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LHC: Machine and Accelerator Physics

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❑ 26 658.883 m
❑ 6.5 TeV x 2

Themes and Topics

- What do protons do in "spare time" before collisions:
  - T1: Betatron oscillations
  - T2: Luminosity, beamlifetime lifetime
  - T3: Emittance growth
  - T4: Halo collimation
- What sets the LHC store duration
  - T5: Cryogenics trips
  - T6: UFOs
  - T7: Turnaround time, ramp
- What do LHC "machinists" do between/before collision runs
  - T8: Fix splices
  - T9: Clean beampipes
  - T10: Execute upgrades

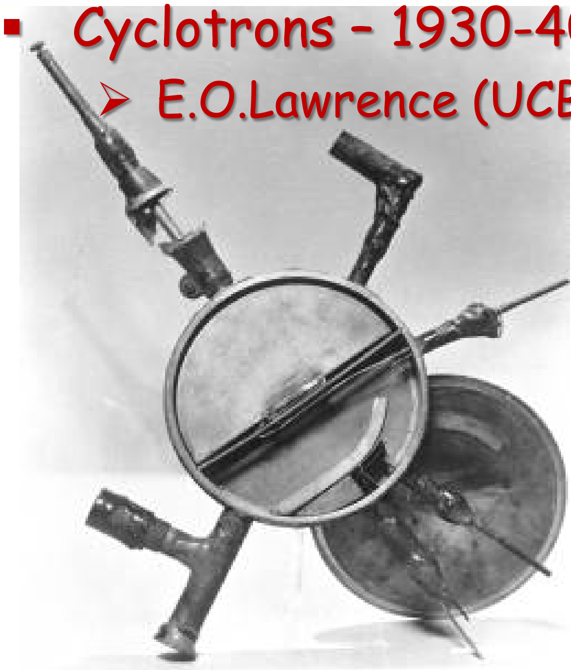
T1: Betatron Oscillations

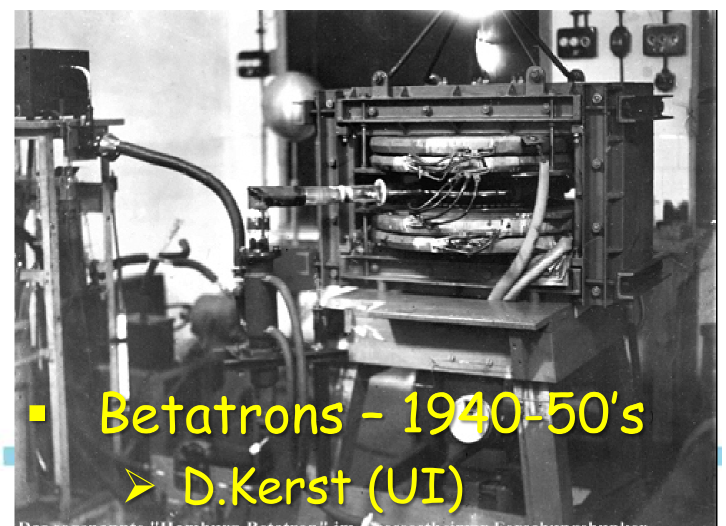
- 2800 bunches/beam x ~1.1e11/bunch = 3e14 /beam
- 11,000 revolutions/s x 10 hrs = 0.4 billion turns
  - Only ~ 1 billion protons die in collisions per second
- Transverse betatron oscillations ~60 times/revolution:
  - Also called *betatron oscillations*
  - Rms amplitude = beam size
  - 200-300 micron in arcs, 16 micron at IPs
  - Angular divergence : ~2 microrad in arcs, 30 microrads at IPs
- Longitudinal oscillations – slow – 7 Hz:
  - Also called *synchrotron oscillations*
  - Particles change positions in the bunch, rms bunch length ~8 cm
  - Particle's energies vary, too – rms 1 GeV (dE/E_rms=1.1e-4)

Accelerator Nomenclature Reflects History

LHC is a synchrotron

- Cyclotrons – 1930-40's
  - E.O.Lawrence (UCB)





- Betatrons – 1940-50's
  - D.Kerst (UI)

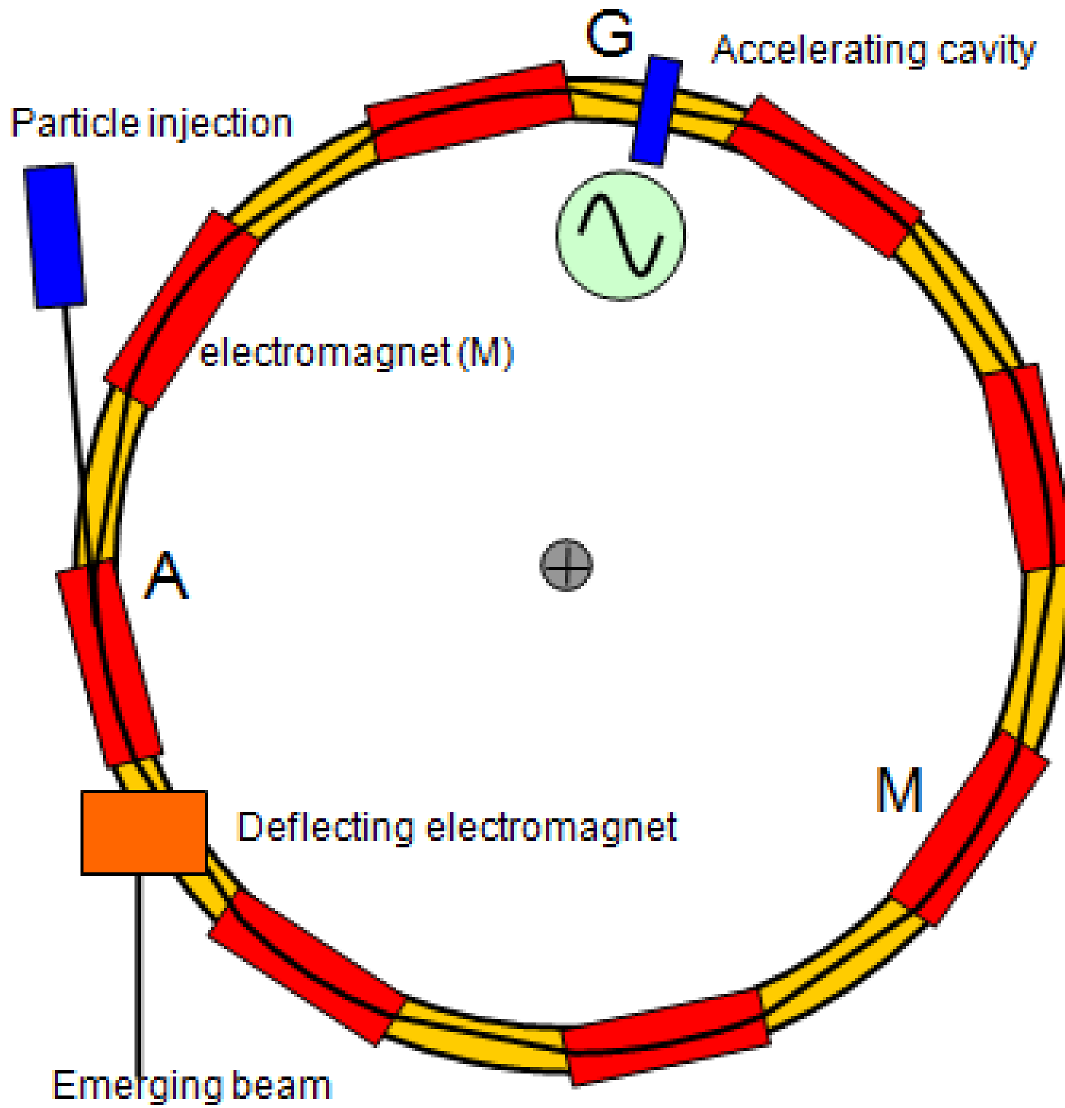
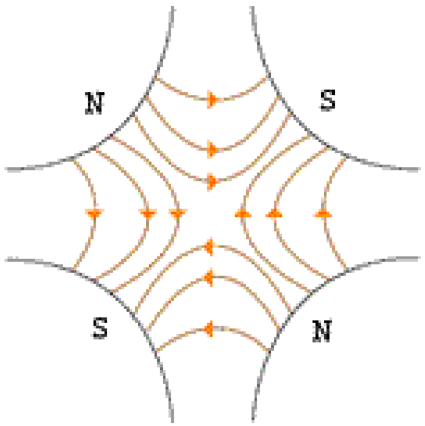
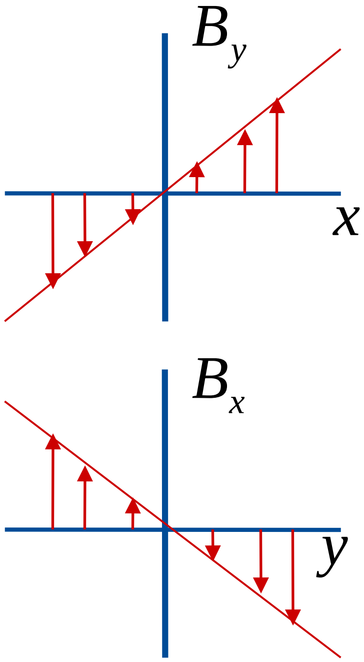
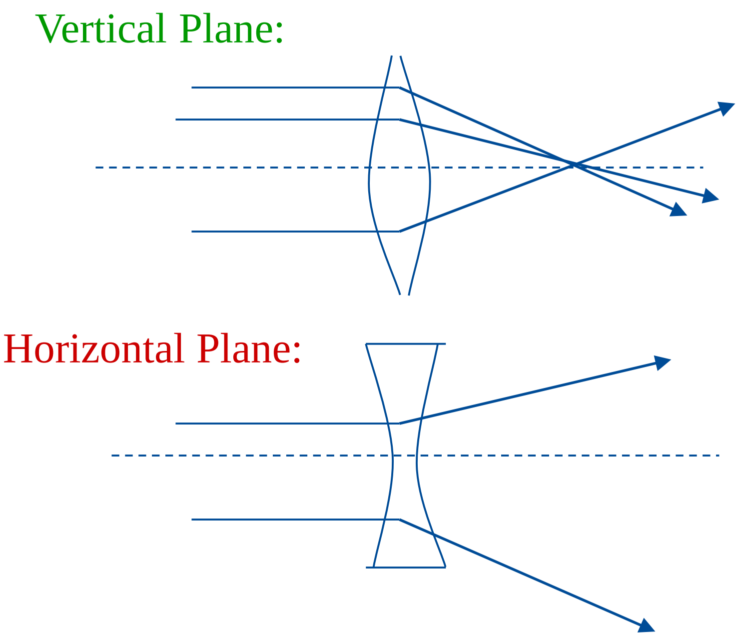


Figure 1

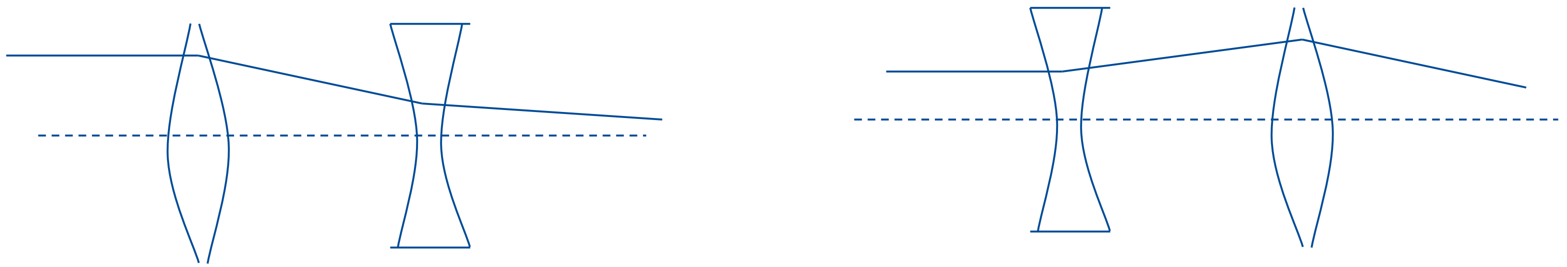
Focusing Beams with Quadrupole Magnets







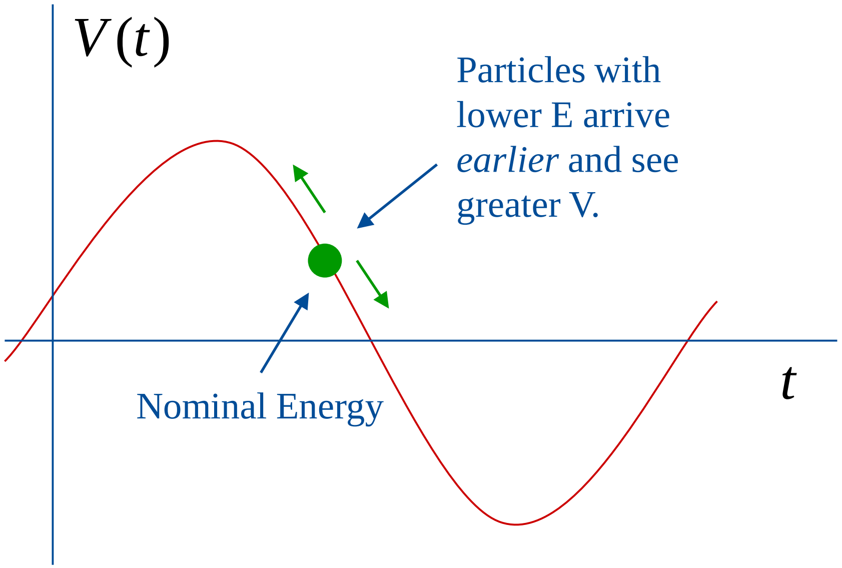
Luckily…



…pairs give net focusing in *both* planes! -> “FODO cell”

Longitudinal Motion: Phase Stability

Particles are typically accelerated by radiofrequency ("RF") structures. Stability depends on particle arrival time relative to RF phase. Note: the speed = fixed = speed of light , so time of arrival depends only on the energy (in the bunch – energy deviation wrt "reference central particle")



