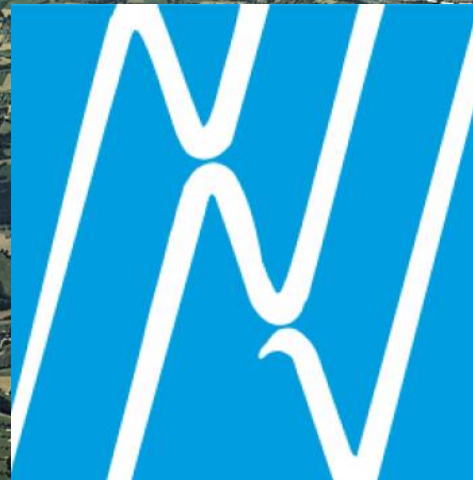


# *The LHC: How does it work?*

**NNV**

**Profielwerkstukreis**

**4 – 8 oktober 2021**



***Accelerating Science and Innovation***  
***Jan Uythoven, CERN***



*Compact Muon Solenoid*

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



*Cern Control Centre*





# The LHC

A black and white photograph showing the interior of the Large Hadron Collider (LHC) tunnel. The view is from a perspective looking down the length of the tunnel, which is filled with complex machinery, including large cylindrical components and structural supports. The lighting is dramatic, with strong highlights and deep shadows, emphasizing the scale and complexity of the facility.

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...

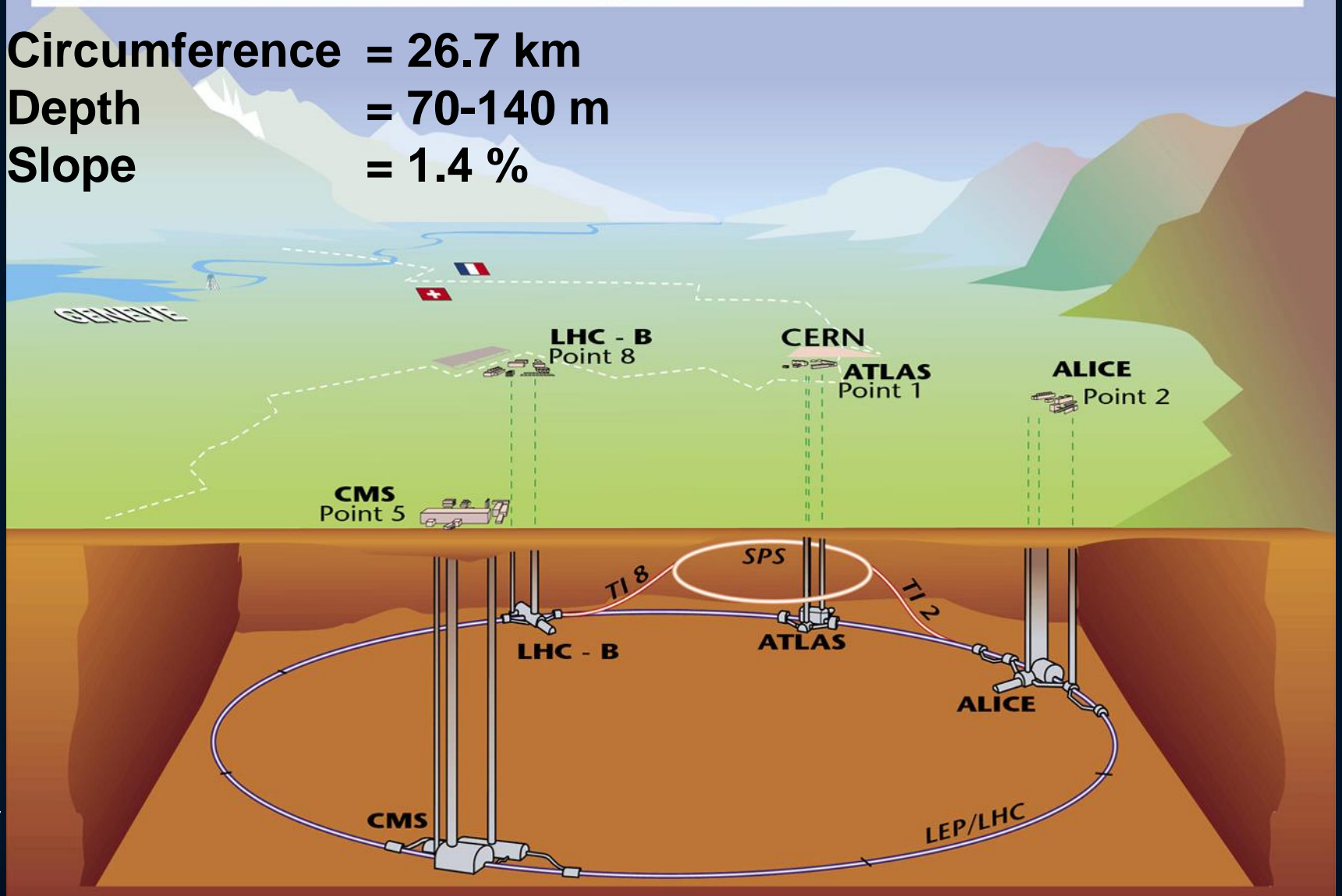


So a particle goes around the LHC  
11'000 times per second !

# LHC tunnel

## Overall view of the LHC experiments.

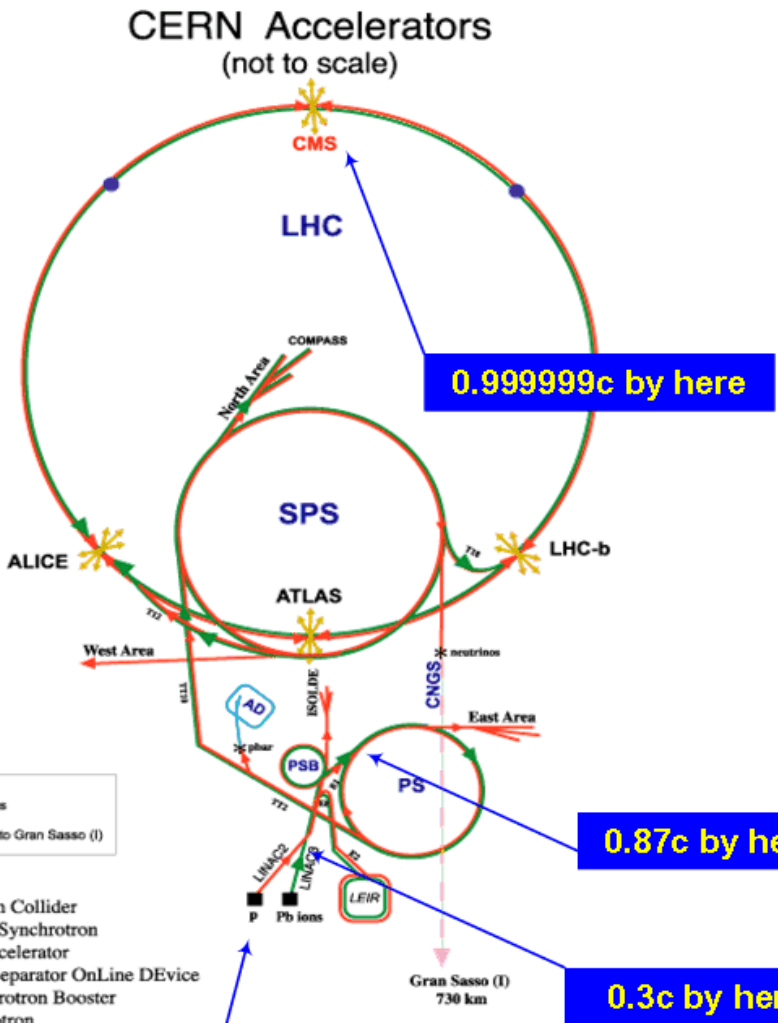
Circumference = 26.7 km  
Depth = 70-140 m  
Slope = 1.4 %



# LHC Injector Chain

New Linac4 in 2020: H<sup>-</sup>

	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: Large Hadron Collider  
 SPS: Super Proton Synchrotron  
 AD: Antiproton Decelerator  
 ISOLDE: Isotope Separator OnLine DEvice  
 PSB: Proton Synchrotron Booster  
 PS: Proton Synchrotron  
 LINAC: LINear ACcelerator  
 LEIR: Low Energy Ion Ring  
 CNGS: Cern Neutrinos to Gran Sasso

Radolf LEY, PS Division, CERN, 02.09.96  
 Revised and adapted by Antonella Del Zotto, ETT Div.,  
 in collaboration with B. Desforges, SE Div., and  
 D. Manglinski, PS Div. CERN, 23.05.01



# Where do the Protons come from?





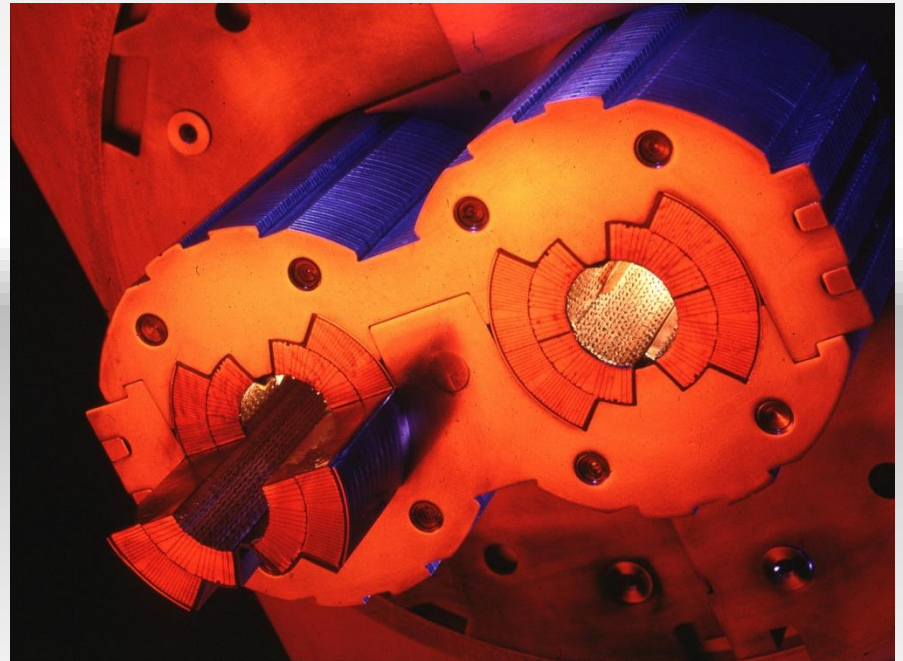
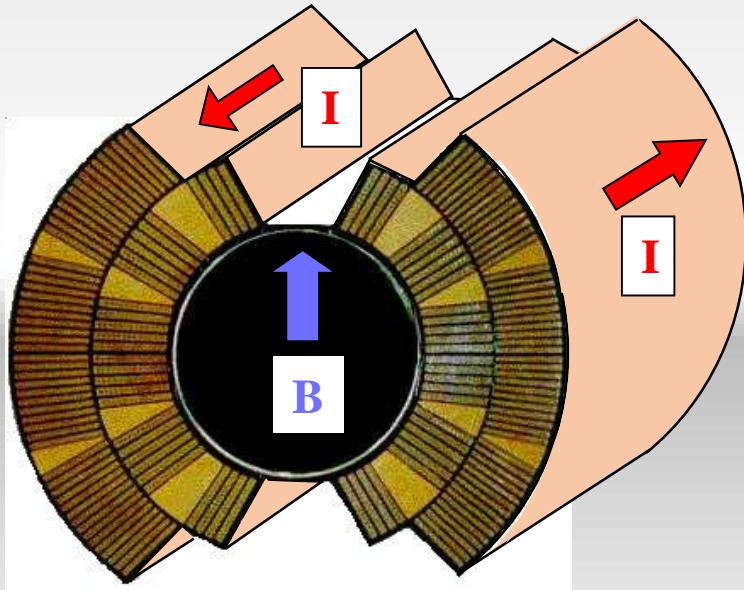
# Basic ingredients of a particle accelerator

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

- **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

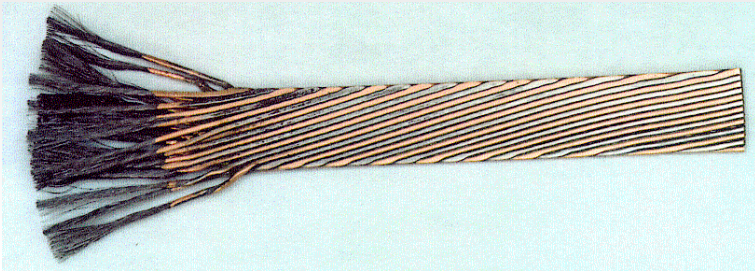


**SUPERCONDUCTING!**  
Cooled with superfluid helium at 1.9 K

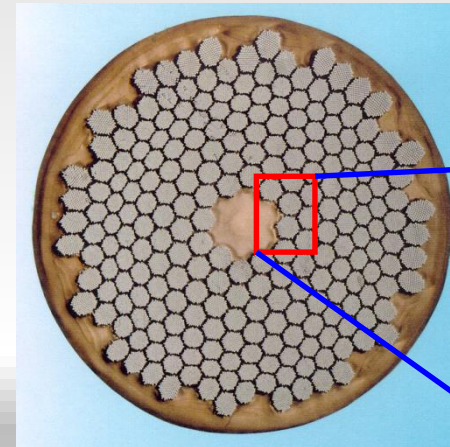
# The superconductor

## Niobium-titanium Rutherford cable

Cable



Strand

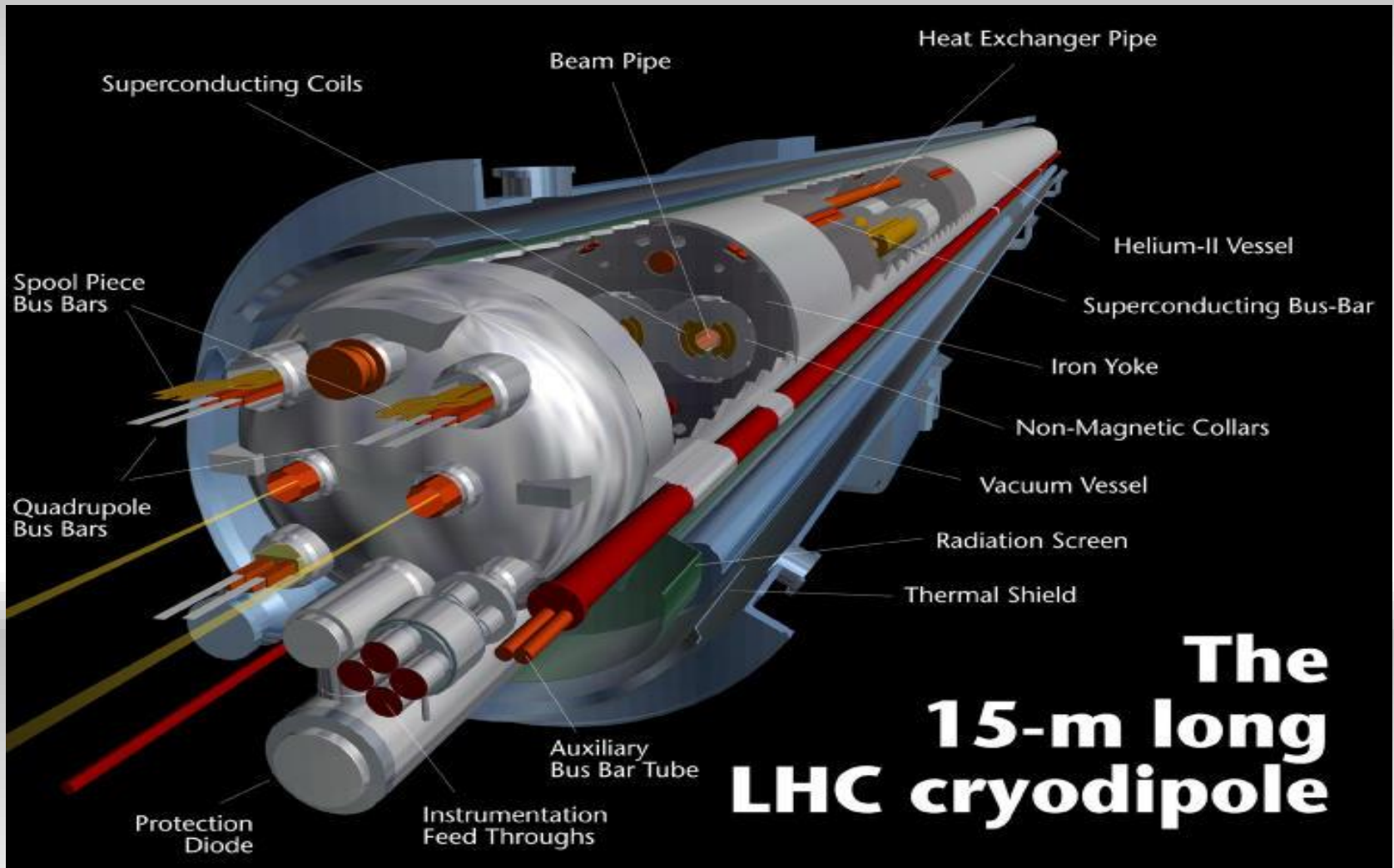


Filament



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

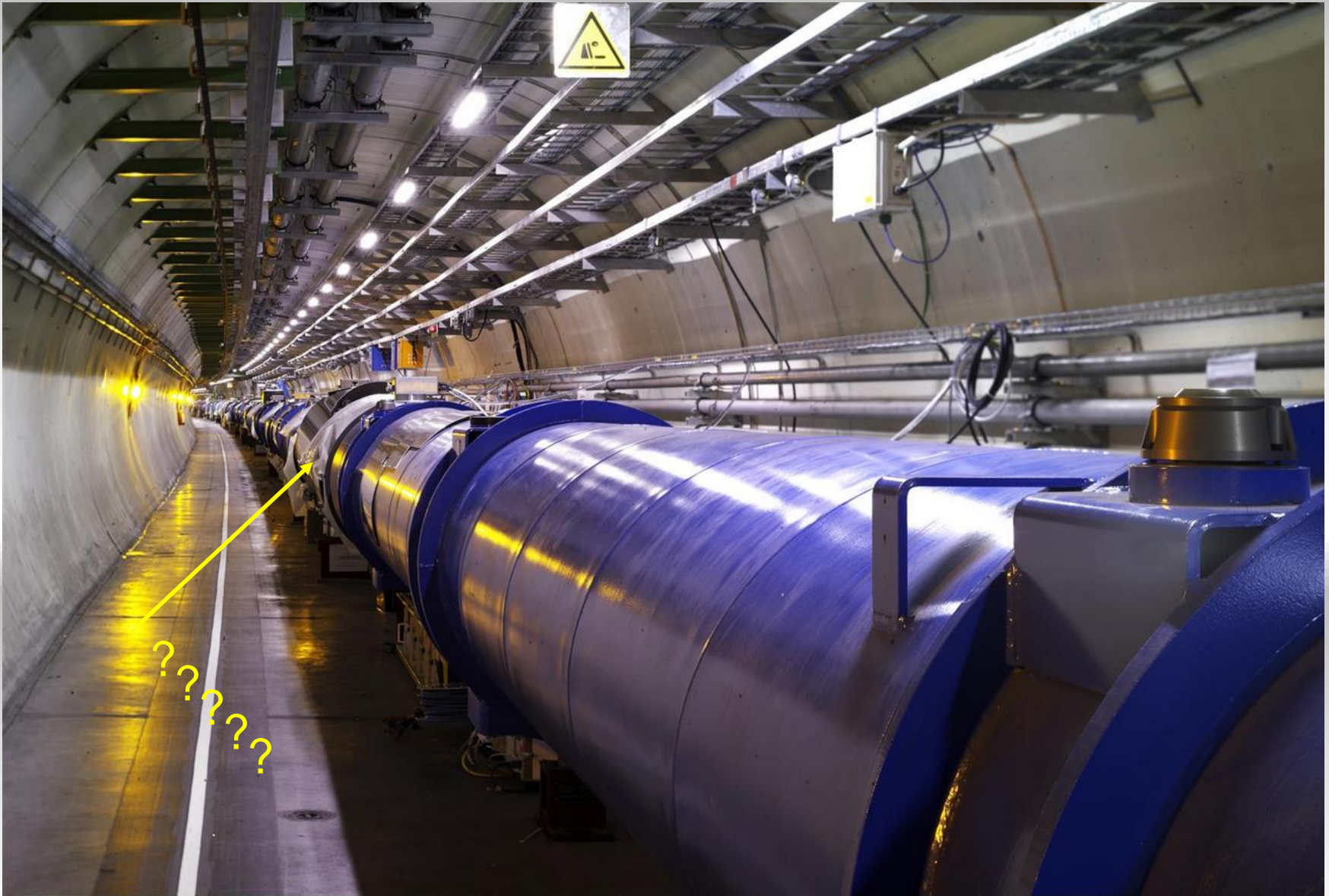
# More than just some coils...



