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LHC: Machine and Accelerator Physics

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CMS Data Analysis School, 09 Jan 2017

- 26 658.883 m
- 6.5 TeV x 2

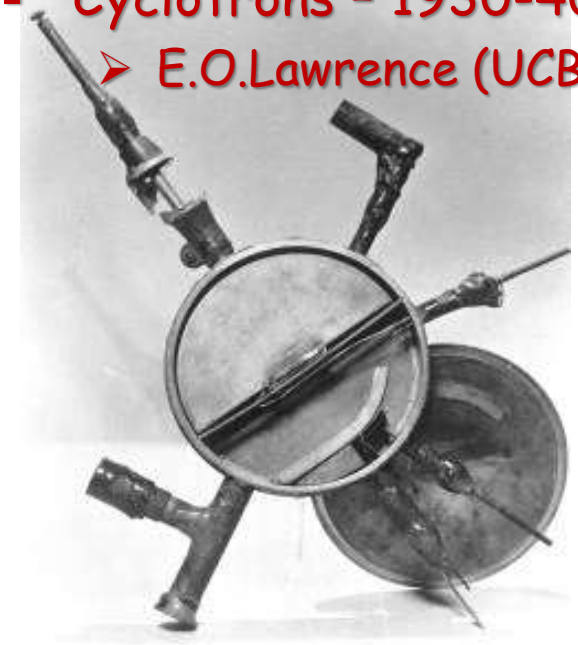
Themes and Topics

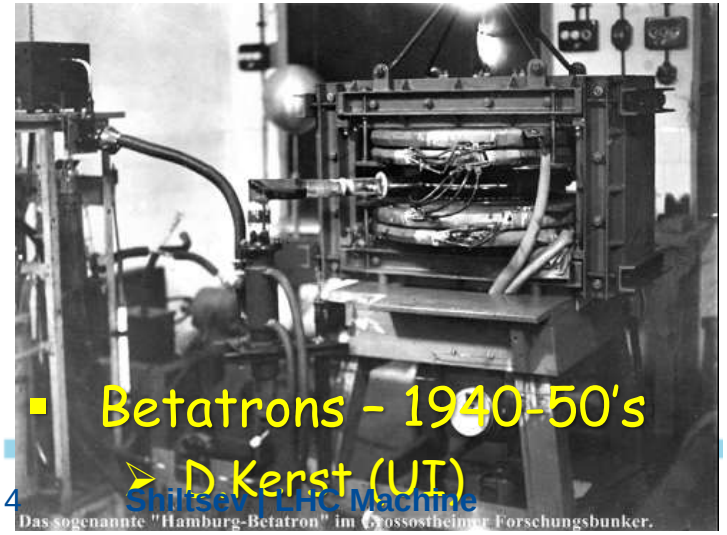
- "Level 0" Issues: Make it run
  - T1: LHC machine overview… consequences of SC magnets:
  - T2: Clean beampipes
  - T3: UFOs
  - T4: Halo collimation
- "Level 1" Issues: Performance (luminosity)
  - T5: Turnaround time, availability
  - T6: Collisions, pileups, proton lifetime
  - T7: Upgrades

T1: Types of Accelerators

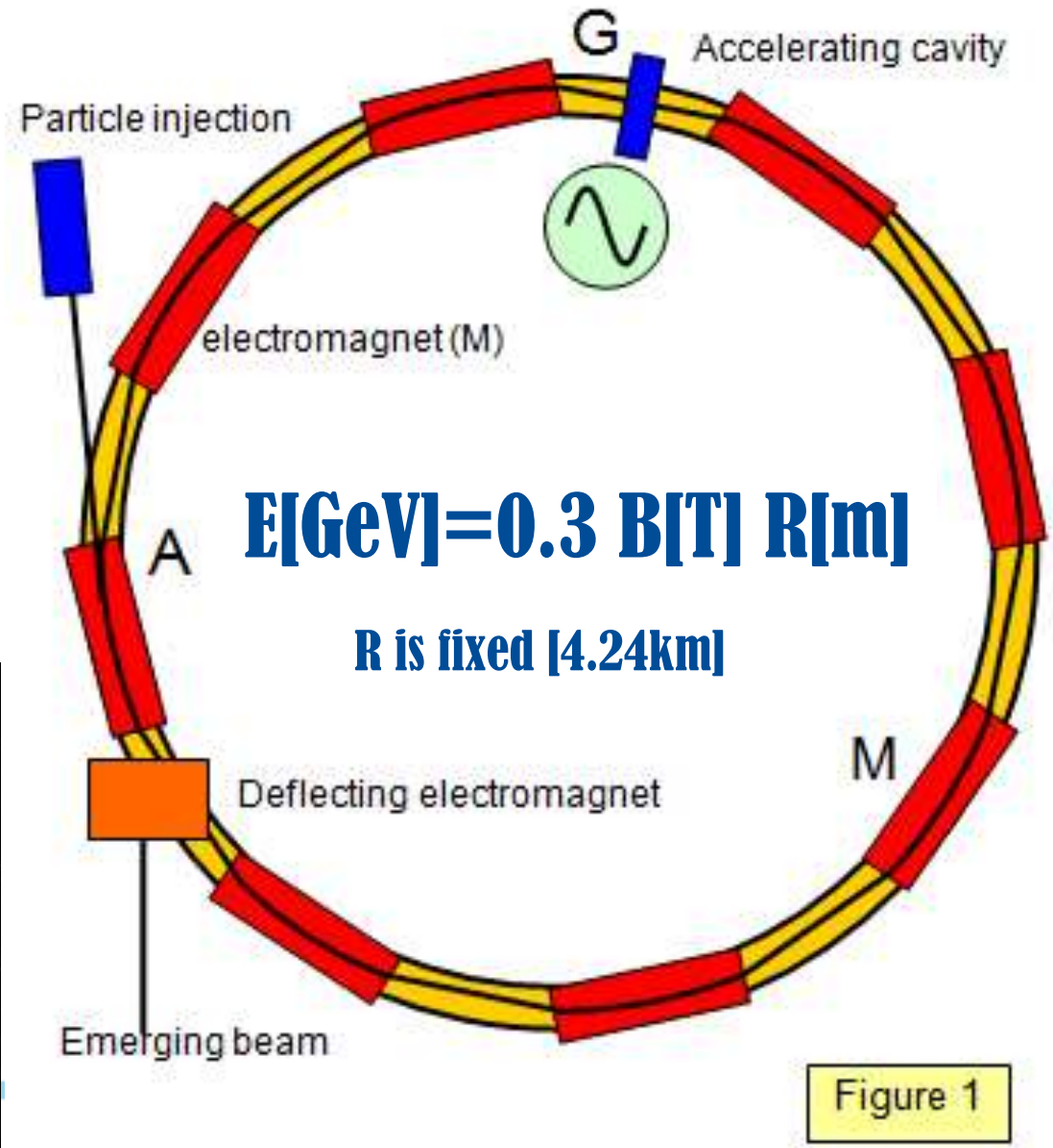
LHC is a synchrotron

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





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



E[GeV]=0.3 B[T] R[m]

R is fixed [4.24km]

State of the Art SC Magnets

1232 bending magnets 15m
NbTi cables, 13 кA@1.9 K 10 GJ

4.5T

Tevatron,
6 m, 76 mm
774 dipoles

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

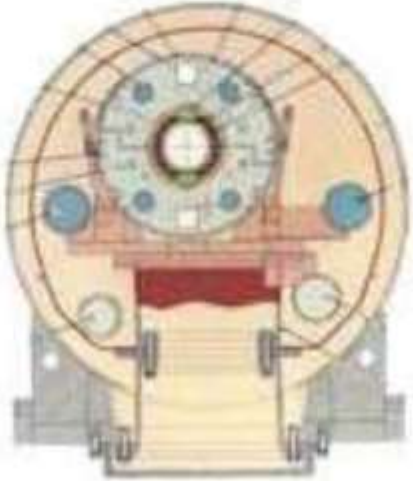
5.3T

HERA,
9 m, 75 mm
416 dipoles

NbTi cable
cold iron
Al collar

3.5T

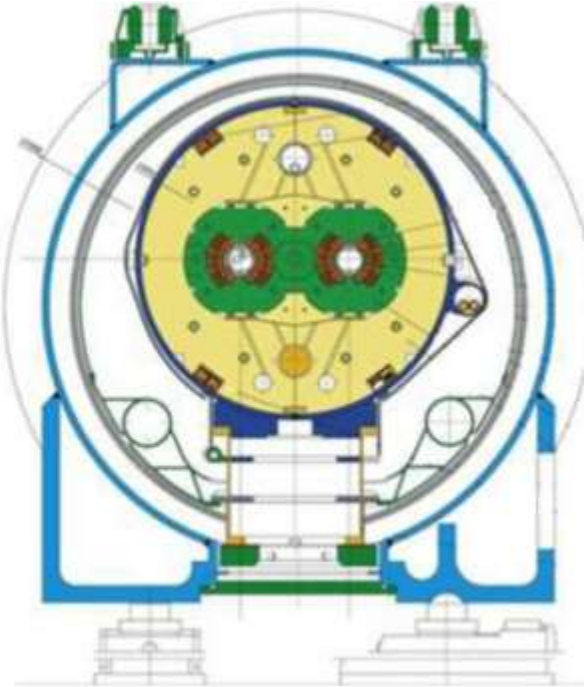
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

8.3T

LHC,
15 m, 56 mm
1276 dipoles



NbTi cable
2K He
two bores

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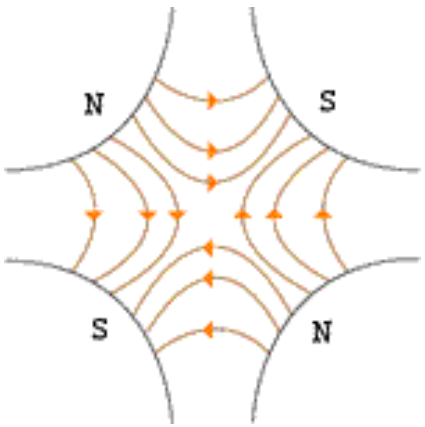
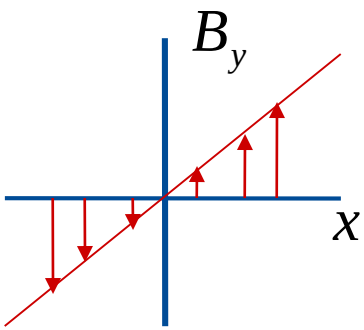
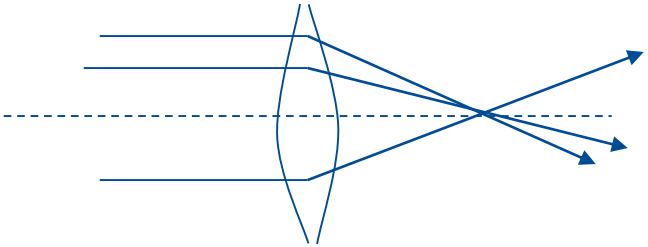
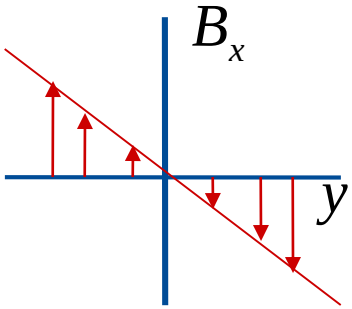
Focusing Beams with Quadrupole Magnets



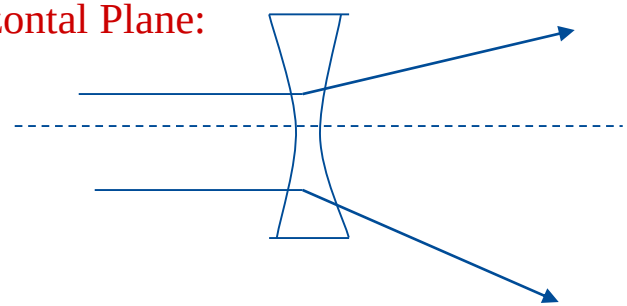


Vertical Plane:

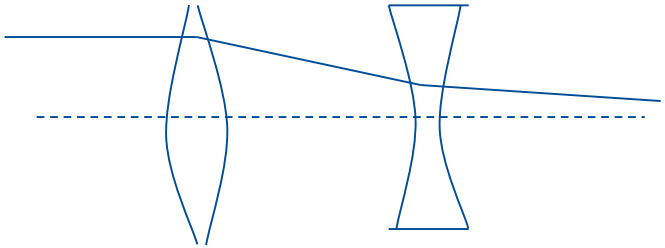


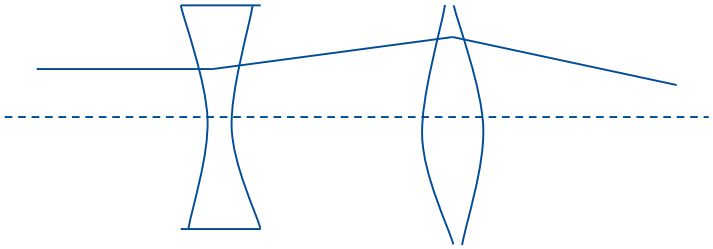


Horizontal Plane:



