel.

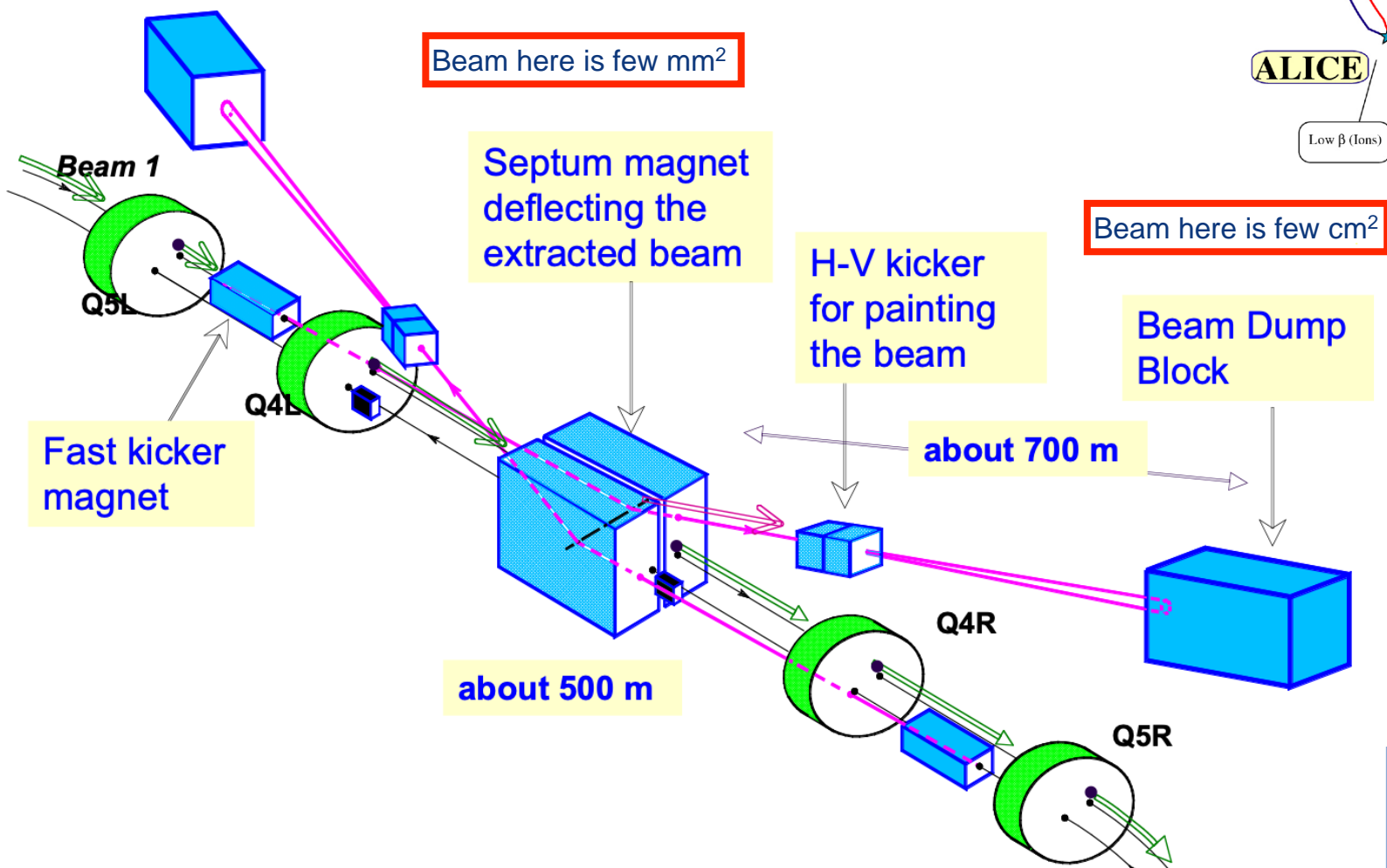
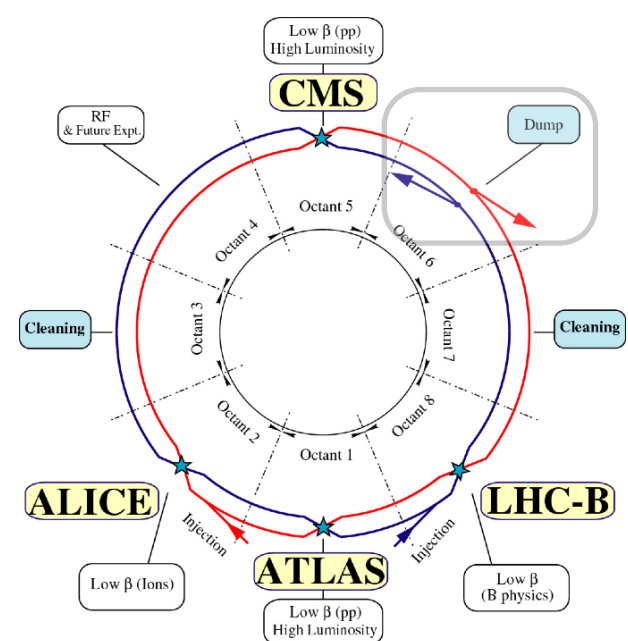


# LHC Operational cycle as synchrotron

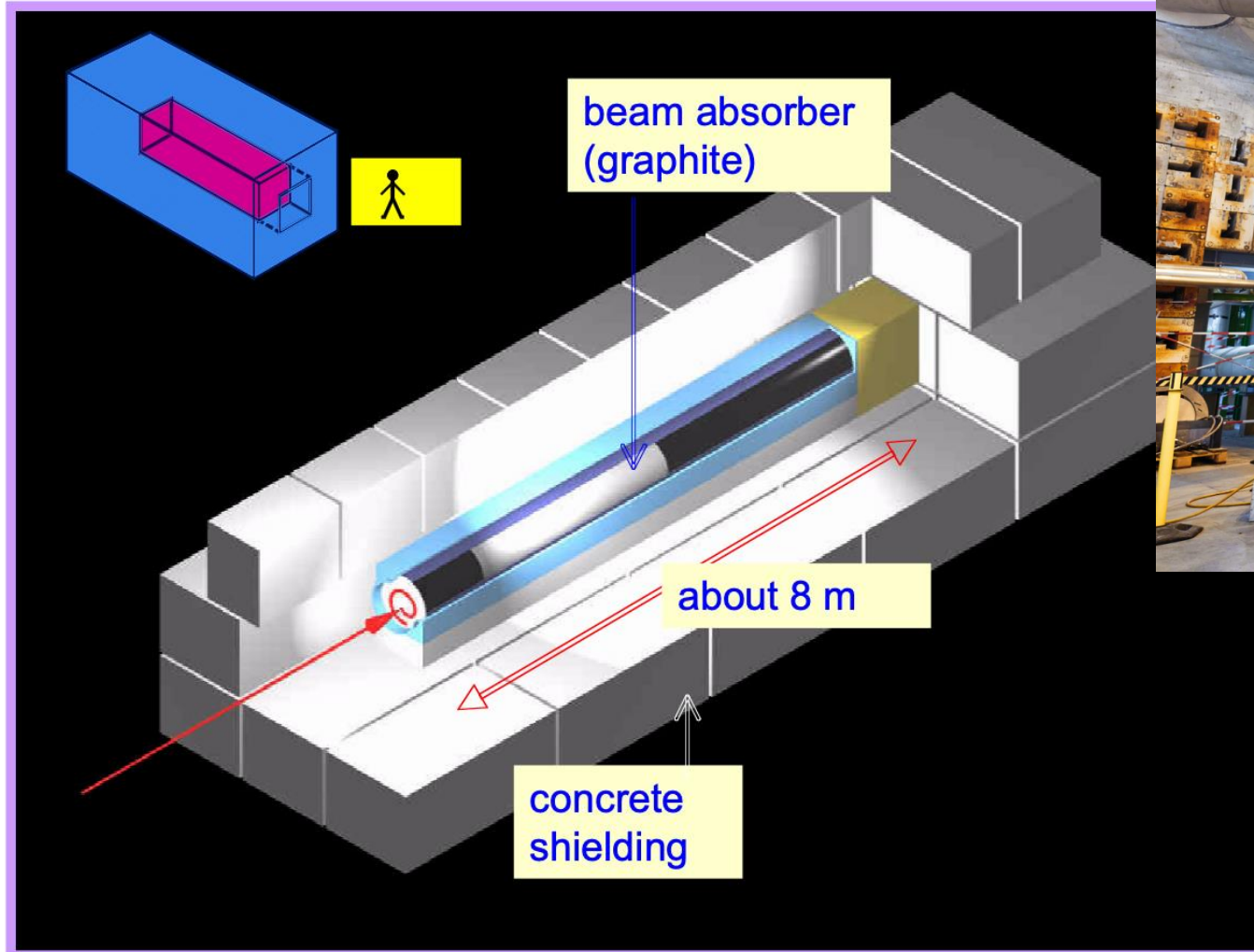


# Beam extraction, emergency or not...

At the end of every "fill", when too low luminosity, or when BLM system triggers, both beams extracted on an external beam dump, in one turn. Beam dump built to absorb full power at full energy.

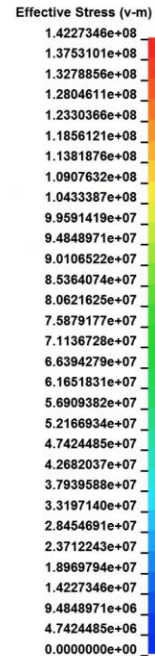
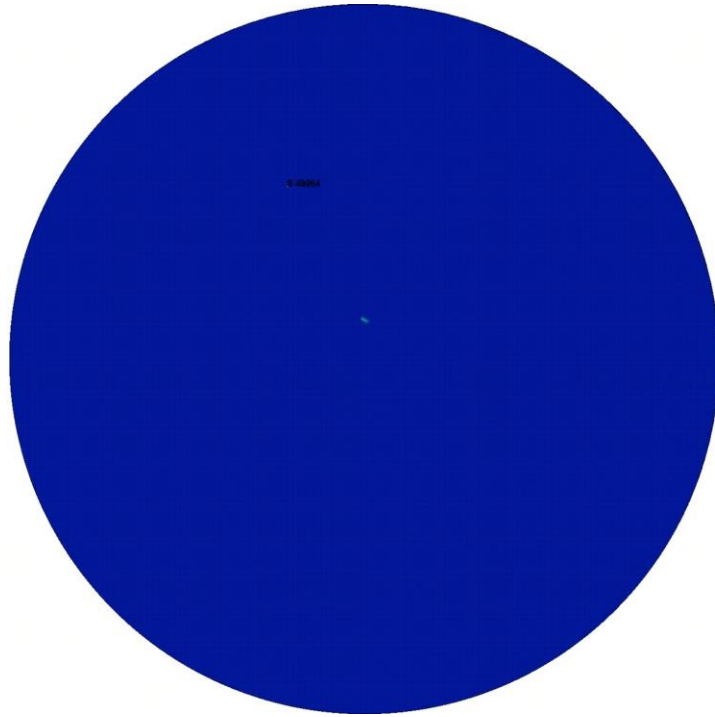


