The LHC - Accelerator Aspects (a crash course in accelerators ?)

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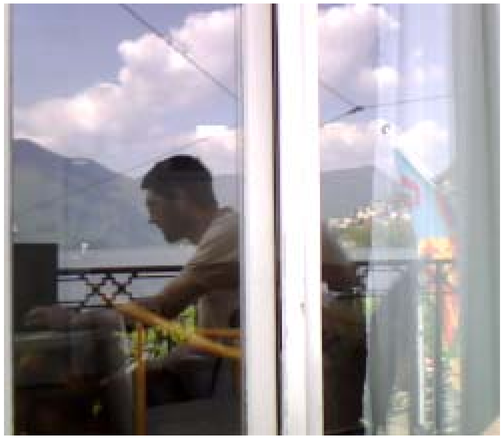


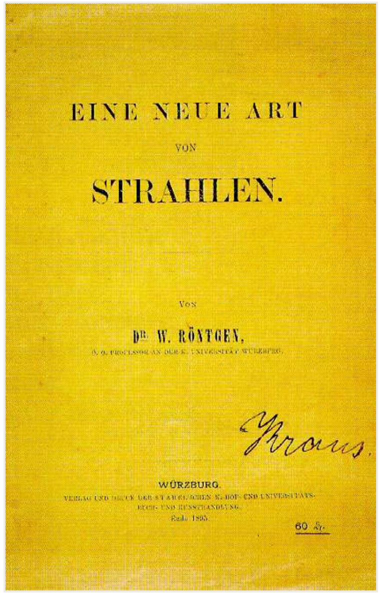
Overview

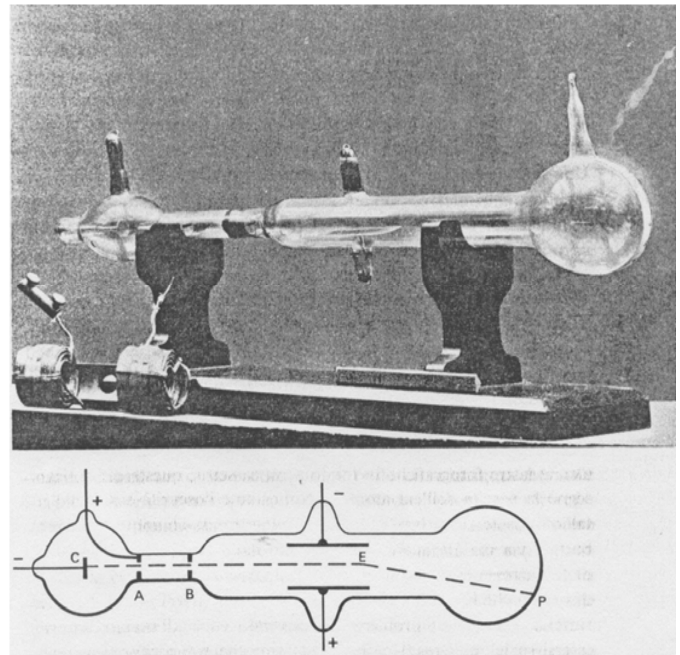
- L H C
- Accelerator elements
- What makes the LHC special
- LHC commissioning and plans

The beginning…

1895 discovery of X rays

Wilhelm Conrad
Röntgen





An accelerator
Cathode rays

J.J. Thomson 1897:
the electron

Accelerators running in the world

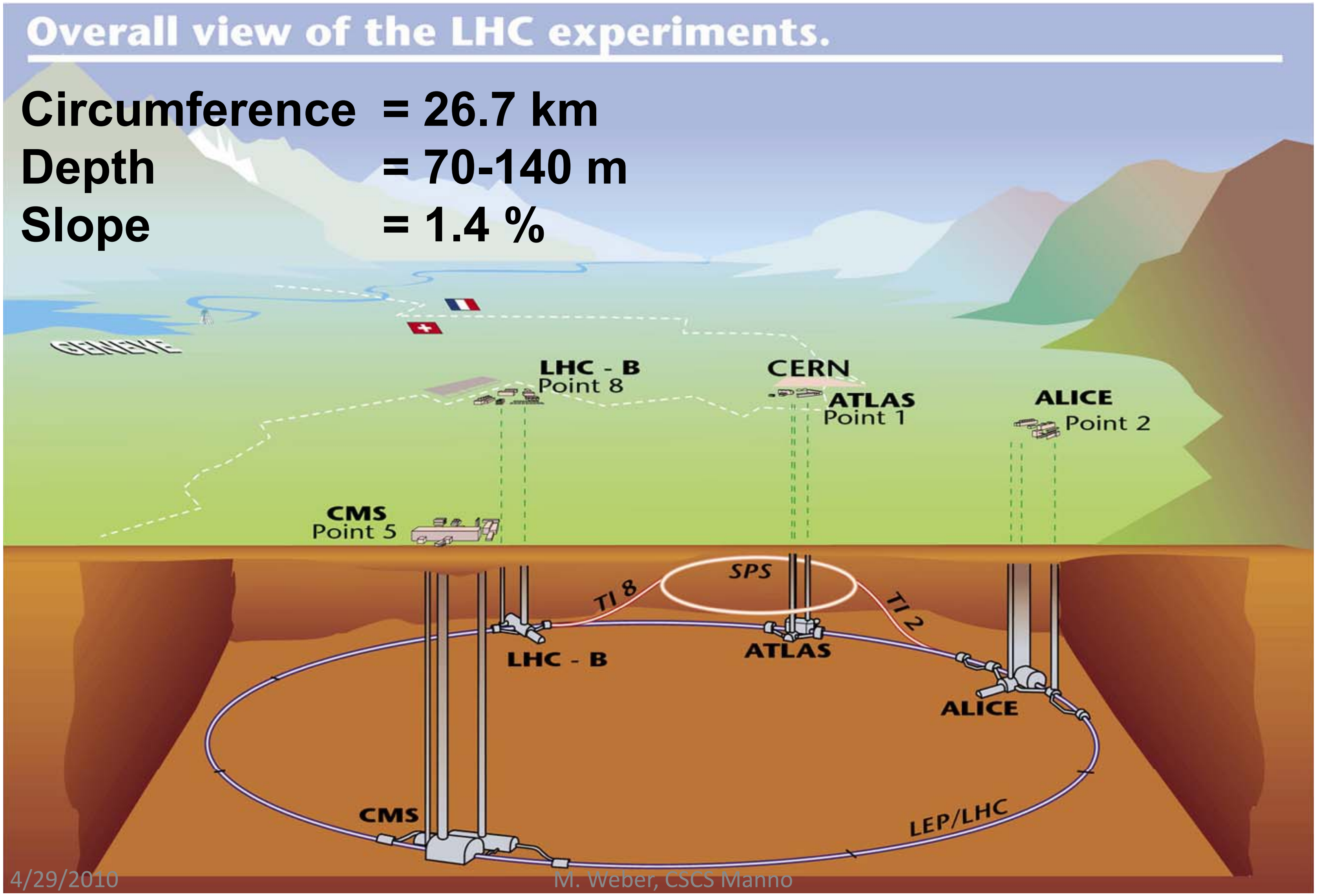
CATEGORY OF ACCELERATORS	NUMBER IN USE (*)
High Energy acc. (E >1GeV)	~120
Synchrotron radiation sources	>100
Medical radioisotope production	~200
Radiotherapy accelerators	> 7500
Research acc. included biomedical research	~1000
Acc. for industrial processing and research	~1500
Ion implanters, surface modification	>7000
TOTAL	**> 17500**

9000 (Medical radioisotope production + Radiotherapy accelerators + Research acc. included biomedical research)

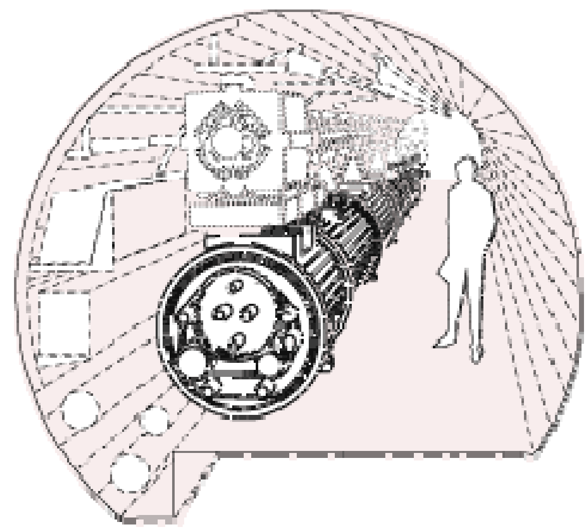
(*) W. Maciszewski and W. Scharf: Int. J. of Radiation Oncology, 2004

About half are used for bio-medical applications

LHC layout – above and below ground



LHC timeline



1984: Project start in Lausanne

1989: First experiment ideas / collaborations

1994: Approval by CERN council

1996: CMS and ATLAS are approved

1998: Civil engineering work for ATLAS and CMS start
Successful prototype dipole magnet test
LHCb is approved

2000: Dismantling of LEP starts

2001: European Data Grid is launched
LHC computing Grid is approved

2004: Transfer line SPS to LHC tested

2005: First dipole lowered into LHC tunnel
LHC computing grid becomes the largest scientific computing grid

2006: CERN Central Control room starts operation

2007: Last dipole is lowered to the LHC tunnel, all interconnects finished

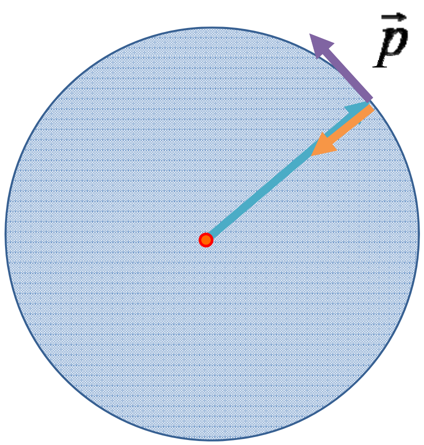
2008: The LHC is complete

Why **Large** ?

