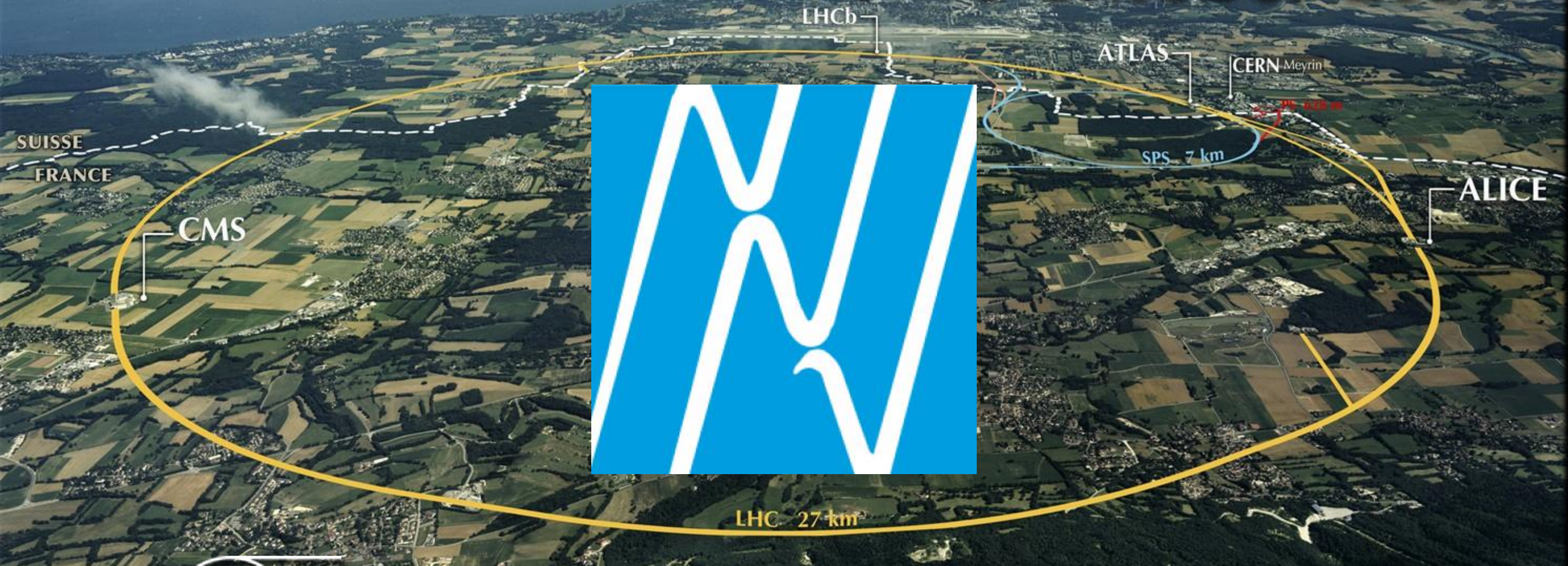
The LHC: How does it work?
NNV
Profielwerkstukreis
4 – 8 oktober 2021



CERN

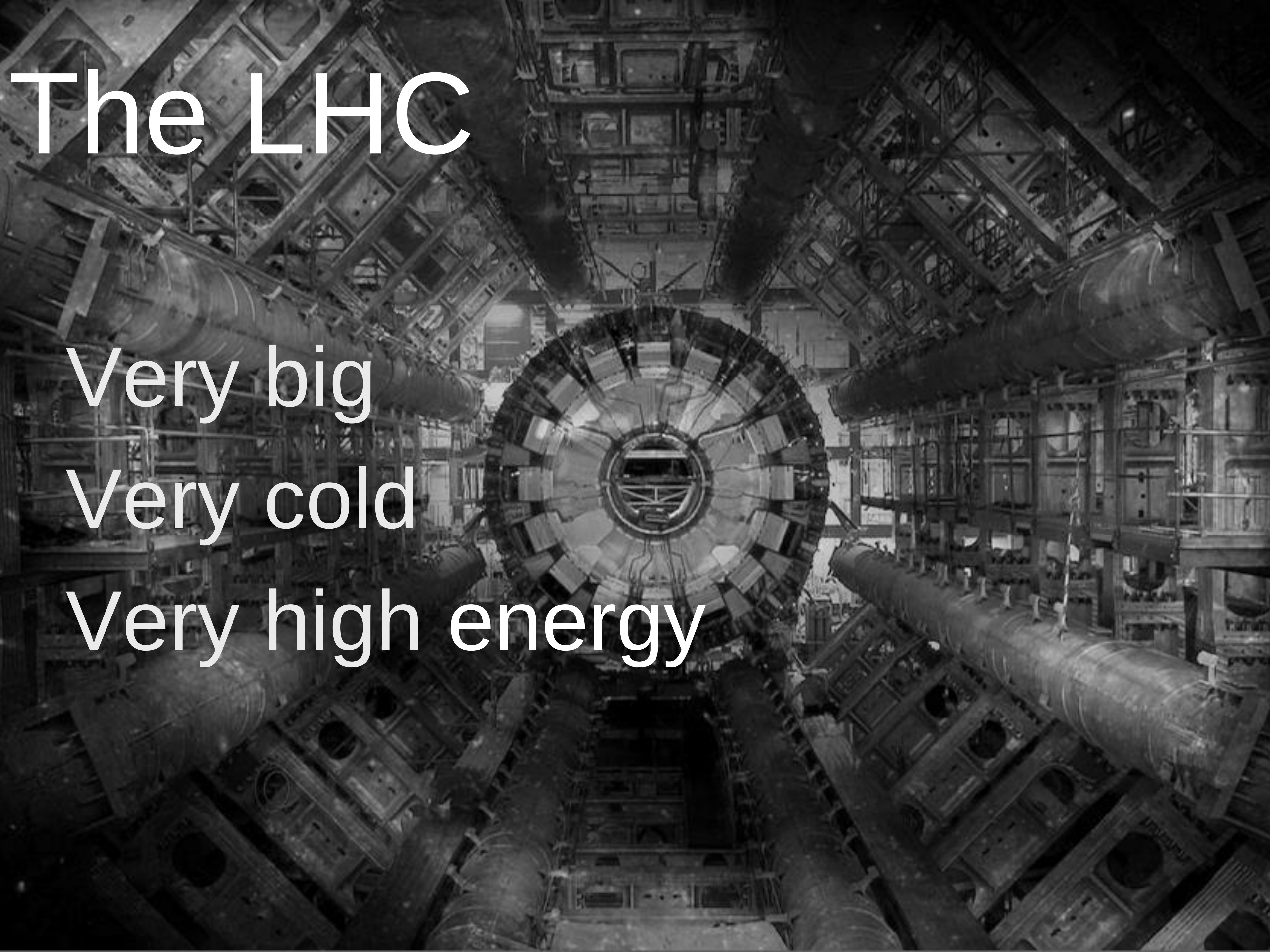
Accelerating Science and Innovation

Jan Uythoven, CERN

- How does the accelerator work?
  - Magnets
  - Radio Frequency
  - …
- Energy in the beam
- The future

Compact Muon Solenoid

Cern Control Centre

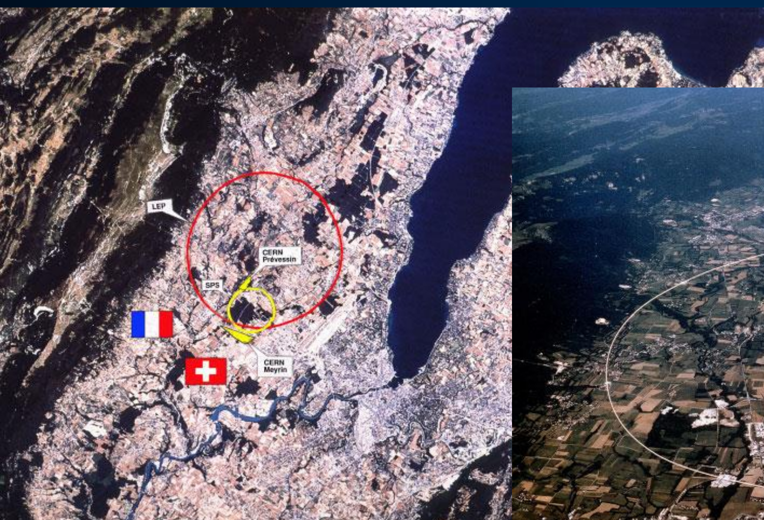


The LHC

- Very big
- Very cold
- Very high energy

The LHC

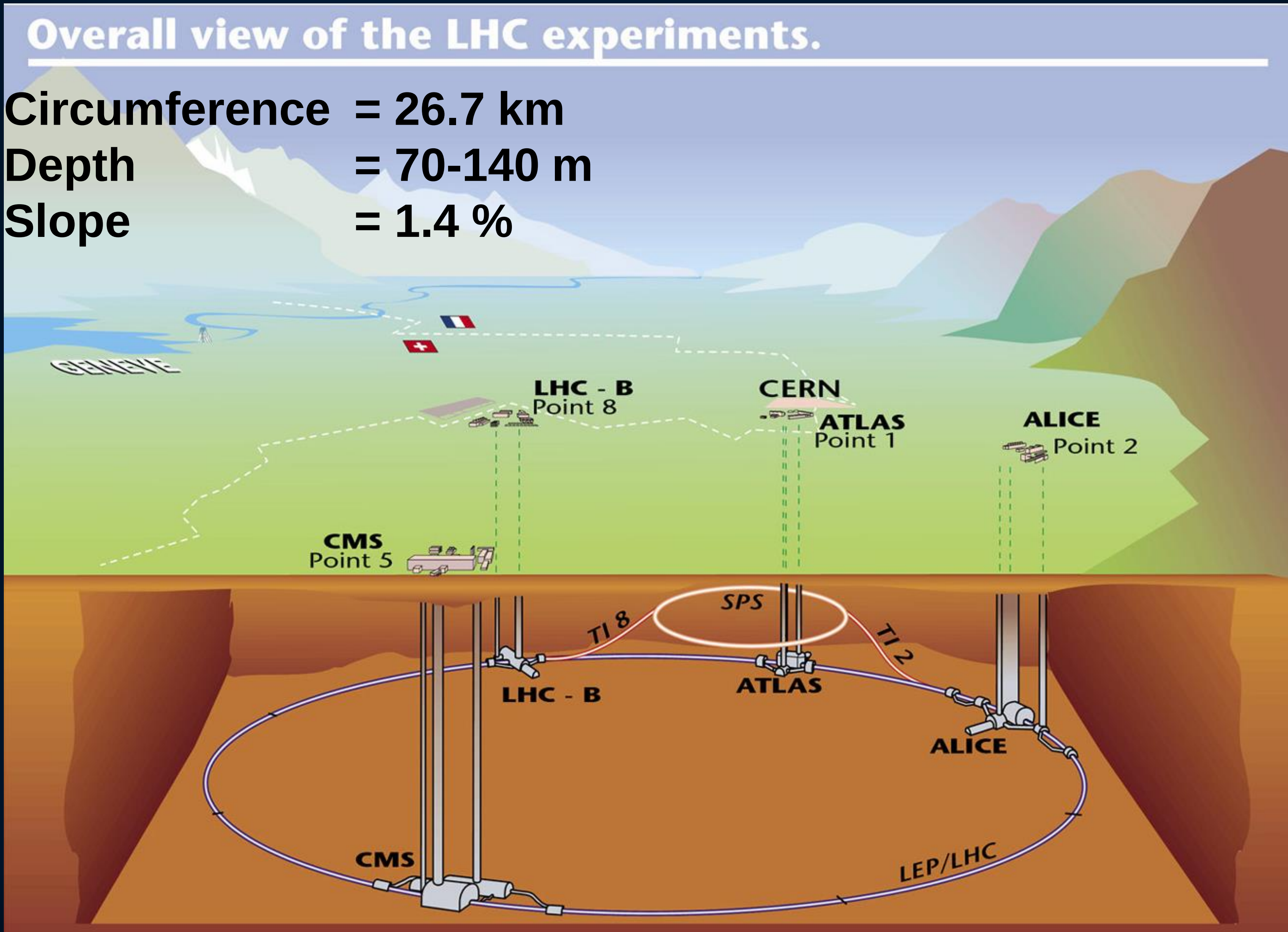
Two beams of trillions of protons race around the 27 km ring at 0.999999991 times the speed of light in opposite directions…



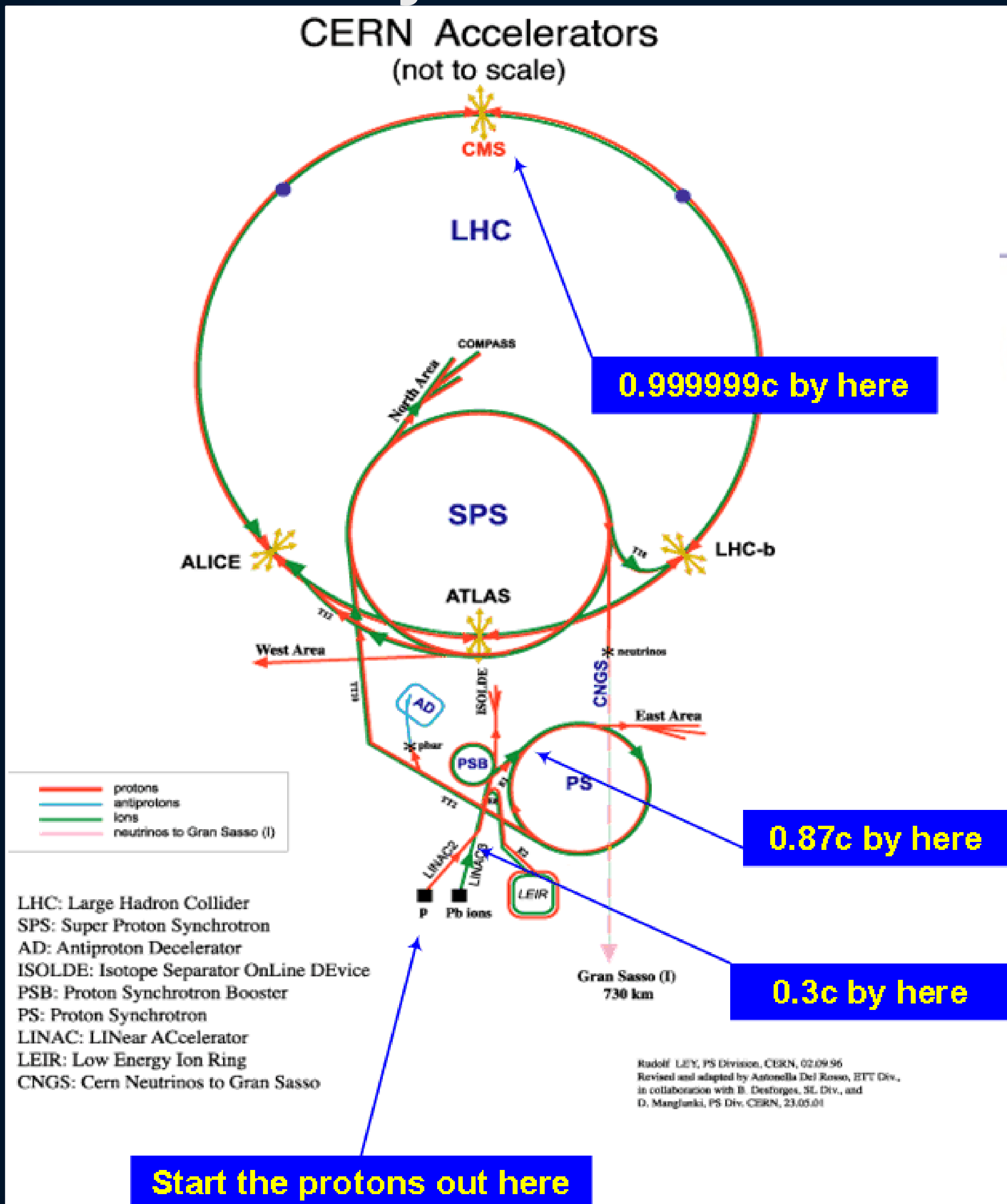

So a particle goes around the LHC 11’000 times per second !

LHC tunnel

Circumference = 26.7 km
Depth = 70-140 m
Slope = 1.4 %



LHC Injector Chain



New Linac4 in 2020: H^-

	Year	Top energy [GeV]	Length [m]
Linac	1979	0.05 0.16	30
PSB	1972	1.4 2.0	157
PS	1959	26.0	628
SPS	1976	450.0	6'911
LHC	2008	7000.0	26'657

Normal operation with protons, but every year few weeks of operation with heavy ions (Pb^{82+})

Where do the Protons come from?

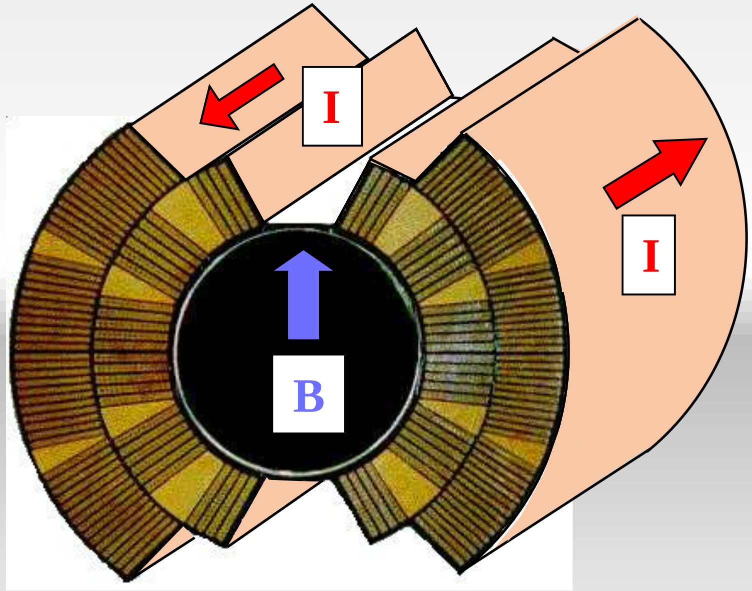
Basic ingredients of a particle accelerator

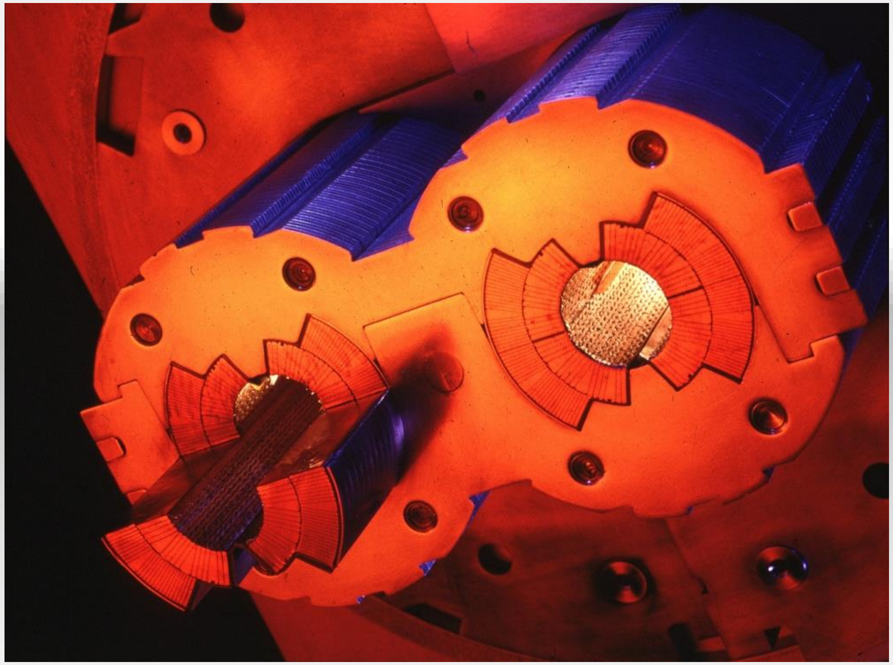
$$F = q\left[E + \left(v \times B\right)\right]$$

- **Magnetic field** to
  - Bend the beam around the circle (dipole magnets)
  - Keep the particles together (quadrupole magnets = lenses)
- **Electric field** to accelerate the particles
  - Very fast varying electric fields = Radio Frequency cavities

Dipole Magnets

- Bend the beam around the circle
- Number of dipoles 1232
- Dipole field at 450 GeV 0.535 T
- Dipole field at 7 TeV 8.33 T
- Bending radius 2803.95 m
- Main Dipole Length 14.3 m
- Openings (full aperture) 56 mm