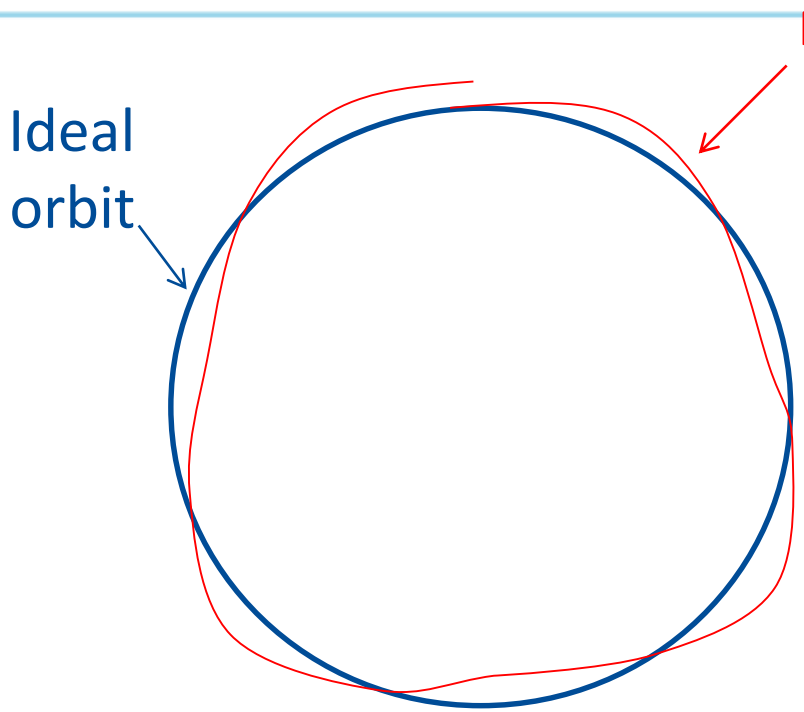
Luckily…





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

Betatron Oscillations, Tune



- As particles go around a ring, they will undergo a number of betatron oscillations *ν* (sometimes Q) given by

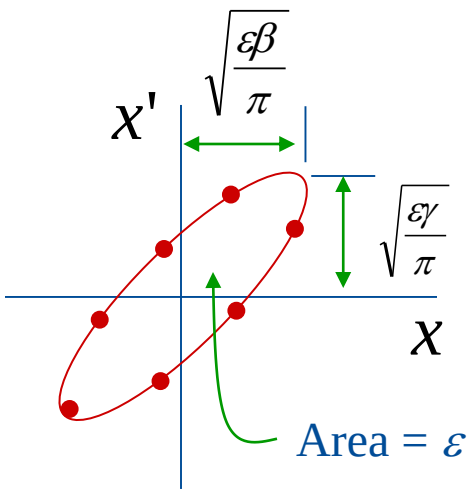
$$\nu = \frac{1}{2\pi}\oint \frac{ds}{\beta(s)}$$

- This is referred to as the **"tune"**

- We can generally think of the tune in two parts:

Integer : magnet/aperture optimization → **64.31** ← **Fraction: Beam Stability**

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

Numerical Example: LHC (γ »1, β=v/c ≈1)

$$\varepsilon_{n\,(x,y)} = \gamma \cdot \sigma_{x,y} \sigma'_{x,y}$$

$$\varepsilon_n = 2.9\ mm \cdot mrad \quad (10^{-6}\,m)$$

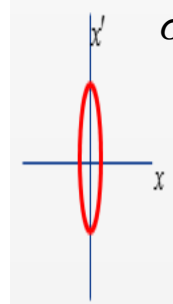
$$\gamma = 6930$$

$$\sigma_{x,y} = \sqrt{\frac{\varepsilon_n \cdot \beta_{x,y}}{\gamma}}$$

$$\sigma'_{x,y} = \sqrt{\frac{\varepsilon_n}{\gamma \cdot \beta_{x,y}}} = \frac{\sigma_{x,y}}{\beta_{x,y}}$$

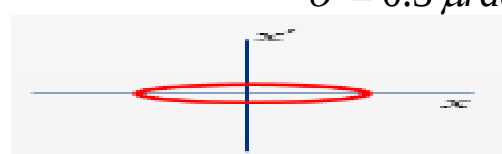
β*	Sigma*
40 cm	13 um

$\sigma' = 30\ \mu rad$



$\beta_{triplet}$	Sigma triplet
~4.5 km	1.5 mm

$\sigma' = 0.3\ \mu rad$



Squeeze in ATLAS/CMS

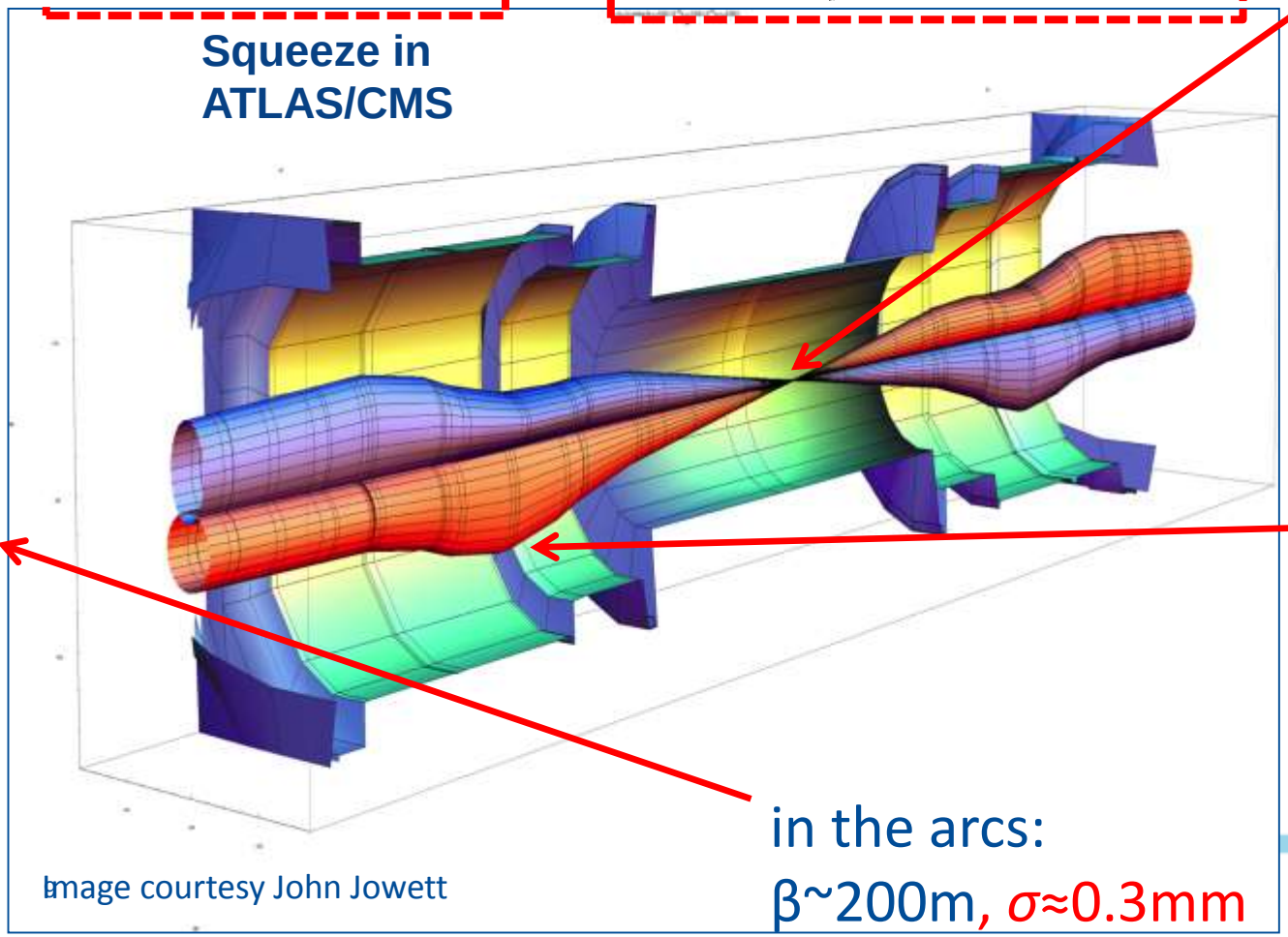


Image courtesy John Jowett

in the arcs:
β~200m, σ≈0.3mm

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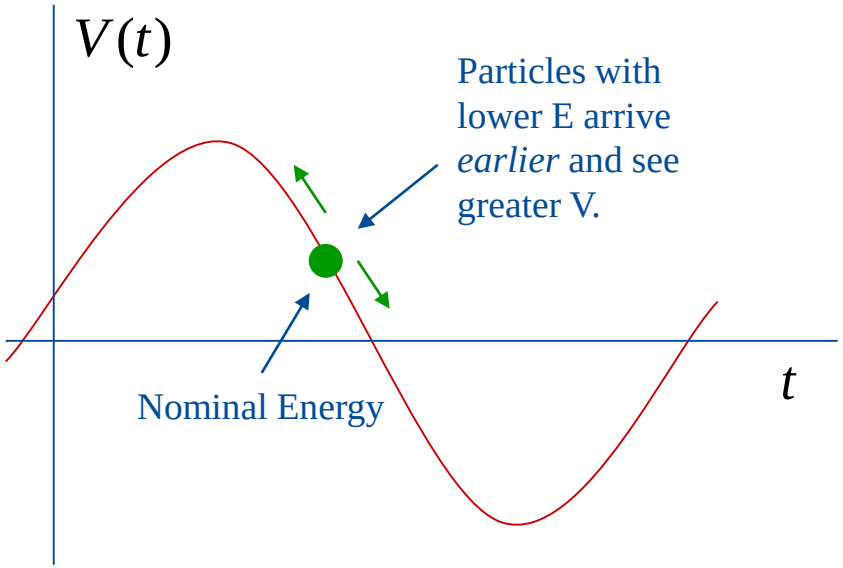
Longitudinal Motion: Phase Stability

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")



Example: LHC

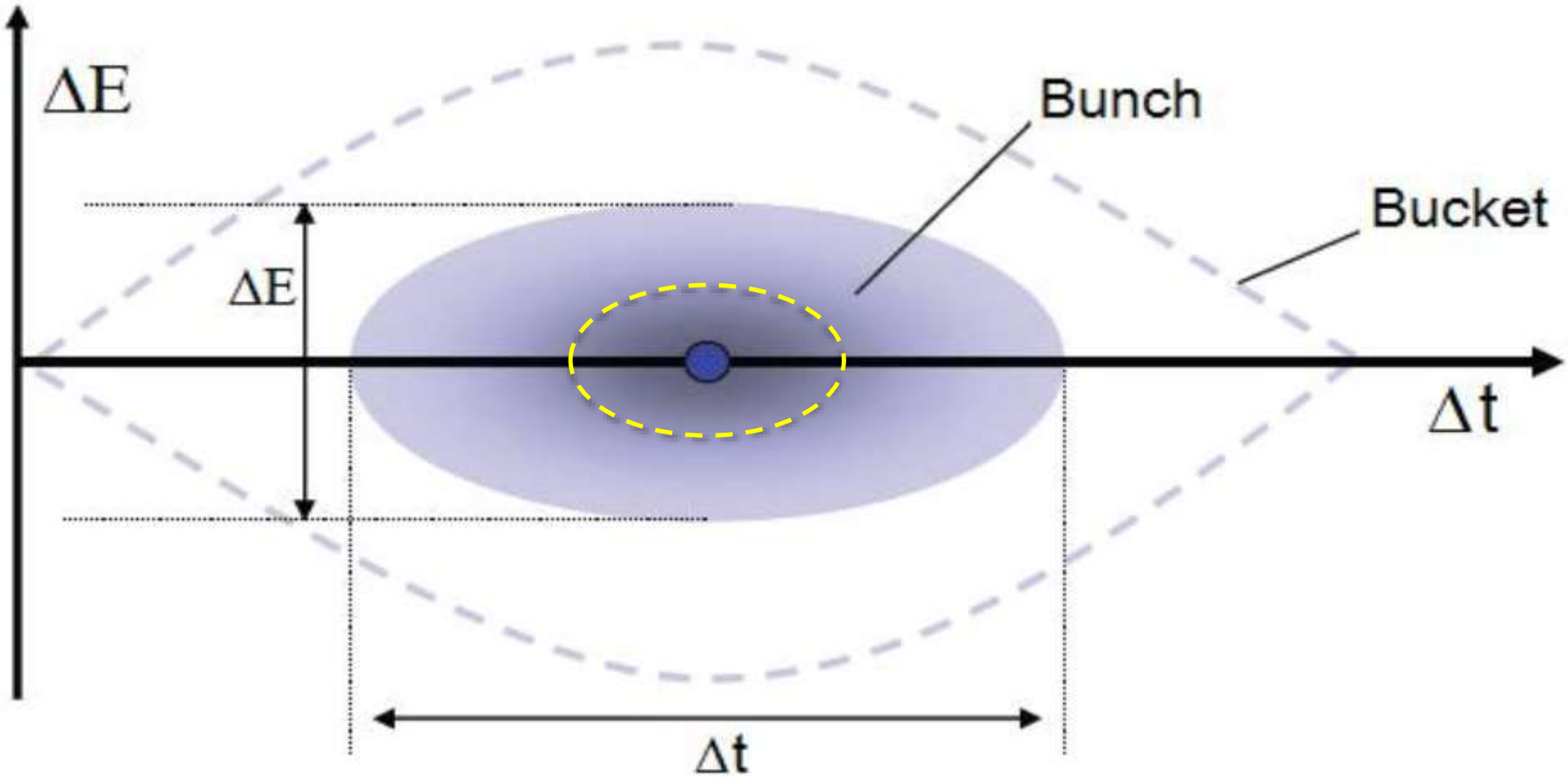
RF Frequency 400 MHz
(35640 times revolution frequency)

