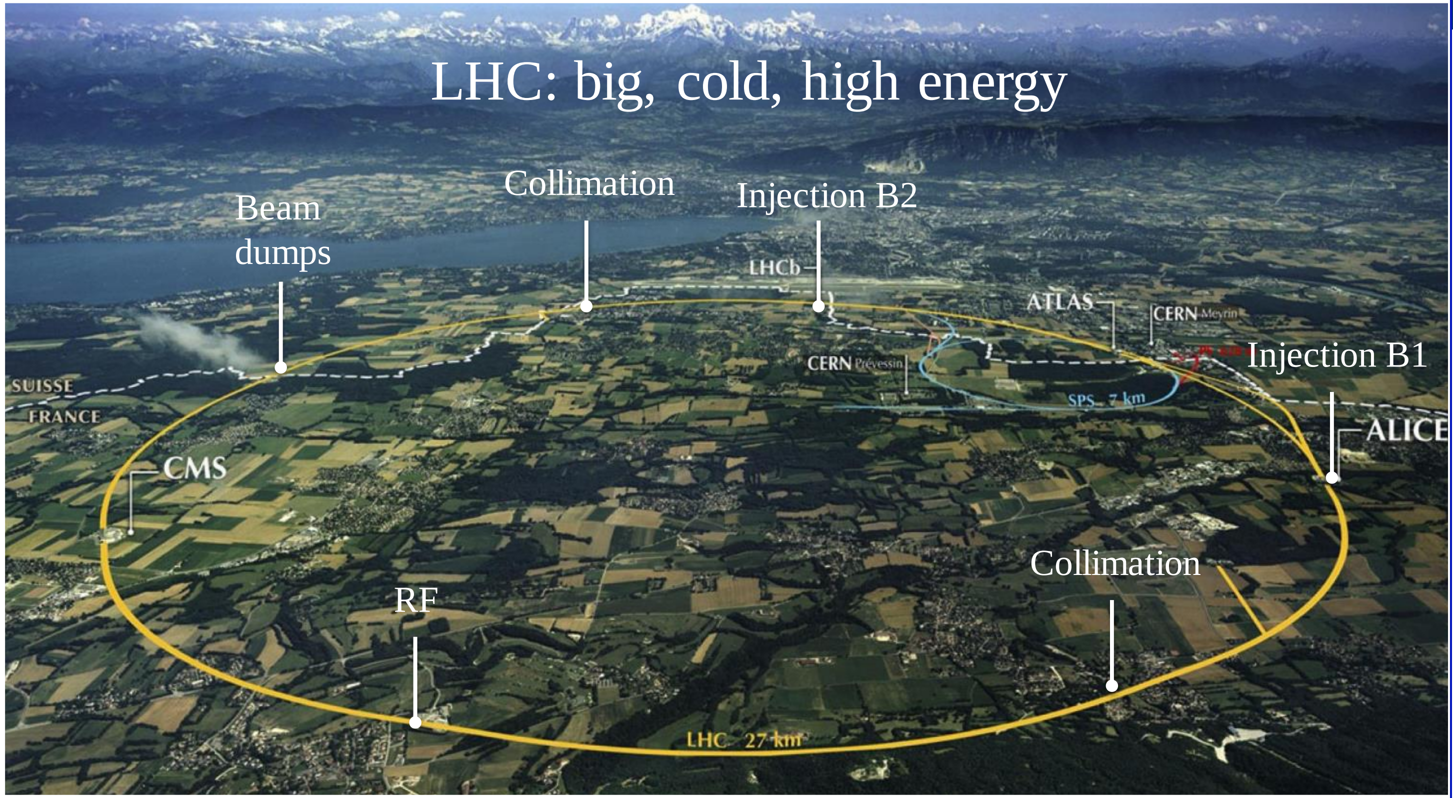
The Large Hadron Collider : the LHC

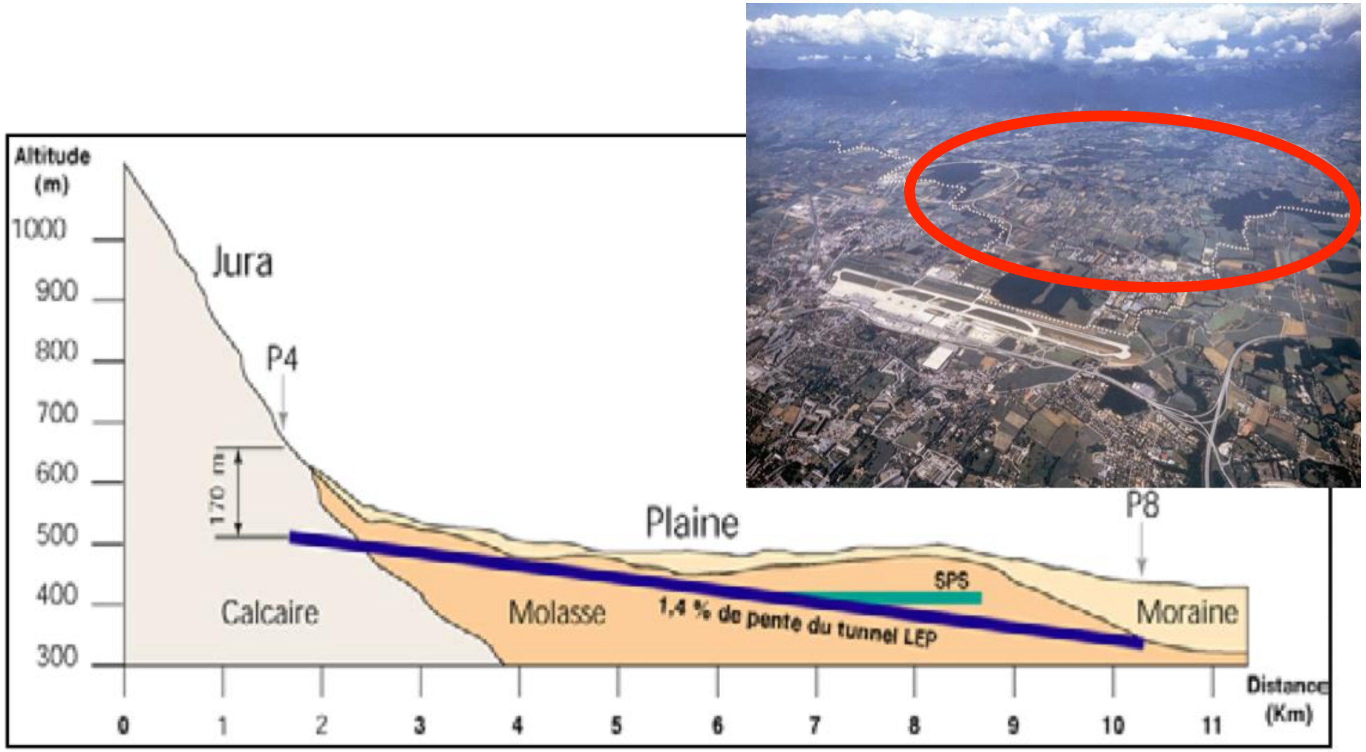
The largest machine and scientific instrument ever built by mankind

…. For the moment….



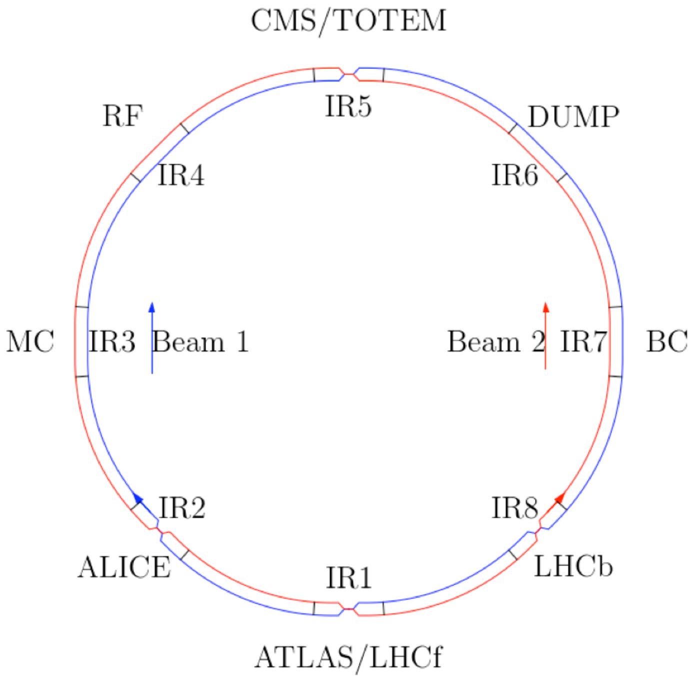
Quantity	Number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Nominal energy, protons	6.5 TeV (6.8 TeV)
Nominal energy, protons collisions	13 TeV (13.6 TeV)
No. of protons	Some 10^{14}
Number of turns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