# During construction: Dipoles all over

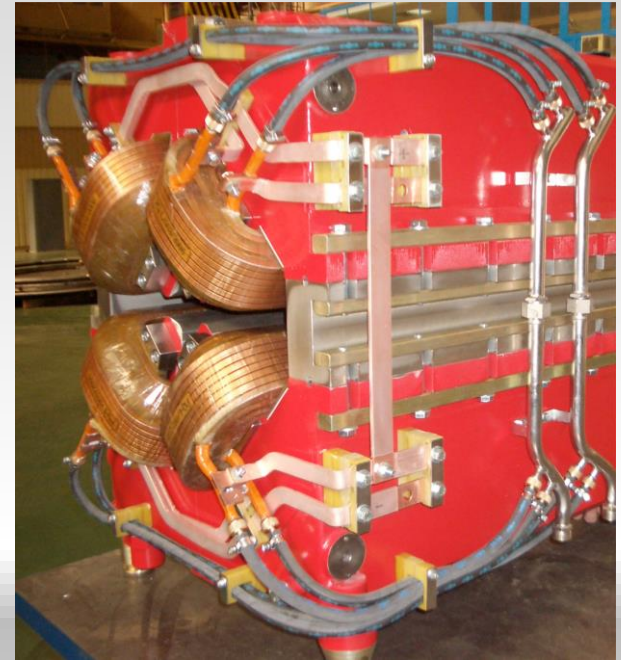
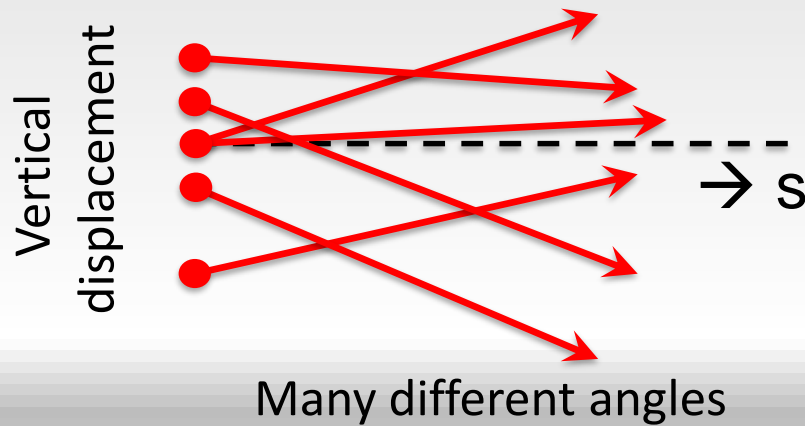


# In the LHC tunnel



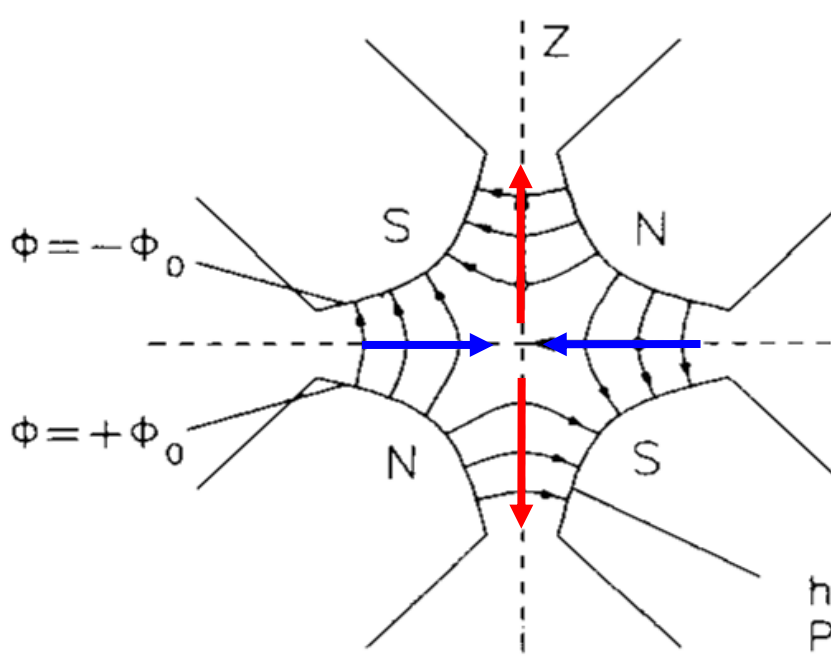
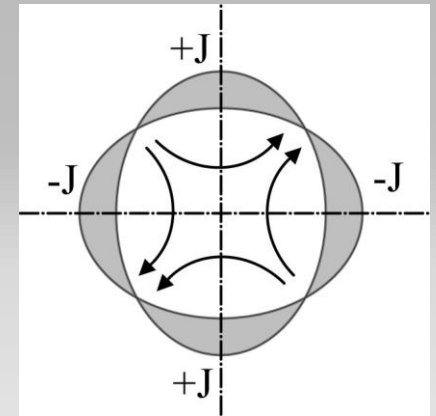
# Beam is divergent

Many particles many initial conditions



Quadrupole magnet

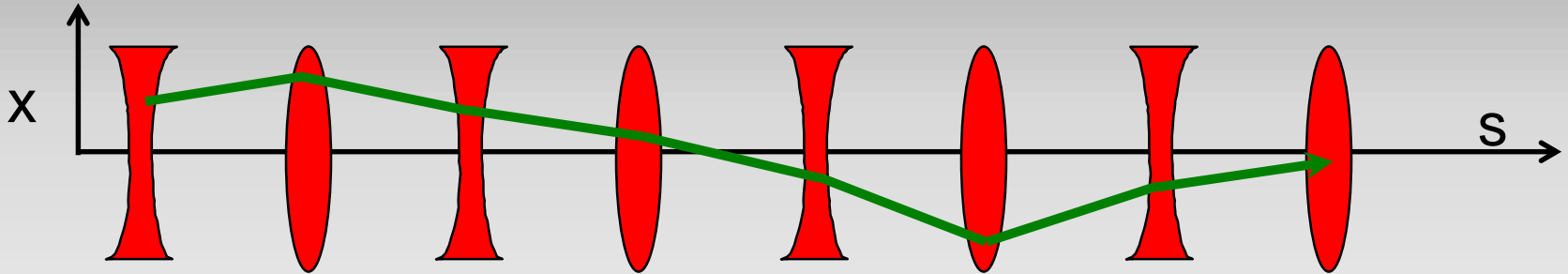
# Quadrupole magnets



- 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',  $K=K(s)$ .

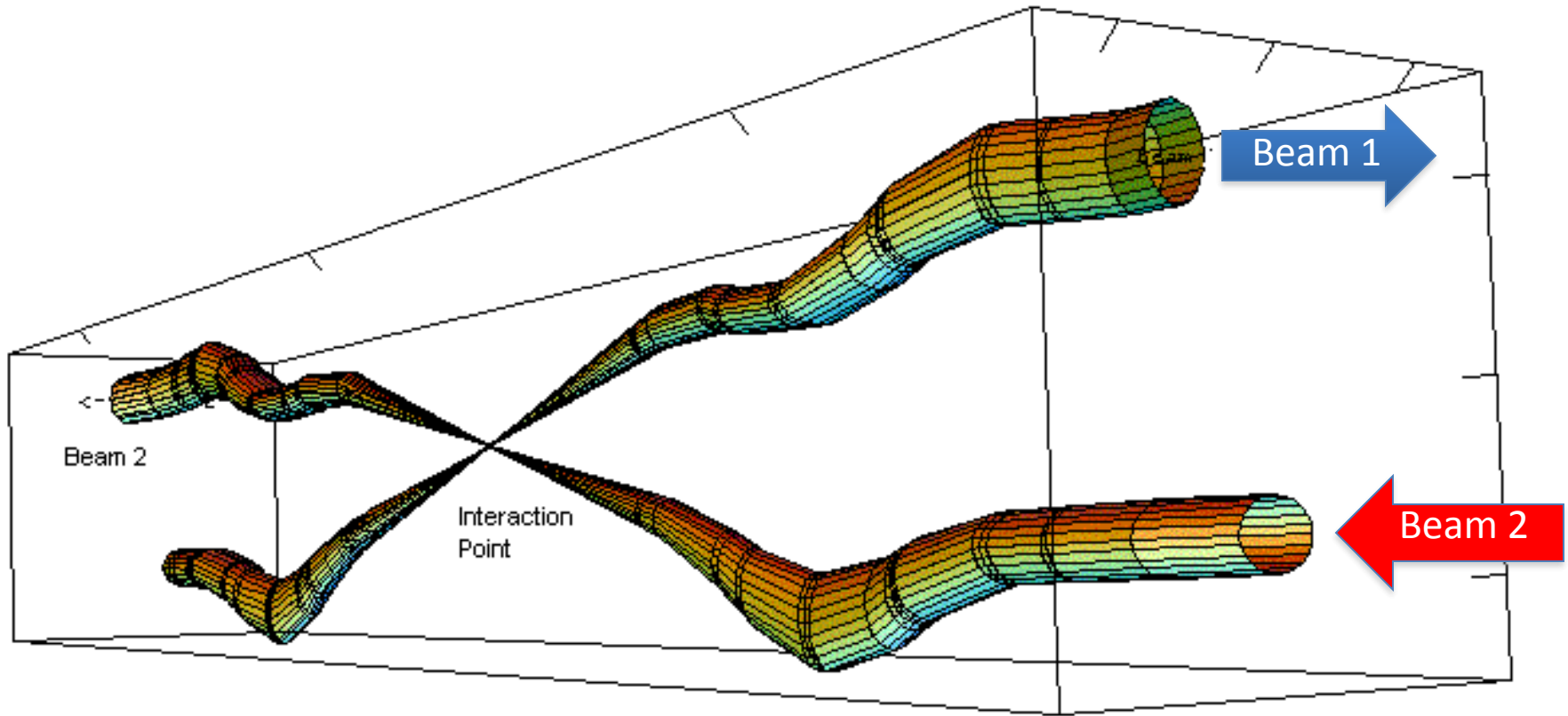
$K(s)$  describes the distribution of focusing strength along the lattice and is periodic.

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

(and similarly for the vertical plane  $y$ )

This is Hill's equation.

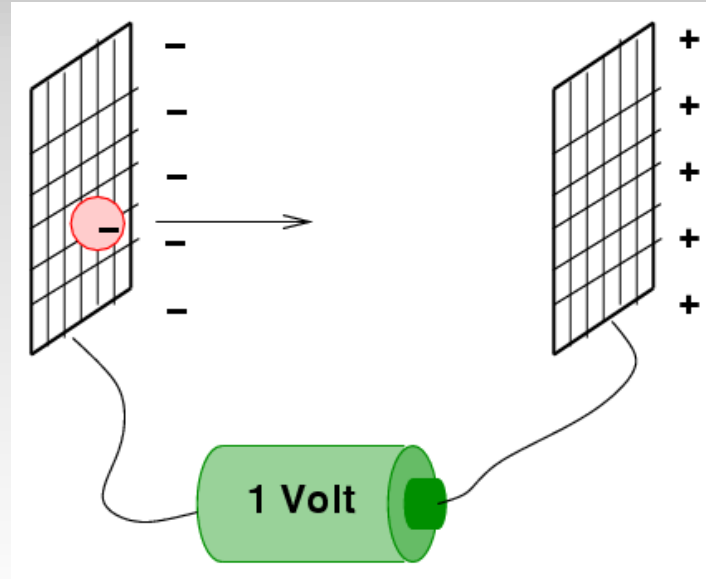
# Squeeze



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

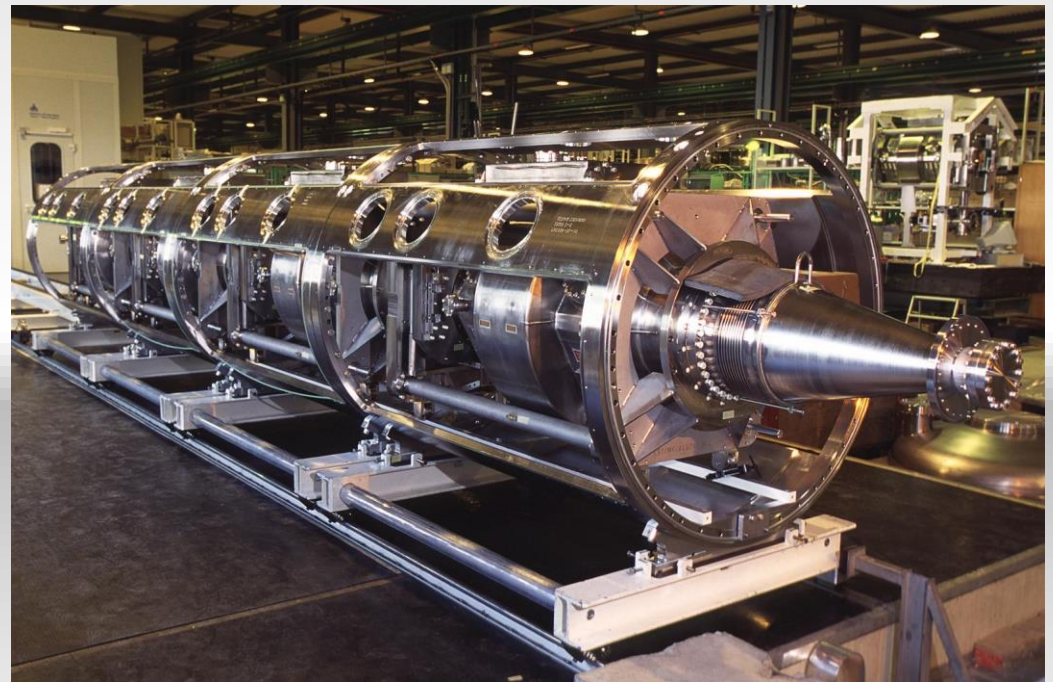
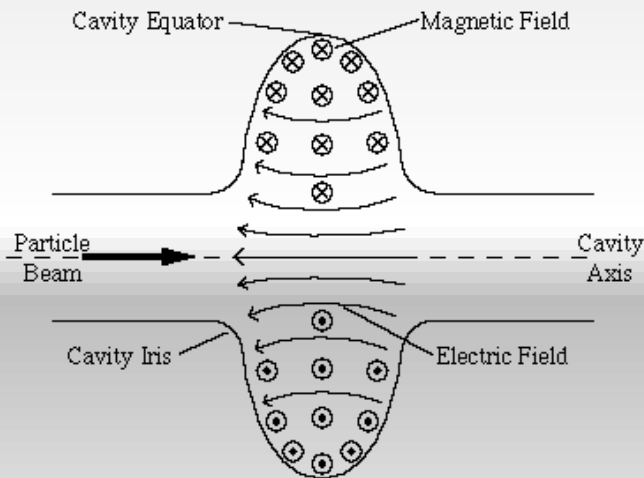
=

6 500 000 000 000 V

Tera Giga Mega kilo

# Radio Frequency Cavities

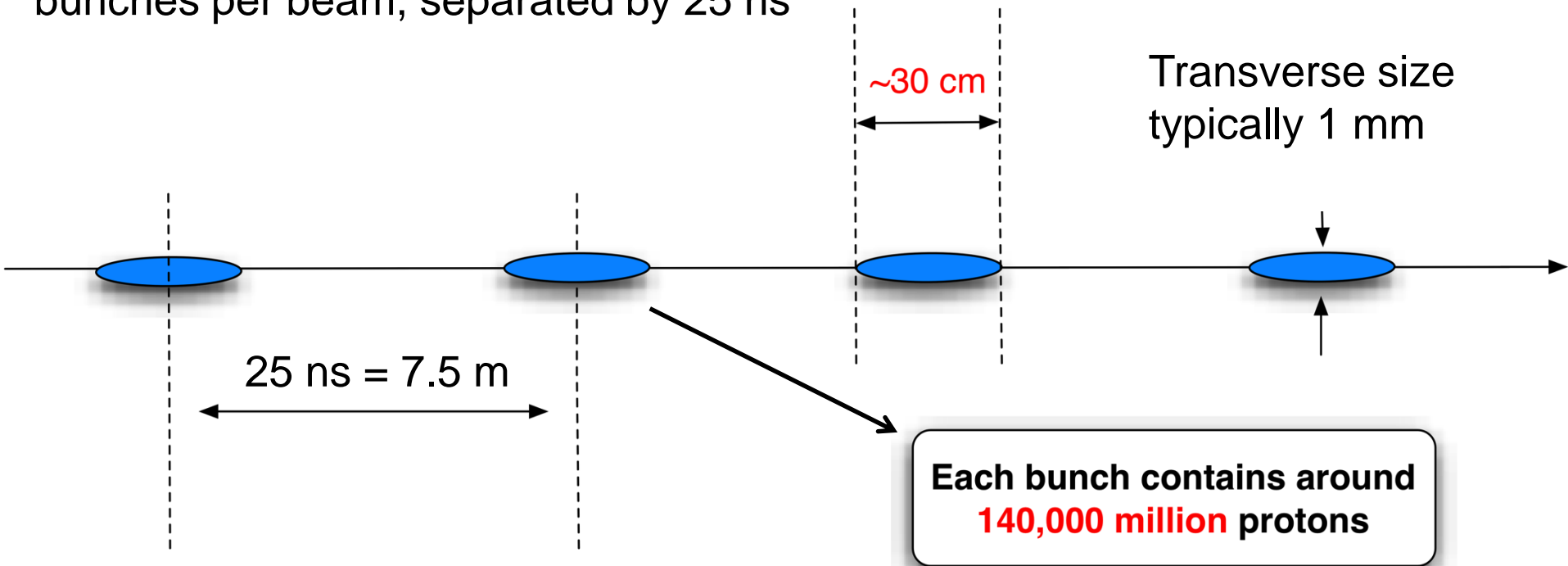
- RF = Oscillation of field at 400 MHz (Radio Frequency)
- Use the Electrical Field at each passage
- 4 cavities/module - 2 modules/beam - 16 MV (5.5 MV/m)
- Superconducting to reduce Beam Impedance



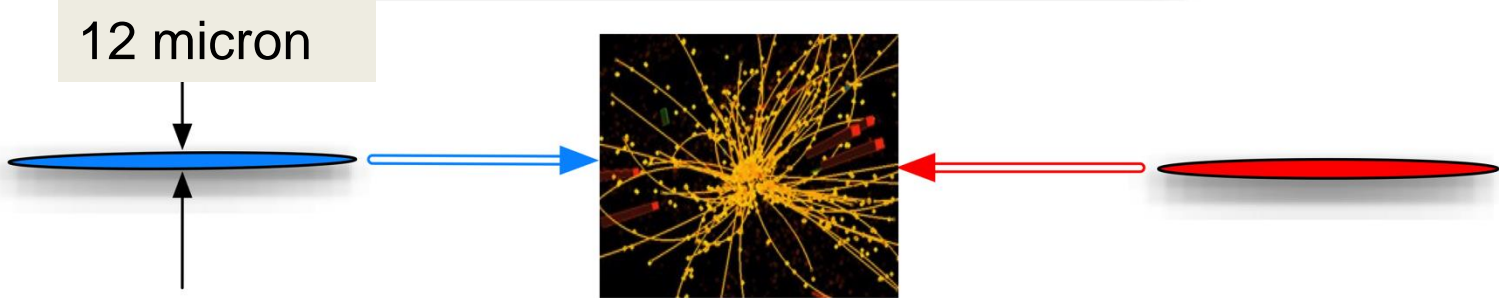
4 Cavity RF Module

# Lots of bunches

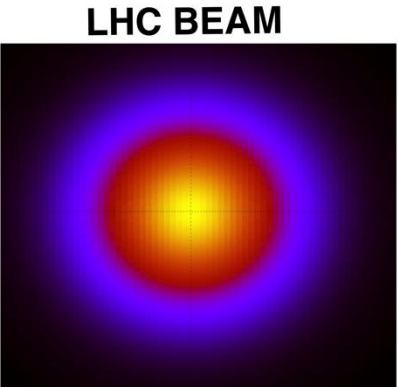
In 2017 the LHC operated with 2300 bunches per beam, separated by 25 ns

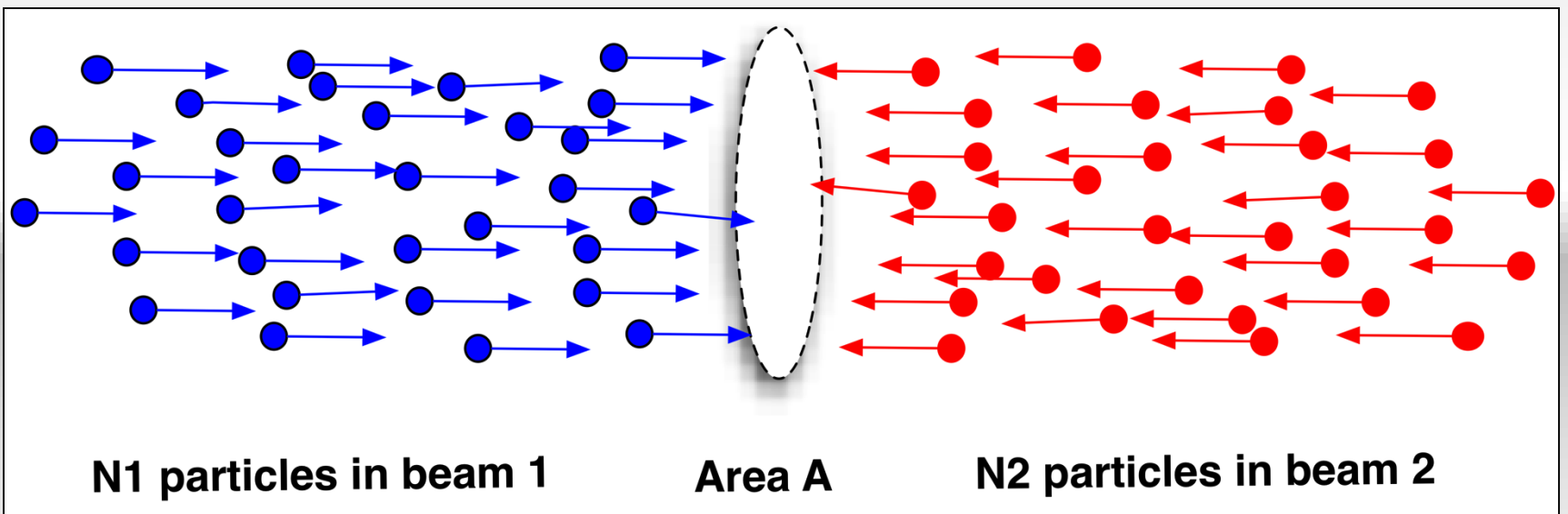


**140,000,000,000 protons a bunch**  
**~30 collide at each bunch crossing**



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





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
<b>Energy</b>	<b>311 MJoules</b>

Kinetic Energy of the car

Mass car	1800 kg
<b>Kinetic energy</b>	<b>306 MJoules</b>
v	583 m/s
<b>v</b>	<b>2100 km/h</b>



***But at the size smaller than a hair ....***



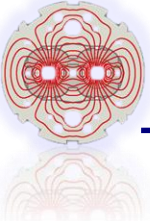
# Don't break the machine!

