Commissioning Large Low-Emittance Rings: LEP and LHC

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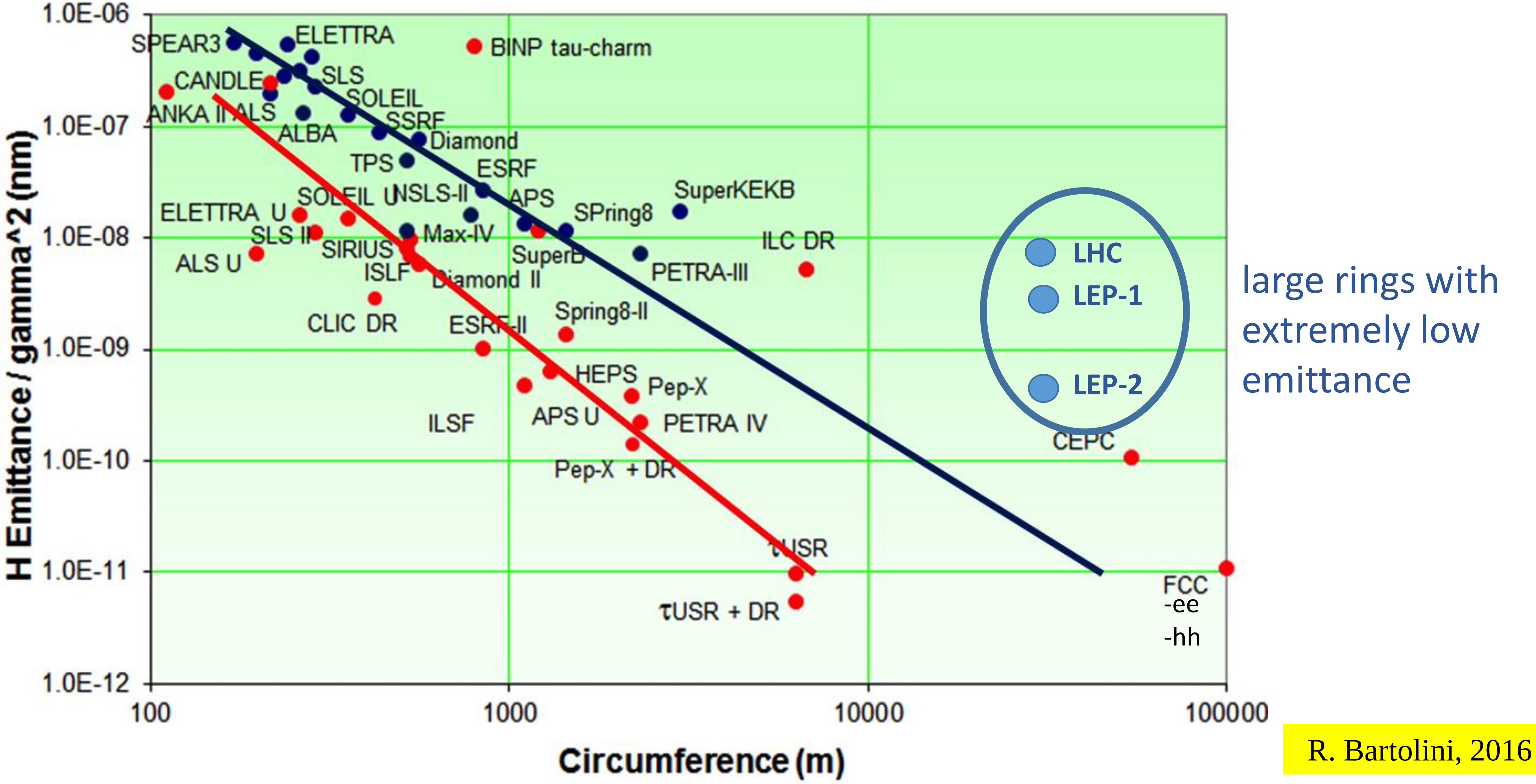
landscape of low emittance rings



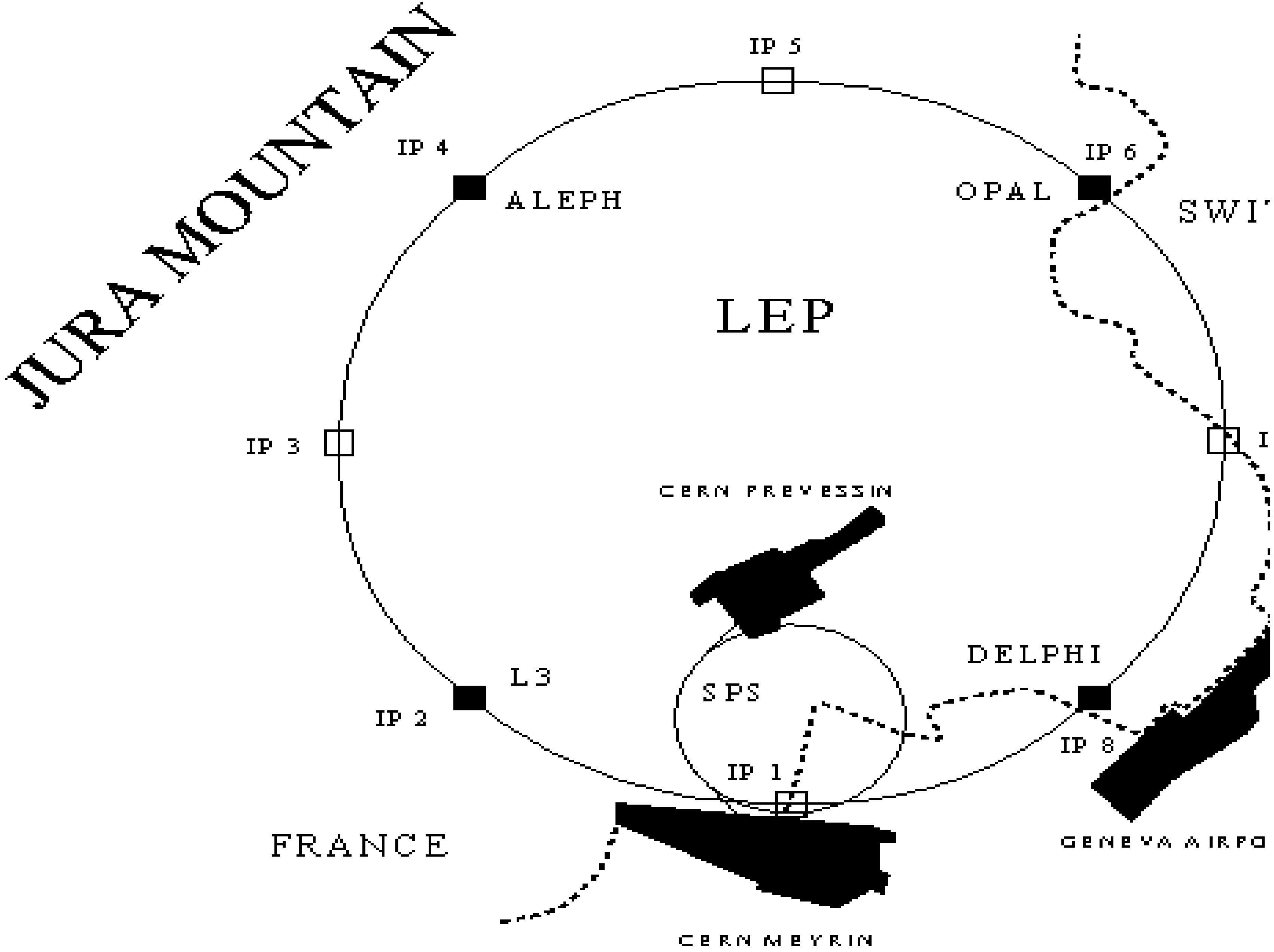
R. Bartolini, 2016

Emittance normalized to beam energy vs. circumference for storage rings in operation (blue dots) and under construction or being planned (red dots). The ongoing generational change is indicated by the transition from the blue line to the red line.

26.7 km
LEP/LHC tunnel

depth 70-140 m

Layout of the Large Electron Positron collider (LEP)



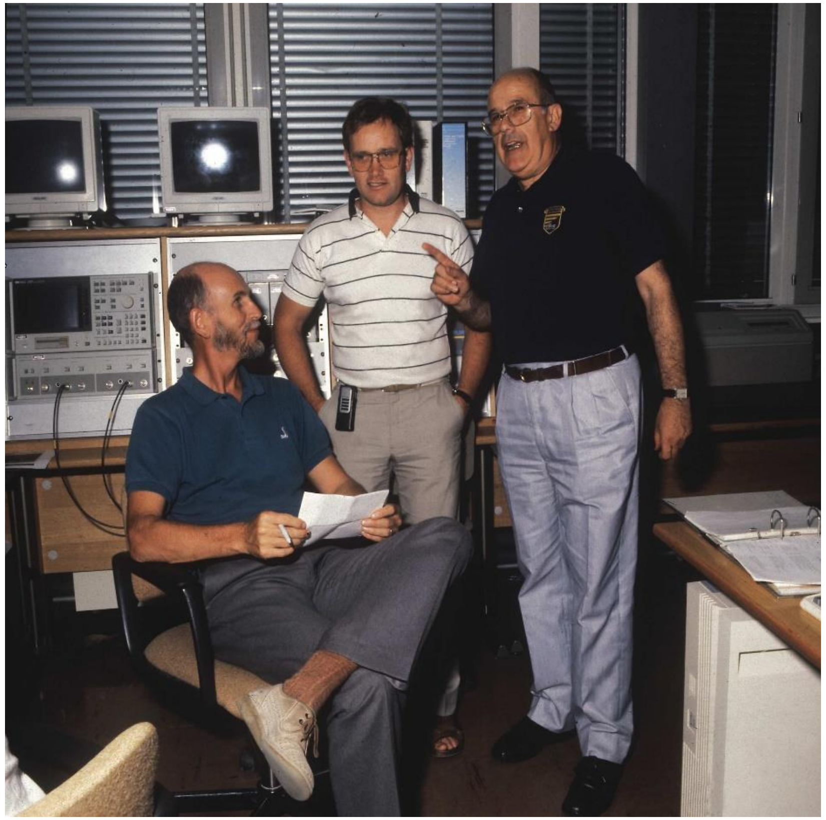
S. Myers, Twelve years of beam in LEP, UK_LEPfest, Birmingham, June 2001

LEP Commissioning 1989

S. Myers, The LEP Collider, from Design to Approval and Commissioning, CERN 91-08
S. Myers, The Performance of LEP and Future Developments, Proc. EPAC 1990

preparation:

- **careful planning and coordination,** e.g. to avoid any conflicts between system tests and transport
- **component tests after installation** (magnets, RF, instrumentation, controls, injection devices, el.-static separators, cabling, water cooling and ventilation)
- **individual tests of more than 800 power converters, magnet polarity checks and double checks**
- **vacuum chamber bakeout** (superheated water and electrical jackets) and **leak tests**
- RF cavity conditioning up to maximum power (16 MW)
- **software preparation** in close collaboration with collider operators and accelerator physicists
  - clear definition of priorities (***software available when needed***)
- **global testing without beam; complete cold check out** (incl. ramping) one week before start of beam operation

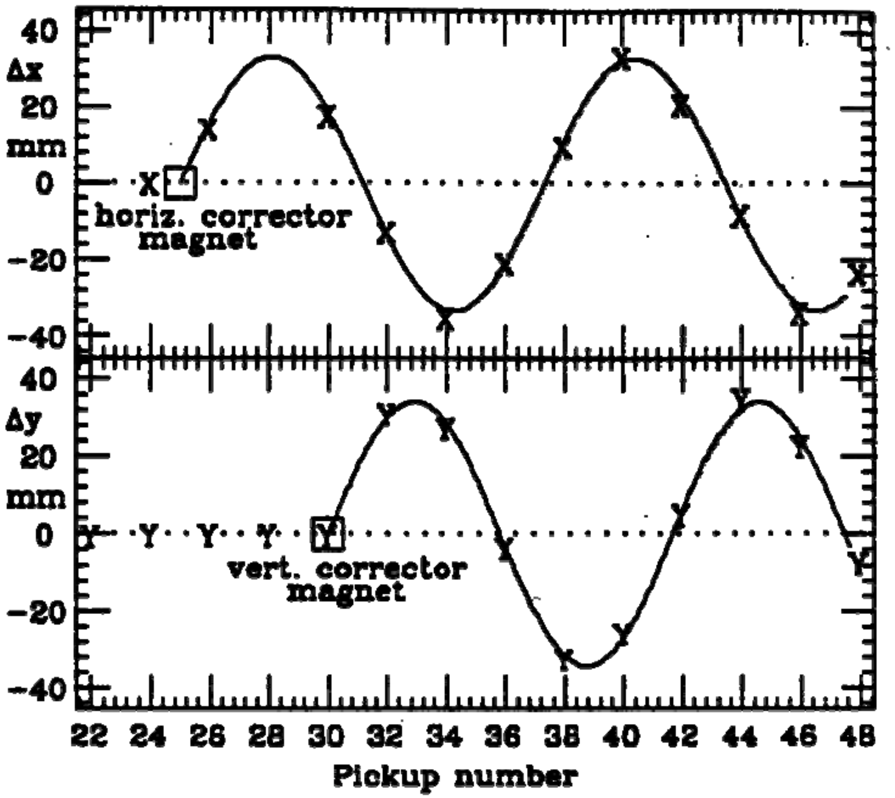


LEP Pre-Commissioning 1988

S. Myers, Injection and Transport of Beams of Positrons into and Through an Octant of LEP, Proc. Chamonix XI, 2001

Sector test:

- In July **1988 injection and transport of an e+ beam** of ~18 GeV through **1st completed octant of LEP** achieved on 'first shot'. Subsequently, many beam tests on various **LEP hardware and optics parameters**. Test lasted 100 h in total.
- Inferred **alignment errors** significantly smaller than expected.
- The **betatron phase advances** showed a slight phase difference between the horizontal and vertical planes, later explained by the presence of a minute amount of ferromagnetic material.
- The **off-axis injection and the 90° lattice** were successfully tried out.
- These injection tests proved **extremely useful for the preparation of the ultimate commissioning of LEP**.



