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LHC status

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Beams Department
Operation Group

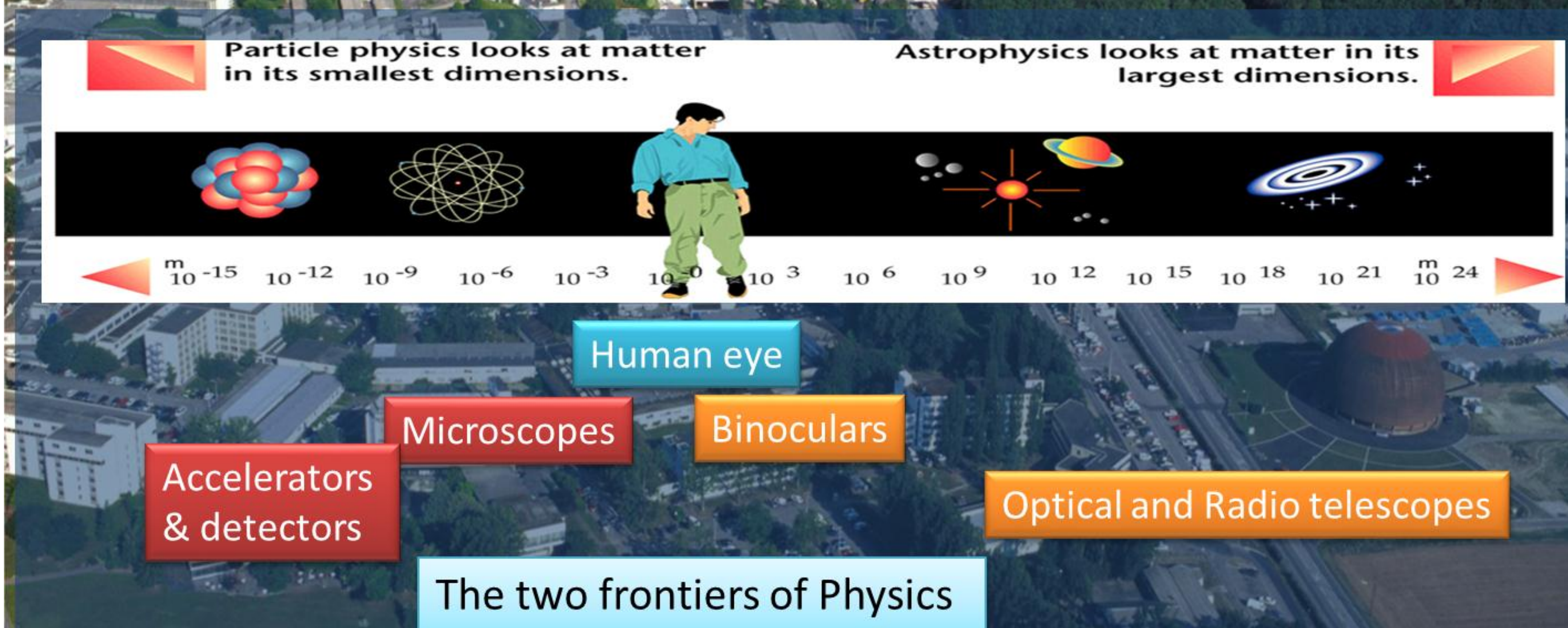
International symposium on Higgs boson and beyond standard model physics

outline

- **LHC layout and history**
- **LHC status and plan**
  (performance & operational challenges)
- **The future…**

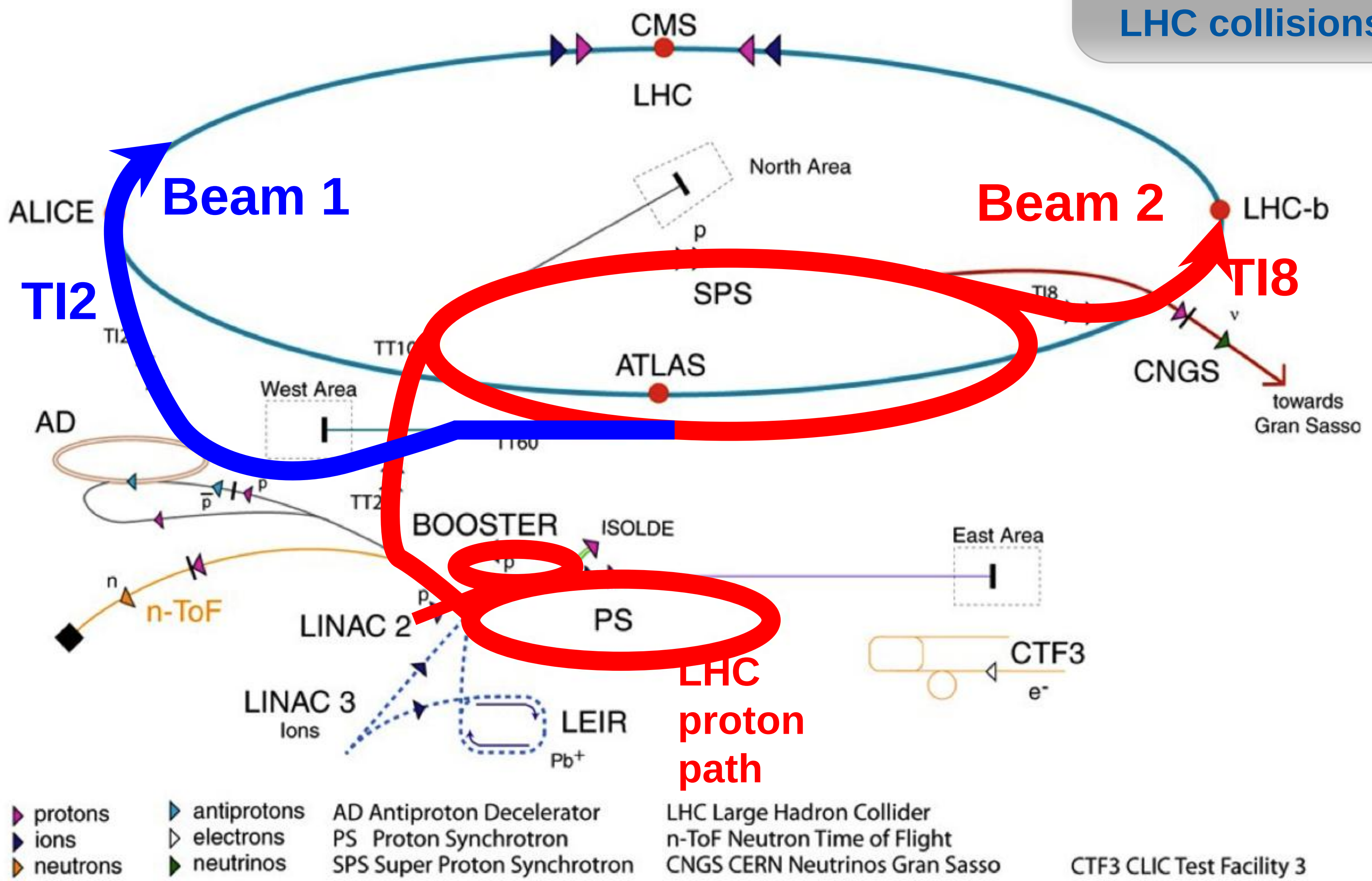
CERN

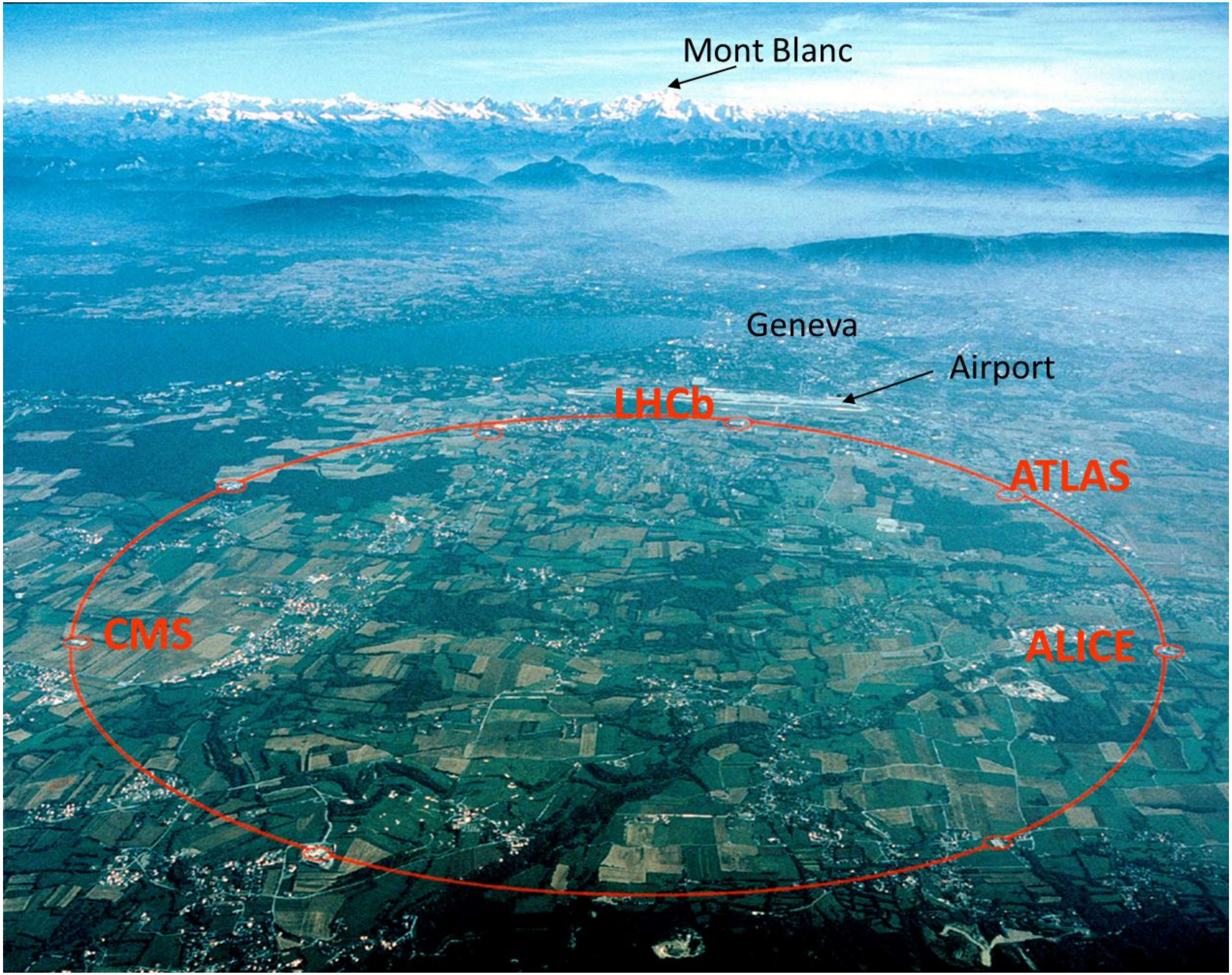
- Founded in 1954 by 12 countries
- Today: 22 member states
- More than 7000 users
- ~1000 MCHF yearly budget
- 2400 permanent staff



The accelerator complex

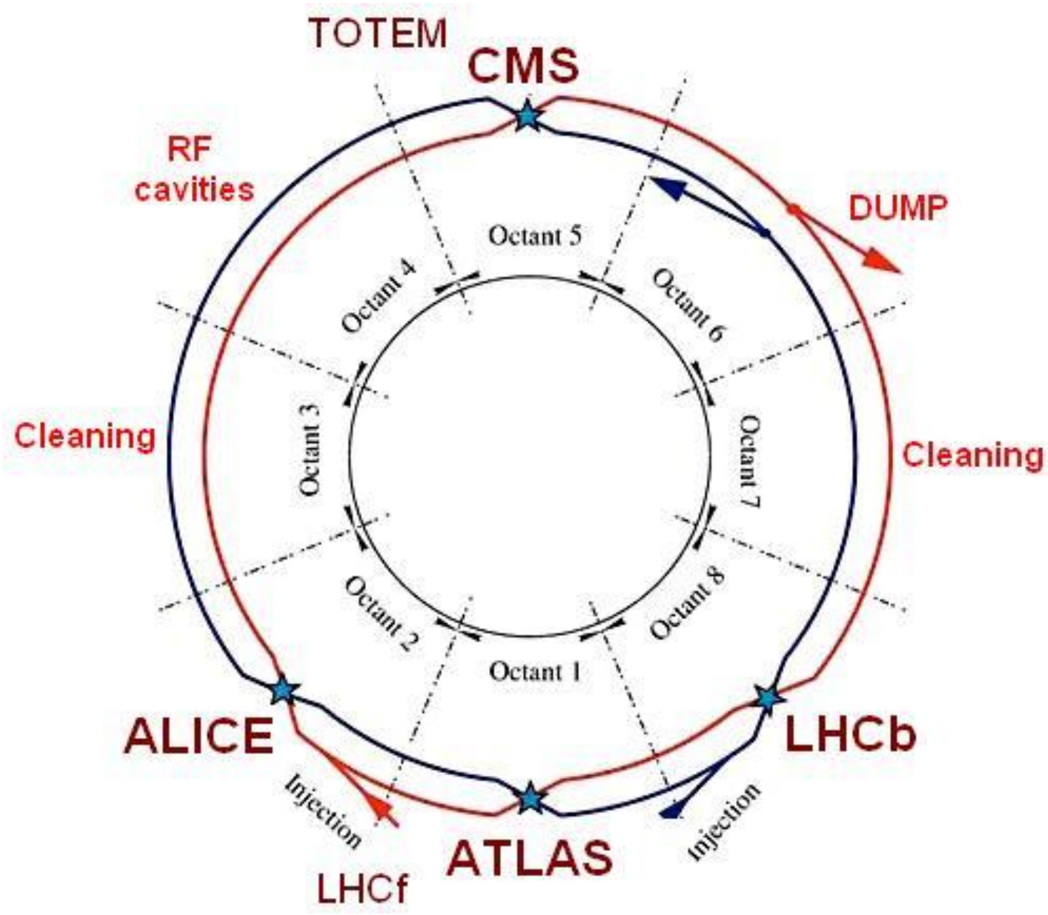
Nearly 40 km of tunnels from proton source to LHC collisions