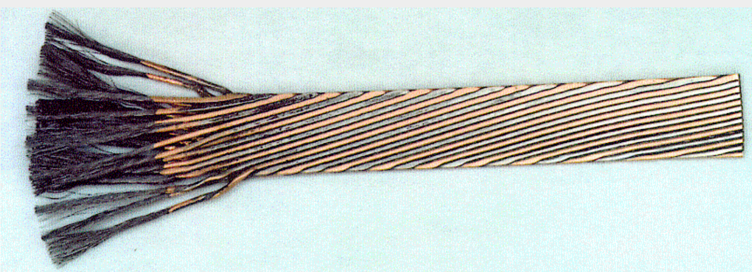


SUPERCONDUCTING!
Cooled with superfluid helium at 1.9 K

The superconductor

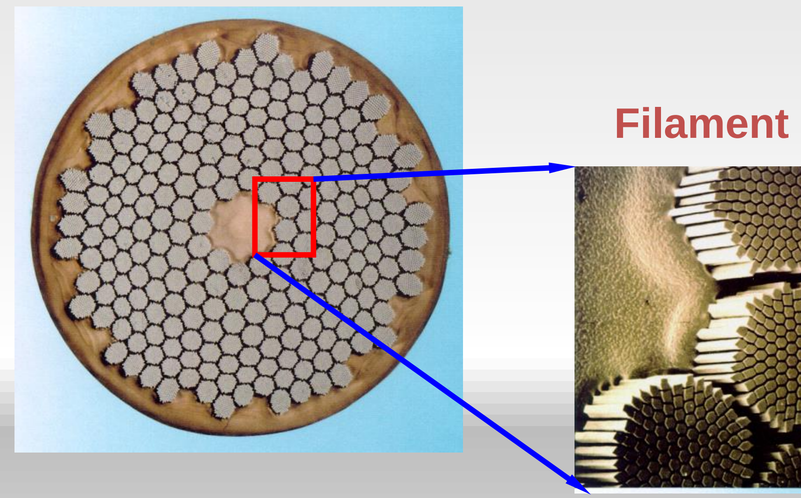
Niobium-titanium Rutherford cable

Cable



Strand

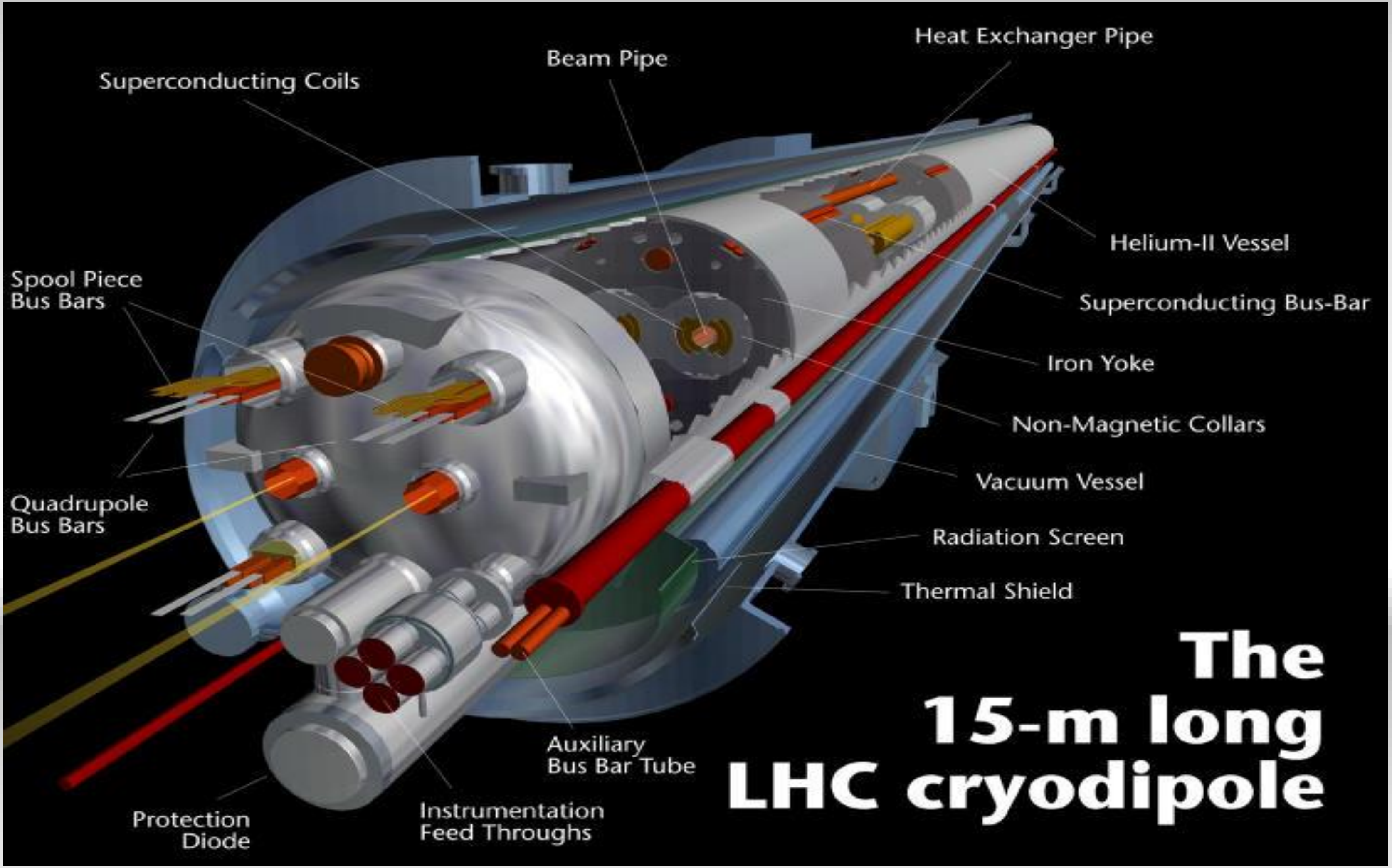
Filament



Used 1200 tonnes/7600 km of cable

Single cable carries current up to 12 kA

More than just some coils…

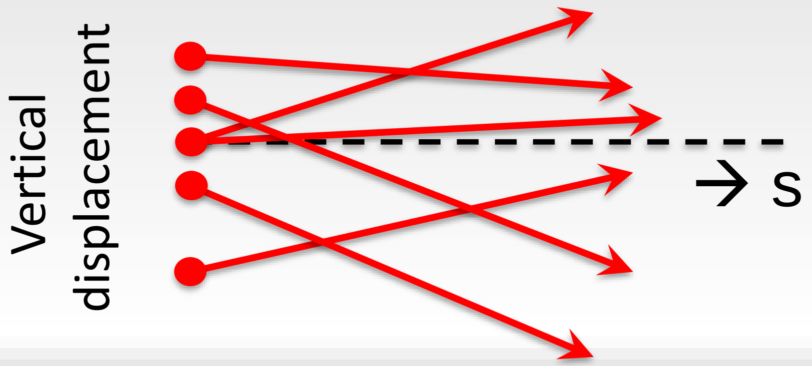


During construction: Dipoles all over

In the LHC tunnel

Beam is divergent

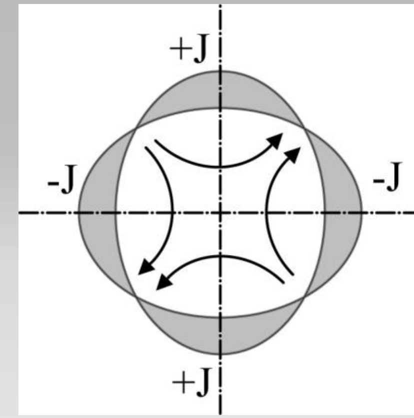
Many particles many initial conditions

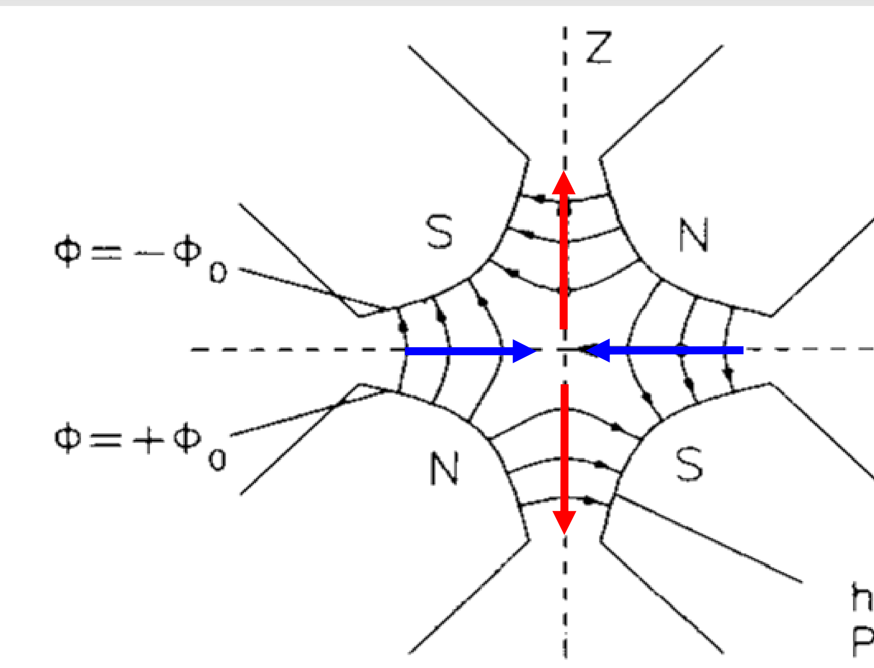


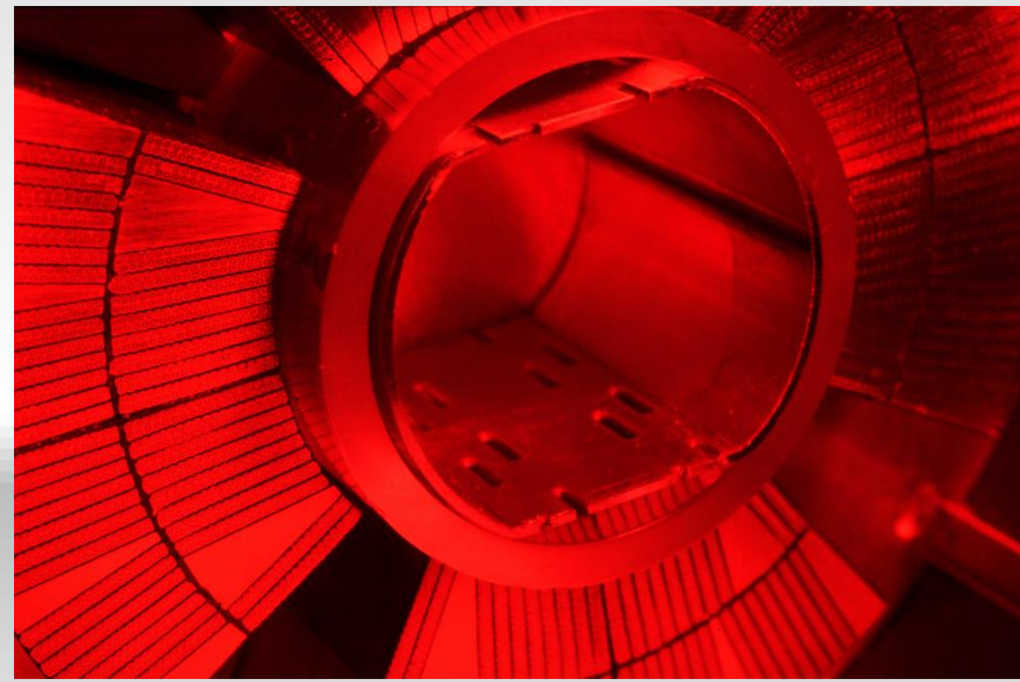
Many different angles

Quadrupole magnet

Quadrupole magnets

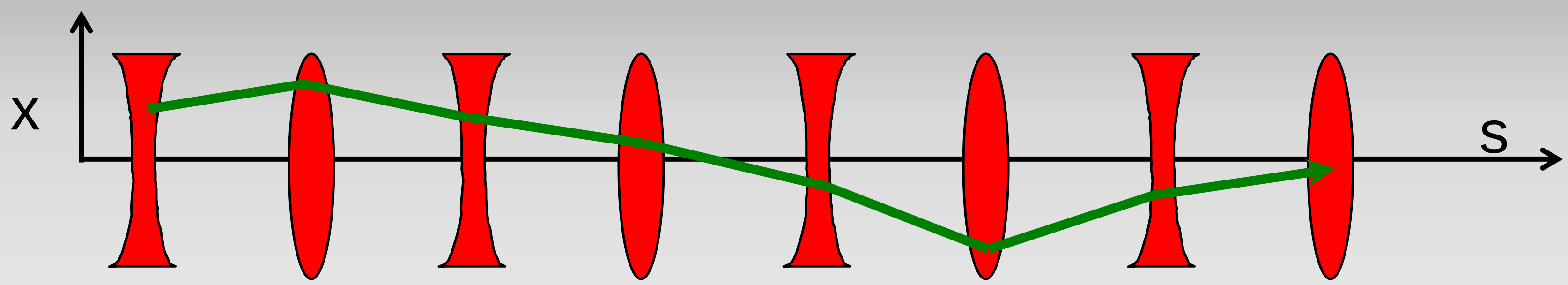






- A quadrupole magnet will focus in one plane and de-focus in the other.
- Convention: a “focusing” quadrupole focuses in the horizontal plane

Alternate gradient focusing



The general linear magnet lattice can be parameterized by a 'varying spring constant', K=K(s).

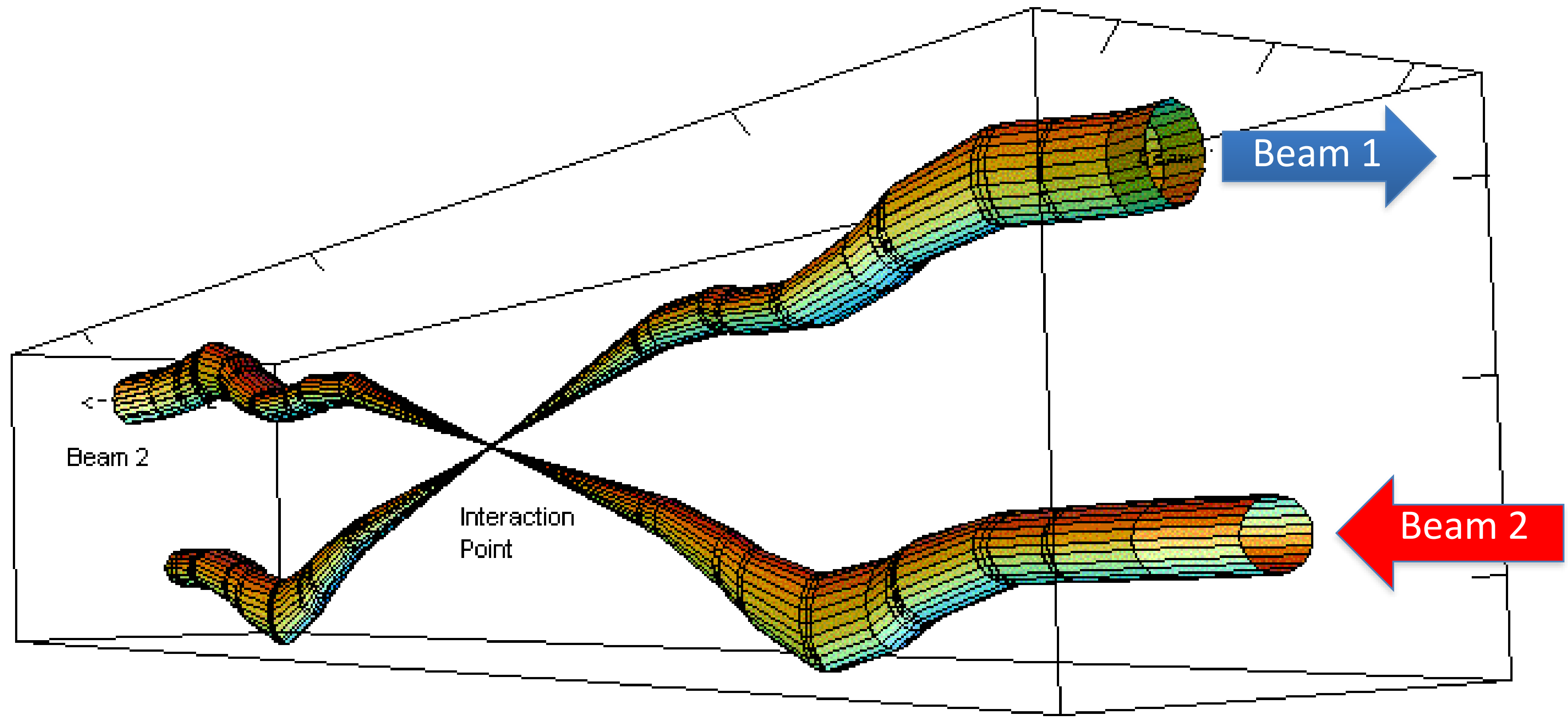
K(s) describes the distribution of focusing strength along the lattice and is periodic.

$$\frac{d^2x}{ds^2} + K(s)\,x = 0$$

(and similarly for the vertical plane y)

This is Hill's equation.

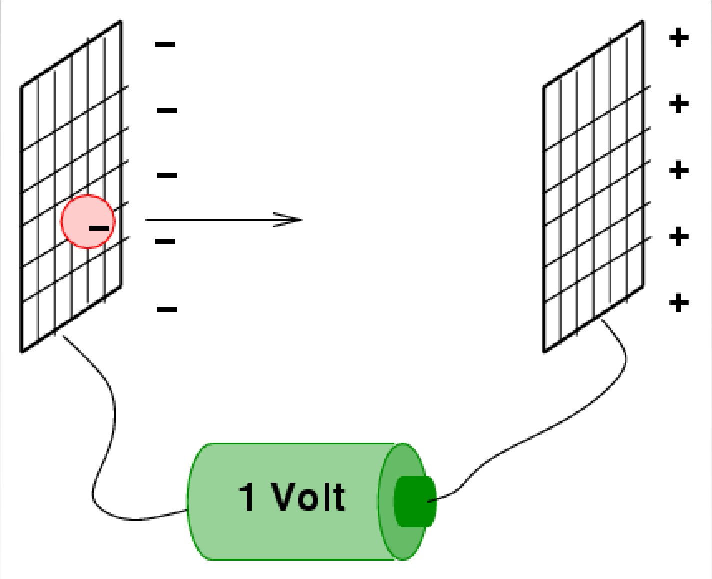
Squeeze



Relative beam sizes around IP1 (Atlas) in collision

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

Accelerating the Particles



LHC: beams with an energy of 6.5 TeV

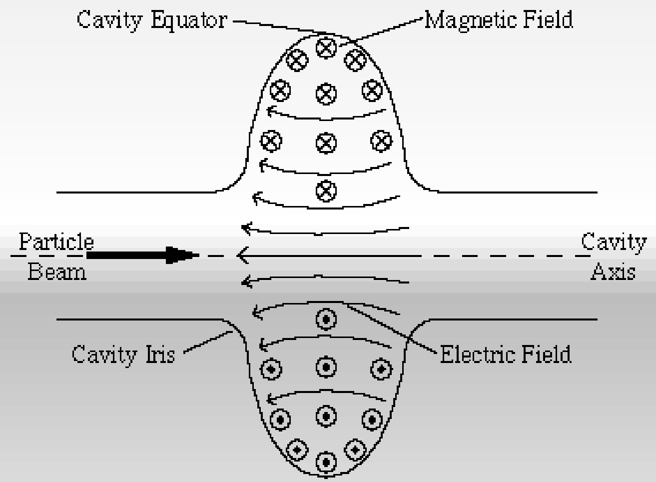
=

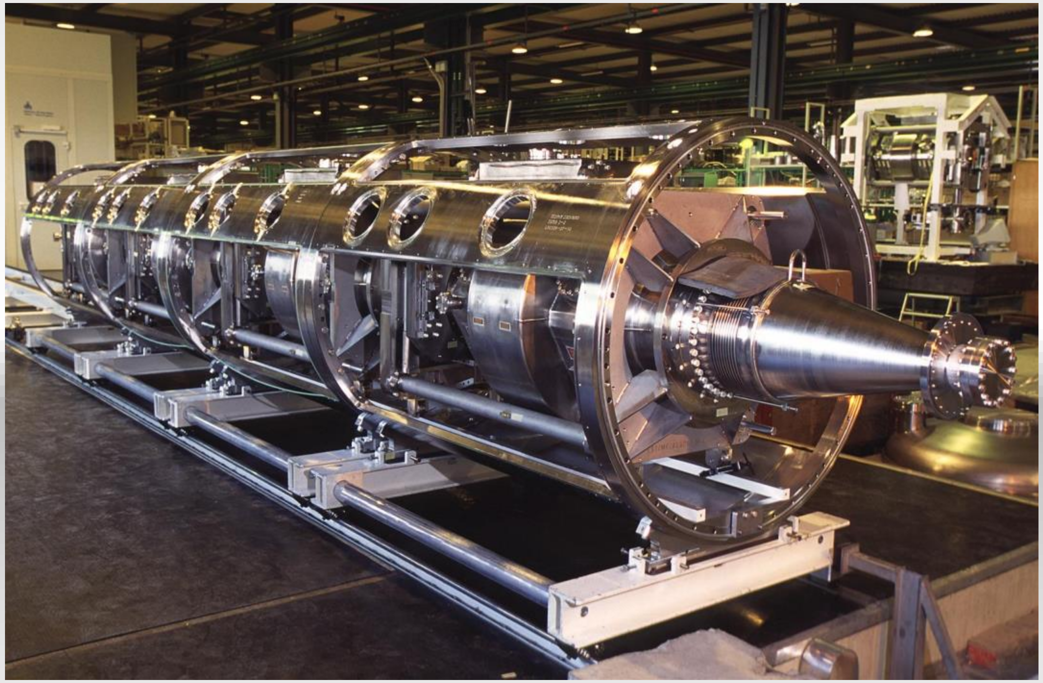
6 500 000 000 000 V

Tera Giga Mega kilo

Radio Frequency Cavities

- RF = Oscillation of field at 400 MHz (Radio Frequency)
- Use the Electrical Field at each passage
- 4 cavities/module - 2 modules/beam - 16 MV (5.5 MV/m)
- Superconducting to reduce Beam Impedance

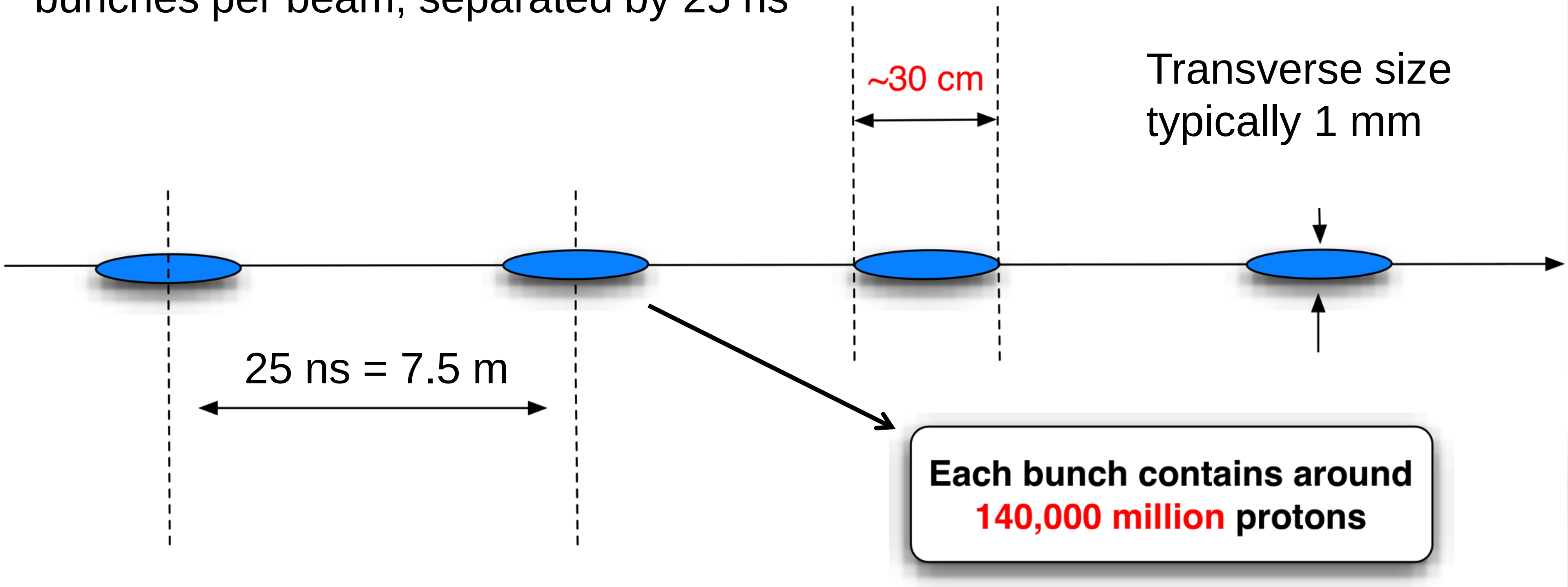




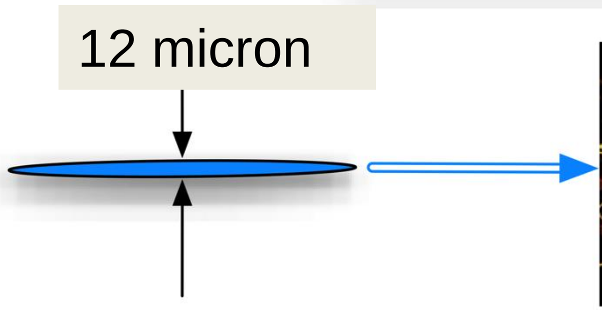
4 Cavity RF Module

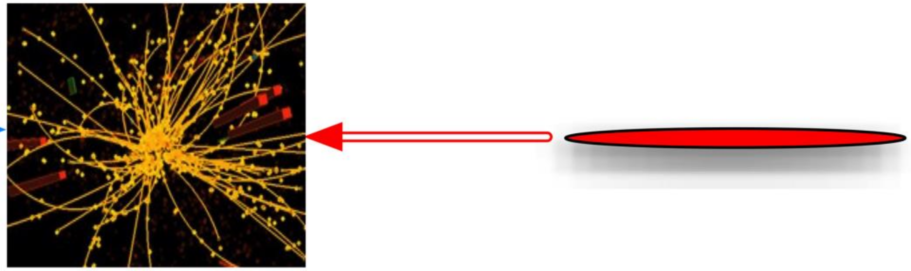
Lots of bunches

In 2017 the LHC operated with 2300 bunches per beam, separated by 25 ns



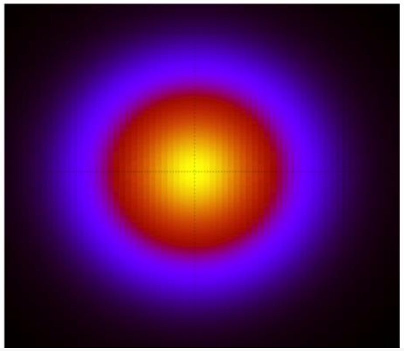
140,000,000,000 protons a bunch
~30 collide at each bunch crossing



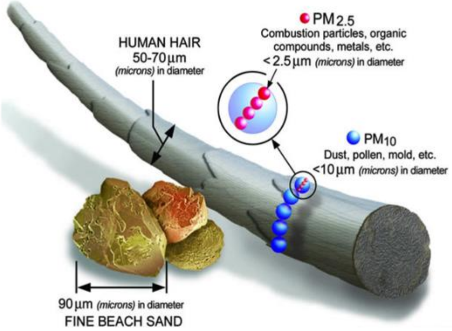


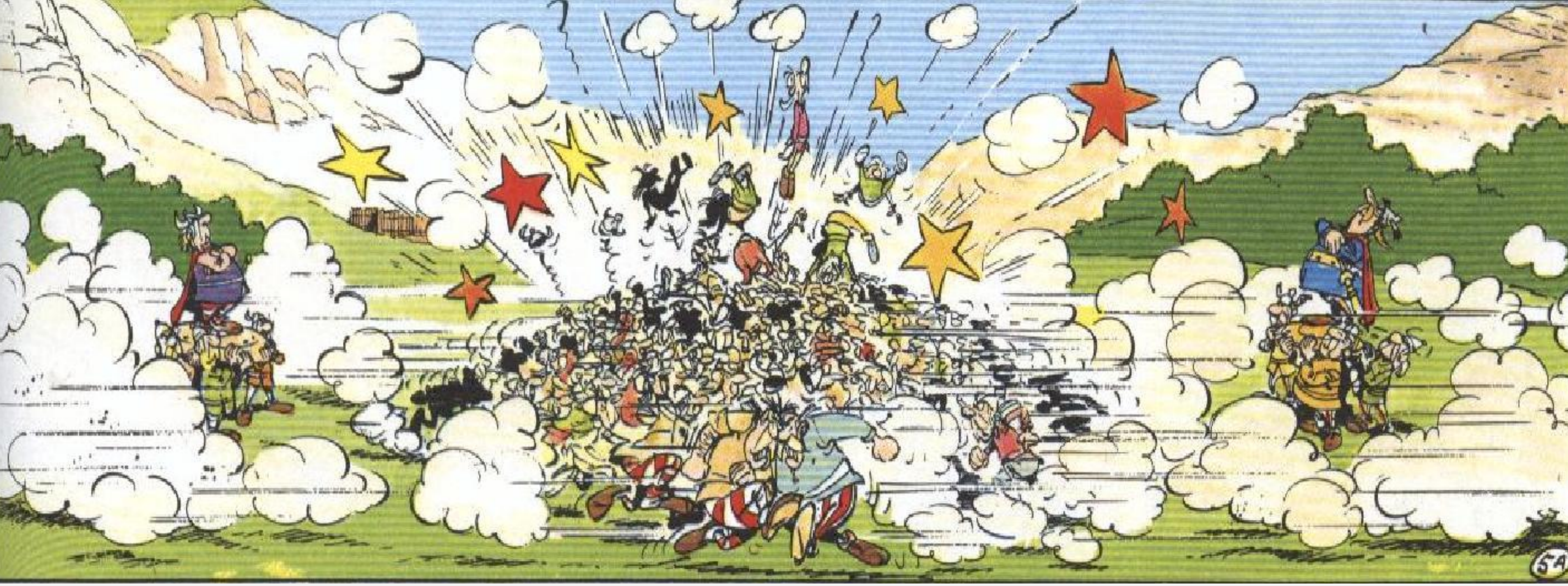
Up to 50 collisions per crossing
11’000 crossings per second
2200 bunches per beam (2016)
1 Billion Collissions Per Second → GRID

