El LHC y los experimentos

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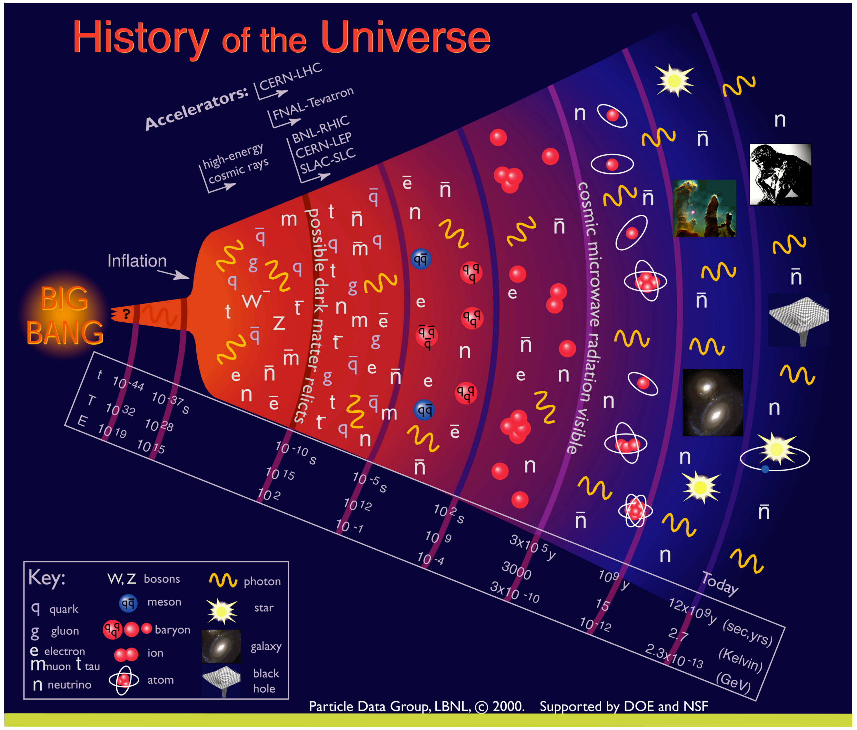
TAE2012 (18-19 July 2012)

Outlook

- El accelerador Jueves
- Detectores de trazas Jueves
- Calorimetros electromagneticos, detectores de muones y reconstruccion Viernes
- Busqueda del boson de Higgs en el LHC Viernes

To Understand the Universe

BIG BANG



NOW

What is the LHC for ?

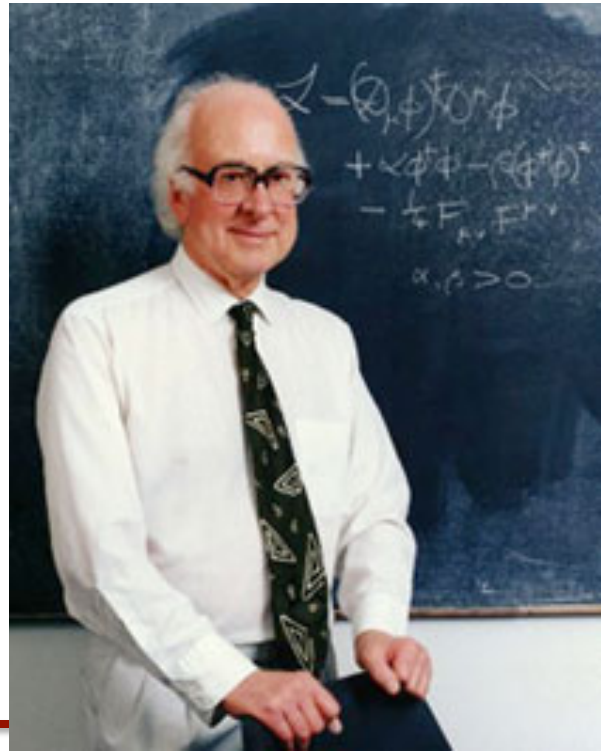
- The LHC was built to help answer some key unresolved questions in physics

  - What is the origin of mass ? Is it the Higgs boson ?
  - What is 96% of the universe made of ?
  - Why is there no more antimatter ?
  - What was matter like in the first second of the Universe ?

What is the mass?

- What is the origin of mass?
- Why do tiny particles weigh the amount they do?
- Why do some particles have no mass at all?

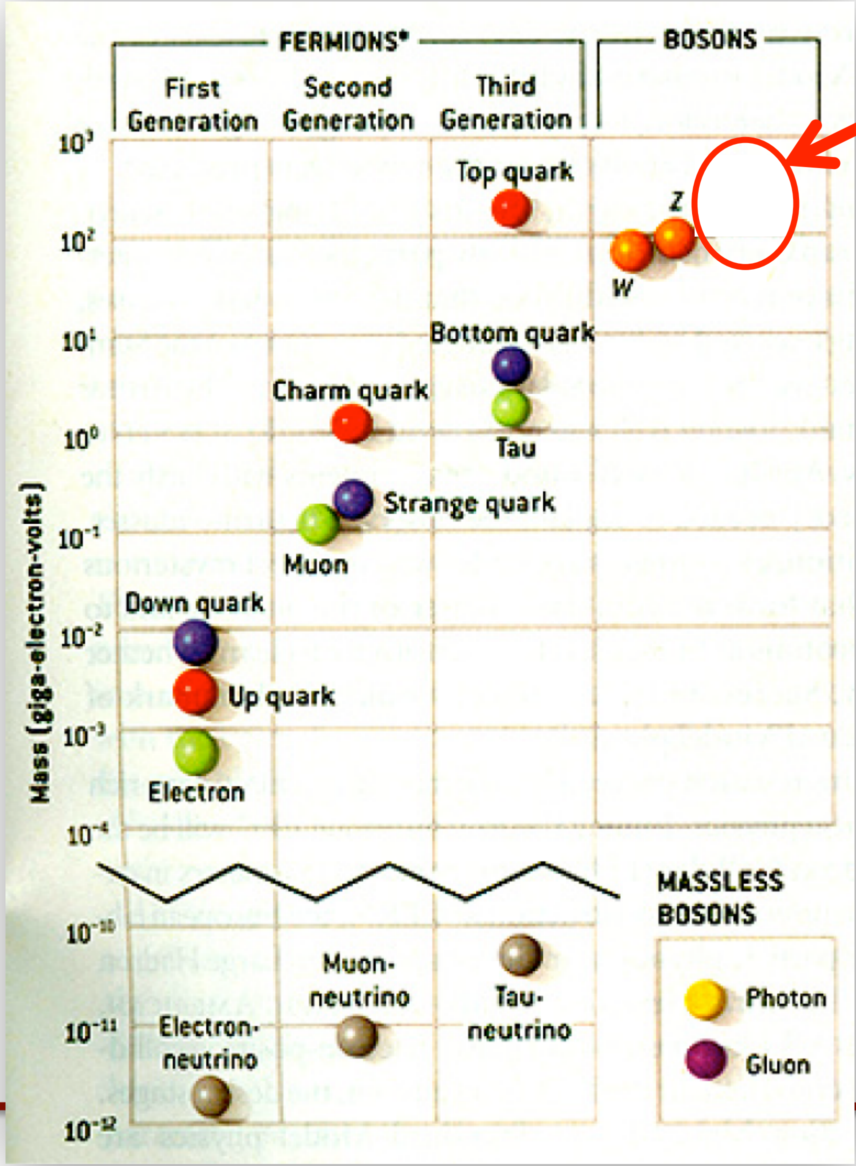
- An explanation may be found in the Higgs mechanism. First hypothesised in 1964

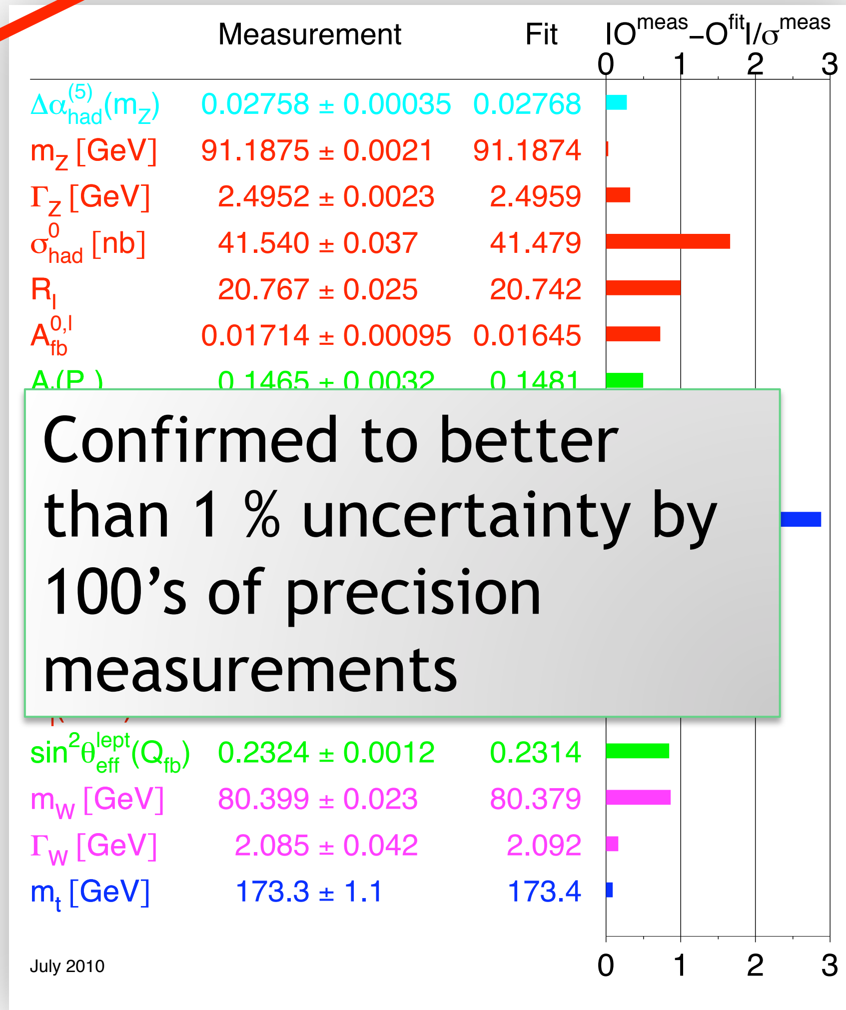


- **The ATLAS and CMS experiments are actively searching for signs of this elusive particle.**

The standard Model

1 Missing piece: Higgs





Confirmed to better than 1 % uncertainty by 100's of precision measurements

What is 96% of the universe made of ?

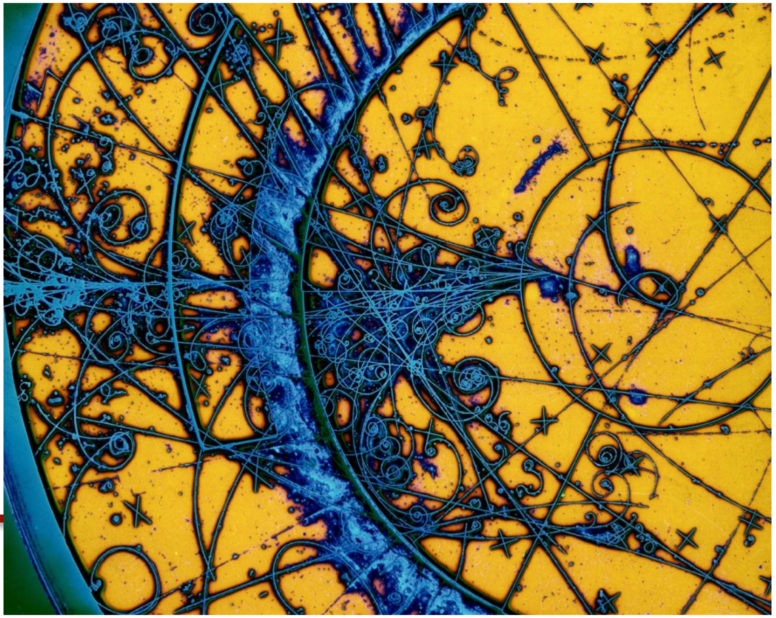
- Everything we see in the Universe is made up of particles (matter)
- Matter accounts for 4% of the Universe.
- Dark matter and dark energy are believed to make up the remaining proportion, but they are incredibly difficult to detect and study, other than through the gravitational forces they exert.

- The **ATLAS** and **CMS** experiments will look for supersymmetric particles to test a hypothesis for the make-up of dark matter.

Why is there no more antimatter ?

- Antimatter is like a twin version of matter, but with opposite quantum numbers.
- At the birth of the Universe, equal amounts of matter and antimatter should have been produced in the Big Bang.
- Matter and antimatter particles annihilate transforming into energy.
- Somehow, a tiny fraction of matter must have survived to form the Universe we live in today, with hardly any antimatter left. Why does Nature appear to have this bias for matter over antimatter?

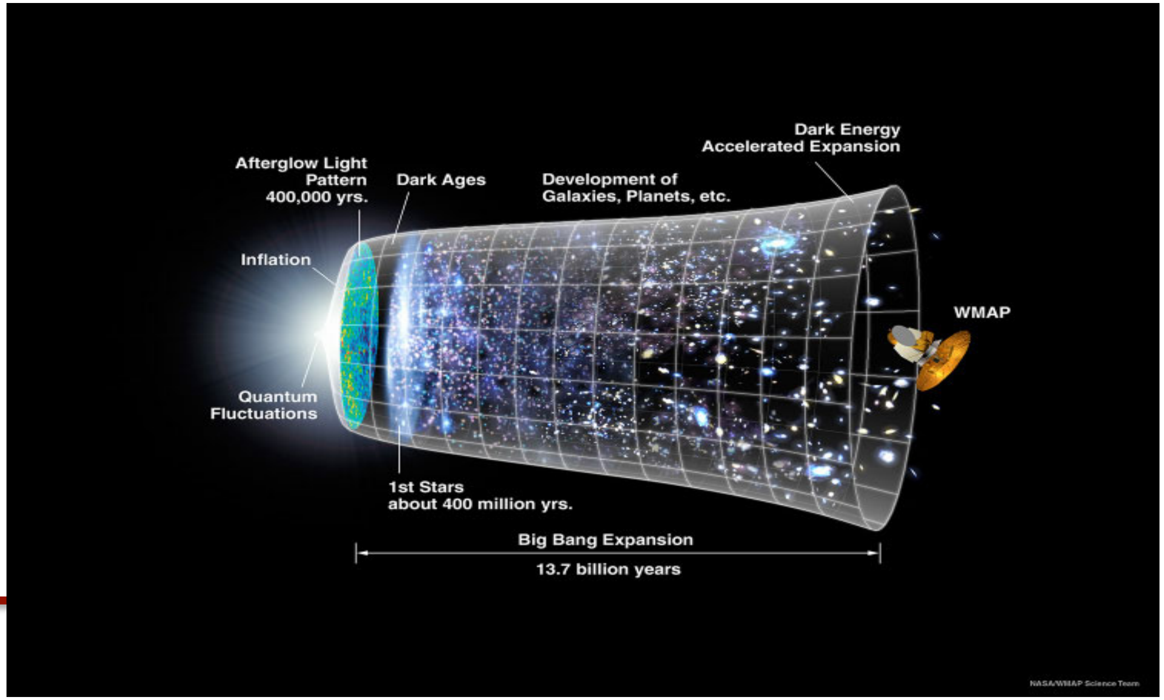
- **The LHCb experiment will be looking for differences between matter and antimatter to help answer this question.**



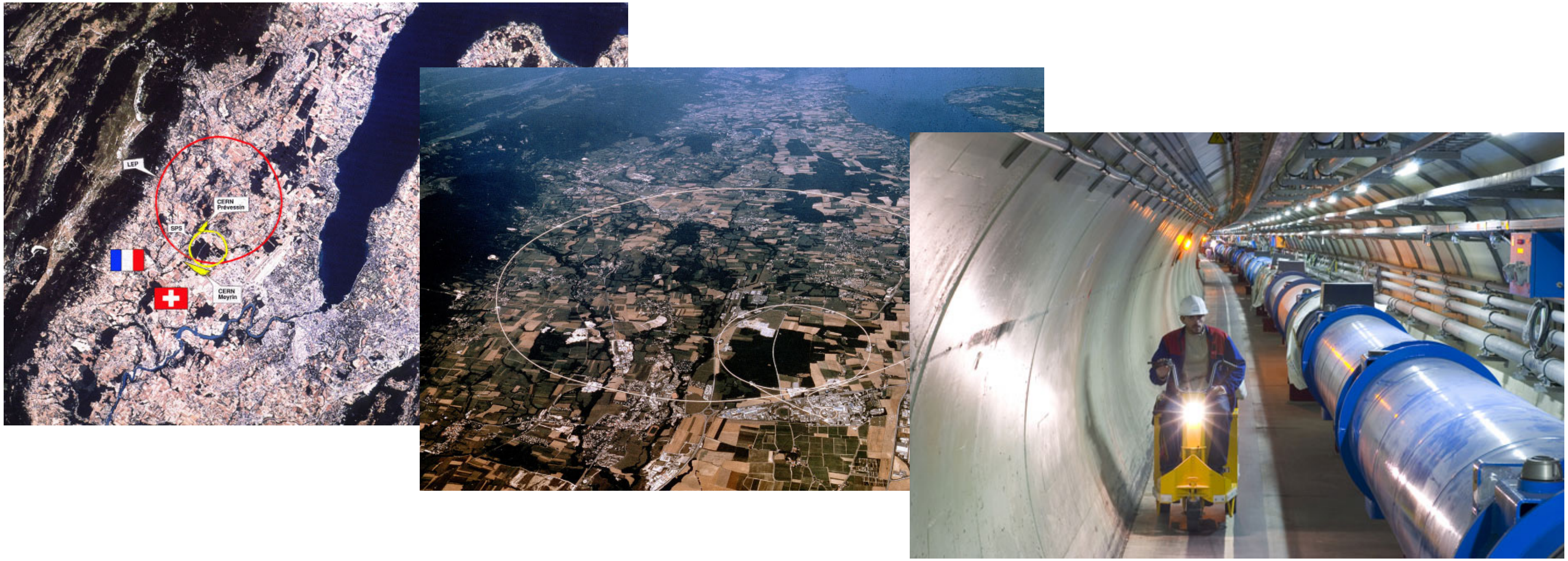
What was matter like in the first instants?