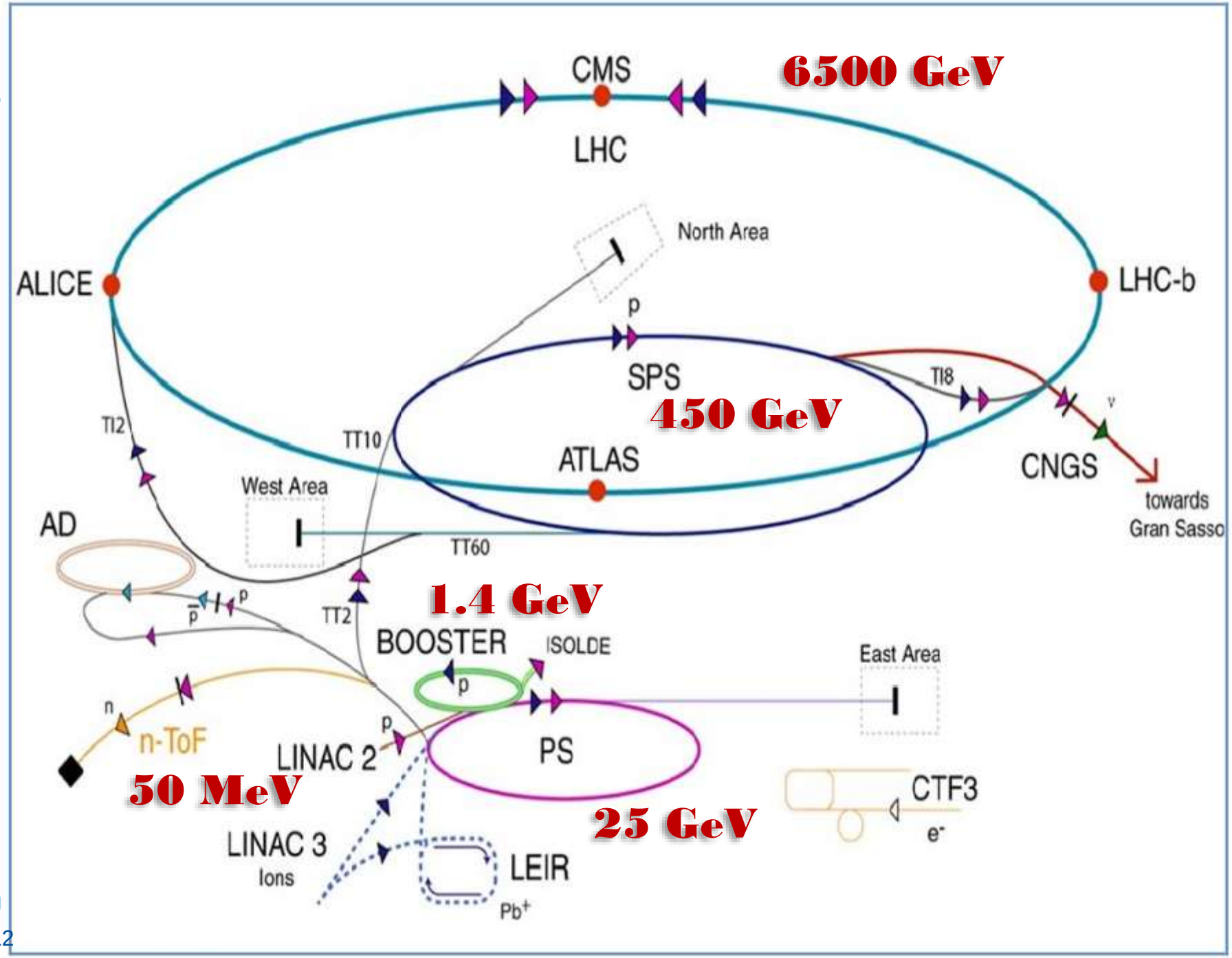
- RF Voltage = 8 cavities x 2 MV = 16 MV / turn (max)

In collisions dE/dn= 0 V/turn (synchronouse phase ~0)

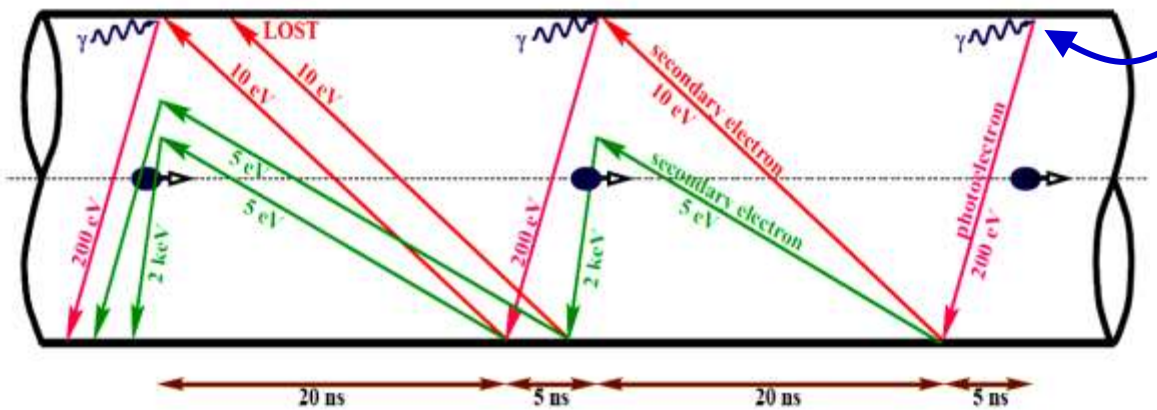
Slow energy-position oscillations (23 Hz or ~500 turns)

rms energy spread 1.3e-4 (1GeV) rms bunch length ~ 8cm




CMS
6500 GeV
LHC
North Area
ALICE
LHC-b
p
SPS
TI8
450 GeV
TI2
TT10
ATLAS
CNGS
ν
towards
Gran Sasso
West Area
AD
TT60
p̄
p
TT2
1.4 GeV
BOOSTER
ISOLDE
East Area
p
n
n-ToF
p
LINAC 2
PS
50 MeV
CTF3
e⁻
25 GeV
LINAC 3
Ions
LEIR
Pb+

T2: Electron Cloud & Need of Scrubbing

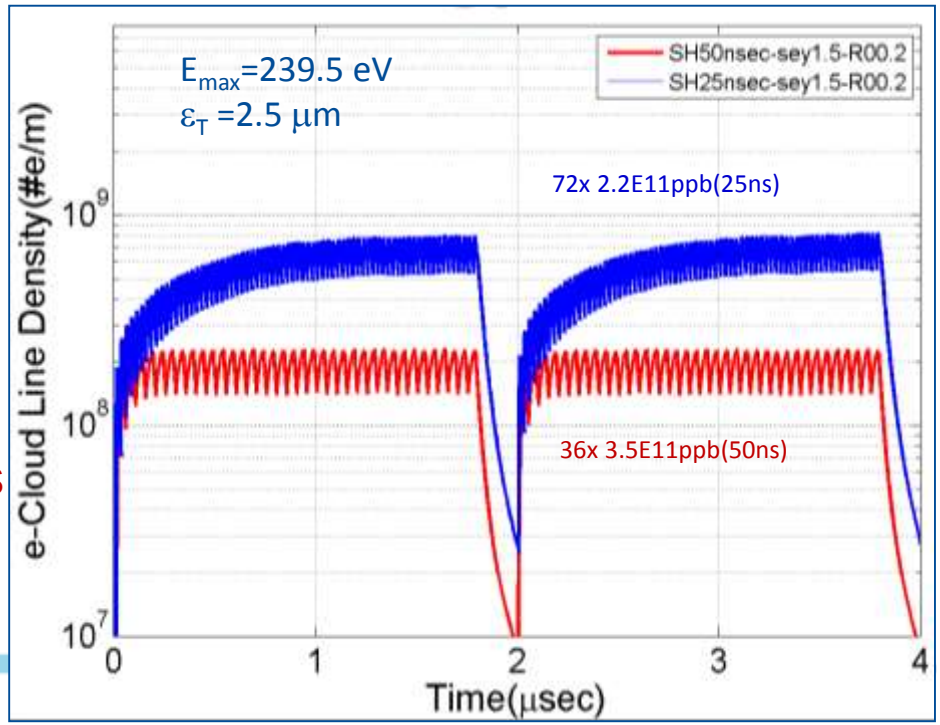


The critical energy of the photons at 7 TeV ~ 44 eV

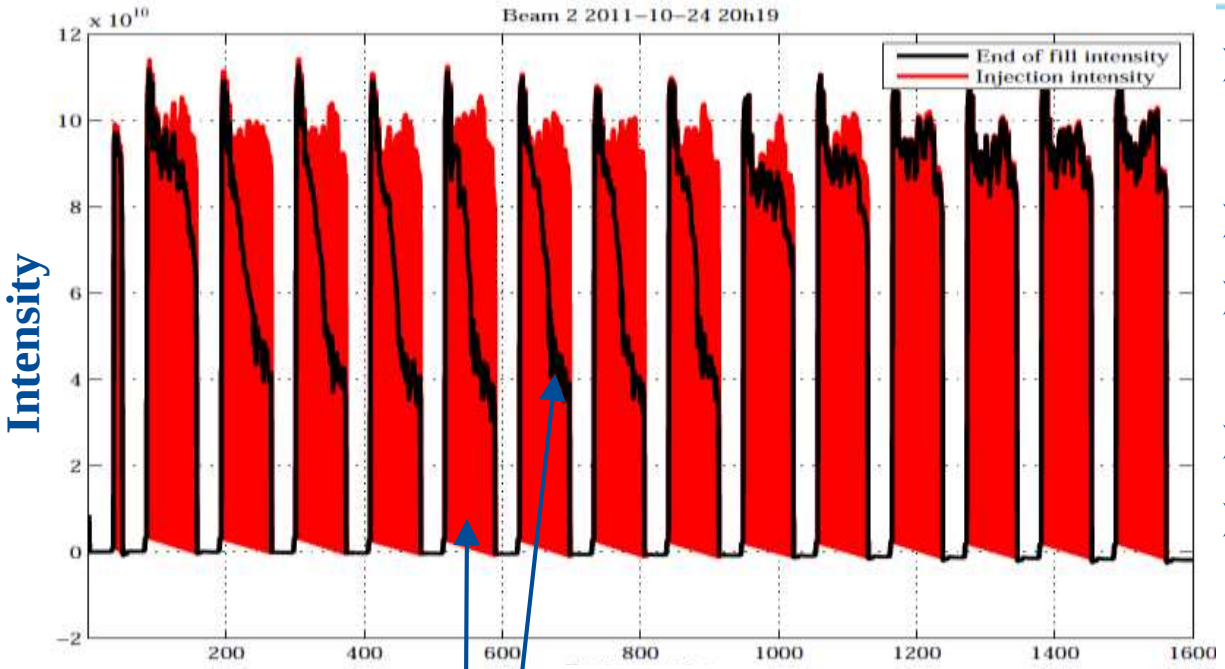
- Primary sources of electrons in the LHC
  - At Injection (450 GeV) gas ionization
  - At 7 TeV Synchrotron Radiation

Consequences:

- instabilities, emittance growth, desorption ←bad vacuum, beam loss
- excessive energy deposition in the cold sectors

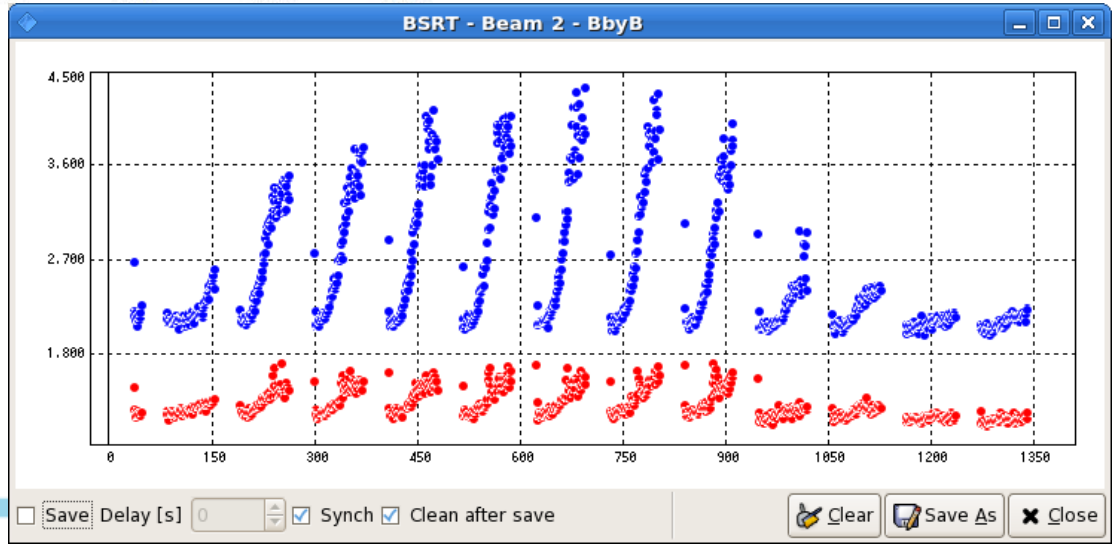


What e-cloud can do to the Beam?