T2: Luminosity

The relationship of the beam to the rate of observed physics processes is given by the "Luminosity"

$$R = L\sigma$$

Rate → R; "Luminosity" → L; Cross-section ("physics") → σ

Standard unit for Luminosity is $cm^{-2}s^{-1}$

Example: total *p-p* inelastic+elastic cross section at 13 TeV cme is ~110 mbarn (60 inel+ 12 ssd+40 el not seen)→ ~40 interactions per crossing (NB: pile up is only ~20!) x 40,000,000 collision/sec= 1.6B protons leave each beam every second

Beam lifetime due to such "Burn up" *T=N/(dN/dt)=*
3e14 protons/(1.6e9/s) =46 hours

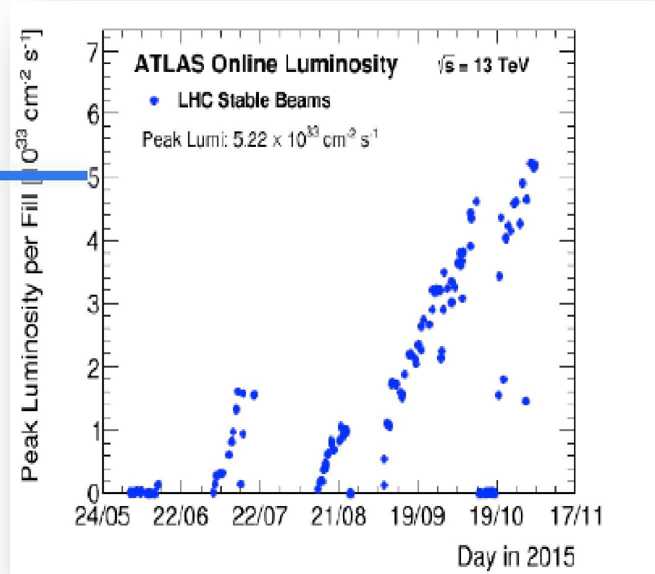
E.g., 2015 Luminosities

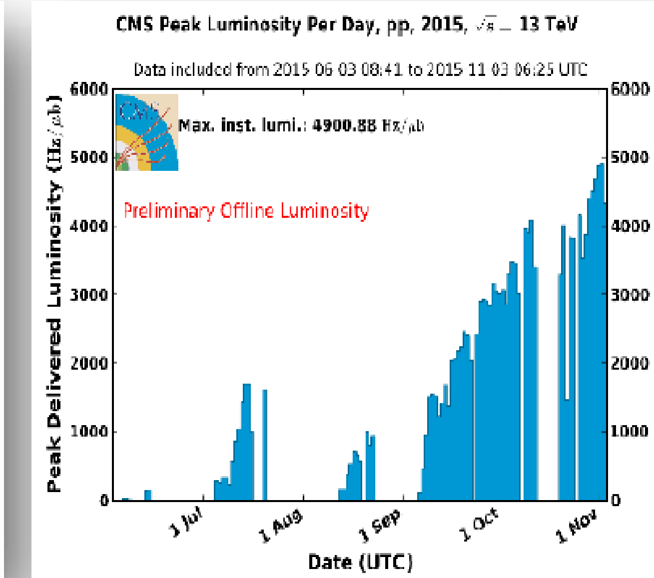
ATLAS | CMS

Peak

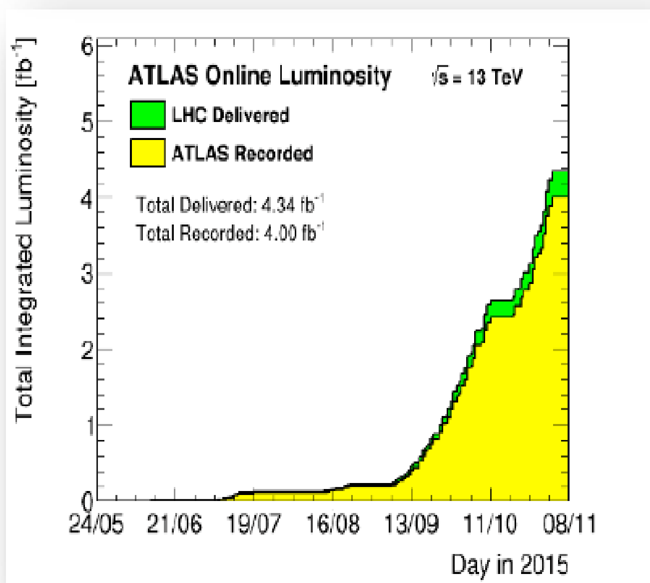
5×10^{33} cm^{-1} s^{-1}

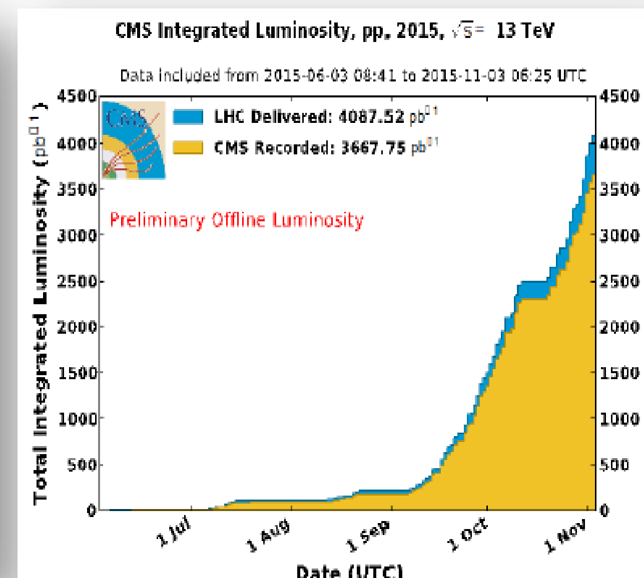
Design 10^{34} cm^{-1} s^{-1}





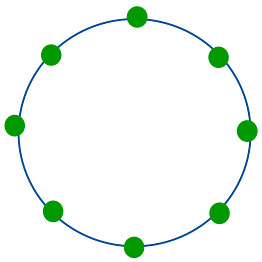
Integrated

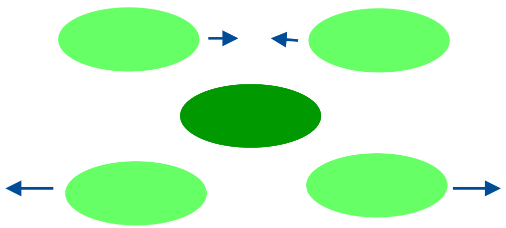




Colliding Beams Luminosity

Circulating beams typically “bunched”





(number of interactions)

$$= \left(\frac{N_1}{A}\right) N_2 \sigma$$

Cross-sectional area of beam

Rate of collisions

Total Luminosity:

$$L = \left(\frac{N_1 N_2}{A}\right) r_b = \left(\frac{N_1 N_2}{A}\right) n \frac{c}{C}$$

Number of bunches

Circumference of machine

Record Hadronic Luminosity (LHC): 0.8E34 $cm^{-2}s^{-1}$

(80% of the LHC design; x20 Tevatron lumi)

Record e+e- Luminosity (KEK-B): 2.1E34 $cm^{-2}s^{-1}$

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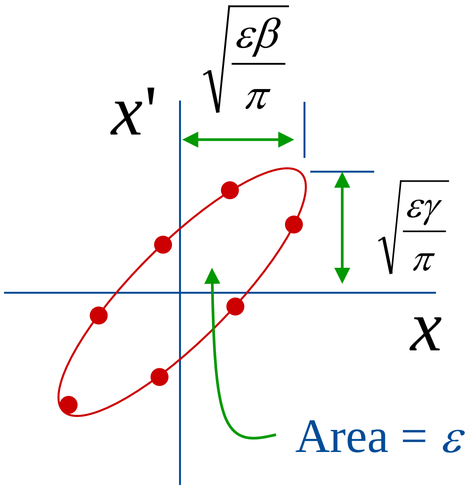
T3: Emittance



As a particle returns to the same point on subsequent revolutions, it will map out an ellipse in phase space, defined by

$$\gamma_T x^2 + 2\alpha_T x x' + \beta_T x'^2 = \frac{\varepsilon}{\pi}$$

$$\gamma_T \beta_T - \alpha_T^{\;2} = 1$$

Twiss Parameters

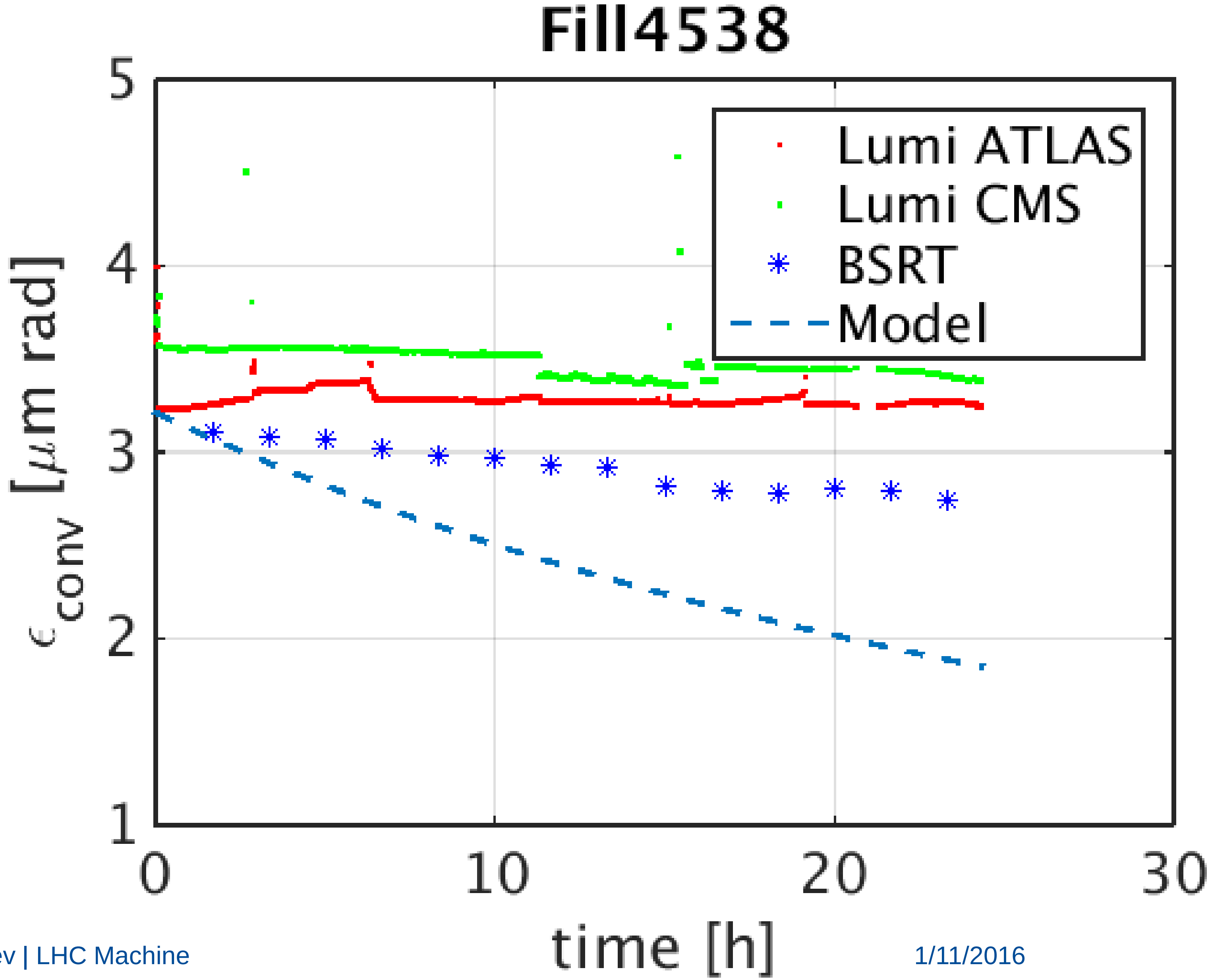
- Product *size x angle* *X_rms x X'_rms* is called emittance
- *Emittance x gamma* is adiabatic invariant
- In LHC: at IP 16 um x 30 urad x 7000=3 mm mrad, in arcs 300 um x 1.6 urad x 7000 = 3 mm mrad
- Luminosity ~ *1/ε*

T3: Emittance growth

$$T_x = \varepsilon_x / (d\varepsilon_x / dt)$$

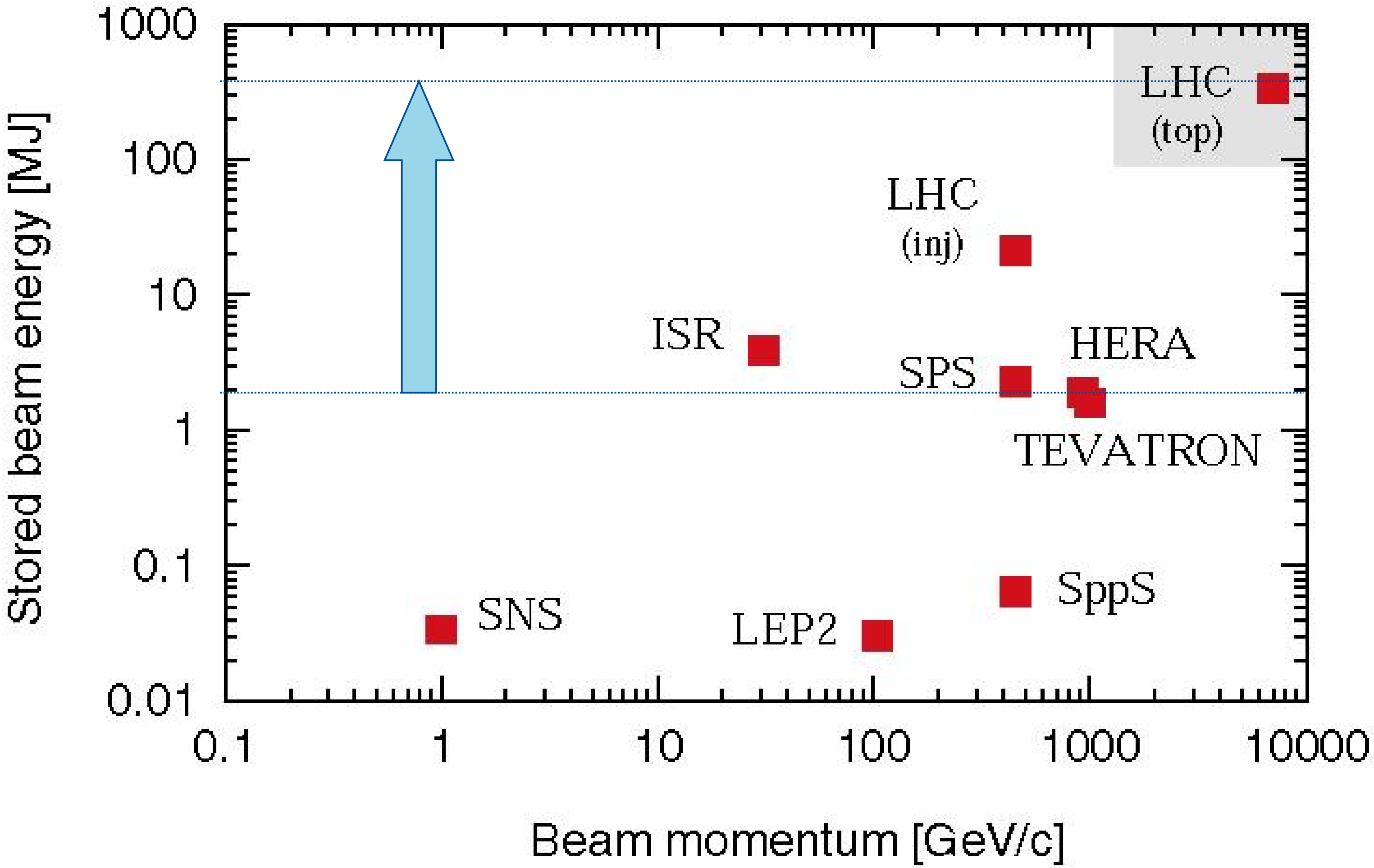
- Intra-beam scattering: 80 hrs (growth)
- Synchrotron radiation: 26 hours (cooling)
  - Each proton loses 67 keV/turn (many 44 eV photons… yes, LHC beams shine!)
  - 0.17 W/m/aperture (total cryo capacity O(1) W/m)
- Scattering on residual gas 1000 hrs (growth)
- So the total is **cooling** (26 < 80 <1000) ???

