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LHC Operation at Higher Energy and Luminosity

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special acknowledgements to and material from:

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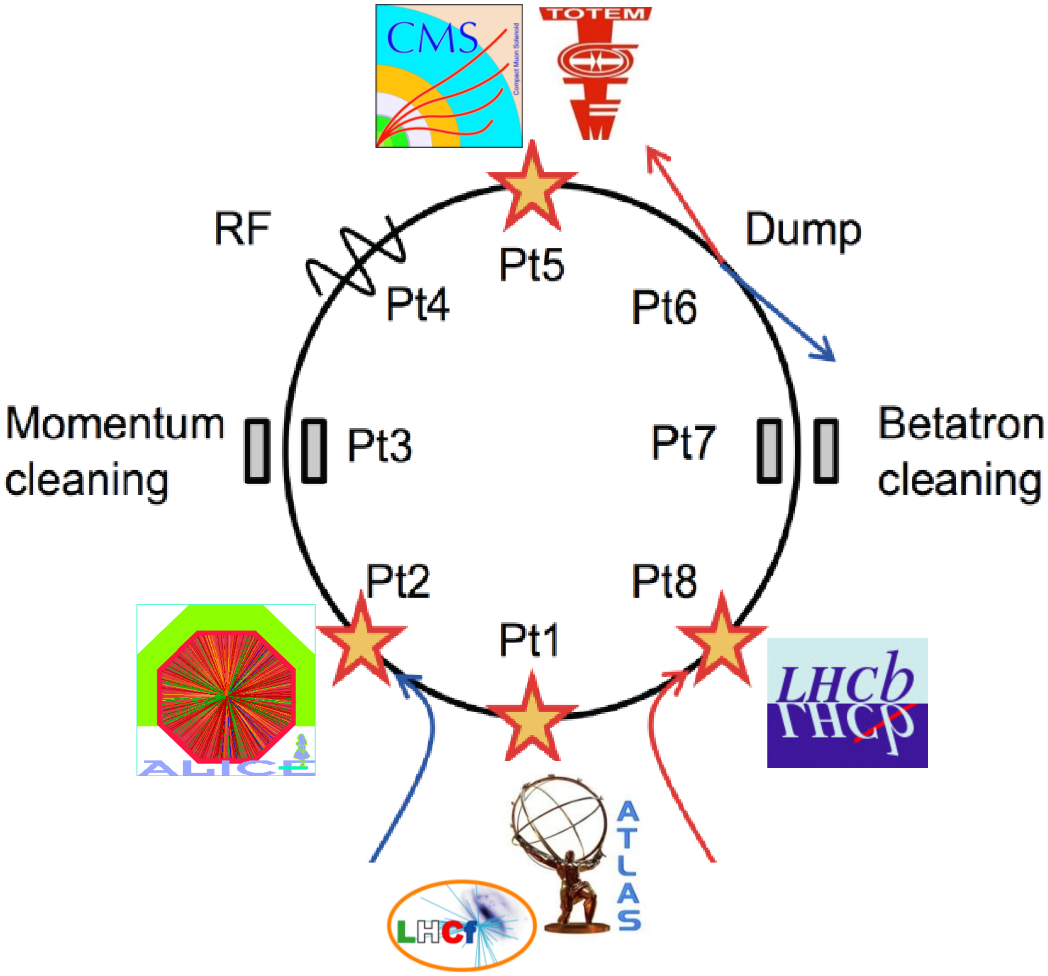
outline

- introduction
  - LHC layout
  - luminosity in a proton-proton collider
  - CERN accelerator complex and beam production schemes
- history of run 1 (2010-2012)
  - with an eye on commissioning
- ongoing shutdown and consolidation
  - including preparation for beam
- after the shutdown
  - beam commissioning and intensity ramp up
  - parameter space for peak luminosity
  - e-cloud and scrubbing, UFOs, beam stability, R2E
- (upgrade plans)

LHC layout

- total length: ~26.7 km
  - 8 arcs (aka sectors): ~2.8 km each
  - 8 long straight sections: ~700 m each
- 2-in-1 magnet design with separate vacuum chambers
  - p-p, ion/ion, or p/ion collisions
  - beams cross in 4 points
    - Alice, ATLAS, CMS, LHCb, LHCf, TOTEM



luminosity

definition: $N = \sigma \int L\,dt$

- N: number of events (e.g. 5)
- σ: cross section (e.g. 0.5 fb, 1 fb = 10^{-39} cm^2)
- L: instantaneous luminosity (e.g. integrate to 10 fb^{-1})

from machine parameters:

$$L = \frac{k N_b^2 f}{4\pi\sigma_x^* \sigma_y^*} F = \frac{k N_b^2 f \gamma}{4\pi\beta^* \varepsilon} F$$

with $\sigma_x^* = \sigma_y^* = \sqrt{\frac{\beta^* \varepsilon}{\gamma}}$

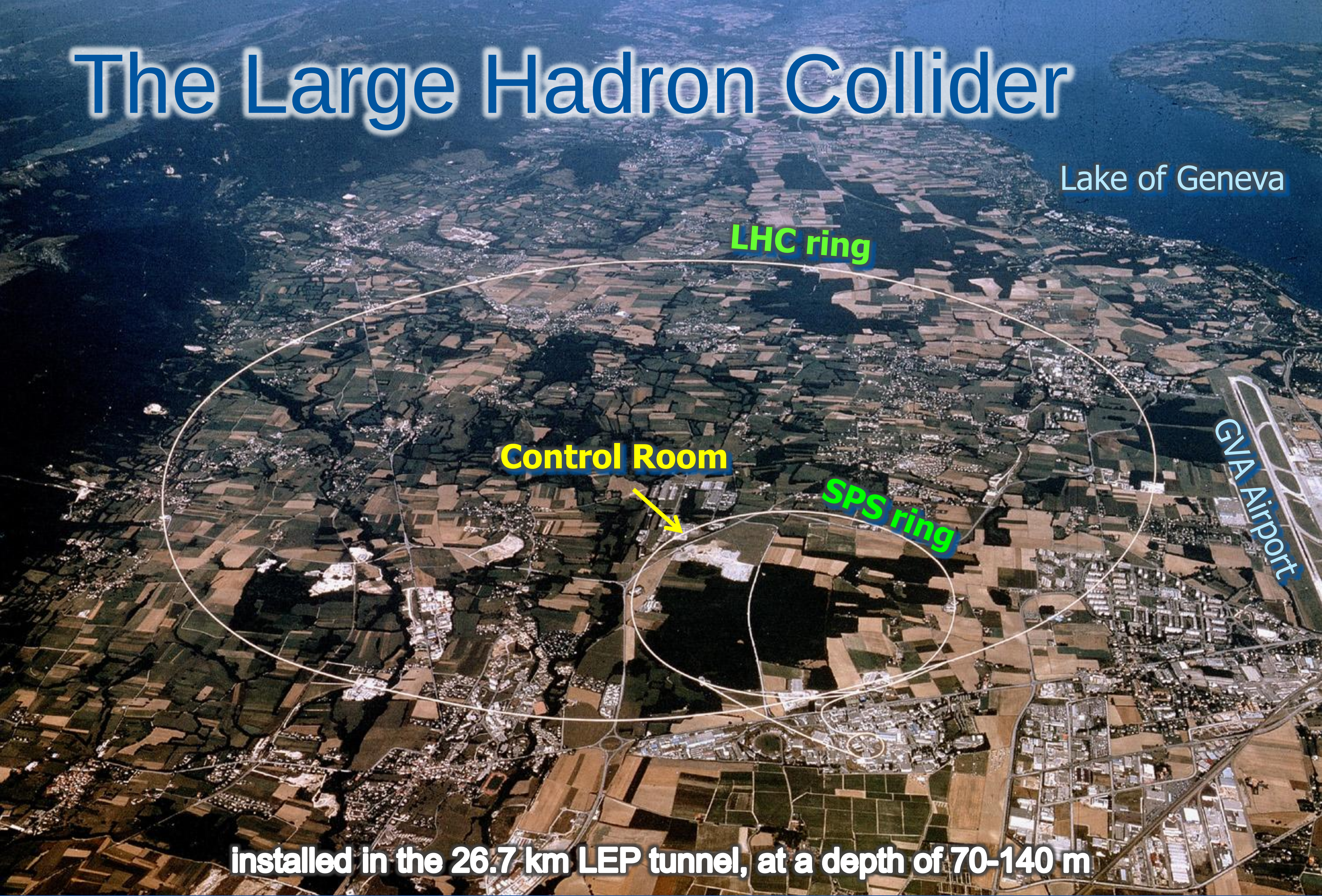
- k: number of colliding bunch pairs (e.g. 1368)
- N_b: bunch population (e.g. 1.5 10^{11} ppb)
- f: revolution frequency (11.25 kHz)
- F: geometric factor from the crossing angle (e.g. 0.8)
- σ*: beam size at IP (e.g. 18 10^{-6} m)
- γ = E/m (e.g. 4264)
- ε: normalized emittance (e.g. 2.4 μm rad)
- β*: betatron (envelope) function at the IP (e.g. 0.6 m)