Energy per beam up to 360 MJ



British aircraft carrier at 12 knots

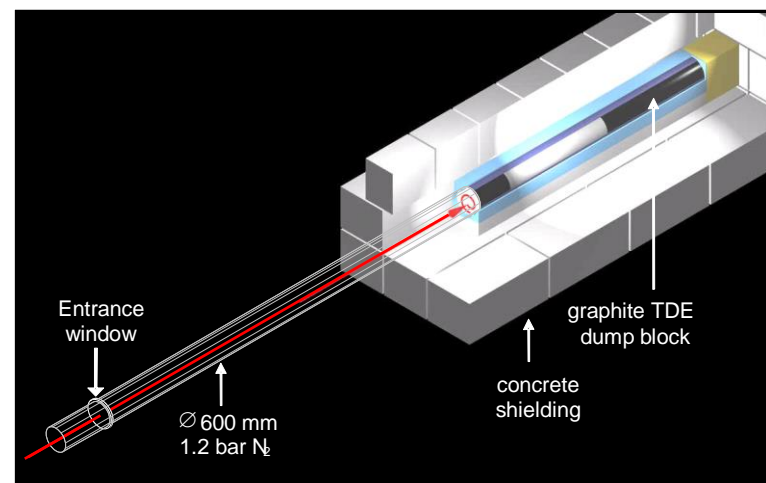
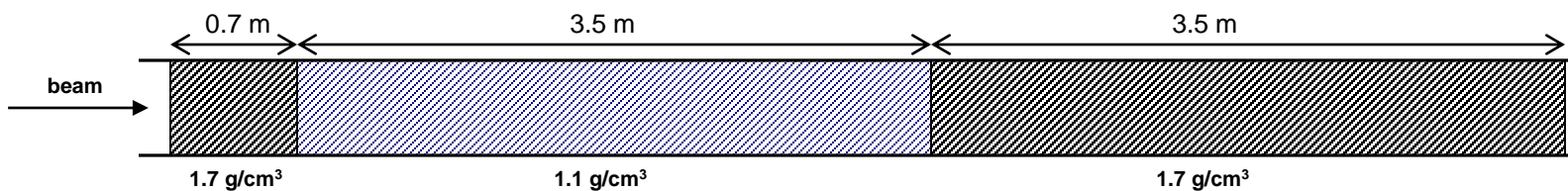
Thread through a very cold, very dark, very small hole...



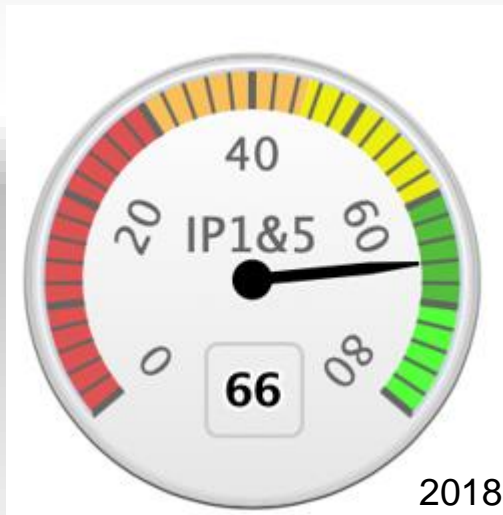
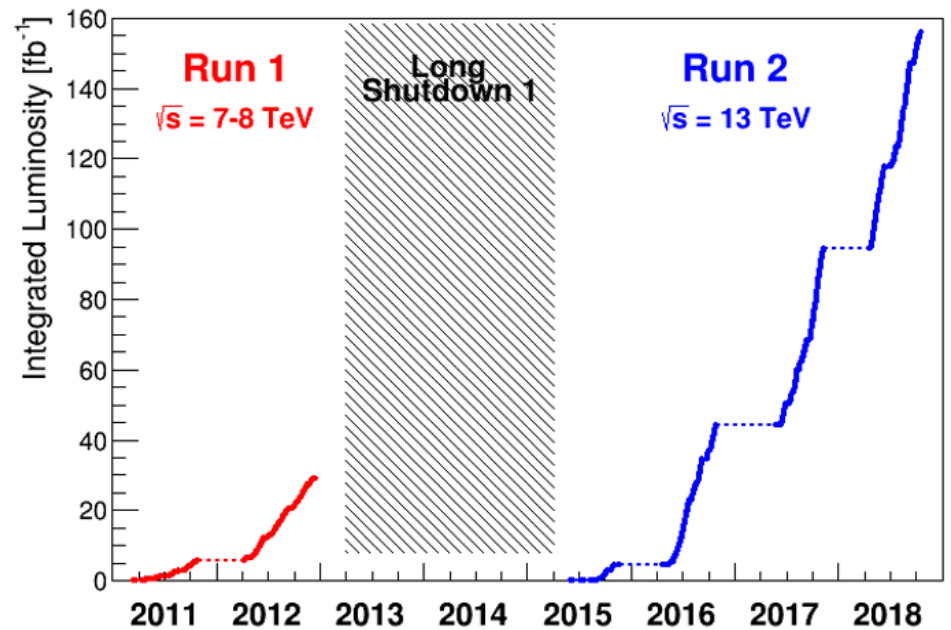
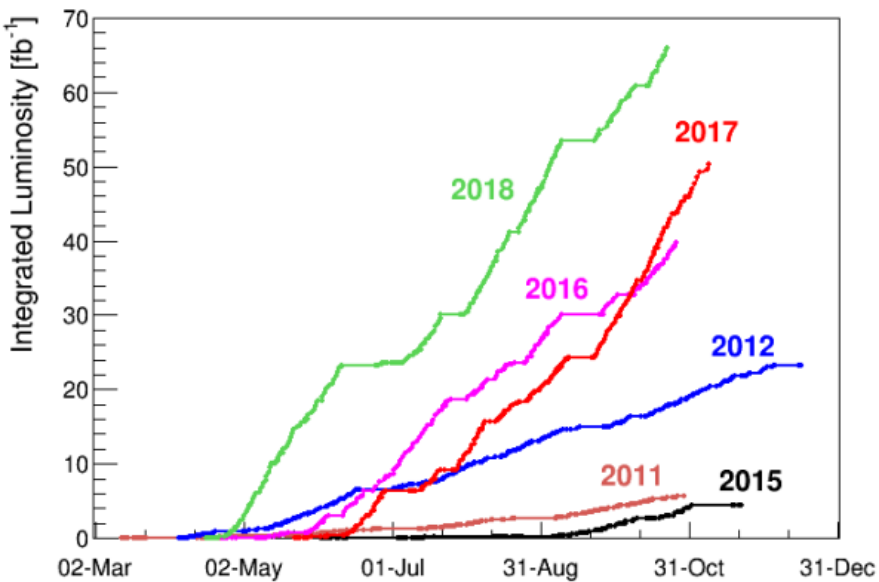
# Beam dump block (TDE)



- 700 mm  $\varnothing$  graphite core, with graded density of 1.1 g/cm<sup>3</sup> and 1.7 g/cm<sup>3</sup>
- 12 mm wall, stainless-steel welded pressure vessel, at 1.2 bar of N<sub>2</sub>
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks



# It is all about Luminosity



Period	Int. Luminosity [fb <sup>-1</sup> ]
Run 1	29.2
Run 2: 2015	4.2
Run 2: 2016	39.7
Run 2: 2017	50.2
Run 2: 2018	66
<b>Total Run 1+ 2</b>	<b>189.3</b>

# Luminosity

$$L = \frac{N^2 k_b f}{4\rho s_x^* s_y^*} F = \frac{N^2 k_b f g}{4\rho e_n b^*} F$$

**N** Number of particles per bunch

**k<sub>b</sub>** Number of bunches

f Revolution frequency

**σ\*** Beam size at interaction point

F Reduction factor due to crossing angle

ε Emittance

**ε<sub>n</sub>** Normalized emittance

**β\*** Beta function at IP

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

$$e_N = 2.5 \cdot 10^{-6} \text{ m.rad}$$

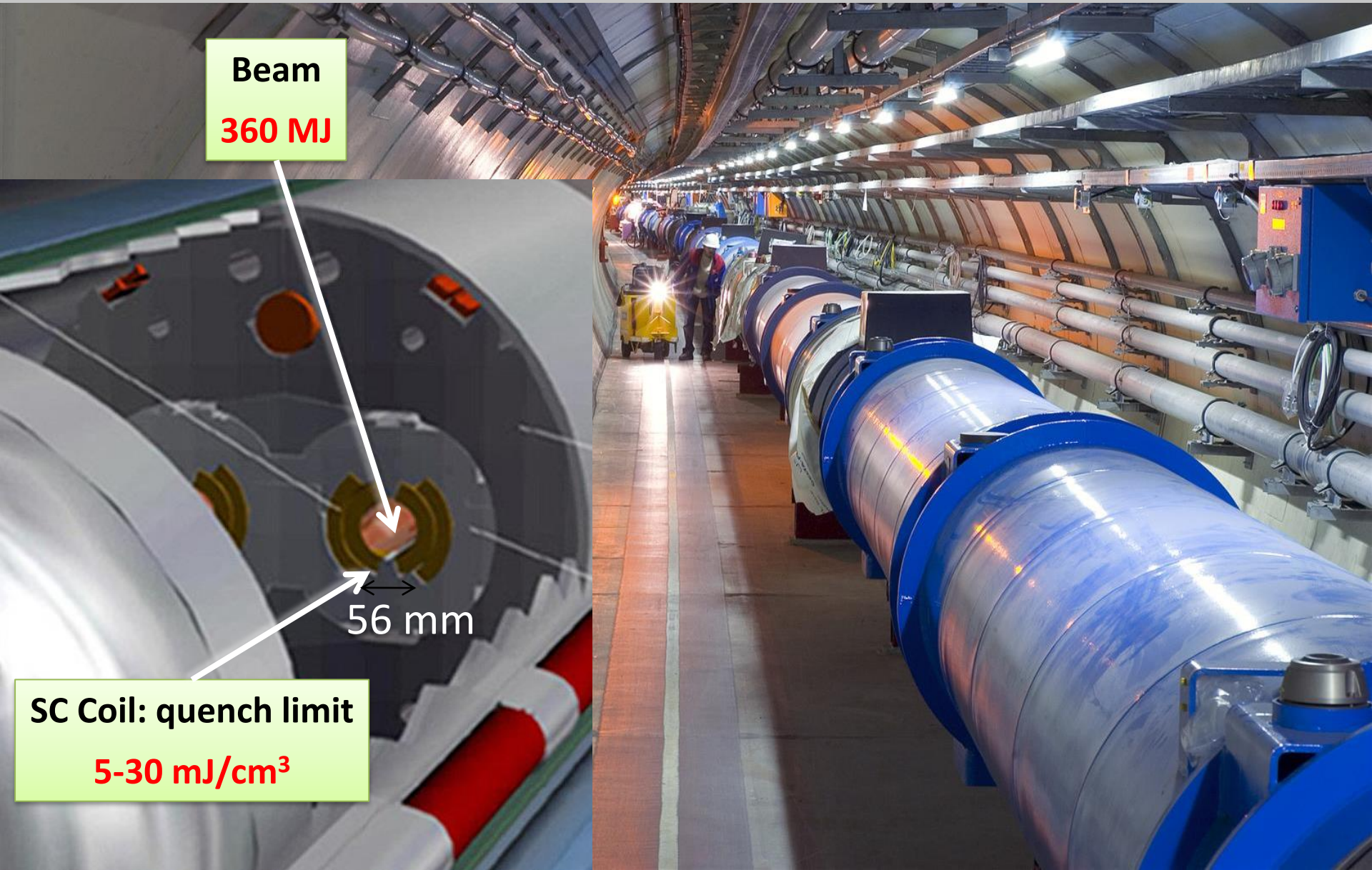
$$e = 3.35 \cdot 10^{-10} \text{ m.rad}$$

$$s^* = 11.6 \cdot 10^{-6} \text{ m}$$

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

# Quench Limit of LHC Super-Conducting Magnets

Nominal design at 7 TeV

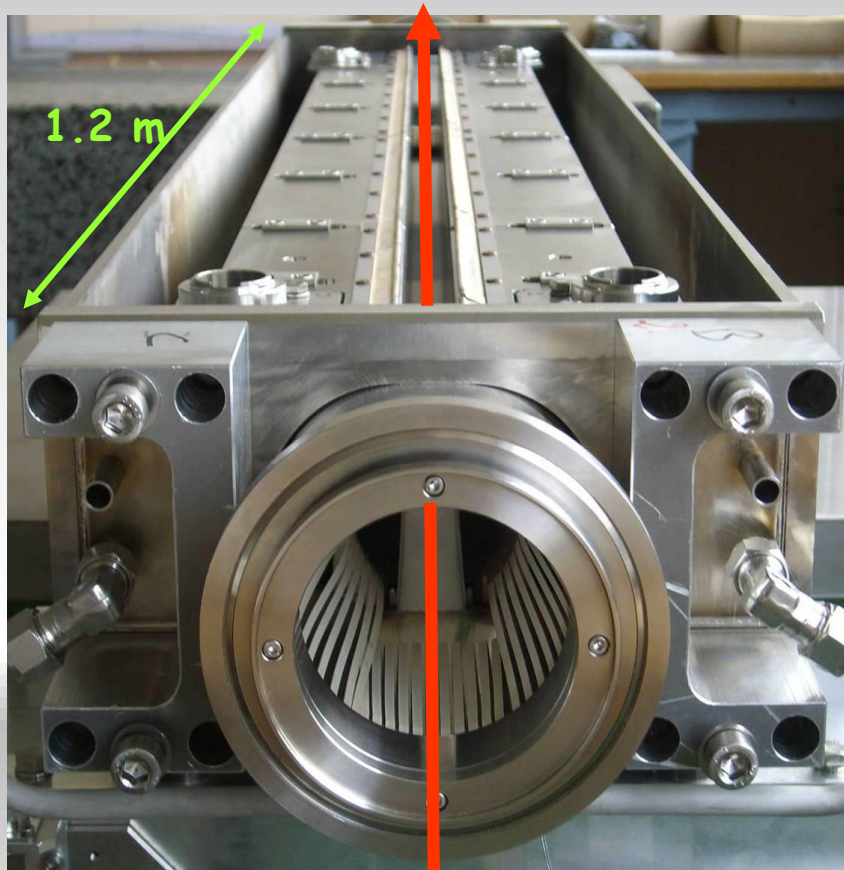


Beam  
360 MJ

56 mm

SC Coil: quench limit  
5-30 mJ/cm<sup>3</sup>

# Collimation

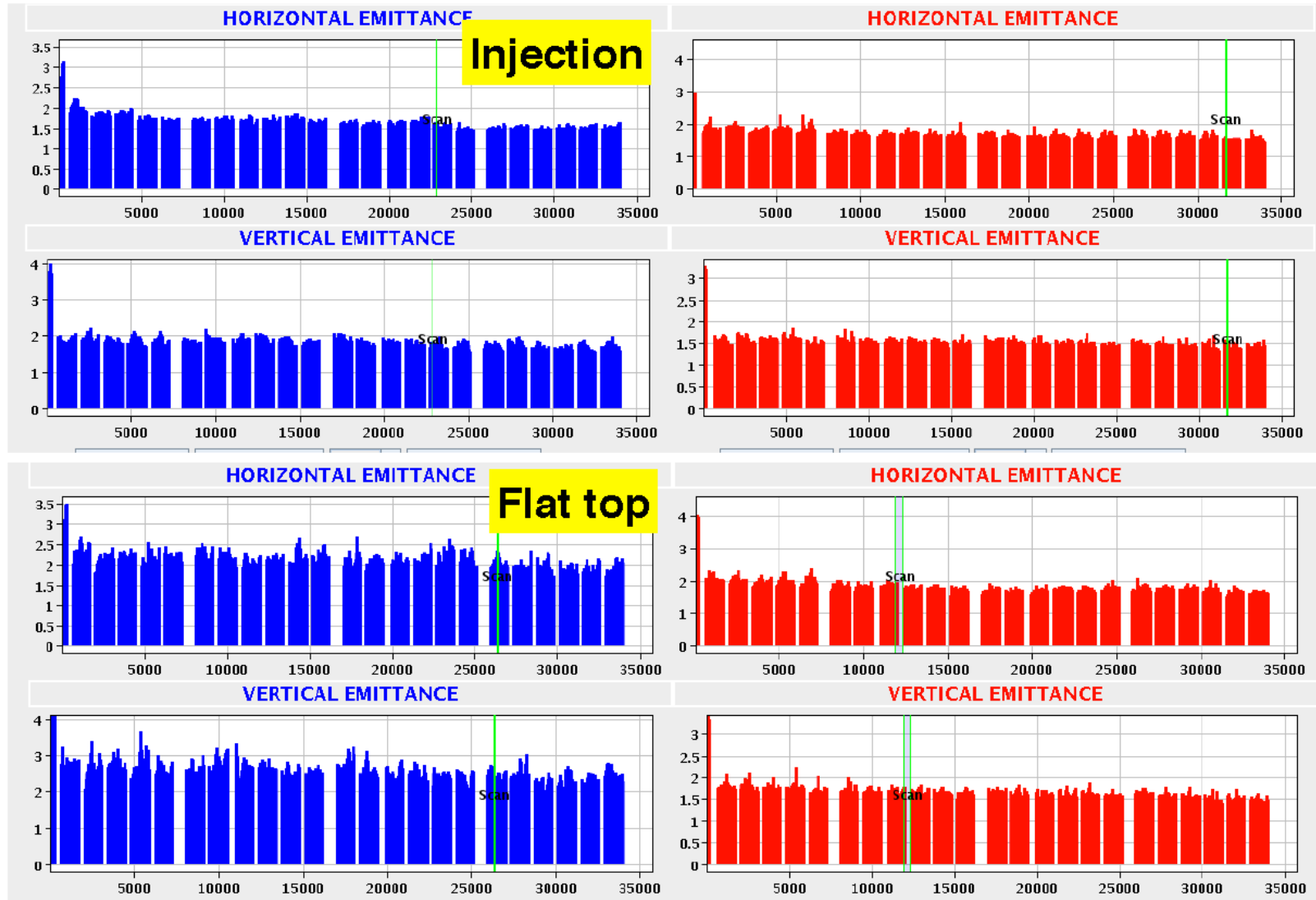


**beam**

Almost 100 collimators and absorbers.

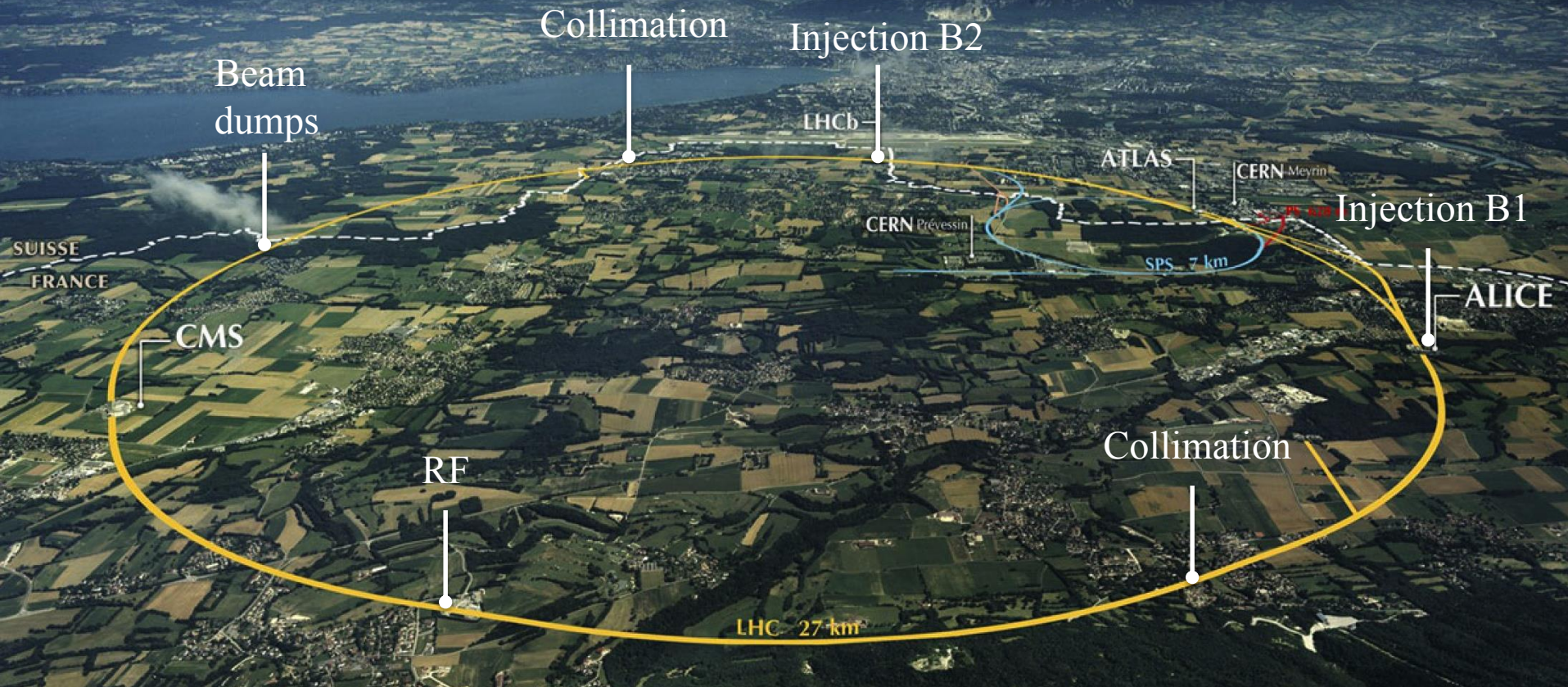
Alignment tolerances  $< 0.1$  mm to ensure that over 99.99% of the protons are intercepted. Primary and secondary collimators are made of reinforced graphite – robust.