$$E^2 = m^2c^4 + p^2c^2$$

- The size of an accelerator is related to the maximum momentum/energy obtainable
- The radius of the machine and the strength of the dipole magnetic field that keeps particles in their orbits.
- For the LHC the radius is fix, it uses the 27 km circumference tunnel that was built for the previous big accelerator, LEP

$$BR = \frac{p}{e}$$



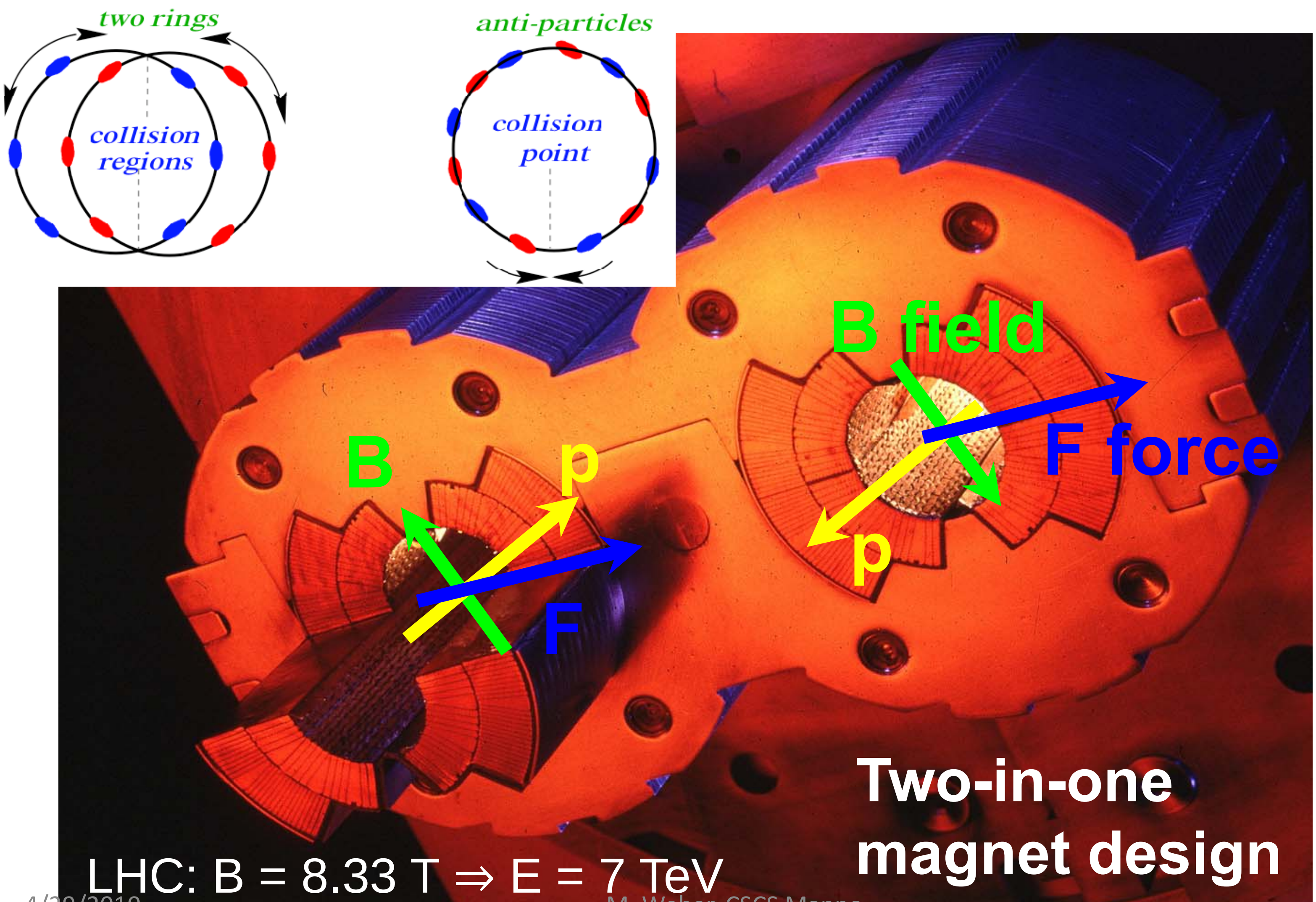
$$F = evB = \frac{mv^2}{R}$$

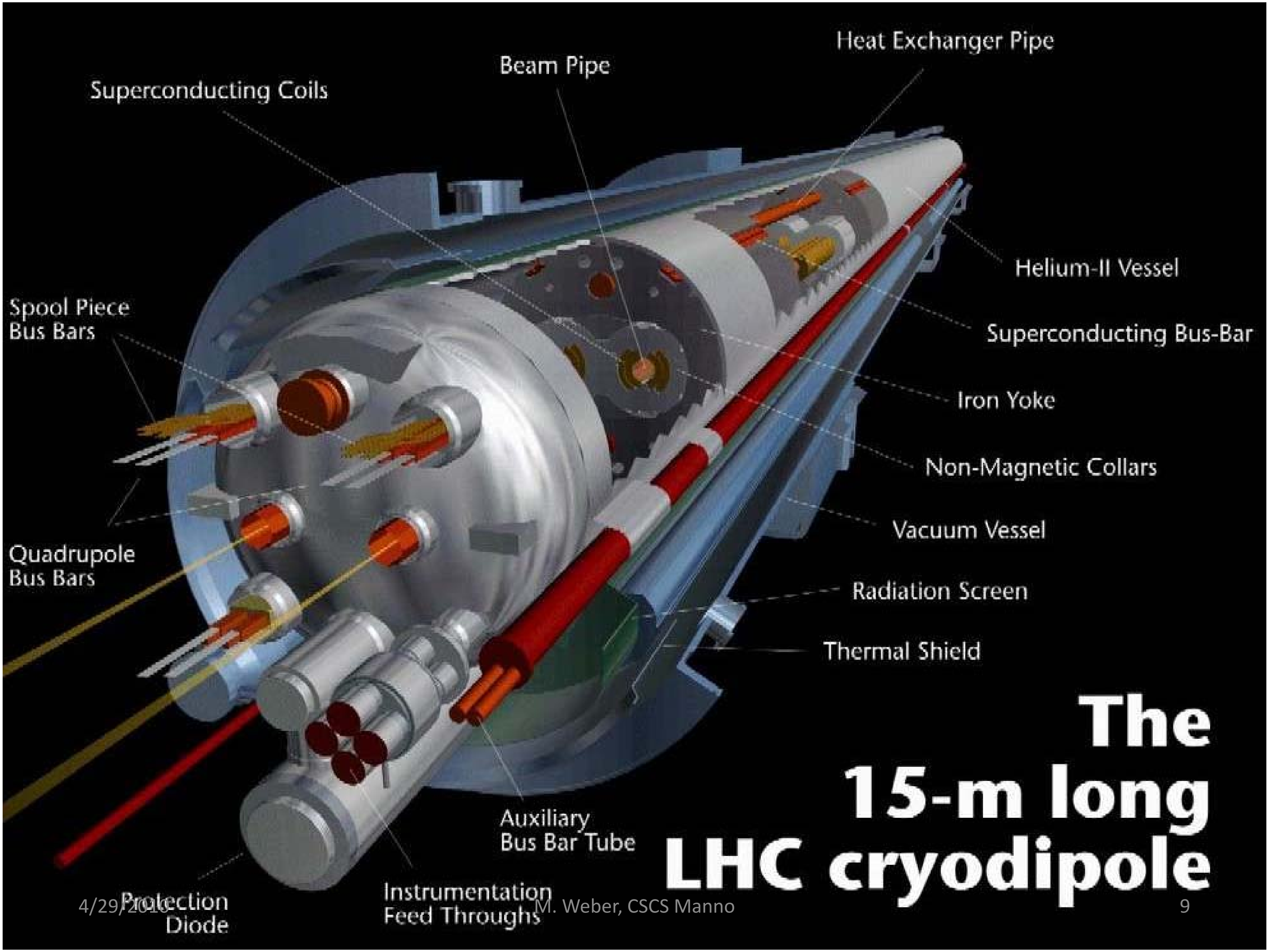
Large momentum:

Strong magnets

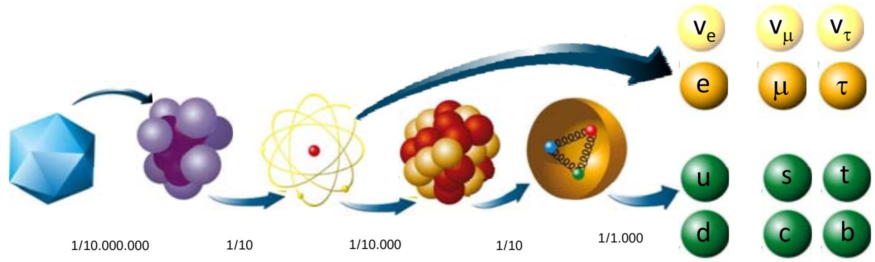
Large Radius

Magnets


two rings
collision regions
anti-particles
collision point
B field
F force
B
p
F
p
Two-in-one magnet design
LHC: B = 8.33 T ⇒ E = 7 TeV


Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole
Bus Bars
Radiation Screen
Thermal Shield
The
15-m long
LHC cryodipole
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs

Why **Hadron** ?



- *What is a "hadron" ?*
  Hadrons (from the Greek 'adros' meaning 'bulky') are particles composed of quarks (like protons and neutrons that make atomic nuclei)
- **Protons** (which are hadrons) are arbout 2000 times **more massive** than electrons and loose much less energy per turn through synchrotron radiation.
- Hadrons are **composite** particles. In the collisions the partons (quarks) collide with varying energy fraction. This allows for a broader discovery band in energy.

Why **collider** ?

- When two beams collide, the energy available (for example to produce new particles) is the sum of the energies of the two beams

$$E = E_{\text{beam 1}} + E_{\text{beam 2}}$$

- A beam of the same energy that hits a fixed target would produce a collision of much less energy

$$E \propto \sqrt{E_{\text{beam}}}$$

Why **accelerator** ?

