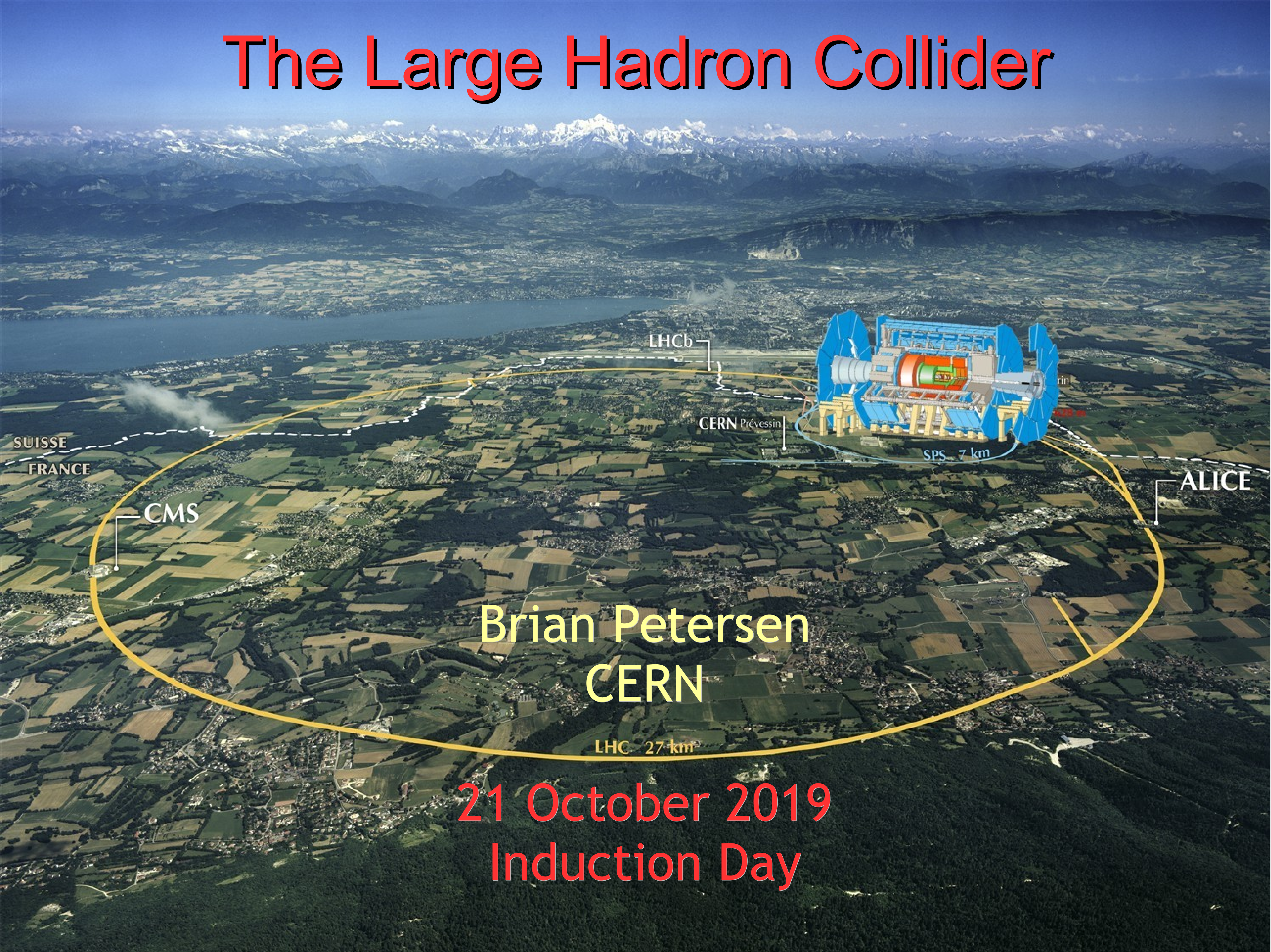
The Large Hadron Collider



Brian Petersen
CERN

21 October 2019
Induction Day

The LHC Accelerator in a Slide

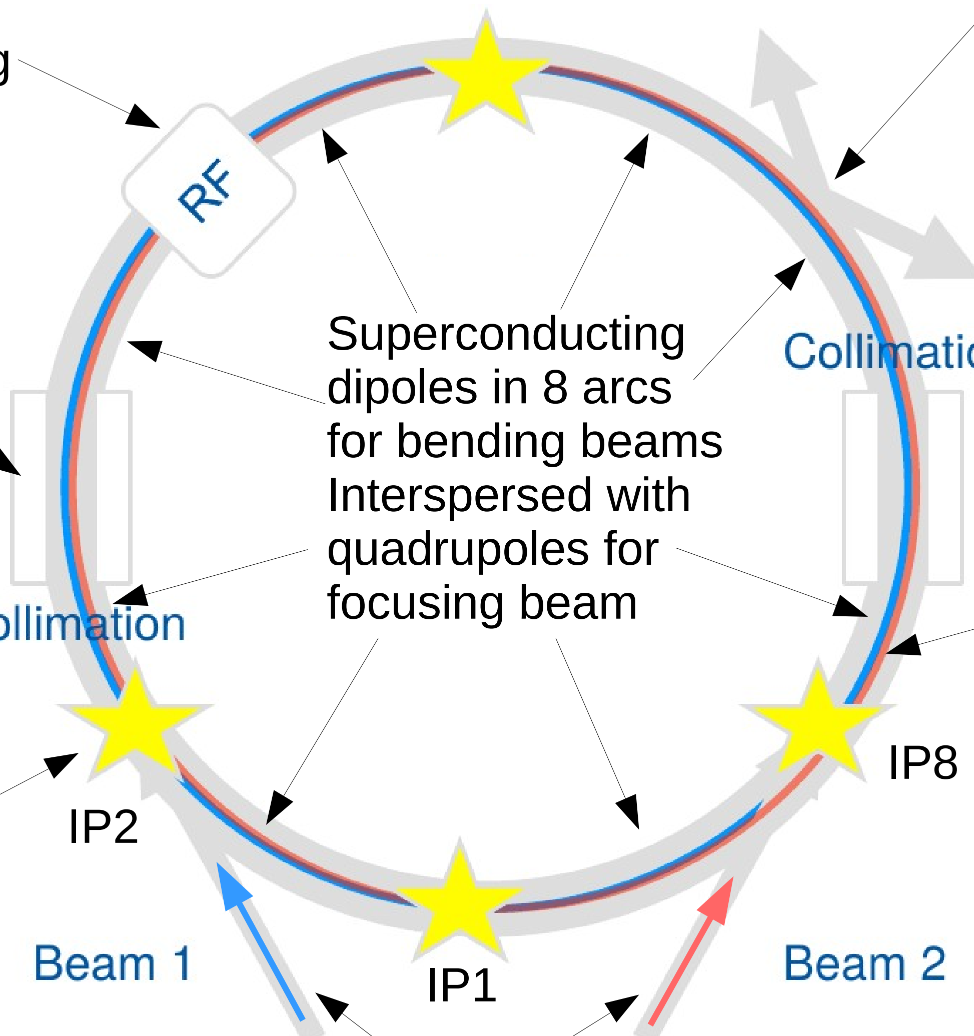
Worlds largest synchrotron

RF system for accelerating particles around ring

Beam dump system

Collimators for removing off-orbit and off-energy particles

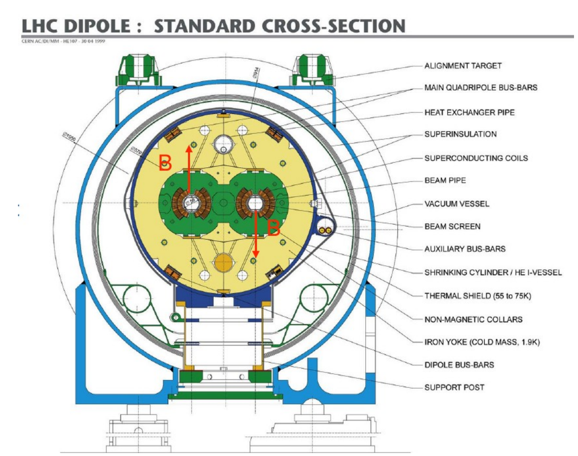
Superconducting dipoles in 8 arcs for bending beams Interspersed with quadrupoles for focusing beam



Two vacuum beam pipes for counter-circulating beams

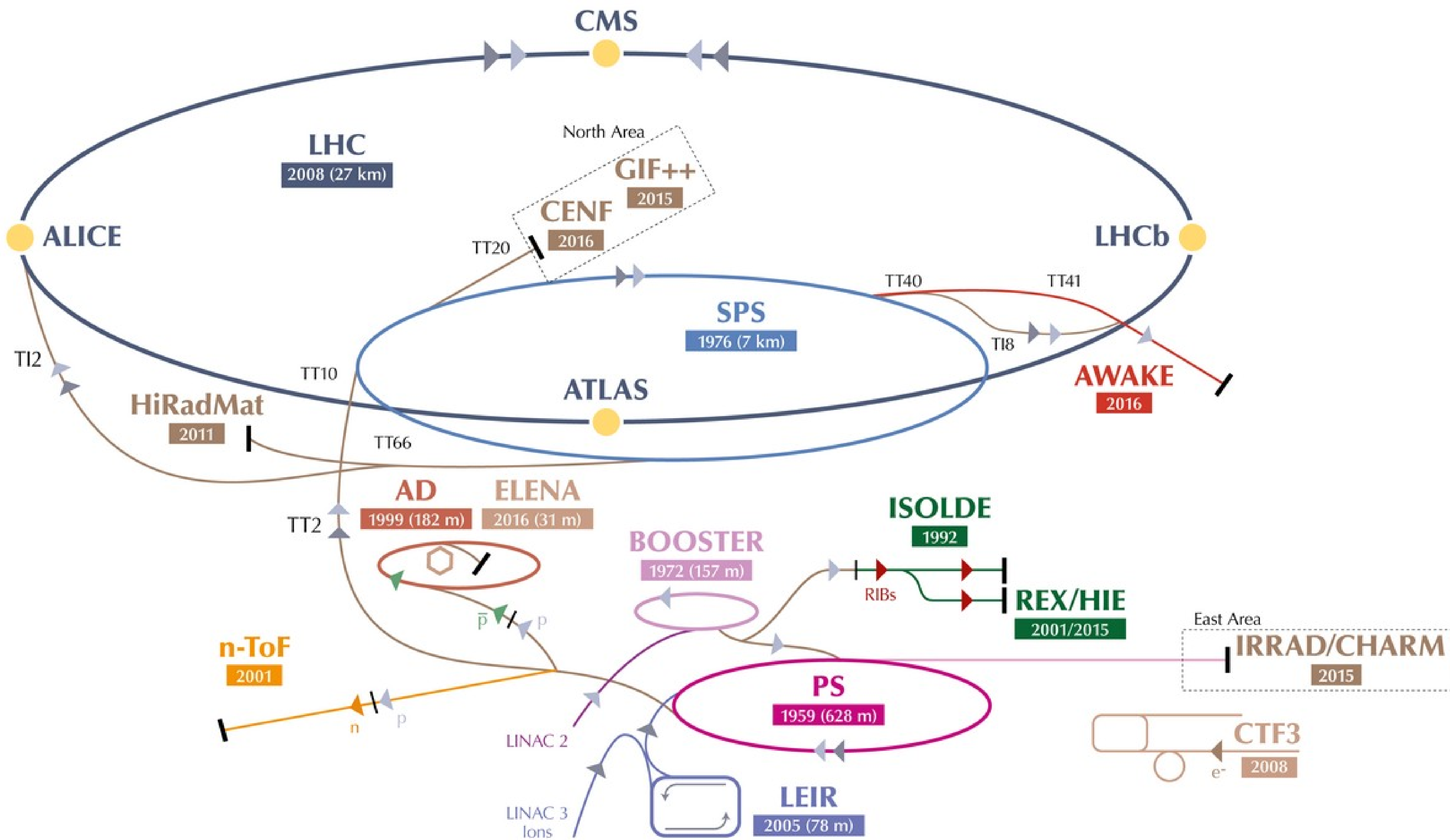
Collision points in 4 of 8 straight sections with special focusing magnets

Beam injection (protons and ions)



The CERN Accelerator Chain

LHC cannot accelerate protons from 0 to 7000 GeV directly
→ use other CERN accelerators first



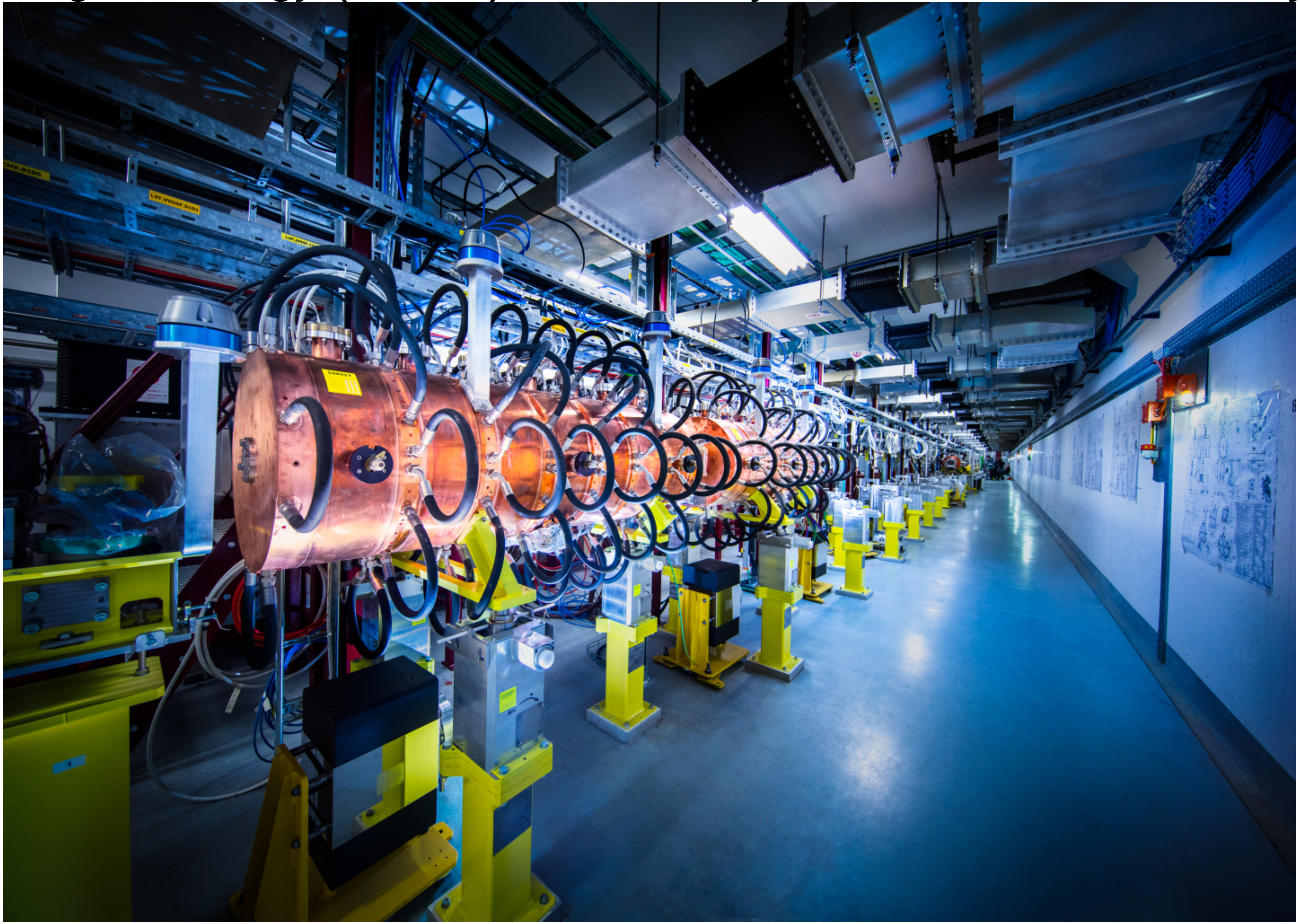
The source (and RF Quadrupole: 750 keV)