trajectory difference measurements during LEP injector test

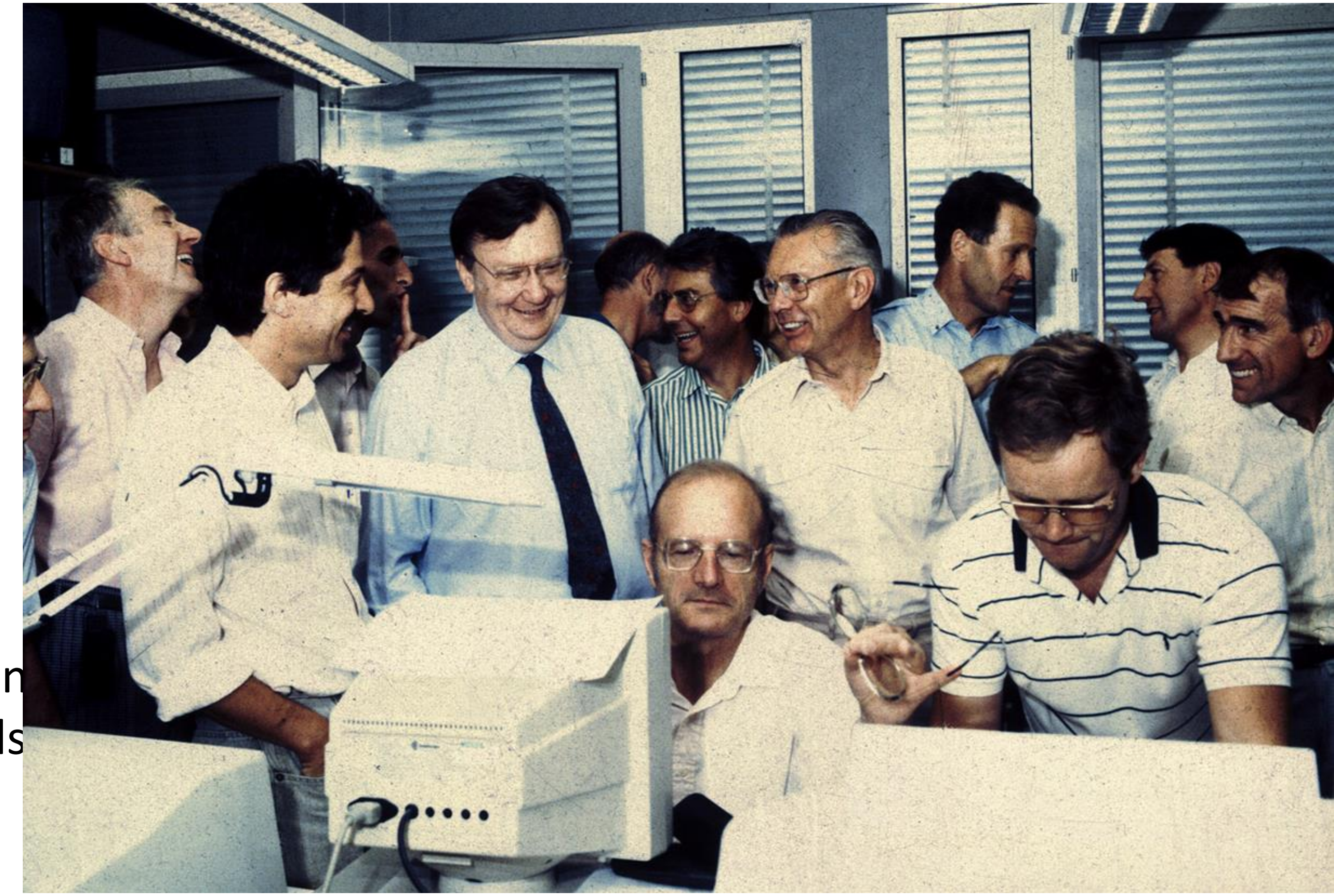
LEP Commissioning 1989

S. Myers, The LEP Collider, from Design to Approval and Commissioning, CERN 91-08
S. Myers, The Performance of LEP and Future Developments, Proc. EPAC 1990

execution:

1 month

14 July: first beam, **single turn** for e+ beam
18 July **beam capture by RF,** $\sim$100 turns
20 July beam-orbit monitoring system used to measure and **correct single-turn orbit**
22 July **revolution frequency: $\Delta C<1$ cm**
22 July **betatron tunes** measured & corrected
23 July **circulating e+ beam, lifetime** 20 minutes
25 July e- injection
30 July C.O. measurement & automatic correction
30 July **accumulation**, effect on vacuum pressure
31 July **SR monitor** commissioned
1 August **injection studies** $\rightarrow$ good accumulation
2 August **Q' correction** with 6 SX families
3 August, **energy ramp** to 47.5 GeV,
el-static separators commissioned
5 August **measured impedance** $\sim$65% of expectation
8 August **compensation of coupling** due to solenoids
10 August energy ramp followed by **β squeeze**
12 August accumulation of both e+ and e-
13 August **first stable beam for physics**



LEP Commissioning 1989

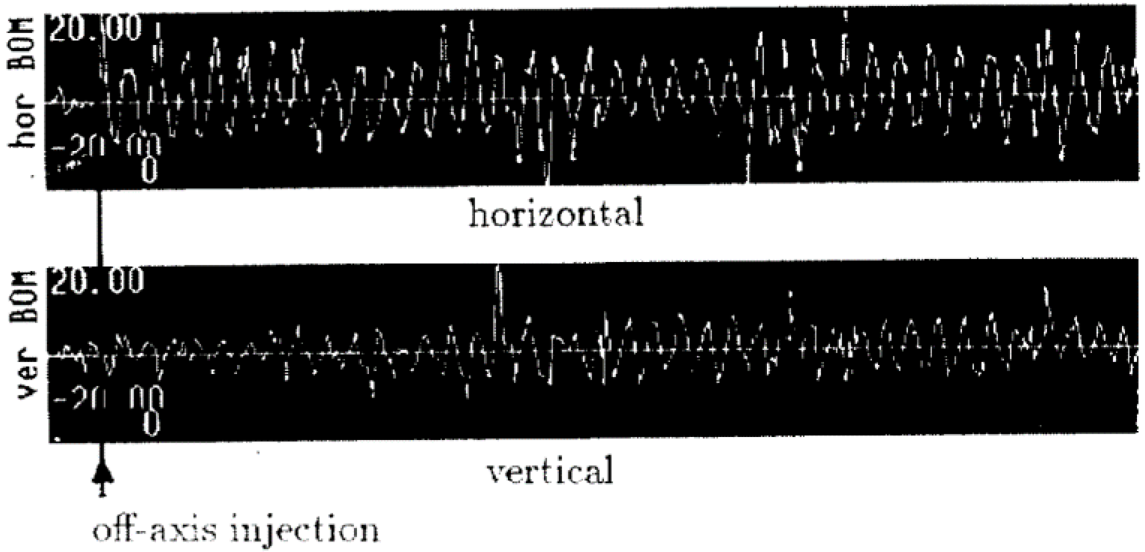
one early observation:

- ***abnormally large horizontal-to-vertical coupling*** in the vicinity of Q_x-Q_y=-8; measurements of closed tune approach, coupling of H&V orbits, and coupling of dispersion
  → ***source field within dipoles, independent of energy, not constant around the ring***

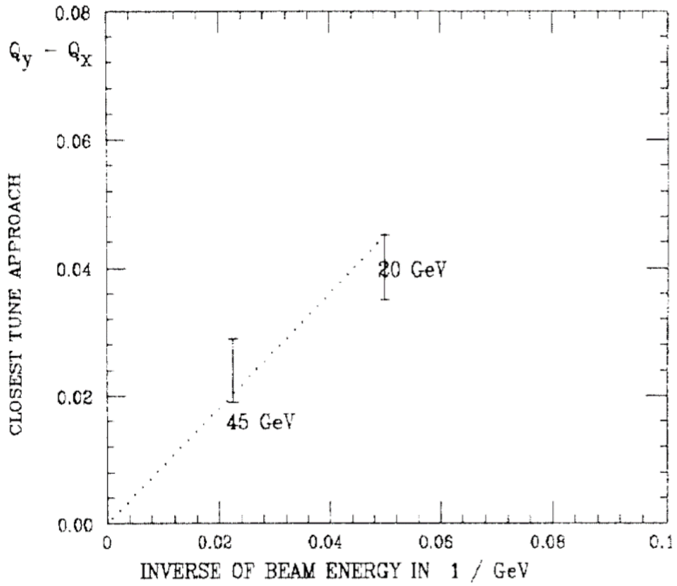
culprit: magnetized thin layer of nickel used to clad lead shielding onto Al chamber

- *retuning the optics away from this resonance (to Q_x-Q_y=-6) allowed near normal operation*

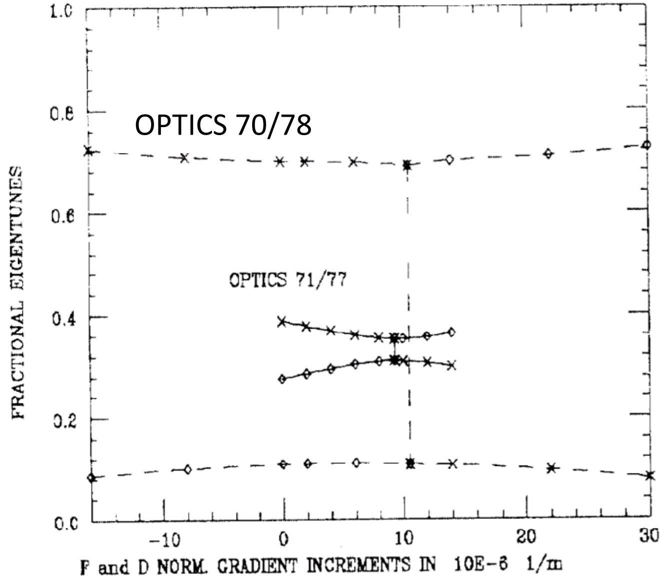
J. Billan et al., Measurement of the LEP Coupling Source, EPAC1990



vertical oscillation due to coupling with horizontal injection oscillation



closest-tune approach at two energies



simulated closest-tune approach for two different optics

LEP Beam History 12 years of physics operation

- 1988: July 12: Octant test
- 1989:
  - July 14, First turn
  - August 13, First Collisions
  - Aug13--Aug 18: Physics pilot run
  - Aug 21--Sept 11: Machine Studies
  - Sept 20-- Nov 5 Physics
- 1990--1994: Z physics
- 1995: Z + 65 & 70 GeV
- 1996: 80.5--86 GeV
- 1997: 91--92 GeV
- 1998: 94.5 GeV
- 1999: 96--102 GeV
- 2000: 102--104.4 GeV

S. Myers, Twelve years of beam in LEP, UK_LEPfest, Birmingham, June 2001

LEP legacy

Physics data (luminosity, energy, energy calibration)

Experience in running large accelerators

- technical requirements to control a large-scale facility
- operational procedures for high efficiency
- orbit optimization in long machines
- alignment, ground motion and emittance stability in deep tunnels
- designing and running a large SC RF system
- impedance and TMCI in long machines
- optics designs from 60/60 to 102/90 and 102/45

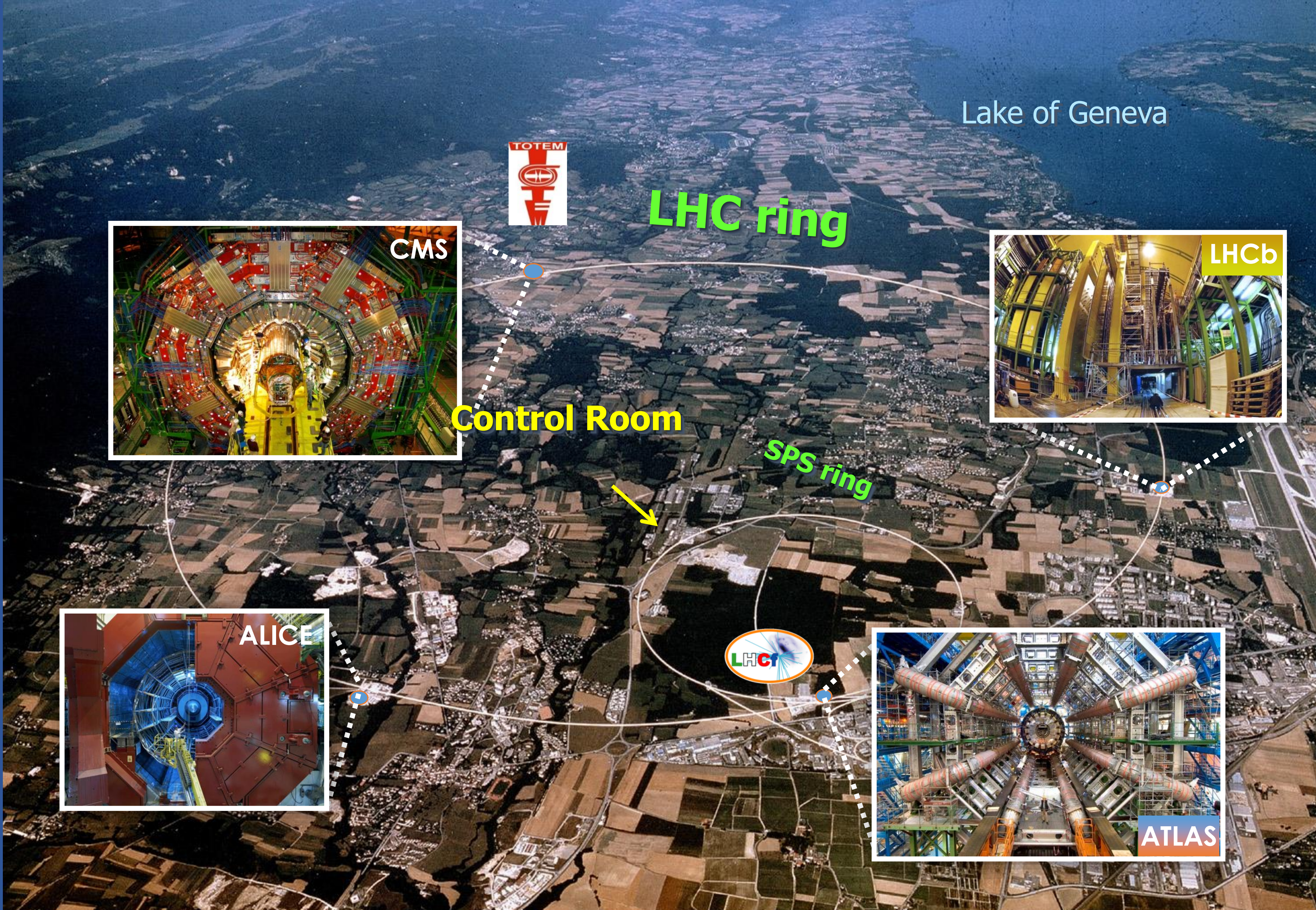
Operation in unique regime of ultra-strong damping:

- vertical emittance with small solenoid effects (dispersion-dominated)
- beam-beam limit with strong damping
- first confirmation of theory of transverse spin polarization

LEP is THE reference for any future e^+e^- ring collider design (FCC-ee, CEPC,…)