- Matter is made of atoms, which contain a nucleus composed of protons and neutrons, which in turn are made of quarks bound together by other particles called gluons.
- In the very early Universe conditions would have been too hot and energetic for the gluons to hold the quarks together.
- Instead, during the first microseconds after the Big Bang the Universe would have contained a very hot and dense mixture of quarks and gluons.

  - The **ALICE** experiment will use the LHC to recreate conditions similar to those of the early universe, in particular to analyse the properties of the quark-gluon plasma.



The LHC

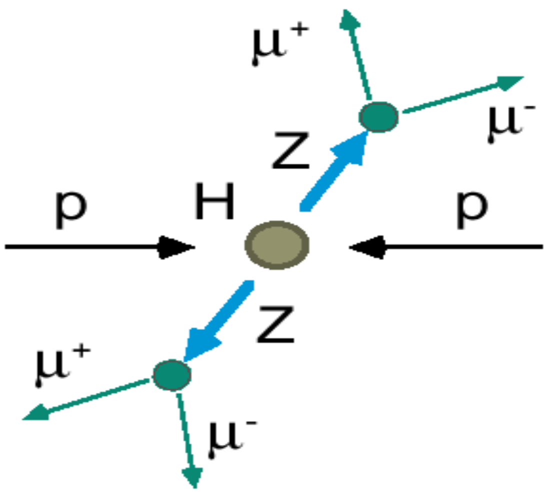


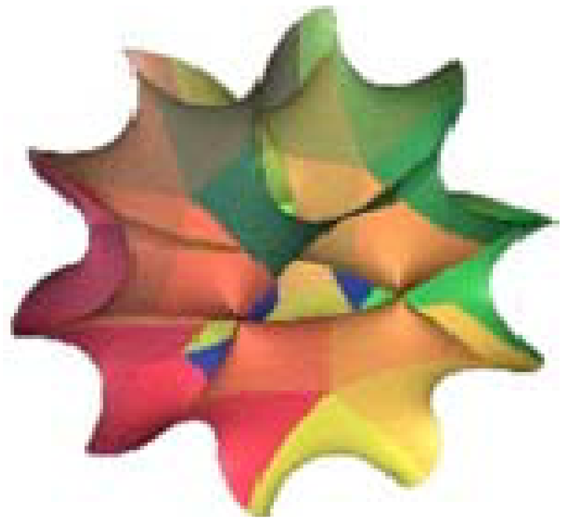
Two beams of trillions of protons race around the 27km ring at 0.999999991 times the speed of light in opposite directions…

Mike Lamont
CERN

Aim of the game

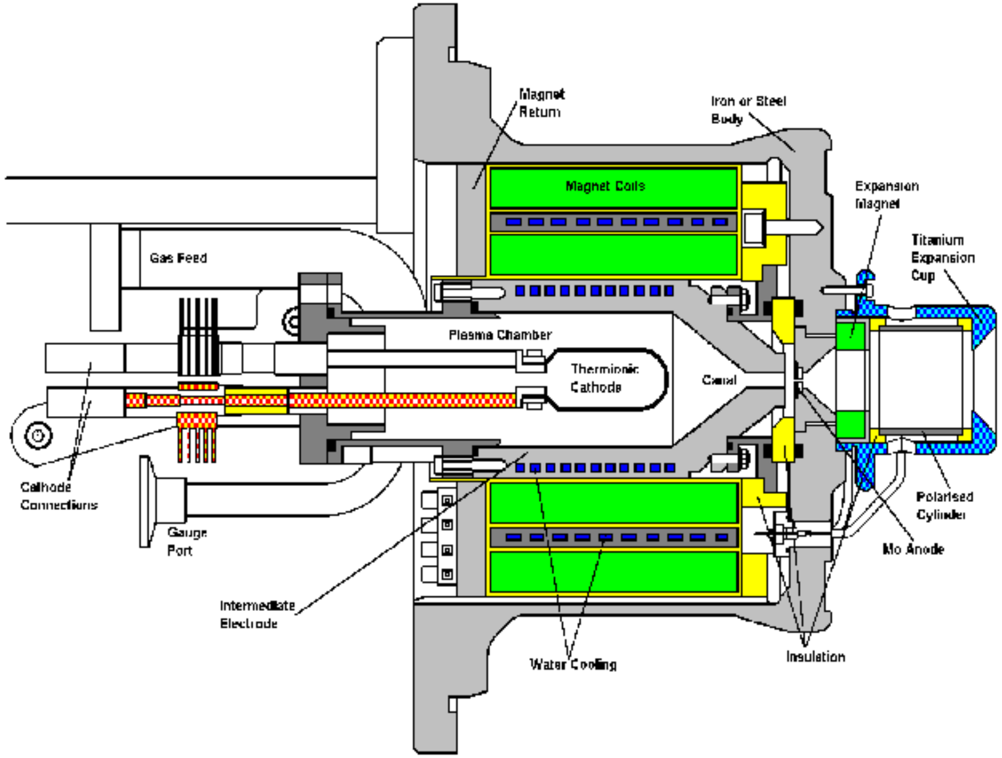
- We want to deliver maximum number of collisions at the maximum beam energy for maximum physics reach



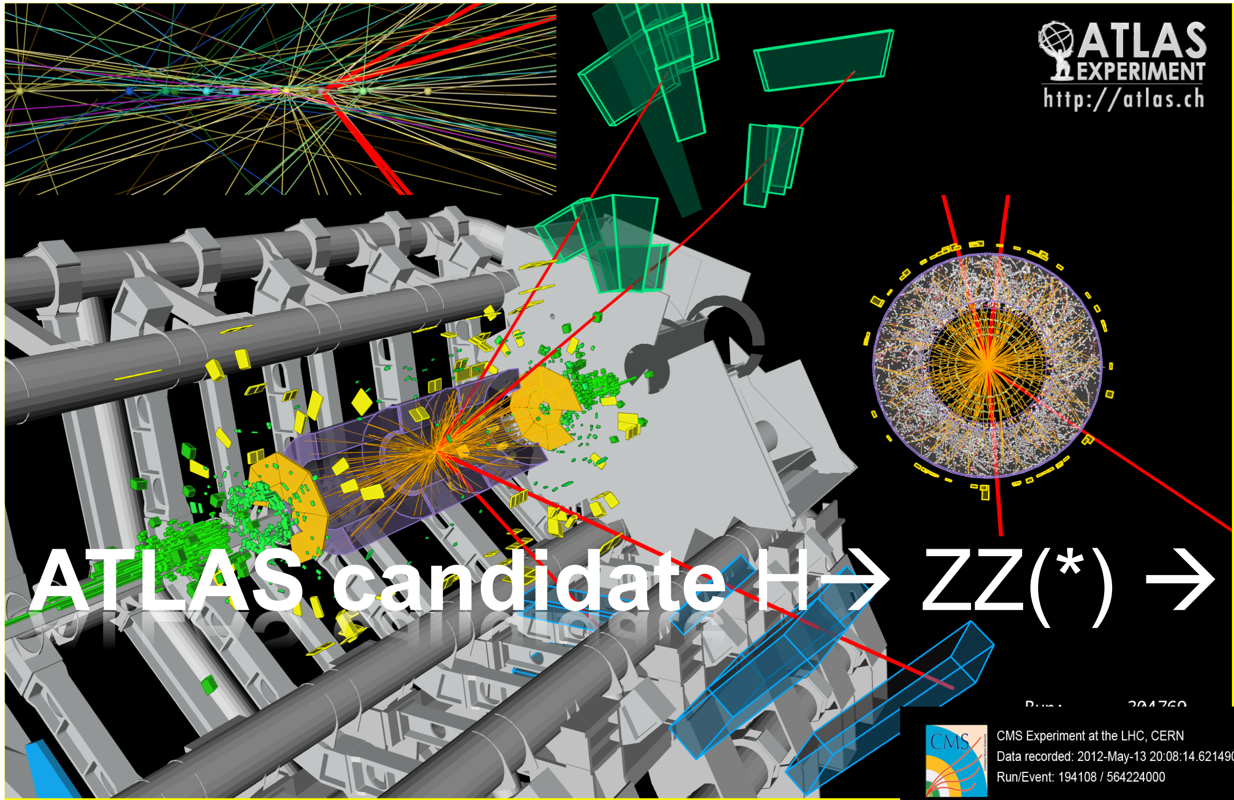


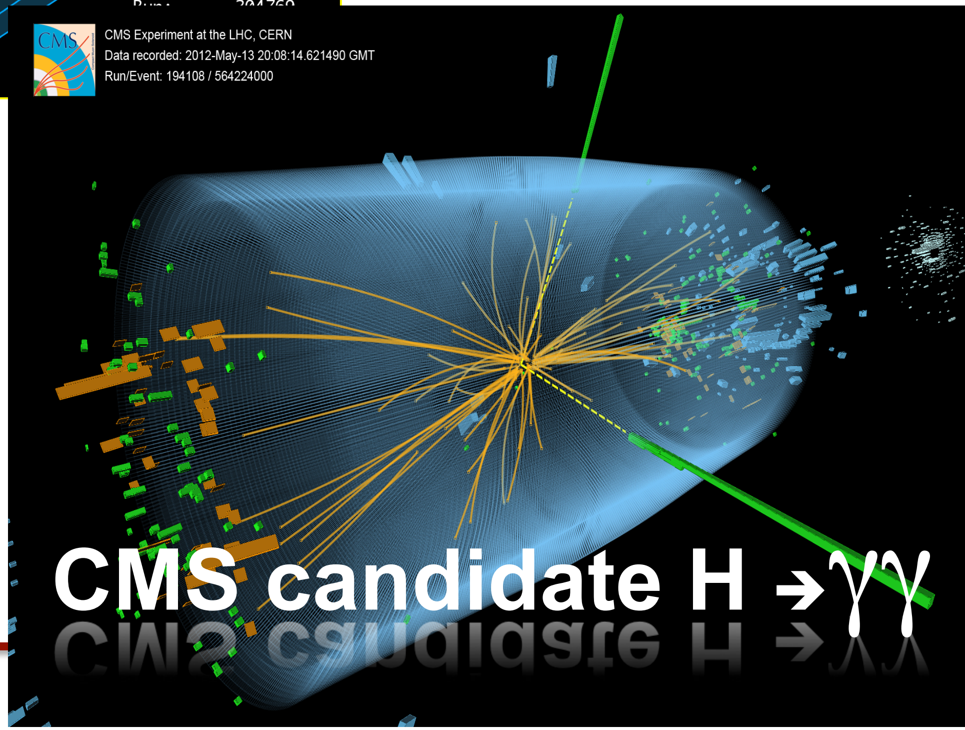
The question is: How do we get from this,

