The LHC: How does it work?
Dutch Language Teacher Programme
30 November 2023

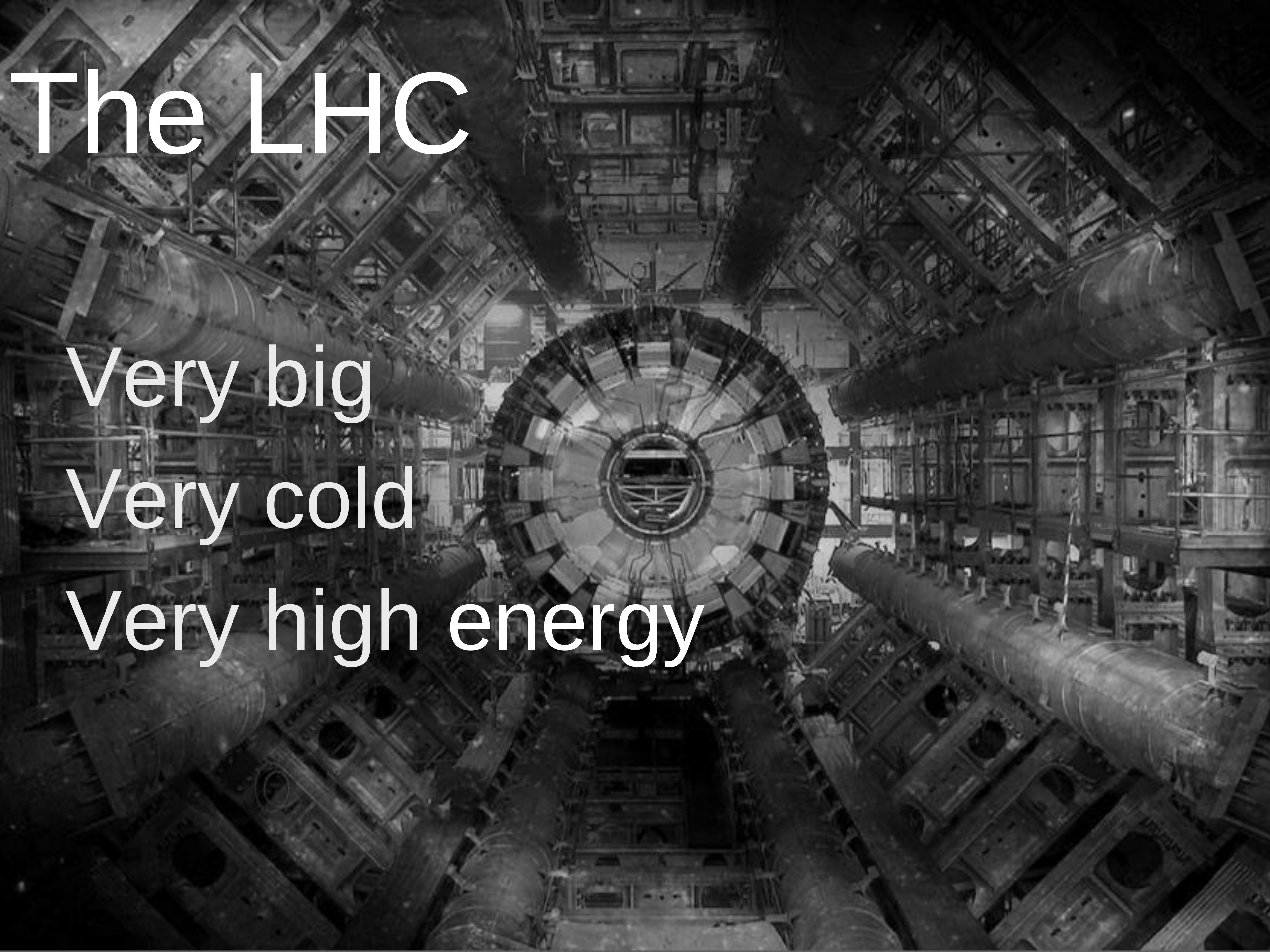
Accelerating Science and Innovation

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

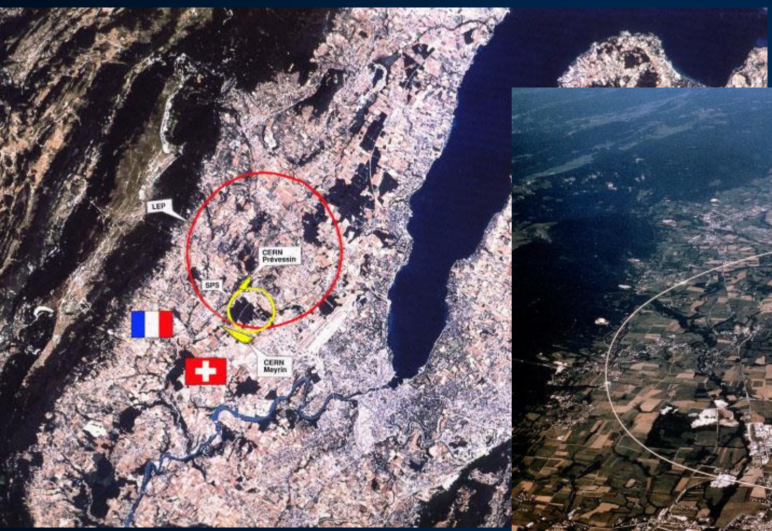
Very big

Very cold

Very high energy

The LHC

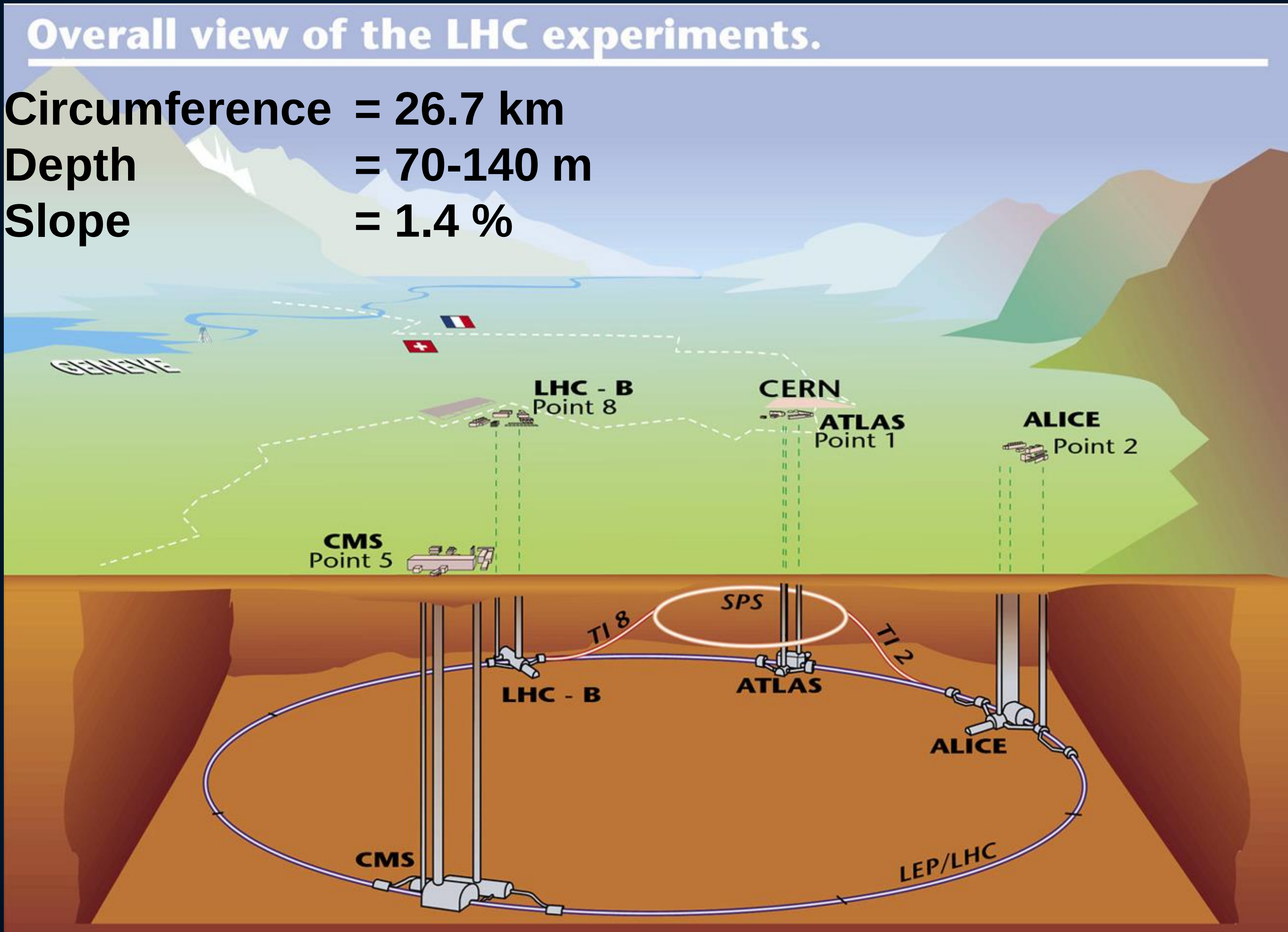
Two beams of trillions of protons race around the 27 km ring at 0.999999991 times the speed of light in opposite directions…



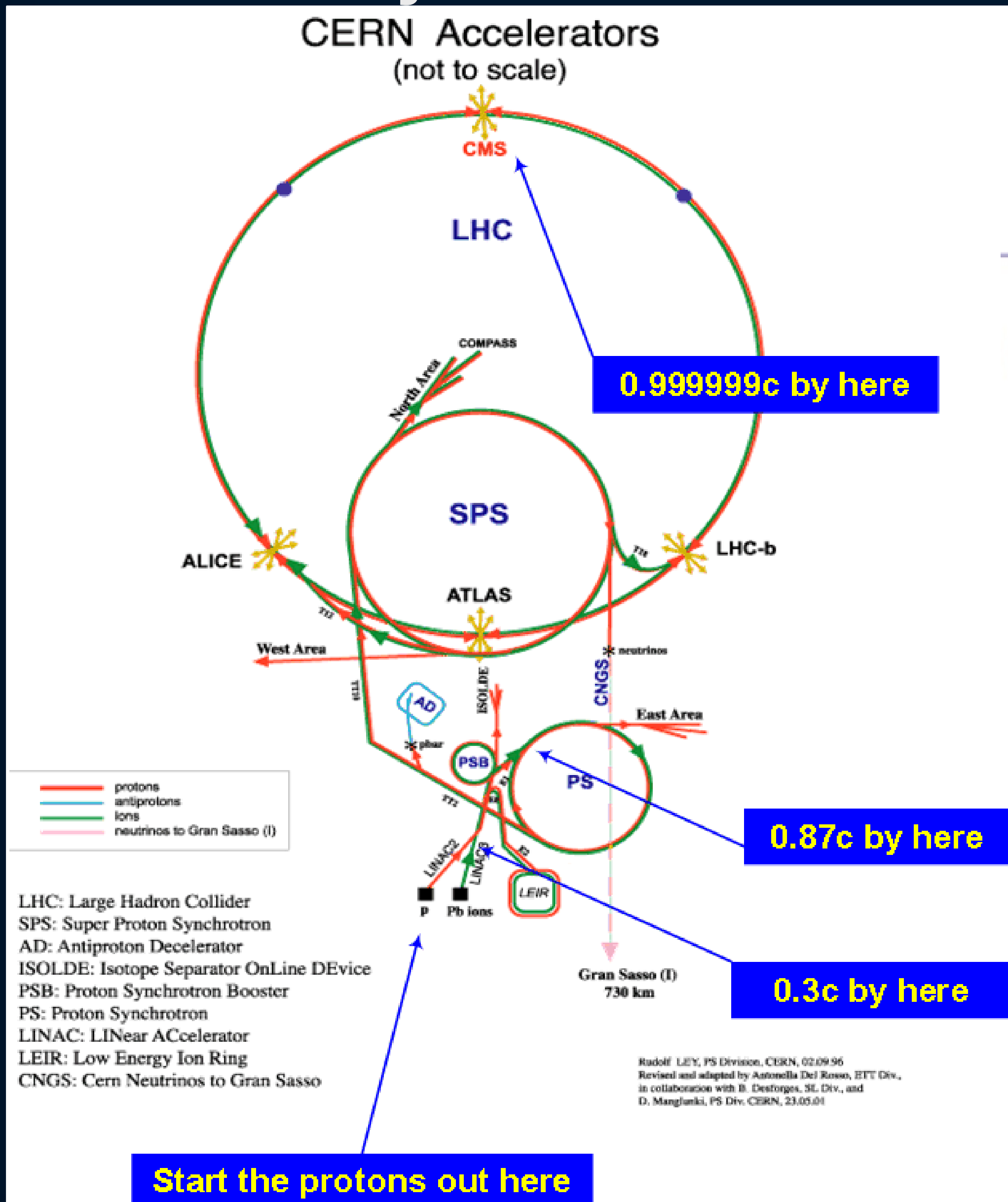

So a particle goes around the LHC 11’000 times per second !

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?

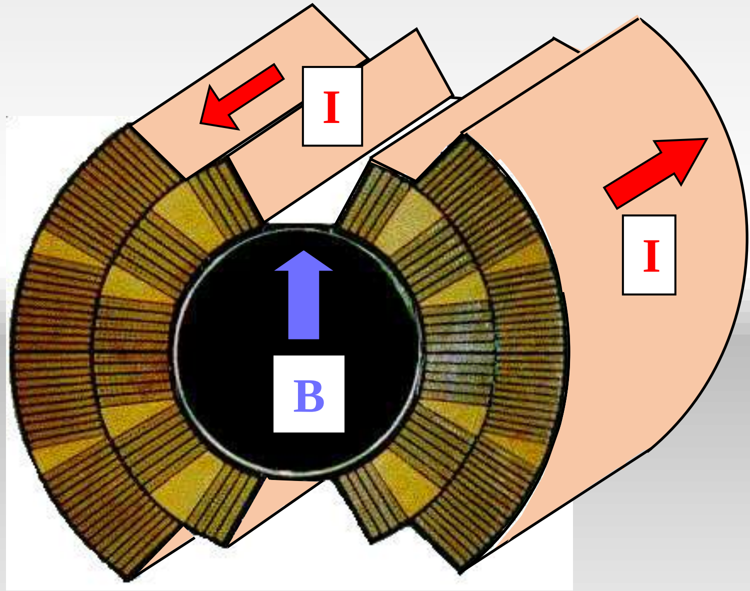
Basic ingredients of a particle accelerator

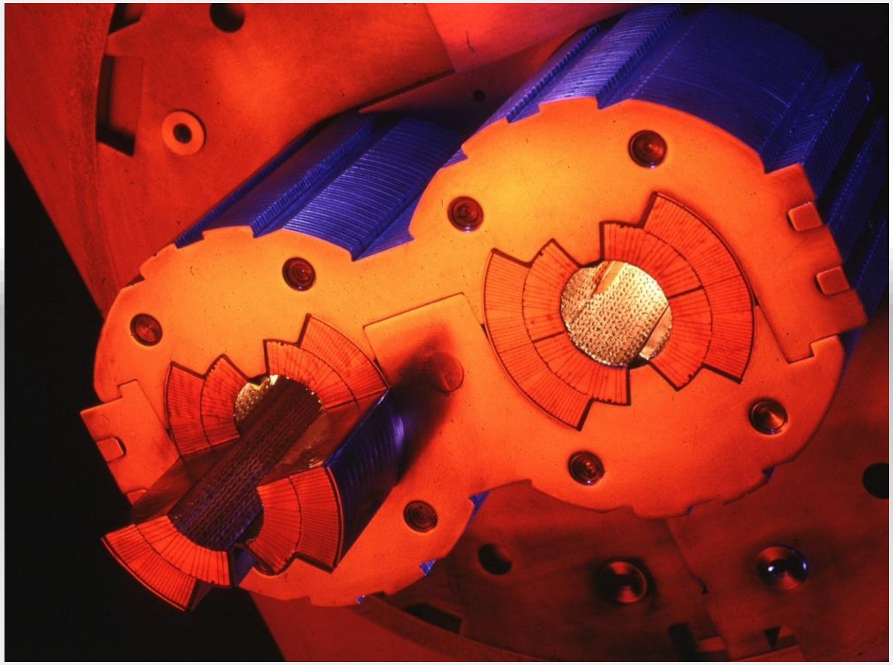
$$F = q\left[E + \left(v \times B\right)\right]$$

- **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



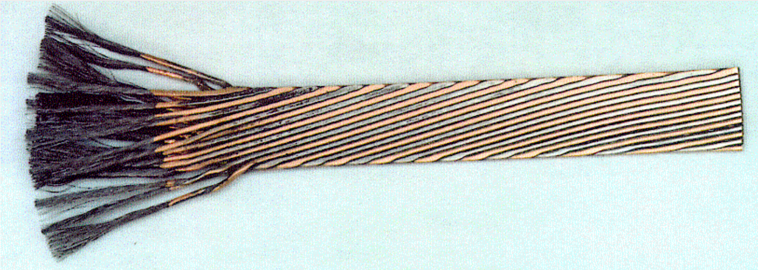


SUPERCONDUCTING!
Cooled with superfluid helium at 1.9 K

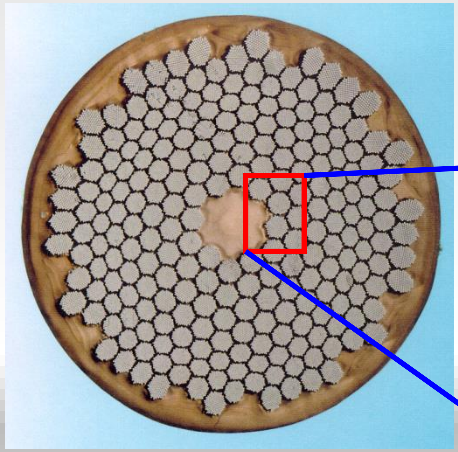
The superconductor

Niobium-titanium Rutherford cable

Cable



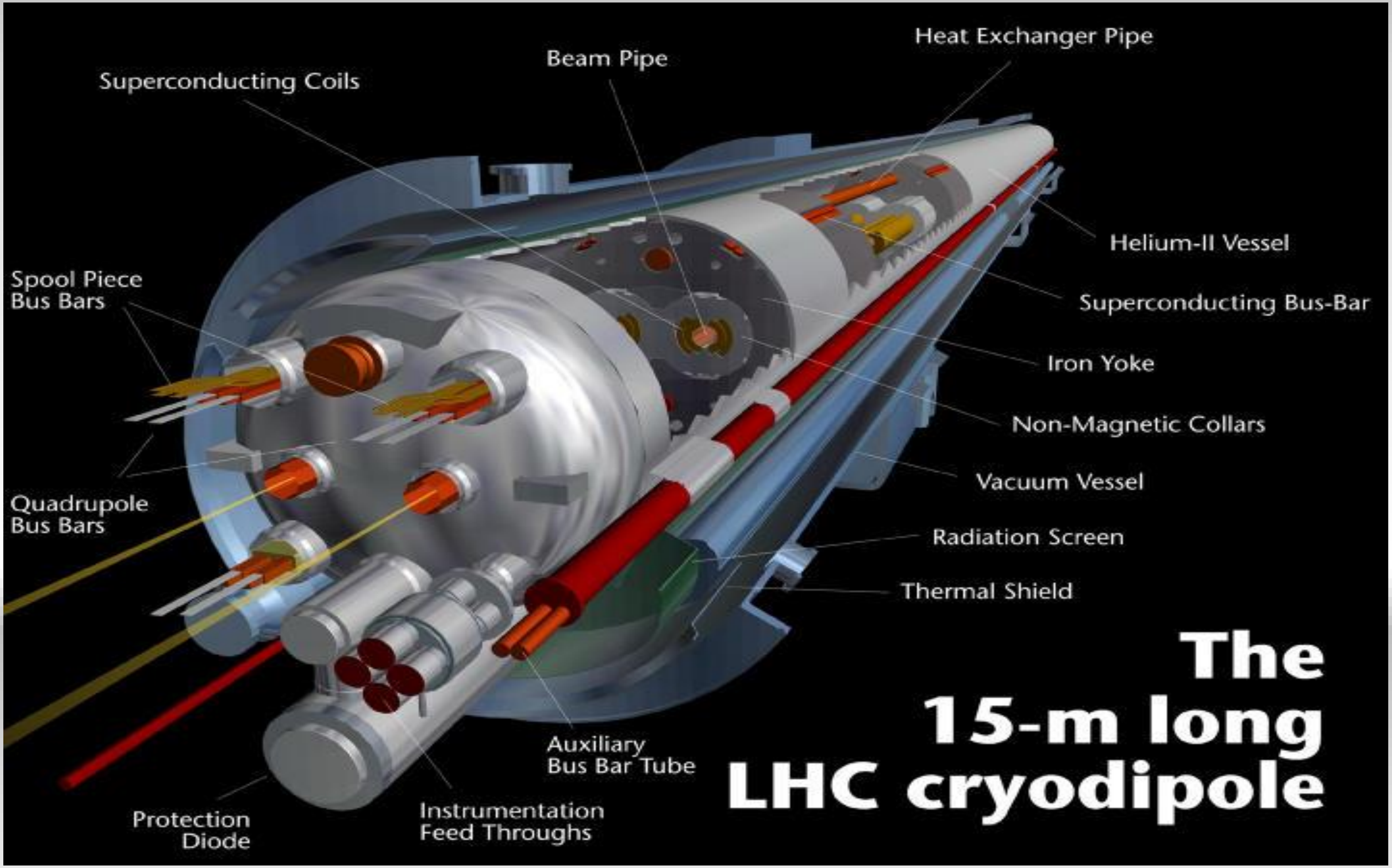
Strand



Filament

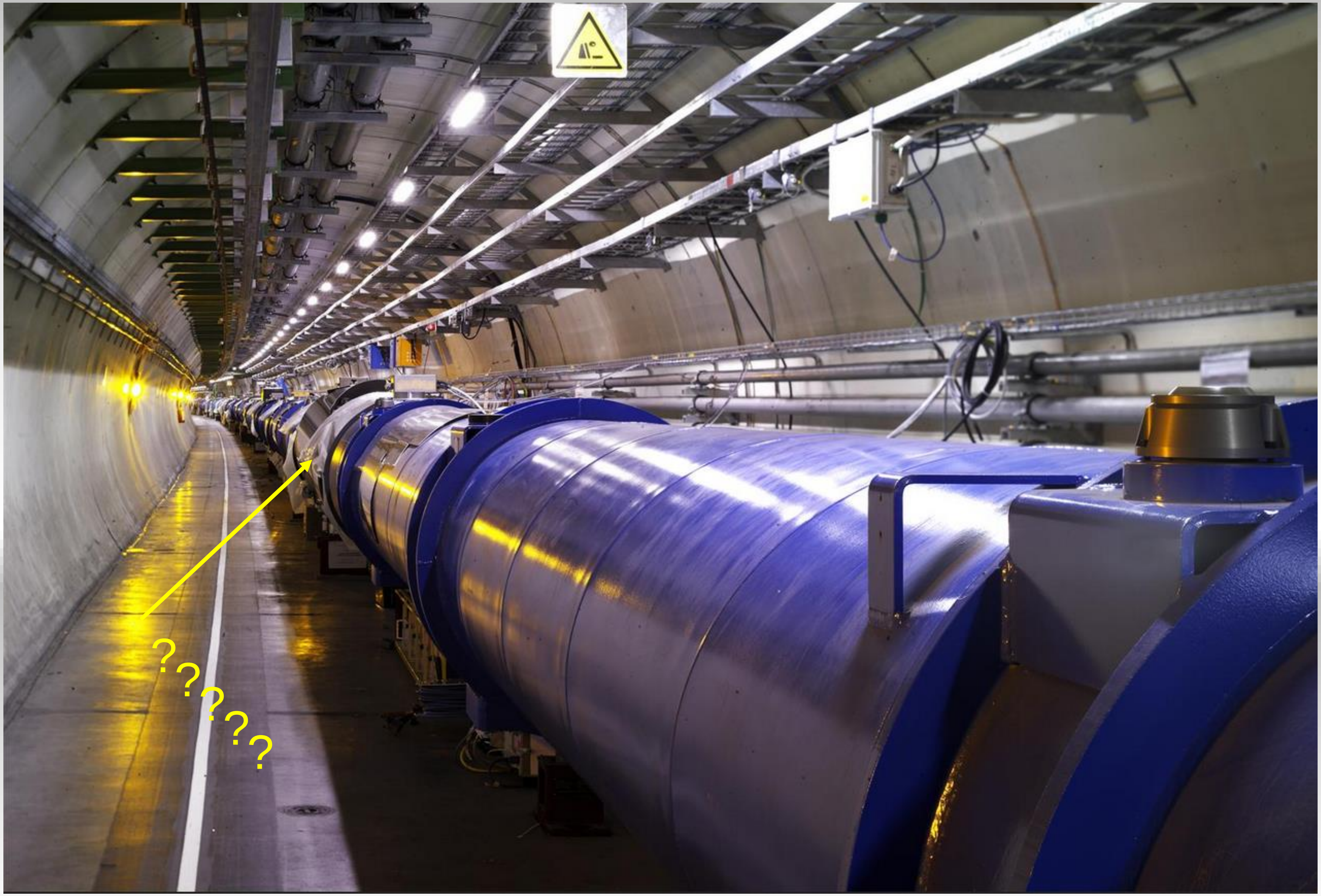
Used 1200 tonnes/7600 km of cable
Single cable carries current up to 12 kA