# 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

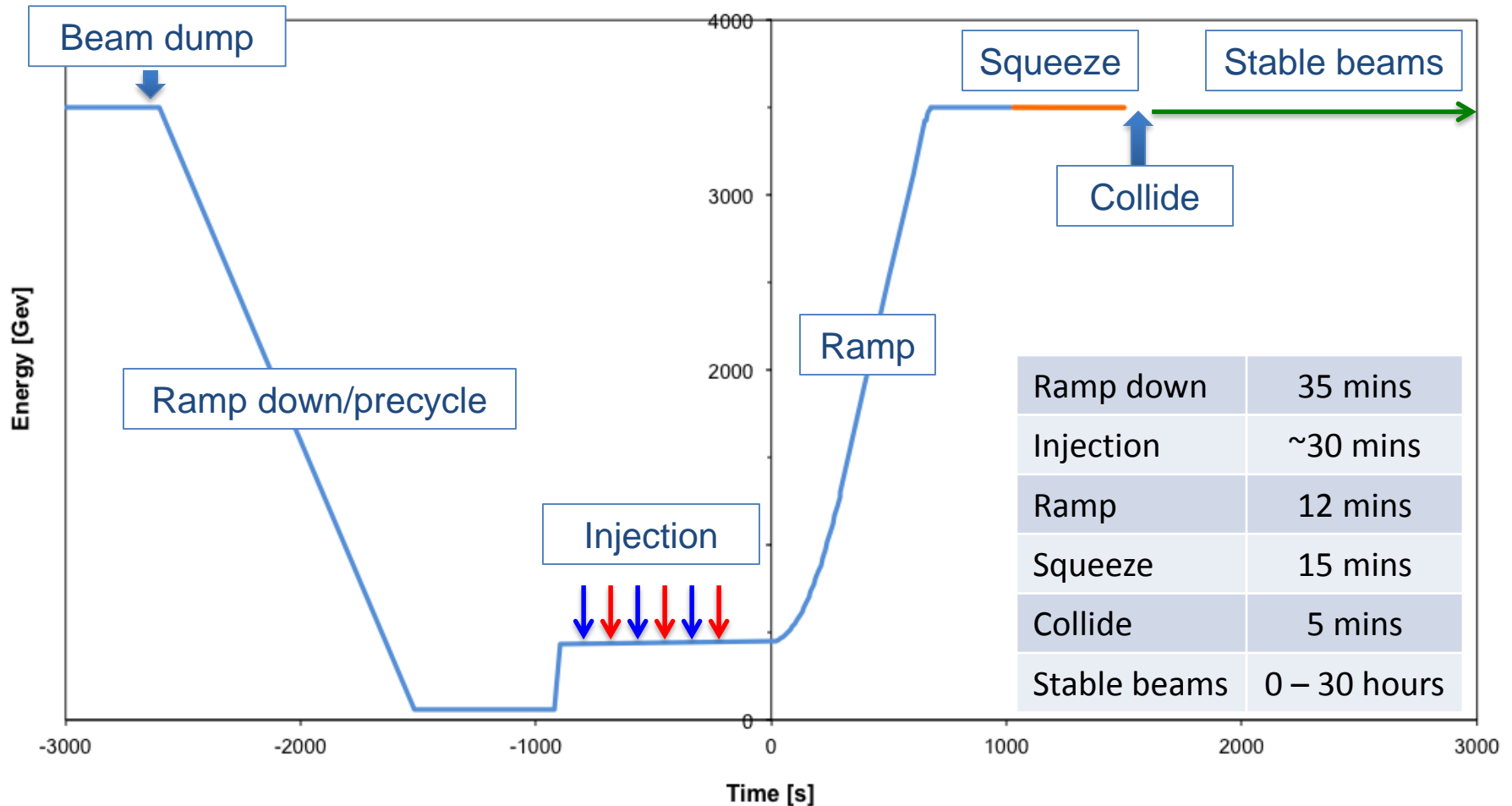
120 tonnes of Helium, down to 1.9 K  
360 MJ stored beam energy per beam  
11 GJ total stored energy in magnetic systems

# 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

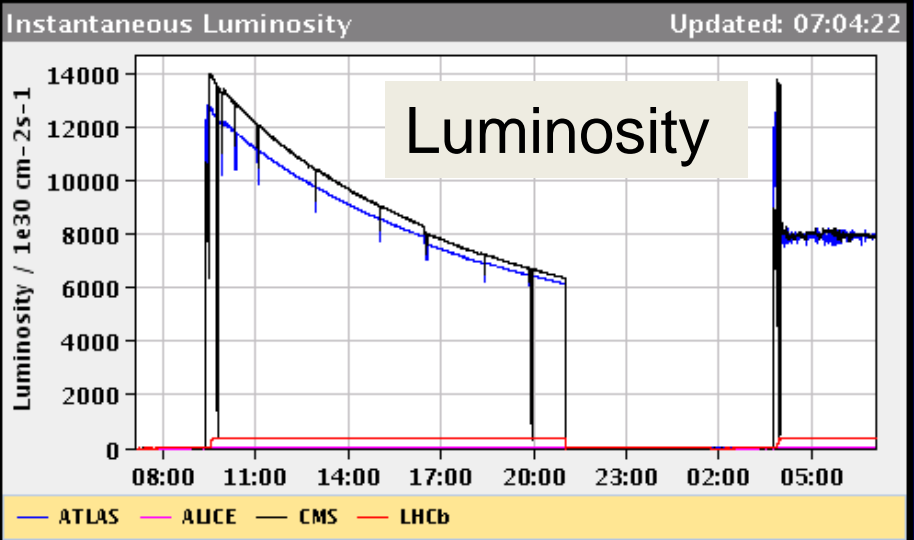
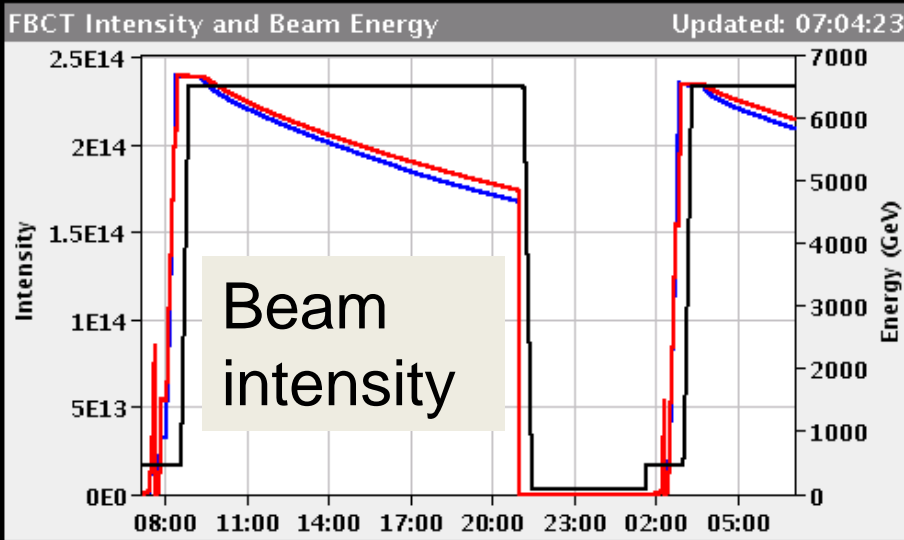


Turn around from stable beams to stable beams - 2 to 3 hours on a good day, followed by Stable Beams, average 6 hours.

# 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

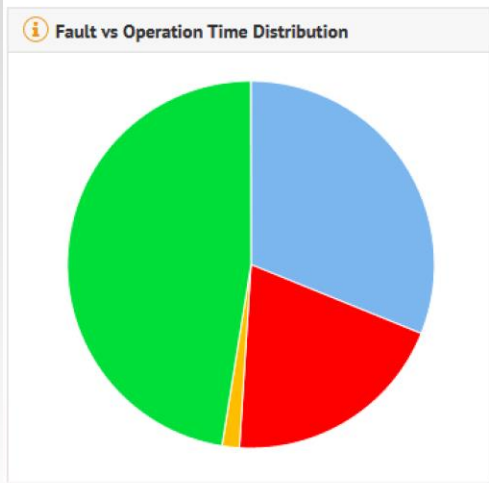
BIS status and SMP flags

	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

# Machine Performance 2018

**Availability** 80.1%

**Stable beams** 47.5%



**Fault labels**

- 60A BPM Interaction
- BLM Sanity Checks
- TIOC

**Fault count**

185

**Min Turnaround**

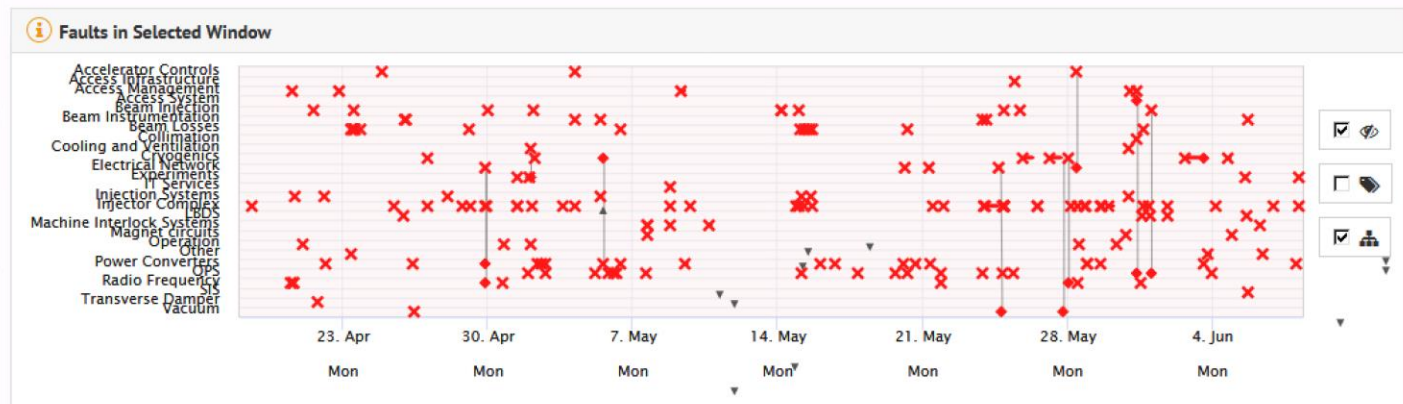
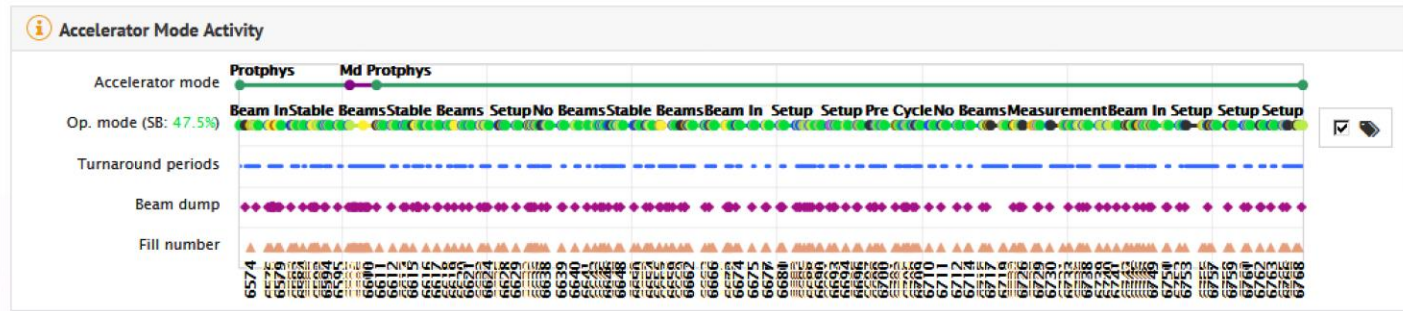
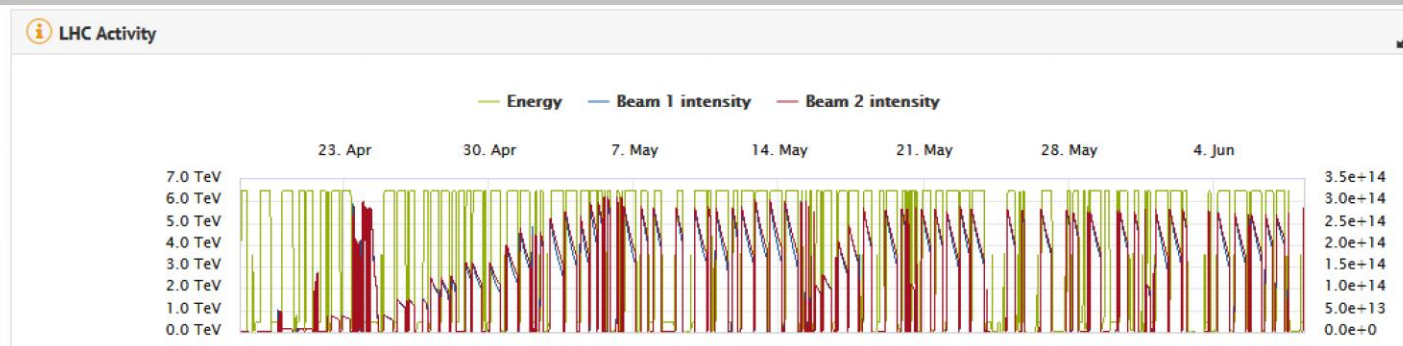
0.5h

**Avg Turnaround**

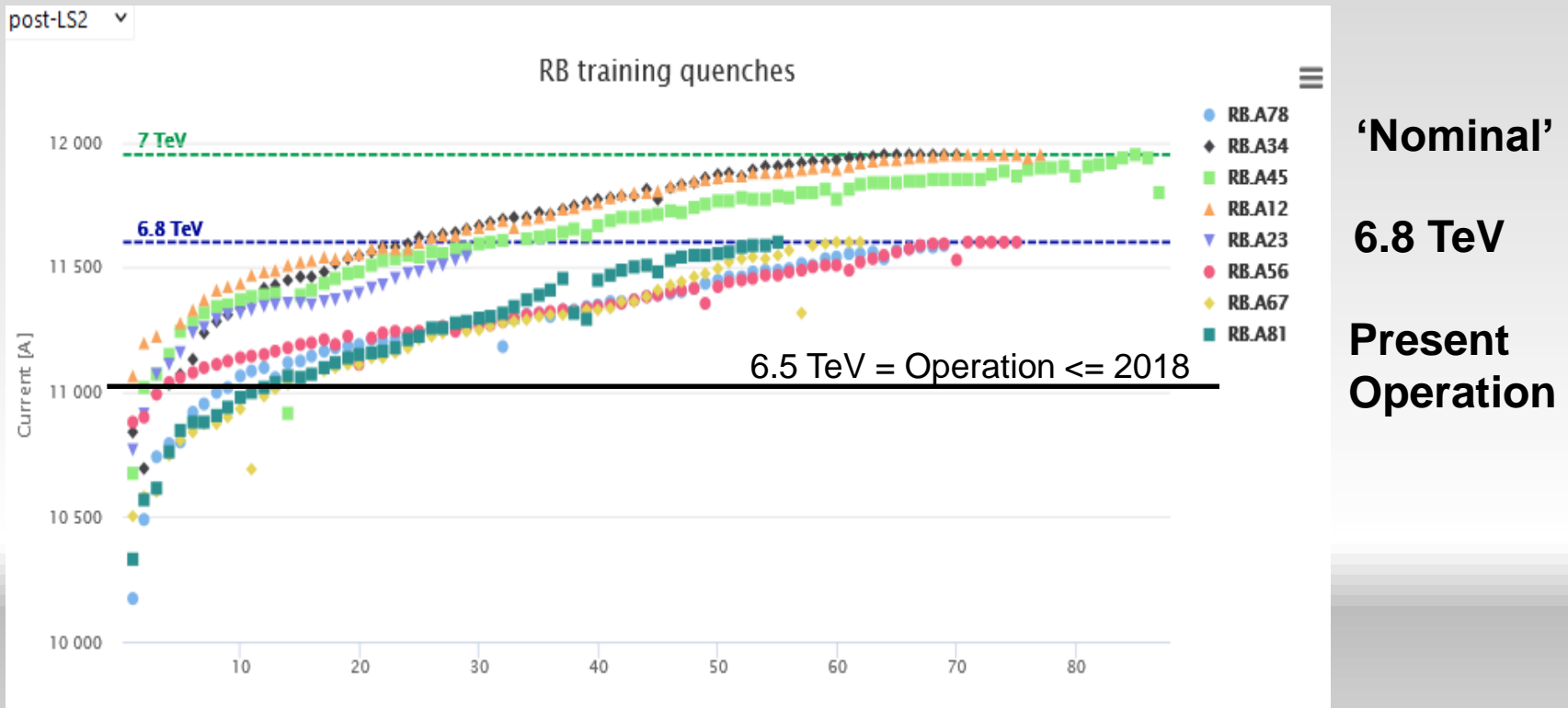
7.5h

**Max Turnaround**

39.3h



# Magnet Training to reach 7 TeV Beam Energy



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.

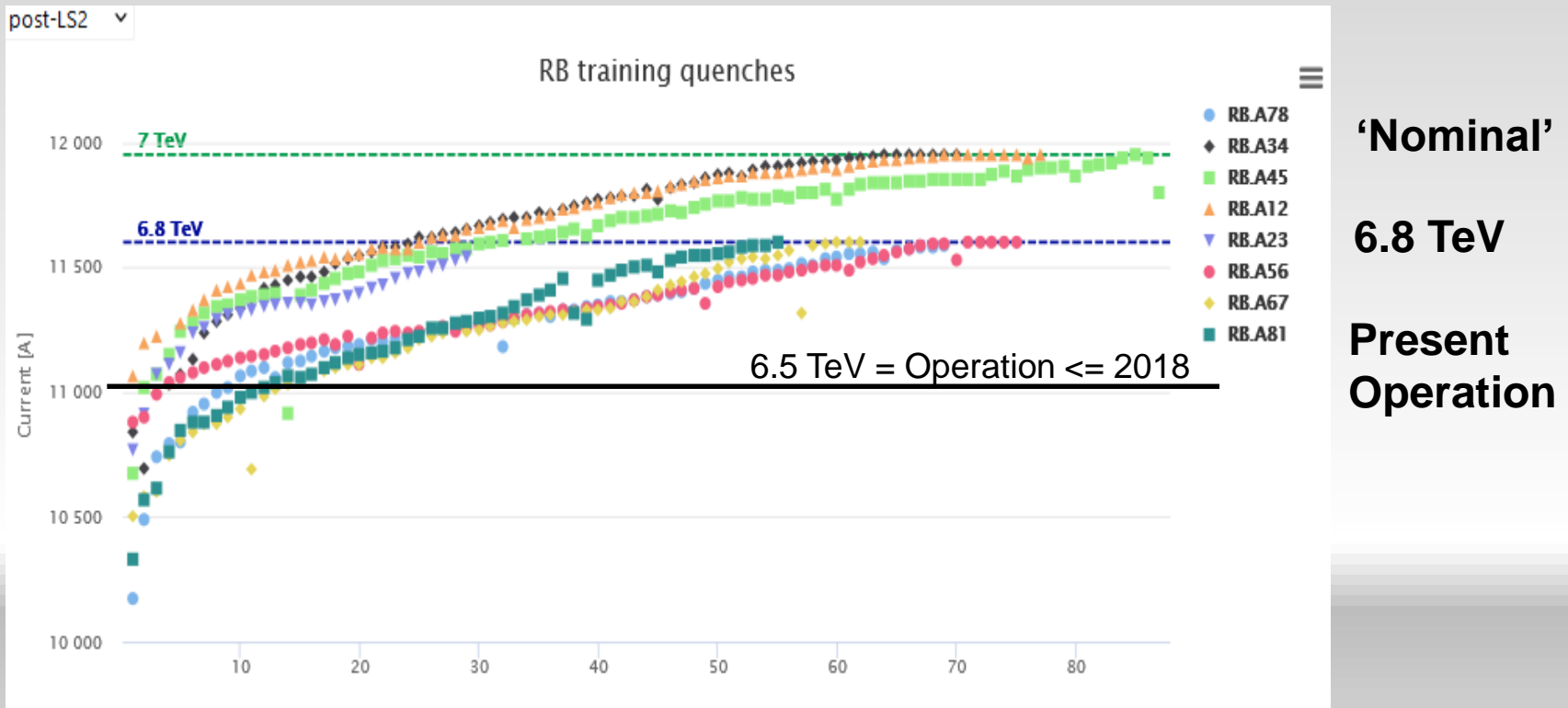
	12	23	34	45	56	67	78	81
#Q to reach 11600 A (6.8 TeV) (including flat-top quenches at 11600 A)	0	23	0	0	0	0	42	0
#Q to reach 11950 A (7 TeV) (starting at 11600 A)	0	70	0	0	71	54	67	53
#Q at 11950 A flat-top	0	6	0	1	5	5	5	4