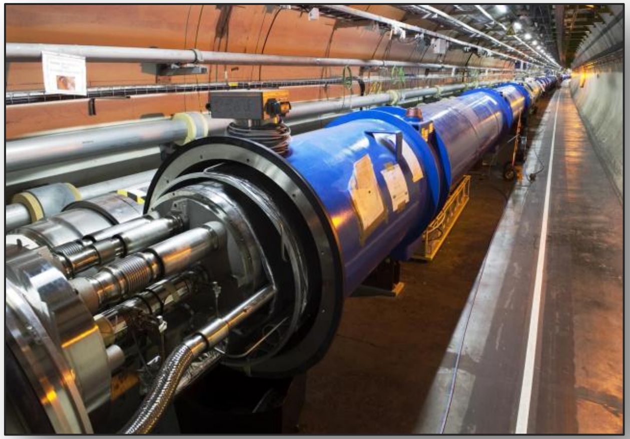


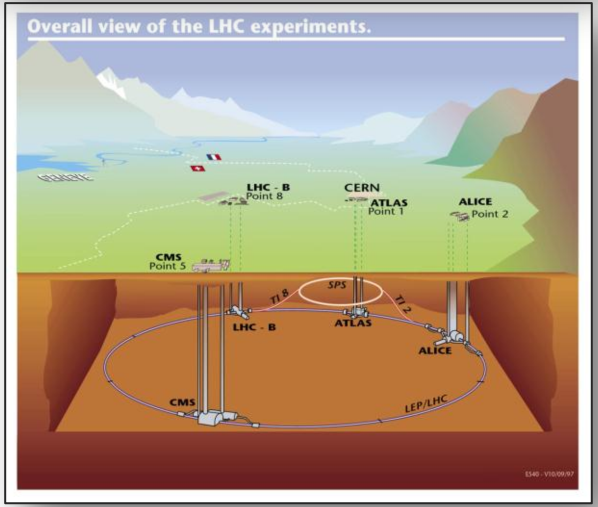

Mont Blanc
Geneva
Airport
LHCb
ATLAS
CMS
ALICE

The LHC

150 tonnes helium
(~90 tonnes at 1.9 K)





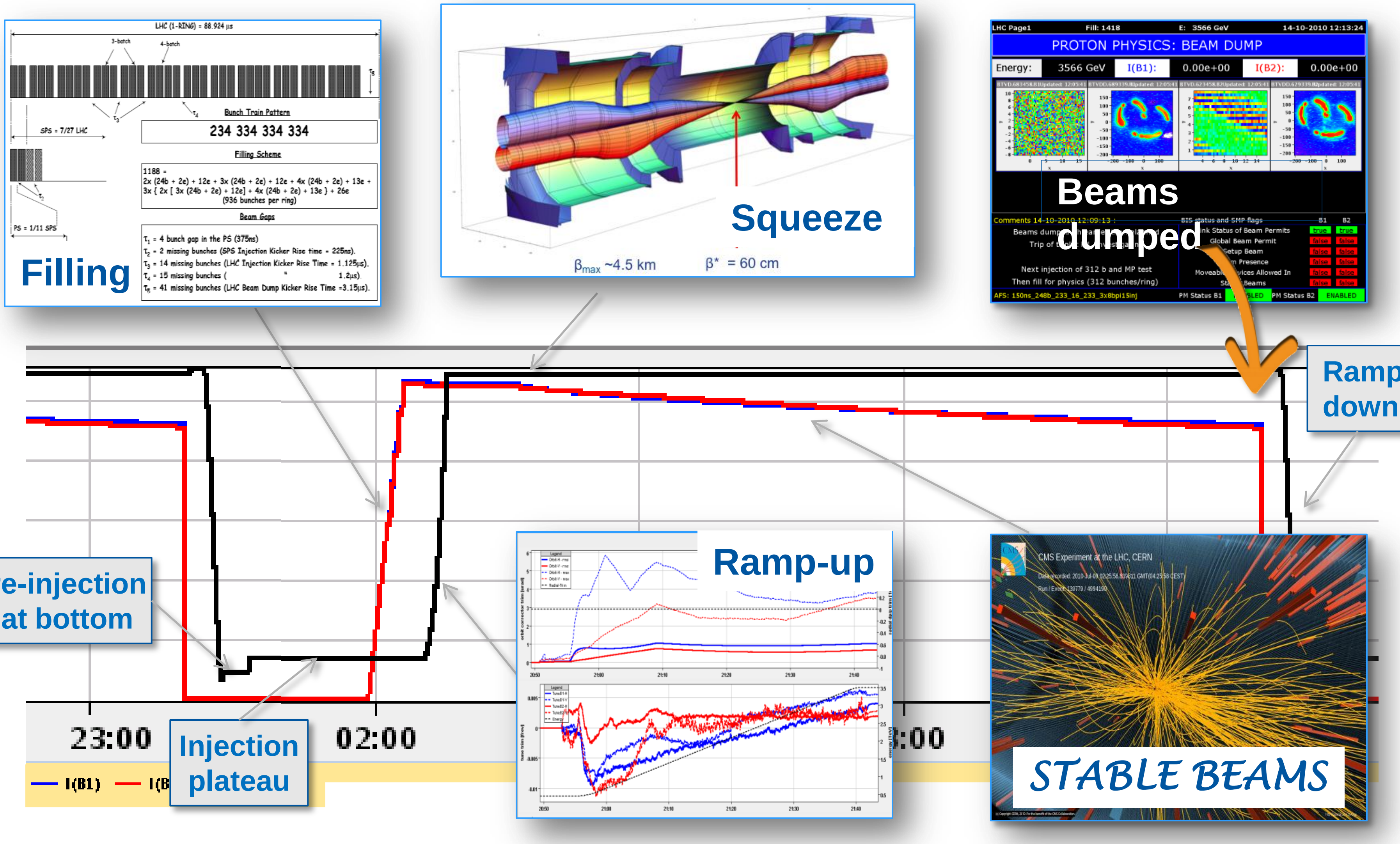


2 counter-rotating beams
14 TeV collision energy

27 km circumference
~100 m underground

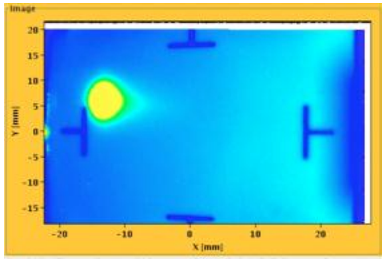
1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

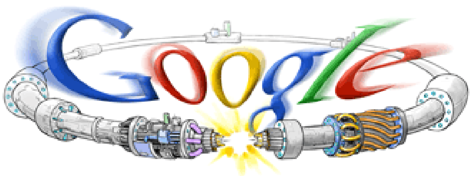
The LHC nominal cycle



LHC Run1 timeline

August 2008
First injection test



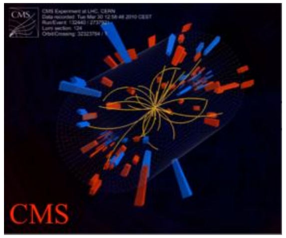


10th September
First beams around the LHC

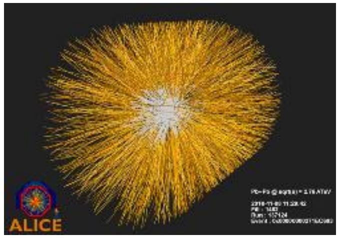
19th September
'Incident'
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

29th November
Beams back

30th March
Collisions at 3.5 TeV



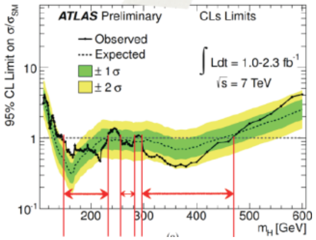
November
Ions



28th June
1380 bunches (50ns)

1380

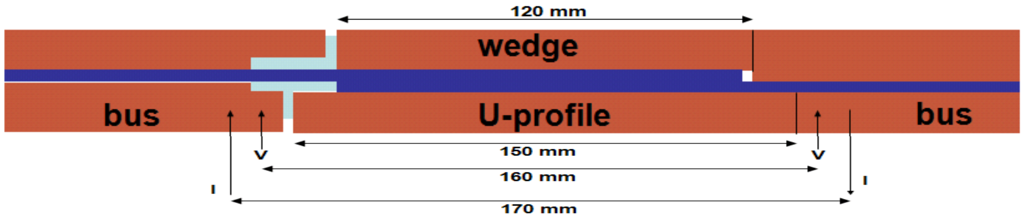
4th July
Higgs discovery



2008 | **Repair** | 2010 | **4 TeV**

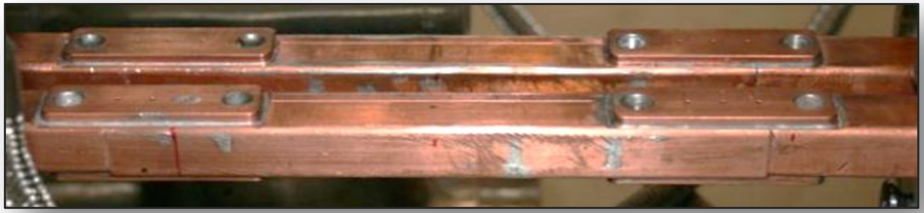
End of Run1
23.3 fb^{-1}

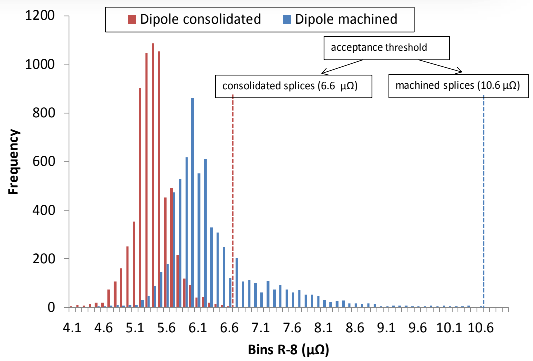
LS1 timeline

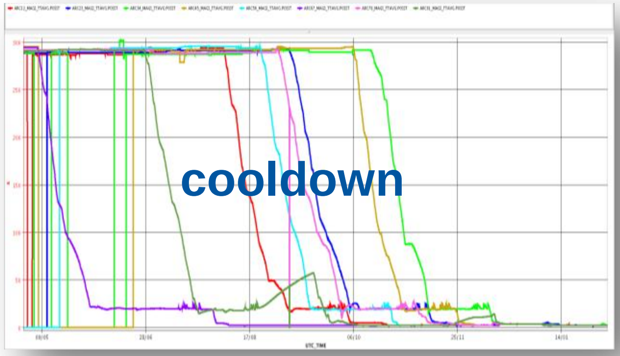


2013

2014

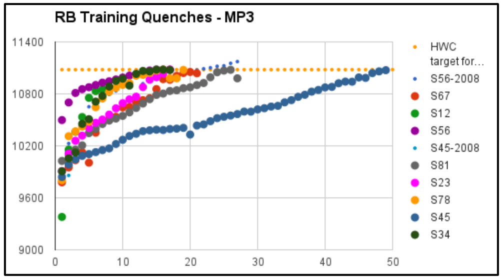




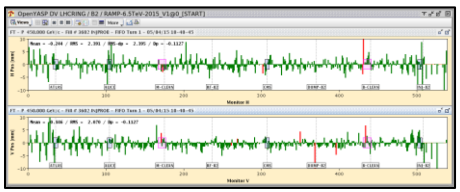


LHC Run2 timeline

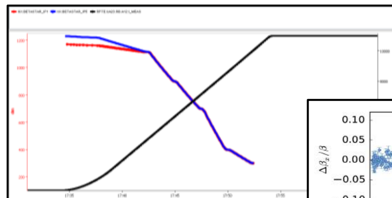
3rd April Completion of PT campaign

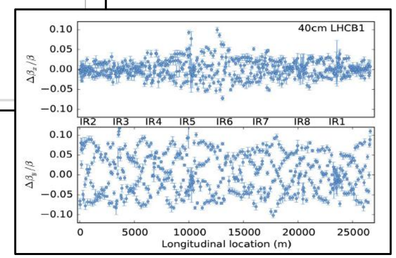


5th April First circulating beam

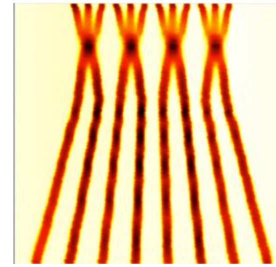


30th March
Combined Ramp & Squeeze
and final beta* 40 cm





8th July
BCMS beam, smaller emittances => 20% luminosity gain



8th August
2173 bunches

2173 2173

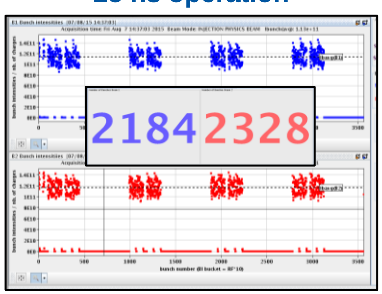
2015
4.2 fb^{-1}

2015

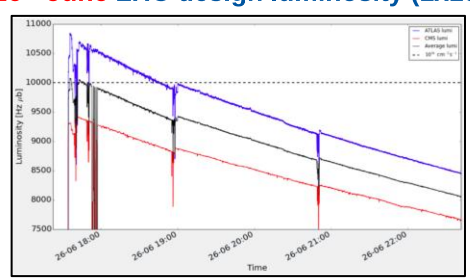
2016

10th April
6.5 TeV for the first time

7th August
25 ns operation



26th June LHC design luminosity (1x10^{34})



Production…
Production…
Production…

outline

- LHC layout and history
- LHC status and plan
  (performance & operational challenges)
- The future…