S. Myers, LEP Operation,
From the Proton Synchrotron to the Large Hadron Collider - 50 Years of Nobel Memories in High-Energy Physics, CERN, 2009

The Large Hadron Collider (LHC)



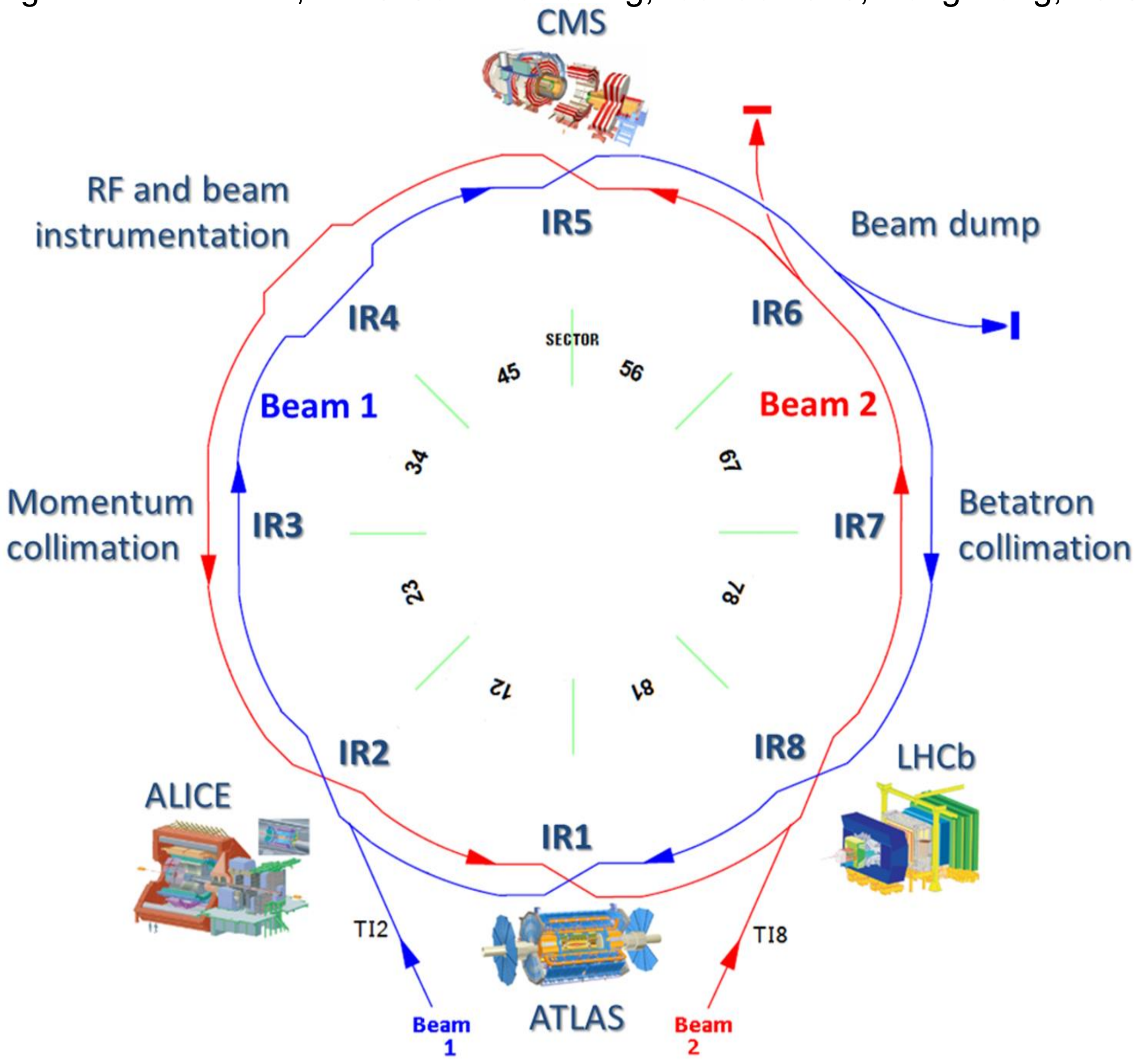
LHC ring layout

J. Wenninger & R. Giachino, "LHC Commissioning," eeFact2018, Hong Kong, 25 Sep. 2018

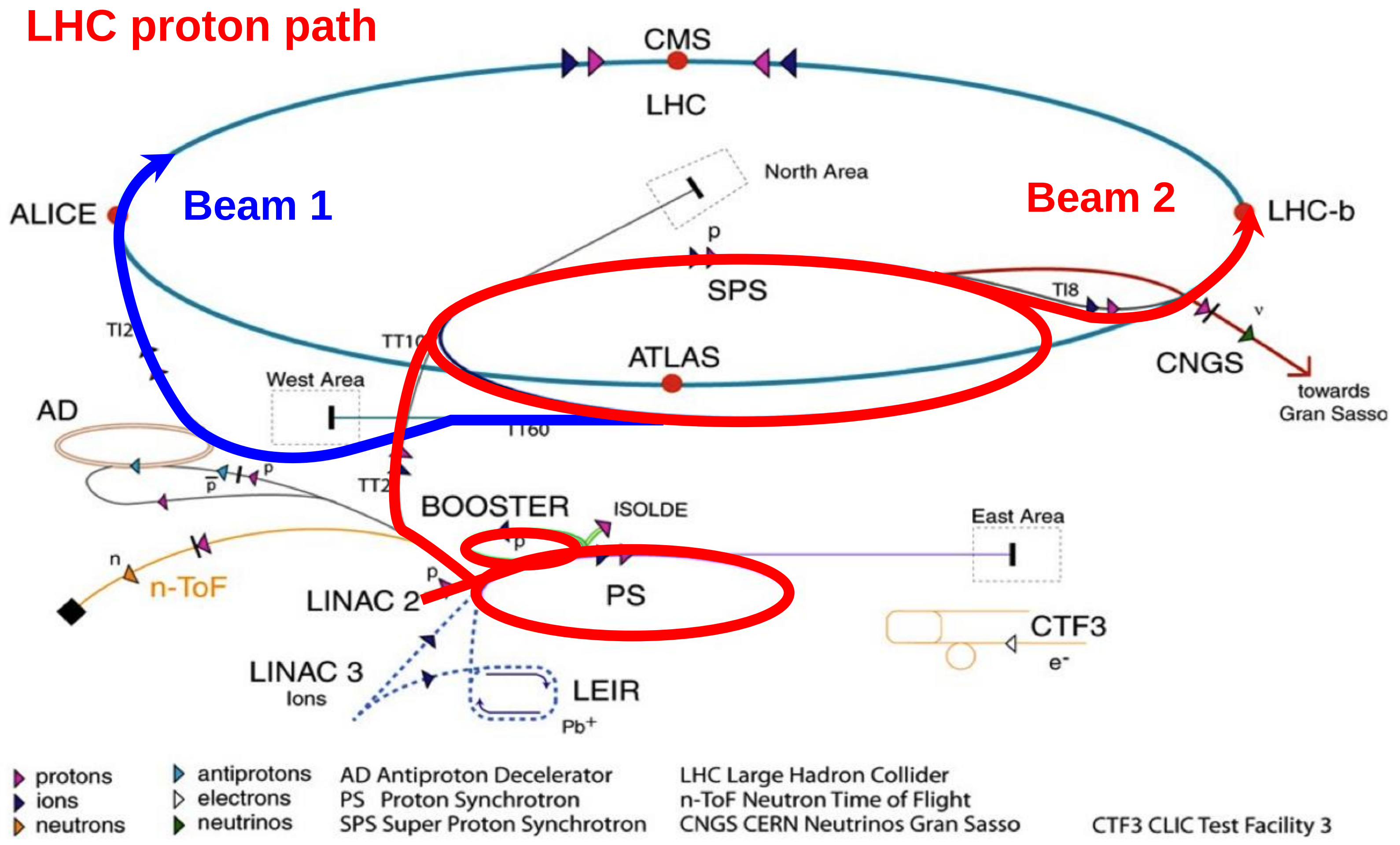
- ❑8 arcs (sectors), ~3 km each.
- ❑8 straight sections of 700 m.
- ❑Beams cross in 4 points.
- ❑Design energy 7 TeV obtained with superconducting magnets operating at 8.3 T.

- ❑2-in-1 magnet design with separate vacuum chambers.
- ❑**2 COUPLED rings**.

The LHC can be operated with protons and ions (so far Pb and Xe).

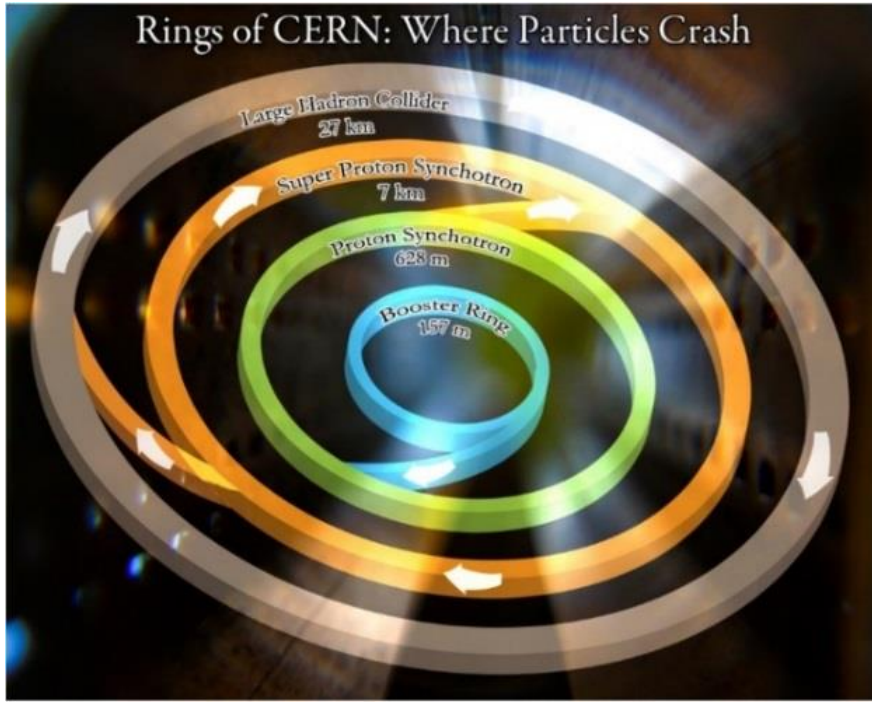


LHC injector complex



	Max. P (GeV/c)	Length / Circ. (m)
LINAC2*	0.050	30
Booster*	1.4	157
PS	26	628
SPS	450	6'911
LHC	6'500	26'657

**: kinetic energy*



J. Wenninger & R. Giachino, "LHC Commissioning," eeFact2018, Hong Kong, 25 Sep. 2018

LHC main machine phases

J. Wenninger & R. Giachino, “LHC Commissioning,”
eeFact2018, Hong Kong, 25 Sep. 2018

- **Powering tests**
  - — commissioning of every LHC circuit (~1600 in total) to nominal current
- **Machine check out**
  - — machine equipment testing without beam, hardware and software
    - partly interleaved with powering tests & magnet training.
  - — full equipment integration and machine operation without beam.
- **Beam commissioning**
  - — setting up with low intensities, commissioning of equipment with beam
- **Beam operation**
  - — Intensity ramp up & regular physics production at highest energy & intensity

Powering tests

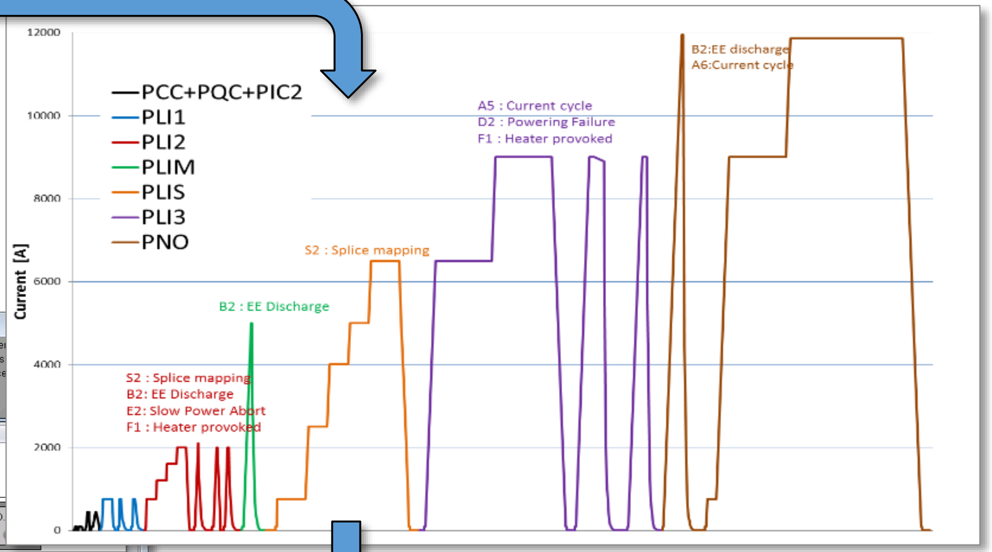
J. Wenninger & R. Giachino, “LHC Commissioning,” eeFact2018, Hong Kong, 25 Sep. 2018