- f, γ, β^*, k are set
- during a fill
  - beam size increases (e.g. IBS, noise in PCs, non-lin resonances)
  - intensity decreases (e.g. burn-off, scattering on residual gas, on collimators from emittance growth)
  - overlap from orbit drifts (compensate by performing regular scans and corrections)

beam production

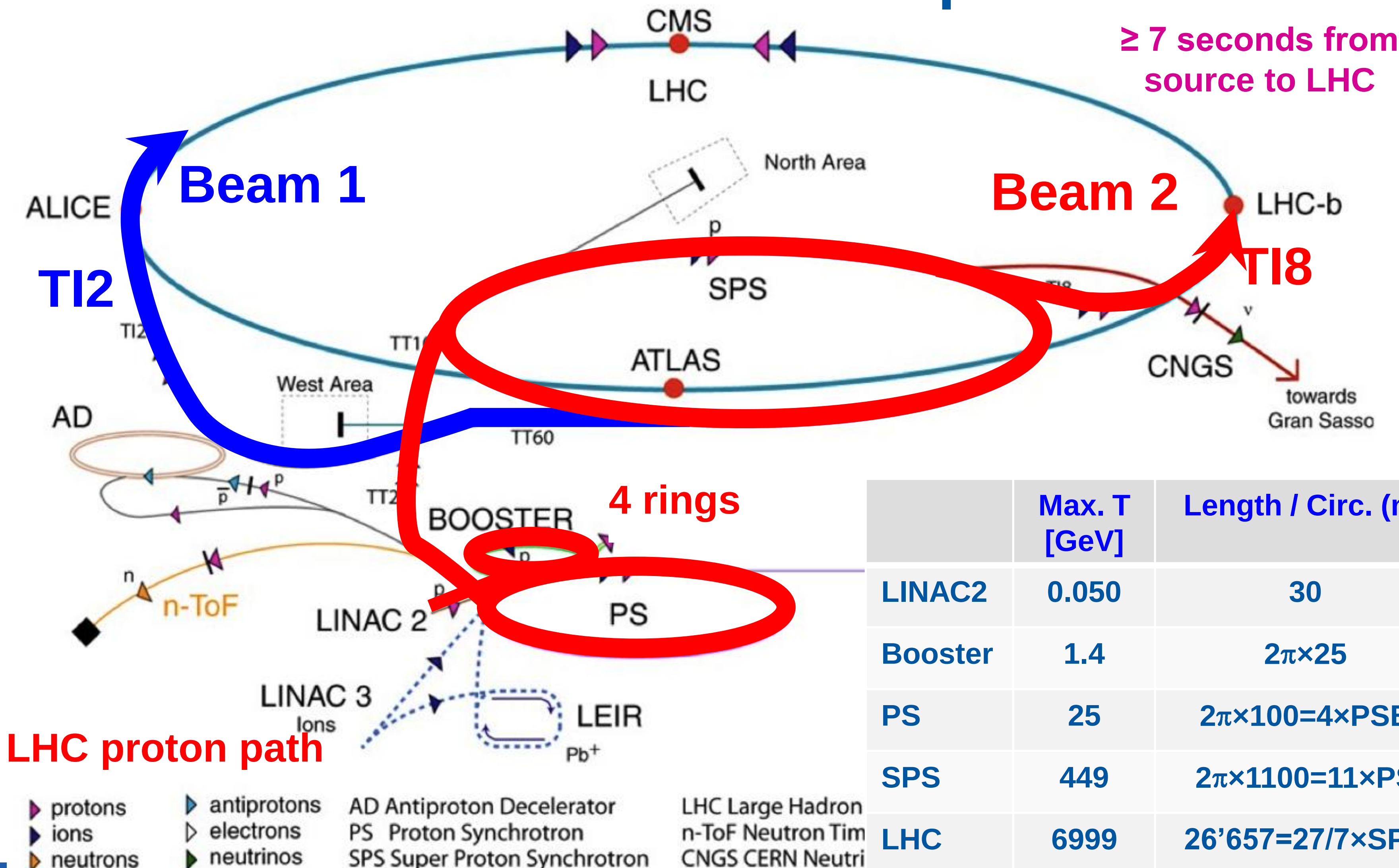
- accelerator chain
- injectors cycling
- RF manipulations
- LHC beam structure

The Large Hadron Collider



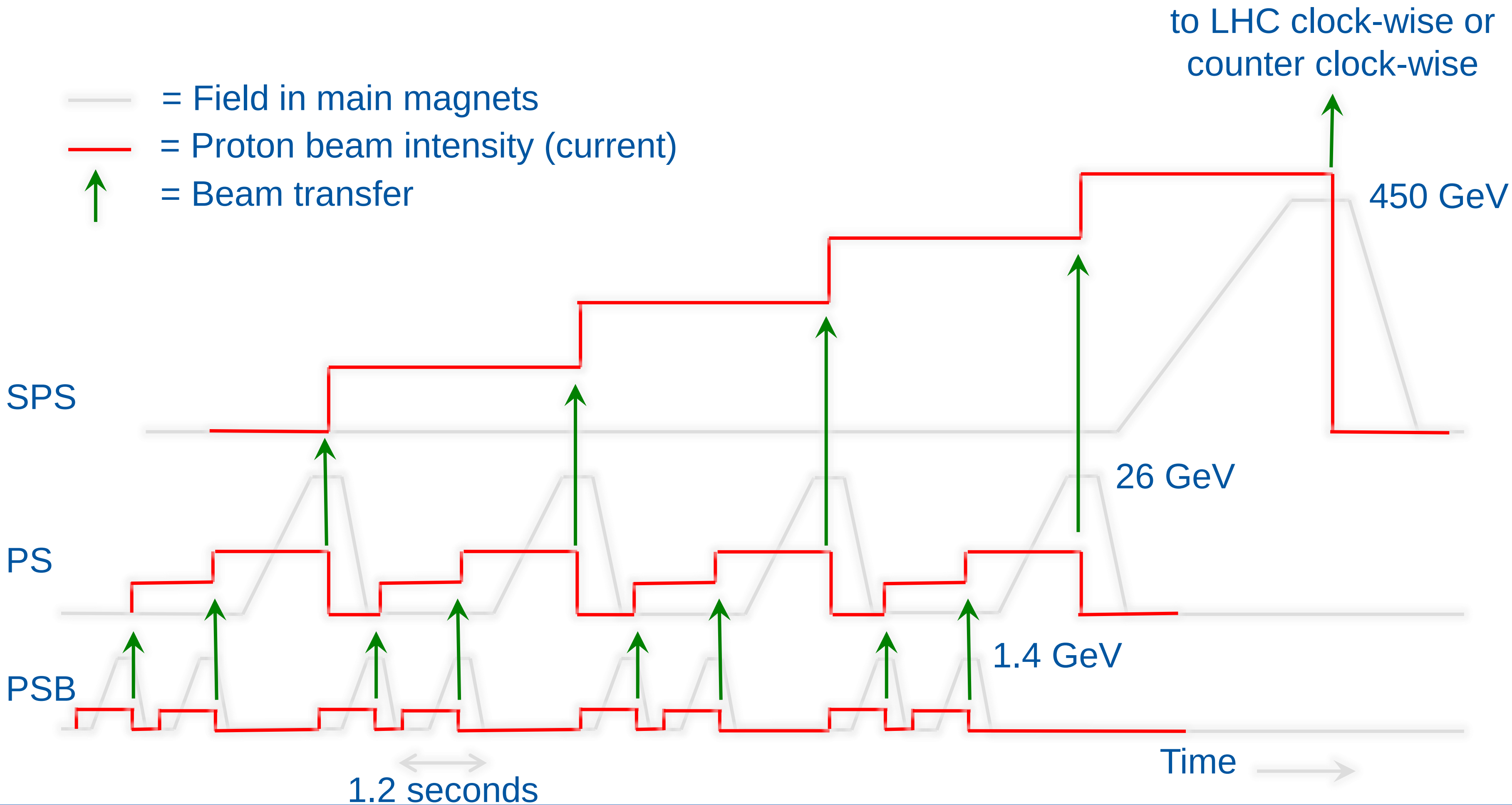
installed in the 26.7 km LEP tunnel, at a depth of 70-140 m

LHC accelerator complex

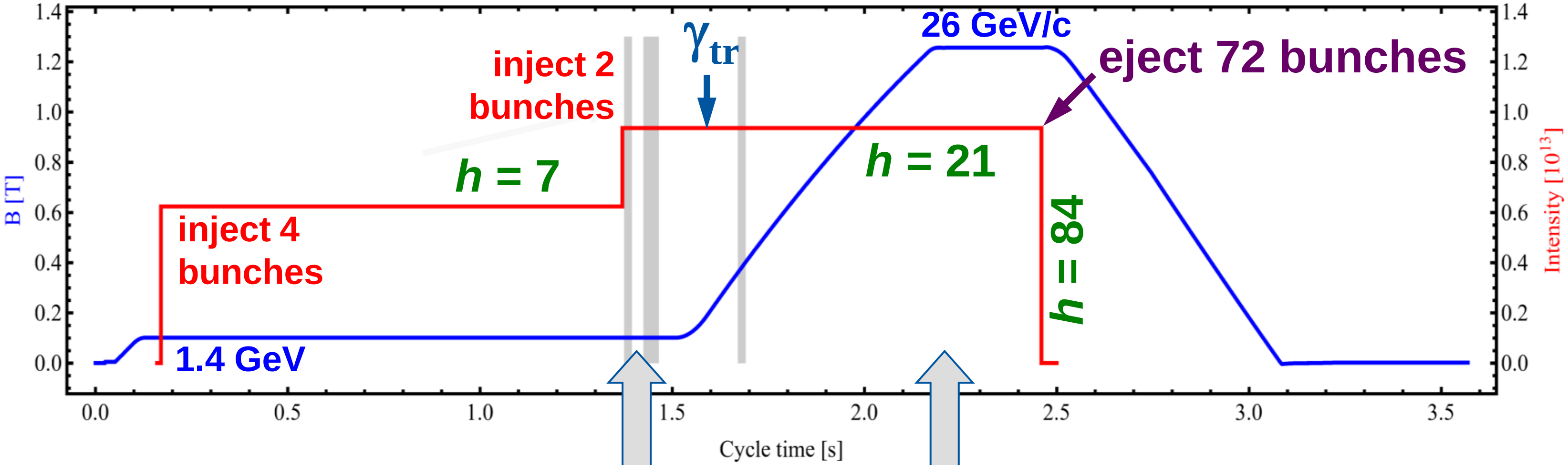


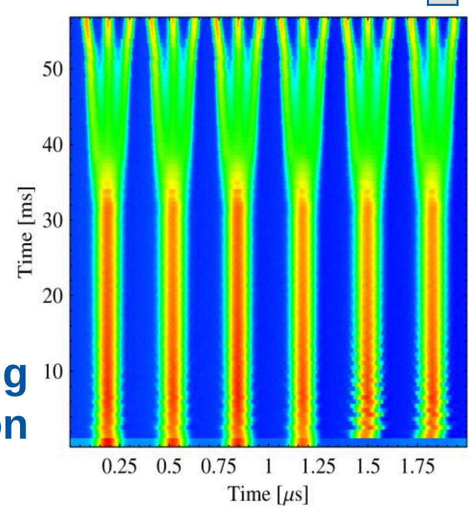
	Max. T [GeV]	Length / Circ. (m)
LINAC2	0.050	30
Booster	1.4	$2\pi\times 25$
PS	25	$2\pi\times 100 = 4\times$PSB
SPS	449	$2\pi\times 1100 = 11\times$PS
LHC	6999	26’657=27/7×SPS