LINAC2 (1978-2018)

Accelerated protons to 50 MeV over 33m every 1.2s

LINAC4 (2016)

Accelerates H^- to 160 MeV over 80m every 0.5s
Higher energy (and H^-) allows to inject with twice the intensity



PS Booster (PSB, 1972)

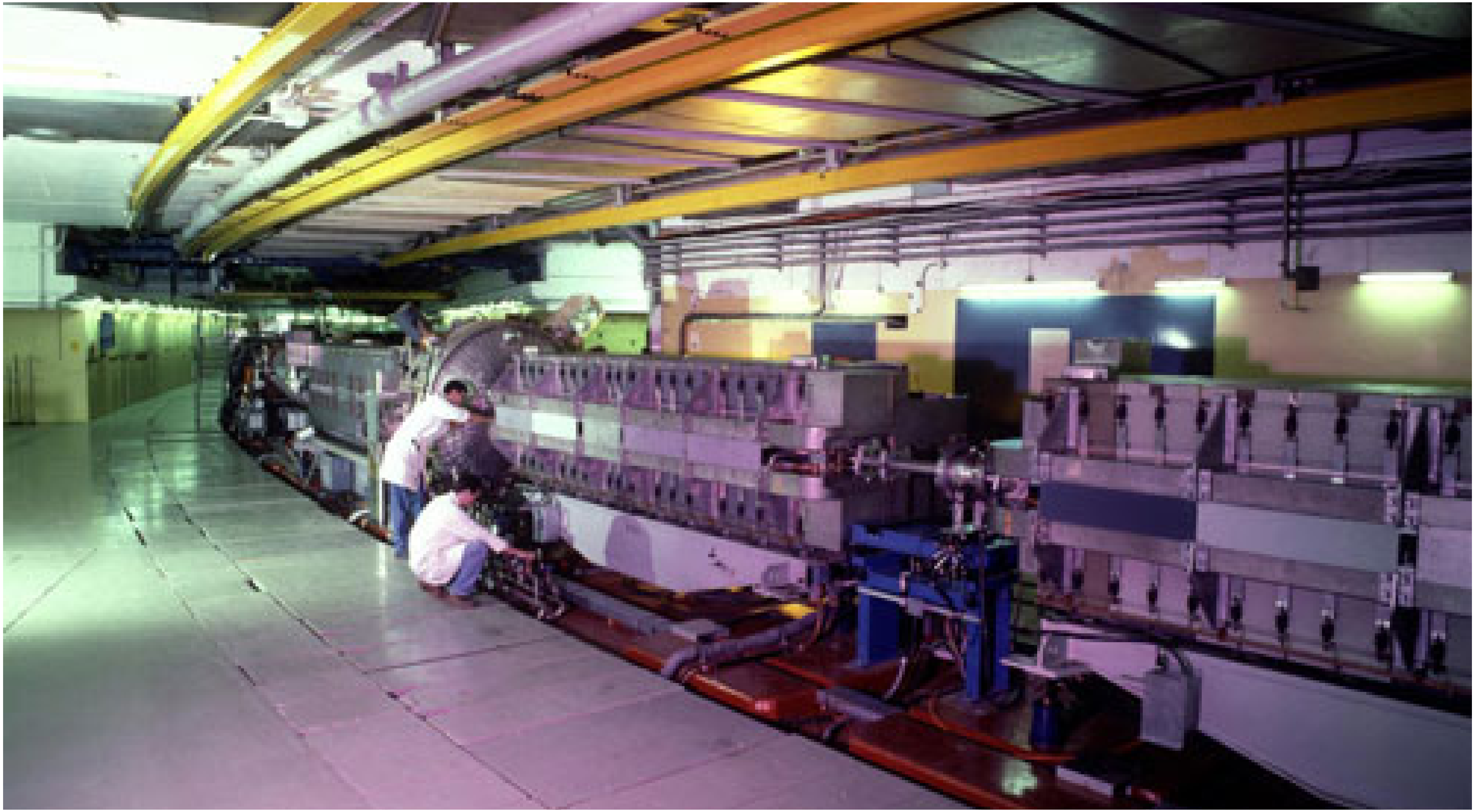
Accelerates protons (up to 10^{13} protons) from 50 MeV to 1.4 GeV in four synchrotron rings (diameter 50m) every 1.2s

Initial beam density is set by the booster and only grows in following steps

Will be upgraded to accelerate from 140 MeV to 2 GeV in 2019-2020

Proton Synchrotron (PS, 1959)

Oldest operating synchrotron at CERN (diameter: 200m)
Accelerates protons from 1.4 GeV up to 26 GeV in 3.6s
Advanced RF system allow complex bunch manipulation (see backup)
Upgrades to RF system on-going (2019-2020)



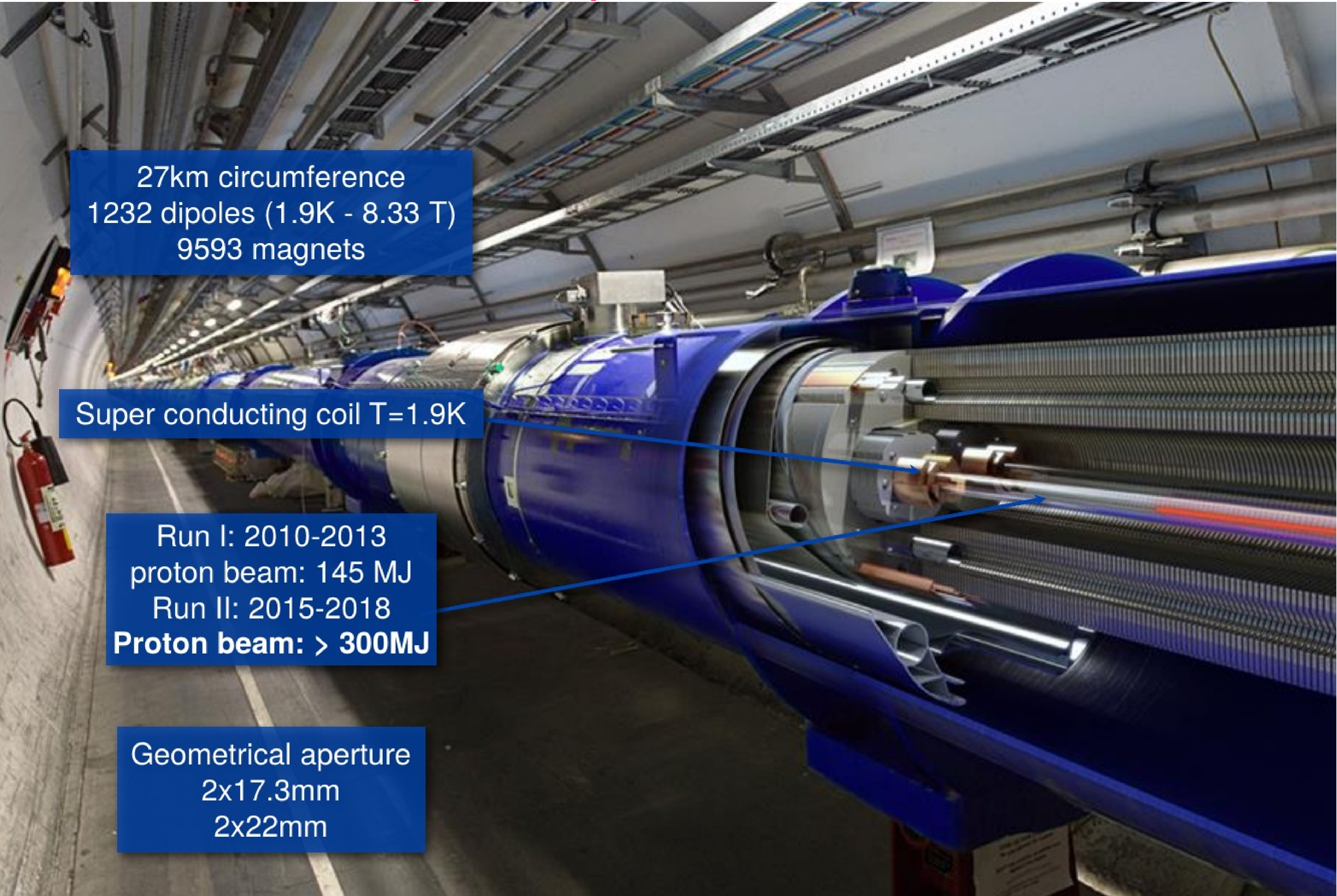
Super Proton Synchrotron (SPS, 1976)

Accelerates protons to 450 GeV

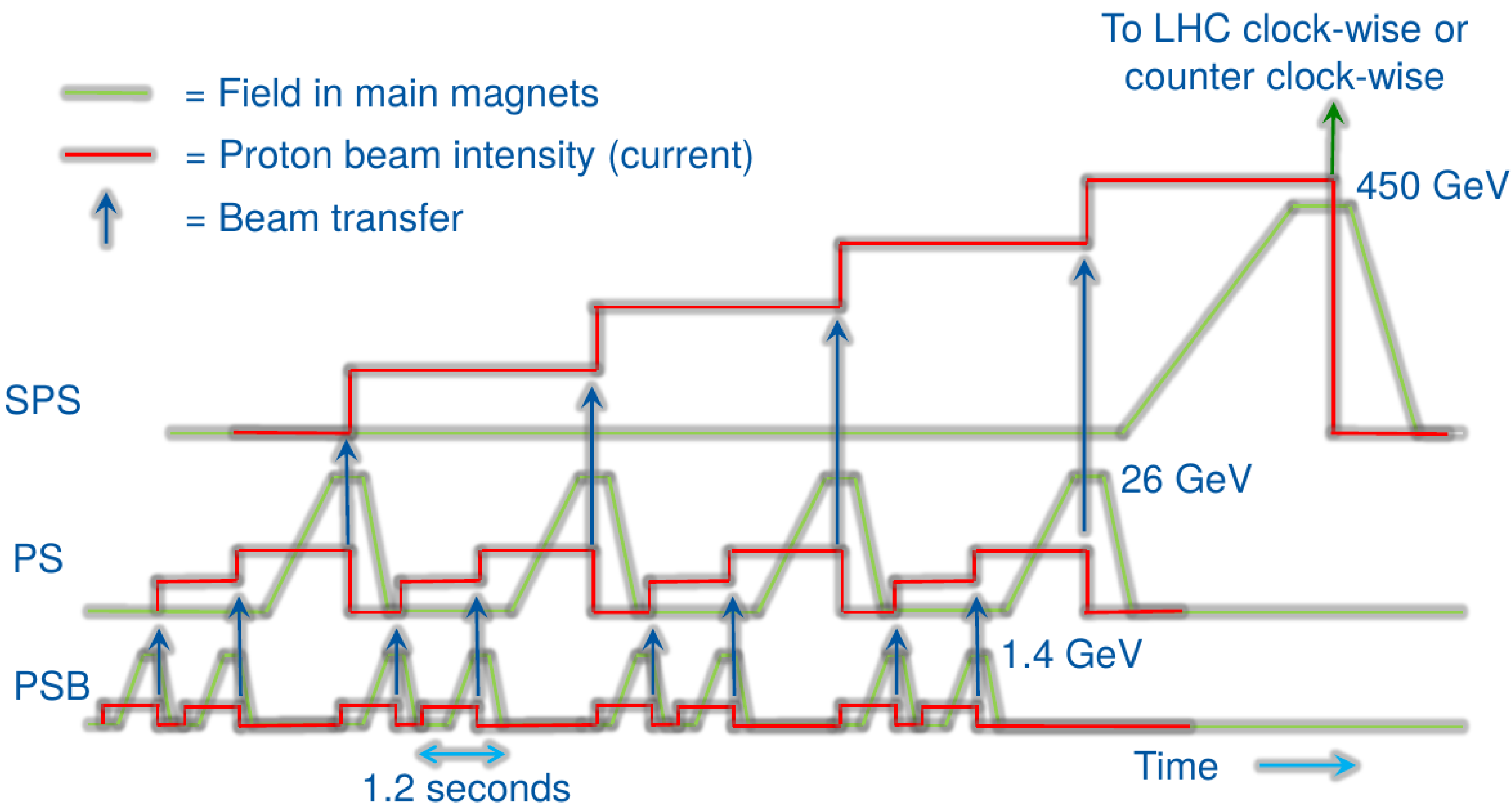
2.2km diameter and 30m underground

Upgrades in 2019/20 for higher intensities

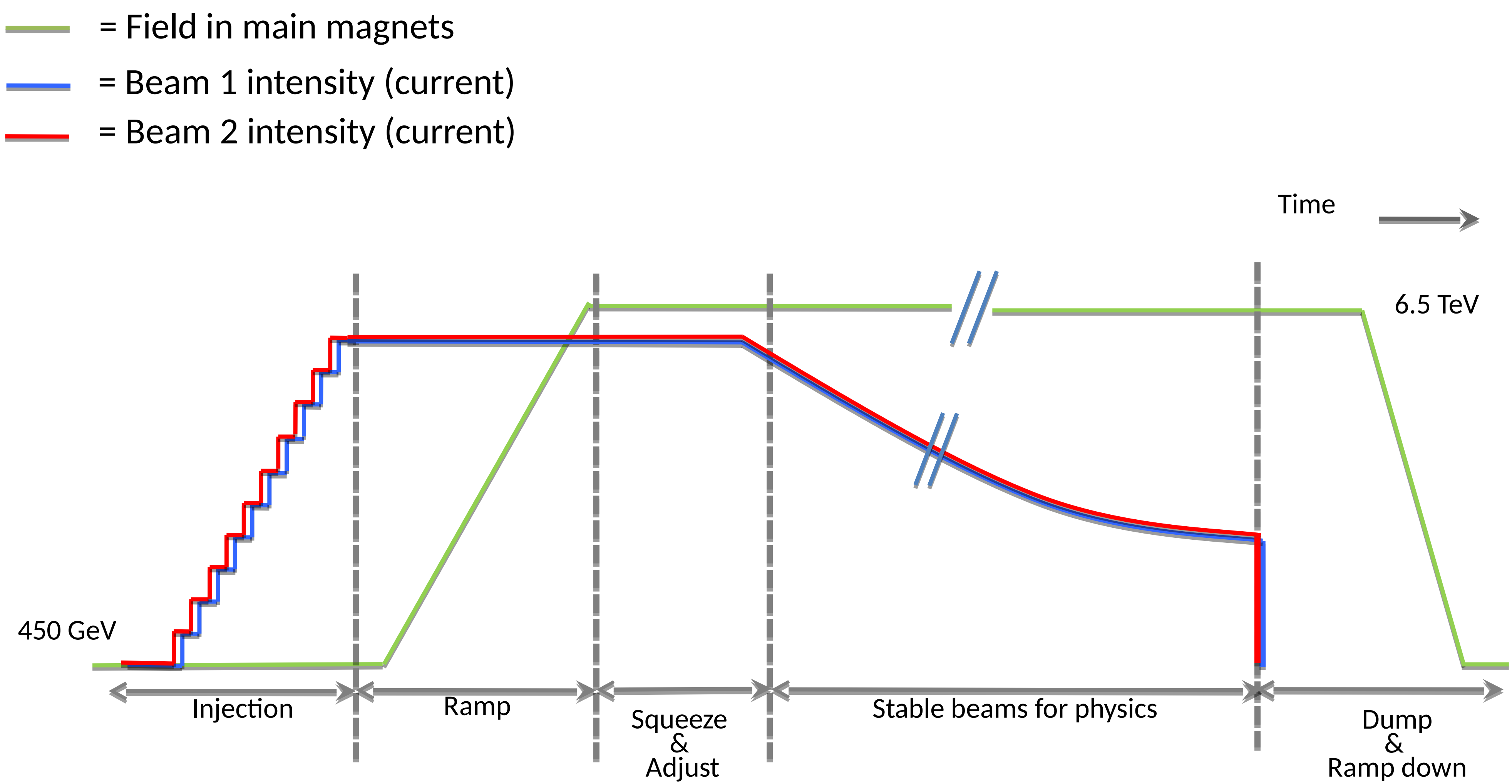
LHC (2008) – up to ~7 TeV



Injection Cycle



LHC Operational Cycle



Typical times for a good cycle in 2018:

~1 hour 20min 1/2 hour ~12 hours ~1 hour

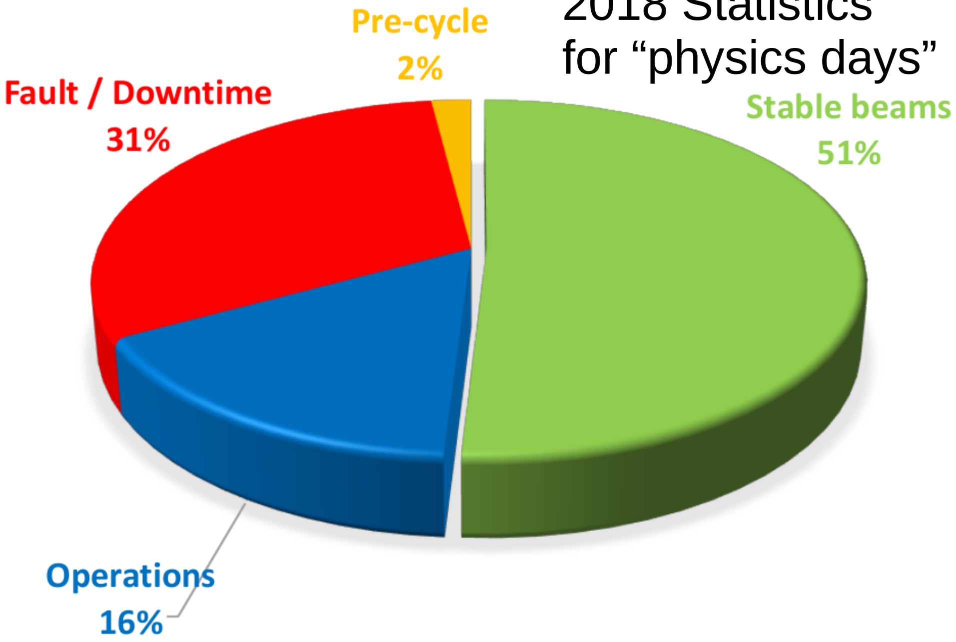
LHC Operations

- Ideally LHC would be in continuous cycle of stable beam and refilling
  - Up to 80% of time in collisions
- Quite frequently interrupted
  - Component failures, lightning, water leaks, animals, ...
  - No single major cause in 2018, but more interruptions from injectors
- Do still get very good uptime

18kV transformer failure for PS

SPS magnet being replaced

2018 Statistics for “physics days”



Luminosity

For us, the key performance is rate of collisions (luminosity)

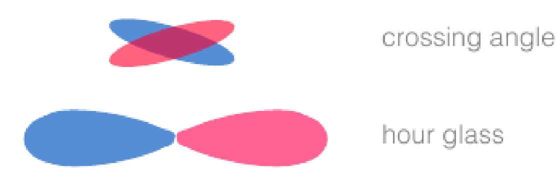
#Physics events = σ(√s) x ∫ L *dt*

#protons/bunch (1.1-1.4x10^{11} p)

#bunches (up to 2808)

Revolution frequency (11.245 kHz)

Geometric reduction factor (0.3-1)



$$L = \frac{N^2 n_b f}{4\pi\sigma_x^*\sigma_y^*}F = \frac{N^2 n_b f\gamma}{4\pi\varepsilon_n\beta^*}F$$

Increases with beam energy

Beam sizes at interaction point (10-20μm)

Normalized emittance (1.8-3.75μm)

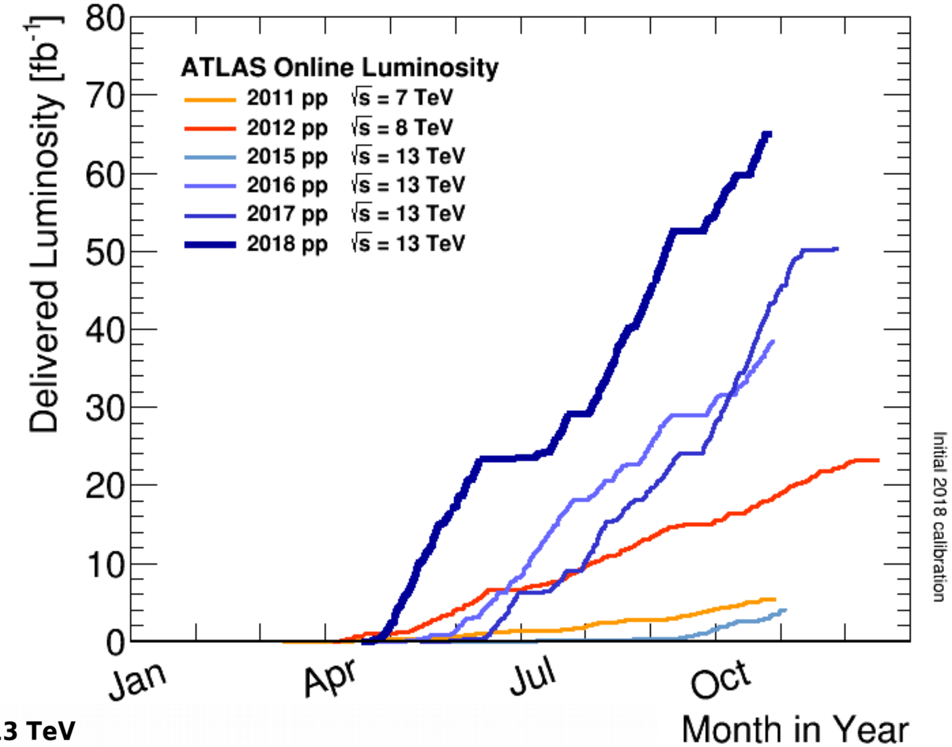
Beta function at interaction point (25cm-2.5km)

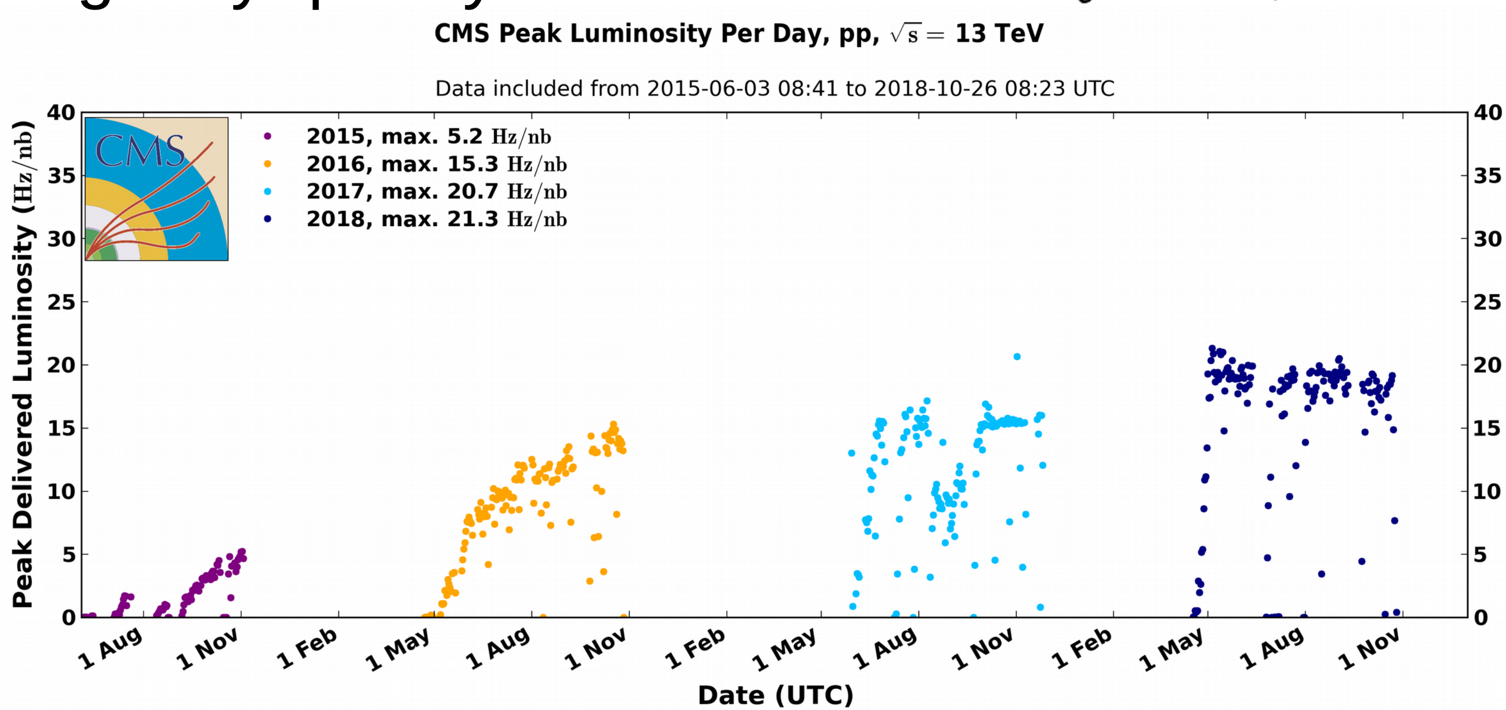
Luminosity Evolution

LHC has worked superbly, breaking records every year

Design luminosity reached in 2016, double design in 2017 and regularly at double in 2018

Integrated luminosity also rising very quickly





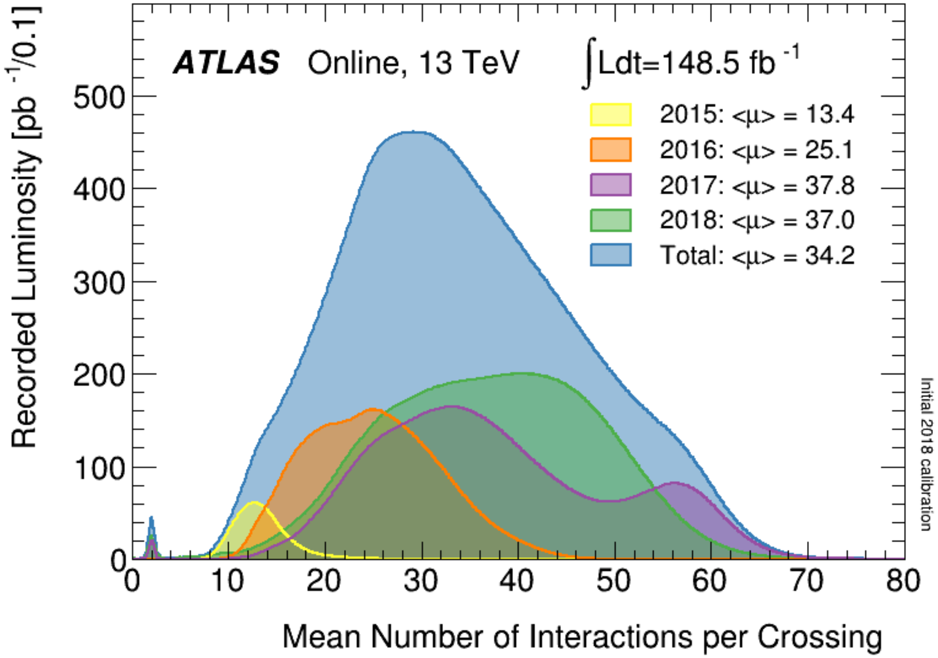
Pile-up Interactions

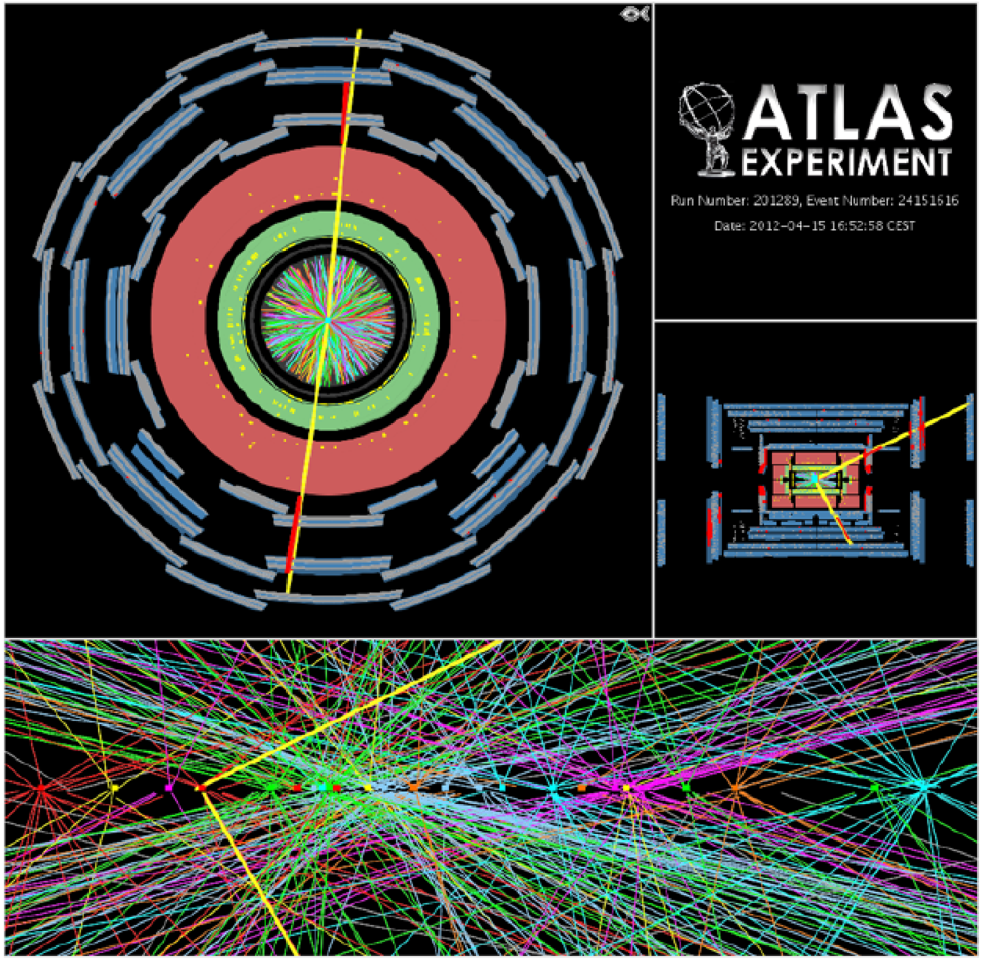
Down-side to high luminosity:
multiple simultaneous interactions per crossing (pile-up)

$$\mu = \frac{L\,\sigma_{inel}}{n_b\, f}$$

25 collisions for design 10^{34} cm^{-2}s^{-1} and 2808 bunches

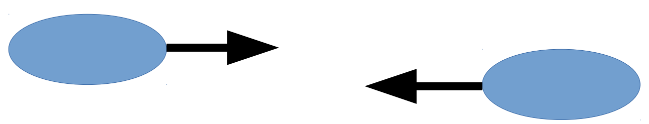
Introduces potential confusion and performance degradation as not all particles are coming from collision of interest