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

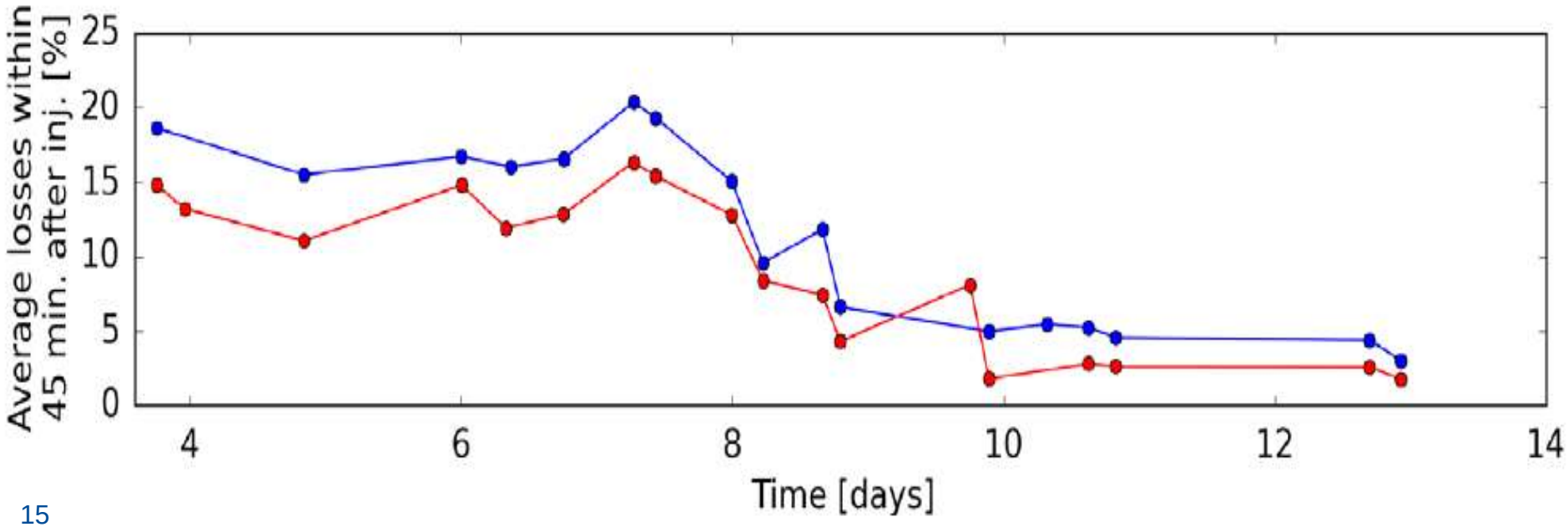
~110% Vertical

Associated beam loss

Scrubbing @ 25 ns bunch spacing

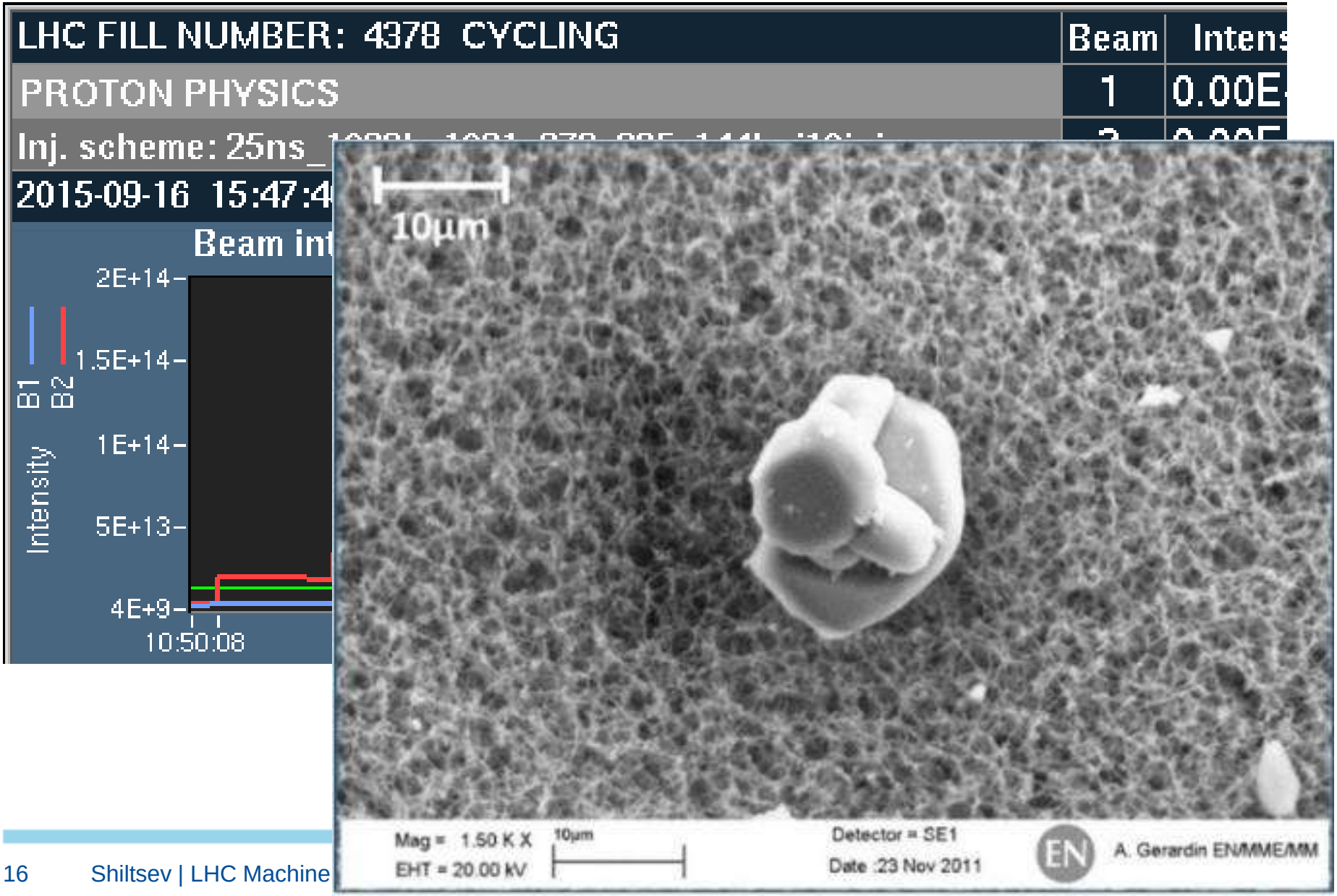
So far it is the only cure in the LHC….Takes time to clean the surface and reduce SEY (secondary electron yield) from ~2.2 to ~1.5

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



T3: UFOs

'Unidentified Falling Objects'

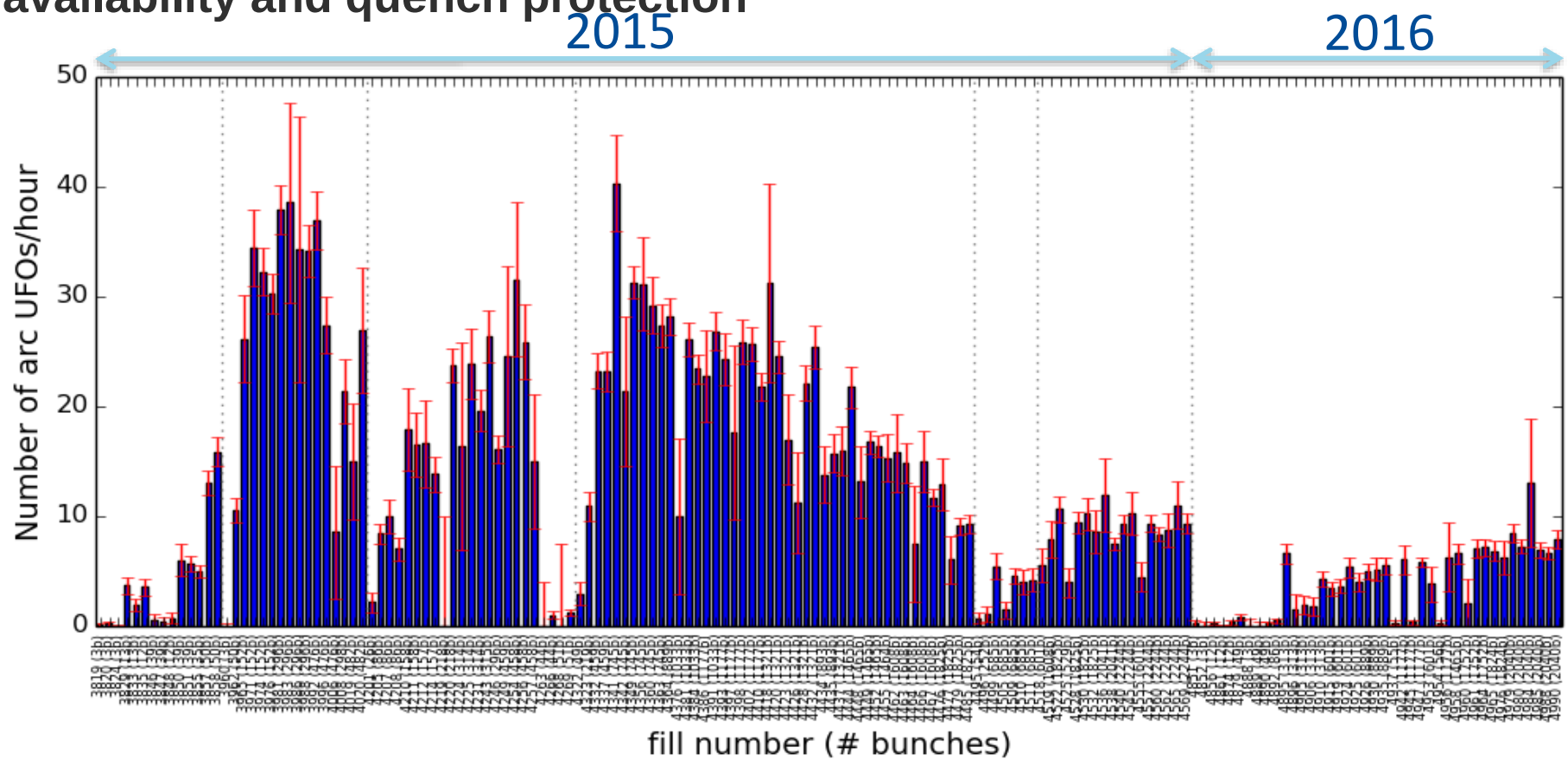


UFOs: there are many of them, they are frequent !

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

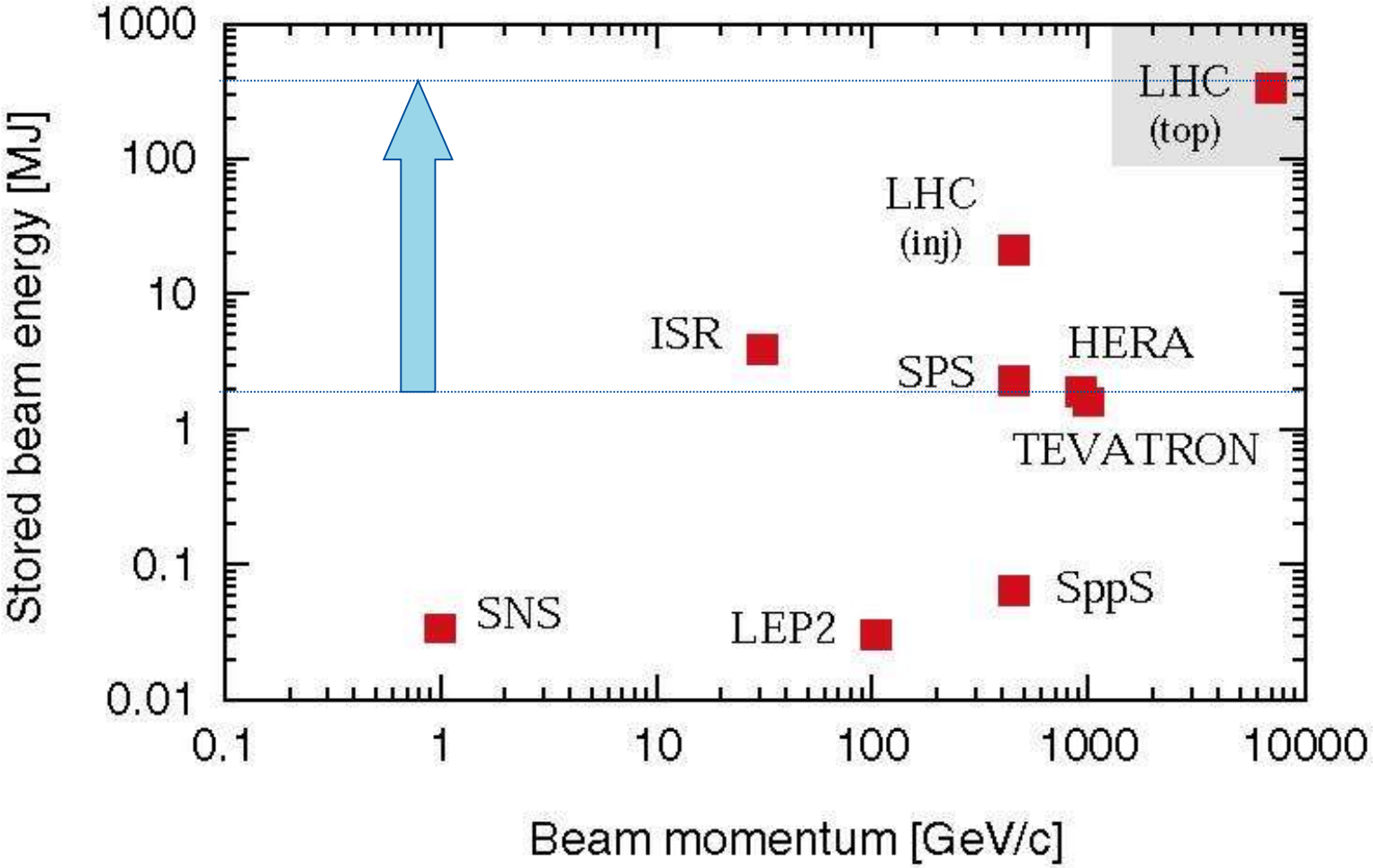
BLM thresholds being optimize to find a **good compromise between availability and quench protection**