More than just some coils…



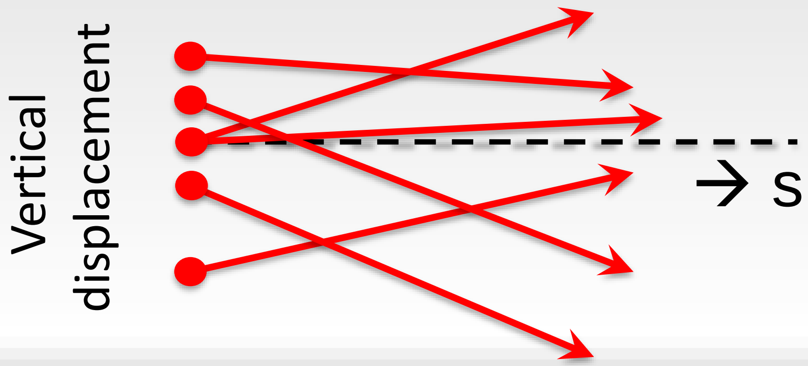
During construction: Dipoles all over

In the LHC tunnel



Beam is divergent

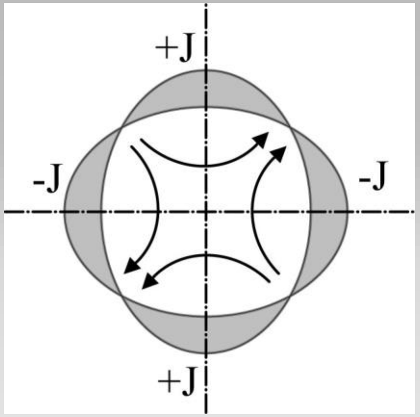
Many particles many initial conditions

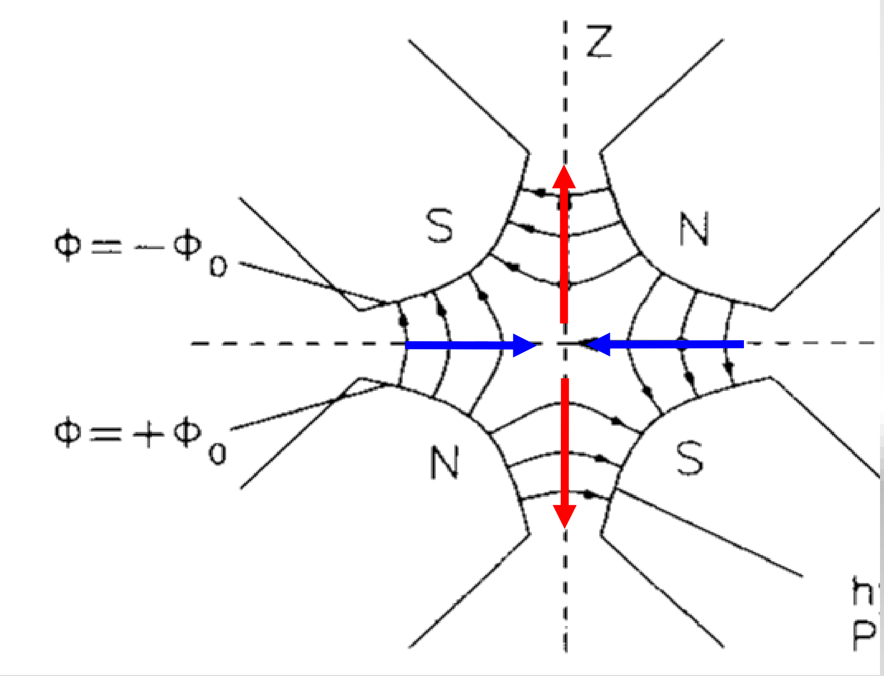


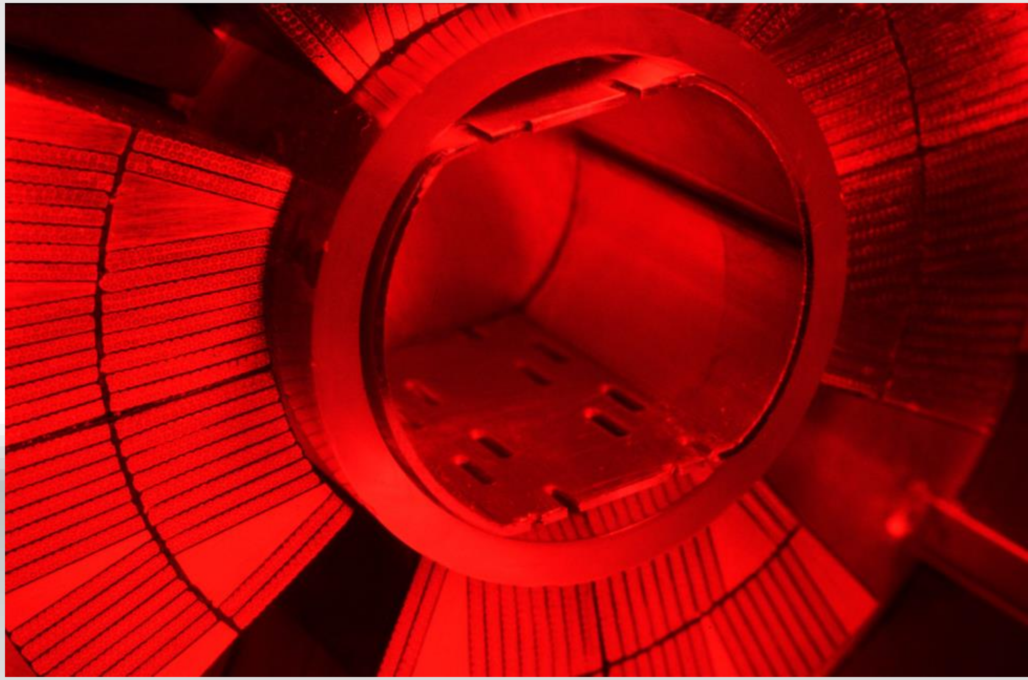
Many different angles

Quadrupole magnet

Quadrupole magnets

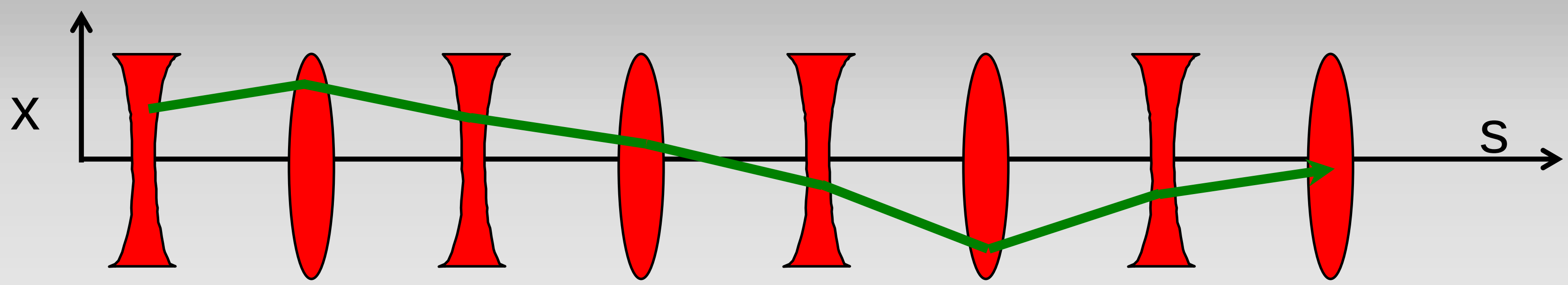






- A quadrupole magnet will focus in one plane and de-focus in the other.
- Convention: a “focusing” quadrupole focuses in the horizontal plane

Alternate gradient focusing



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

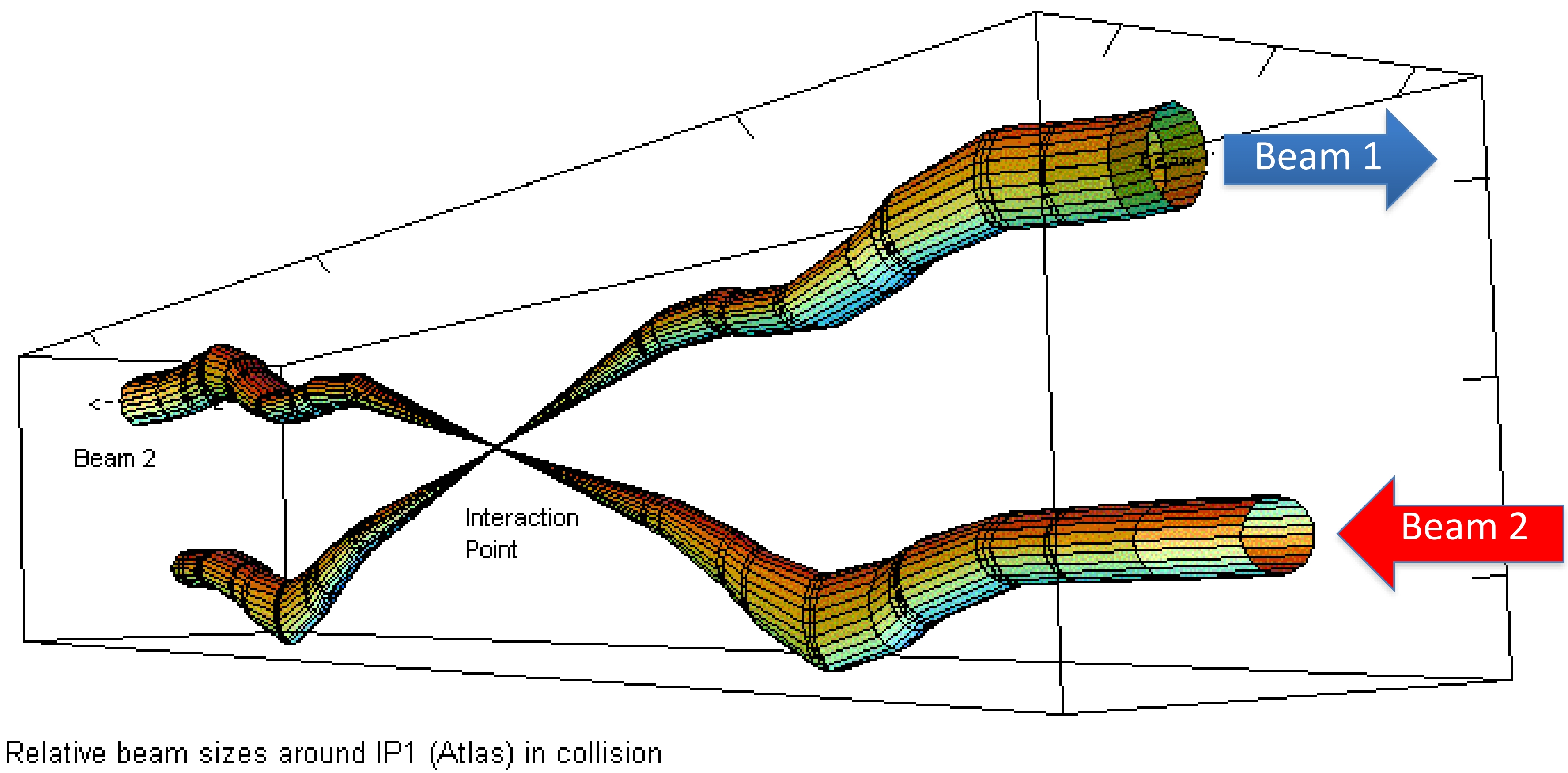
K(s) describes the distribution of focusing strength along the lattice and is periodic.

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

(and similarly for the vertical plane y)

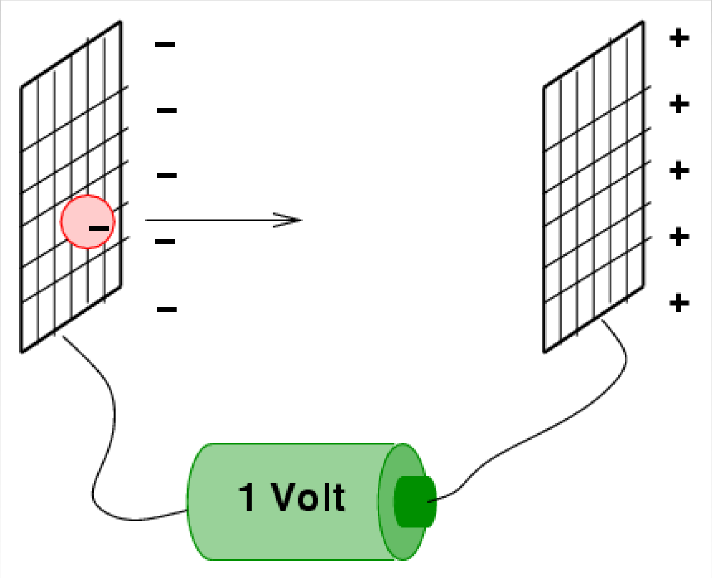
This is Hill's equation.

Squeeze



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

Accelerating the Particles



LHC: beams with an energy of 6.8 TeV

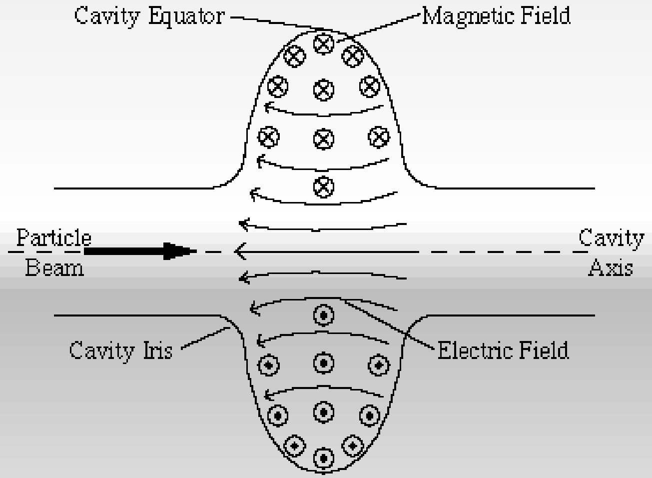
=

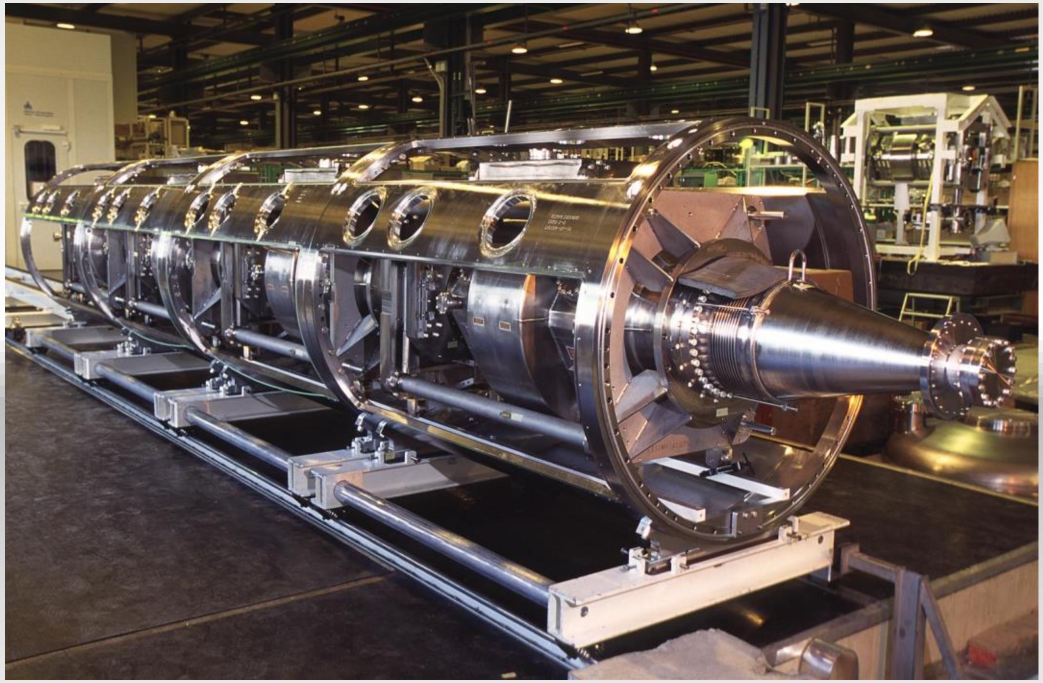
6 800 000 000 000 V

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

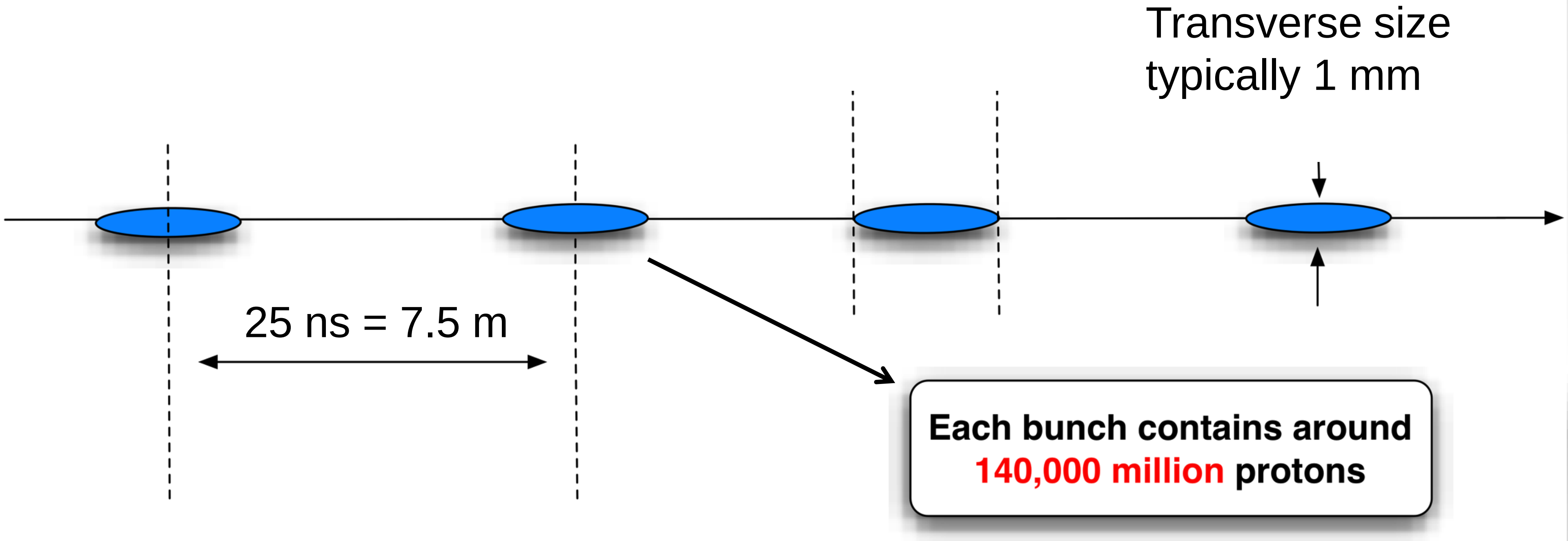




4 Cavity RF Module

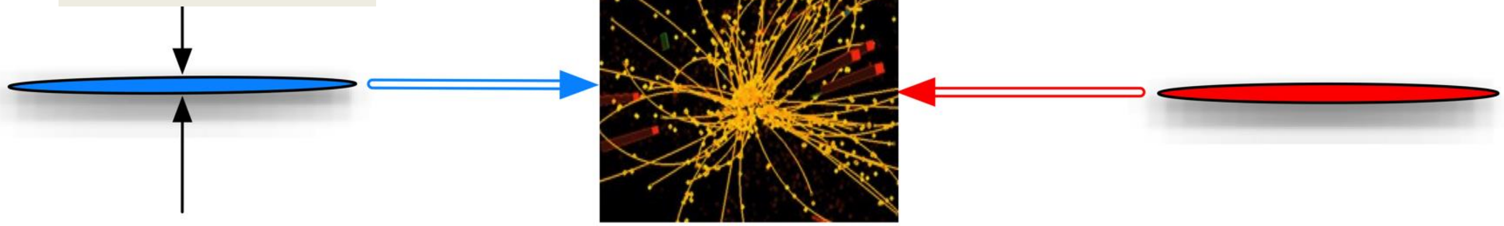
Lots of bunches

In 2023 the LHC has been operation with up to 2500 bunches per beam, separated by 25 ns



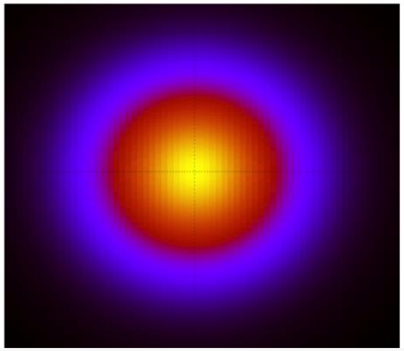
140,000,000,000 protons a bunch
~30 collide at each bunch crossing

12 micron

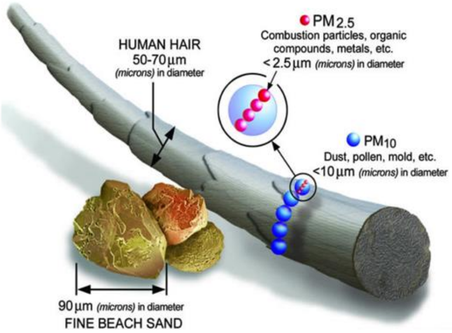


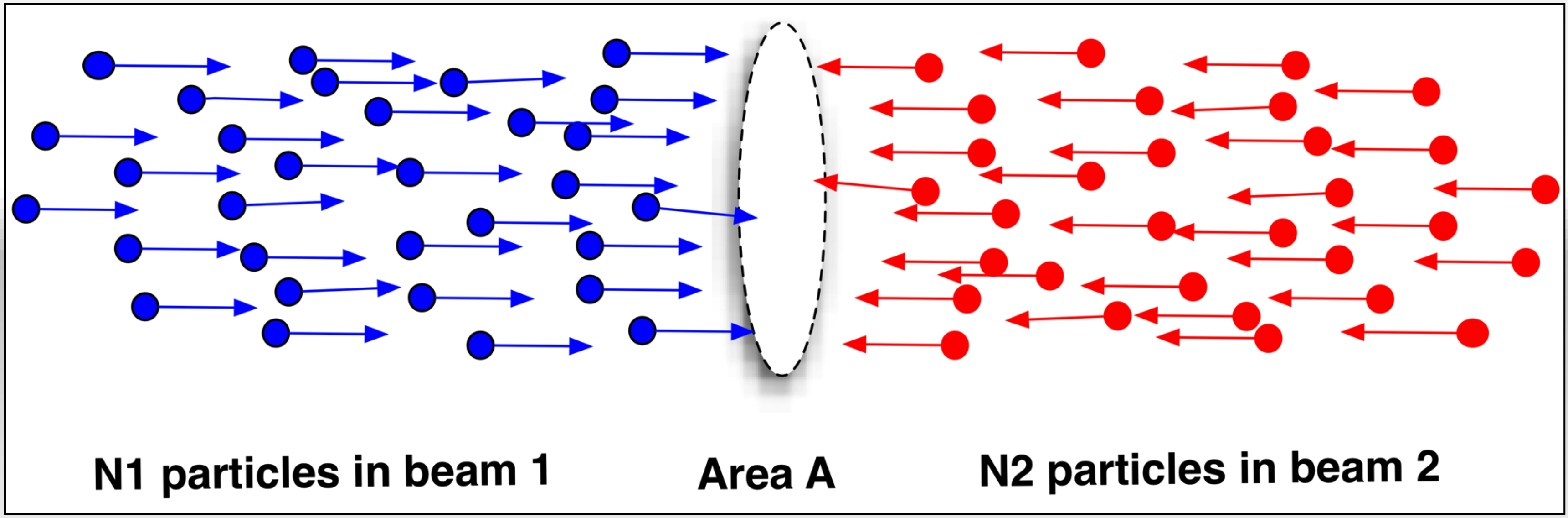
Up to 50 collisions per crossing
11’000 crossings per second
2200 bunches per beam (2016)
1 Billion Collissions Per Second → GRID