The CERN Duoplasmatron Proton Ion Source

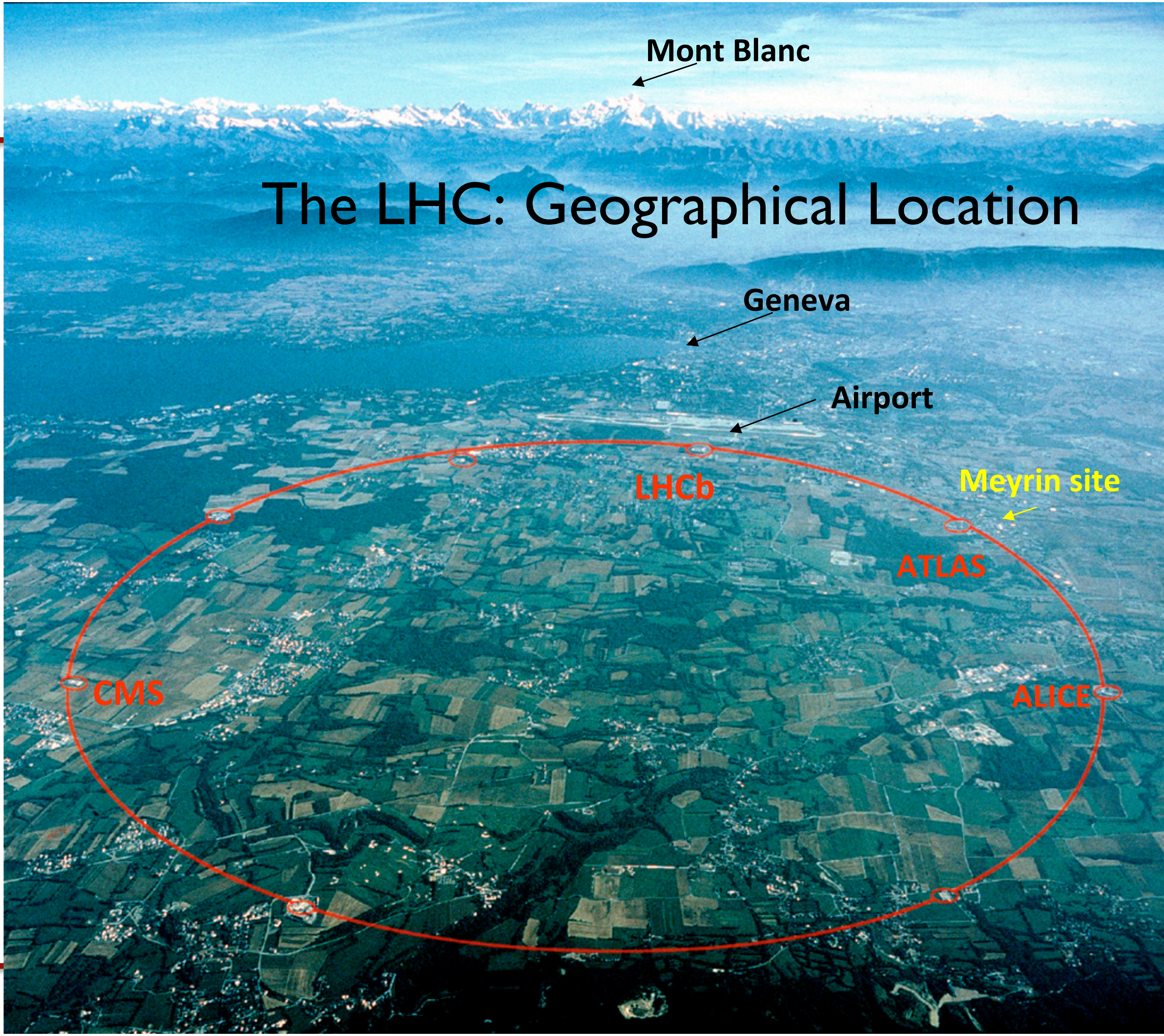


To this…

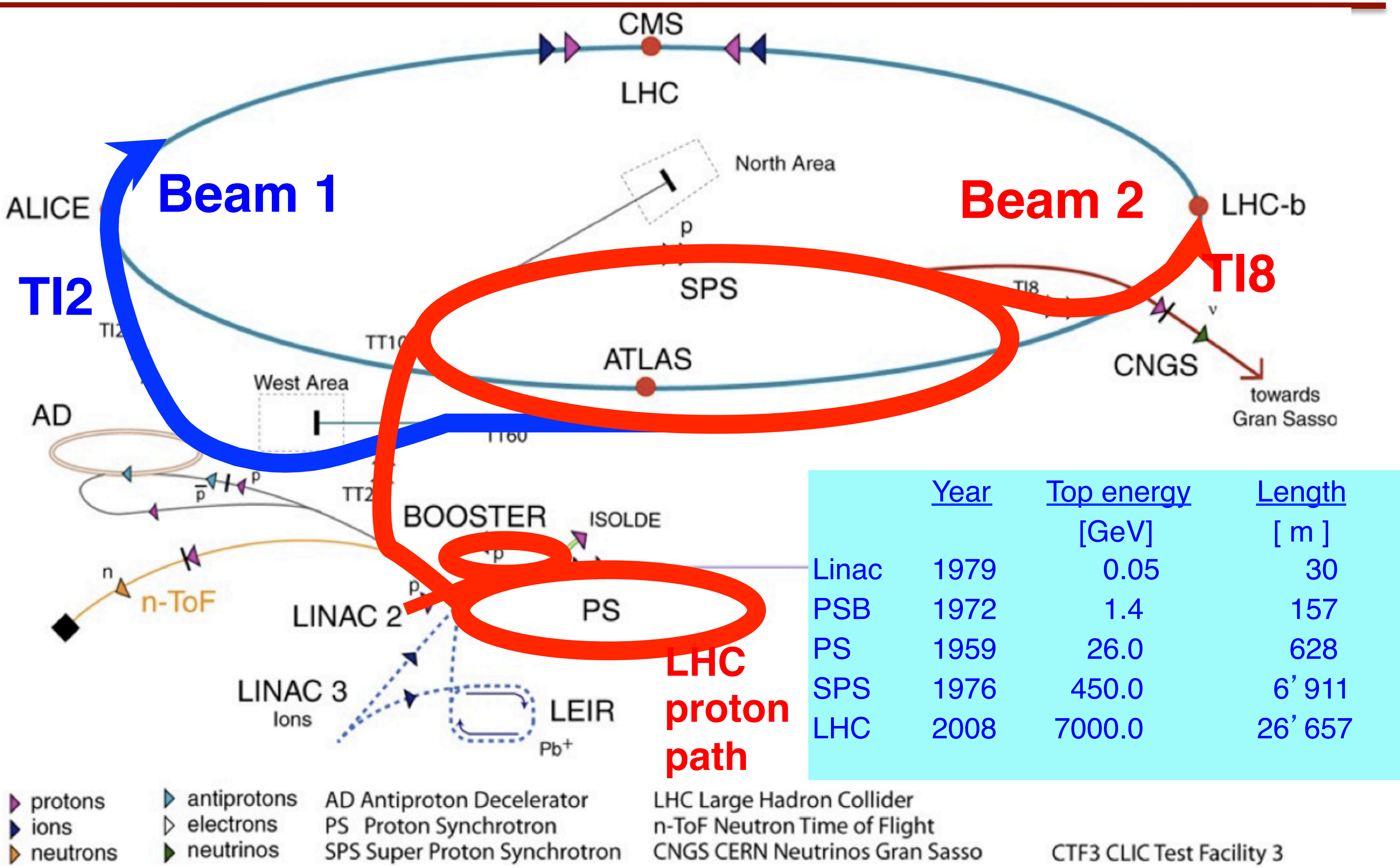

ATLAS EXPERIMENT
http://atlas.ch
ATLAS candidate H→ ZZ(*) →


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
CMS candidate H →γγ

The LHC: Geographical Location

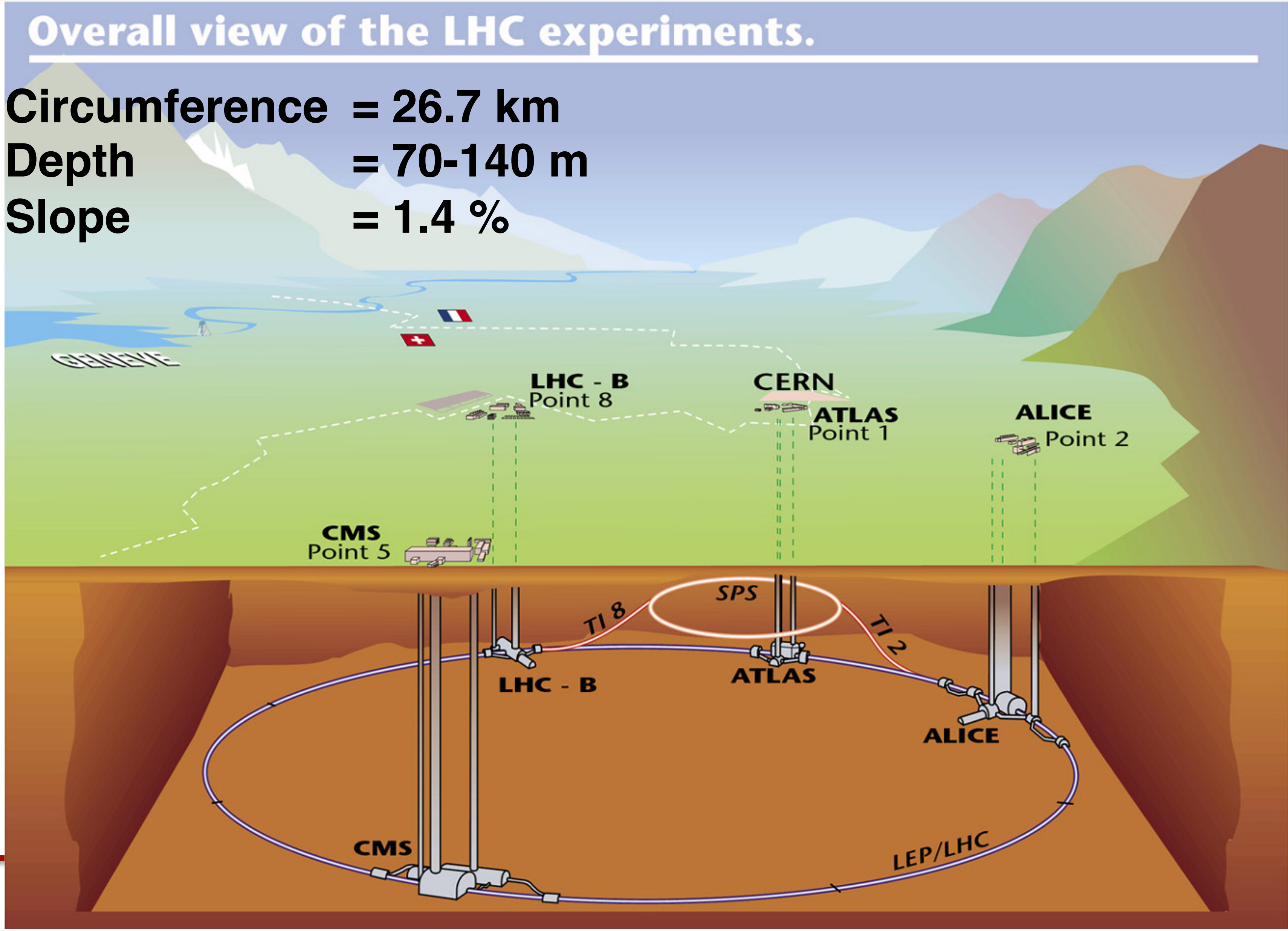


LHC injector complex



	Year	Top energy [GeV]	Length [m]
Linac	1979	0.05	30
PSB	1972	1.4	157
PS	1959	26.0	628
SPS	1976	450.0	6’911
LHC	2008	7000.0	26’657

LHC tunnel

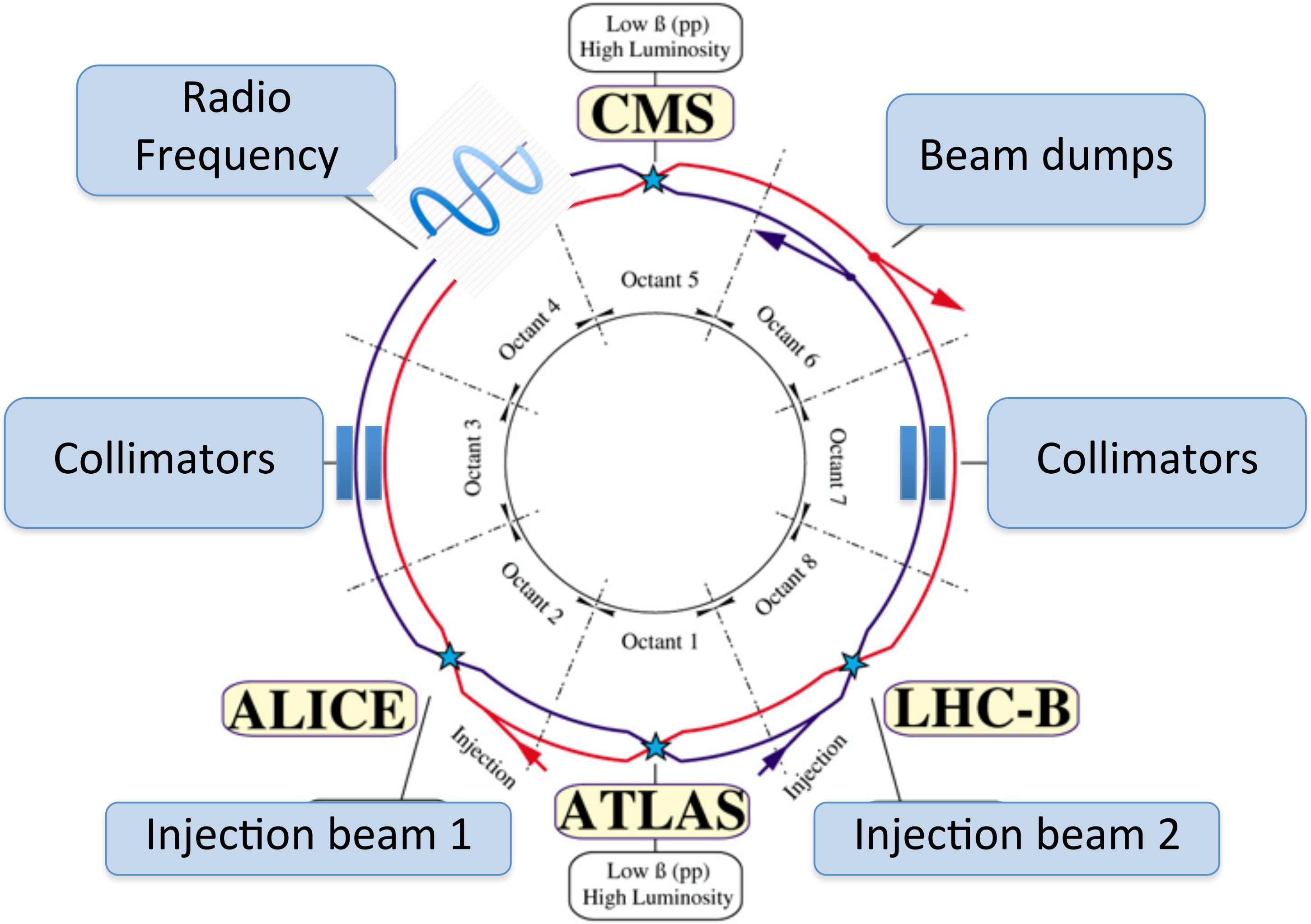

Overall view of the LHC experiments.
Circumference = 26.7 km
Depth = 70-140 m
Slope = 1.4 %
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

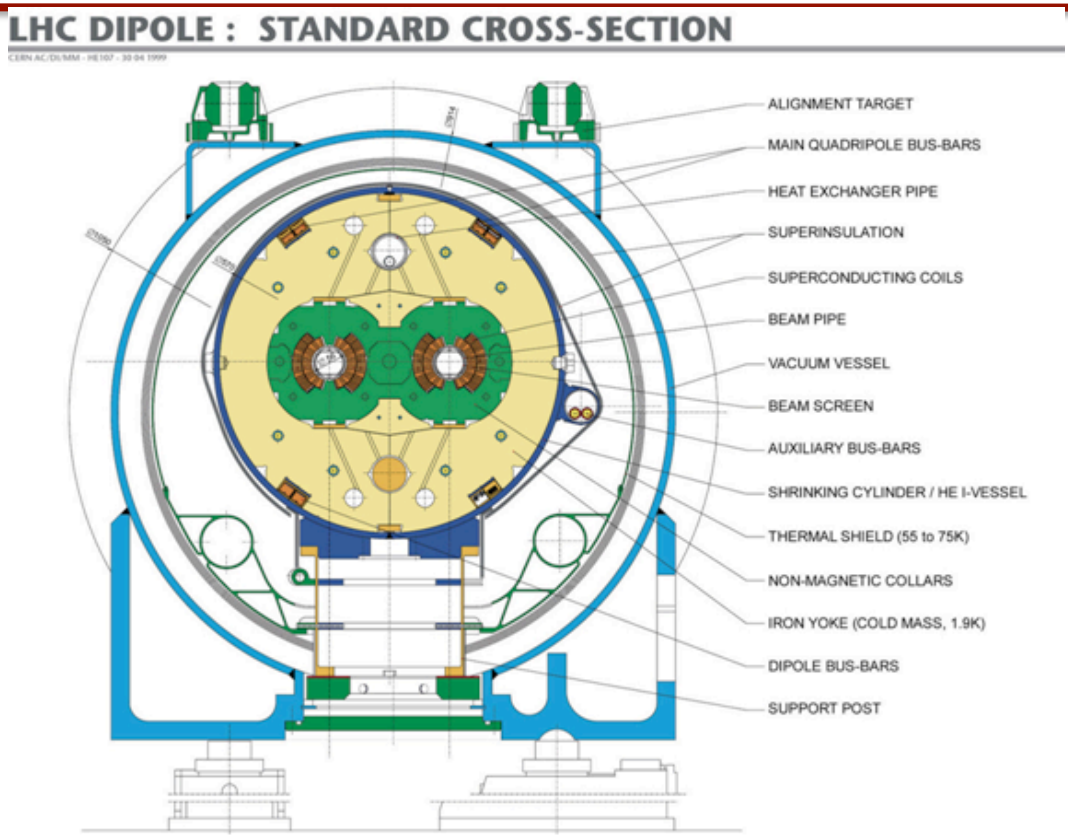
SPS physics beams

	Machine	E_{inj}	γ	Circumference (m)	Factor	T_{rev} (μs)
Linac 2 ➔	PSB	50 MeV	1	157		1.67
	PS	1.4 GeV	2.5	628	4	2.29
	SPS	14 GeV	27.6	6911	11	23
	LHC	450 GeV	480	26658	27/7	89

- PSB (4 rings)
  - Increases energy from 50 MeV to 1.4 GeV
  - Fills PS machine with successive extraction from 4 rings
- PS
  - Increases energy from 1.4 GeV to 14 GeV
  - Fills SPS machine with 2 x 5 turn slow extraction
- SPS
  - Increases energy from 14 GeV to 450 GeV
  - Delivers a continuous stream of 450 GeV protons (slow extraction)

Schematics of the LHC



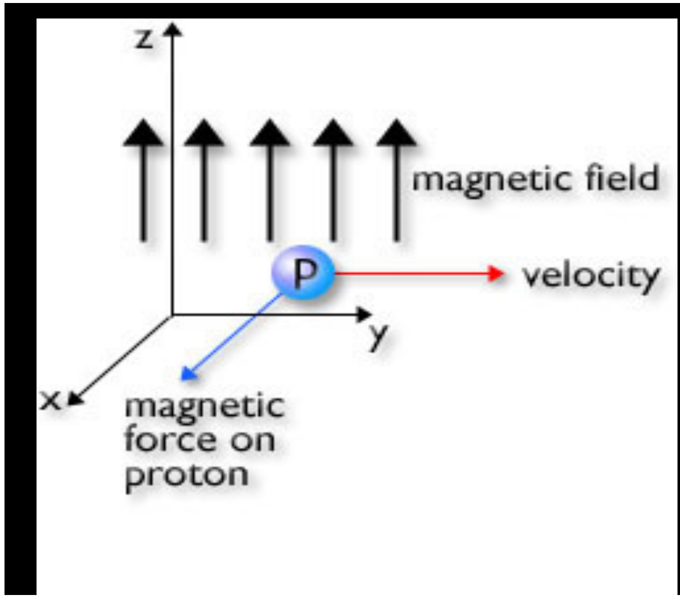


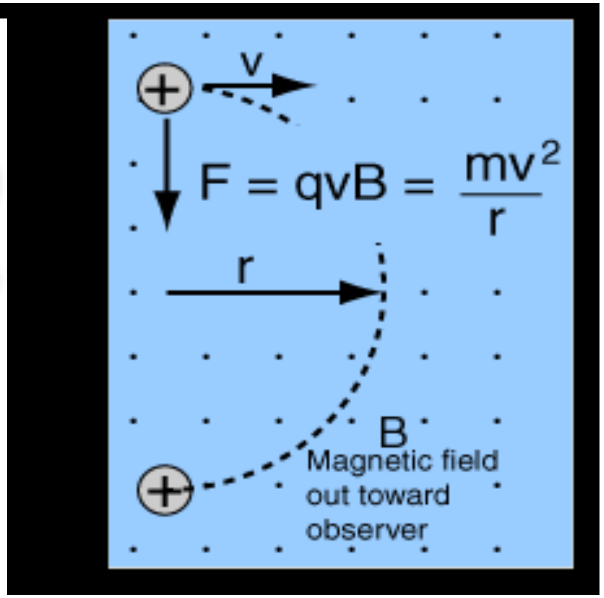
LHC MAIN COMPONENTS

LHC magnets

LHC dipoles

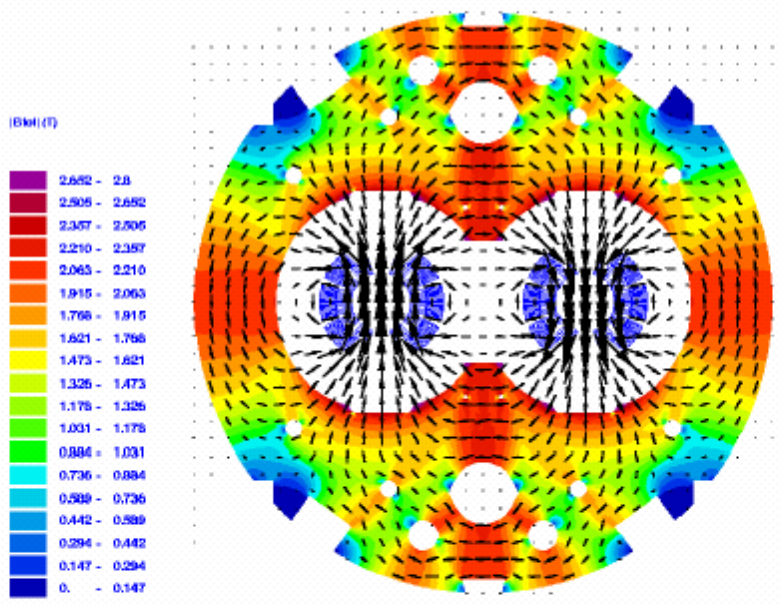
- Most of the 27km is filled with magnets
- Dipole magnets bend the beam
- The more energy, the greater the magnetic field