Initial goals for Run2

Increase collision energy = 13 TeV

Operate with 25 ns (estimated pile-up of 40 events/bunch crossing)

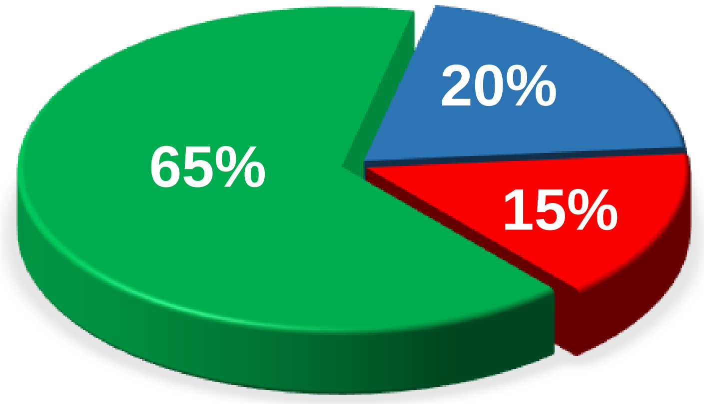
Increase total number of bunches = 2808 (288 trains)

Reduce beam size (β*): start with a conservative approach (80 cm) then envisage reduction later in 2015 → 40 cm

Peak luminosity = $1.3\text{-}1.7\times10^{34}\ cm^{-2}\ s^{-1}$

2015 commissioning year (expected 10 fb^{-1})
2016 first production year (expected 40 fb^{-1})
….(100-120 fb^{-1} for Run2)

Overall machine efficiency

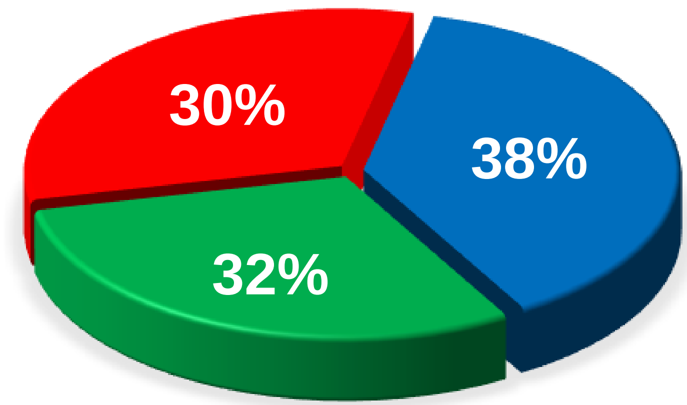


STABLE BEAMS

FAULTS

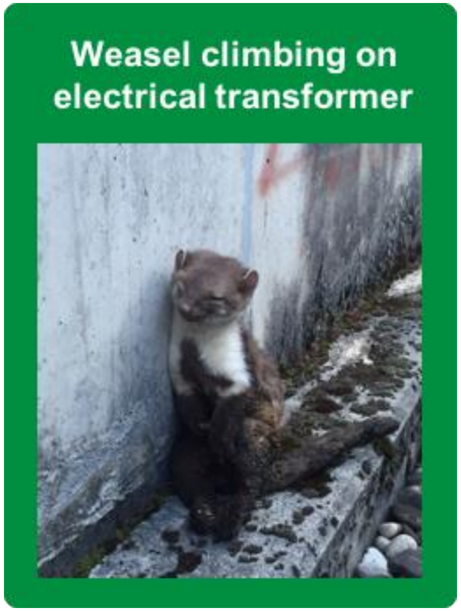
OPERATION

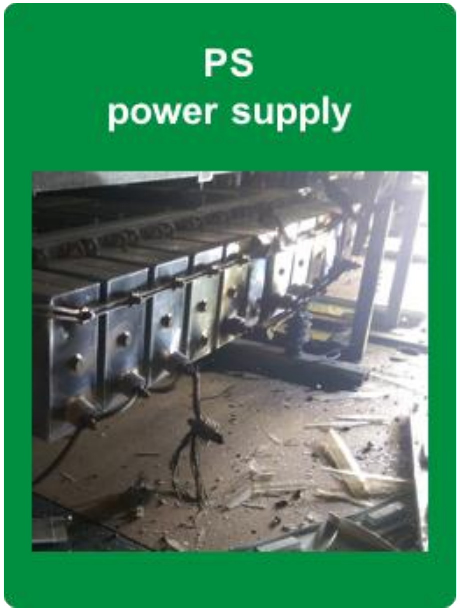
2015 efficiency



Performance of data production
(no commissioning, MD, …)

A few problems

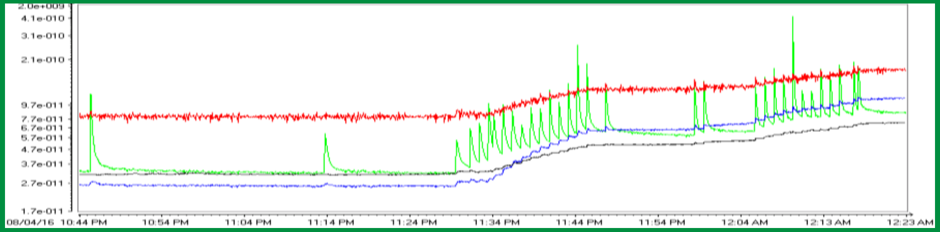




SPS BEAM DUMP

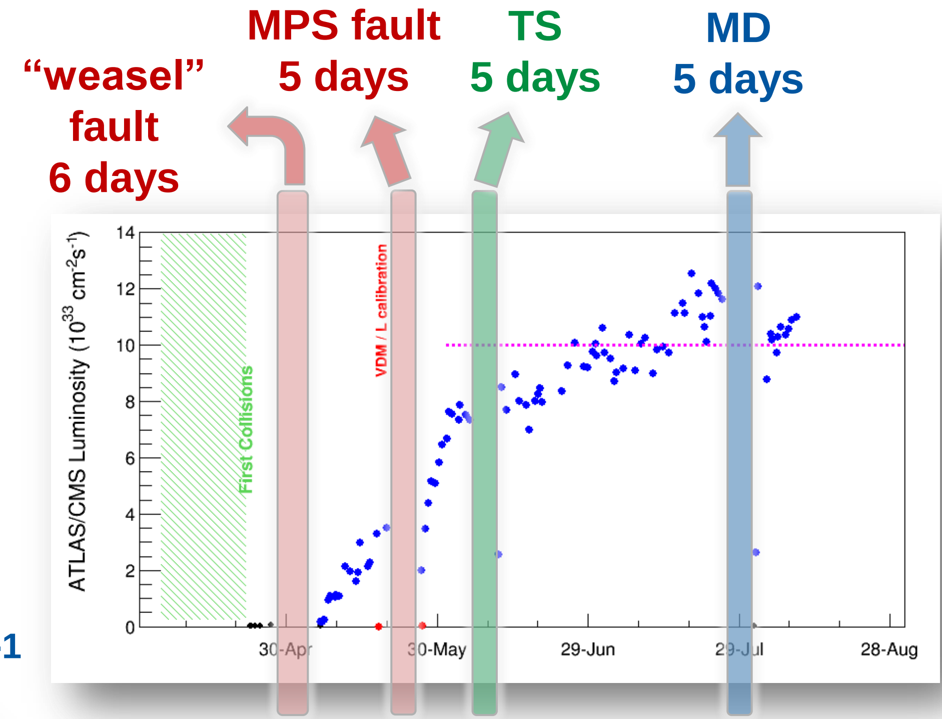
- Limitation to 96 b/inj => 2173 bunches

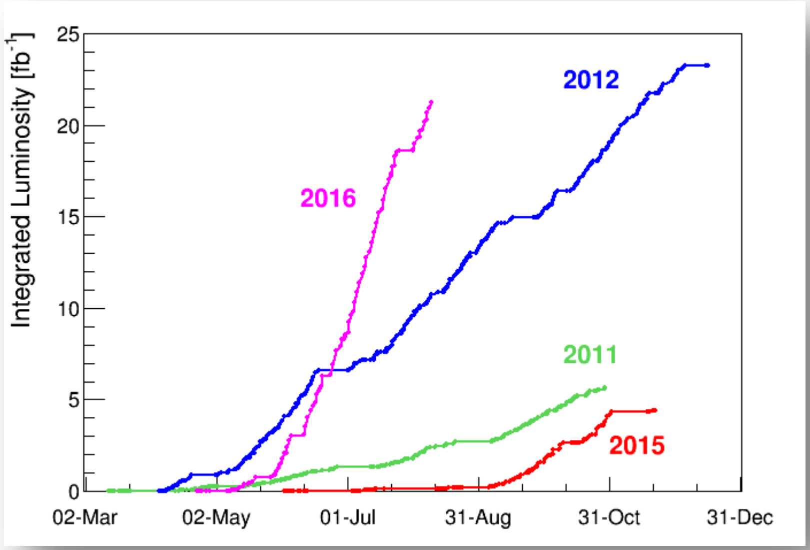
INJECTION KICKER
Limit total intensity
(number of bunches vs intensity/bunch)

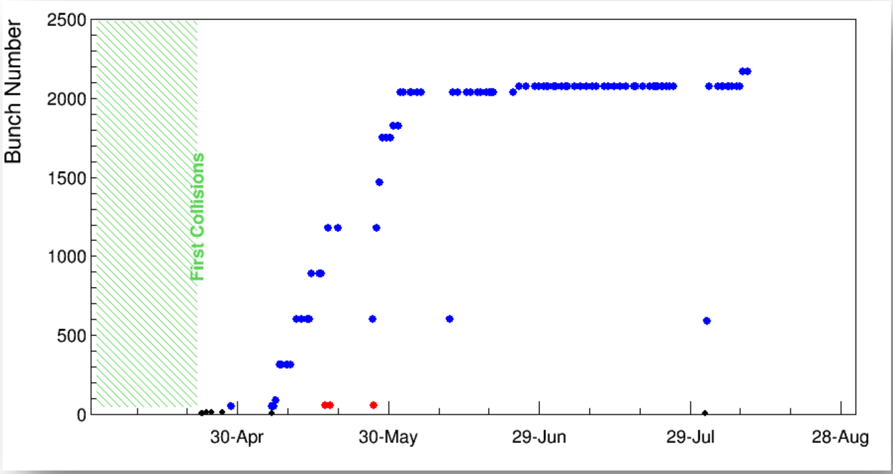


The big numbers

- Peak luminosity ~1.29 x 10^{34} $cm^{-2}s^{-1}$
- Delivered luminosity:
  - >20 fb^{-1} ATLAS & CMS
  - >1 fb^{-1} to LHCb
  - ~7 pb^{-1} to ALICE
- 3 fb^{-1} per (good) week
- Longest fill = 37 h
- Max luminosity in one fill = 725 pb^{-1}

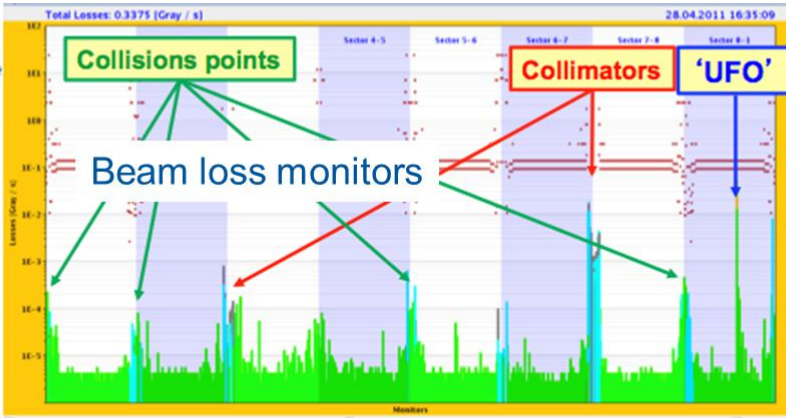


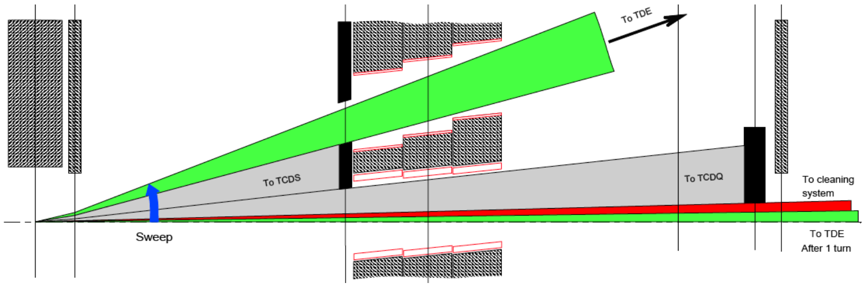


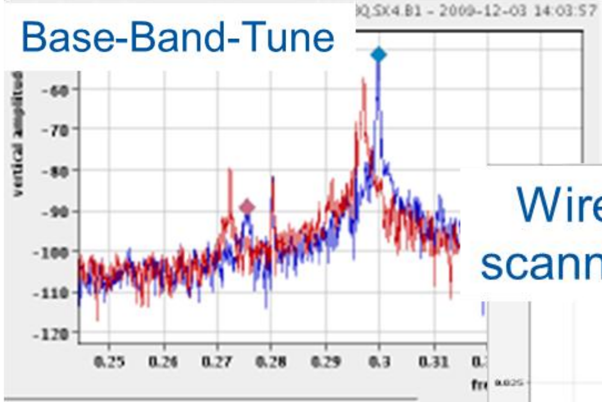


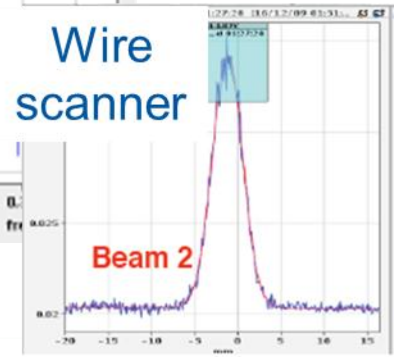
The essentials

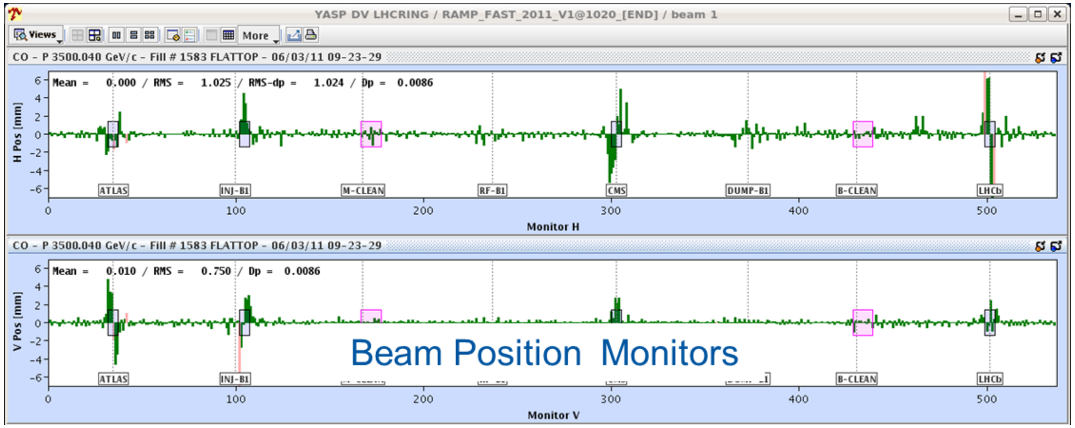
- **Enhanced** system performance:
  - Beam Instrumentation
  - RF & transverse feedbacks
  - Collimators
  - Vacuum
  - Machine protection & beam dump system