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~~ Beam Energy 6.8 TeV



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

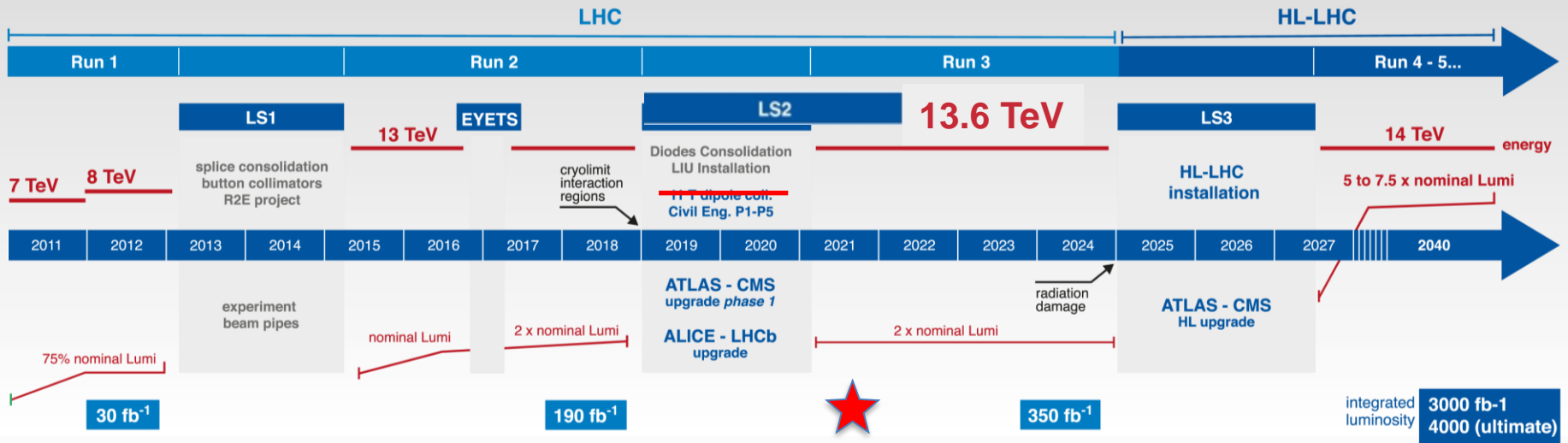


# What's Next ?

## High-Luminosity LHC



### LHC / HL-LHC Plan



#### HL-LHC TECHNICAL EQUIPMENT:



#### HL-LHC CIVIL ENGINEERING:



Injectors upgrade and LHC civil engineering

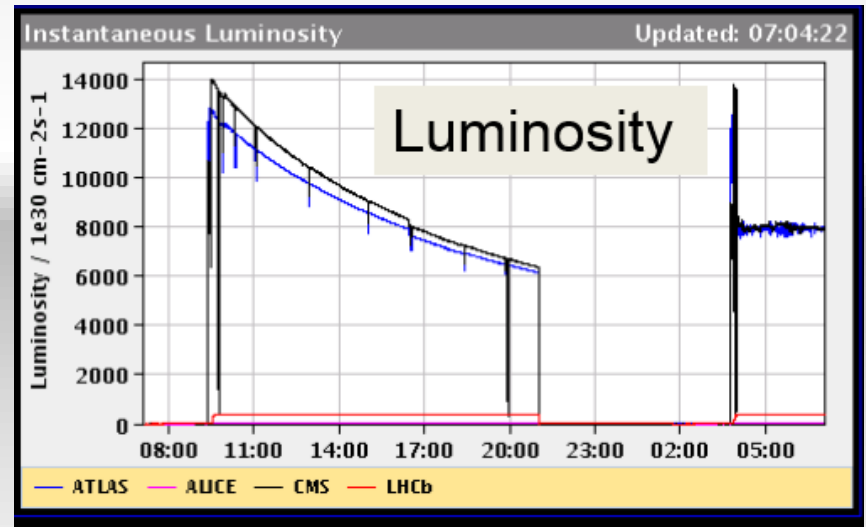
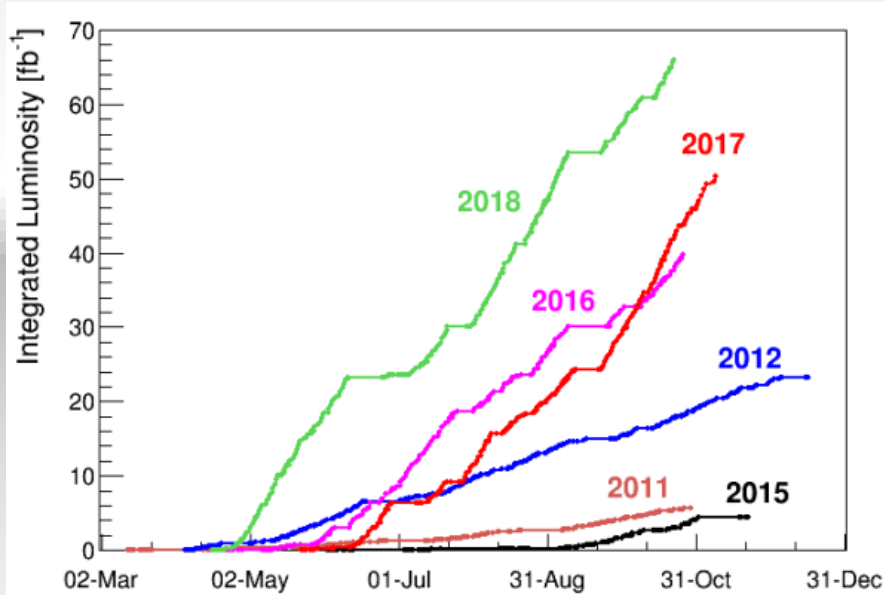
HL-LHC upgrade

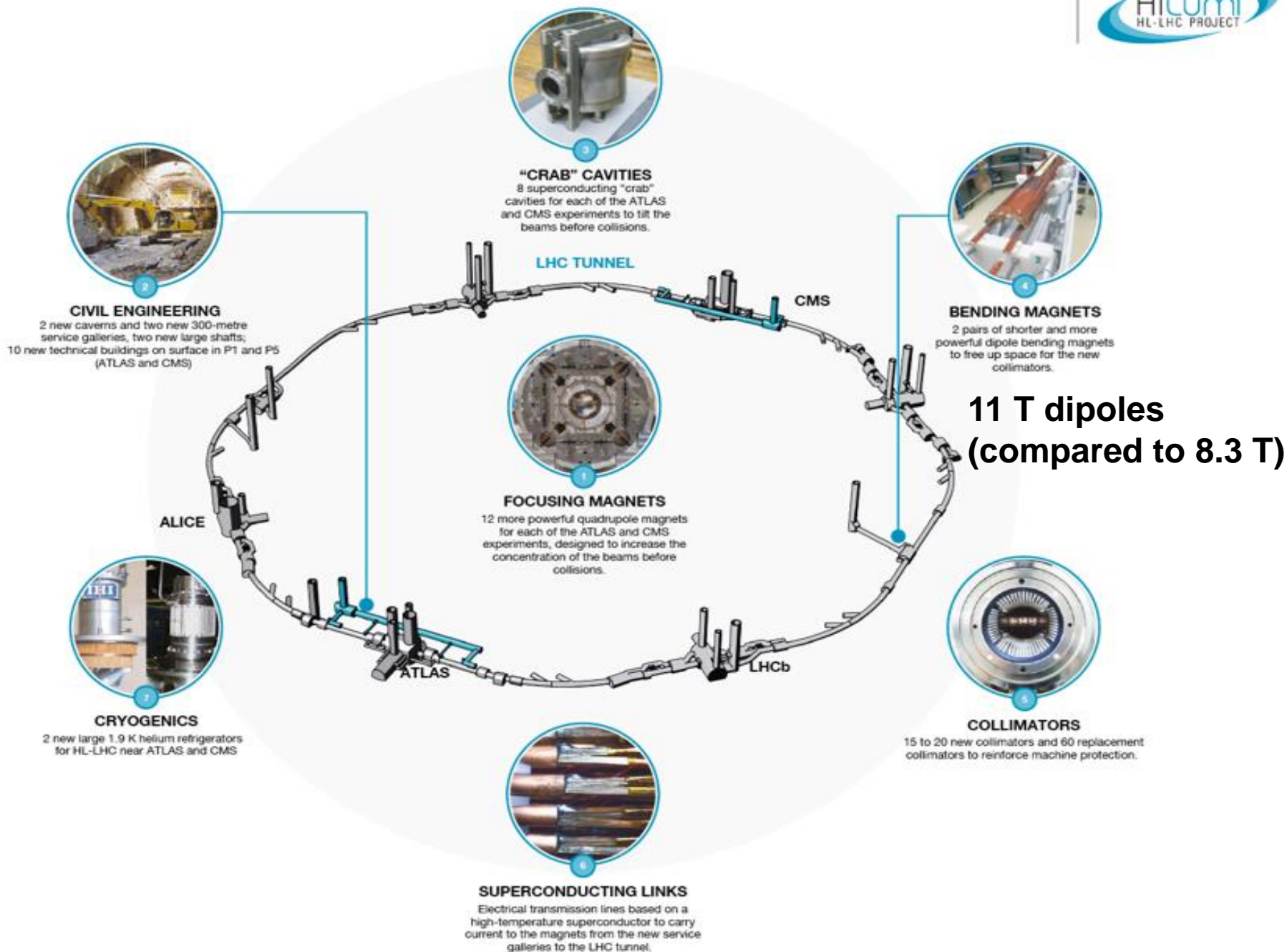
# HL-LHC

A peak luminosity of  $L_{\text{peak}} = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  with levelling, allowing:

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

## Luminosity so far





# In Two Weeks from Now

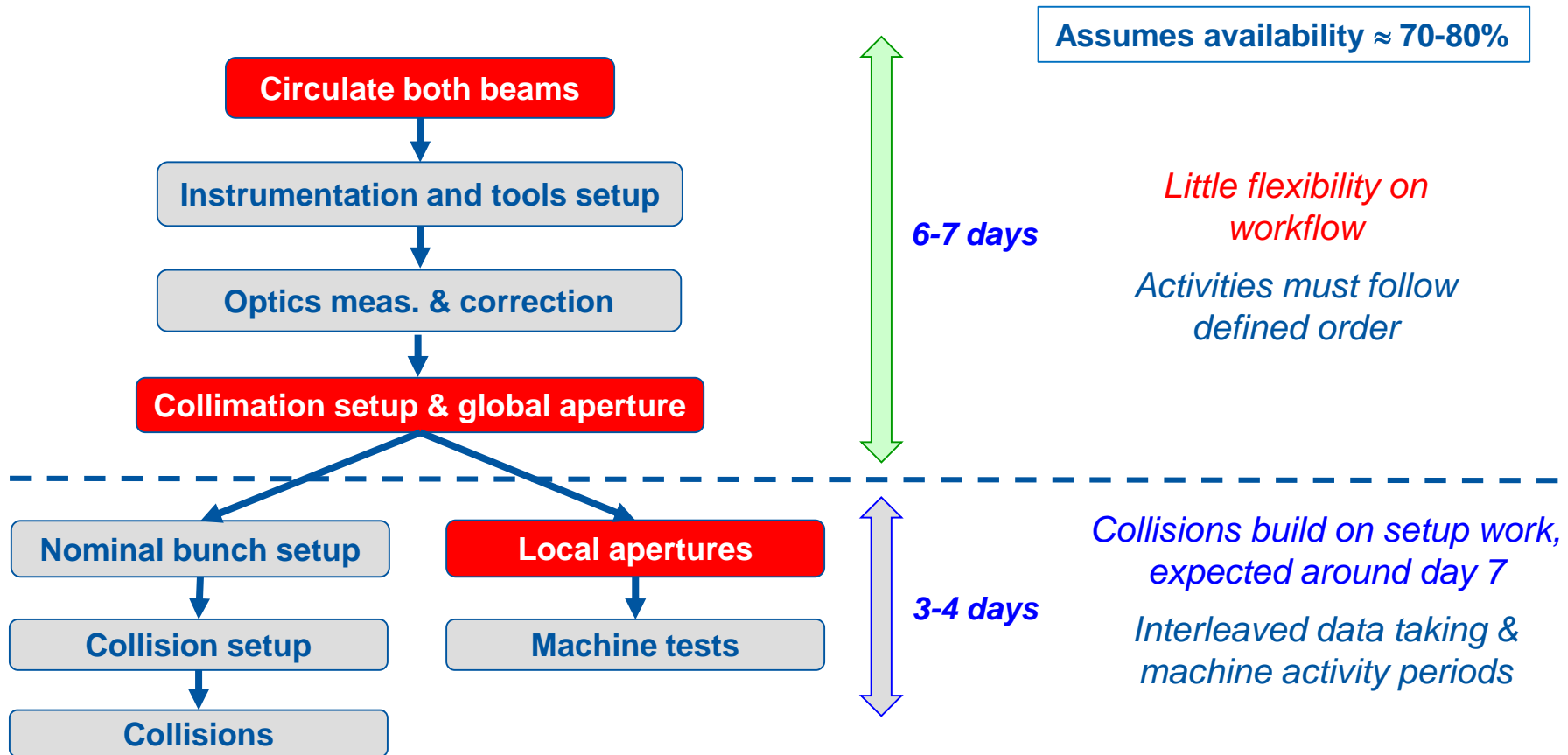
- Beams again in the LHC after > 2.5 years

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.



# Beam test outline



# **The Future @ CERN after the HL-LHC**

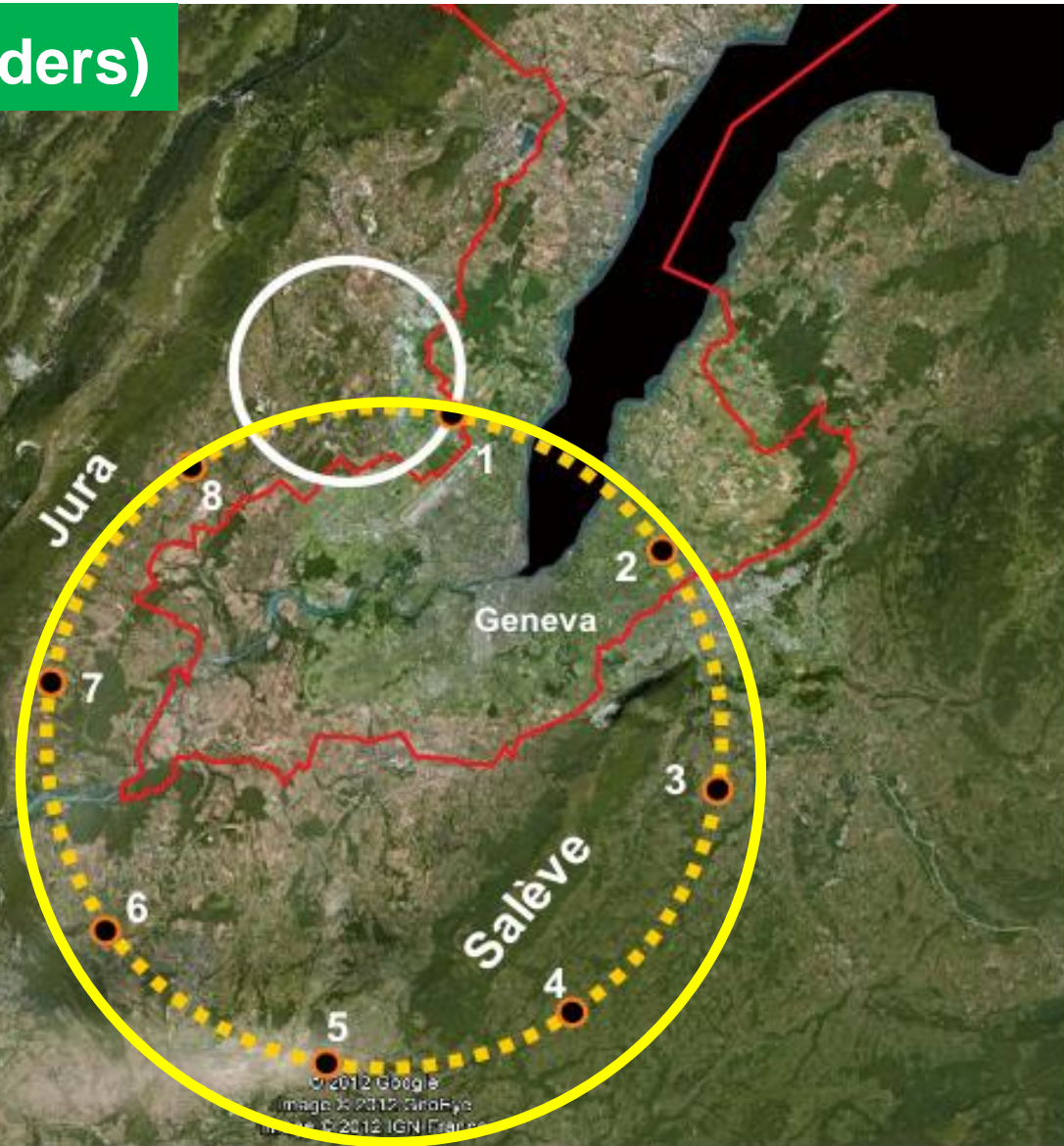
# 80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements with possibility of e<sup>+</sup>-e<sup>-</sup> (TLEP) and p-e (VLHeC)

## FCC (Future Circular Colliders)

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

**LEGEND**

- LHC tunnel
- HE\_LHC 80km option
- potential shaft location



Future Circular Collider Conference

[fcc.web.cern.ch](http://fcc.web.cern.ch)

# FCCWEEK 2018





# CLIC near CERN: e+e- Collider

## Legend

— CERN existing LHC

Potential underground siting :

●●●● CLIC 500 GeV

●●●● CLIC 1.5 TeV

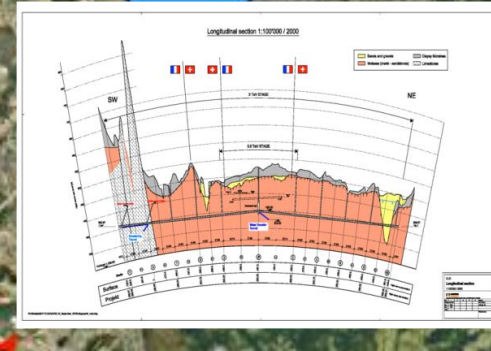
●●●● CLIC 3 TeV

Jura Mountains

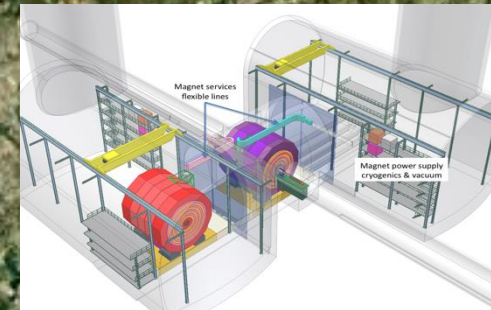
IP

Geneva

Lake Geneva



Tunnel implementations  
(laser straight)



Central MDI & Interaction  
Region



## 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

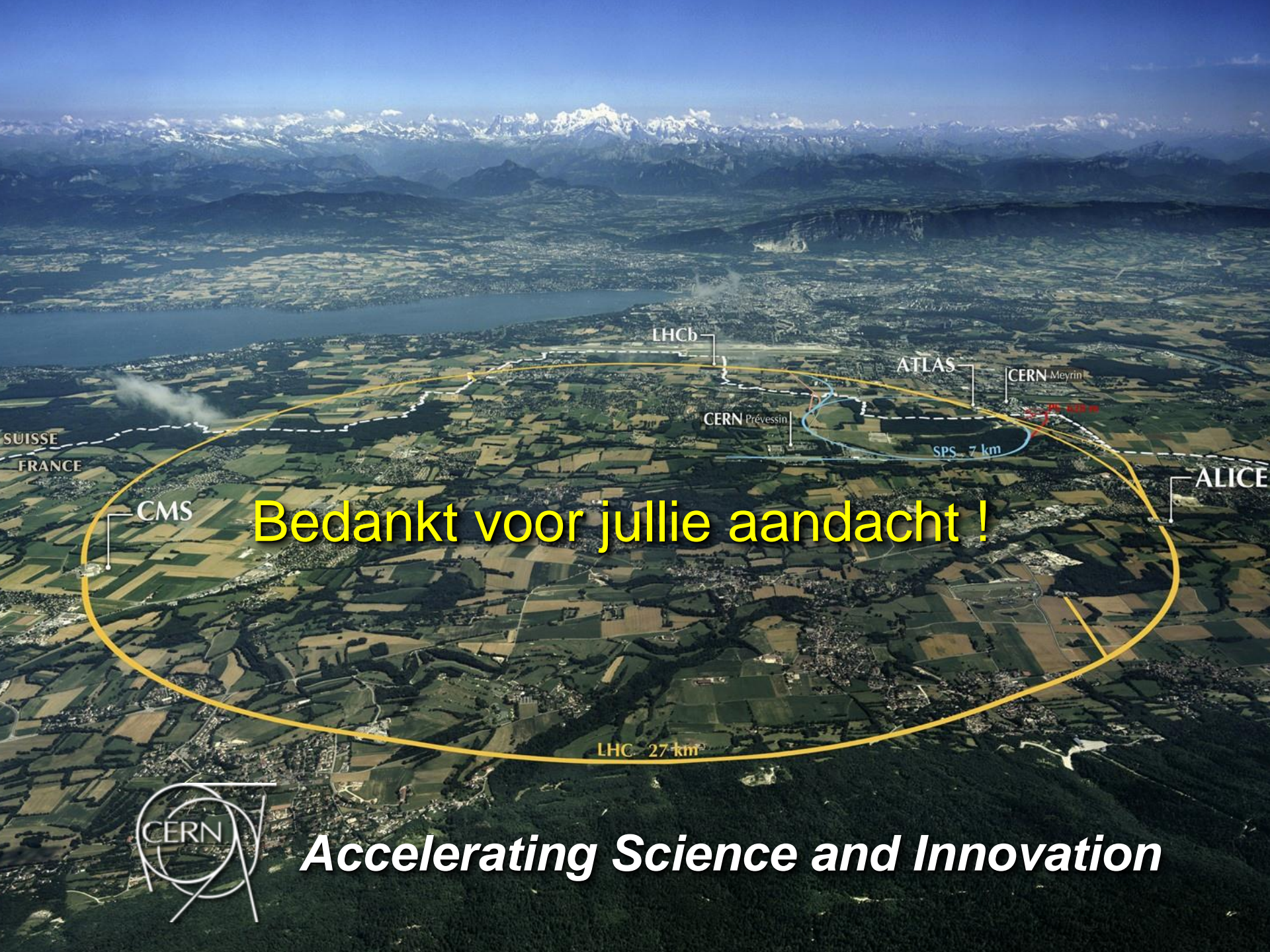
Cost of tunnel: ~5.5 BCHF; FCC-ee: ~5-6 BCHF; FCC-hh: ~17 BCHF (if after FCC-ee)

→ 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



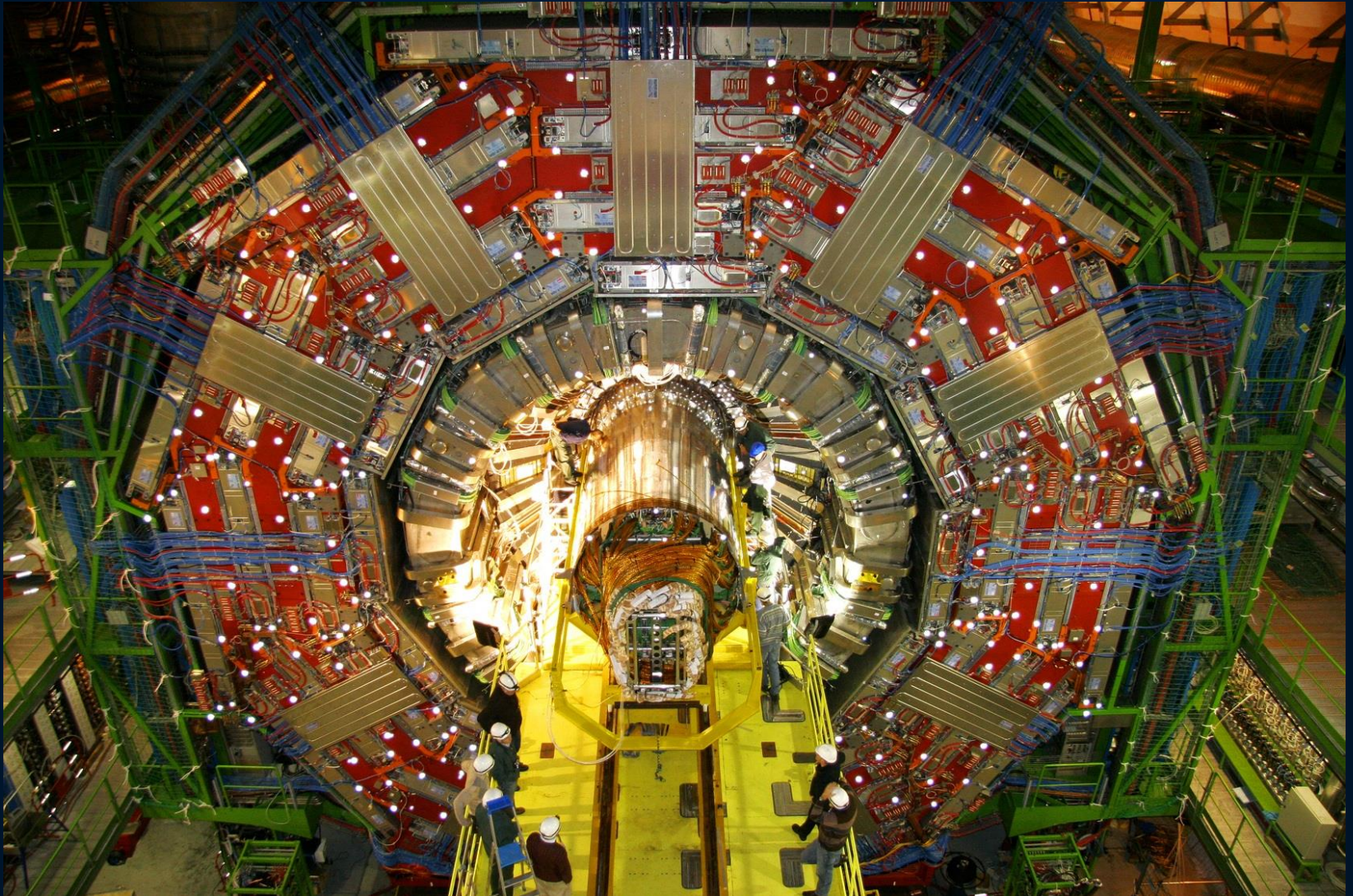
Bedankt voor jullie aandacht !