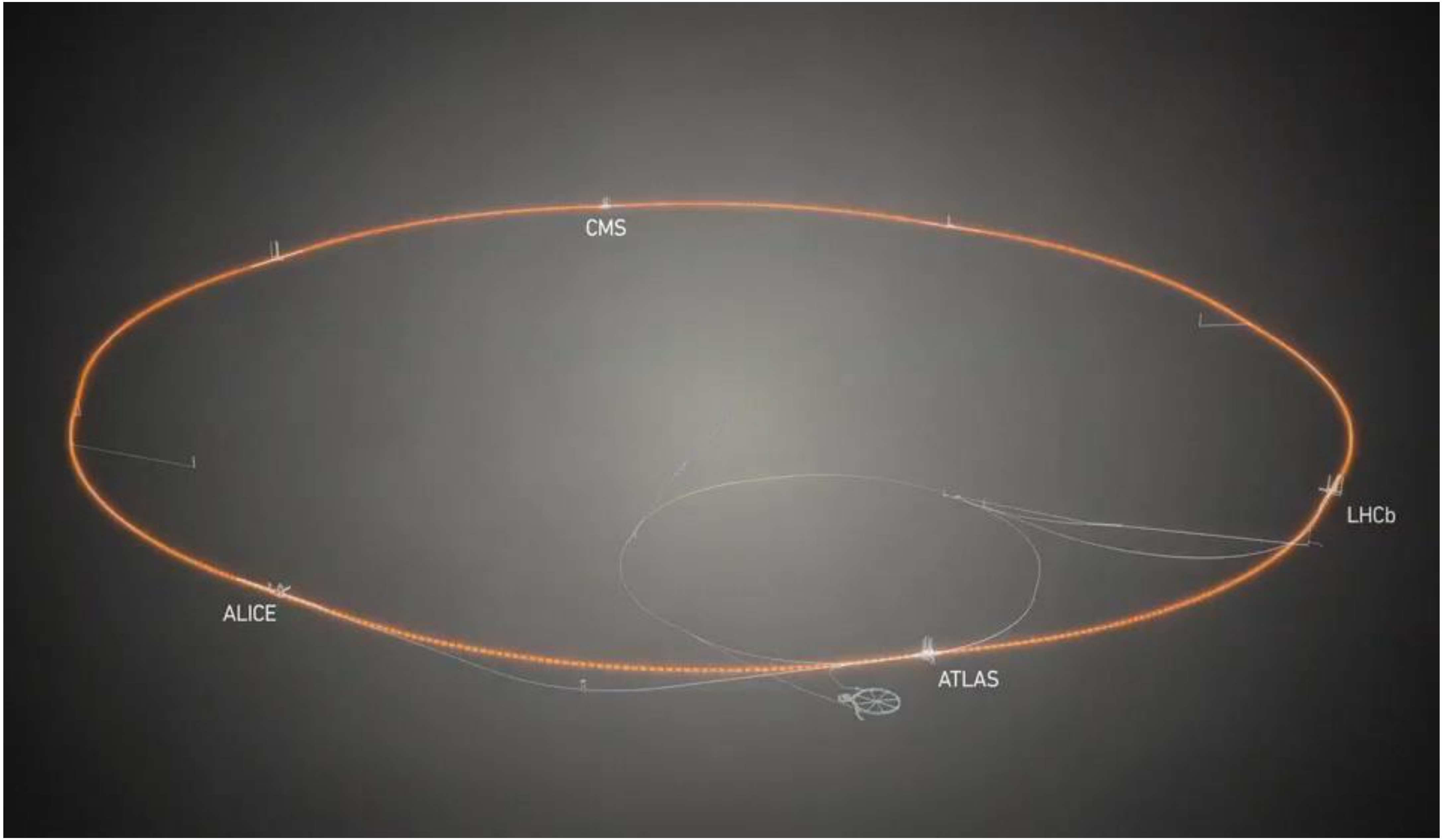
Slope is 1.4%



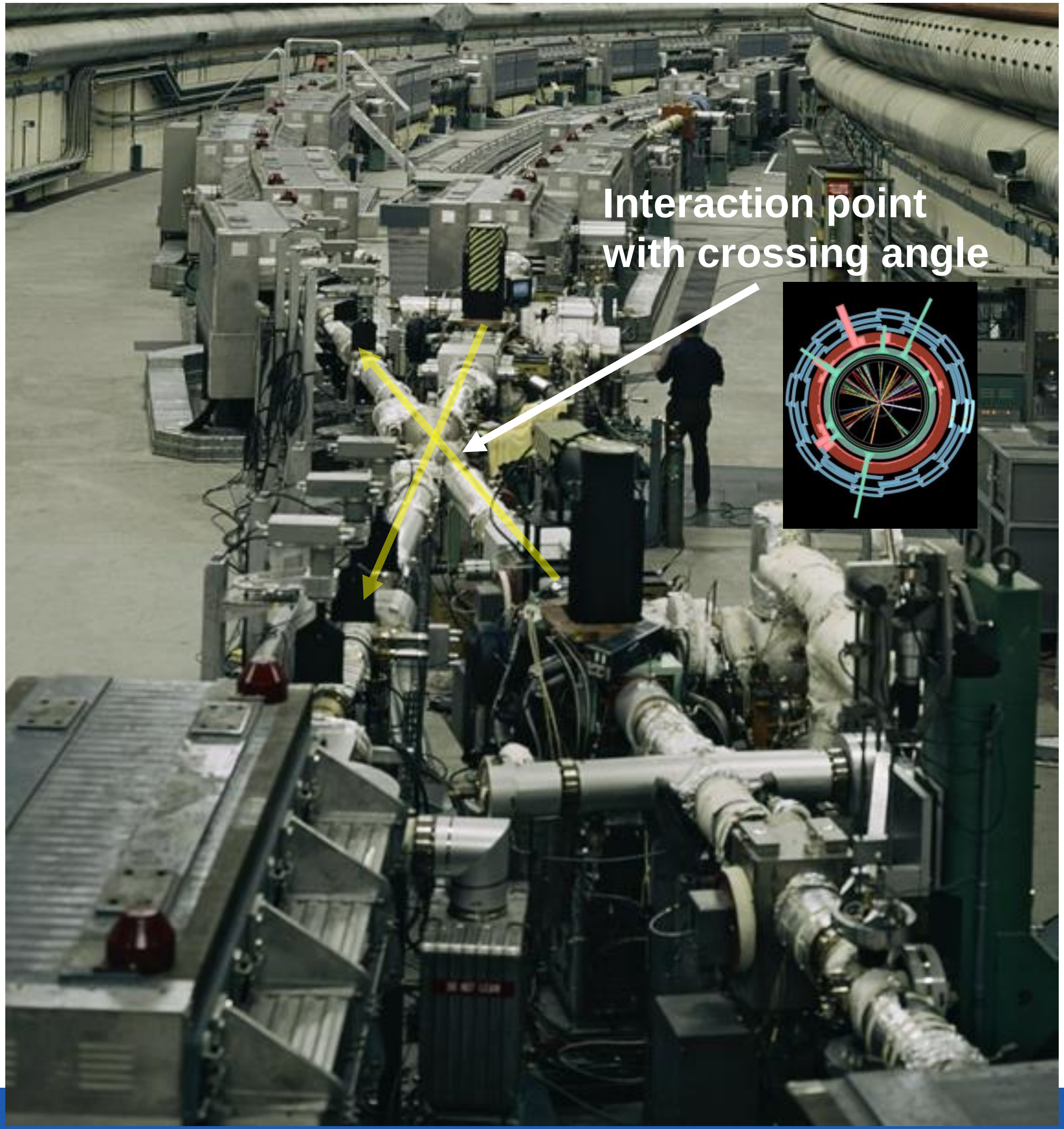
LHC: 8 independent sectors

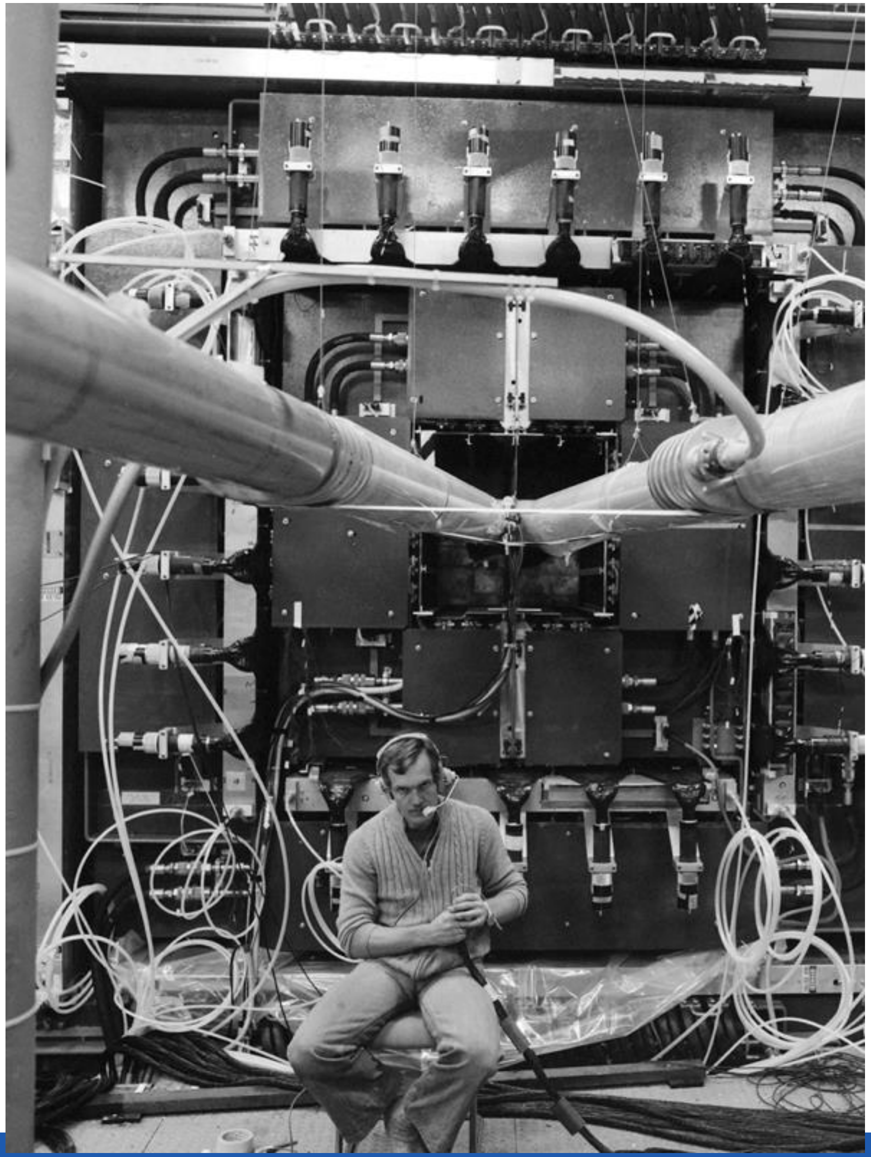
8 straight sections

8 arcs


CMS
LHCb
ALICE
ATLAS

ISR: first proton-proton collider



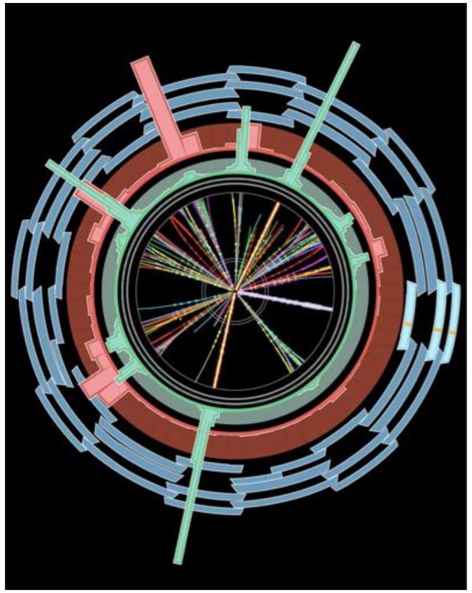


Luminosity of a collider

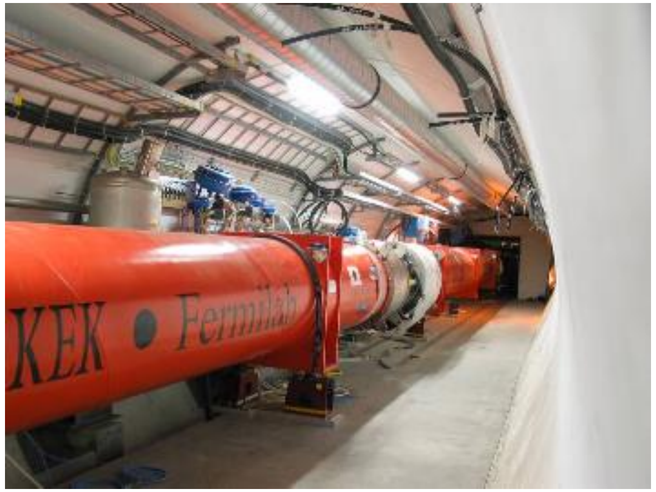
Given by Nature: what we want to study

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

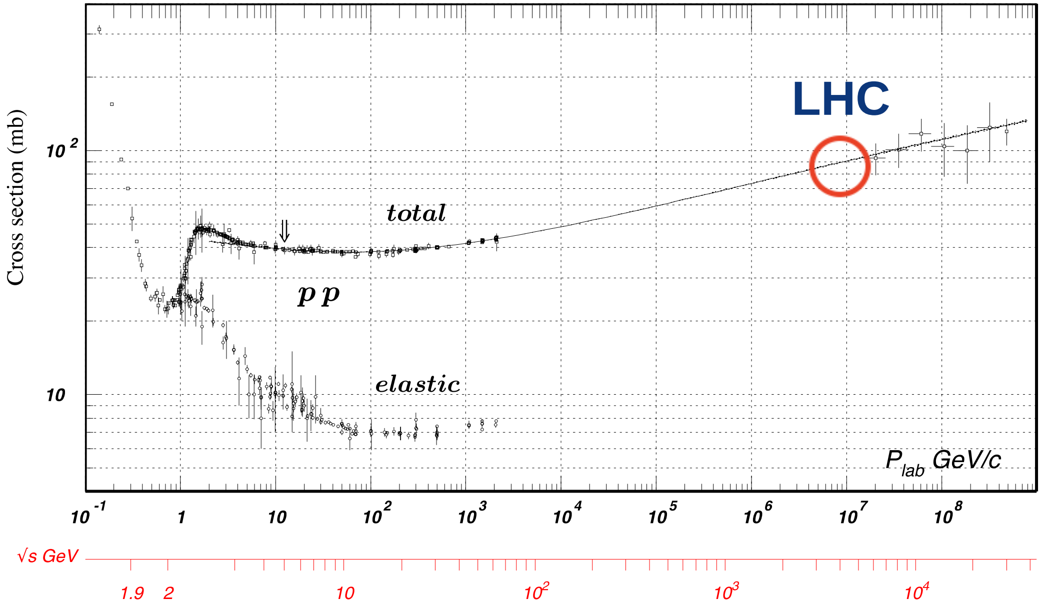
What we can measure



Accelerator Technology

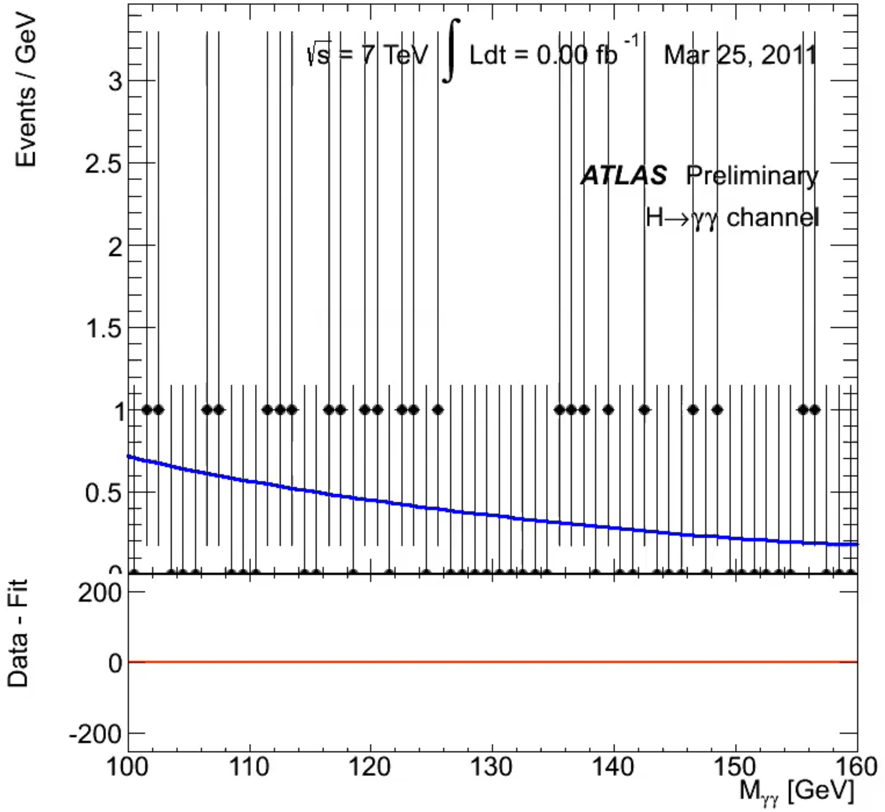


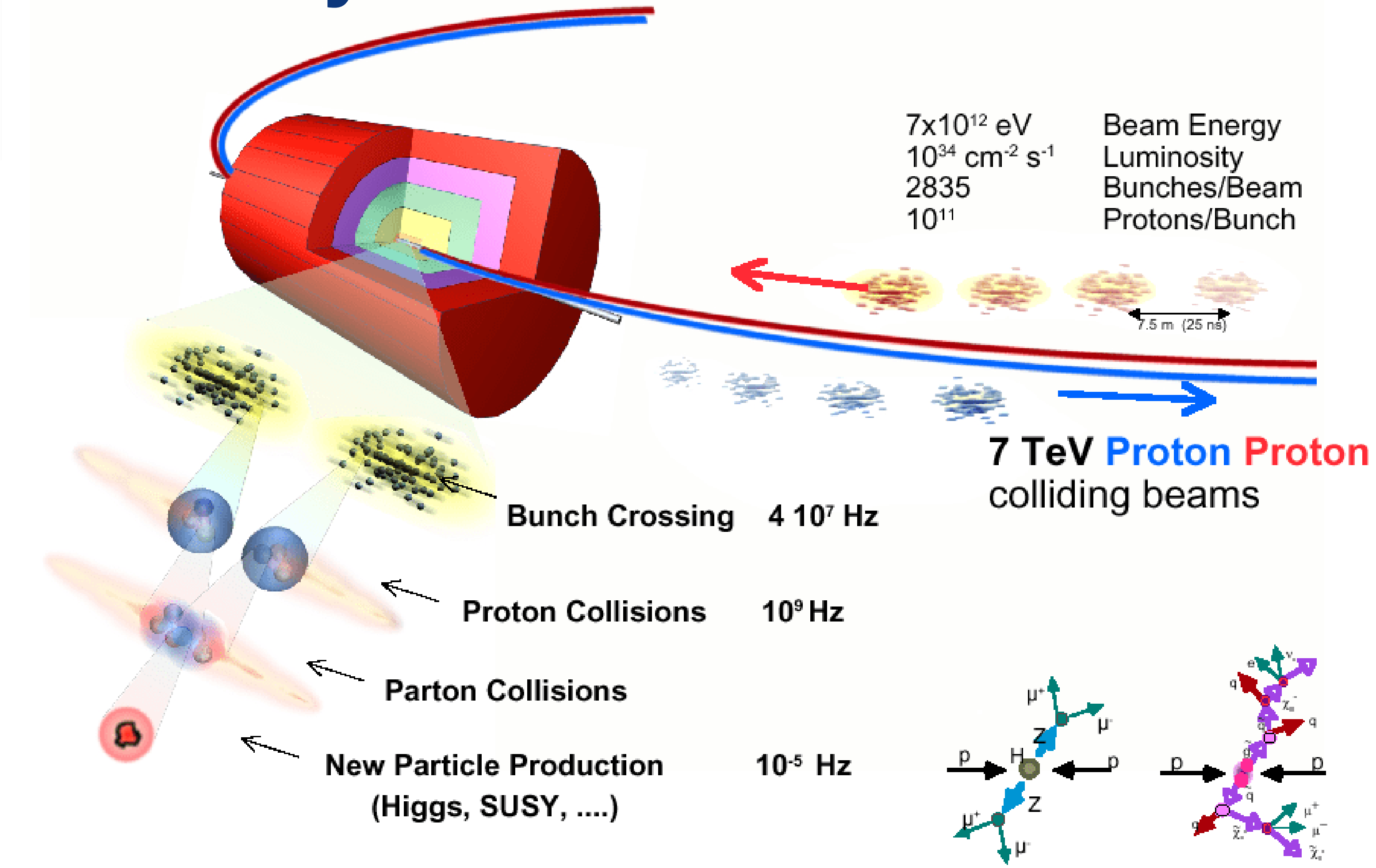
Cross section
→ **probability** that something occurs in p-p collisions



The events we want to study are rare

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





Selection of 1 event in 10,000,000,000,000

We want to have the maximum Luminosity

Revolution frequency
This is fixed by the LHC circumference

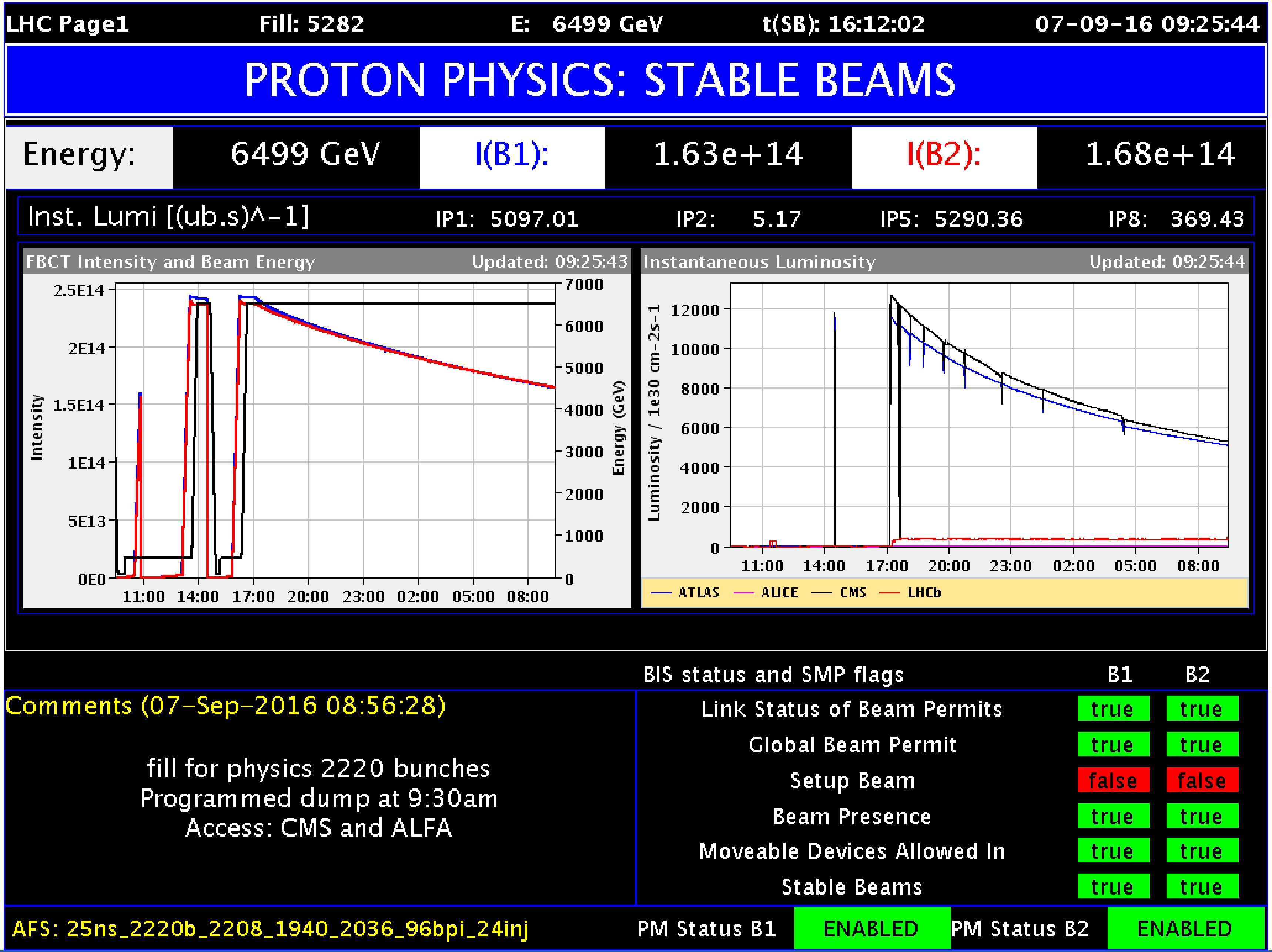
Proton Intensity per bunch
This comes from the injectors
10 years of development
Being done now

Number of bunches
This is more or less fixed

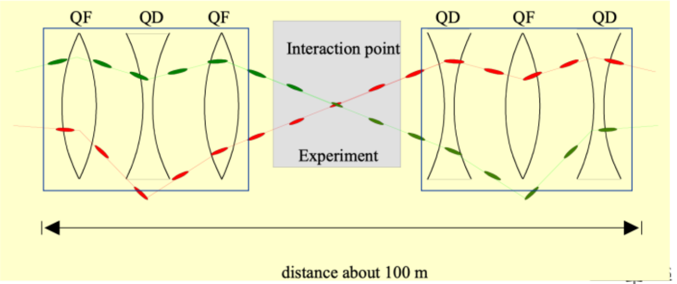
$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

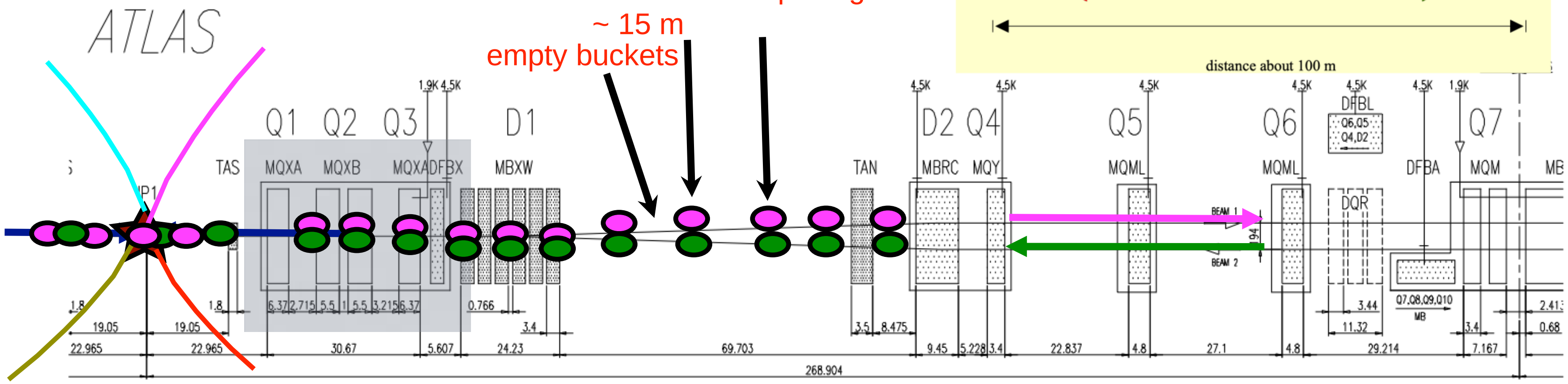
How the bunches collides
This can be changed

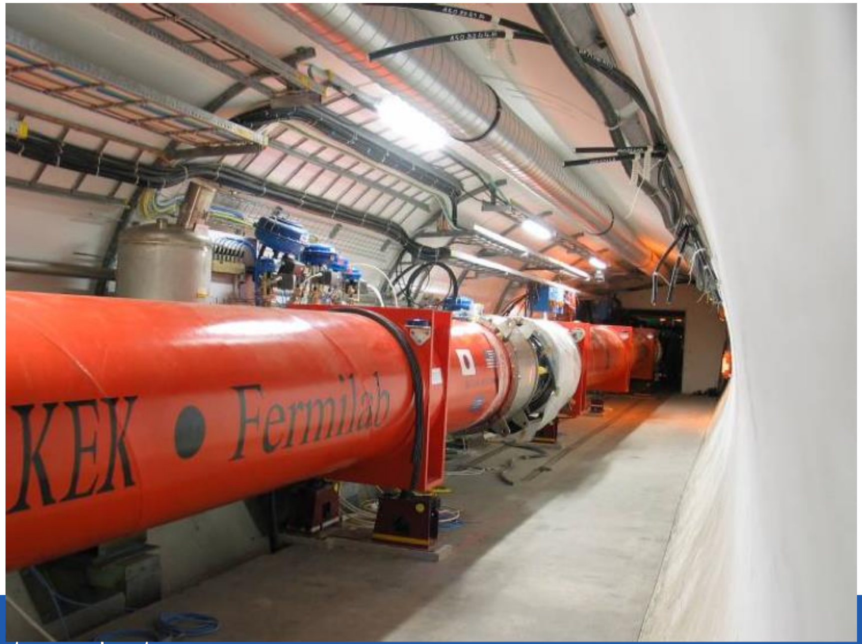
Beam Spot size at collision point
This can be minimised by building new magnets→ **LS3 → post 2029**
Technology development 10-15 years long


LHC Page1
Fill: 5282
E: 6499 GeV
t(SB): 16:12:02
07-09-16 09:25:44
PROTON PHYSICS: STABLE BEAMS
Energy:
6499 GeV
I(B1):
1.63e+14
I(B2):
1.68e+14
Inst. Lumi [(ub.s)^-1]
IP1: 5097.01
IP2: 5.17
IP5: 5290.36
IP8: 369.43
FBCT Intensity and Beam Energy
Updated: 09:25:43
Intensity
Energy (GeV)
2.5E14
2E14
1.5E14
1E14
5E13
0E0
7000
6000
5000
4000
3000
2000
1000
0
11:00 14:00 17:00 20:00 23:00 02:00 05:00 08:00
Instantaneous Luminosity
Updated: 09:25:44
Luminosity / 1e30 cm-2s-1
12000
10000
8000
6000
4000
2000
0
11:00 14:00 17:00 20:00 23:00 02:00 05:00 08:00
ATLAS
ALICE
CMS
LHCb
BIS status and SMP flags
B1
B2
Comments (07-Sep-2016 08:56:28)
fill for physics 2220 bunches
Programmed dump at 9:30am
Access: CMS and ALFA
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