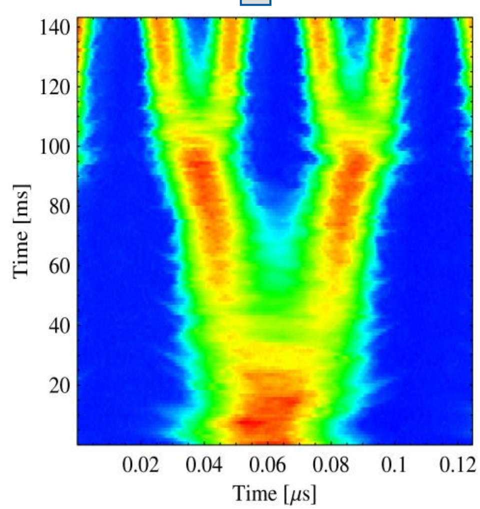
LHC Injector Cycling



LHC 25 ns beam in the PS







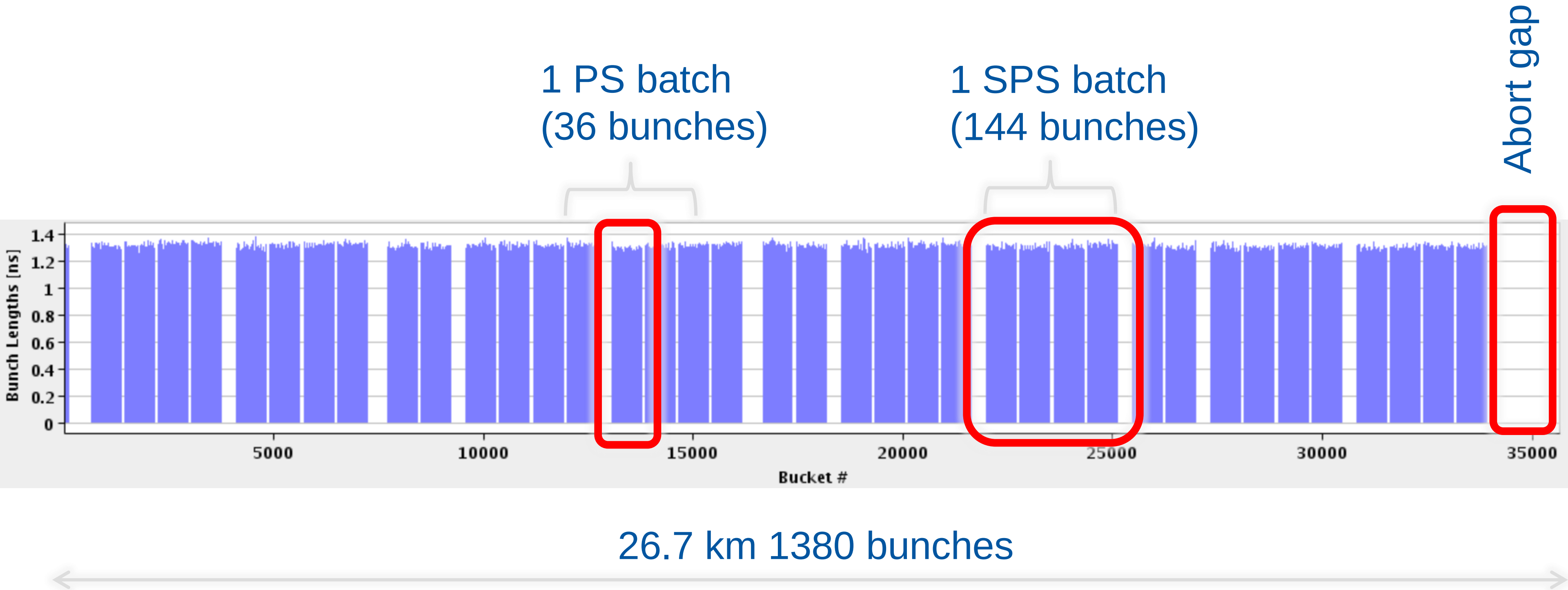
triple splitting after 2nd injection

split in four at flat top energy

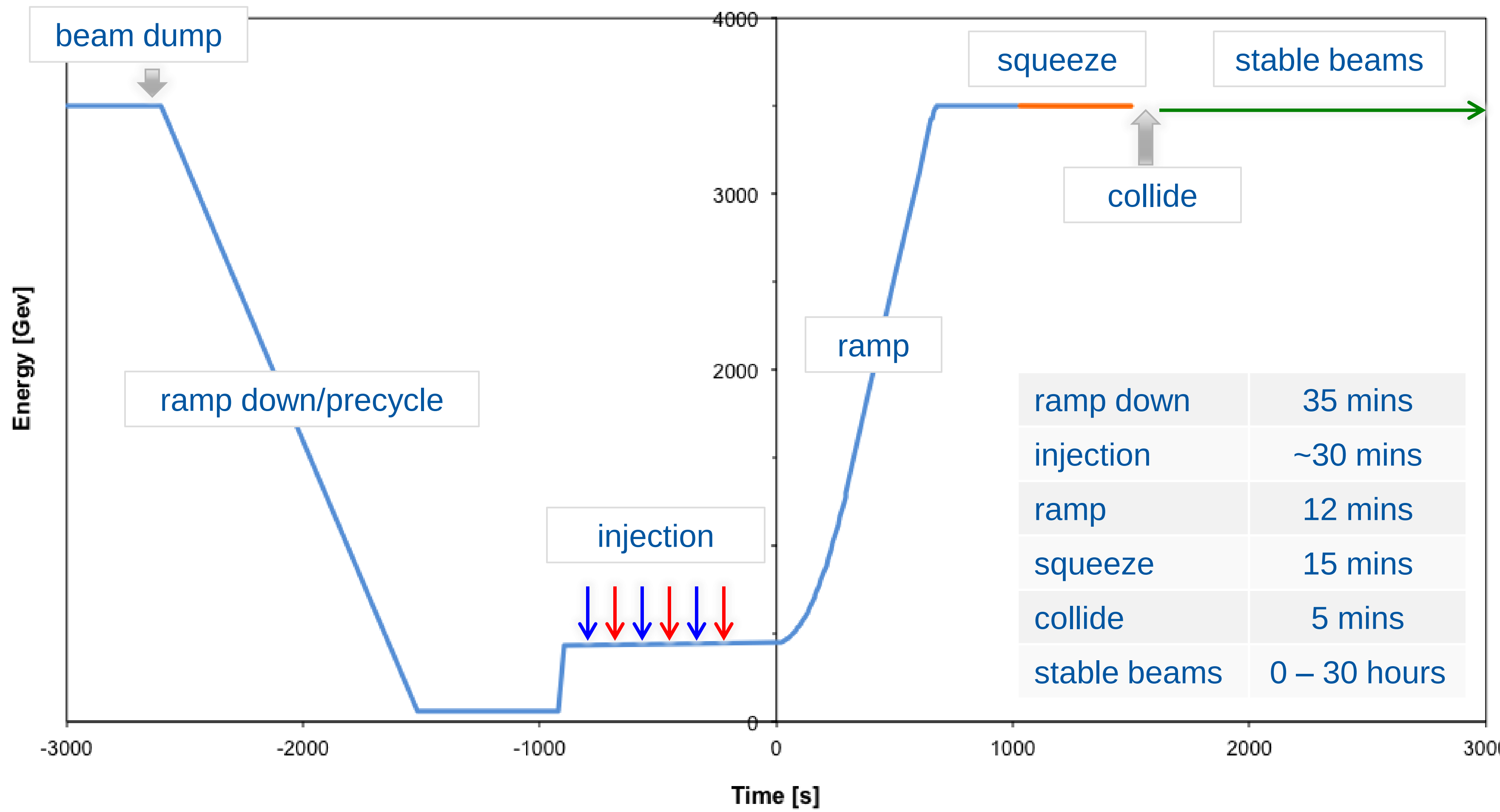
each bunch from the PSB divided by **12**:
(4+2) x3 x2 x2 = 72

LHC bunch structure - 2012

- 50 ns bunch spacing: **(4+2) x3 x2 ~~x2~~ = 36**
  - maximum bunch intensity 1.7 x 10^{11} protons per bunch