# Scheme of one of the beam absorbers



# Spot size on the beam dump

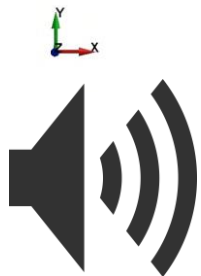
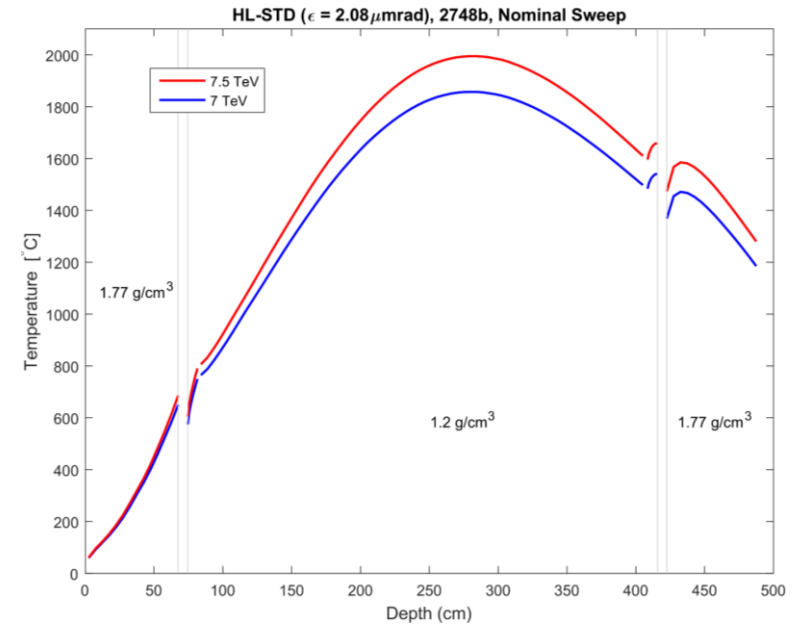
TDE - Front Window - R3 - 6V4H  
Time = 2.9862e-007  
Contours of Effective Stress (v-m)  
max IP. value  
max=5.5808e+07, at elem# 46521



To reduce energy deposition peak, proton swept by fast kickers to for a spiral on the transverse face of the dump.

**Beam impact in less than 0.1 ms**

Even like this, maximum temperature rise about 1500 C – 2000 C in the future.



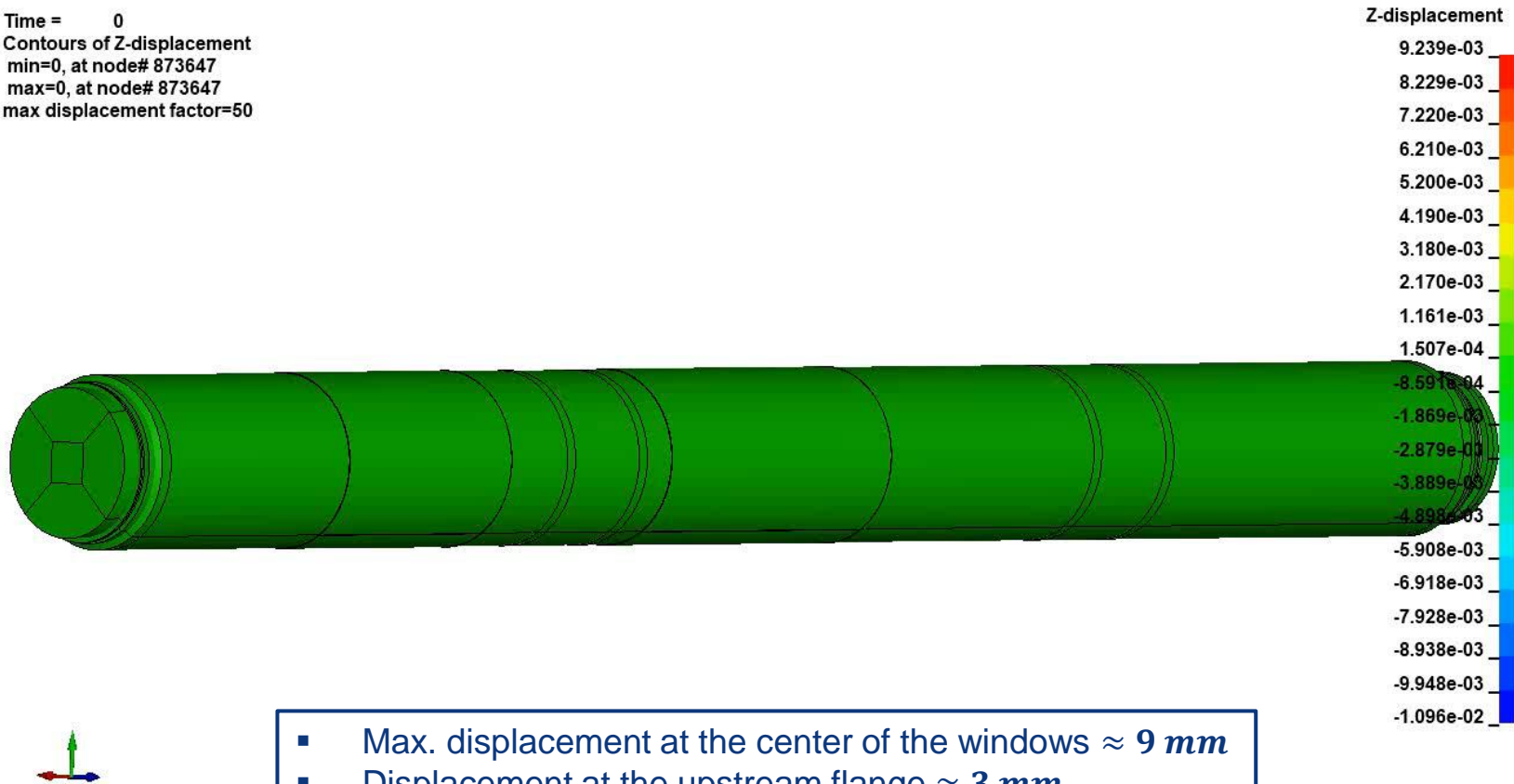


# FE simulations during LS2

Acceleration up to 600 g

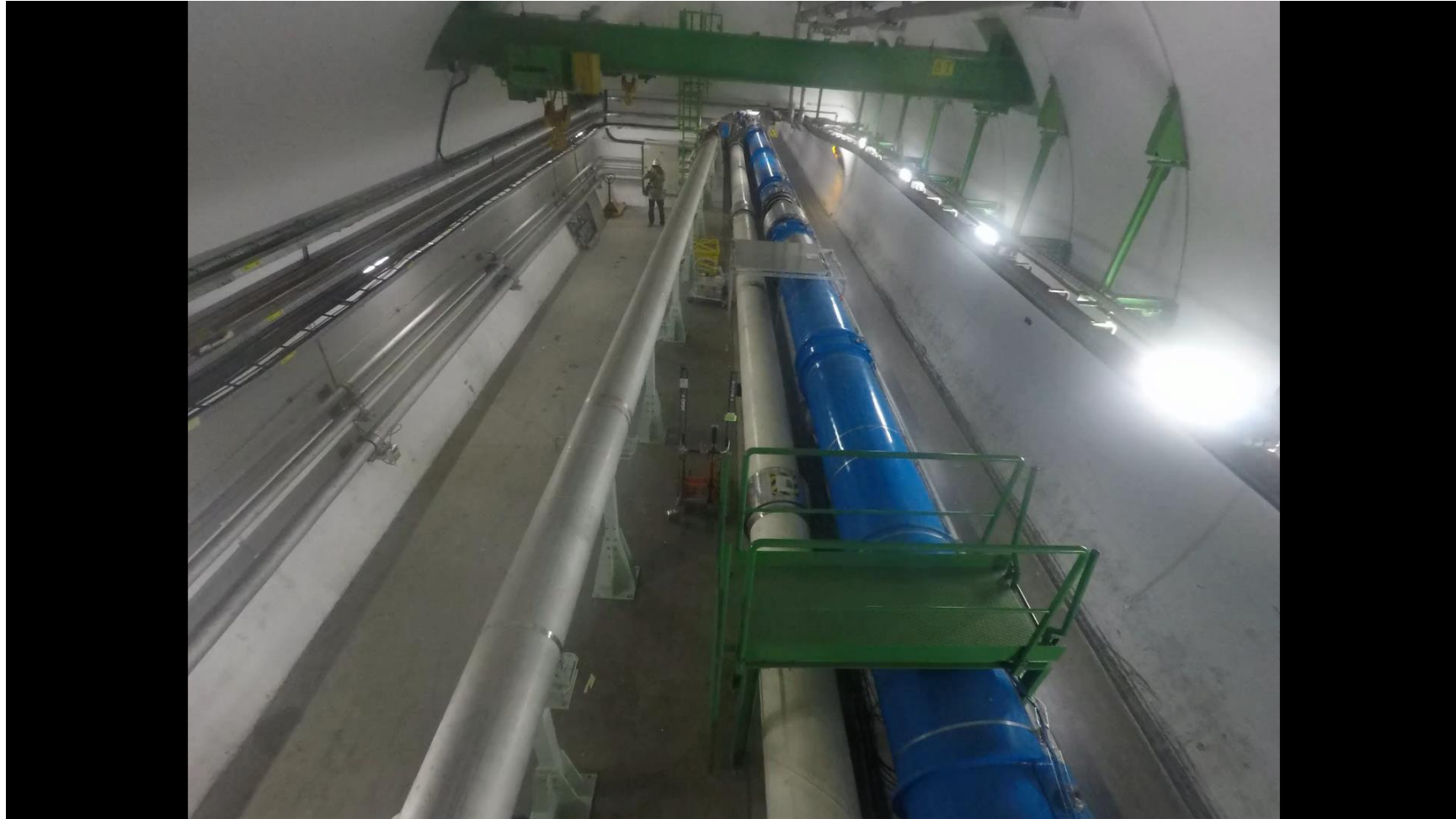
25 ms

Time = 0  
Contours of Z-displacement  
min=0, at node# 873647  
max=0, at node# 873647  
max displacement factor=50



- Max. displacement at the center of the windows  $\approx 9 \text{ mm}$
- Displacement at the upstream flange  $\approx 3 \text{ mm}$