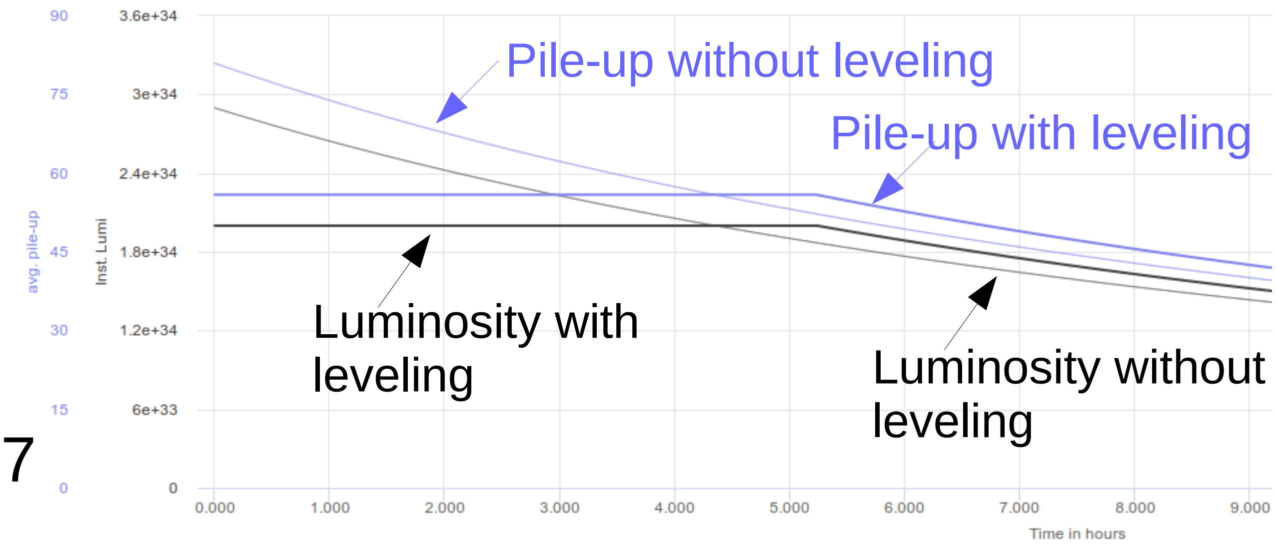


Luminosity Leveling

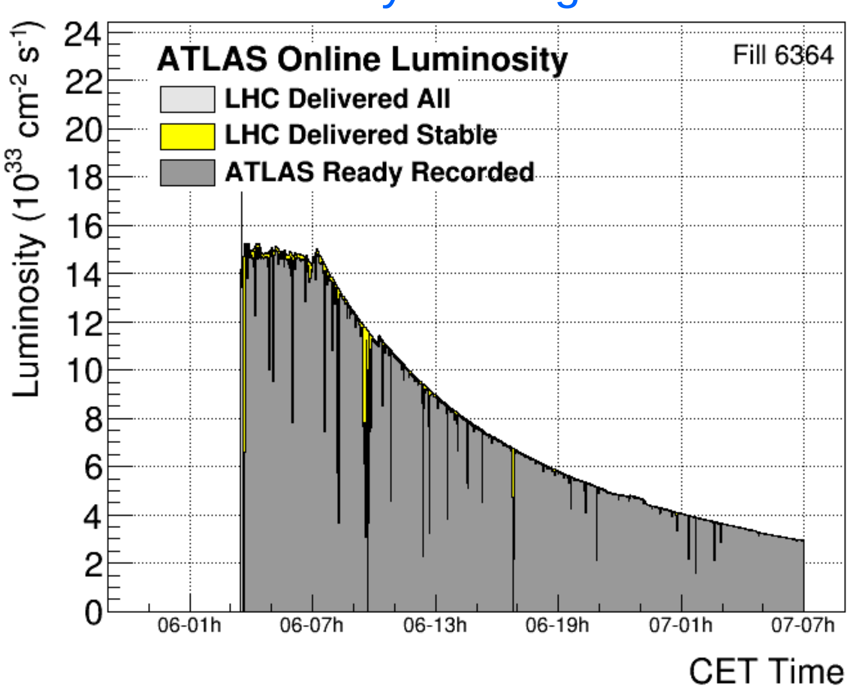
If pile-up too high, can do “luminosity leveling” by separating beams:



Used extensively in 2017



Luminosity leveling in 2017



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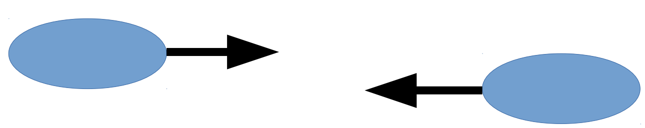

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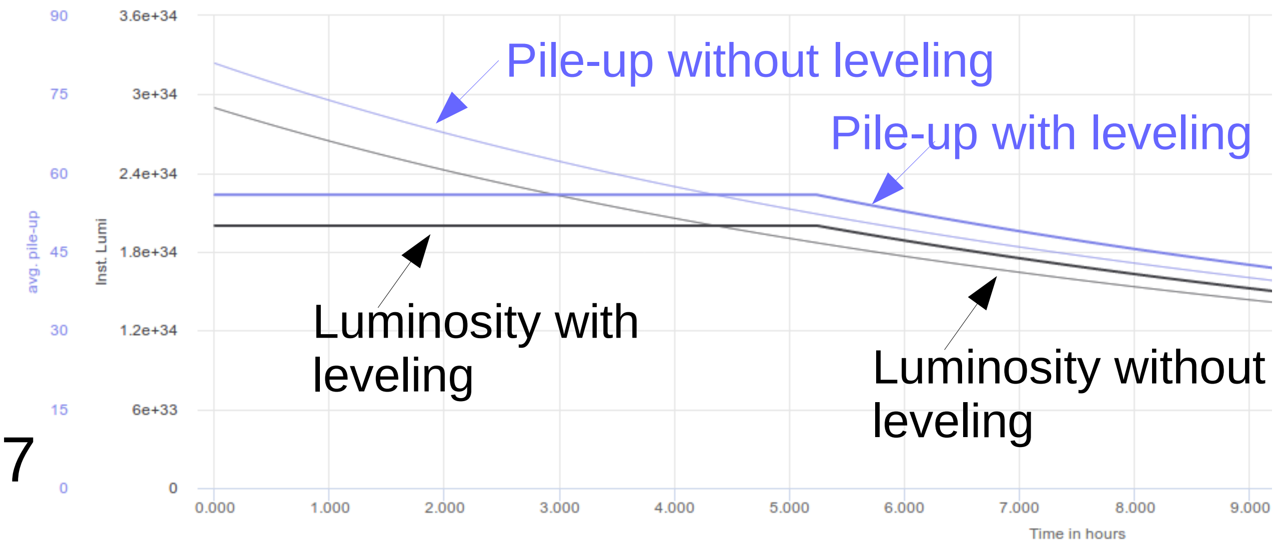
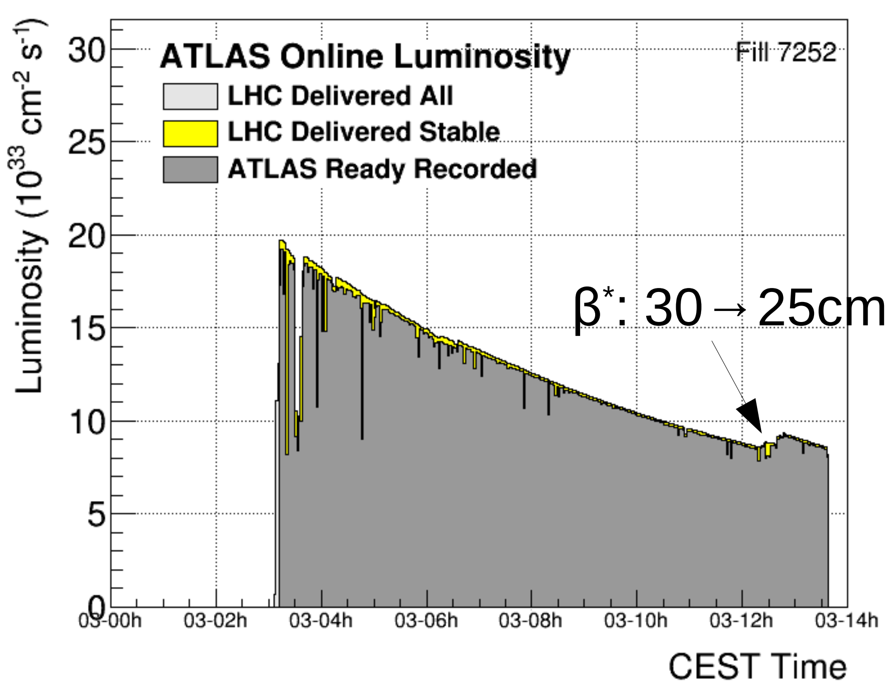


Alternative is to start with higher β* and reduce it when less protons left

β* leveling used in 2018:

30cm→27cm→25cm (small gain)

Luminosity leveling in 2018



Luminosity Leveling

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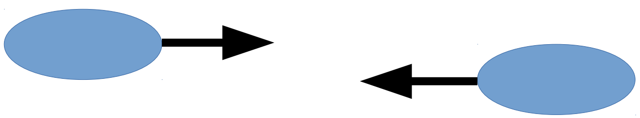
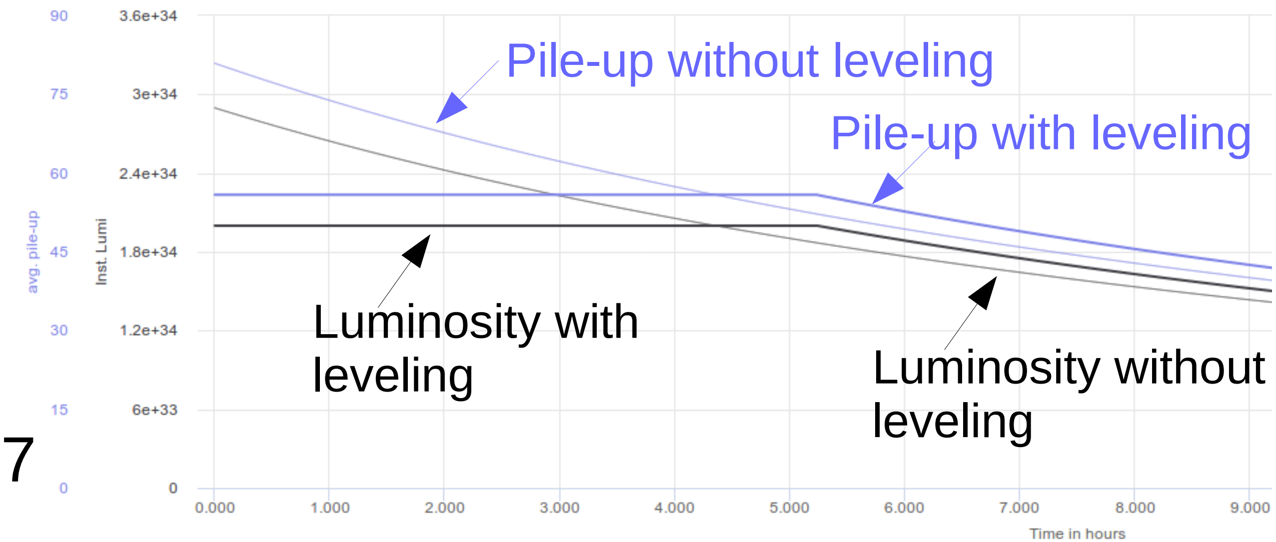


Used extensively in 2017



Alternative is to start with higher β* and reduce it when less protons left

β* leveling used in 2018:

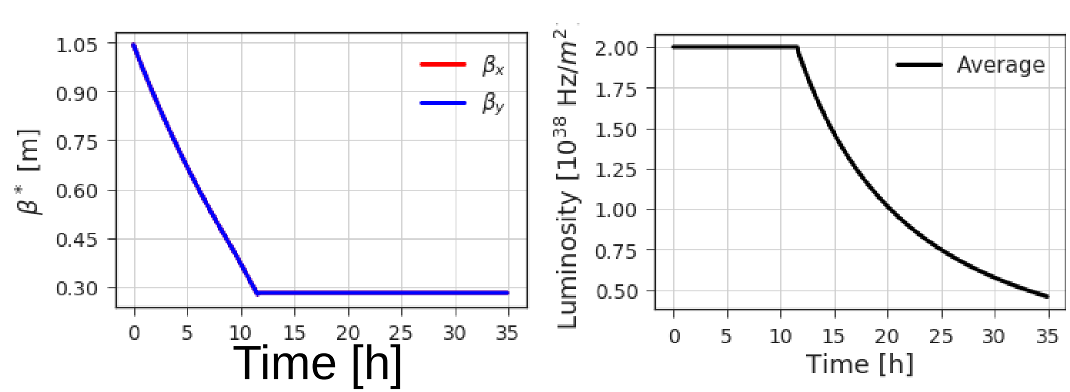
30cm→27cm→25cm (small gain)

Current plan for 2021-2023 has extensive use of β* leveling:

150 cm → 28cm (many steps)

β* leveling safer for avoiding too high peak luminosity

Luminosity leveling in Run-3



Run-3 Expectations

- Injectors doing major upgrades in this shutdown
  - Also upgrades in LHC, primarily to go 14 TeV collision energy
- LHC Run-3 configuration still under study
  - Aim to make maximum use of upgraded injectors
  - Expect baseline to be settled by end of this year

- Possible integrated luminosity in Run-3:
  - 2021: 10-20 fb^{-1}, (large uncertainty from injector upgrade)
  - 2022: up to 85 fb^{-1}
  - 2023: up to 100 fb^{-1}
  - 2024?: up to 100 fb^{-1}?