T3: Emittance growth in reality

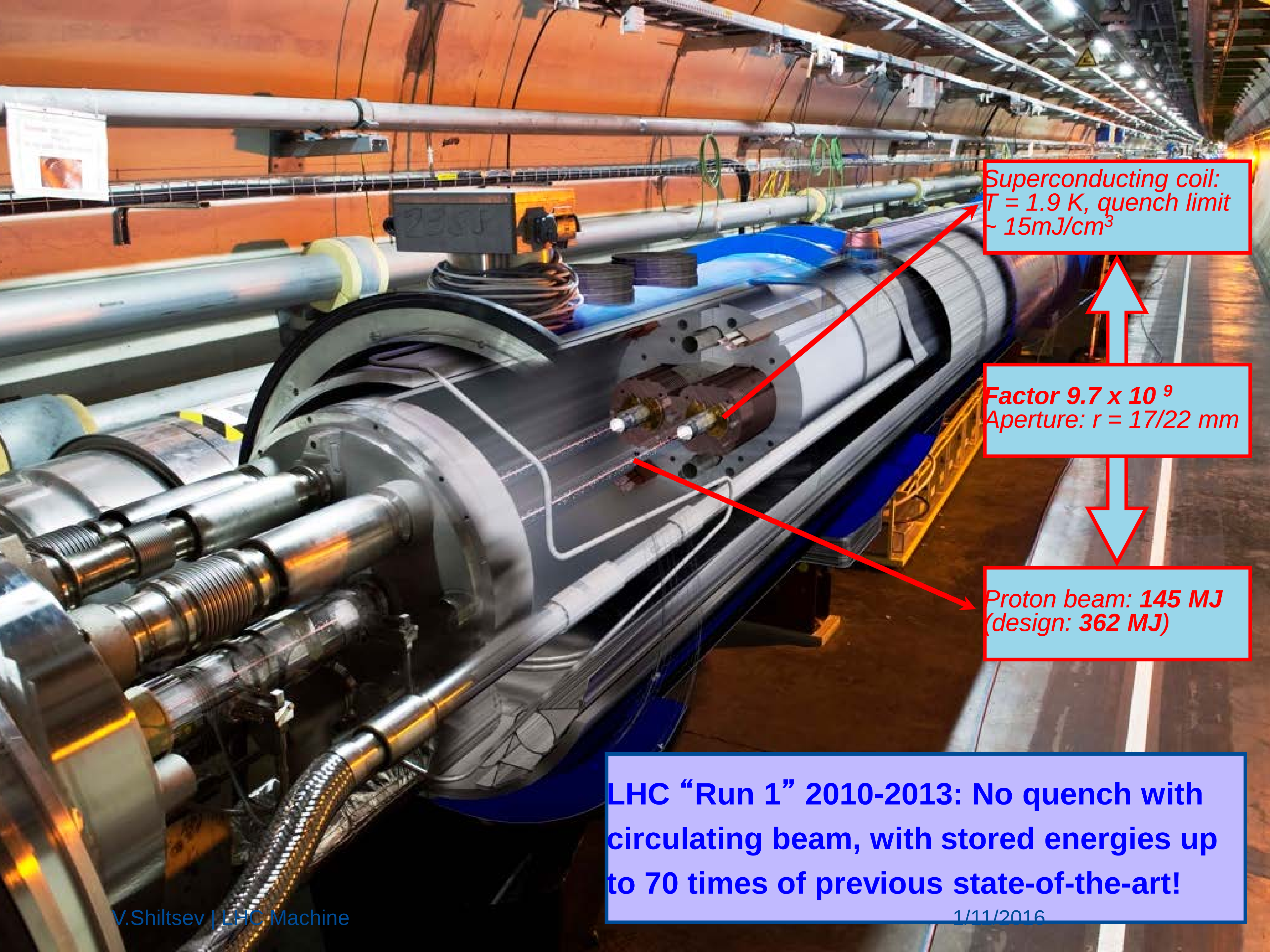


T4: Halo Collimation

LHC particles are not 100% contained! They diffuse! – need control !



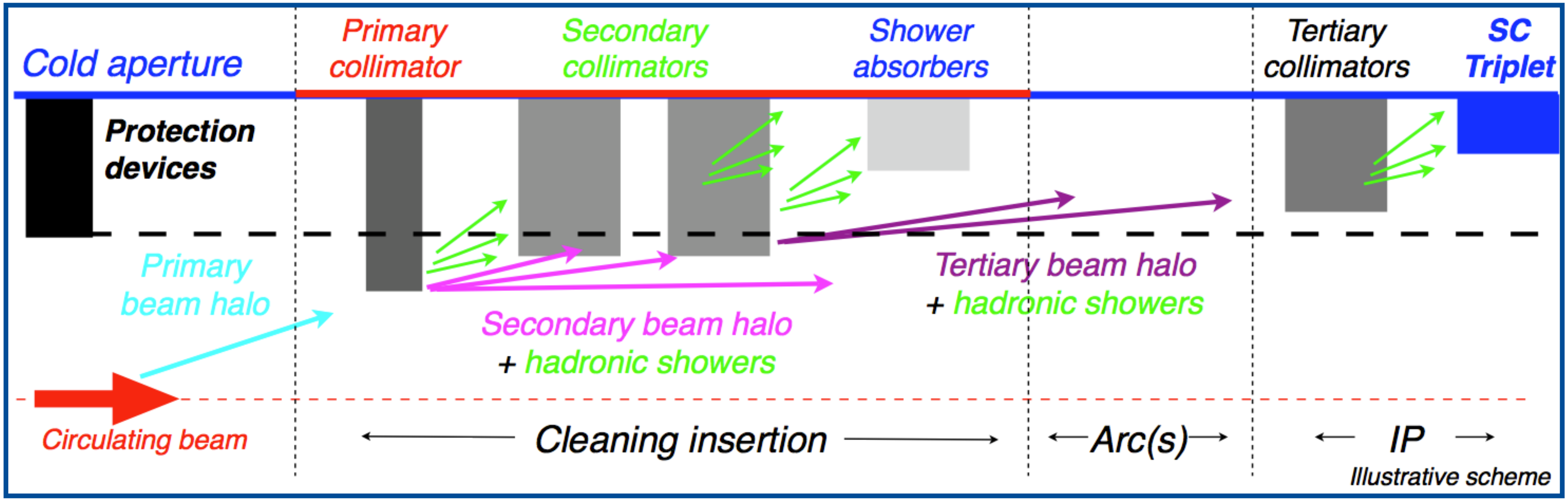
The LHC beam energy is 350 MJ. Already at injection the beam can damage a magnet.



LHC "Run 1" 2010-2013: No quench with circulating beam, with stored energies up to 70 times of previous state-of-the-art!

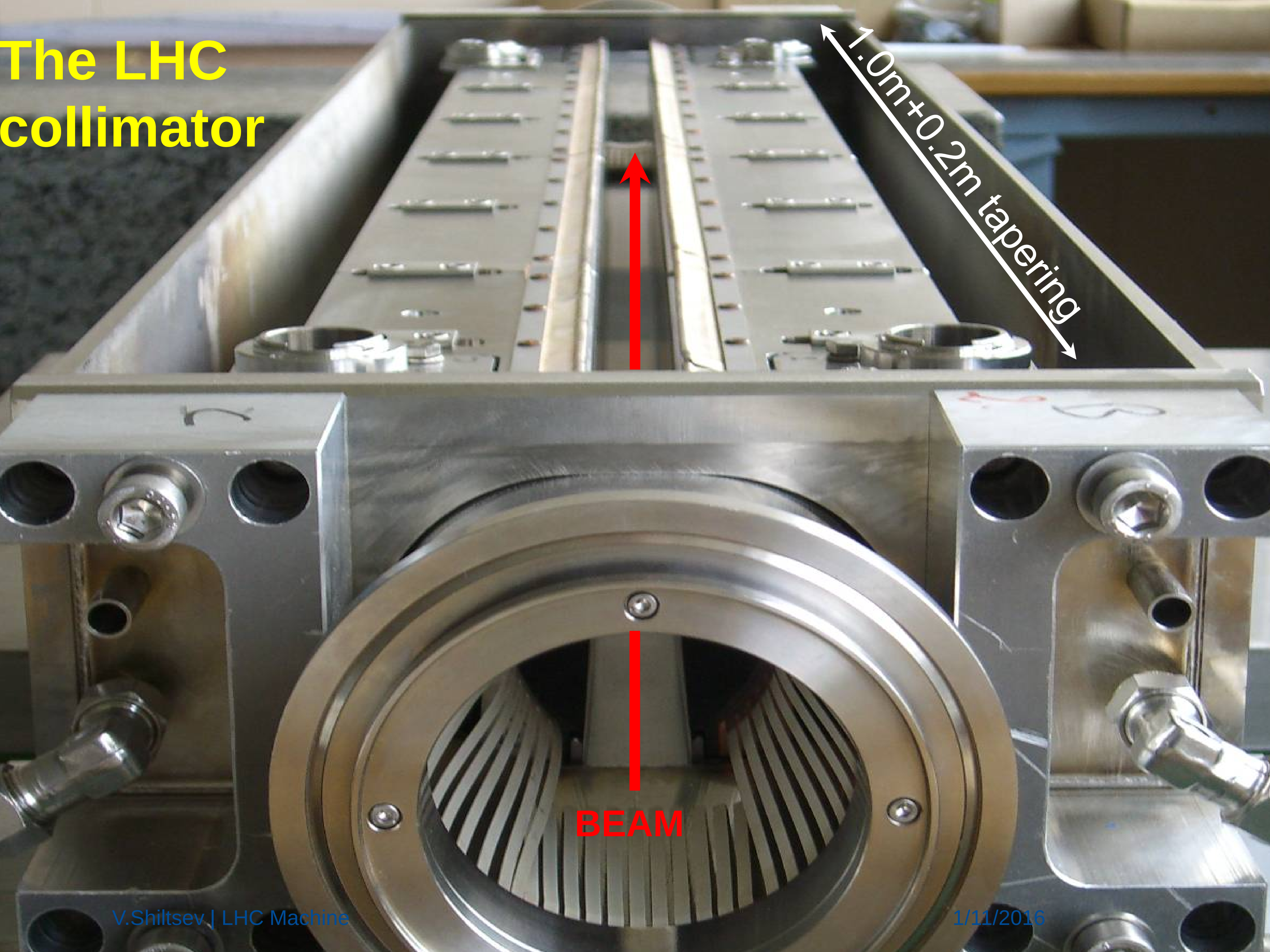
LHC collimation system

- LHC has **complex** and **distributed collimation** system of >100 collimators
  → *several stages to protects LHC components as well as detectors*



- **Collimation** is designed to provide cleaning efficiencies > 99.99%
  → *need **good statistical accuracy** at limiting loss locations;*
  → *simulate only halo particles that interact with collimators, not the core.*

The LHC collimator



LHC Collimation System Layout

Two warm cleaning insertions, 3 collimation planes

- **IR3: Momentum cleaning**
  - **1 primary (H)**
  - **4 secondary (H)**
  - **4 shower abs. (H,V)**
- **IR7: Betatron cleaning**
  - **3 primary (H,V,S)**
  - **11 secondary (H,V,S)**
  - **5 shower abs. (H,V)**