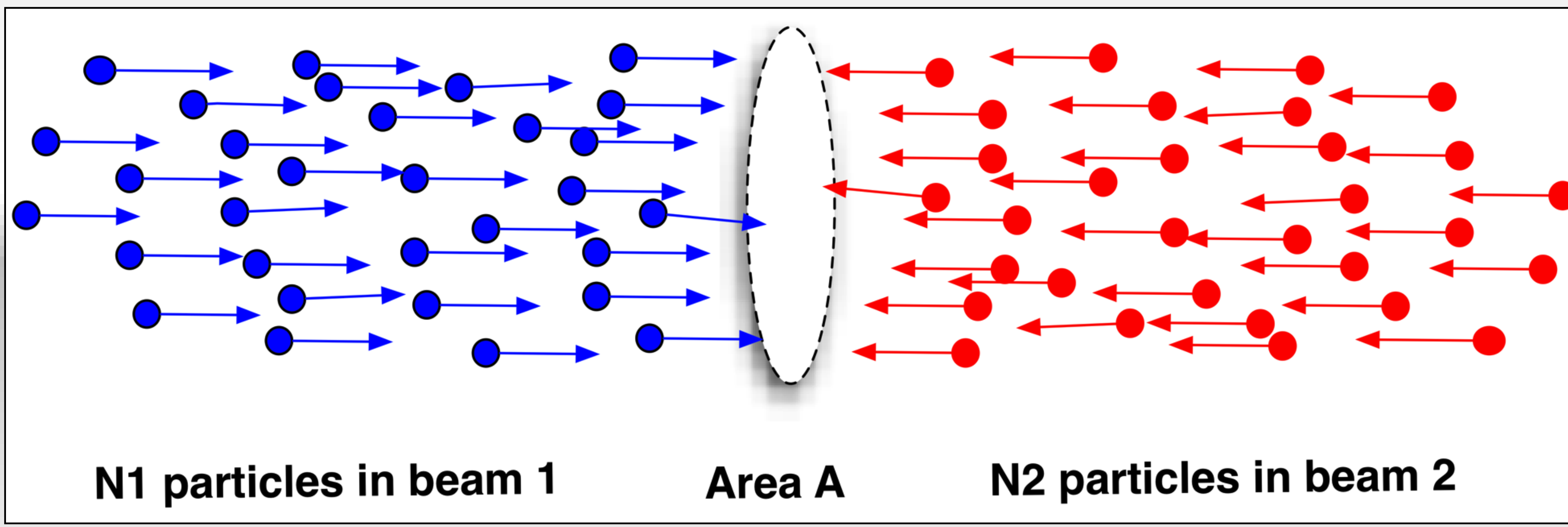
LHC BEAM



HUMAN HAIR







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

Energy in the Beam

- Electric Energy (RF cavity) → Kinetic energy

E-beam	**6.5 TeV = 6.5e12 eV**
1 eV	1.6e-19 Joules
Number of bunches	2300
Number of protons per bunch	1.3e11 protons
Energy	311 MJoules

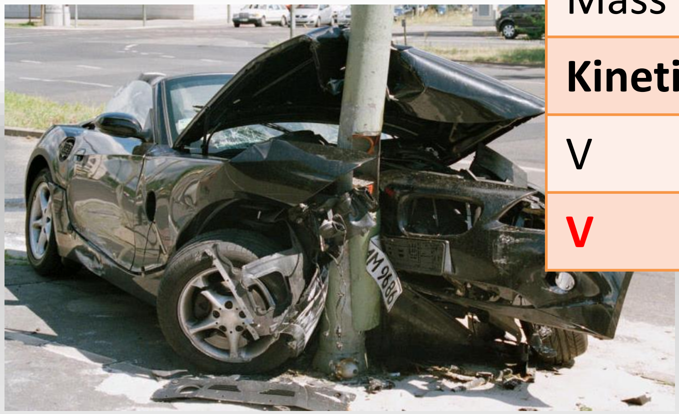
What would be the speed of a car to have the same kinetic energy ?

Car Versus Beam

Electric Energy of the beam → Kinetic energy

E-beam	6.5 TeV = 6.5e12 eV
1 eV	1.6e-19 Joules
Number of bunches	2300 (for 2016)
Number of protons per bunch	1.3e11 protons
Energy	**311 MJoules**

Kinetic Energy of the car



Mass car	1800 kg
Kinetic energy	**306 MJoules**
V	583 m/s
V	**2100 km/h**

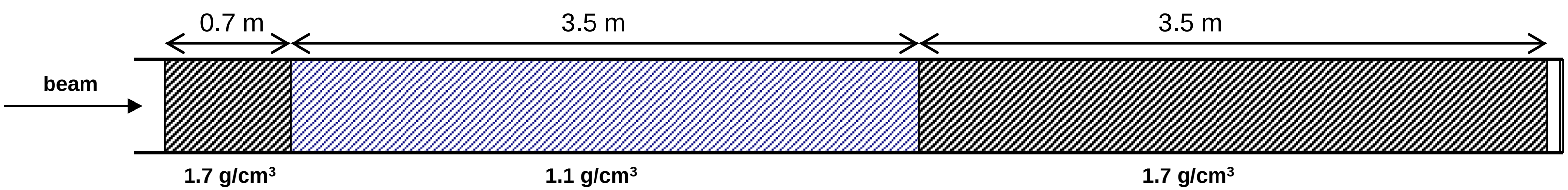
But at the size smaller than a hair ….

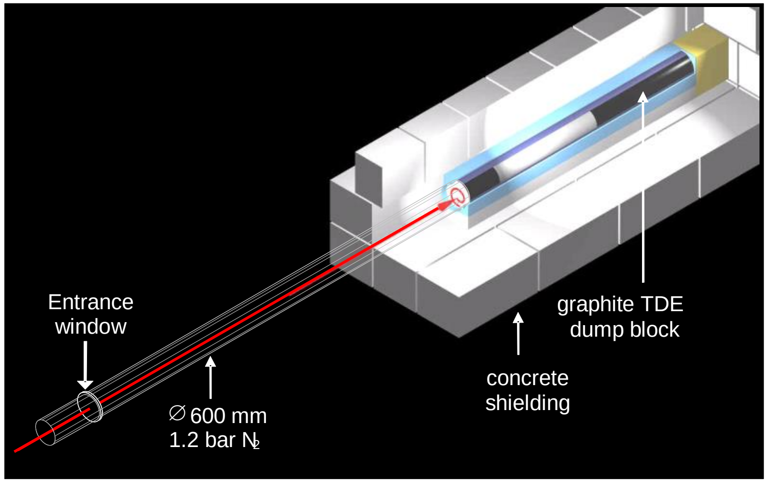
Don’t break the machine!

Thread through a very cold, very dark, very small hole...

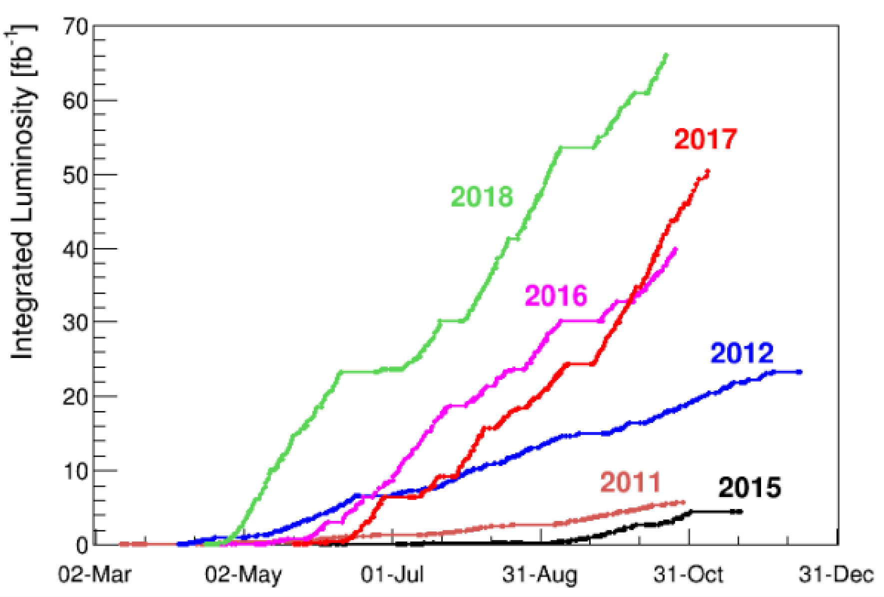
Beam dump block (TDE)

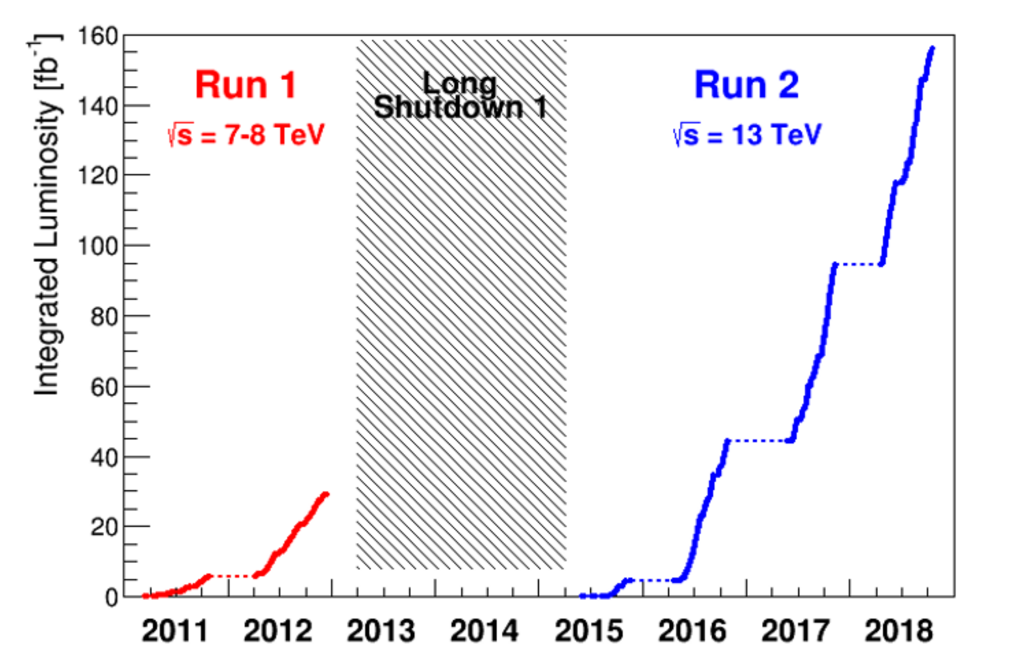
- 700 mm ∅ graphite core, with graded density of 1.1 g/cm^3 and 1.7 g/cm^3
- 12 mm wall, stainless-steel welded pressure vessel, at 1.2 bar of N_2
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks

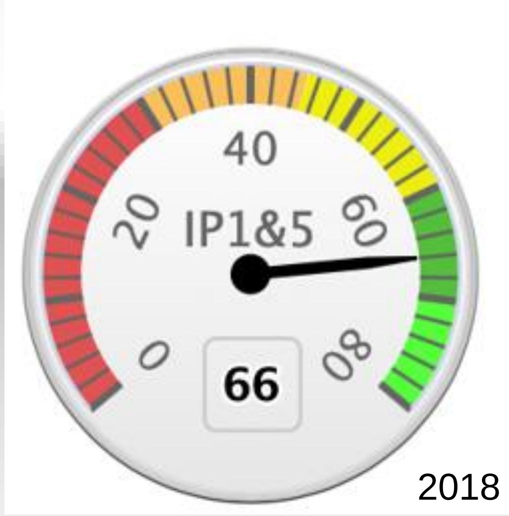




It is all about Luminosity







Period	Int. Luminosity [fb^{-1}]
Run 1	29.2
Run 2: 2015	4.2
Run 2: 2016	39.7
Run 2: 2017	50.2
Run 2: 2018	66
Total Run 1+ 2	189.3

Luminosity

$$L = \frac{N^2 k_b f}{4ps^*_x s^*_y} F = \frac{N^2 k_b f g}{4pe_n b^*} F$$

N	**Number of particles per bunch**
k_b	**Number of bunches**
f	Revolution frequency
σ*	**Beam size at interaction point**
F	Reduction factor due to crossing angle
ε	Emittance
$ε_n$	**Normalized emittance**
β*	**Beta function at IP**

$$s^* = \sqrt{b^* e}$$

$$e_N = 2.5´\ 10^{-6}\ \text{m.rad}$$

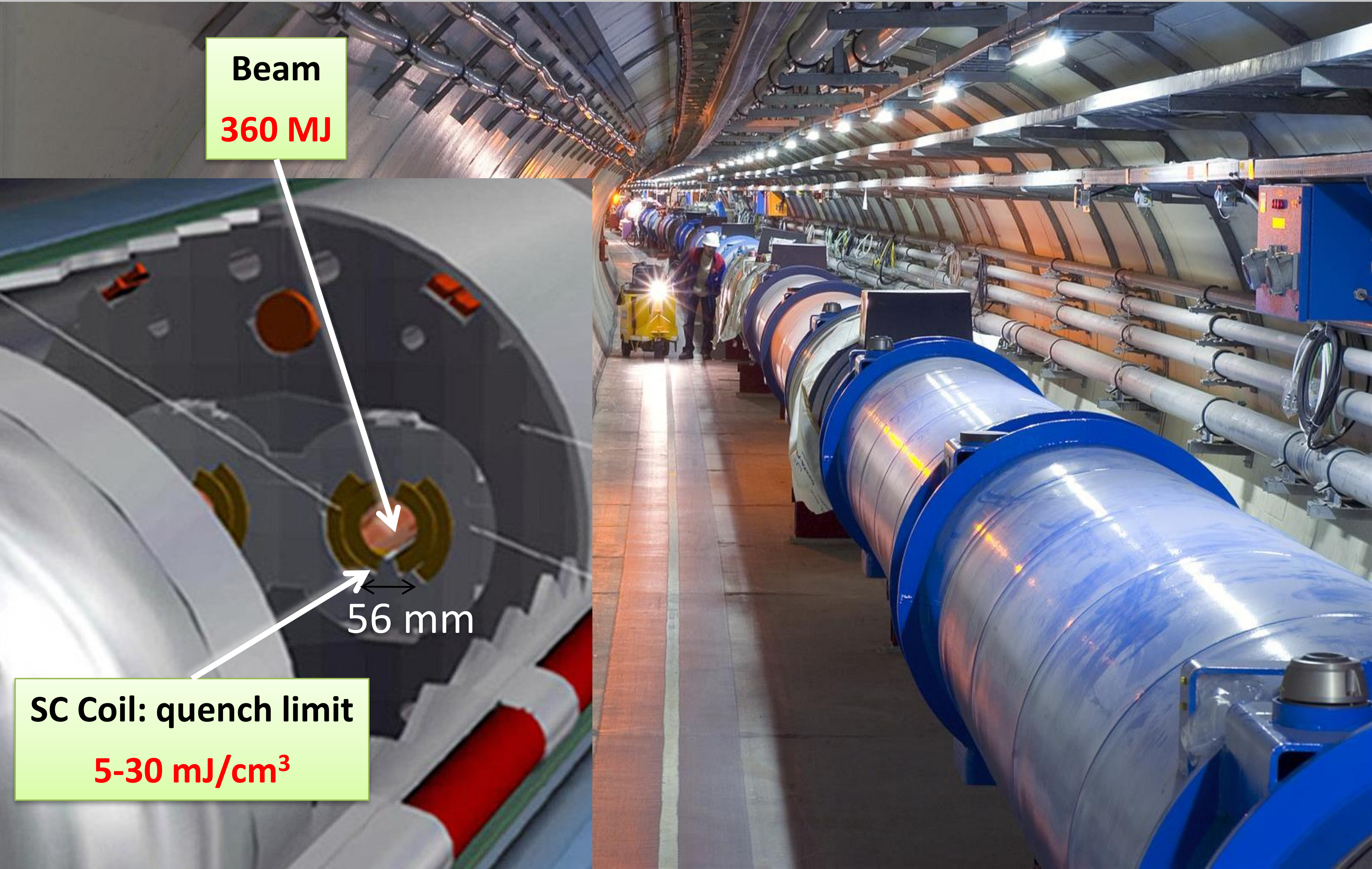
$$e = 3.35´\ 10^{-10}\ \text{m.rad}$$

$$s^* = 11.6´\ 10^{-6}\ \text{m}$$

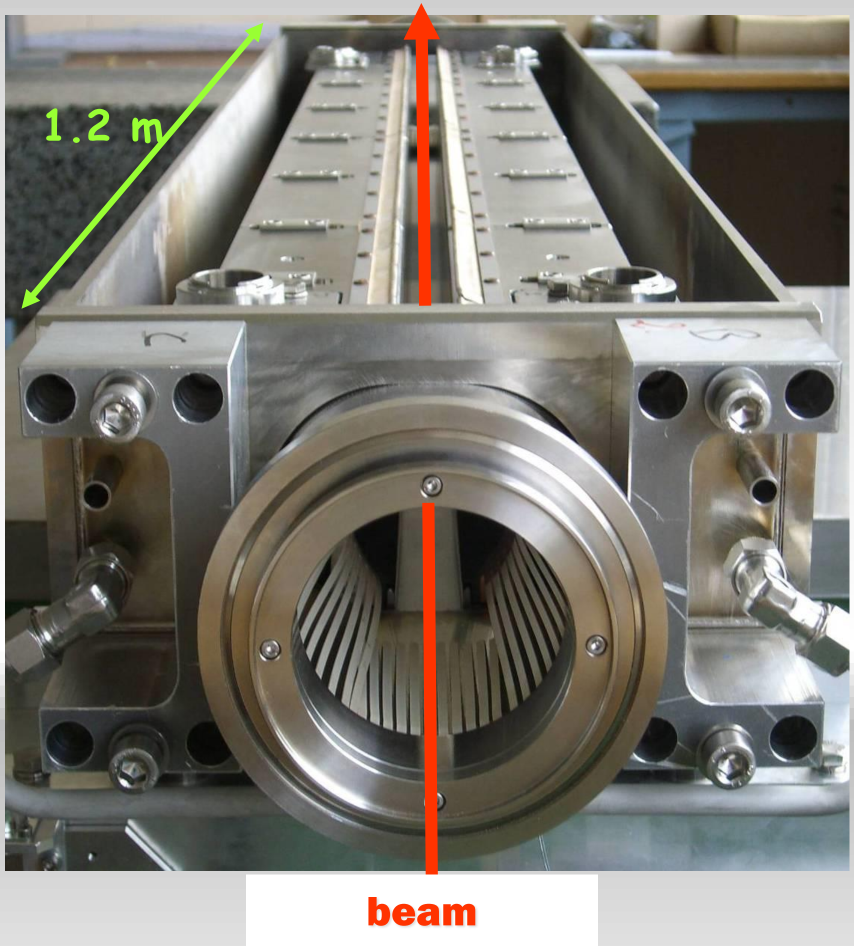
$$\left(p = 7\ \text{TeV},\ b^* = 0.4\ \text{m}\right)$$

Quench Limit of LHC Super-Conducting Magnets

Nominal design at 7 TeV



Collimation

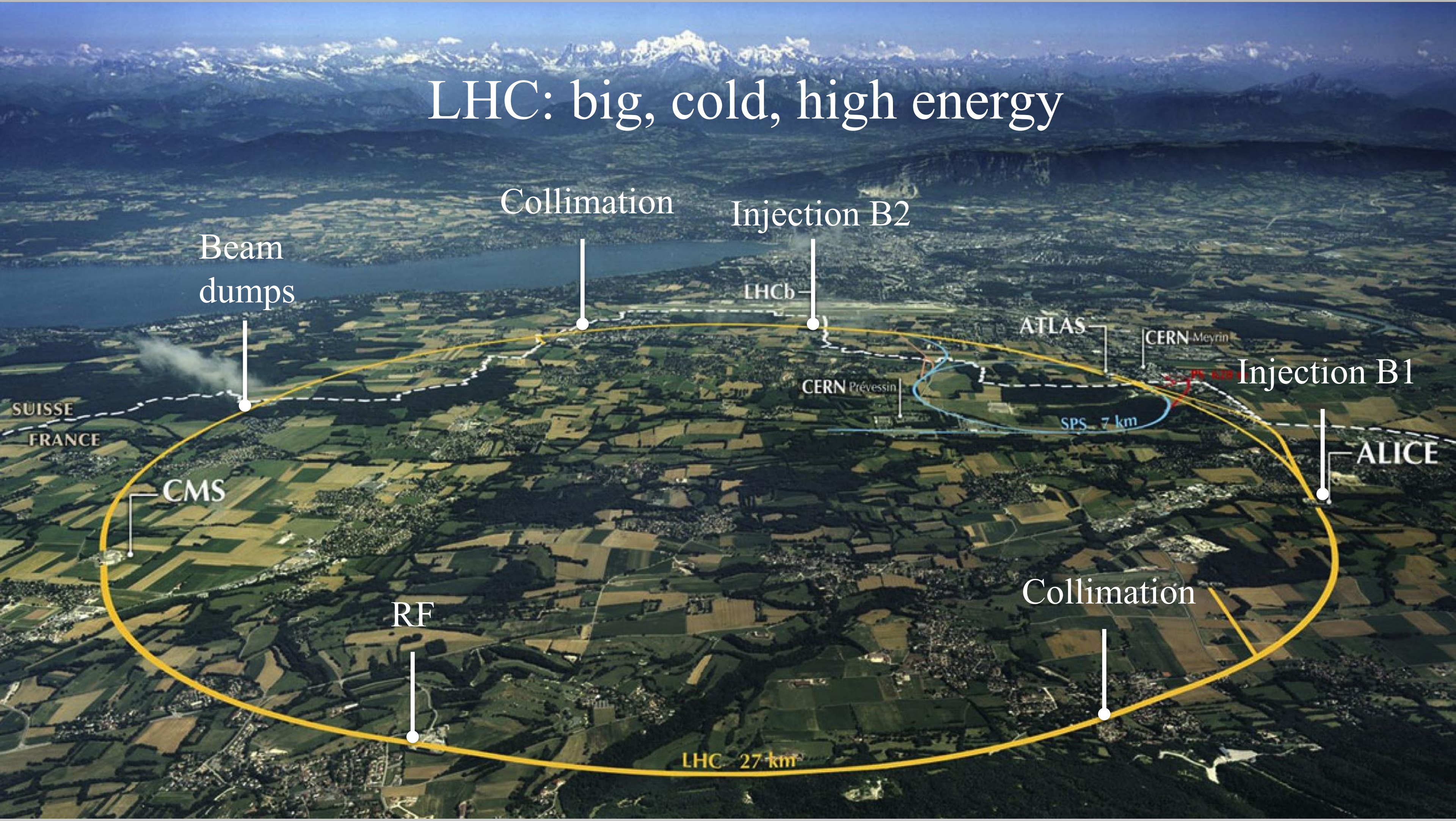


Almost 100 collimators and absorbers.

Alignment tolerances < 0.1 mm to ensure that over 99.99% of the protons are intercepted. Primary and secondary collimators are made of reinforced graphite – robust.