Inner triplet: final focusing
⇒ how to make the beam small at the IP

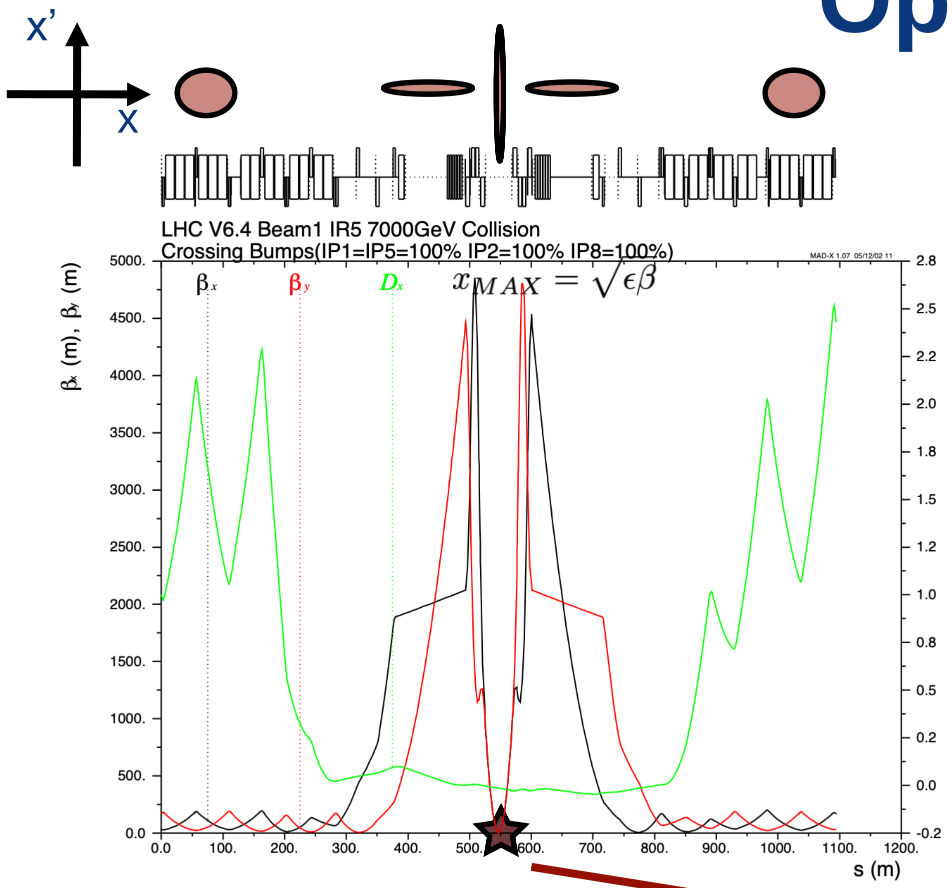


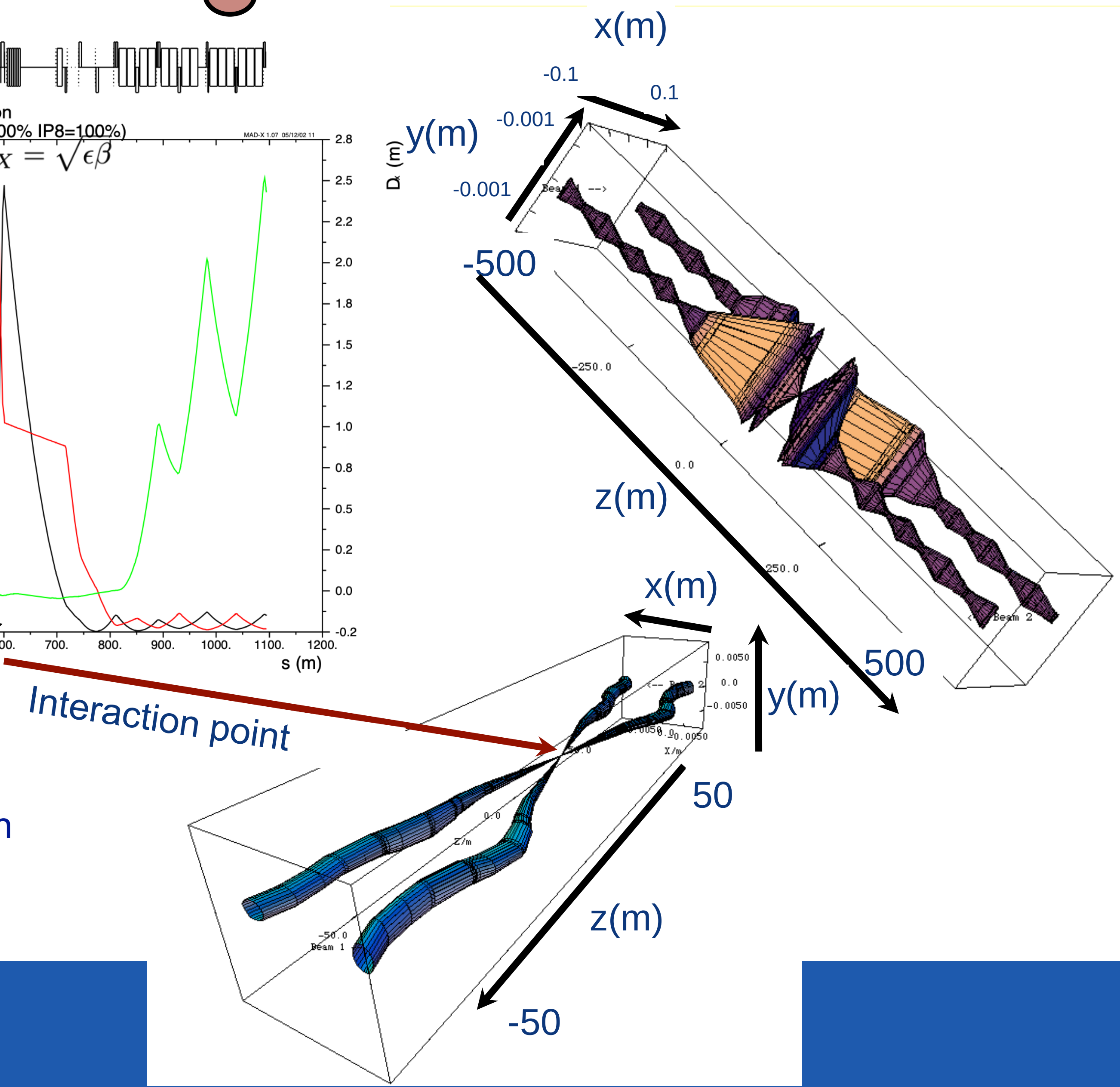




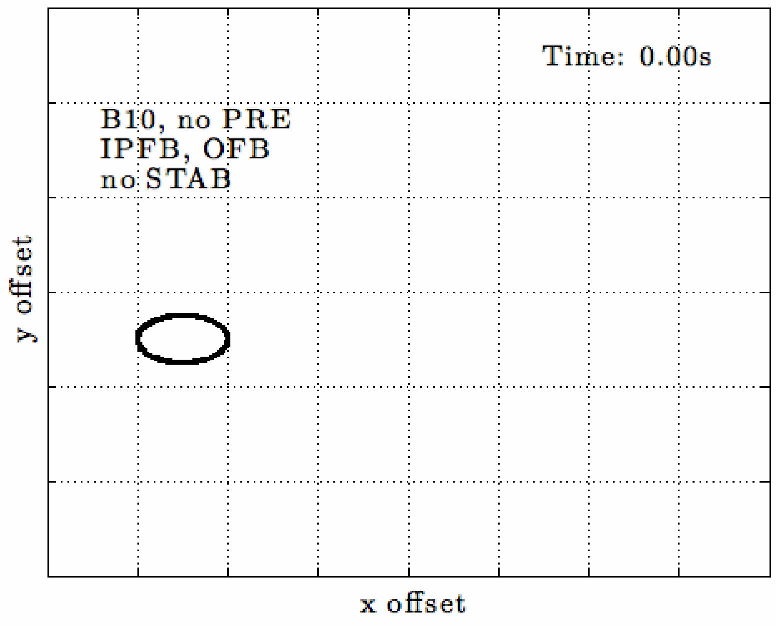
Triplets before lowering in the tunnel

Optics at collision IP5- CMS

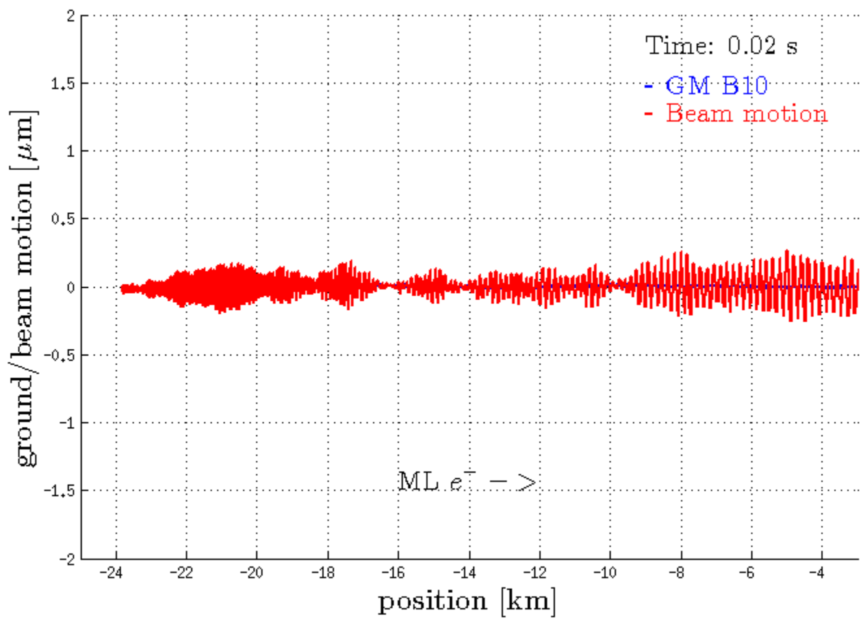




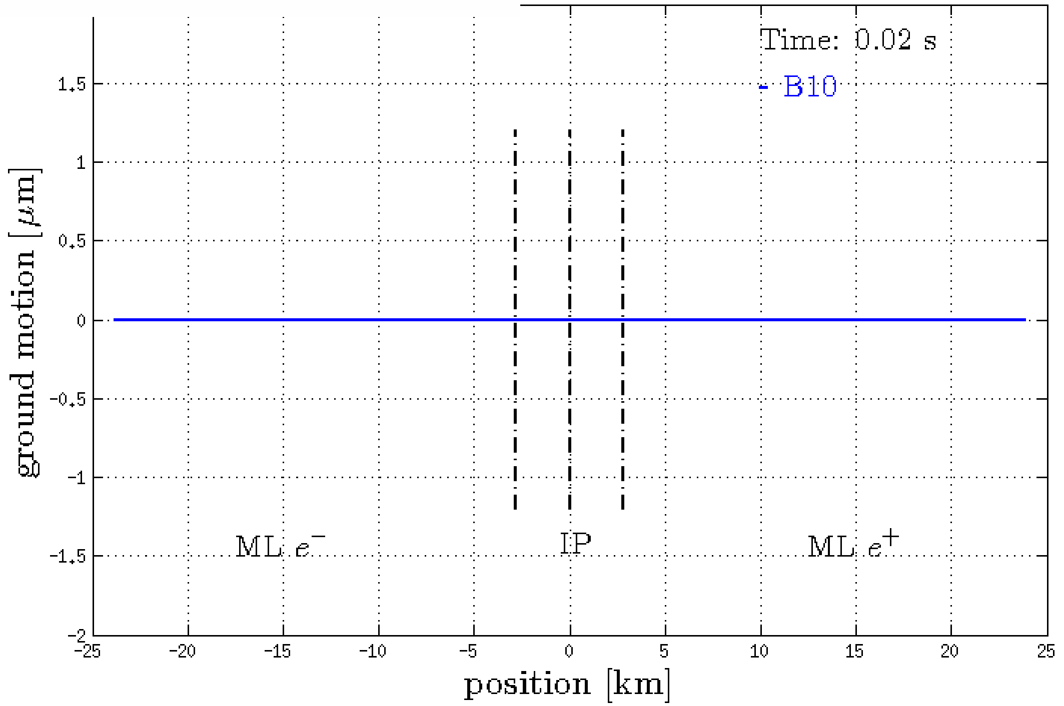
At collision the beams are "squeezed" down
to few microns at the interaction point



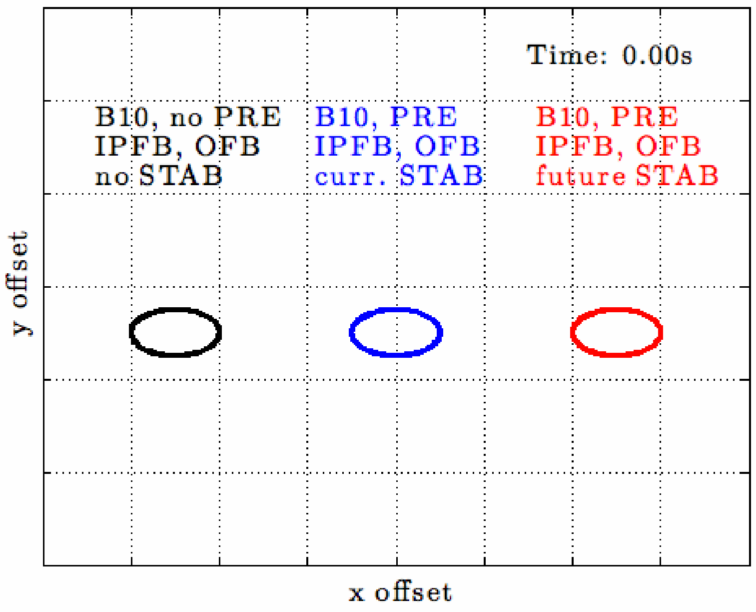
Time: 0.00s
B10, no PRE
IPFB, OFB
no STAB
y offset
x offset

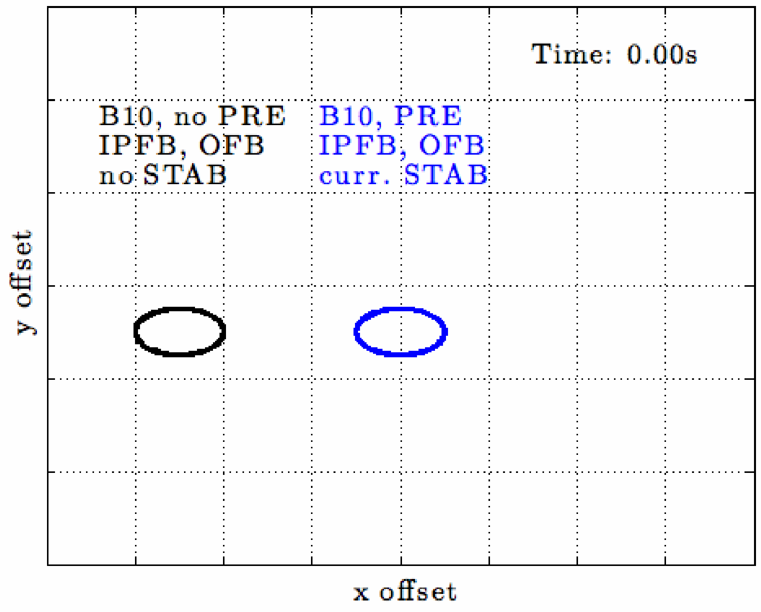


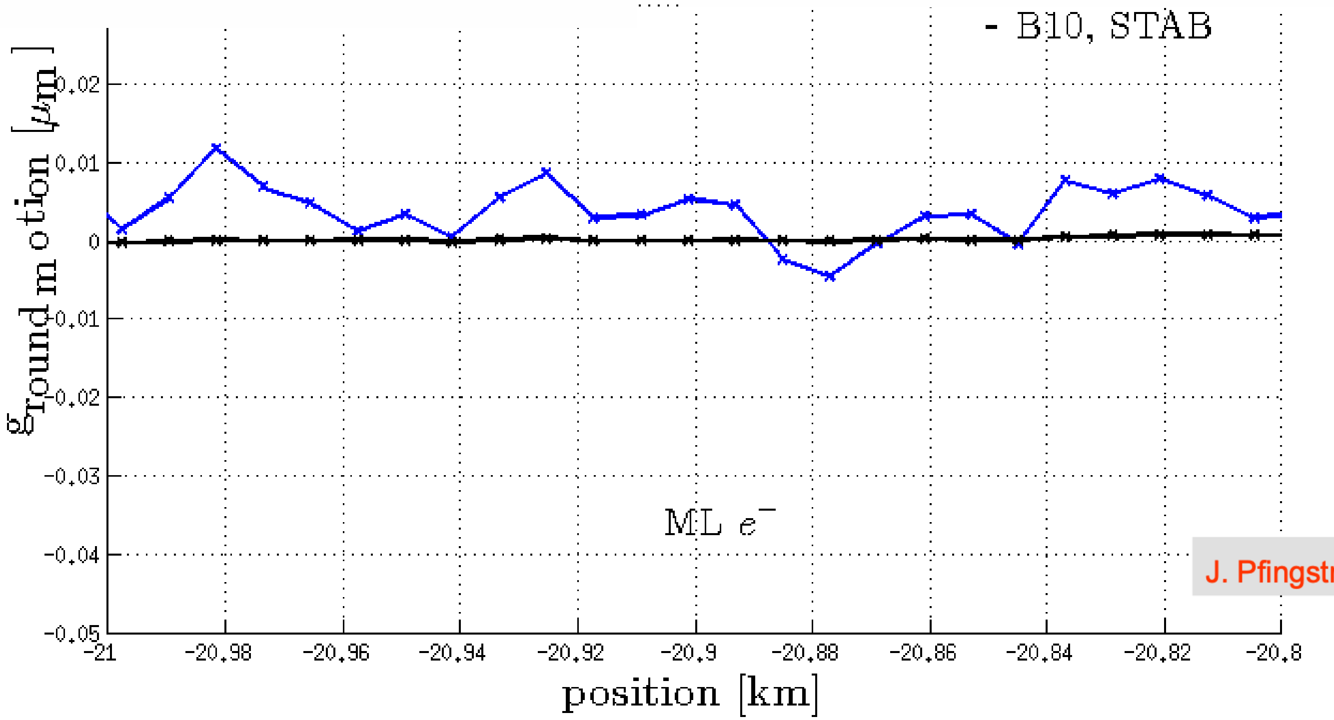
Time: 0.02 s
- GM B10
- Beam motion
ground/beam motion [μm]
ML e+ − >
position [km]



Time: 0.02 s
- B10
ground motion [μm]
ML e−
IP
ML e+
position [km]

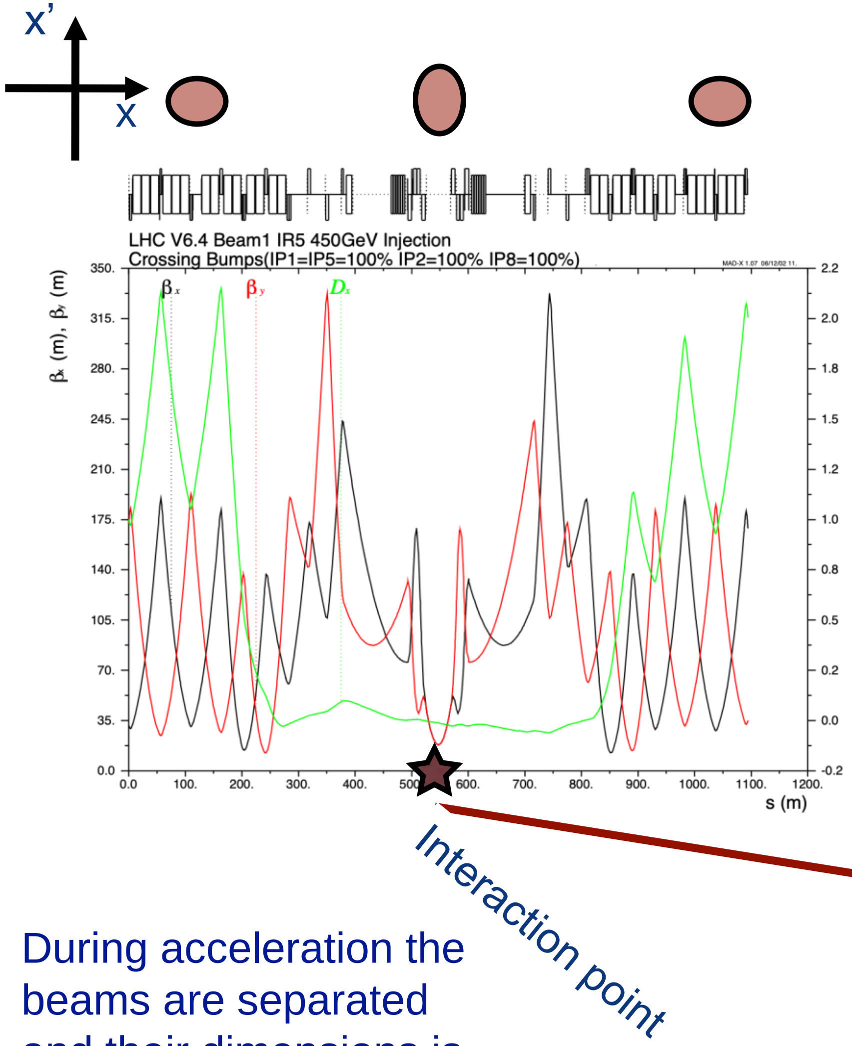


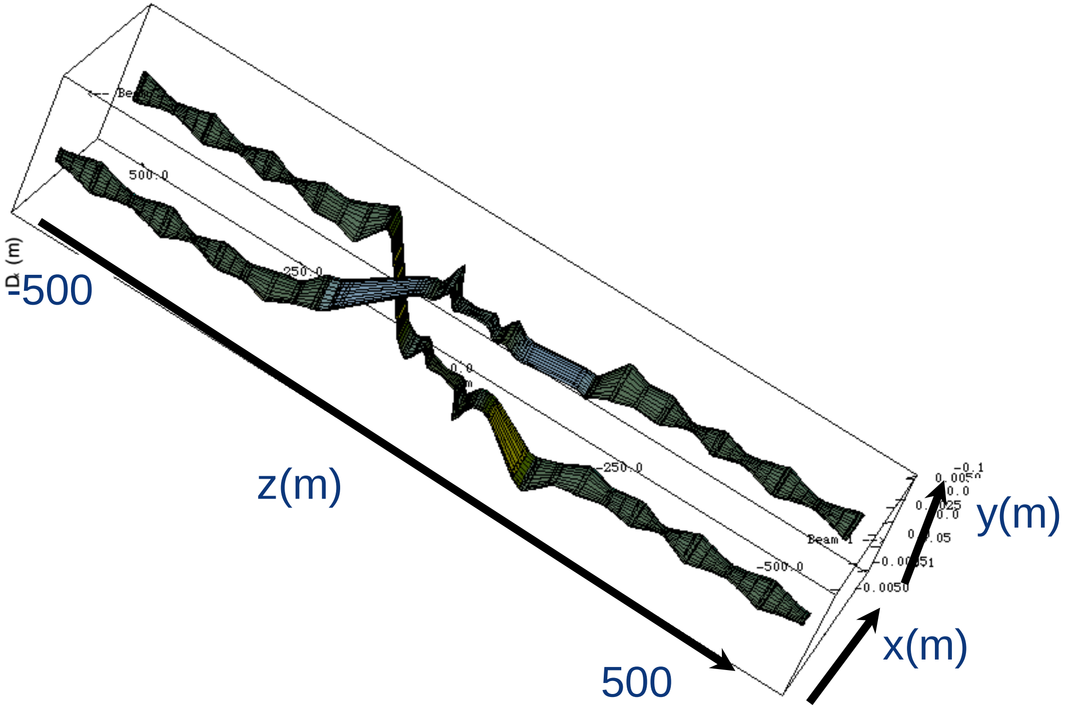


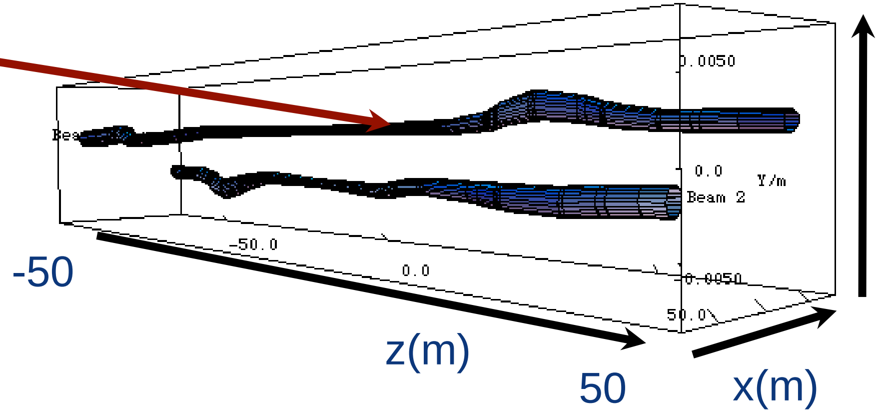


J. Pfingstner

Injection optics and during acceleration IP5- CMS







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

We want to have the maximum Luminosity

Revolution frequency
This is fixed by the LHC circumference

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

Number of bunches
This is more or less fixed

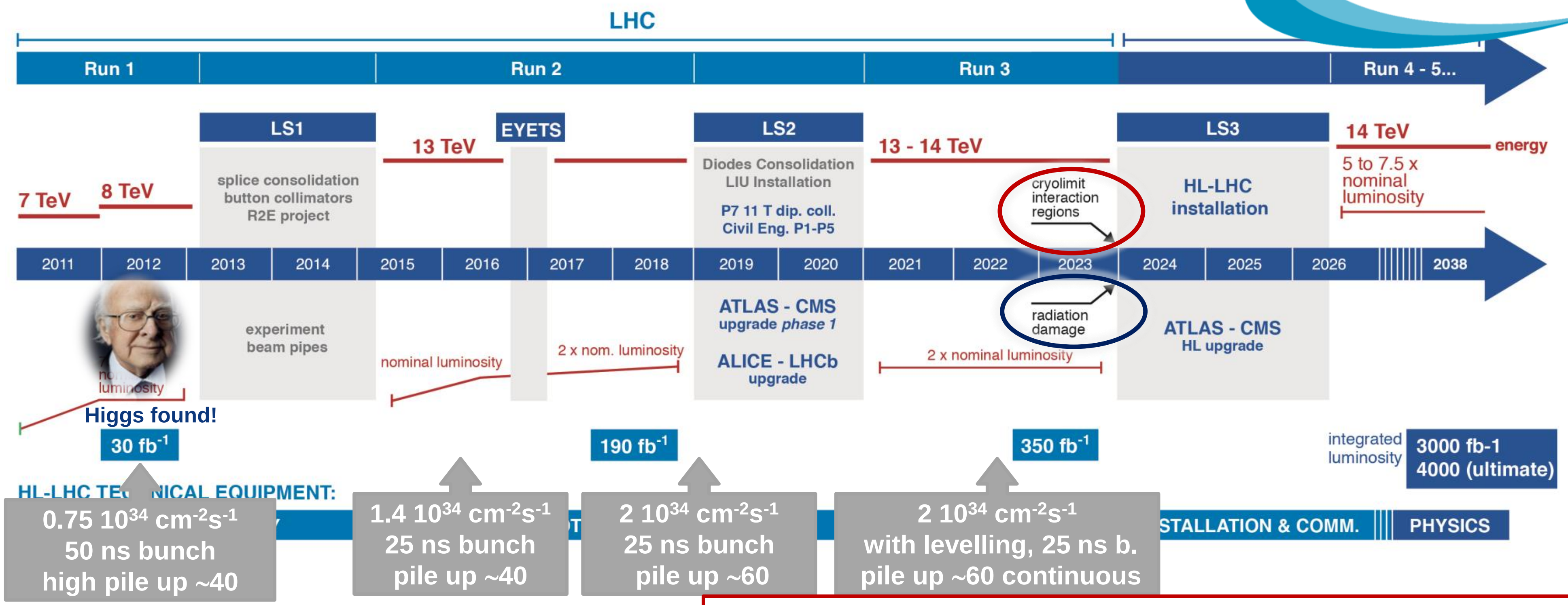
$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