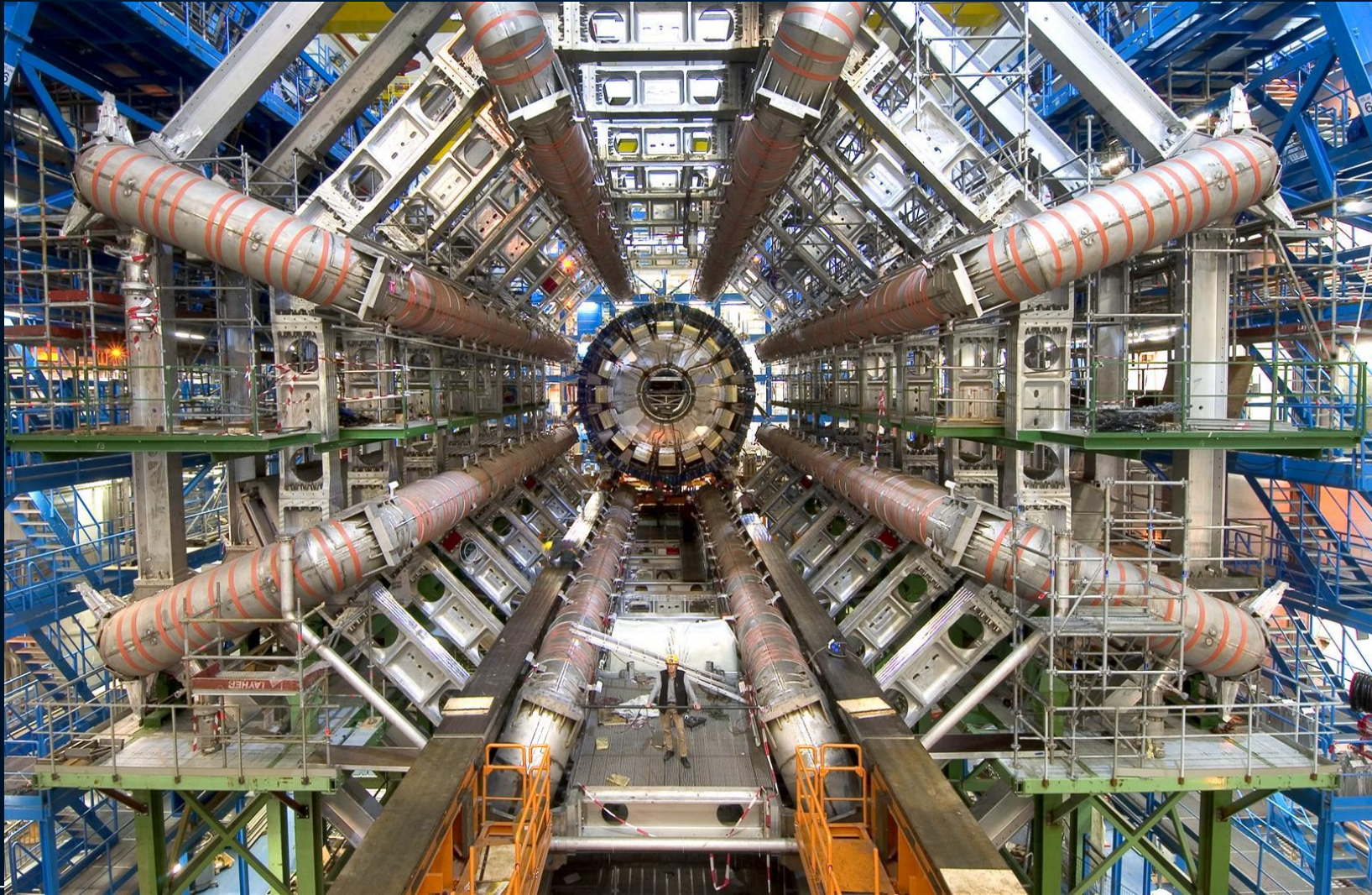
*Accelerating Science and Innovation*

**SPARE SLIDES**

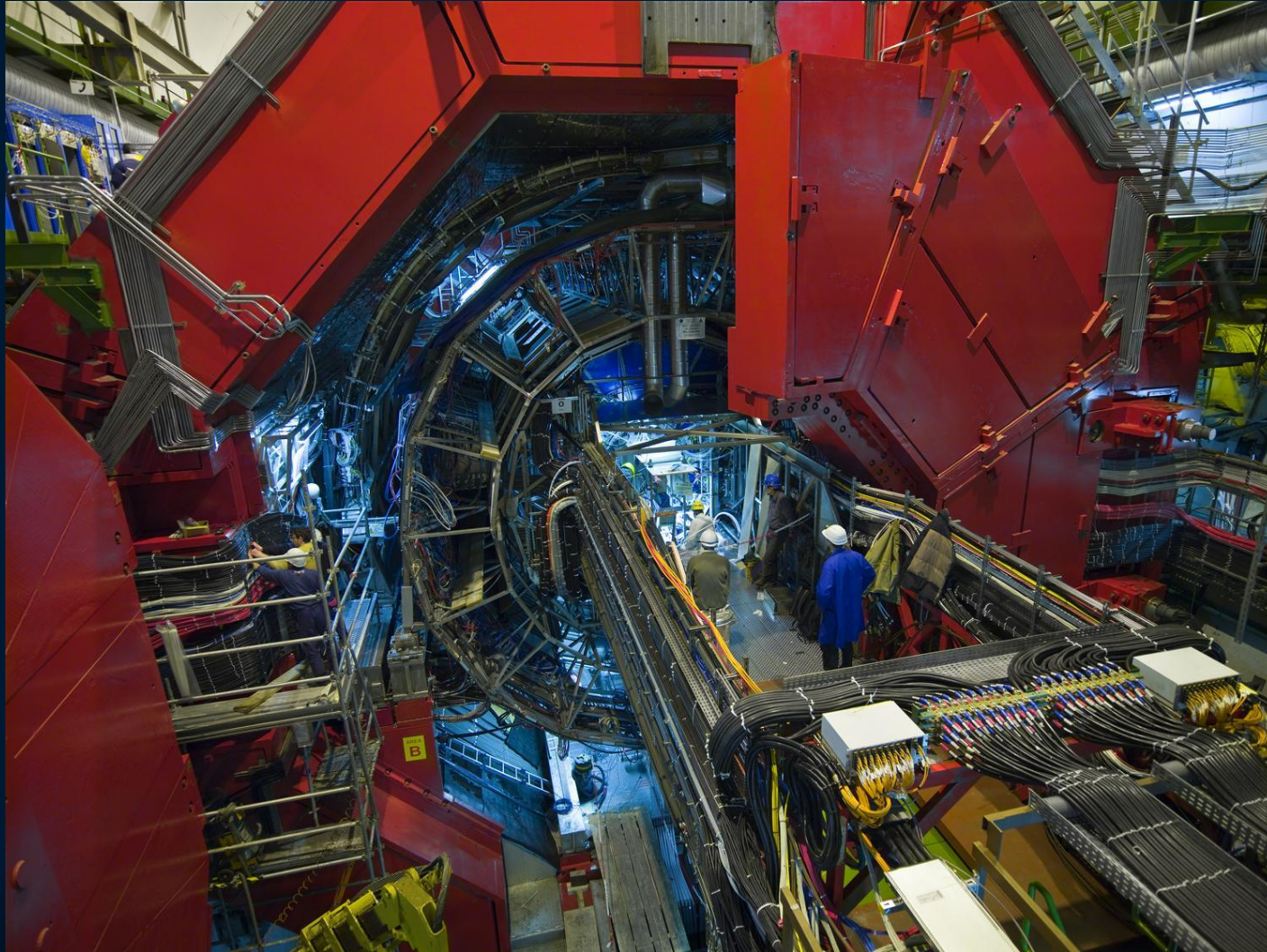
# CMS: heavier than the Eiffel tower



# ATLAS: large as a building of 5 floors



# ALICE: very sensitive, optimised for ion collisions



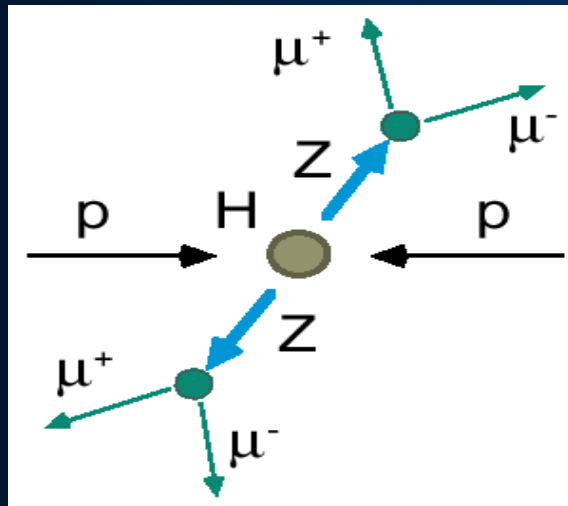
# LHCb: asymmetric, B-physics





# Aim of the game

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



$$E = m \cdot c^2$$

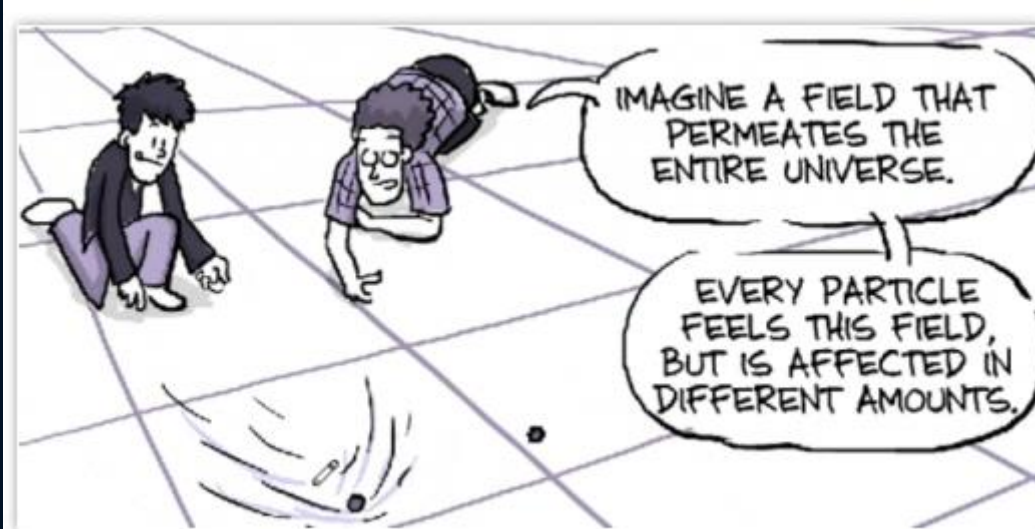
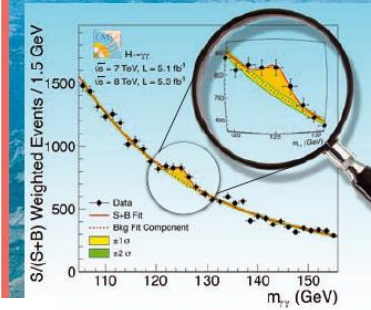
# The Higgs field gives mass to other particles



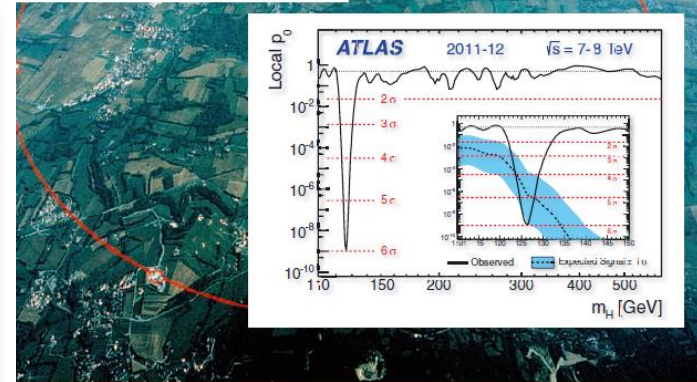
## PHYSICS LETTERS B

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

SciVerse ScienceDirect



(Credit: PHD Comics)

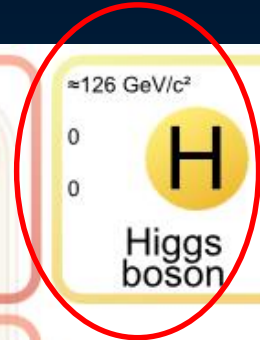


<http://www.elsevier.com/locate/physletb>



# Why is the Higgs so special?

	mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0	0	0
spin →	$1/2$	$1/2$	$1/2$	1	0	0
		<b>u</b>	<b>c</b>	<b>t</b>	<b>g</b>	<b>H</b>
		up	charm	top	gluon	Higgs boson
<b>QUARKS</b>		$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	charge →	$-1/3$	$-1/3$	$-1/3$	0	
	spin →	$1/2$	$1/2$	$1/2$	1	
		<b>d</b>	<b>s</b>	<b>b</b>	<b><math>\gamma</math></b>	
		down	strange	bottom	photon	
<b>LEPTONS</b>		$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	charge →	-1	-1	-1	0	
	spin →	$1/2$	$1/2$	$1/2$	1	
		<b>e</b>	<b><math>\mu</math></b>	<b><math>\tau</math></b>	<b>Z</b>	
		electron	muon	tau	Z boson	
<b>LEPTONS</b>		$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	charge →	0	0	0	$\pm 1$	
	spin →	$1/2$	$1/2$	$1/2$	1	
		<b><math>\nu_e</math></b>	<b><math>\nu_\mu</math></b>	<b><math>\nu_\tau</math></b>	<b>W</b>	
		electron neutrino	muon neutrino	tau neutrino	W boson	
						<b>GAUGE BOSONS</b>

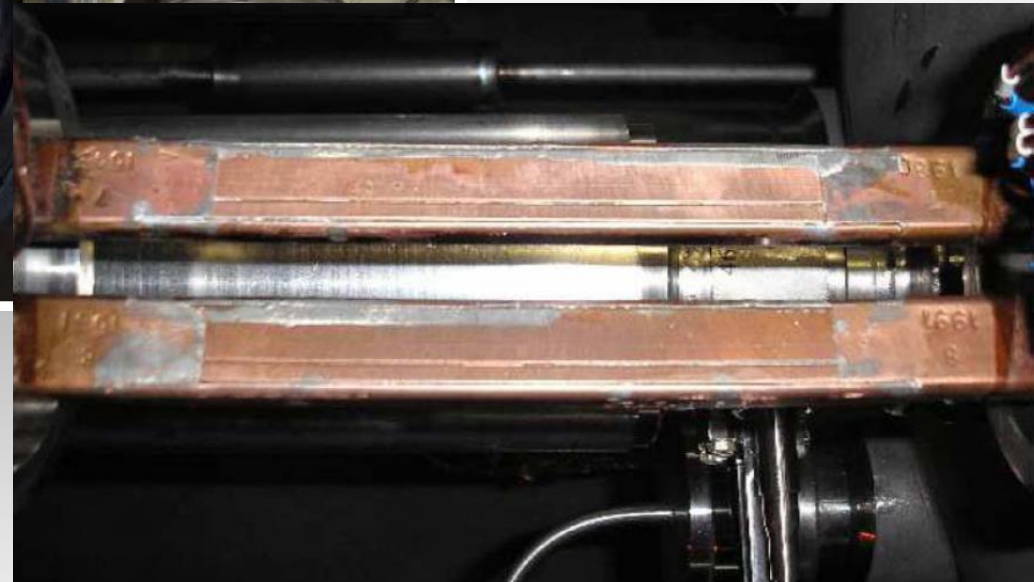
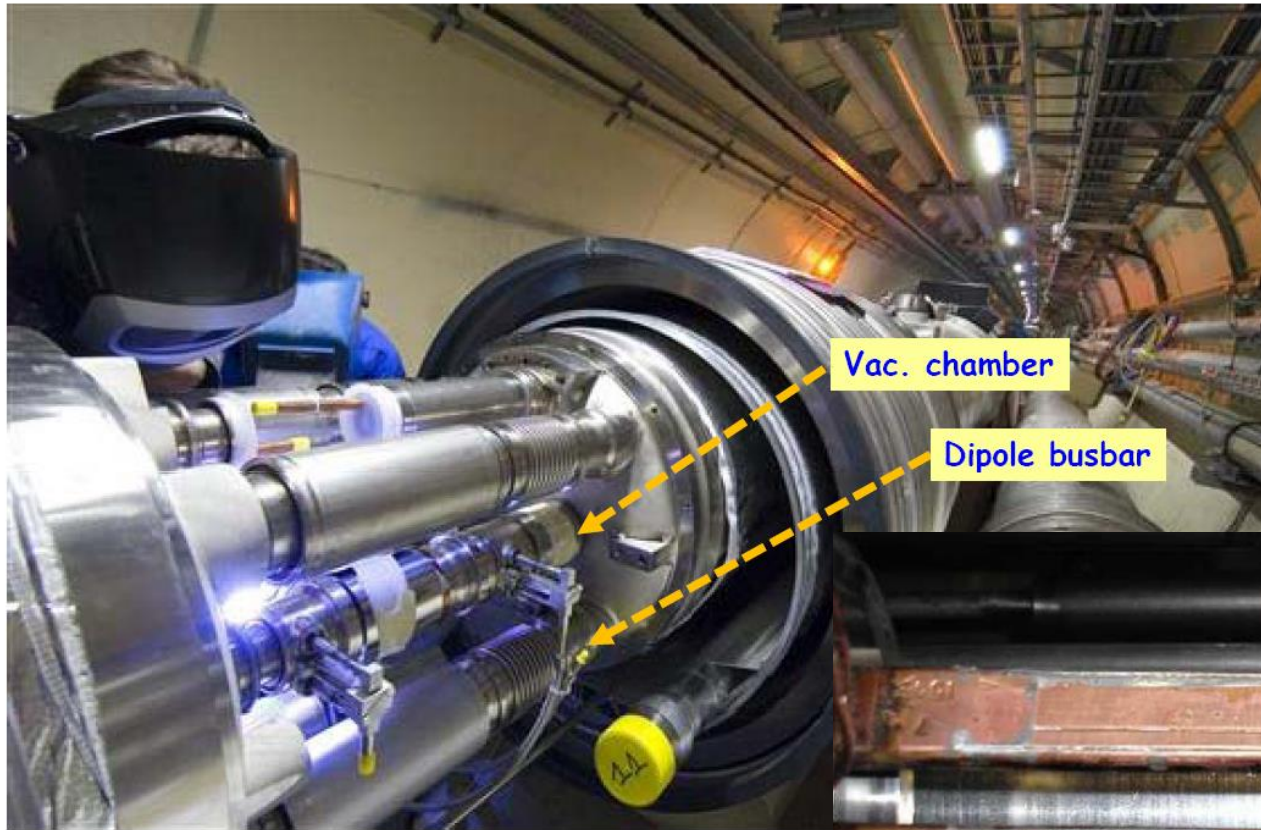