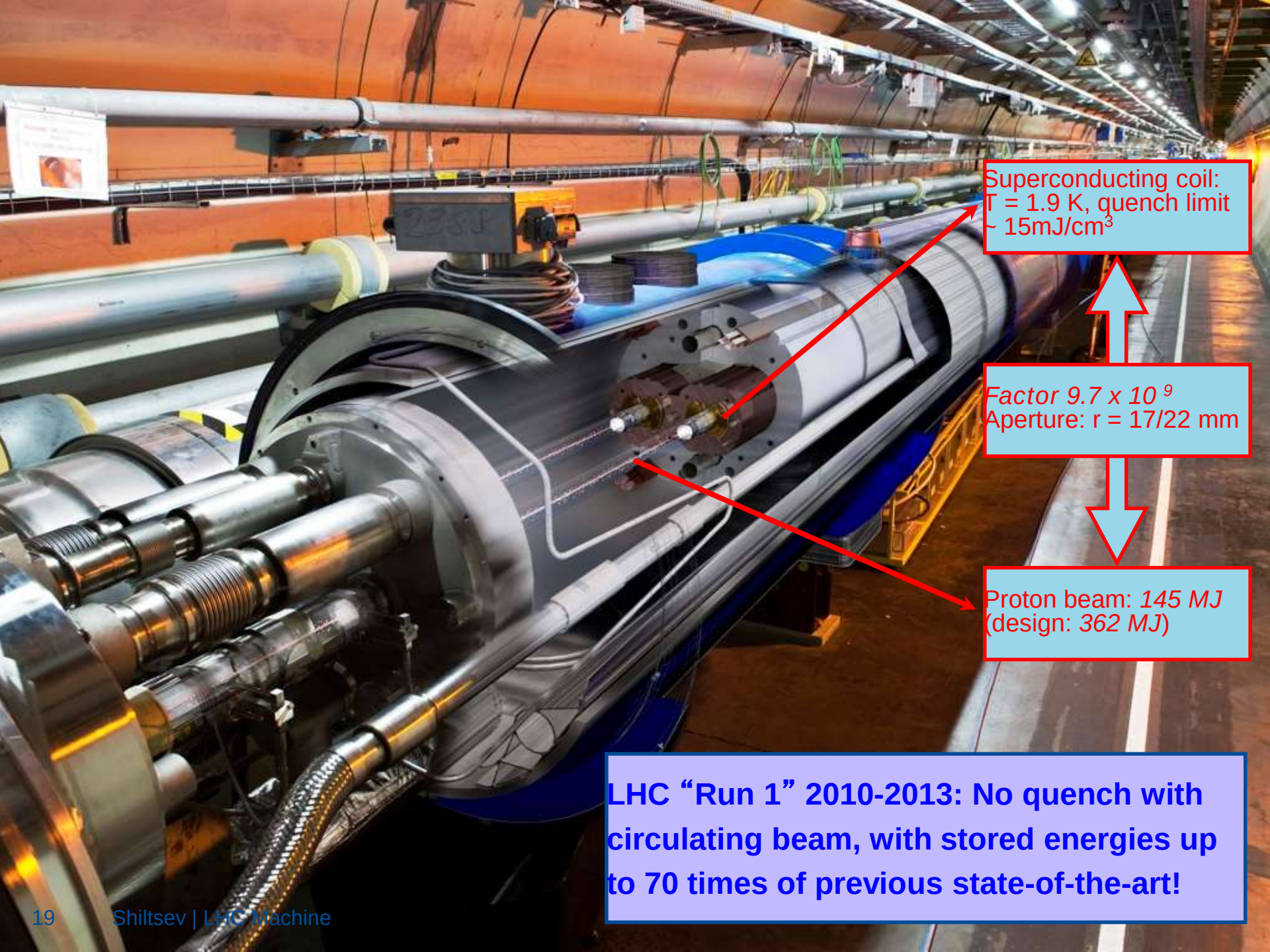
- arc UFOs (cell >11): rates similar to end of 2015
  - did not lose conditioning over the Xmas stop

T4: Halo Collimation

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



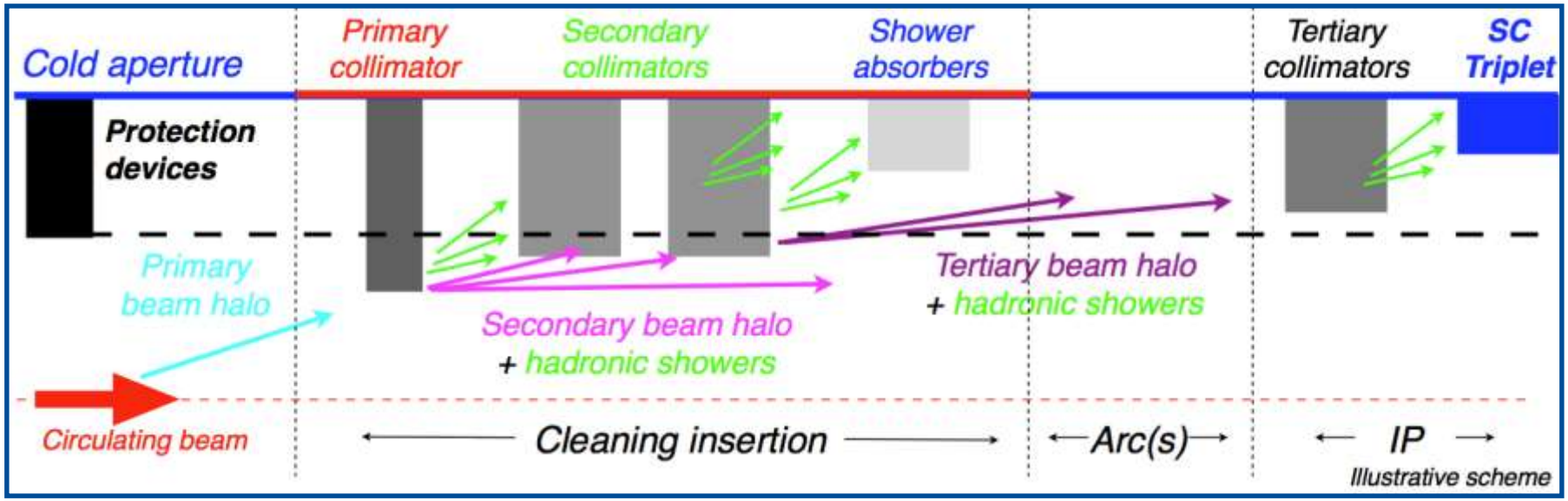
The LHC beam energy is 350 MJ. Already at injection the beam can damage a magnet.



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

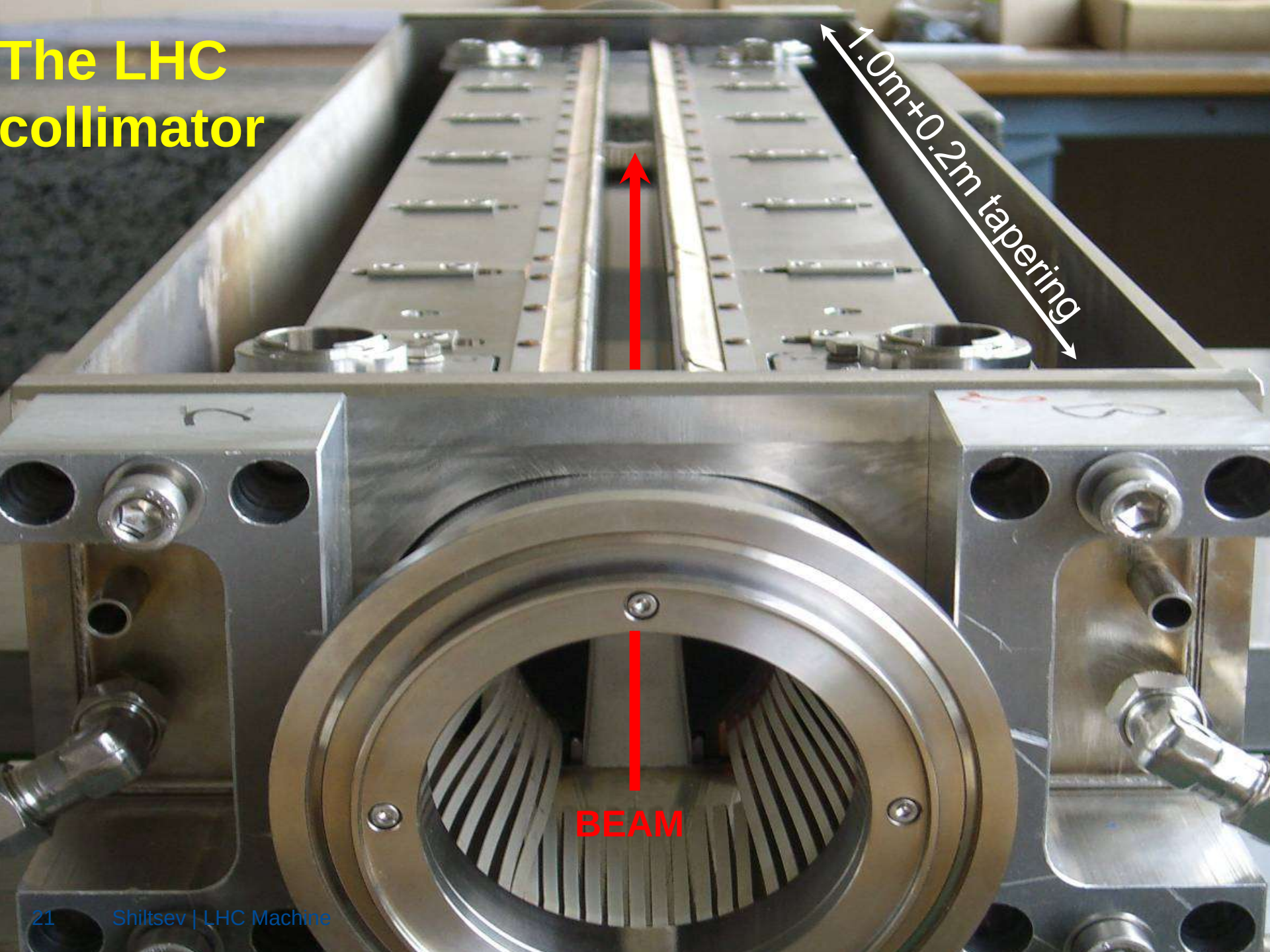
LHC collimation system

- 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

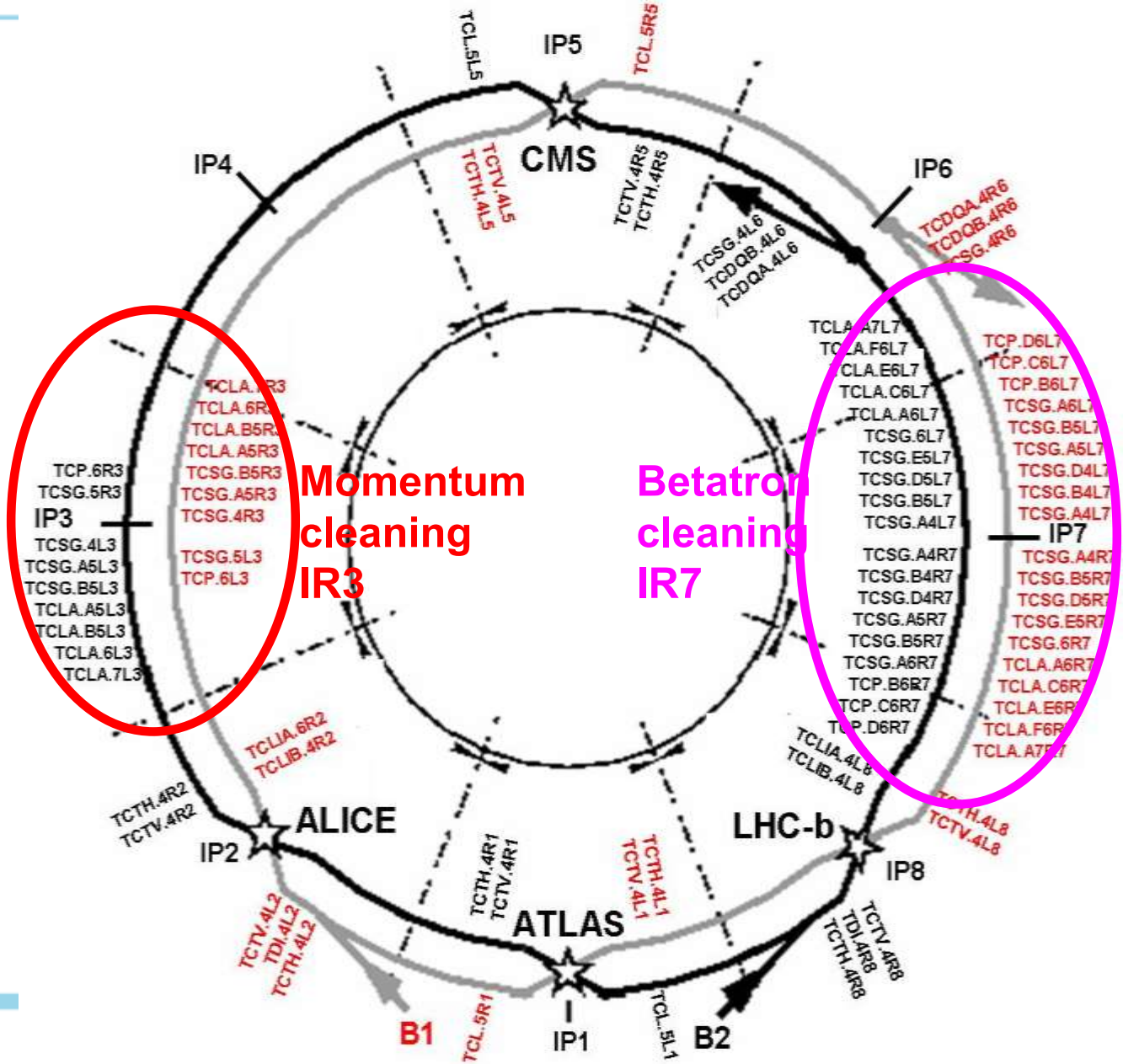
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