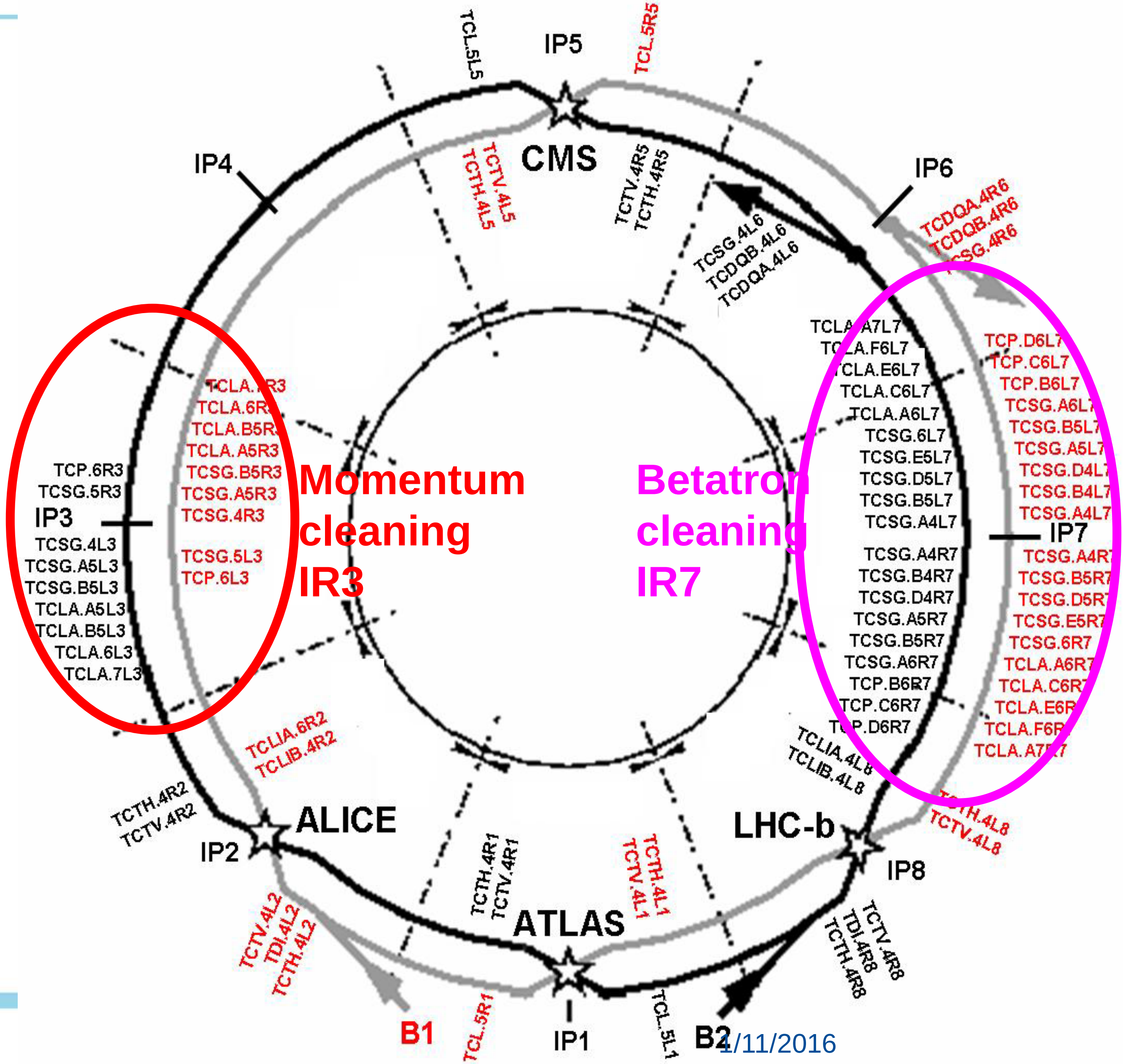
Local cleaning at triplets

- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

Physics debris absorbers

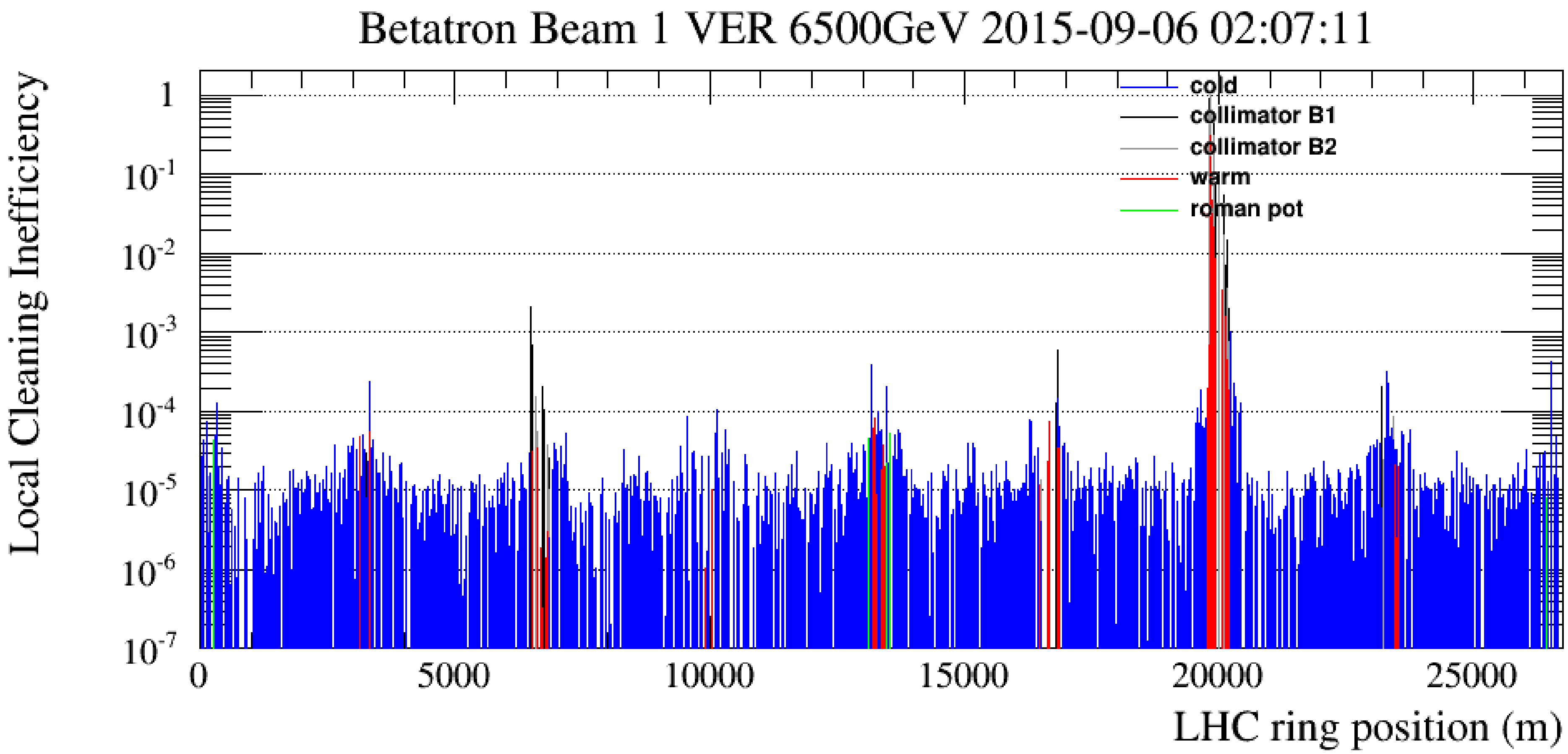
Transfer lines (13 collimators)
Injection and dump protection (10)



Total of 108 collimators (100 movable).
Two jaws (4 motors) per collimator!

Super-Effective Halo Cleaning in LHC

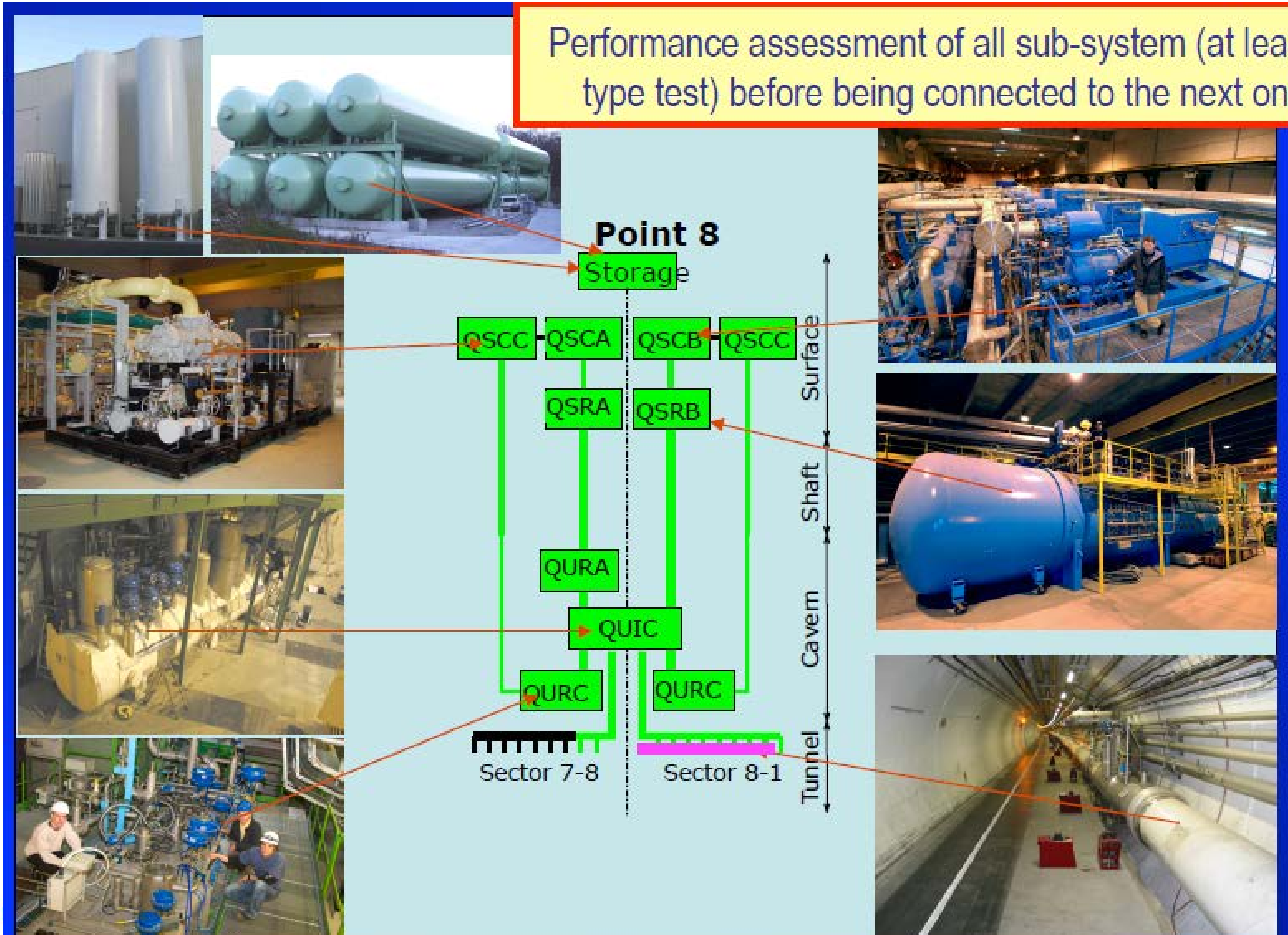
- 2015



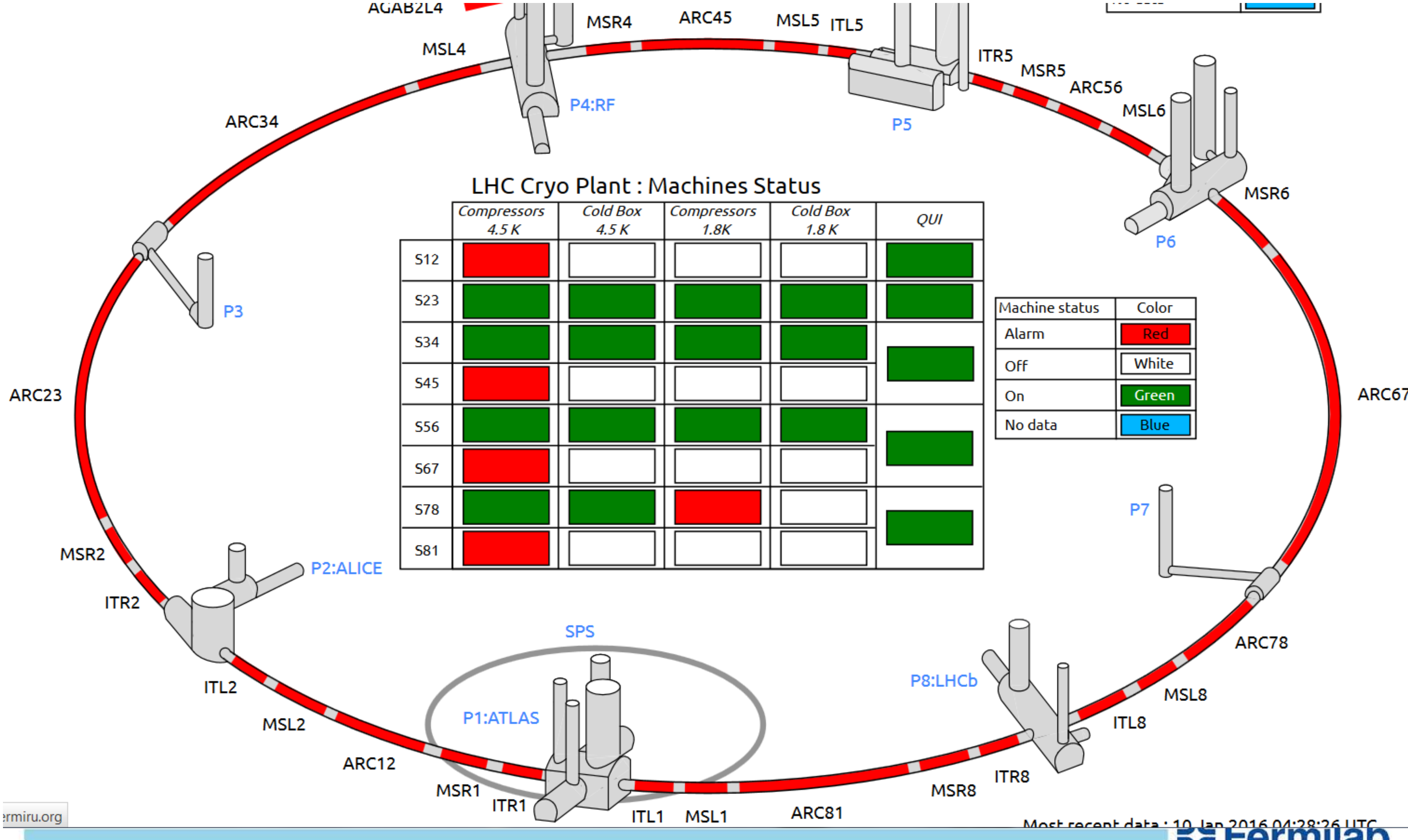
T5: Cryogenics , Trips

- LHC: 8 cryoplants total 35 MW wall plug; 130 tons of LHe to keep 36,000 tons at 1.9K
- Efficiency ~250 W wall plug power per Watt at 4.5 K
  - CERN cryocapacity of 150 kW @4.5K and 20kW at 1.9K
- Three Temperatures:
  - 50-70 T-shield
  - 4.6 K Heat Intercept
  - 4.6-20 K Beam Screen
  - 1.9K cold mass
- Safety factor 1.6 (design)
- Reality: ~none (1.1?)