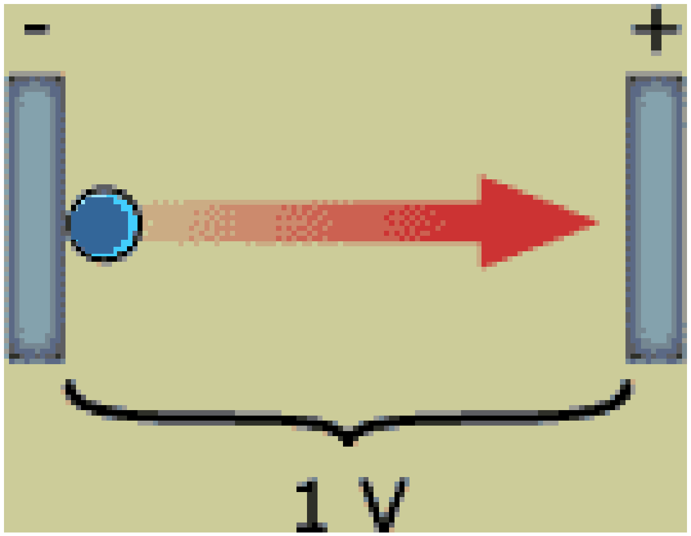
- Well… it isn't really… this is historic
- The LHC is more an "energizer"

Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC

Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c^2

- No particle can move faster than the speed of light in vacuum
- Protons are injected into the LHC at 99.999783 % of the speed of light and "accelerated" to 99.999996 % of the speed of light
- The Energy goes from 450 GeV to 3500 GeV

Electrostatic acceleration



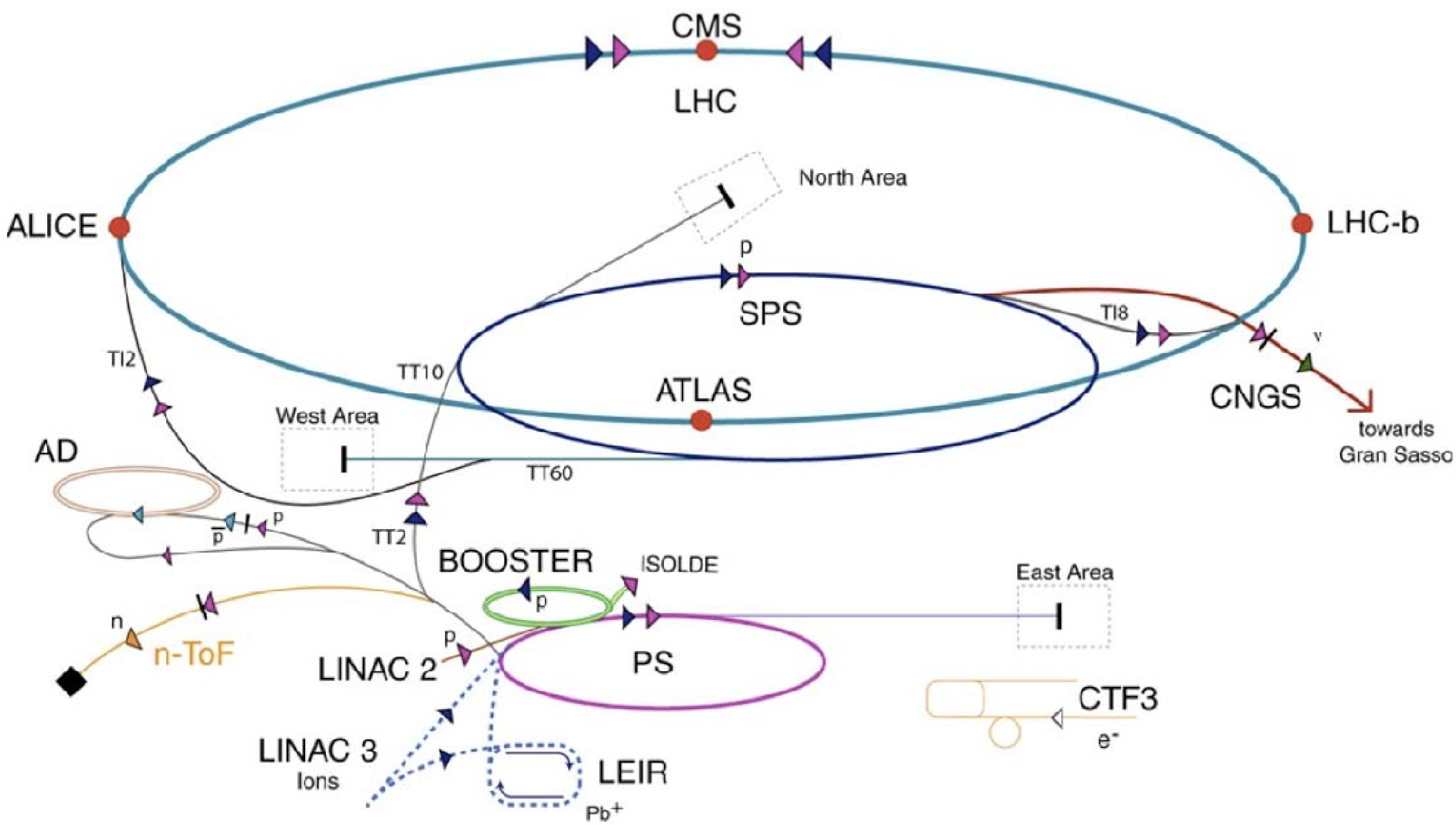
$$eV = E_{kin}$$

$$F = eE = e\frac{V}{d}$$

$$Fd = E_{kin} = eV$$

- 1 eV : kinetic energy gained by a unit charged particle after passing an electrostatic potential of one volt
- 1 eV = 1.6 x 10-19 J [Joule]
- 1 V -> 1 eV
- 1 TeV = 1‘000‘000‘000‘000 eV -> 1‘000‘000‘000‘000 V

CERN accelerator complex



protons
ions
neutrons

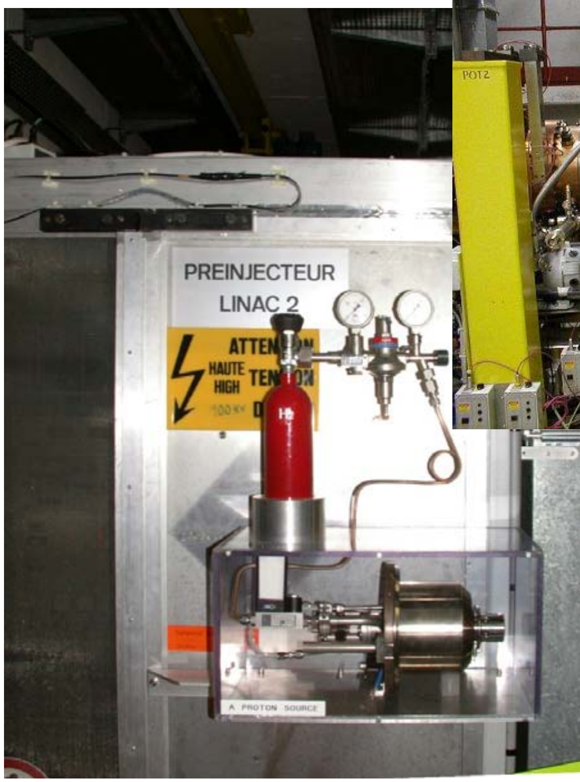
antiprotons
electrons
neutrinos

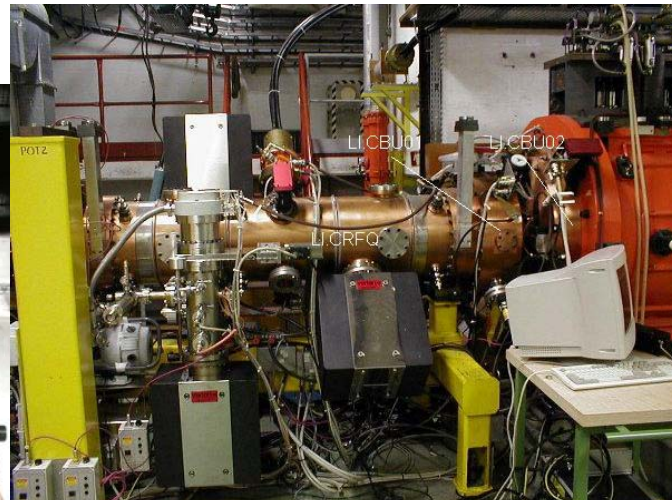
AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS CERN Neutrinos Gran Sasso

CTF3 CLIC Test Facility 3

Linear accelerators at CERN





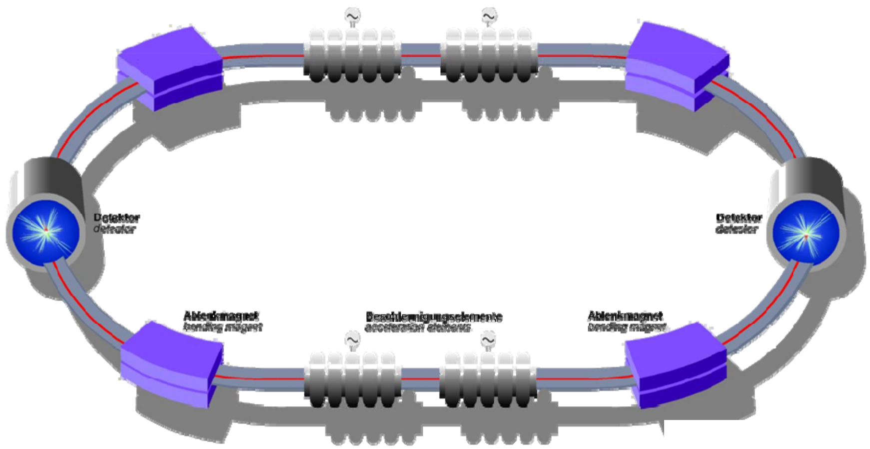
Starting from a bottle of Hydrogen !
First stages of the accelerator chain are linear.

(old name)

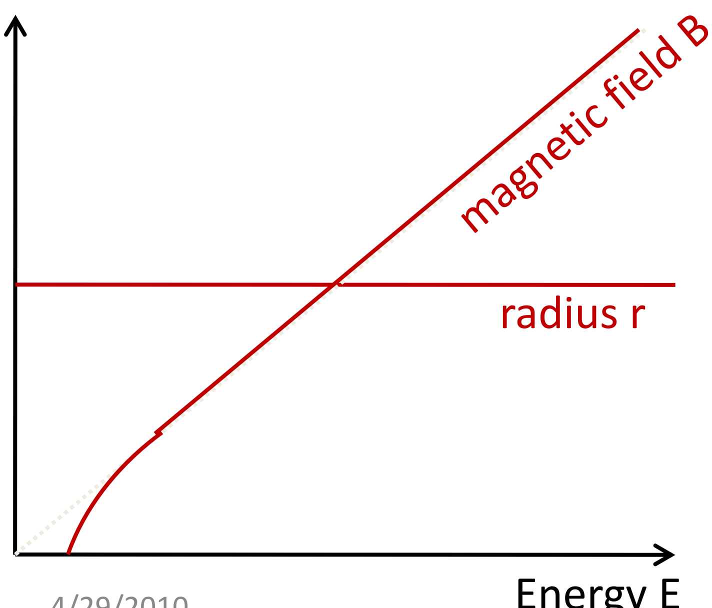
Stanford **Linear** Accelerator Center

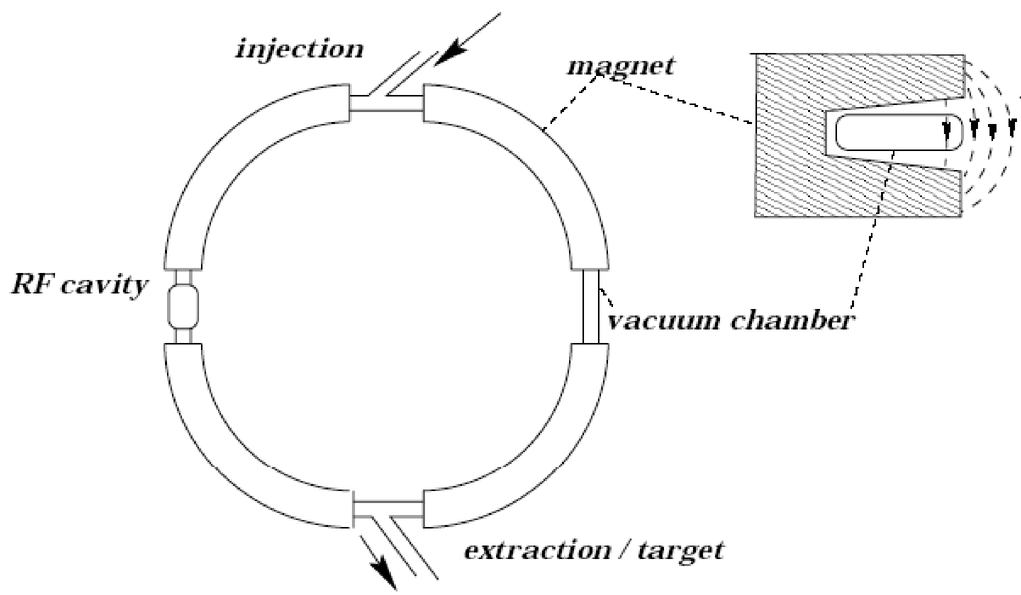
(SLAC National Accelerator Center)