Physics debris absorbers

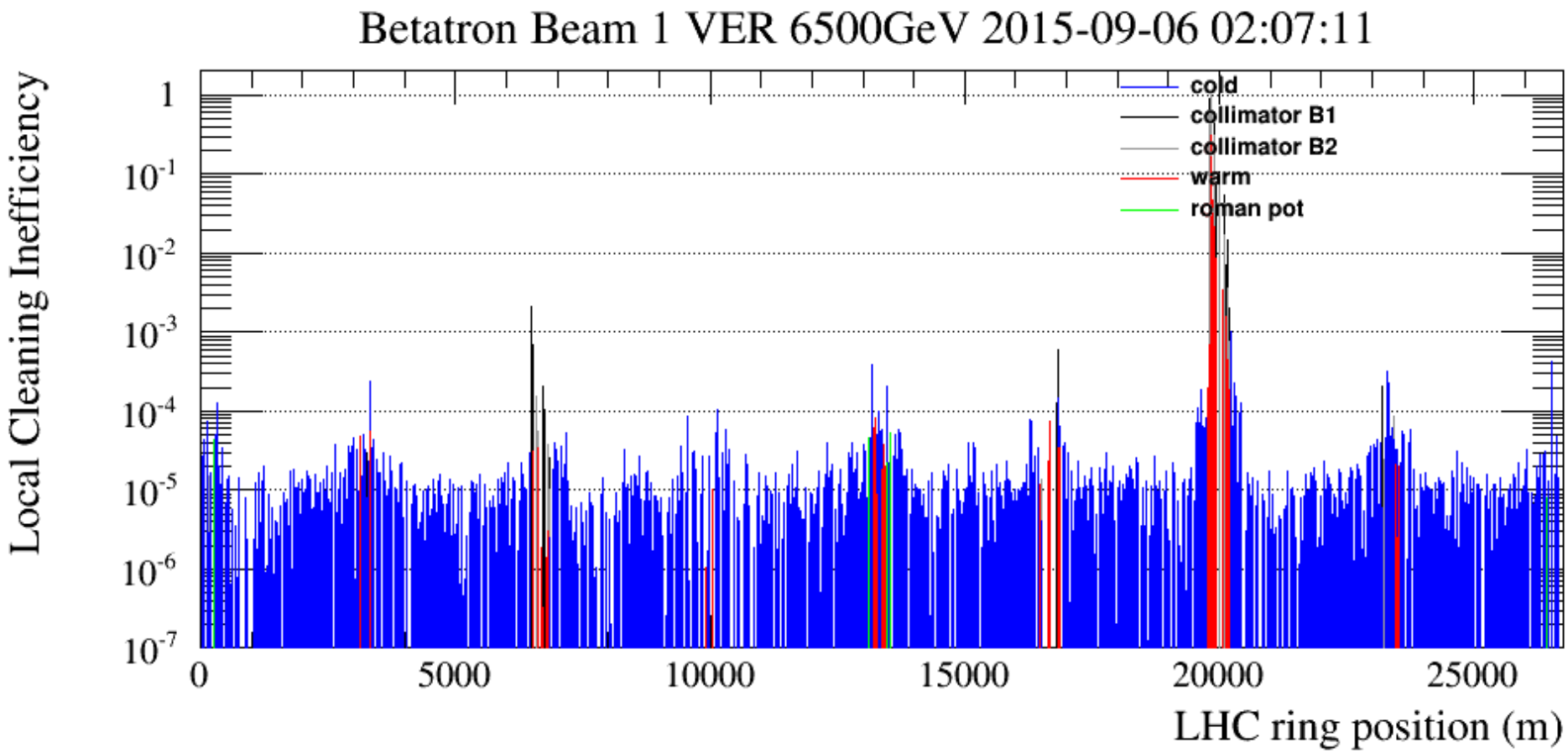
Transfer lines (13 collimators)
Injection and dump protection (10)

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



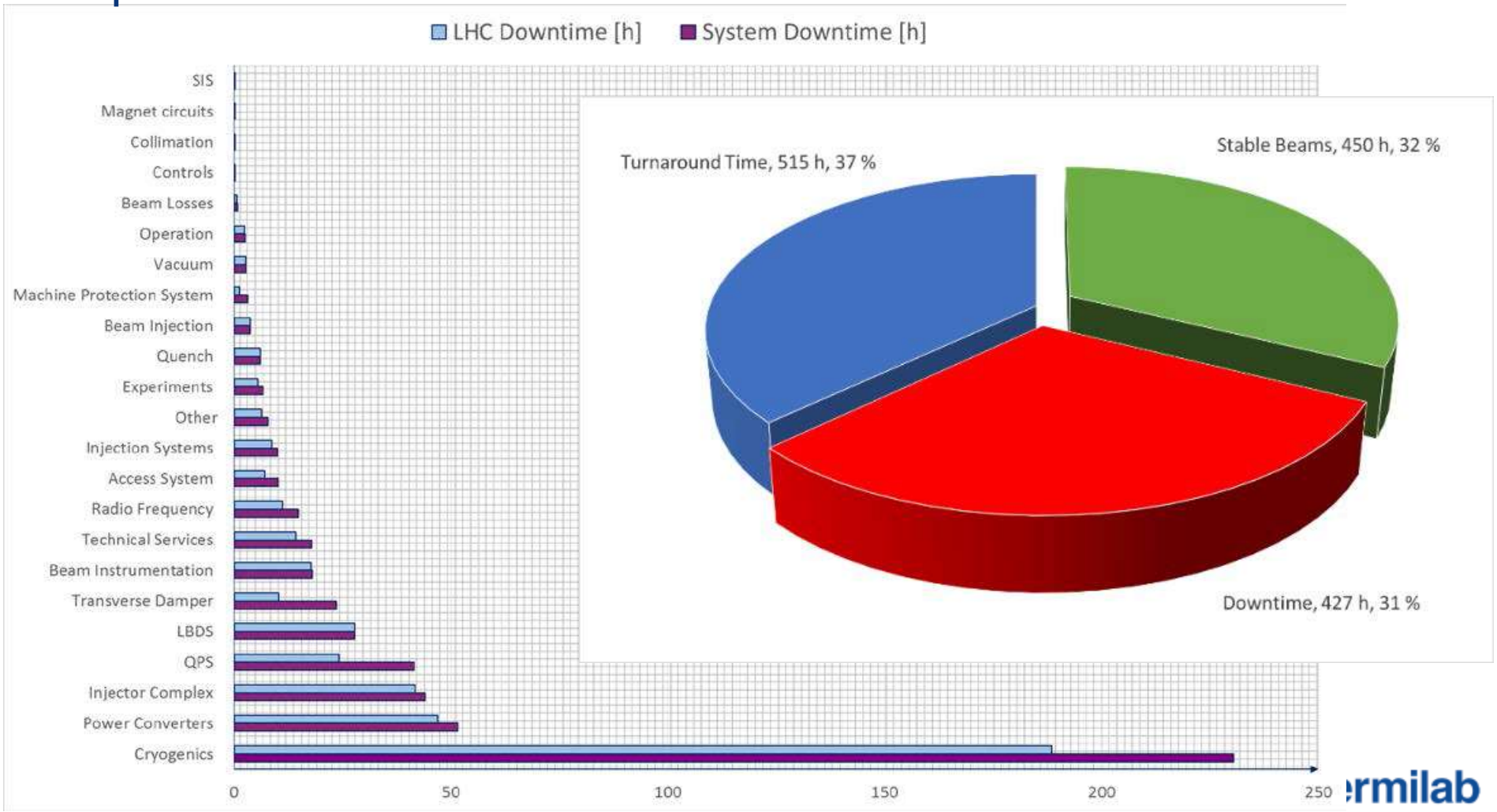
Super-Effective Halo Cleaning in LHC

- 2015

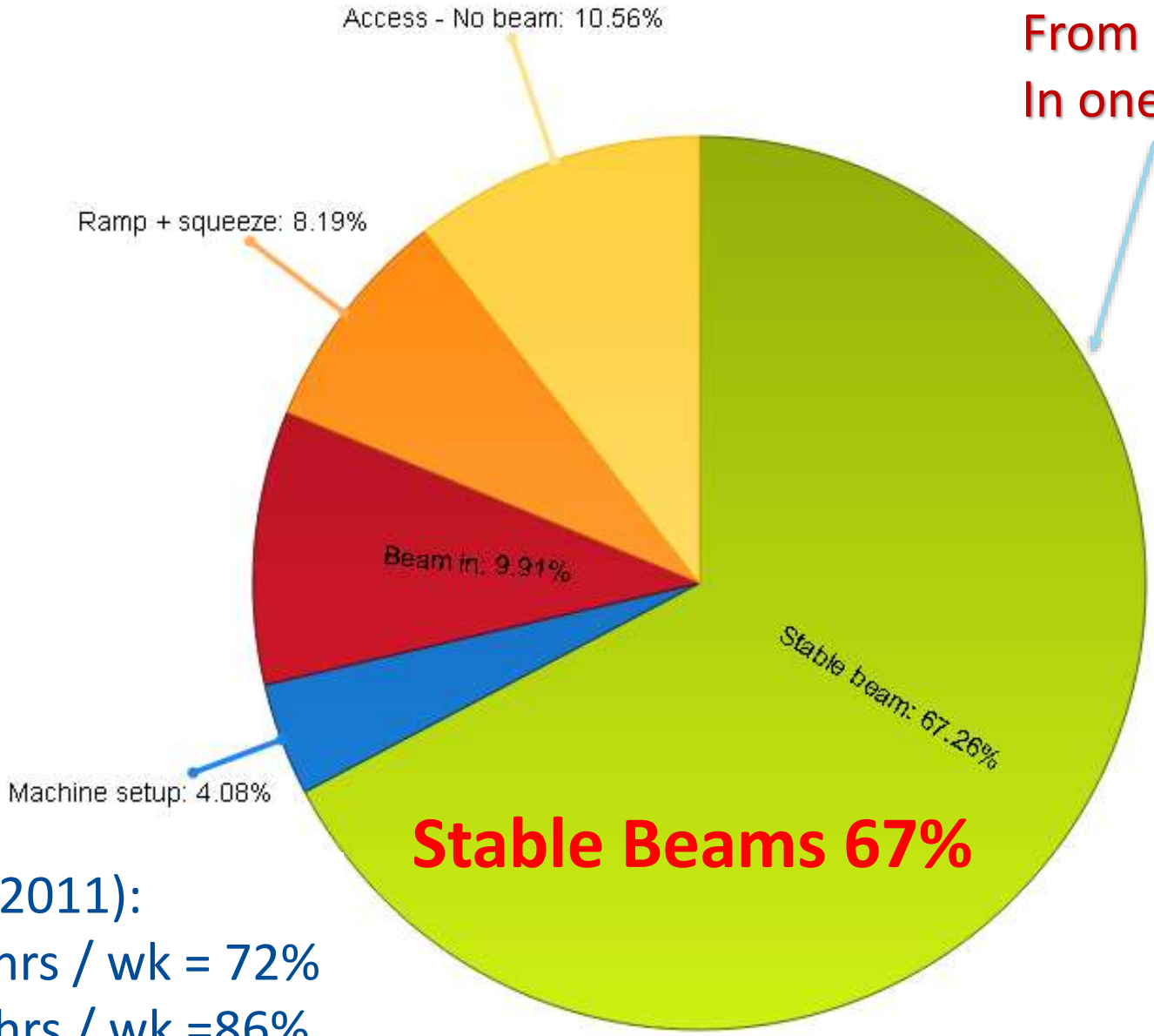


T5: LHC Machine availability -2015

Statistics for 25 ns run from
September 7 to November 3



2016 Availability: 11th June – 23rd July



From 32% to 67%
In one year!