How the bunches collides
This can be changed

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

LHC / HL-LHC Plan

HiLumi HL-LHC PROJECT



Technical limitation on **integrated luminosity:**

1. **Collider** (radiation damage to the IT magnets – correctors and quadrupoles)

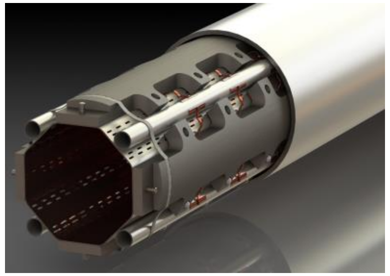
2. **Experiments** (radiation damage in the Inner Tracker)

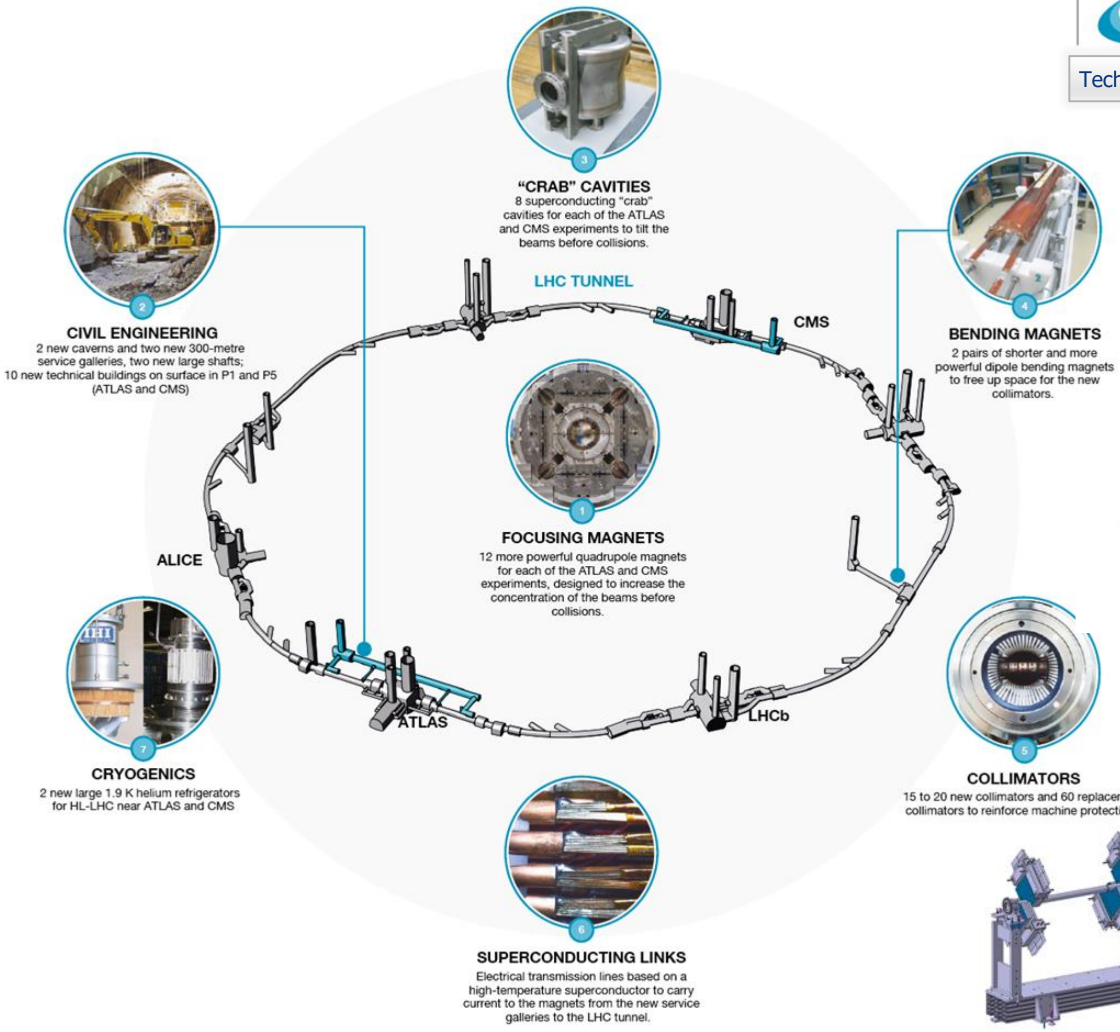
Technical limitation on the **istantaneous luminosity:**

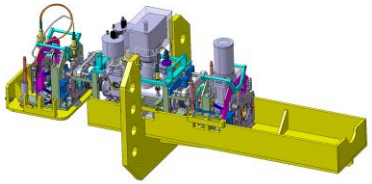
1. **Collider** (cryolimit in the triplet region) at 2×10^{34} $cm^{-2}s^{-1}$ twice the nominal design luminosity)

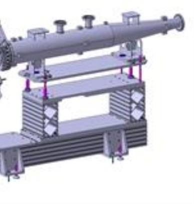
2. **Experiments** (pile up in the detectors). Designed for PU 40 they are actually dealing with 60 (average)

HL-LHC: High Luminosity LHC in a nutshell

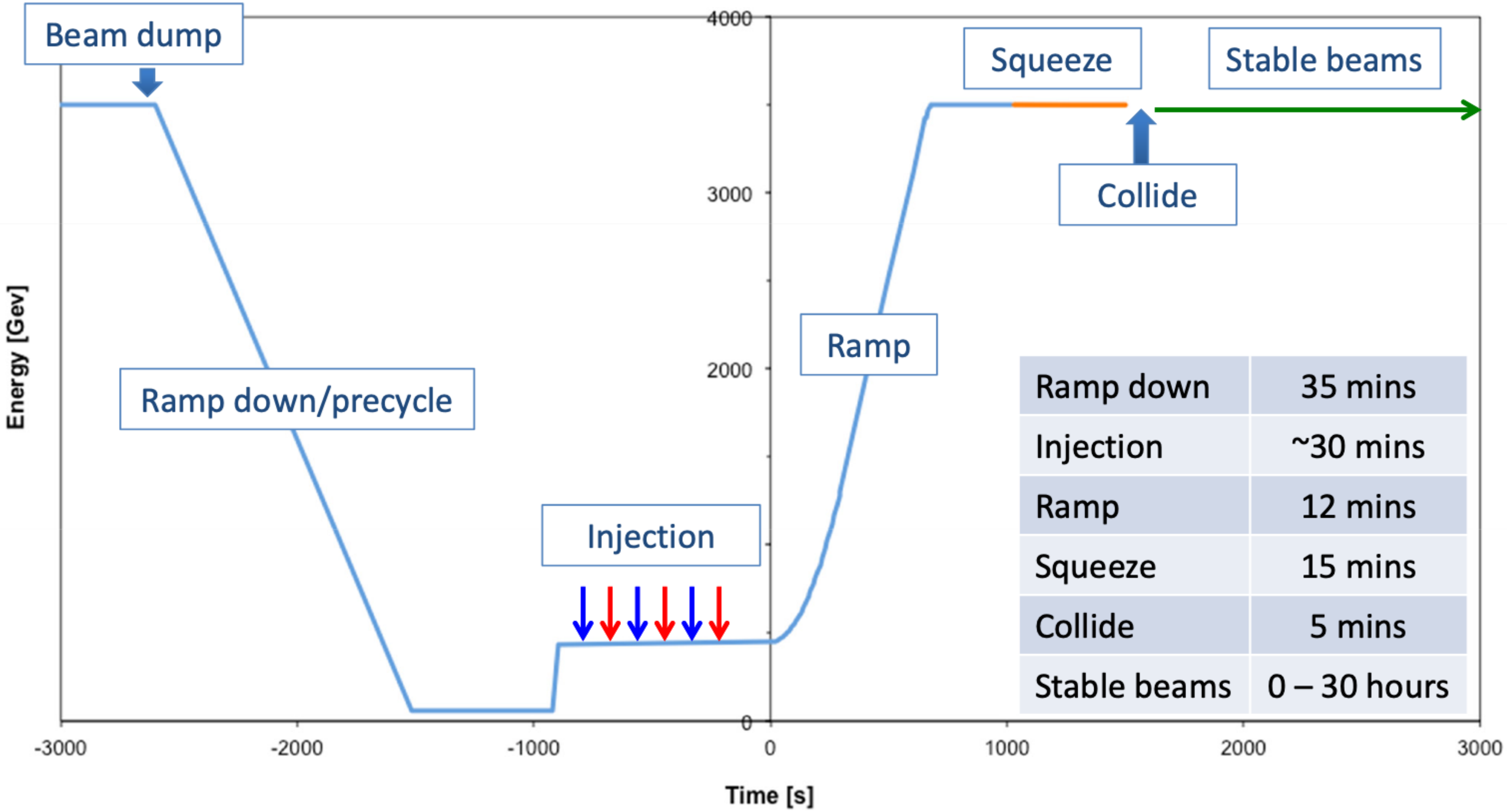








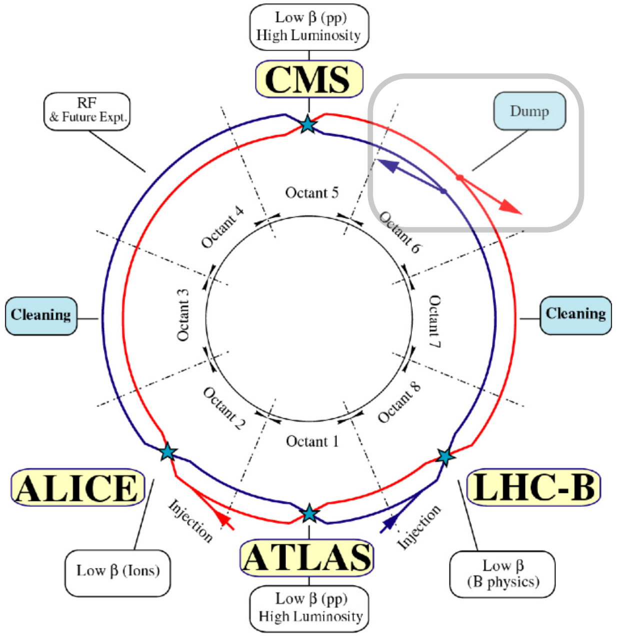
LHC Operational cycle as synchrotron

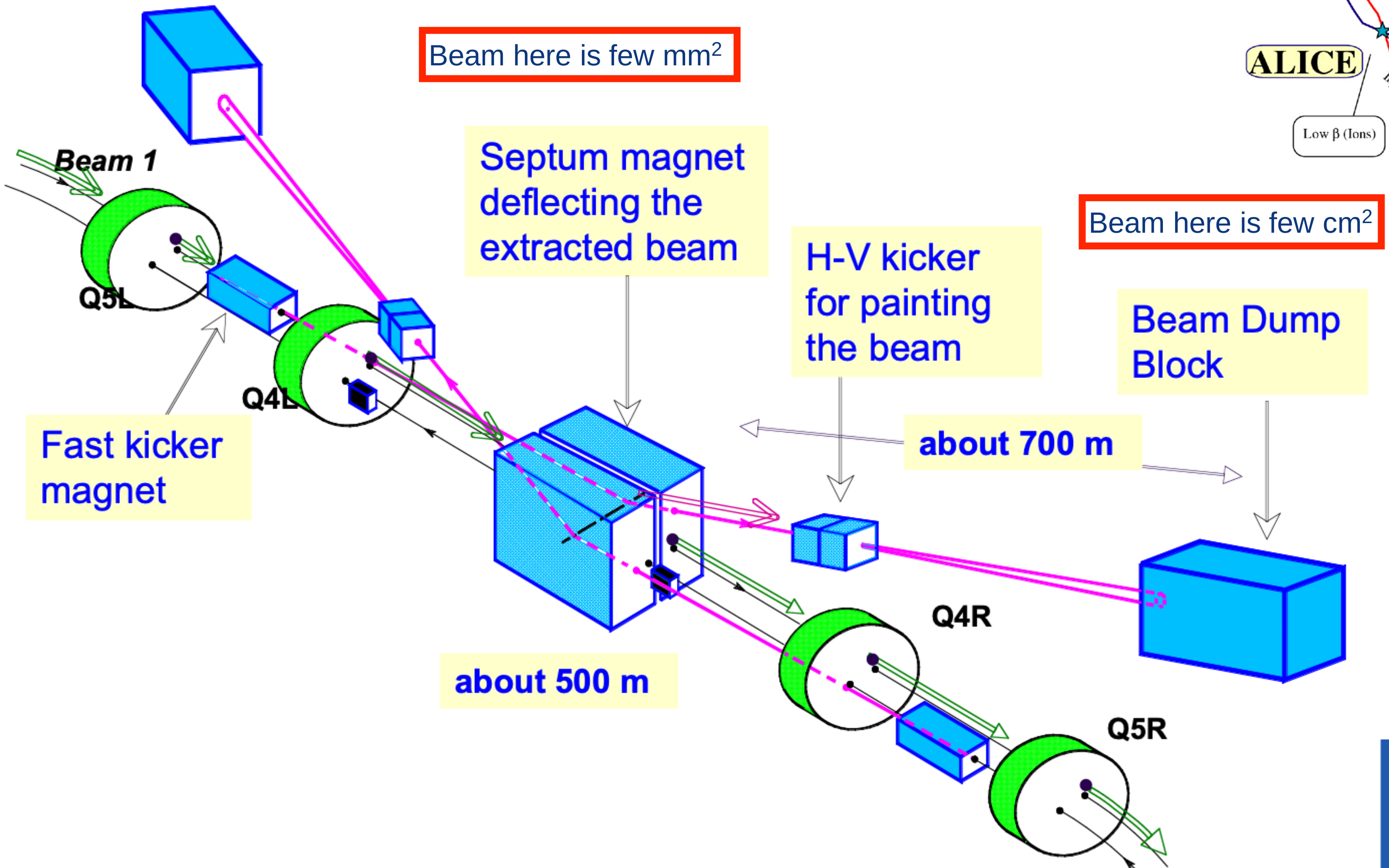


Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

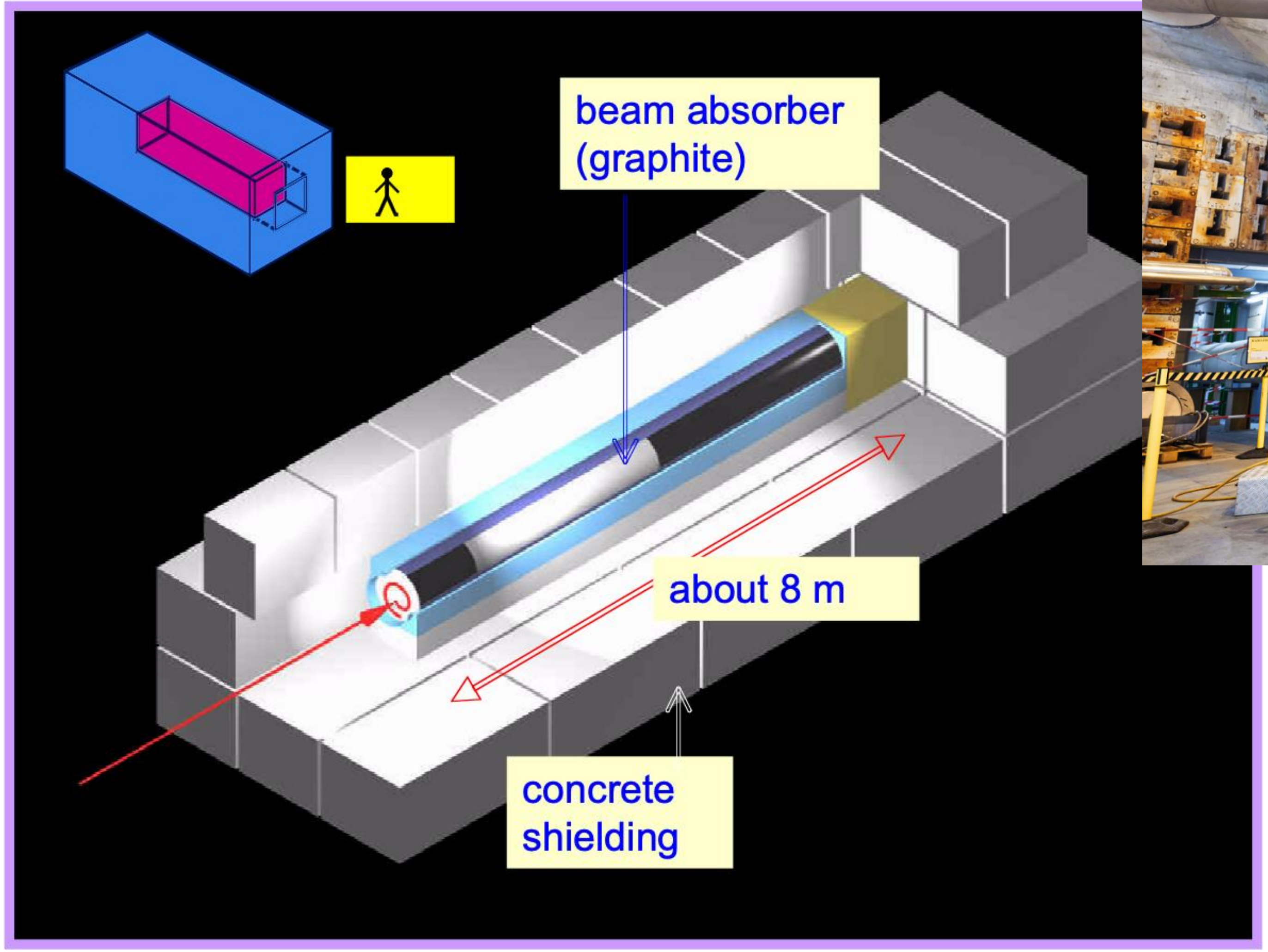
Beam extraction, emergency or not...

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 absorbe full power at full energy.





Scheme of one of the beam absorbers



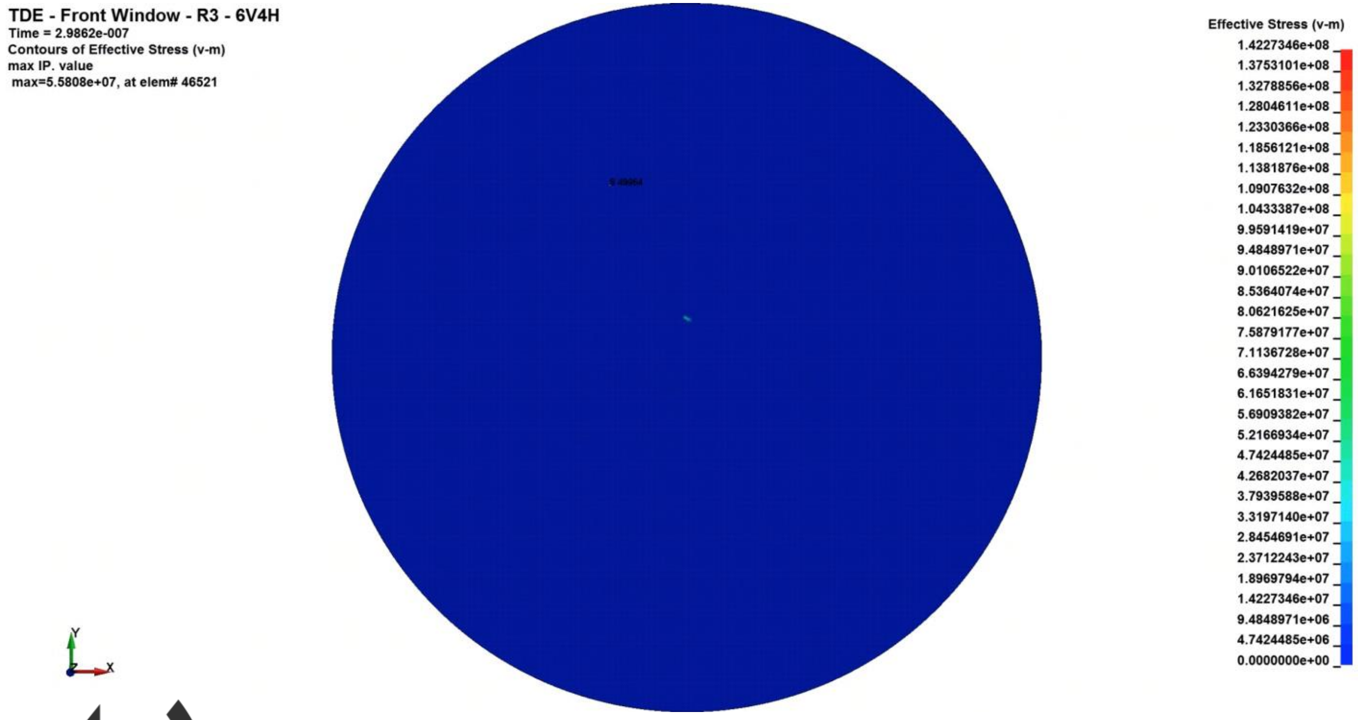
L.Bruno

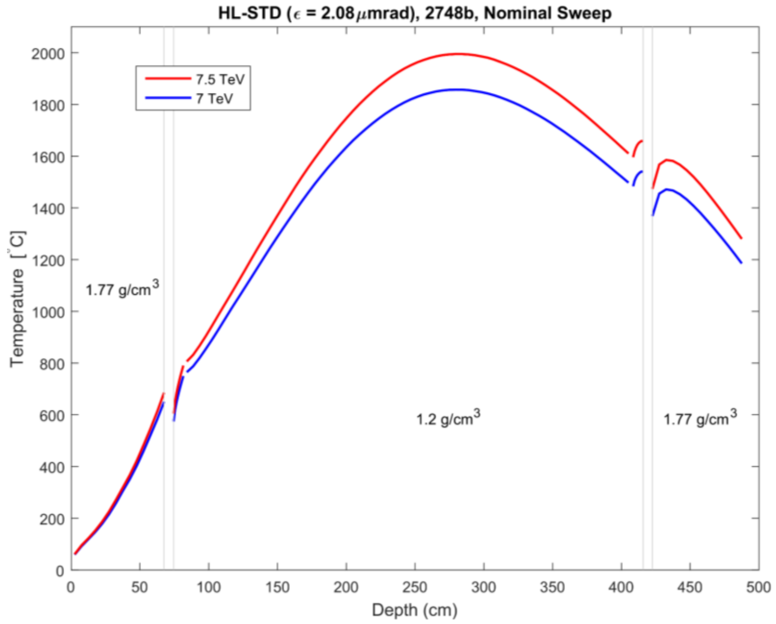
Spot size on the beam dump

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.