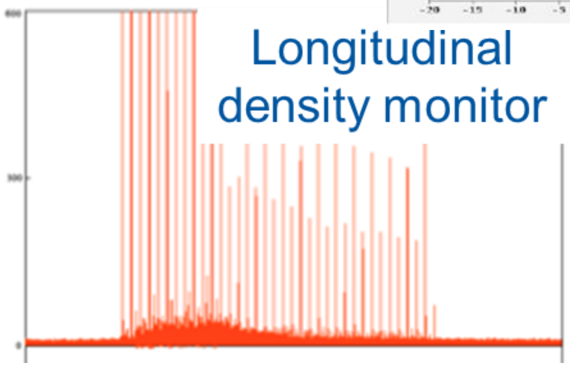






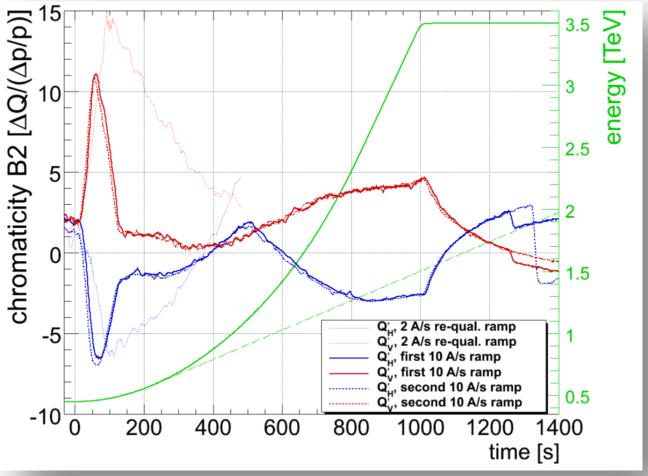


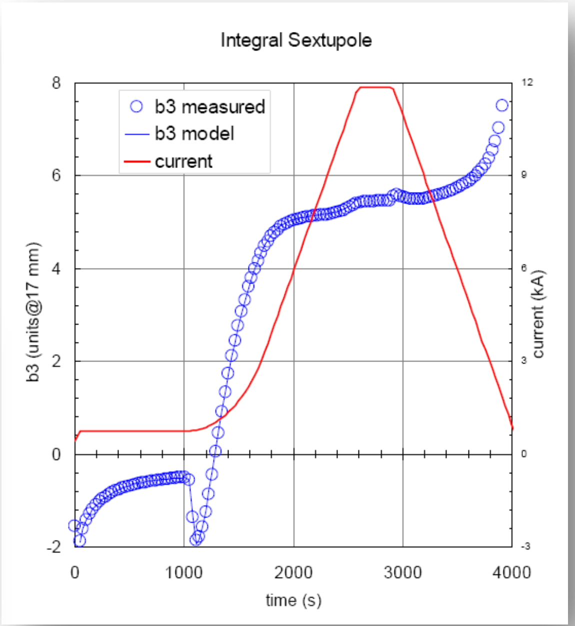


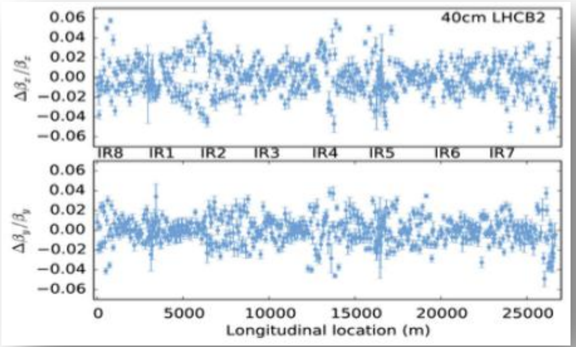


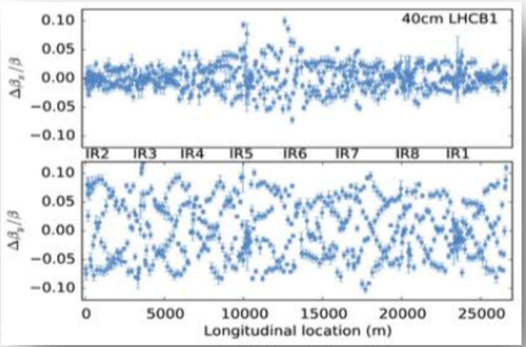
The essentials

- **Enhanced** system performance:
  - Beam Instrumentation
  - RF & transverse feedbacks
  - Collimators
  - Vacuum
  - Machine protection & beam dump system
- Aperture **better than expected**
- Feedbacks on orbit and tune **provide stability**
- **Good** magnetic reproducibility
- **Optically good**, corrected to excellent (< 2%)
- **Excellent** operation control…EXPERIENCE!









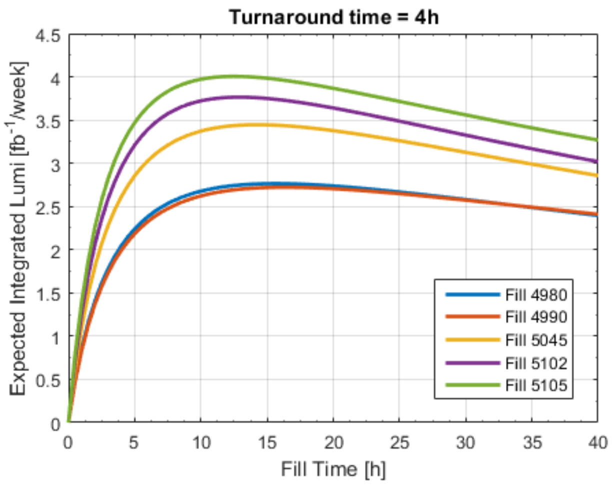
Performance increase & limitations

2016 PERFORMANCE INCREASE

- **Smaller** β* (40 cm)
- **Smaller** emittance (BCMS scheme)
- **Higher** number of bunches

FURTHER PERFORMANCE INCREASE

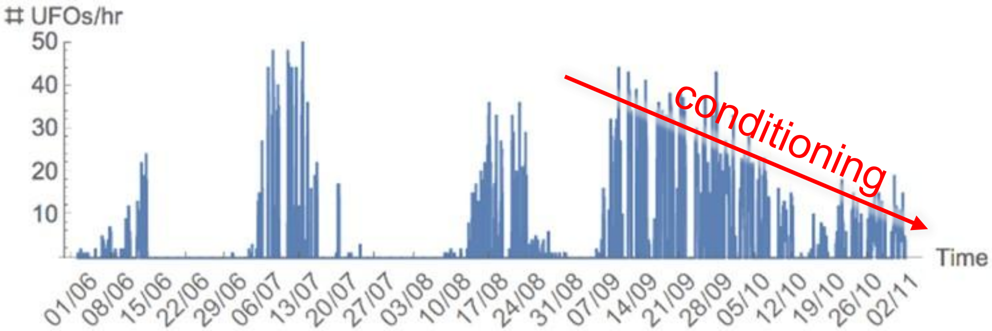
- **Maximize** number of bunches (once SPS dump exchanged)
- **Reduce** Xing angle (following analysis of MD results)
- Levelling in IP1/5 to **reduce** the initial particle losses
- **Further** squeeze (flat beams, new optics)
- **Optimize** fill duration (shorter turnaround)
- Energy **increase** (toward 7 TeV)

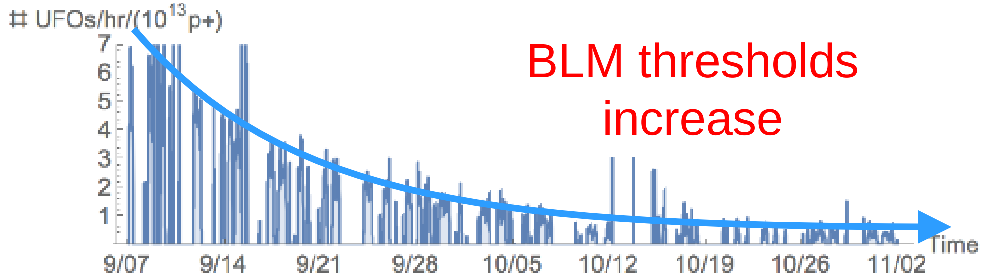


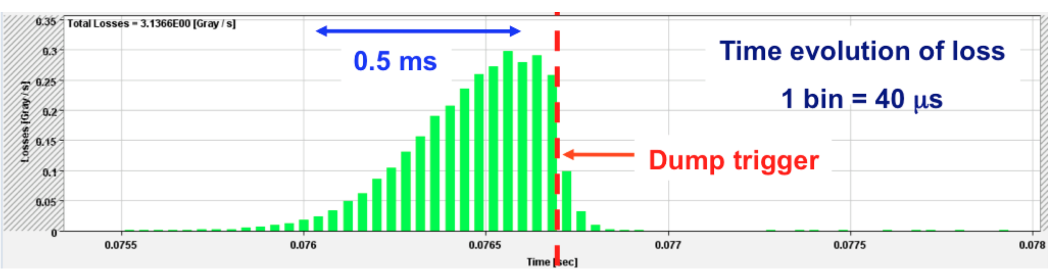
KNOWN LIMITATIONS

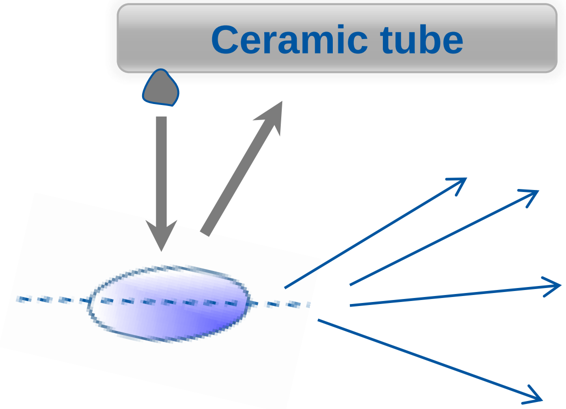
- E-cloud
- UFO
- Triplet, cryogenic limit ~1.7×10^{34} cm^{-2}s^{-1}

*U*n-identified *F*alling *O*bjects







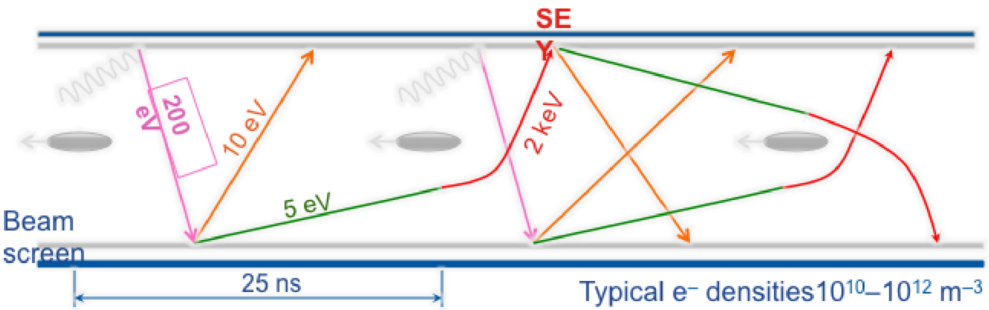


Dust particle dynamics model predicts:

- *Loss duration few ms* ✓
- *Faster losses for larger beam intensities* ✓

Electron cloud

When operating with small bunch spacing an avalanche-like process, **(Electron Cloud)** can develop in the beam chamber due to the Secondary Emission from the chamber's wall



Consequences:

– **impact on beam quality** (instabilities, emittance growth, particle losses)
– **bad vacuum**
– **excessive energy deposition**