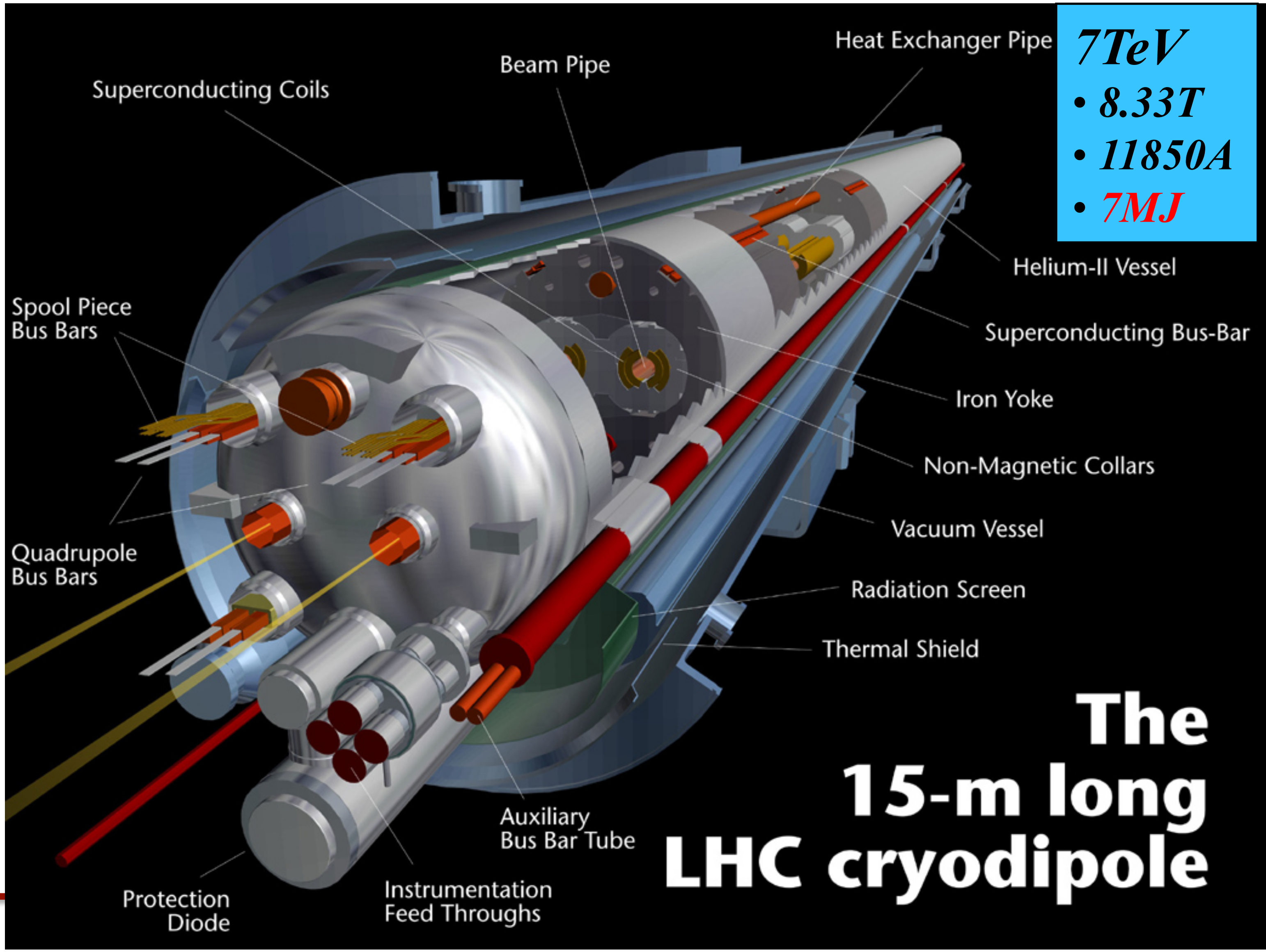


Principal LHC design parameters

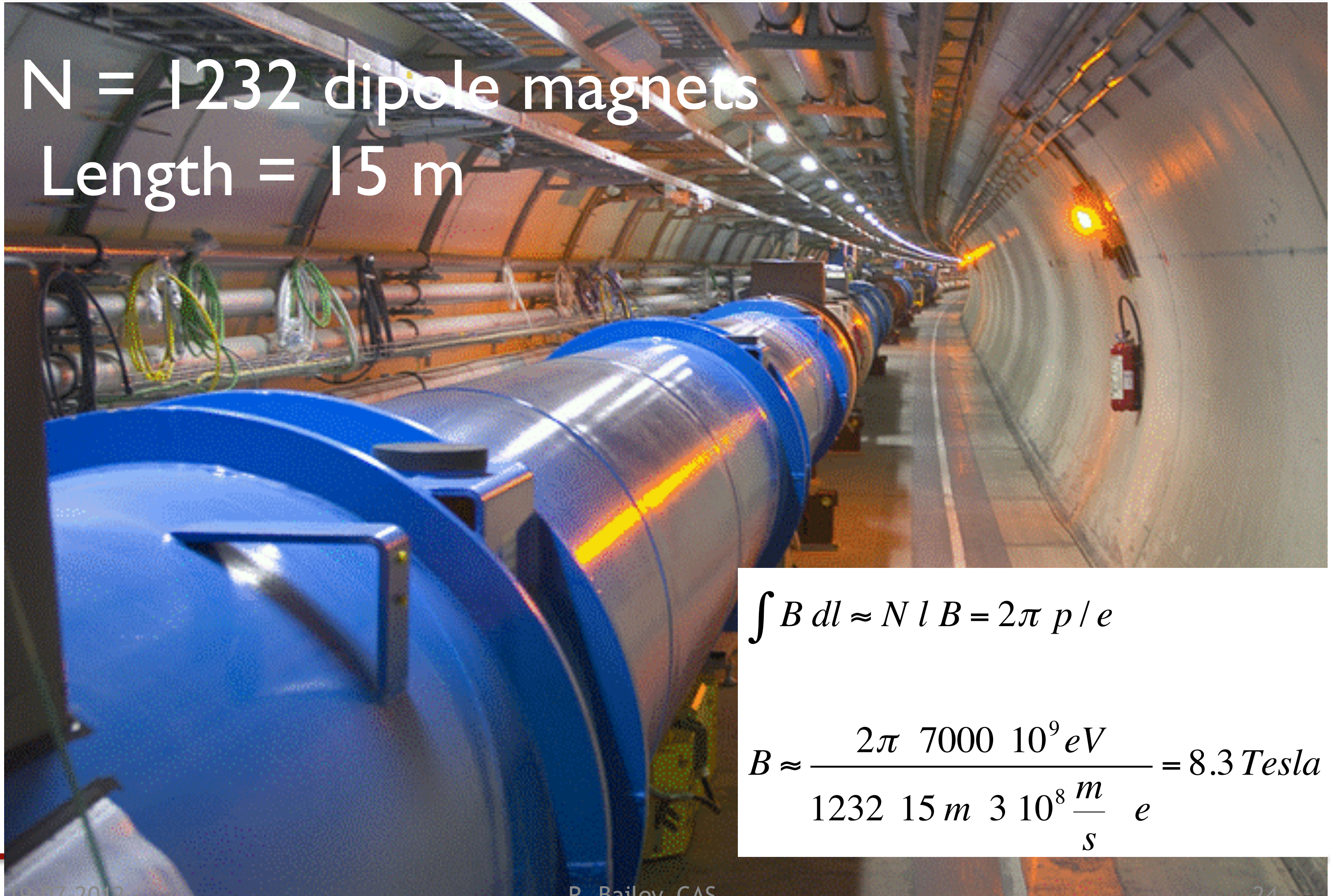
- Energy 7 TeV per beam ⇔ Dipole field 8.33Tesla
  - Superconducting technology needed to get such high fields
  - Tunnel cross section (4m) excludes 2 separate rings (unlike RHIC)
  - Hence twin aperture magnets in the arcs



LHC dipoles (1232 of them) operating at 1.9K



Superconducting magnets inside the LHC tunnel



N = 1232 dipole magnets

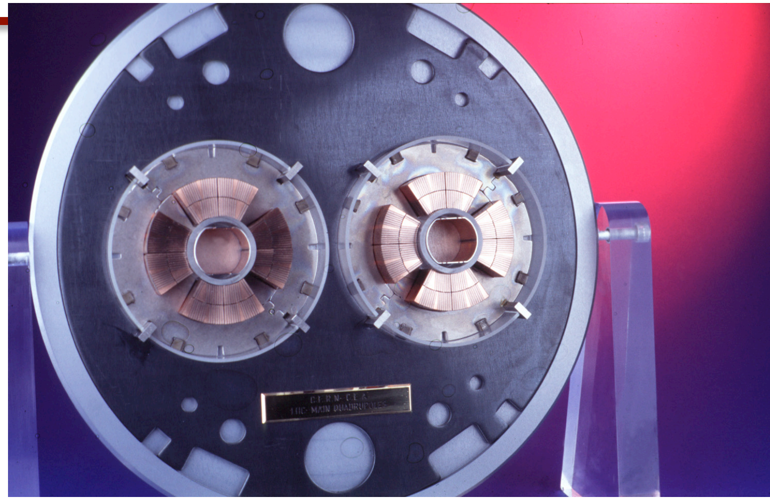
Length = 15 m

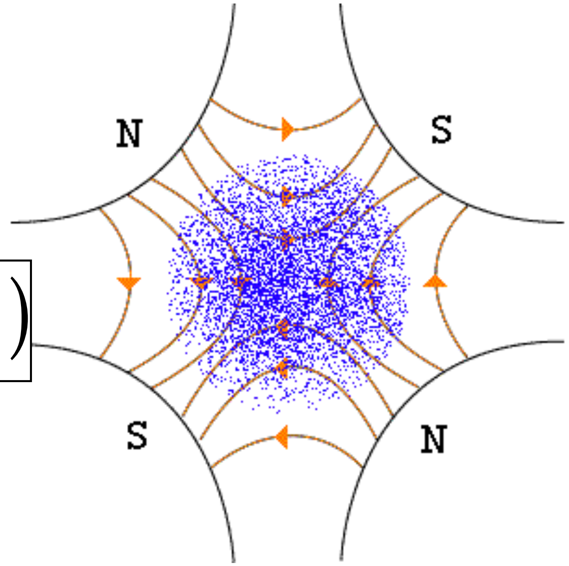
$$\int B\, dl \approx N\, l\, B = 2\pi\ p / e$$

$$B \approx \frac{2\pi\ \ 7000\ \ 10^{9}\, eV}{1232\ \ 15\, m\ \ 3\ 10^{8}\, \frac{m}{s}\ \ \ e} = 8.3\, Tesla$$

Quadrupole Magnets

- Keep the beams together
- Focus the beams at the collision points
- No magnetic field at the centre of the quadrupole
- The magnetic field increases linearly with the distance to the centre of the quadrupole
- One magnet focuses in one plane at a time, defocuses in the other





Single particle movement:

$$x(s) = A\sqrt{\beta_x(s)}\cos\left(\phi(s)+\phi_0\right)$$

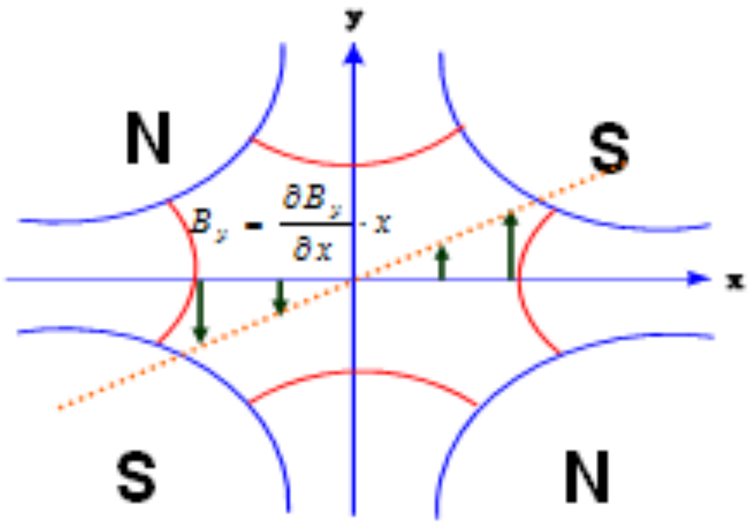
Beam envelope:

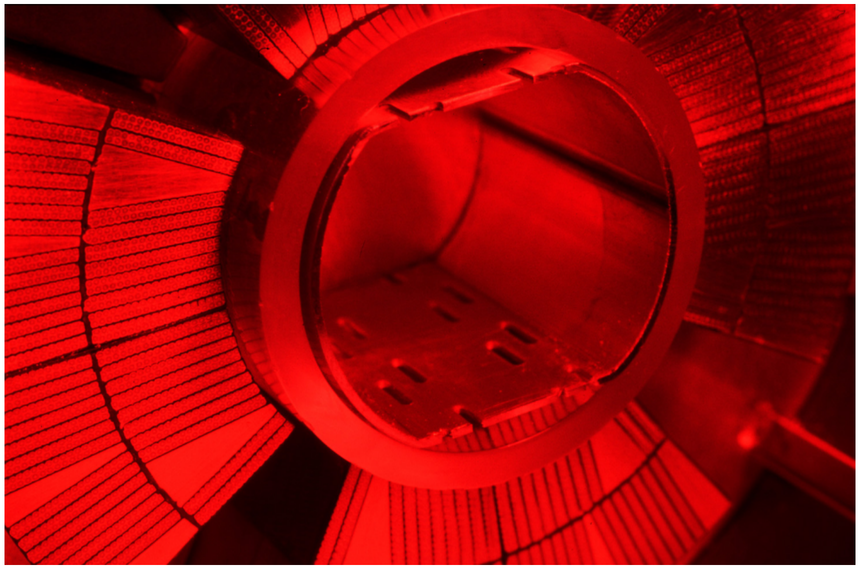
$$\sigma_x(s) = \sqrt{\varepsilon_x \beta_x(s)}$$

Focus beam at experiment, β very small: β*

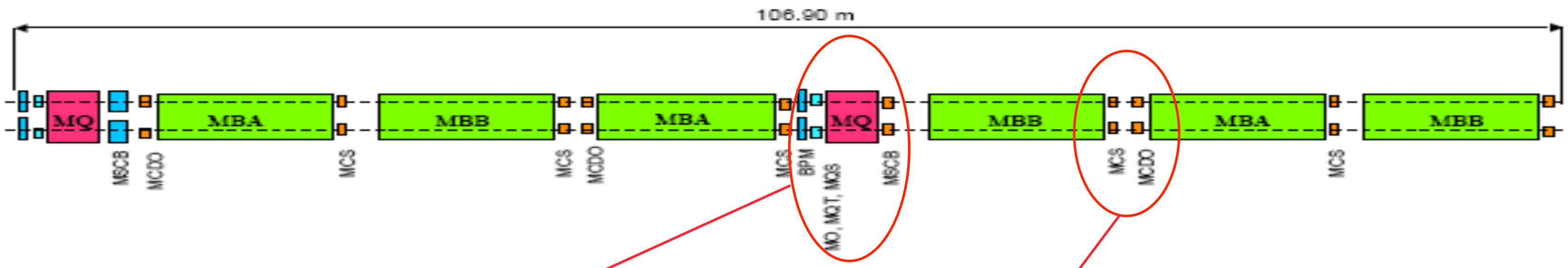
Quadrupoles

- Quadrupole magnets focus the beam at the collision point
- Focus in one plane, defocus in the other ~400 superconducting
- FODO cell (alternate gradient focusing)





The arcs



MQT: trim quadrupole

MQS: skew trim quadrupole

MO: lattice octupole

MSCB: sextupole (skew sextupole) + orbit corrector

MCS: spool piece sextupole

MCDO: spool piece octupole + decapole

- 23 regular FODO cells in each arc
  - 2 Quadrupoles, 6 dipole magnets,
- 106.9m long, made from two 53.45m long half-cells

Cryogenics system

Cooled by liquid helium, distributed over 27km

Superconductivity for accelerators

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

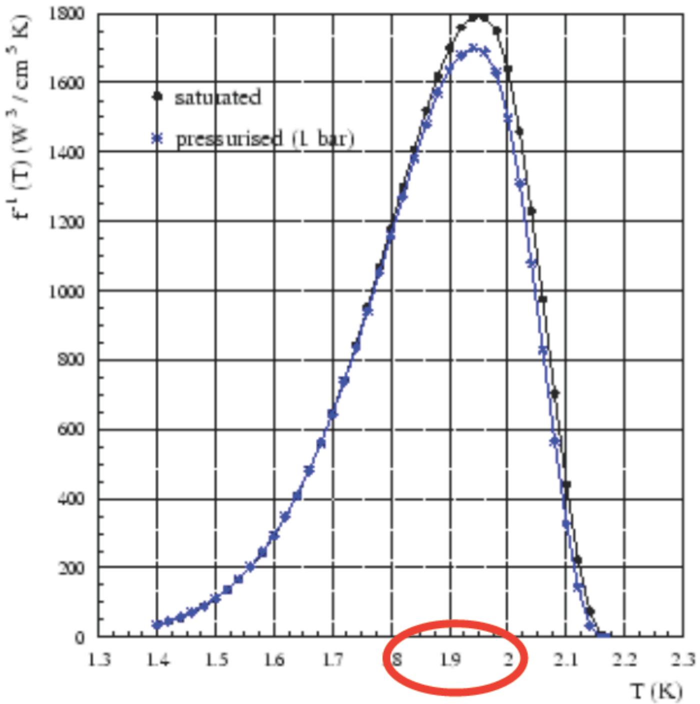
- The distance between the working point and the critical surface for a fixed B field and Current Density is the temperature margin (critical temperature)

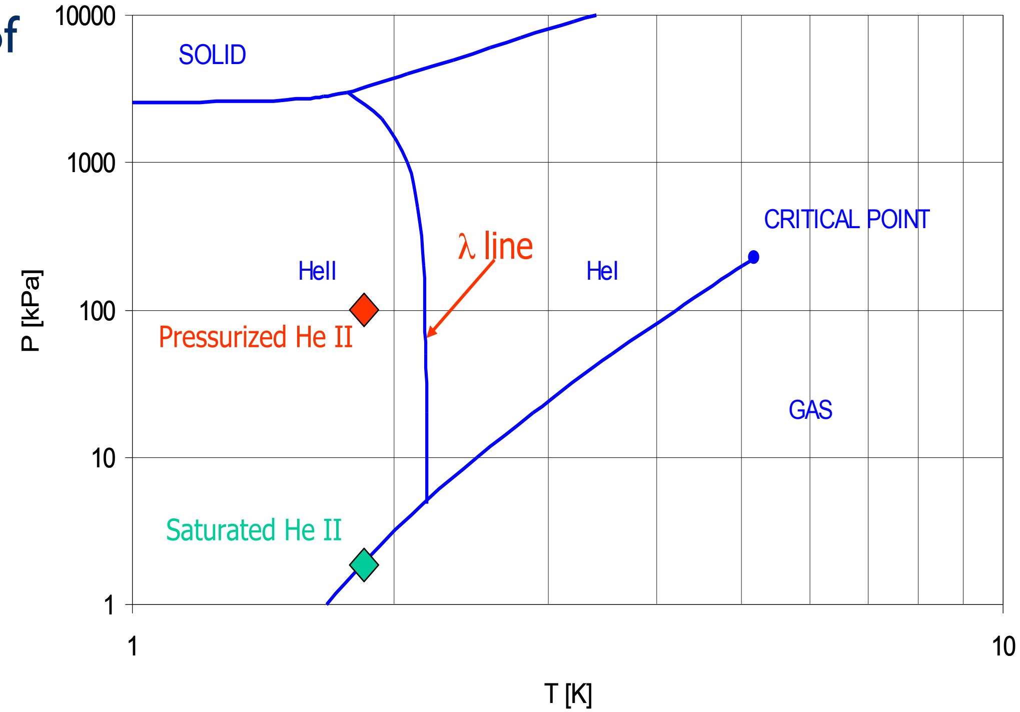
- Transition to a normal conducting state is called magnet quench