Emittances F5448

LHC: big, cold, high energy



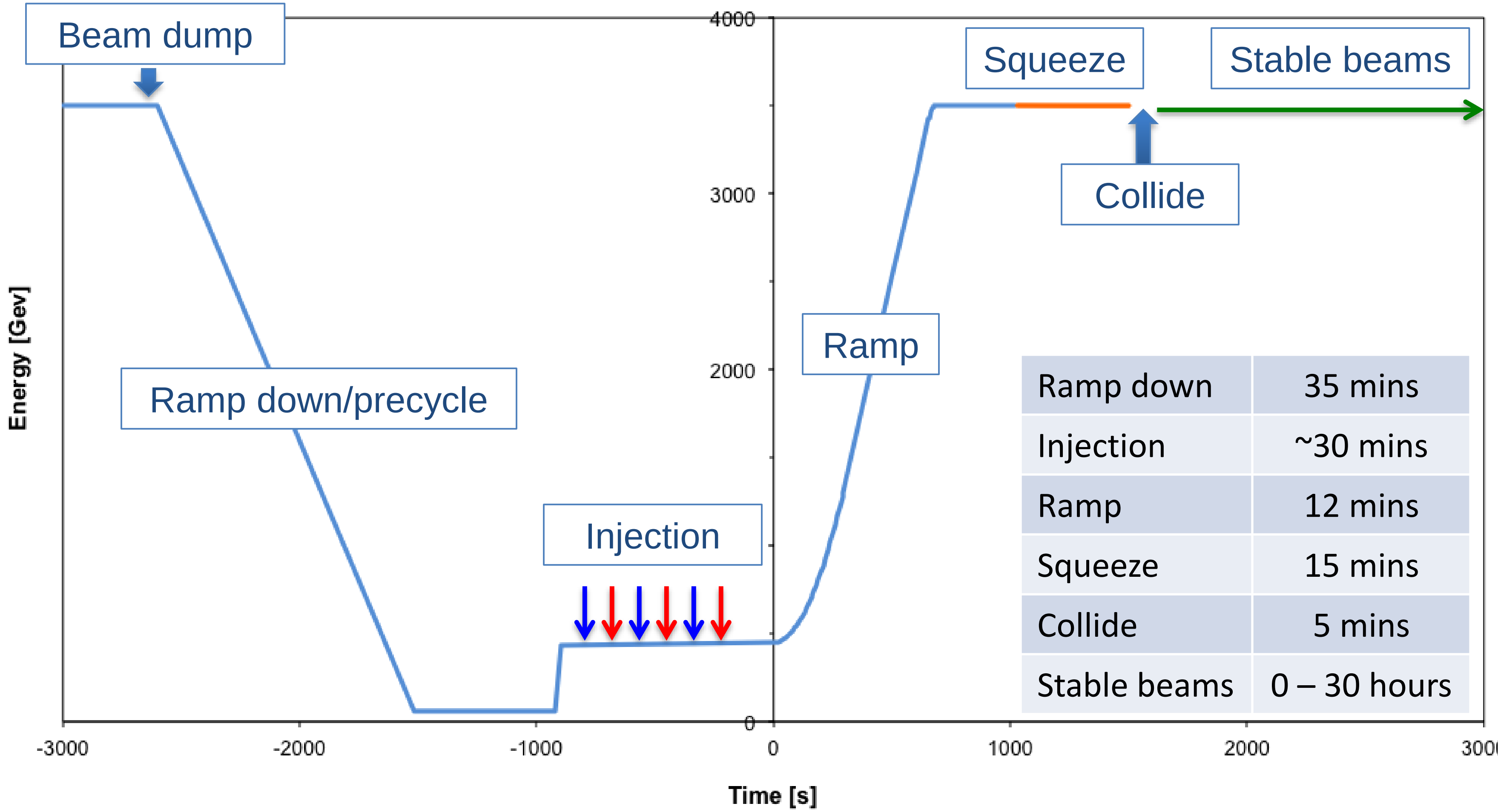
1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

120 tonnes of Helium, down to 1.9 K
360 MJ stored beam energy per beam
11 GJ total stored energy in magnetic systems

Machine Elements

- Magnets: guidance and transverse ‘stability’
  - Dipoles, Quadrupoles, Sextupoles, Octupoles
- Radio Frequency – Longitudinal motion
  - Acceleration
  - Feedback
- Injection and Beam Dumping Systems
  - Fast Pulsed Magnets (‘Kicker Magnets’)
  - Septum Magnets
  - Beam dump block
- Machine Protection
  - Collimation System, other absorbers, Interlock Systems
- Beam Diagnostics & Protection
  - Beam Position, Beam Loss Monitors, Tune Measurement, Synchrotron Light Measurements, Beam Size Measurements
- Cryogenics & Vacuum

Operational cycle



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

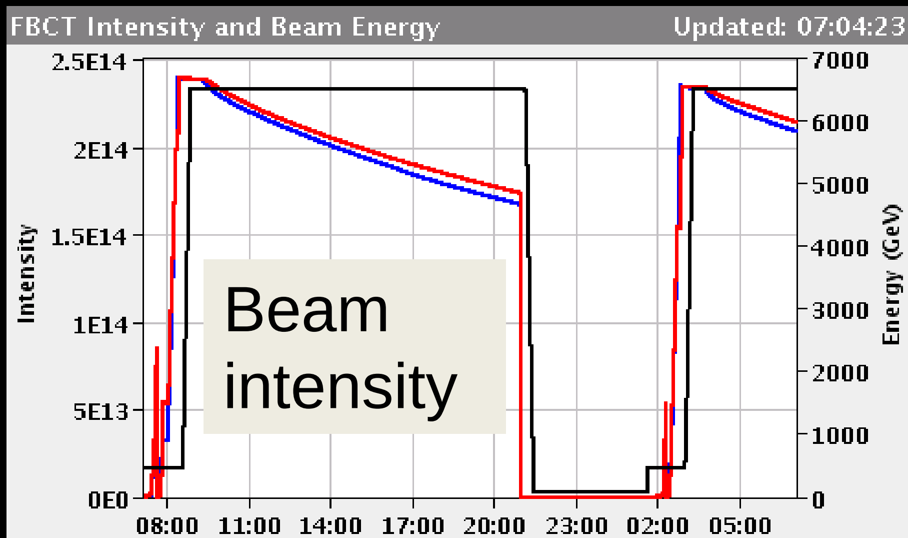
Turn around from stable beams to stable beams - 2 to 3 hours on a good day, followed by Stable Beams, average 6 hours.

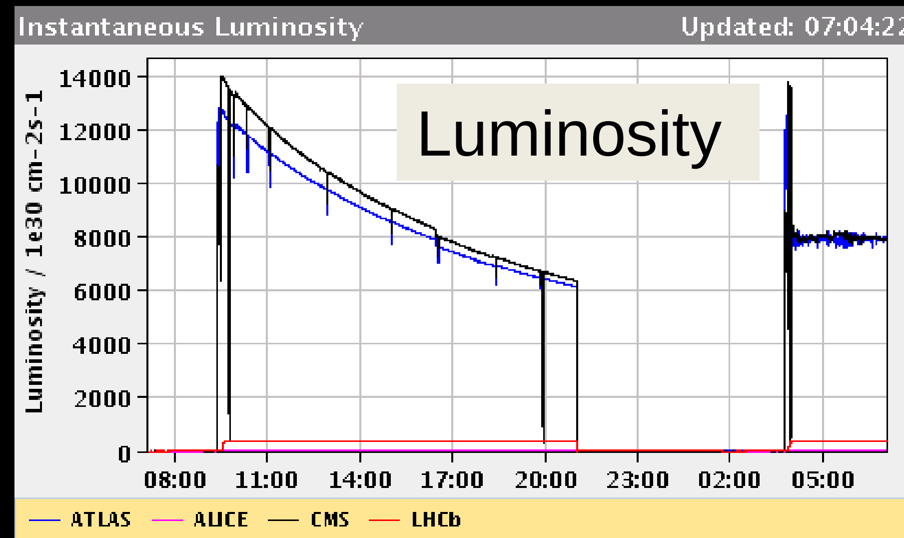
LHC Page1 | Fill: 5450 | E: 6499 GeV | t(SB): 03:11:57 | 26-10-16 07:04:23

PROTON PHYSICS: STABLE BEAMS

Energy:	6499 GeV	I(B1):	2.10e+14	I(B2):	2.16e+14

Inst. Lumi [(ub.s)^-1]	IP1: 7906.63	IP2: 1.69	IP5: 7897.24	IP8: 379.44





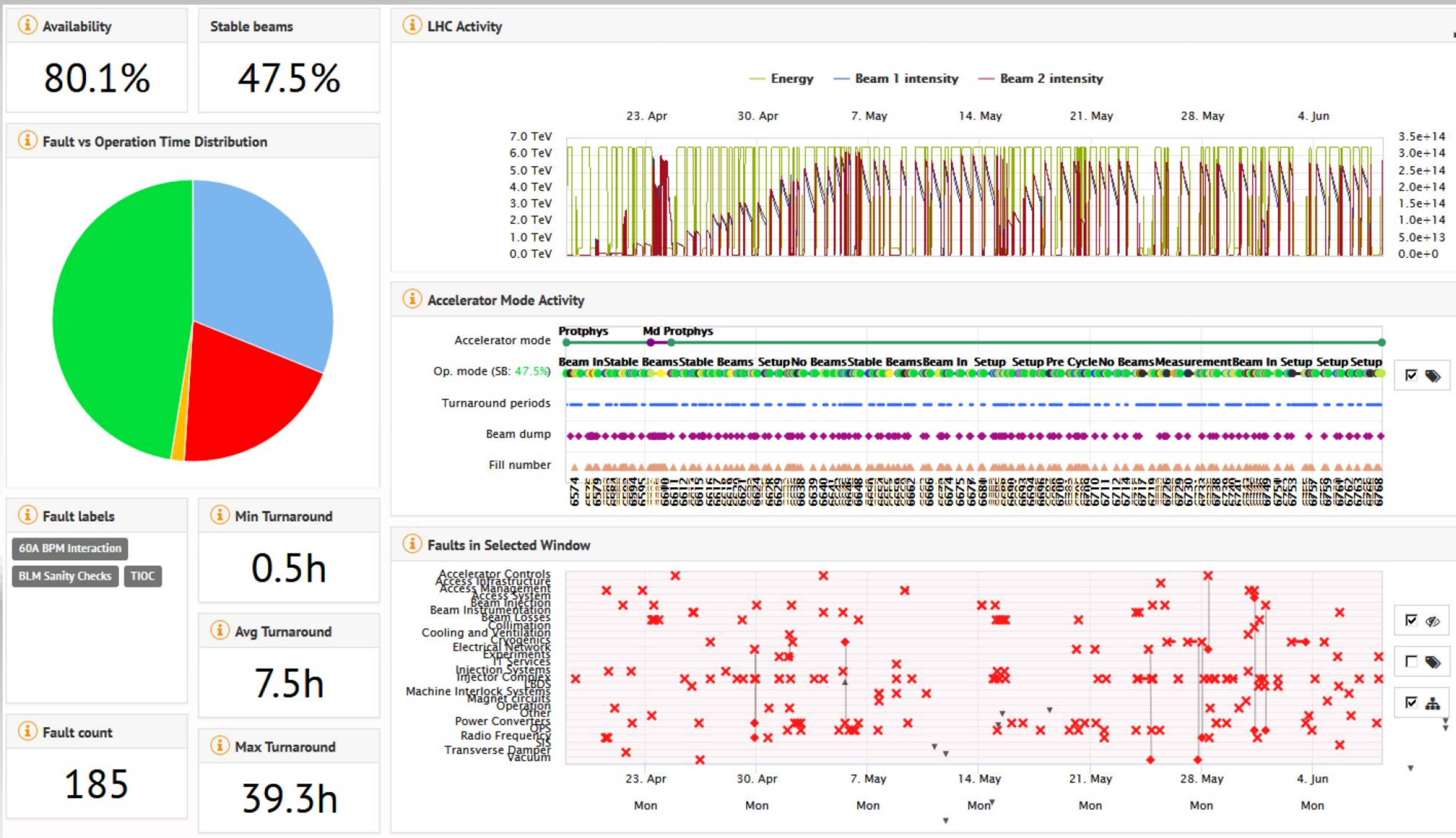
Comments (26-Oct-2016 02:29:17)

physics 2220 bunches/beam
with levelled luminosity at IP1 and IP5

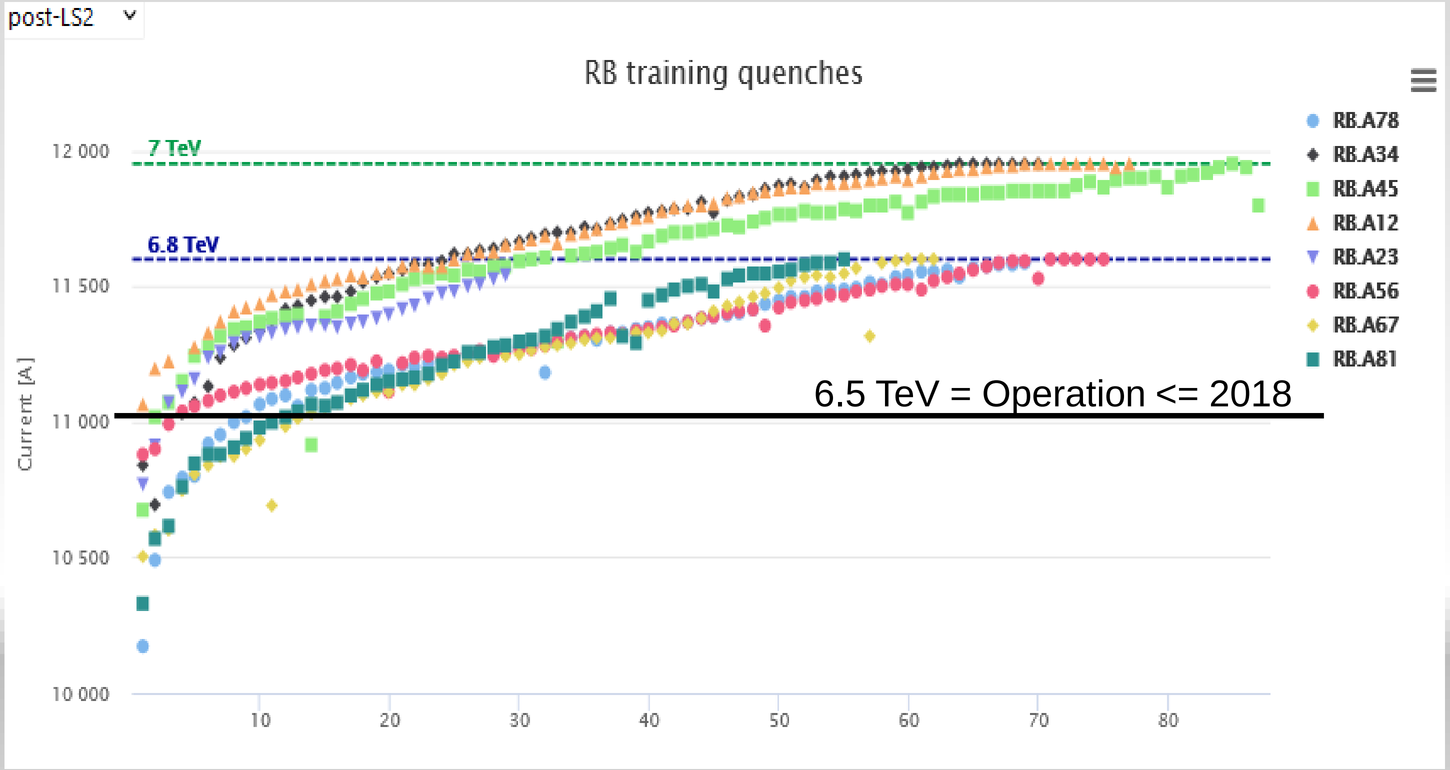
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 25ns_2220b_2208_1940_2036_96bpi_24inj | PM Status B1: ENABLED | PM Status B2: ENABLED

Machine Performance 2018



Magnet Training to reach 7 TeV Beam Energy



‘Nominal’

6.8 TeV

Present Operation

During the training after LS2 (2021) we needed 3x a sector warm-up – delay of about 3 months each time, partly in parallel

Number of quenches needed to reach 7 TeV

We have had 274 magnet training quenches from 2008-2018
and 614 magnet training quenches in 2021.

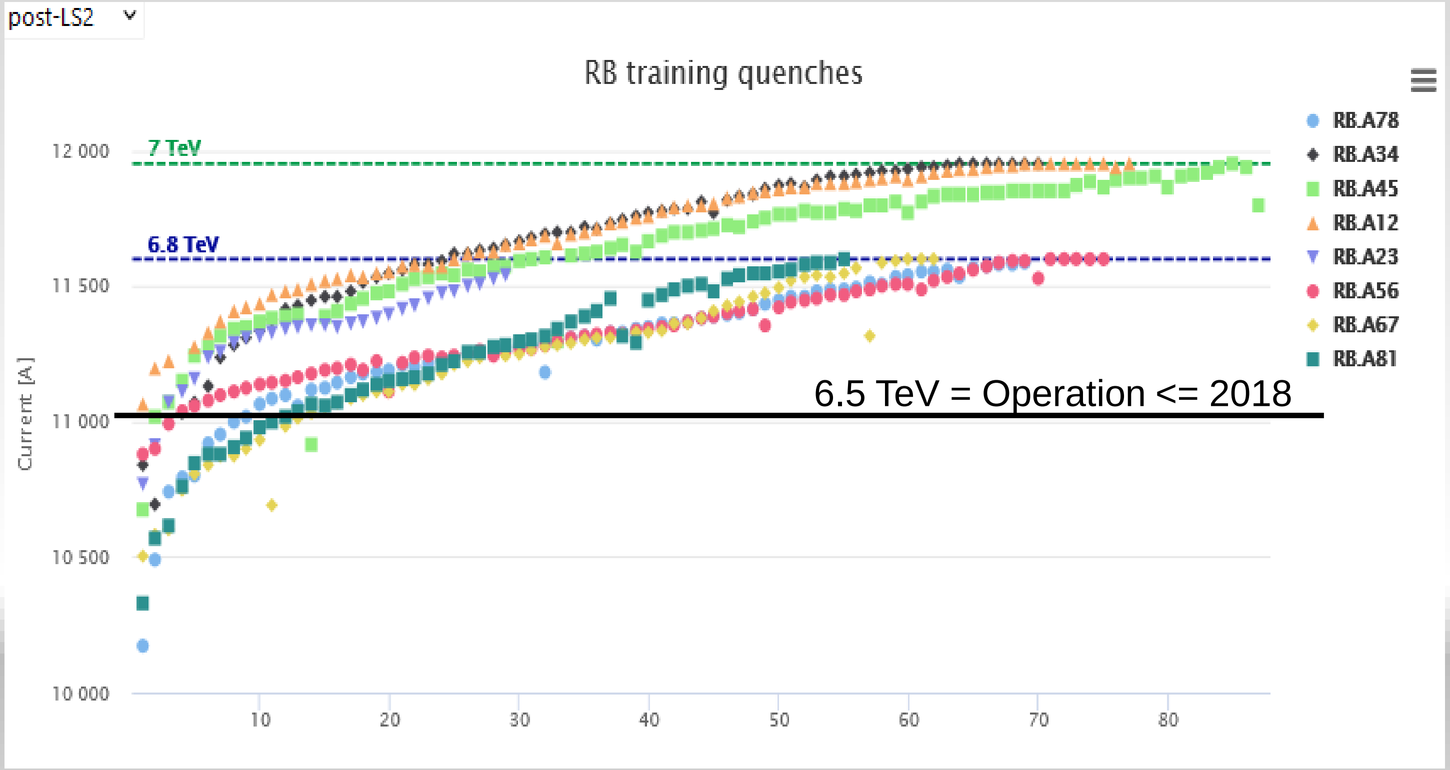
	12	23	34	45	56	67	78	81
#Q to reach 11600 A (6.8 TeV) (including flat-top quenches at 11600 A)	0	23	0	0	0	0	42	0
#Q to reach 11950 A (7 TeV) (starting at 11600 A)	0	70	0	0	71	54	67	53
#Q at 11950 A flat-top	0	6	0	1	5	5	5	4

A total of about **65** magnet quenches (corresponding to about 55 circuit quenches) are still needed to bring S23 and S78 to 6.8 TeV.

A total of about **340** magnet quenches (corresponding to about 280 circuit quenches) are still needed to bring the remaining 5 sectors from 6.8 to 7 TeV.

We calculated a **63 % probability** for another sector warm-up if we continue training to 7 TeV → Experiments want to run → Run at 6.8 TeV

Magnet Training to reach ~~7 TeV~~ 6.8 TeV Beam Energy



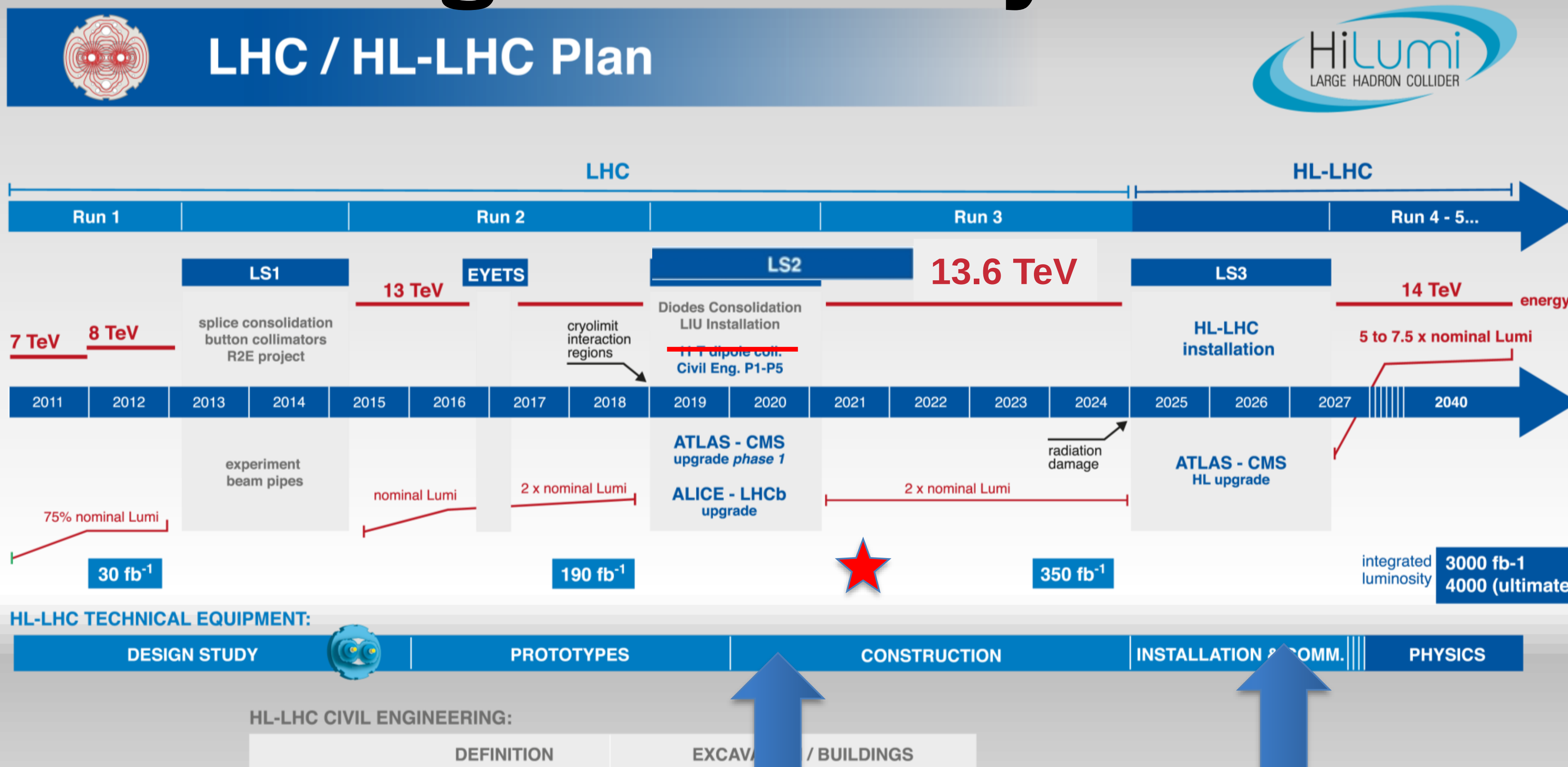
'Nominal'

6.8 TeV

Present Operation

During the training after LS2 (2021) we needed 3x a sector warm-up – delay of about 3 months each time, partly in parallel