Temp. level	Heat load source		LHC nominal
TS	Heat inleaks	[W/m]	7.7
	Total TS	[W/m]	**7.7**
HI	Heat inleaks	[W/m]	0.23
	Total HI	[W/m]	**0.23**
BS	Heat inleaks	[W/m]	0
	Synchrotron radiation	[W/m]	0.33
	Image current	[W/m]	0.36
	Photo-electron cloud	[W/m]	0.90
	Total BS	**[W/m]**	**1.82**
CM	Heat inleaks	[W/m]	0.21
	Resistive heating	[W/m]	0.10
	Beam-gas scattering	[W/m]	0.05
	Total CM	**[W/m]**	**0.36**

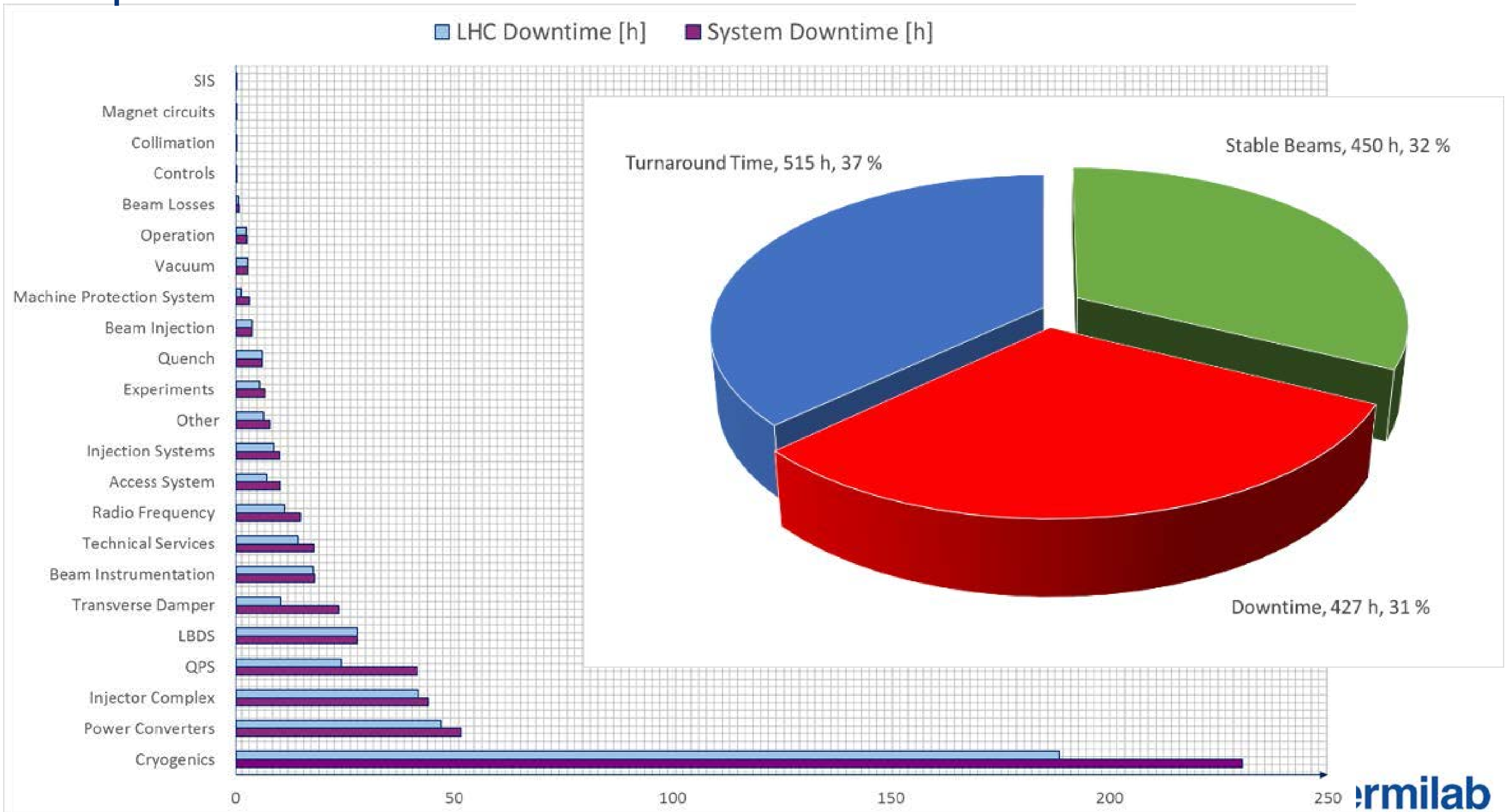

Performance assessment of all sub-system (at lea
type test) before being connected to the next on
Point 8
Storage
QSCC
QSCA
QSCB
QSCC
QSRA
QSRB
QURA
QUIC
QURC
QURC
Sector 7-8
Sector 8-1
Surface
Shaft
Cavern
Tunnel

Cryo: Complex and Large Machinery



2015 LHC Machine availability

Statistics for 25 ns run from
September 7 to November 3



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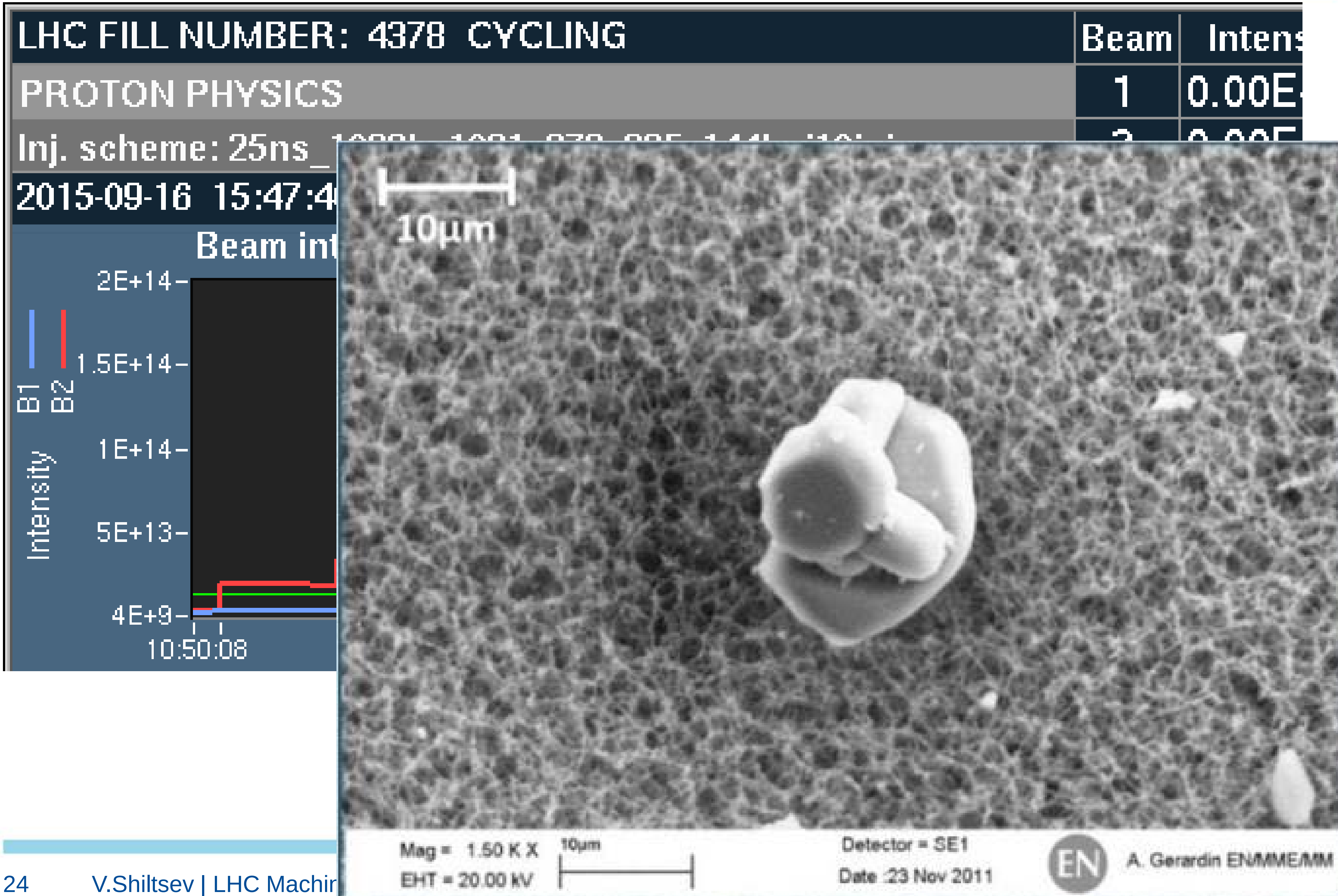
T6: UFOs

‘Unidentified Falling Objects’

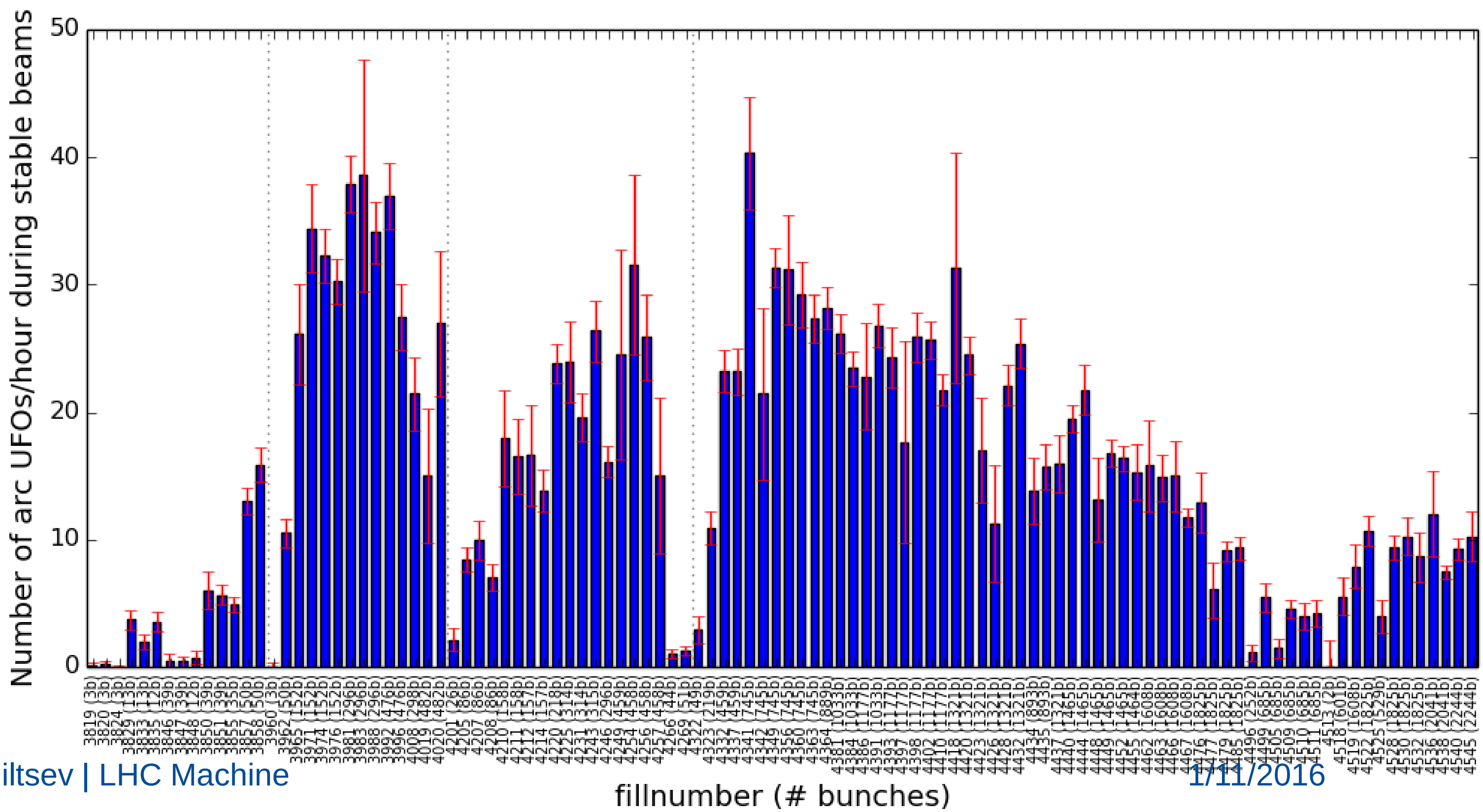


UFOs: there are many of them, they are frequent !