Stable Beams 67%

Tevatron(2011):
Avg. 120 hrs / wk = 72%
Best 144 hrs / wk =86%

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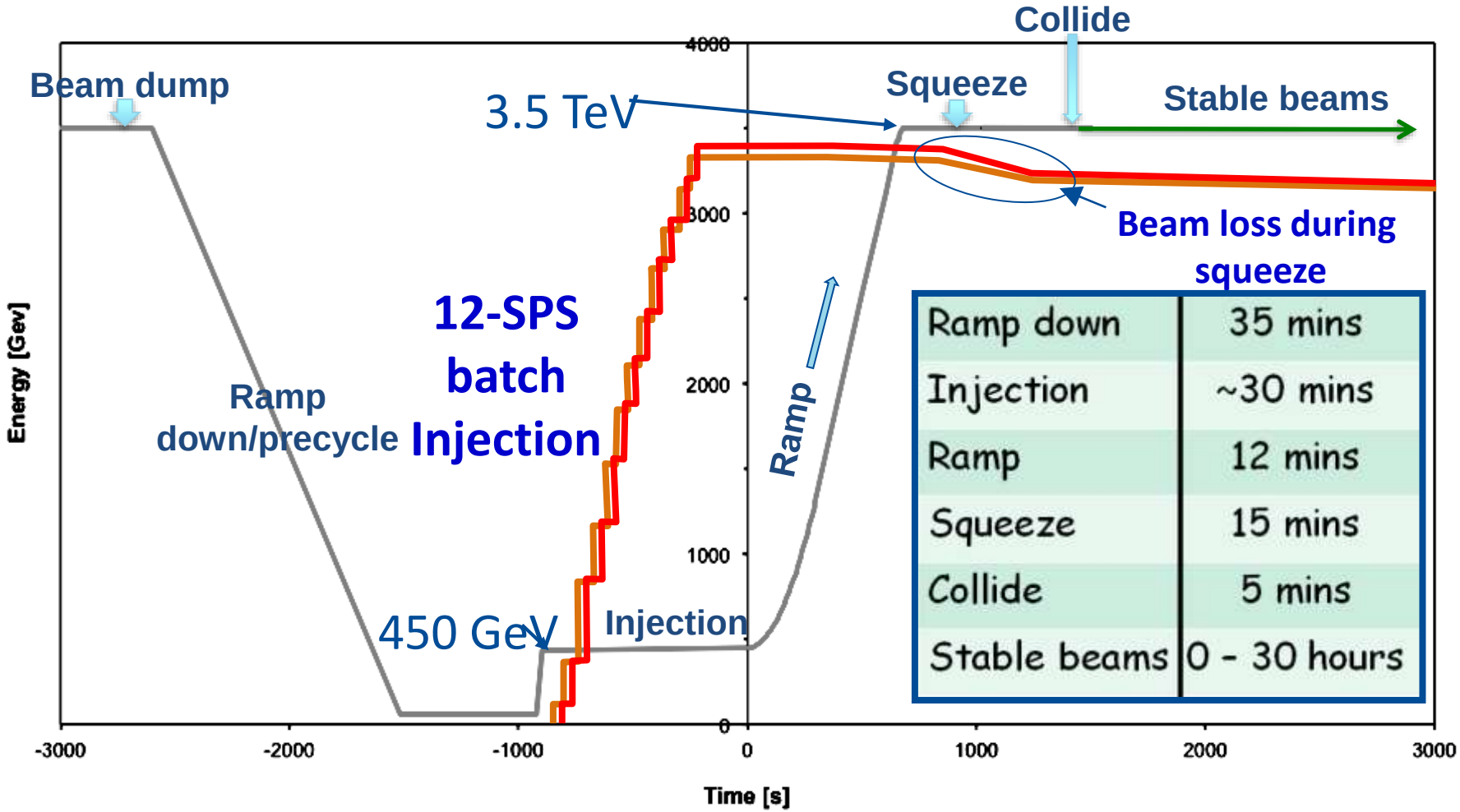
Turnaround times, ramps, etc

A Schematic of LHC Operational Cycle at half nominal energy



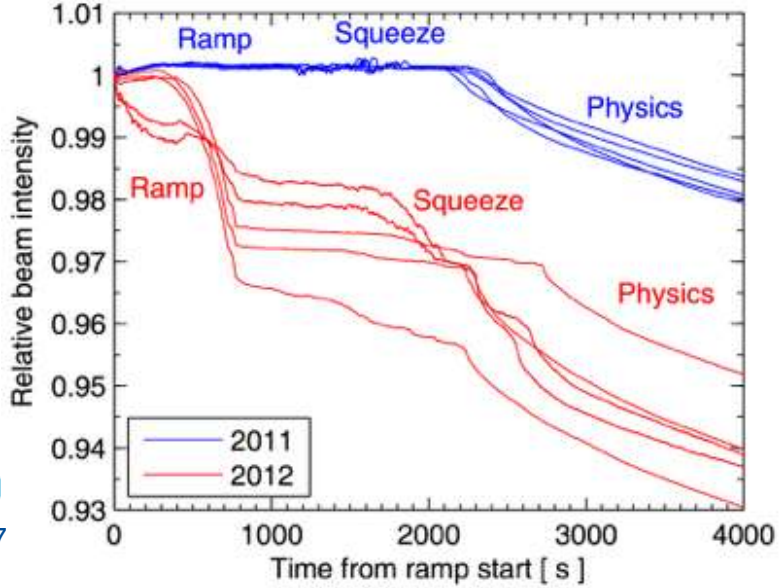
Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 - 30 hours

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.

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



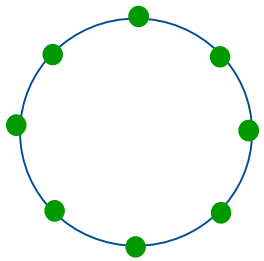
Additional delays:

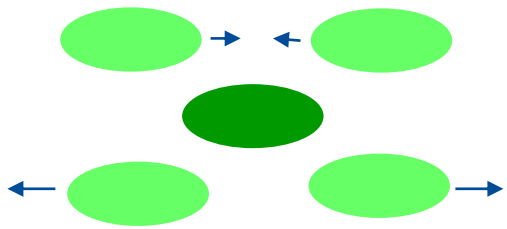
- Transfer and injection optimization and general wrestling with the injection process (respecting tight demands on beam quality etc.).
- controls and data acquisition problems; kicker overheating; problems in the injectors; etc.
- access recovery, precycle faults
- Fills lost in the ramp and squeeze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

T6: Colliding Beams Luminosity

$$R = \boxed{L}\sigma$$

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:

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

Circumference of machine

Number of bunches

Record Hadronic Luminosity (LHC): 1.5E34 $cm^{-2}s^{-1}$

(50% over LHC design; x35 Tevatron lumi)

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

E.g., 2016 Luminosities

ATLAS

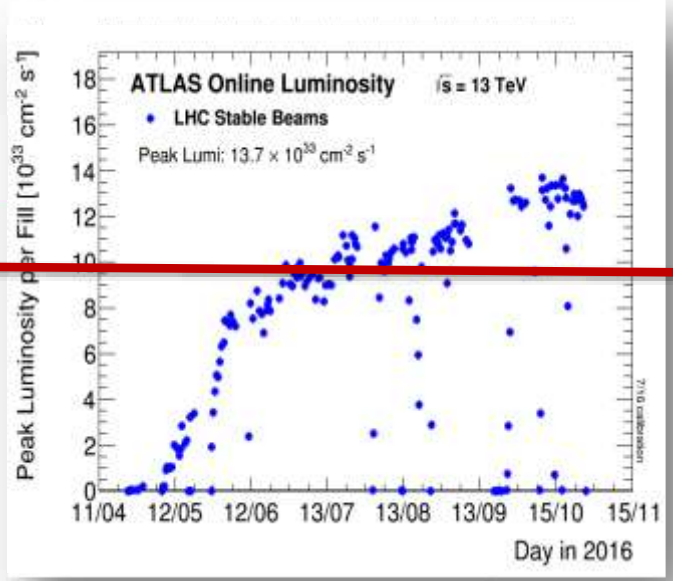
CMS

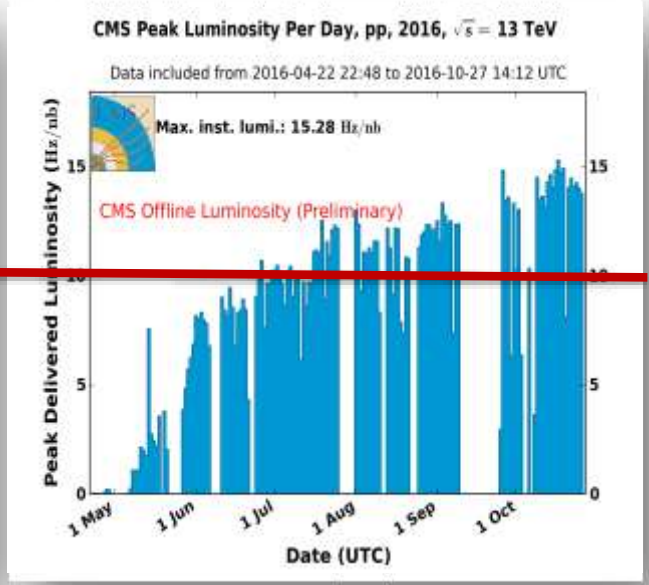
10% diff?

Peak

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

6 years since 1st collisions in April'2010

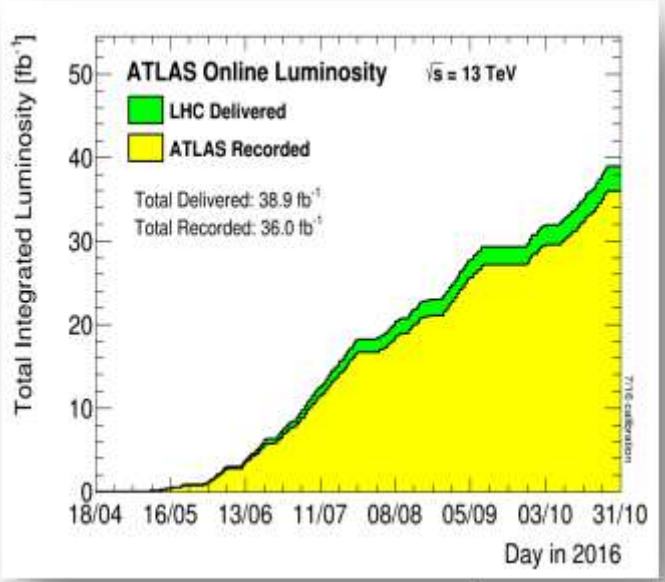


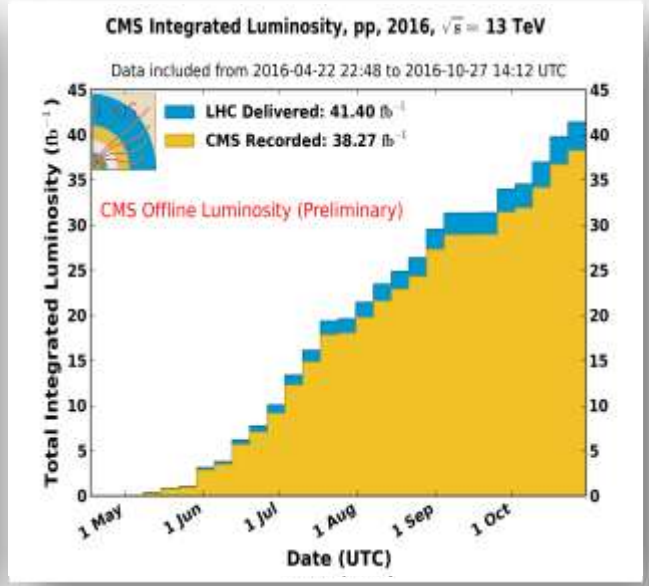


6% diff

Integrated

- **~40 fb^{-1} delivered to ATLAS & CMS**
- **3 fb^{-1}/very good week**





Luminosity and Burn-Up

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

Rate

$$R = L\sigma$$

"Luminosity"

Cross-section ("physics")

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

Example: total *p-p* inelastic+elastic cross section at 13 TeV cme is ~*110* mbarn (58 inel+ 12 ssd+40 el not seen)→ ~30 interactions per crossing (NB: pile up is only ~20!) x 40,000,000 collision/sec= 1.1B protons leave each beam every second