Synchrotron

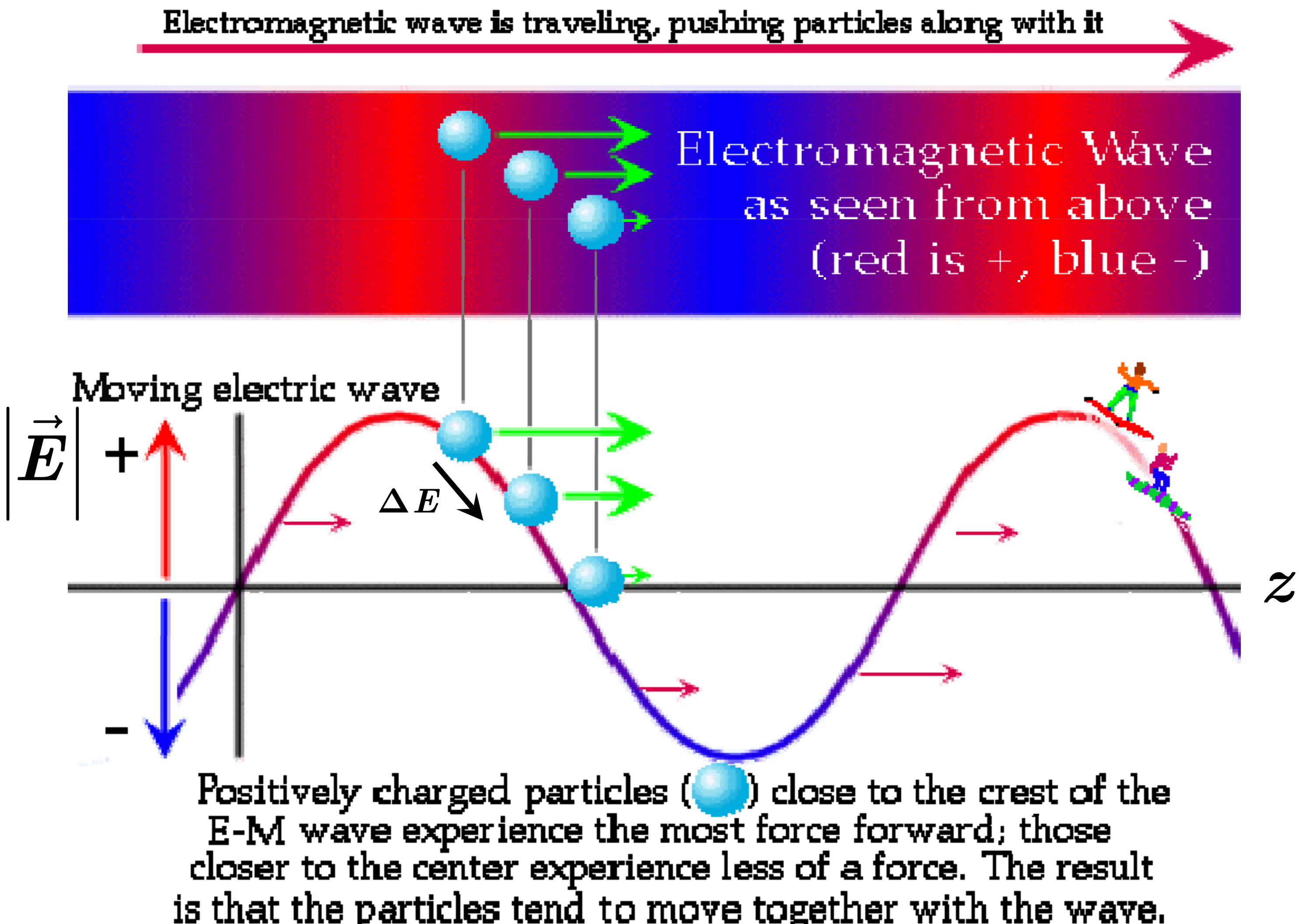


Synchronous **ramping** of the magnetic field with Energy

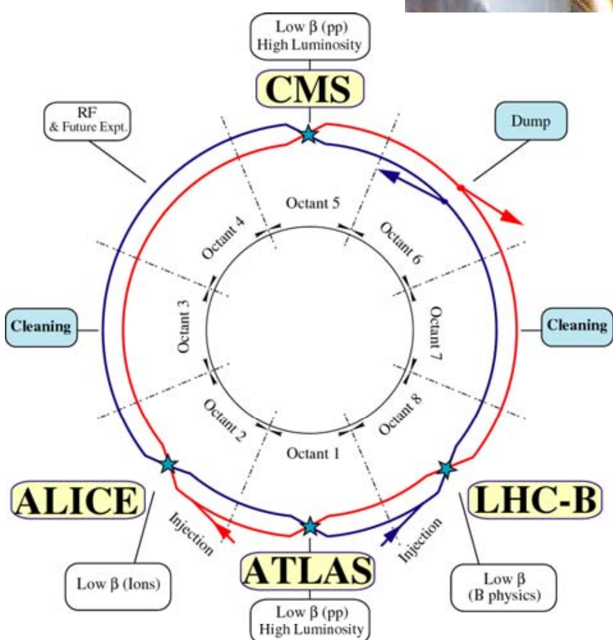


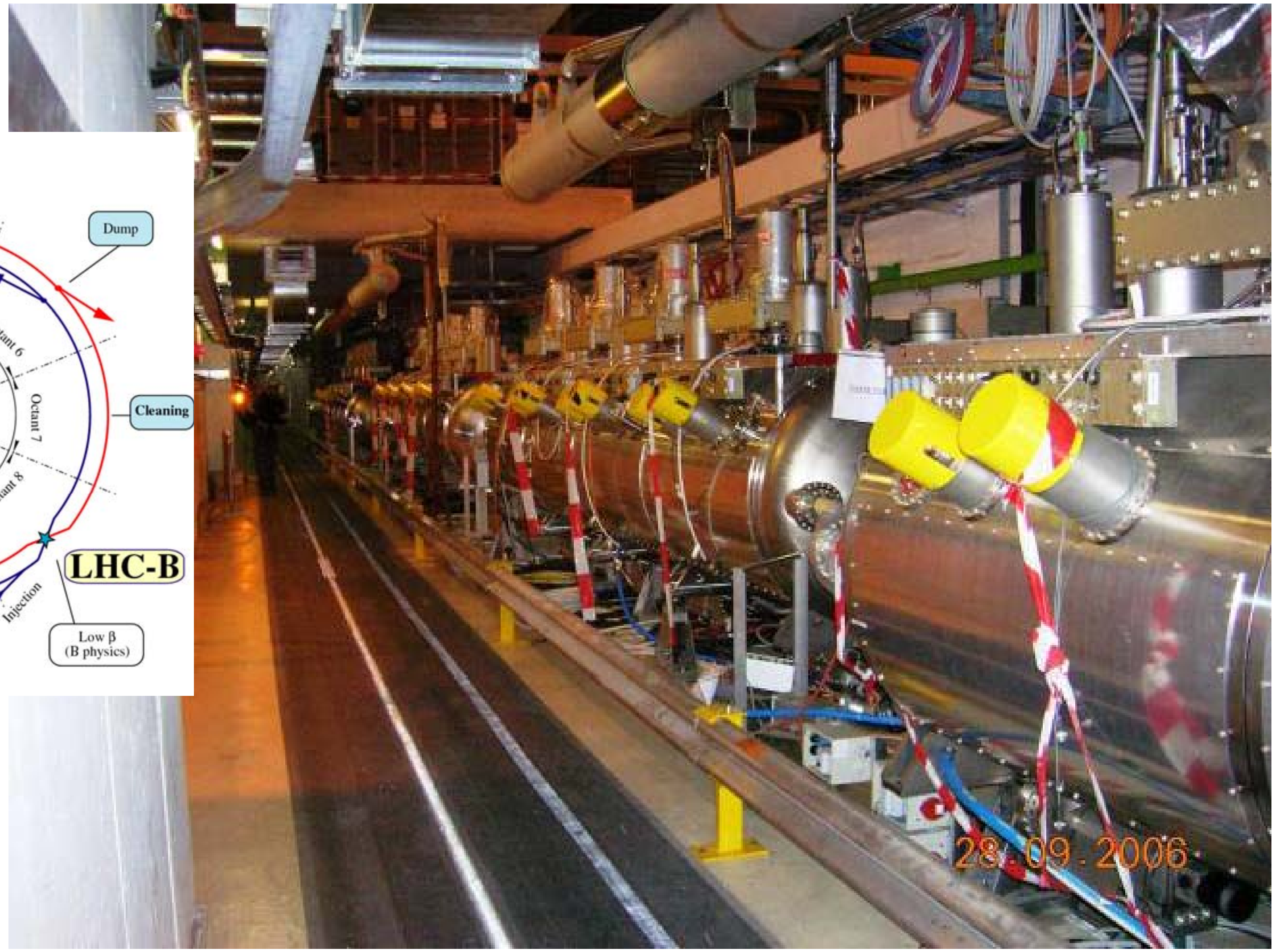


Radio Frequency (RF) acceleration



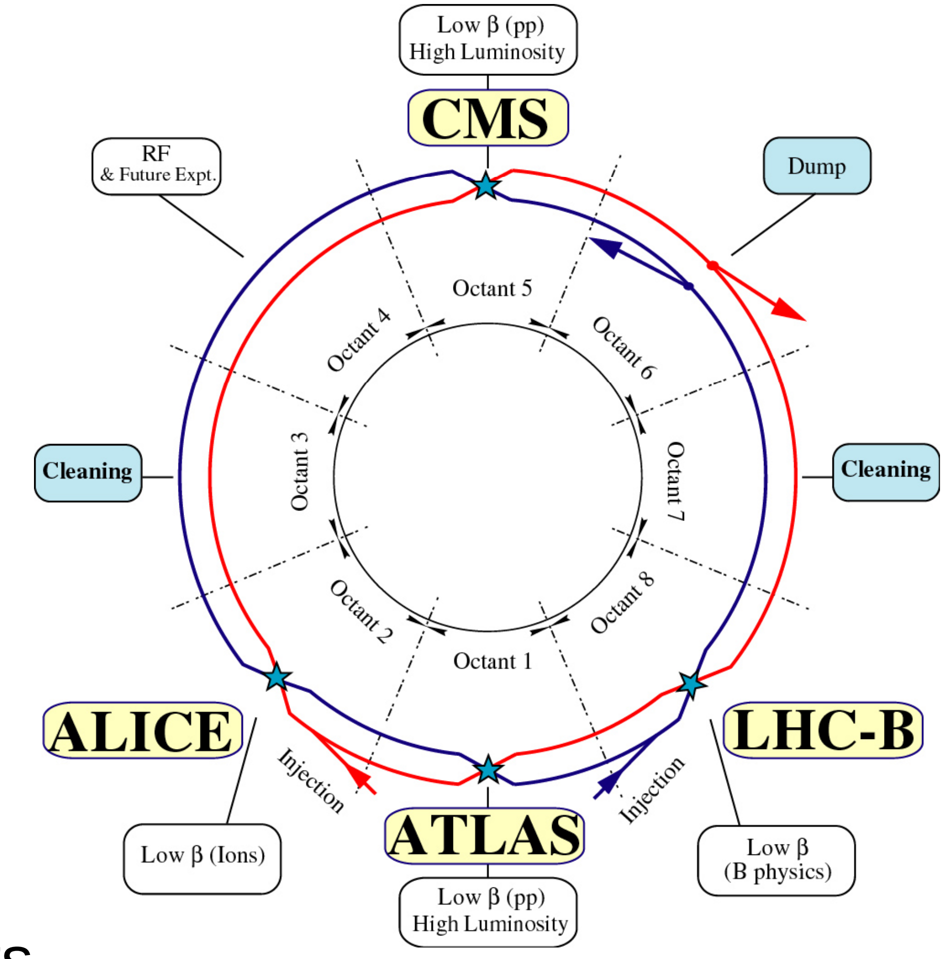
RF - tunnel view



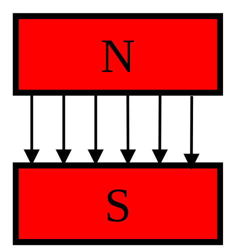


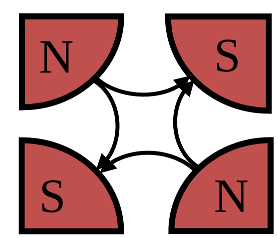
LHC elements

- Charged particles are accelerated, guided confined/focused by **electric and magnetic fields**



Acceleration:	RF cavities
Bending:	Dipole magnets
Focusing:	Quadrupole magnets





- **Why is the LHC special ???**

What do experiments want?

High energy

B = bending field