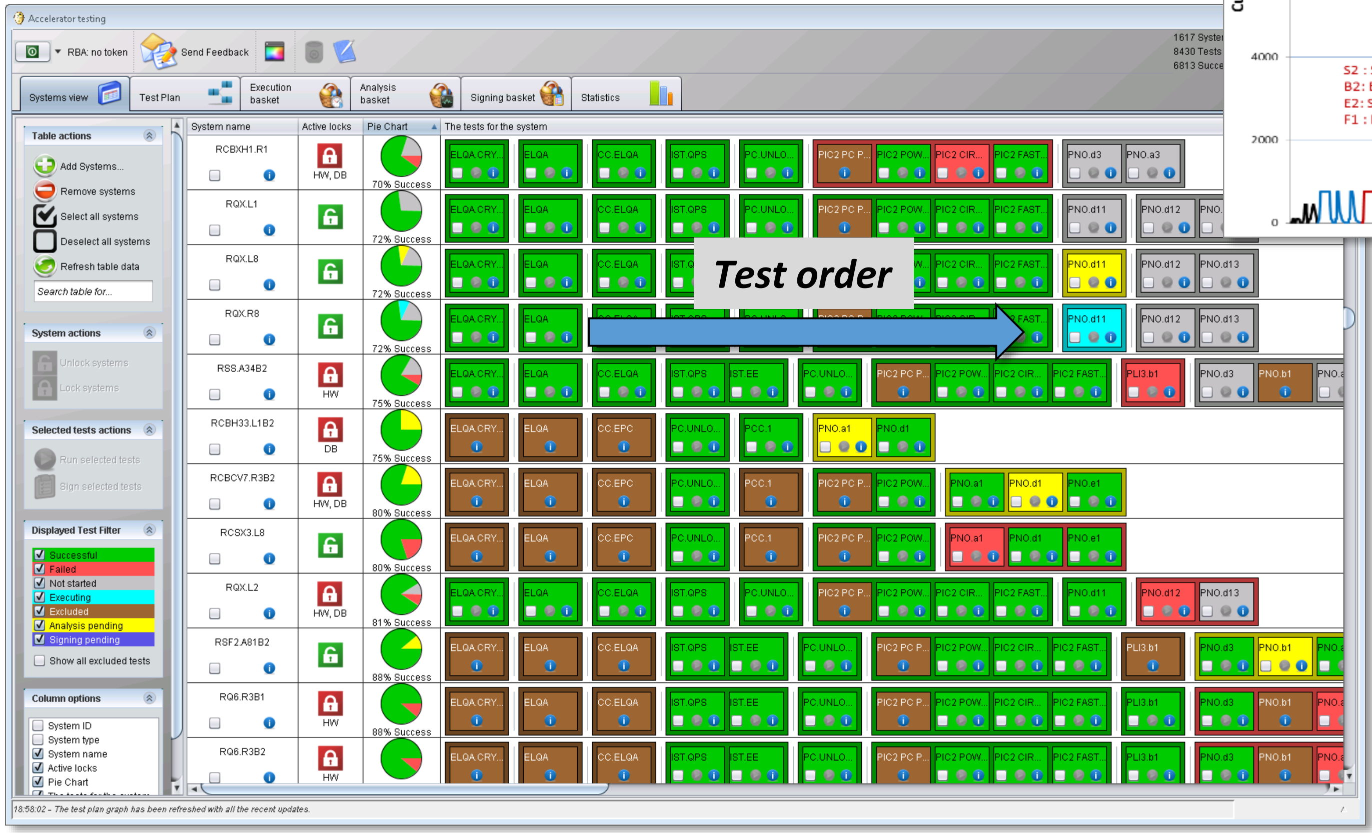
- Powering tests of LHC **circuits** (=power converter, busbar, magnet, interlocks and quench protection) began in **2006**
  - Segmentation into 8 main sub-sectors allows parallel circuit commissioning and installation
- Crucial integration exercise for power converters, quench protection and circuit interlock systems
  - individual test campaigns for every circuit type
  - sequenced tests with expert / automated validation (as of 2012)
  - a full commissioning campaign involves **~20’000 tests** – 2-3 months
  - ends with magnet (~dipole) training campaigns to nominal field
- Commissioning campaigns are repeated after every shutdown or intervention on a circuit
- Over the years a **high level software to orchestrate and automate test campaigns** was developed

Powering tests

J. Wenninger & R. Giachino, “LHC Commissioning,”
eeFact2018, Hong Kong, 25 Sep. 2018

- the powering tests of the LHC super-conducting magnet system:
  - *predefined and approved test sequences*
  - *automated execution of the tests that are ready*
  - *test sequence blocked until tests are signed*
  - *tracking of results – no step is missed !*





encoding in a test sequence

1 block = 1 test

Incident !

J. Wenninger & R. Giachino, “LHC Commissioning,”
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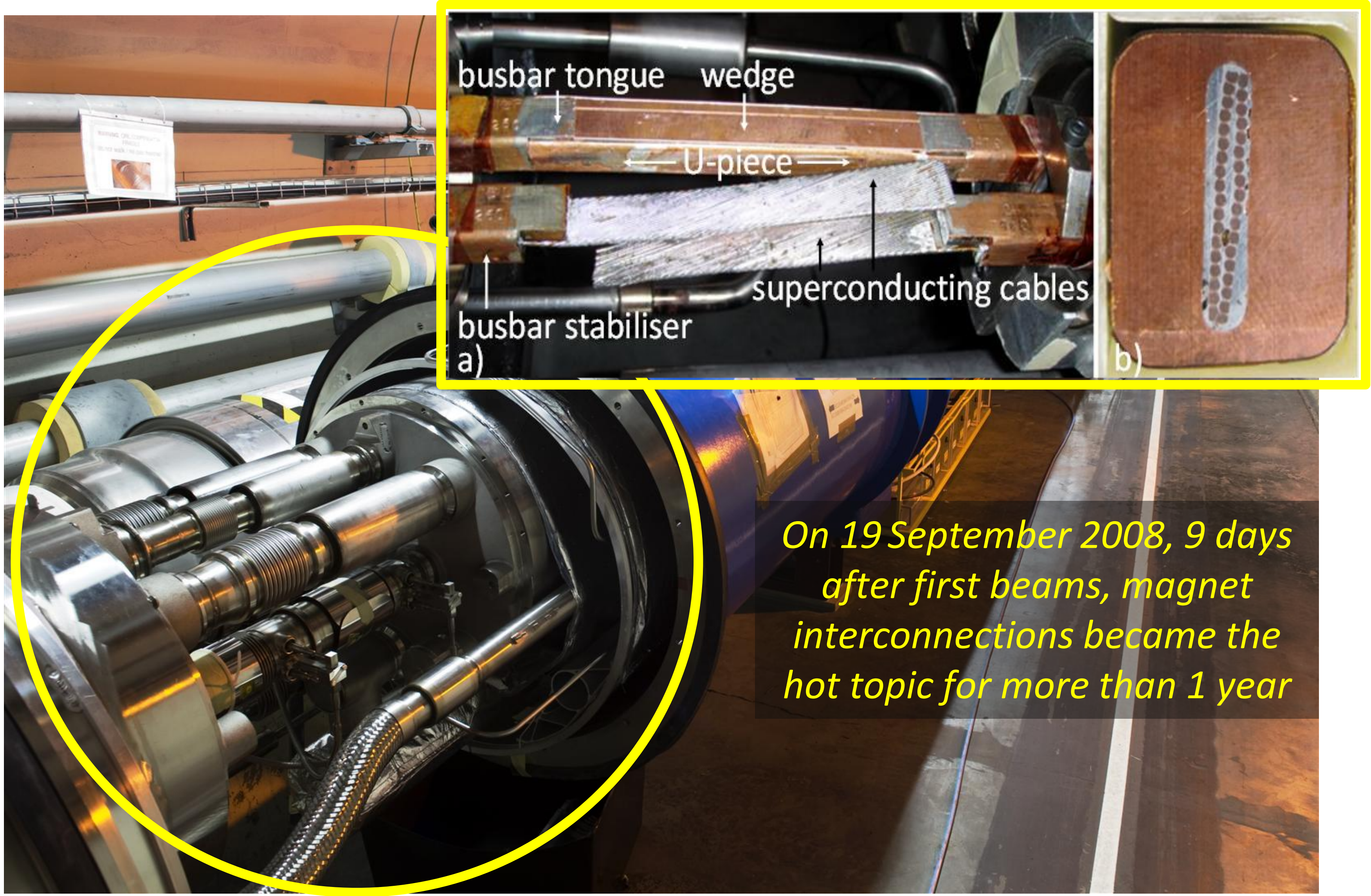
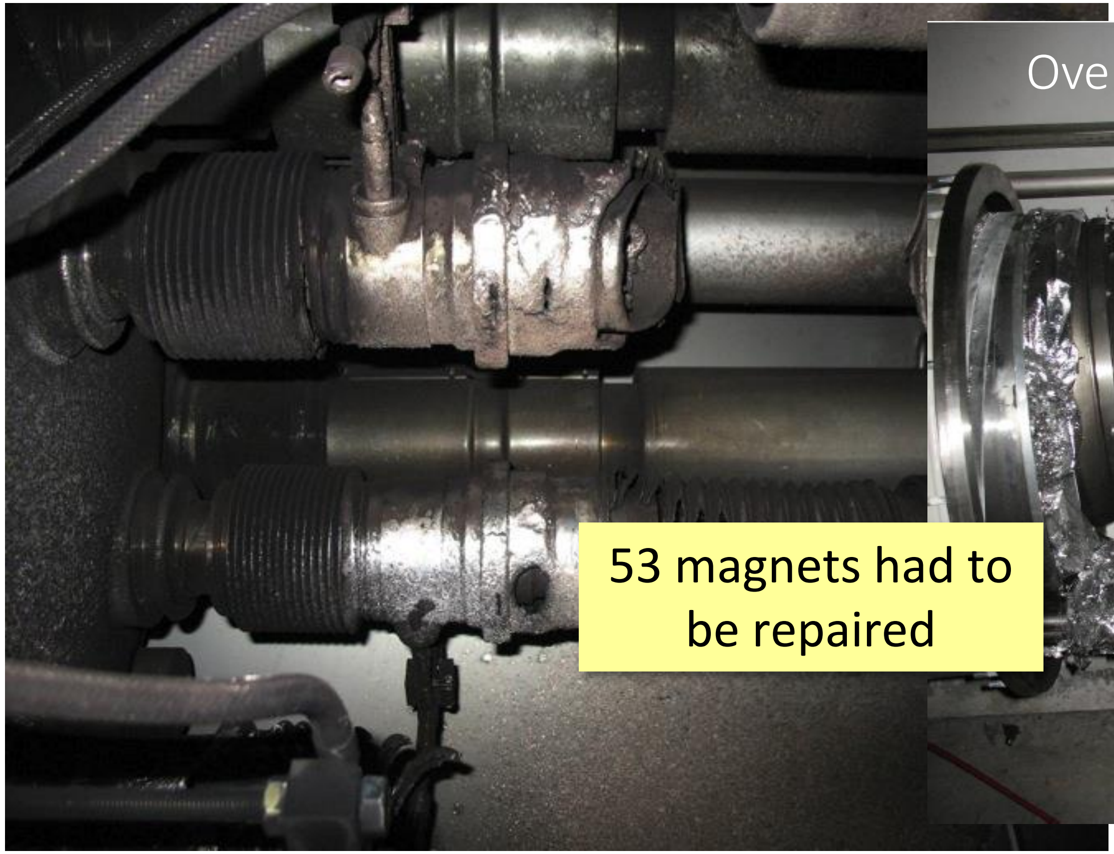


Damage

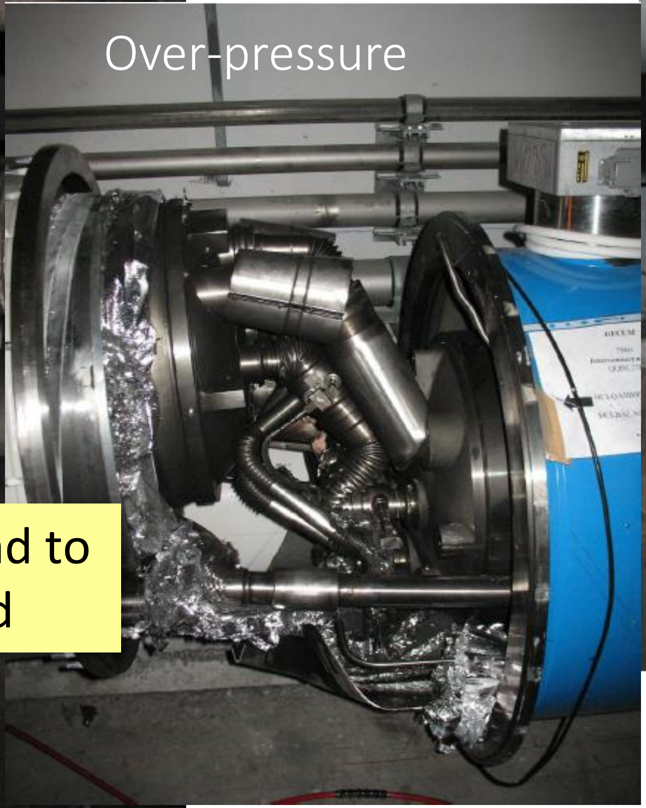
On 19 September 2008 an electrical arc in a non-conform interconnection provoked a He pressure wave that damaged ~700 m of the LHC and polluted beam vacuum over > 2 km

