LHC Description, Performance and Prospects

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Third International Workshop on Recent LHC Physics Results and Related Topics in Tirana

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- The Large Hadron Collider — Introduction and Operational Concepts
- LHC Proton Physics Run 2018
- HL-LHC High Luminosity LHC Upgrade
- CERN's Small Experiments
  - ISOLDE
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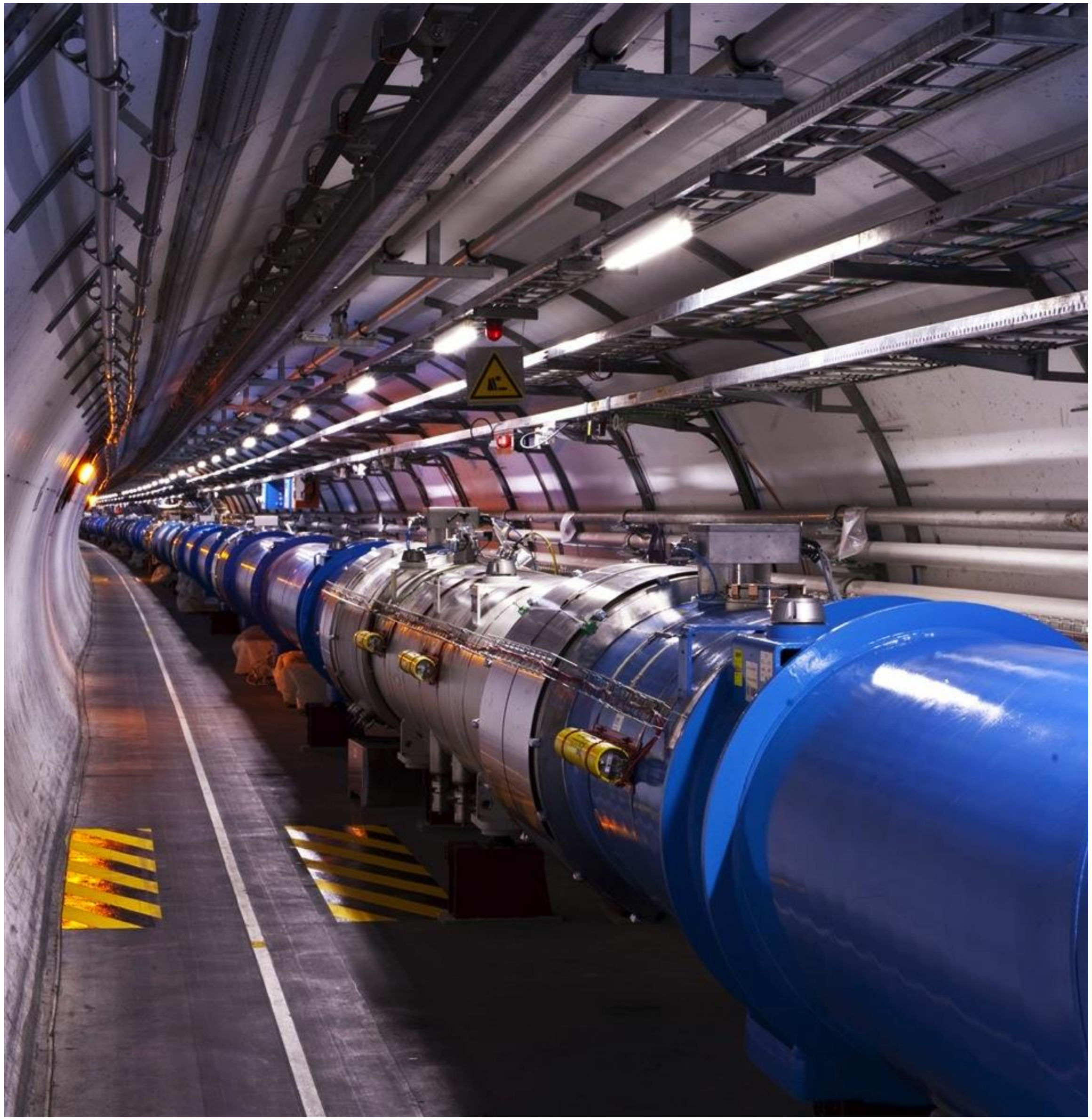
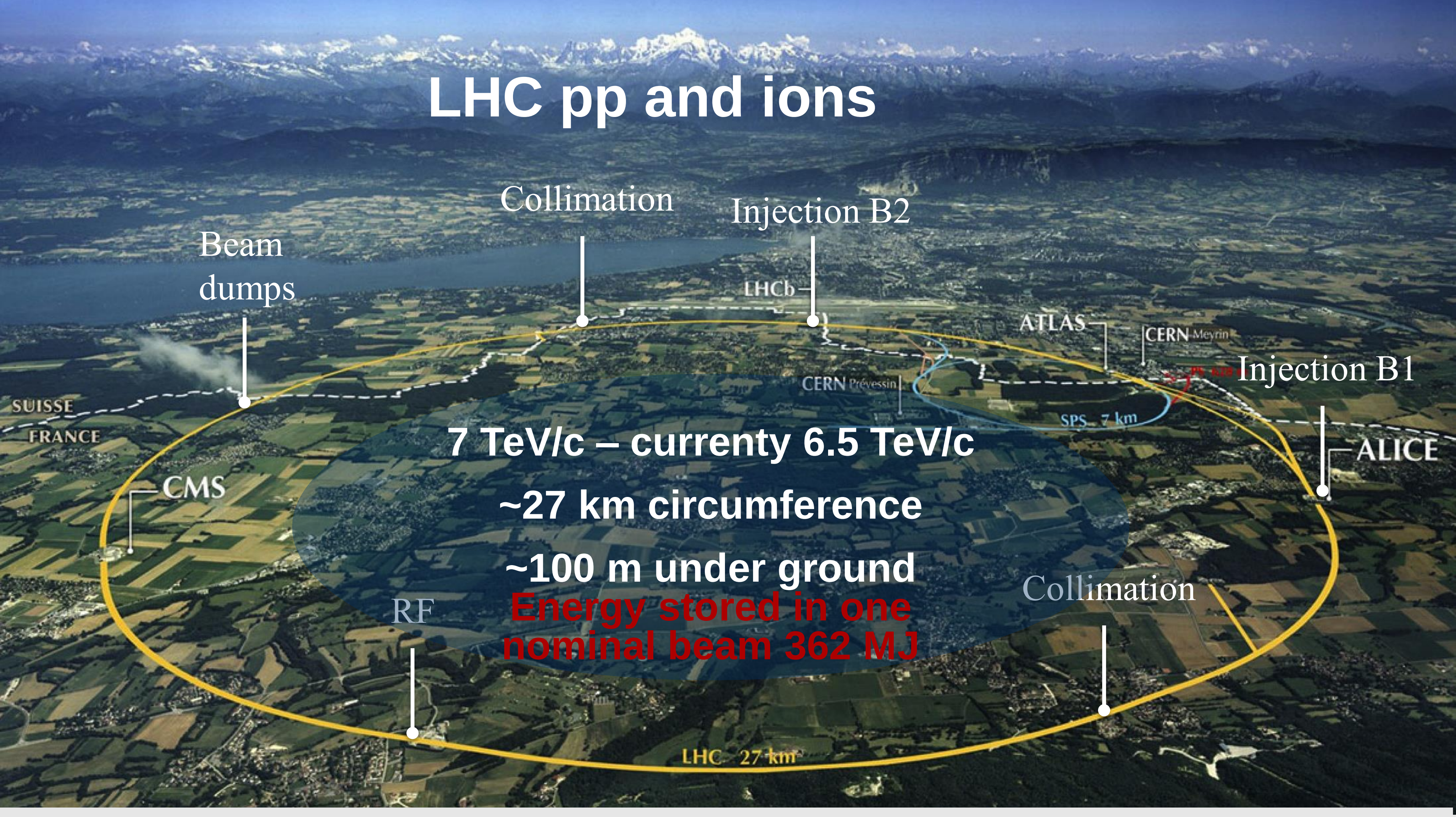