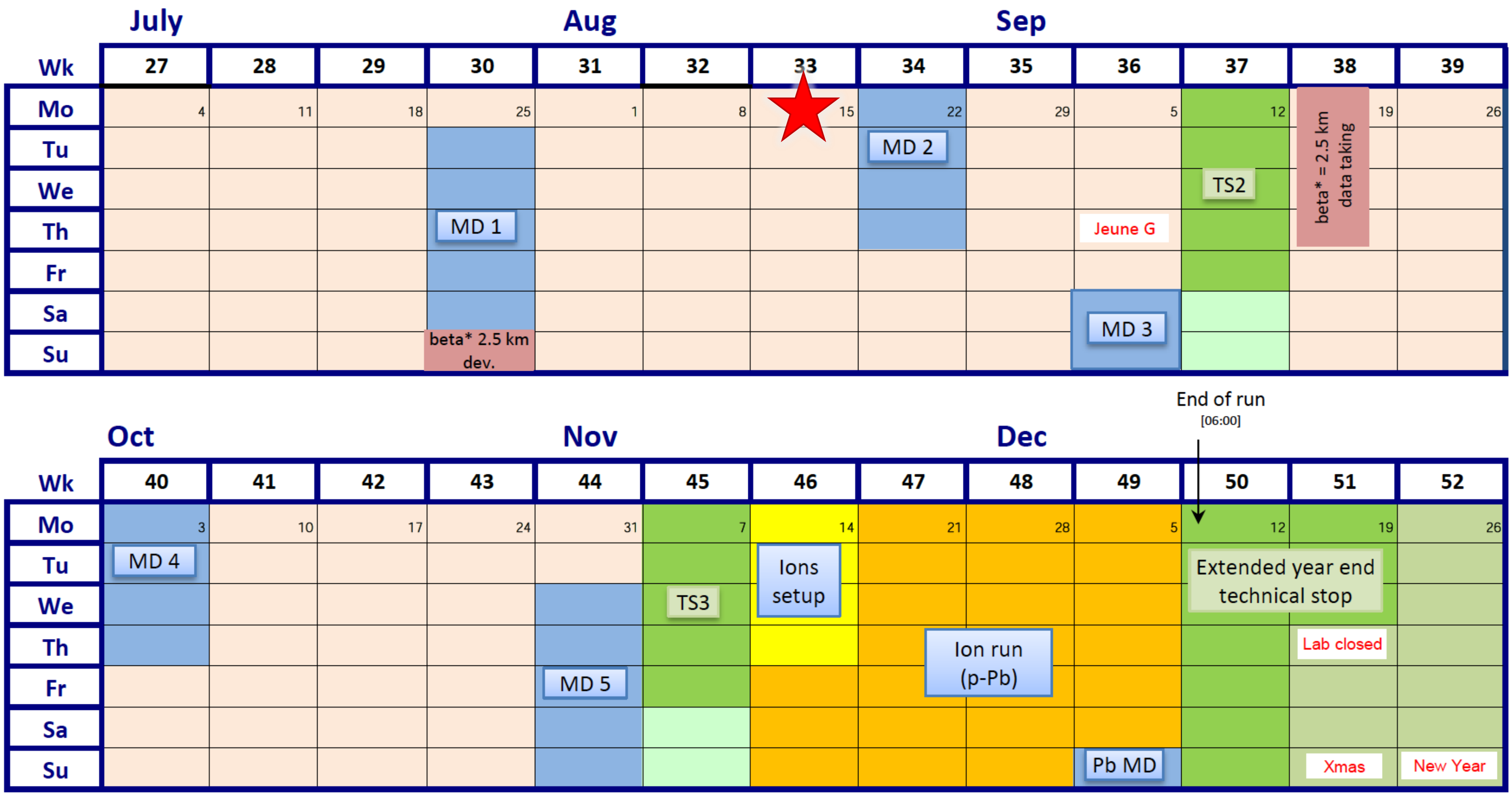
Electron bombardment of a surface proved to reduce drastically the **secondary electron yield (SEY)**

This technique **(scrubbing)** provides a mean to suppress e-cloud build-up

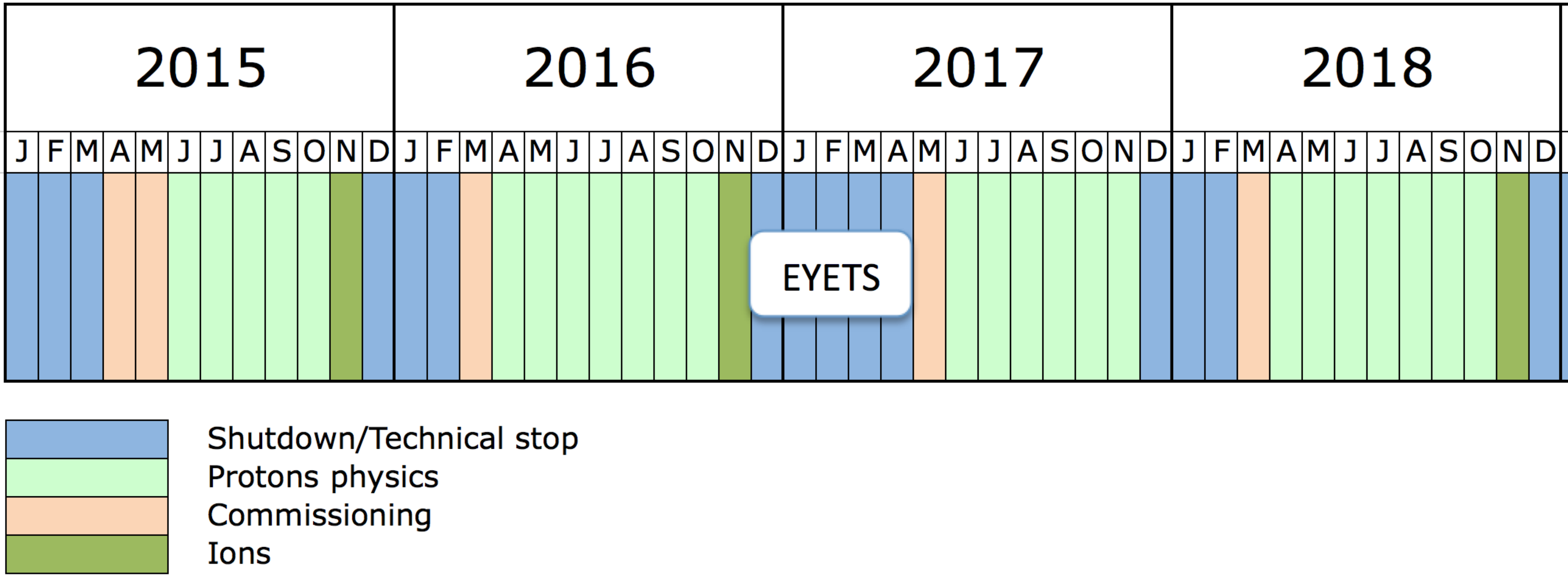
Observations confirmed a clear improvement of beam quality thanks also to scrubbing

LHC 2016 schedule

…still 58 days of pp physics ahead!!



LHC Run 2 schedule



EYETS – Extended Year End Technical Stop – 20 weeks

- CMS pixel upgrade
- Push 2 sectors towards 7 TeV

outline

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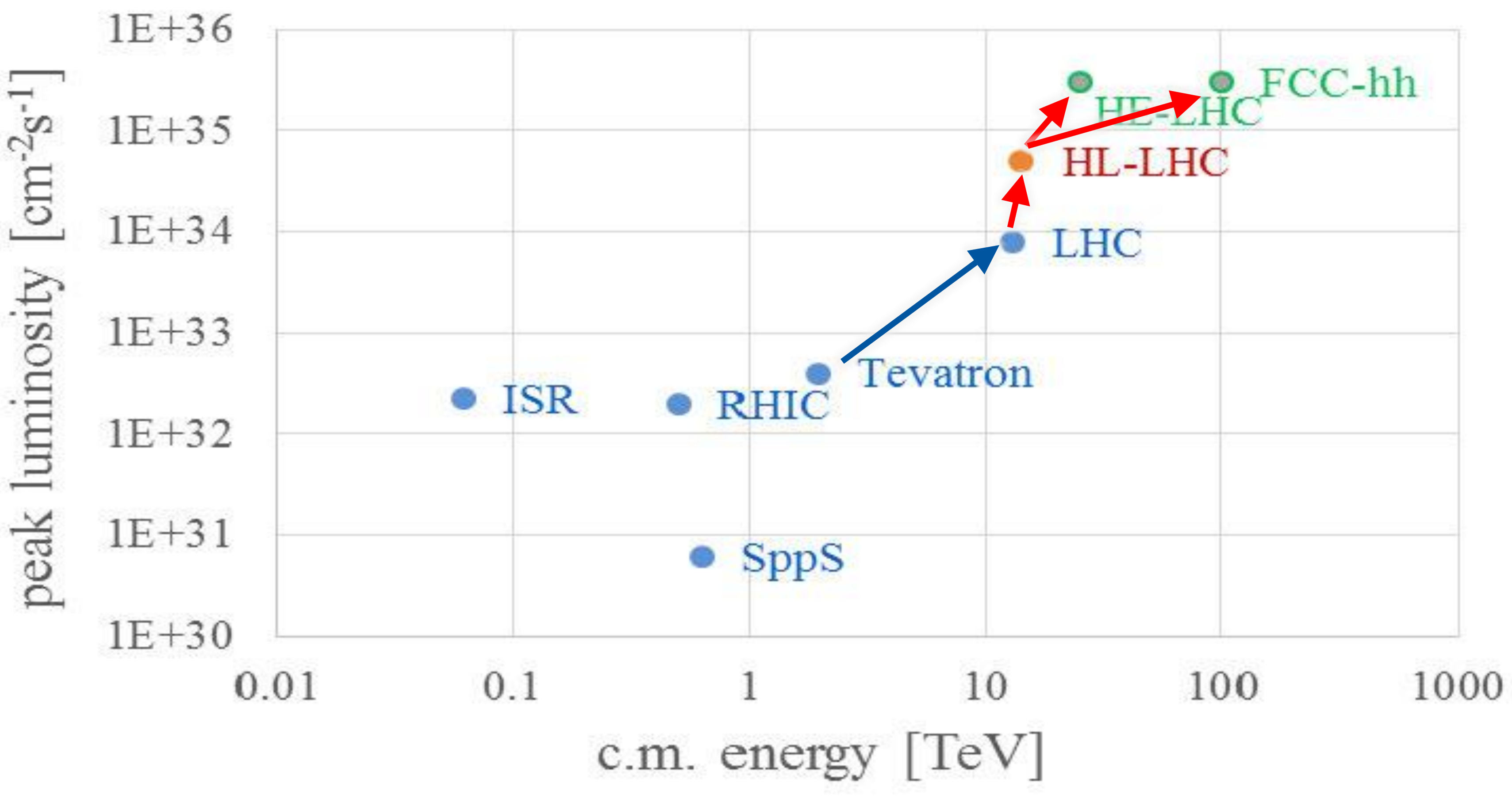
- ☑ **LHC status and plan**
  (performance & operational challenges)
- ☑ **The future…**

Future projects



HL-LHC

$$L = \frac{n_b \times N_1 \times N_2 \times \gamma \times f_{rev}}{4\pi \times \beta^* \times \varepsilon_n} \times F(\phi, \beta^*, \varepsilon, \sigma_s)$$

- **Maximize beam intensity**
- **Minimize beam emittance**

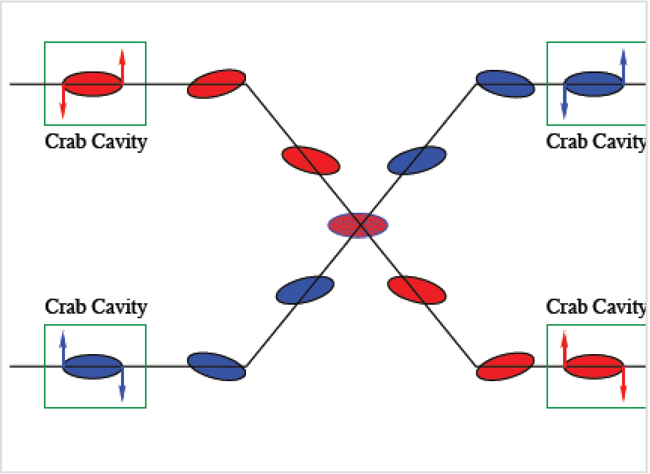
→ Injector complex (upgrade LIU)

- **Minimize beam size (**beta*)

→ Wide aperture triplet magnets (Nb_3Sn)

- **Compensate for ‘F’**

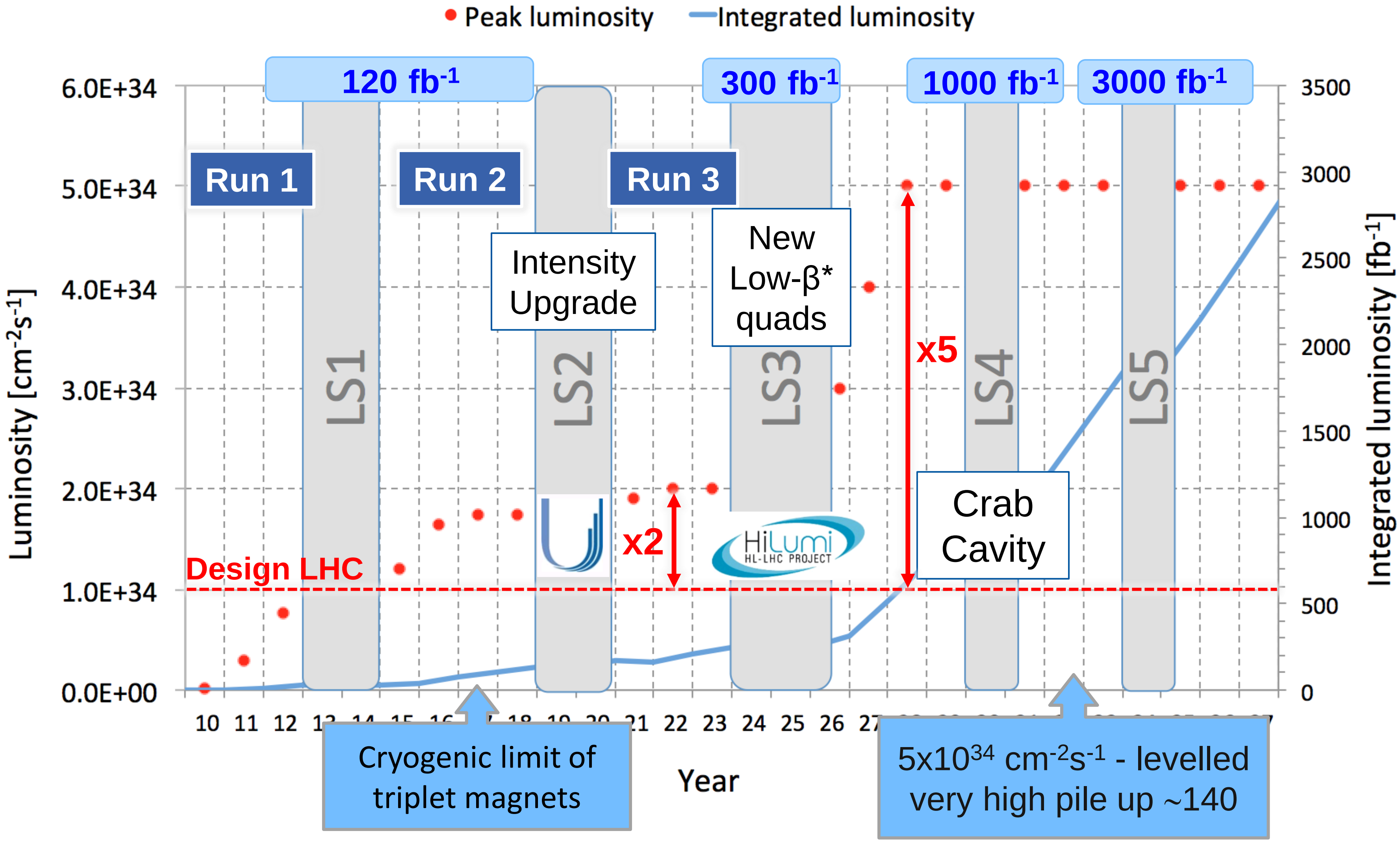
→ Crab Cavities



Crab cavity test in the SPS foreseen for 2018

Protons per bunch	2.2×10^{11}
Beta*	15 cm
Peak luminosity	5×10^{34} cm^{-2}s^{-1}
Crossing angle	590 μrad
Geometric reduction factor	0.305
Normalized emittance	2.5 micron
Virtual luminosity	24×10^{34} cm^{-2}s^{-1}
Levelled luminosity	5×10^{34} cm^{-2}s^{-1}
Levelled <pile-up>	140