What’s Next ?
High-Luminosity LHC



Injectors upgrade and LHC civil engineering

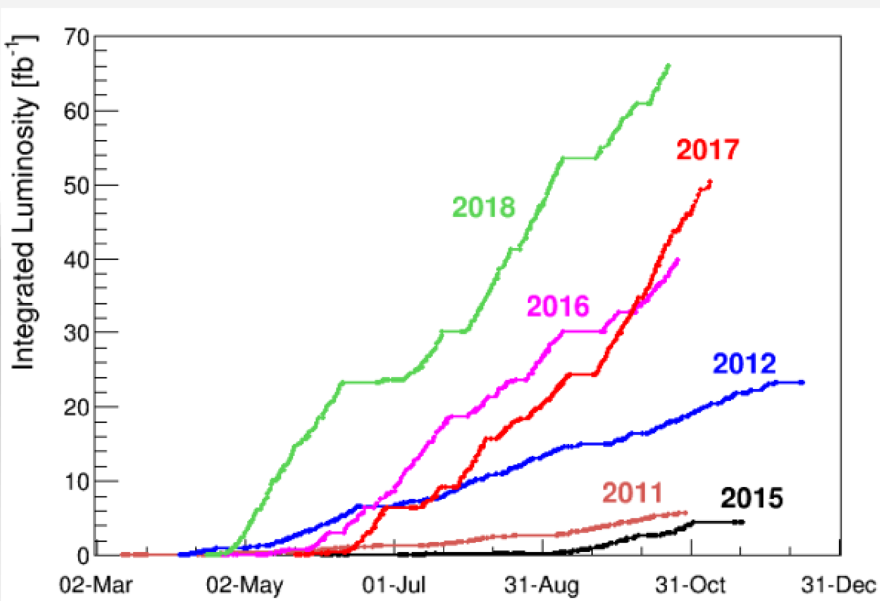
HL-LHC upgrade

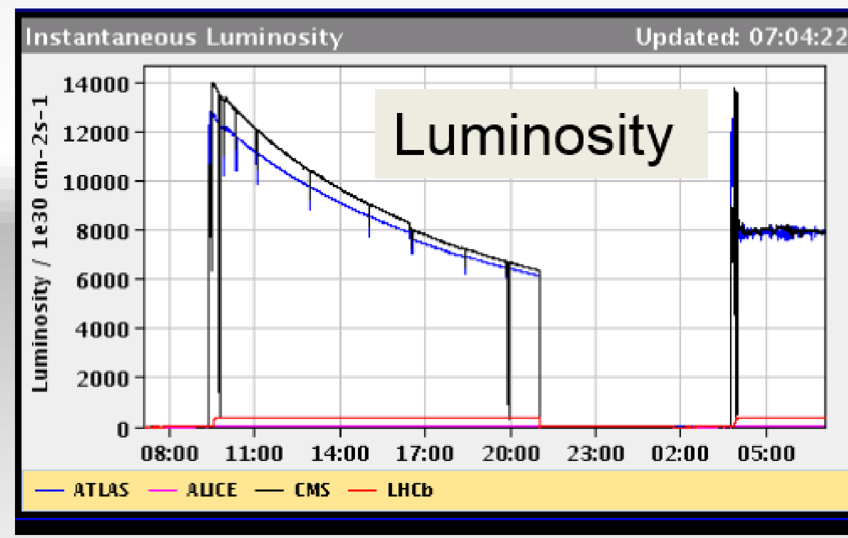
HL-LHC

A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing:

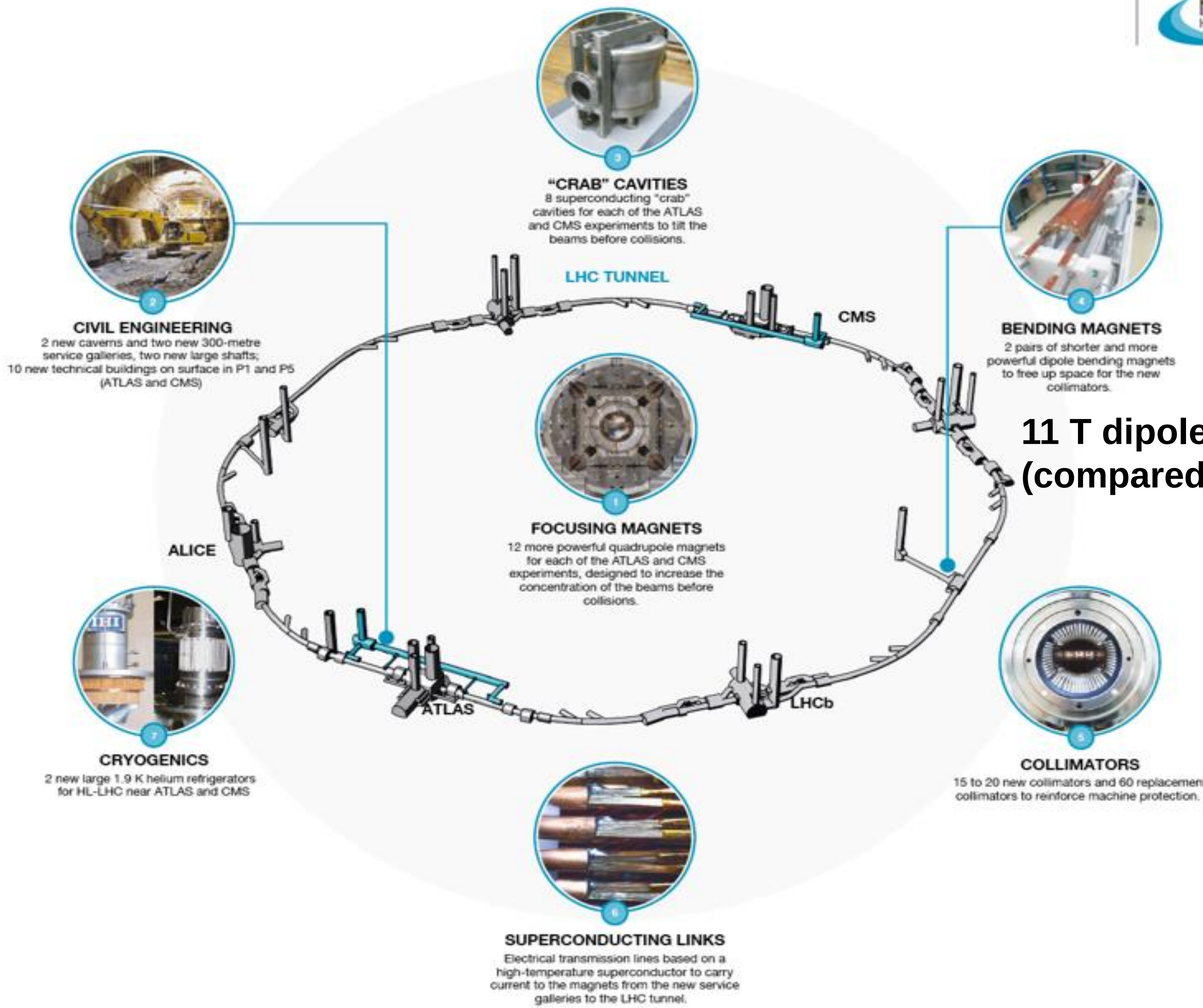
An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

Luminosity so far





HiLumi LHC landmarks



11 T dipoles (compared to 8.3 T)

In Two Weeks from Now

- Beams again in the LHC after > 2.5 years

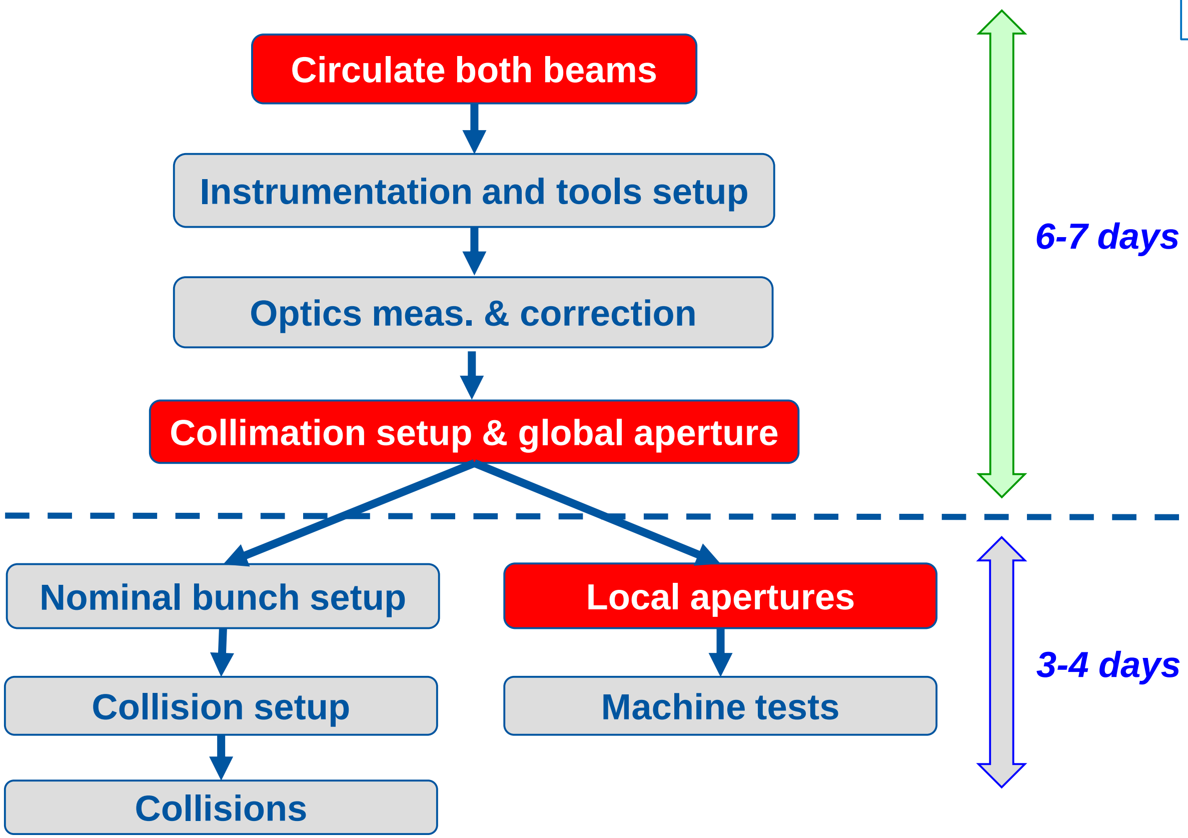
Two week long beam test period:

- **Machine checkout** : **3 days** (estimated).
- **Beam operation** : **11 days**, end 01.11.2021 @ 6AM followed by radio protection survey.

W42							W43							W44		
Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We
18.10			21.10				25.10							01.11		

Beam test outline

Assumes availability ≈ 70-80%



Little flexibility on workflow

Activities must follow defined order

Collisions build on setup work, expected around day 7

Interleaved data taking & machine activity periods

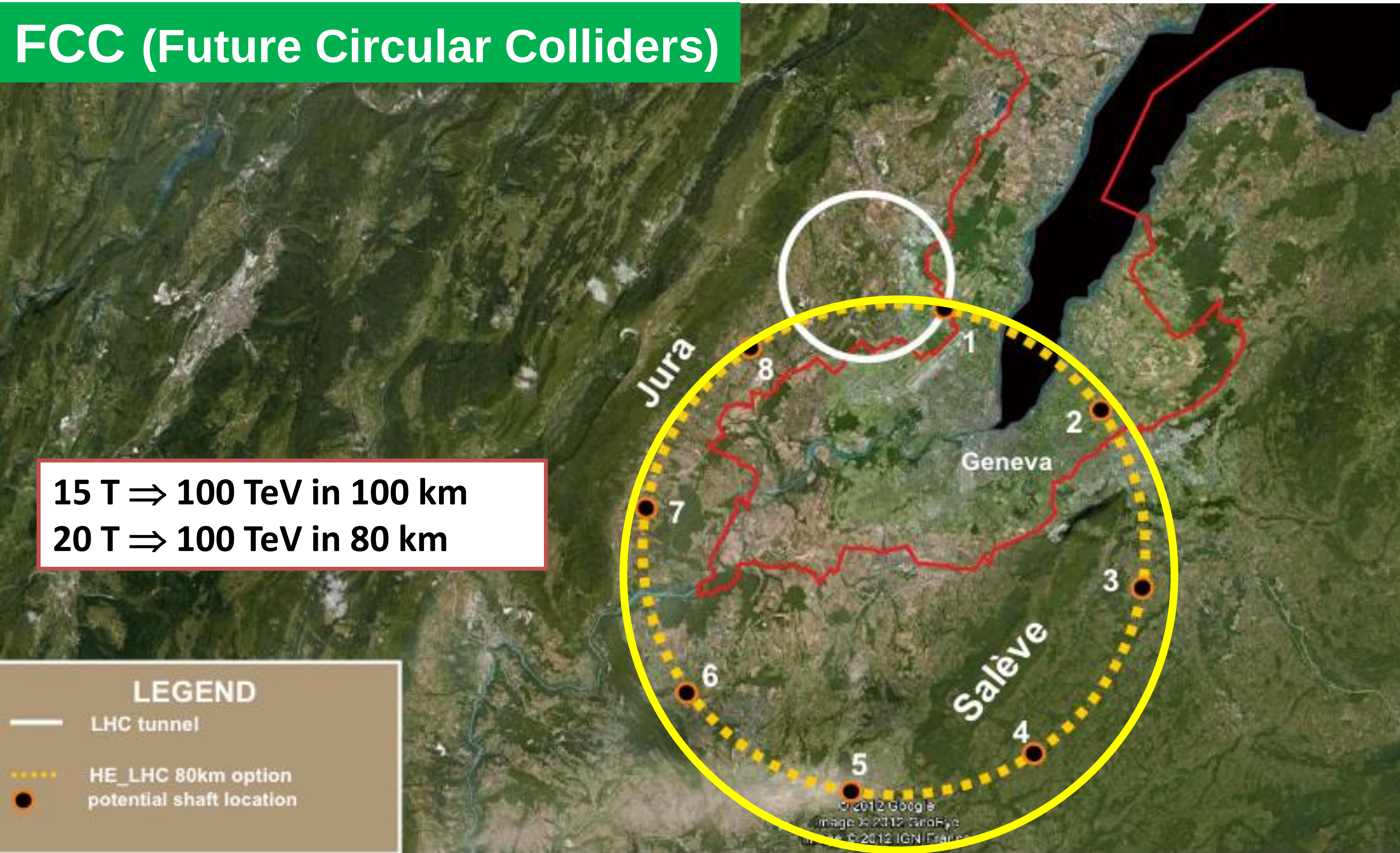
The Future @ CERN after the HL-LHC

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements

with possibility of e+-e- (TLEP) and p-e (VLHeC)

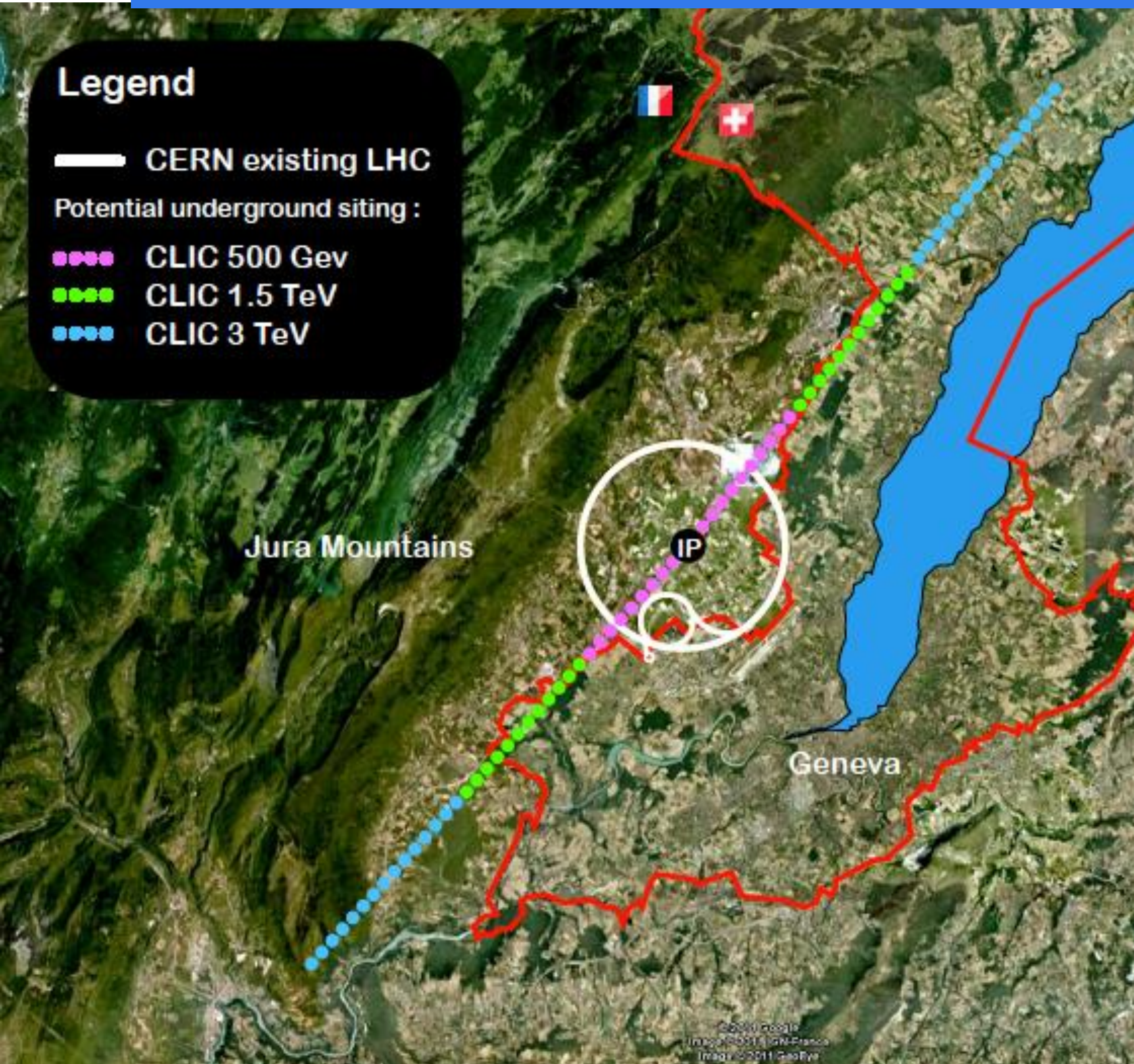
FCC (Future Circular Colliders)

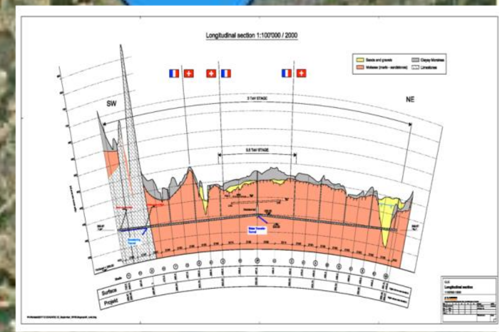
15 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km



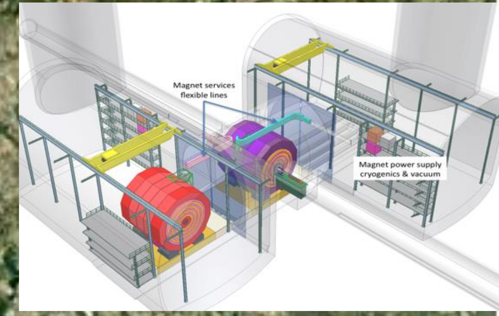

Future Circular Collider Conference
fcc.web.cern.ch
FCCWEEK2018
EuroCirCol
EASITrain
ARIES
IEEE CSC
UNIVERSITY OF TWENTE.
Nikhef

CLIC near CERN: e+e- Collider





Tunnel implementations (laser straight)



Central MDI & Interaction Region

CERN-ESU-014

5 March 2020

Deliberation Document on the 2020 update of the European Strategy for Particle Physics

The European Strategy Group (prepared by the Strategy Secretariat)

European Strategy for Particle Physics (ESPP)
Council decided, unanimously and with enthusiastic support, to update the Strategy

Medium-Term Plan 2021-2025

Draft version, which includes preliminary implementation of ESPP, received strong support
→ final version for approval in September

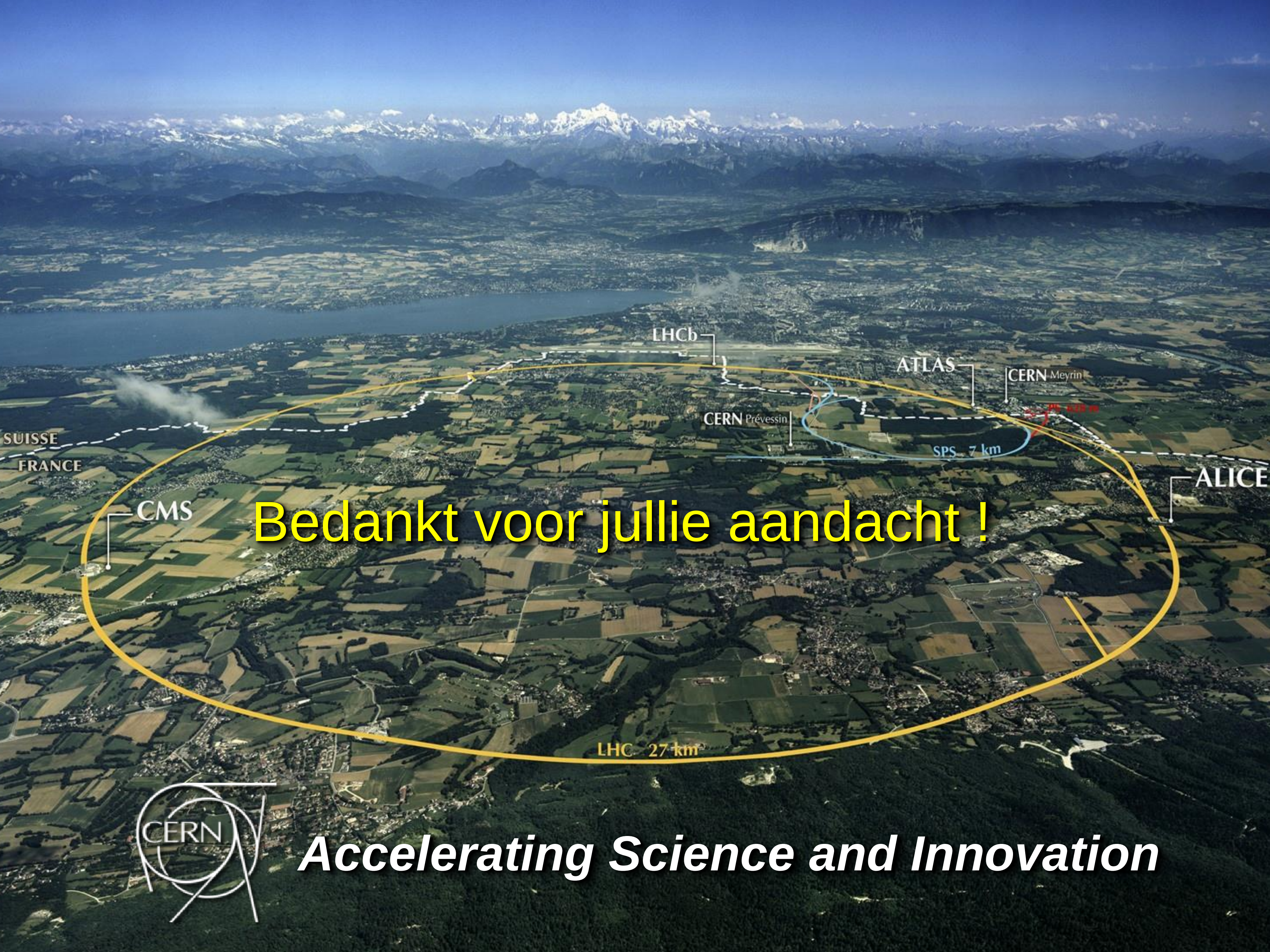
Financial feasibility

Cost of tunnel: ~5.5 BCHF; FCC-ee: ~5-6 BCHF; FCC-hh: ~17 BCHF (if after FCC-ee)
→ cannot be funded only from CERN's (constant) budget + additional "*ad hoc*" contributions from Member and other States → need innovative mechanisms: EC? private funds? donations?