The Large Hadron Collider — CERN’s Flagship Accelerator

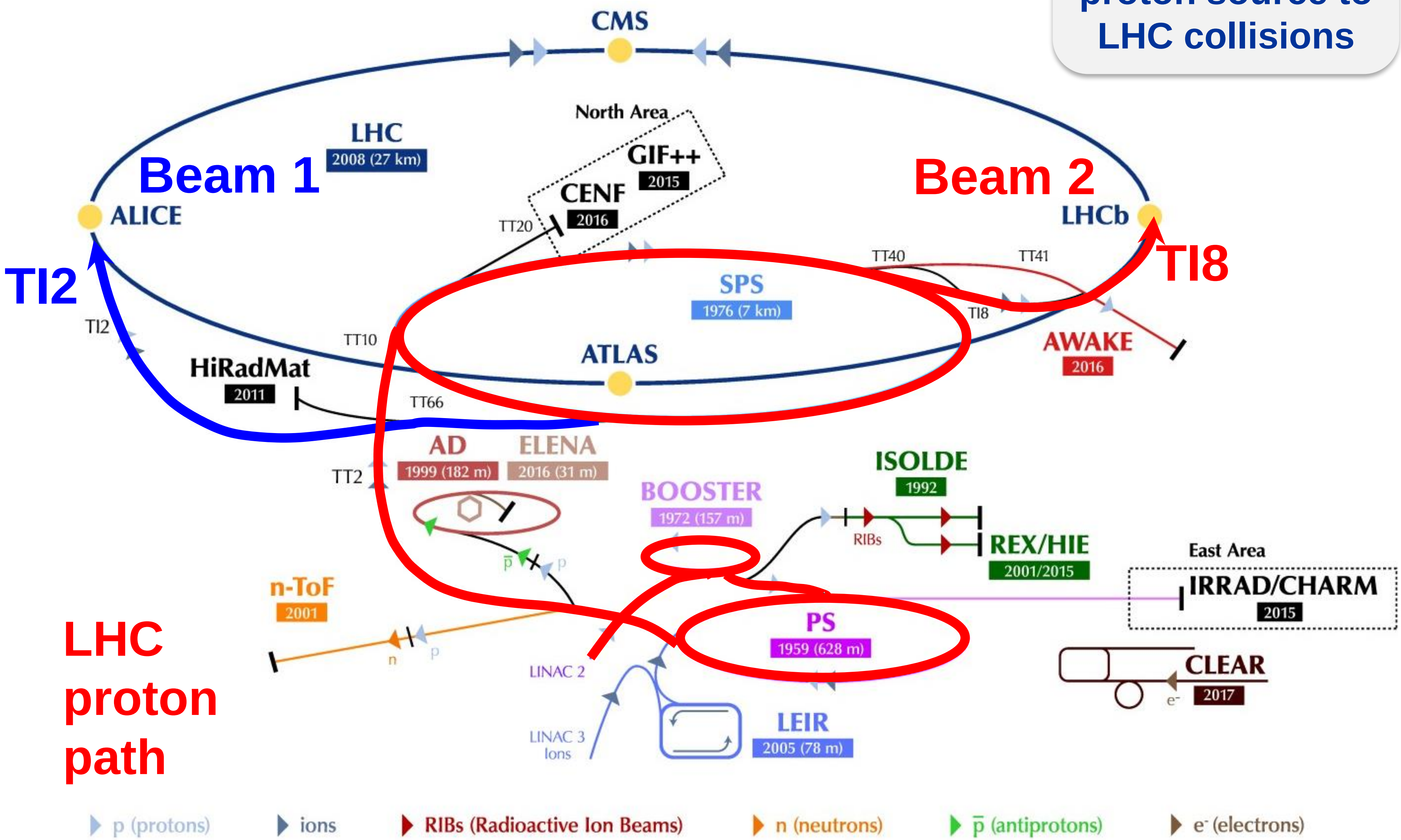
LHC pp and ions



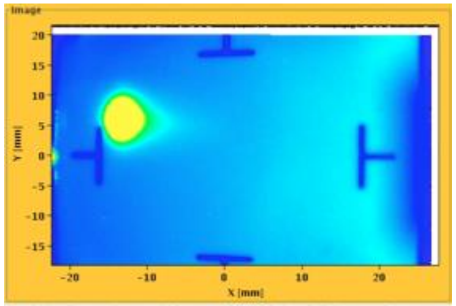
- Two beams in separate beam pipes going through the same cold mass 19.4 cm apart
- Four major experiments
- 150 tonnes of liquid helium to keep the magnets cold and superconducting
- > 9000 magnetic elements
- 1232 main dipoles – 12’000 A provides a nominal field of 8.33 Tesla - Operating in superfluid helium at 1.9K

The CERN Accelerator Complex

Nearly 40 km of tunnels from proton source to LHC collisions



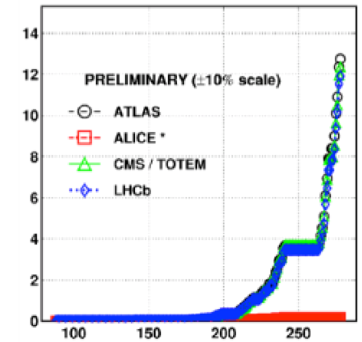
A Rocky Start



August 2008
First injection test

September 10, 2008
First beams around

November 29, 2009
Beams back

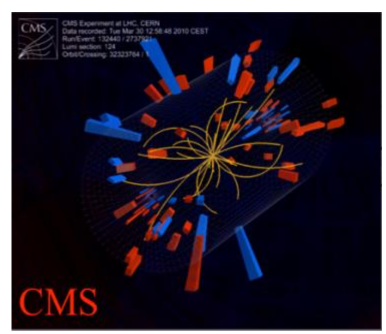


October 14, 2010
1e32
248 bunches

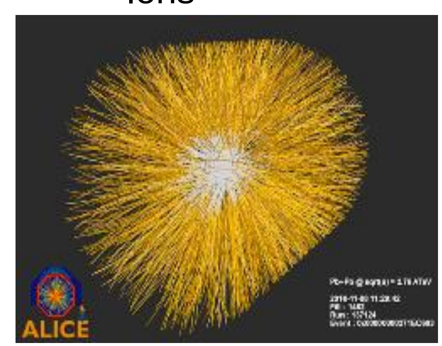
2008 | 2009 | 2010

September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

March 30, 2010
First collisions at 3.5 TeV

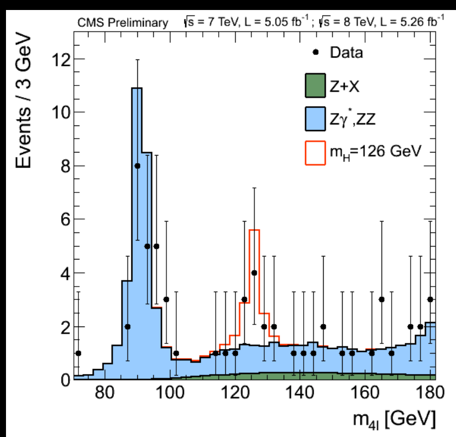


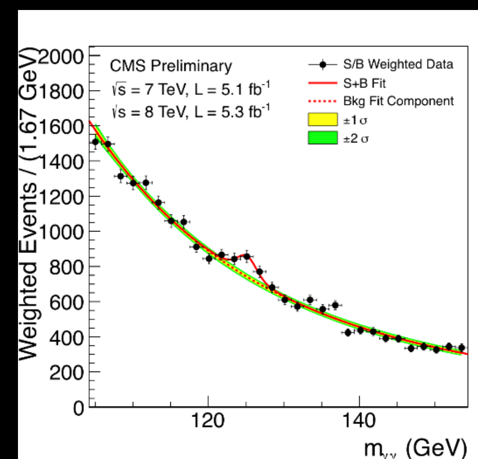
November 2010
Ions



And the Rest is History

4th July 2012:
Higgs discovery
announced at CERN





8 October 2013: Nobel prize to
François Englert and Peter Higgs

Two main Collider Performance Parameters:

1. Beam Energy
2. Luminosity

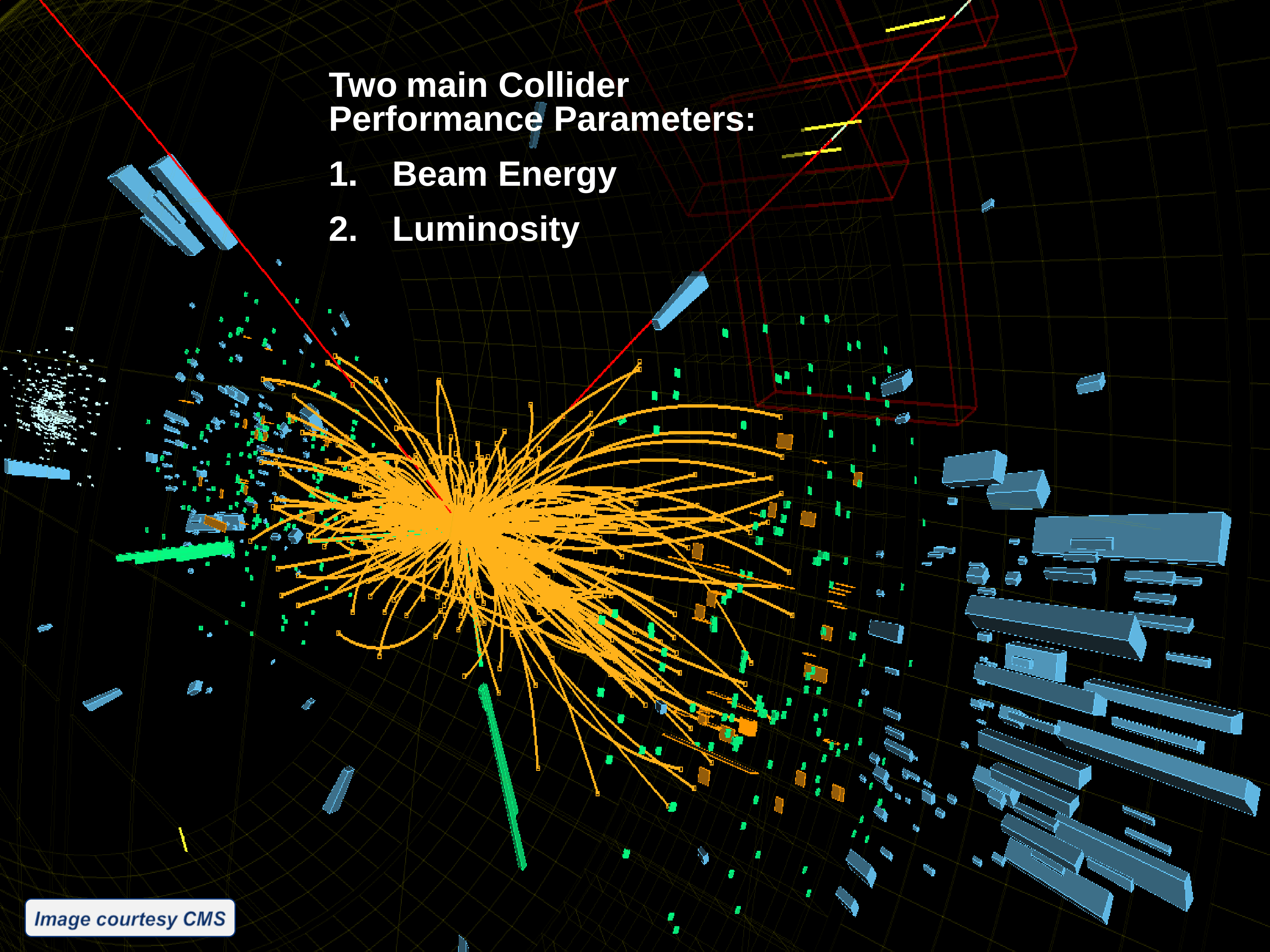
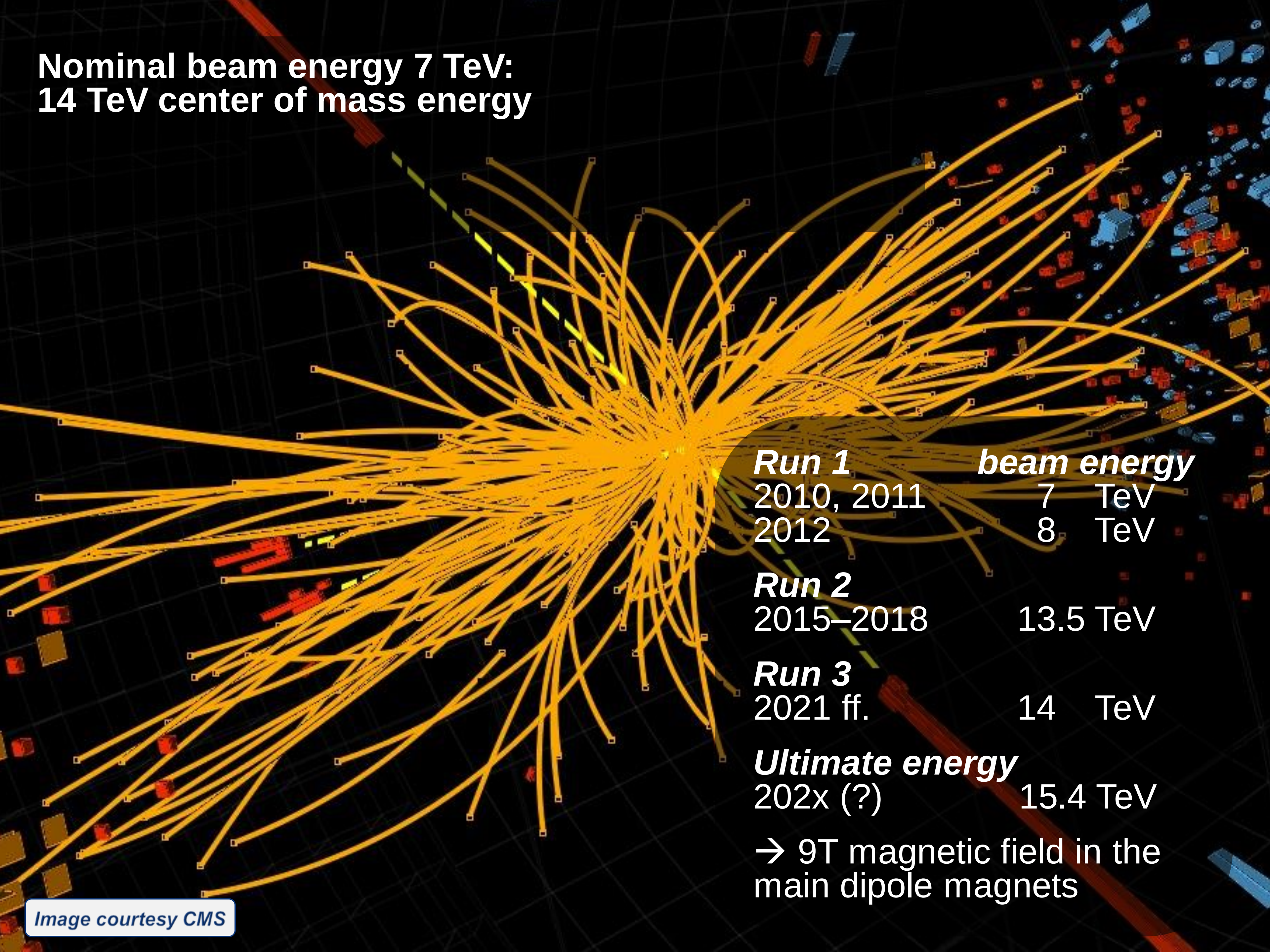


Image courtesy CMS

Nominal beam energy 7 TeV:
14 TeV center of mass energy



Run 1	***beam energy***
2010, 2011	7 TeV
2012	8 TeV
Run 2	
2015–2018	13.5 TeV
Run 3	
2021 ff.	14 TeV
Ultimate energy	
202x (?)	15.4 TeV

→ 9T magnetic field in the main dipole magnets

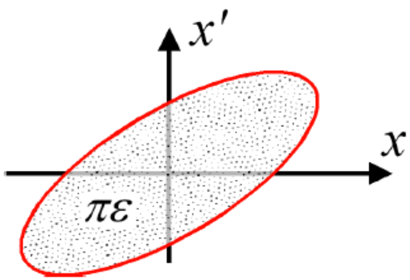
Image courtesy CMS

Recap: Luminosity for Particle Colliders

- The rate of events equals the interaction cross-section times the luminosity, L
- Assuming both beams equal and round and head on collisions

$$\frac{dN}{dt} = \sigma \times L$$

$$L = \frac{N^2 n_b f_{rev}}{4\pi\sigma_x^*\sigma_y^*} F = \frac{N^2 n_b f_{rev}}{4\pi\,\epsilon_n \beta^*/\gamma} F$$



$e_n = bge$

$s^* = \sqrt{b^* e}$

N	Number of particles per bunch
n_b	Number of bunches per beam
f_{rev}	Revolution frequency
σ^*	Beam size at interaction point
F	Reduction factor due to crossing angle
ε_n	Normalized emittance
β^*	Beta function at interaction point

} transverse beam size at interaction point, σ*

LHC optics

from injectors

Performance Parameter: Integrated Luminosity

- Tuning “knobs” to increase luminosity:

Intensity per bunch

Number of bunches

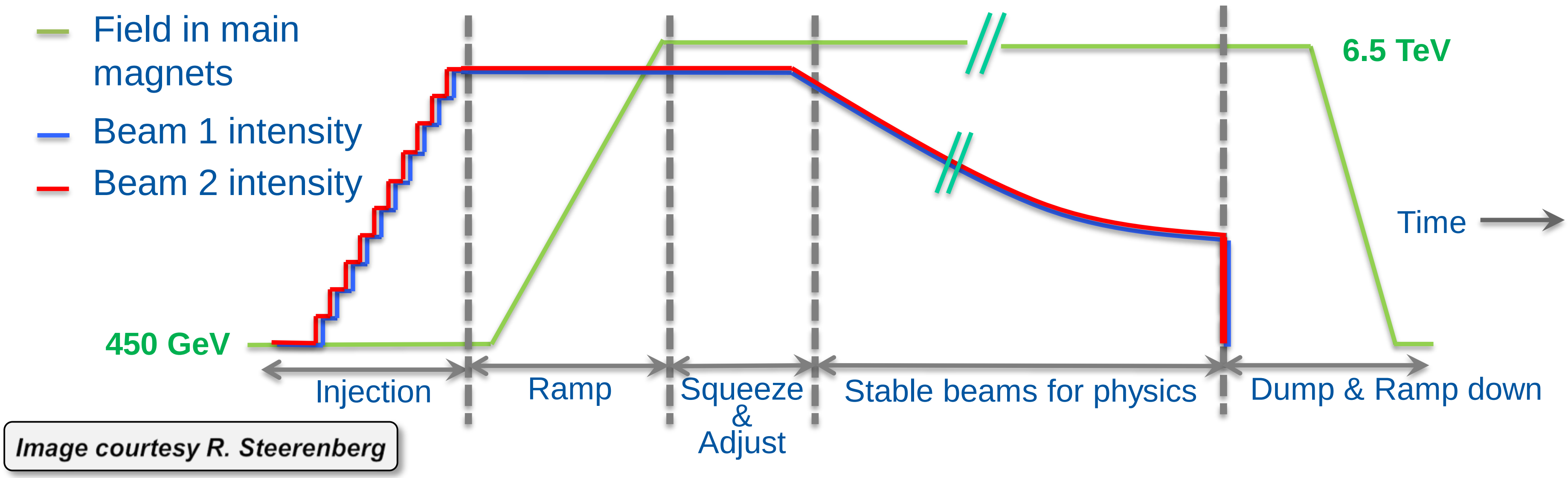
$$L = \frac{N^2 n_b f_{rev}}{4\pi \, \epsilon_n \beta^* / \gamma} F$$