HL-LHC luminosity reach



HE-LHC / FCC

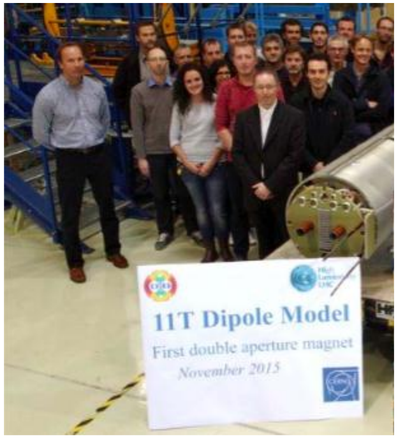
“Natural” continuation of LHC and HL-LHC programs

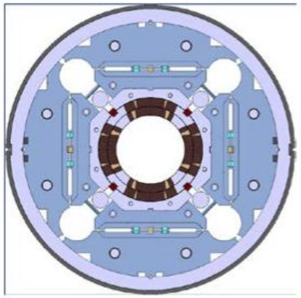
Step-wise approach → each step deployed and operated in a (big) accelerator:

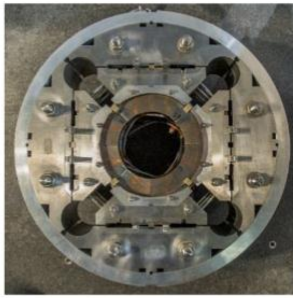
- HL-LHC: Nb_3Sn technology:
  - 11 T dipoles in dispersion suppression collimators
  - 12-13 T field low-β quads for ATLAS and CMS IR’s

December 2015:
short Nb_3Sn dipole reached 11.3 T

March 2016:
short Nb_3Sn quadrupole reached 18 kA

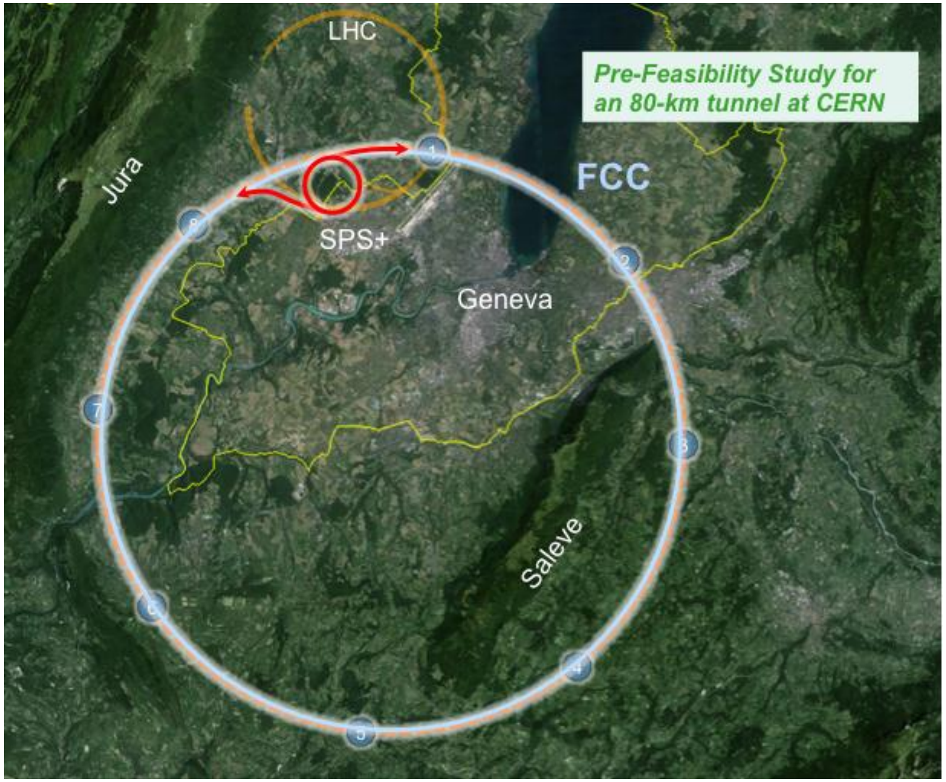




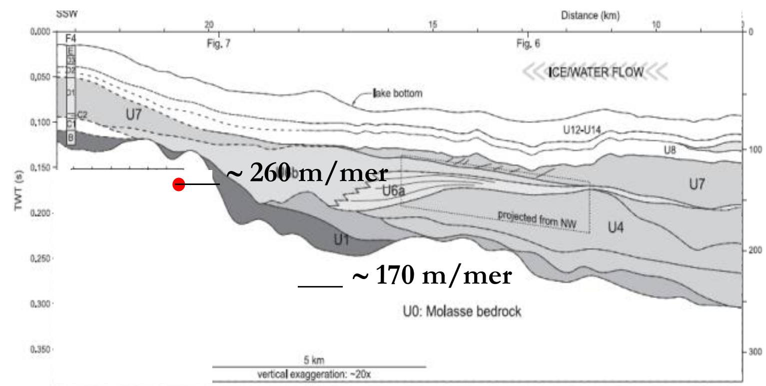


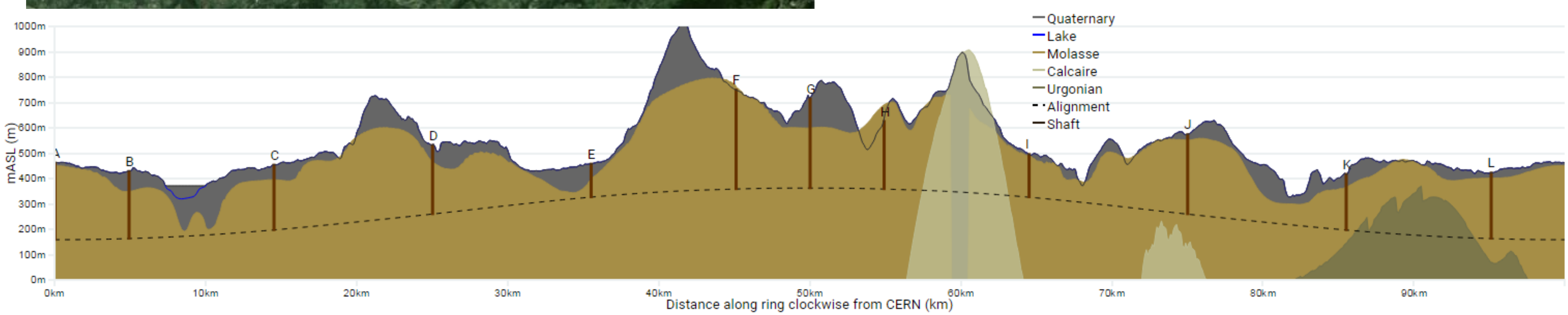
Parameter	HE-LHC	FCC
Collision energy [TeV]	25	100
Circumference [km]	27	80/100
Dipole field [T]	16	16 or 20
Injection energy [GeV]	450	3000
Peak luminosity [$cm^{-2}s^{-1}$]	34×10^{34}	30×10^{34}
#event/bunch crossing	1070	Up to 1020
Stored energy [GJ]	1.4	8.4

FCC



LAYOUT OPTIMIZATION





Conclusions

- **The tremendous LHC performance is due to outstanding design and excellent preparation**
  - Superb models
  - Brilliant performance of all system
  - Impressive work
  - Huge amount of experience and understanding
- **There is still much to do**
  - Keep improving models and knowledge
  - Overcome limitations
  - Push further
- **A bright future is in front of us**
  - Increase LHC performance
  - HL-LHC
  - FCC/HE-LHC...

Thank you for the attention!

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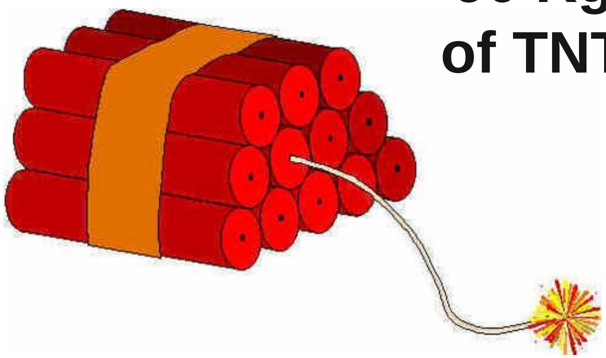
The LHC nominal beam

- 2808 bunches
- $1.15e^{11}$ p/bunch

90 Kg of TNT



Energy per beam ~ 360 MJ

Magnetic energy per sector (6.5 TeV)

1.2 GJ

FCC

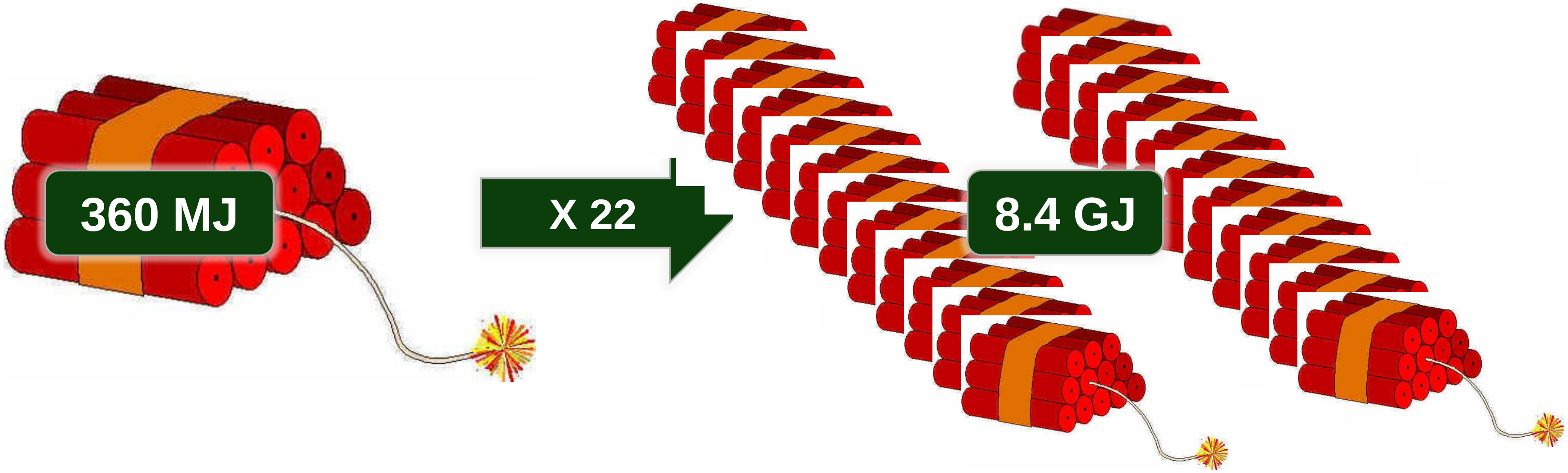
Circumference	80 or 100 km
Maximum dipole field	20 or 16 T
Injection energy	> 3.0 TeV
Maximum energy	100 TeV
Peak luminosity	5 x 10^{34} $cm^{-2}s^{-1}$
Stored beam energy	~5500 MJ

Among the many challenges:

- Synchrotron radiation heat load
- Collimation
- Interaction region quadrupoles
- Arc quadrupoles (naïve scaling gives 1593 T/m at 50 TeV)