LHC BEAM



HUMAN HAIR





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

Luminosity

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

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**

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

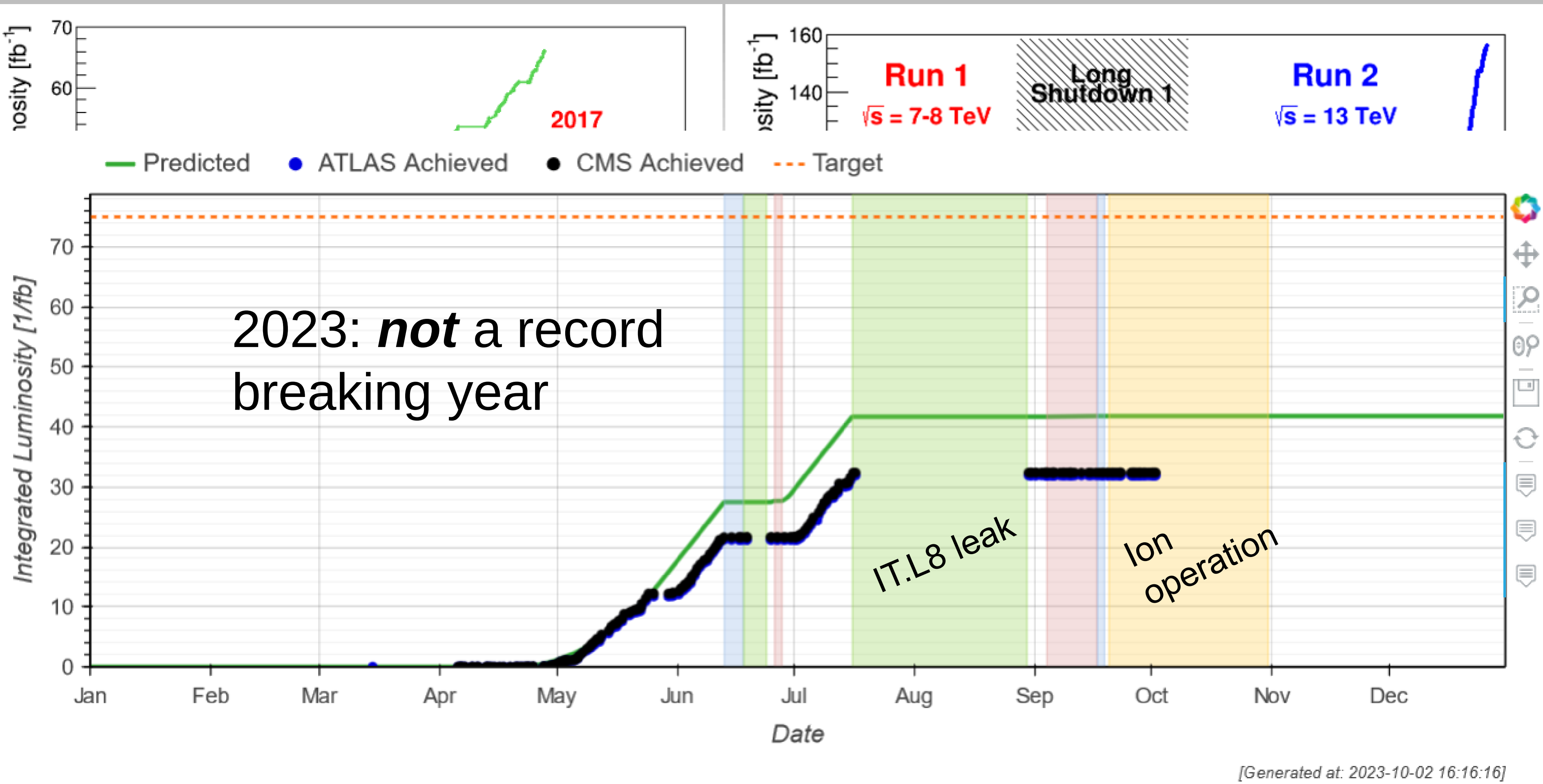
$$\varepsilon_N = 2.5 \times 10^{-6} \text{ m.rad}$$

$$\varepsilon = 3.35 \times 10^{-10} \text{ m.rad}$$

$$\sigma^* = 11.6 \times 10^{-6} \text{ m}$$

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

It is all about Luminosity



[illegible]	[illegible]
Run 2: 2017	50.2
Run 2: 2018	66
Total Run 1+ 2	**189.3**

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

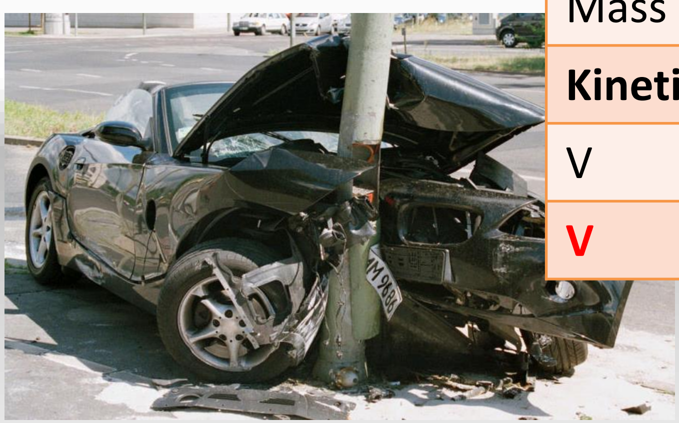
What would be the speed of a car to have the same kinetic energy ?

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**

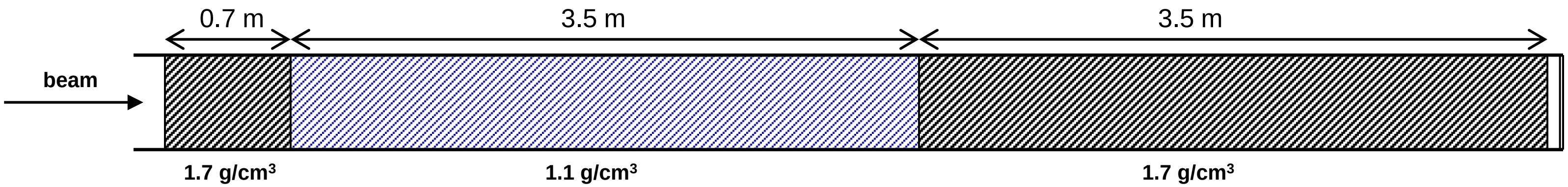
But at the size smaller than a hair ….

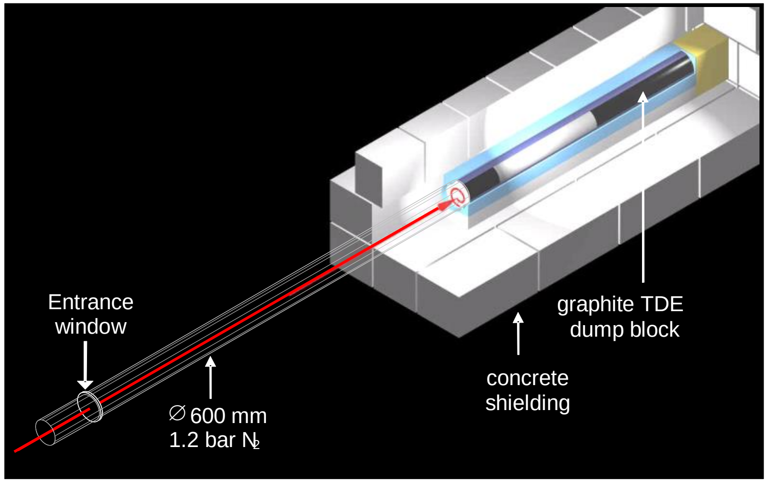
Don't break the machine!

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

Beam dump block (TDE)

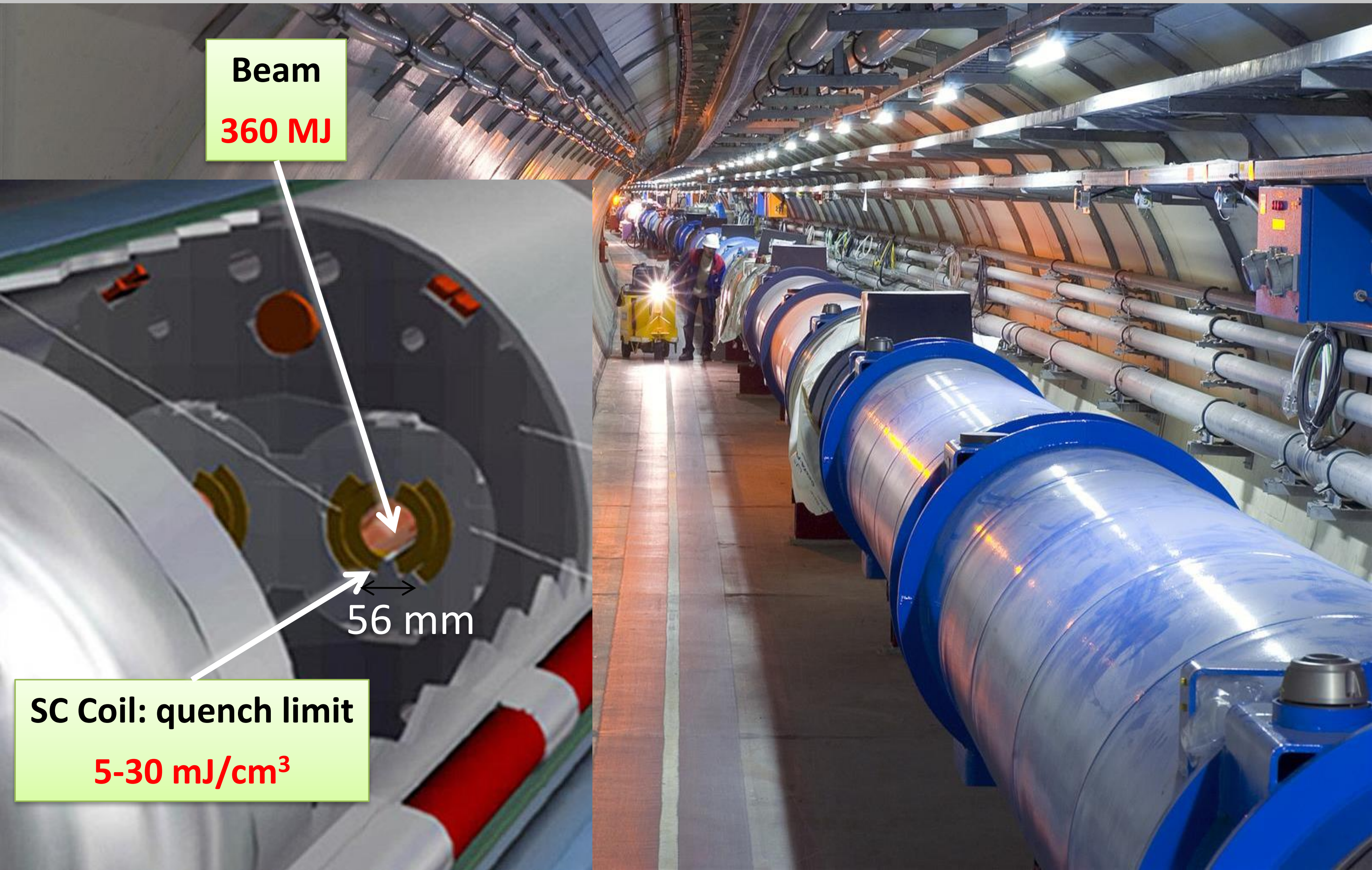
- 700 mm ∅ graphite core, with graded density of 1.1 g/cm^3 and 1.7 g/cm^3
- 12 mm wall, stainless-steel welded pressure vessel, at 1.2 bar of N_2
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks



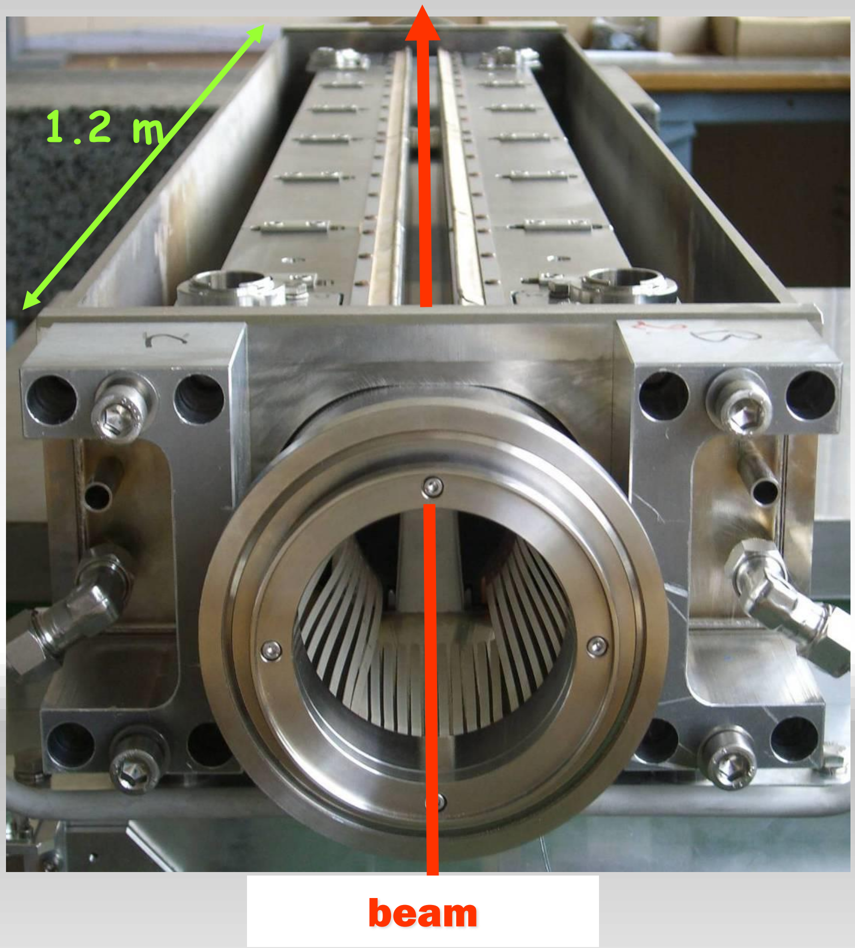


Quench Limit of LHC Super-Conducting Magnets

Nominal design at 7 TeV



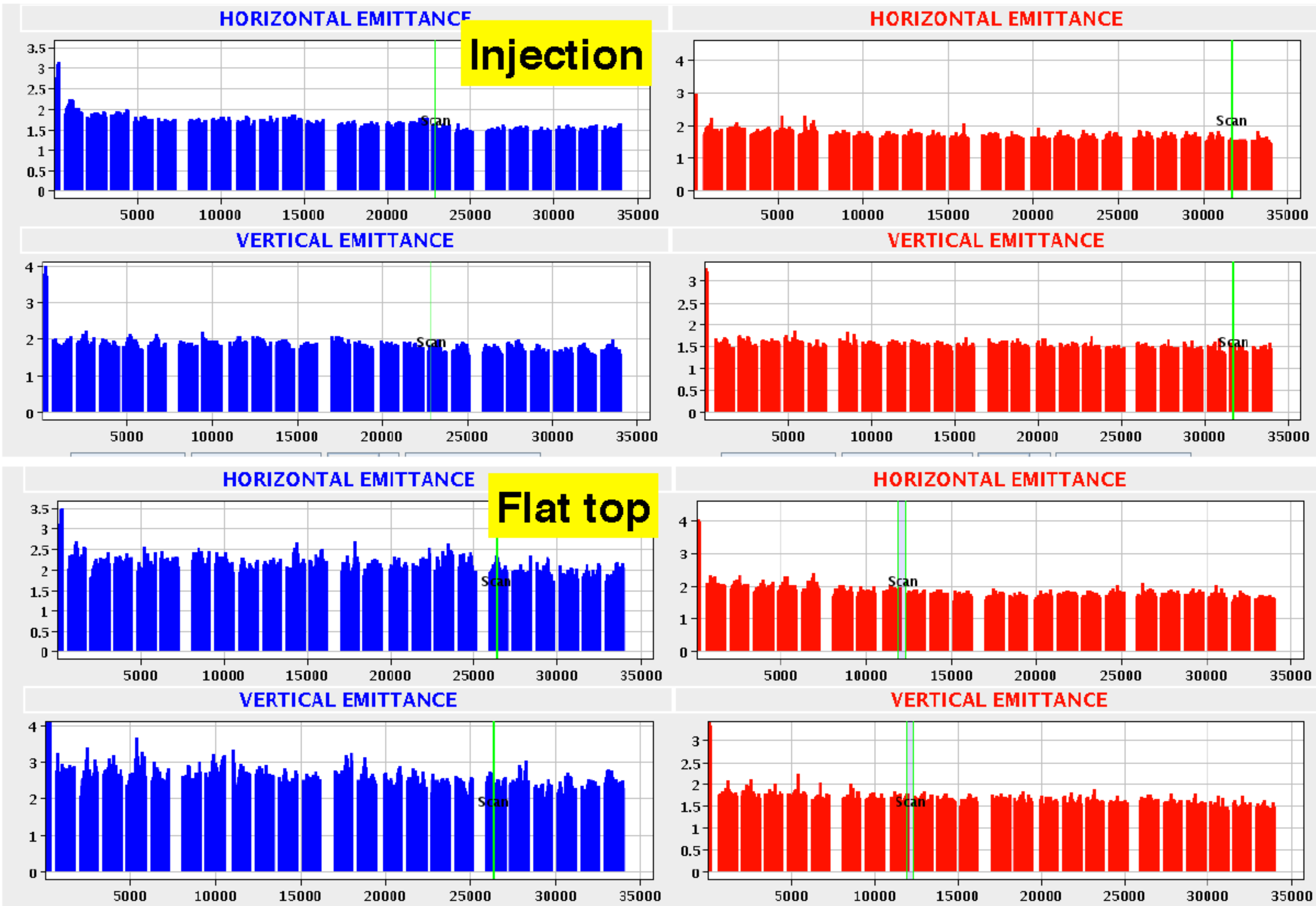
Collimation



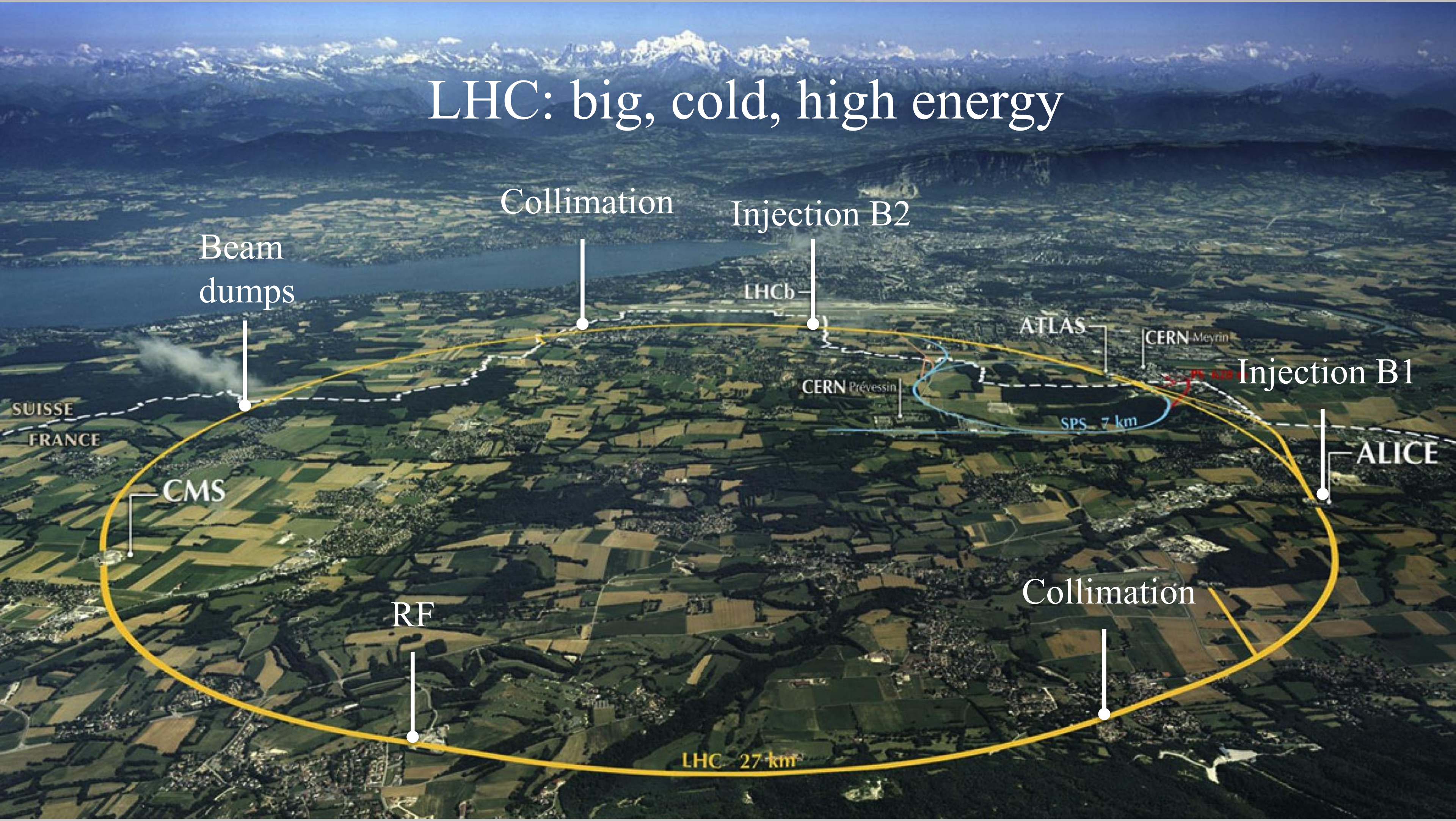
Almost 100 collimators and absorbers.

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



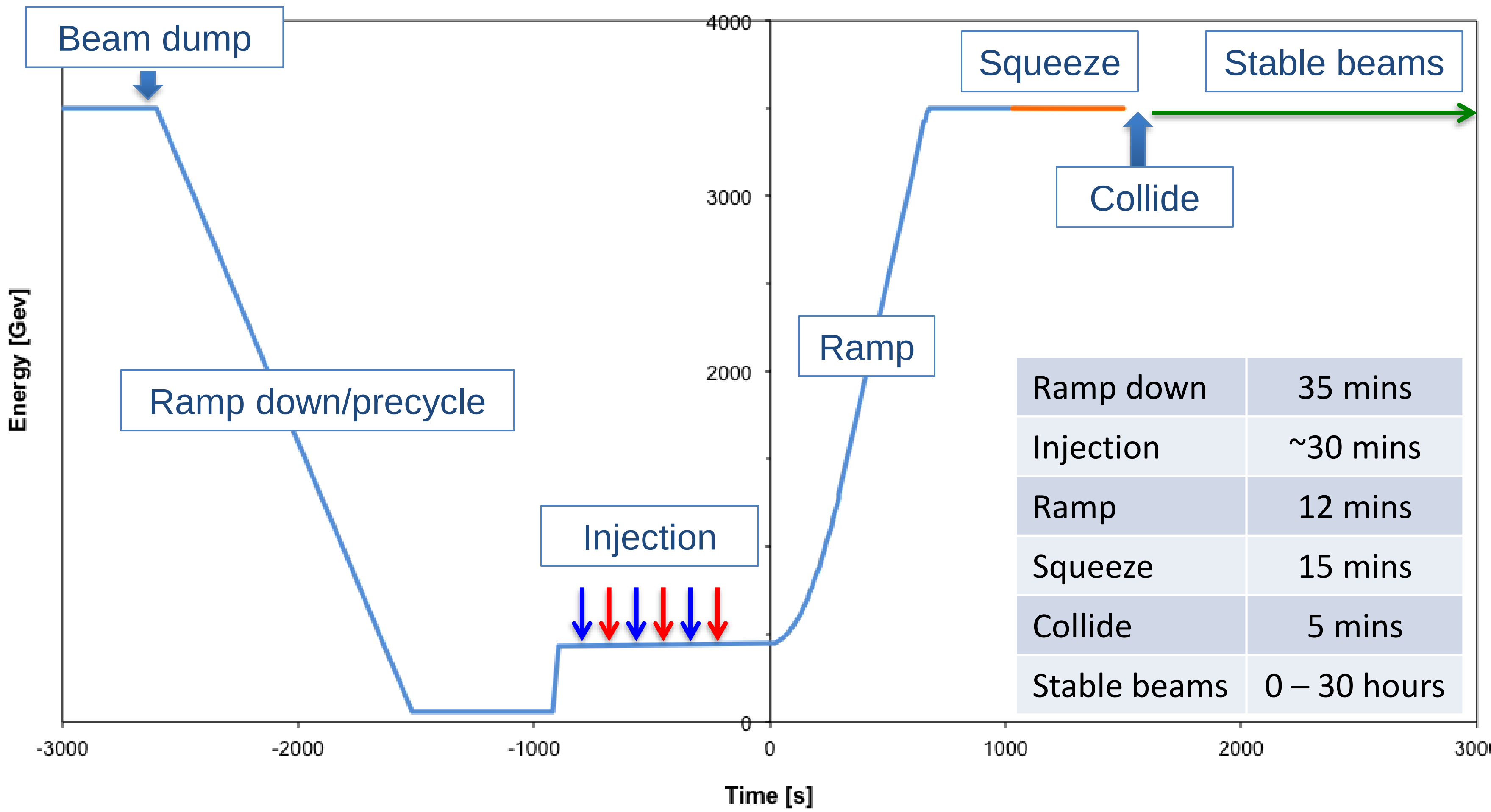
1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

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

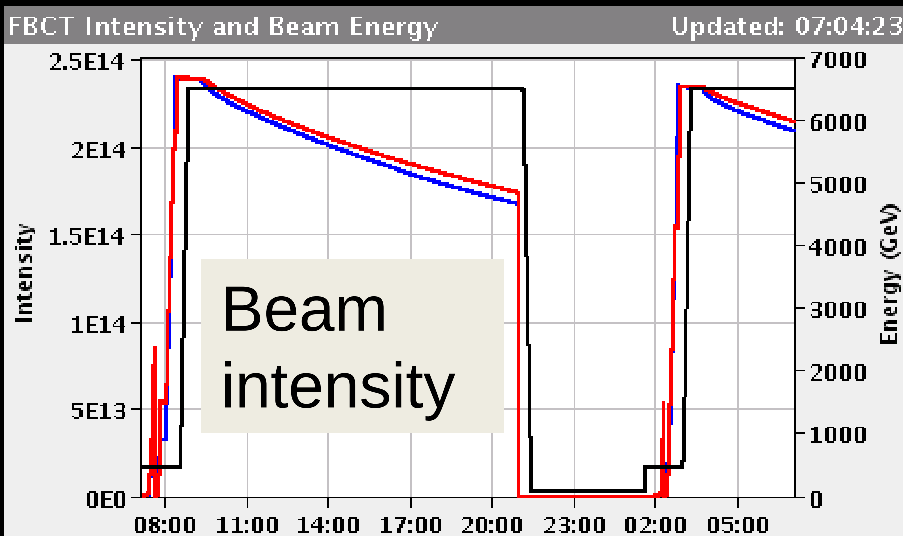
Turn around from stable beams to stable beams - 2 to 3 hours on a good day, followed by Stable Beams, average 6 hours.