operational cycle

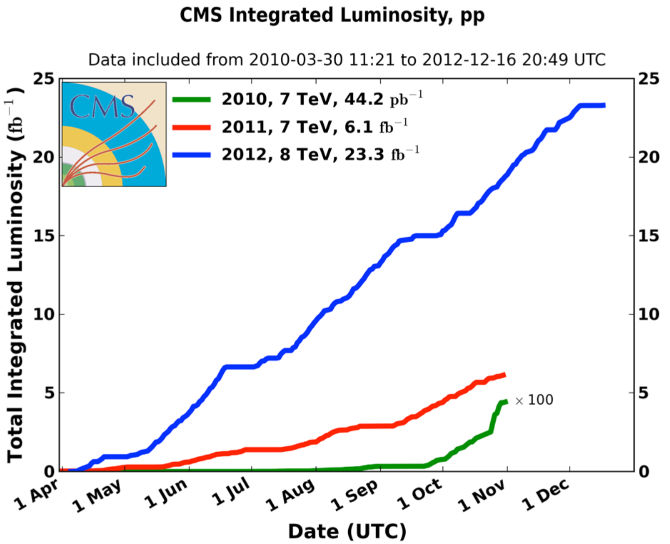


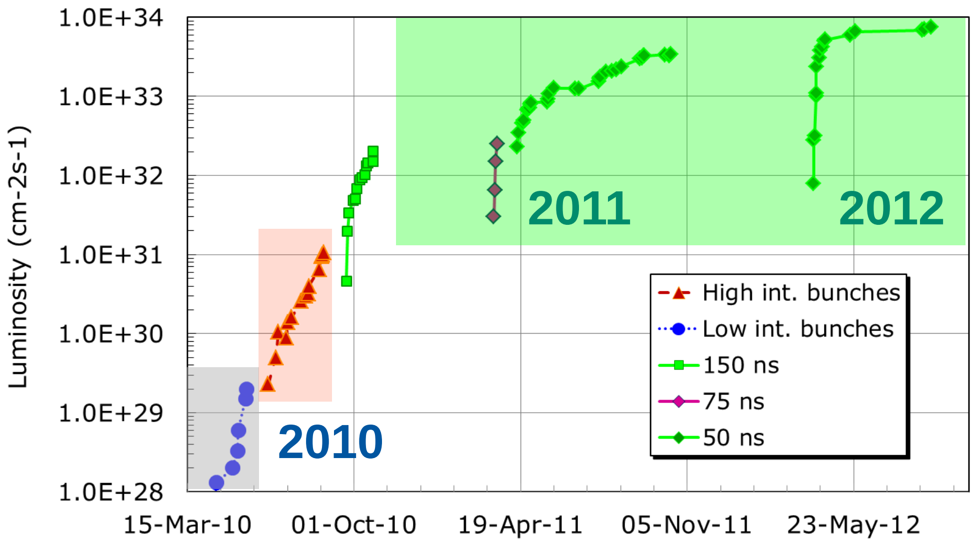
ramp down	35 mins
injection	~30 mins
ramp	12 mins
squeeze	15 mins
collide	5 mins
stable beams	0 – 30 hours

Turn around from stable beams to stable beams - 2 to 3 hours on a good day

luminosity 2010-2012

- 2010, commissioning: 0.04 fb^{-1}
- 2011, exploring the limits: 6.1 fb^{-1}
- 2012, production: 23.3 fb^{-1}

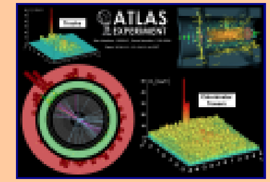




- first operational experience with low bunch intensity
- learn to handle intense beams (~1 MJ stored energy)
- production and Higgs hunt

2010

November: jet "quenching" in HI



November 4
switch to lead ions

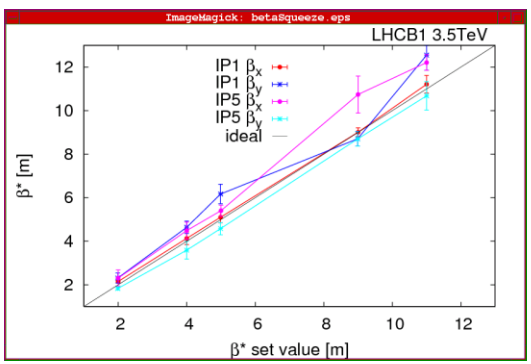
Feb 27
beam back

March 30
first collisions 3.5 TeV

QUALIFICATION

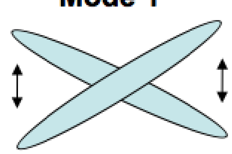
February	March	April	May	June	July	August	September	Octobe	November

April
commission squeeze

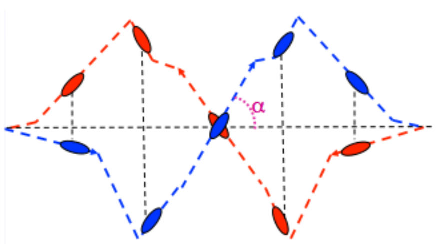


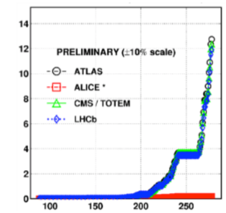
June
commission
nominal bunch
intensity

Mode 1



September
crossing angles on

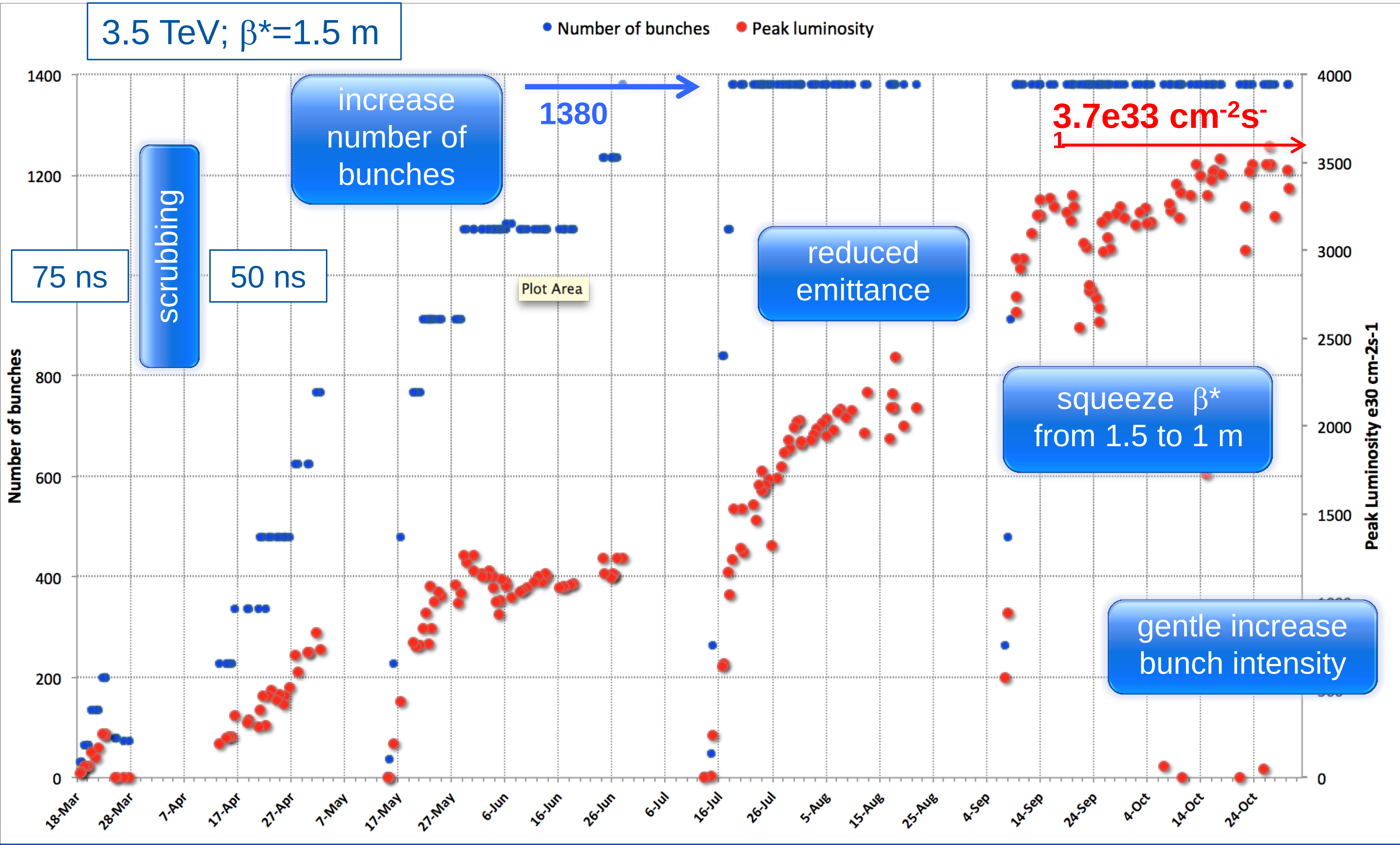




October 14 2010
1e32
248 bunches

Total for year: 50 pb^{-1}

2011


3.5 TeV; β*=1.5 m
Number of bunches
Peak luminosity
increase number of bunches
1380
3.7e33 cm-2s-1
scrubbing
75 ns
50 ns
Plot Area
reduced emittance
squeeze β* from 1.5 to 1 m
gentle increase bunch intensity
Number of bunches
Peak Luminosity e30 cm-2s-1
1400
1200
800
600
400
200
0
4000
3500
3000
2500
2000
1500
0
18-Mar
28-Mar
7-Apr
17-Apr
27-Apr
7-May
17-May
27-May
6-Jun
16-Jun
26-Jun
6-Jul
16-Jul
26-Jul
5-Aug
15-Aug
25-Aug
4-Sep
14-Sep
24-Sep
4-Oct
14-Oct
24-Oct

2012

15 March
beam back

18 April
1380 bunches
5.5e33 $cm^{-2}s^{-1}$

4 July

13-14 September
proton-lead test

March	April	May	June	July	August	September	Octobe	November	December

18 March
squeezed to 60 cm

6 June
6.8e33 $cm^{-2}s^{-1}$

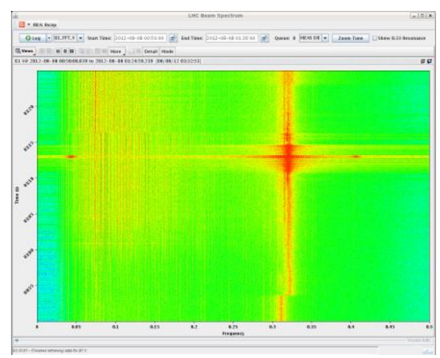
7 August
flip octupole polarity
raise chromaticity