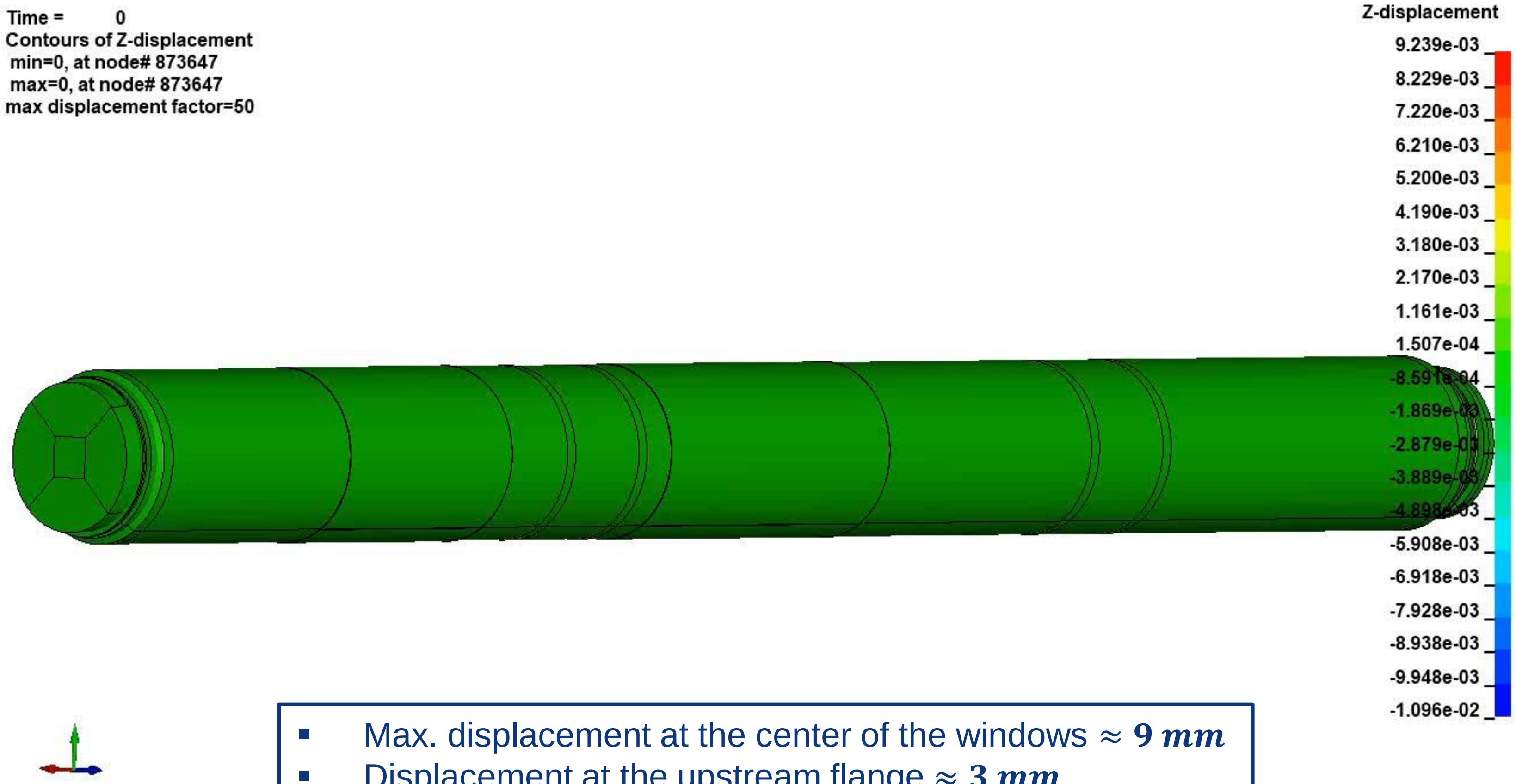




FE simulations during LS2

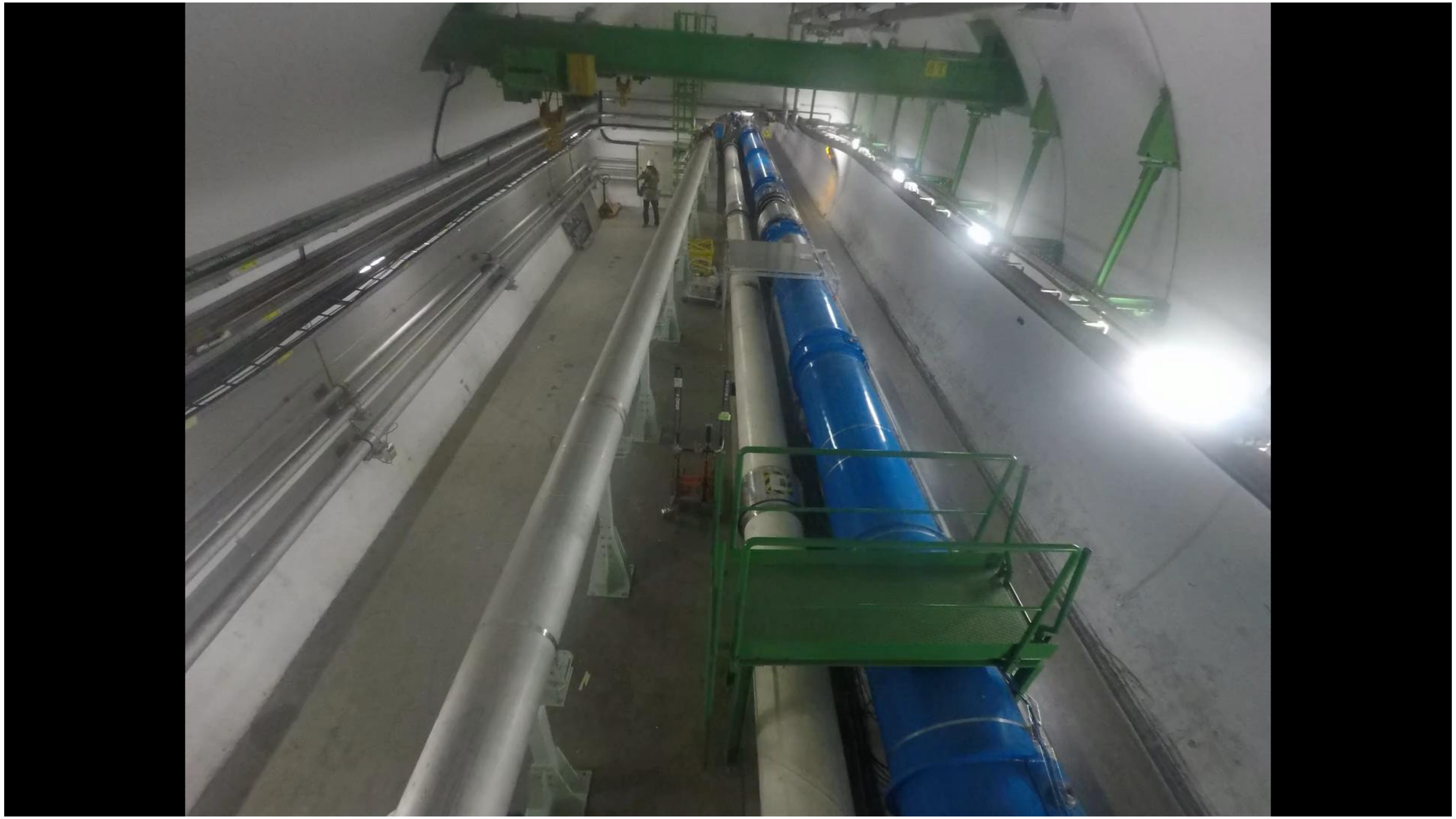
Acceleration up to 600 g

25 ms



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

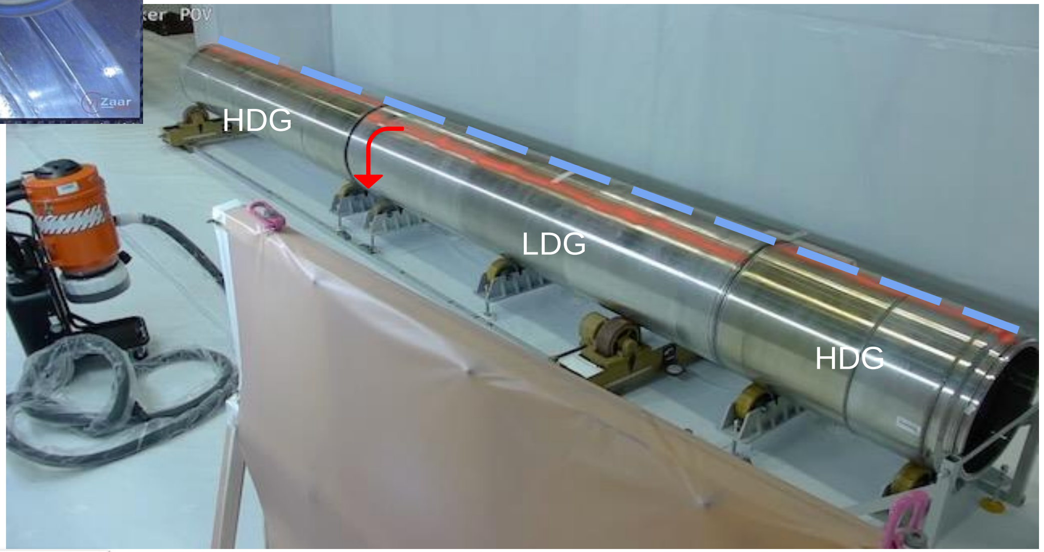
Dump removal for replacement



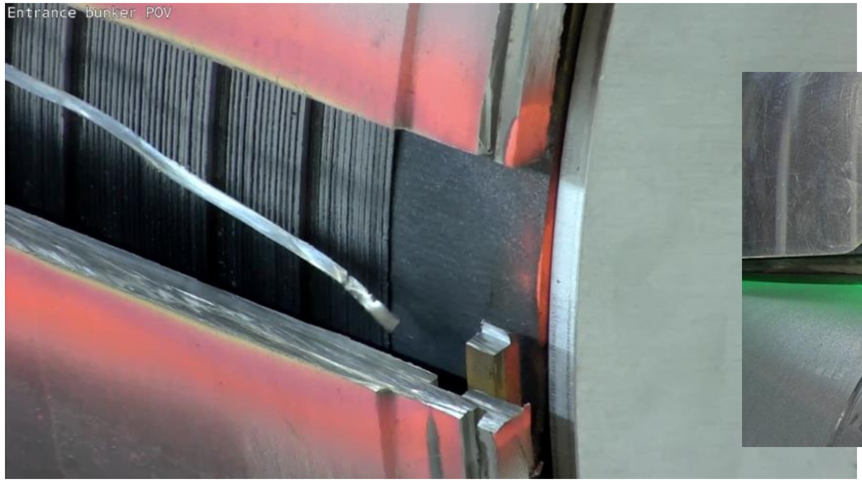
Autopsy Cuts

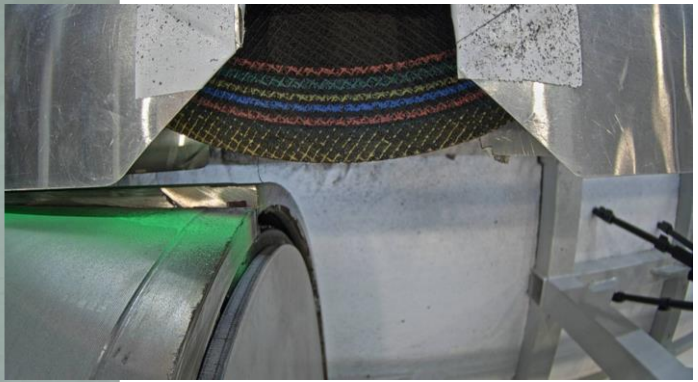
Radial cut

Max dose rate :
3.5 mSv/h at contact



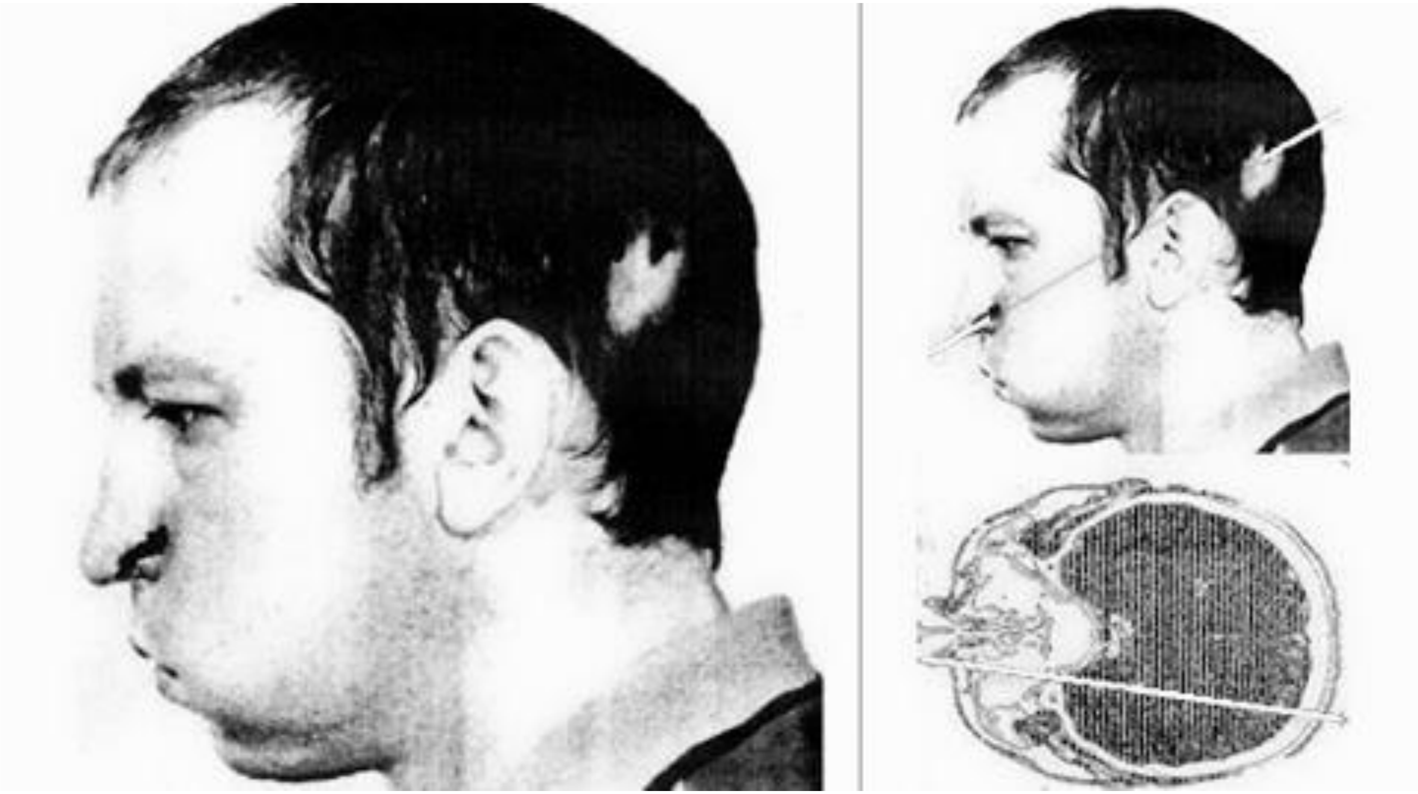
Longitudinal cut



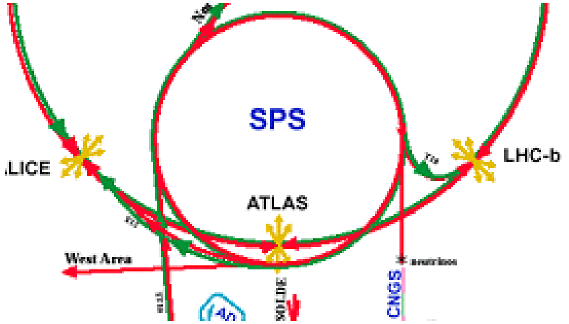


What happens if I put a hand in front of the beam?

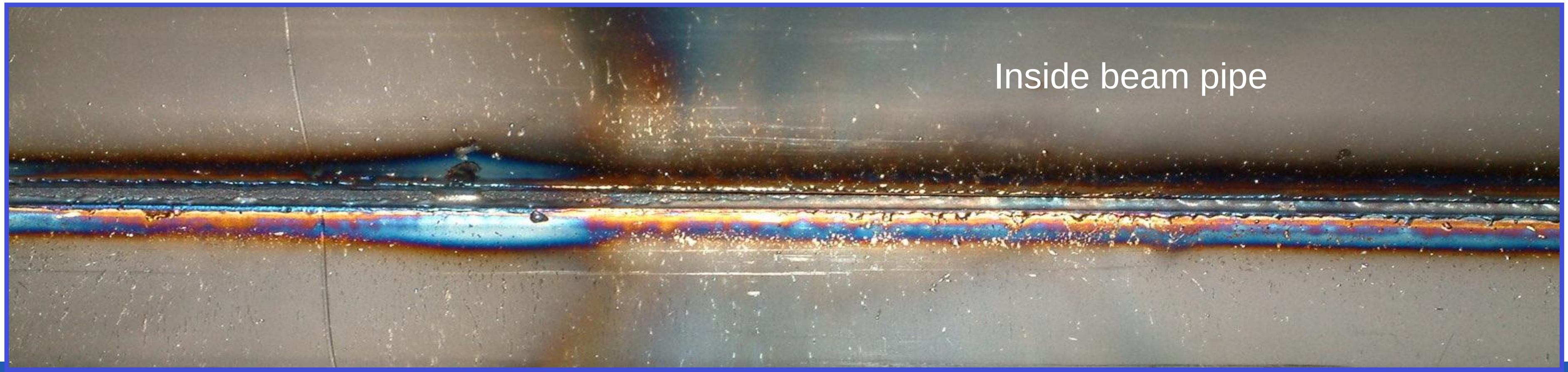
Anatoli Bugorski



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 σ)
1.15 x 10^{11} p+ per bunch, for total intensity of 3.3 x 10^{13} p+
Total beam energy is 2.4 MJ, lost in extraction test (LHC 334 MJ)

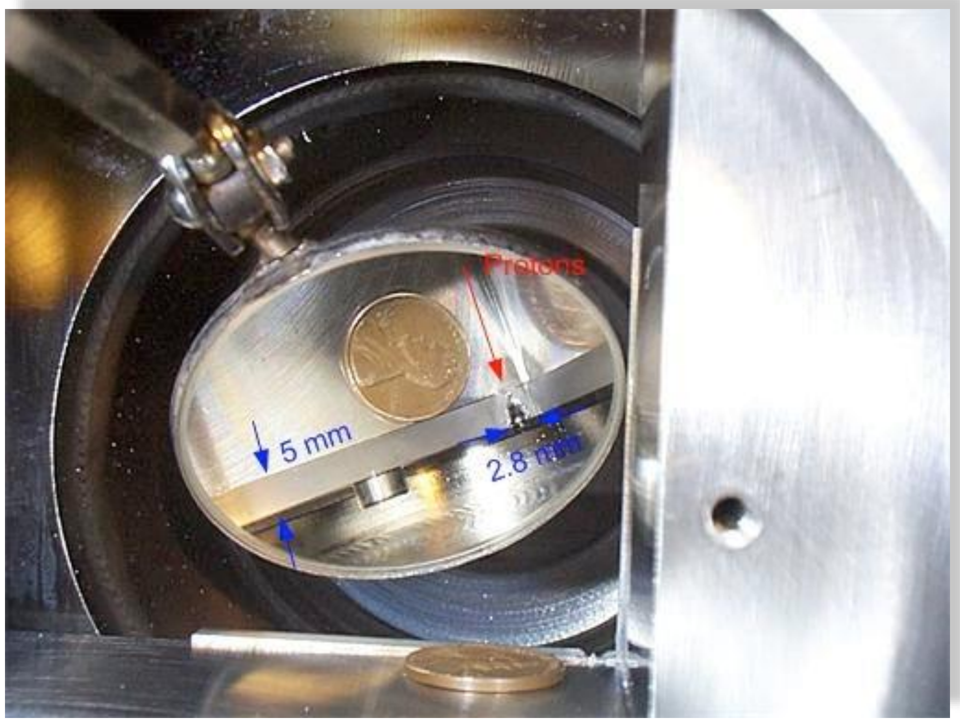


B.Goddard CERN AB/BT

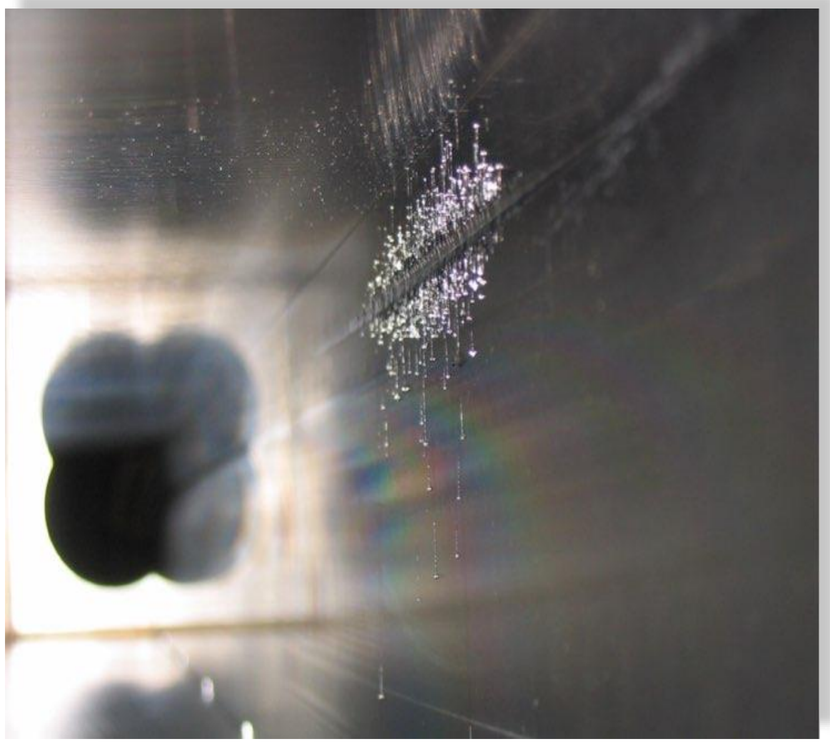
Tevatron accident in 2003 (courtesy of N. Mokhov)