First priority of feasibility study: find funds for the tunnel

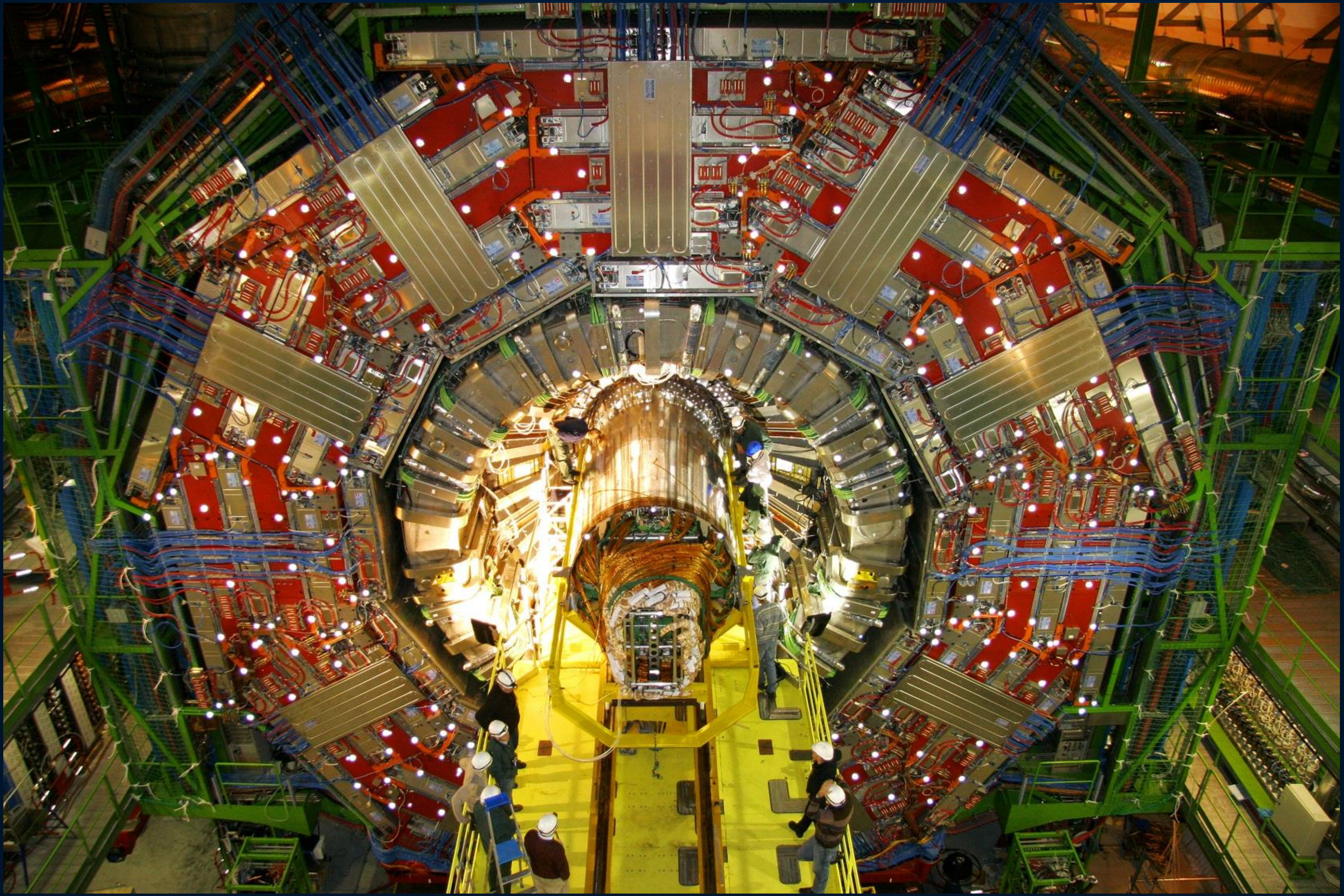
First priority of feasibility study: no show-stoppers for ~100 km tunnel in Geneva region

First priority of feasibility study: magnet technology; how to minimise environmental impact

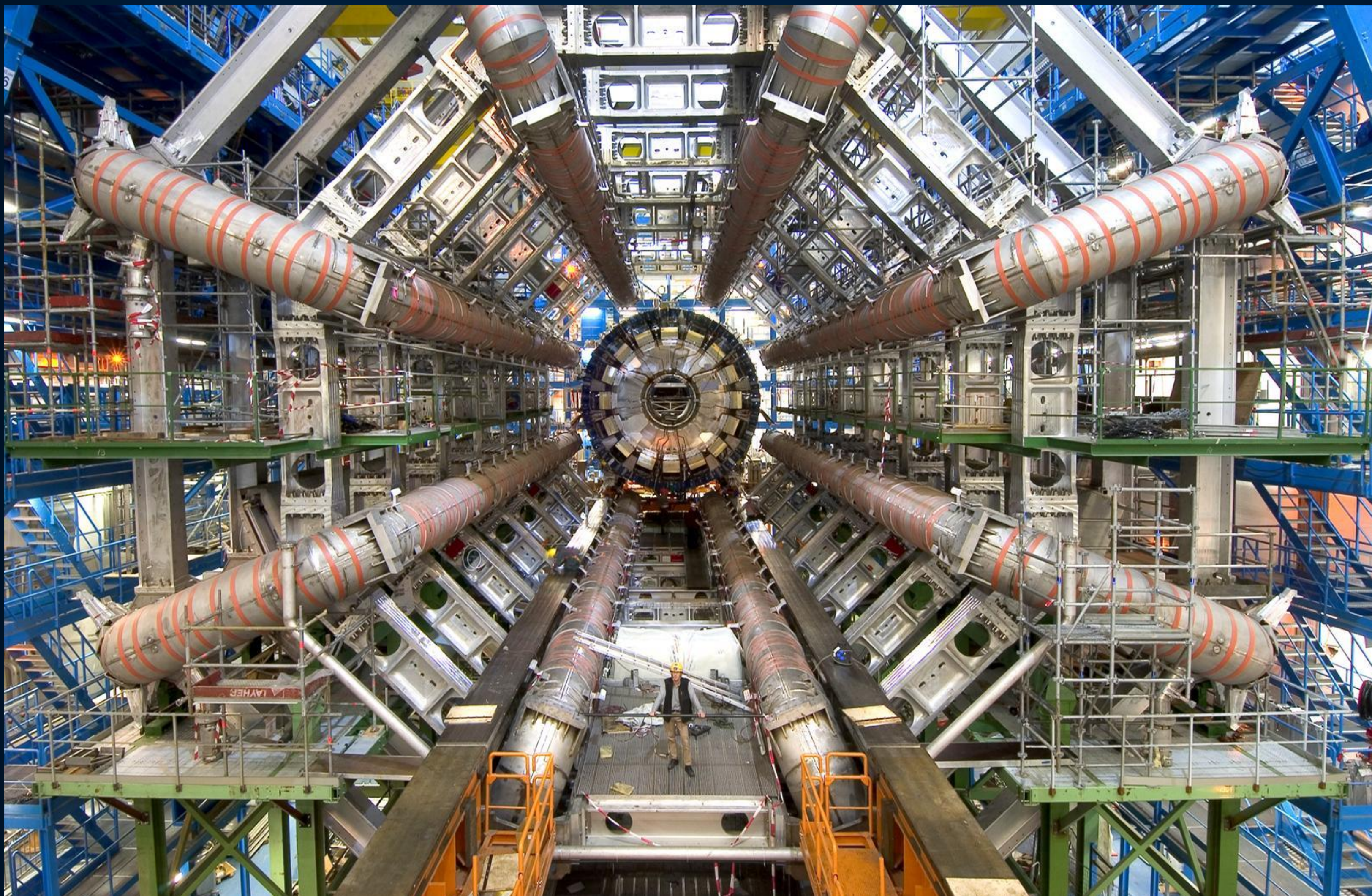

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km
Bedankt voor jullie aandacht !
CERN
Accelerating Science and Innovation

SPARE SLIDES

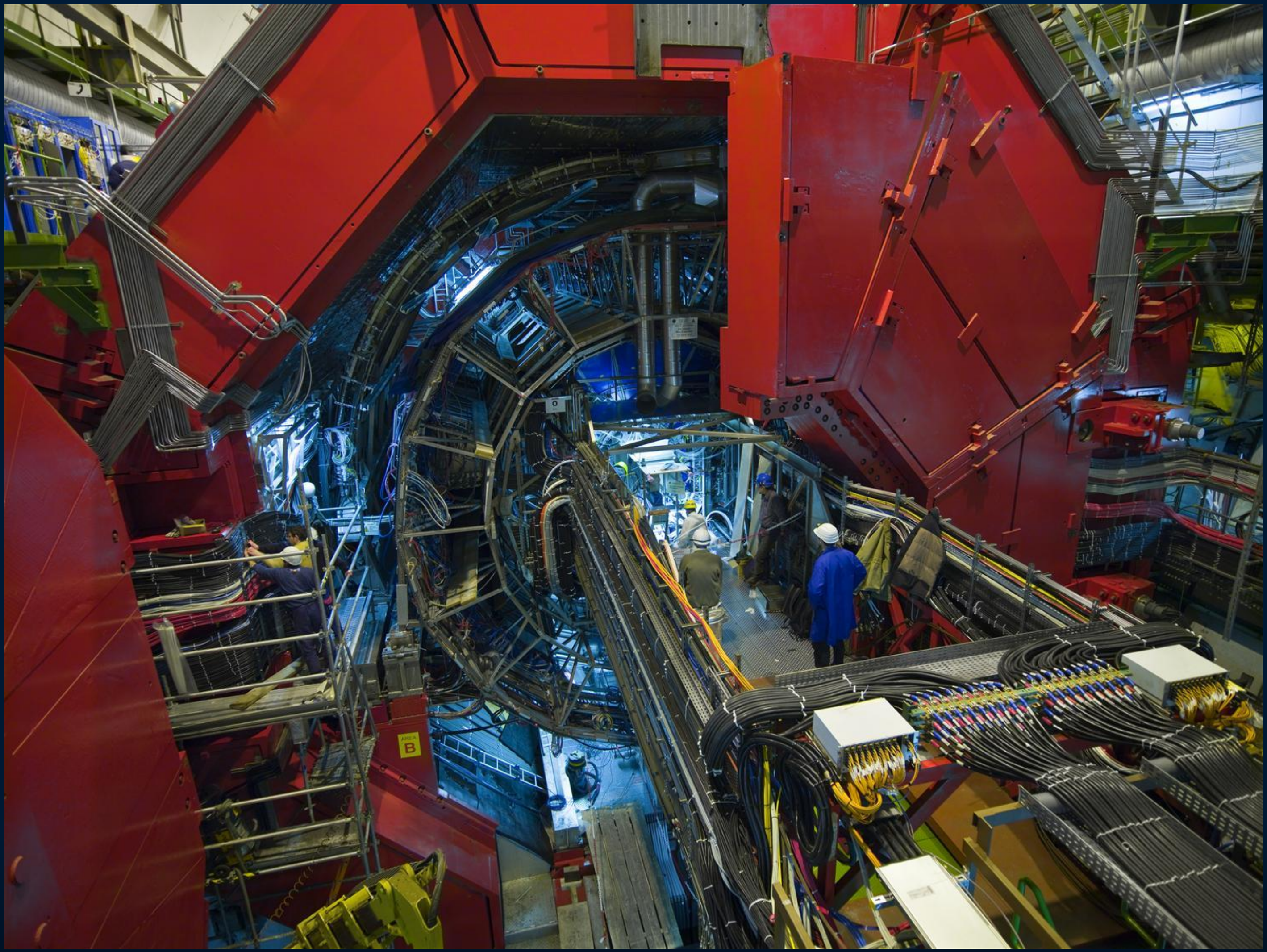
CMS: heavier than the Eifel tower



ATLAS: large as a building of 5 floors



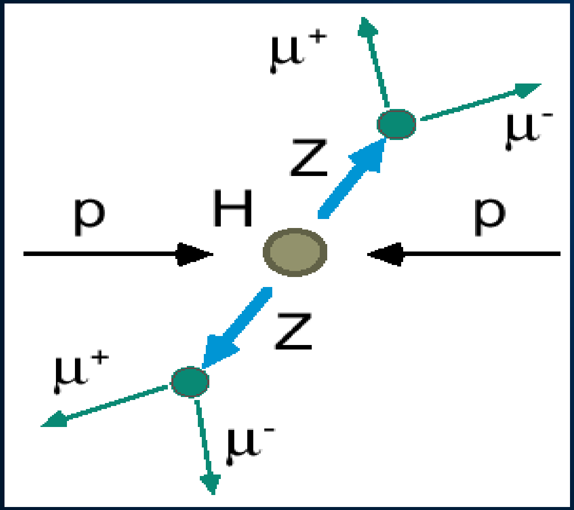
ALICE: very sensitive, optimised for ion collisions



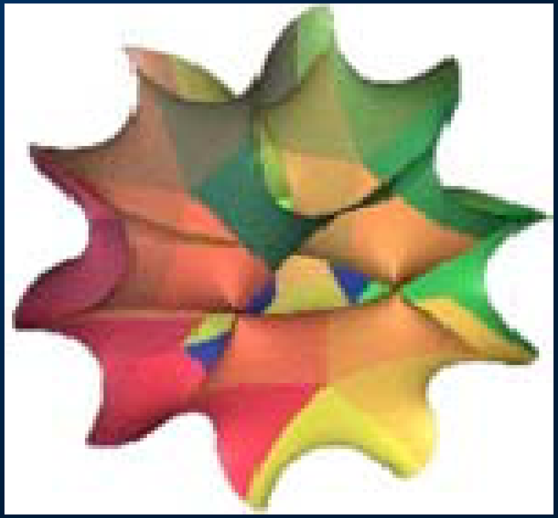
LHCb: asymmetric, B-physics

Aim of the game

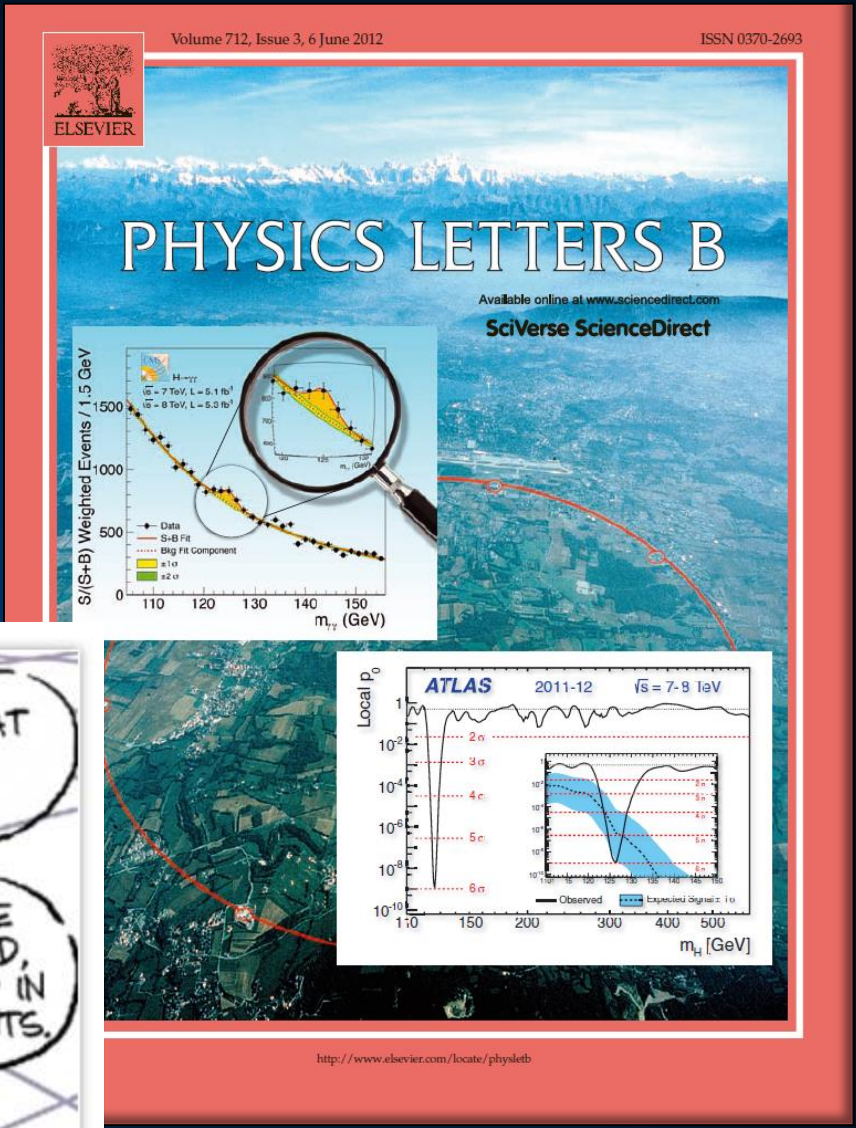
We want to deliver maximum number of collisions at the maximum beam energy for maximum physics reach

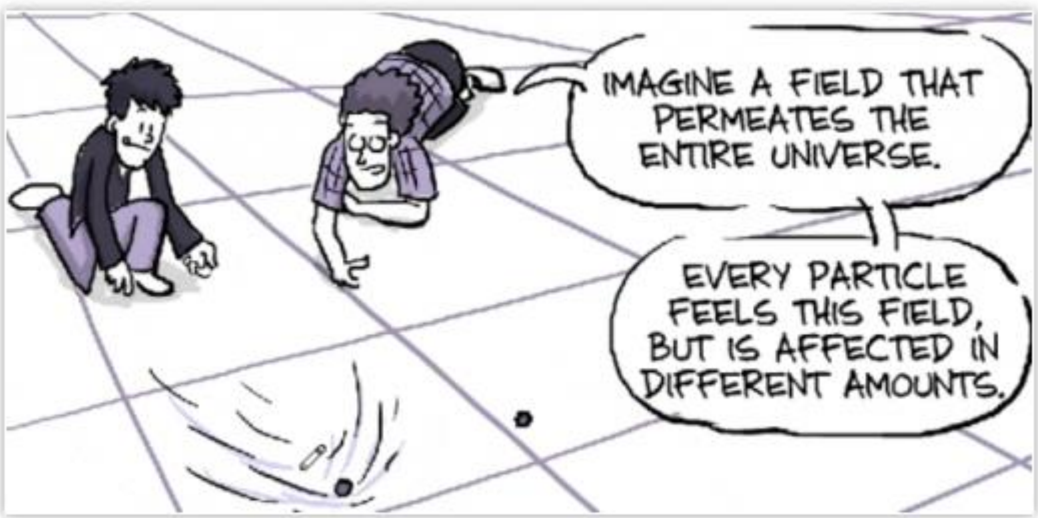


$E = m \cdot c^2$



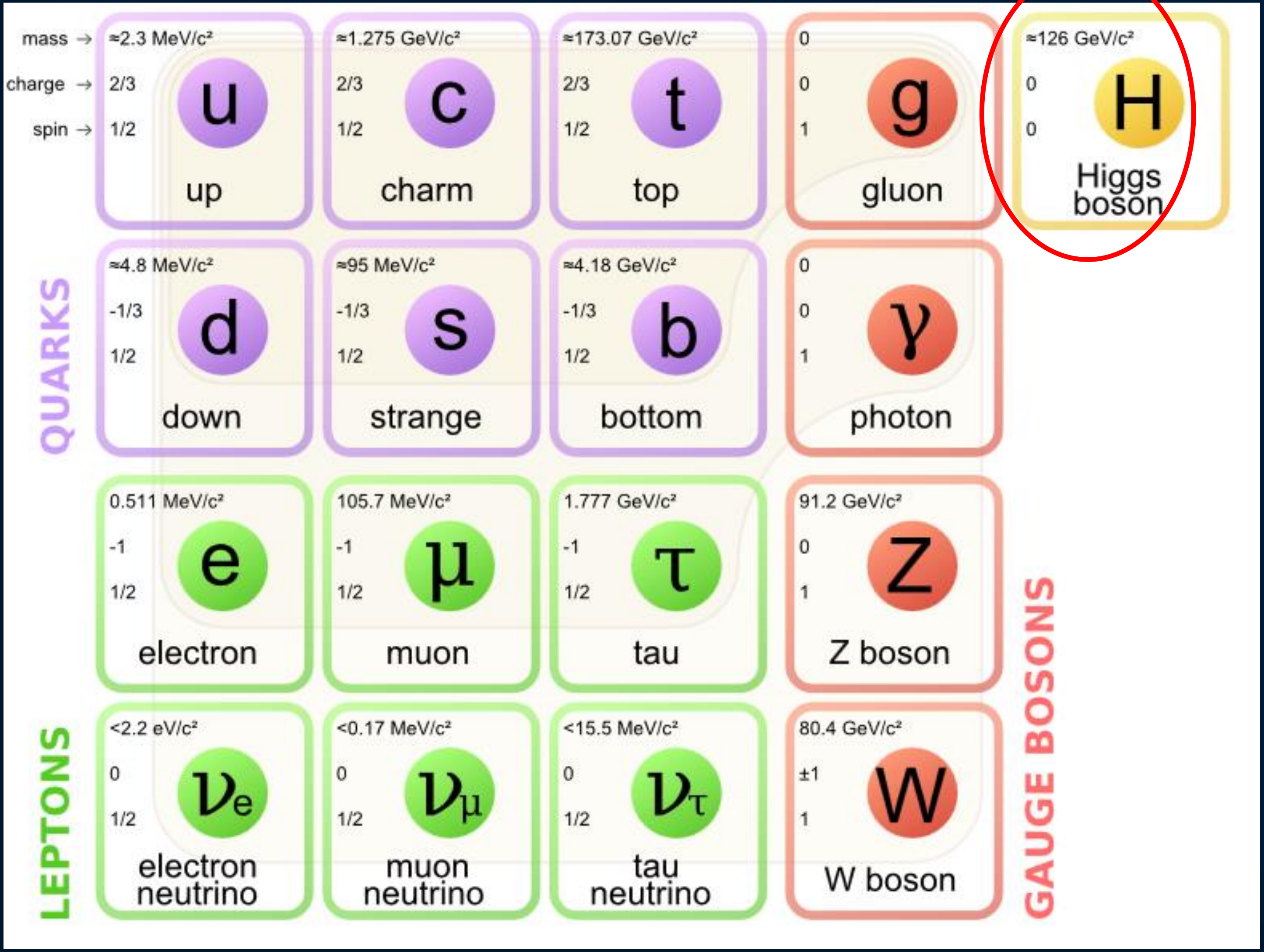
The Higgs field gives mass to other particles





(Credit: PHD Comics)

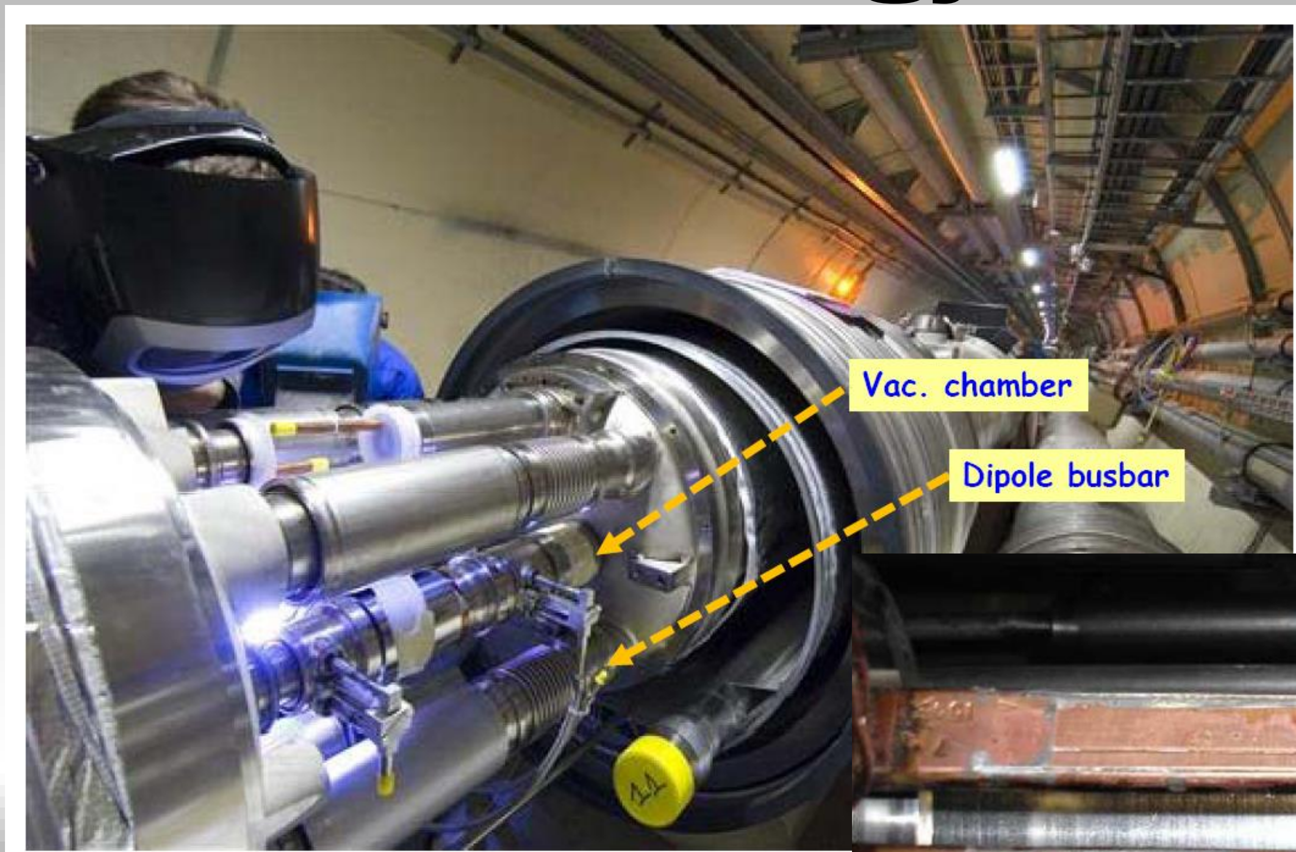
Why is the Higgs so special?