Not official projections!
Official target is still 150 fb^{-1} over 3 years
Will change over next year

Welcome to ATLAS
Enjoy and have fun

Additional material:

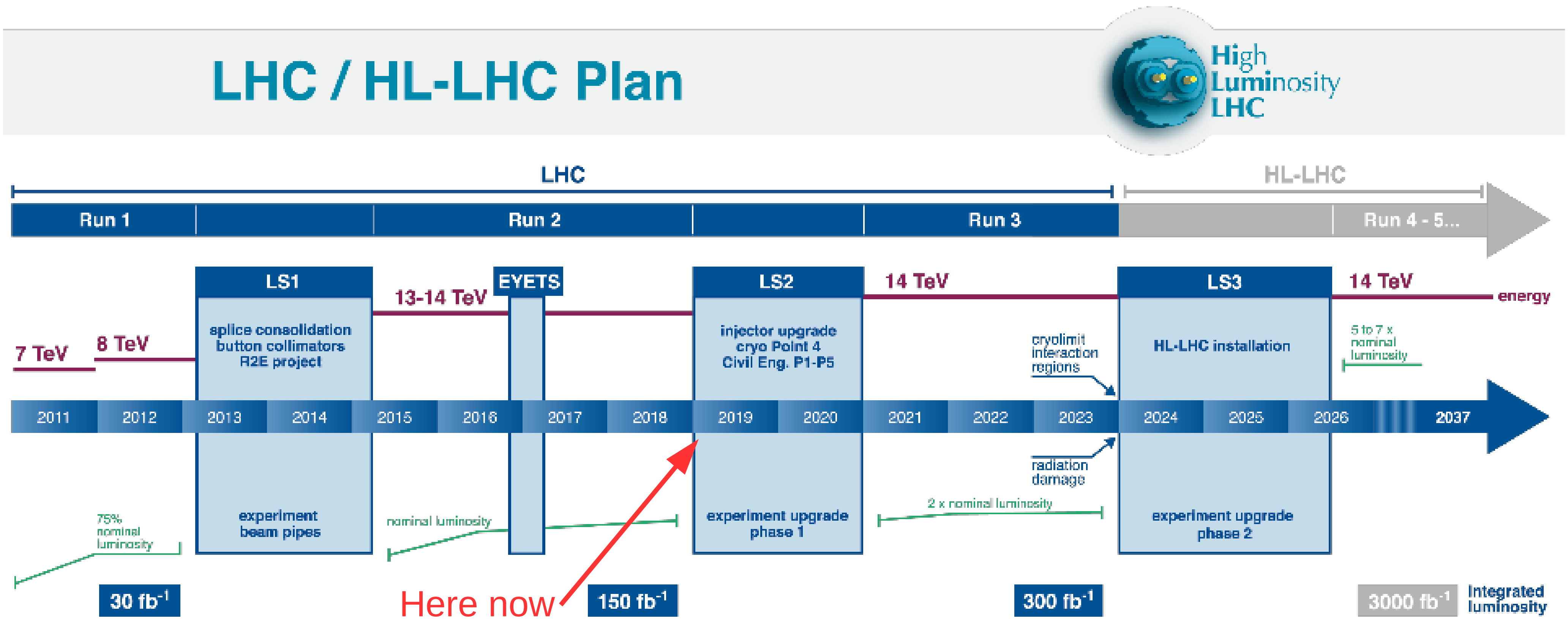
HL-LHC: Mike Lamont Summer student lecture (2017):
https://indico.cern.ch/event/634016/attachments/1491712/2319041/HL-LHC-SummerStudents-July17.pdf

Hadron colliders: Rende Steerenberg CERN/Fermilab summer school (2017):
https://indico.cern.ch/event/598530/contributions/2547206/attachments/1516215/2366657/HadronAcc-1_2017.pdf
https://indico.cern.ch/event/598530/contributions/2547240/attachments/1517505/2368925/HadronAcc-2_2017.pdf

Backup

HL-LHC Upgrade Plans

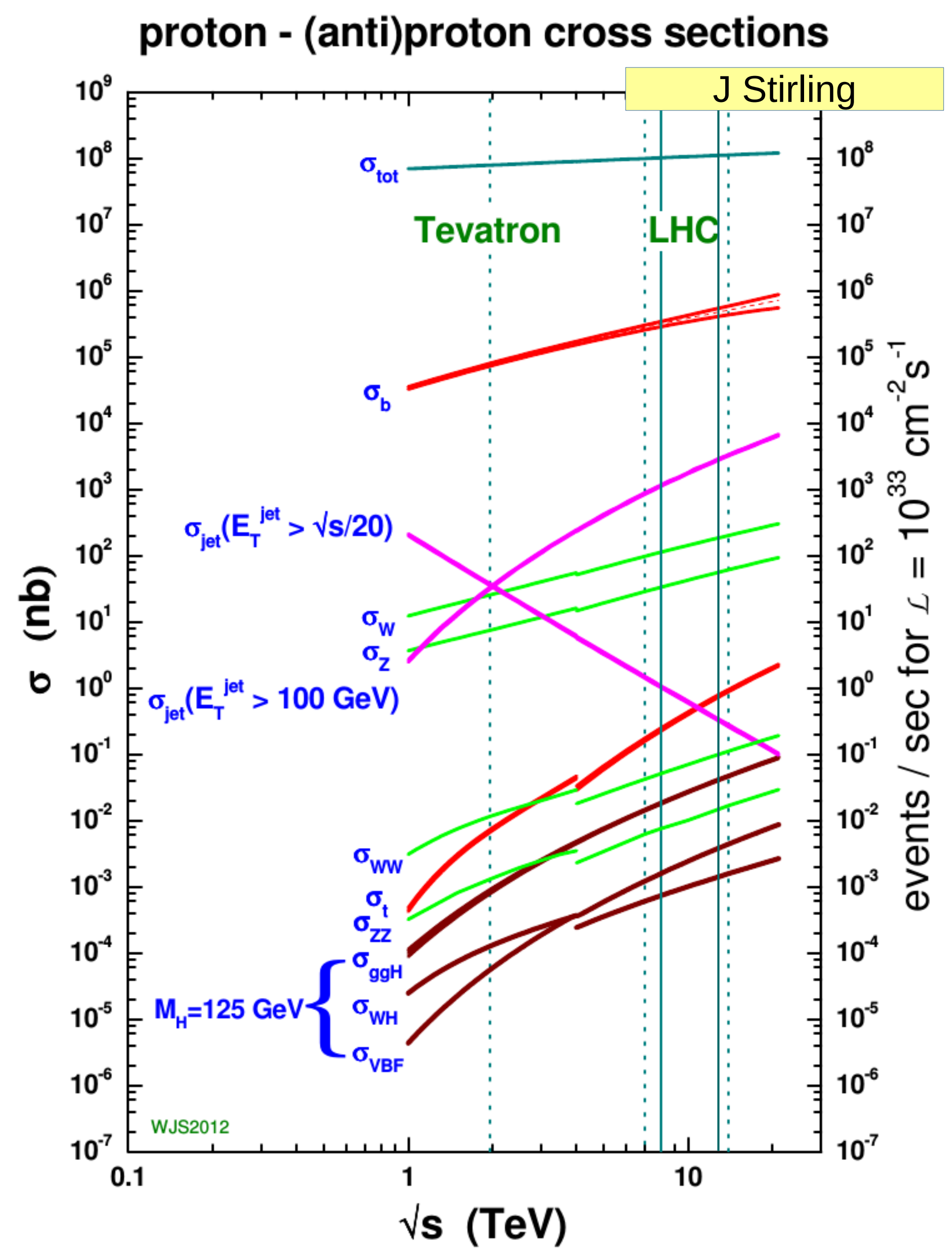
- LHC to deliver >300 fb^{-1} by 2023 (end of Run-3)
- HL-LHC goal is deliver 3000 fb^{-1} in 10 years
  - Implies integrated luminosity of 250-300 fb^{-1} per year
  - Requires peak luminosities of 5-7x10^{34} $cm^{-2}s^{-1}$ while using luminosity leveling (3-5 hours at peak luminosity)
- Design for "ultimate" performance 7.5x10^{34} $cm^{-2}s^{-1}$ and 4000 fb^{-1}



Actual: 160 (190) fb^{-1} in Run-2 (total)

Collision Energy and Luminosity

- Particle production in LHC driven by two parameters
  - Center-of-mass energy ($\sqrt{s}$)
    – sets the cross-section (σ)
    (probability of interaction)
  - Luminosity (L)
    – measure of collision rate



- Instantaneous production rate:

  Rate = $\sigma(\sqrt{s})$ x L

  [10^{34} cm^{-2}s^{-1}]

  [barn = 100 fm^2 = 10^{-24} cm^2]
  [femtobarn = 10^{-39} cm^2]

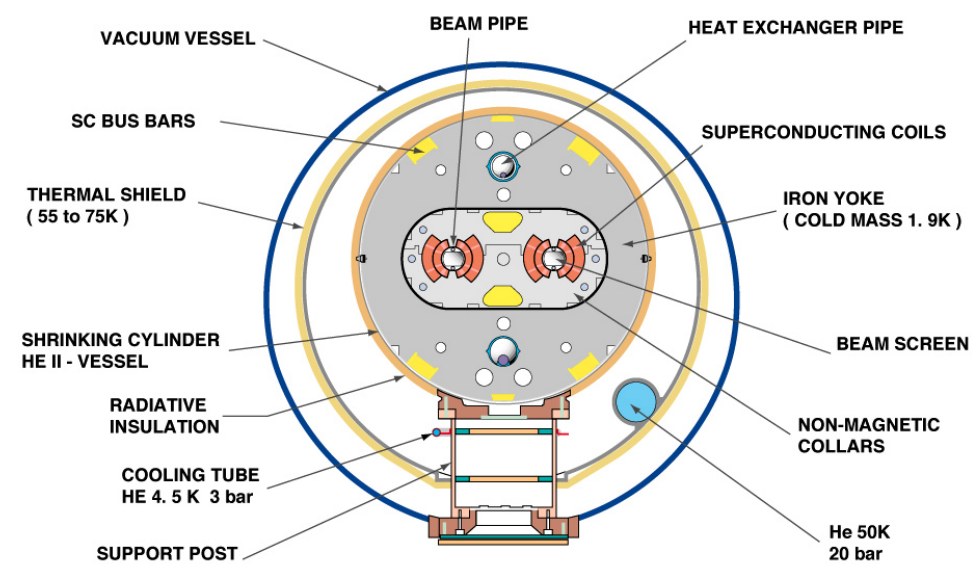
- Integrated rate most important:

  Events = $\sigma(\sqrt{s})$ x $\int L\, dt$

  [fb^{-1}]

Collision Energy

- Center-of-mass energy is limited by bending power in main dipole magnets
  - Superconducting magnets producing 8.3 T at 11,850 A



Not yet at design field/energy

- Started at $\sqrt{s}$=7 TeV
- Now at $\sqrt{s}$=13 TeV after safety upgrade in 2013/14
- Design is $\sqrt{s}$=14 TeV and target for 2021 and beyond
- Ultimate could be $\sqrt{s}$=15.4 TeV

LHC Collimators

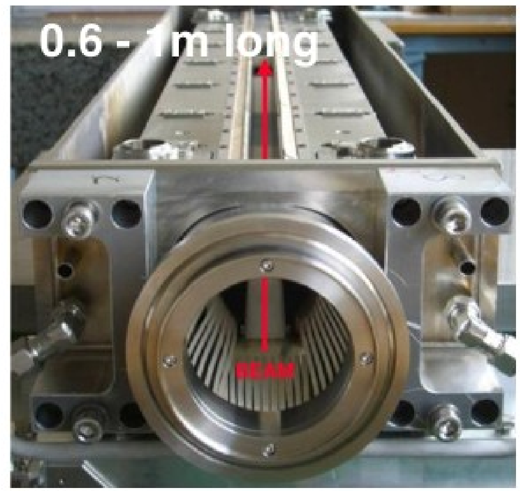
Collimator Design

Two parallel jaws in a vacuum tank at different orientations.

Jaw material depends on its functionality:

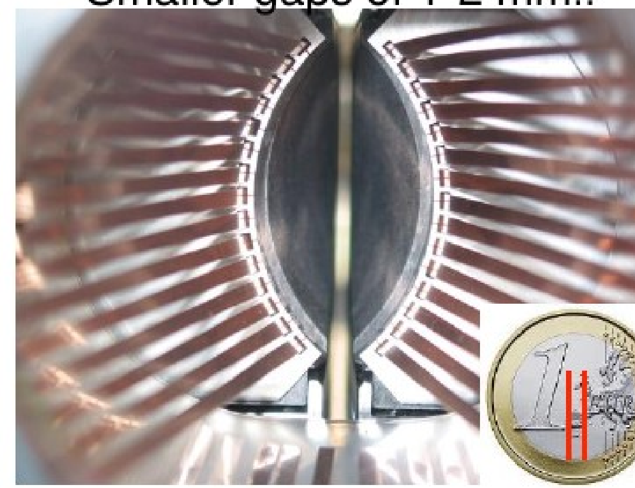
- **Carbon** (primary and secondary collimators)
- **Copper and Tungsten** (absorbers and tertiary collimators)

Movable jaws, controlling **gap and jaw angle with precision of 5 microns**

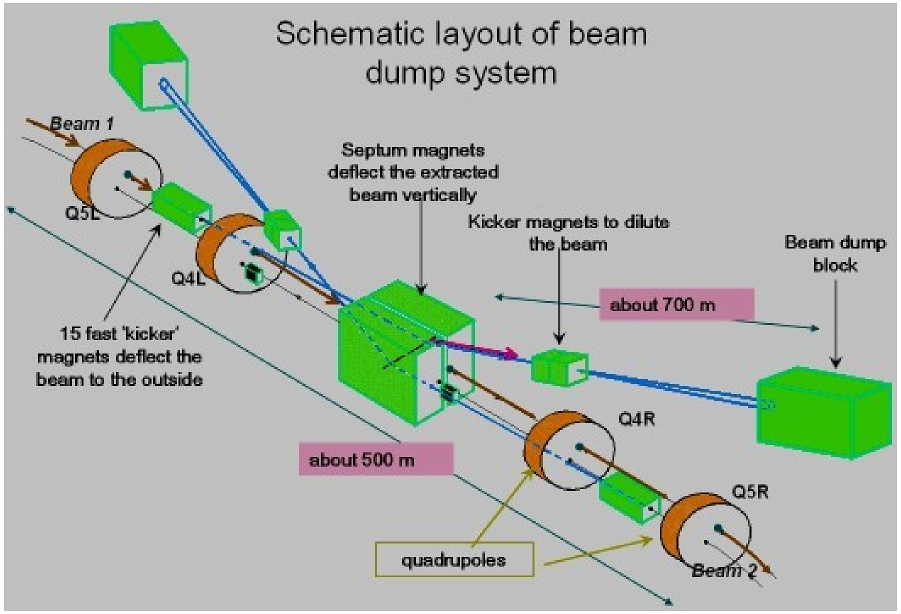


LHC Collimator with vacuum tank opened

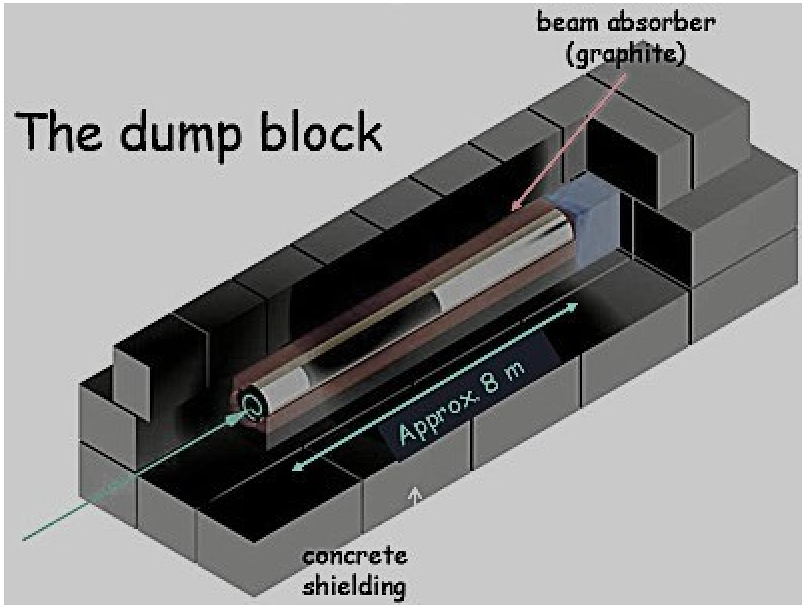
Smaller gaps of 1-2 mm!!