Crossing Angle

Beam dimensions

- Maximize integrated luminosity:
  - Machine availability, turn around time, optimal cycle length, …

The LHC Cycle



The LHC Cycle: Injection, bunch distance 25 ns

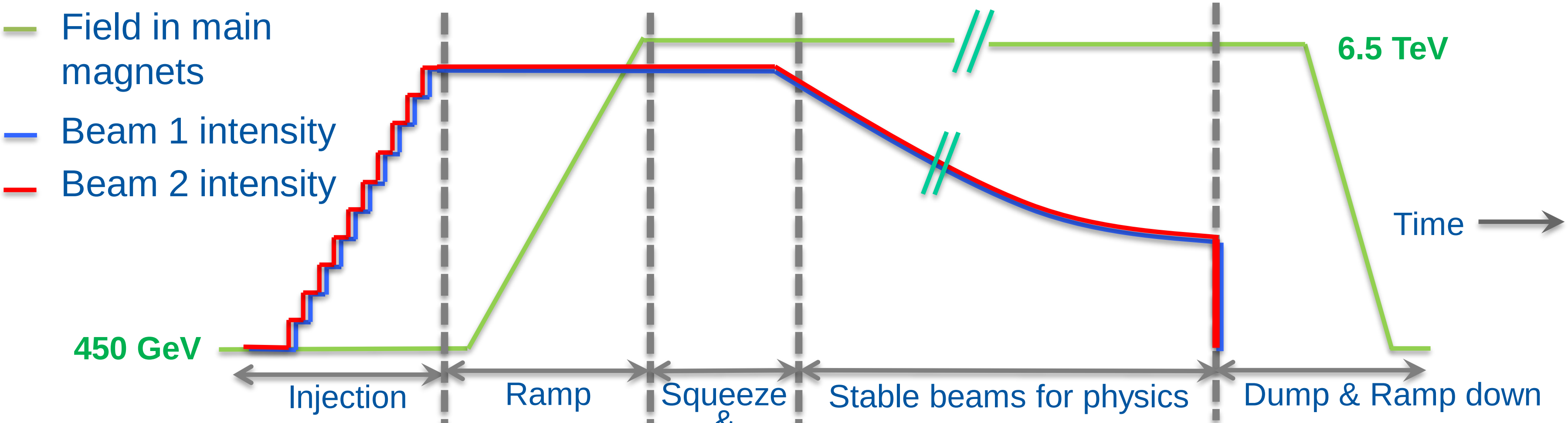
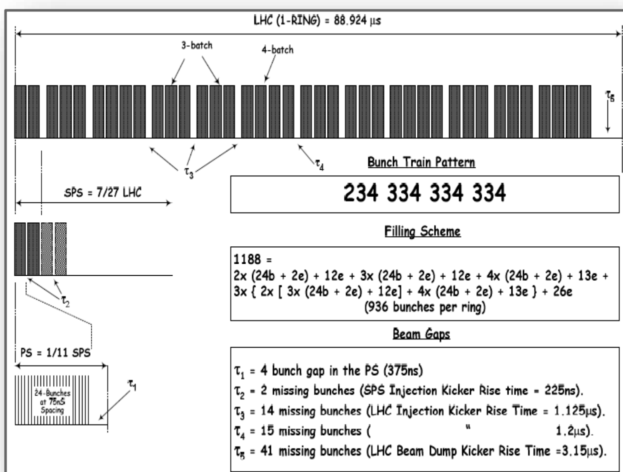
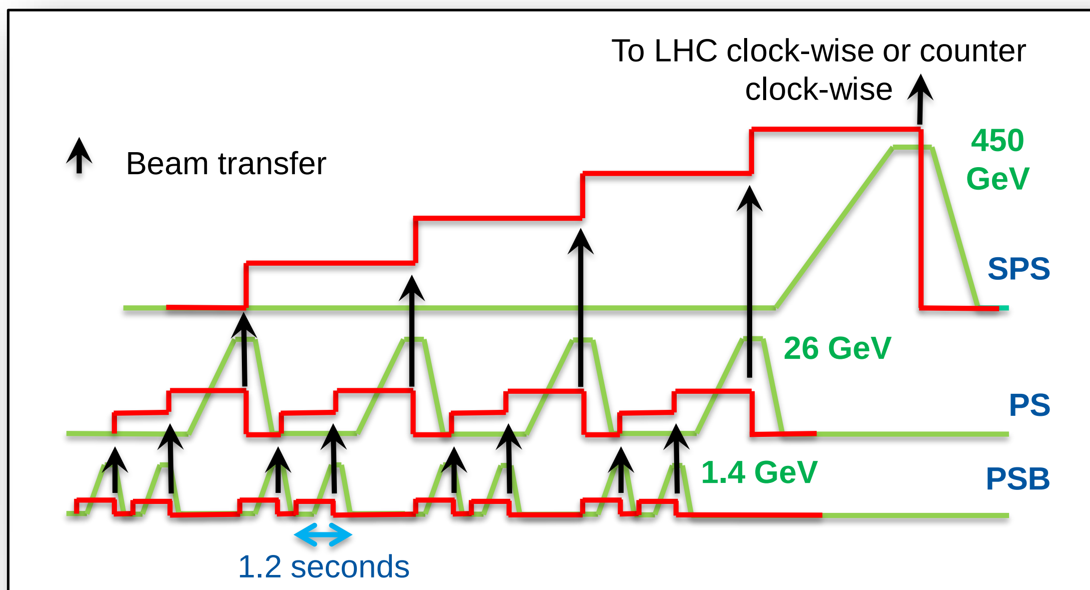