# Reduced Energy – the history



10<sup>th</sup> September 2008: First circulating beams – all smiles

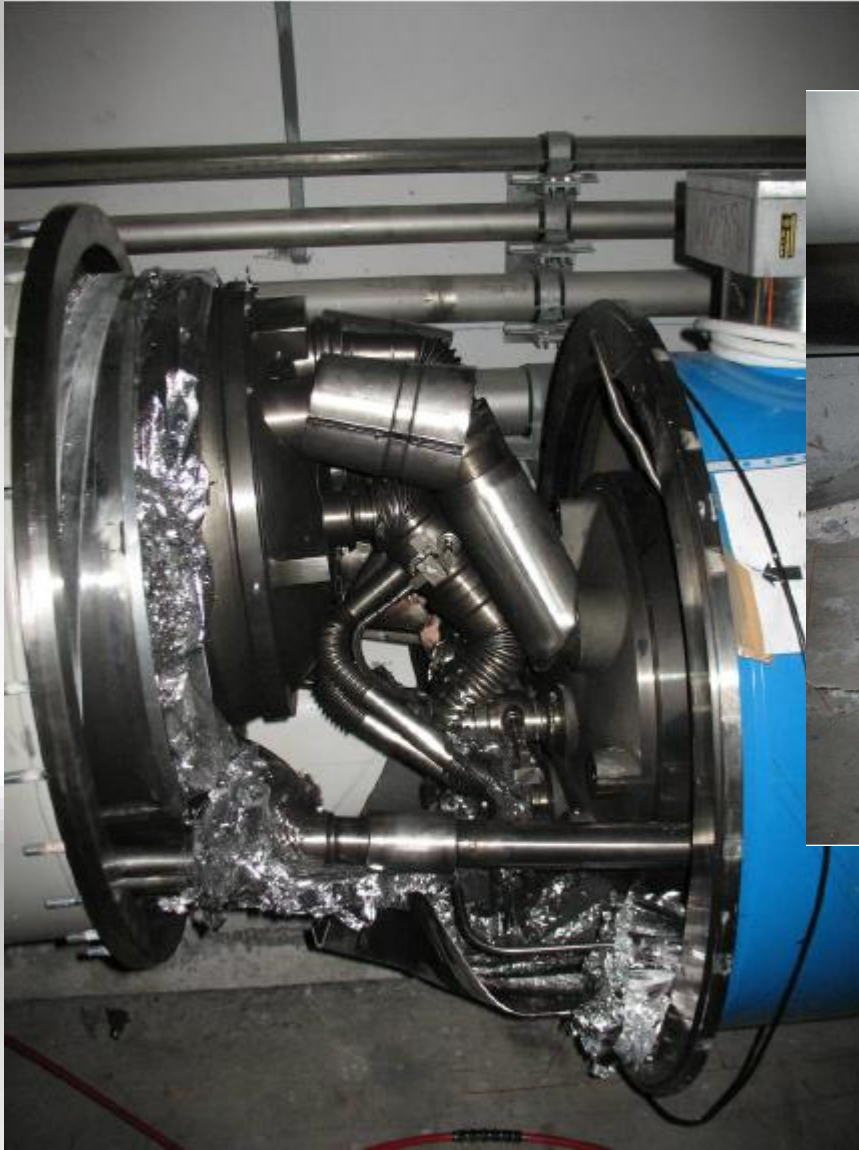
# Reduced energy – the history



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

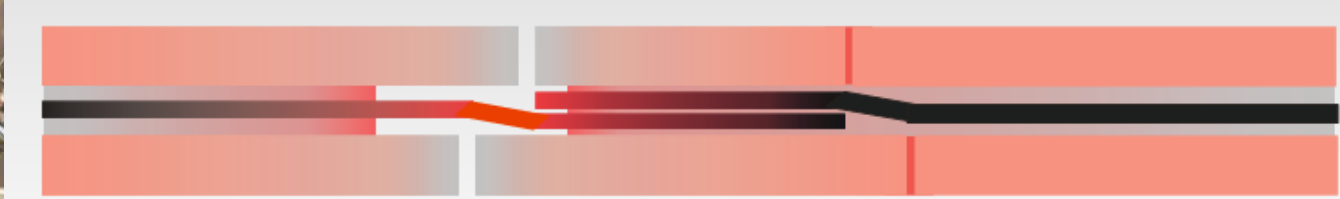
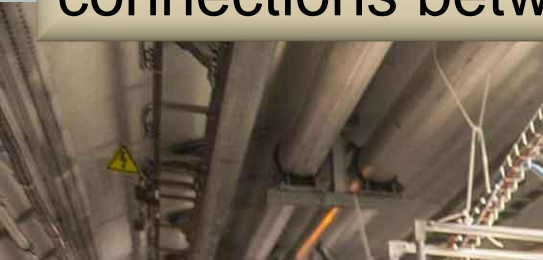


# Reduced energy – the history



*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... Experiments' consolidation and upgrades
2014		
2015	Run II	6.5 to 7 TeV, peak luminosity $1.7e34$
2016		
2017		
2018	LS2	LHC phase 1 and <b>injector</b> upgrades Experiments' consolidation and upgrades
2019	Run III	7 TeV, peak luminosity $2.0e34$
2020		
2021		
2022	LS3	HL-LHC upgrade (insertions, crab cavities...) Experiments' HL upgrades
2023		

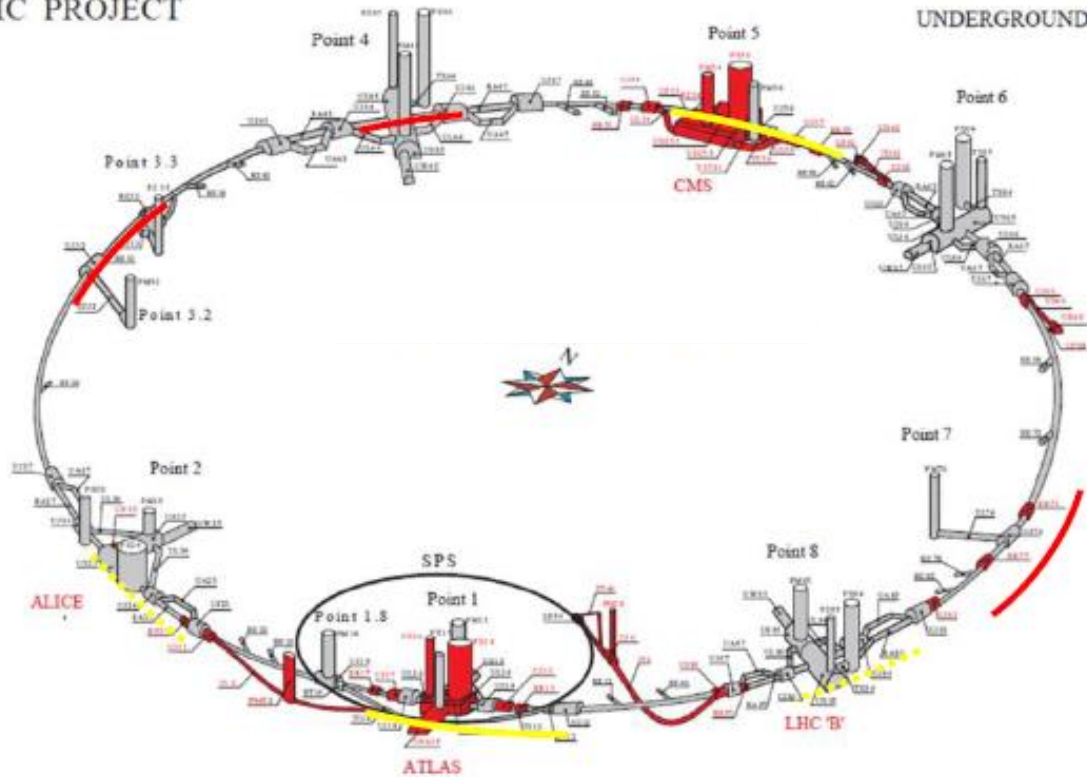
**Followed by many years of HL-LHC running**

***The LHC has a long future ahead ....***



# The HL-LHC Project

HC PROJECT



UNDERGROUND

- New IR-quads Nb<sub>3</sub>Sn (inner triplets)
- New 11 T Nb<sub>3</sub>Sn (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



Science & Technology  
Facilities Council



UNIVERSITY OF  
LIVERPOOL

LANCASTER  
UNIVERSITY

MANCHESTER  
1824



UNIVERSITY OF  
Southampton



ÉCOLE POLYTECHNIQUE  
FÉDÉRALE DE LAUSANNE

CSIC  
Comissió Interdepartamental de Recerca i Innovació Tecnològica

Ciemat  
Centro de Investigaciones  
Energéticas, Medioambientales  
y Tecnológicas



INFN  
Istituto Nazionale  
di Fisica Nucleare

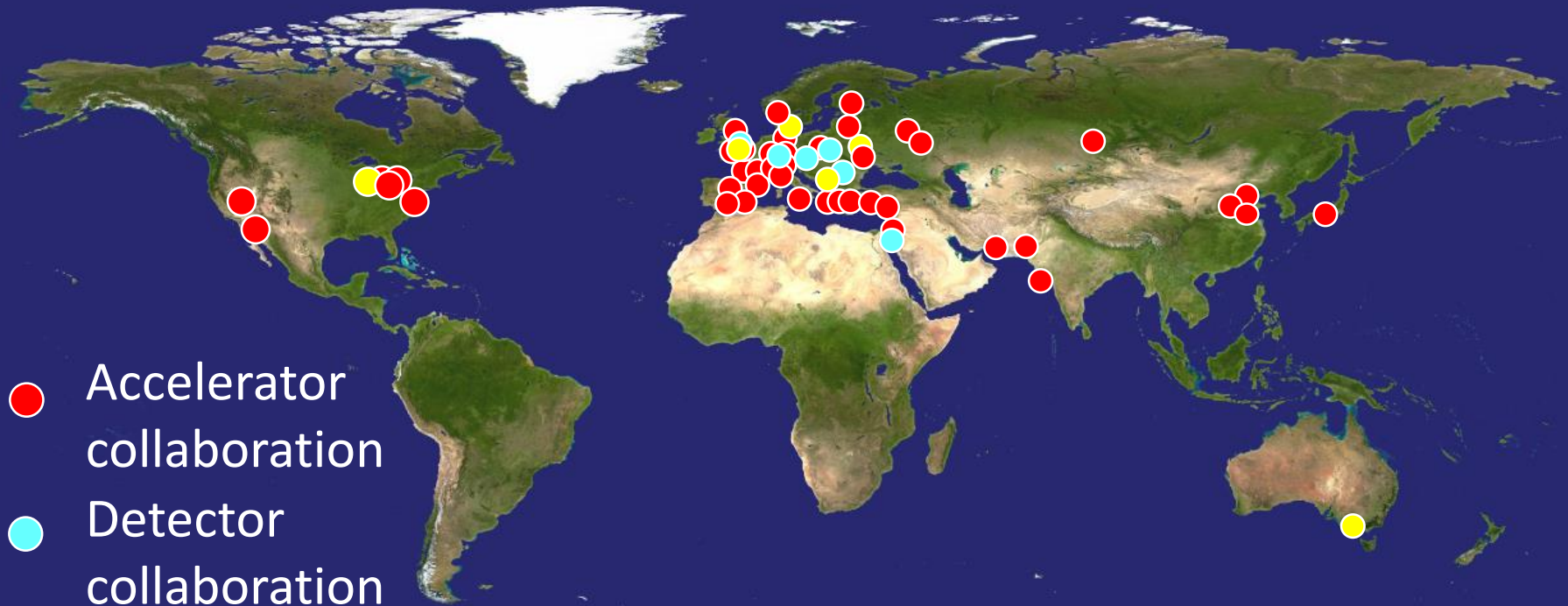


KEK  
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION



# CLIC Collaboration

29 Countries – over 70 Institutes



- Accelerator collaboration
- Detector collaboration
- Accelerator + Detector collaboration





# CERN: Particle Physics and Innovation

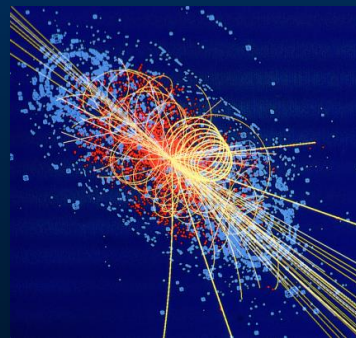
- **Interfacing** between fundamental science and key technological developments



- **CERN Technologies and Innovation**



Accelerating particle beams



Detecting particles



Large-scale computing (Grid)

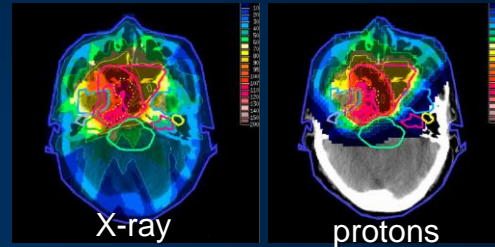
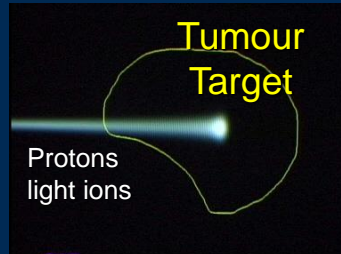
# Medical Application as an Example of Particle Physics Spin-off

Combining Physics, ICT, Biology and Medicine to fight cancer



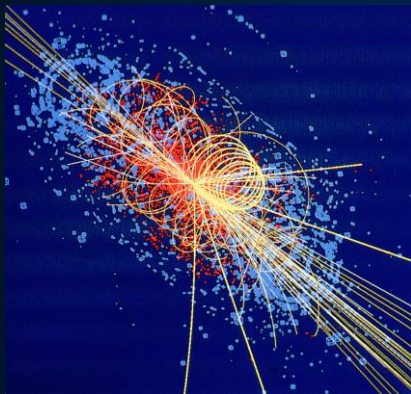
## Hadron Therapy

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



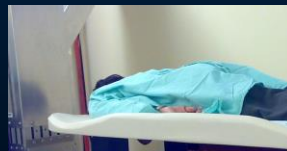
Leadership in Ion Beam Therapy now in Europe and Japan

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

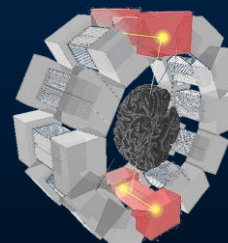


## Imaging

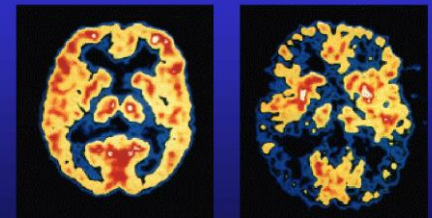
Clinical trial in Portugal for new breast imaging system (ClearPEM)



## PET Scanner



Brain Metabolism in Alzheimer's Disease: PET Scan



Normal Brain

Alzheimer's Disease



Detecting particles

# CERN Education Activities

## Scientists at CERN

Academic Training Programme



Latin American School  
Natal, Brazil, 2011  
Arequipa, Peru, 2013



## Young Researchers

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



## Physics Students

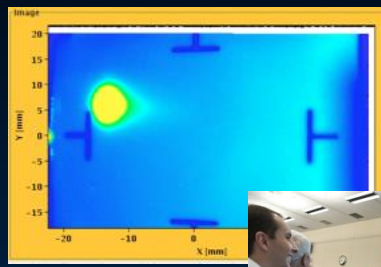
Summer Students  
Programme



## CERN Teacher Schools

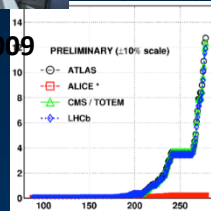
International and National  
Programmes

August 2008  
First injection test

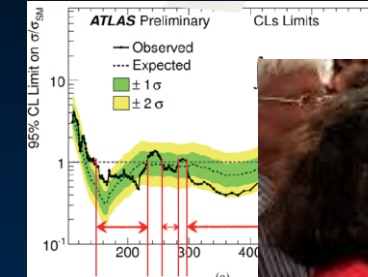


September 10, 2008  
First beams around

November 29, 2009  
Beam back



October 14  
2010  
1e32  
248 bunches



June 28 2011  
1380 bunches

1380

August  
2.3e33,  
1380 b



4 July, 2012

6 June, 2012  
6.8e33

2008

2009

2010

2011

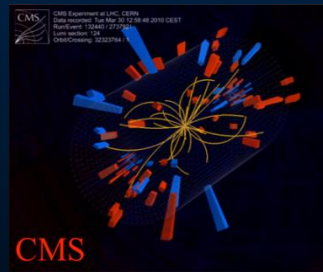
2012

September 19,  
2008  
Disaster

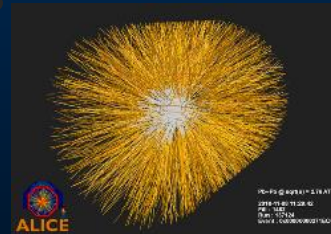
Accidental release  
of 600 MJ stored  
in one sector of  
LHC dipole  
magnets



March 30, 2010  
First collisions at  
3.5 TeV



November 2010  
Ions



18 June, 2012  
6.6 fb<sup>-1</sup>  
to ATLAS & CMS

# LHC Timeline

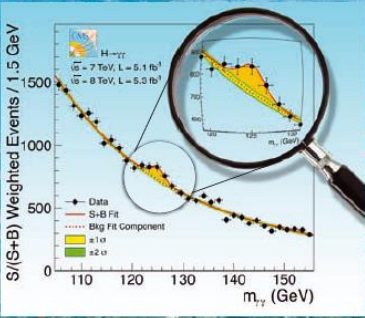
# The highlight of a remarkable year 2012

Volume 712, Issue 3, 6 June 2012 ISSN 0370-2693

ELSEVIER

## PHYSICS LETTERS B

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)  
SciVerse ScienceDirect

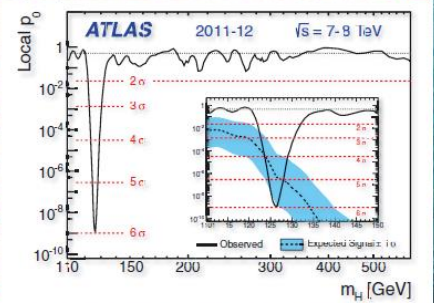


$S/(S+B)$  Weighted Events / 1.5 GeV

$m_H$  (GeV)

Legend:  
• Data  
— S+B Fit  
--- Big Fit Component  
■ 1 $\sigma$   
■ 2 $\sigma$

Parameters:  
 $\sqrt{s} = 7$  TeV,  $L = 5.1$  fb $^{-1}$   
 $\sqrt{s} = 8$  TeV,  $L = 5.3$  fb $^{-1}$



ATLAS 2011-12  $\sqrt{s} = 7-8$  TeV

Local  $p_0$

$m_H$  [GeV]

Legend:  
— Observed  
— Expected Signal: 1 $\sigma$

Significance levels: 2 $\sigma$ , 3 $\sigma$ , 4 $\sigma$ , 5 $\sigma$ , 6 $\sigma$

<http://www.elsevier.com/locate/physletb>

## The Economist

JULY 7TH - 13TH 2012 Economist.com

In praise of charter schools  
Britain's banking scandal spreads  
Volkswagen overtakes the rest  
A power struggle at the Vatican  
When Lonesome George met Nora