ρ = bending radius
p = momentum
e = charge

$$B\rho = \frac{p}{e}$$

High luminosity

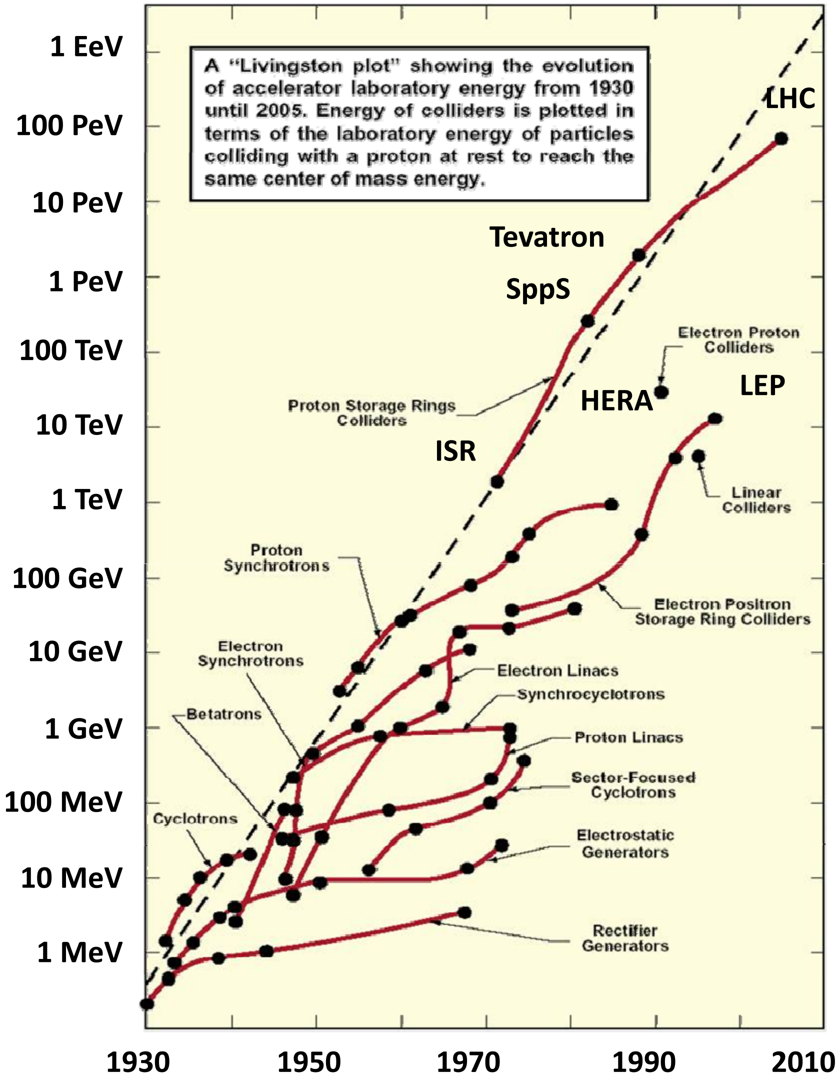
$$\mathcal{L} = \frac{N^2 n_b f_{rev}}{4\pi\sigma_x\sigma_y}F$$

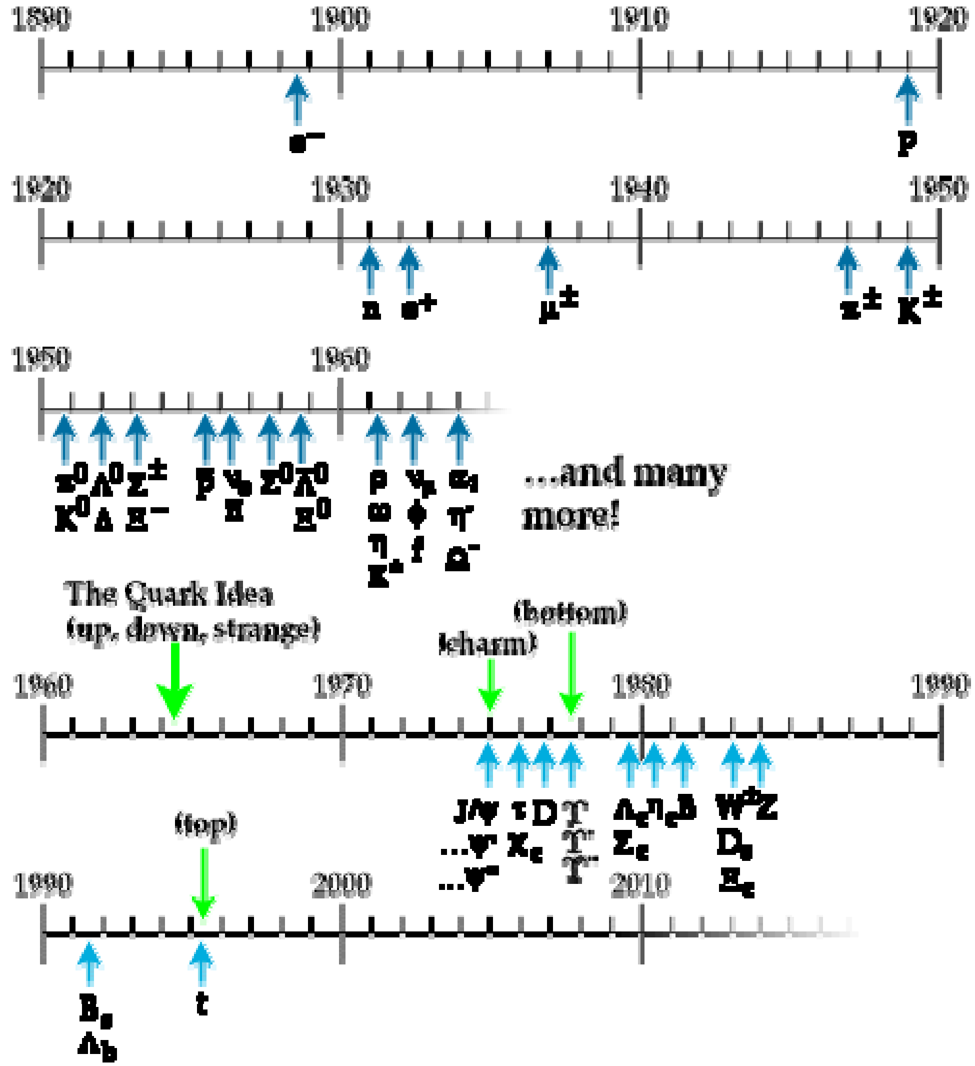
N = bunch population
n_b = number of bunches
f_{rev} = revolution frequency
$\sigma_{x,y}$ = colliding beam sizes
F = geometric factor

"Thus, to achieve high luminosity, all one has to do is make (lots of) high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible." PDG 2005, chapter 25

$$E^{FT}_{Lab} = E^2_{cm}/2m_p$$

Livingston Plot





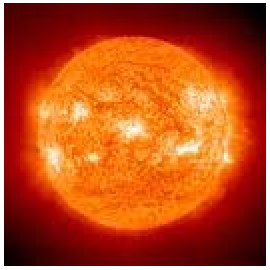
The largest machine in the world...