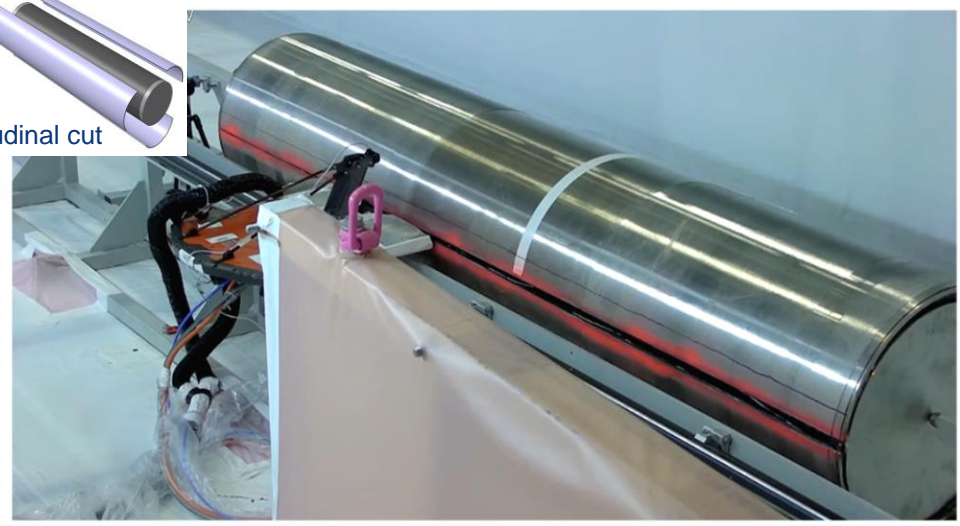
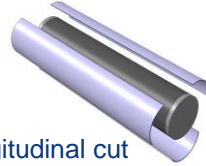
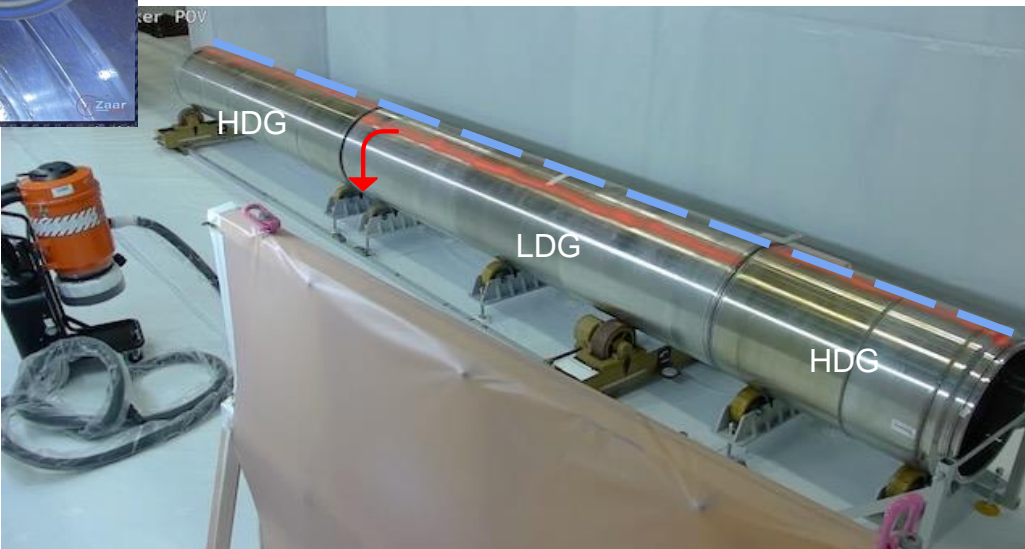
# Dump removal for replacement



# Autopsy Cuts



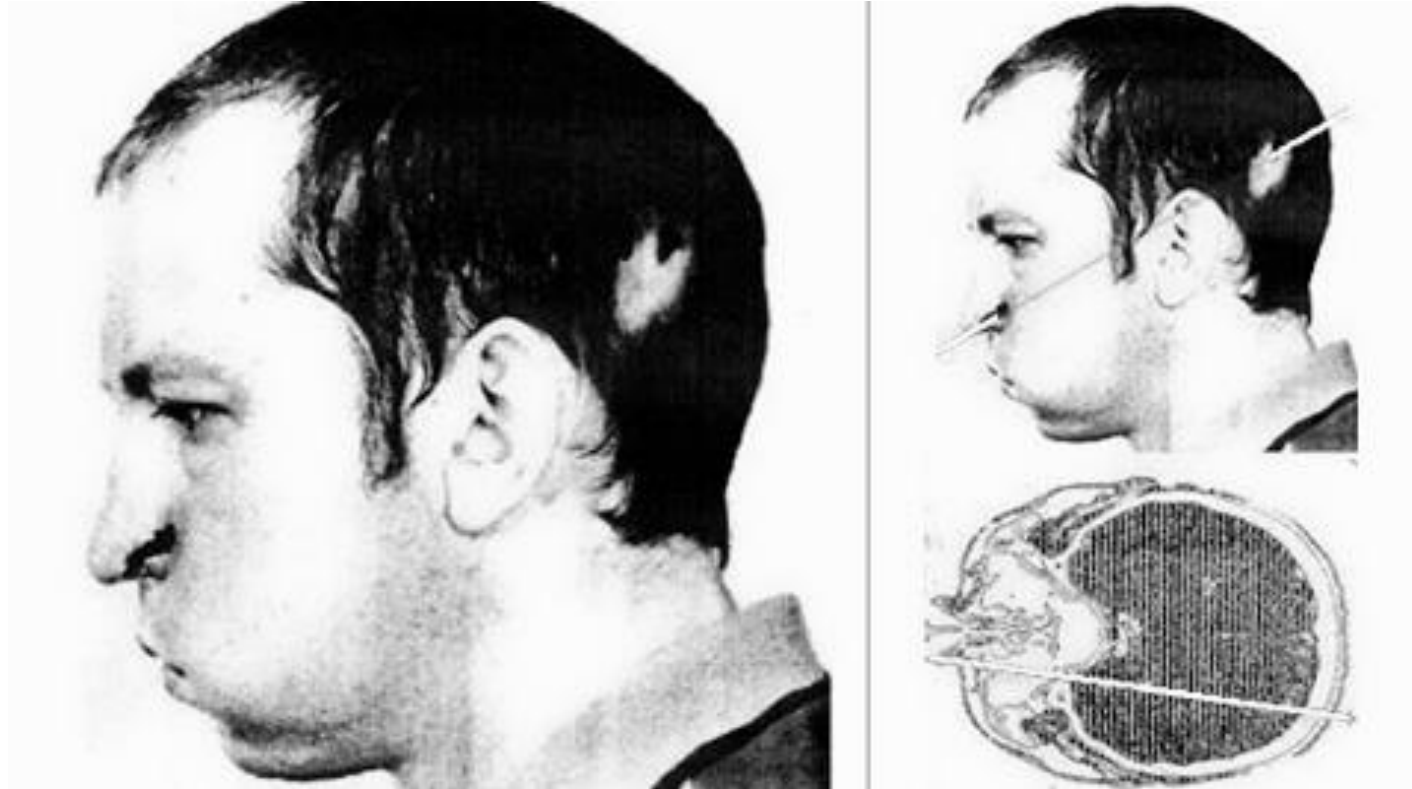
Max dose rate :  
3.5 mSv/h at contact



# What happens if I put a hand in front of the beam?



# Anatoli Bugorski



# Few years ago something went wrong during a test ...

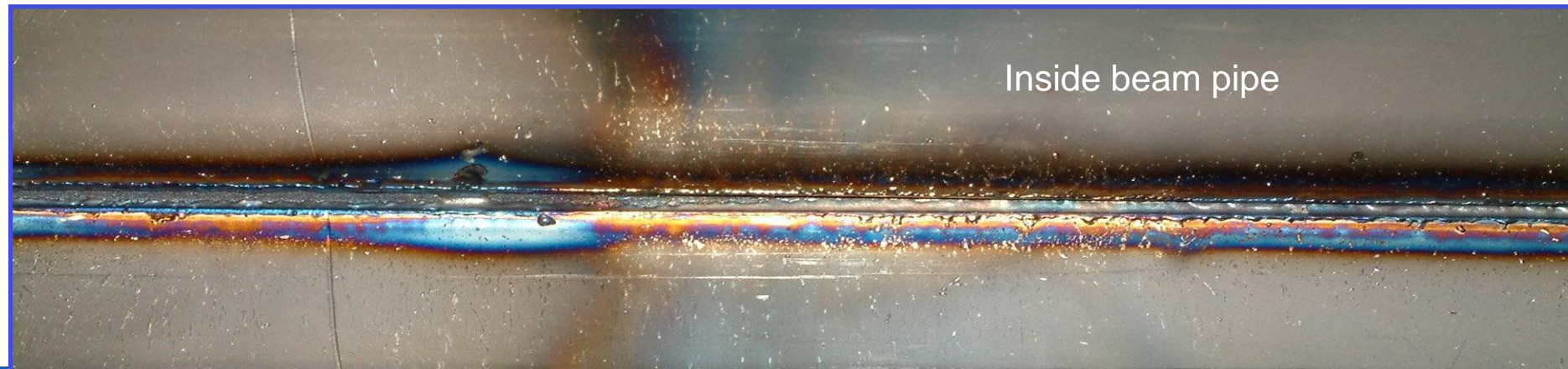
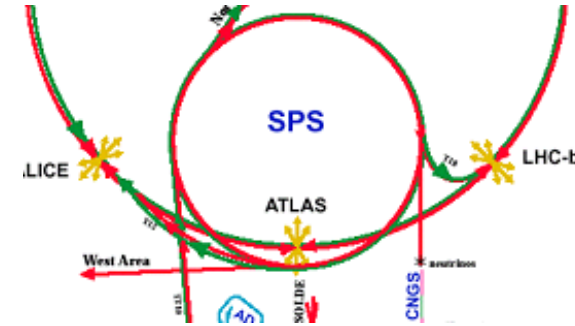
LHC extraction from the SPS

450 GeV/c, 288 bunches

Transverse beam size 0.7 mm ( $1\sigma$ )

$1.15 \times 10^{11}$  p+ per bunch, for total intensity of  $3.3 \times 10^{13}$  p+