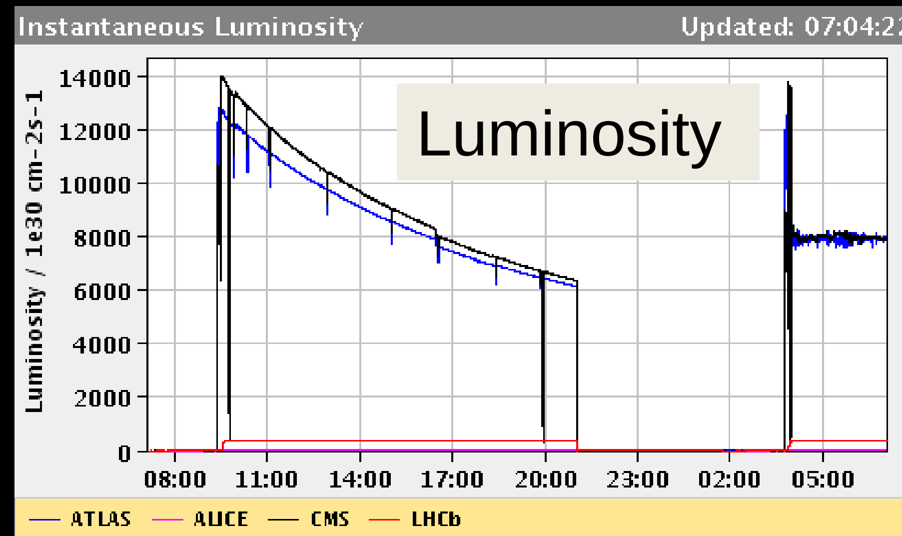
LHC Page1 | Fill: 5450 | E: 6499 GeV | t(SB): 03:11:57 | 26-10-16 07:04:23

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





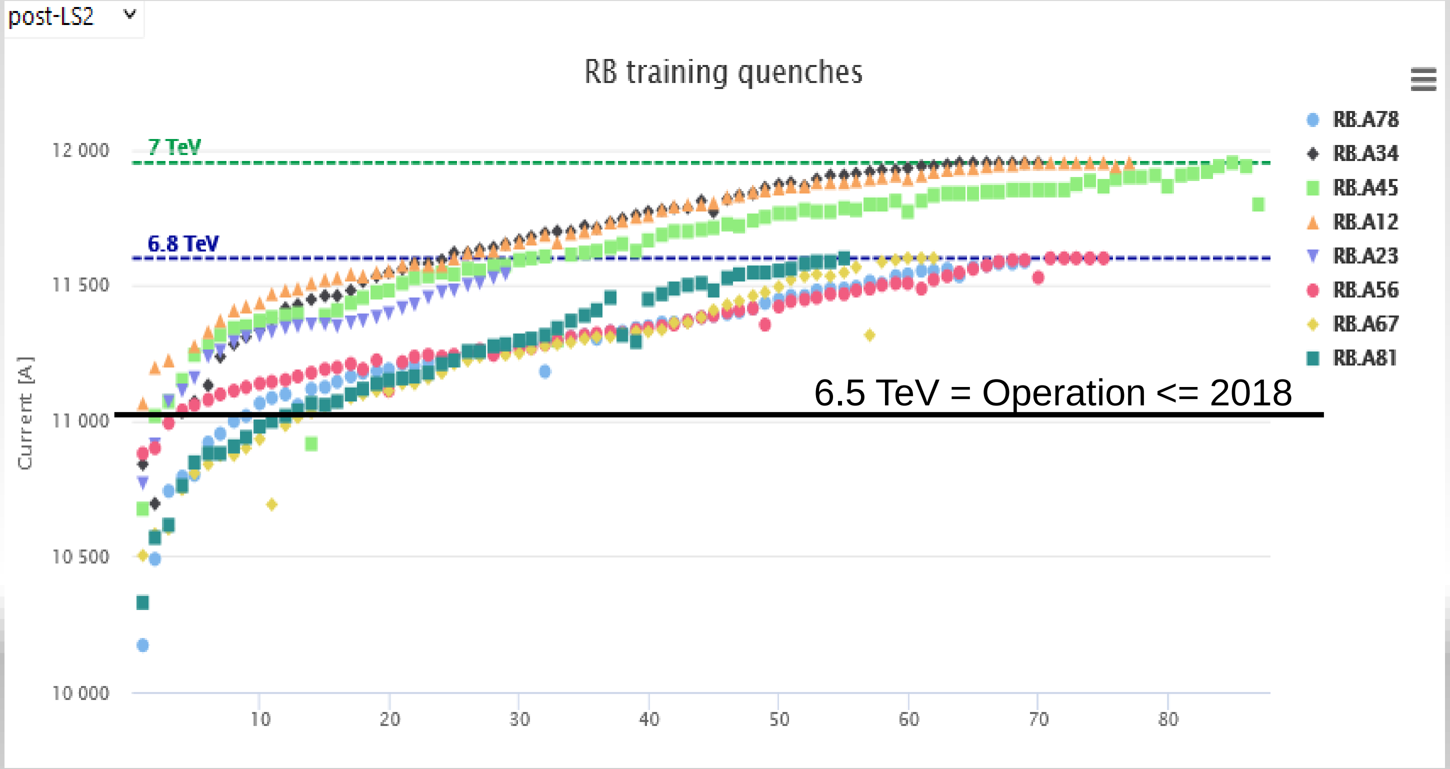
Comments (26-Oct-2016 02:29:17)

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

Magnet Training to reach 7 TeV Beam Energy



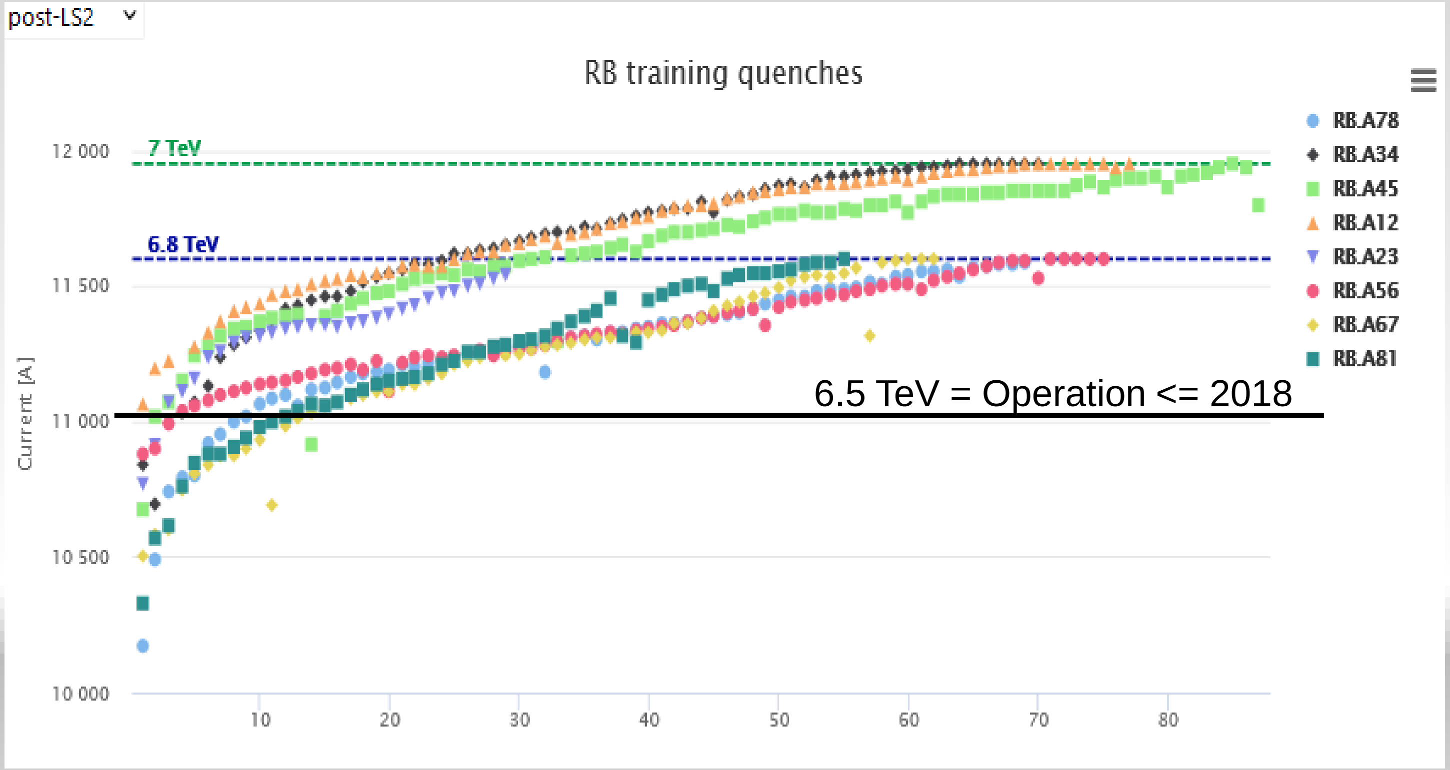
'Nominal'

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

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



'Nominal'

6.8 TeV

Present Operation

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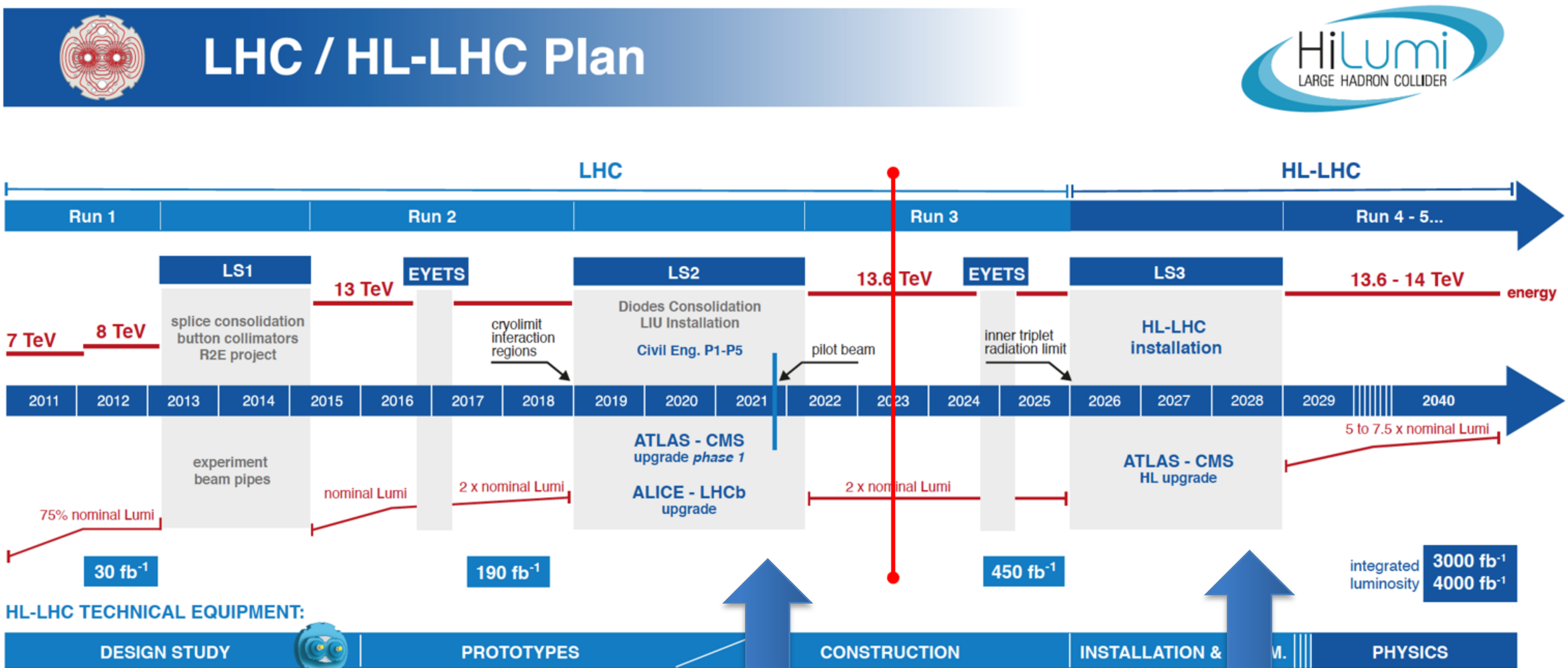
What's Next ?
High-Luminosity LHC



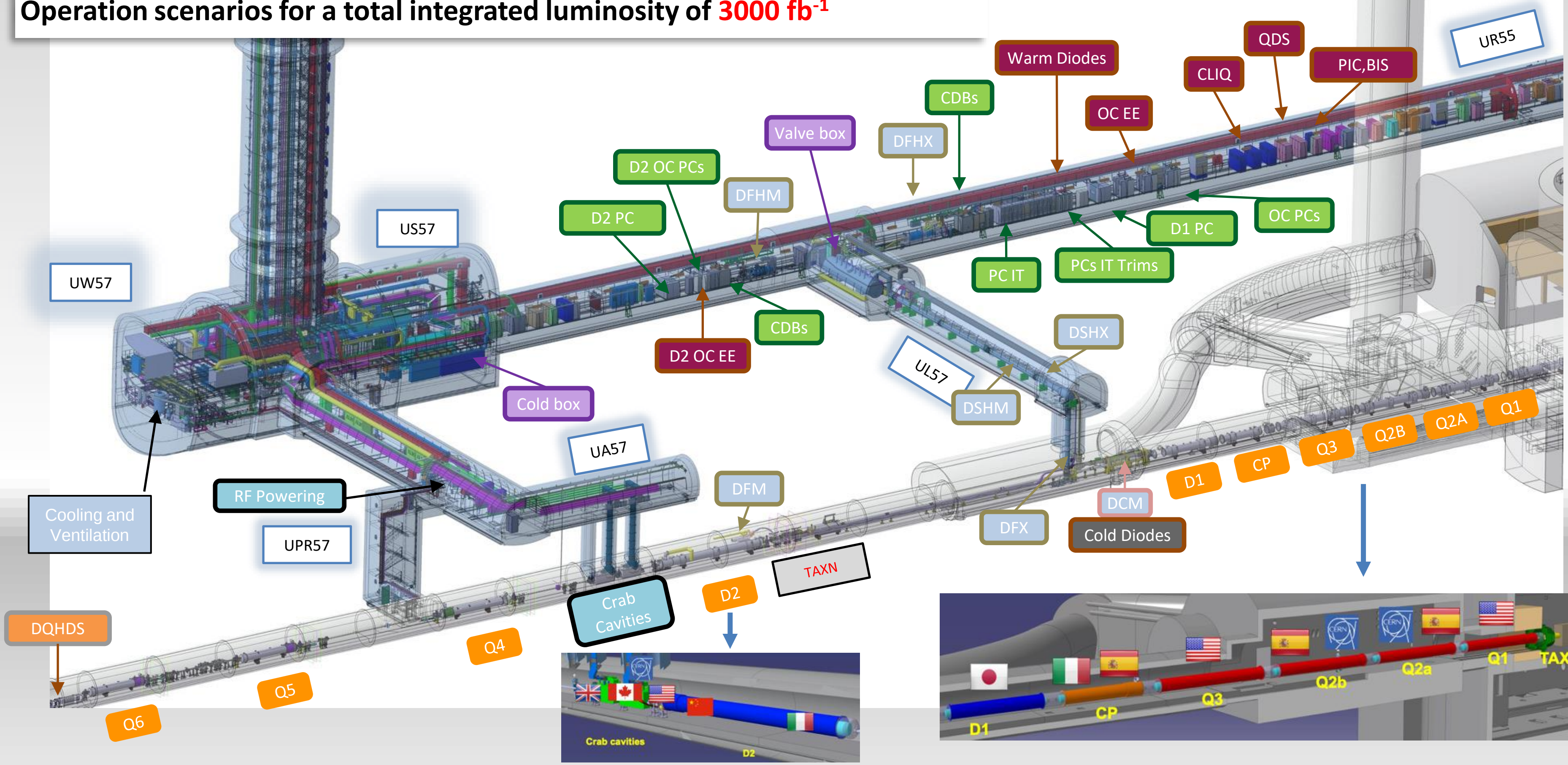
Injectors upgrade and LHC civil engineering

HL-LHC upgrade

High Luminosity LHC

Prepare the machine for operation beyond 2025 and up to ~2041

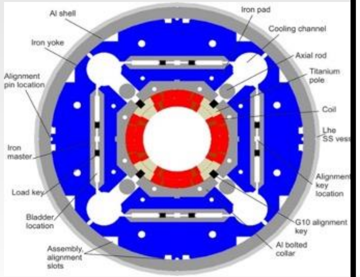
Operation scenarios for a total integrated luminosity of 3000 fb^{-1}



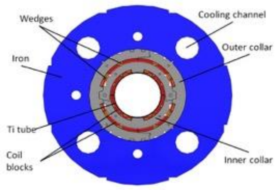
New wide-a

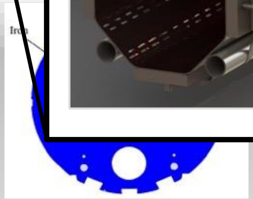
interaction

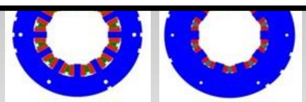
Final focus quadrupole (MQXF)



Dipole corrector

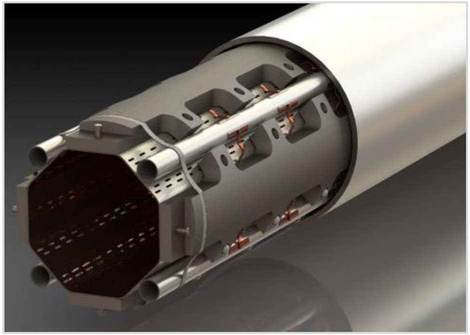






Final focus quadrupoles

- **Nb_3Sn technology** → Larger operational peak fields (~12 T)
- **Large aperture**: 150 mm
  - → Allows for **smaller beam size** at the experiments
  - → Allows introducing **tungsten shielding** to protect the magnet from radiation generated by collisions
- **Series production in progress**



The Future @ CERN after the HL-LHC

European Strategy for Particle Physics Update 2020

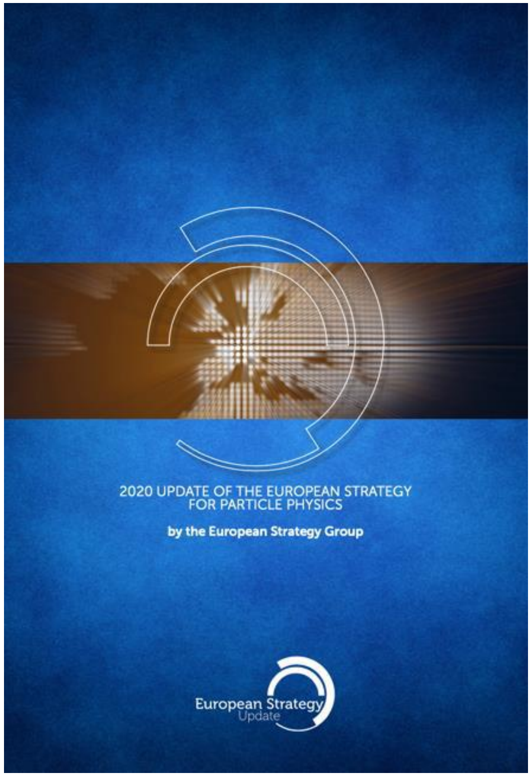
"An electron-positron Higgs factory is the highest-priority next collider."

"For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."

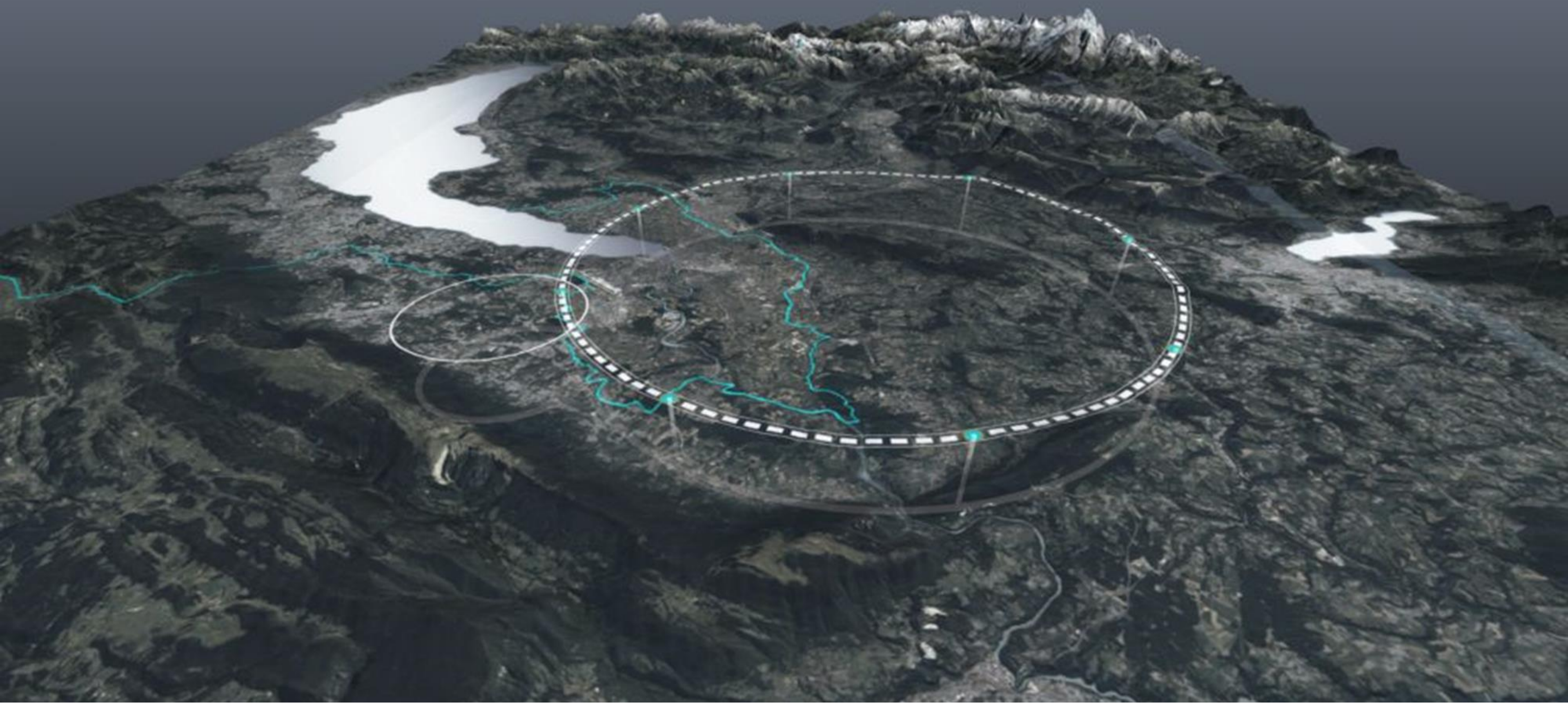
"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage."