- 26 659 m in circumference
- A total of 9300 magnets
- 1/8 of its cryogenic distribution system would qualify as the world's largest fridge
- 10'080 tons of liquid nitrogen to pre-cool to -193.2°C (80 K)
- Nearly 60 tons of liquid helium to get down to -271.3°C (1.9 K)

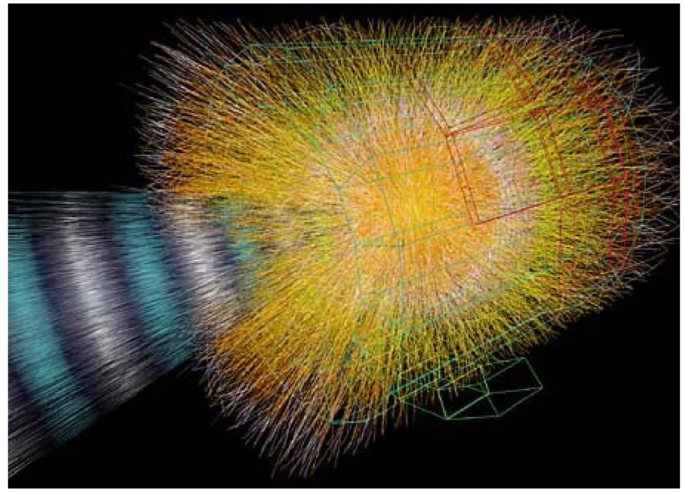
The emptiest space in the Solar System…

- To avoid colliding with gas molecules inside the accelerator, the beams of particles travel in an ultra-high vacuum – a cavity as empty as interplanetary space.

- The internal pressure of the LHC is 10^{-13} bar, ten times less than the pressure on the Moon!



The hottest and coldest place in the Universe

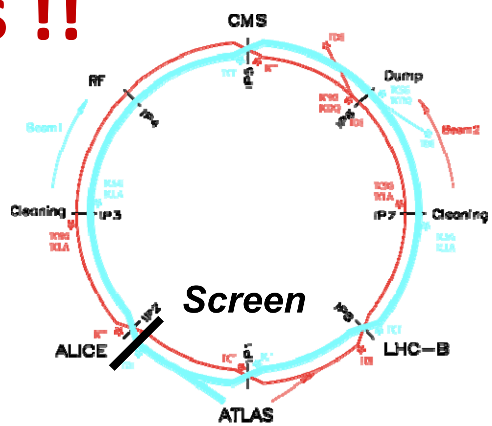


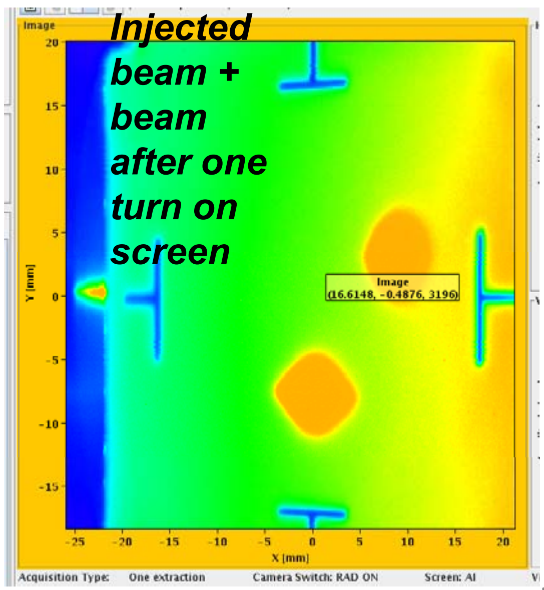
- The LHC is a machine of extreme hot and cold
- When two beams of protons collide, they will generate temperatures more than 100 000 times hotter than the center of the Sun
- The 'cryogenic distribution system', which circulates superfluid helium around the accelerator ring, keeps the LHC at a super cool temperature of -271.3°C (1.9 K) – even colder than outer space!

The most powerful supercomputer system in the world...

Does it work ??

- **Yes !!**





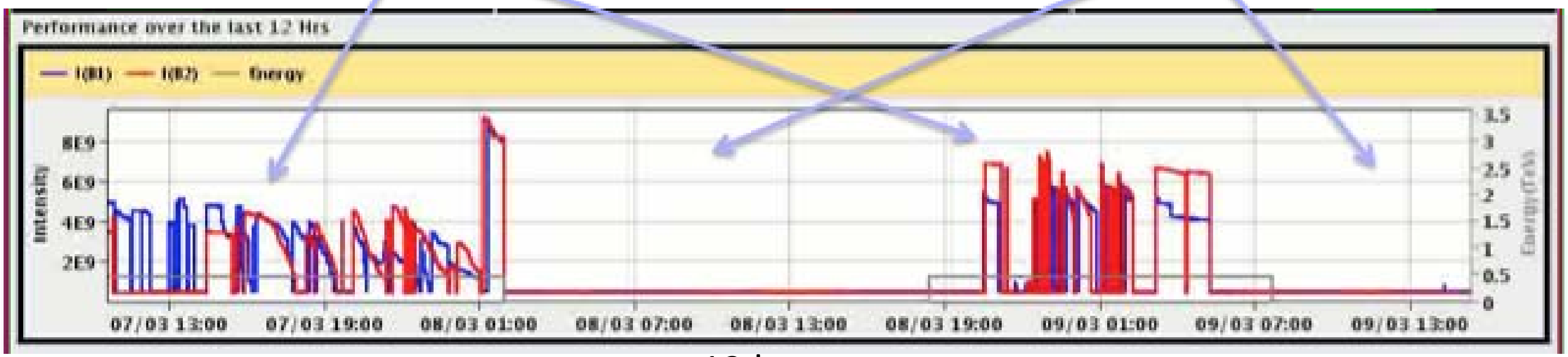
3.5 TeV collisions on March 30th

Typical pictures

Beam 1
Beam 2

Very busy beam work by CCC team and many experts (single bunch up to 1e10 p)

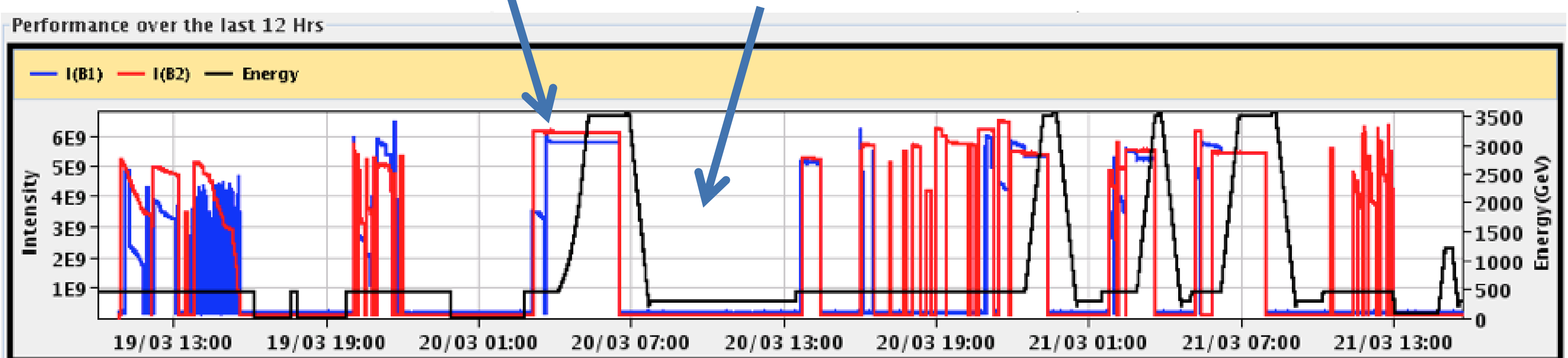
Very busy hardware work by experts: no beam