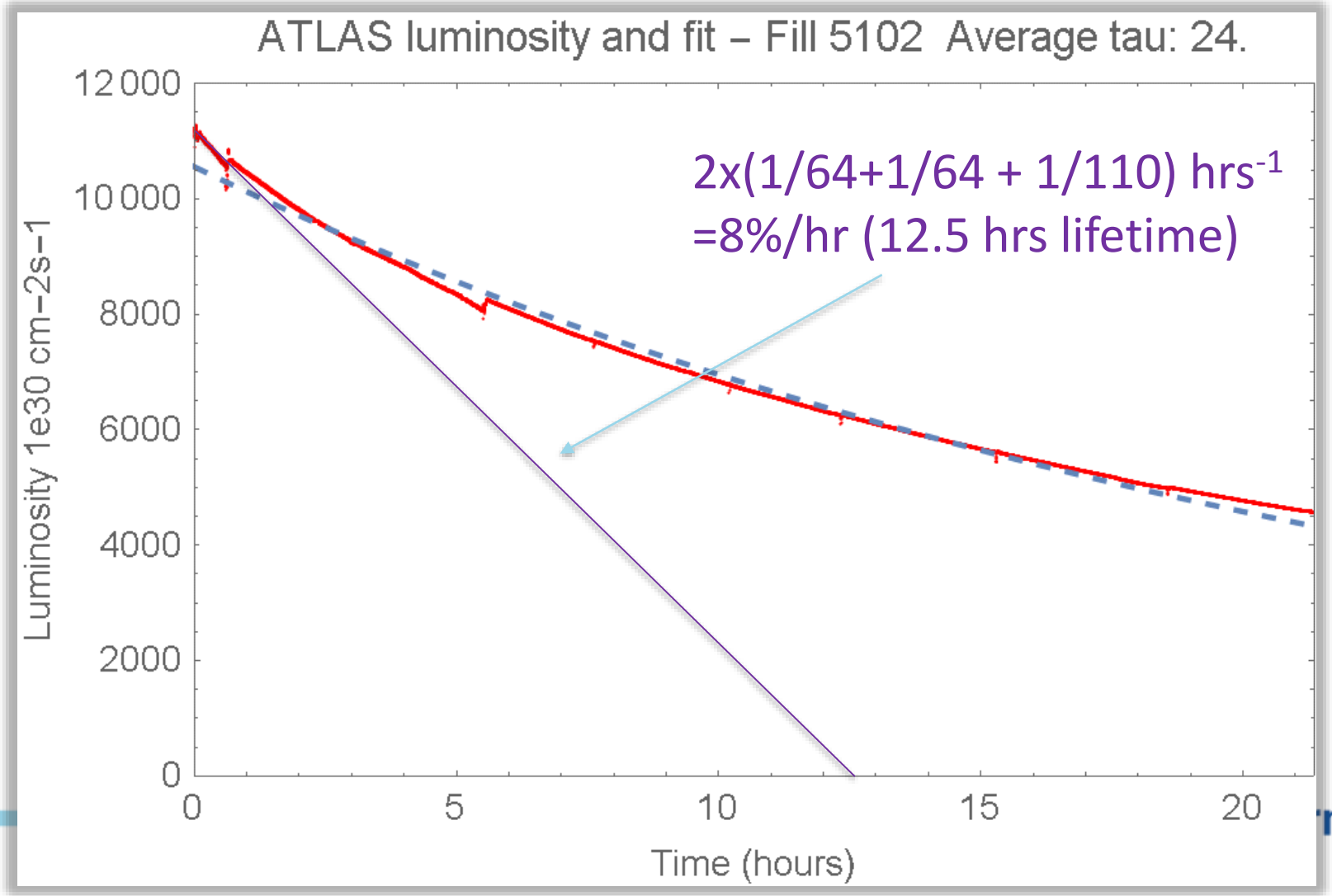
Beam lifetime due to such "Burn up" *T=N/(dN/dt)=*

2.5e14 protons/(1.1e9/s) =63 hours

Luminosity lifetime

Take into account two IPs (ATLAS, CMS and 3% LHCb) 1/64+1/64 hrs^{-1}

Take into account beam gas 1/110hrs^{-1} and that *Lumi~N^2* → x2



T9: 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** now ~40
    - design for μ ~ **140 (~ 200)**
    - (peak luminosity of **5 (7) e34 cm-2 s-1**) now ~1.4
  - 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 :

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

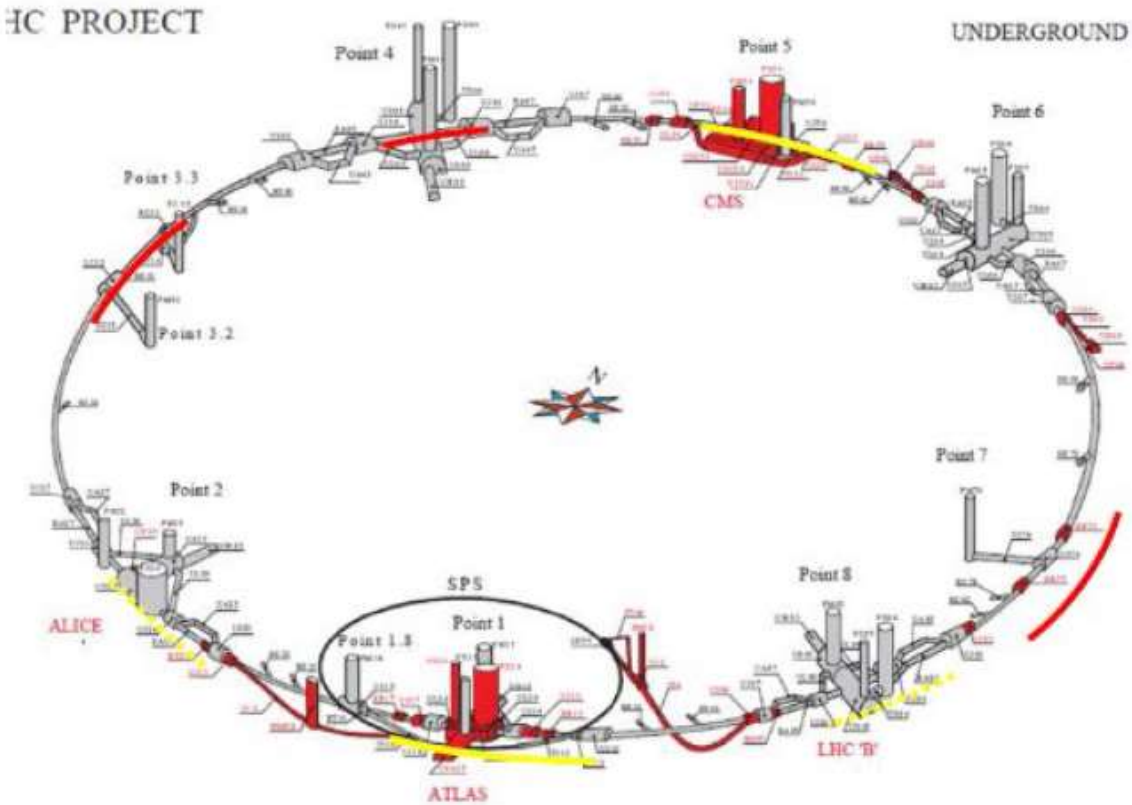
- → 1) maximize bunch intensities → Injector complex — 1.15 → 2.2e9
- → 2) minimize the beam emittance — LIU ⇔ IBS — 3.75 → 2.5 μm
- → 3) minimize beam size (constant beam power); → triplet aperture
- → 4) maximize number of bunches (beam power); → 25ns
- → 5) compensate for 'F'; → Crab Cavities — Avoid 0.3 w/o Crabs : 0.83 w. Crabs as now
- → 6) Improve machine 'Efficiency' → minimize number of unscheduled beam aborts

With all these changes luminosity could peak at **~20e34** → 20x design and 20x pile up, ie μ>540 → luminosity leveling will be done at **~5e34**

HL-LHC Scale: Hardware and Cost

The HL-LHC Project

976MCHF (-142 +208)
~2,500 man-years



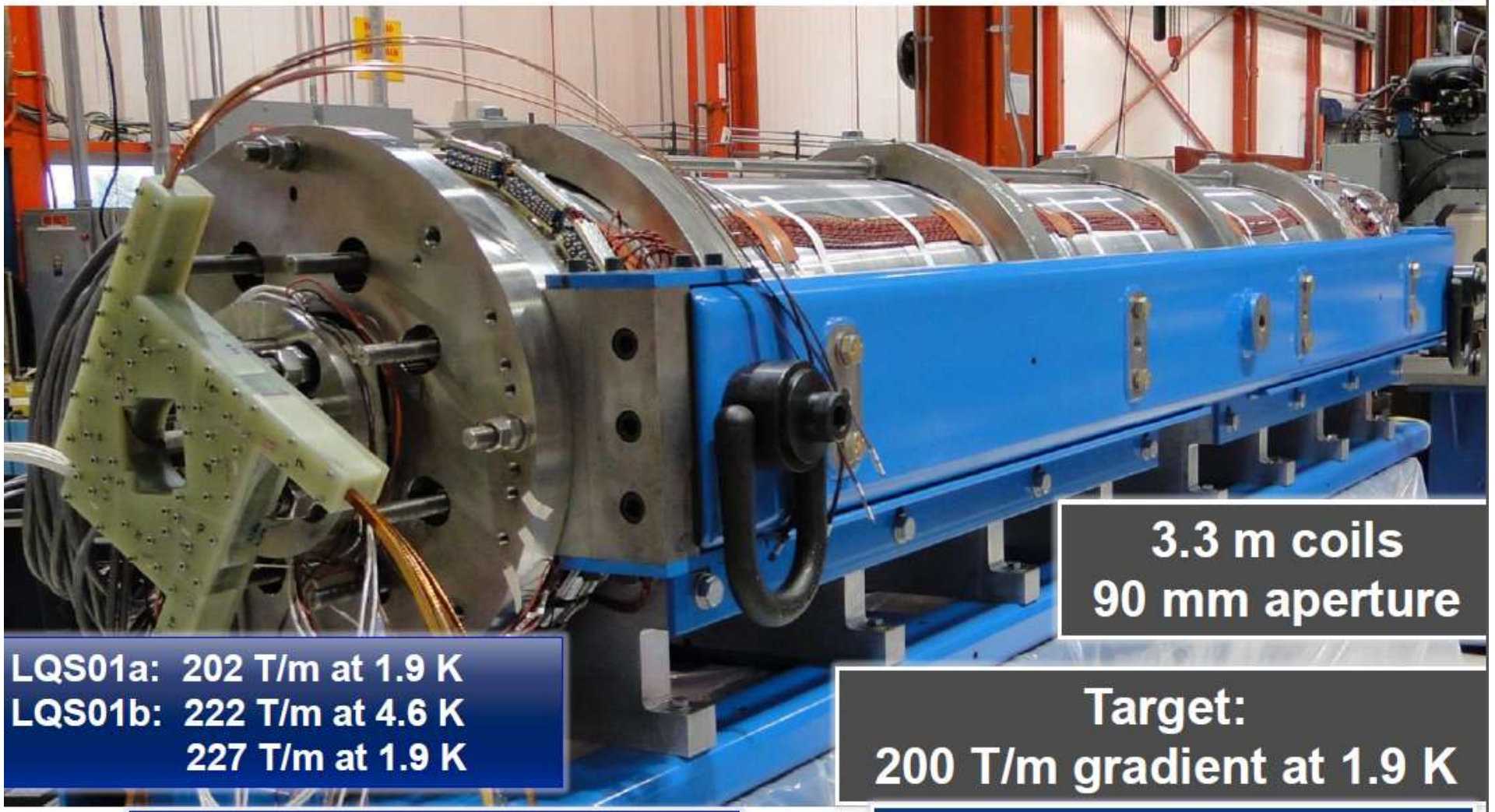
- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

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

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Thanks for Your Attention !

Questions !?

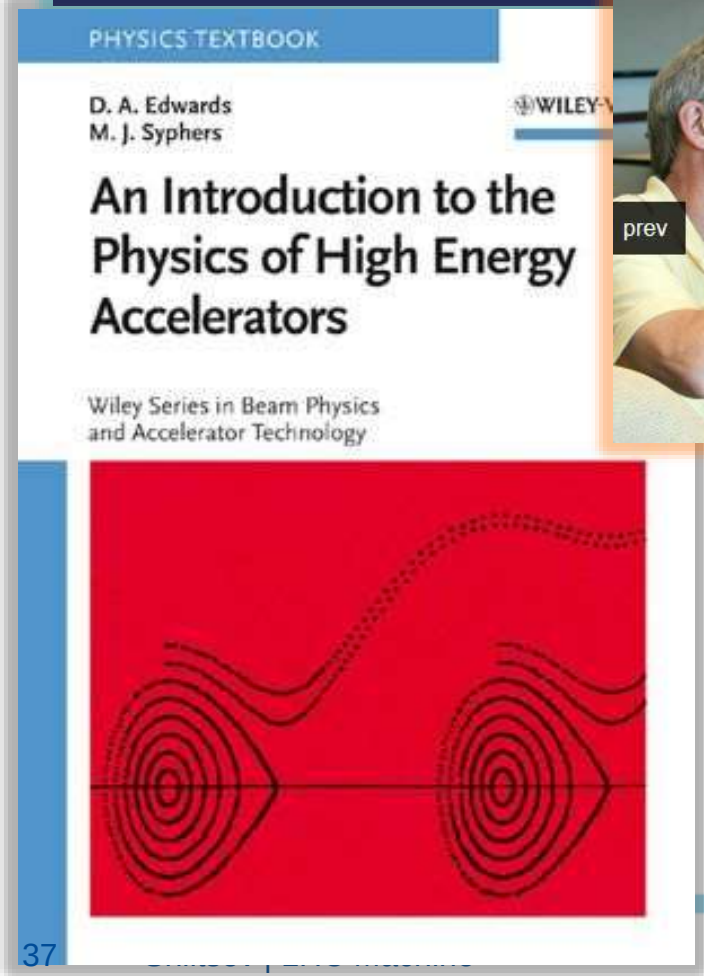
Acknowledgements

Materials and slides used here come from many sources, including the USPAS lectures, Eric Prebys, Mike Lamont, various conferences, workshops, LHC and LARP reviews, etc

Best Way to Get Introduced to Accelerators

U.S. Particle Accelerator School

Education in Beam Physics and Accelerator Technology



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)