Image courtesy R. Steerenberg





The LHC Cycle: Ramp, Squeeze, bring into collisions

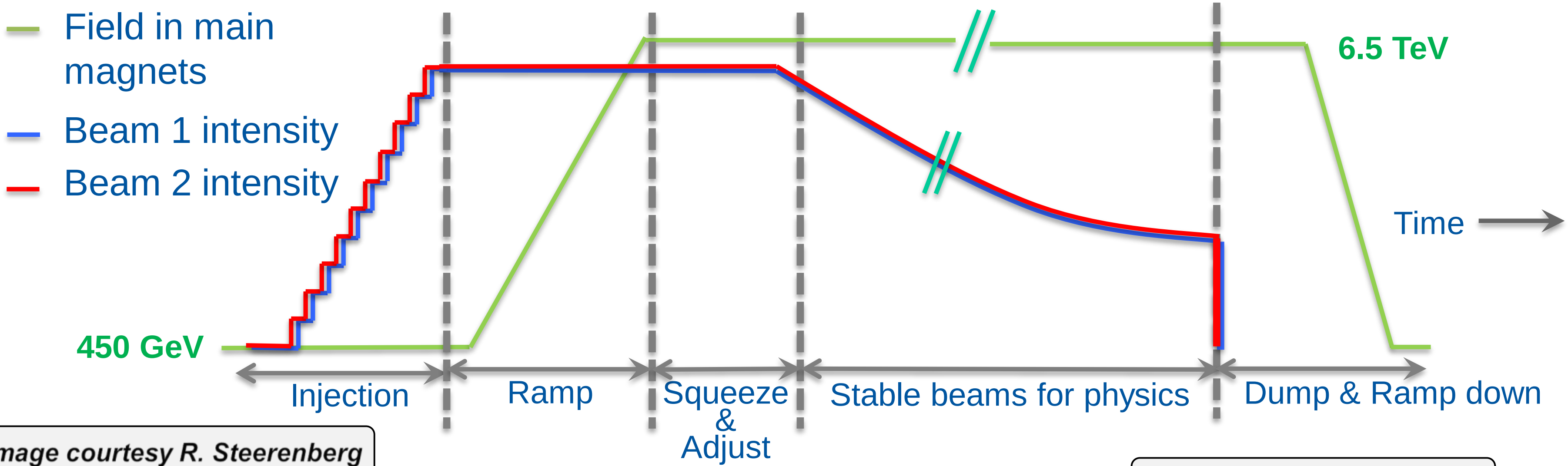


Image courtesy R. Steerenberg

Ramp-up

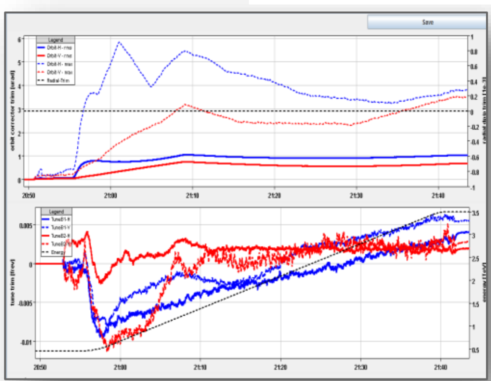
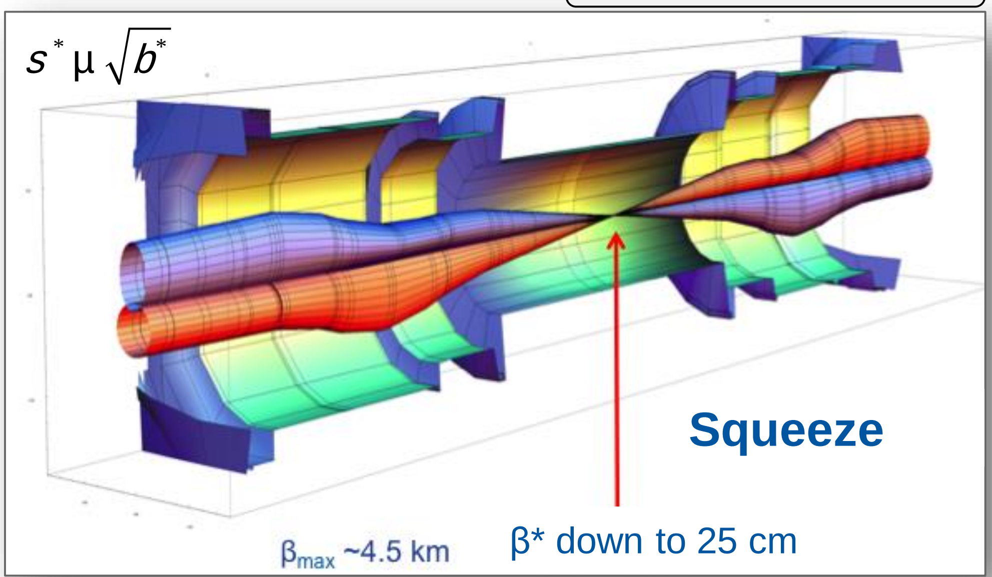


Image courtesy J. Jowett



The LHC Cycle: Declare Stable Beams

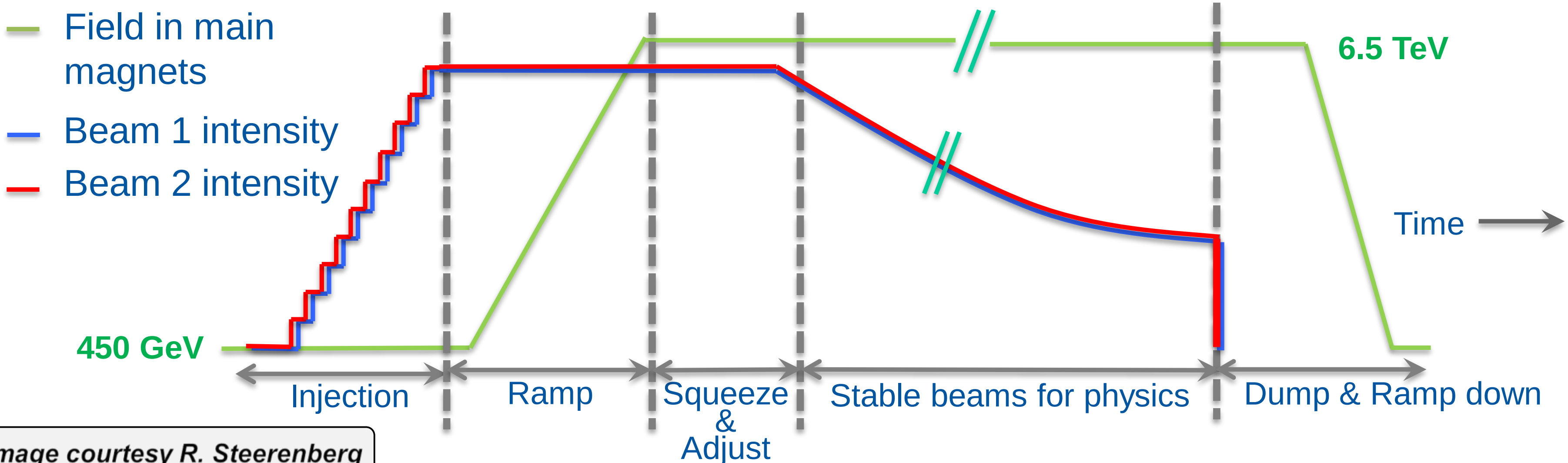
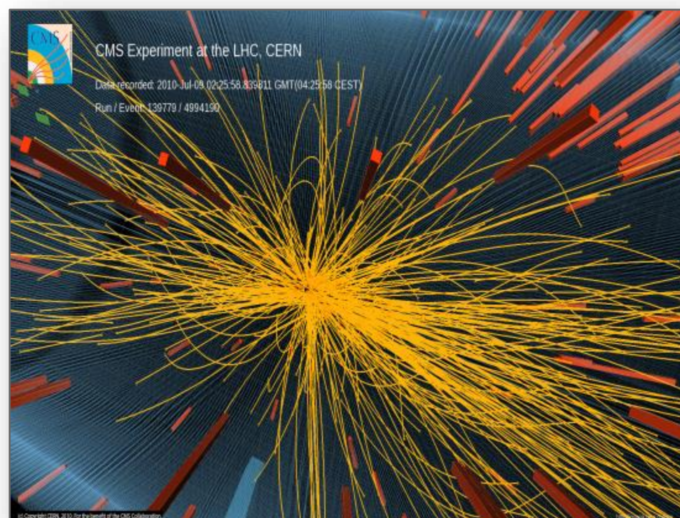


Image courtesy R. Steerenberg



The LHC Cycle: Beam Dump and Ramp Down

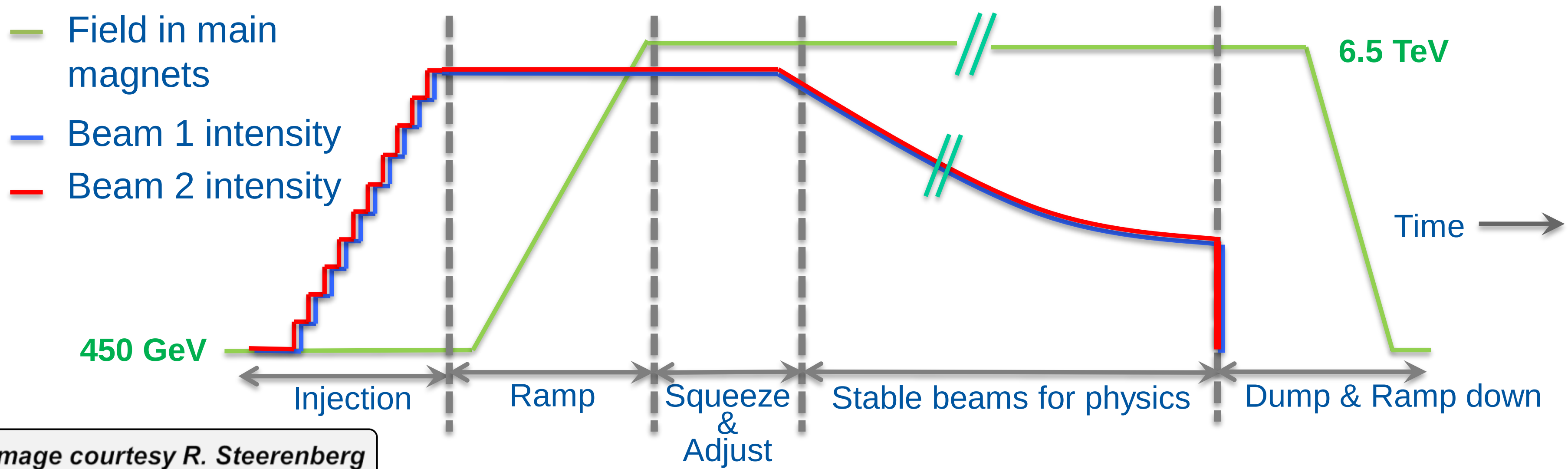
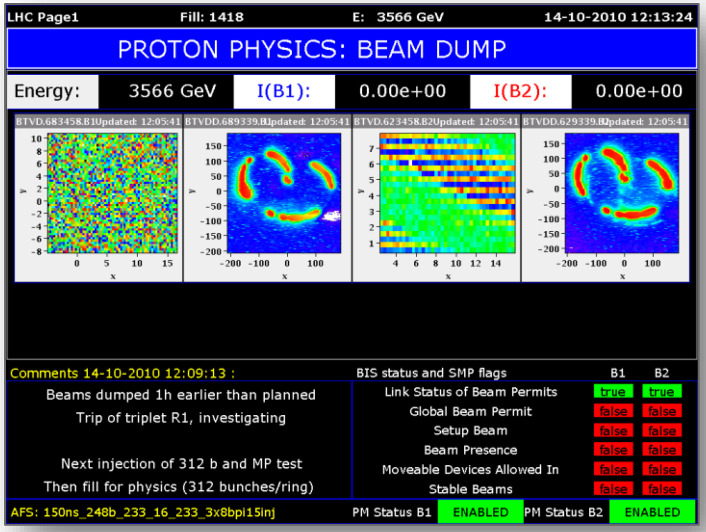