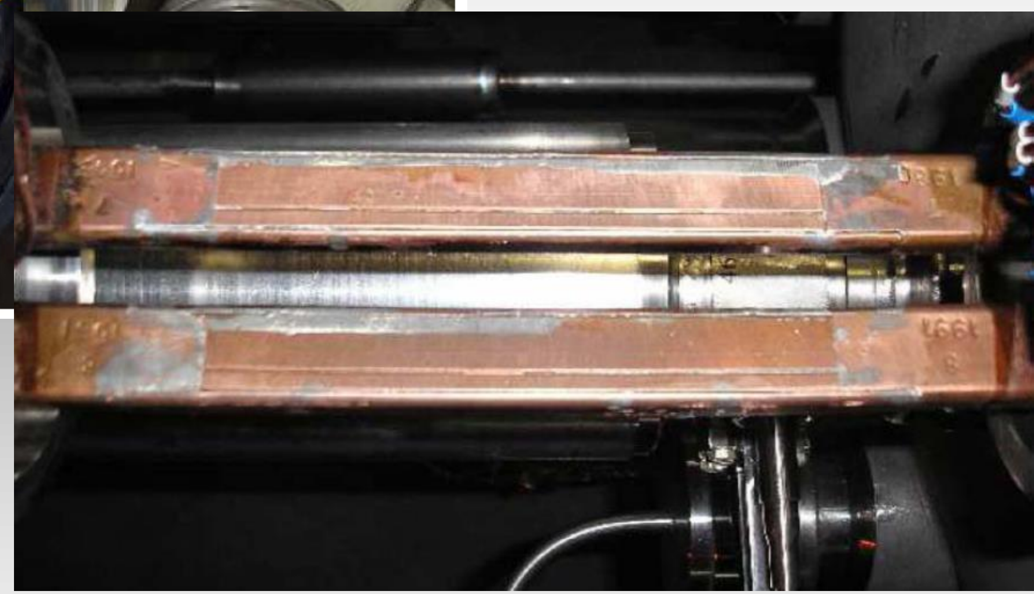


Reduced Energy – the history

10th September 2008: First circulating beams – all smiles

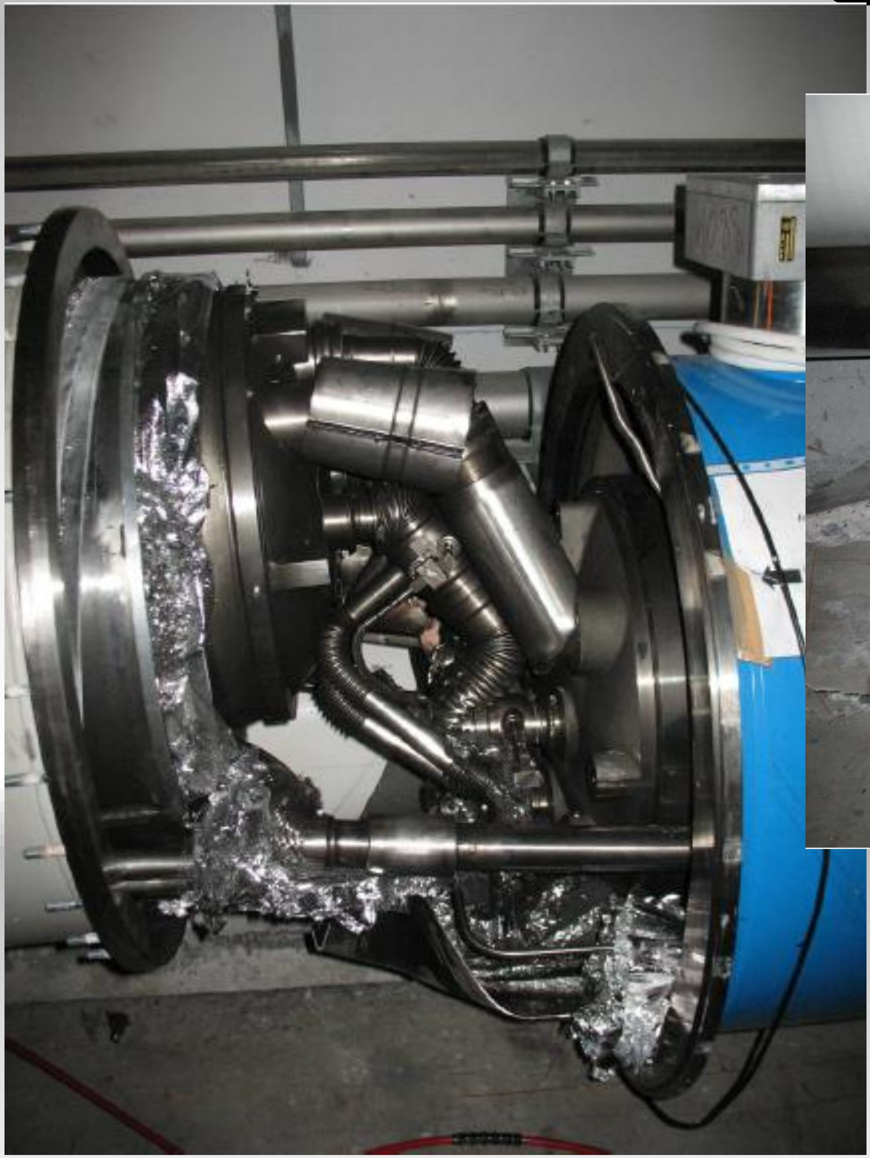
Reduced energy – the history





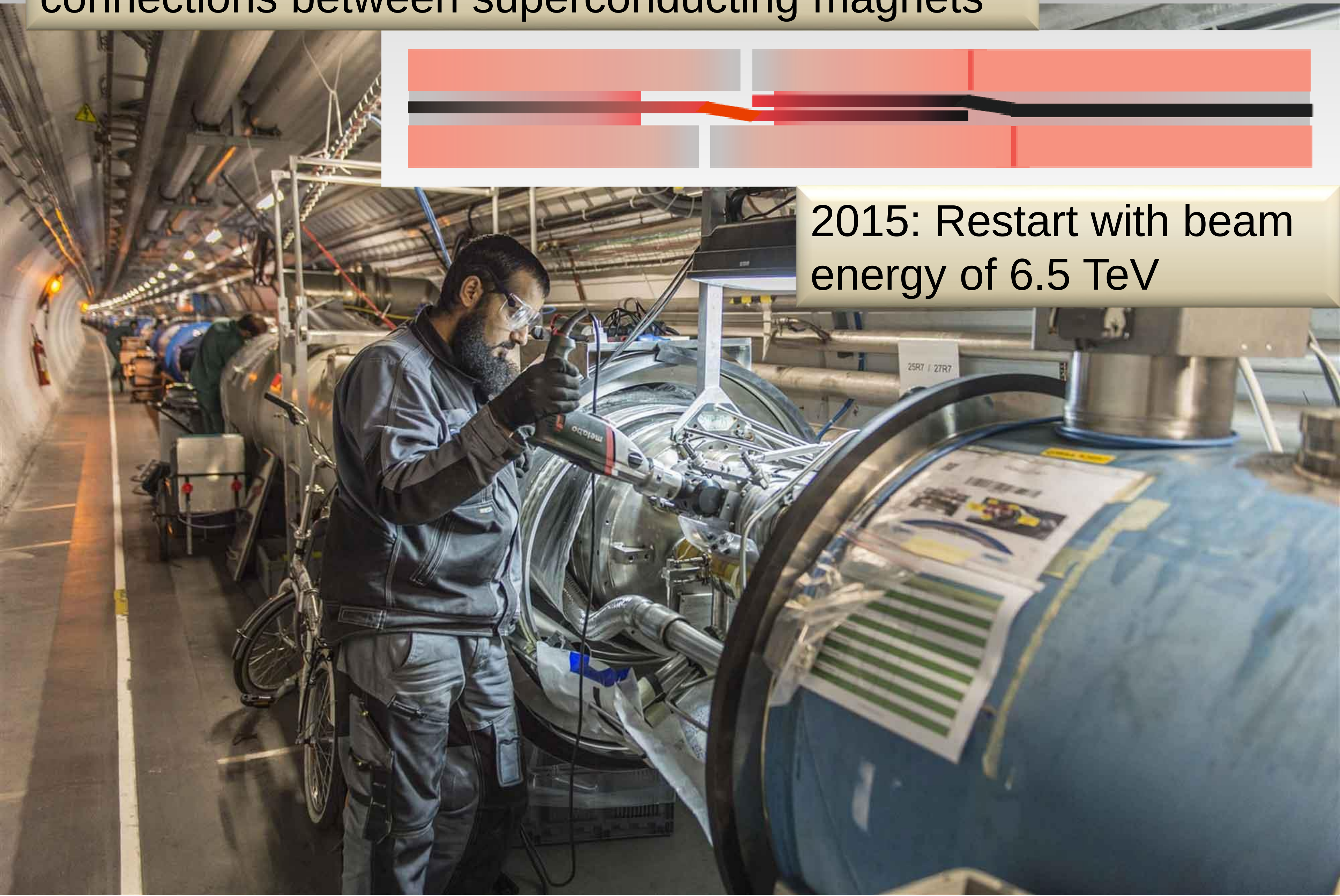
19th September 2008: electrical arc ruptured bus-bar interconnection during tests without beam – violent He blow-off

Reduced energy – the history



Major damage over a few hundred meters. Back in operation 1 year later.

2013 – 2014: Long Shutdown to repair defective connections between superconducting magnets



2015: Restart with beam energy of 6.5 TeV

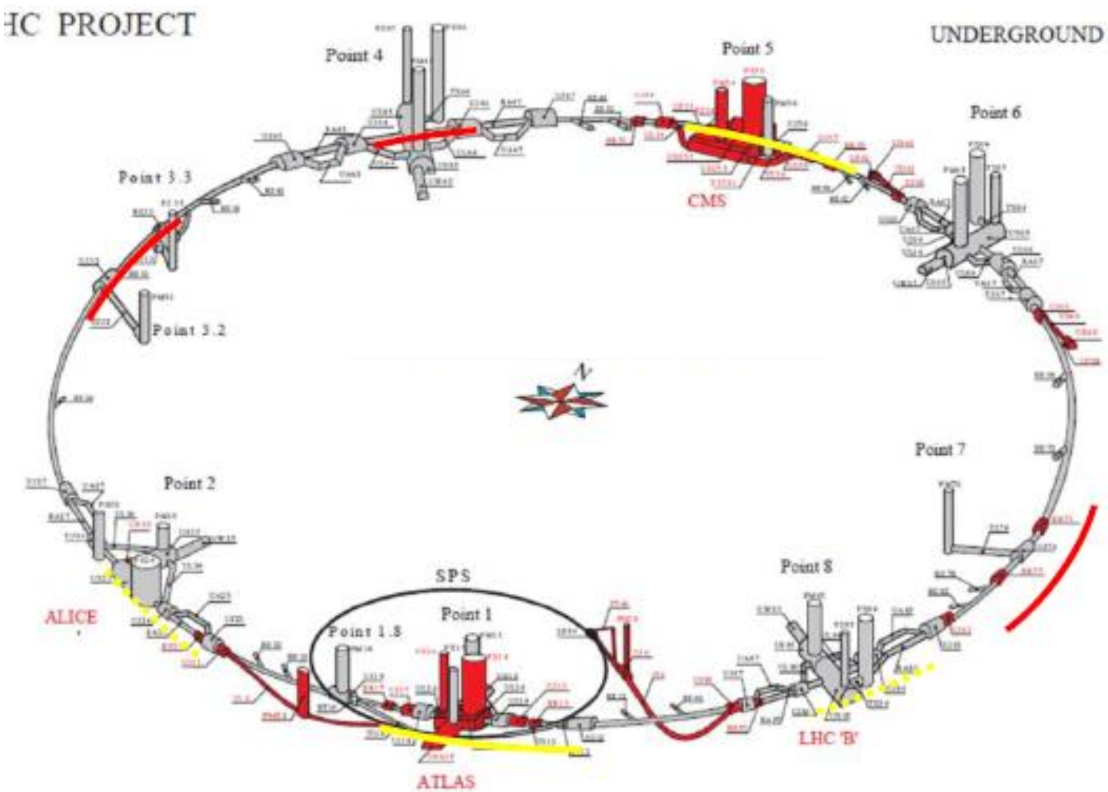
Next 10 years

2012	Run I	4 TeV, peak luminosity 7.7e33
2013	LS1	Splice consolidation, R2E, DN200…
2014		Experiments' consolidation and upgrades
2015	Run II	6.5 to 7 TeV, peak luminosity 1.7e34
2016		
2017		
2018	LS2	LHC phase 1 and **injector** upgrades Experiments' consolidation and upgrades
2019	Run III	7 TeV, peak luminosity 2.0e34
2020		
2021		
2022	LS3	HL-LHC upgrade (insertions, crab cavities…)
2023		Experiments' HL upgrades

Followed by many years of HL-LHC running

The LHC has a long future ahead ….

The HL-LHC Project



- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

High Luminosity LHC Participants

CLIC Collaboration

29 Countries – over 70 Institutes

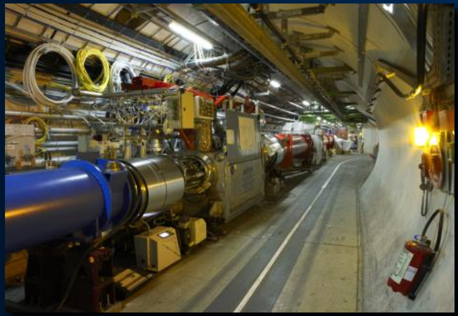
- Accelerator collaboration
- Detector collaboration
- Accelerator + Detector collaboration

Innovation
Education
CERN
uniting people
Research

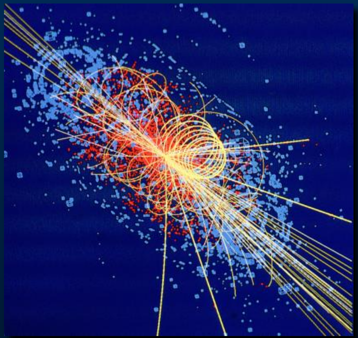
CERN: Particle Physics and Innovation

- **Interfacing** between fundamental science and key technological developments

- **CERN Technologies and Innovation**



Accelerating particle beams

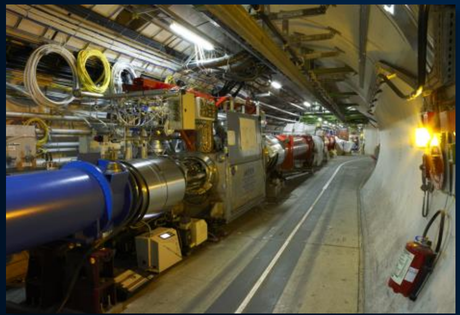


Detecting particles

Large-scale computing (Grid)

Medical Application as an Example of Particle Physics Spin-off

Combining Physics, ICT, Biology and Medicine to fight cancer

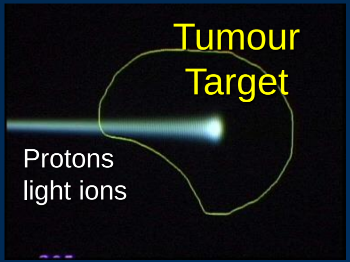


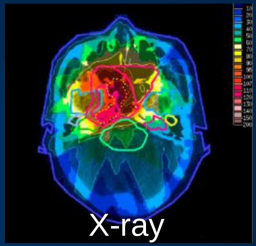
Accelerating particle beams

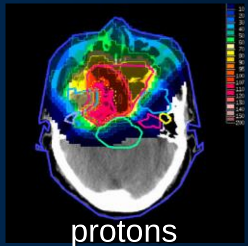
~30’000 accelerators worldwide

~17’000 used for medicine

Hadron Therapy



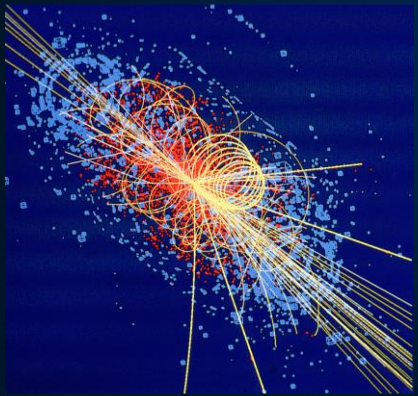




Leadership in Ion Beam Therapy now in Europe and Japan

>70’000 patients treated worldwide (30 facilities)

>21’000 patients treated in Europe (9 facilities)

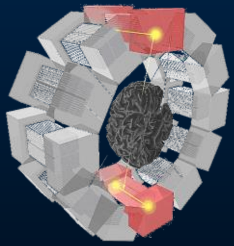


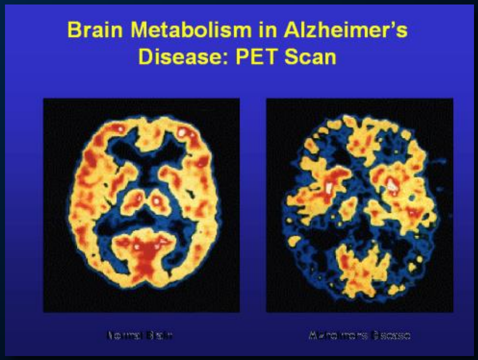
Detecting particles

Imaging

Clinical trial in Portugal for new breast imaging system (ClearPEM)

PET Scanner





CERN Education Activities

Scientists at CERN

Academic Training Programme

Young Researchers

CERN School of High Energy Physics
CERN School of Computing
CERN Accelerator School

Physics Students

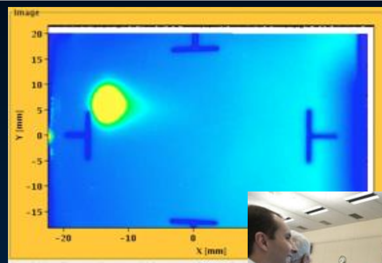
Summer Students Programme

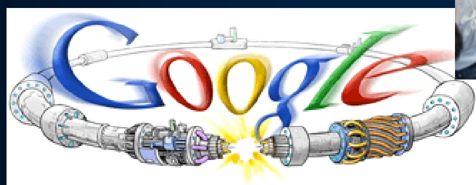
CERN Teacher Schools

International and National Programmes

LHC Timeline

August 2008
First injection test



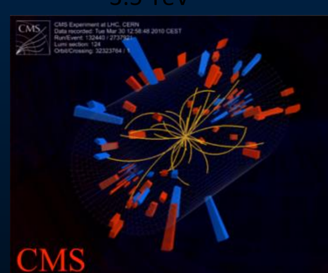


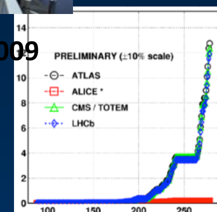
September 10, 2008
First beams around

September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

November 29, 2009
Beam back

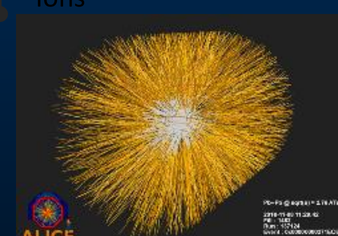
March 30, 2010
First collisions at 3.5 TeV





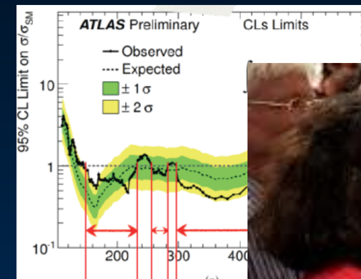
October 14 2010
1e32
248 bunches

November 2010
Ions



June 28 2011
1380 bunches

1380



August
2.3e33,
1380 b

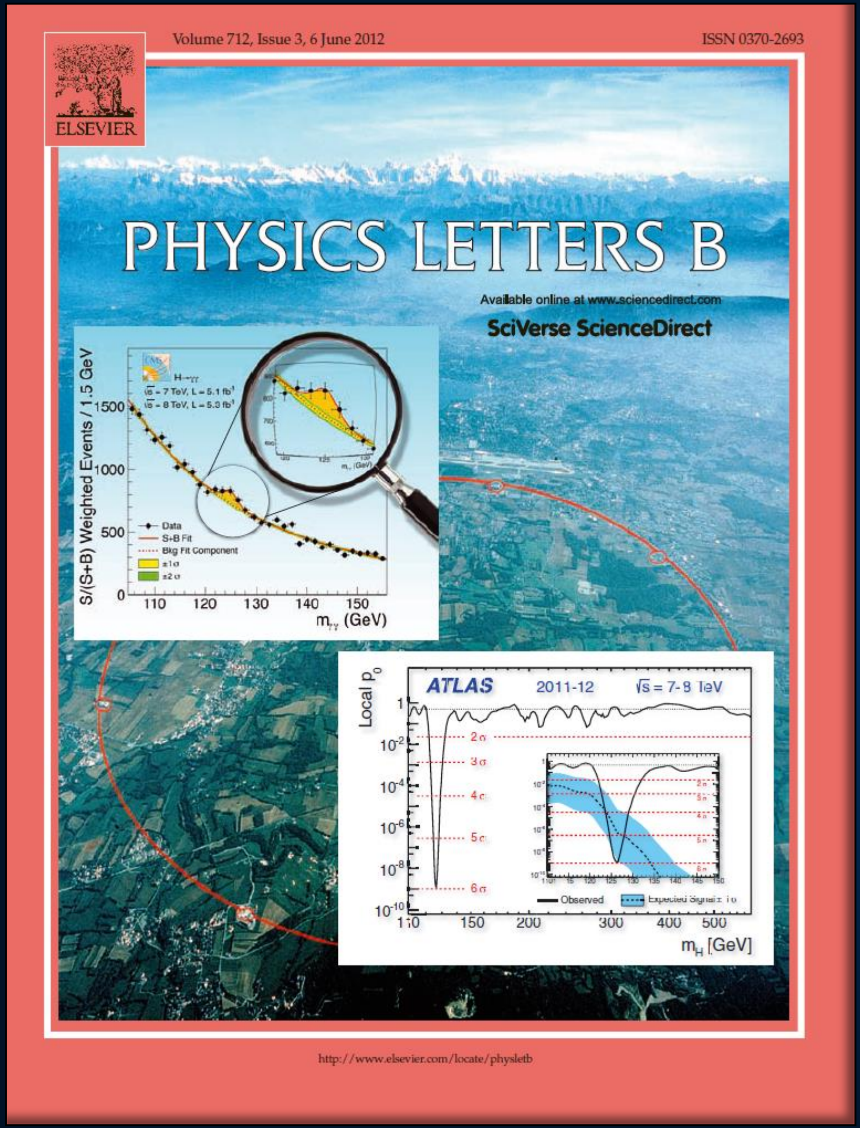
6 June, 2012
6.8e33

18 June, 2012
6.6 fb^{-1}
to ATLAS & CMS

4 July, 2012

2008	2009	2010	2011	2012

The highlight of a remarkable year 2012



Nobel Prize in Physics 2013

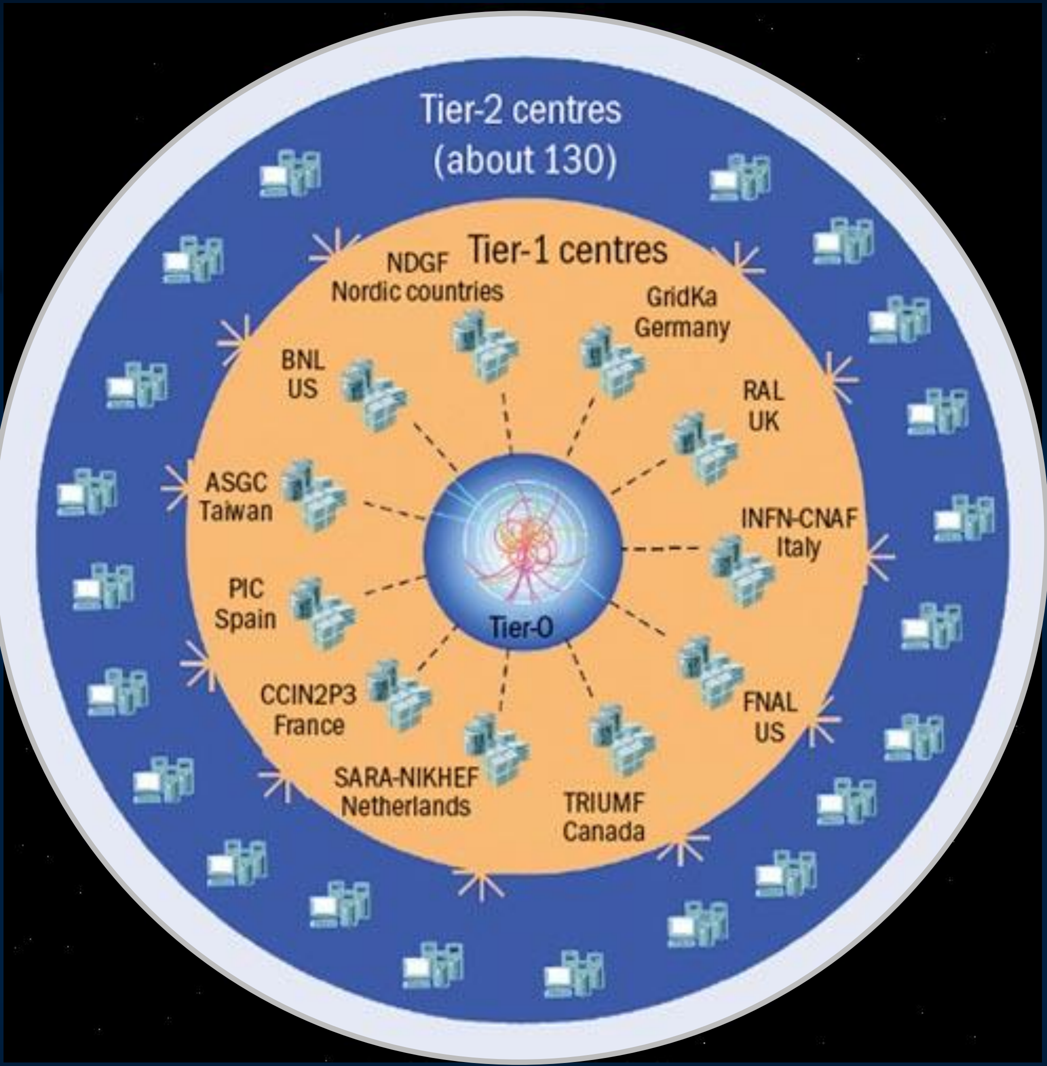
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