December
25 ns scrubbing run

4 TeV
50 ns
β^* = 60 cm
“tight” collimators

ICHEP2012
Melbourne

18 June: end running period ~6.7 fb^{-1} for summer conferences



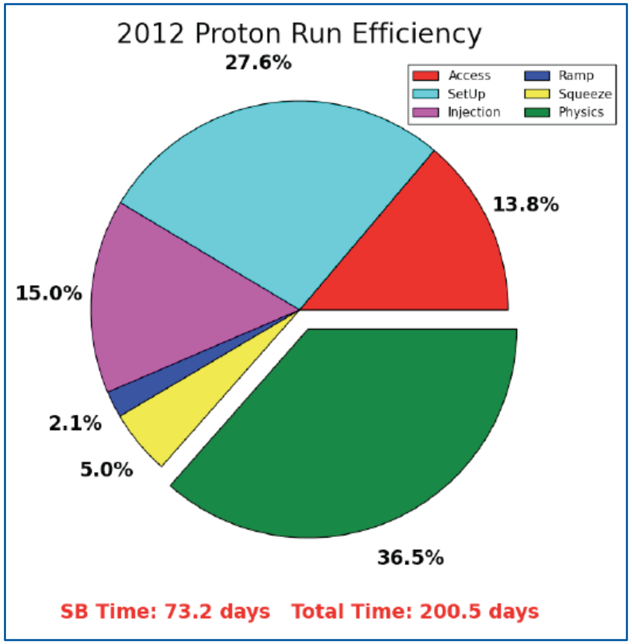
beam parameters 2010-2012

$$L = \frac{kN_b^{\ 2} f \gamma}{4\pi \beta^* \varepsilon^*} F$$

Parameter	2010	2011	2012	Nominal
beam energy (TeV)	3.5	3.5	4.0	7.0
bunch spacing	150	75 / 50	50	25
k (no. bunches)	368	1380	1380	2808
N_b (10^{11} p/bunch)	1.2	1.45	1.6	1.15
ε (μm rad)	2.4	2.4	2.5	3.75
β^* (m)	3.5	1.5 → 1	0.6	0.55
L ($cm^{-2}s^{-1}$)	2×10^{32}	3.5×10^{33}	7.6×10^{33}	10^{34}
average pile-up @ start of fill	8	17	38	26
stored energy (MJ)	25	112	140	362

reasons for success

- 77% of nominal peak luminosity
  - high intensity and low emittance from injectors, low beta*
  - despite lower energy and lower number of bunches
- combined with healthy availability



- 2011 end of run party
  - 5.6 fb^{-1} delivered to ATLAS

main 2013-2014 consolidations

1695 Openings and final reclosures of the interconnections

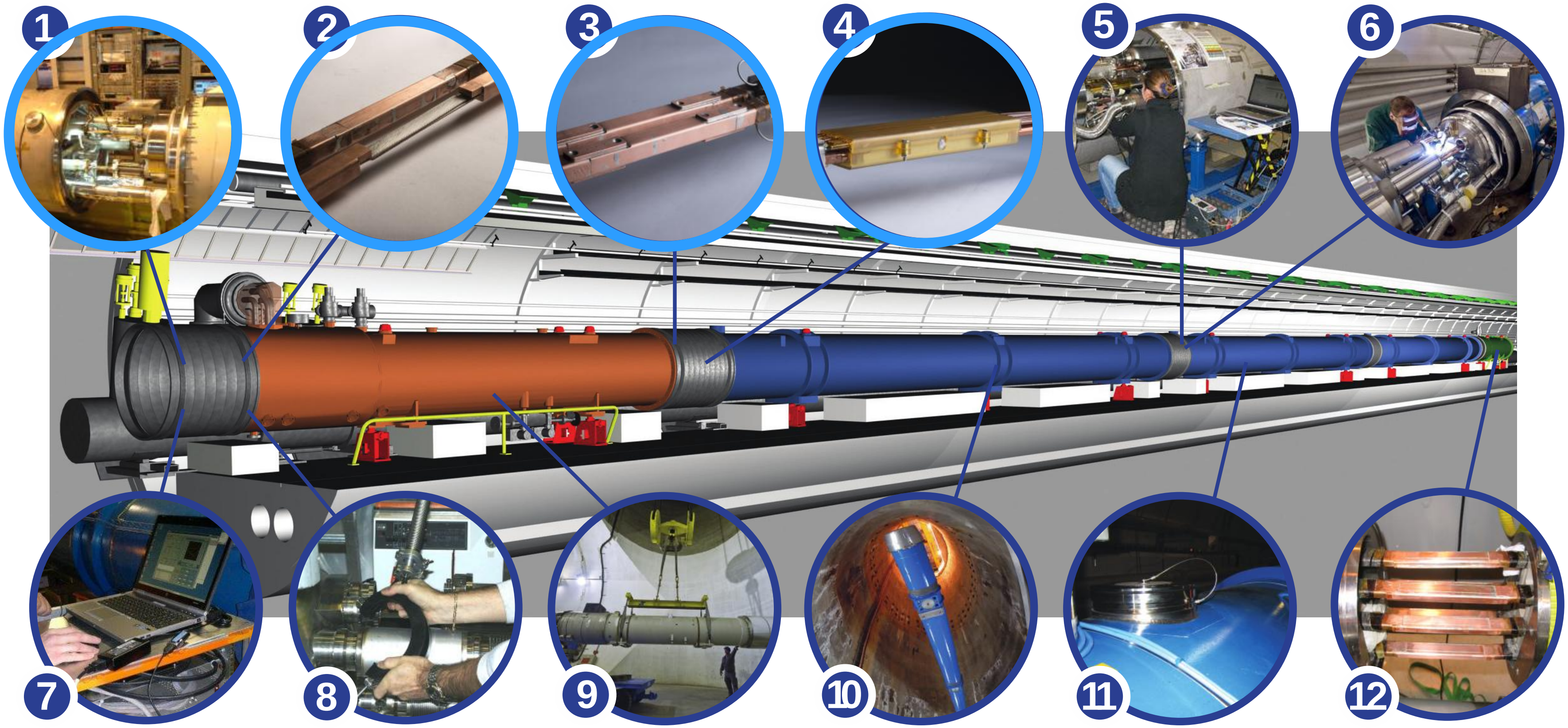
Complete reconstruction of 3000 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

3 quadrupole magnets to be replaced

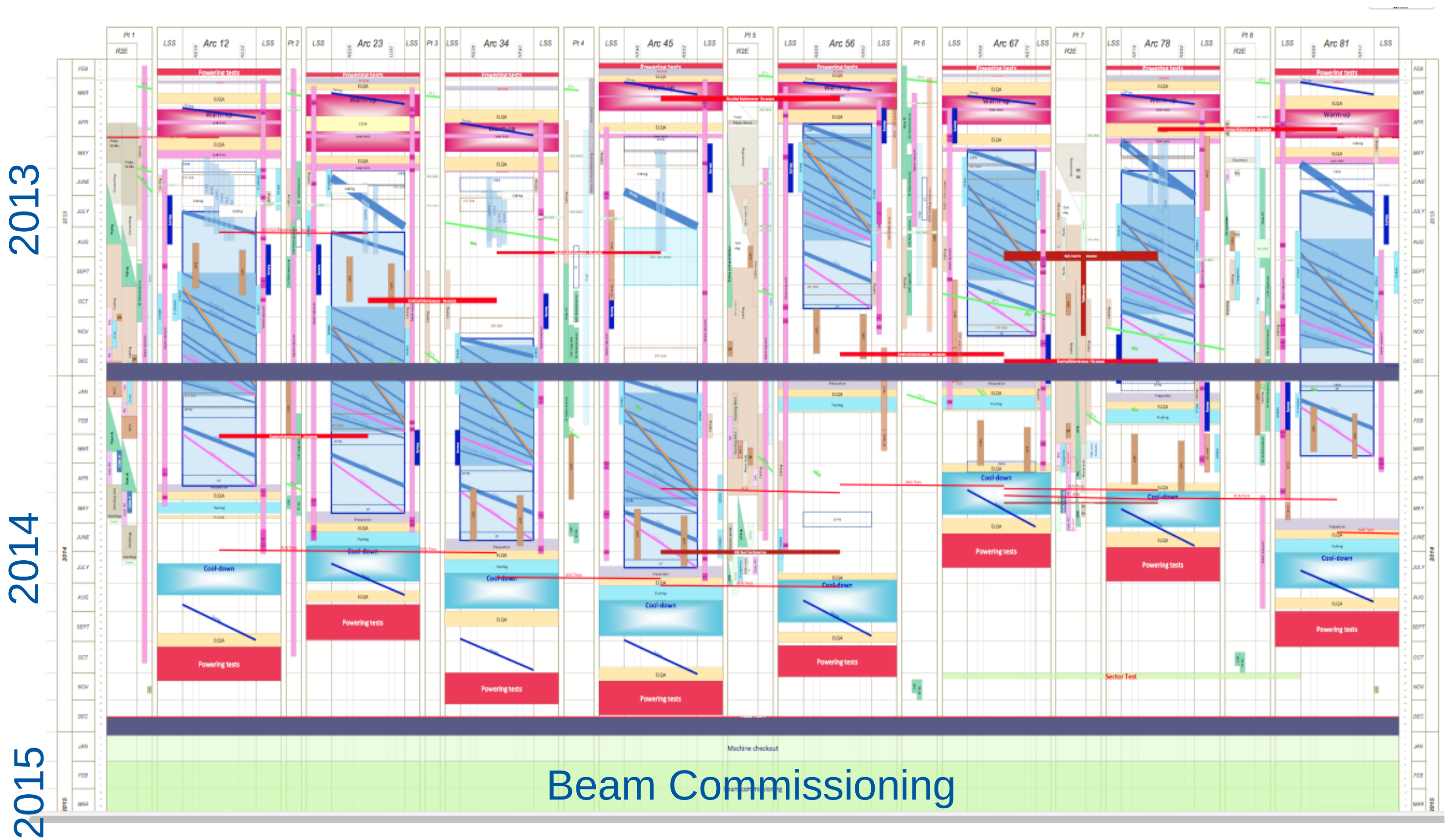
15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to 1344

Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

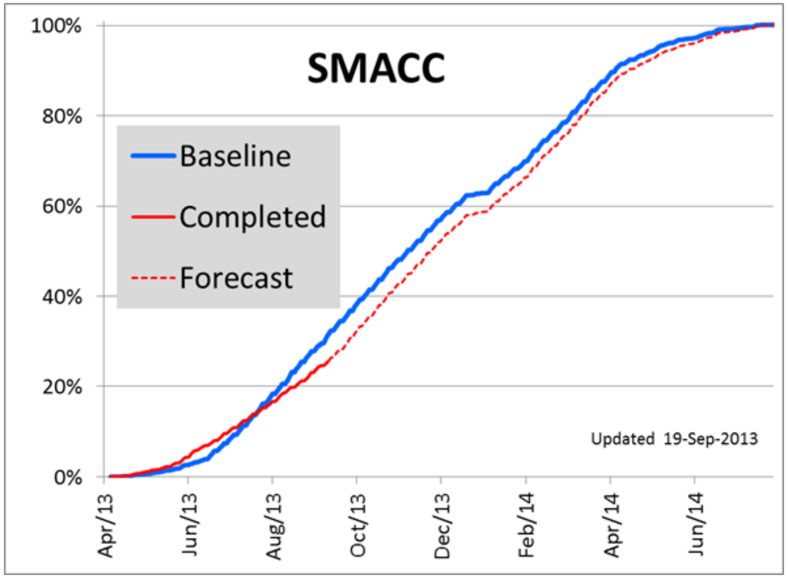
splice: joint between busbars of main dipoles or quads

shutdown schedule



latest news on the shutdown

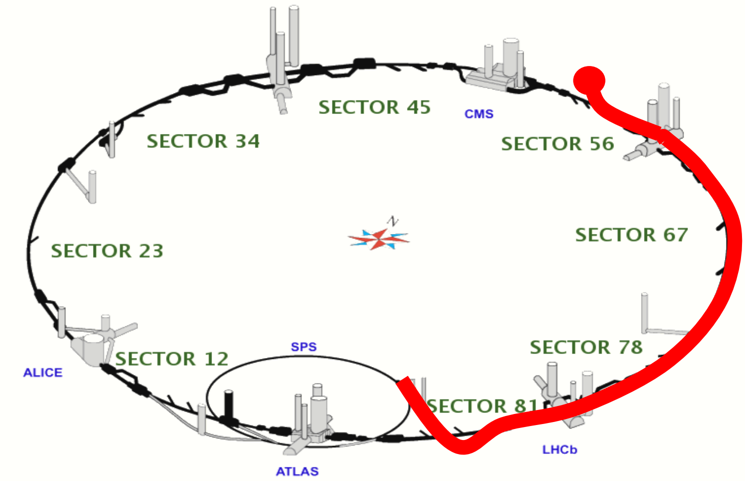
- progressing well
  - splice consolidation procedures well established
    - more than half the machine open
    - first sector completed (except non conformities)
  - had a few surprises
    - e.g. damaged bellows in cryogenic supply line and electrical feed boxes



- present delay: ~3 weeks
  - redo more splices than expected (30% vs 15%, confirmed in 40% of the machine)
  - other technical issues being solved
- resources increased

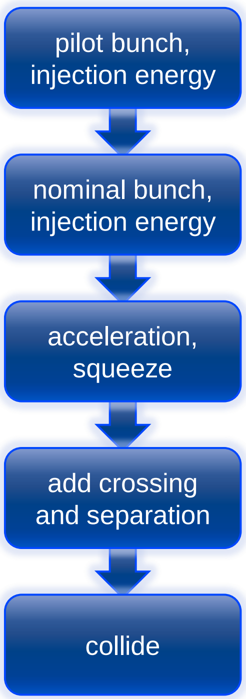
preparing for restart

- powering tests (Q3-Q4 2014) for hardware commissioning
  - for superconducting circuits and relative systems
  - training of dipole magnets towards 7 TeV
    - start presumably at 6.5 TeV (~100 training quenches)
- sector test (Q4 2014)
  - beam 2, sectors 78 and 67
  - goal: switch on beam dump, inject & dump on first turn



- dry runs (from Q2 2014) and machine checkout (Q1 2015)
  - checks of equipment control from the control room, until running through full cycle without beam
  - control software, interlocks, beam dump, injection, RF, transverse damper, communication with experiments, …

beam commissioning

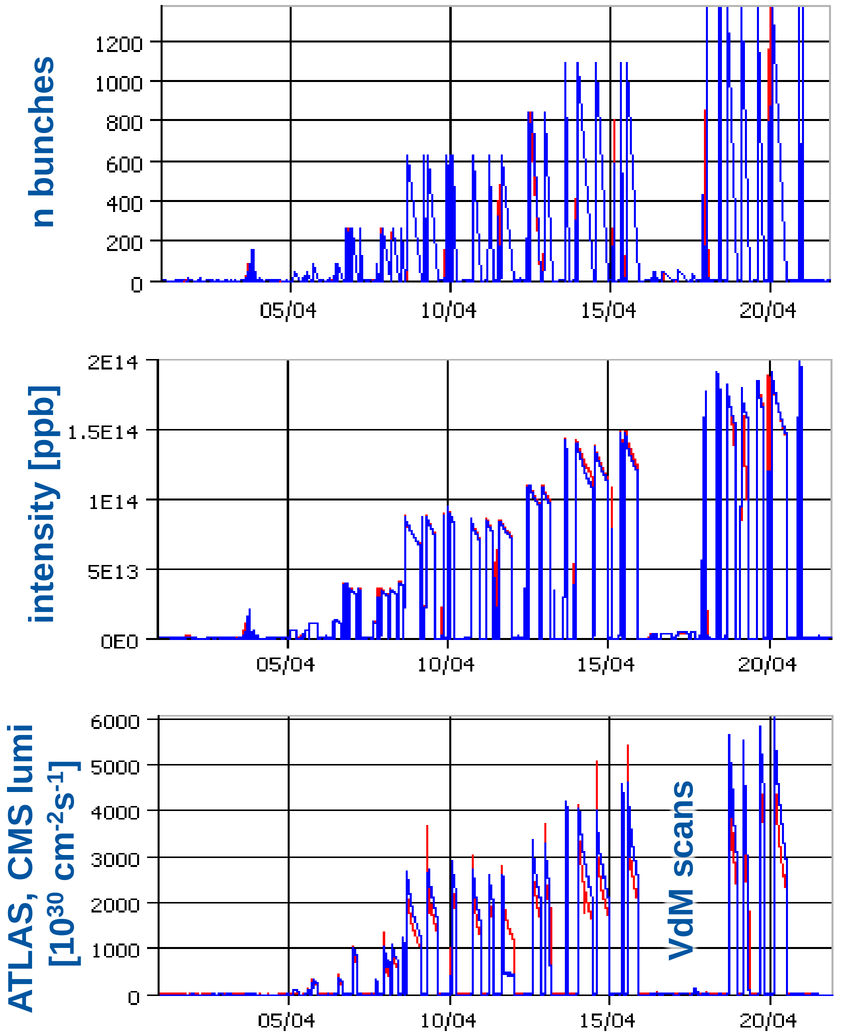


- a new machine to be commissioned after cold checkout
- beam commissioning phases:
  - first injection to circulating beam
    - threading, RF capture, BPM polarity checks
  - flat orbit reference with nominal bunch
    - RF/instrumentation/transverse damper setup, primary collimators setup
    - with pilot beam: measure aperture, magnet current decays
  - first ramp and squeeze
    - commission feedbacks (orbit/Q/radial), measure optics
  - add crossing and separation bumps
    - aperture and beta* measurements, setup tertiary collimators, tests of collimator functions
  - collide 2/3 nominal bunches
    - RF cogging, setup tertiary collimators
  - verify protection with controlled losses
    - at injection, flat top, after squeeze and in collisions
- total: about 2 months in Q1 2015

intensity ramp up

- beam commissioning done with single bunches (max 2-3)
  - includes most machine protection tests
- then inject bunch trains
  - staged approach: “intensity ramp-up”
  - effects of vacuum activity, Single Event Upsets, Unidentified Falling Objects kick in at higher intensity
- example: 7 steps in April 2012
  - few short fills for cycle validation
    - 2-3 fills and 4-6 hours with 48, 84, 264 and 624 bunches
  - few longer fills for intensity or luminosity related problems
    - 3 fills and 20 hours with 840, 1092, 1380 bunches
- 2015: expect 1-2 months
  - higher energy, 25 ns scrubbing?

2012 experience

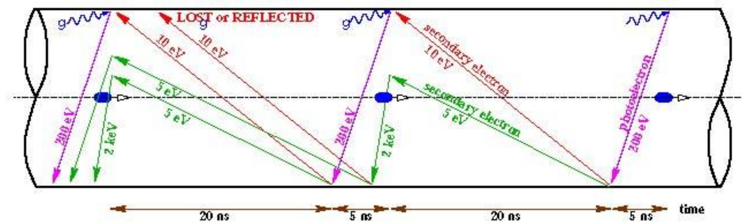


some of our worries

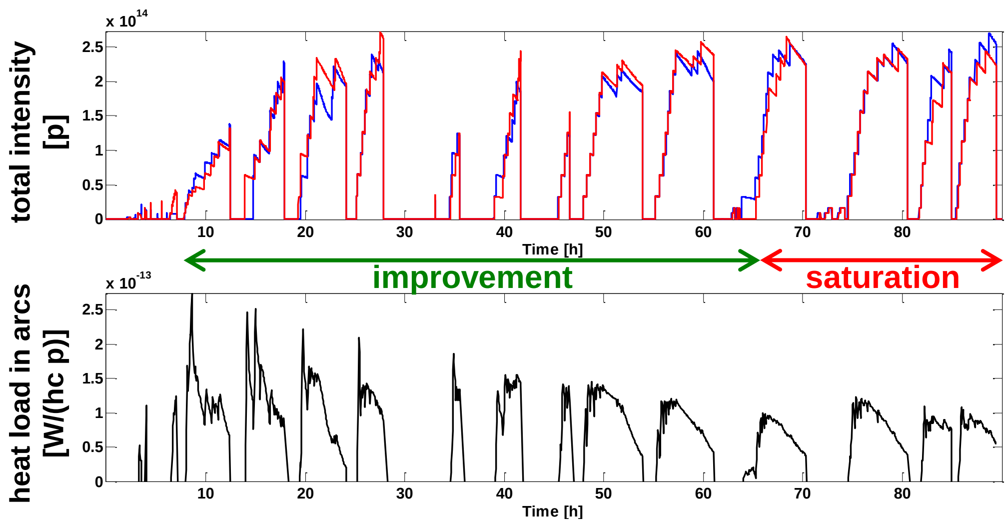
- electron-cloud and scrubbing
- Unidentified Falling Objects (UFOs)
- beam stability
- parameter space and expected peak performance
- radiation to electronics (R2E)