Arcing in the interconnection



53 magnets had to be repaired

Over-pressure

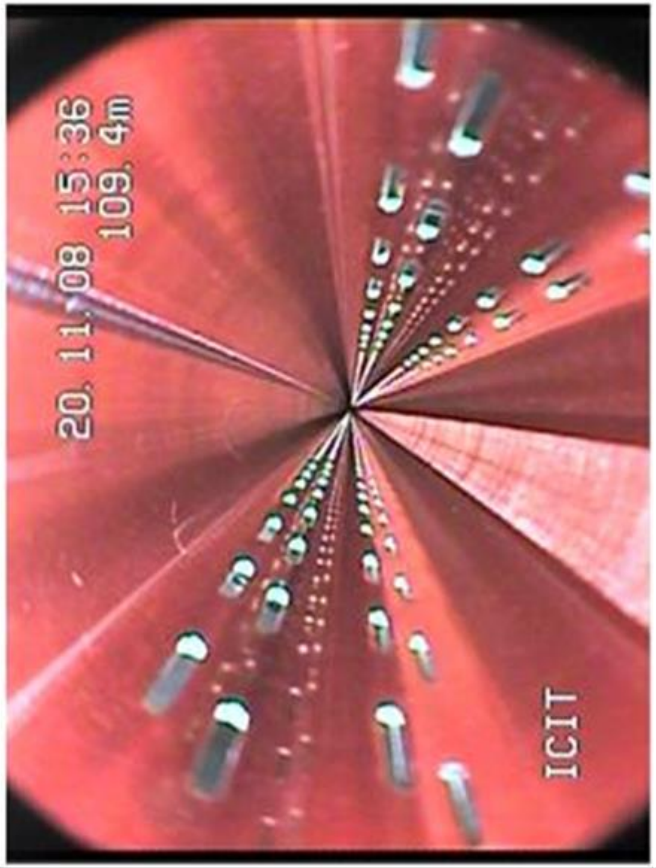
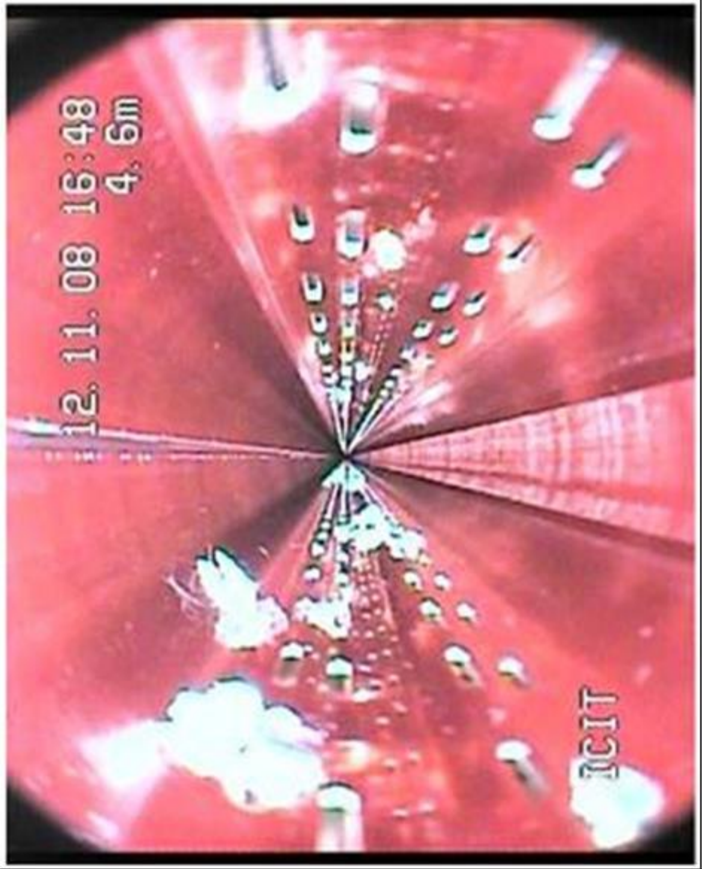
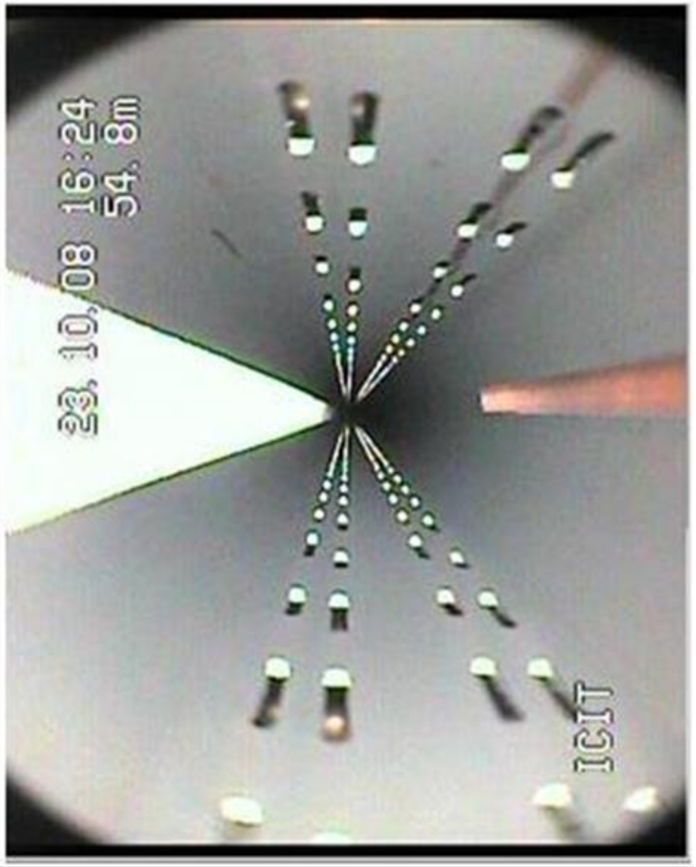


Magnet displacement

Collateral damage

J. Wenninger & R. Giachino, “LHC Commissioning,”
eeFact2018, Hong Kong, 25 Sep. 2018

Beam vacuum was affected over entire 2.7 km length of the arc

Clean Copper surface.	Contamination with multi-layer magnet insulation debris.	Contamination with soot
		
	≈ 60% of the chambers	≈ 20% of the chambers

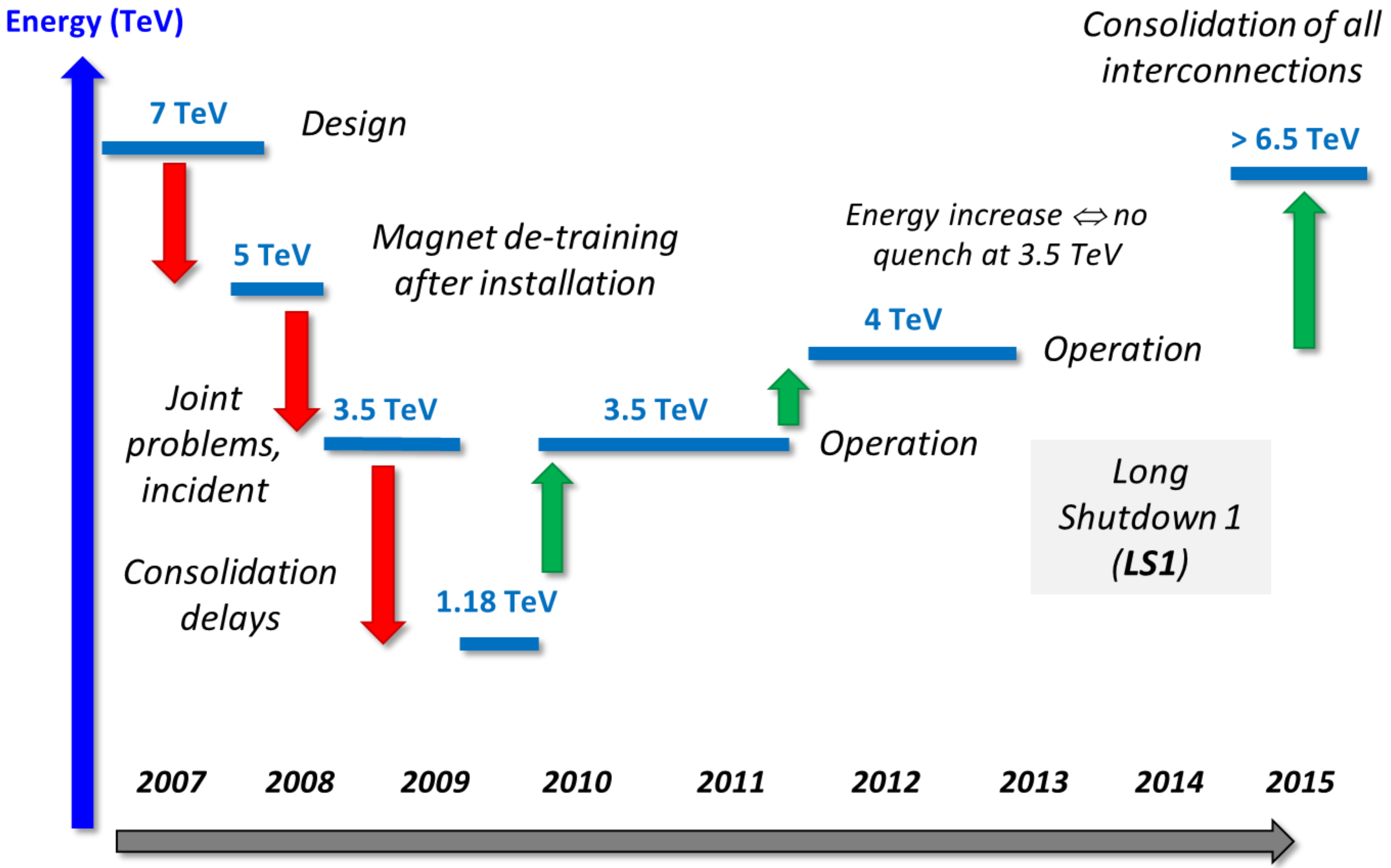
Bus-bar interconnects

J. Wenninger & R. Giachino, “LHC Commissioning,”
eeFact2018, Hong Kong, 25 Sep. 2018

- Inspection of the magnets in the damaged sector during repair work revealed **systematic QA issues** on the bus-bar interconnections.
  - As a consequence the LHC was operated at 3.5 / 4 TeV until 2012
- **Inspection, repair and consolidation** of over **10’000 high current interconnections** (12 kA) required a **two year long shutdown** and recommissioning period (spring 2013 – spring 2015)
- In large machines never “short-circuit” your **Quality Control** !!

LHC beam energy

J. Wenninger & R. Giachino, “LHC Commissioning,” eeFact2018, Hong Kong, 25 Sep. 2018



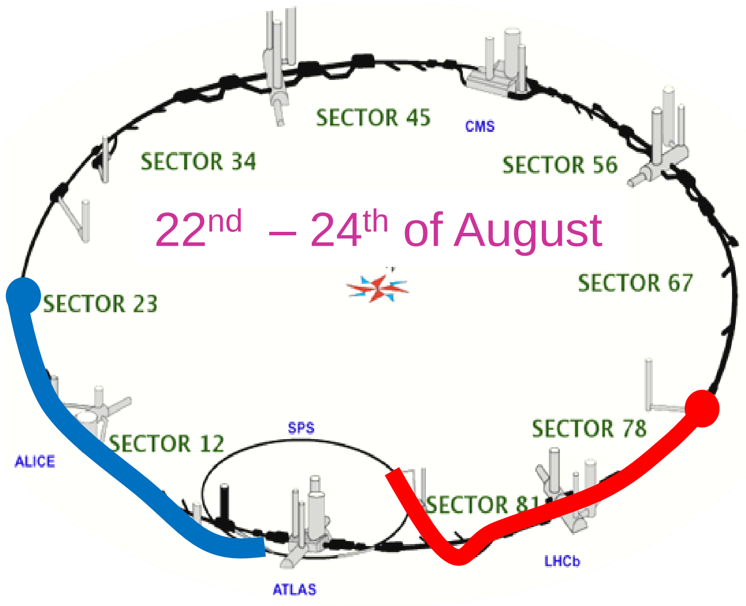
Beam commissioning preparation

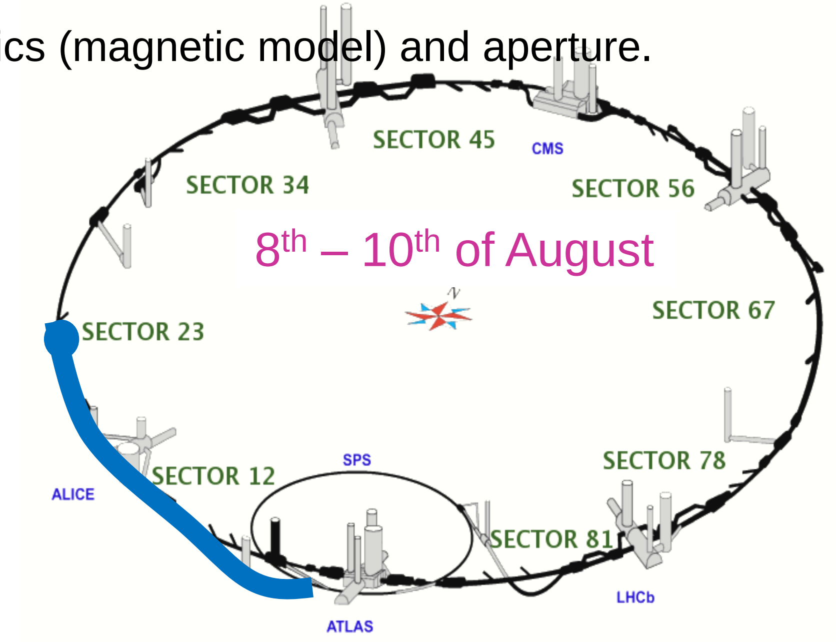
- The core LHC operation team with **experience from LEP** drove the preparation for the commissioning:
  - Software, software, software !
  - Commissioning procedures
  - Planning
  - Test, test, test !
- The LHC control system was put in place on other CERN machines as early as **2005** (-3 years) giving ample time for debugging
  - Dry tests (machine checkout) of all components including the control system started in 2007 (-1 years)
  - First beam tests of the 2.7 km long transfer lines to the LHC took place in 2007 (beam at the door to the LHC)
  - Preparation of the beams in the LHC injector chain

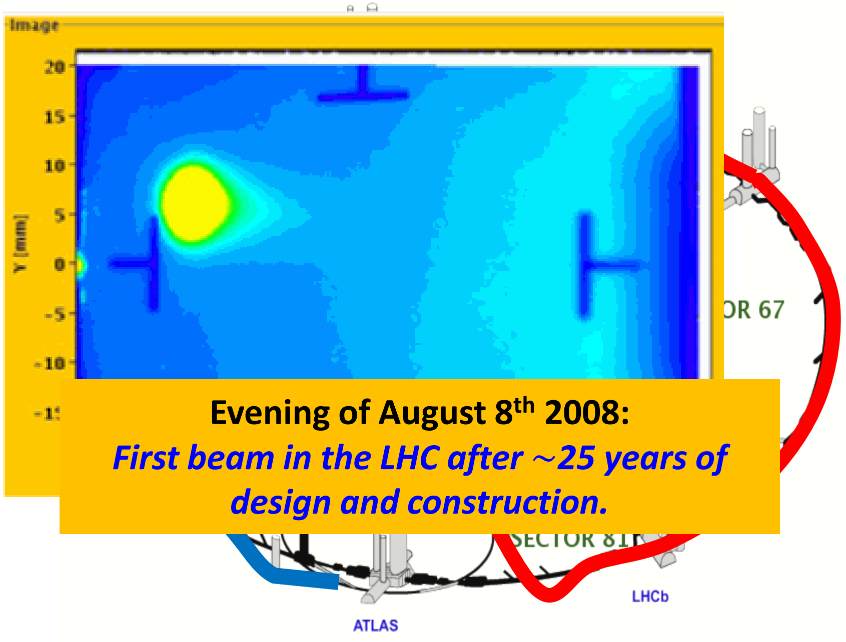
Beam preparation

August – September 2008:

- Injection tests of up to 4 adjacent sectors.
- Almost all HW systems involved in tests.
- Essential checks for:
  - Control system.
  - Beam instrumentation.
  - Optics (magnetic model) and aperture.







D-day for LHC 10th September 2008

J. Wenninger & R. Giachino, “LHC Commissioning,” eeFact2018, Hong Kong, 25 Sep. 2018

Avoid such shows !

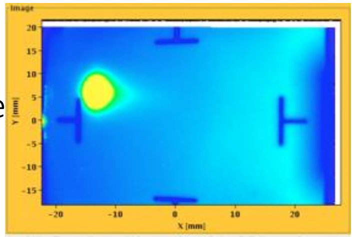
Great if there is success, but **if it fails…**

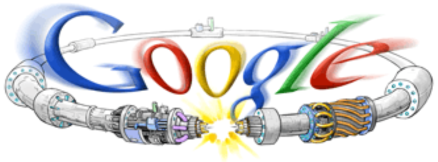
The incident happened 9 days later !