UFO events observed quite often during operation at 6.5 TeV

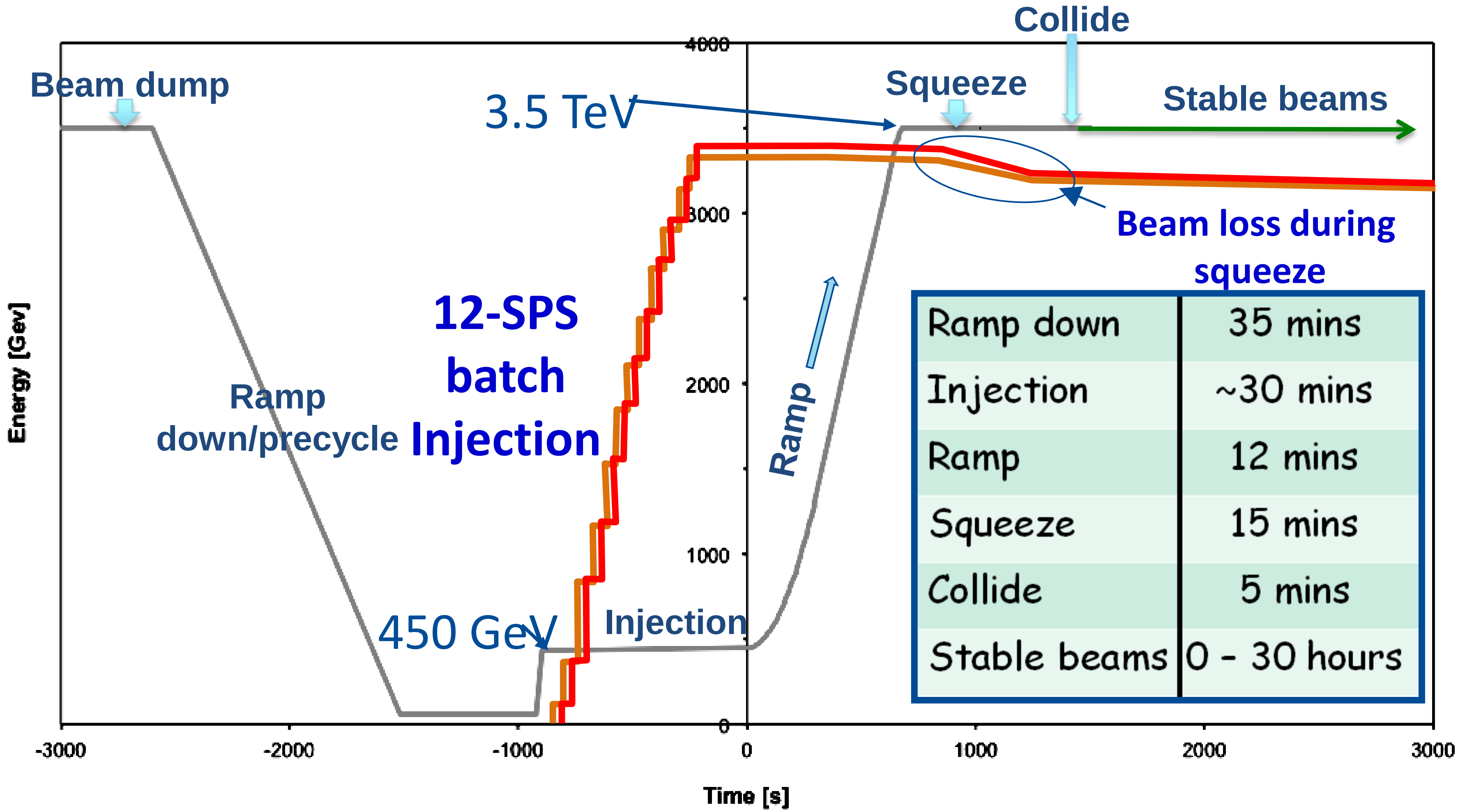
Conditioning is observed on the UFO rate in spite of the increasing number of bunches

BLM thresholds being optimize to find a **good compromise between availability and quench protection**



T7: Turnaround times, ramps, etc

A Schematic of LHC Operational Cycle at half nominal energy



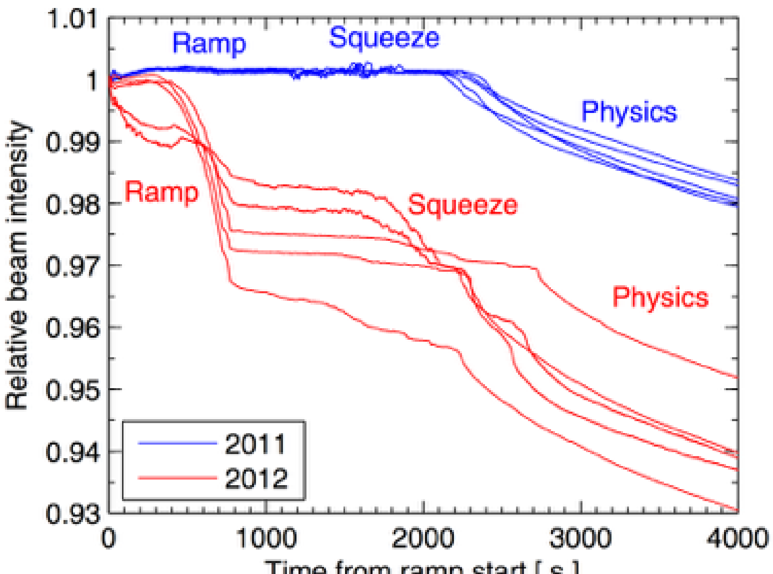
Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 - 30 hours

The fastest turnaround in 2012 was 2 hours 8 minutes. This was close to the theoretical minimum for 4 TeV operation. The average for the year was around 5 hours 30 minutes.

T7: Turnaround @ 13 TeV - longer

Table 1: Breakdown of turnaround with estimated minimum times shown

Phase	Time [minutes]
Ramp down/pre-cycle	60
Pre-injection checks and preparation	15
Checks with set-up beam	15
Nominal injection sequence	20
Ramp preparation	5
Ramp	25
Squeeze	30
Adjust/collisions	10
Total	180



Additional delays:

- Transfer and injection optimization and general wrestling with the injection process (respecting tight demands on beam quality etc.).
- controls and data acquisition problems; kicker overheating; problems in the injectors; etc.
- access recovery, precycle faults
- Fills lost in the ramp and squeeze to beam induced problems (instabilities) or, feedback system faults

T8: State of the Art SC Magnets

1232 bending magnets 15м
NbTi cables, 13 кА@1.9 К 10 GJ

4.5T

Tevatron,
6 m, 76 mm
774 dipoles

4.5 K He, NbTi
+ warm iron
small He-plant

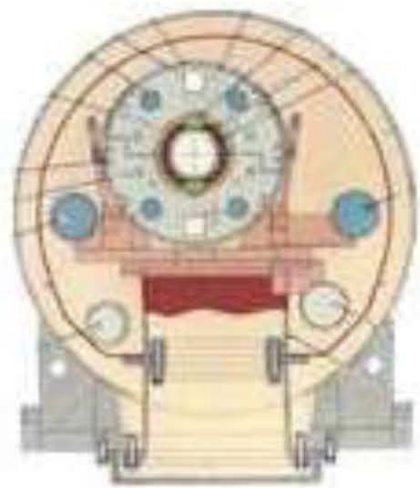
5.3T

HERA,
9 m, 75 mm
416 dipoles

NbTi cable
cold iron
Al collar

3.5T

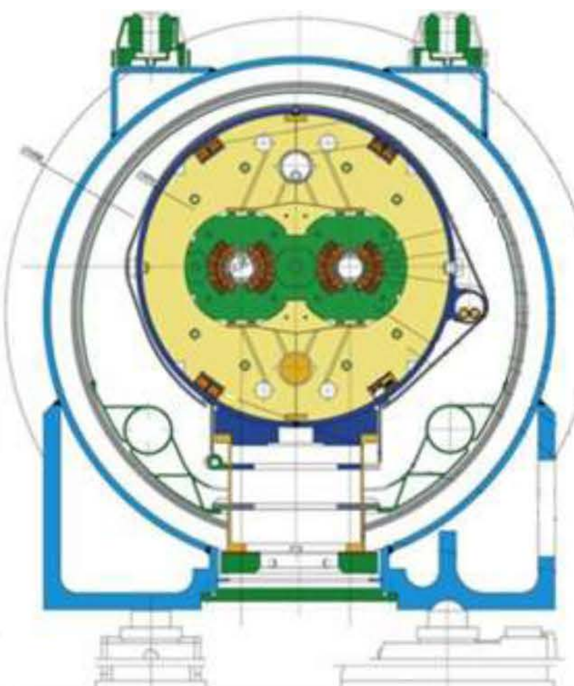
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

8.3T

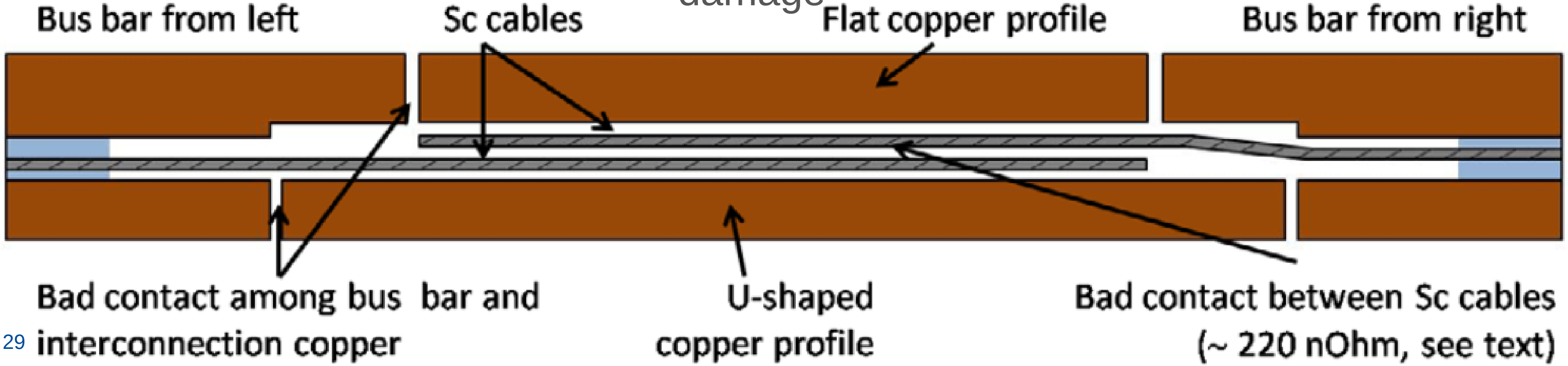
LHC,
15 m, 56 mm
1276 dipoles



NbTi cable
2K He
two bores

September 19 2008

- A splice with bad thermal and electrical contact between the superconductor and the copper produced sufficient resistive heating to lead to thermal runaway.
- This provoked the melting of the material surro-unding the splice, and subsequently an electric arc developed between two exposed cable ends.
- This arc melted through the helium line in which the cable travels, releasing Helium into the insulation vacuum of the interconnect.
- The rapid and voluminous expansion of the Helium caused a pressure wave that propagated along the insulation vacuum causing extensive damage

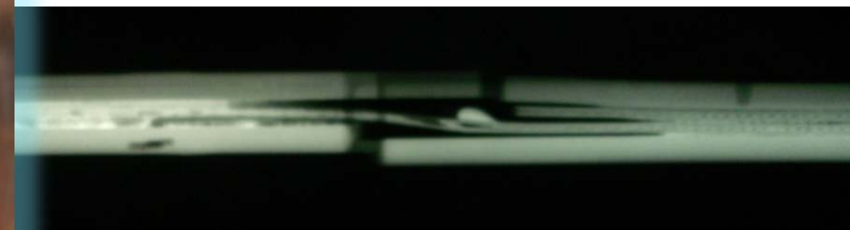


Quench : MRI magnet* (~1/30,000 of LHC)

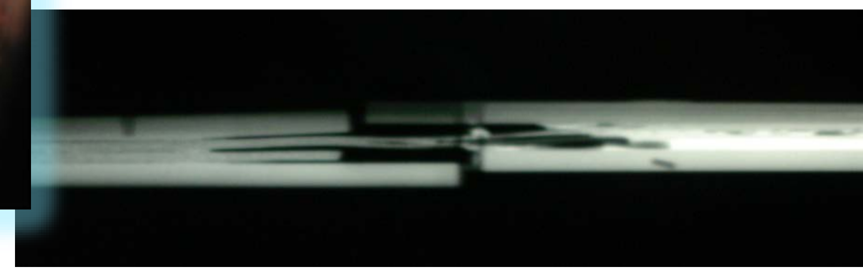
№1 how LHC was fixed
№2 LHC vacuum chamber

*pulled off the web. We recover our Helium.

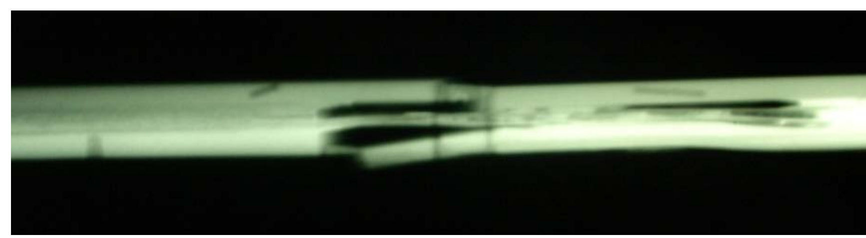
Sample Joint X-Rays



Sample 3A left (26 μΩ)

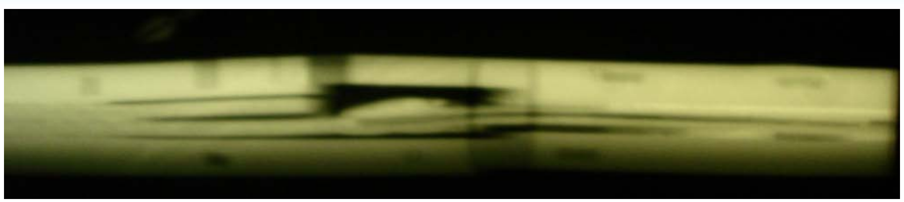


Sample 3A right (43 μΩ)

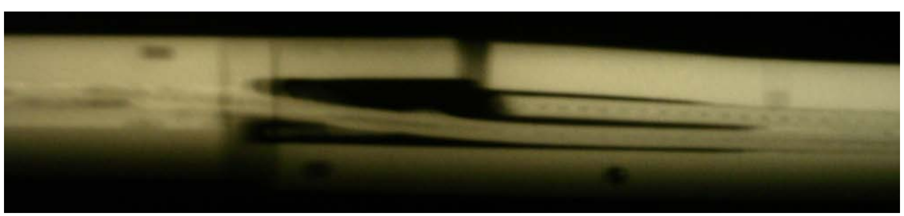


Sample 3B (21 μΩ)