Liquid helium diagram

- Liquid helium at a temperature of 1.9K is used to cool the superconducting magnets

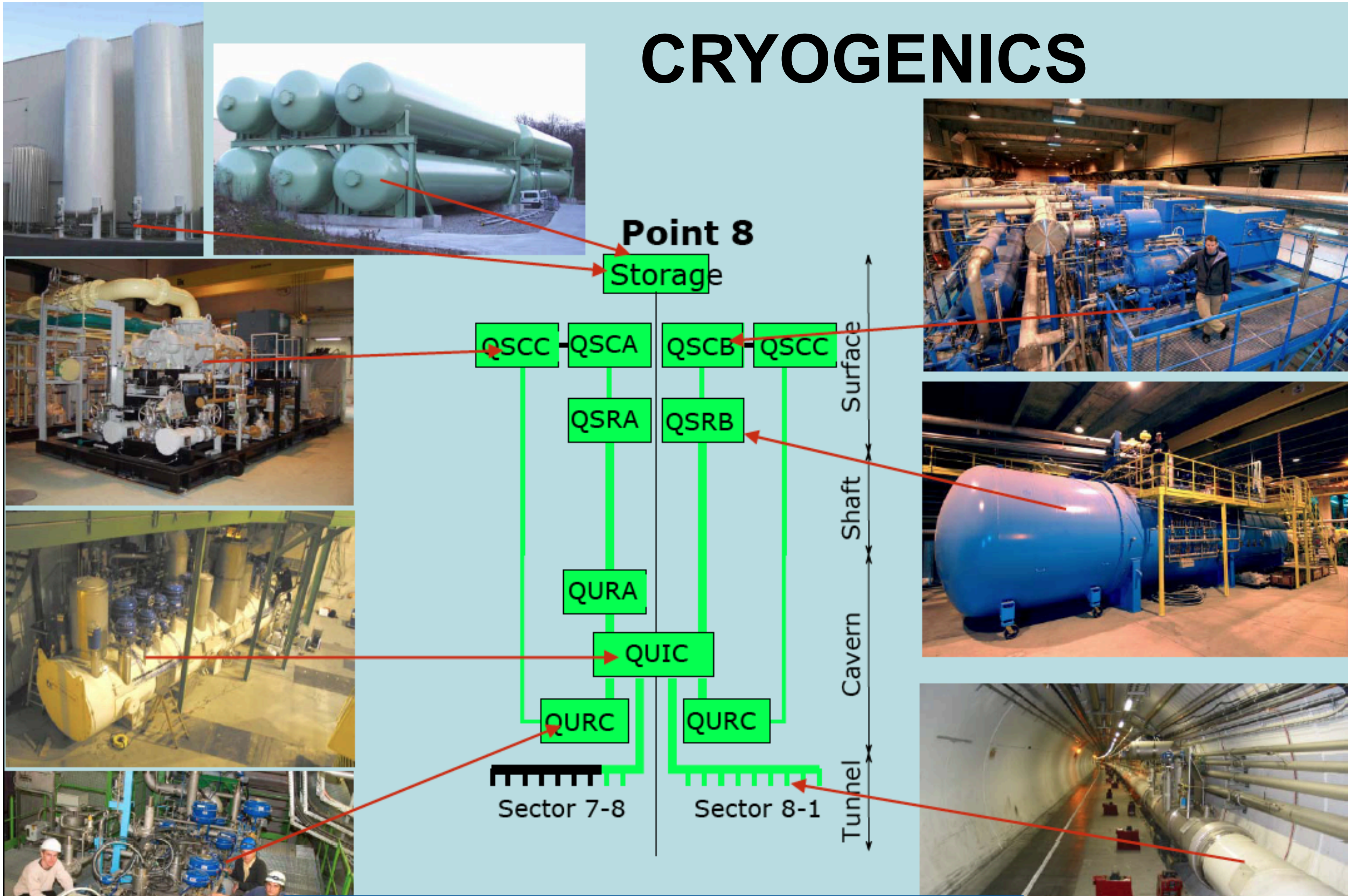
Thermal conductivity of He vs T





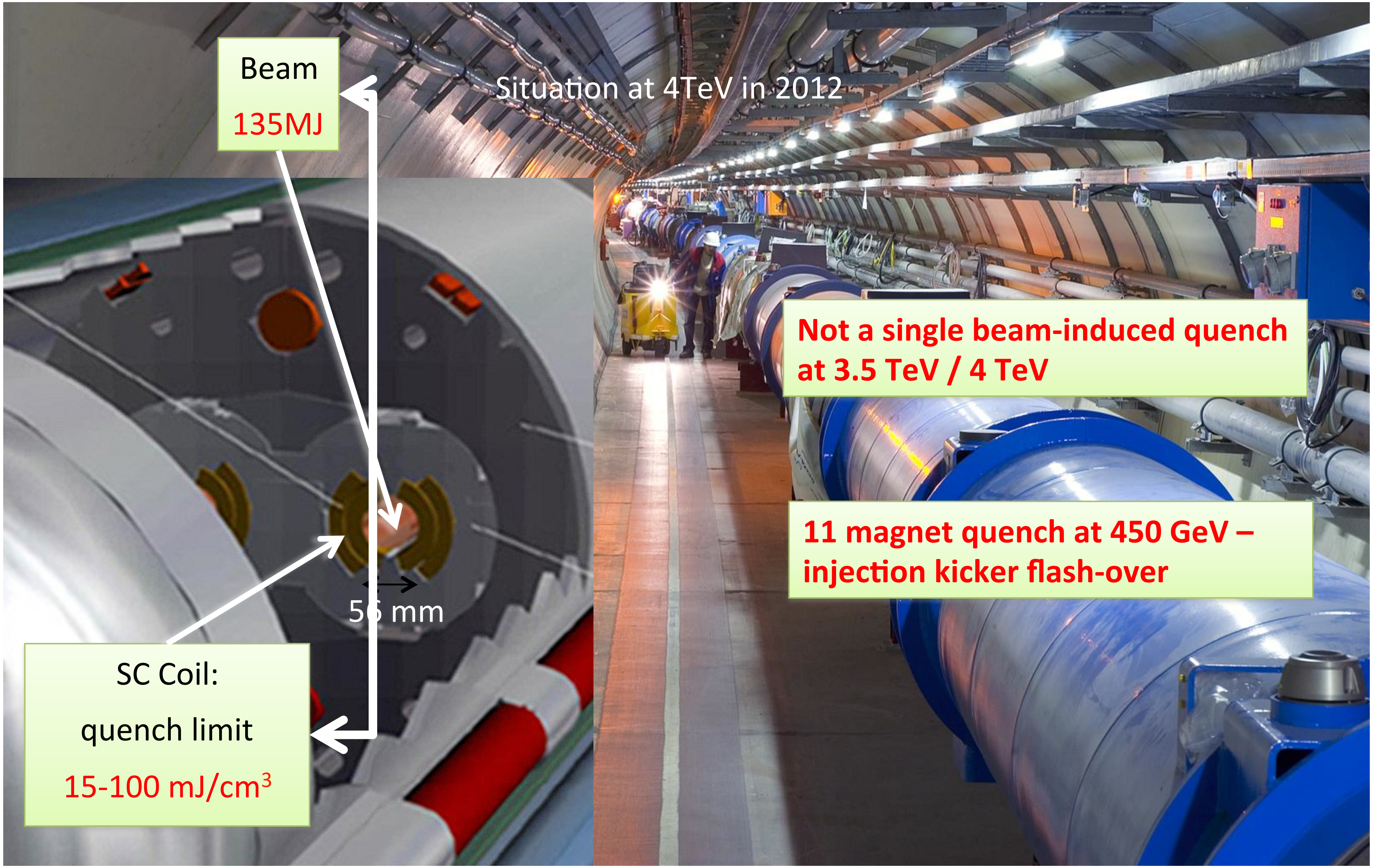
- Around 1.9K the thermal conductivity of liquid helium reaches a maximum
- If the beam heats the He the heat is dissipated with very high efficiency

CRYOGENICS



- **24 km of superconducting magnets @1.9 K**
- **88 tons of superfluid helium at 1.9 K**

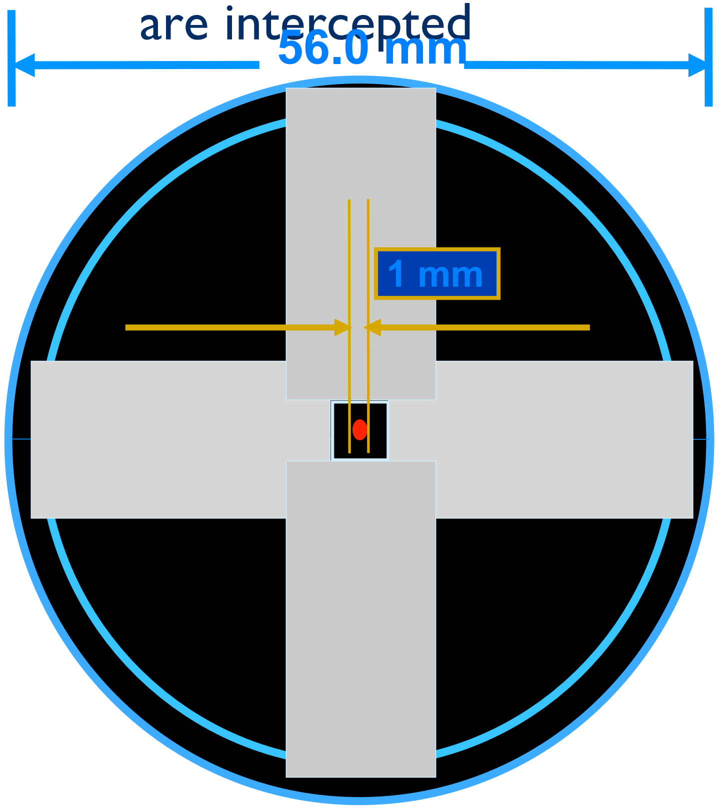
Machine protection – the challenge

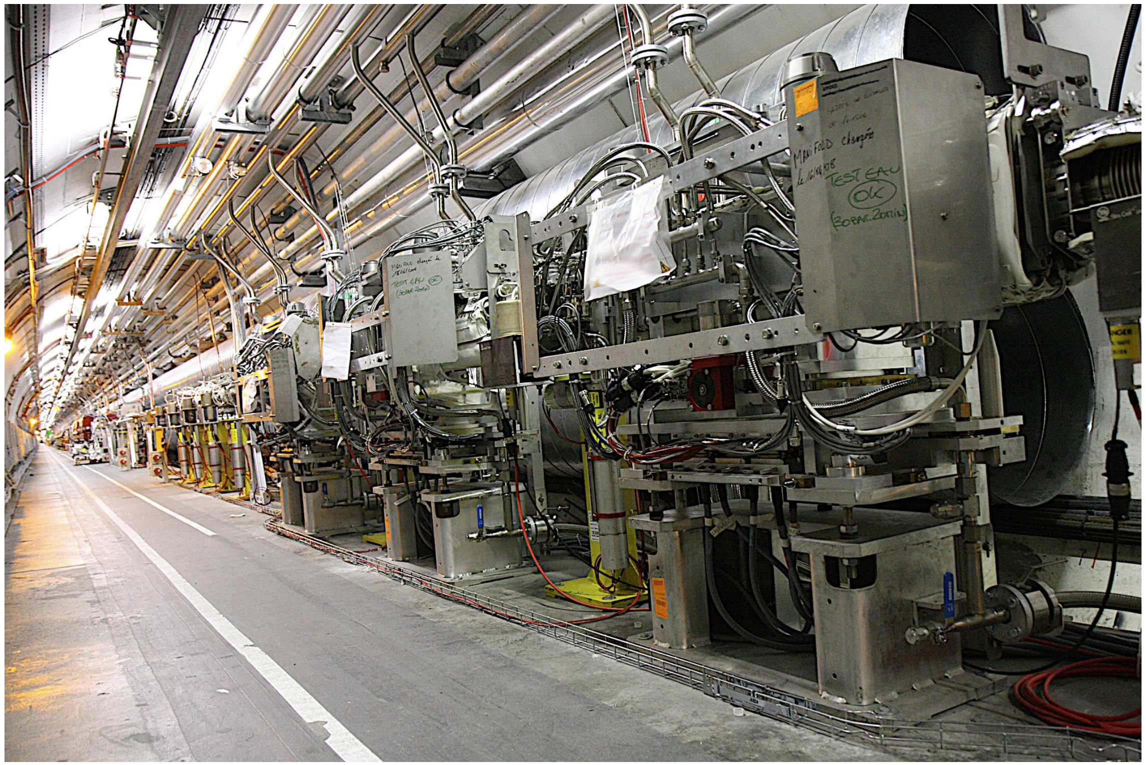


Collimators

Collimators (points 3 and 7)

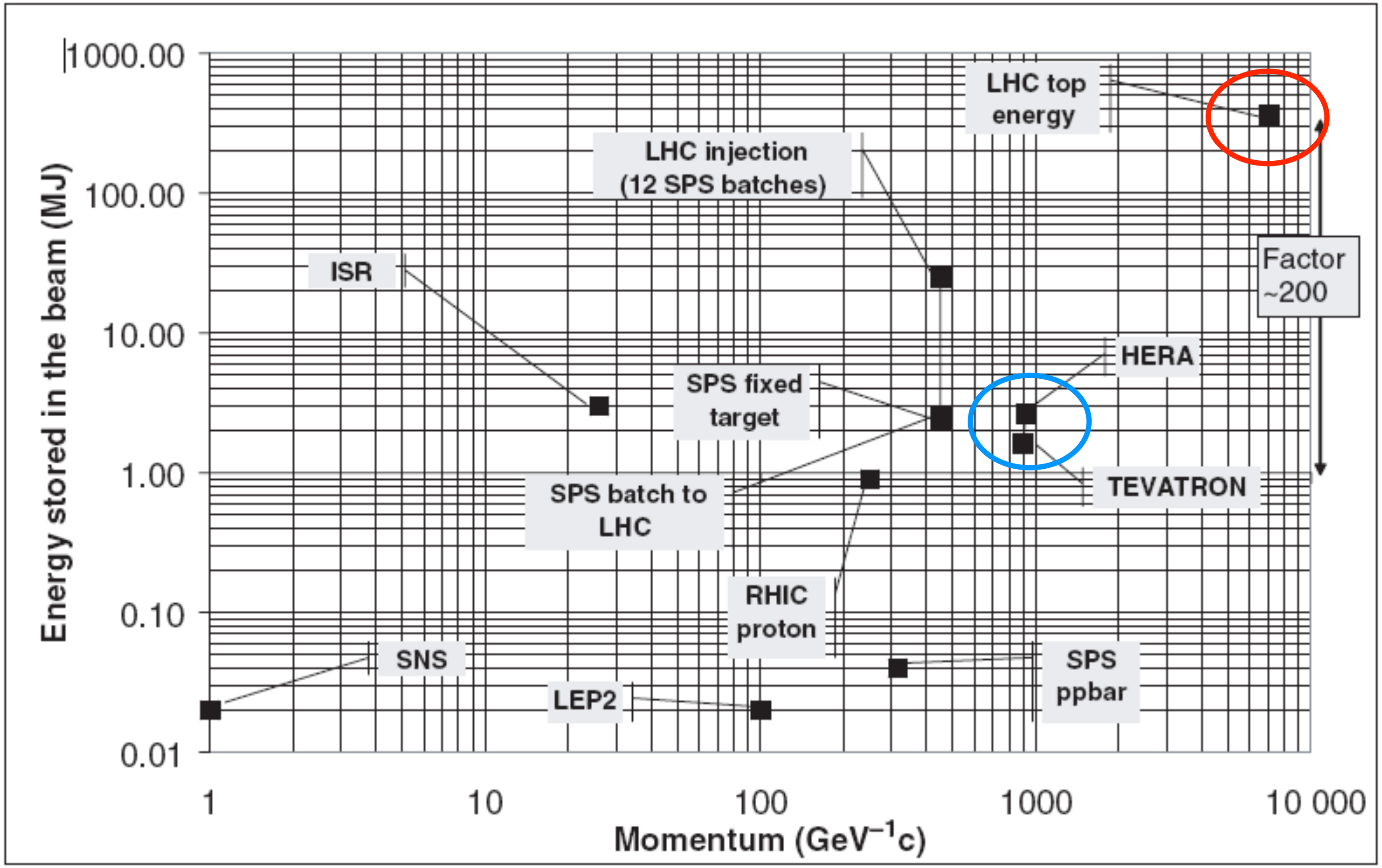
- Protect machine elements by removing particles oscillating away from the design orbit
- Almost 100 collimators and absorbers
- Alignment tolerances < 0.1 mm to ensure that over 99.99% of the protons are intercepted