# A giant leap for science



**Finding the Higgs boson**



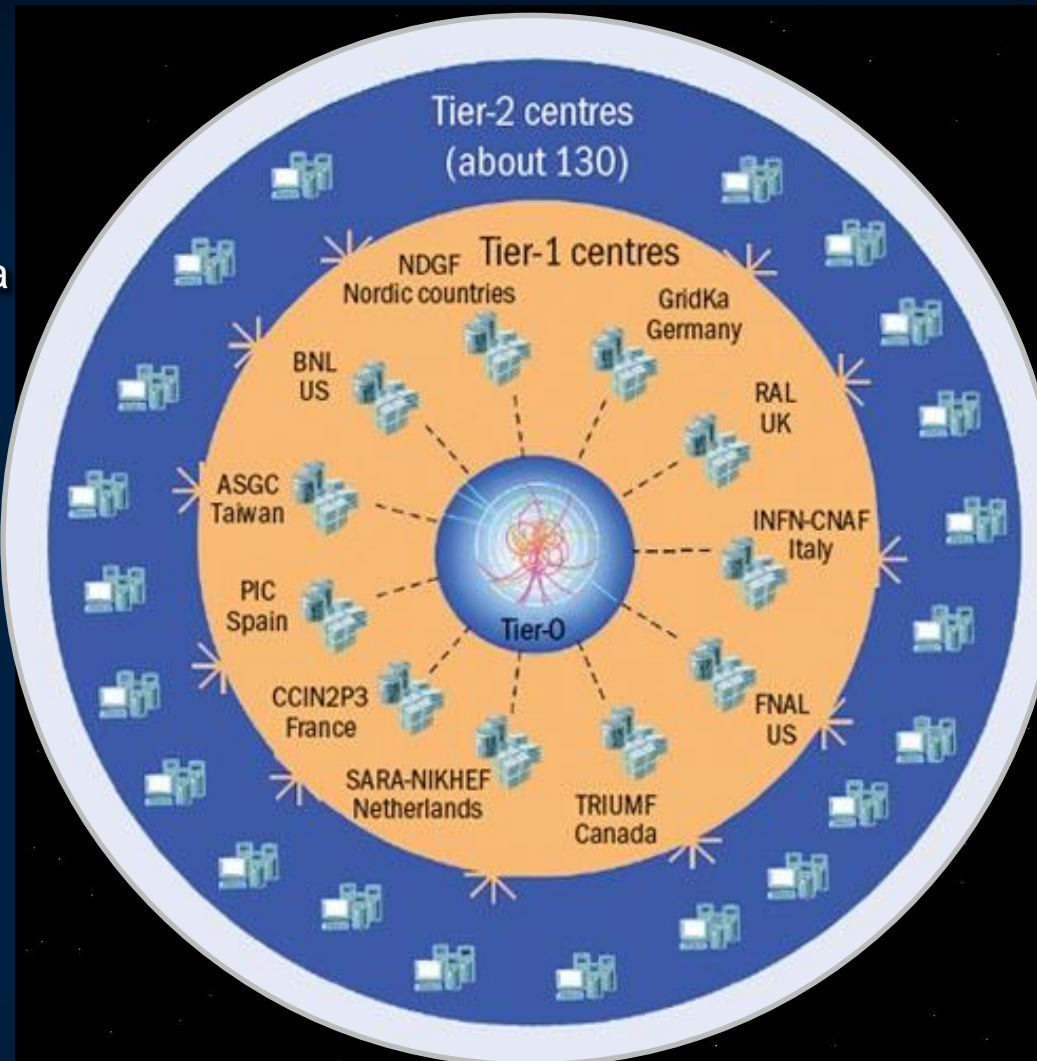


# Nobel Prize in Physics 2013



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

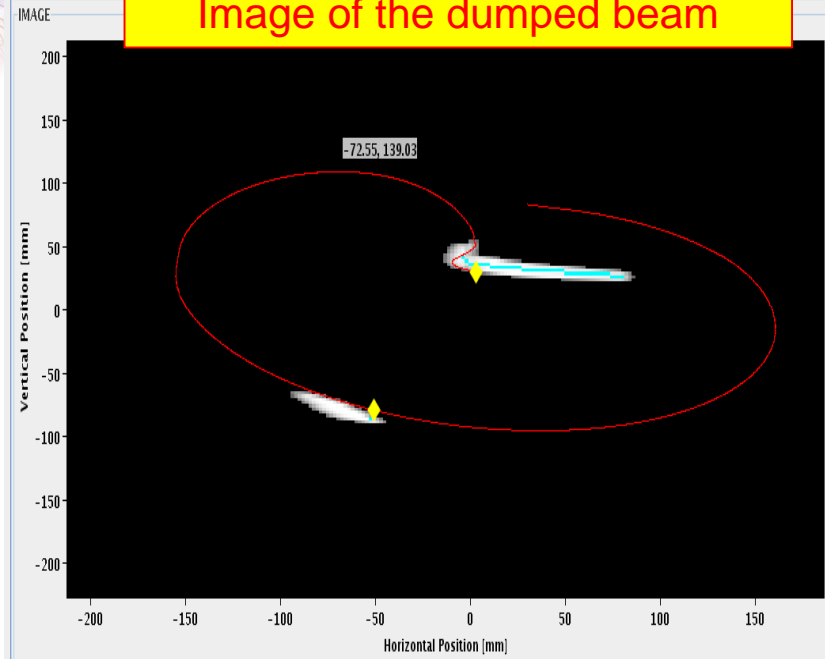
10 Gb links

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

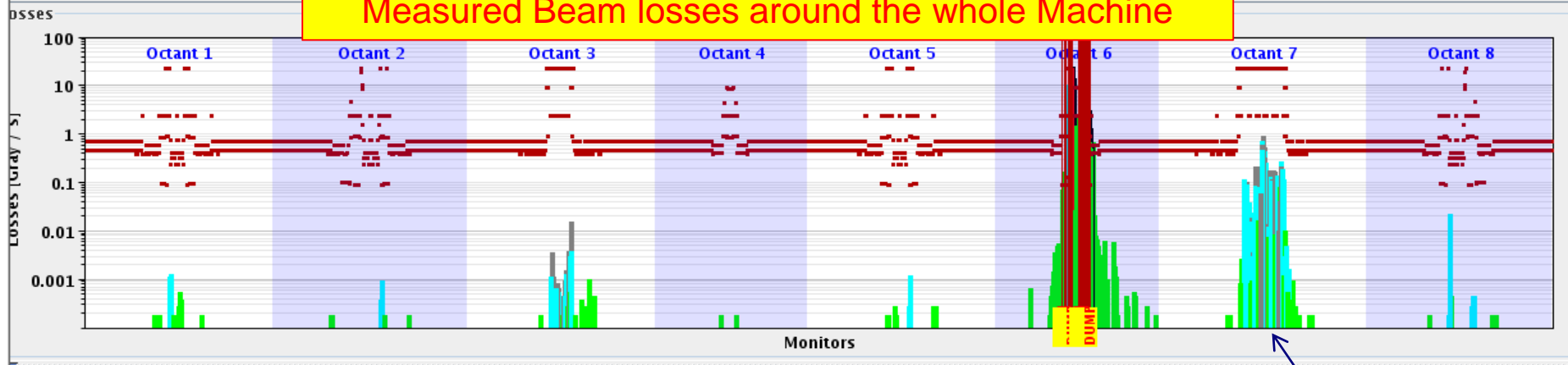
# Verification of Dump Protection

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

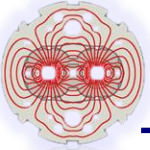
Measured Beam losses around the whole Machine



Rest of the machine is clean

Dump

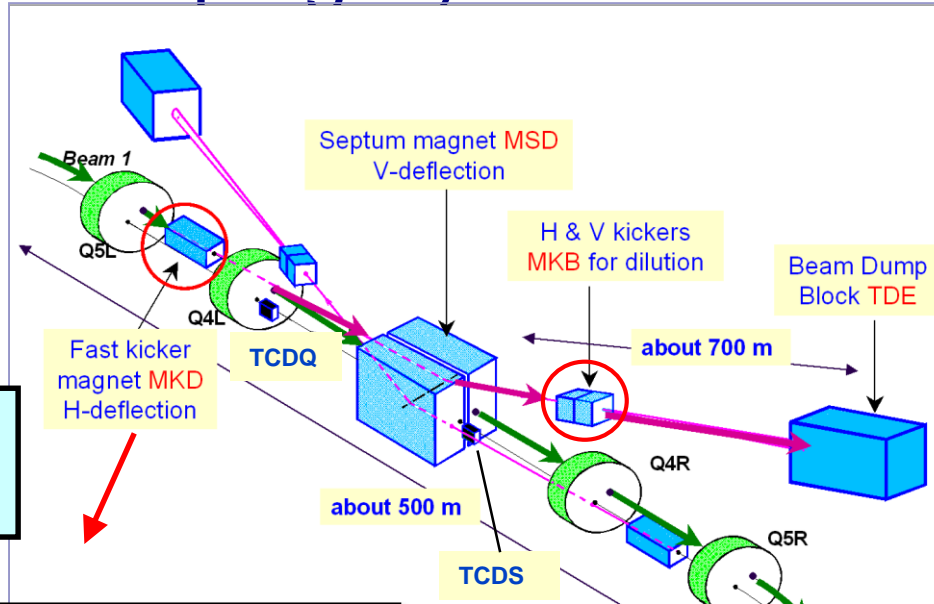
Collimation



# Only one way to safely get rid of the beam



## LHC Beam Dumping System

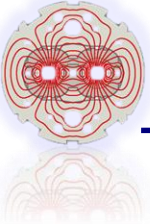


Extraction Kickers

2 x 15 Systems

10 Dilution kickers MKB

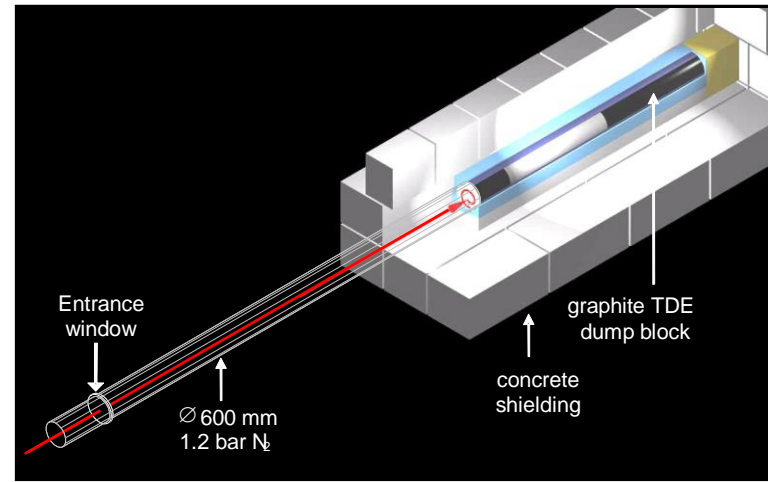
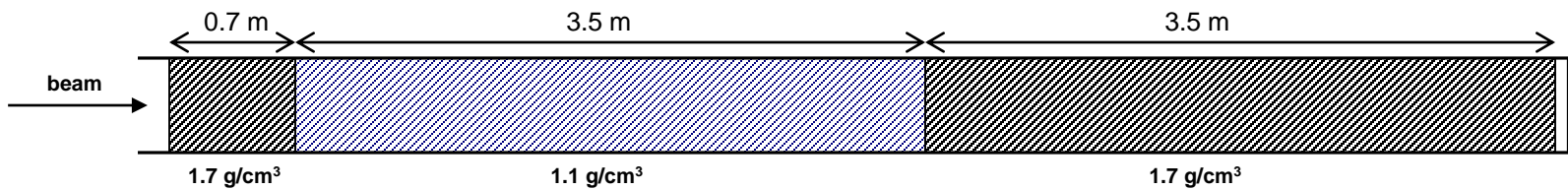


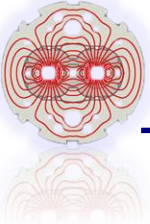


# Beam dump block (TDE)



- 700 mm  $\varnothing$  graphite core, with graded density of 1.1 g/cm<sup>3</sup> and 1.7 g/cm<sup>3</sup>
- 12 mm wall, stainless-steel welded pressure vessel, at 1.2 bar of N<sub>2</sub>
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks





# Extraction kicker – Abort Gap

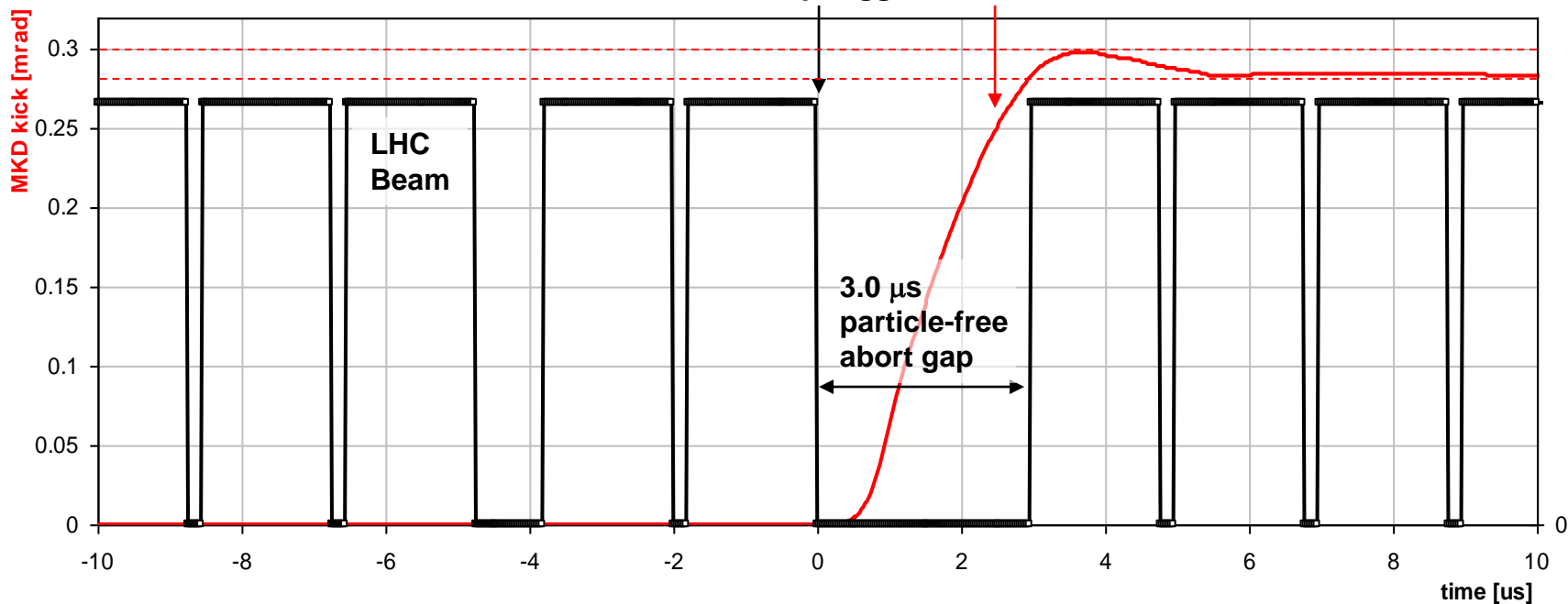


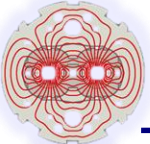
Within 3 turns of dump request



Synchronised  
dump trigger

Extraction kicker MKD deflection





# At every dump: Check the Extraction Kickers



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

Module: MKD

State: FINISHED

Analysis: OK

Check: OK

MKD

Results Journal

MKB

BLM

VAC

BT VDD

BPMD

BCT

BSRA

TSU

Source

- MKD.UA67.XPOC1.MB2
- MKD.UA67.XPOC2.CB2
- MKD.UA67.XPOC2.GB2
- MKD.UA67.XPOC2.BB2
- MKD.UA67.XPOC1.LB2
- MKD.UA67.XPOC2.HB2
- MKD.UA67.XPOC1.HB2
- MKD.UA67.XPOC2.NB2
- MKD.UA67.XPOC2.DB2
- MKD.UA67.XPOC1.BB2
- MKD.UA67.XPOC1.OB2
- MKD.UA67.XPOC2.EB2
- MKD.UA67.XPOC1.AB2
- MKD.UA67.XPOC1.CB2
- MKD.UA67.XPOC2.JB2
- MKD.UA67.XPOC1.NB2
- MKD.UA67.XPOC1.DB2
- MKD.UA67.XPOC2.JB2
- MKD.UA67.XPOC1.JB2
- MKD.UA67.XPOC1.GB2
- MKD.UA67.XPOC2.MB2
- MKD.UA67.XPOC2.LB2
- MKD.UA67.XPOC1.FB2
- MKD.UA67.XPOC2.AB2
- MKD.UA67.XPOC2.OB2
- MKD.UA67.XPOC1.KB2
- MKD.UA67.XPOC1.JB2
- MKD.UA67.XPOC1.EB2
- MKD.UA67.XPOC2.KB2
- MKD.UA67.XPOC2.FB2

Source: MKD.UA67.XPOC2.IB2

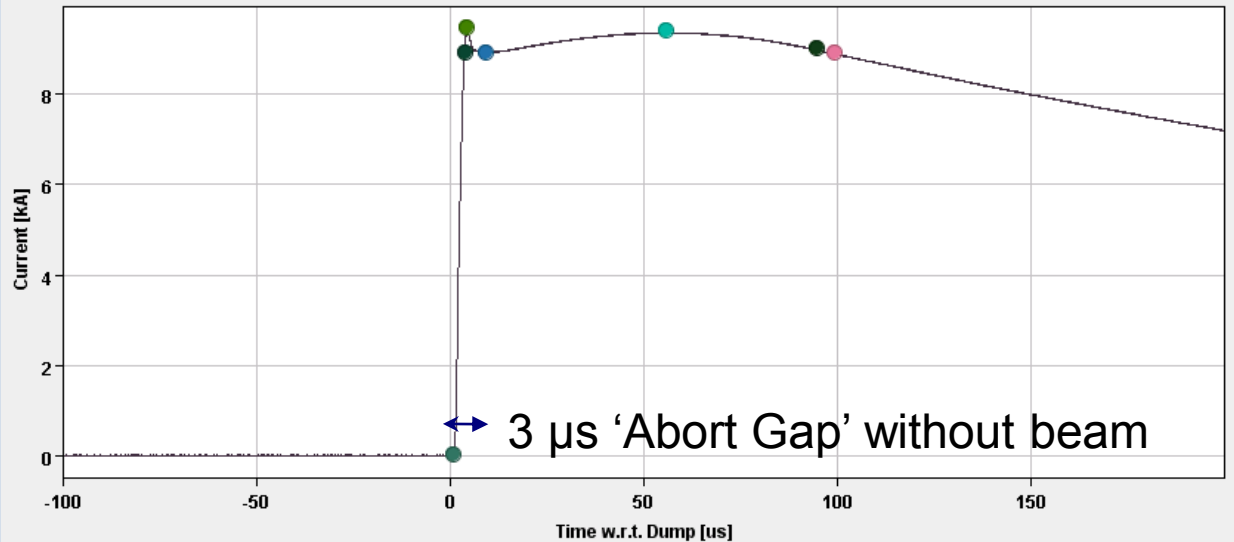
Analysis: OK

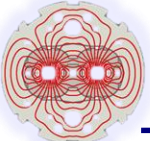
Check: OK

CHECKS

Property	Value	Min.Value	Ref.Value	Max.Value	Units	Check
endRatio	9.132E-1	4.921E-1	9.921E-1	1.492E0	%	OK
ref100pctCurrent	8.942E3	8.865E3	8.955E3	9.045E3	kA	OK
overShoot1Ratio	6.066E0	5.361E0	6.061E0	6.761E0	%	OK
delay	3.817E0	3.762E0	3.812E0	3.862E0	us	OK
riseTime	2.756E0	2.699E0	2.749E0	2.799E0	us	OK
overShoot2Ratio	5.176E0	4.717E0	5.217E0	5.717E0	%	OK

Waveform & Points





# 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

Module: BTVDD State: FINISHED

Analysis: OK

Check: OK

MKD

Results Journal

MKB

Checks Measures References

CHECKS

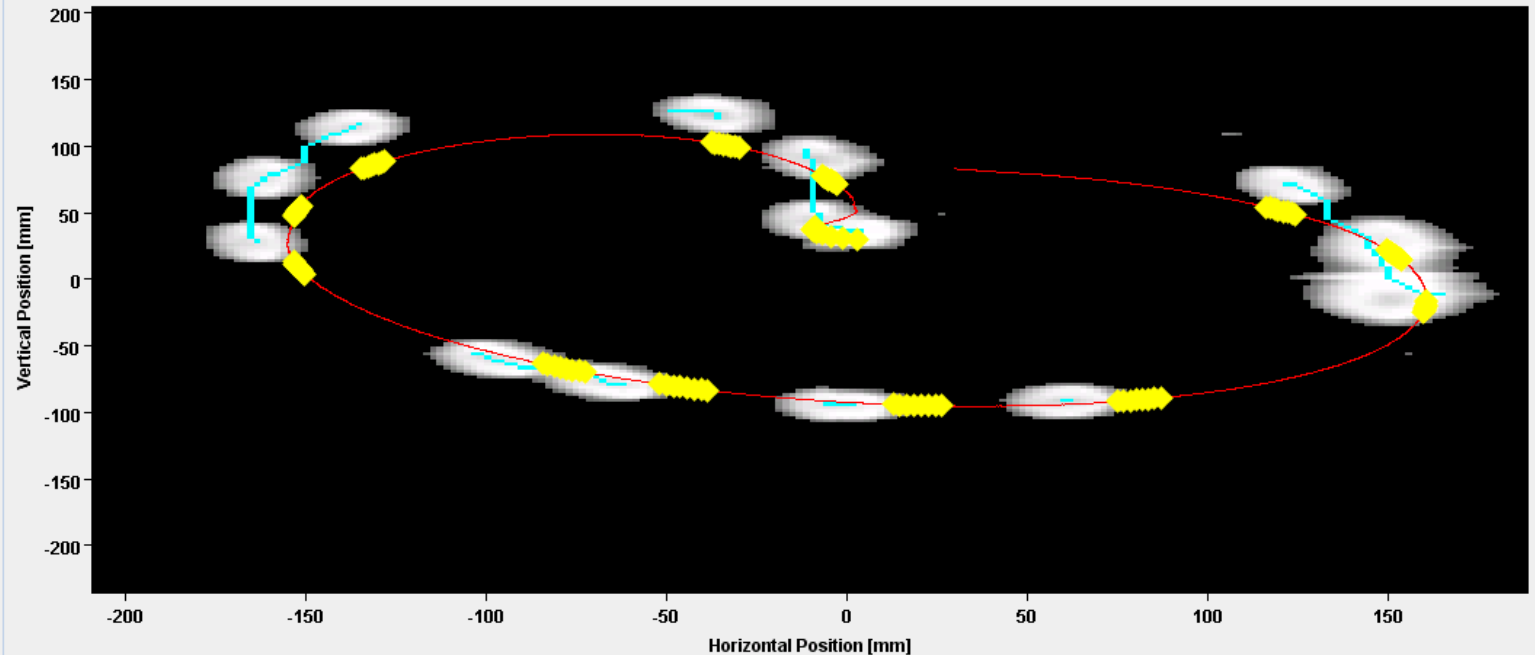
Property	Value	Min.Value	Ref.Value	Max.Value	Units	Check
height	2.014E2	1.580E2	1.980E2	2.380E2	mm	OK
centerV	1.373E1	-3.608E1	3.923E0	4.392E1	mm	OK
centerH	0.000E0	-3.621E1	3.785E0	4.379E1	mm	OK
width	3.320E2	2.640E2	3.140E2	3.640E2	mm	OK

BLM

IMAGE

VAC

BTVDD



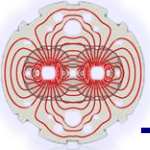
BPMD

BCT

BSRA

TSU





# At every dump: Check the Beam Losses



XPOC : XPOC\_B1 : 27.09.2010 10:33:08 (1285576388150488525) Final analysis is confirmed

XPOC **Modules graph** Results

Session: BEAM 1    3500.16 GeV    27.09.2010 - 10:33:08:150.237300

Module: BLM    State: FINISHED    **Analysis: OK**    **Check: OK**

CONTEXT MKD MKB BLM VAC BTVDD BPMD BCT BSRA TSU

**Results** Journal

Group: ALL BLMs

Group	Analysis	Check	Loss Max	Nb BLM	Nb Faulty	Nb Invalid	Nb Masked	Nb Missing	Nb Unconnected
ALL BLMs	OK	OK	3.355E4	91	0	0	0	0	0

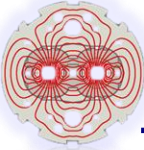
BLM Name	Loss [Gy/s]	Limit [Gy/s]	Limit Min [...]	Limit Max [...]	Low Limit	RC Factor [-]	Check	Valid	Masked	Missing	Connected
BLMDL683243.D1E1_MKBH	2.353E-3	5.000E0	1.000E0	1.000E5	NO	1.000E0	OK	YES	NO	NO	YES
BLMDL683290.D1E1_MKBV	0.000E0	5.000E0	1.000E0	1.000E5	NO	1.000E0	OK	YES	NO	NO	YES
BLMDL683325.D1E2_MKBV	0.000E0	5.000E0	1.000E0	1.000E5	NO	1.000E0	OK	YES	NO	NO	YES
BLMDL683780.D1T1_MQY.4R6	3.373E-1	5.000E0	1.000E0	1.000E5	NO	1.000E0	OK	YES	NO	NO	YES
BLMDL683840.D1L1_175_R9	3.620E-4	5.000E0	1.000E0	1.000E5	NO	1.000E0	OK	YES	NO	NO	YES
BLMDL683841.D1R1_175_R9	8.145E-4	5.000E0	1.000E0	1.000E5	NO	1.000E0	OK	YES	NO	NO	YES

BLM Losses & Limits for Group 'ALL BLMs'

Losses for BLM 'BLMDL683243.D1E1\_MKBH'



# 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  $\sigma$  from the beam at all times**