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 ^{O}C



1.5 m long stainless steel collimator



Movable collimators, they have to be robust

Materials chosen:
Mtals where possible or C-C fibers

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

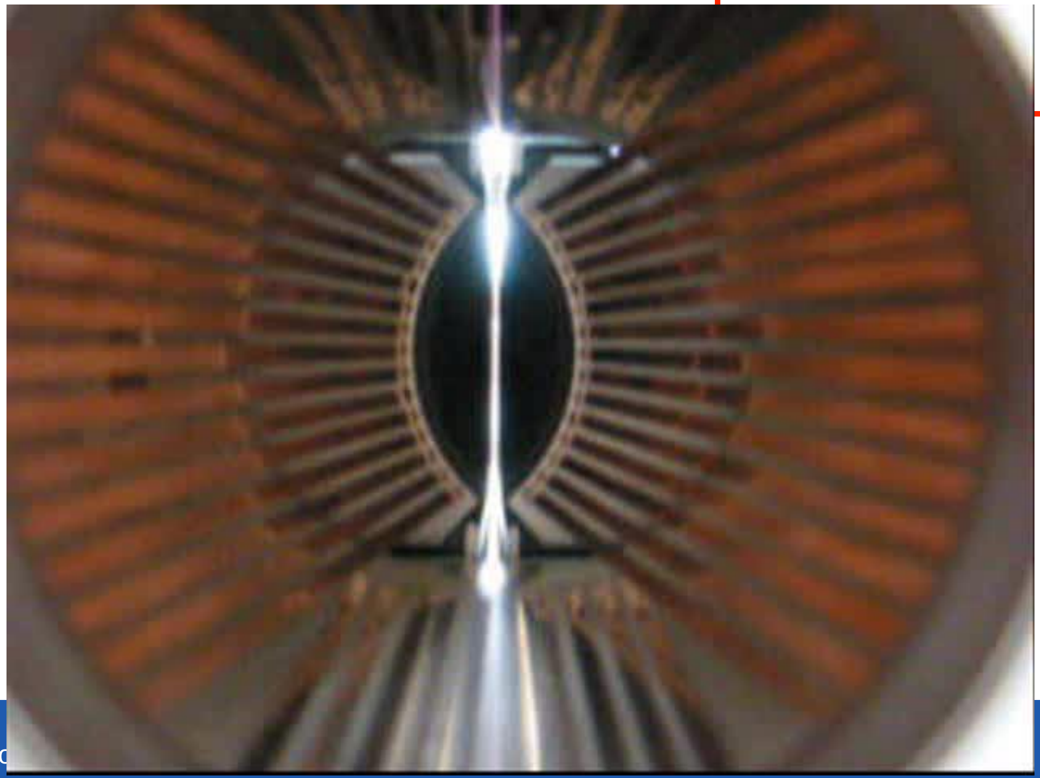
SPS experiment:

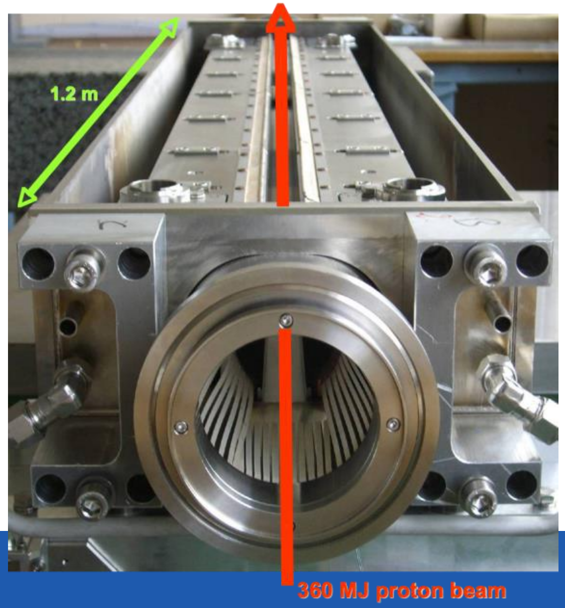
a) 1.5e13 protons, 450 GeV, 0.7*1.2 mm^2 (rms) on CC jaw

b) 3e13 protons , 450 GeV, 0.7*1.2 mm^2 (rms)
on CC jaw ⇒ full design CASE

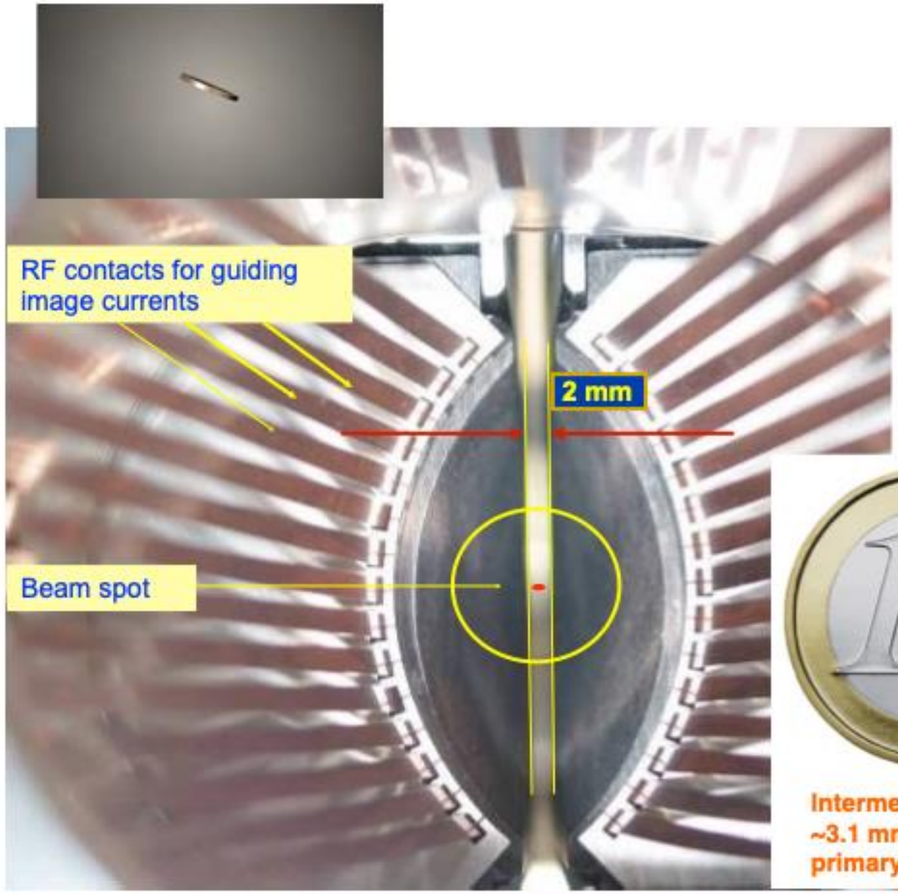
equivalent to about 1/2 kg of TNT

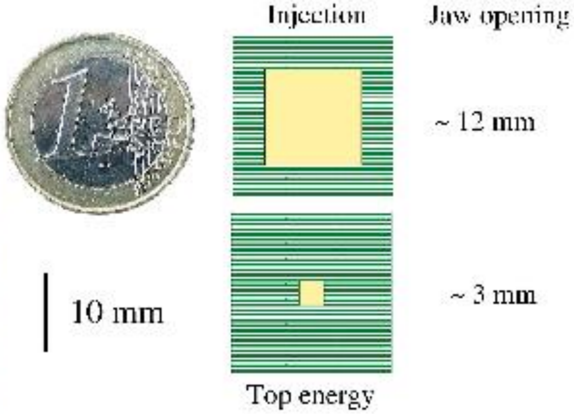
from S. Redaelli

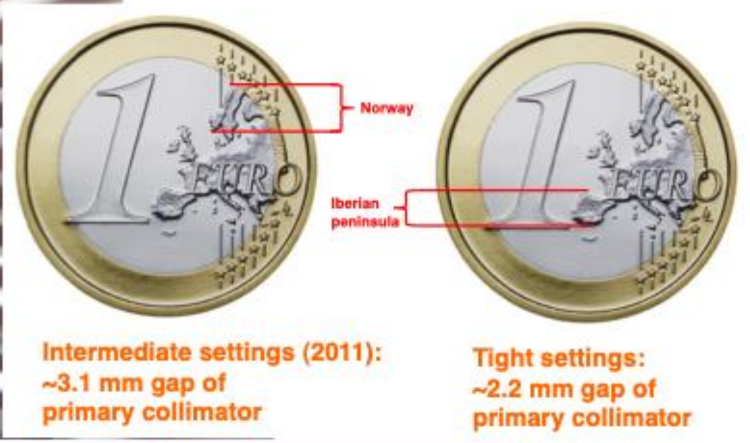


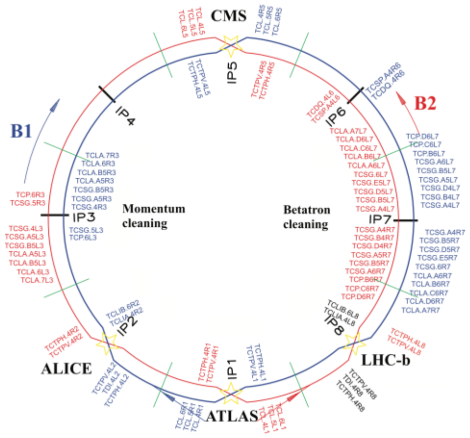


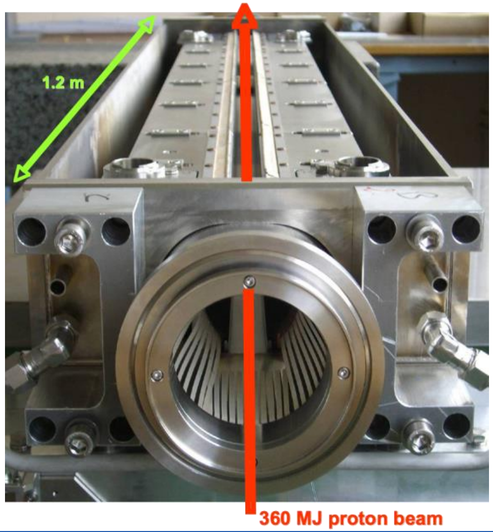
How to protect the LHC against the beam







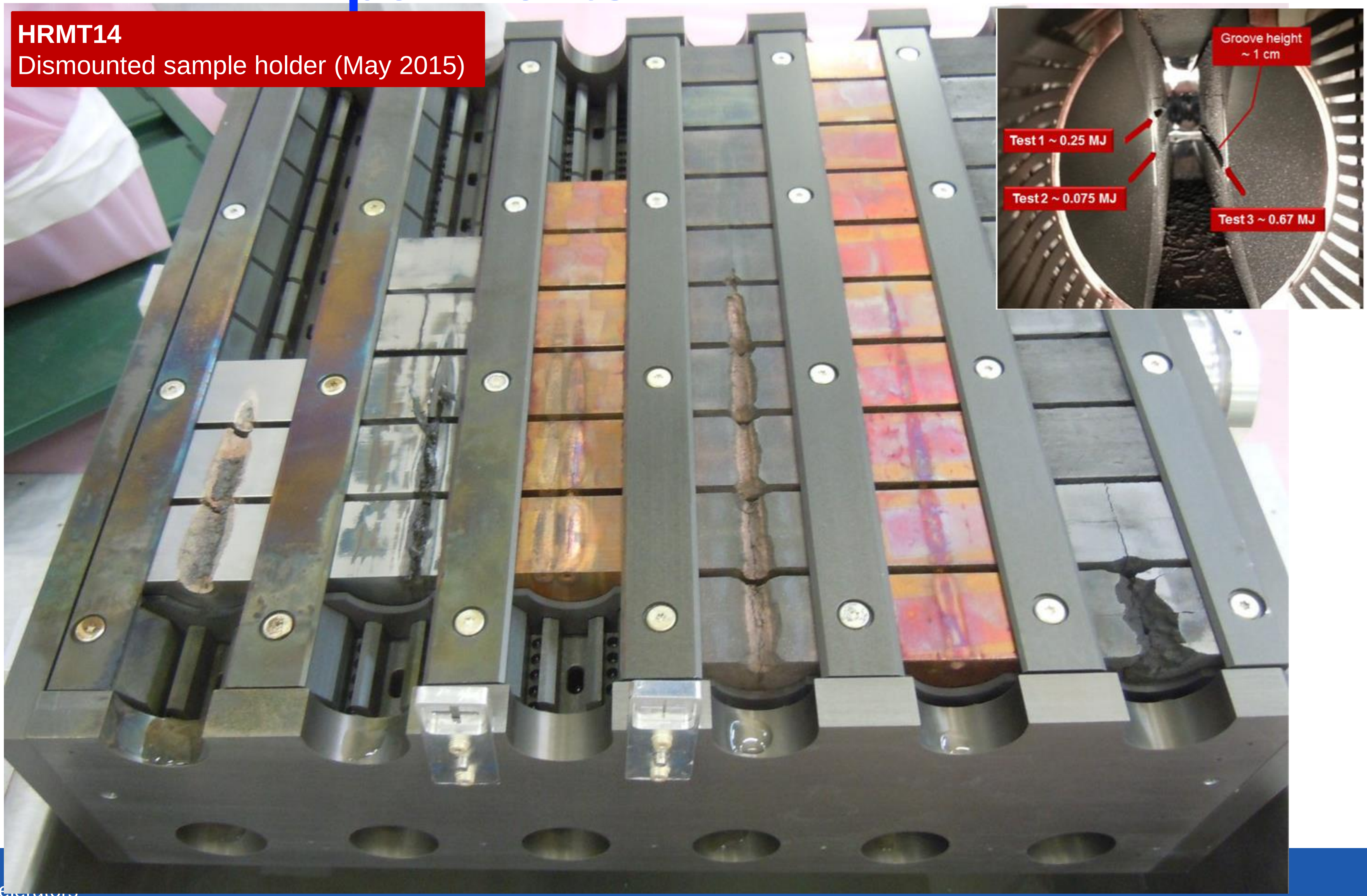




Precision required for collimator movements about 25 µm

Collimator animation 2013

Update on HRMT09 and HRMT14 Experiments



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First Results Overview – CuCD

Impacts on CuCD jaw.
48 b. σ 0.35 mm. Impact depth 0.5 σ

Needs for robotic solutions @ CERN

- **Operation and maintenance of radioactive objects**
  - ✓ Most of them are obsolete, without proper documentation and drawings, any intervention may lead to **surprises**
  - ✓ Risk of **contamination**

- **Inspection of hazardous and unstructured environments**

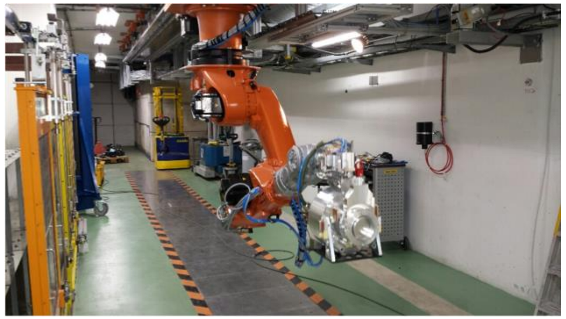
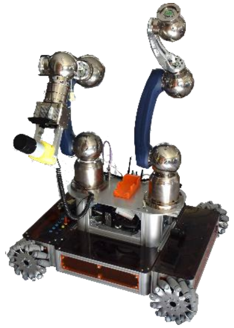
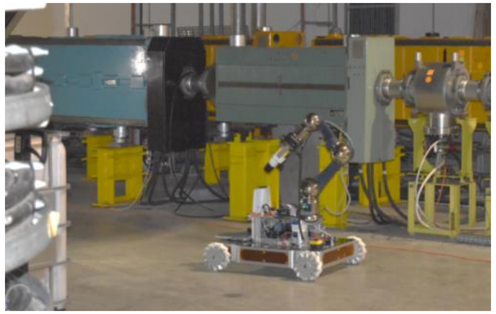
- **From an analysis of ALARA interventions, about 50% of the dose to personnel originated from very simple actions, such as visual inspections**

- **We decided therefore to use robots for those dose-costly operations**

Robotics Support at CERN

➢ **Robotic pool to support CERN accelerators**

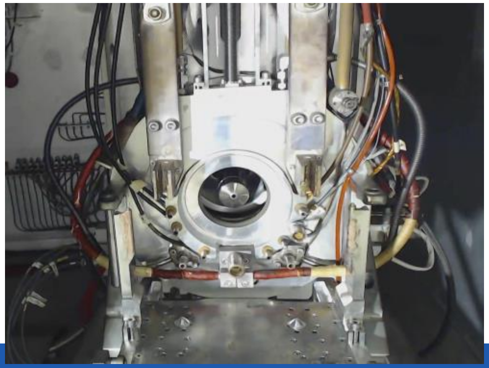
Autonomous navigation and inspection, Assisted Telemanipulation, Artificial intelligence Augmented reality, Haptic devices …



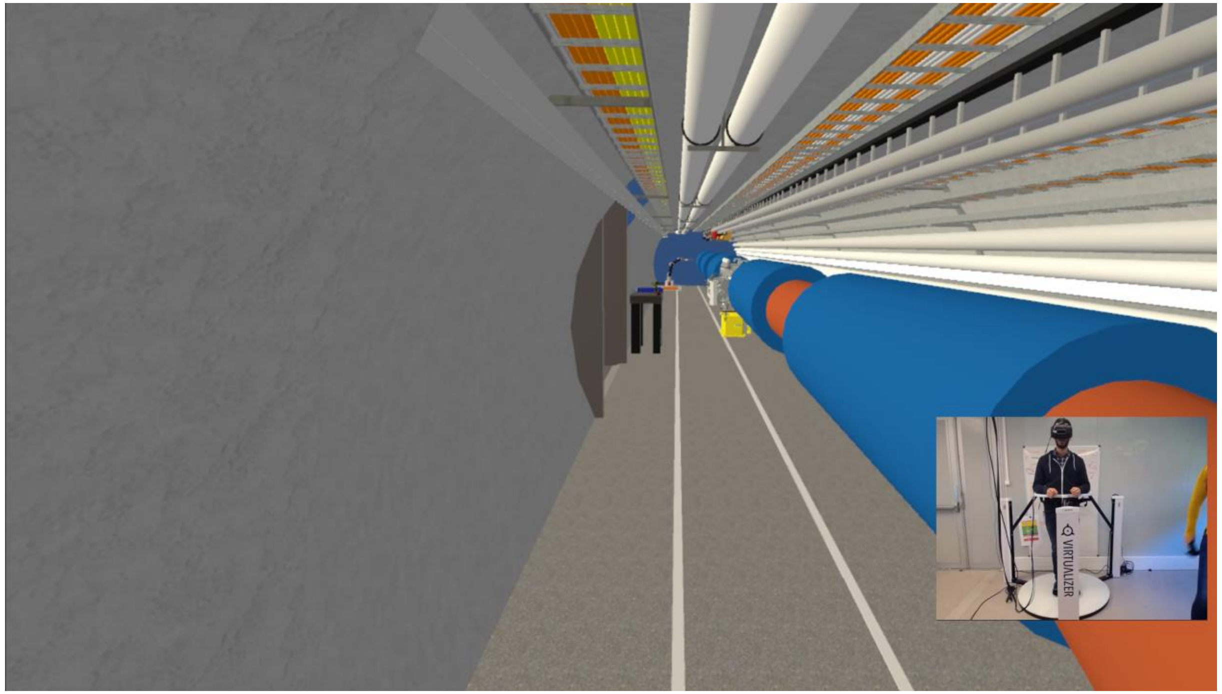






Human Intervention Simulation

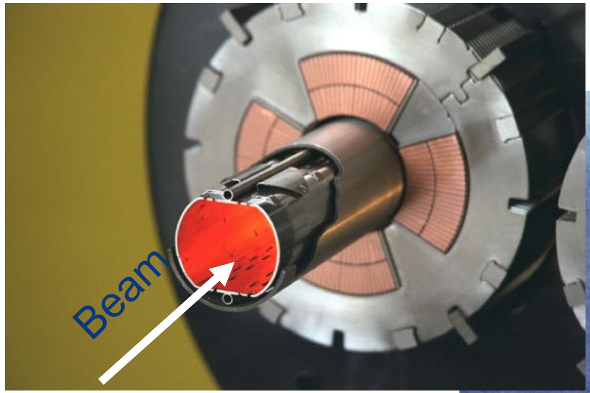
- Walking navigation in the environment using the treadmill
  - ✓ Very effective for navigation simulations
  - ✓ Custom algorithm for automatic floors detection

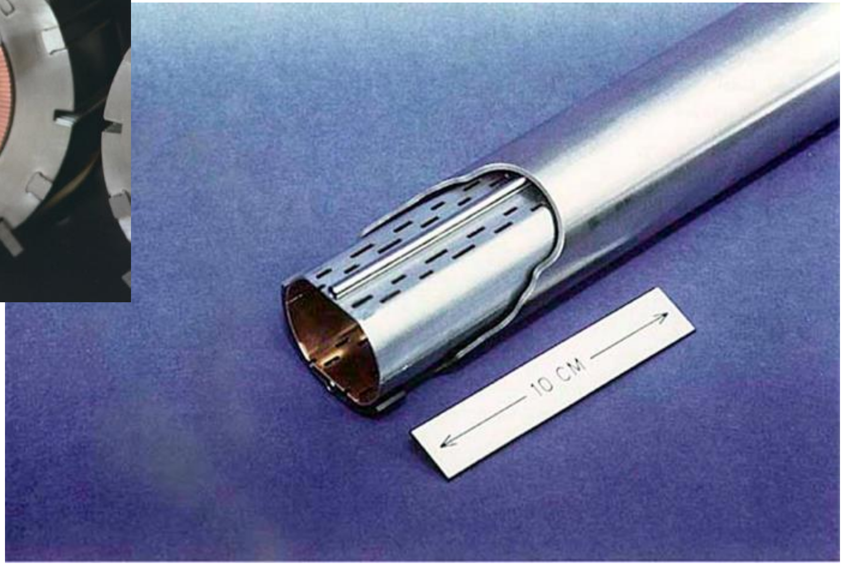


Robot as Partner to work alone in the tunnel

Real Time Vision Tracking System + Novel Slam → **The robot con follow autonomously a person avoiding obstacles**

LHC beam screen with cooling pipes





Beam screen to protect Superconducting magnets from Synchrotron radiation.