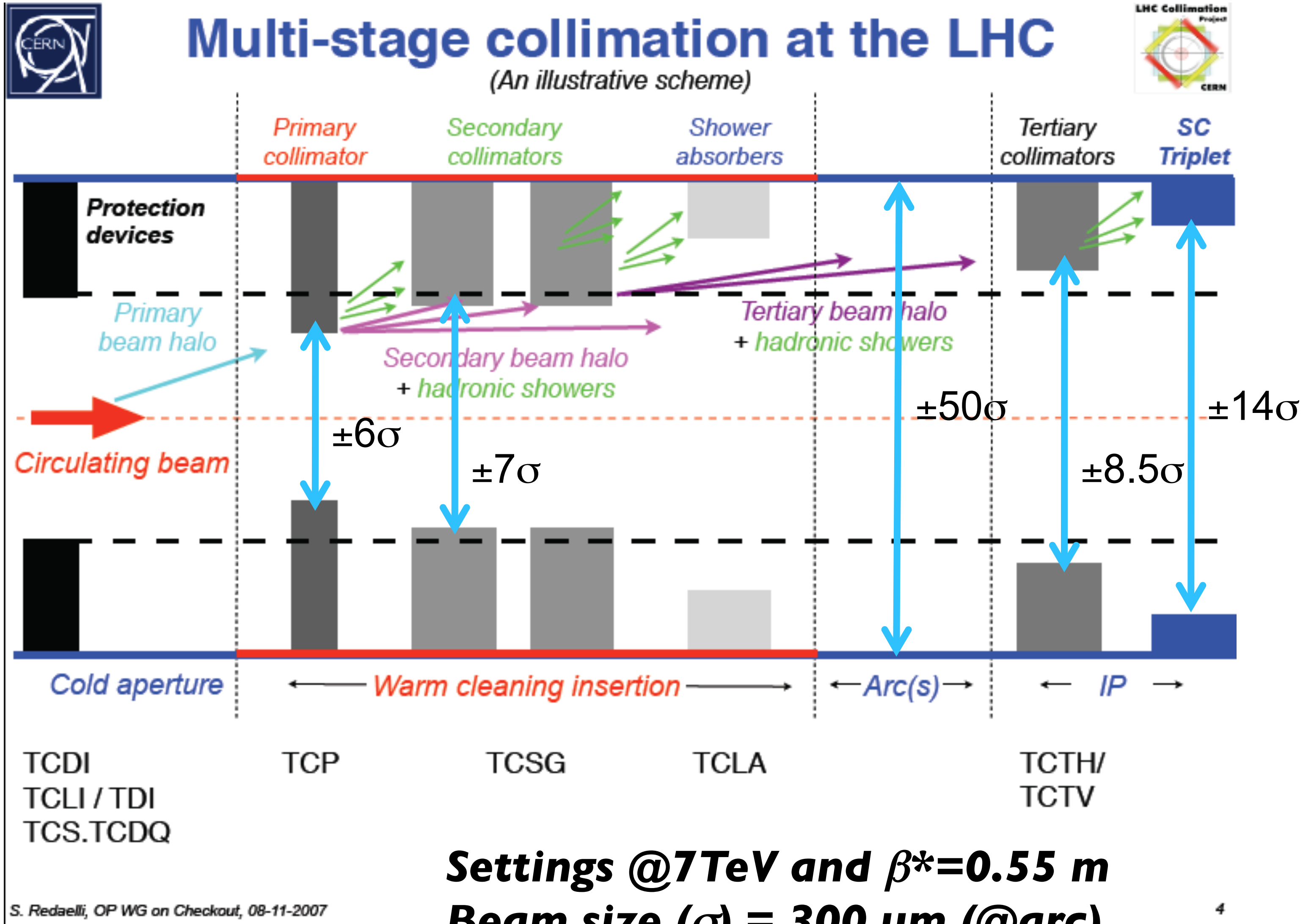


Energy stored in the beams

362 MJ at 7 TeV



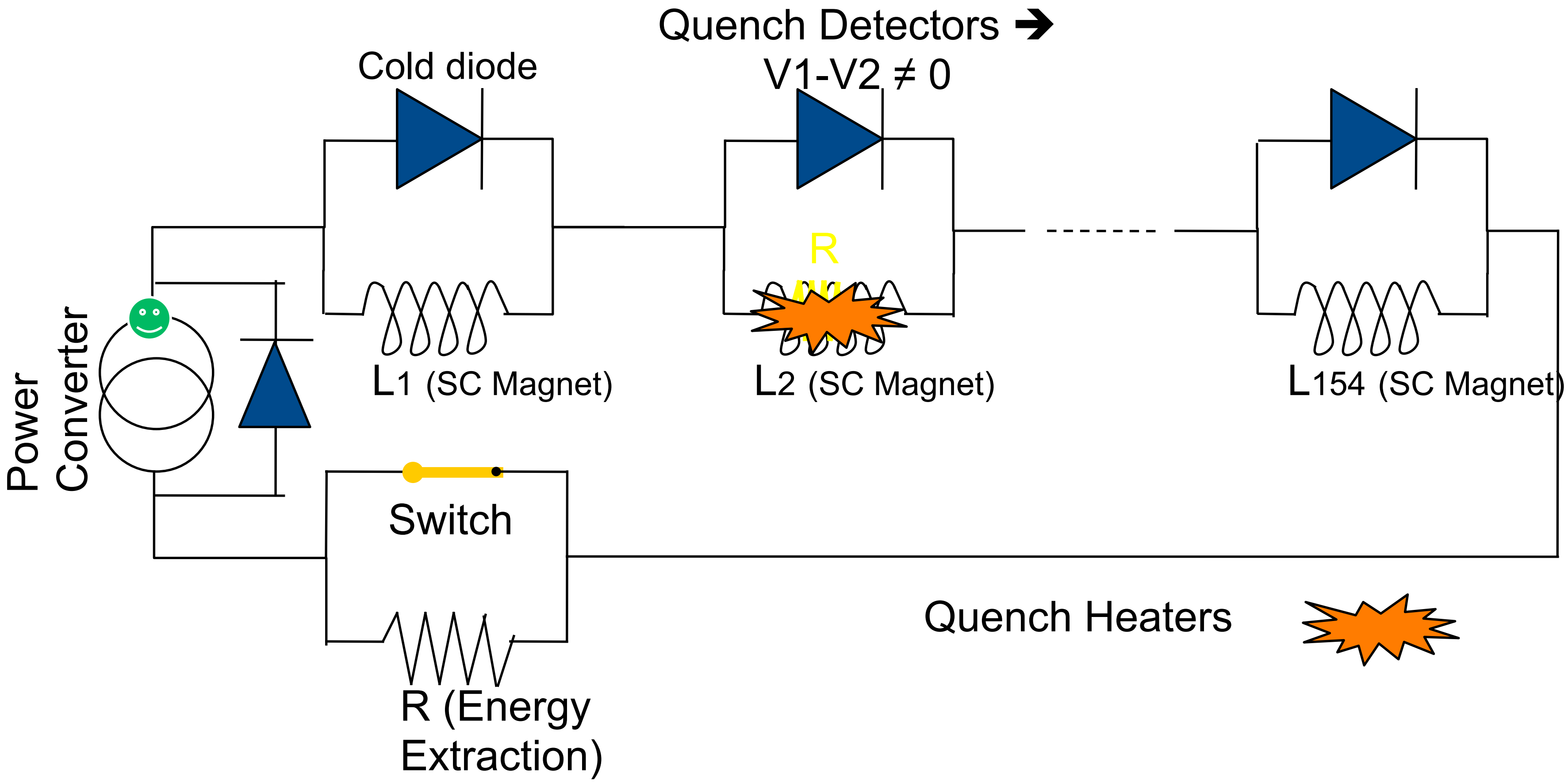
LHC aperture and collimators



Settings @7TeV and β^*=0.55 m
Beam size (σ) = 300 μm (@arc)
Beam size (σ) = 17 μm (@IR1, IR5)

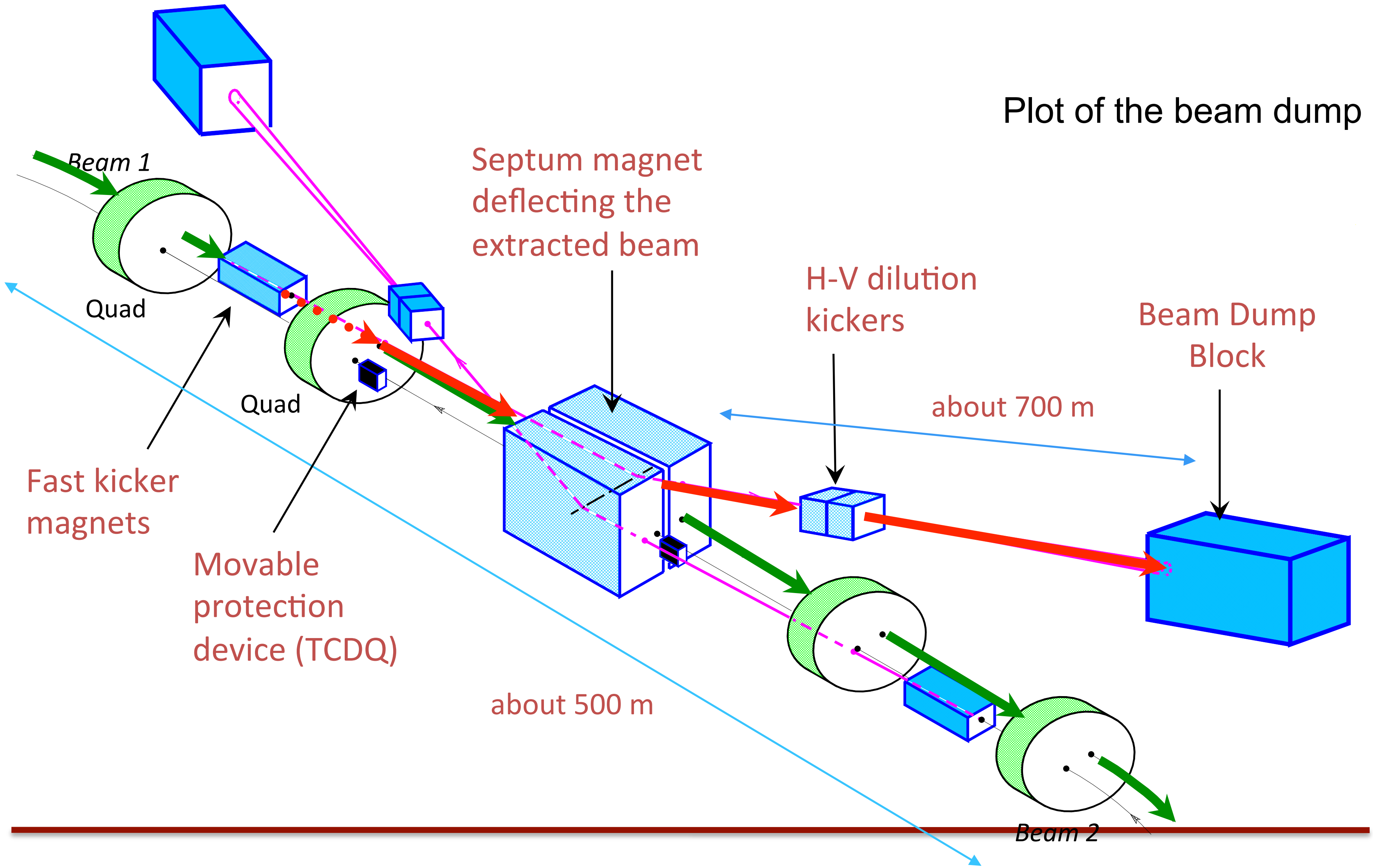
Quench Protection System

- Extracts the energy stored in the magnets in a safe way

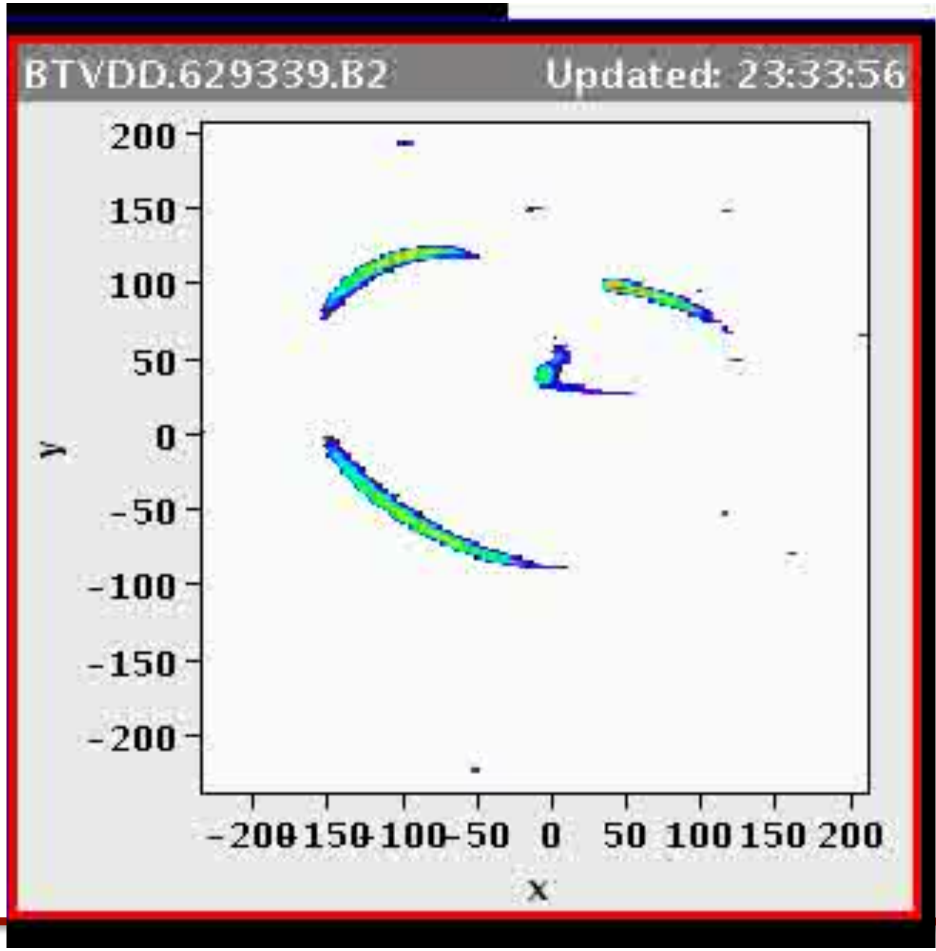


Beam dump system

Layout of LHC beam dumping system



- Beam gets diluted before it is dumped in the beam dump block



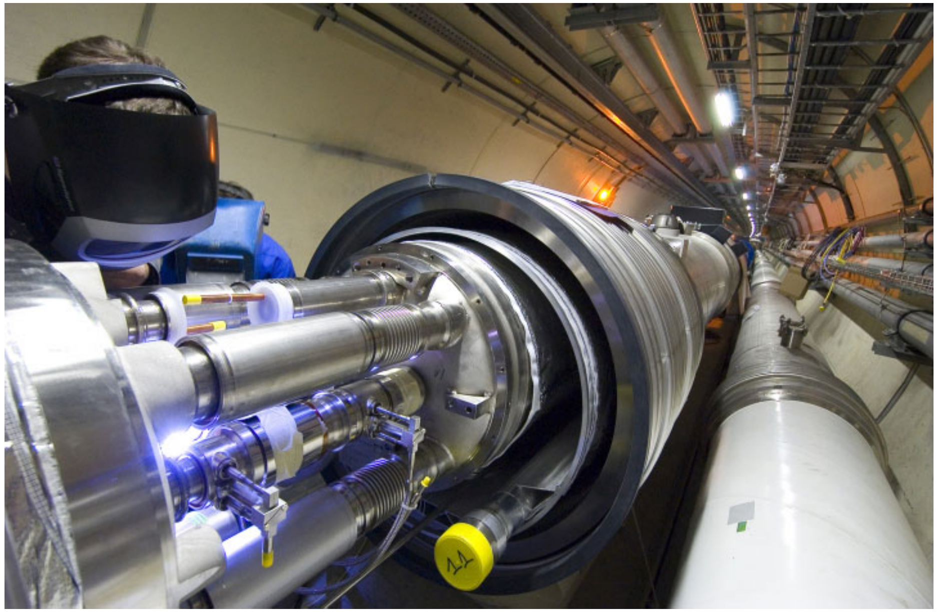
Vacuum

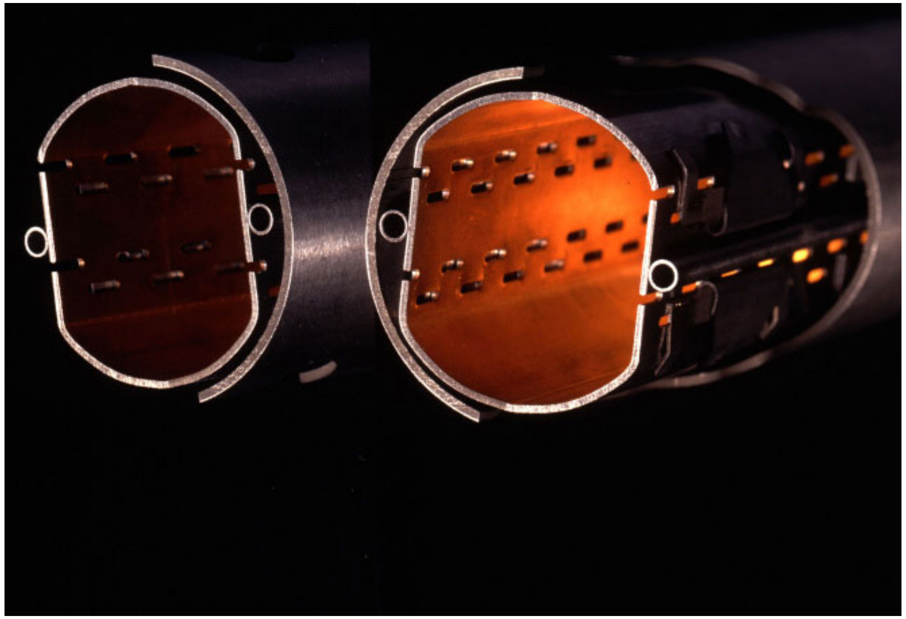
LHC Vacuum

- To avoid unwanted collisions between the beam and molecules inside the beam pipe

Beam vacuum ~10^{-10} mbar

(~3 million molecules/cm^3)