**Total beam energy is 2.4 MJ, lost in extraction test (LHC 334 MJ)**

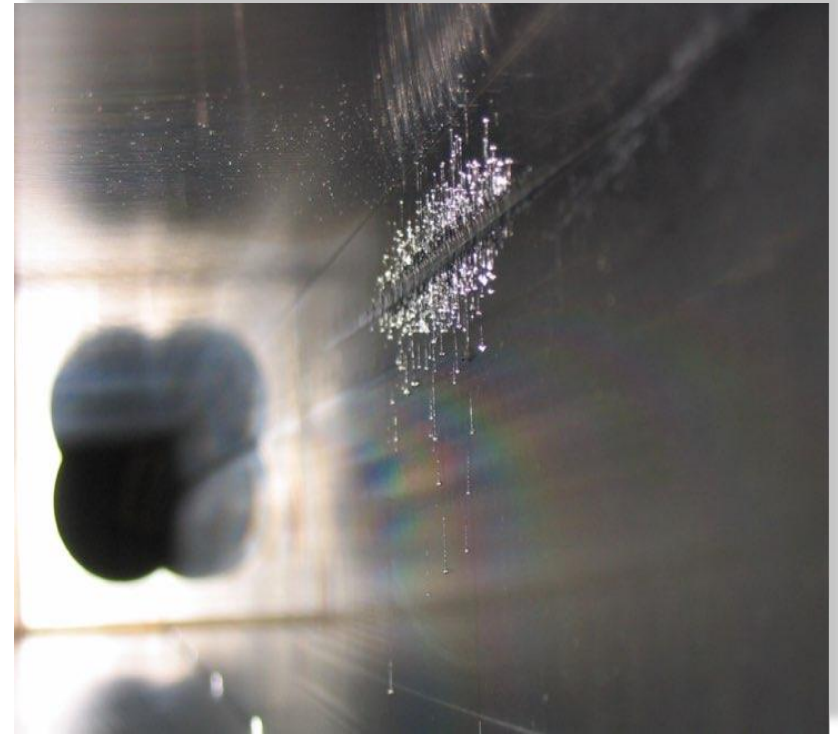
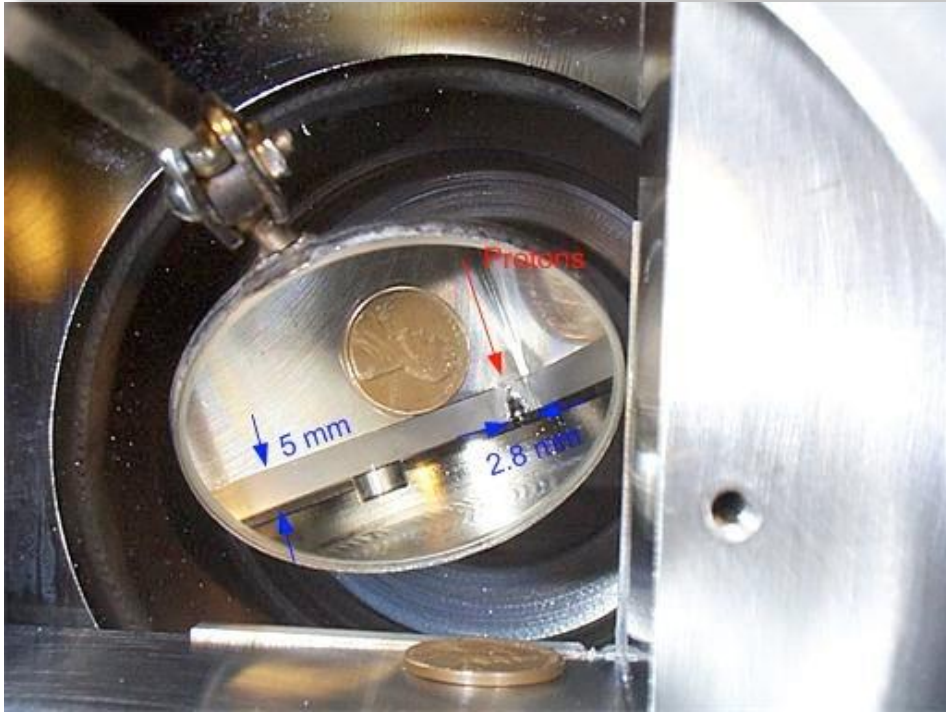


# Tevatron accident in 2003 (courtesy of N. Mokhov)

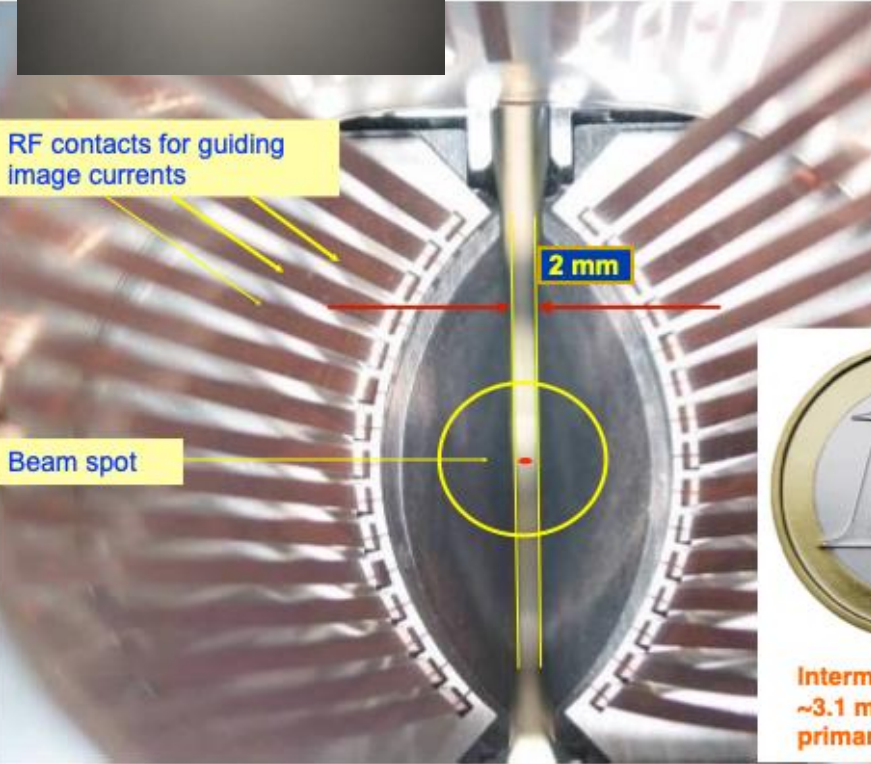
Accident caused by uncontrolled movement of beam detectors (Roman Pots) which caused a secondary particle shower  
magnet quench → no beam dump → damage on approximately 550 turns

Tungsten collimator.  $T_{\text{melting}} = 3400 \text{ }^{\circ}\text{C}$

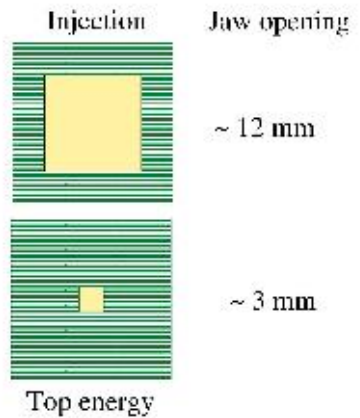
1.5 m long stainless steel collimator



# How to protect the LHC against the beam



10 mm



Norway

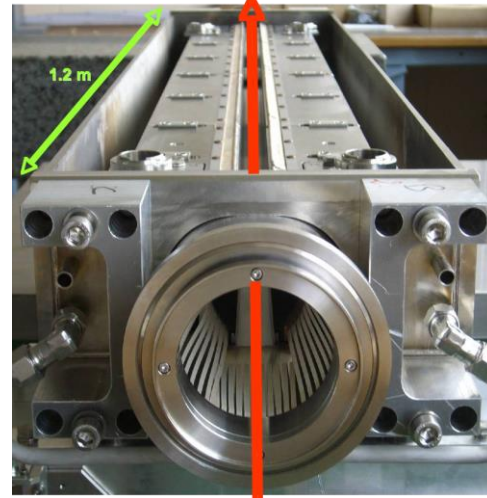
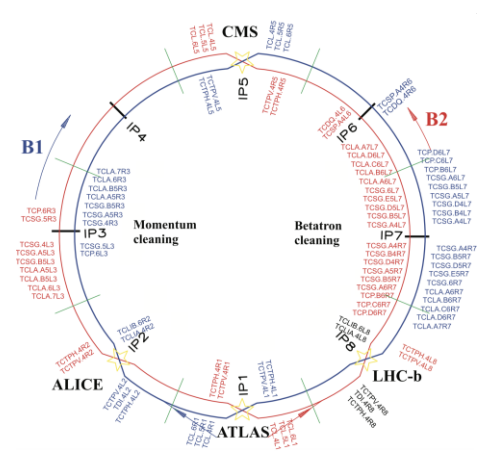


Iberian peninsula

Intermediate settings (2011):  
~3.1 mm gap of primary collimator

Tight settings:  
~2.2 mm gap of primary collimator

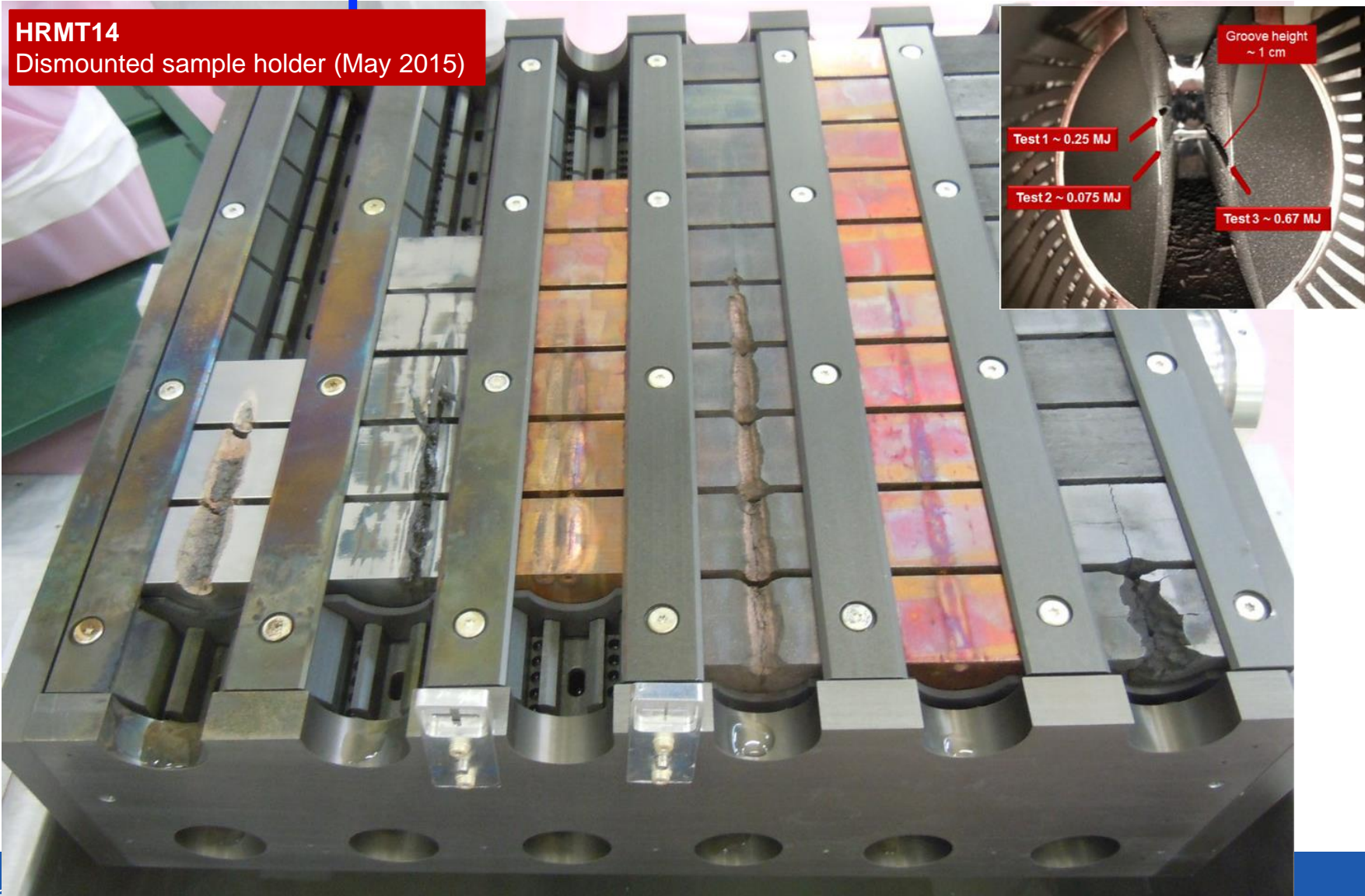
Precision required for collimator movements about 25  $\mu$ m