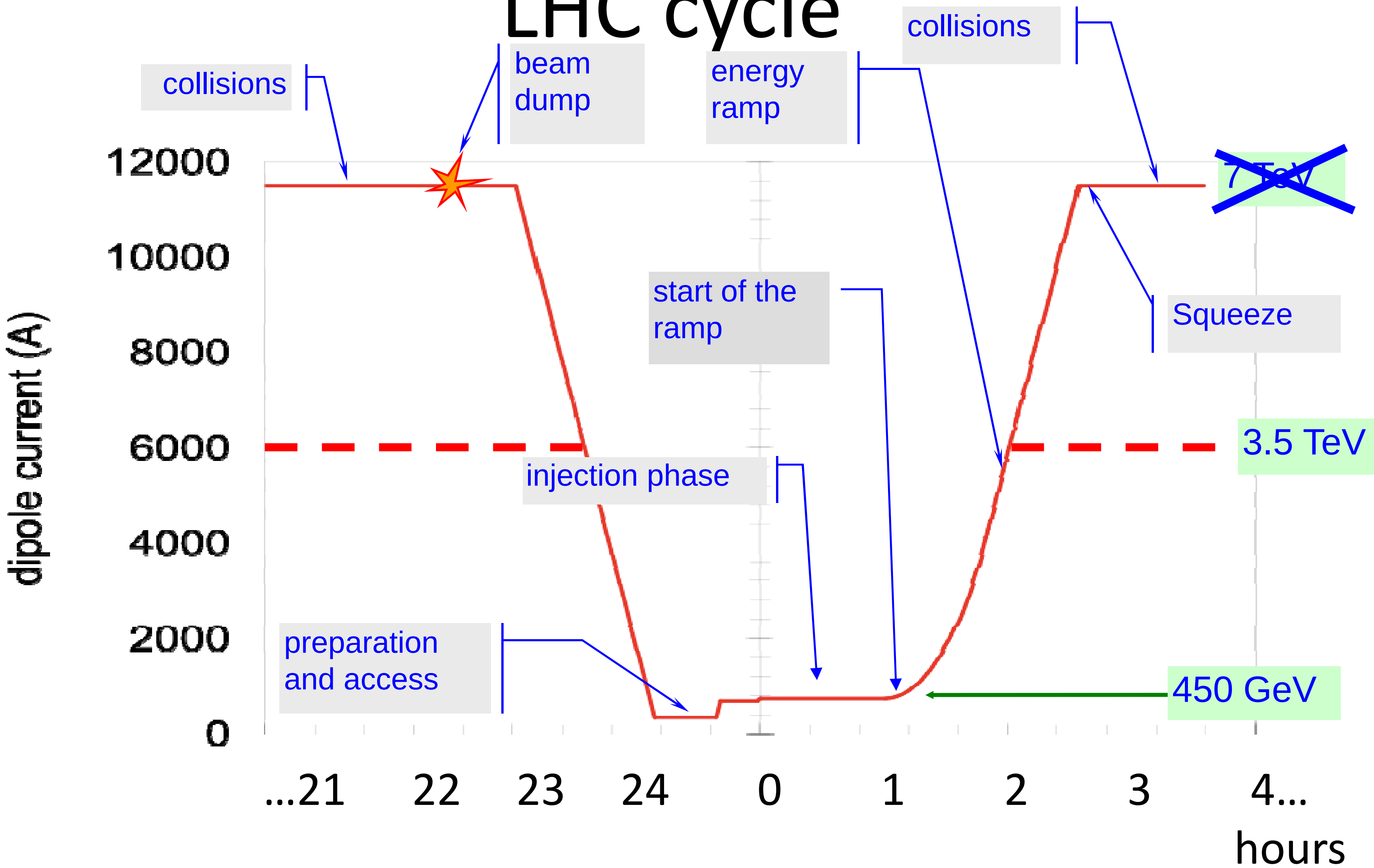
12 hours

Ramp

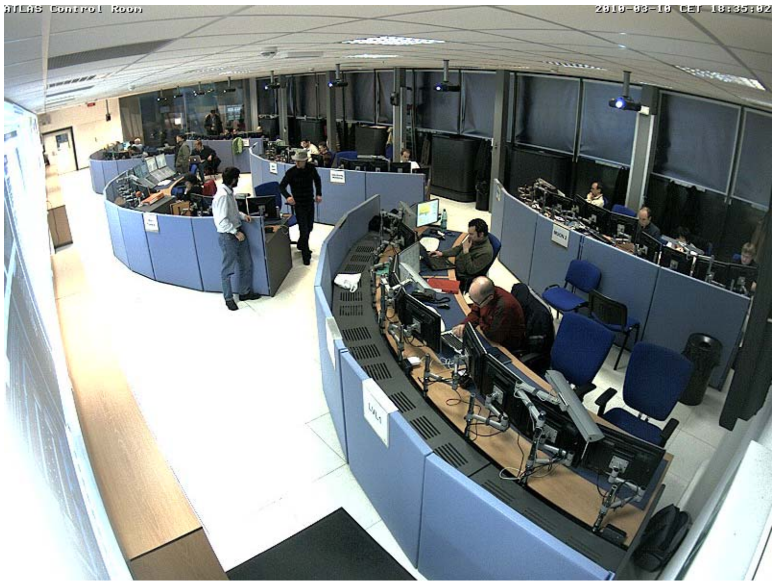
Problems

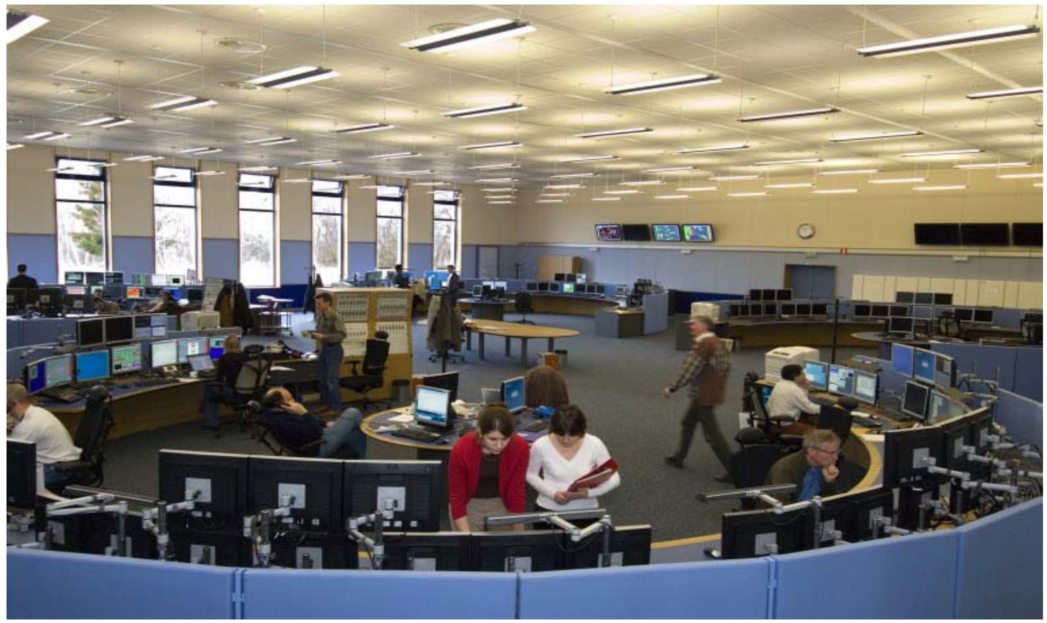


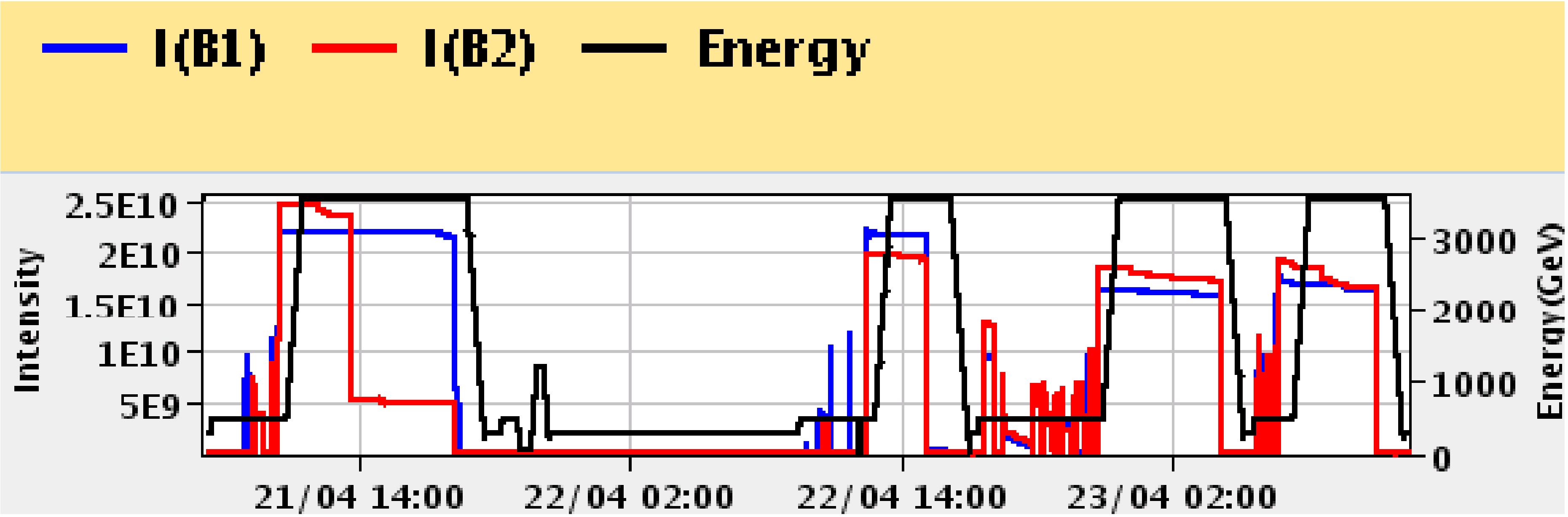
LHC cycle


collisions
beam dump
energy ramp
collisions
12000
10000
8000
6000
4000
2000
0
dipole current (A)
7 TeV
start of the ramp
Squeeze
3.5 TeV
injection phase
preparation and access
450 GeV
...21
22
23
24
0
1
2
3
4...
hours

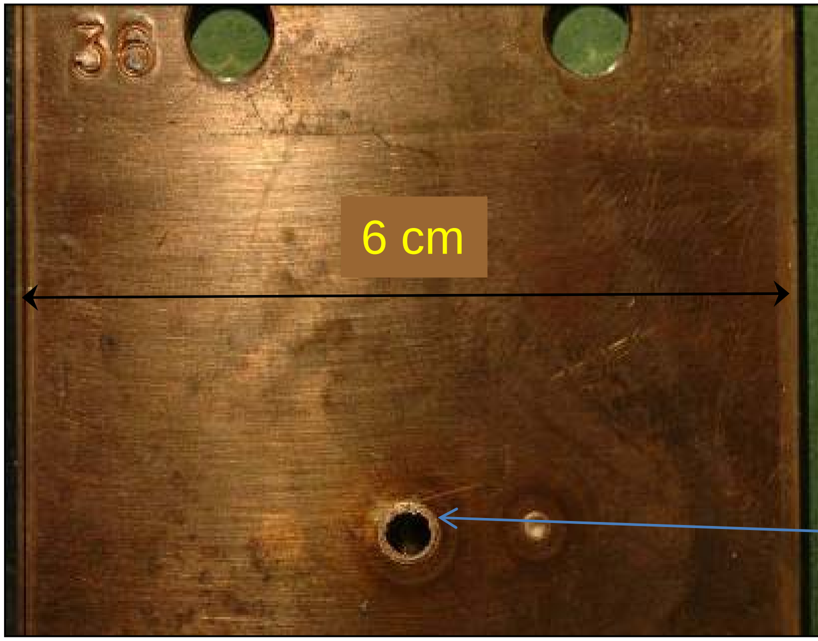
24/7 operation for experiments and accelerator






I(B1)
I(B2)
Energy
Intensity
2.5E10
2E10
1.5E10
1E10
5E9
3000
2000
1000
0
Energy(GeV)
21/04 14:00
22/04 02:00
22/04 14:00
23/04 02:00

27th Feb	First injection
28th Feb	Both beams circulating
5th March	Canonical two beam operation
8th March	Collimation setup at 450 GeV
12th March	Ramp to 1.18 TeV
15th - 18th March	Technical stop – bends good for 6 kA
19th March	Ramp to 3.5 TeV
26th - 29th March	Preparation of 'stable' beam conditions
30th March	First 3.5 TeV collisions in all experiments (media event)
1st April	Betatron squeeze to 5 m in IP1 and IP5
4th - 5th April	19h-long store with collisions in all IPs
7th April	Betatron squeeze to 2 m in IP1 and IP5