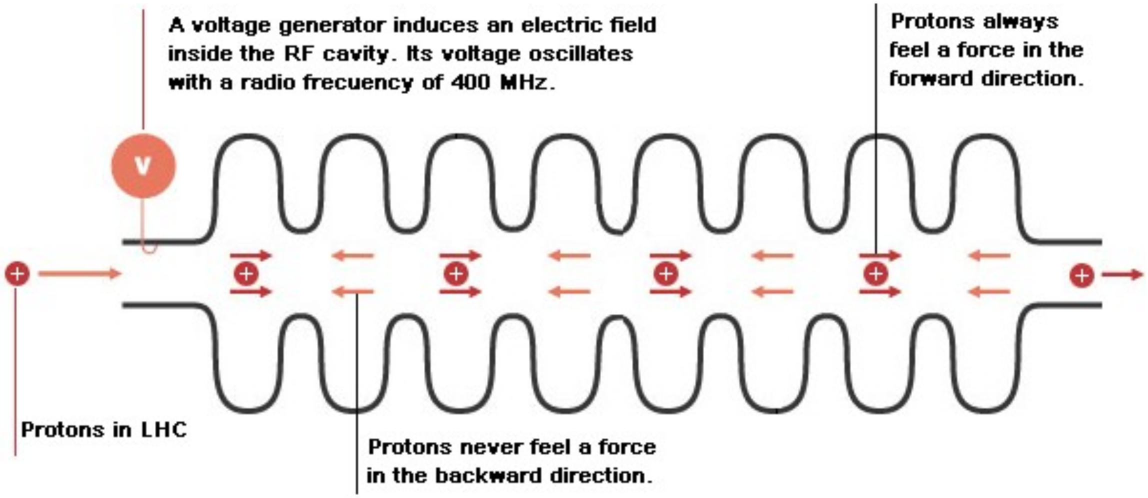




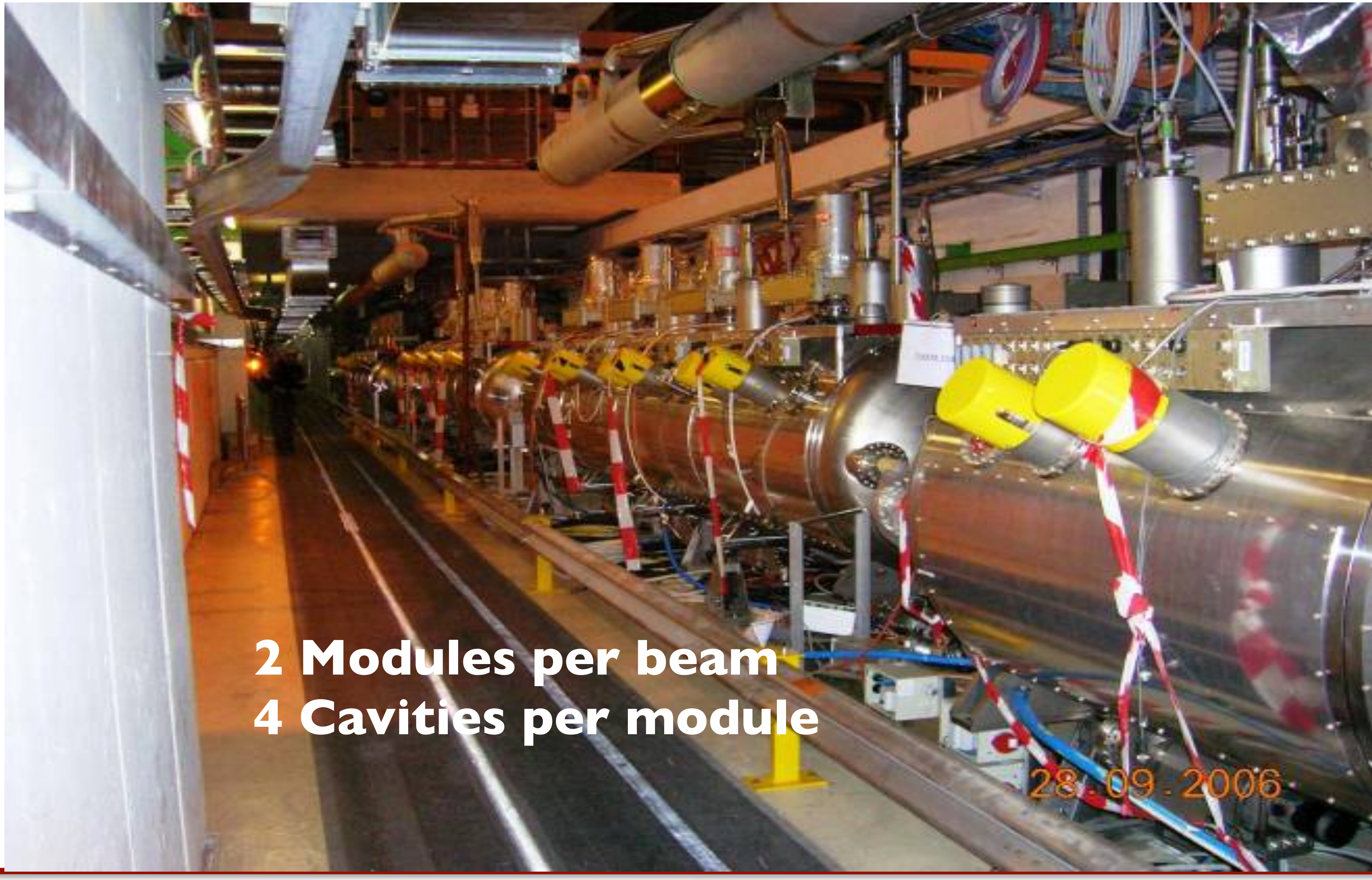
Radio Frequency Cavities

Radio Frequency Cavities

- Provide power to the beam during the accelerating process from 450 GeV to top energy
- To keep the proton bunches tightly bunches to ensure high luminosity
- Superconducting to reduce Beam Impedance
- RF = Oscillation of field at 400 MHz (Radio Frequency)



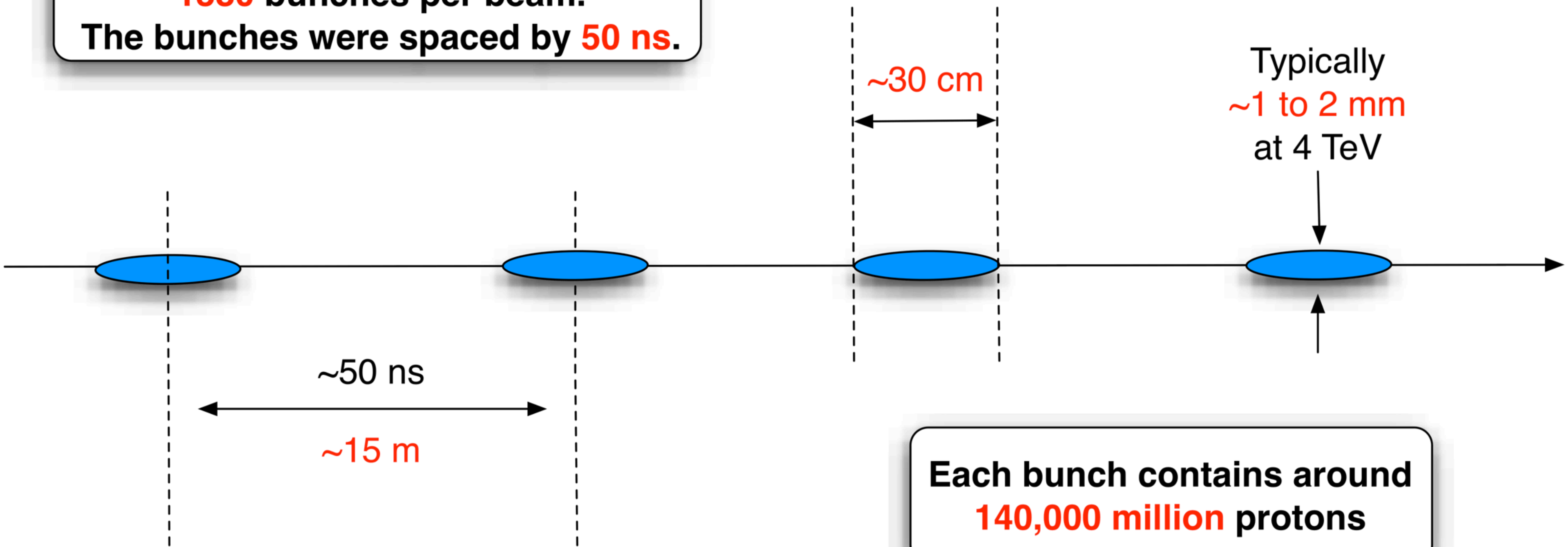
Radio Frequency systems (point 4)



The LHC beam

LHC beams

In 2011 the LHC operated with
1380 bunches per beam.
The bunches were spaced by 50 ns.



Each bunch contains around
140,000 million protons

LHC parameters

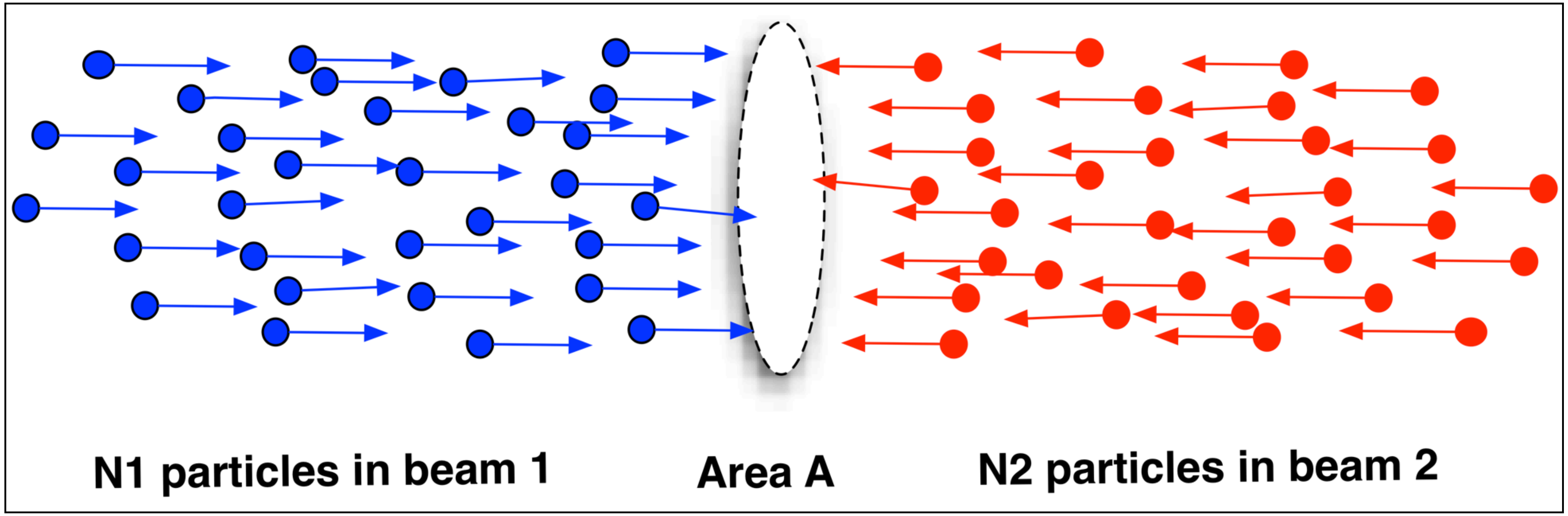
Controlled parameters	Nominal	2011	Aim for 2012
Beam energy (TeV)	7.0	3.5	4.0
Number of particles per bunch	$1.15\ 10^{11}$	$1.5\ 10^{11}$	$1.7\ 10^{11}$
Number of bunches per beam *	2808	1380	1380
Bunch spacing (ns)	25	50	50
Crossing angle (μrad)	285	240	290
Norm transverse emittance (μm rad)	3.75	2.5	2.5
Bunch length (cm)	7.55	10.1	10.1
Beta function at IP 1, 2, 5, 8 (m)	0.55,10,0.55,10	1,3,1,10	0.6,3,0.6,3

Derived parameters	Nominal	2011	Aim for 2012
Luminosity in IP 1 & 5 ($cm^{-2}\ s^{-1}$)	10^{34}	$3.5\ 10^{33}$	$6\ 10^{33}$
Luminosity in IP 8 ($cm^{-2}\ s^{-1}$) **	$\sim 5\ 10^{32}$	$3\ 10^{32}$	$4\ 10^{32}$
Transverse beam size at IP 1 & 5 (μm)	16.7	25.9	18.8
Stored energy per beam (MJ)	362	116	132

* A few % of bunches do not contribute to luminosity

** Luminosity in IP 8 optimized as needed

Luminosity



$$\text{Number of potential collisions per unit area} = \frac{N_1 N_2}{A}$$

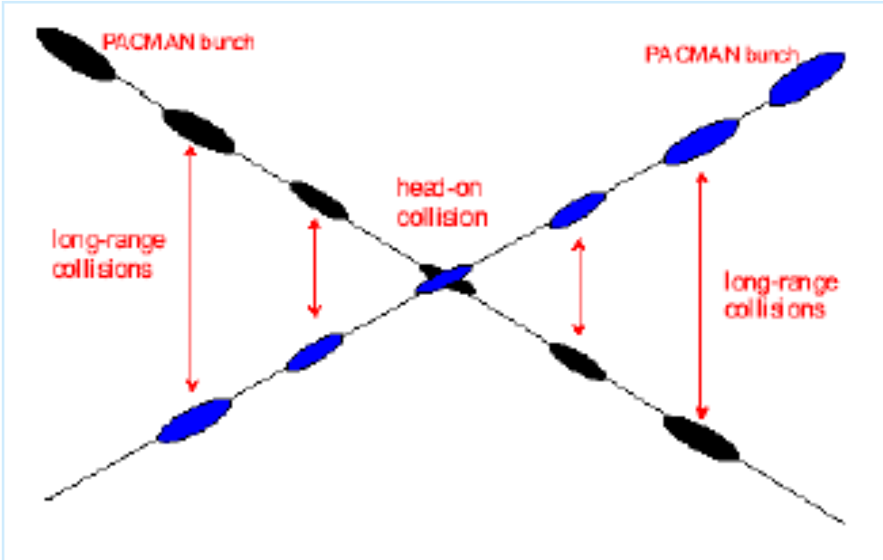
Luminosity

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n \beta^*} F$$

$$\sigma = \sqrt{\varepsilon\beta}$$

$$\varepsilon_n = \varepsilon\gamma$$

- Nearly all the parameters are variable
  - Number of particles per bunch N
  - Number of bunches per beam k_b
  - Relativistic factor (E/m_0) γ
  - Normalised emittance ε_n
  - Beta function at the IP β^*
  - Crossing angle factor F
    - Full crossing angle θ_c
    - Bunch length σ_z
    - Transverse beam size at the IP σ^*



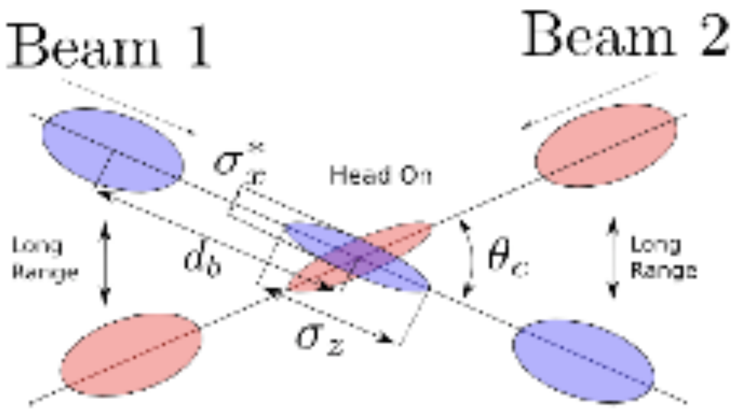
$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

Luminosity and pile up

- To have high luminosity we need:
  - High number of bunches
  - High populated bunches
  - Small beam sized at the interaction point

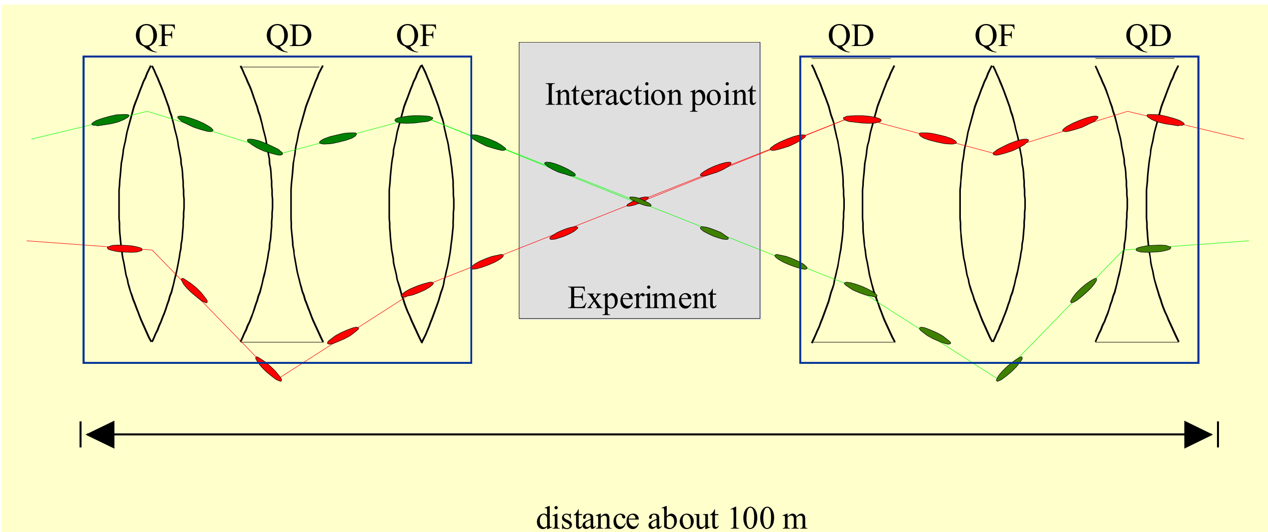
- « Pile up » is the number of events that occur in the same crossing
  - Depends on the bunch charge and beams sizes