Image courtesy R. Steerenberg

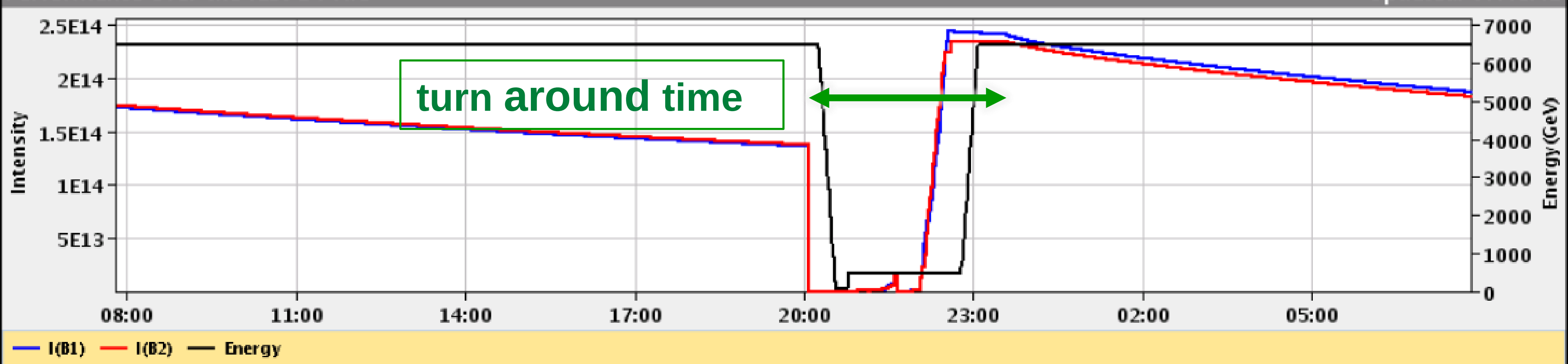


16-Oct-2016 07:48:46 Fill #: 5418 Energy: 6499 GeV I(B1): 1.87e+14 I(B2): 1.83e+14

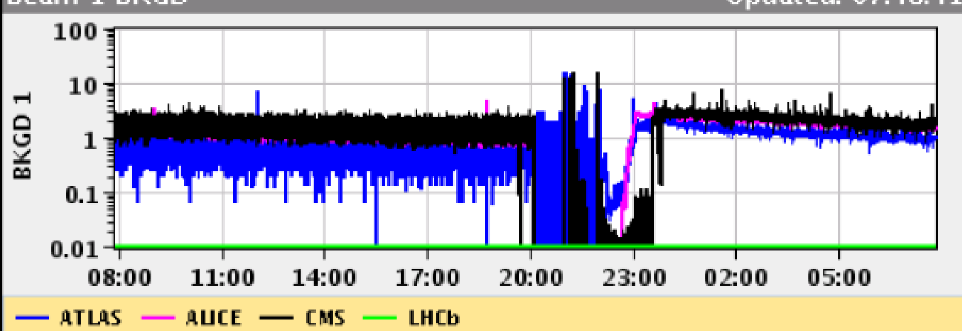
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	7346.231	1.672	7730.174	355.048
BRAN Luminosity [(ub.s)^-1]	7462.0	1.8	6917.8	181.2
Fill Luminosity (nb)^-1	265785.063	49.302	293245.594	10312.992
Beam 1 BKGD	0.927	1.401	1.645	0.000
Beam 2 BKGD	4.488	0.042	1.143	0.001

LHCb VELO Position IN Gap: -0.0 mm | STABLE BEAMS | TOTEM: PHYSICS

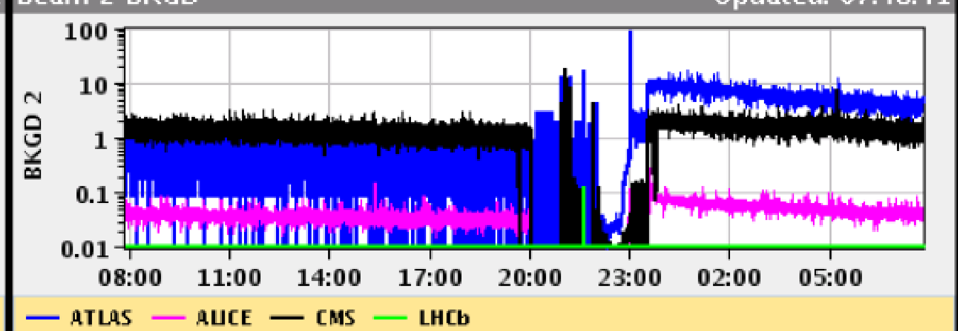
Performance over the last 24 Hrs Updated: 07:48:42



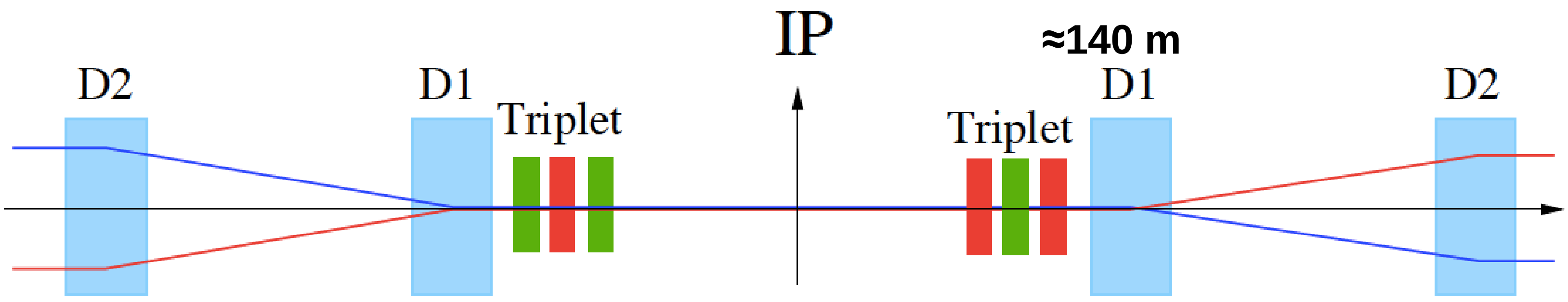
Beam 1 BKGD Updated: 07:48:41



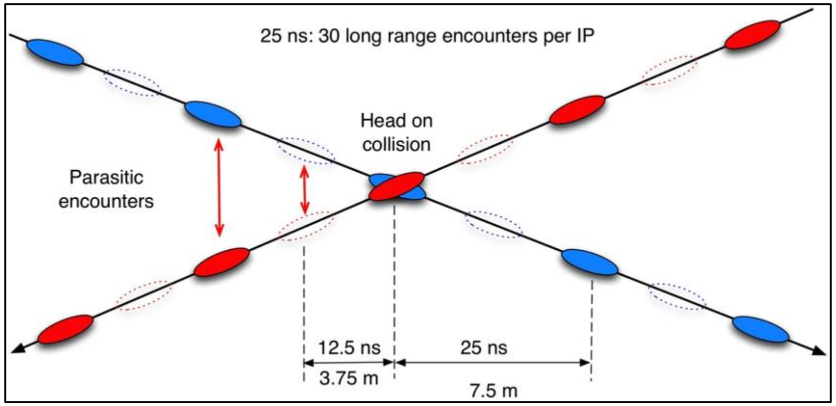
Beam 2 BKGD Updated: 07:48:41

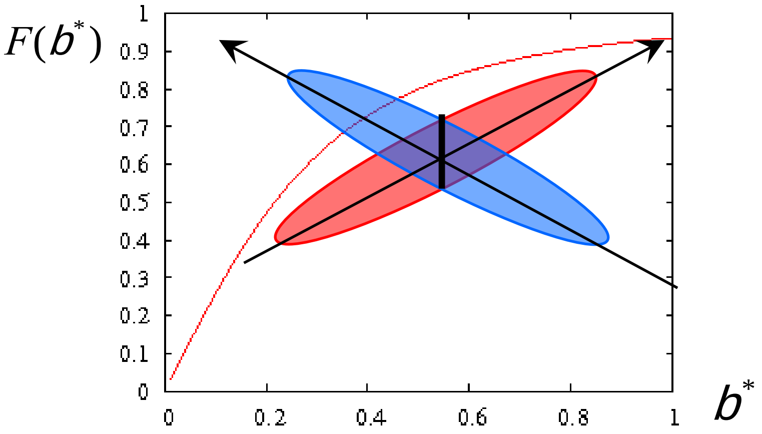


Interaction region



Crossing angle: Avoid parasitic collisions in the common beam pipe

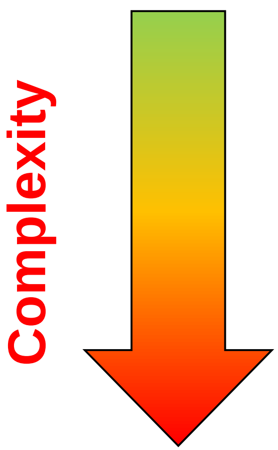




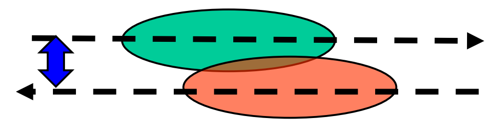
Luminosity reduction factor: $F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$