360 MJ proton beam



# Update on HRMT09 and HRMT14 Experiments

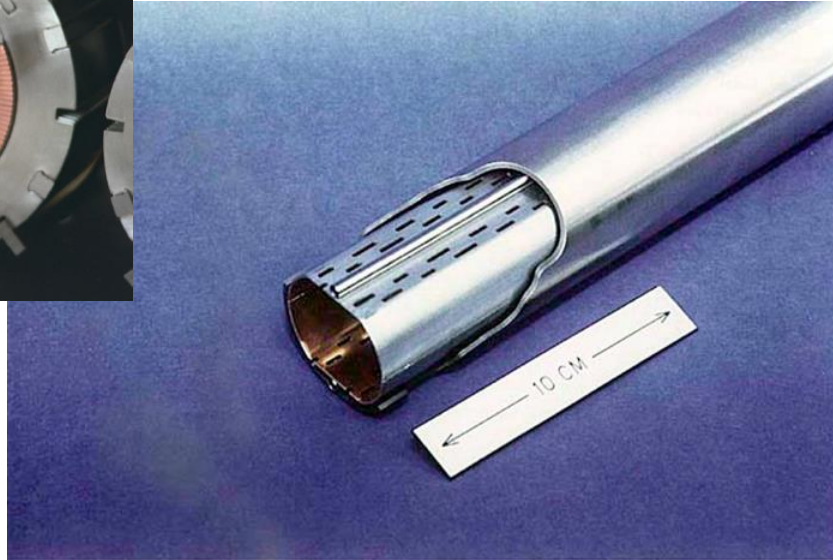
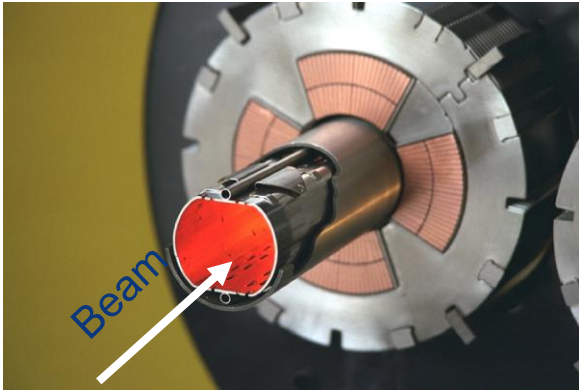


# First Results Overview – CuCD

- Impacts on CuCD jaw.
- 48 b.  $\sigma$  0.35 mm. Impact depth 0.5  $\sigma$



# LHC beam screen with cooling pipes



Beam screen to protect Superconducting magnets from Synchrotron radiation.



Atmosphere pressure = 750 Torr

Moon atmospheric pressure =  $5 \cdot 10^{-13}$  Torr

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

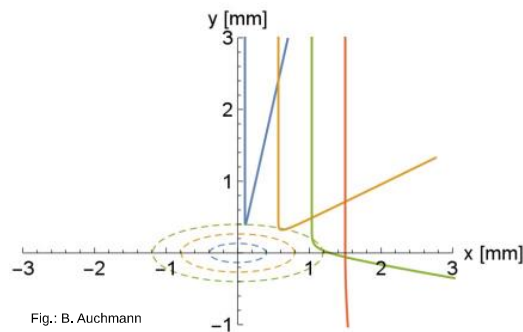
Typical vacuum:  $10^{-13}$  Torr

There is  $\sim 6500 \text{ m}^3$  of total pumped volume in the LHC, like pumping down a cathedral.

# UFO's in the LHC : Unidentified Falling Objects

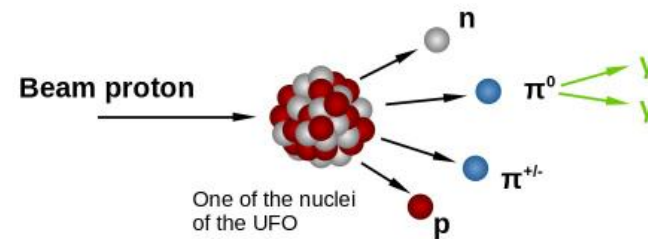
- UFOs = Unidentified Falling Objects
- Likely negatively charged dust particles which are attracted by the beam
- Maximum radius of a few tens of  $\mu\text{m}$
- Give rise to loss events all around the LHC

## 1 **Electromagnetic interactions:** ionising energy loss of protons traversing the UFO



Dust particle falls into the beam  
→ gets ionized because of traversing protons  
→ gets repelled from the beam

## 2 **Hadronic interactions:** inelastic nuclear collisions between protons and nuclei



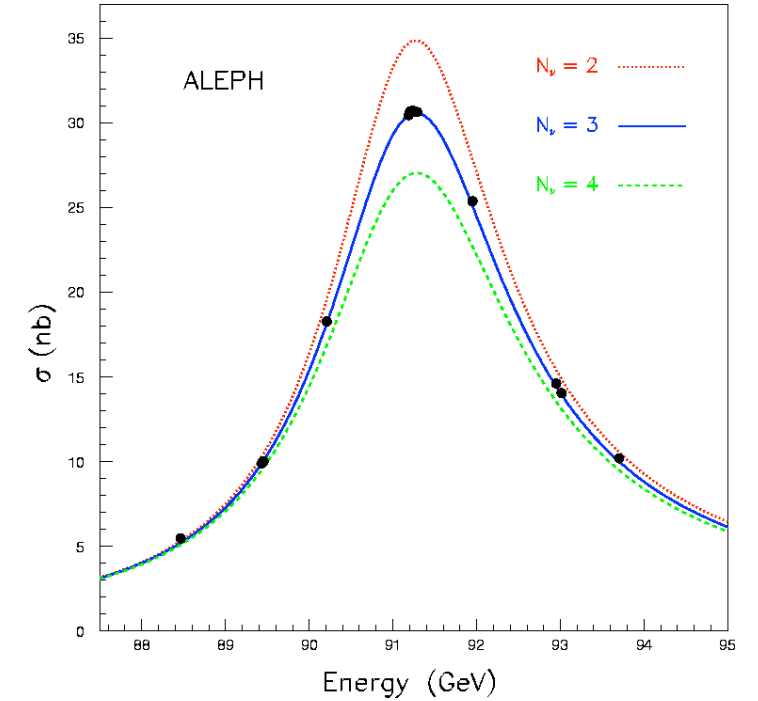
Secondary particles impact on aperture and induce particle showers:  
→ magnet quench  
→ BLM dumps

# 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	$180.826 \pm 0.050$
182	$181.708 \pm 0.050$
183	$182.691 \pm 0.050$
184	$183.801 \pm 0.050$
Combined	$182.652 \pm 0.050$



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

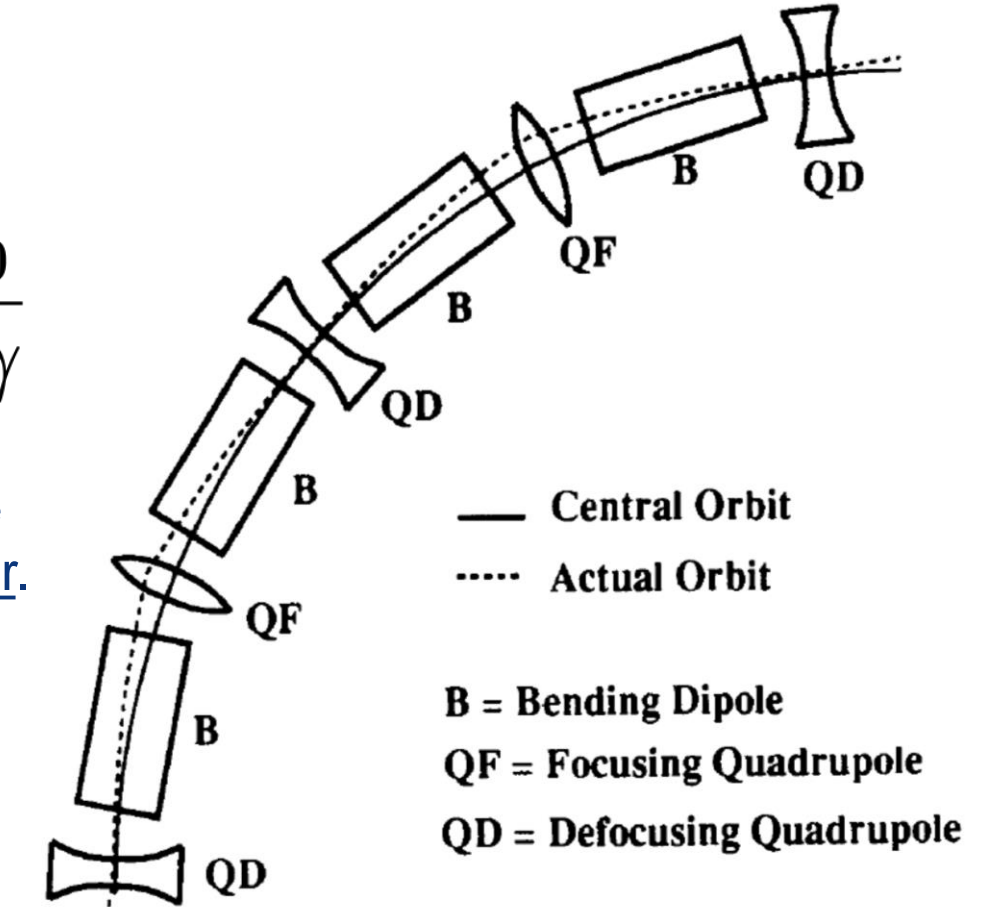
Energy fixed by bending strength and cavity frequency

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

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

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

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



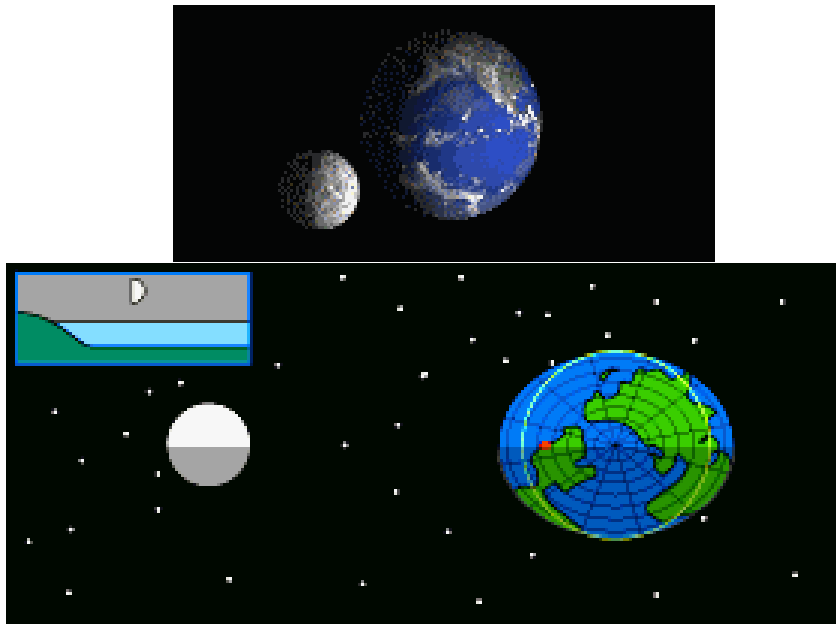
# Moon tides can change earth geometry

Moon induces a earth deformation similar to water tide.