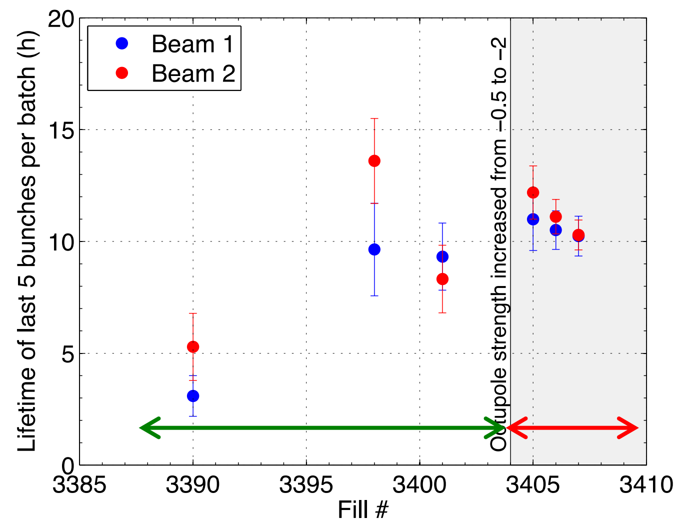
electron-cloud & scrubbing

Secondary Emission Yield



- $SEY > SEY_{th}$: avalanche effect (multipacting)
  - SEY_{th} depends on bunch spacing and population
- e-cloud effects observed in LHC with bunch trains
  - for 150, 75, 50 and 25 ns bunch spacing
  - vacuum pressure rise, heat load on cryogenic systems
  - beam size growth, single- and multi-bunch instabilities
- e-cloud studies (Q4 2012) indicate a very slow improvement in SEY with 25 ns scrubbing
  - extended scrubbing probably required in 2015
  - or physics with degraded beam parameters





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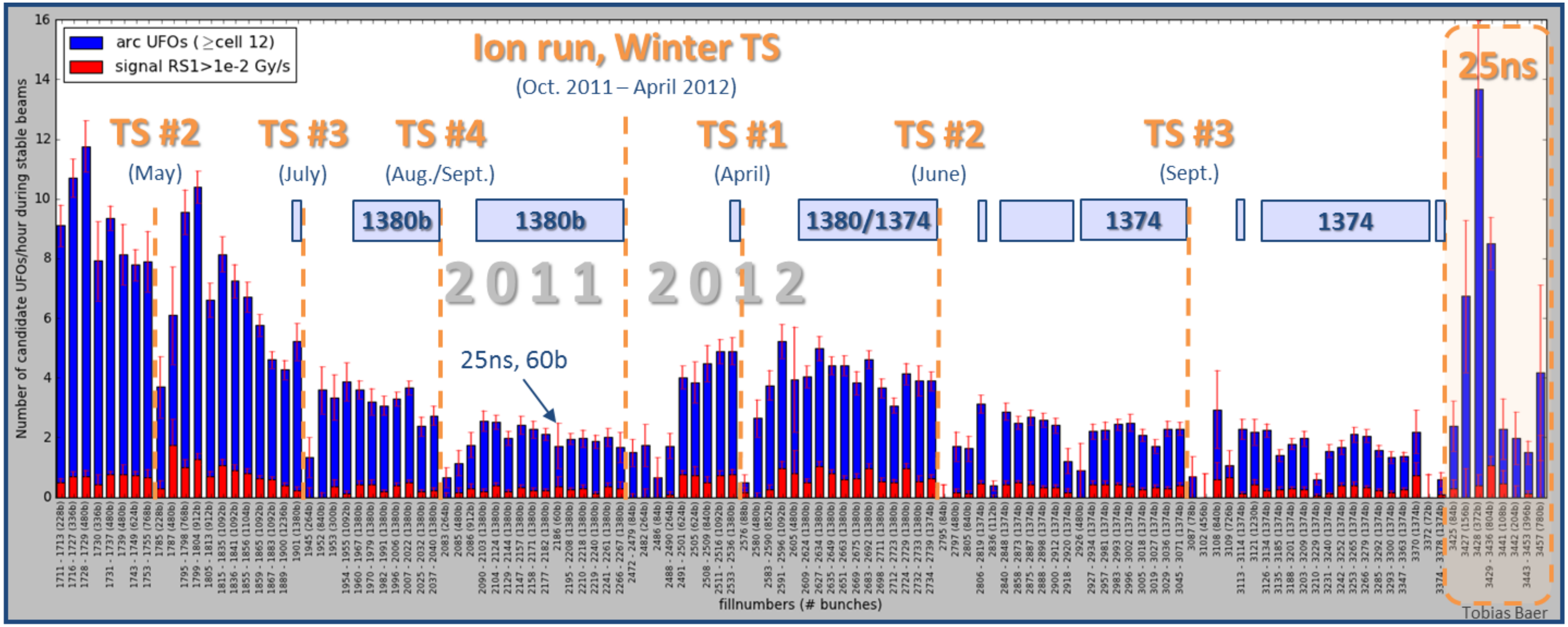
Unidentified Falling Objects



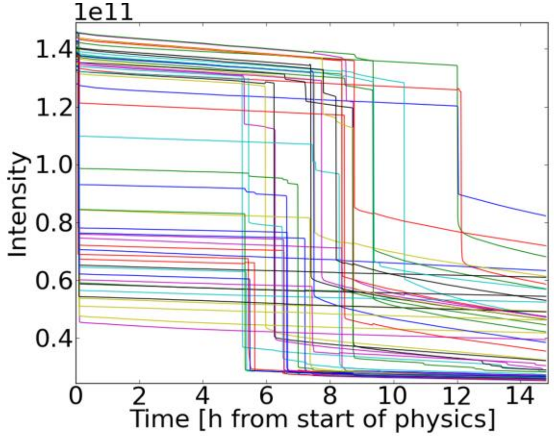
- fast loss events (ms timescale) due to dust particles falling into the beam, caused ~20 dumps/year
- "scrubbing" observed over the course of 2011 and 2012
  - deconditioning after technical stops, thus expected after this shutdown
- up to 10x increased rates for arc UFOs for 25 ns beams at 4 TeV
  - at higher energy, quench margin goes down and generated losses go up: extrapolate to >100 dumps
- might impose to start with 50 ns beam and/or lower energy in the very worst case

T. Baer

beam (in)stability

- many instabilities observed during run 1…
  - transverse and longitudinal
  - cured by high chromaticity, octupoles, transverse damper, beam-beam head-on tune spread, controlled longitudinal blow up
- but not all understood

example: "snowflake" instability



- …expect instabilities also at 6.5-7 TeV
  - octupoles will be less efficient (smaller beam size and less strength)
  - profit from Landau damping by head-on beam-beam
    - collide already during the squeeze is an option
  - probably high chromaticity and high gain on transverse damper
  - question of collimator settings still open (impedance!)

	50 ns	vs 25 ns
:)	• lower total beam current • higher brightness • less e-cloud and UFOs	• lower pile-up • cleaner physics events
:(	• high pile-up • need to level luminosity • high bunch intensity: instabilities	• more long range collisions: larger crossing angle; higher beta* • higher emittance • higher injected bunch train intensity • higher total beam current • higher UFO rate • more electron cloud: need for scrubbing, emittance blow-up;

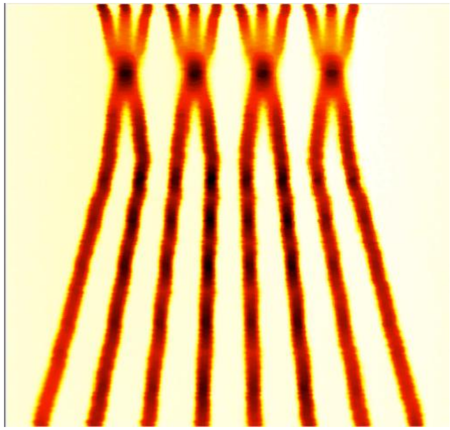
- pile-up is an issue for 50 ns beams
  - design report is 20
  - challenging 35-40 at start of fill in 2012 operation;
  - probed up to 70 in machine studies: cannot be handled by the experiments

- **25 ns is the baseline**
  - scrubbing might be slow with 25 ns
    - but invest for ~3 years of operation
  - UFOs might impair availability
- **50 ns is the fallback plan**
  - might impose luminosity levelling
    - beta* levelling tried in machine studies

expected peak performance

6.5 TeV

bunch spacing	25 ns
beta* [m]	0.5
ε*[μm] at start of fill	1.9
max. Bunch Population [10^{11} p]	1.15
max. Number of bunches/colliding pairs IP1/5	2508
max. Stored energy [MJ]	300
peak luminosity [10^{34} $cm^{-2}s^{-1}$] in IP1/5	1.5
maximum Average pile-up (σ=85 mb)	44