Too much Luminosity: Luminosity Leveling

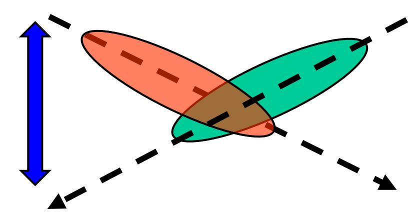
- Event pile-up can limit the maximum luminosity which an experiment can use
  - → maximum luminosity defined by the experiment capability to digest pile-up (and by radiation considerations)
  - → levelling techniques put in place



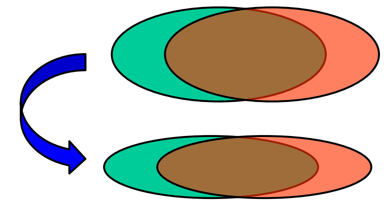
Levelling by **beam offset**



Levelling by **crossing angle**



Levelling by **β*** (= beam size at IP)



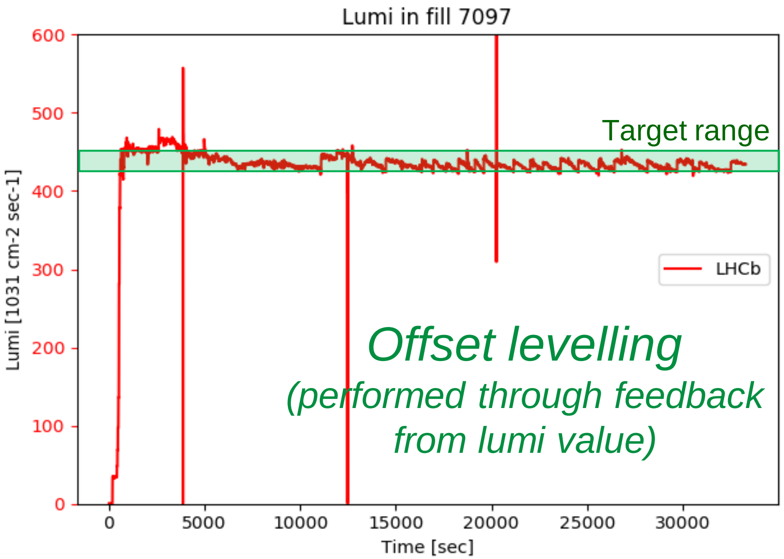
Luminosity Leveling

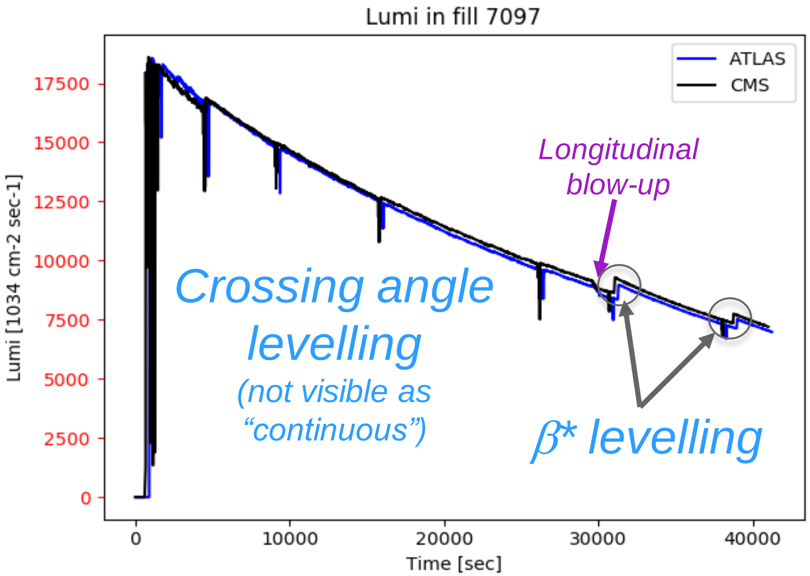
- Reduce event pile-up → maximum luminosity defined by the experiments
- Keep instantaneous luminosity constant despite decreasing beam intensity → increase the integrated luminosity

- What counts is the integrated luminosity

Luminosity Levelling in 2018

- All three levelling techniques have been used in operation:
  - Levelling by **separation** is used in LHCb and ALICE since the beginning of LHC operation. It is performed through feedback from luminosity value.
  - **Crossing angle** levelling is used for ATLAS and CMS throughout the fill in a “continuous” way down to 130 μrad
  - **β*** levelling (new in 2018) is used to enhance luminosity at lower intensity (low pile up): β^*=30 cm → 25 cm
- Vital exercise for future (HL-LHC) levelling





LHC Proton Physics Run 2018

Performance Goals for 2018 Proton Run

- Each year, luminosity goals are defined, which are achievable under reasonably good running conditions and with the improvement options identified.
- Goals for 2018, as presented March 2018 by Frédérick Bordry:
  - … may reach
    - limit on peak luminosity set by pileup in the experiments (55 - 60) and
    - triplet cooling capacity (~2.2 10^{34} cm^{-2} s^{-1}) …
      - → **levelling needed**
  - assuming 50-55% stable beams
  - reducing the time to reach collisions with >1200 bunches to 36 days (was 46 days in 2017)

Performance target for 2018 p-p operation:

≈ 60 fb^{-1} for CMS/ATLAS (leveled at pileup 55-60 if PU higher)

≈ 2 fb^{-1} for LHCb leveled at $4.6x10^{+32}$

Luminosity Goal for LHCb

- On request of LHCb, for the first time, LHCb also has a luminosity goal defined for 2018 by the LHC management.
- For LHCb as a levelled experiment, there are less possibilities to optimise running conditions in order to achieve the luminosity goal (e.g. LHCb cannot profit from any increase of peak luminosity). The delivered luminosity is directly proportional to the time in Stable Beams.

Performance target for 2018 p-p operation:

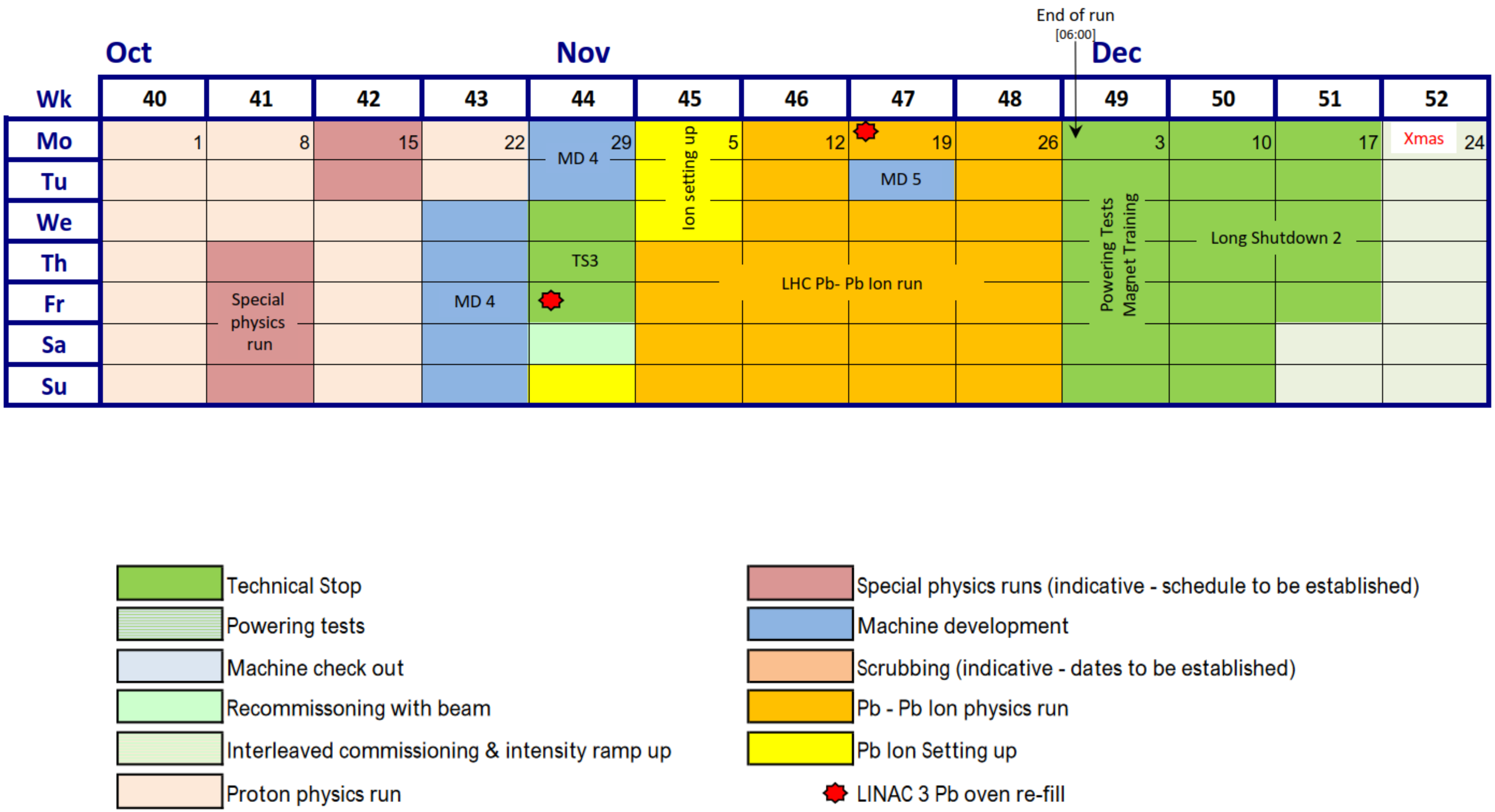
≈ 60 fb^{-1} for CMS/ATLAS (leveled at pileup 55-60 if PU higher)