Total deformation of the LEP about 4 mm

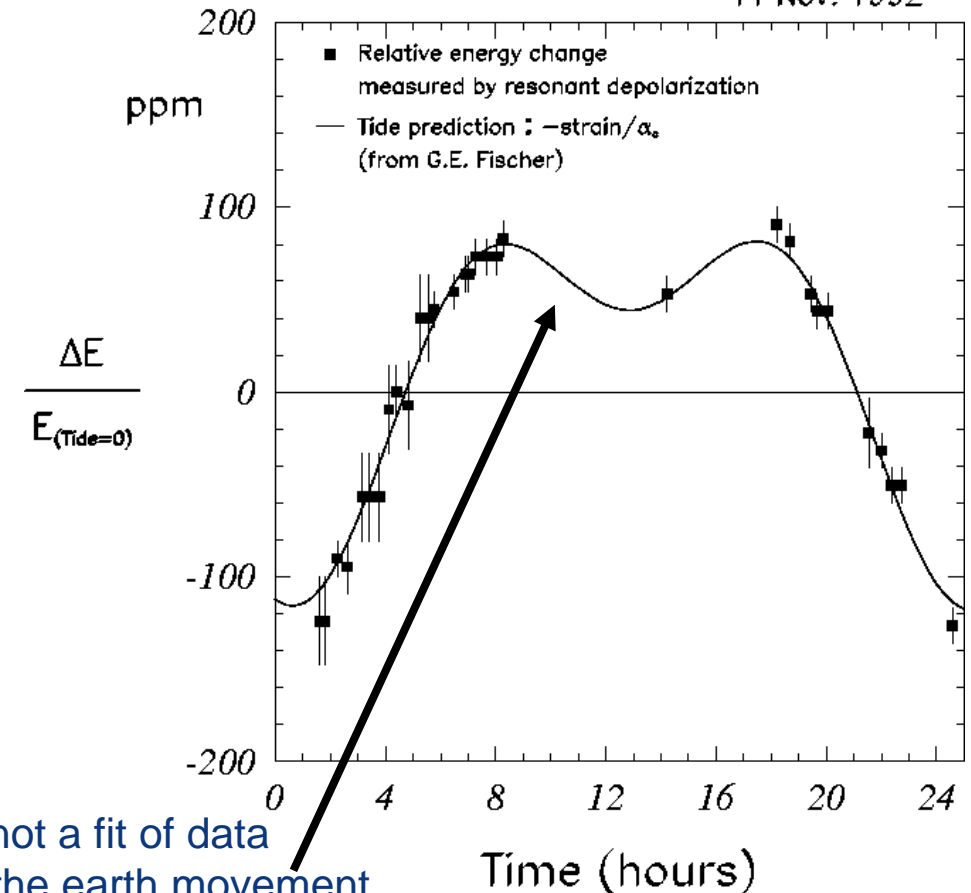
Energy variation of 100 ppm

The 12 h cycle is due to the earth deformation



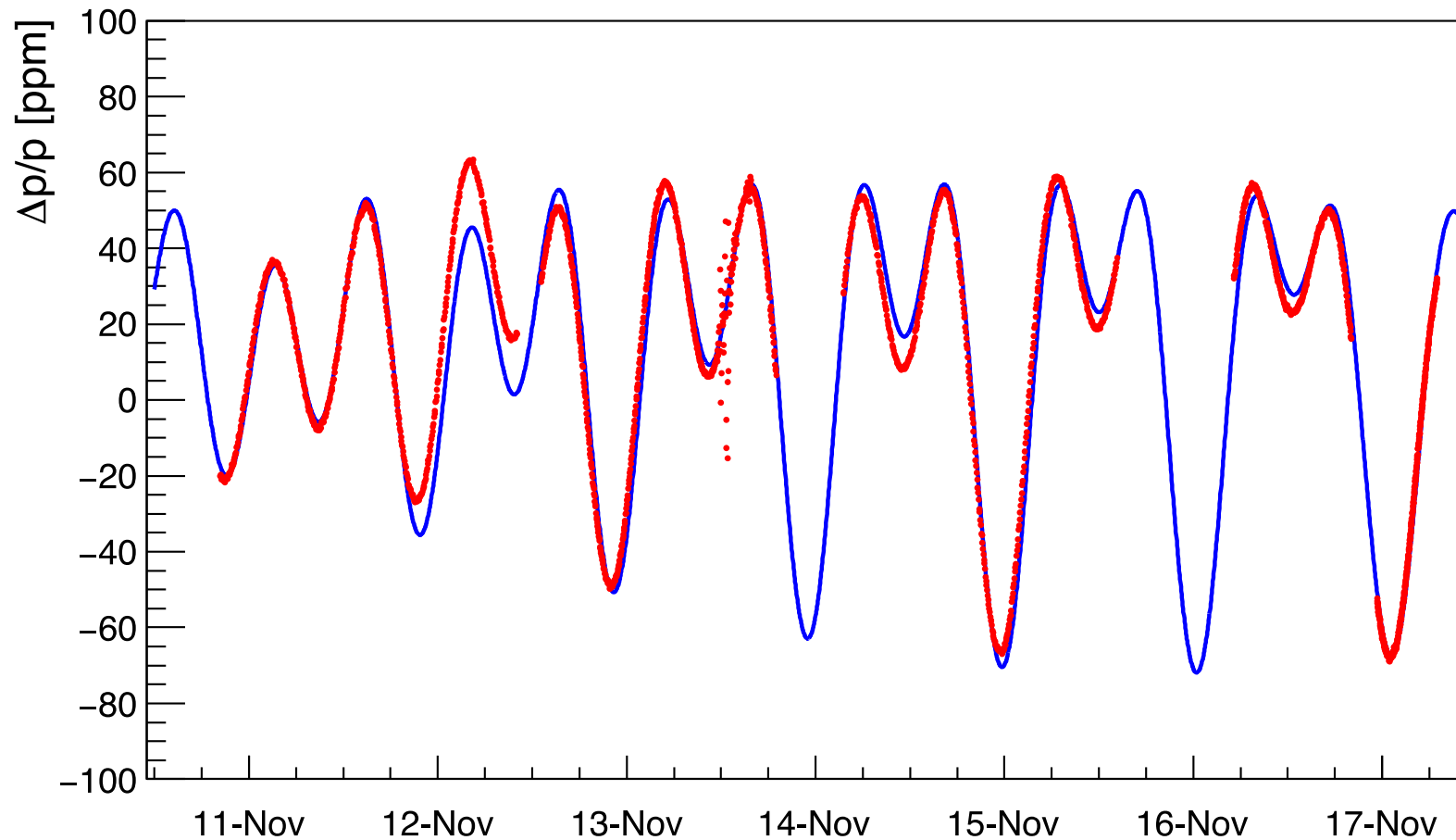
LEP TidExperiment

11 Nov. 1992



Continuous line is not a fit of data but a prediction of the earth movement

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



Predicted (blue line) and observed (red point) tidal energy variations of the LHC ring in November 2016 during long consecutive fills at 4 TeV/c spanning almost an entire week.

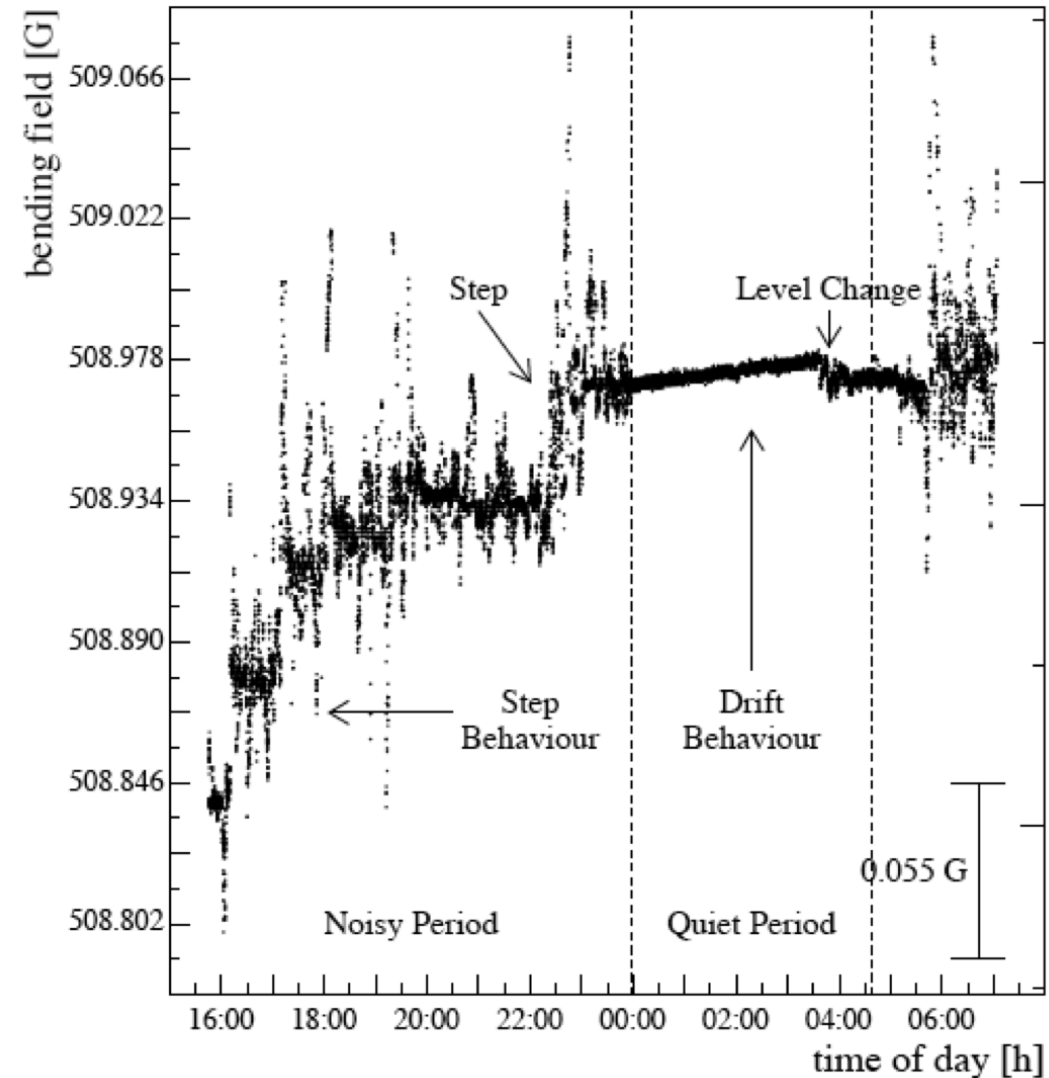
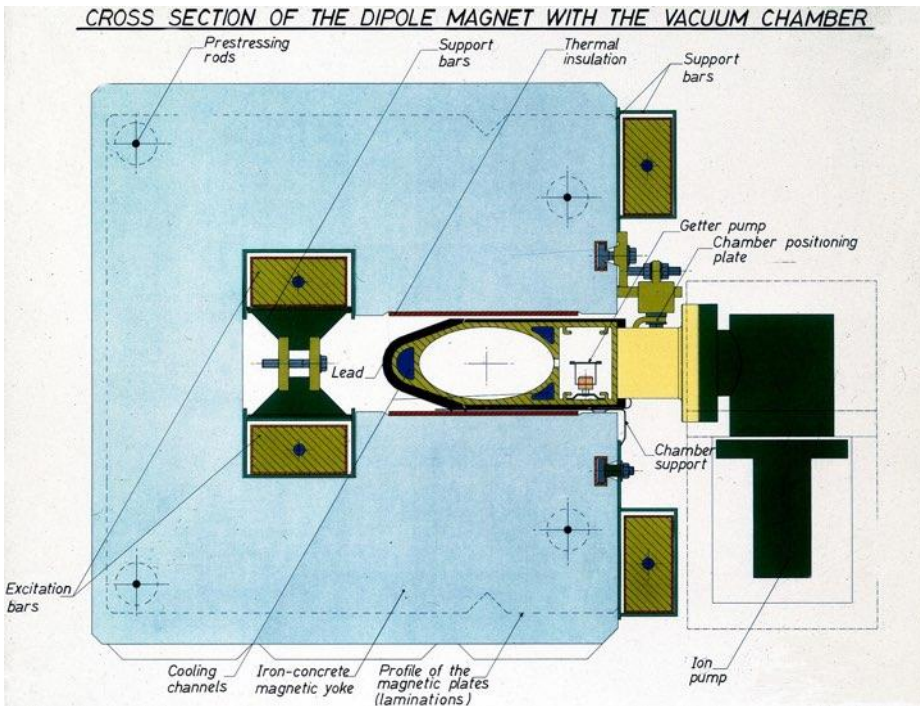
The outliers that can be observed around midday November 13<sup>th</sup> are radial oscillations of the ring induced by the surface waves from a magnitude 7.8 Earthquake in New-Zealand.