Run 1 timeline – 3.5 / 4 TeV

J. Wenninger & R. Giachino, "LHC Commissioning," eeFact2018, Hong Kong, 25 Sep. 2018

August 2008
First Injection te



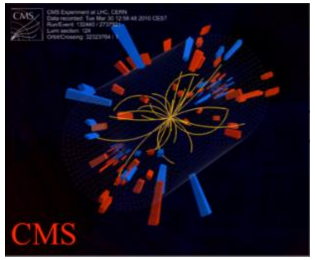


September 10, 2008
Circulating beams

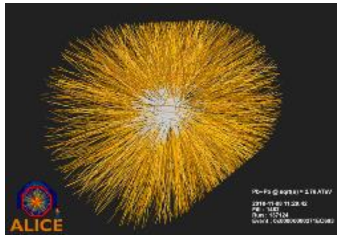
September 19, 2008
Incident

November 20, 2009
Beams back

March 30, 2010
First collisions at 7 TeV CM



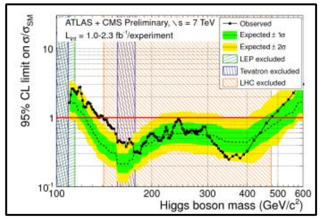
November 2010
First Lead ion run



June 28, 2011
1380 bunches

1380

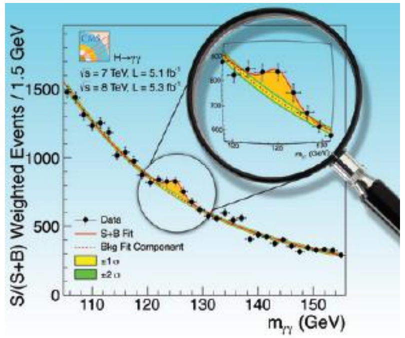
December 2011
5.6 fb^{-1}



Energy: 4 TeV

March 2012
4 TeV

July 4, 2012
Higgs Seminar



2008 | 2009 | 2010 | 2011 | 2012

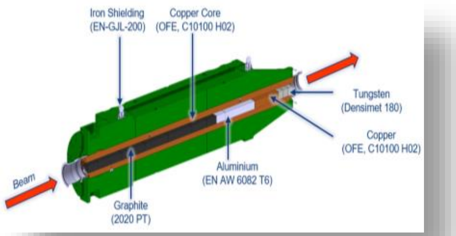
Run 2 timeline – 6.5 TeV

J. Wenninger & R. Giachino, "LHC Commissioning," eeFact2018, Hong Kong, 25 Sep. 2018

April 10
First beam at

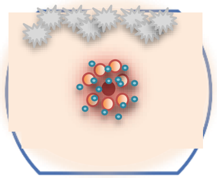
E: 6500 GeV

April 25,
SPS beam dump vacuum leak, limited bunch train length



$\mathcal{L}$ > 2 x $10^{34}cm^{-2}s^{-1}$

October,
2 x design luminosity

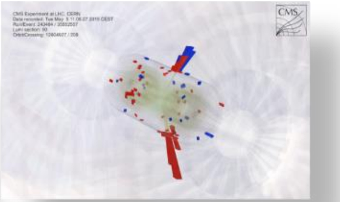


April,
16L2 beam loss events are back !

2015 | 2016 | 2017 | 2018

Easter,
First eam circulating

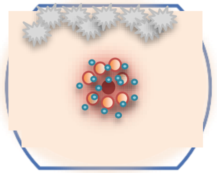
June 3,
Start of physics operation for run 2



July,
Design luminosity

$\mathcal{L}$ >$10^{34}cm^{-2}s^{-1}$

June,
First signs of 16L2 beam loss events

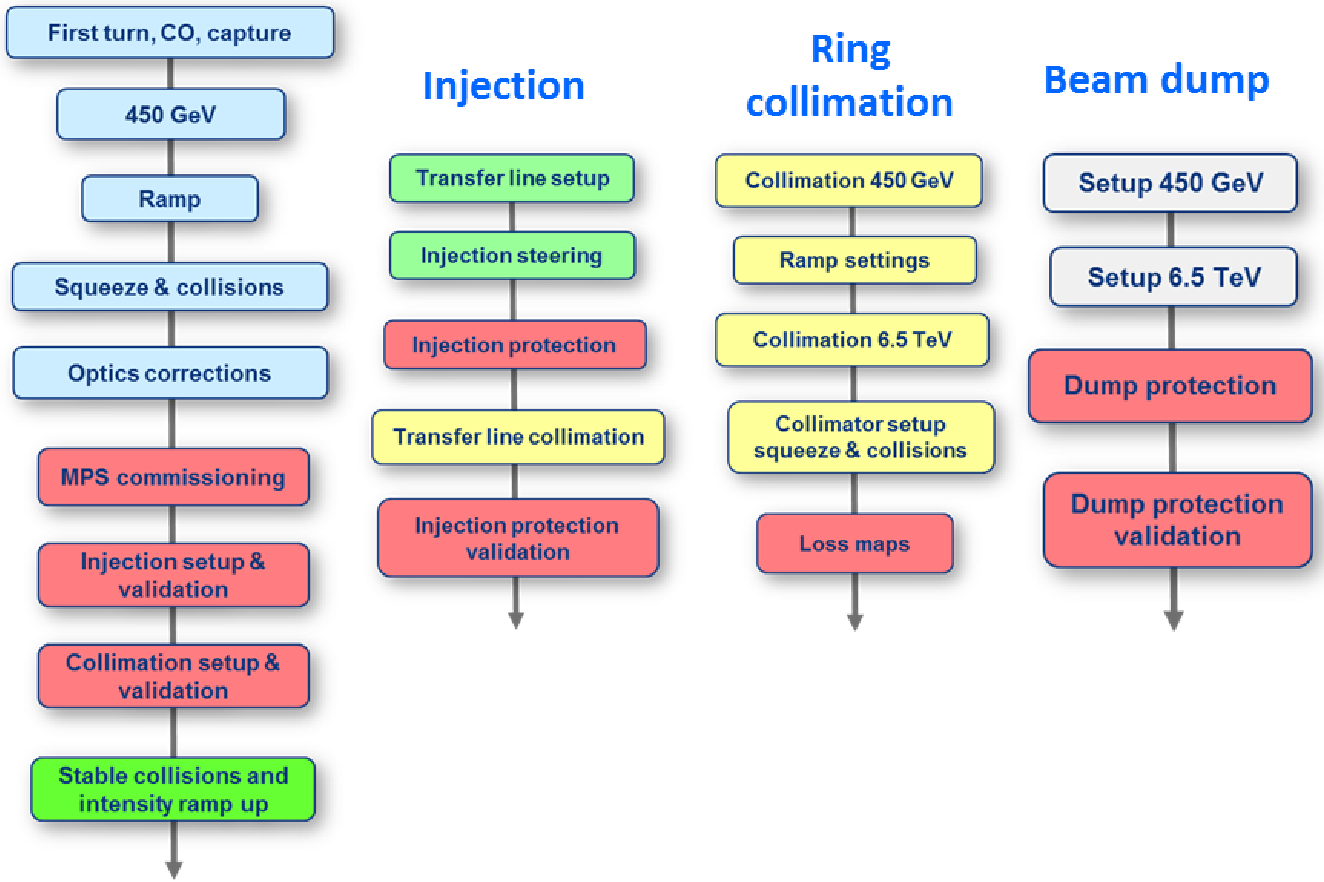


July,
150 fb^{-1} !

Operation

J. Wenninger & R. Giachino, “LHC Commissioning,”
eeFact2018, Hong Kong, 25 Sep. 2018

- The LHC is operated by a stable crew of 8 physicists / engineers and 7 operators supported by some key equipment experts.
  - Gain and share experience,
  - Very well trained and flexible crews that know the machine and its limits.



- Re-commissioning after a winter stop is now done routinely in ~2 weeks with well defined steps.

LHC availability

J. Wenninger & R. Giachino, "LHC Commissioning," eeFact2018, Hong Kong, 25 Sep. 2018

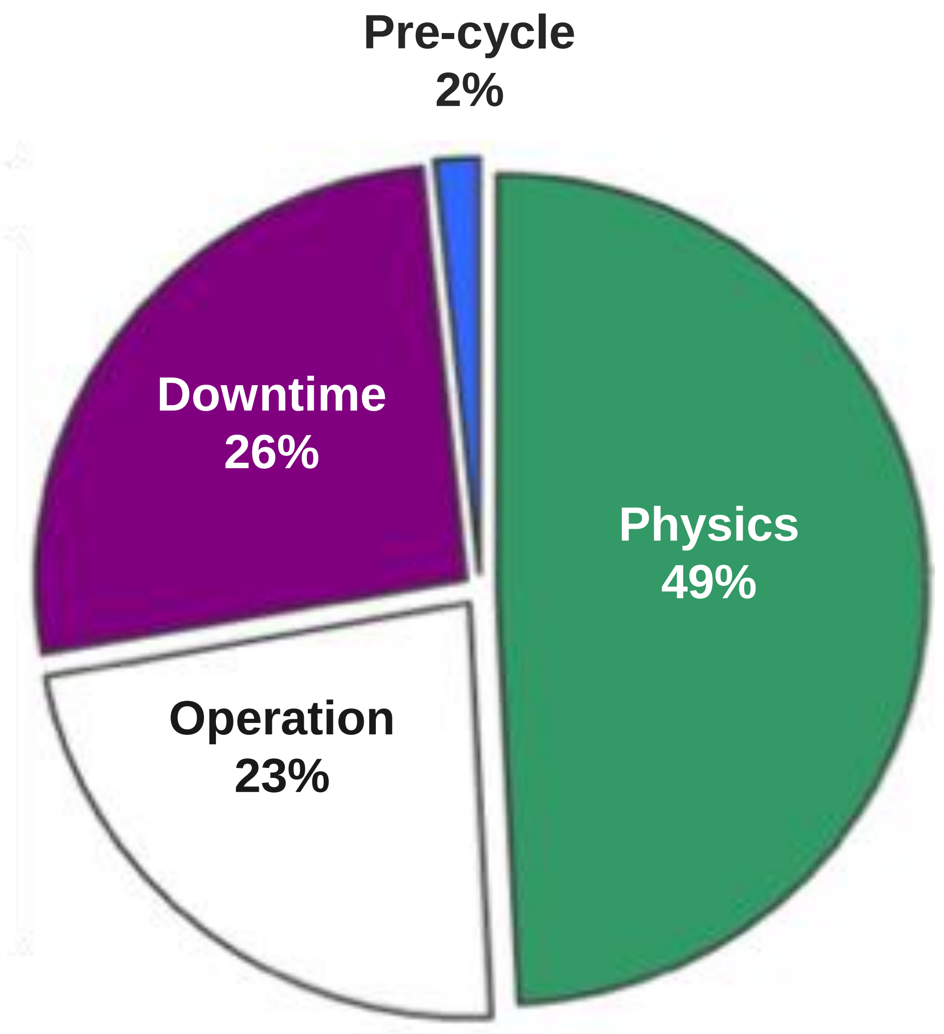
Excellent improvement of availability in 2016-2018:

- ✓ Increased operational efficiency
- ✓ Enhanced system availability
- ✓ Faster magnet cycling strategy

Availability for physics during the high luminosity production period reached **~60%**

Non-availability of beams from the injector complex is the largest source of LHC downtime

Cryogenics system availability ~95%



2016 availability

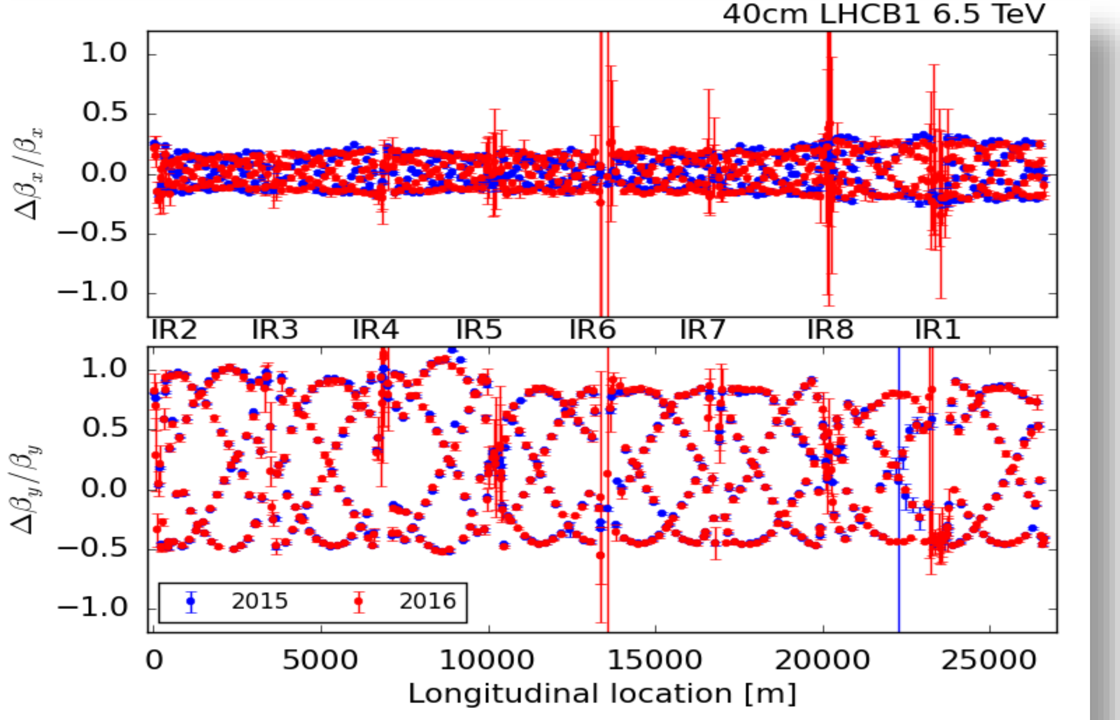
LHC optics

J. Wenninger & R. Giachino, "LHC Commissioning," eeFact2018, Hong Kong, 25 Sep. 2018

- The machine optics is **reproducible from one year to the next** and the beta-beating is corrected down to the % level at 6.5 TeV.
- Improving optics control including NL correction in low beta sections allowed a progressive reduction of **β* to 30 cm** (design 55 cm).