LHC nominal beam
90 kg of TNT

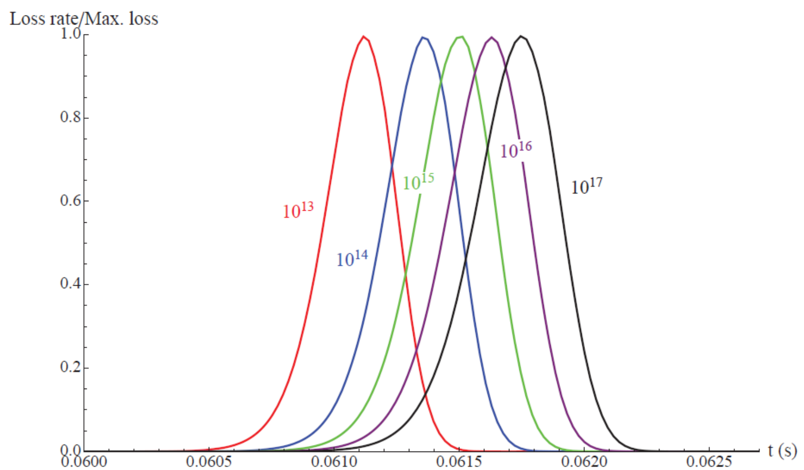
FCC beam ~2 tons of TNT



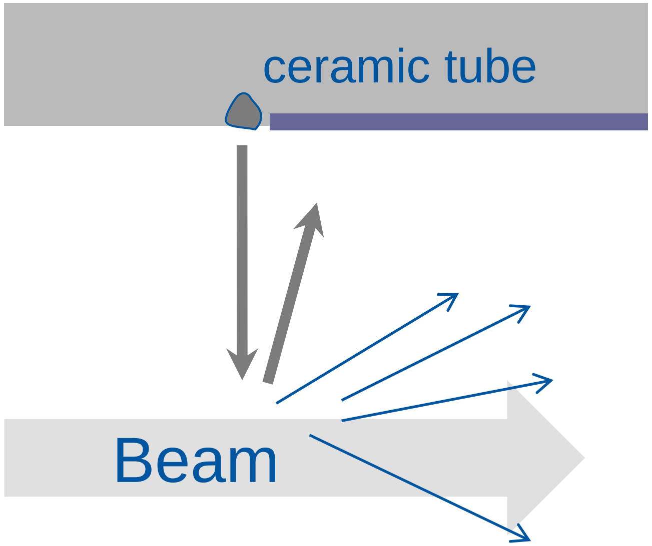
Operational challenges – UFO

Implemented in dust particle dynamics model, which predicts (among others):

- *Loss duration of a few ms*
- *Losses become faster for larger beam intensities*



Beam loss rate as a function of time for different macroparticle masses. Beam intensity: $1.6 \cdot 10^{14}$ p



Despite several corrective measures have been implemented during LS1, UFOs could become critical during Run2 due to:

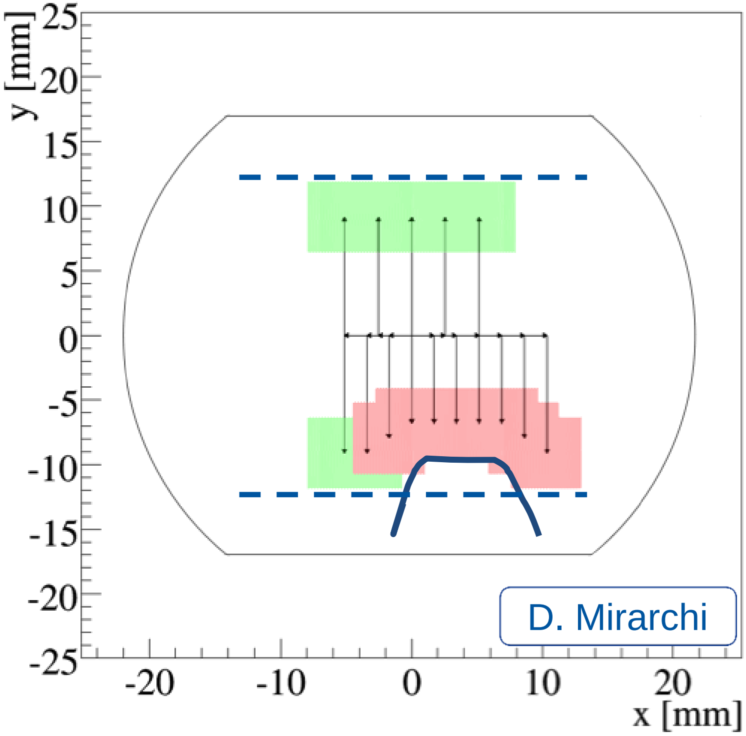
- **Much lower** BLM threshold
- UFO activity increases by about **5-10 times** with **25ns** operation

ULO (*Unidentified Lying Object*)

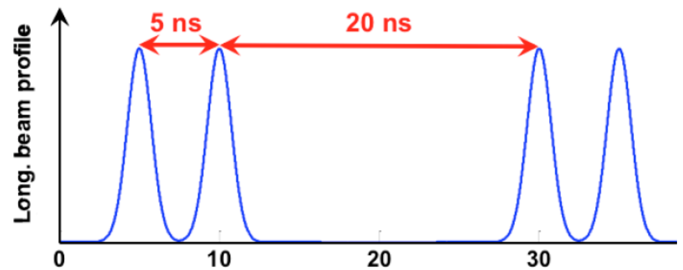
Aperture restriction measured at injection and 6.5 TeV in 15R8

- Presently running with orbit bumps
  - -3 mm in H, +1 mm in V, to optimize available aperture
- UFOs stopped after second beam screen warm-up
- Behaviour with higher intensities looks OK

…stability of the object remains a concern



2015 scrubbing strategy



Non adiabatic splitting at SPS injection

Approach with two scrubbing phases

Phase#1

(**50 ns and 25 ns** beam for 50 ns operation)

50 ns beam → ~1000 bunches

- Excellent beam lifetime, no e-cloud

25 ns beams → ~1000 bunches

- Beam degradation important, slow improvement (main limitation was MKI vacuum)

Phase#2

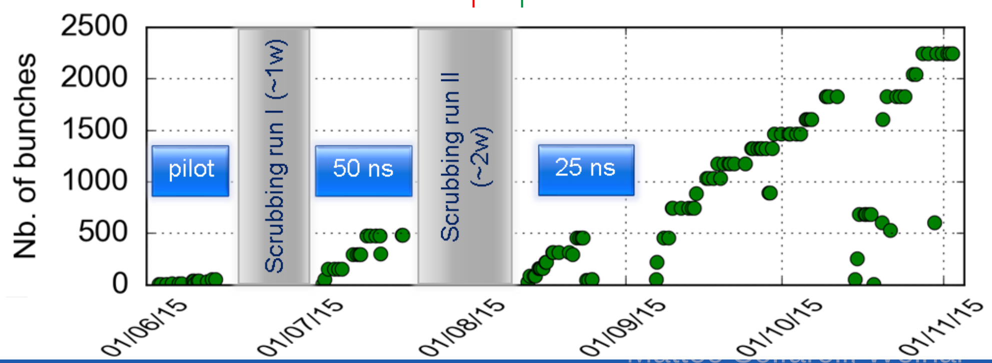
(**25 ns and doublets** for 25 ns operation):

25 ns beam → >2000 bunches

- Injection phase **limited by cryo and vac (TDI and MKI)** for B2

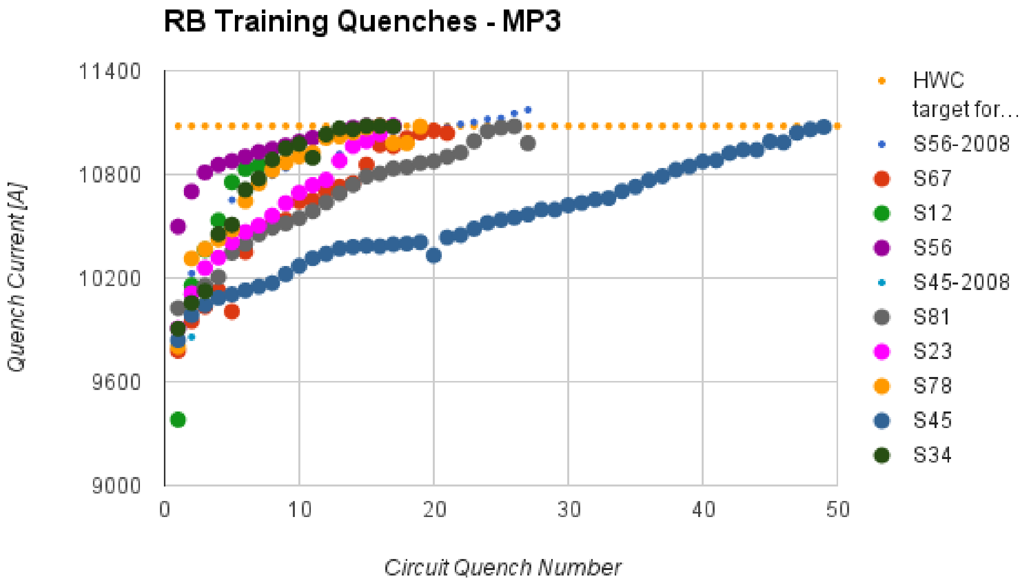
Doublet beams → ~250 bunches

- **Larger e-cloud,** fast beam quality



Possible energy increase

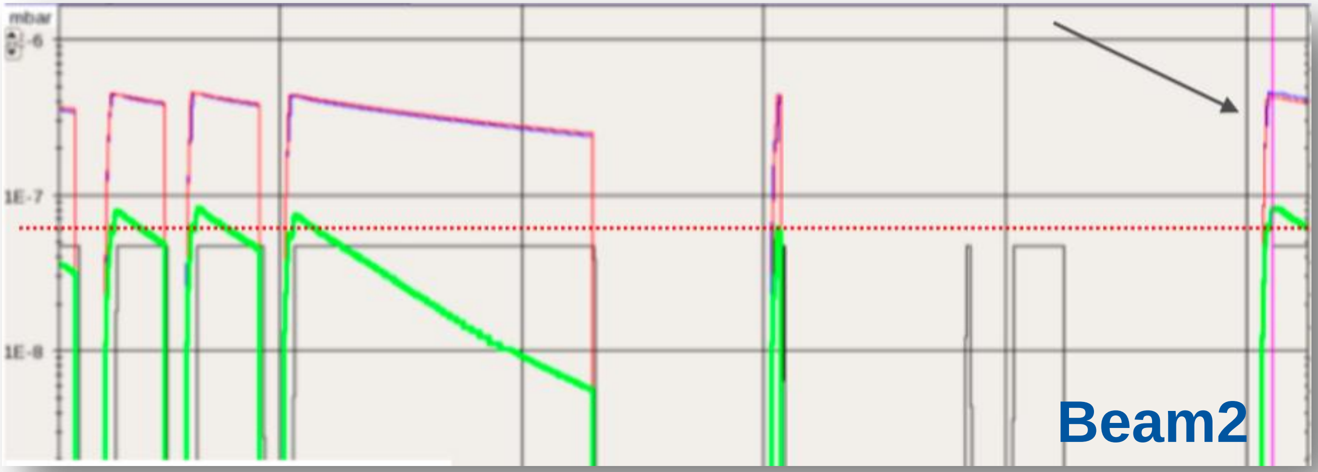
- ➢ Ramp the current until single magnet quenches - "training quench"
- ➢ 164 quenches needed in 2015 to reach 6.5 TeV
- ➢ Up to 49 quenches in a single sector



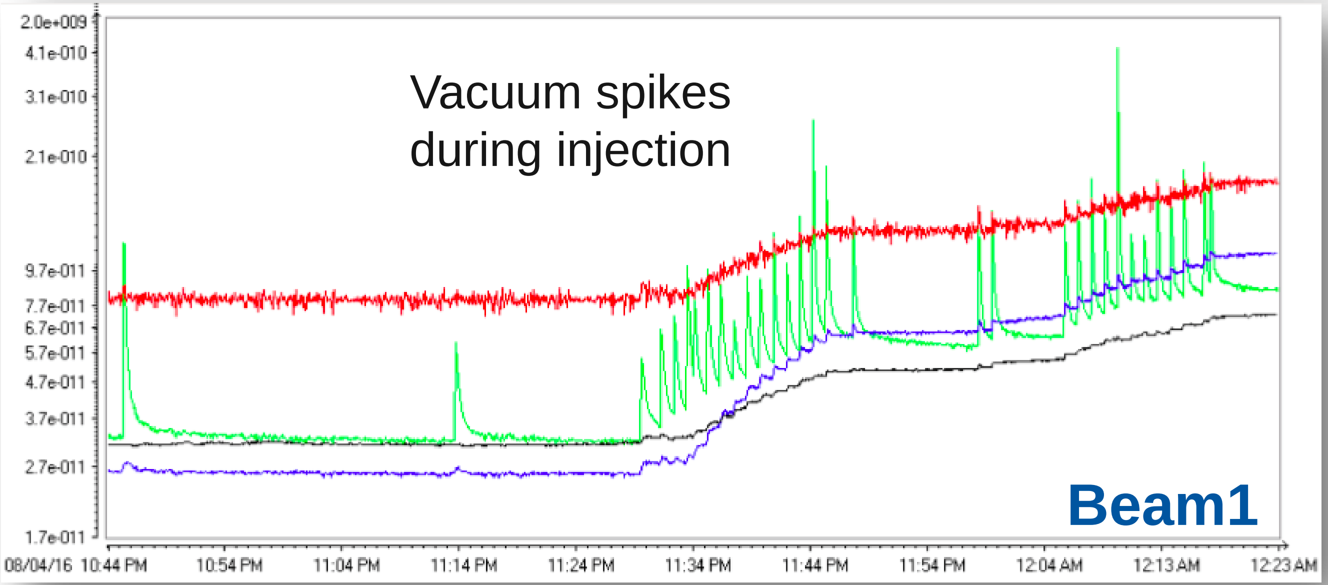
- ➢ Cryogenics recovery time: 6 – 8 hours
- ➢ 2 sectors will be likely used as a type test before the EYETS to estimate the time needed to commission the LHC to 7 TeV

MKIs

Vacuum level prevents further injection



Vacuum spikes during injection



Total intensity limitation

High number of bunches vs high intensity/bunch

Crab cavities

- Create a oscillating transverse electric field
- Kick head and tail of the bunch in opposite directions
- Serving to mitigate the effect of the crossing angle at the IP