From: Large Hadron Collider momentum calibration and accuracy, E.Todesco and J.Wenninger

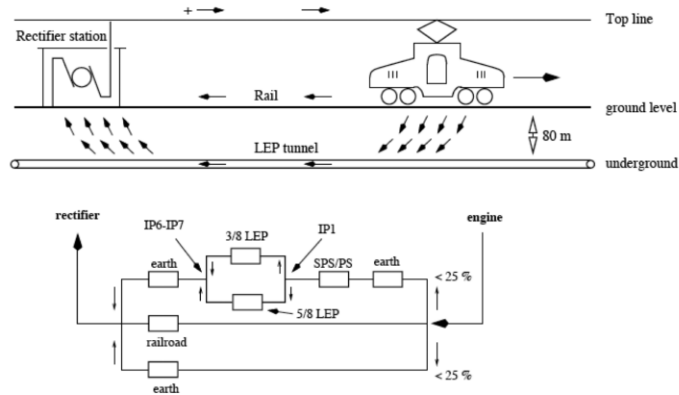


# The problem: an accelerator is not in the middle of nothing

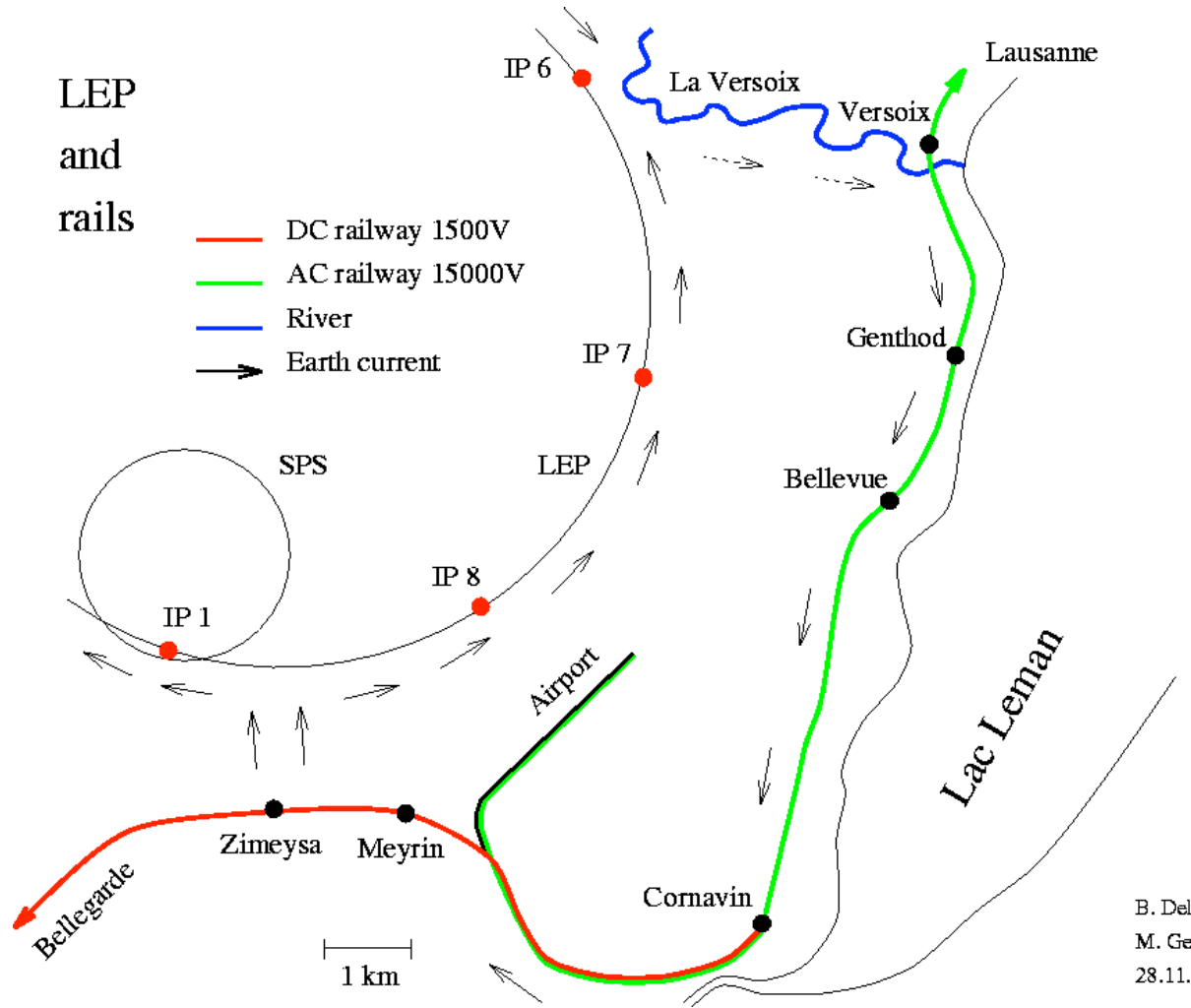
Observed variation of the bending strength of the LEP dipoles during the day



# Influence of train leakage current



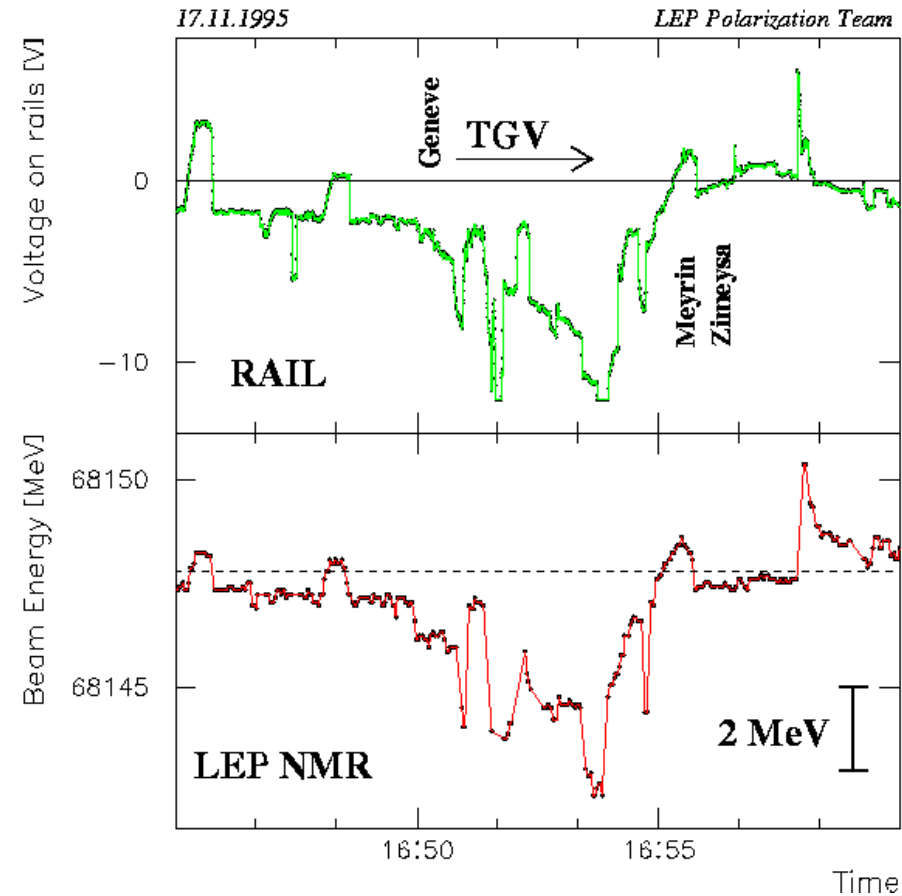
LEP beam pipe as ground for leakage current.  
 Variation of the dipole field due to the current .  
 Change in energy following the SNCF train table