Crossing angle



Angle at the interaction point to avoid that the bunches collides in other places than the IP (for instance in the LSS)

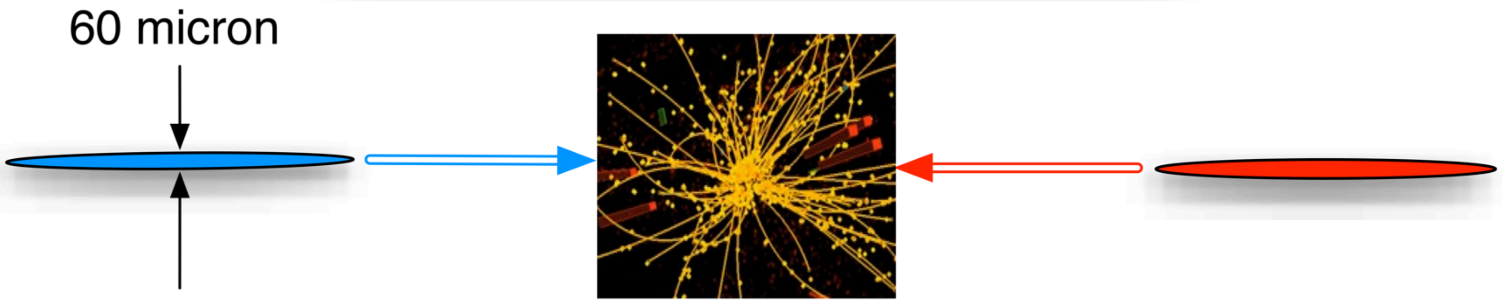
$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2 \cdot \sigma^*}\right)^2}$$



Θ_c	crossing angle	285 μrad
σ_z	RMS bunch length	7.55 cm
σ^*	RMS beam size (ATLAS-CMS)	16.7 μm
F	L reduc. Factor	0.836

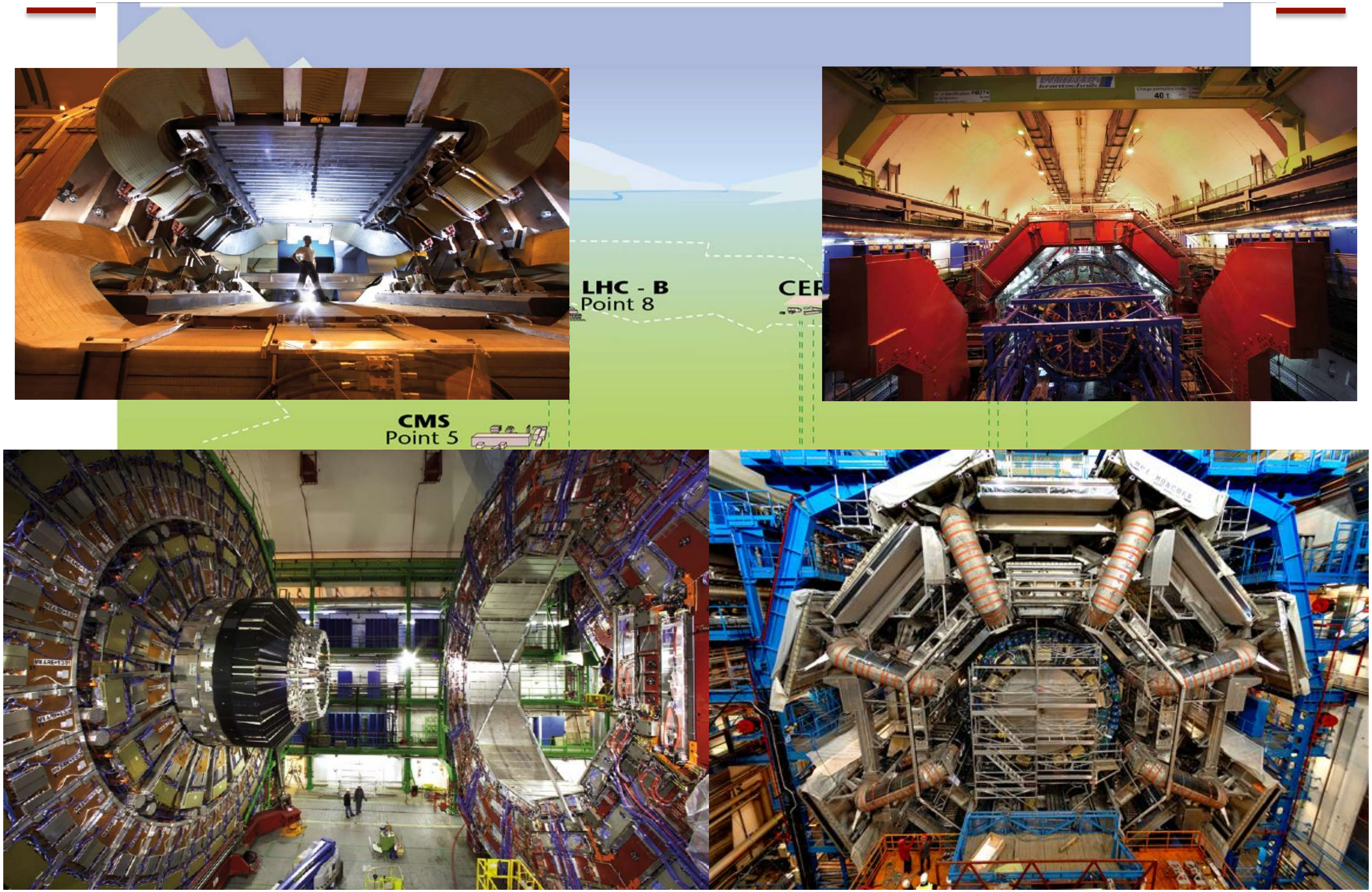
In 2012

140,000,000,000 protons a bunch
~30 collide at each bunch crossing

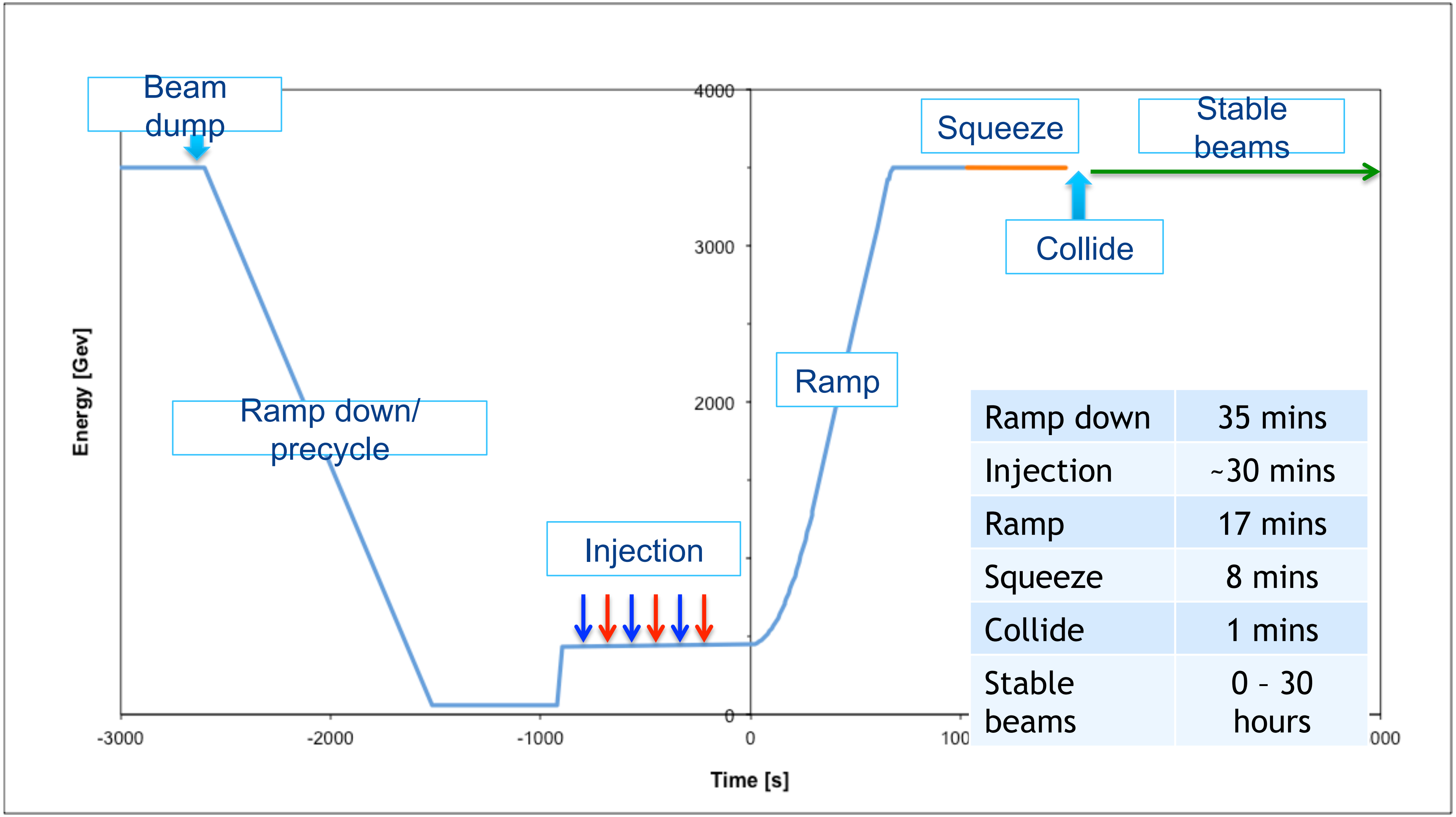


~30 collisions per crossing ← Pile up
11,000 crossings per second per bunch
1380 bunches
~400 million collisions per second

Interaction points (ATLAS, CMS, LHCb, ALICE)



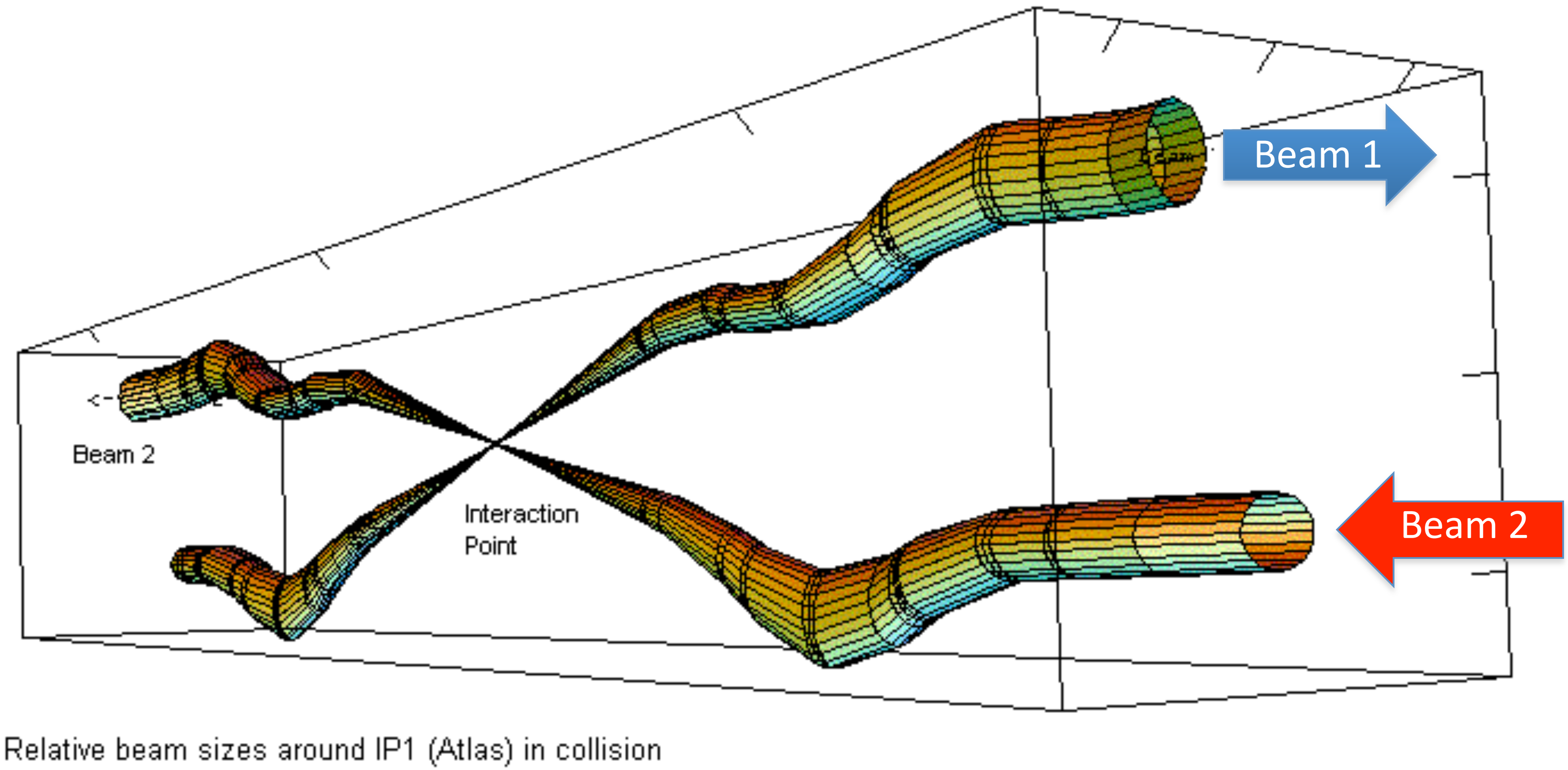
The LHC cycle 2011



Phase	Duration
Ramp down	35 mins
Injection	~30 mins
Ramp	17 mins
Squeeze	8 mins
Collide	1 mins
Stable beams	0 - 30 hours

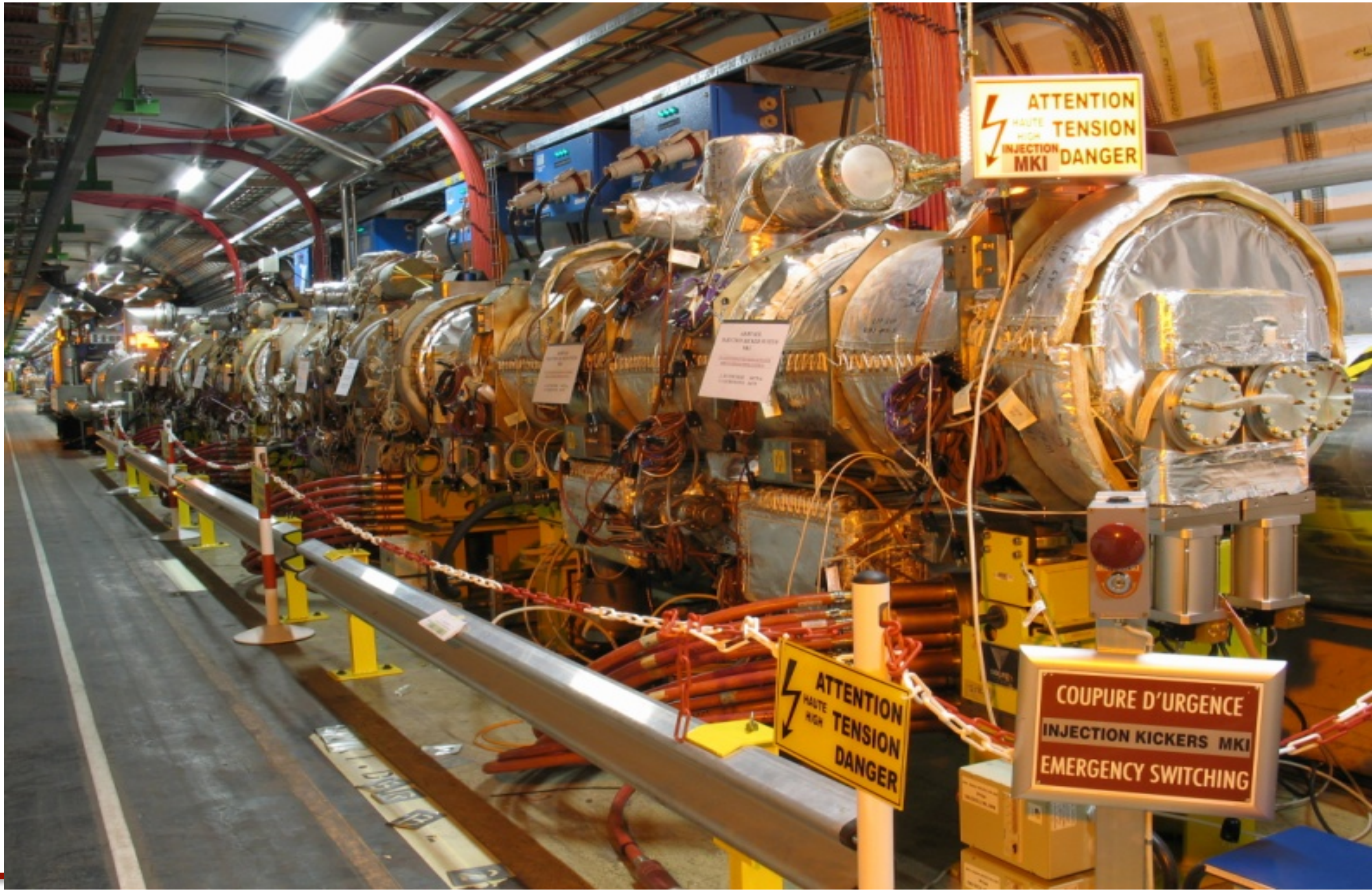
Fastest turn around time 2h07min

Squeeze



Focus beam down to very small sizes in the experiments using quadrupole magnets

Injection systems (points 2 and 8)



Excercises

- Calculate the instantaneous luminosity for the LHC assuming the nominal conditions
- Calculate the instantaneous luminosity for the LHC assuming the target 2012 parameters
- What bunch intensity would be needed to achieve instantaneous luminosity of 10^{34}Hz/cm^2 assuming the 2012 parameters