LHC Beam Dump



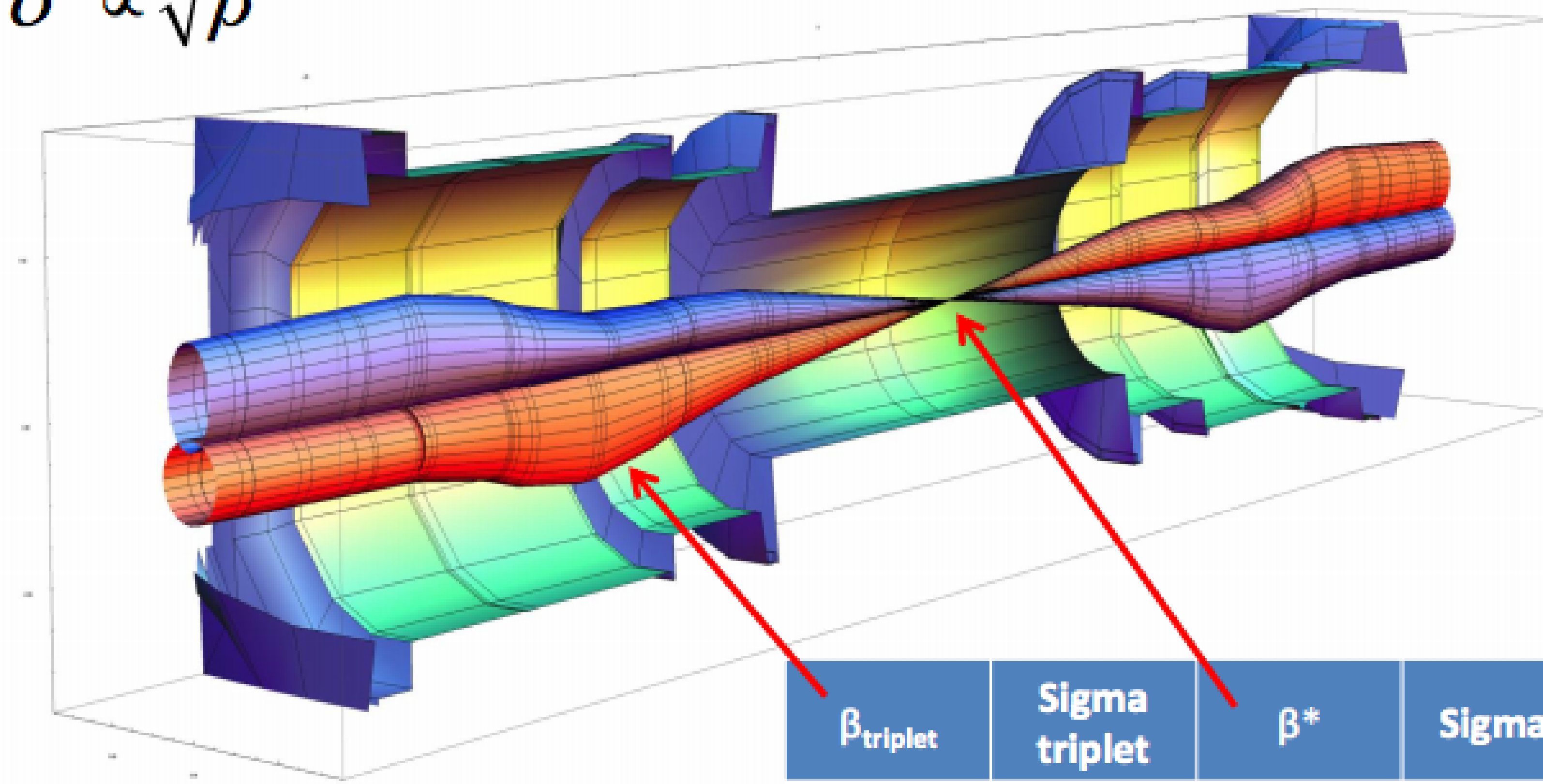
Kicker magnets spread out beam over front surface of beam dump – still gets up to 800°C



β-function and β*

- β-function is envelope function of protons oscillations
  - Set (and changed) by magnet configuration around the ring
- Want smallest possible β at interaction point (β*)
  - Makes for large β at final focusing magnets (triplets)

$$\sigma^* \propto \sqrt{\beta^*}$$

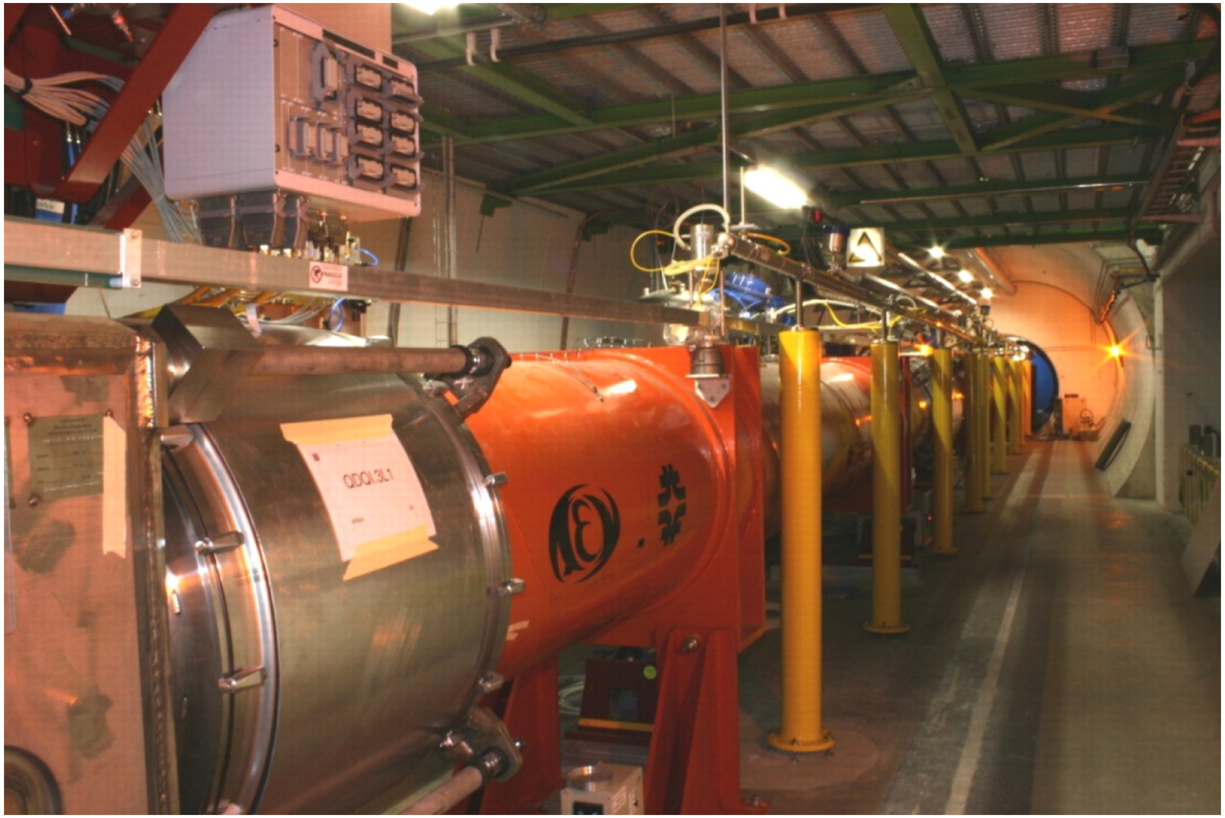


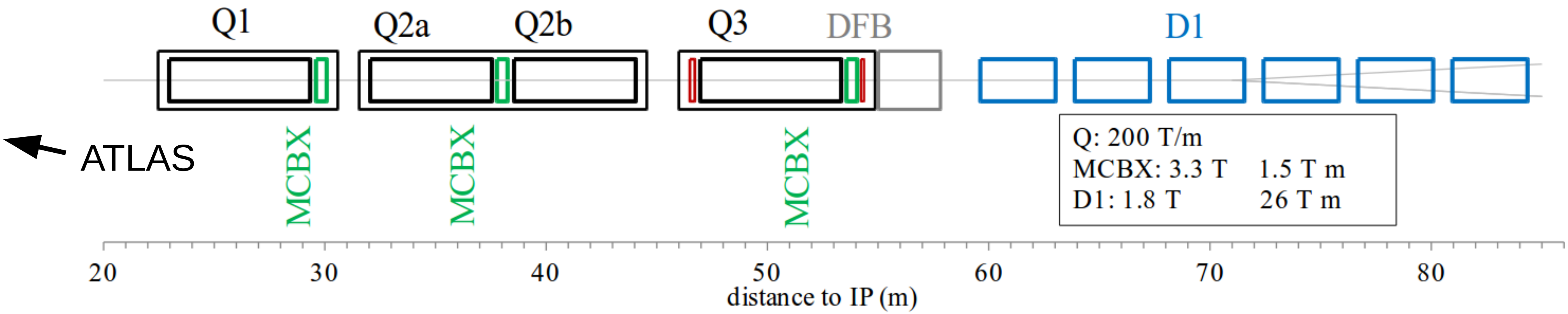
$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

Image courtesy John Jowett

Triplet Magnets

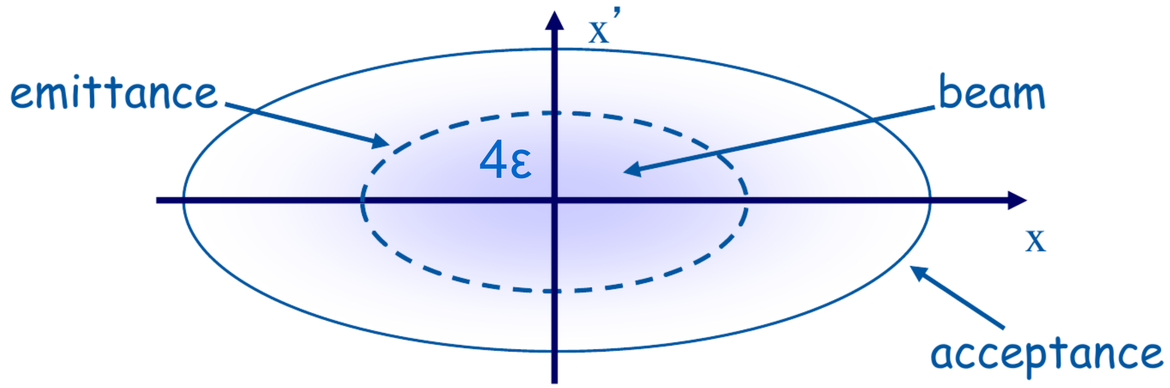
- Focusing for ATLAS done by triplet of quadrupole magnets
- More effective space (aperture) than expected means we can have a lower β*
  - Design: β*=55cm
  - 2017: β*=40→30cm
  - 2018: β*=30→25cm





Emittance

The emittance, ε, is the area of the ellipse, which contains all, or a defined percentage, of the particle phase space
(unit: μm or mm•mrad)



Beam size:
$\sigma_x = \sqrt{\beta_x \varepsilon_x}$

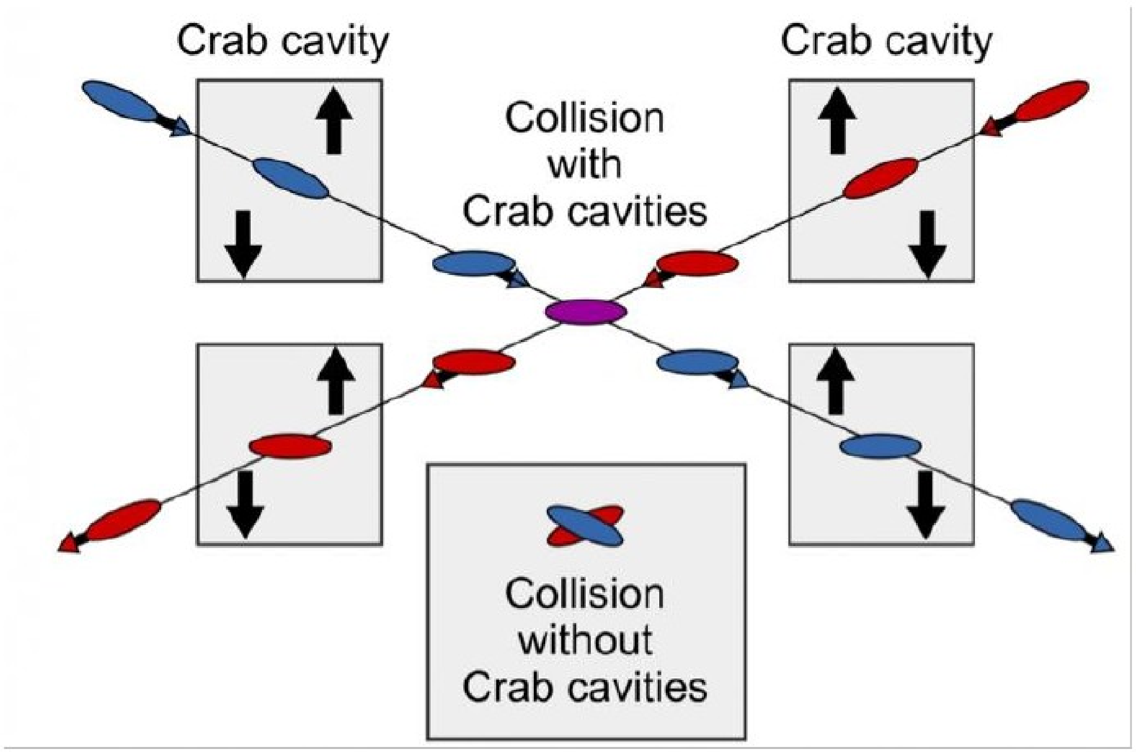
Magnetic fields change phase space shape, but not the area, i.e. the emittance is generally conserved (or grows)