B. Dehning  
 M. Geitz  
 28.11.1995

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

Correlation between trains and LEP energy



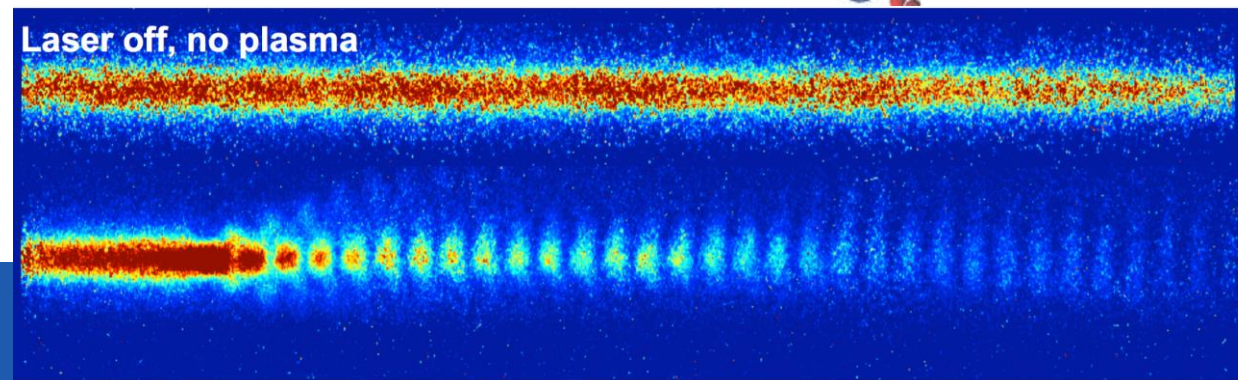
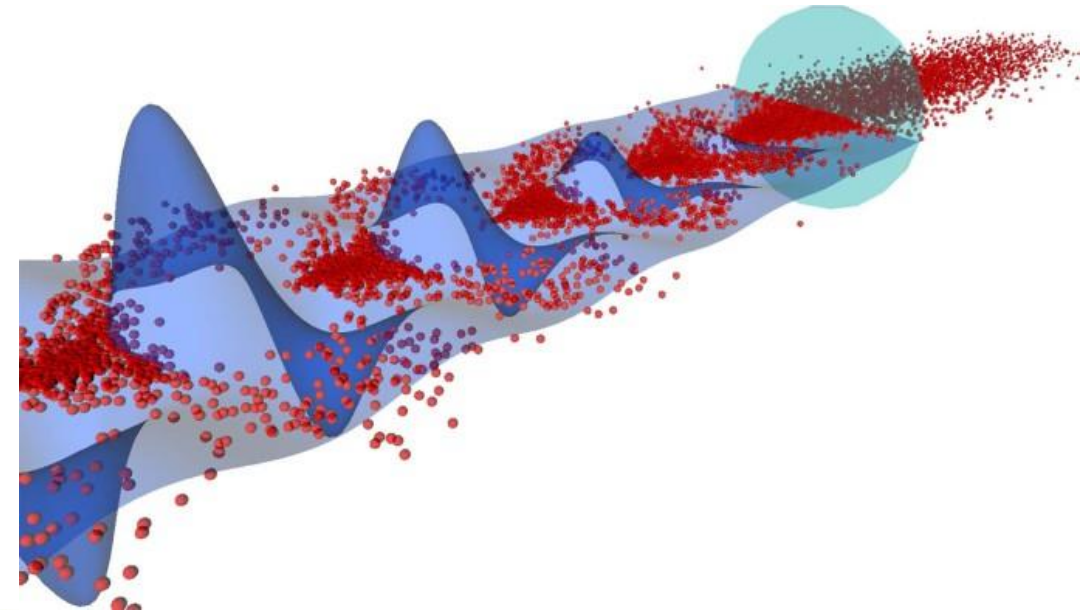
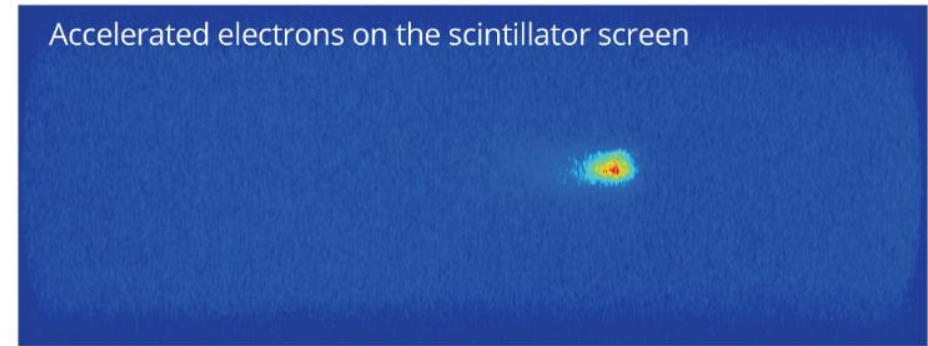
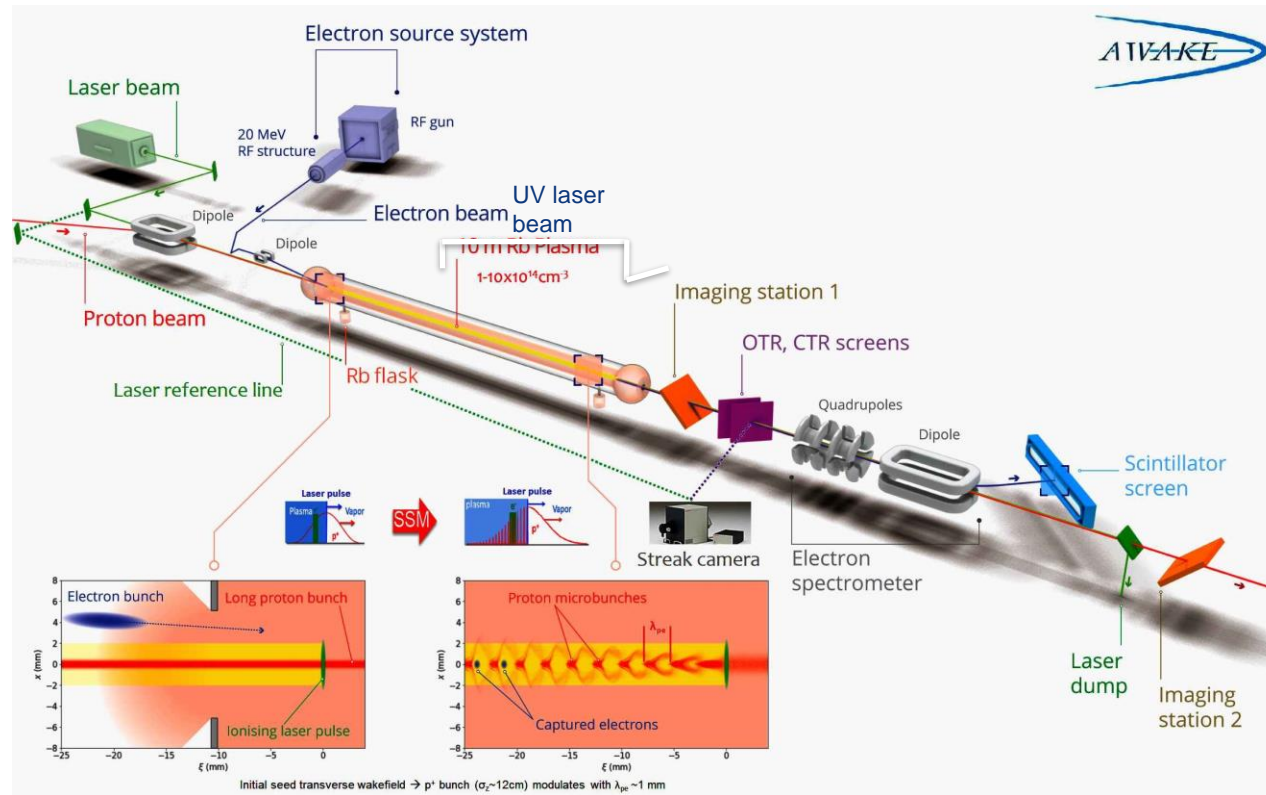
# The future (personal view, pretty long term...)

Laser plasma acceleration : few GeVs per meter ....

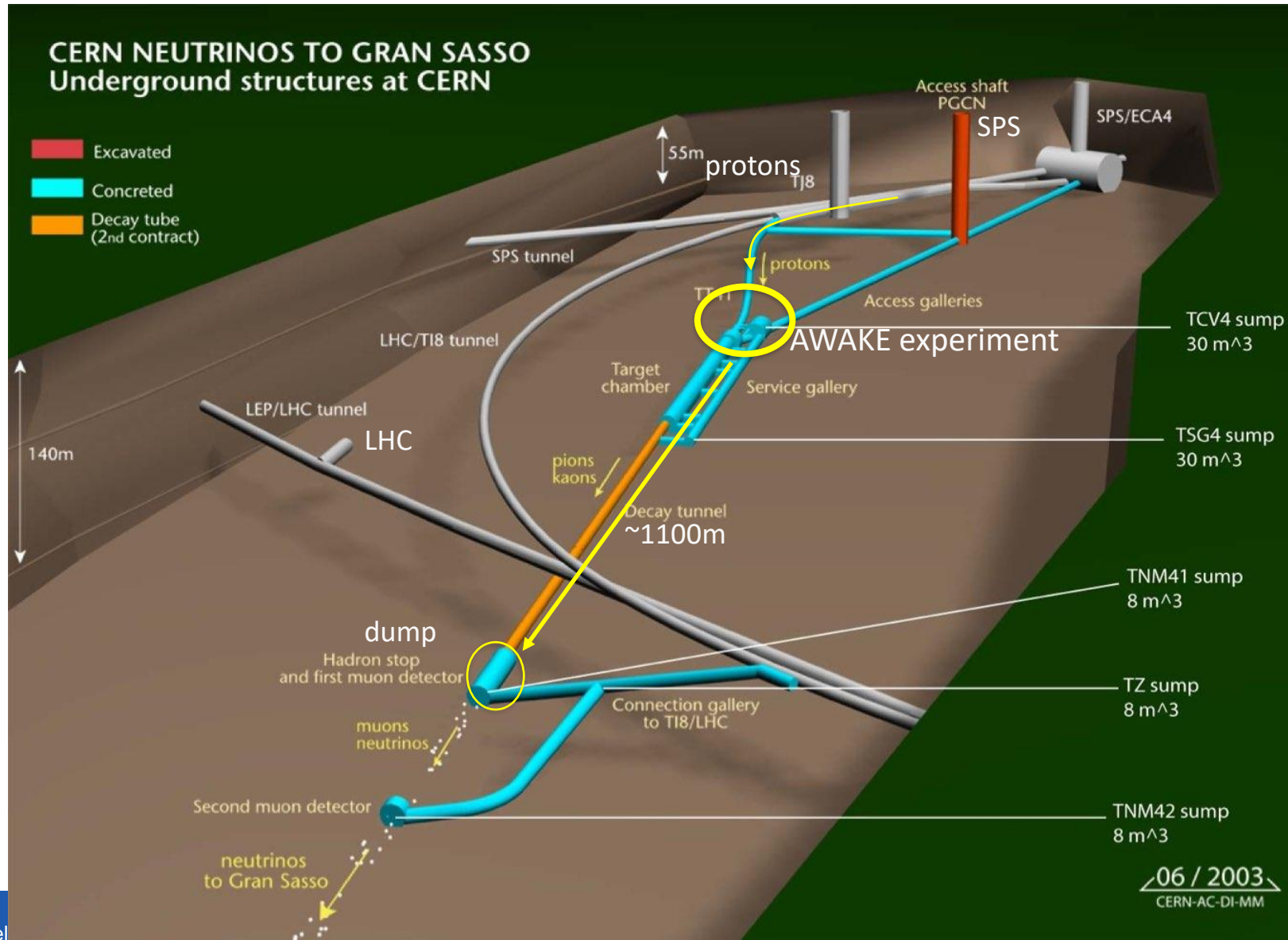


<http://www.youtube.com/watch?v=MINxgmPVF6U>

# Experiment on proton-driven plasma wake acceleration - AWAKE



# AWAKE at CERN



# Thanks for your attention!!!