→

1. e+e- machine as a Higgs factory
2. High energy hadron collider



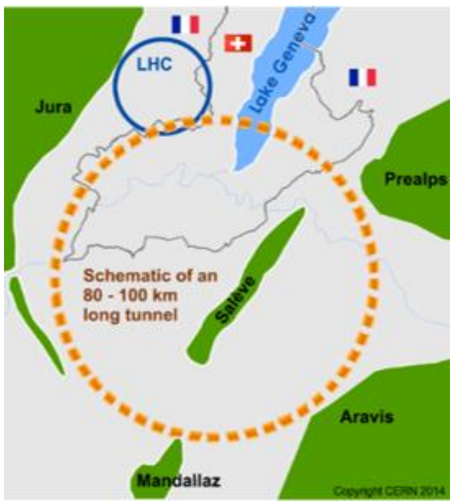
Really going to have make the case because…

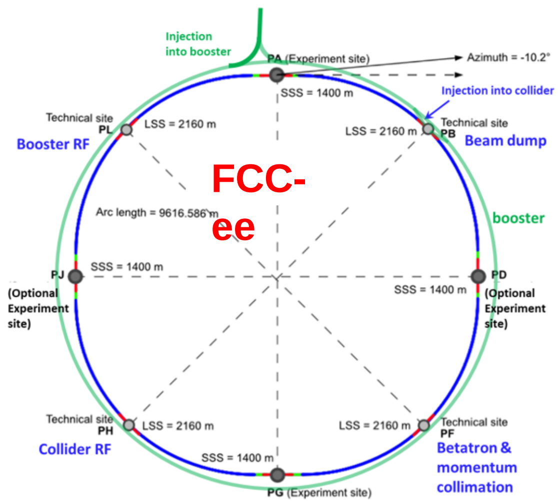


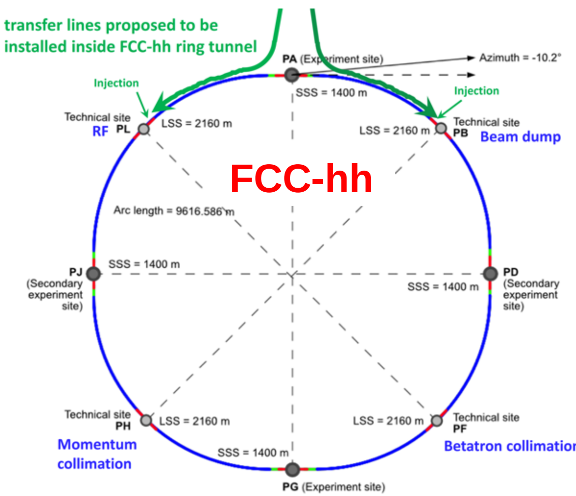
FCC integrated program: inspired by LEP- LHC

Comprehensive long-term program maximizing physics opportunities:

- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**





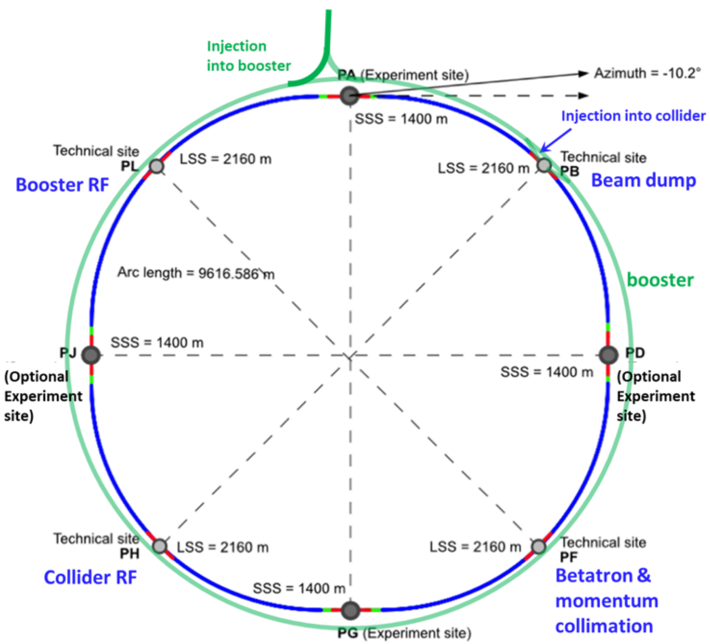


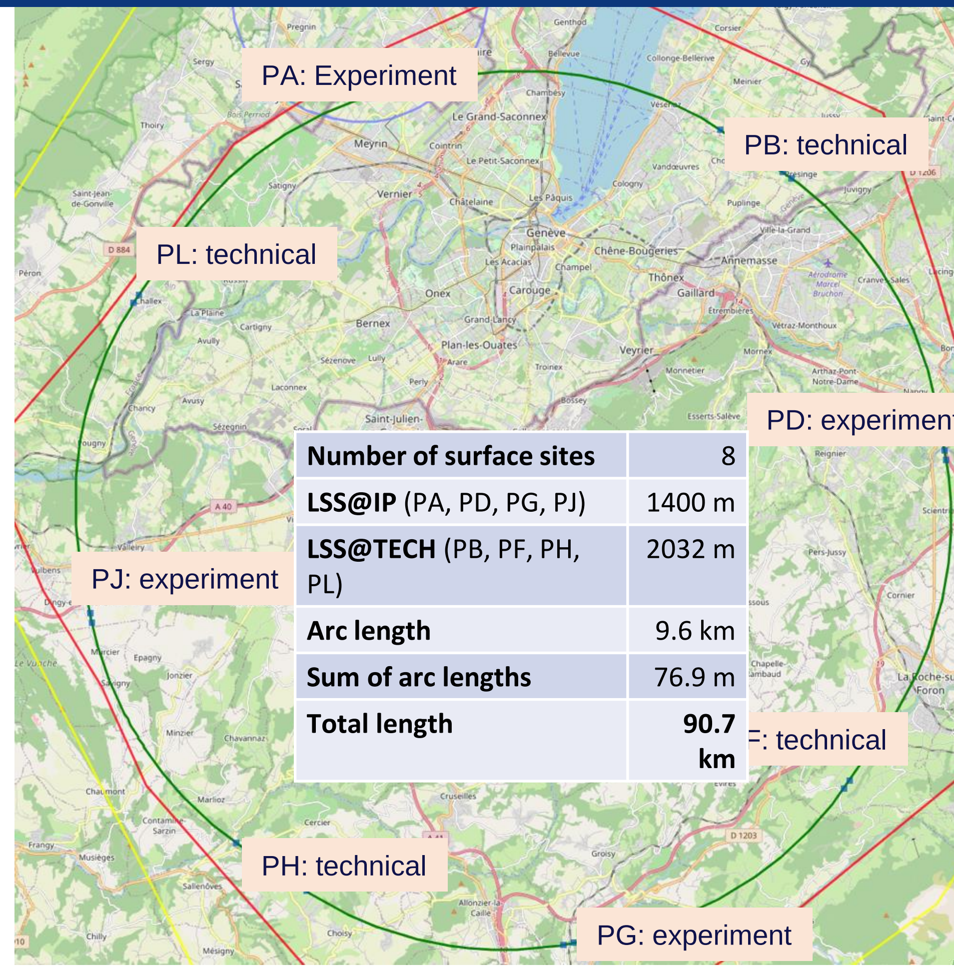
2020 - 2040 | **2045 - 2063** | **2070 - 2095**

Optimized placement and layout for feasibility study

Major achievement: optimization of the ring placement
Layout chosen out of ~100 initial variants, based on geology and surface constraints, environment, infrastructure.

Lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold superperiodicity, possibility of 2 or 4 IPs
Whole project now adapted to this placement

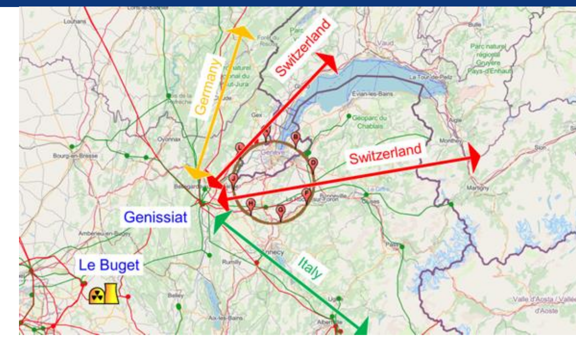




Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

Power consumption and electrical grid infrastructure

Updated FCC-ee energy consumption	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Max. power during beam operation (MW)	222	247	273	357
Average power / year (MW)	122	138	152	202
Total yearly consumption (TWh)	**1.07**	**1.21**	**1.33**	**1.77**

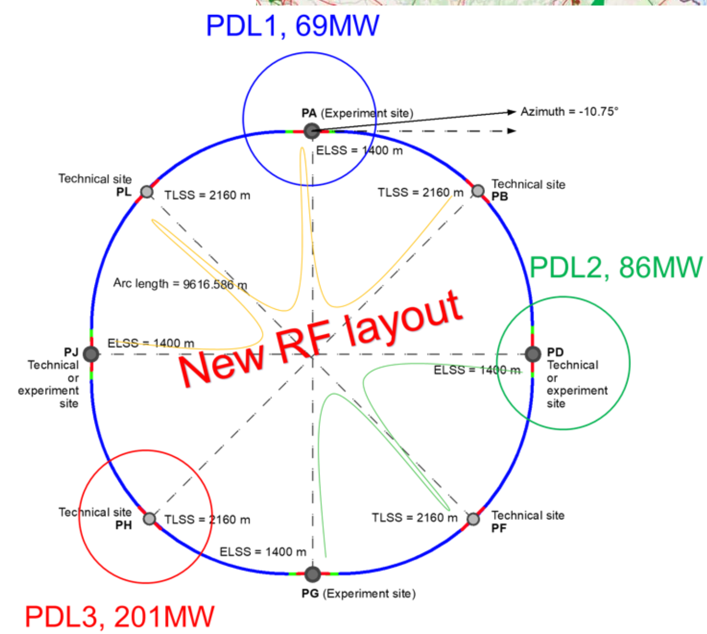


Powering concept and max power load by sub-stations:

The loads could be charged on the three sub-stations (optimum connections to existing regional HV grid):

- **Point D, with a new sub-station** covering PB – PD – PF – PG
- **Point H with a new dedicated sub-station** for collider RF
- Point L, with a sub-station covering PJ – PL – PA
- → Alternative to new sub-station at Point L is **reusing the existing CERN Prevession station to PA**

- **All options pursued with RTE**
- **Powering concept and max. power rating of the three sub-stations compatible FCC-hh.**



Integration of environmental challenges in future accelerators

Very much work in progress

Future machines – full lifecycle

- Starts with choice of fundamental design and technology
- Least resource-heavy designs compatible with the long-term scientific goals
- Footprint given by full lifecycle, civil engineering, construction…

Technology – energy efficiency

- SRF, klystrons, magnets (SC, HTS, permanent) etc. etc.
- Technical infrastructure: efficiency, heat recovery…

Operations

- Source renewable power
- Dynamically follow renewable power availability

Innovative technology

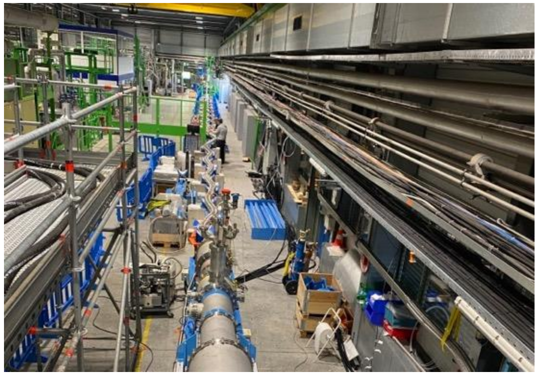
- Power/energy distribution (HTS, smart grids, hydrogen…)
- Energy storage (SC magnets, **hydrogen**…)

Support to alternatives

- Fusion – ITER
- ADS, thorium – **MYRHHA**

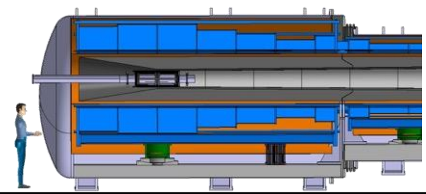
Procurement

- Energy use considered in system design, specifications, arbitration



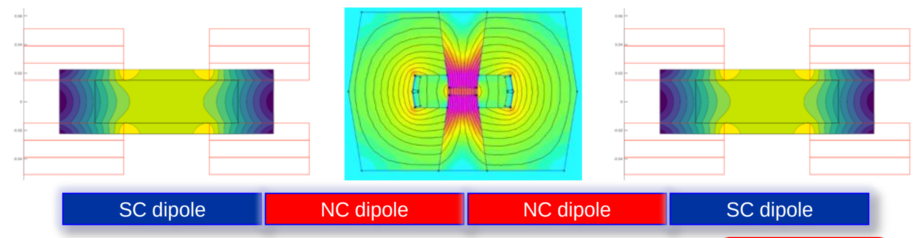
Muon Collider

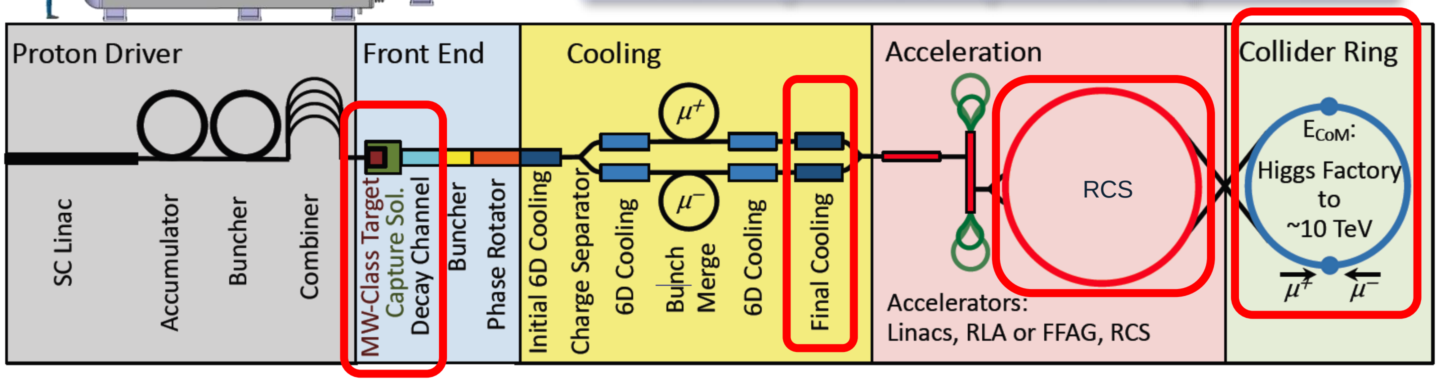
20 T, 200 mm
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy



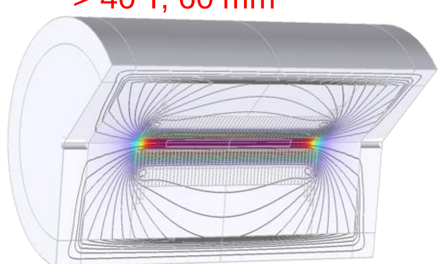
NC ±1.8 T, 400 Hz
100 mm x 30 mm

SC < 10T
100 mm x 30 mm

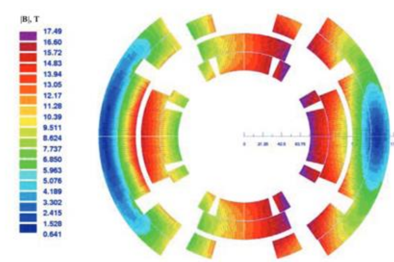




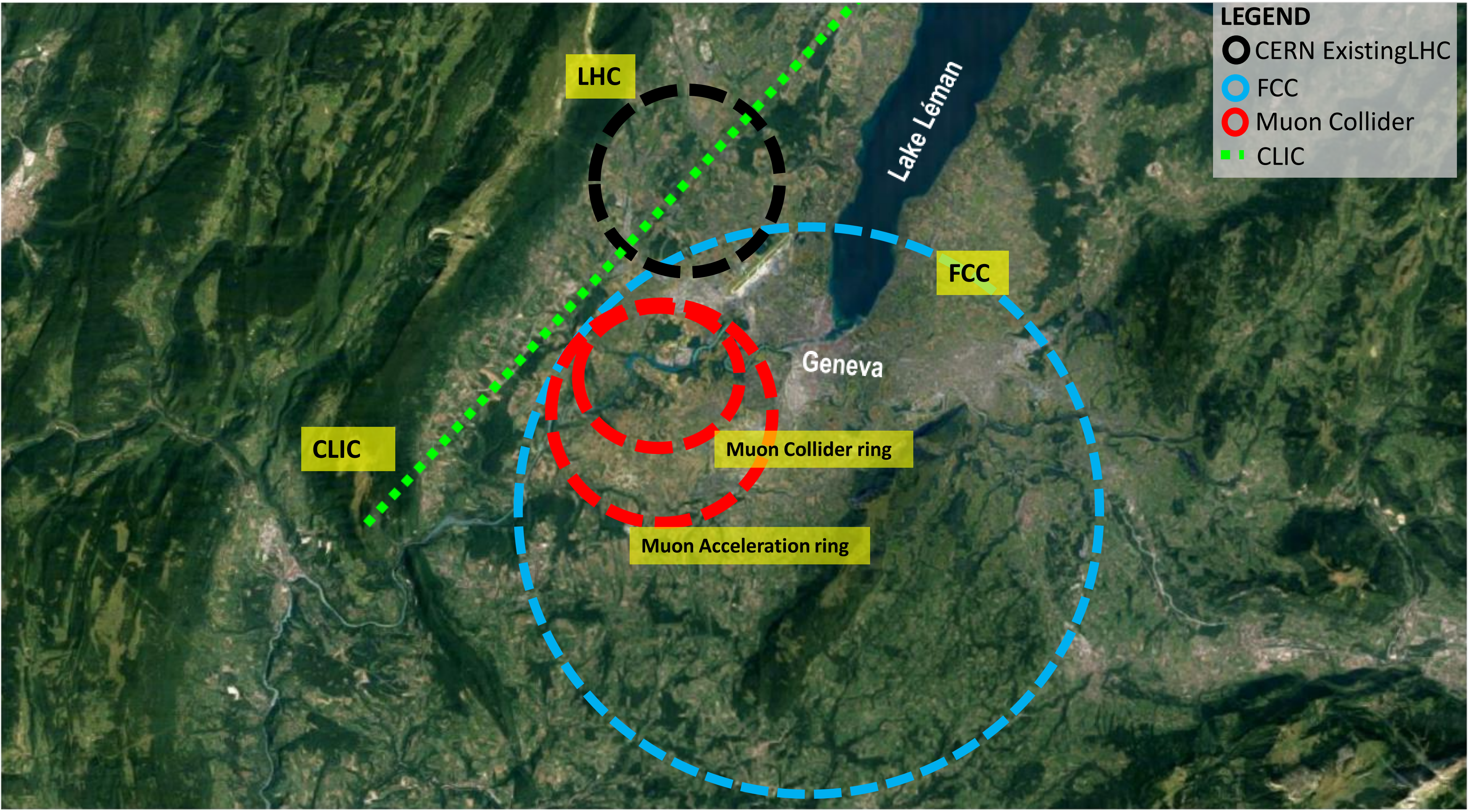
> 40 T, 60 mm



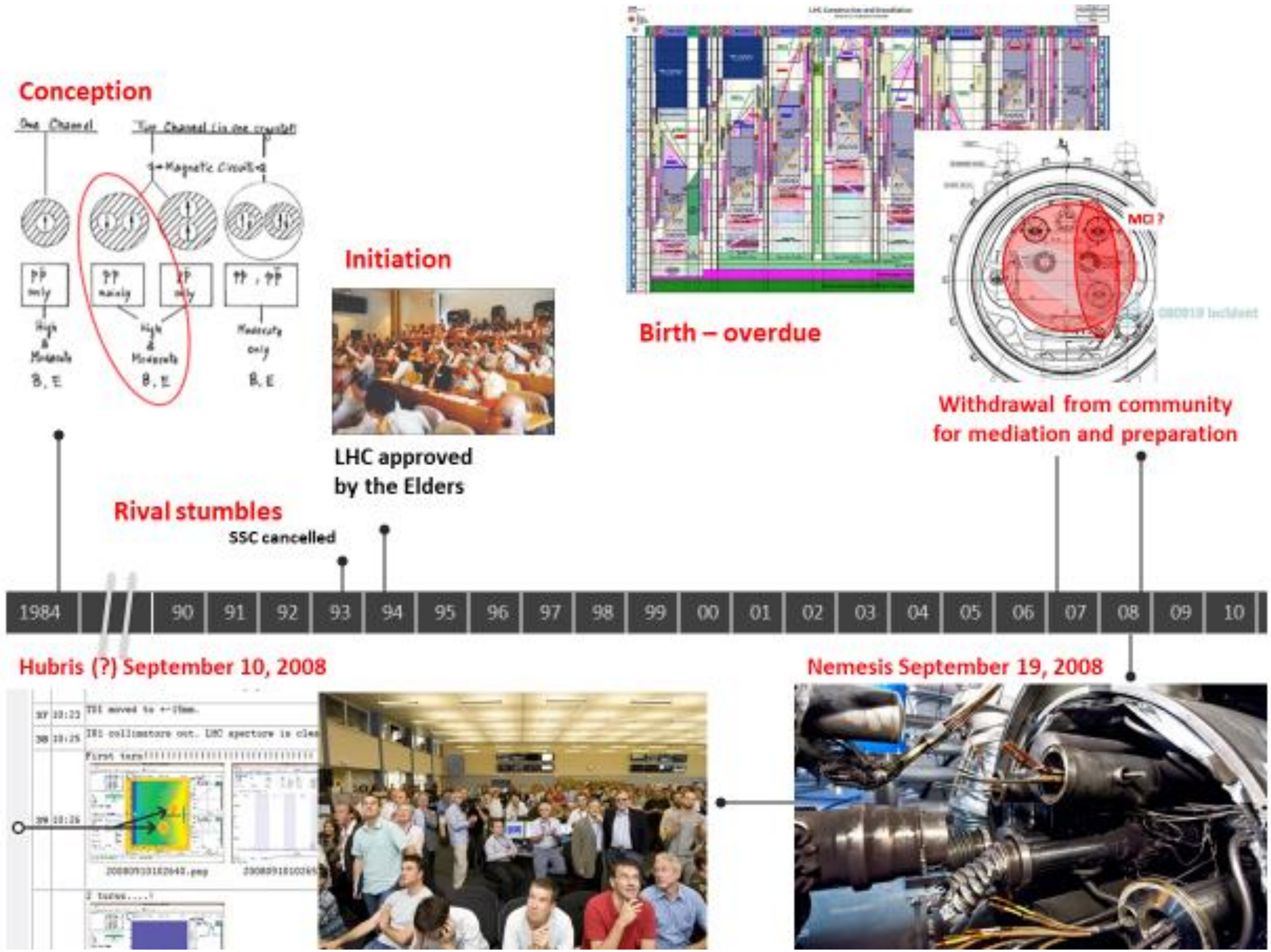
16 T peak, 160 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20…40 MGy



Luca Bottura

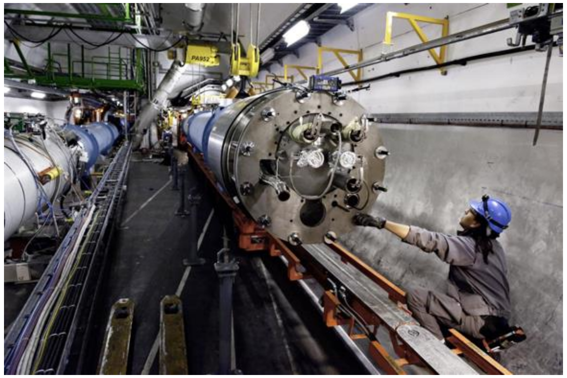

LEGEND
CERN ExistingLHC
FCC
Muon Collider
CLIC
LHC
Lake Léman
FCC
Geneva
CLIC
Muon Collider ring
Muon Acceleration ring