Pictures by J.-M. Dalin

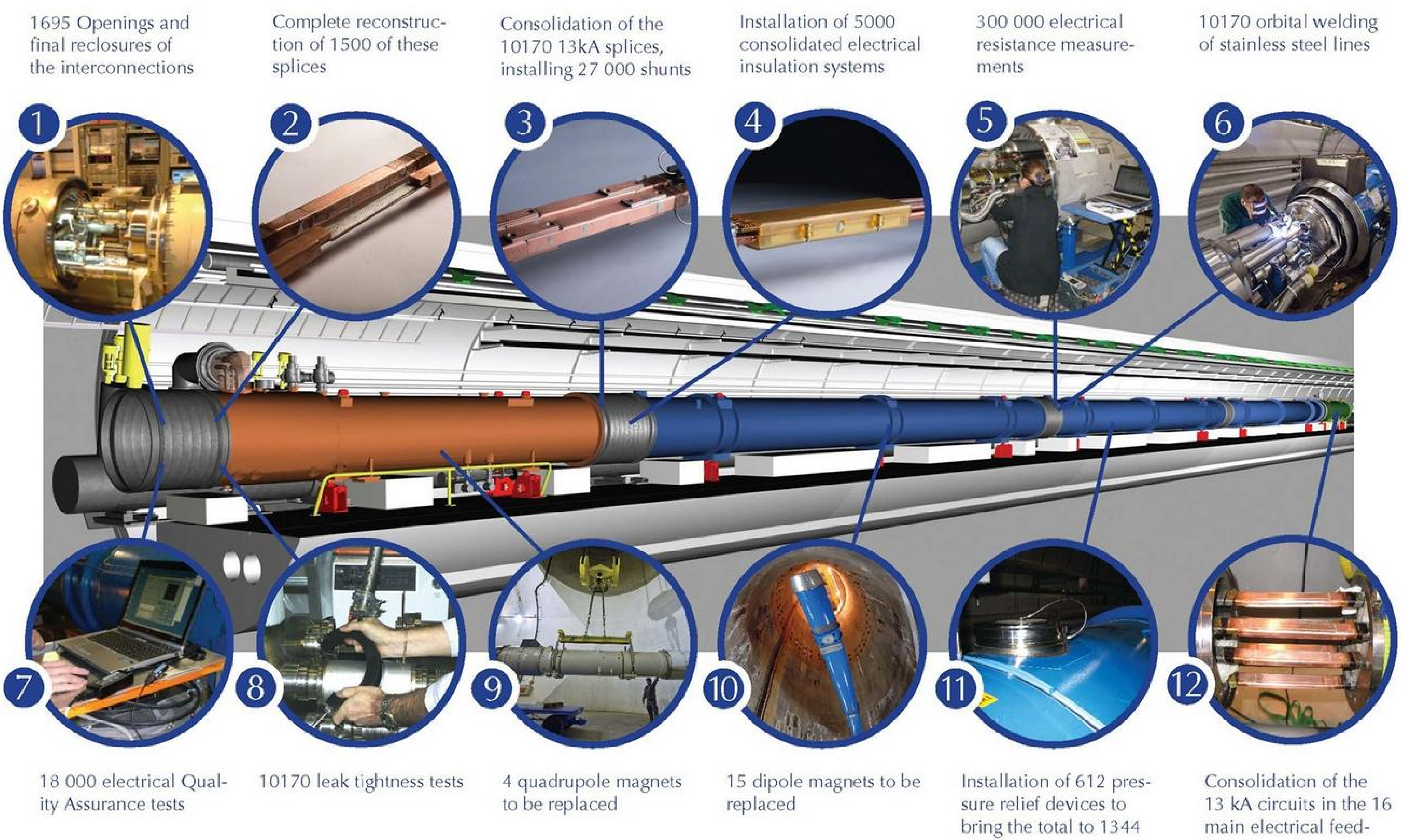


Sample 2A right (43 μΩ)



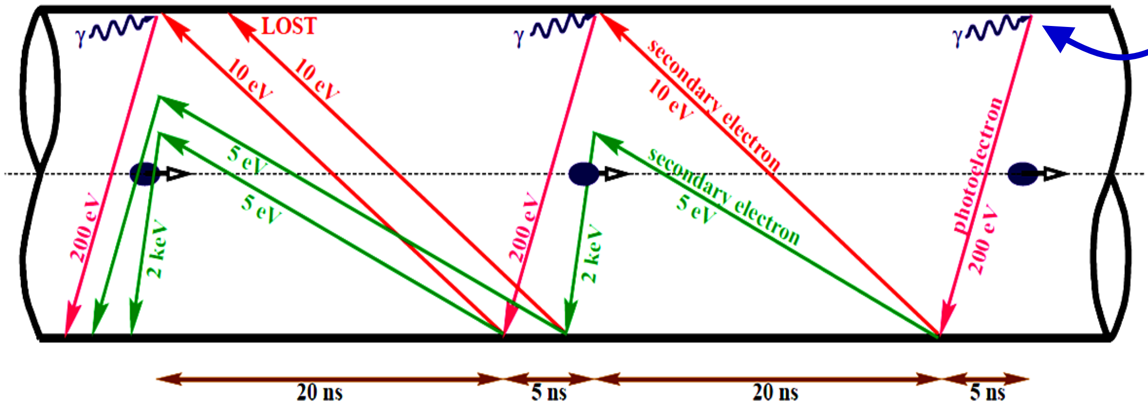
Sample 2B (42 μΩ)

The main 2013-14 LHC consolidations



A 13kA splice has a resistance of about 300 pΩ, which can be measured with a precision ~20pΩ. The acceptance criteria is 10 nΩ. Any splice does not meet this criteria is replaced/repaired. The resistance acceptance criteria at the Cu - superconducting splice joints was 5 μΩ. Any joint does not meet this criteria is replaced or repaired.

T9: Electron Cloud & Need of Scrubbing



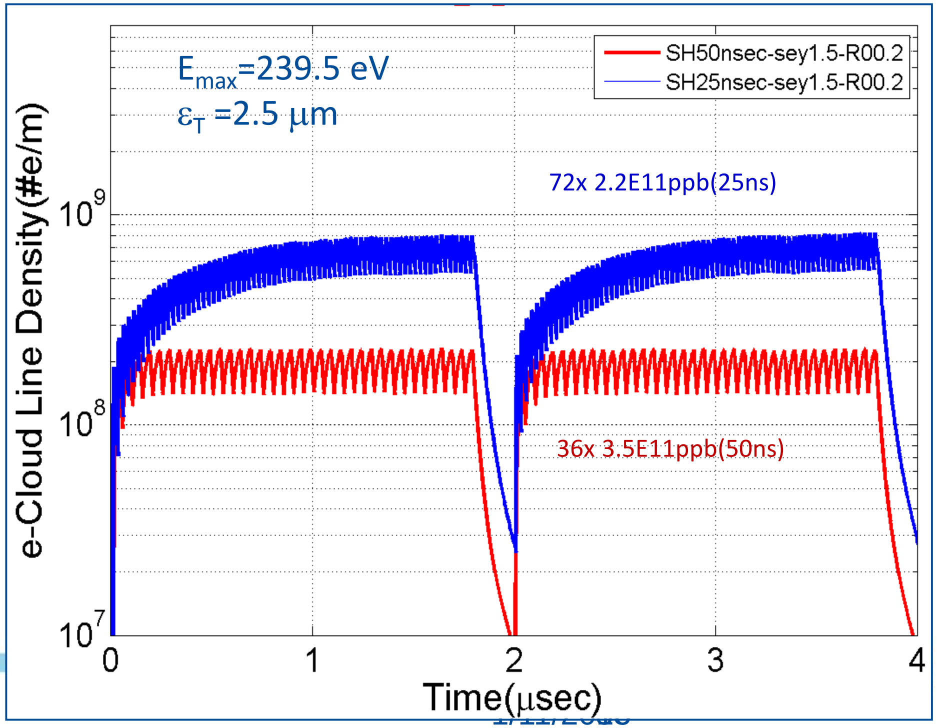
The critical energy of the photons at 7 TeV ~ 44 eV

- Primary sources of electrons in the LHC
  - At Injection (450 GeV) gas ionization
  - At 7 TeV Synchrotron Radiation

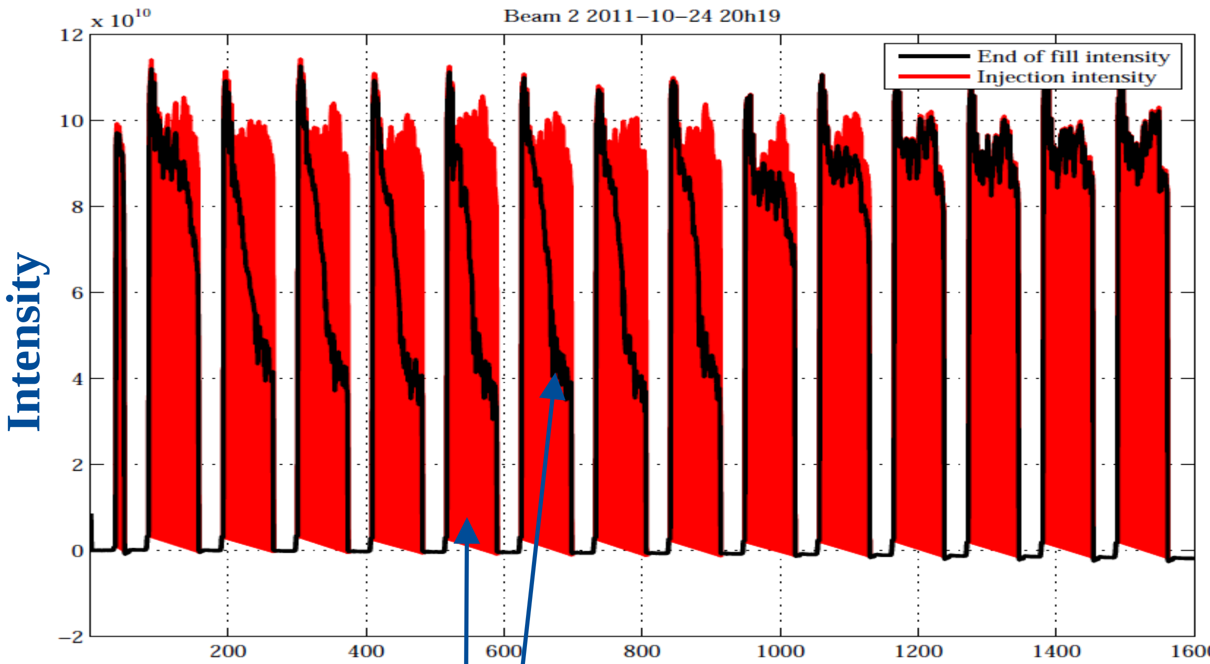
Consequences:

- instabilities, emittance growth, desorption ←bad vacuum, beam loss

- excessive energy deposition in the cold sectors



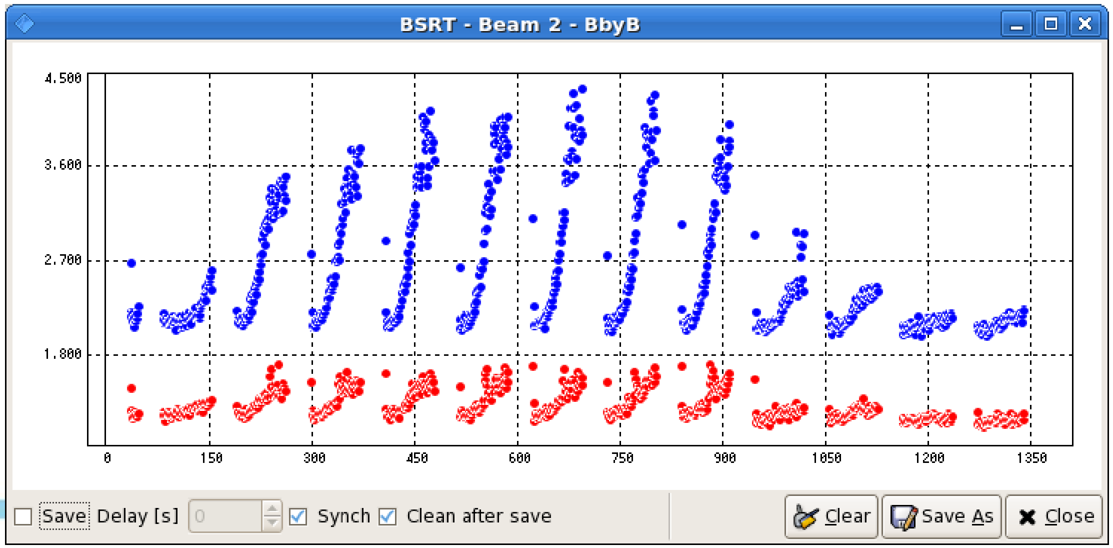
What e-cloud can do to the Beam?