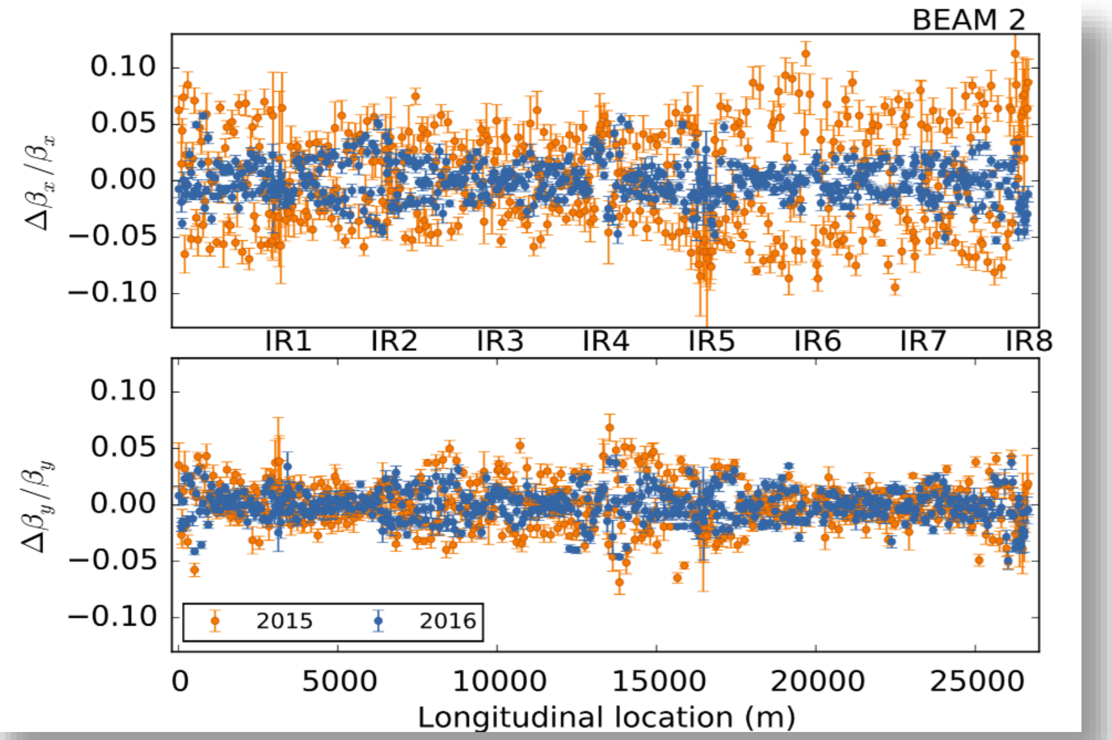
Virgin machine, β* = 40 cm

Beta-beating 50-100%



Corrected machine, β* = 40 cm

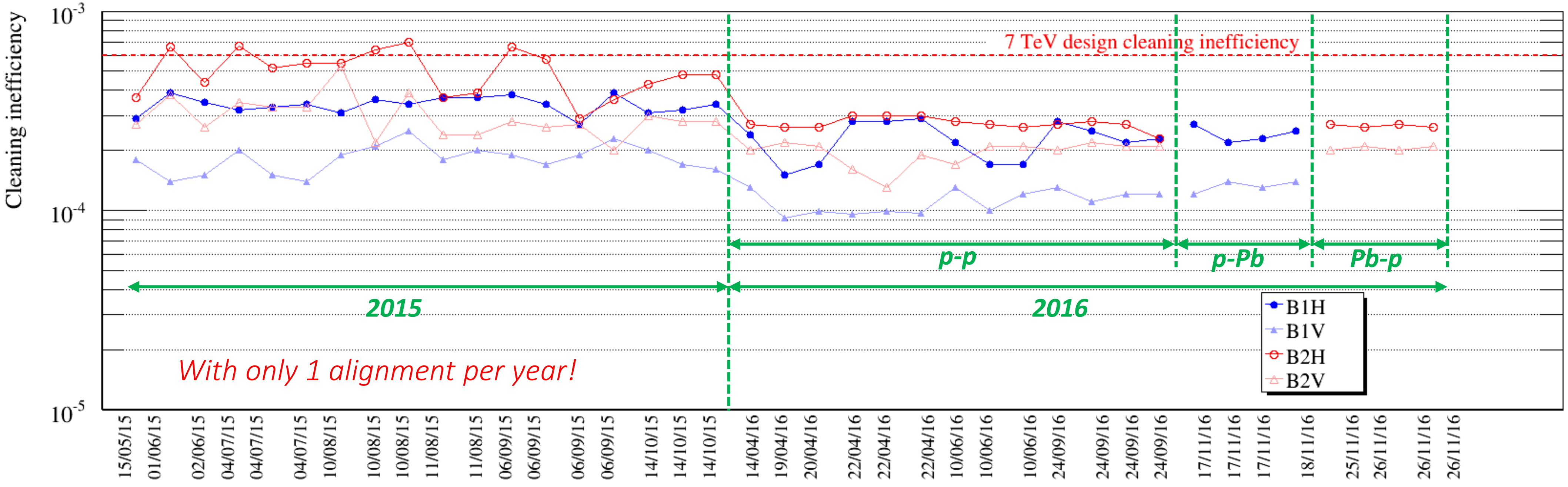
Beta-beating 2%



Collimation

J. Wenninger & R. Giachino, "LHC Commissioning," eeFact2018, Hong Kong, 25 Sep. 2018

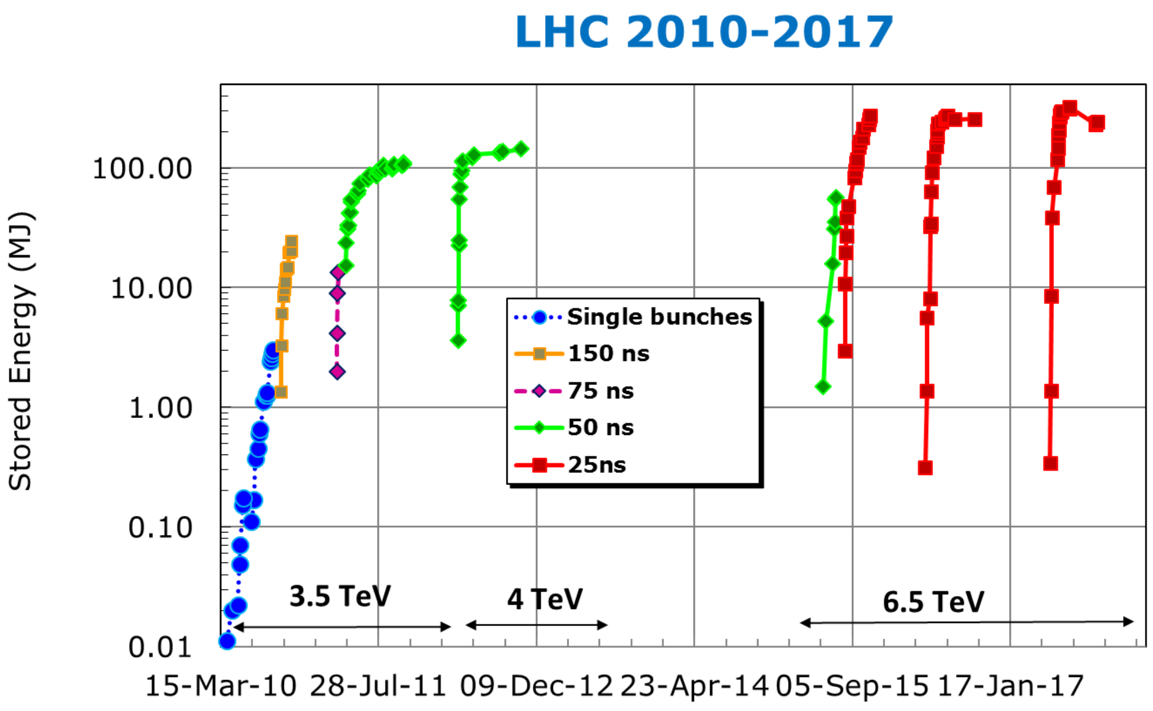
- performance of **over 100 collimators** is excellent and very stable, with inefficiencies of ≤ 0.03% for a **stored energy of 320 MJ/beam**
  - ***no beam induced quench from collimation losses in operation***
  - *a single setup per year is sufficient ⇔ machine reproducibility*
- **tightening the collimation hierarchy** (reduced retractions between collimators) coupled to good understanding of machine aperture allowed to **lower β*** over time



Machine Protection

J. Wenninger & R. Giachino, “LHC Commissioning,”
eeFact2018, Hong Kong, 25 Sep. 2018

- ❑ with over 300 MJ of stored energy (> 100 times Tevatron) each LHC beam has a tremendous destruction power
- ❑ **rigorous design, implementation, testing and operation of the MP system** ensured that so far no beam incident was recorded
  - *an occasional quench is of course part of the life of a super-conducting machine*



- ❑ After any stop or intervention with important impact, MP tests and intensity ramp-ups are scheduled by the MP team
- ❑ Excellent **MP culture** shared by all teams !

Summary, and LHC Run 3

J. Wenninger & R. Giachino, "LHC Commissioning," eeFact2018, Hong Kong, 25 Sep. 2018

- both LEP and LHC were commissioned swiftly thanks careful preparation, detailed automated procedures, multiple tests, hardware commissioning, and early injection tests
- major issues can be triggered by 'trivial problems' – 2008 incident, e-cloud, UFOs, ULO
- both LEP and LHC exceeded their design peak & integrated luminosity
- after 2-year shutdown in 2019-2020, LHC Run 3 will benefit from upgraded injectors that should provide 2x higher bunch currents (at constant emittance) by ~2023
- the projected peak luminosity of Run 3 is more than a factor 2 above the cryogenic limit, opening an area of luminosity levelled operation at the LHC !

Parameter	Design	2018	Run 3
Bunch population N_b (10^{11} p)	1.15	~1.1-1.2	1.7
No. bunches k	2780	~2556	2700
Emittance ε (mm mrad)	3.5	~2.0	1.5-2
β^* (cm)	55	30 - 25	~30
Full crossing angle (μrad)	285	320 - 260	340-250
Peak luminosity (10^{34} cm^{-2}s^{-1})	1.0	~2.1	~4-5

beyond LHC

from LEP/LHC (~65 years) to FCC-ee/hh: a >80 year integrated programme w. ultra-low emittance rings !

http://cern.ch/fcc

photo: J. Wenninger

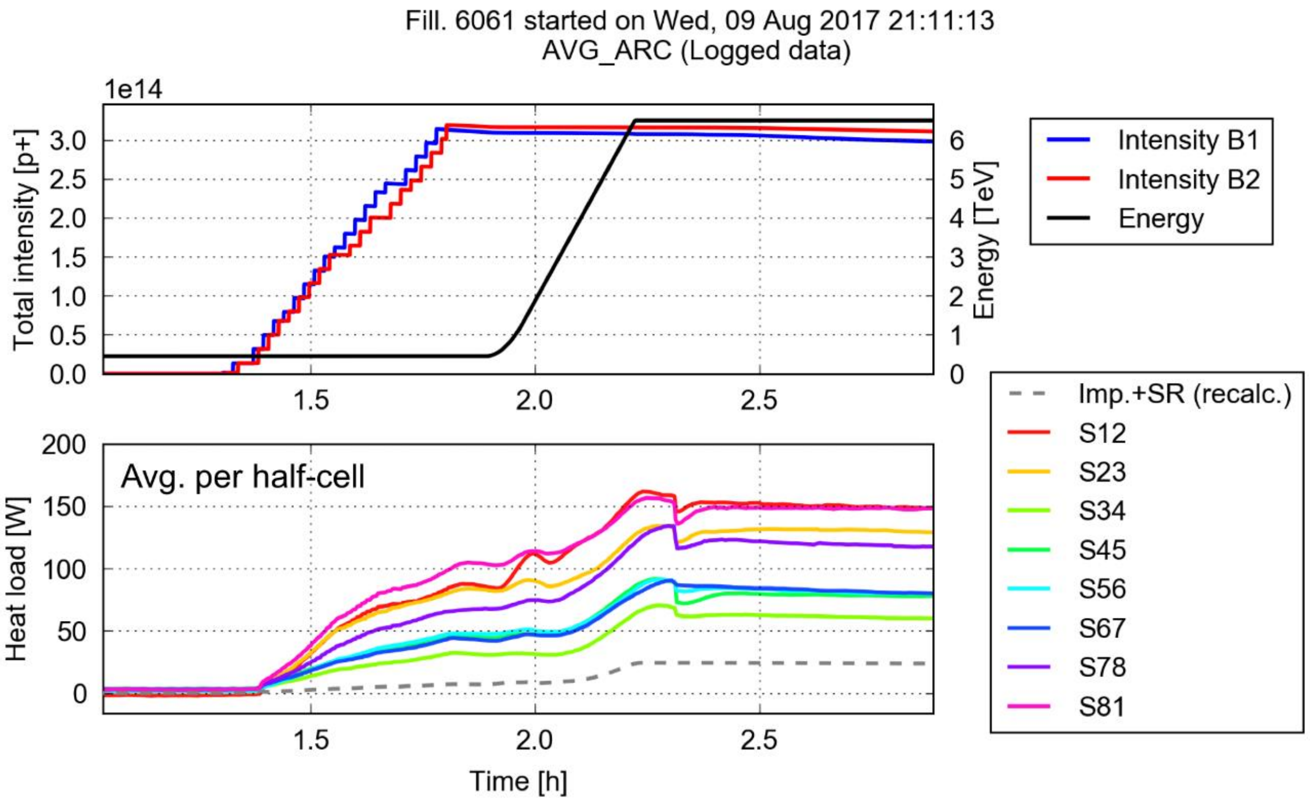
back-up slides

Electron clouds

- at high intensity the LHC is operated in the **presence of electron clouds**
- since Run 2 there are differences in heat load (= electron cloud activity) in the different sectors (arcs) – more than a factor 2 differences !
  - *This was not present in Run 1, it appeared in 2015 – cause not understood*
  - *The high load sectors may be limiting the LHC beam intensity in Run 3*

Beam intensity

Heat load (W/ 100 m)