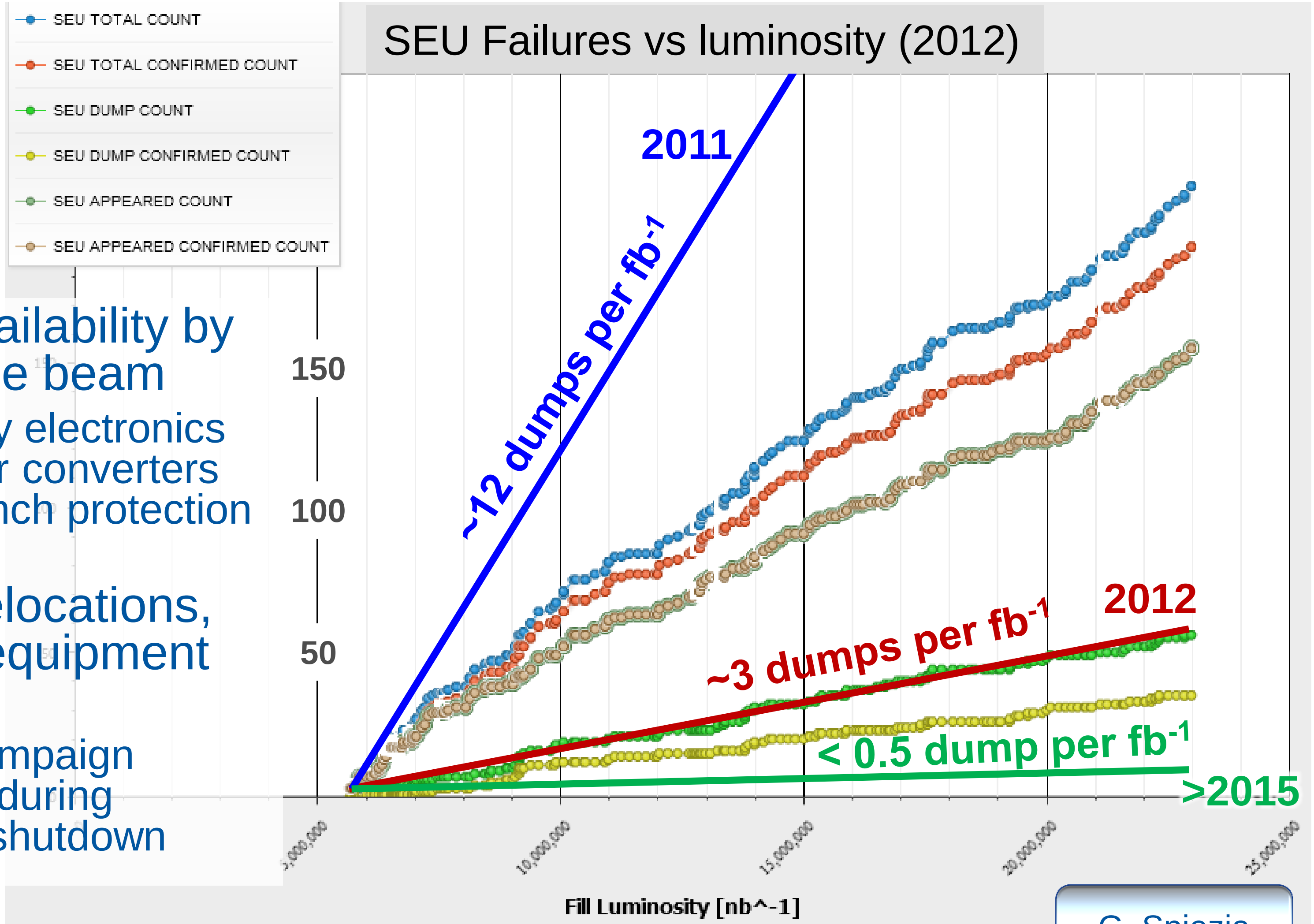
with Batch Compression and Merging and Splitting scheme: nominal intensity in lower emittance

pile-up

our clients' worries

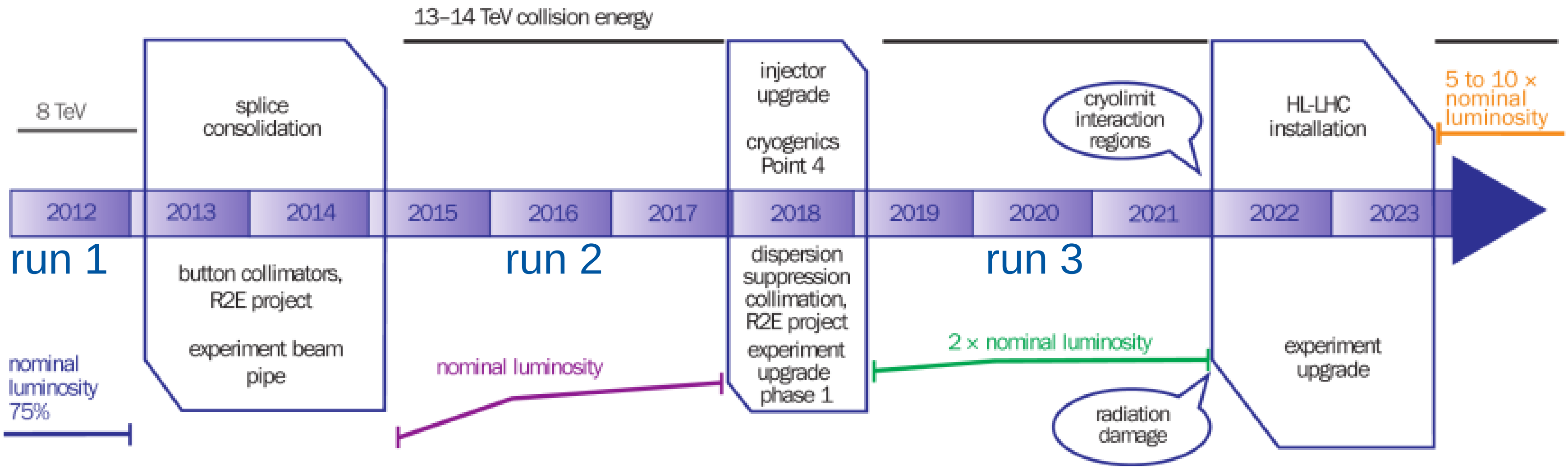
Radiation to Electronics (R2E)

- impacts availability by dumping the beam
  - mostly by electronics for power converters and quench protection systems
- cured by relocations, shielding, equipment upgrades
  - major campaign ongoing during present shutdown



G. Spiezia

the next 10 years

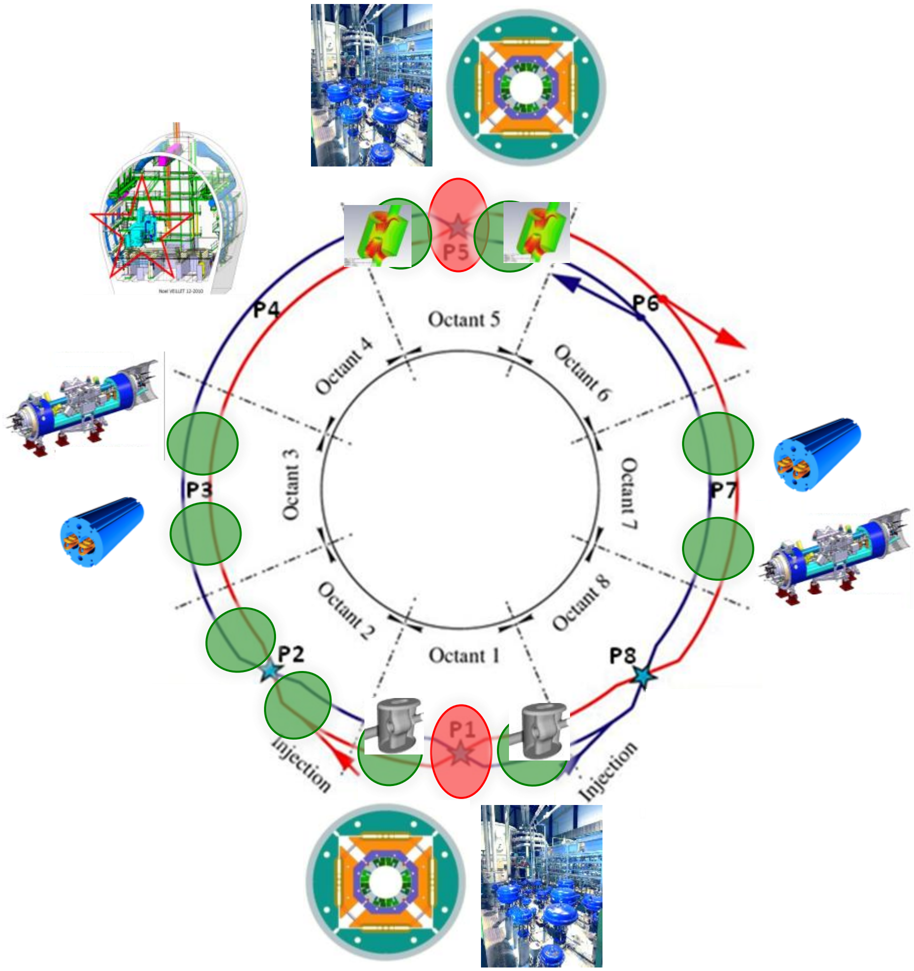


- present LHC will reach its limits in the early 2020s
  - radiation hardness of magnets (lifetime)
    - e.g. triplet and cleaning insertions to be changed in any case
  - cooling and cryogenics (limit at 1.75 10^{34} $cm^{-2}s^{-1}$)
  - radiation and R2E
    - shielding and removing equipment from the tunnel (superconducting link and cold powering)
- HL-LHC goal: 3000 fb^{-1} within twelve years (run until mid 2030s)
  - integrated luminosity of 250 fb^{-1} per year, about ten times present LHC
  - peak luminosity of 5 10^{34} $cm^{-2}s^{-1}$ with levelling (140 events per crossing!)
    - need availability and reliability!

High Luminosity LHC

HL-LHC ongoing studies

- 1.2 km of new equipment:
  - new magnets (Nb_3Sn, 11-13 T)
    - large aperture for IP quads (beta* = 15 cm)
    - high field for dispersion suppressor dipoles
  - add dispersion suppressor collimators
  - additional cryogenics plants for P1, P4, P5 to have the same cooling power in all arcs
  - crab cavities to profit from the small beta* despite the large crossing angle (590 urad)
    - test stand now, beam test in SPS in 2015-16
  - 300-700 m super-conducting links to allow power converters to be moved to surface
    - reduce rad-risks and increase availability
- upgrade of the experiments to cope with higher pile-up density
  - ATLAS / CMS: pile-up of 140
- upgrade in the Injector Chain (LIU)
  - for brightness and reliability
  - also approved project



conclusions

- run 1 performance beyond most optimistic expectations
  - 29 fb^{-1} per main experiment and one new boson
- shutdown consolidation is progressing well
  - some surprises and minor delays being addressed
- a new machine will restart in 2015
  - full campaigns for hardware commissioning, cold check-out, beam commissioning, intensity ramp-up
  - parameter space constrained by pile-up limit, effectiveness of electron cloud scrubbing, UFOs, beam instabilities and their cures
- upgrades:
  - strong R&D program ongoing for HL-LHC
  - design studies ongoing for other machines

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