Emittance is reduced with acceleration, so often use normalized emittance $\varepsilon_n = \beta \gamma \varepsilon$ which is constant with acceleration

Normalized emittance is set at formation of bunches

HL-LHC Crab Cavities

Crab cavities reduce effect of geometrical factor by rotating beam in IPs



LHC Page 1 – When Preparing Fill

[**LHC Page 1:** https://op-webtools.web.cern.ch/vistar/vistars.php?usr=LHC1](https://op-webtools.web.cern.ch/vistar/vistars.php?usr=LHC1)

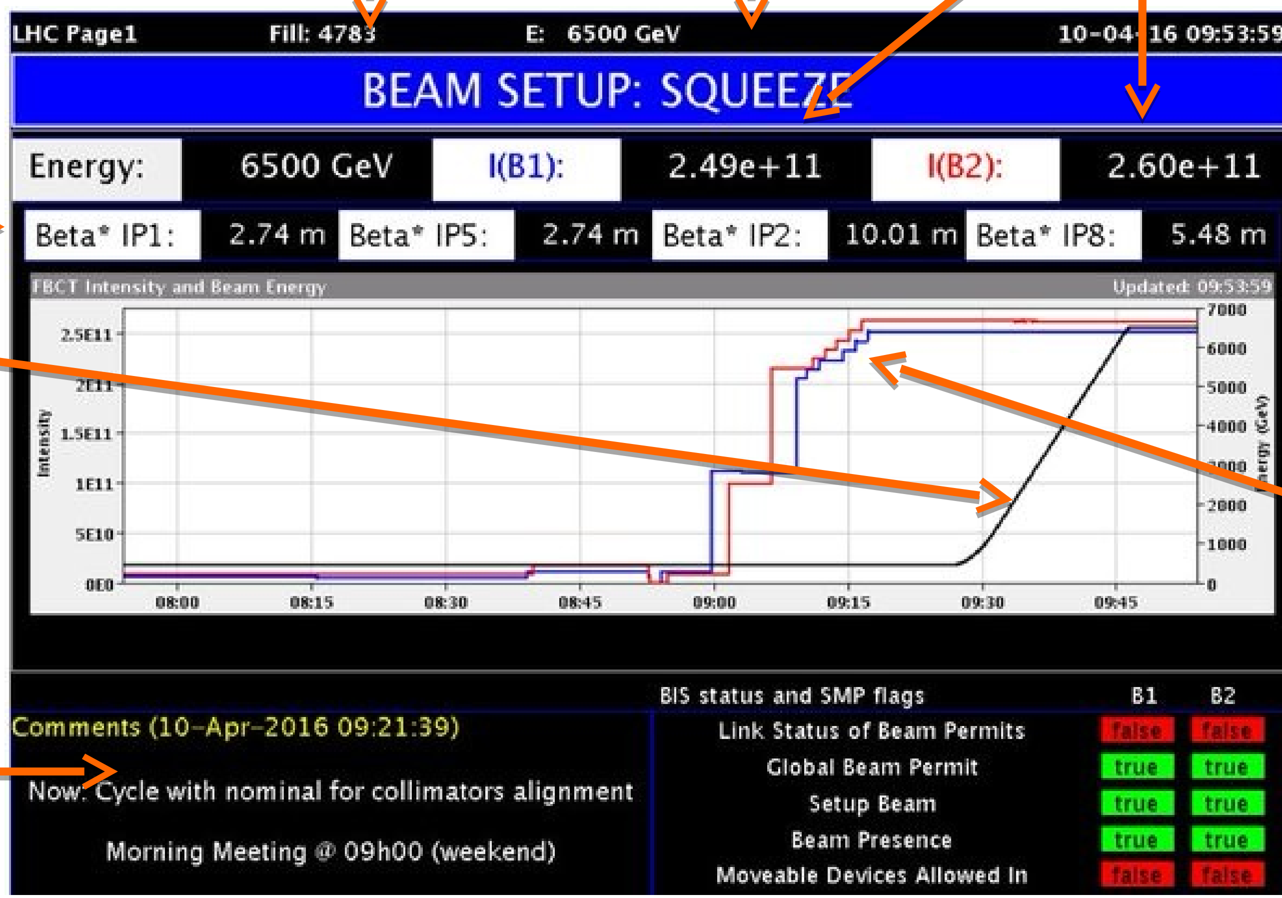
Accelerator mode

Protons per beam

Beam mode

Beta*

Beam energy
(Dipole current)



Beam Intensities
Beam 1
Beam 2

Comment from
Shift crew

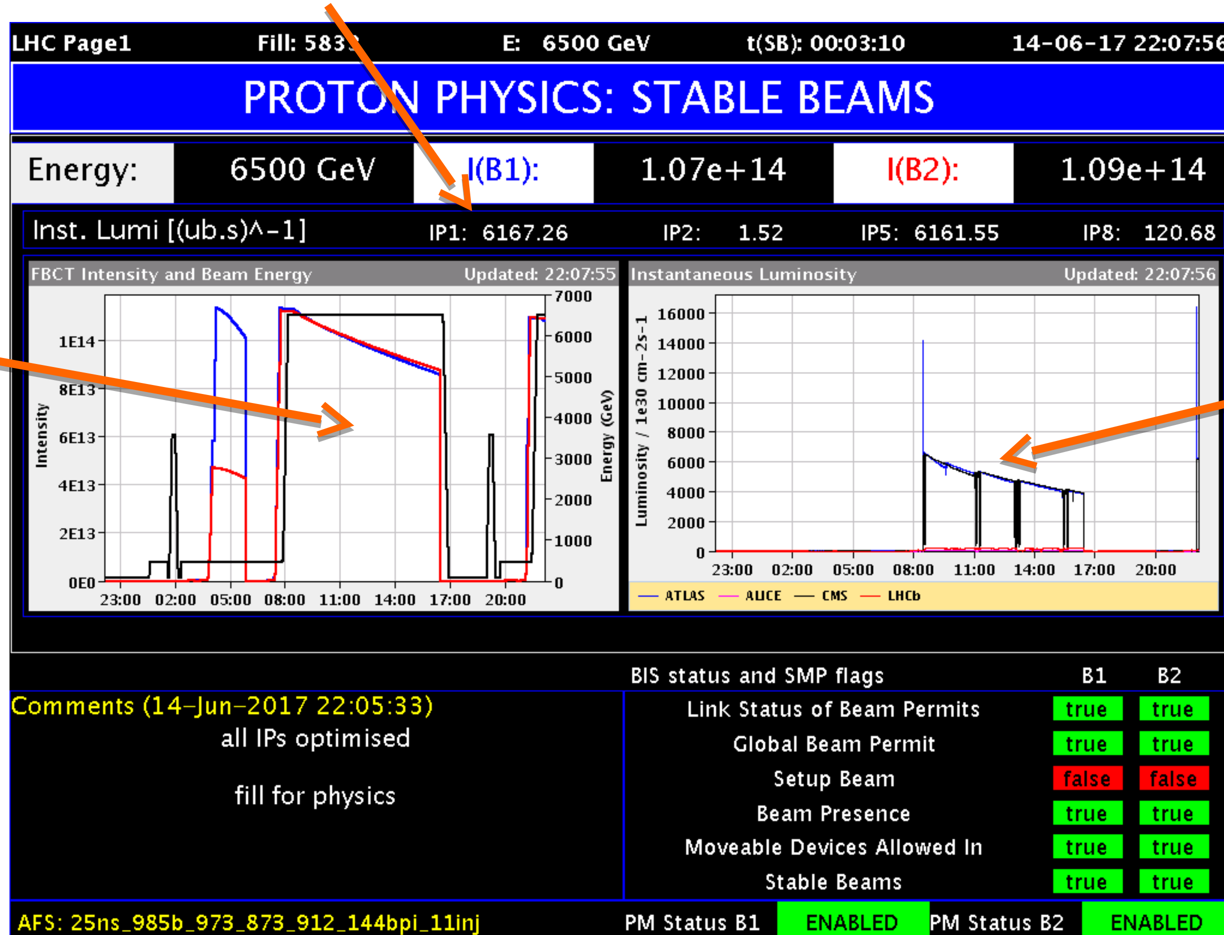
Various Flags

LHC Page 1 – During Stable Beams

LHC Page 1: https://op-webtools.web.cern.ch/vistar/vistars.php?usr=LHC1

ATLAS luminosity

Compressed display of previous slide



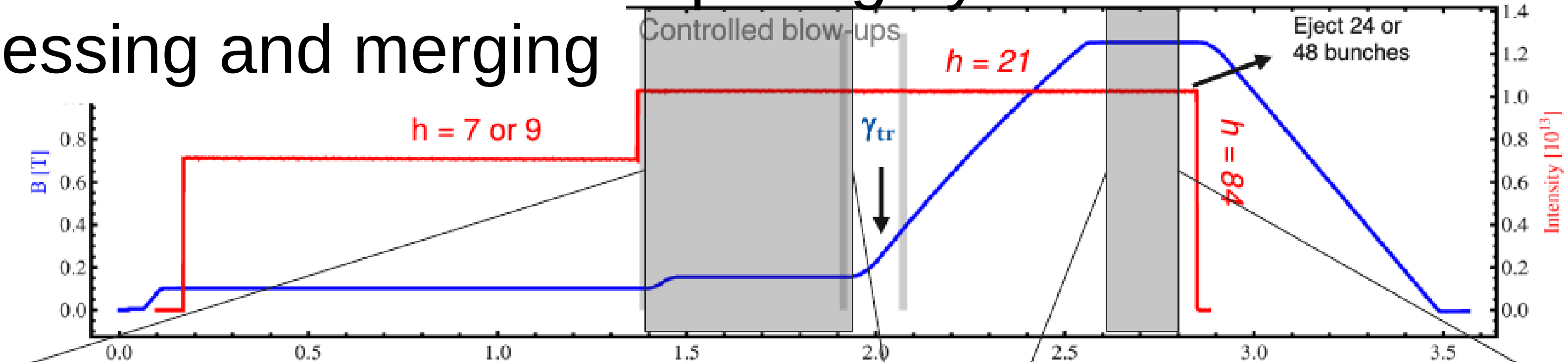
Instantaneous luminosities of experiments

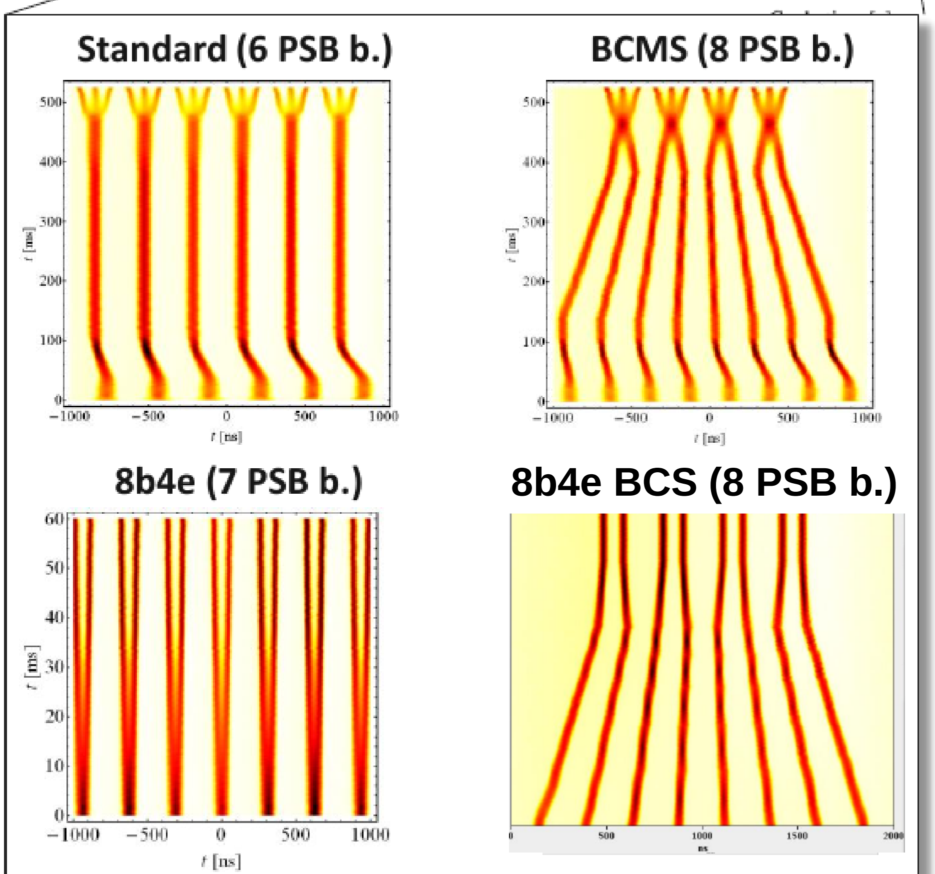
Filling Scheme

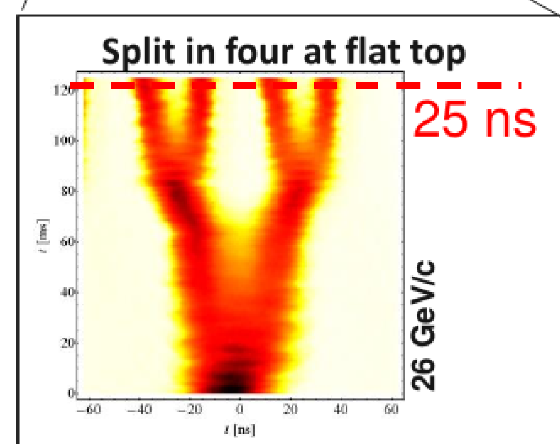
Bunch Compression, Merging and Splitting