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

Vacuum required to avoid unwanted collision far from the IPs 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.

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 µm
- Give rise to loss events all around the LHC

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

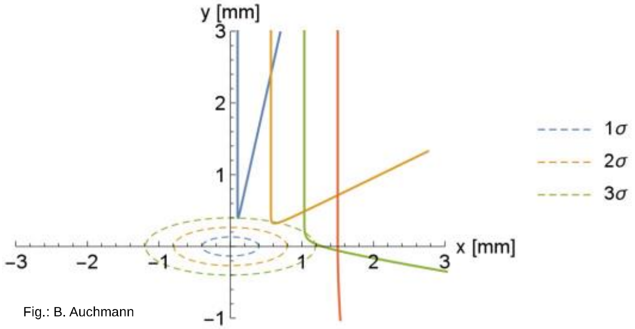
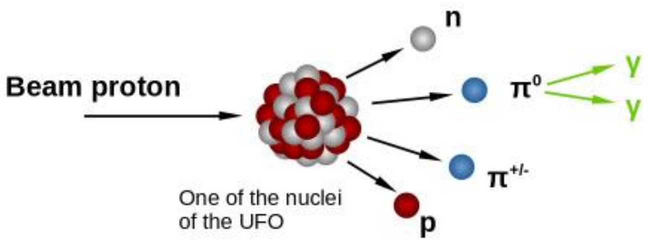


Fig.: B. Auchmann

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

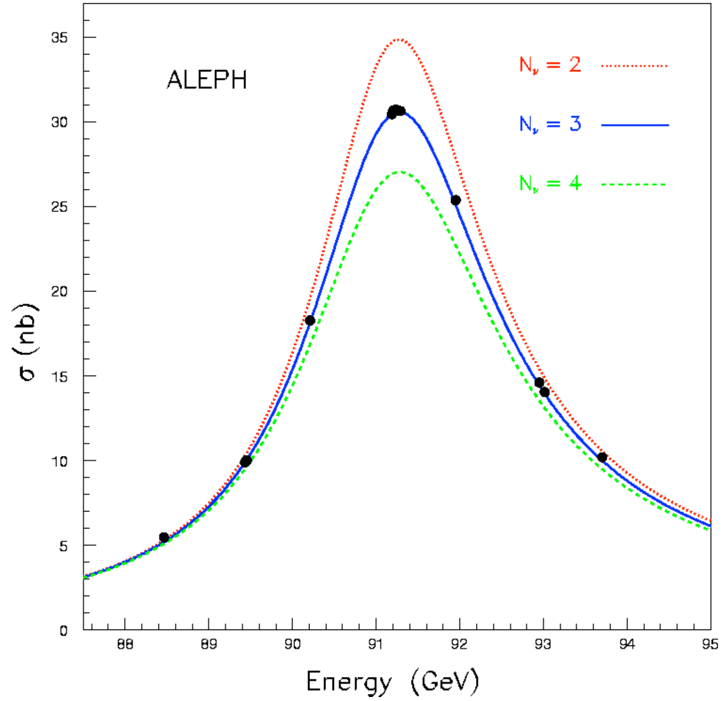
2 **Hadronic interactions:** inelastic nuclear collisions between protons and nuclei



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 ± 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?

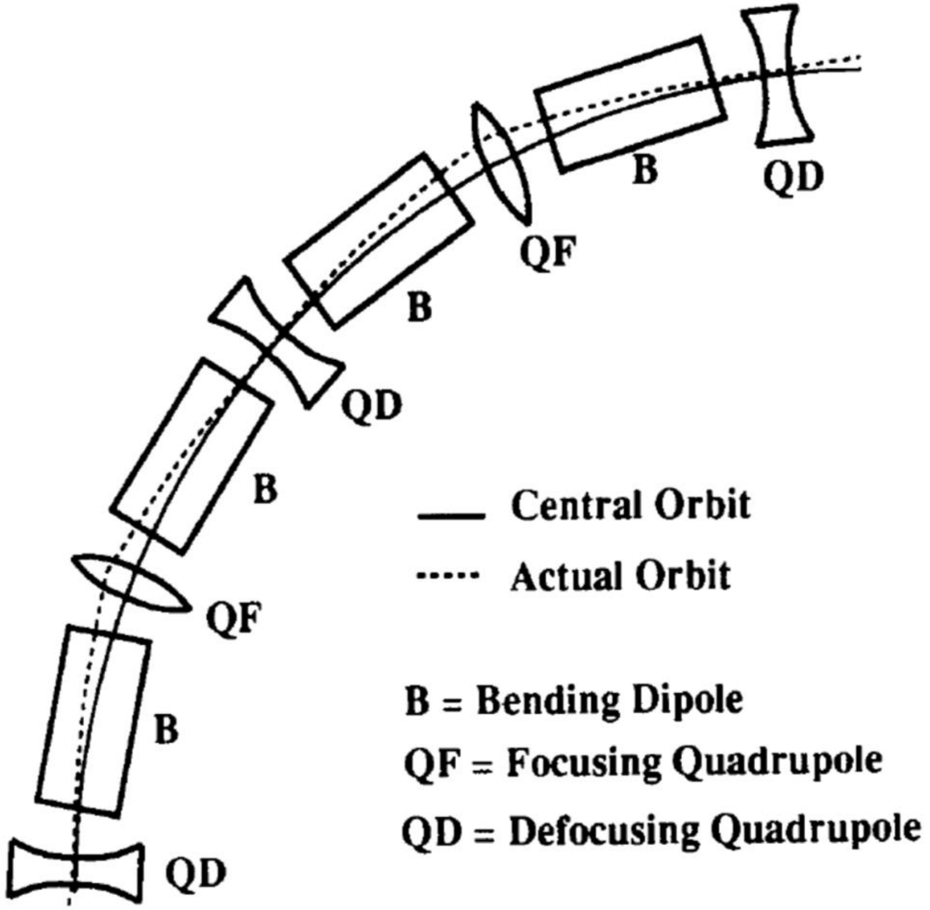
“Rappel”of strong focusing synchrotron optics

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.

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

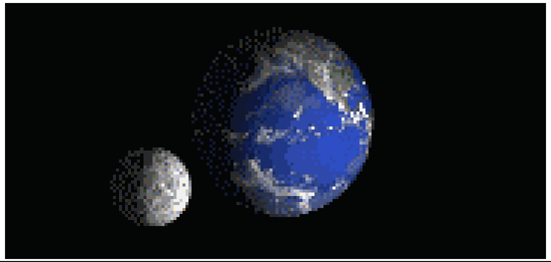
In LEP $\alpha = 1.86\ 10^{-4}$ a small variation the circumference induces a large variation in energy

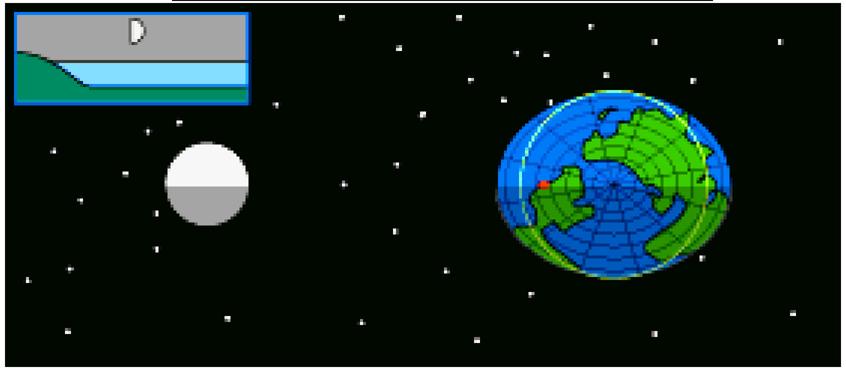
Moon tides can change earth geometry

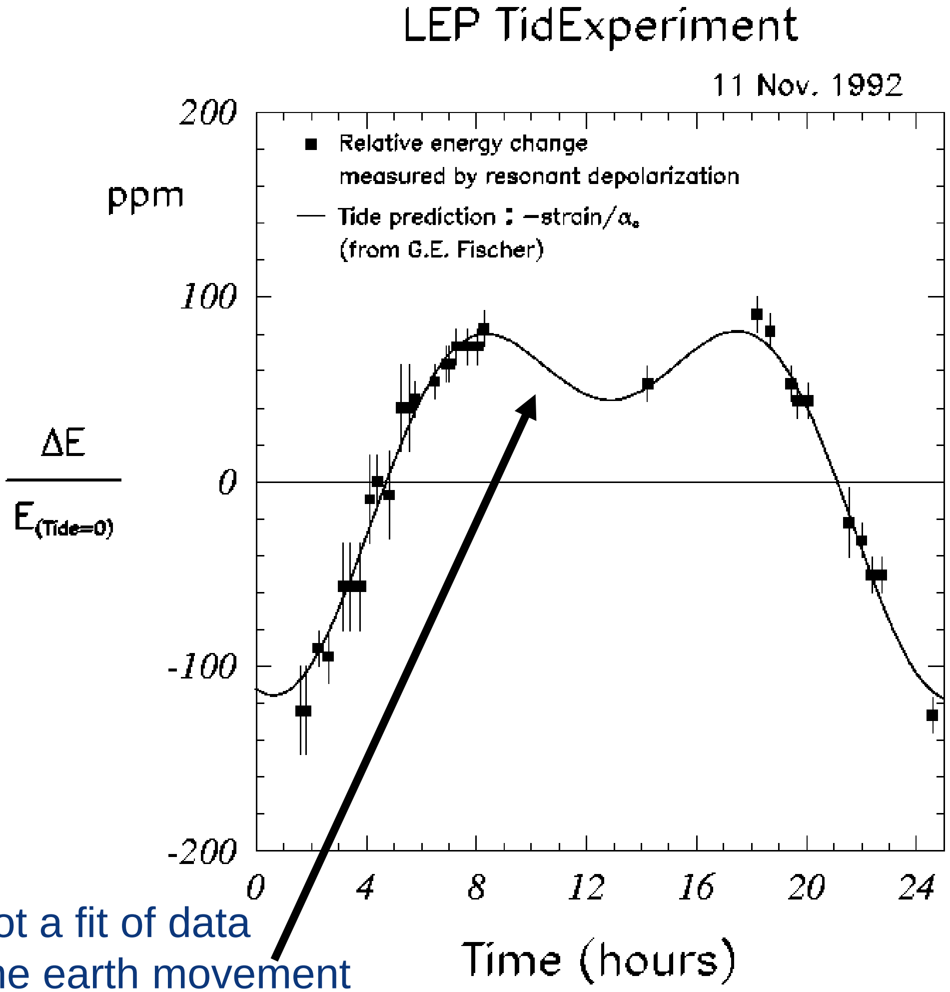
Moon induces a earth deformation similar to water tide.

Total deformation of the LEP about 4 mm
Energy variation of 100 ppm

The 12 h cycle is due to the earth deformation

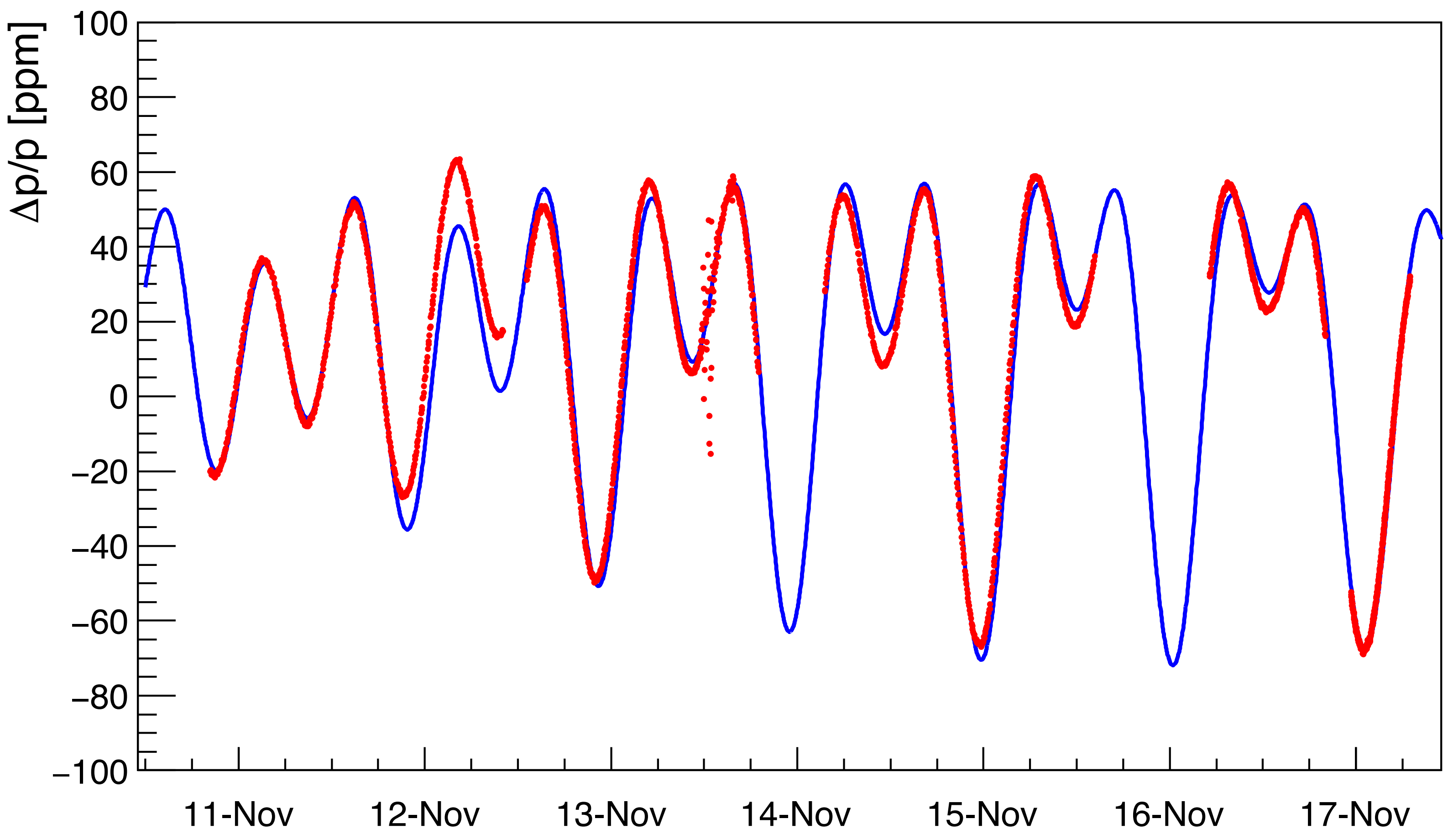






Continuous line is not a fit of data
but a prediction of the earth movement

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



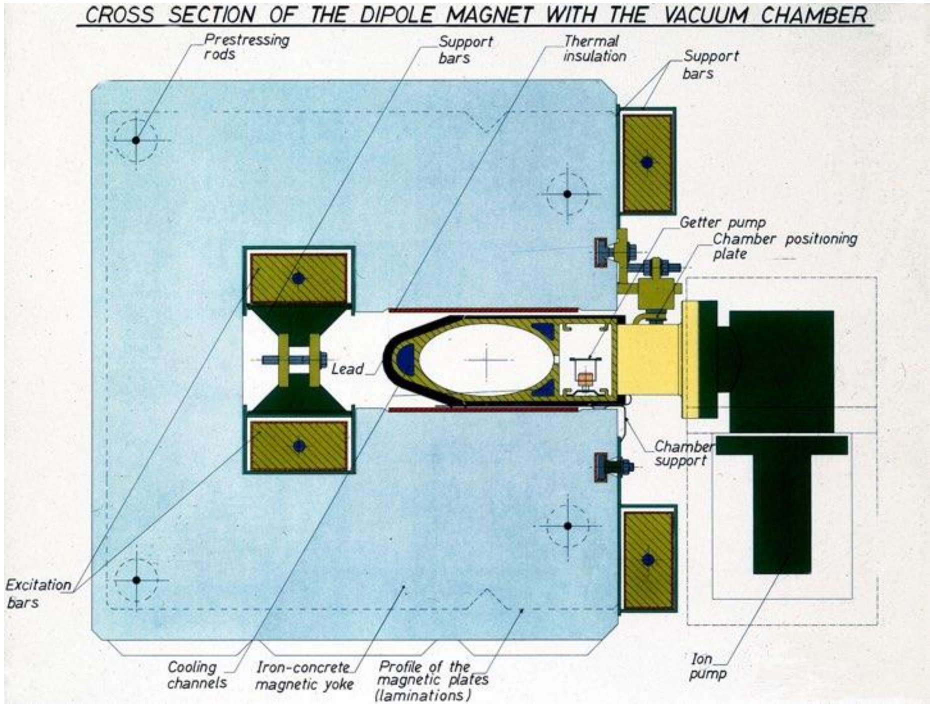
Predicted (blue line) and observed (red point) tidal energy variations of the LHC ring in November 2016 during long consecutive fills at 4 TeV/c spanning almost an entire week.

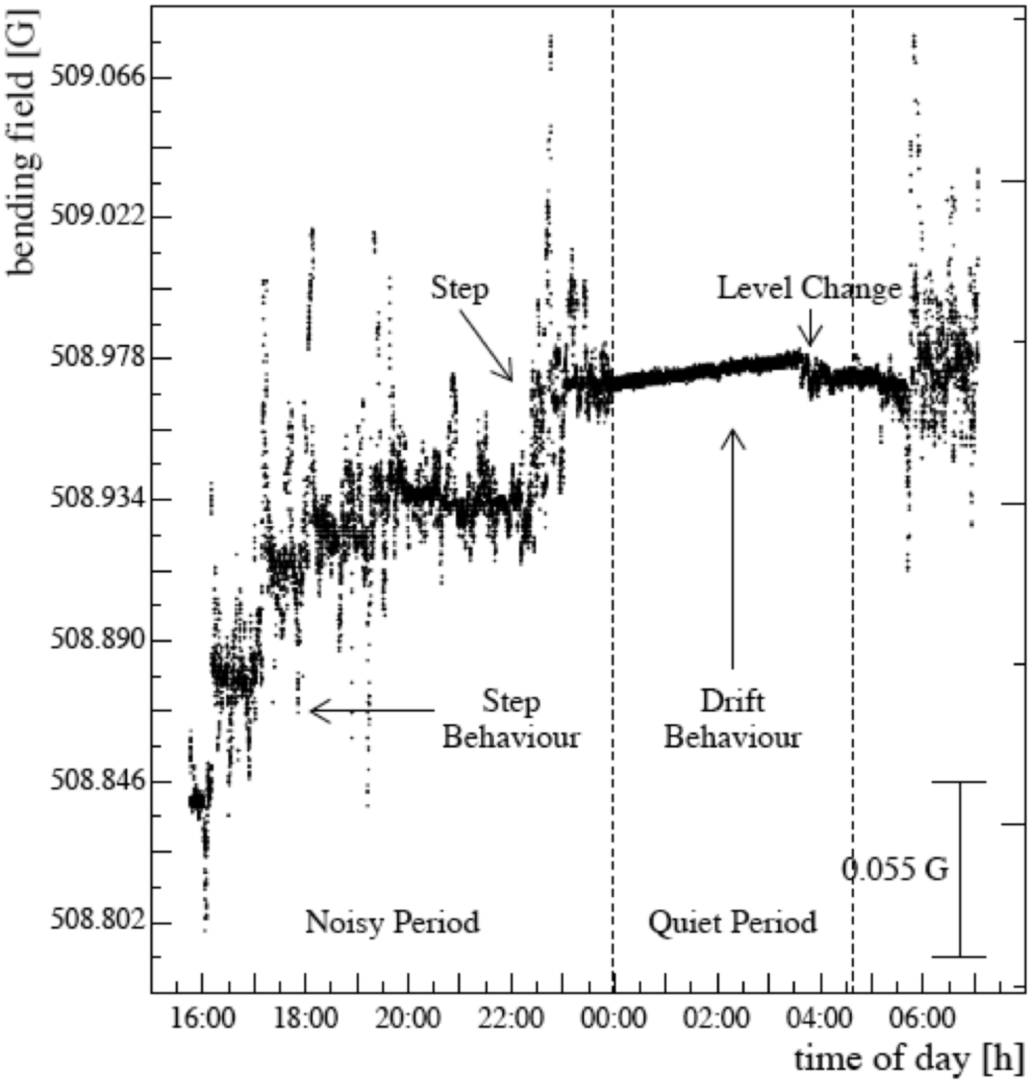
The outliers that can be observed around midday November 13th are radial oscillations of the ring induced by the surface waves from a magnitude 7.8 Earthquake in New-Zealand.