What you can do with a few MJ

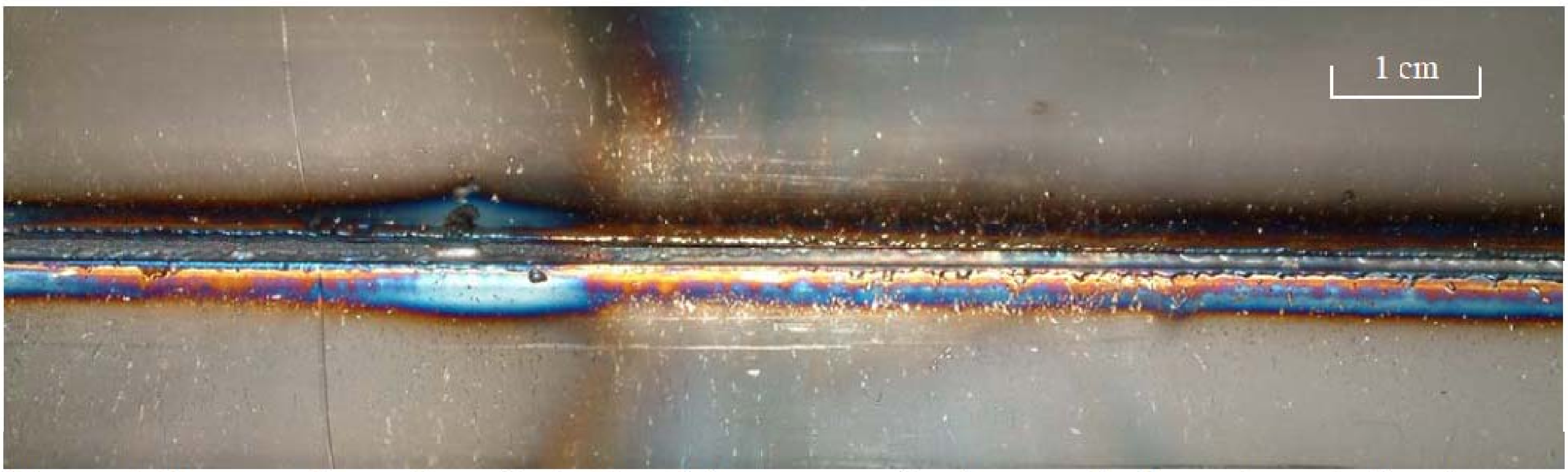
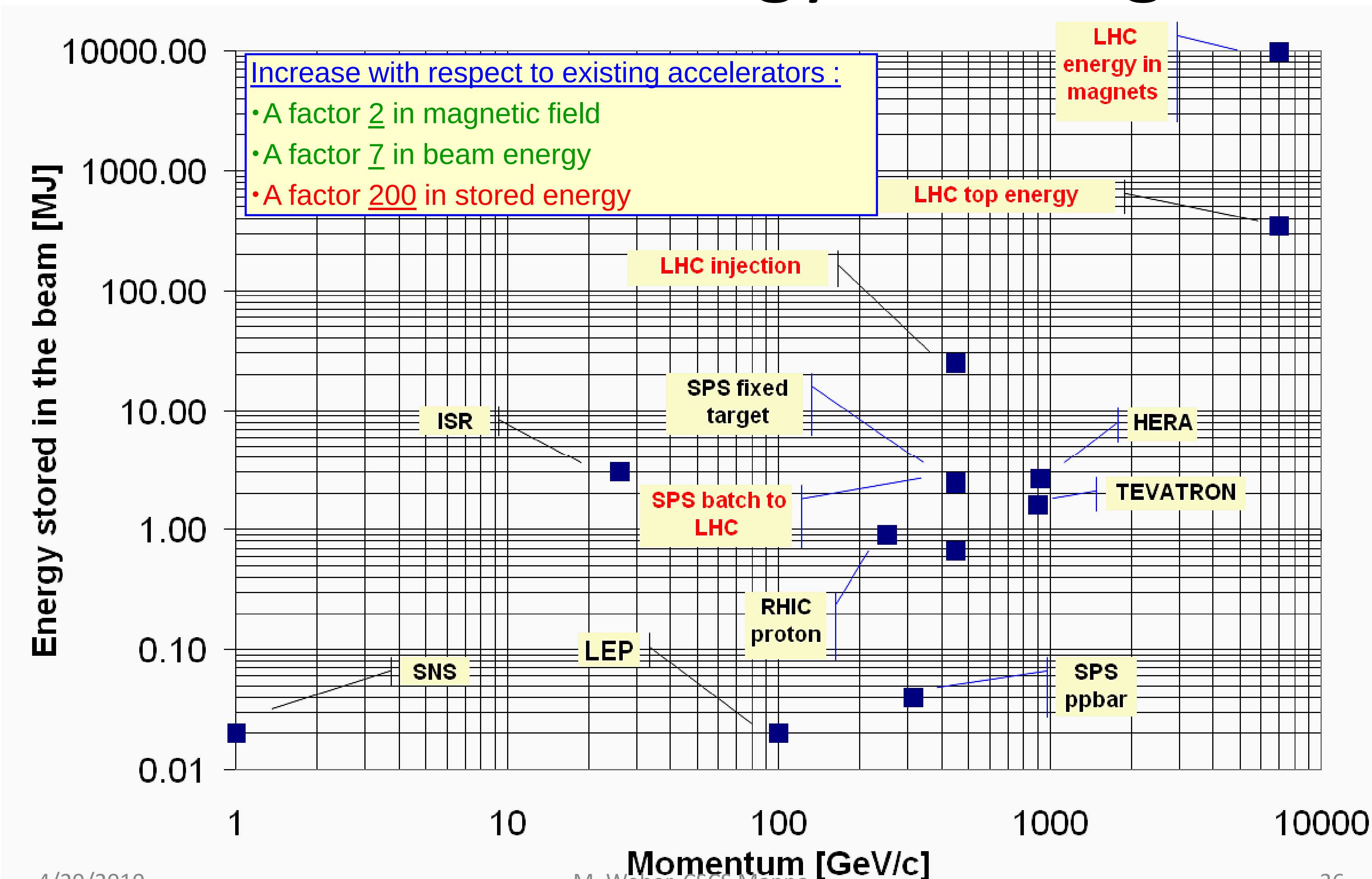


Figure 4. Damage observed on the inside of the vacuum chamber, on the beam impact side. A groove approximately 110 cm long due to removed material was clearly visible, starting at about 30 cm from the entrance.

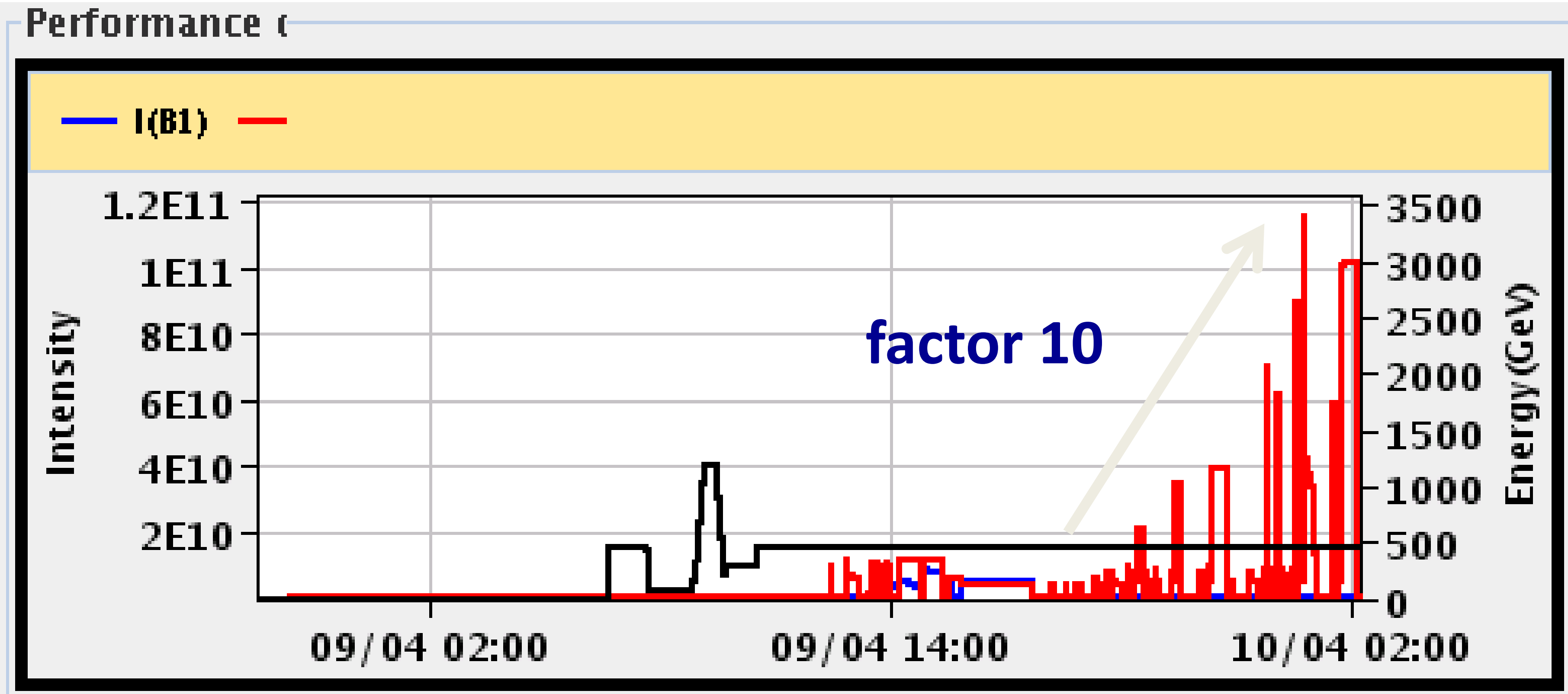
The stored energy challenge



Total design energy stored in one beam at 7 TeV: 362 MJoule

- 1 Proton = 1 Mosquito
- The energy of one ball (5 kg) at 800 km/hour corresponds to the energy stored in one bunch at 7 TeV
- The design is to have 2808 bunches
- Factor 200 compared to HERA, TEVATRON and SPS

Increasing bunch intensity



Major success for the LHC:

Nominal bunch charge at 450 GeV!
25 hours beam lifetime!

Goals for 2010-2011

2009			2010			2011		
Repair of Sector 34	1.18 TeV	nQPS 6kA	3.5 TeV $I_{safe} < I < 0.2\ I_{nom}$ β* ~ 2 m	Ions		3.5 TeV ~ 0.2 I_{nom} β* ~ 2 m	Ions	
No Beam	B		Beam			Beam		

- **<u>Goal</u>** (ambitious!) :
  collect **1 fb^{-1} of data/exp at 3.5 TeV/beam**

- To achieve such this goal the LHC must operate in 2011 with
  - about 700 bunches of 10^8 p/bunch
  - (stored energy of ~ 30 MJ – 10% of nominal)

- **Need:**
  - **Strict and clean machine setup.**
  - **Machine protection systems at near nominal performance**

Summary

- Large hadron Collider
- Largest, hottest, coolest, emptiest, most complex machine
- It works ! Need to carefully increase the intensity
- Goal: 1 fb^{-1} of data to each experiment in 2010/2011 (in the order of 400 days at 300 MB/s)