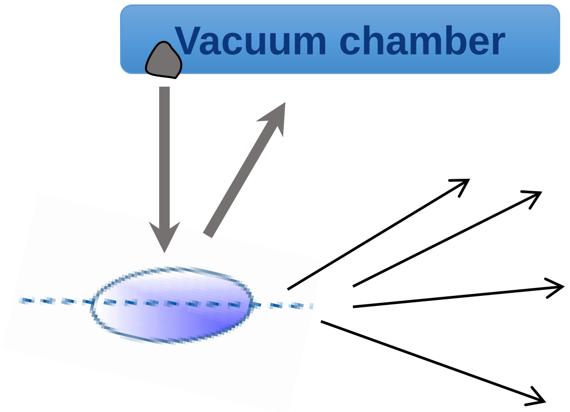


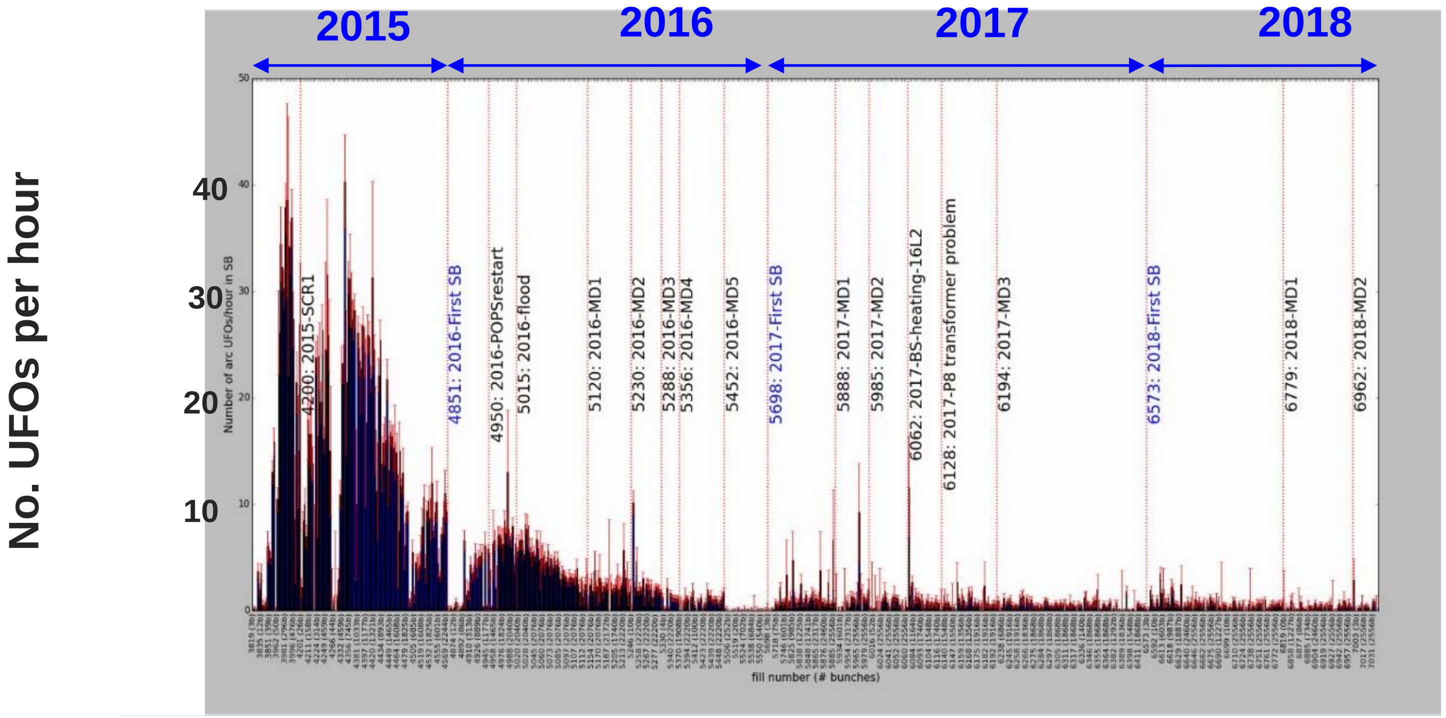
The 8 sectors (arcs) behave differently

S12
S23
S34
S45
S56
S67
S78
S81

Unidentified Falling Objects - UFOs

- The most credible theory for the **Unidentified Falling Objects** observed at the LHC are dust particles that fall into the beam and generate beam losses due to inelastic collisions with the beam. These losses can quench a superconducting magnet.





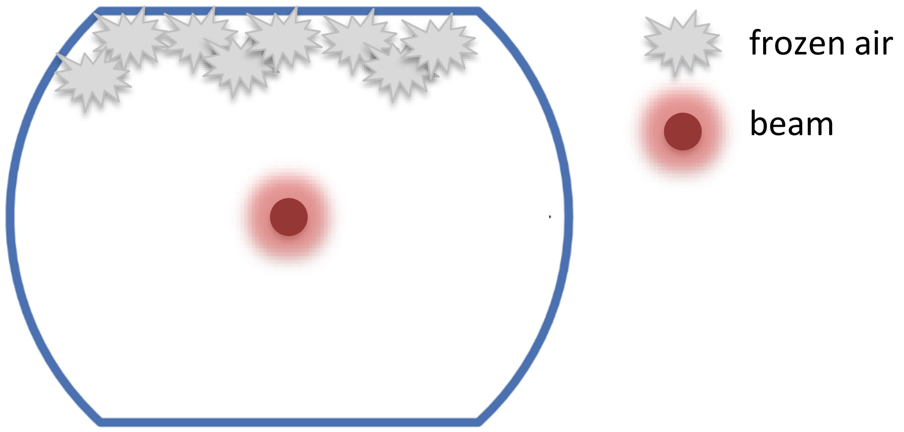
- UFOs cause 10-20 dumps per year, mostly intercepted by beam loss monitors.
  - *Loss monitor thresholds were adjusted to* ***balance the risk of spurious dumps and the need for quench prevention & recovery (~5-8 hours)****.*
  - *A clear* ***conditioning*** *has been observed along the years*

‘16L2’

- During the extended winter shutdown 2016-2017, one LHC sector (S12) was brought to room temperature to exchange a dipole with a suspected inter-turn short (which was confirmed on the test bench).
- During the cool down an issue during the disconnection of vacuum pumps led to **an air inlet** (~few liters) **into the cold vacuum chamber**. The event and its consequences became only clear a few months later.
    - The air condensed as ice on the vacuum chamber.
- In June 2017 **very strange beam loss events** were observed in conjunction with small UFO-like losses in one cell (16L2), eventually operation could only be sustained with a low e-cloud beam and limited beam intensity.
    - Side effect: fewer bunches and higher pile-up, requiring levelling of the luminosity.
- **Partial warm up of the sector to 80K** in the winter stop 2017-2018, pumping of the N2 gas present in the cell.
- **In 2018 the loss events are back**, partial warm up was **insufficient**, but operation with 25 ns beams was possible – better, but something left over…

‘16L2’ dynamics model

- The problems in 16L2 is now understood to be caused by air frozen inside the beam chamber, through the following sequence of events:

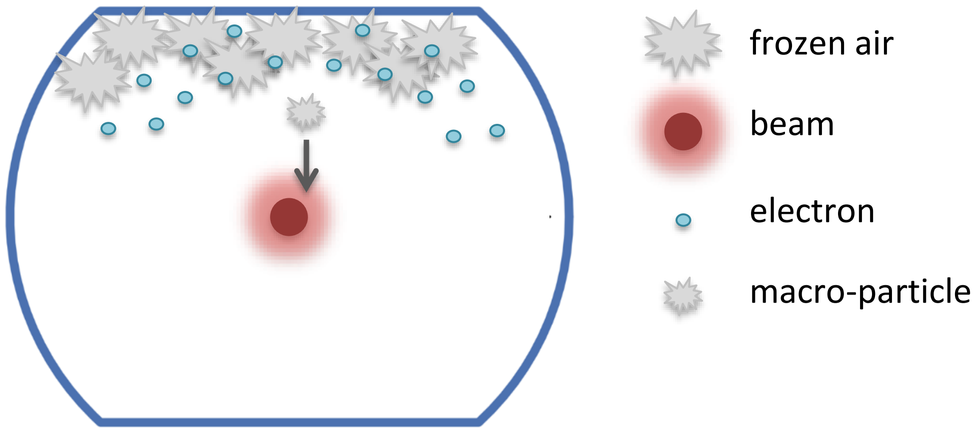


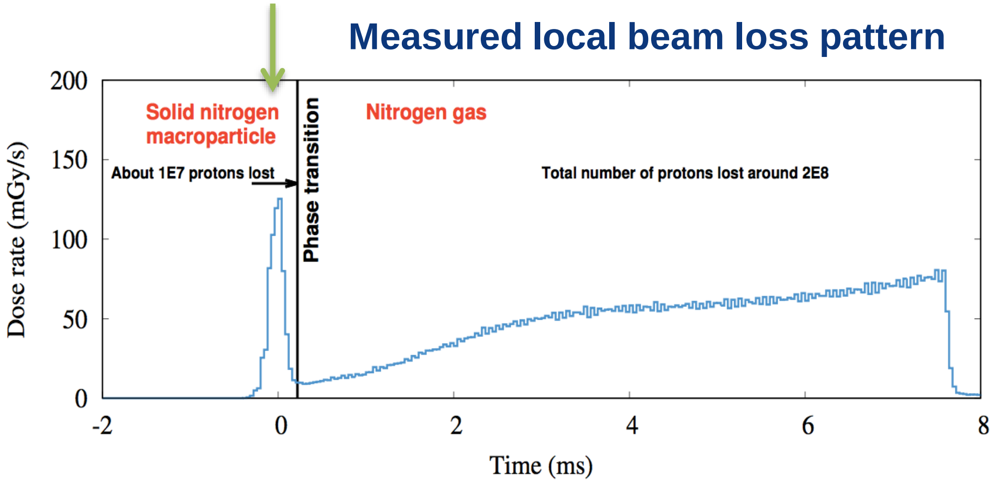
'16L2' dynamics model

- The problems in 16L2 is now understood to be caused by air frozen inside the beam chamber, through the following sequence of events:

A macro-particle of frozen air (N_2, O_2) is detached, triggered by the passage of the beam

The macro-particle interacts with the beam, generating a beam loss spike, and disintegrates due to the heat deposition from the beam





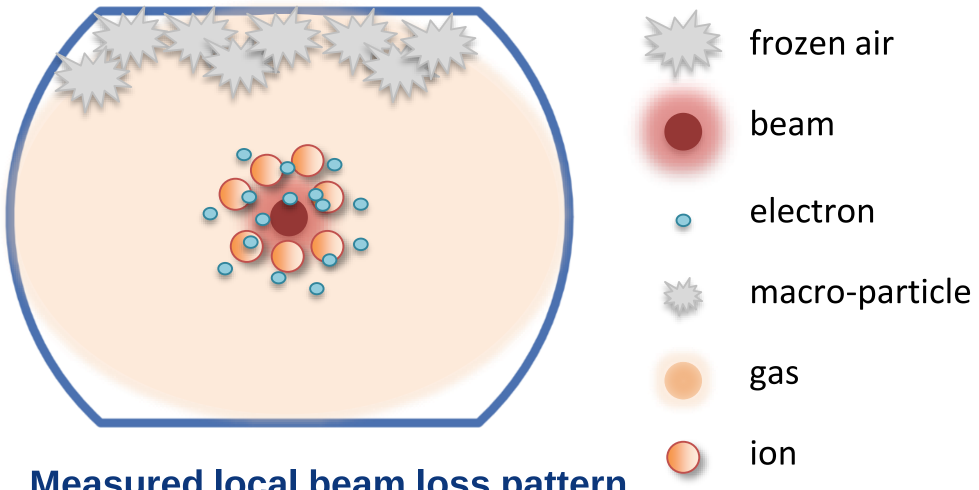
‘16L2’ dynamics model

- The problems in 16L2 is now understood to be caused by air frozen inside the beam chamber, through the following sequence of events:

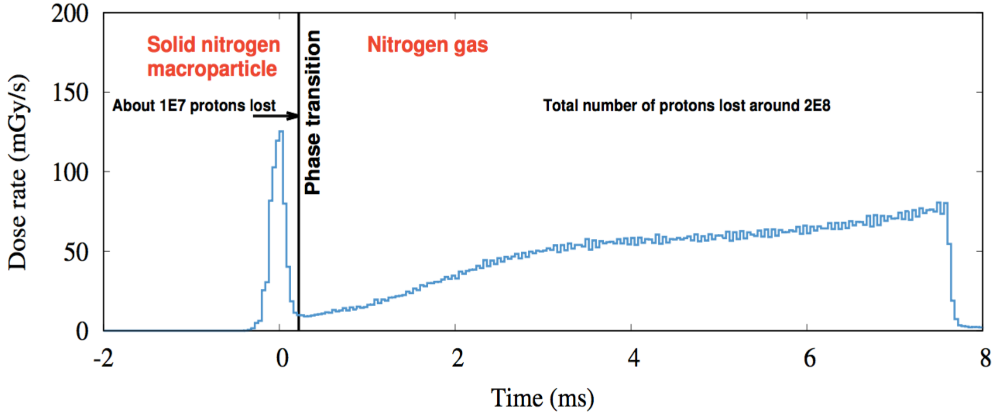
Gas from the evaporated macro-particle fills the vacuum chamber

At the location of the beam a plasma is formed

The fast moving plasma electrons destabilize the beam that has to be dumped due to excessive losses at collimators



Measured local beam loss pattern



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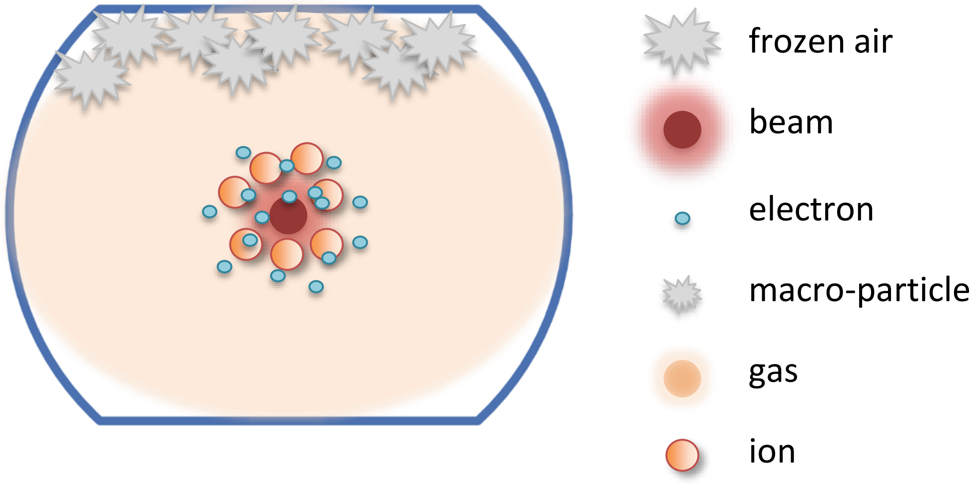

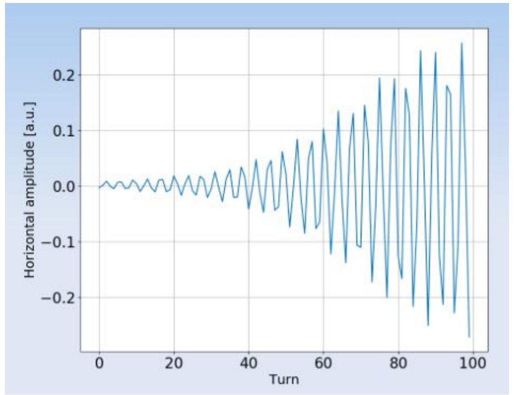

Growing transverse beam oscillations