Final 25ns bunches formed in PS by splitting PSB bunches

New since 2017: Reduced splitting by compressing and merging





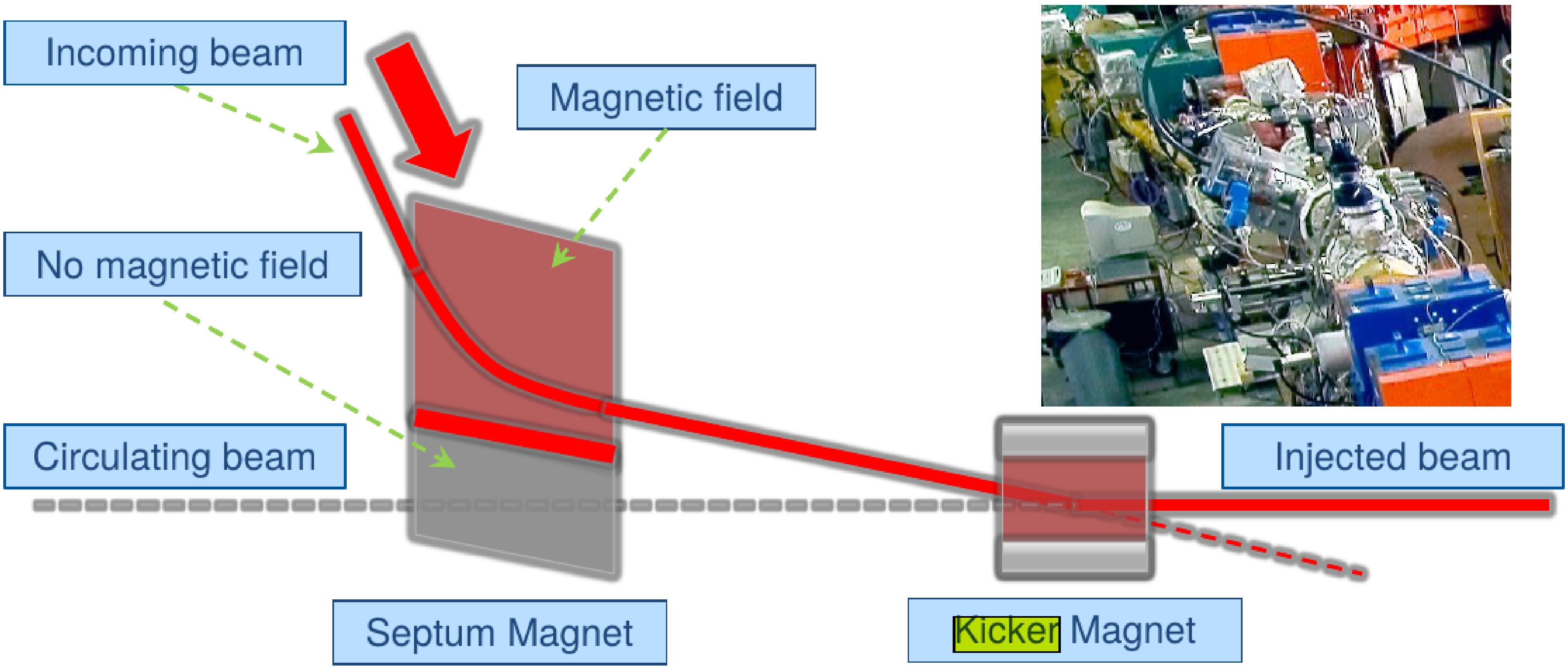


Standard: 72 bunches @ 25 ns (split 12)
BCMS: 48 bunches @ 25 ns (split 6)
8b4e: 4x8 bunches @ 25 ns (split 8)
BCS: 32 bunches @ 25 ns (split 4)

Less splitting → less intensity needed in PSB → lower emittance → **higher lumi**

Bunch Train Formation

- Batches of 32-72 bunches separated by 25ns in PS
- Multiple batches needed to fill SPS (and later LHC)
- Space needed between batches for safe injection:



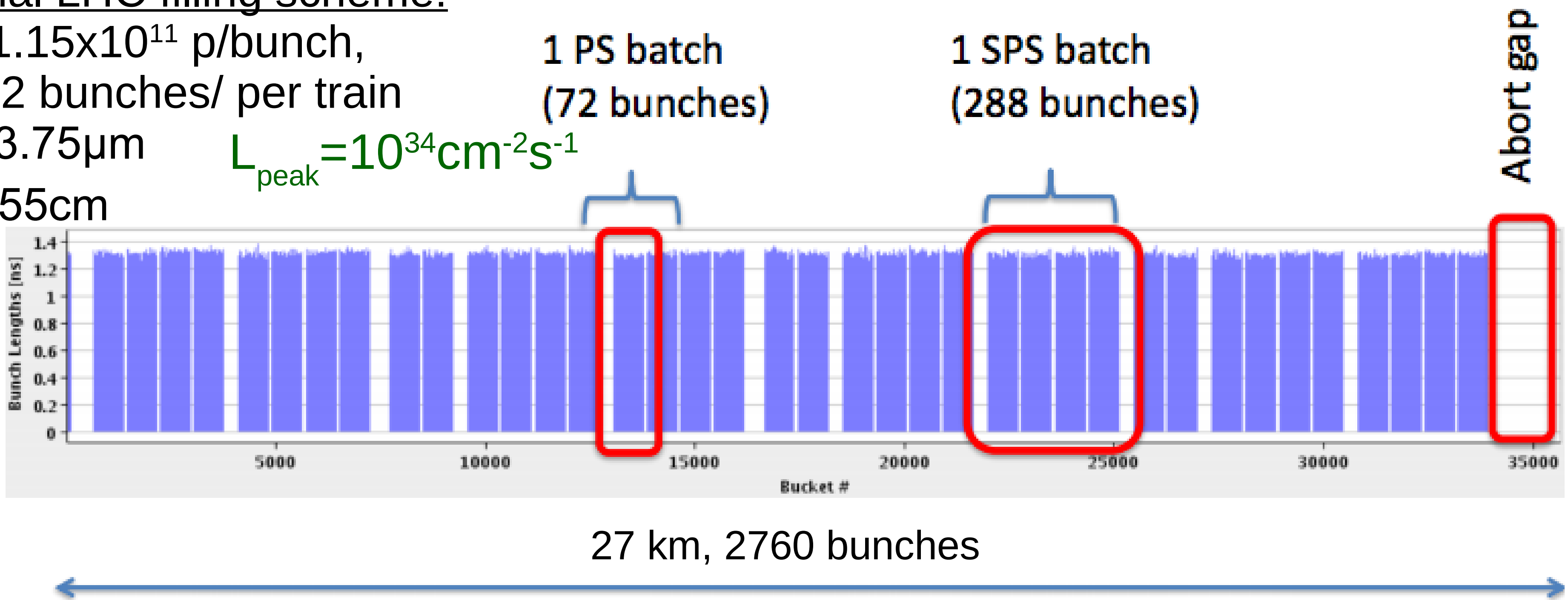
SPS gap: 200 ns
LHC gap: 800 ns

LHC Bunch Train Options

Nominal LHC filling scheme:

- $N = 1.15 \times 10^{11}$ p/bunch,
- 4x72 bunches/ per train
- $\varepsilon_N = 3.75 \mu m$
- $\beta^* = 55 cm$

$L_{peak} = 10^{34} cm^{-2} s^{-1}$



LHC Bunch Train Options

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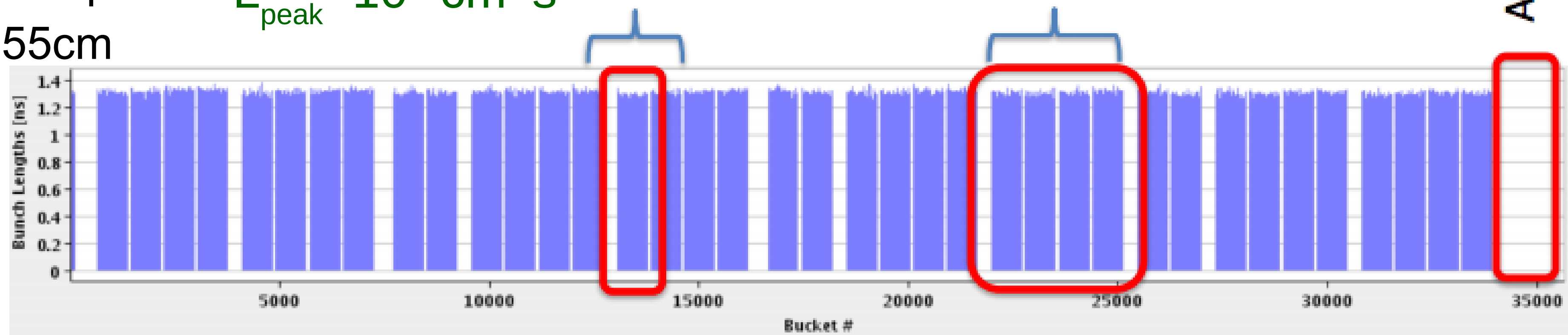
- 4x72 bunches/ per train
- ε_N=3.75µm
- β*=55cm

$L_{peak}=10^{34}cm^{-2}s^{-1}$

1 PS batch (72 bunches)

1 SPS batch (288 bunches)

Abort gap

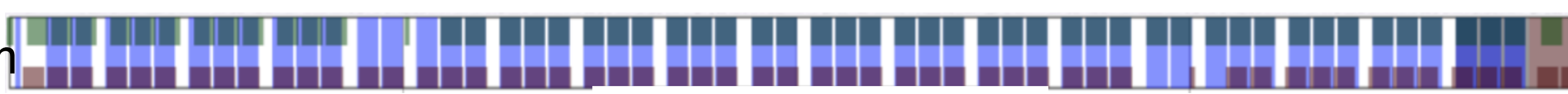


27 km, 2760 bunches

25ns BCMS scheme in 2018:

- N=1.1x10^{11} p/bunch, 3x48 bunches/train
- ε_N=~2.5µm
- β*=25-30cm

$L_{peak}=2.14x10^{34}cm^{-2}s^{-1}$



2556 bunches

LHC Bunch Train Options

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- N=1.15x10^{11} p/bunch,
- 4x72 bunches/ per train
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$L_{peak}=10^{34}cm^{-2}s^{-1}$

1 PS batch (72 bunches)

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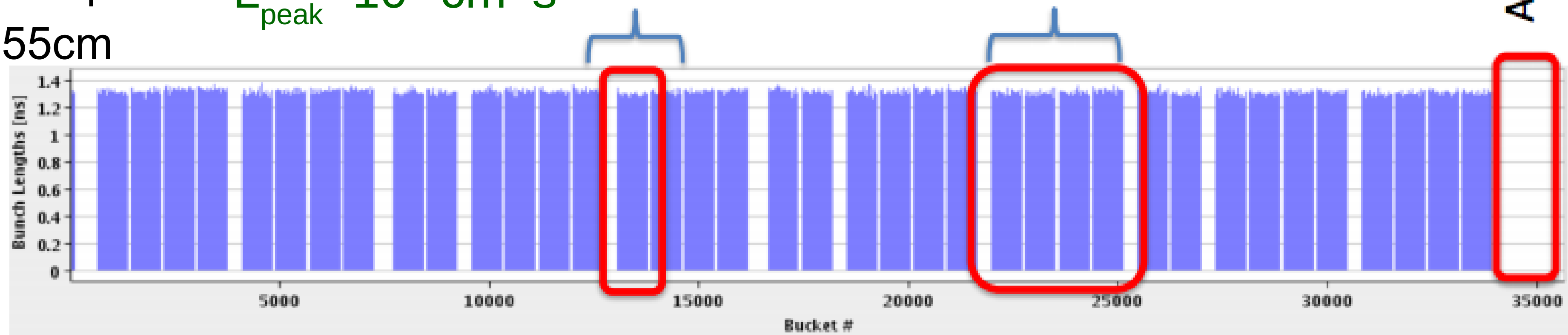

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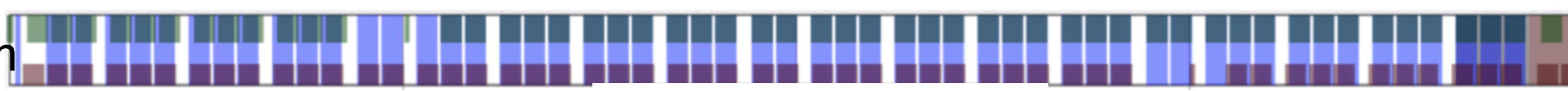
<u>25ns BCMS scheme in 2018:</u>

- N=1.1x10^{11} p/bunch, 3x48 bunches/train
- ε_N=~2.5μm
- β*=25-30cm

$L_{peak}=2.14x10^{34}cm^{-2}s^{-1}$



2556 bunches

<u>25ns BCMS scheme in 2021-2023:</u>

- N=1.4-1.8x10^{11} p/bunch, 5x48 bunches/train
- ε_N=~1.8μm
- β*=28cm

$L_{peak}=3.8-6.4x10^{34}cm^{-2}s^{-1}$

2736 bunches

LHC Bunch Train Options

<u>Nominal LHC filling scheme:</u>

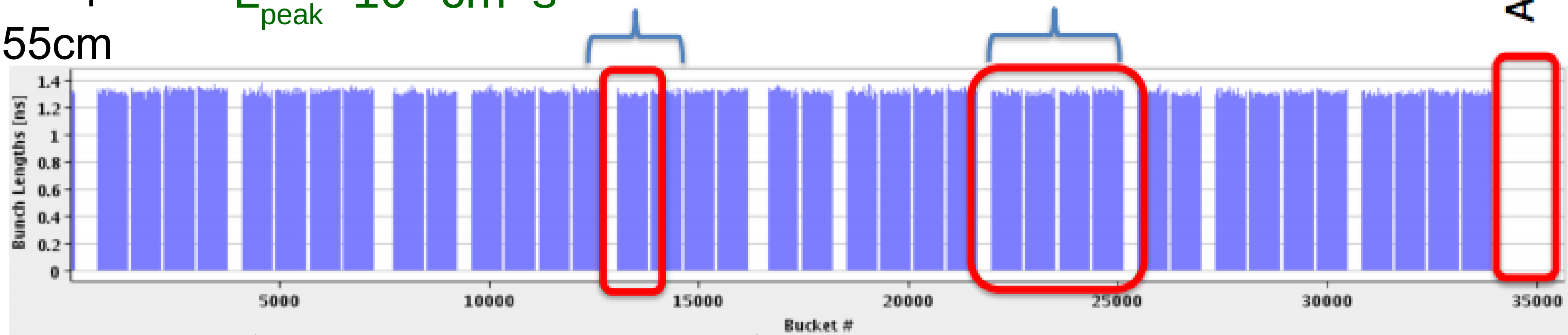
- $N = 1.15 \times 10^{11}$ p/bunch,
- 4x72 bunches/ per train
- $\varepsilon_N = 3.75 \mu m$
- $\beta^* = 55 cm$

$L_{peak} = 10^{34} cm^{-2} s^{-1}$

1 PS batch (72 bunches)

1 SPS batch (288 bunches)

Abort gap

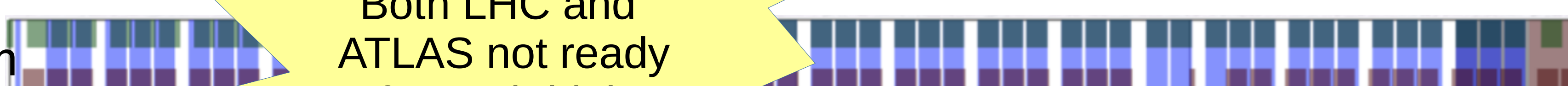


27 km ... 760 bunches

<u>25ns BCMS scheme in 2018</u>

- $N = 1.1 \times 10^{11}$ p/bunch, 3x48 ...
- $\varepsilon_N = \sim 2.5 \mu m$
- $\beta^* = 25\text{-}30 cm$

$L_{peak} = 2.14 \times 10^{34} cm^{-2} s^{-1}$



...nches

<u>25ns BCMS scheme in 20...</u>

- $N = 1.4\text{-}1.8 \times 10^{11}$ p/bun... s/train
- $\varepsilon_N = \sim 1.8 \mu m$
- $\beta^* = 28 cm$

$L_{peak} = 3.8\text{-}6.4 \times 10^{34} cm^{-2} s^{-1}$

2736 bunches

Both LHC and ATLAS not ready for such high luminosity