Bunch #

Injection Intensity
End of fill Intensity

- Fill: 2249 (2011)
  25 ns Bunch Spacing
- Energy = 450 GeV
- Time between Injection to End ~10 min
- Dumped by BPM
- 1020 Bunches



Measured Emittance Growth

~33% Horizontal

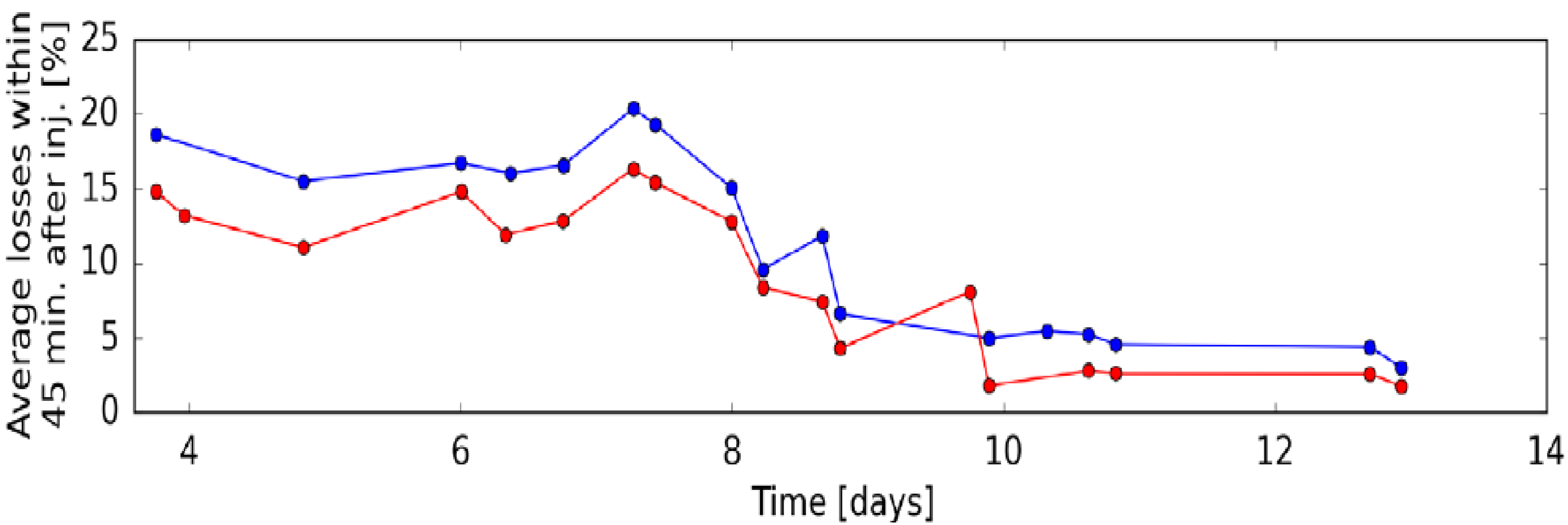
~110% Vertical

Associated beam loss

Scrubbing @ 25 ns bunch spacing

So far it is the only cure in the LHC….Takes time to clean the surface and reduce SEY (secondary electron yield) from ~2.2 to ~1.5

Scrubbing "memory" kept while running with 25 ns beams - **deconditioning** was observed after few weeks of low e-cloud operation



T10: Upgrades

- **The main objective of HiLumi-LHC Upgrade (2022-2024) is to install new hardware and guarantee beam parameters that will allow the LHC to reach the following targets:**
  - Prepare machine for operation **beyond 2025 and up to 2035-37**
  - Devise beam parameters and operation scenarios for:
    - enabling a total integrated luminosity of **3000 fb-1**
    - implying an integrated luminosity of **250-300 fb-1 per year**,
    - design for μ ~ **140 (~ 200)**
    - (peak luminosity of **5 (7) 1034 cm-2 s-1**)
  - Design equipment for 'ultimate' performance of **7.5 1034 cm-2 s-1** and **4000 fb-1 => Ten times the luminosity reach of first 10 years of LHC operation**

LHC Luminosity Upgrade : Machine Goals

Luminosity recipe :

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

→1) maximize bunch intensities → Injector complex

→2) minimize the beam emittance LIU ⇔ IBS

→3) minimize beam size (constant beam power); → triplet aperture

→4) maximize number of bunches (beam power); → 25ns

→5) compensate for 'F'; → Crab Cavities

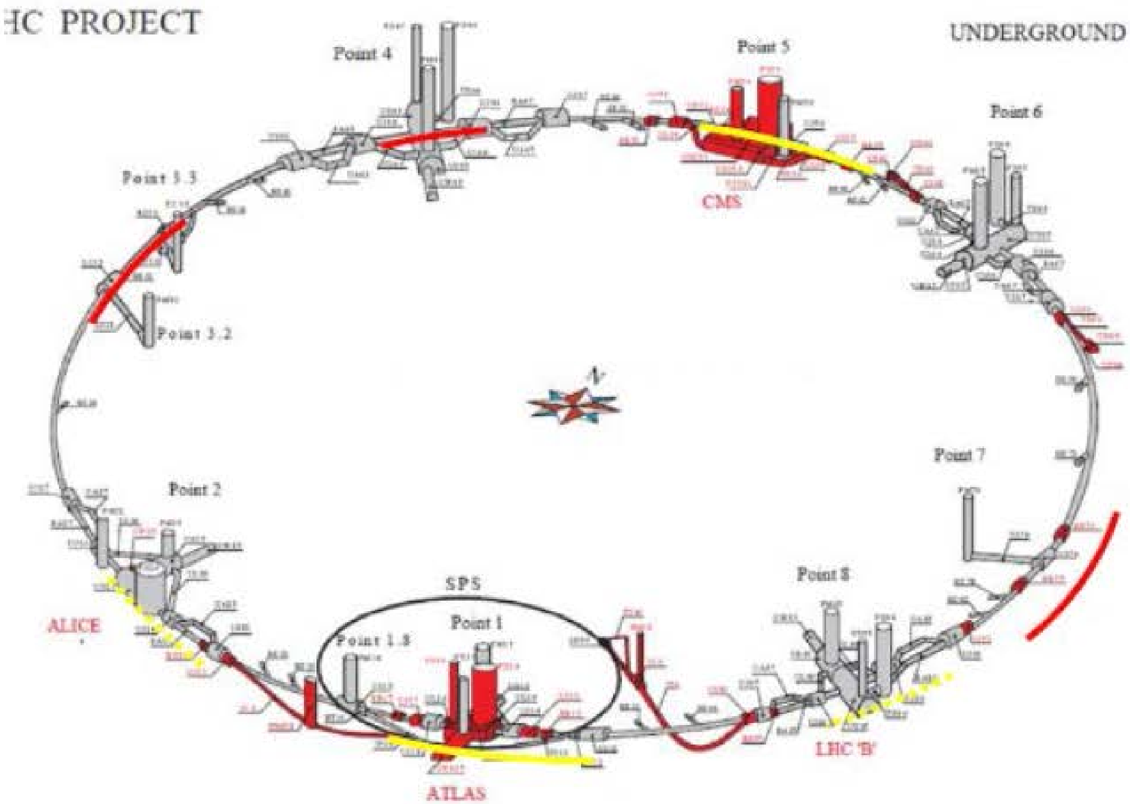
→6) Improve machine 'Efficiency' → minimize number of unscheduled beam aborts

HL-LHC Scale: Hardware and Cost

The HL-LHC Project

976MCHF (-142 +208)

~2,500 man-years



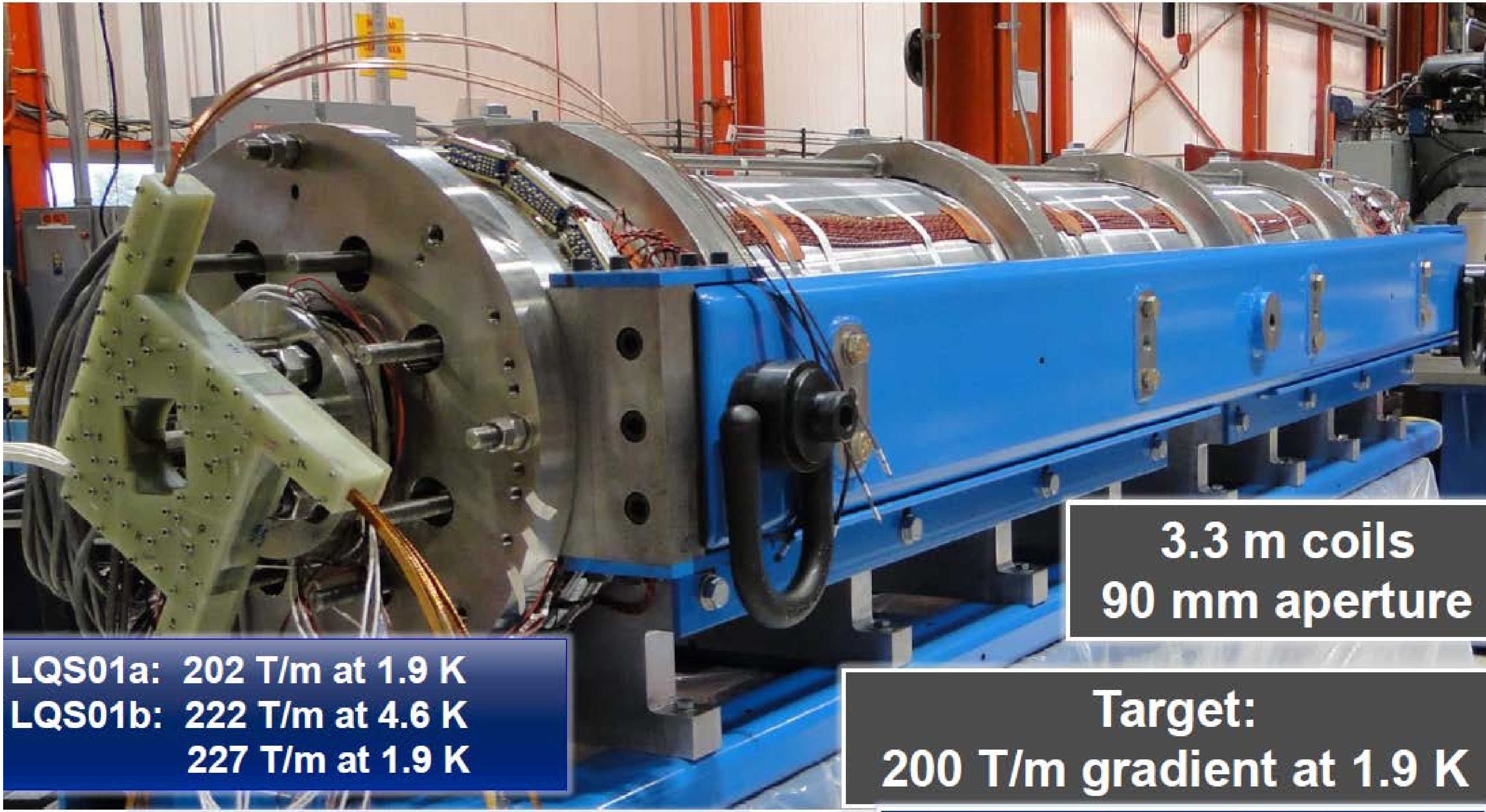
- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

Quadrupoles of LARP

Courtesy: G. Ambrosio FNAL and G. Sabbi , LBNL

LARP



3.3 m coils
90 mm aperture

LQS01a: 202 T/m at 1.9 K
LQS01b: 222 T/m at 4.6 K
227 T/m at 1.9 K

Target:
200 T/m gradient at 1.9 K

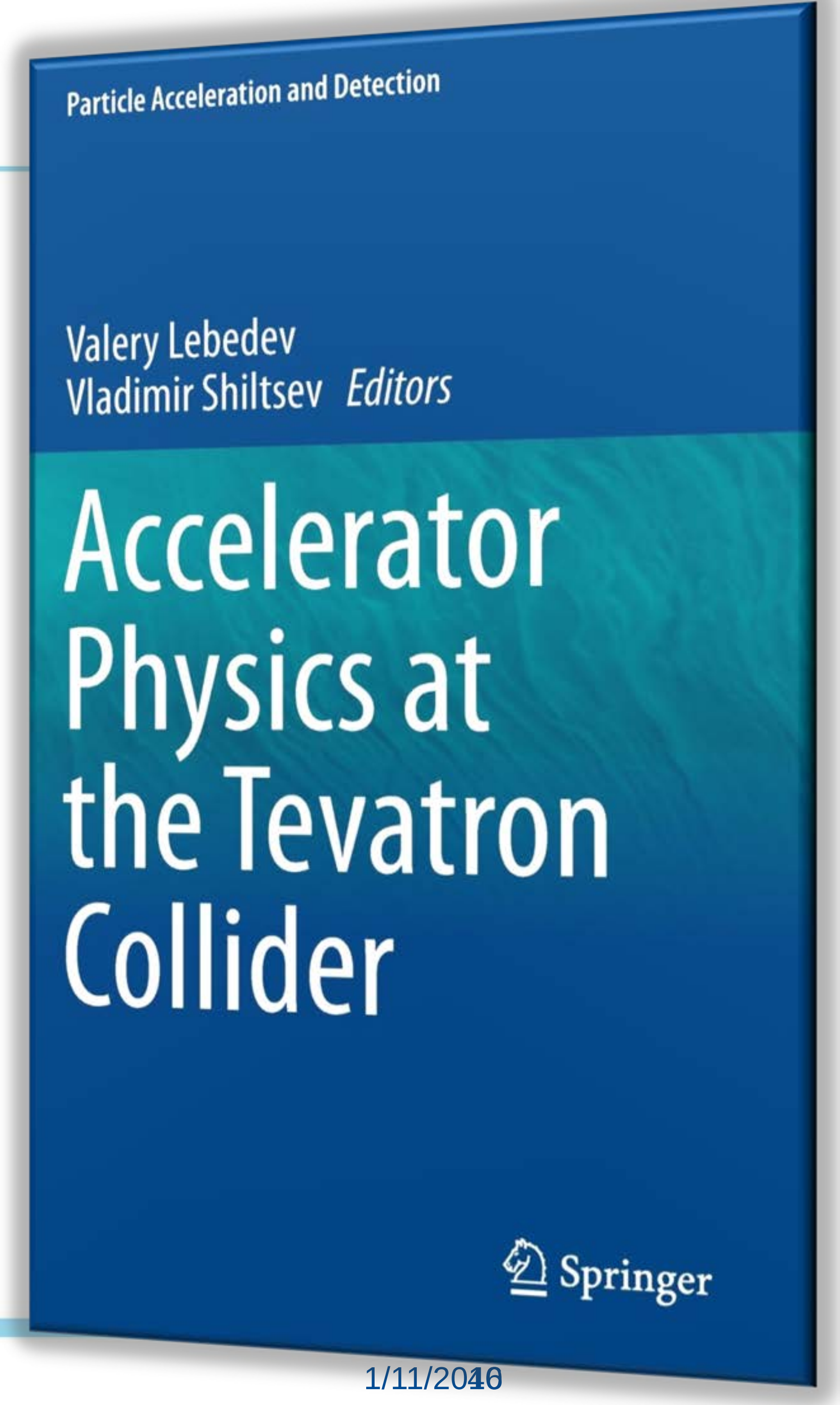
LQS02: 198 T/m at 4.6 K 150 A/s
208 T/m at 1.9 K 150 A/s
limited by one coil

LQS03: 208 T/m at 4.6 K
210 T/m at 1.9 K
1st quench: 86% s.s. limit

CERN

Further Reading on Accelerator Physics

- **An Introduction to Particle Physics High Energy Accelerators**, D. Edwards and M. Syphers (John Wileyand Sons, Inc, 1993)
- **Accelerator Physics**, S.Y. Lee (World Scientific, 1999)
- **Hand Book of Accelerator Physics and Engineering** – Eds. A. Chao and M. Tinger , World Scientific (1999)
- **CAS CERN Accelerator**, Accelerator Physics Courses http://cas.web.cern.ch/
- **Accelerator Physics at the Tevatron Collider** - by V.Lebedev and V.Shiltsev, Springer (2014)



Thank you for your attention!

Questions !?