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

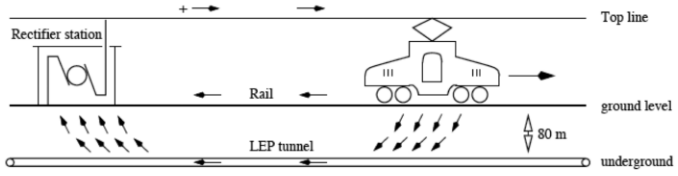
The problem: an accelerator is not in the middle of nothing

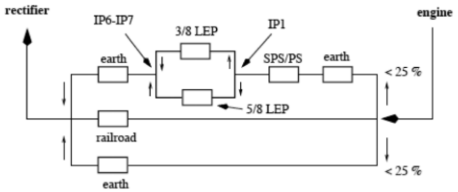
Observed variation of the bending strength of the LEP dipoles during the day

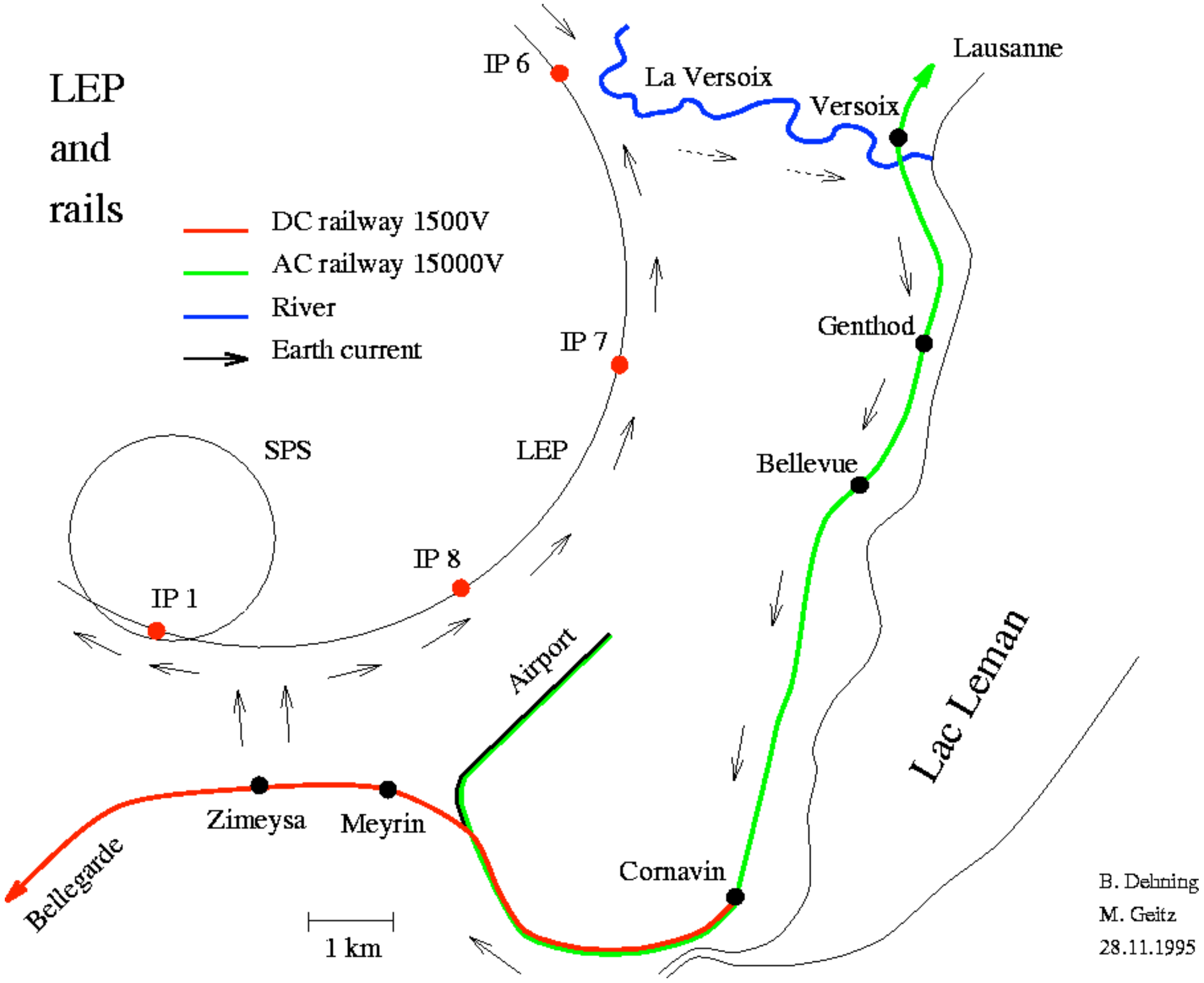




Influence of train leakage current



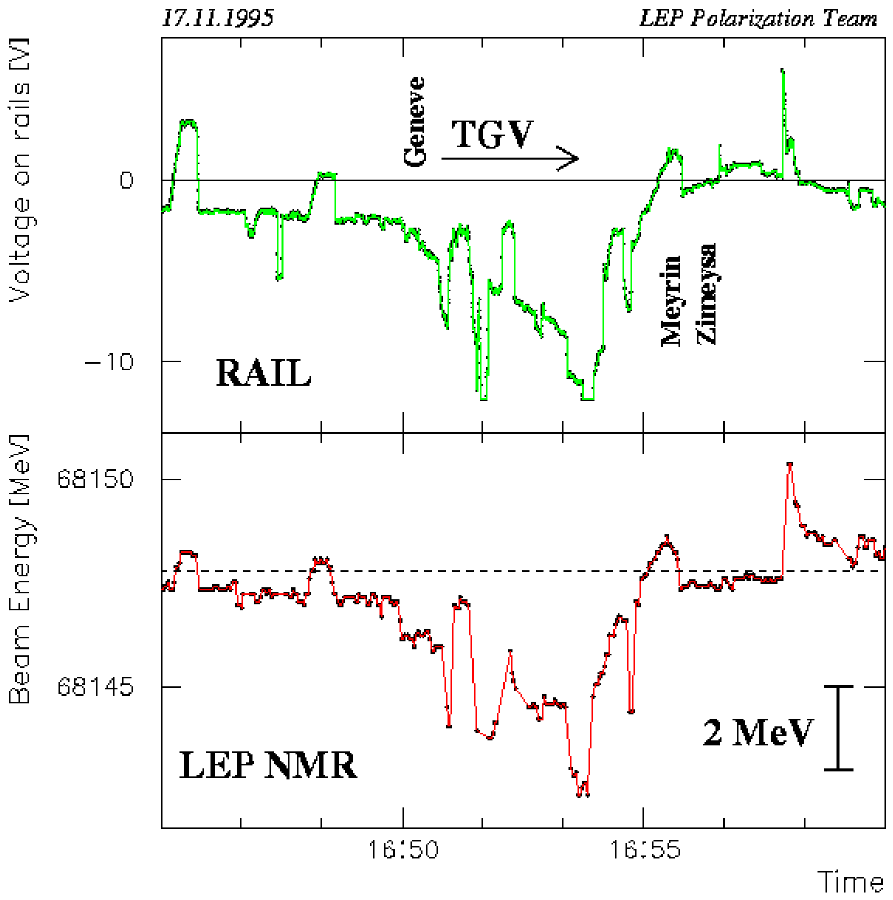




LEP beam pipe as ground for leakage current.
Variation of the dipole field due to the current .
Change in energy following the SNCF train table

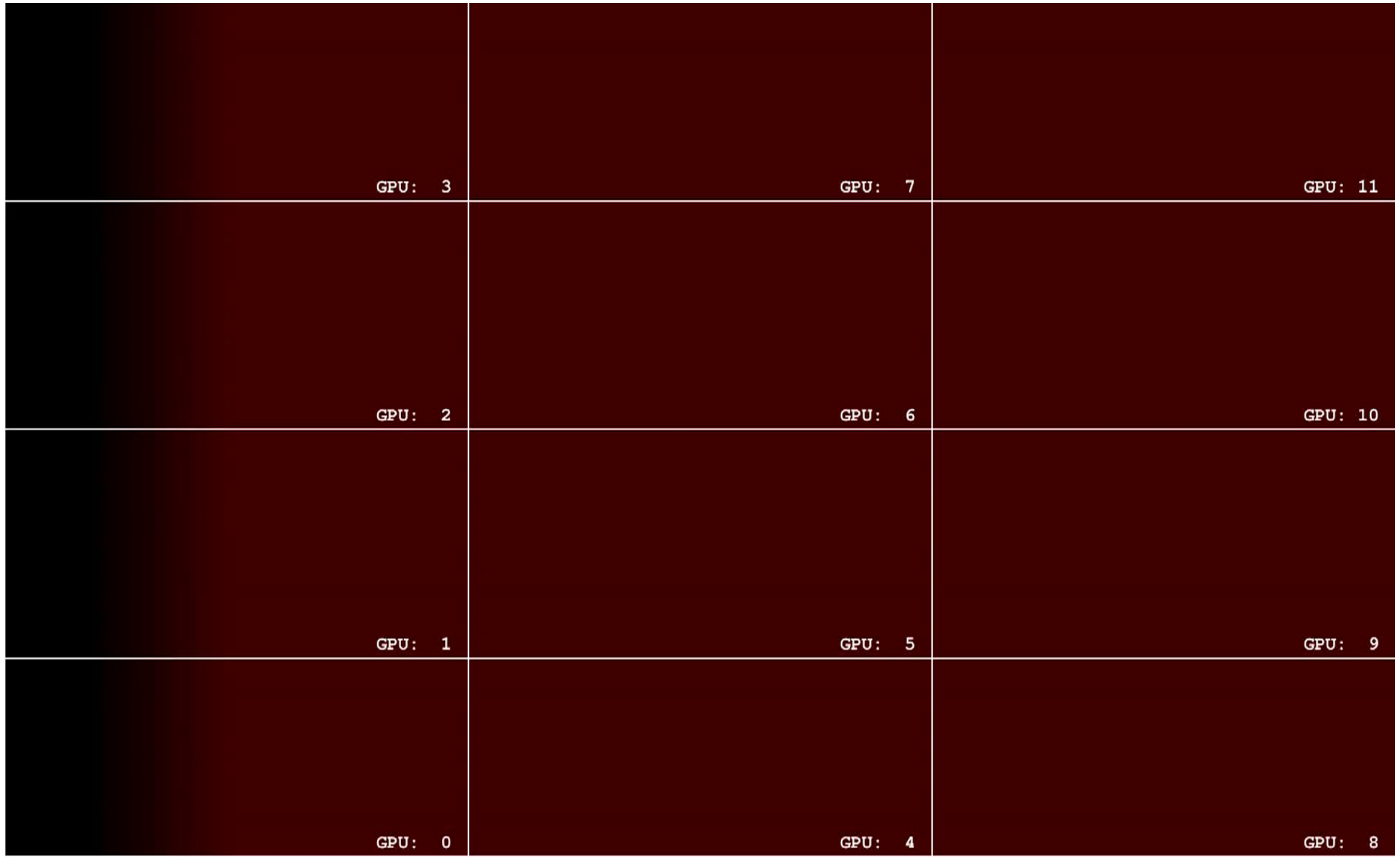
The evidence, TGV to Paris at 16:50 ...

Correlation between trains and LEP energy



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

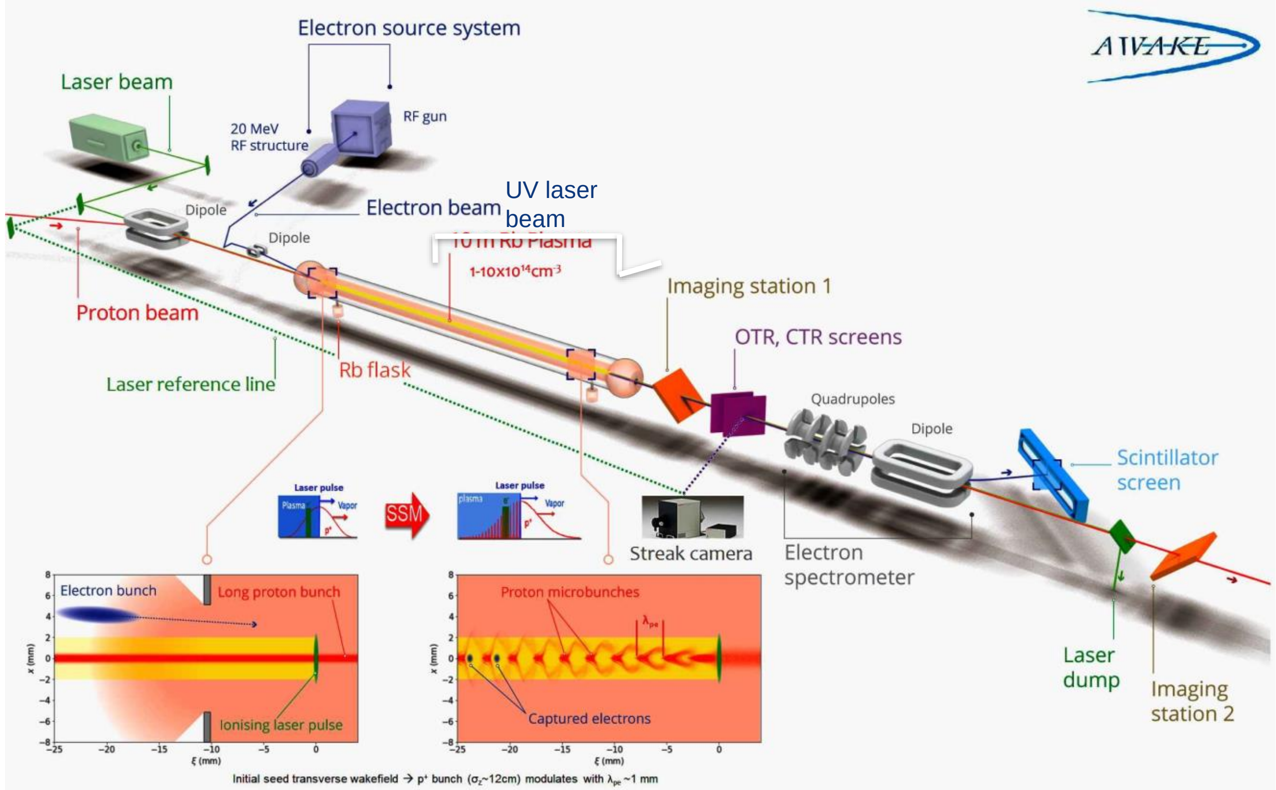
Laser plasma acceleration : few GeVs per meter ....

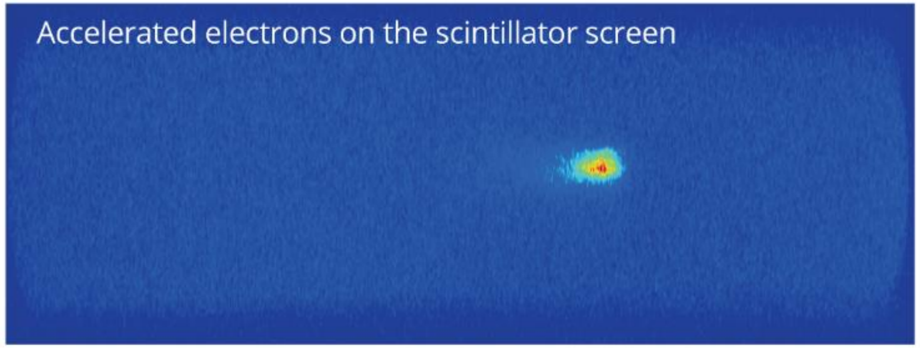


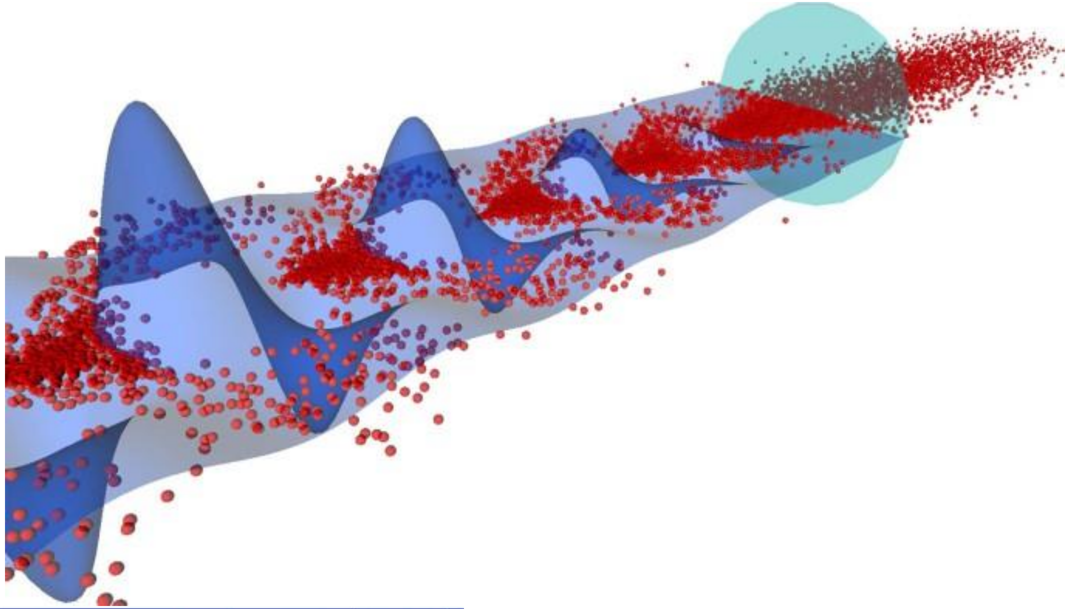
http://www.youtube.com/watch?v=MlNxgmPVF6U

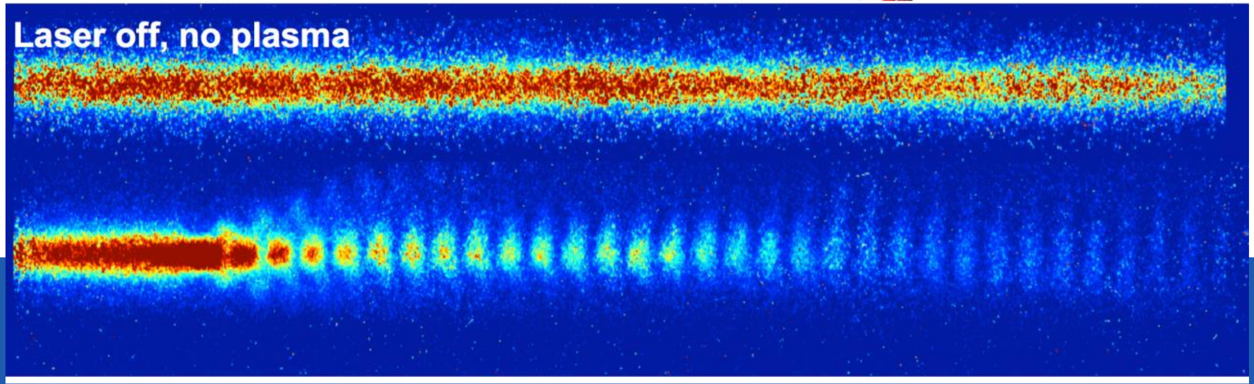
... that's not for tomorrow... yet...

Experiment on proton-driven plasma wake acceleration - AWAKE

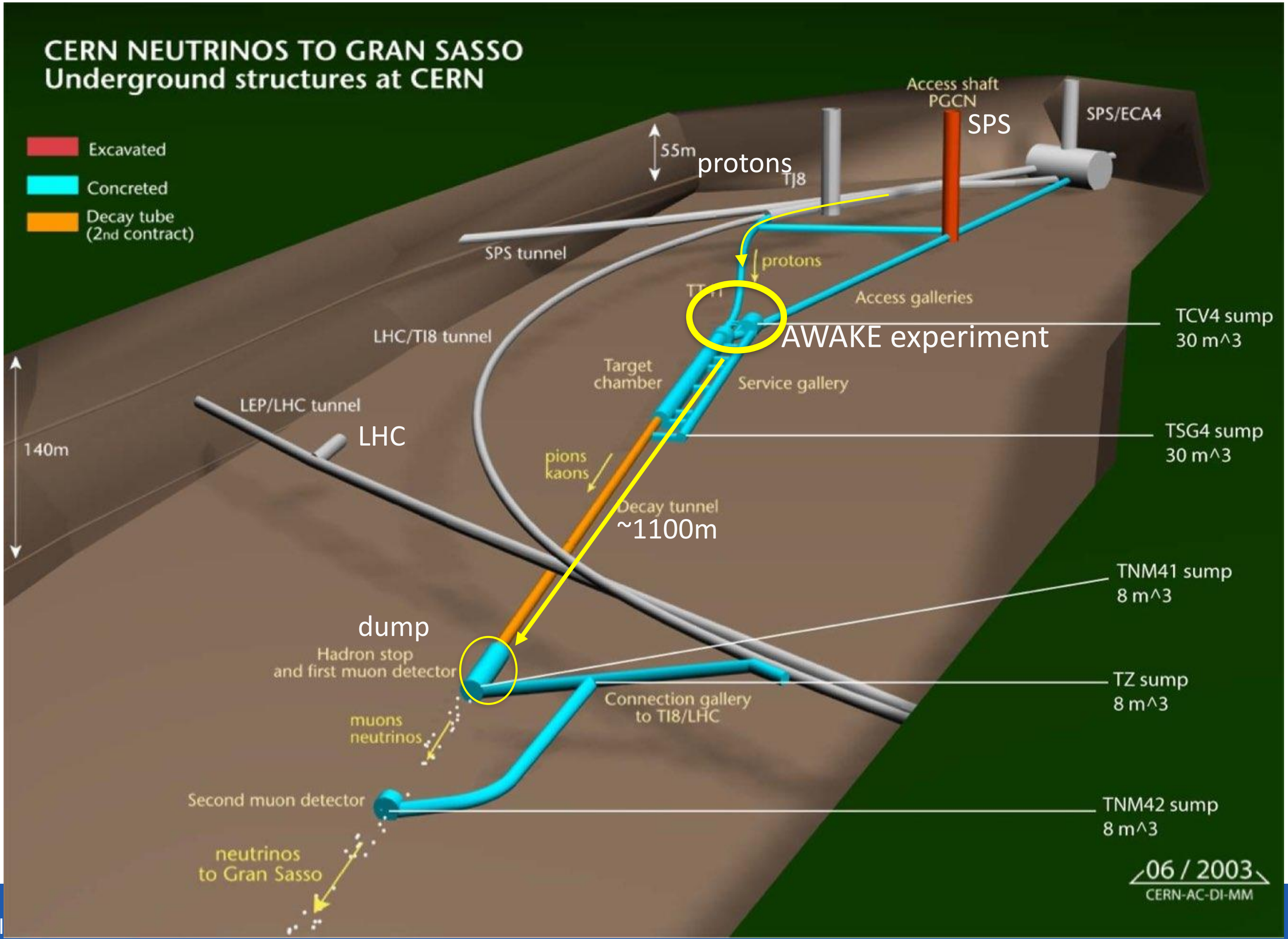








AWAKE at CERN



Thanks for your attention!!!