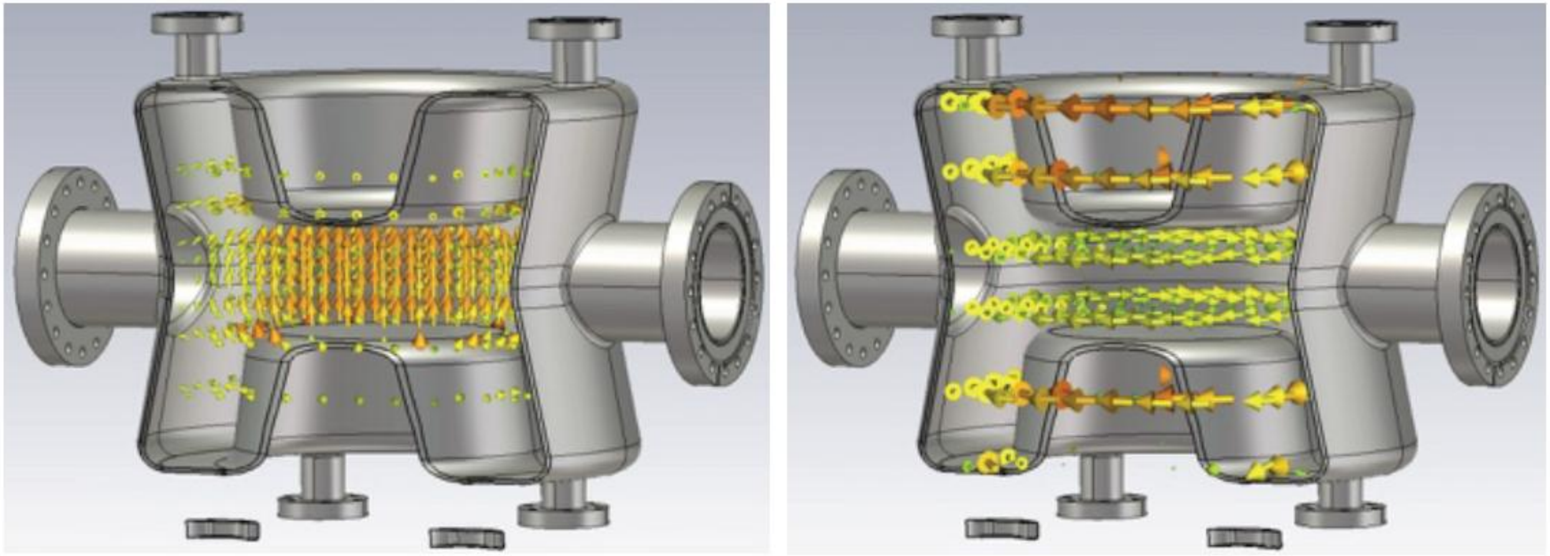
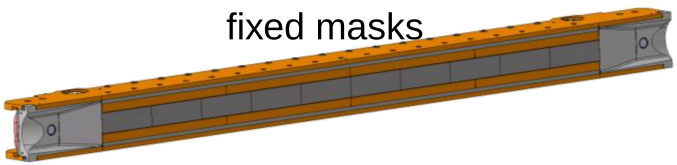


Figure 4. Electric (left) and magnetic (right) field distributions inside the DQWCC.

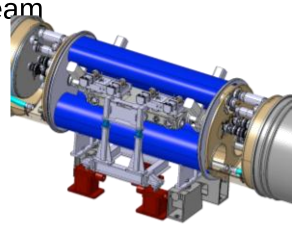
Collimators upgrade

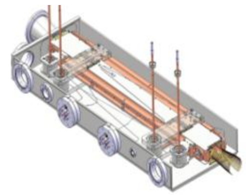
Completely new layouts
Novel materials.
IR1+IR5, <u>per beam</u>:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks

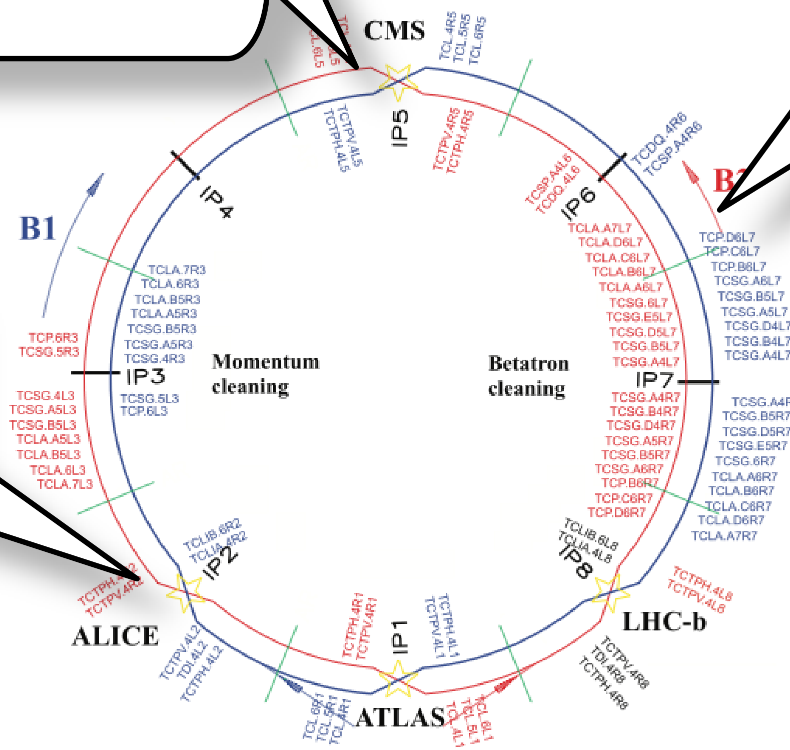


56 new collimators to be produced by LS3 in the present baseline!

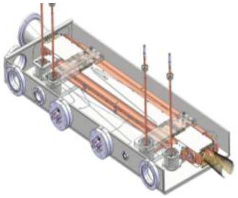
Cleaning: DS coll. + 11T dipoles, 2 units per beam



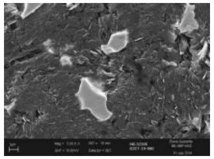


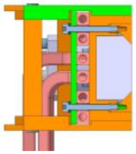


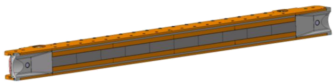
Ion physics debris: DS collimation



Low-impedance, high robustness secondary collimators

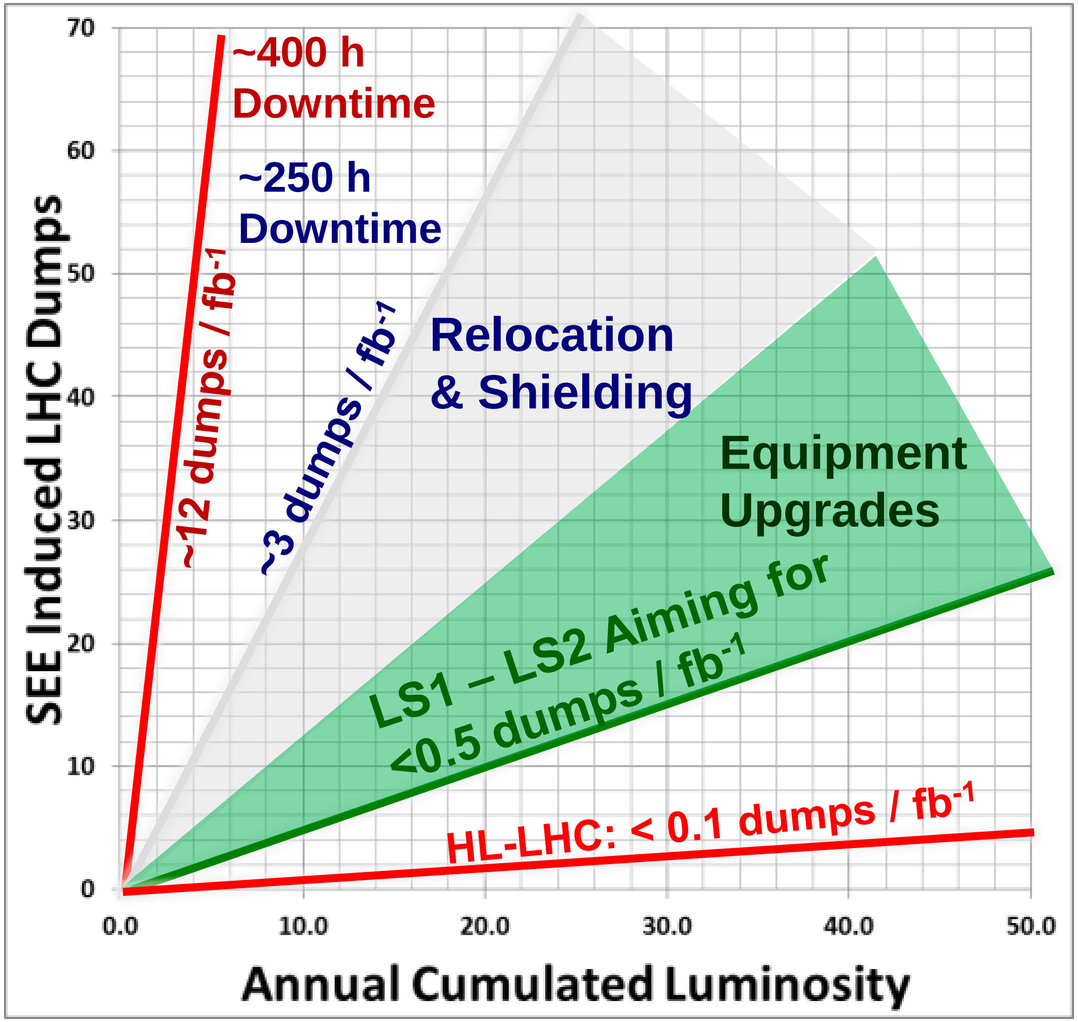






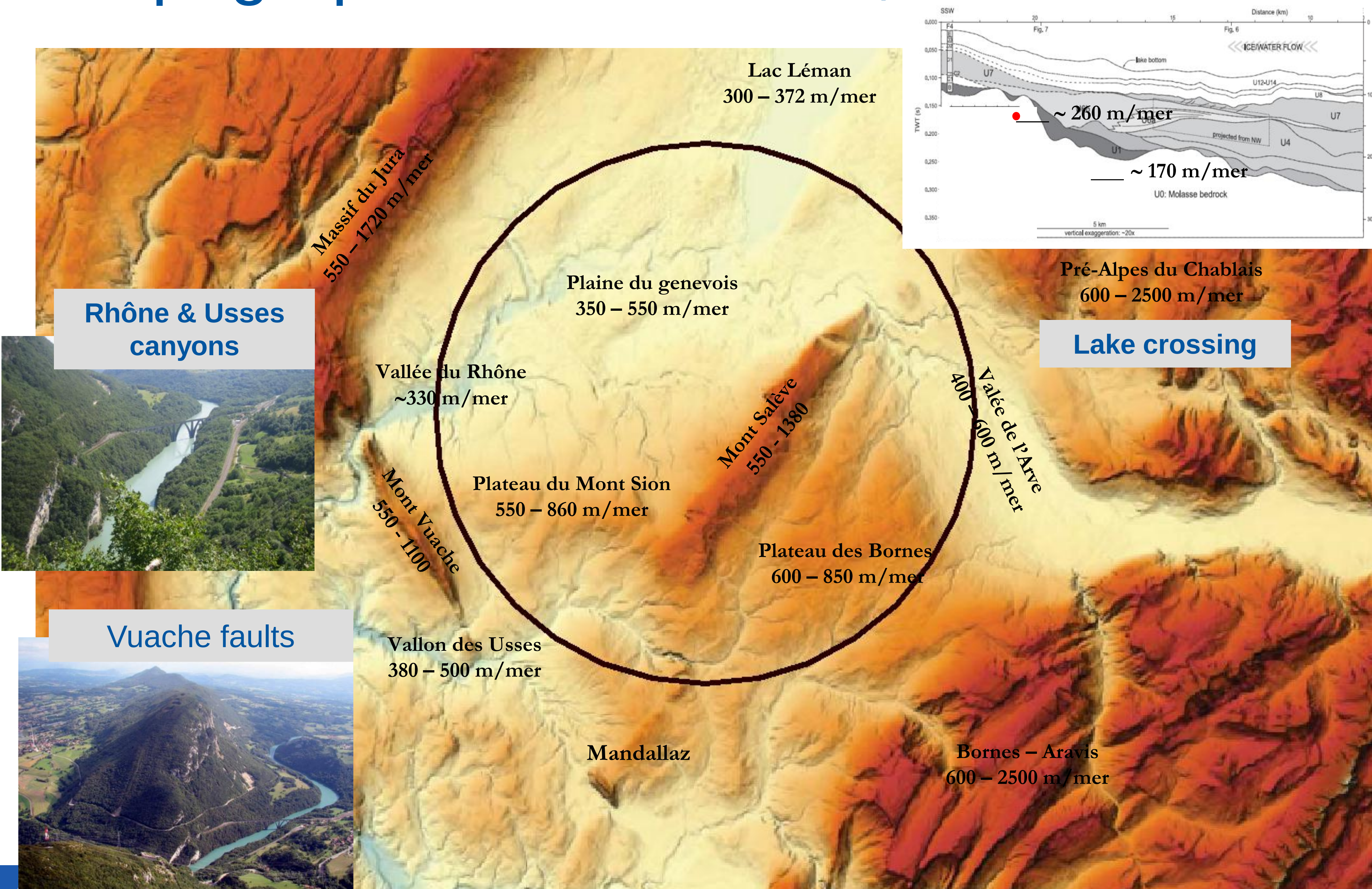
S. Redaelli,
Chamonix 2016, 28-01-2016

R2E SEU Failure Analysis - Actions



- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact
- **2011-2012**
  - Focus on equipment with long downtimes; provide shielding
- **LS1 (2013/2014)**
  - Relocation of power converters
- **LS1 – LS2:**
  - Equipment Upgrades
- **LS3 -> HL-LHC**
  - Remove all sensitive equipment from underground installations

Topographical constraints, critical areas



Lake crossing

Rhône & Usses canyons

Vuache faults