Compare FCC to the LHC timeline …



LHC

Nobel Price and HL-LHC for years to come …

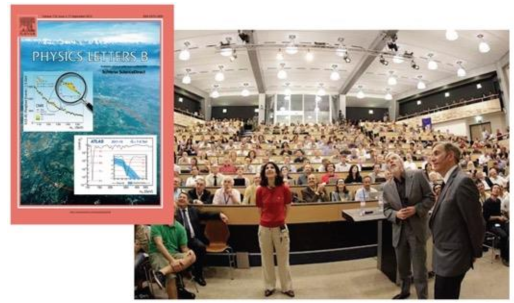


Trial/descent in the underworld

November 29, 2009

Resurrection and rebirth

Apotheosis and atonement

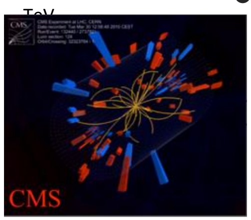


4 July, 2012

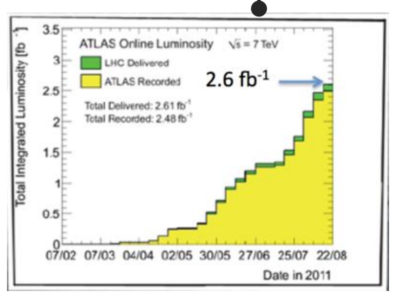
2009 | 2010 | 2011 | 2012 | 2013

March 30, 2010

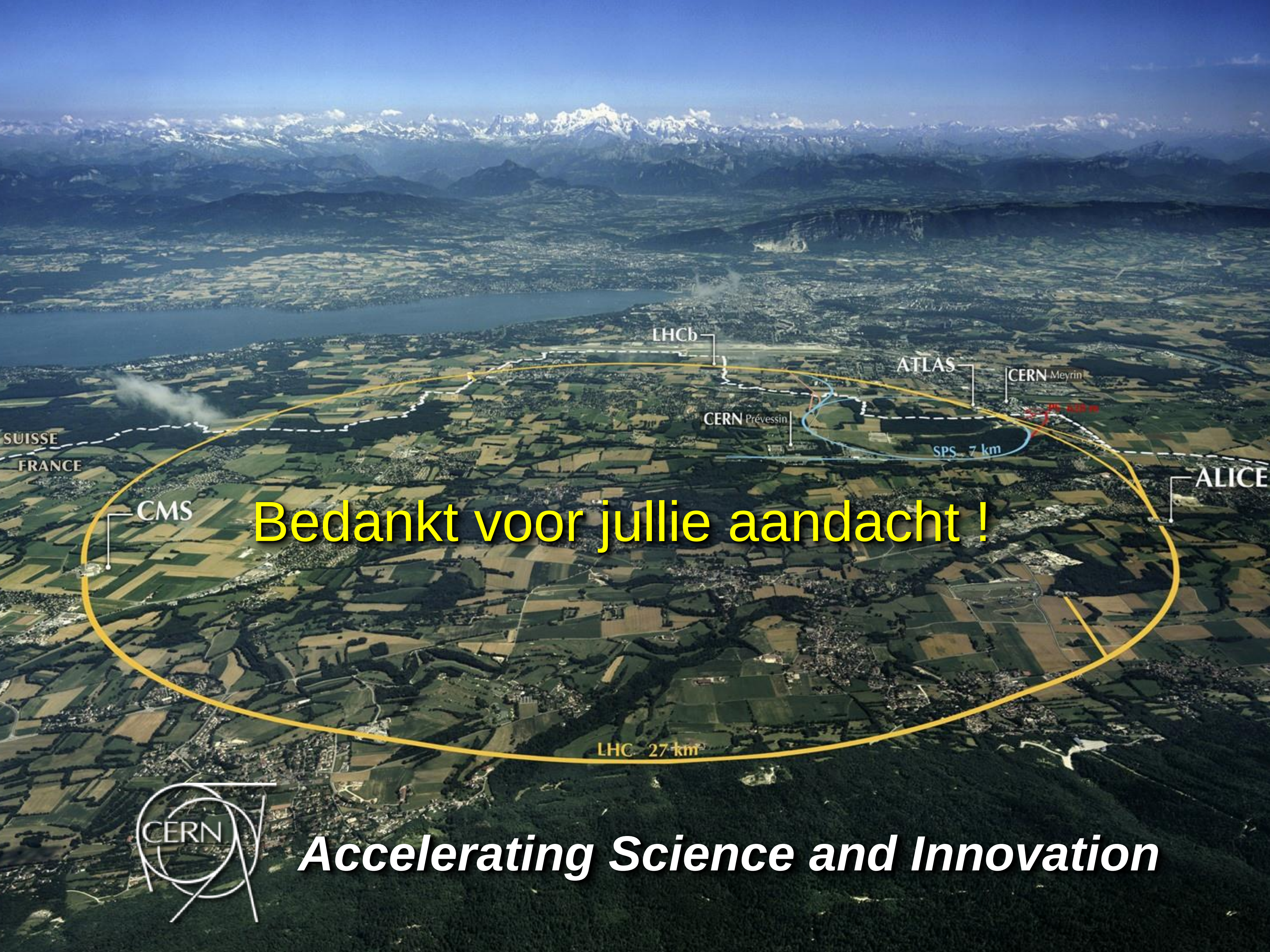
First collisions at 3.5 TeV



Ascension



Heroic subplot

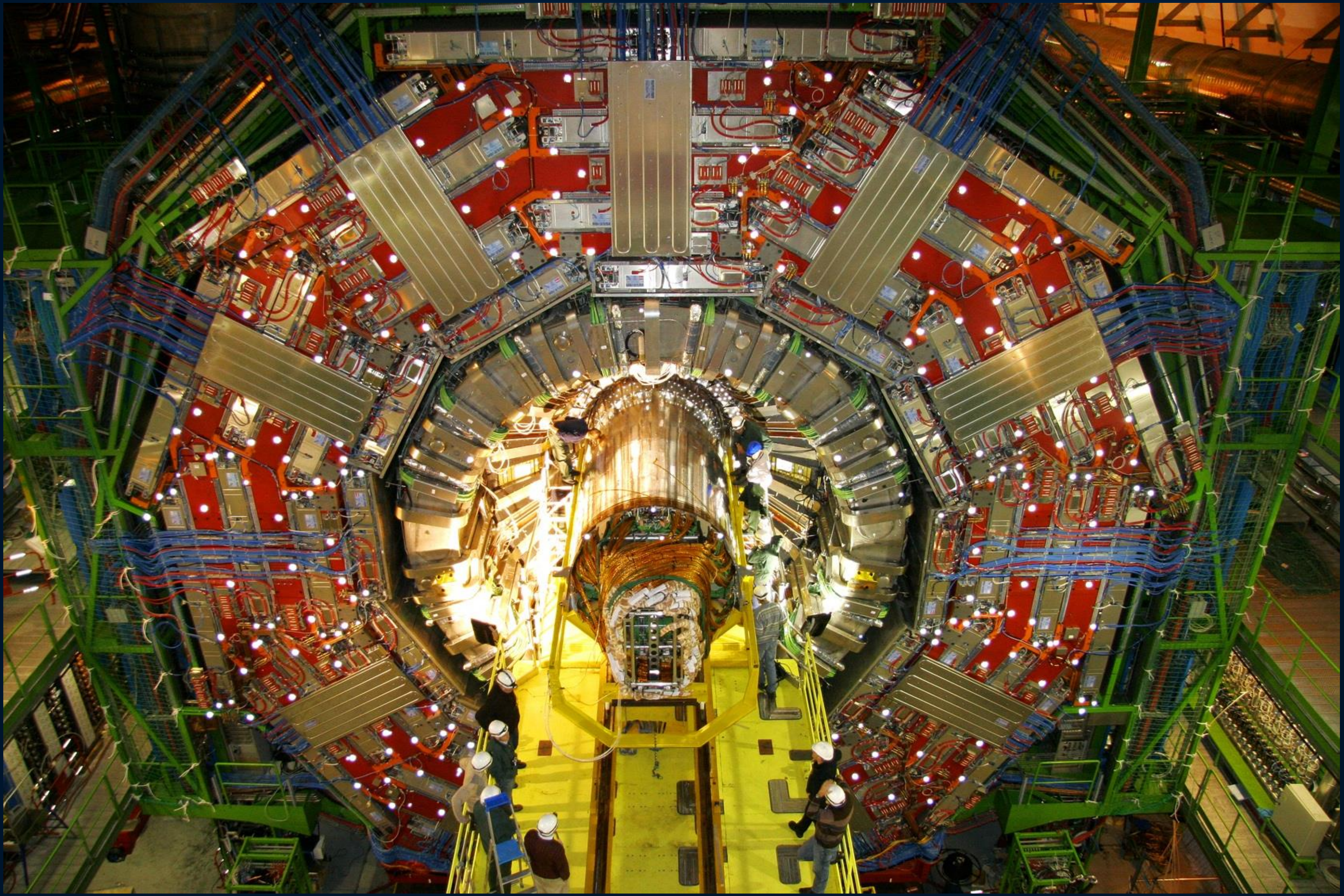


Bedankt voor jullie aandacht !

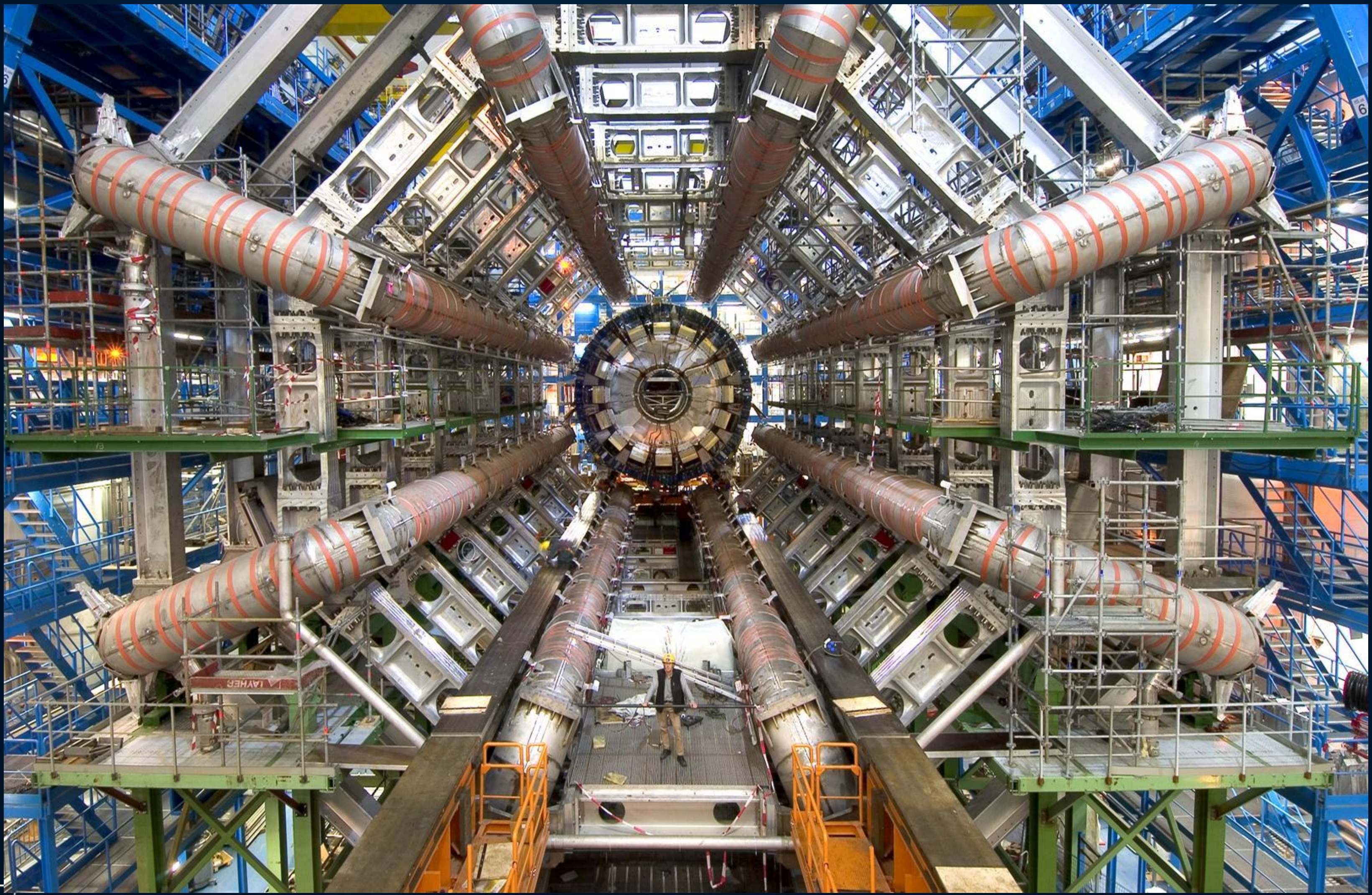
Accelerating Science and Innovation

SPARE SLIDES

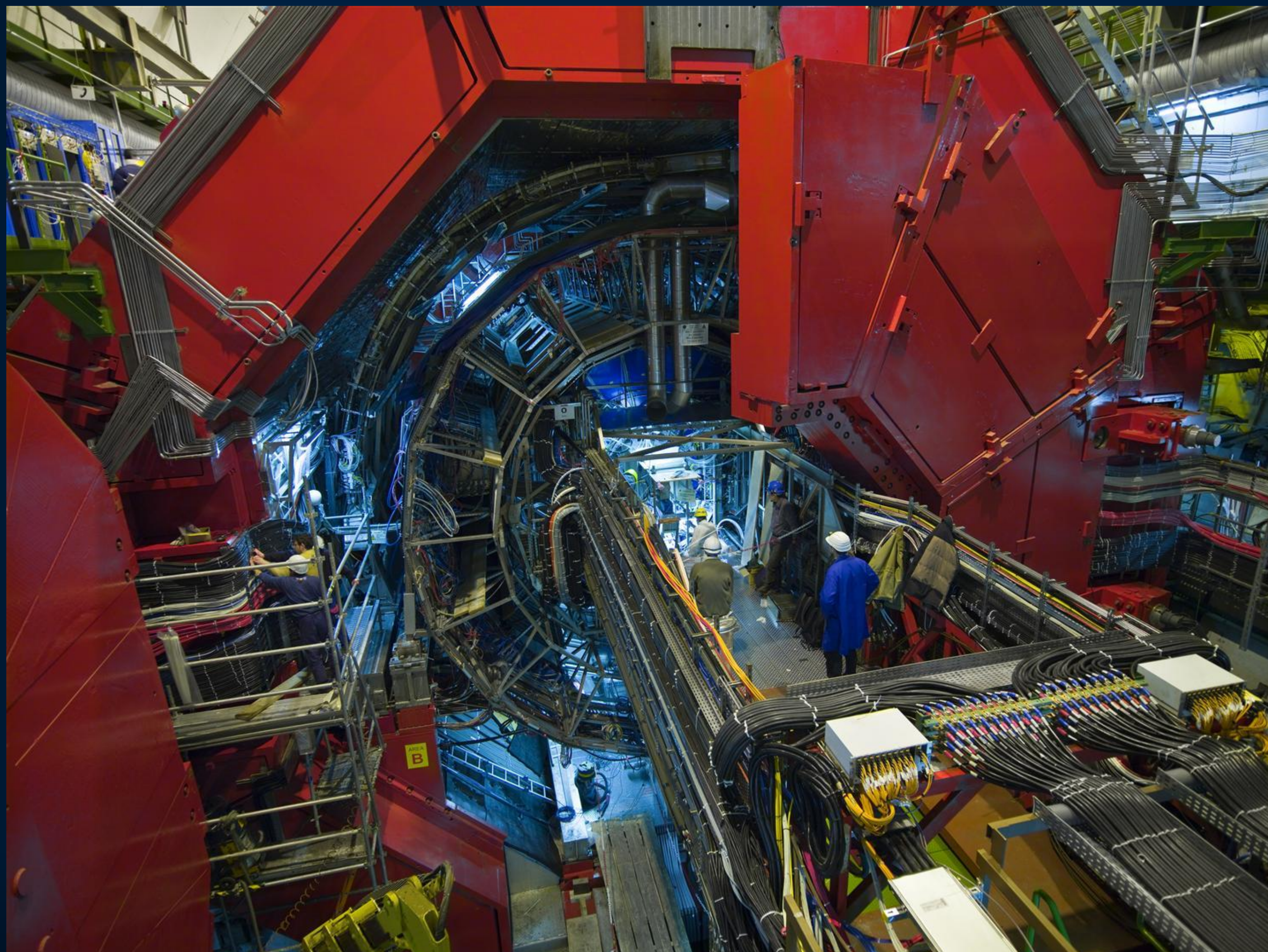
CMS: heavier than the Eifel tower



ATLAS: large as a building of 5 floors



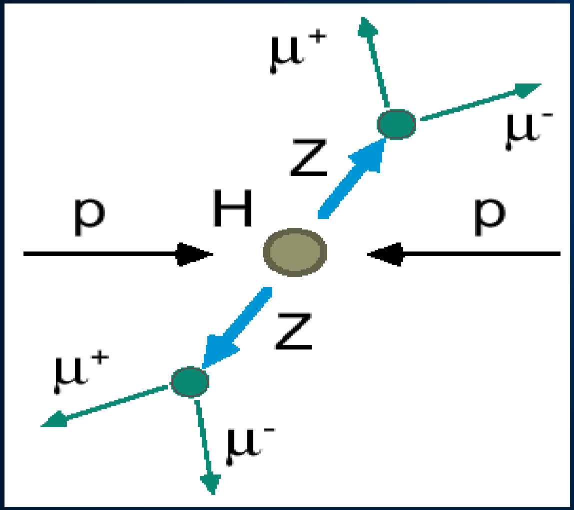
ALICE: very sensitive, optimised for ion collisions



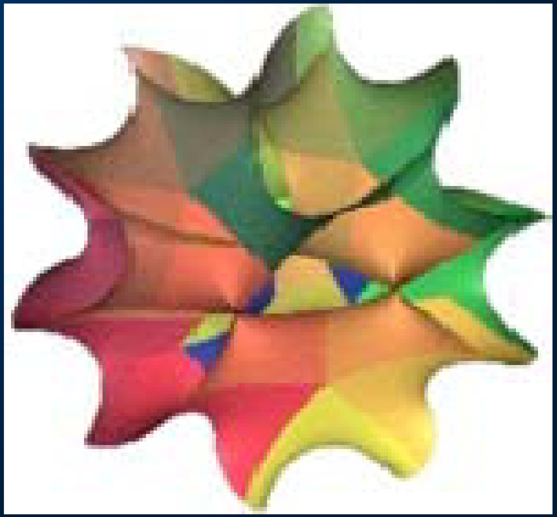
LHCb: asymmetric, B-physics

Aim of the game

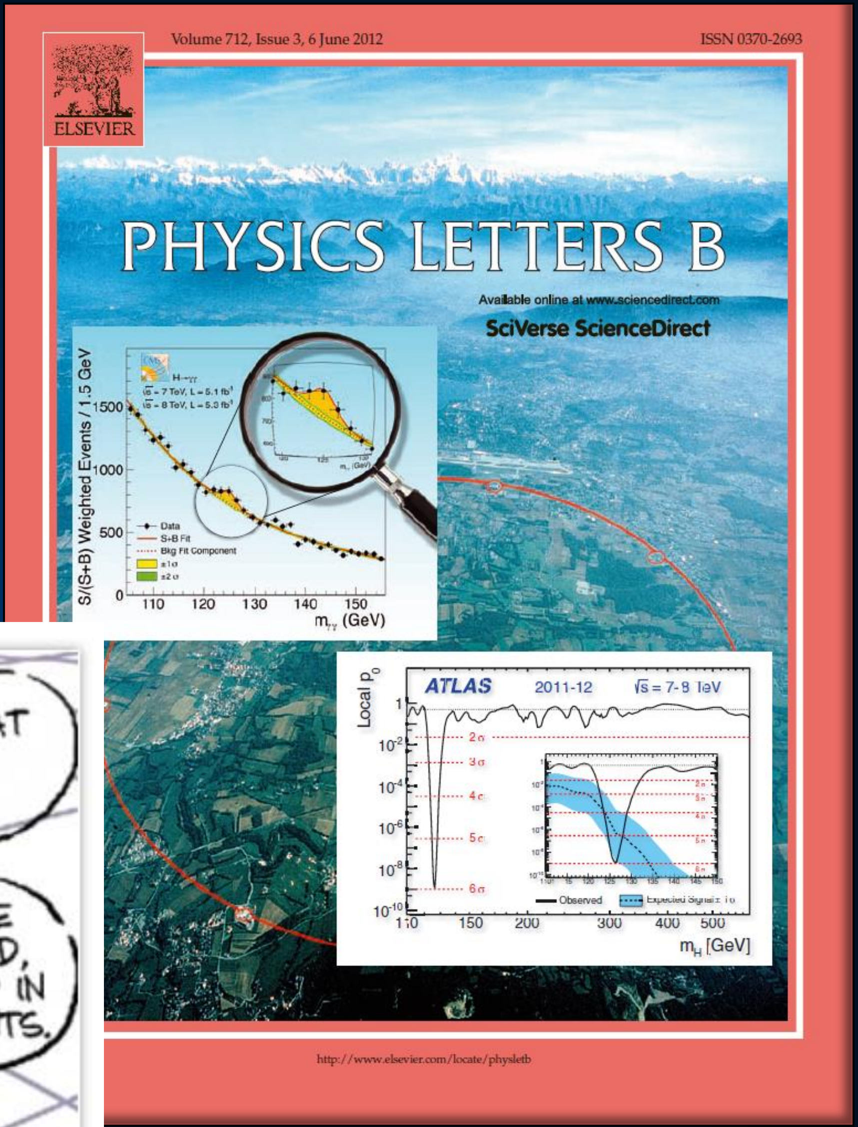
We want to deliver maximum number of collisions at the maximum beam energy for maximum physics reach

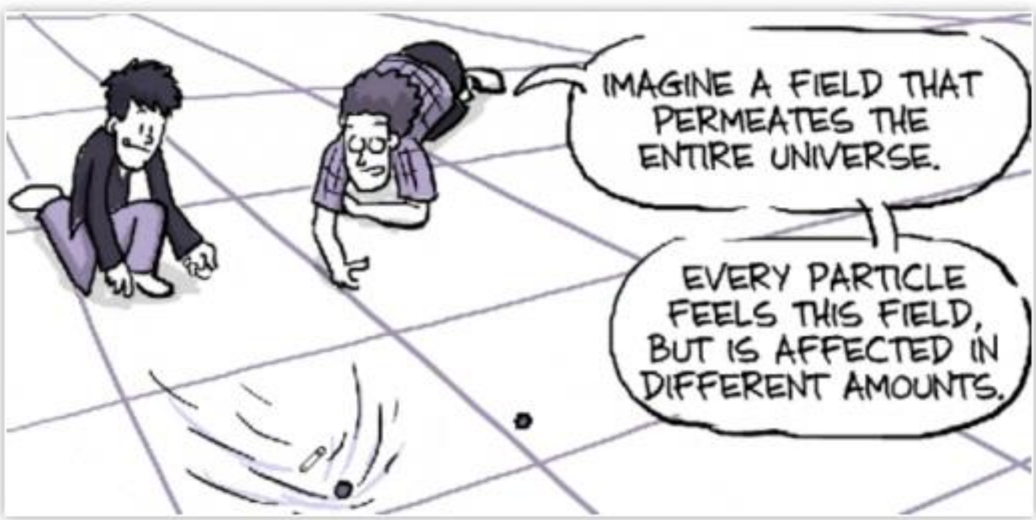


$E = m \cdot c^2$



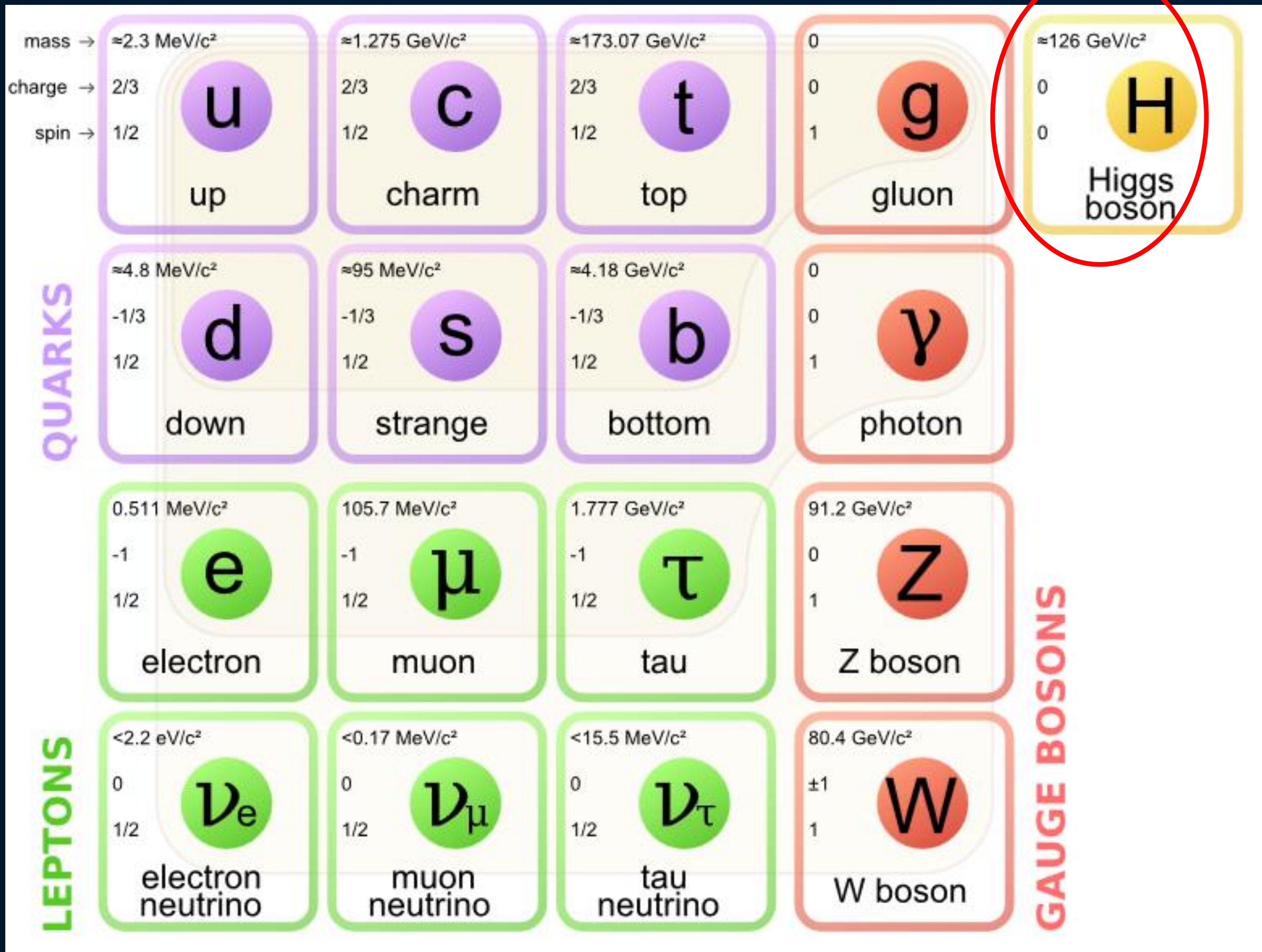
The Higgs field gives mass to other particles