The Worldwide LHC Computing Grid

Tier-0 (CERN): data recording, reconstruction and distribution

Tier-1: permanent storage, re-processing, analysis

Tier-2: Simulation, end-user analysis



nearly 160 sites, 35 countries

~250'000 cores

173 PB of storage

> 2 million jobs/day

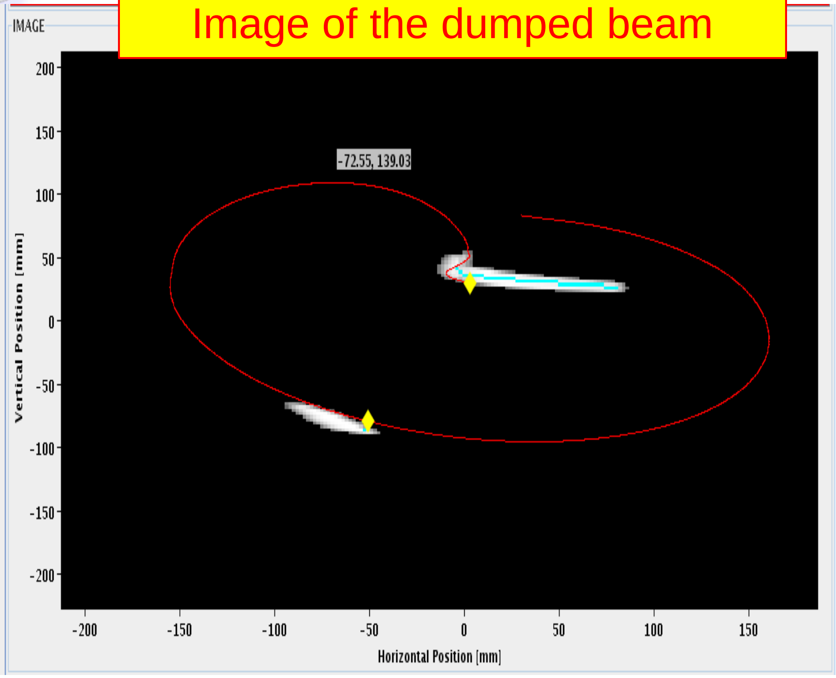
10 Gb links

An International collaboration to distribute and analyse LHC data

Integrates computer centres worldwide that provide computing and storage resource into a single infrastructure accessible by all LHC physicists

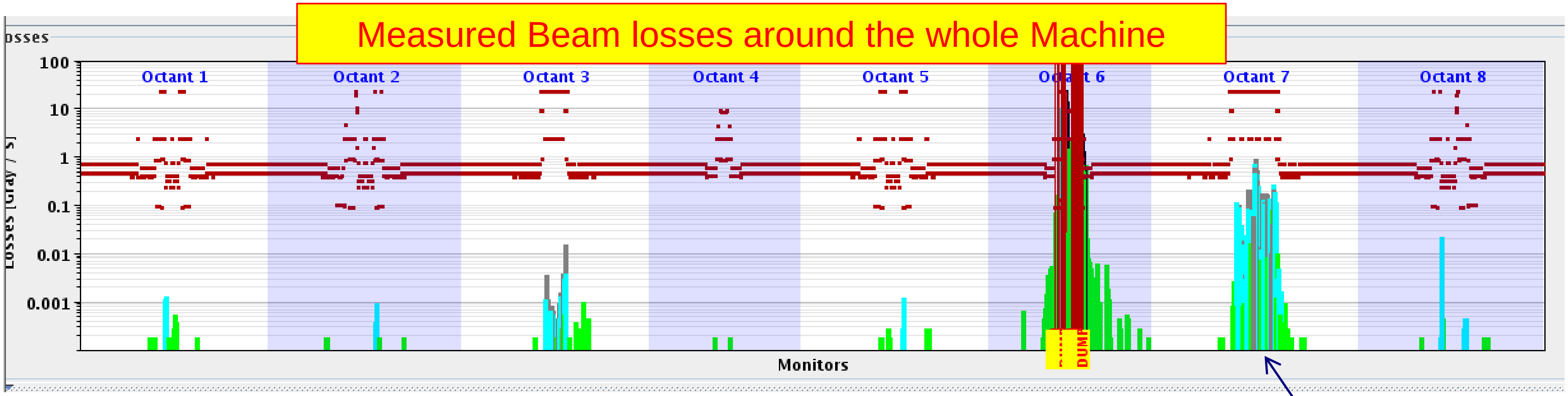
Verification of Dump Protection

Image of the dumped beam



- Switch off the RF
  - Debunching fills the abort gap
- Dump Beam
  - Loss in point 6 on absorber elements
  - Some losses collimation
  - Clean at experiments: factor 1 : 10 000

Measured Beam losses around the whole Machine



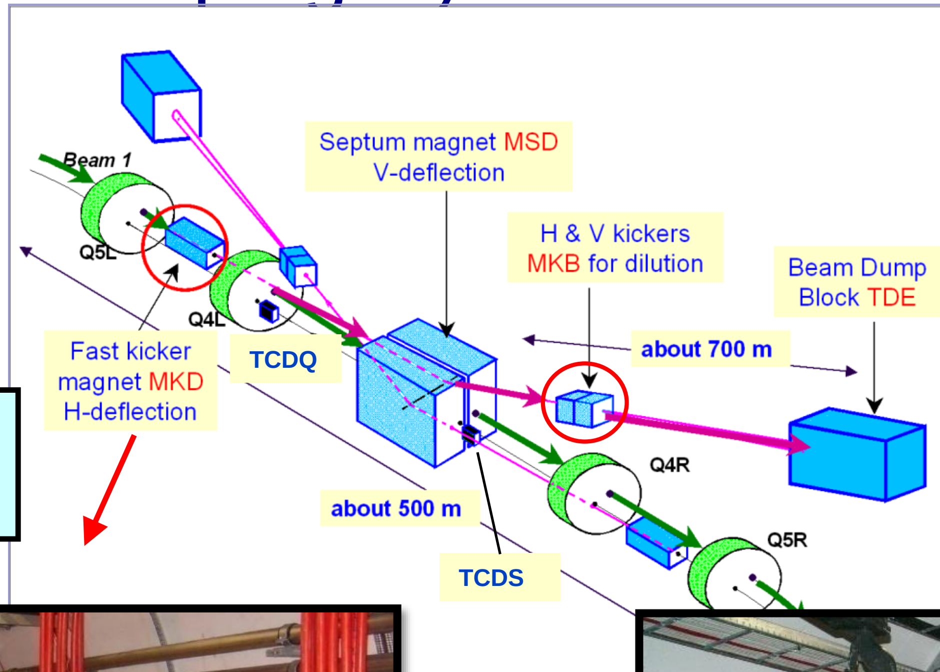
Rest of the machine is clean

Dump

Collimation

Only one way to safely get rid of the beam

LHC Beam Dumping System



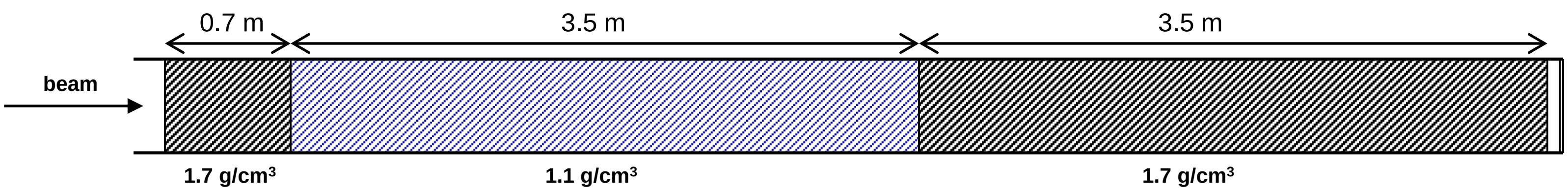
Extraction Kickers

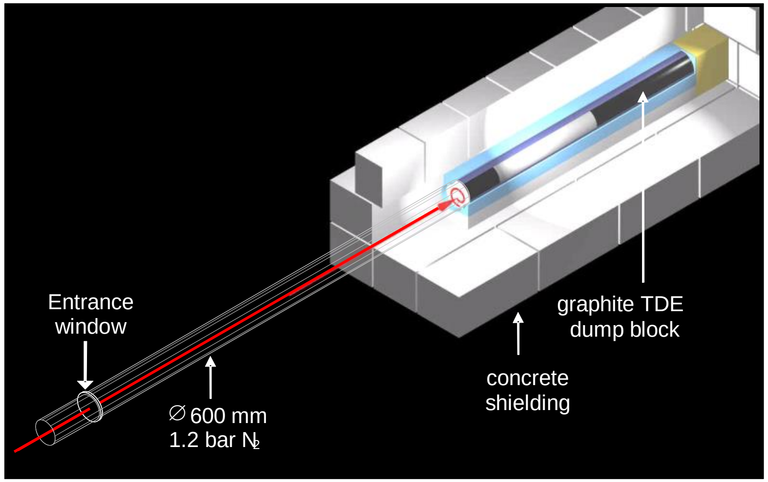
2 x 15 Systems

10 Dilution kickers MKB

Beam dump block (TDE)

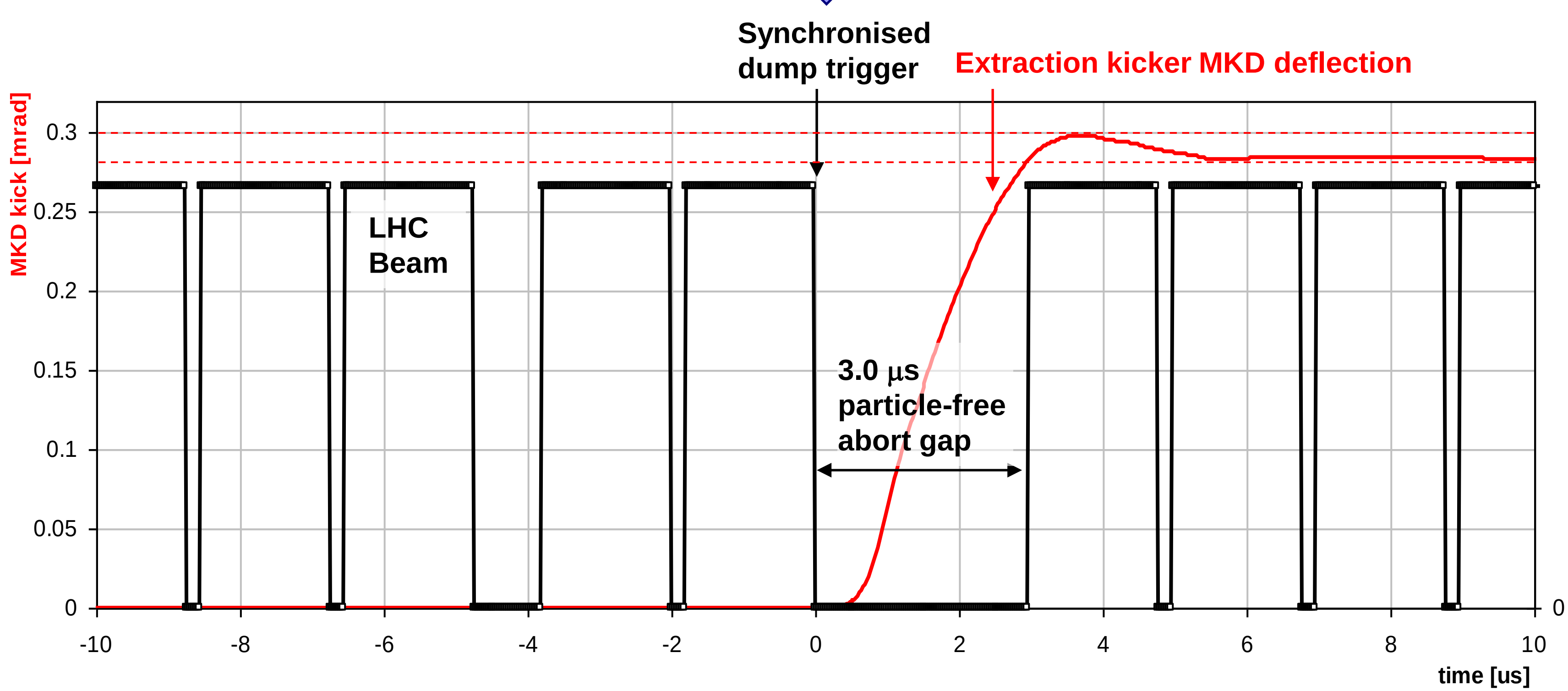
- 700 mm ∅ graphite core, with graded density of 1.1 g/cm^3 and 1.7 g/cm^3
- 12 mm wall, stainless-steel welded pressure vessel, at 1.2 bar of N_2
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks



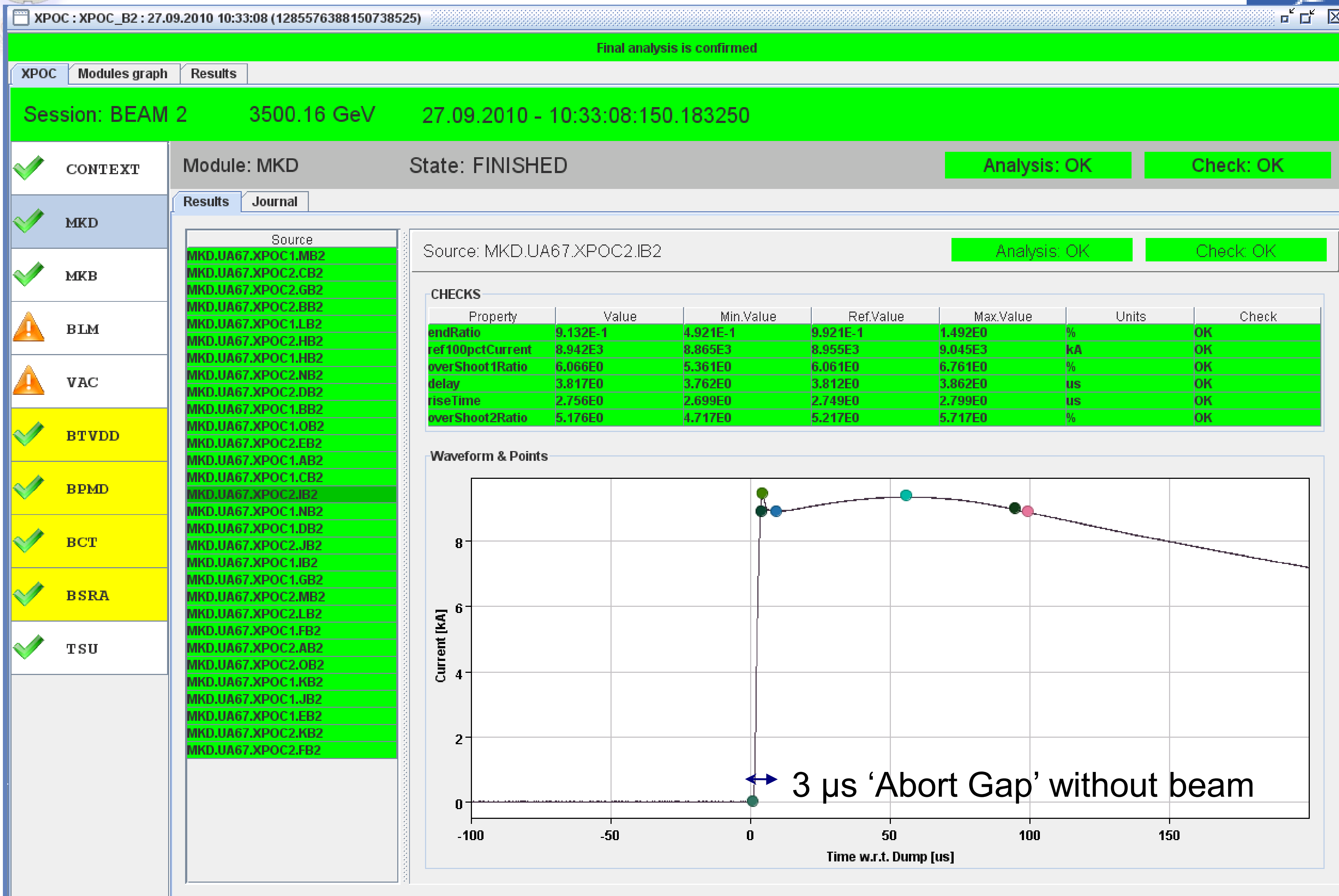


Extraction kicker – Abort Gap

Within 3 turns of dump request



At every dump: Check the Extraction Kickers



At every dump: Check the Dump Pattern

XPOC : XPOC_B2 : 27.09.2010 10:33:08 (1285576388150738525)

Final analysis is confirmed

XPOC | Modules graph | Results

Session: BEAM 2 3500.16 GeV 27.09.2010 - 10:33:08:150.183250

- CONTEXT
- MKD
- MKB
- BLM
- VAC
- BTVDD
- BPMD
- BCT
- BSRA
- TSU

Module: BTVDD State: FINISHED Analysis: OK Check: OK

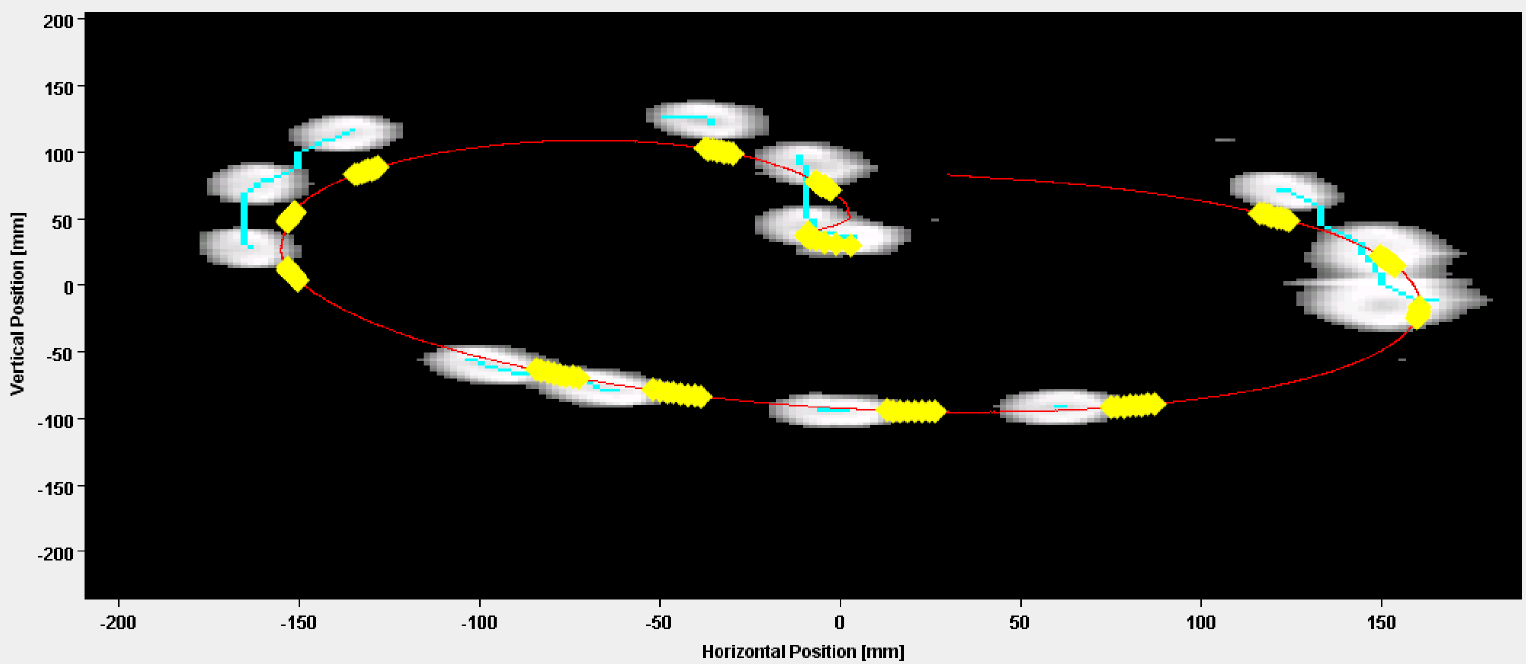
Results | Journal

Checks | Measures | References

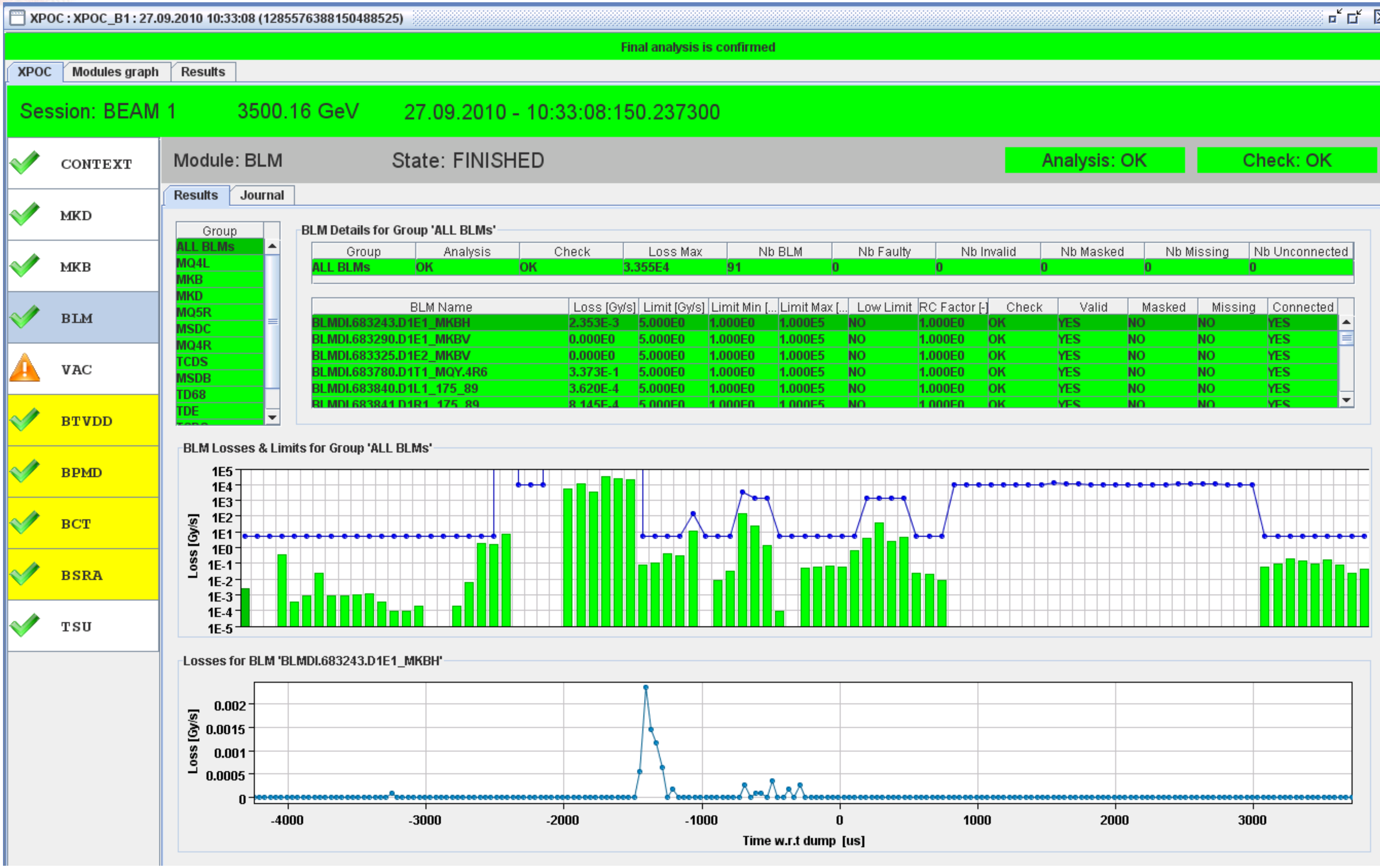
CHECKS

Property	Value	Min.Value	Ref.Value	Max.Value	Units	Check
height	2.014E2	1.580E2	1.980E2	2.380E2	mm	OK
centerV	1.373E1	-3.608E1	3.923E0	4.392E1	mm	OK
centerH	0.000E0	-3.621E1	3.785E0	4.379E1	mm	OK
width	3.320E2	2.640E2	3.140E2	3.640E2	mm	OK

IMAGE



At every dump: Check the Beam Losses



Protection against 'Kicker Sweep'

- Beam in the Abort Gap
- Asynchronous beam dump → quench or damage
  - Several failures possible (synchronisation, MKD erratic)
- Precautionary measures include:
  - TCDS (fixed) – 6 m long diluter protects extraction septum
  - TCDQ/TCS (**mobile**) – 7 m long diluter kept at about **7-8 σ from the beam at all times**