(Credit: PHD Comics)

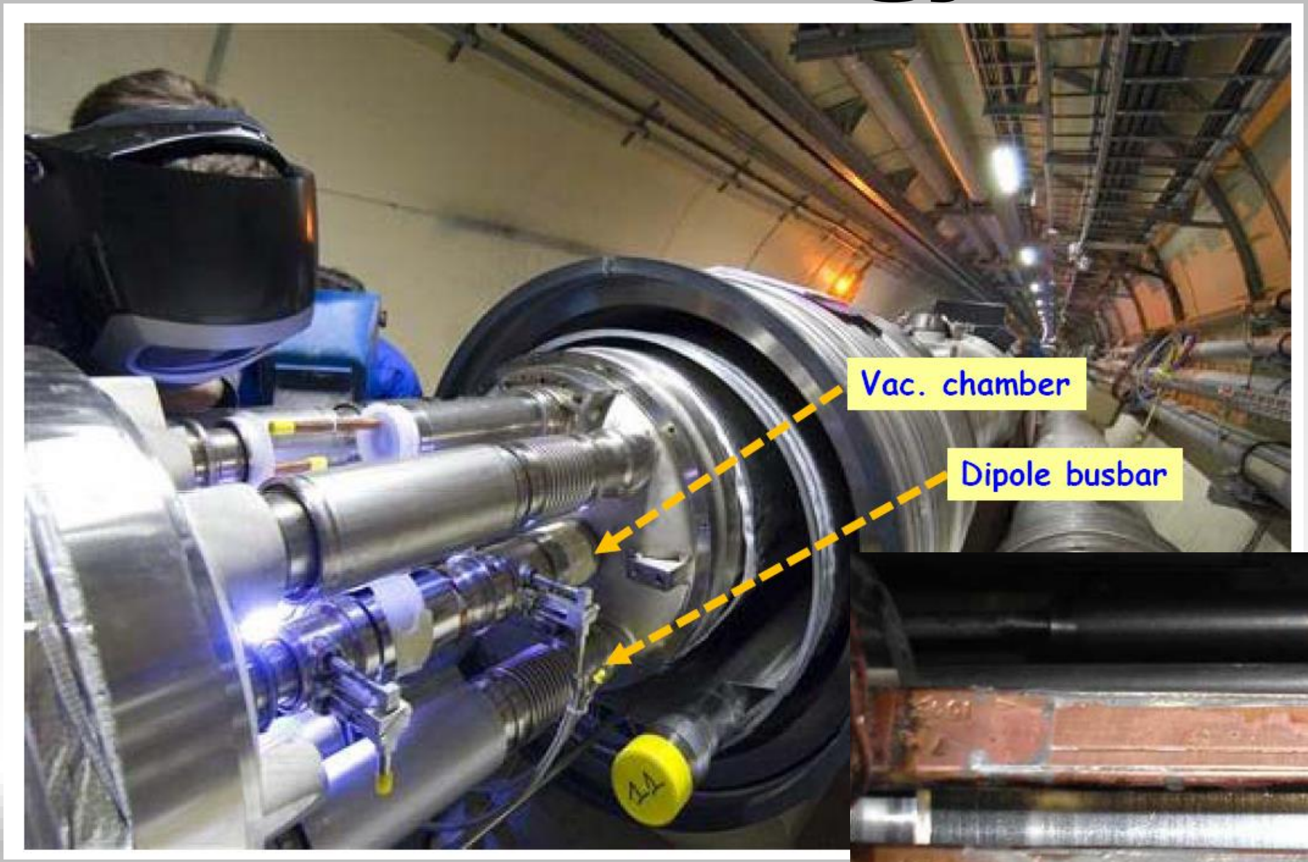
Why is the Higgs so special?

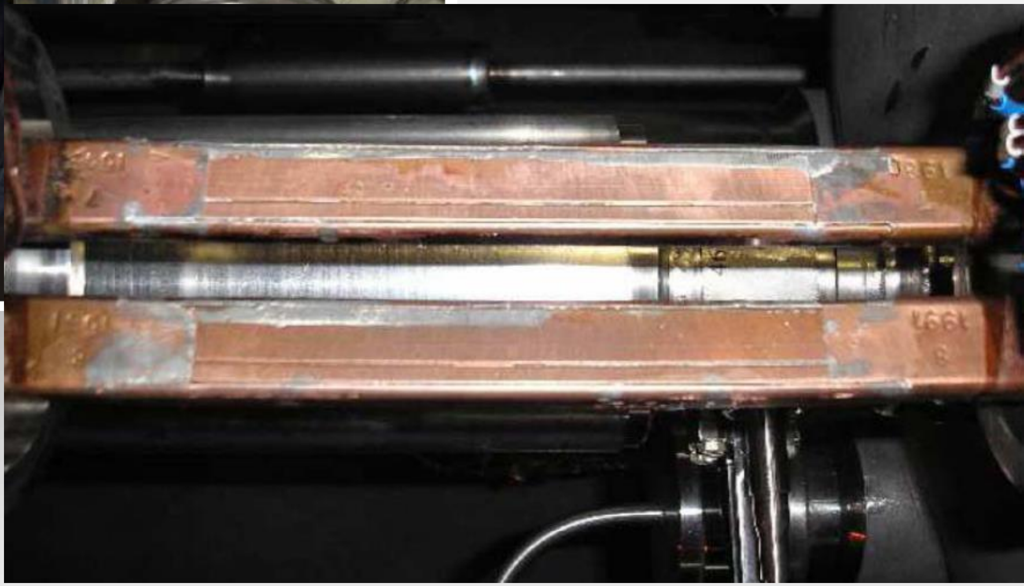


Reduced Energy – the history

10th September 2008: First circulating beams – all smiles

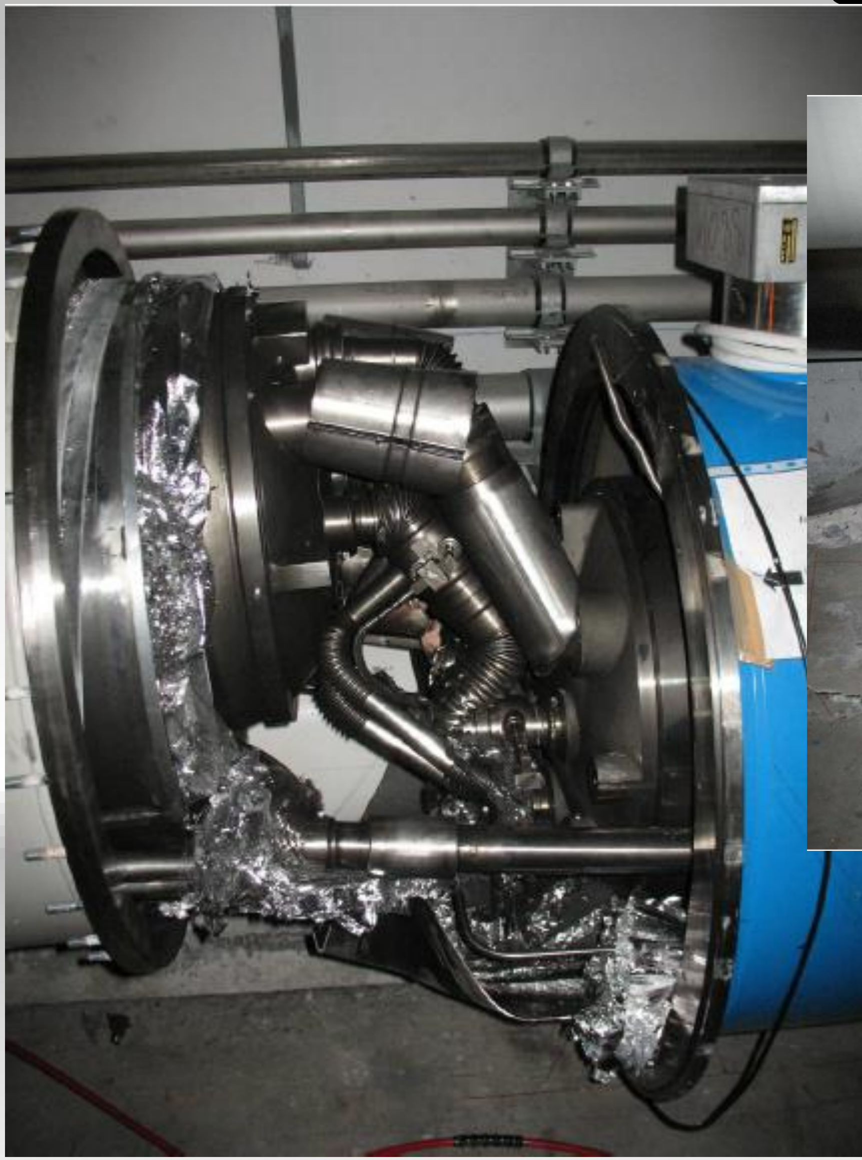
Reduced energy – the history





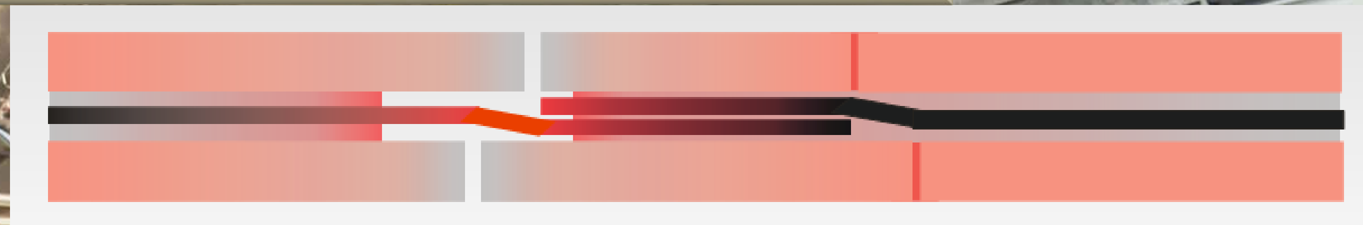
19th September 2008: electrical arc ruptured bus-bar interconnection during tests without beam – violent He blow-off

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

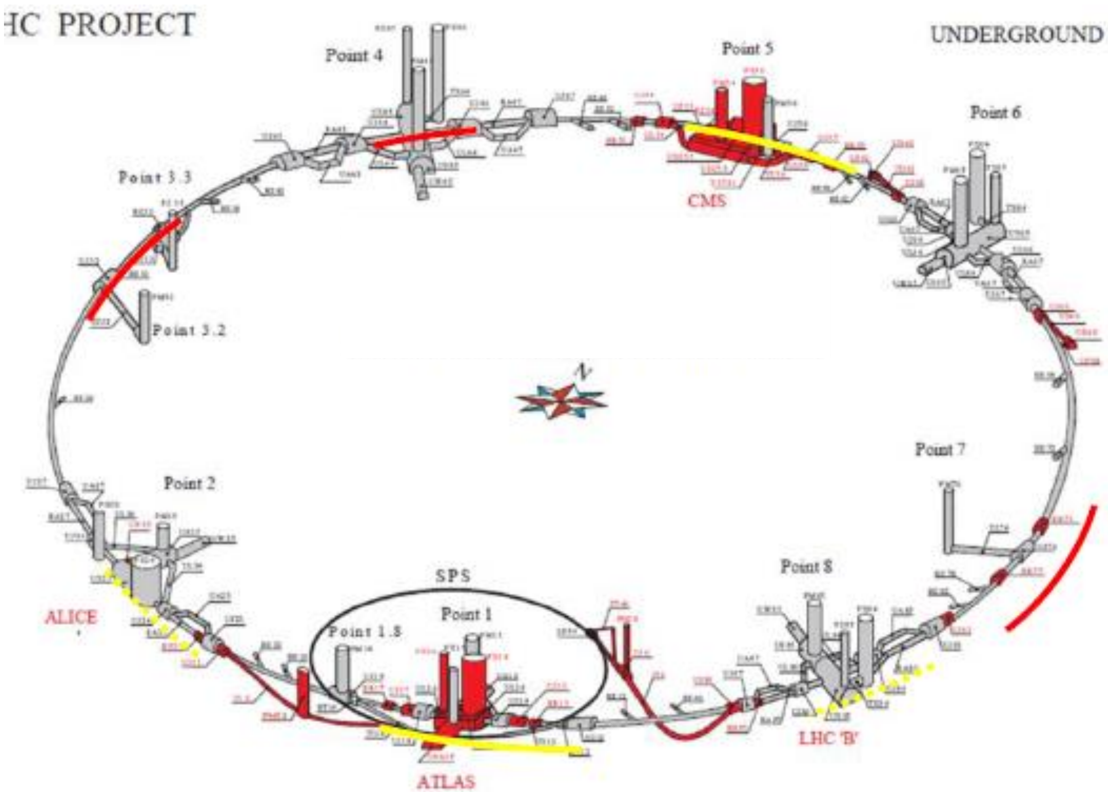
Next 10 years

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

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

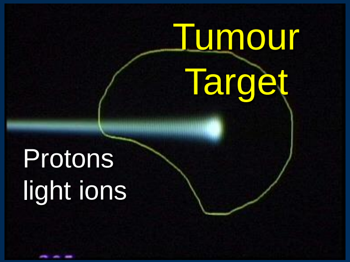

Large-scale computing (Grid)

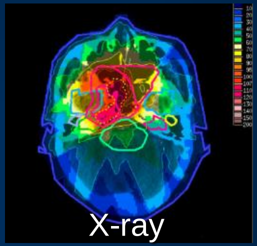
Medical Application as an Example of Particle Physics Spin-off

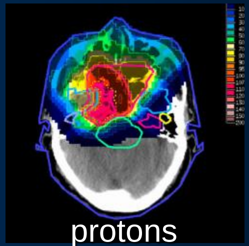
Combining Physics, ICT, Biology and Medicine to fight cancer

Accelerating particle beams
~30'000 accelerators worldwide
~17'000 used for medicine

Hadron Therapy

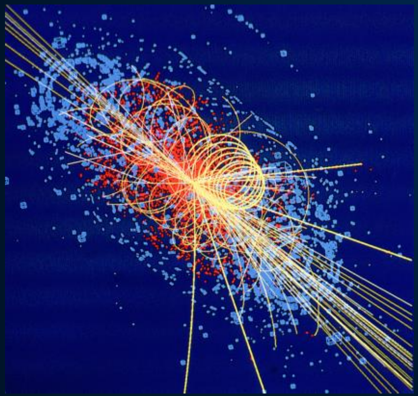






Leadership in Ion Beam Therapy now in Europe and Japan

>70'000 patients treated worldwide (30 facilities)
>21'000 patients treated in Europe (9 facilities)

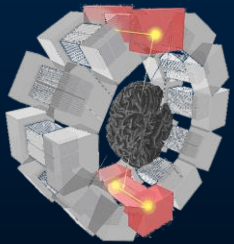


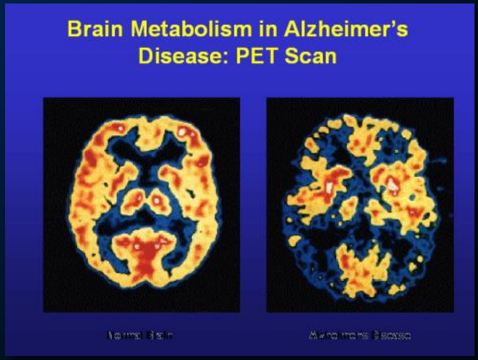
Detecting particles

Imaging

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

PET Scanner





CERN Education Activities

Scientists at CERN
Academic Training Programme

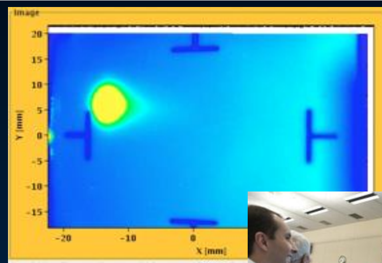
Young Researchers
CERN School of High Energy Physics
CERN School of Computing
CERN Accelerator School

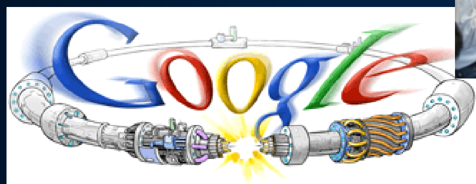
Physics Students
Summer Students Programme

CERN Teacher Schools
International and National Programmes

LHC Timeline

August 2008
First injection test



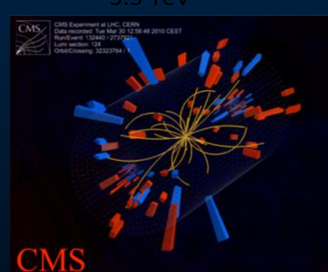


September 10, 2008
First beams around

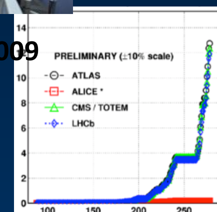
September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

November 29, 2009
Beam back

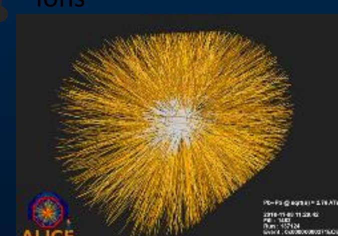
March 30, 2010
First collisions at 3.5 TeV



October 14 2010
1e32
248 bunches



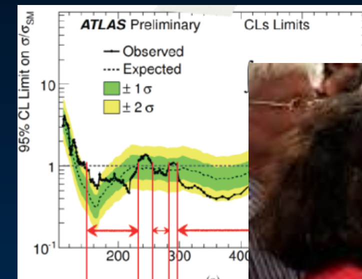
November 2010
Ions



June 28 2011
1380 bunches

1380

August
2.3e33,
1380 b



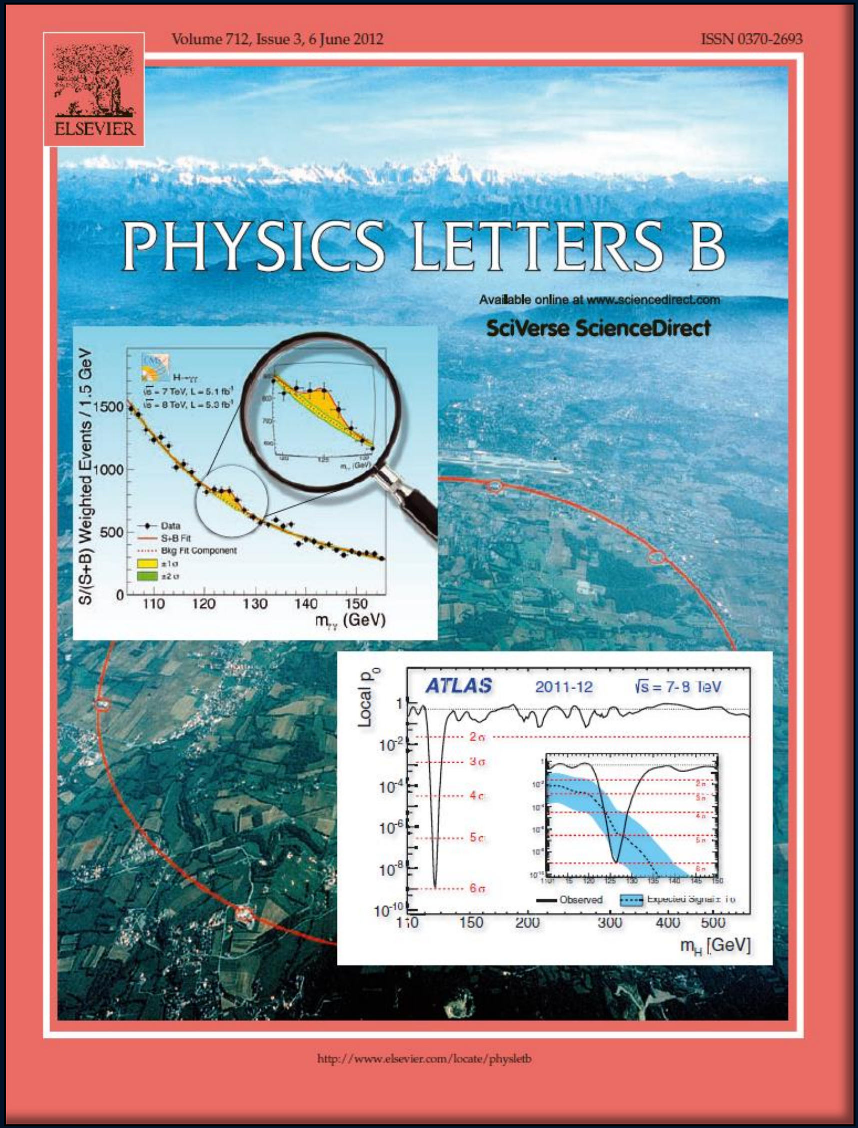
6 June, 2012
6.8e33

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

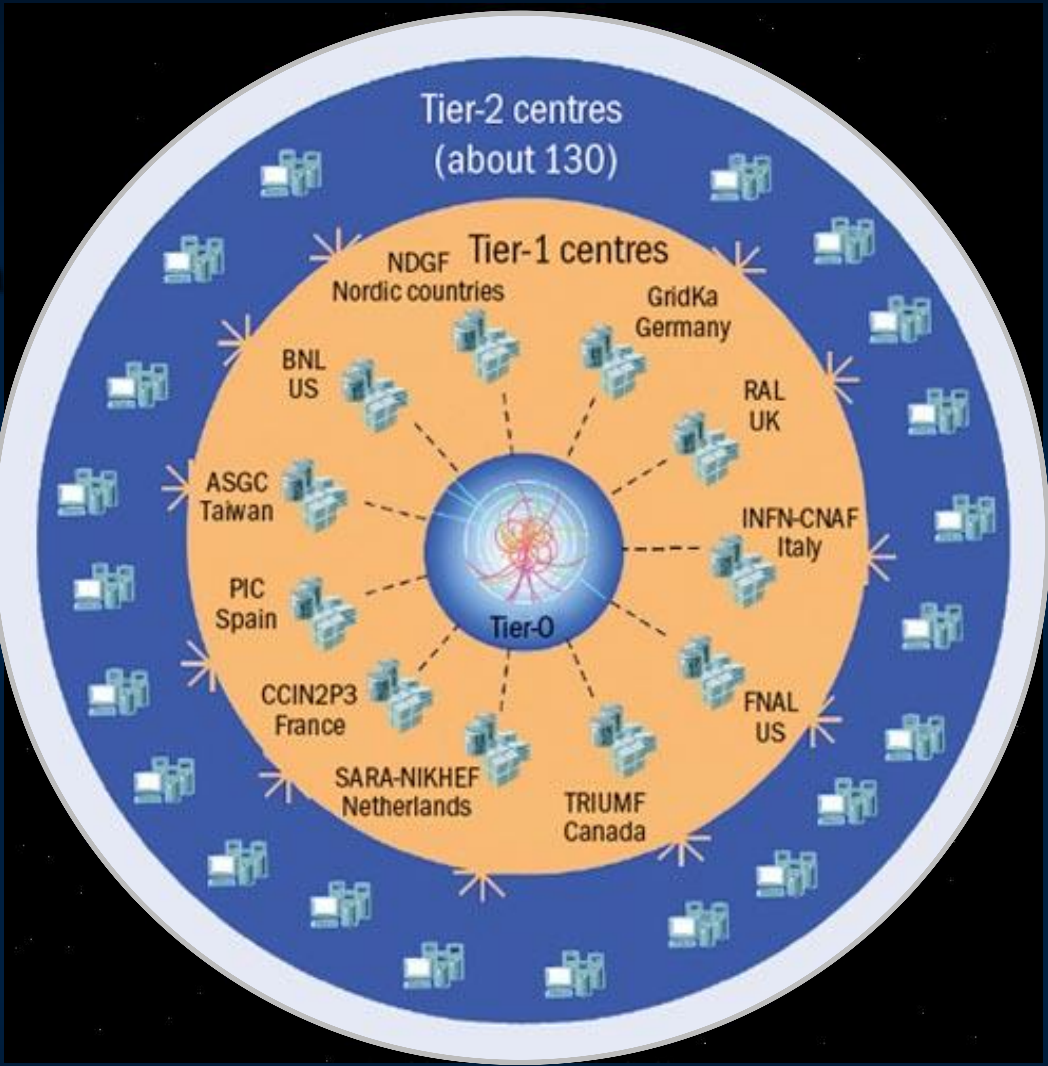
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental 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

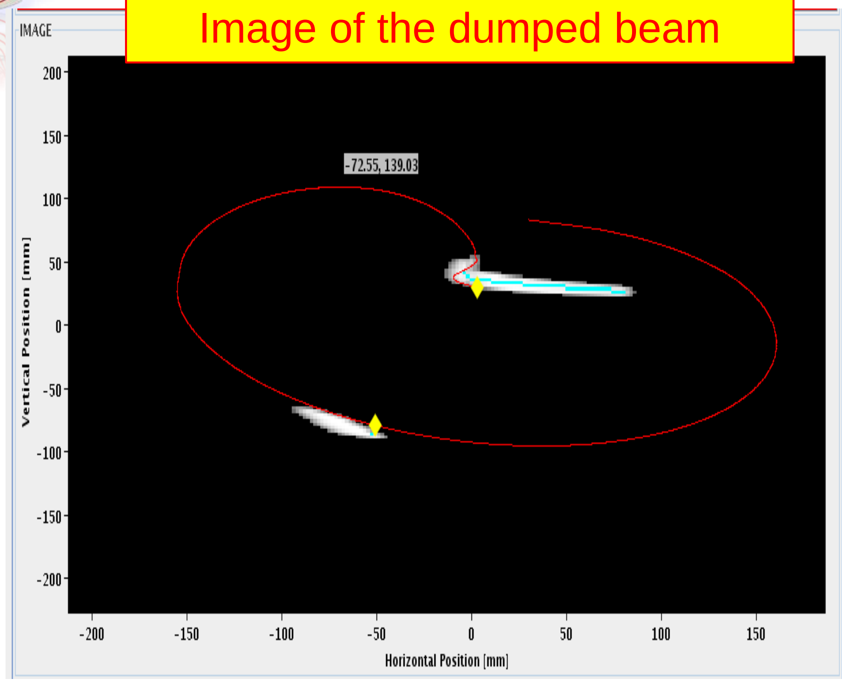
> 2 million jobs/day

10 Gb links

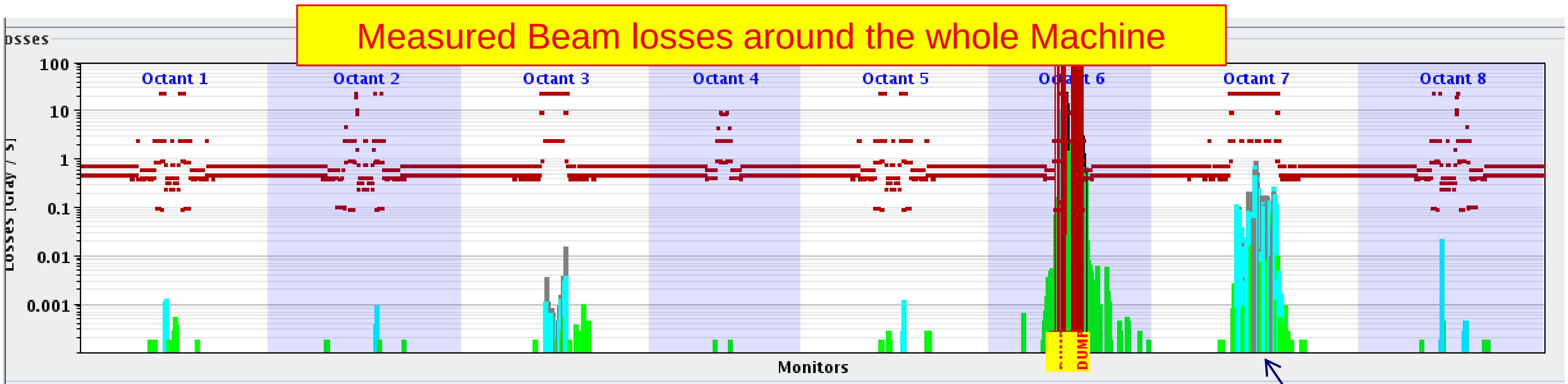
An International collaboration to distribute and analyse LHC data

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

Verification of Dump Protection



- 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



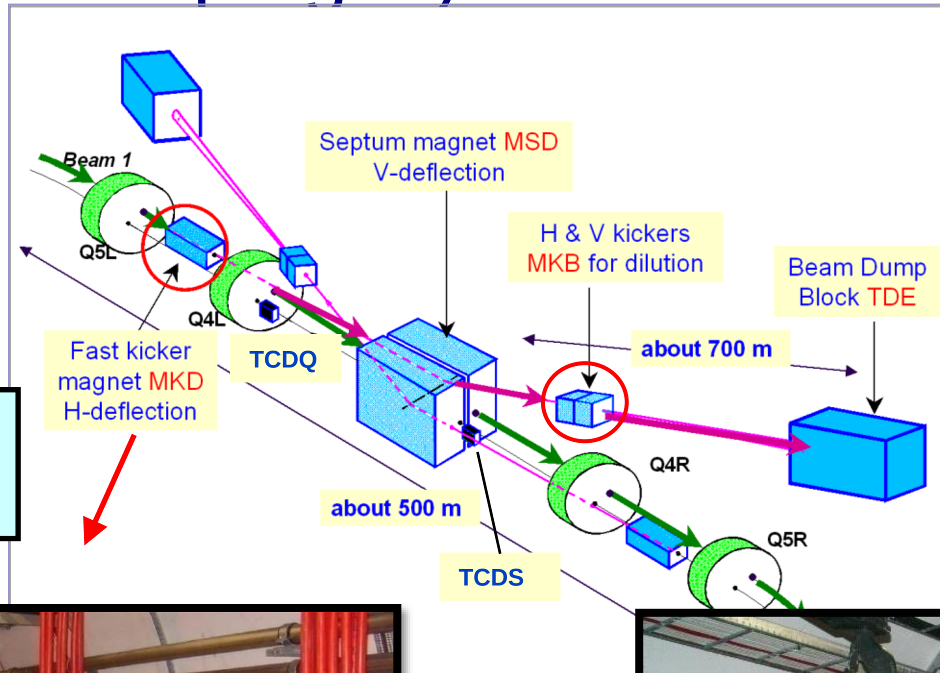
Rest of the machine is clean

Dump

Collimation

Only one way to safely get rid of the beam

LHC Beam Dumping System



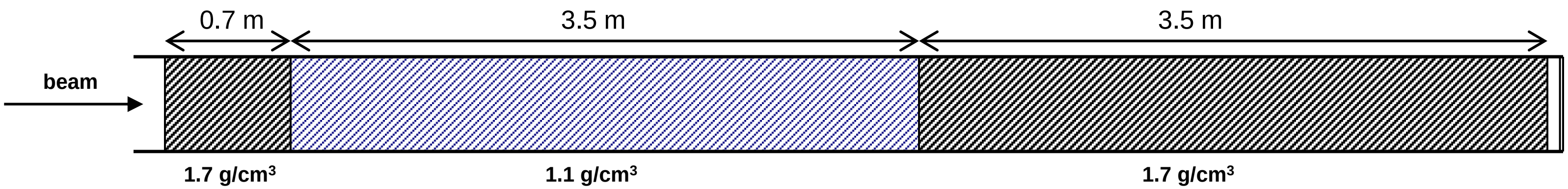
Extraction Kickers

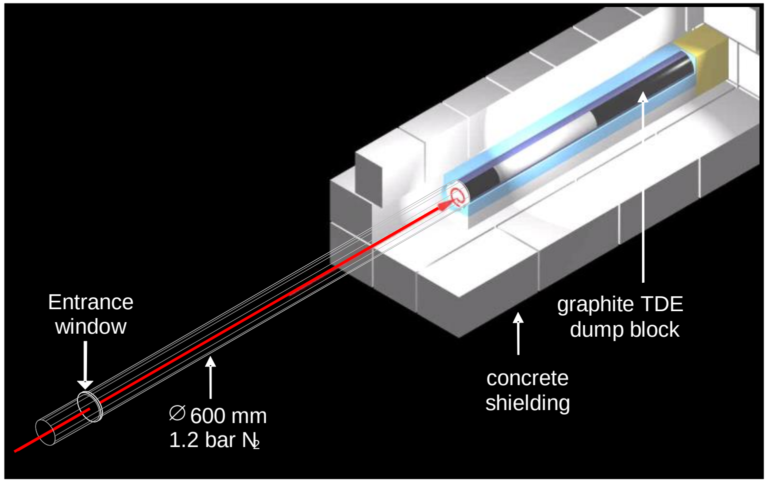
2 x 15 Systems

10 Dilution kickers MKB

Beam dump block (TDE)

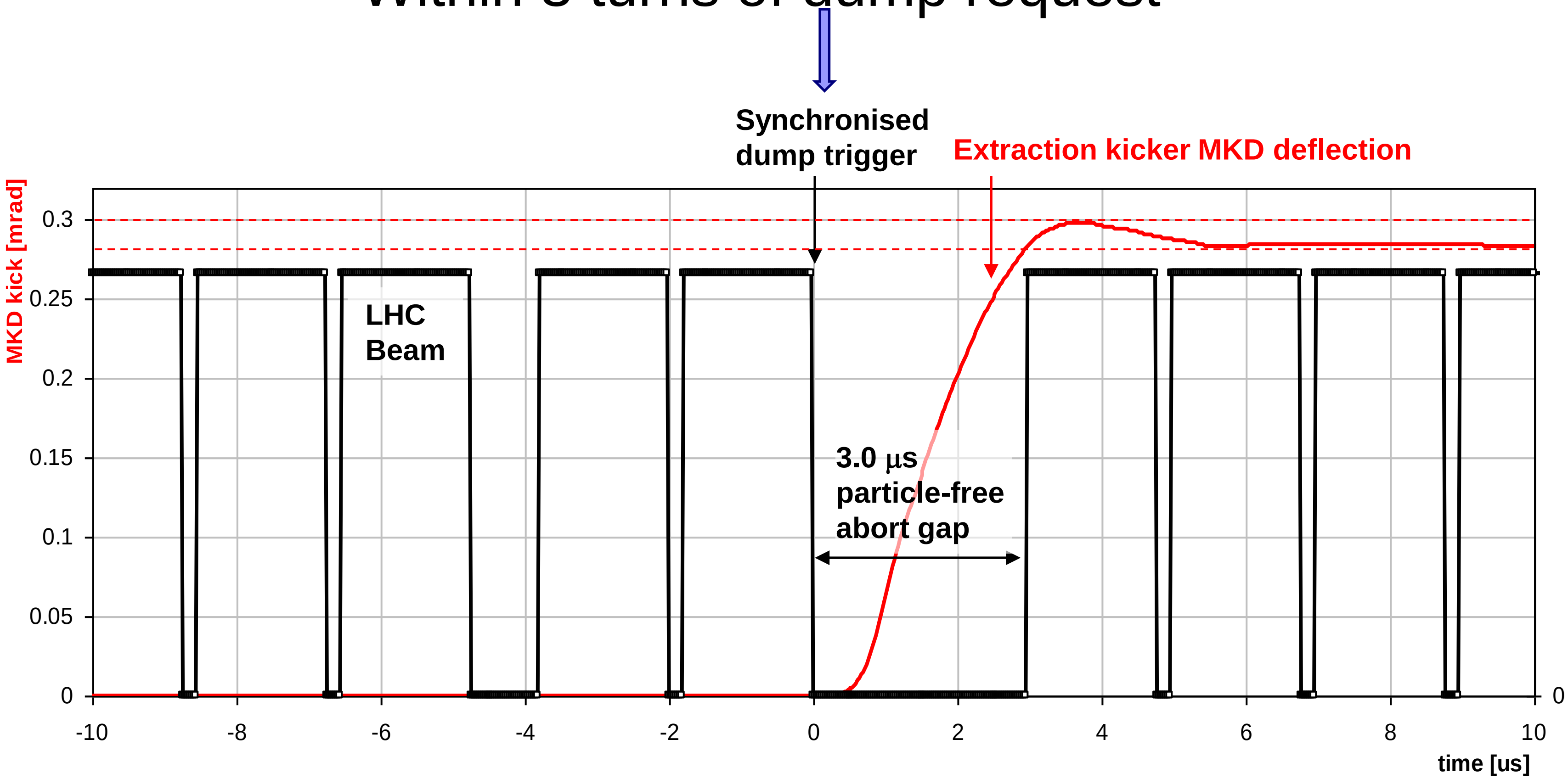
- 700 mm ∅ graphite core, with graded density of 1.1 g/cm^3 and 1.7 g/cm^3
- 12 mm wall, stainless-steel welded pressure vessel, at 1.2 bar of N_2
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks



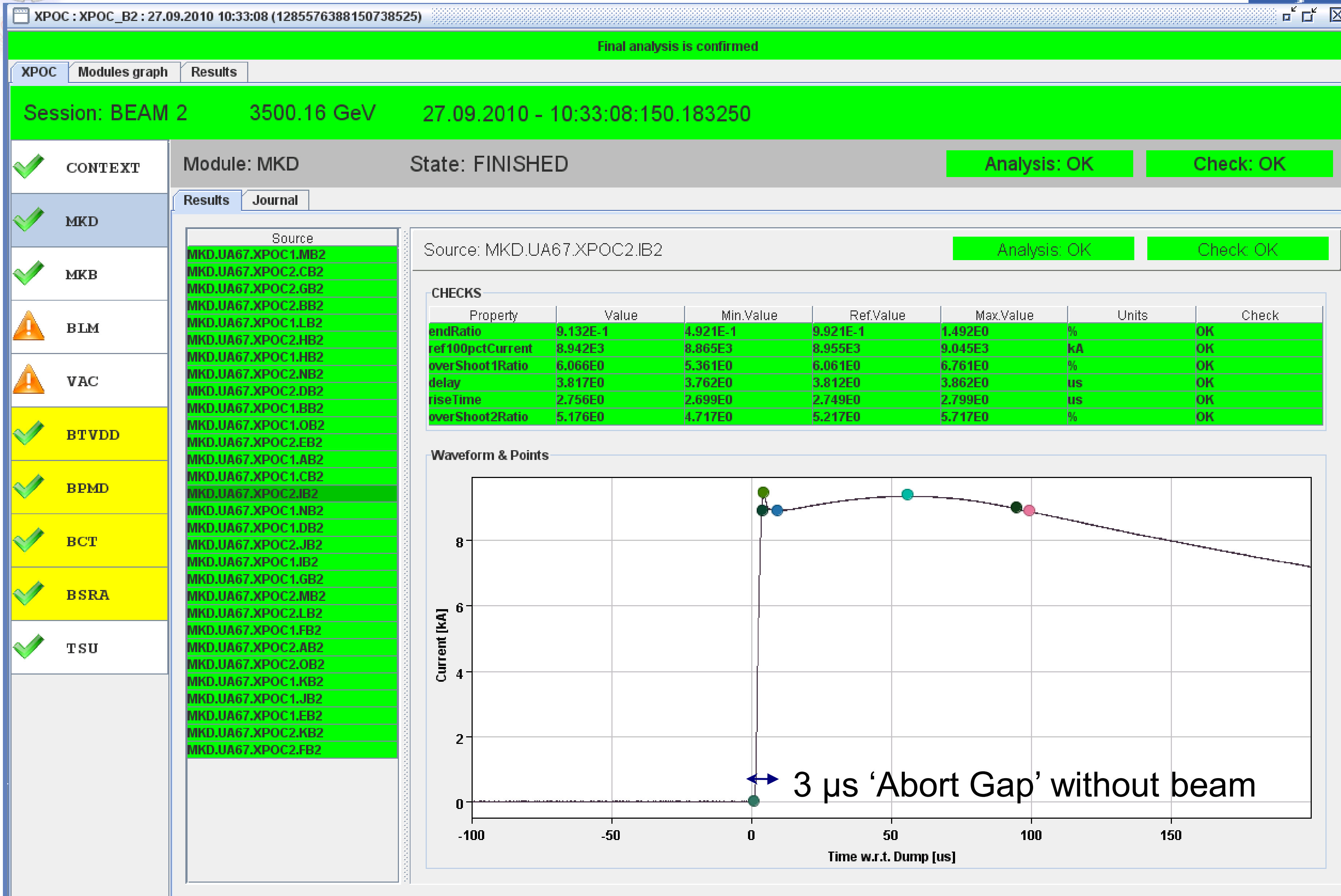


Extraction kicker – Abort Gap

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

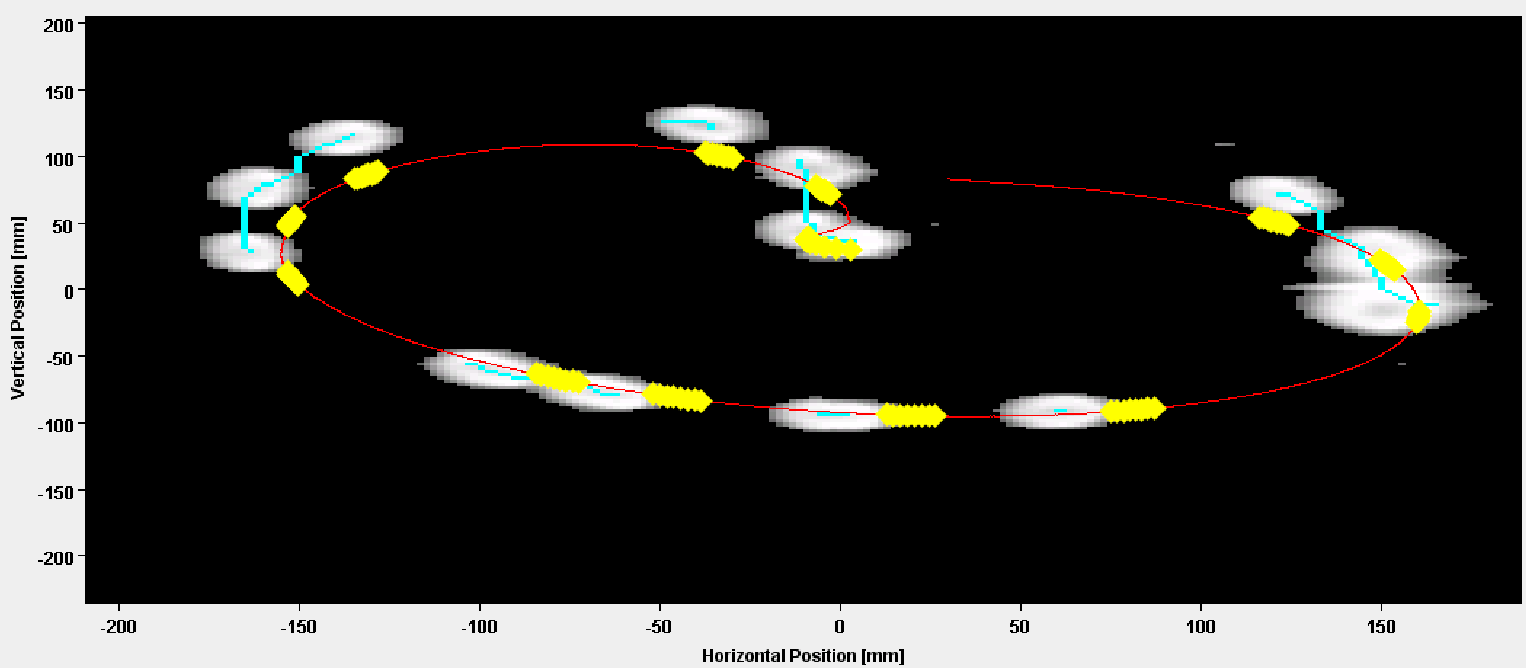
Results | Journal

Checks | Measures | References

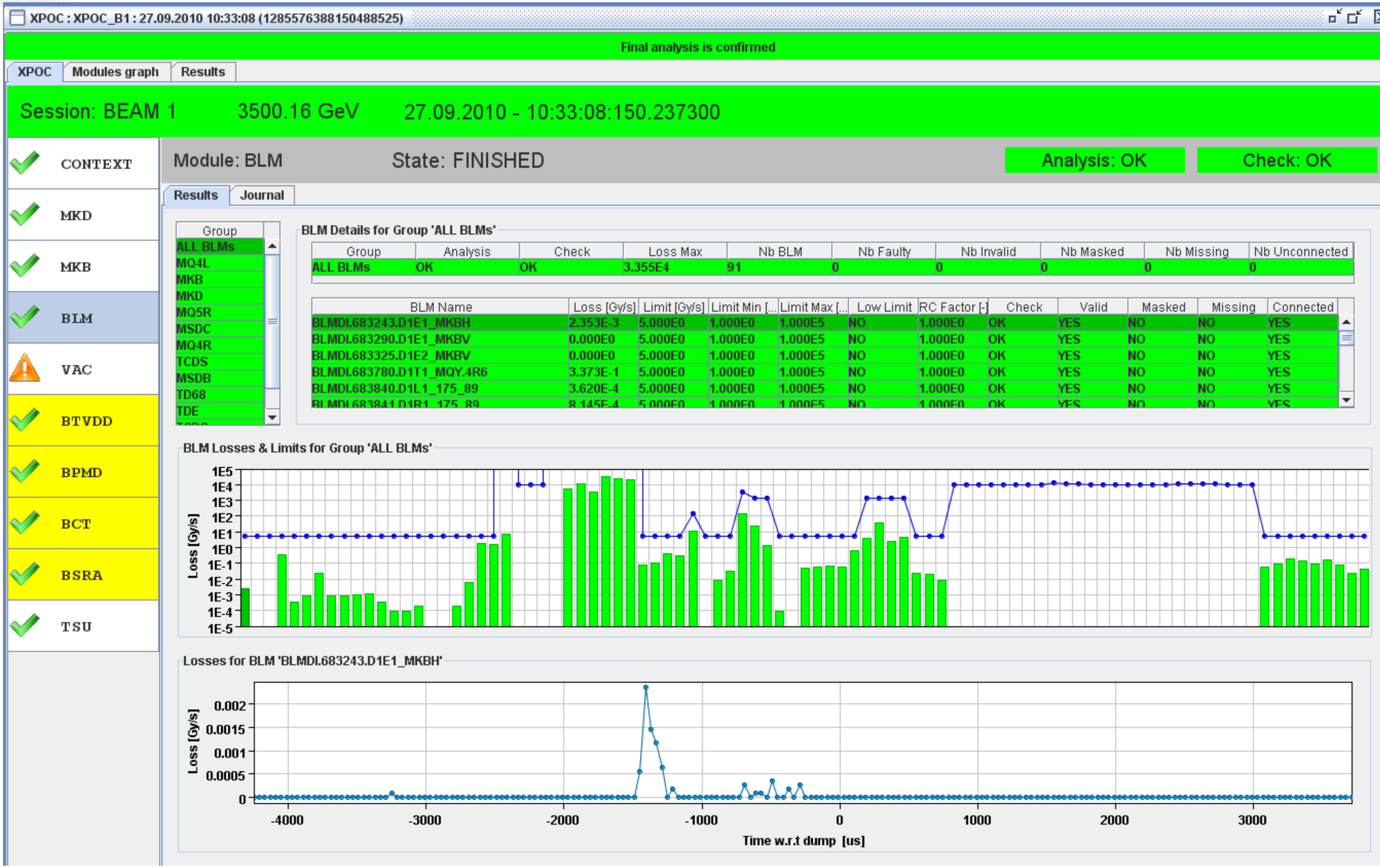
CHECKS

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**