≈ 2 fb^{-1} for LHCb leveled at $4.6x10^{+32}$

2018 Typical Beam Parameters

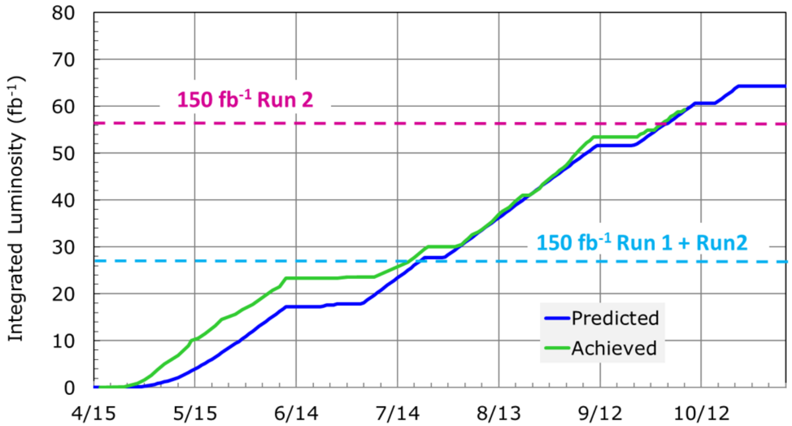
Parameter	Design	2018
Energy [TeV]	7.0	6.5
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	2.1
Typical normalized emittance [μm]	3.75	≈1.8
p/bunch (typical value) [10^{11}]	1.15	1.1
β* [cm]	55	30→25
Number of bunches	2808	2556
Maximum Bunches per injection	288	144
Max. stored energy per beam [MJ]	362	312

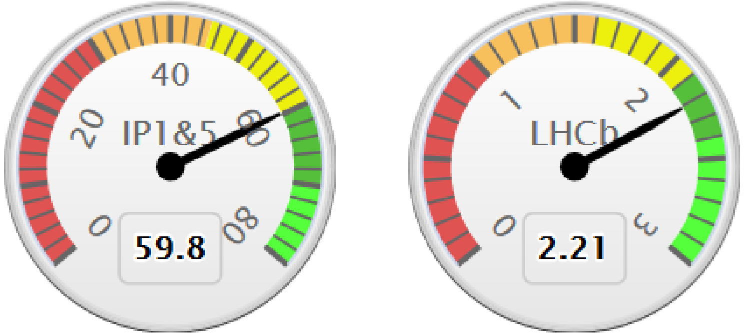
Remainder of 2018 and of Run 2



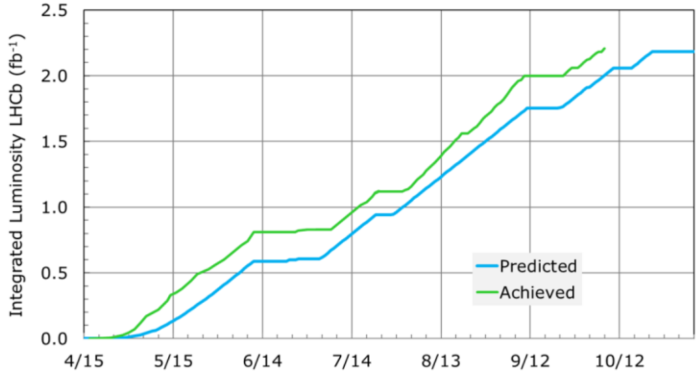
Luminosity Production: 60 fb^{-1} on 8.10.2018!

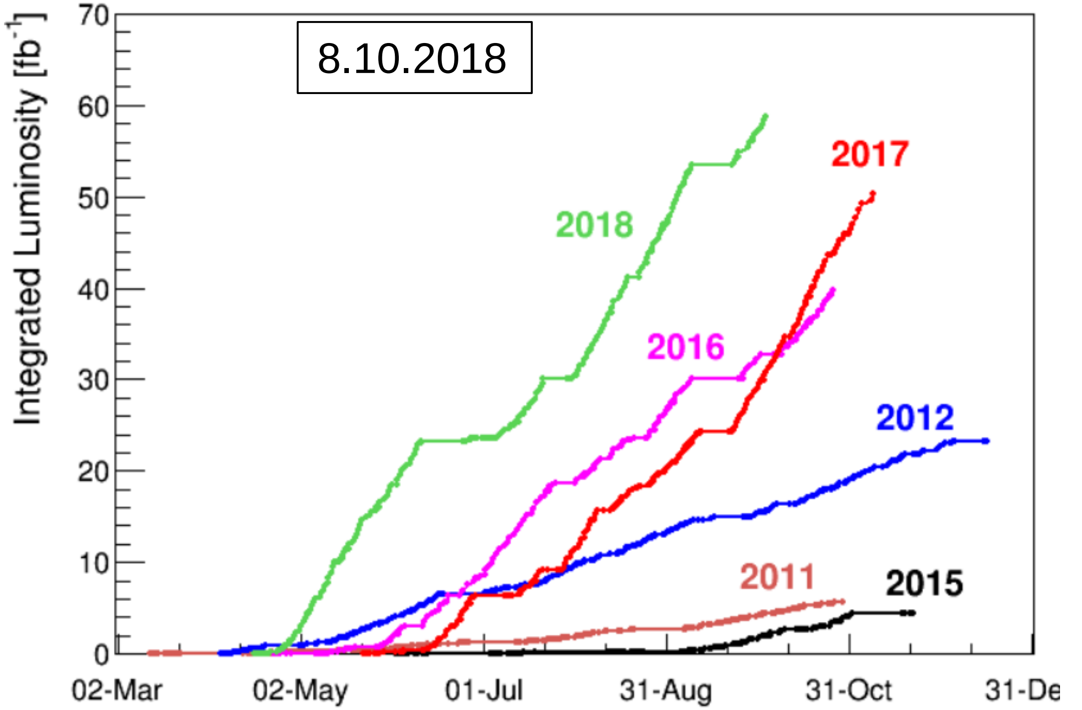
Atlas / CMS





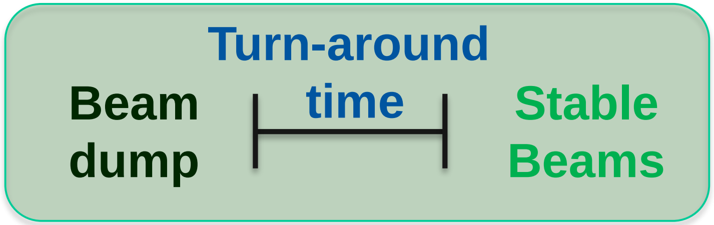
LHCb: 2018 best production year – high availability, long fills

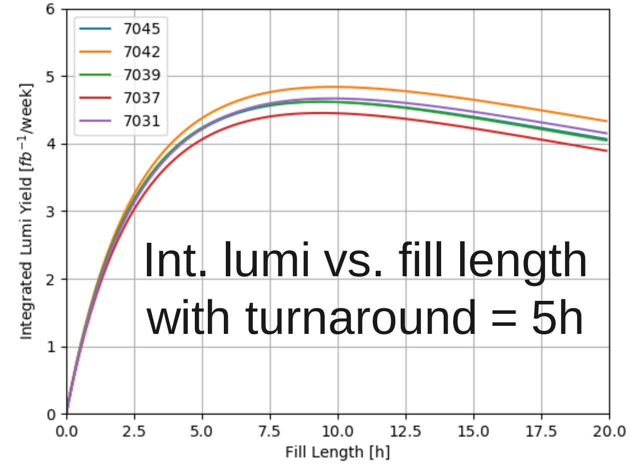




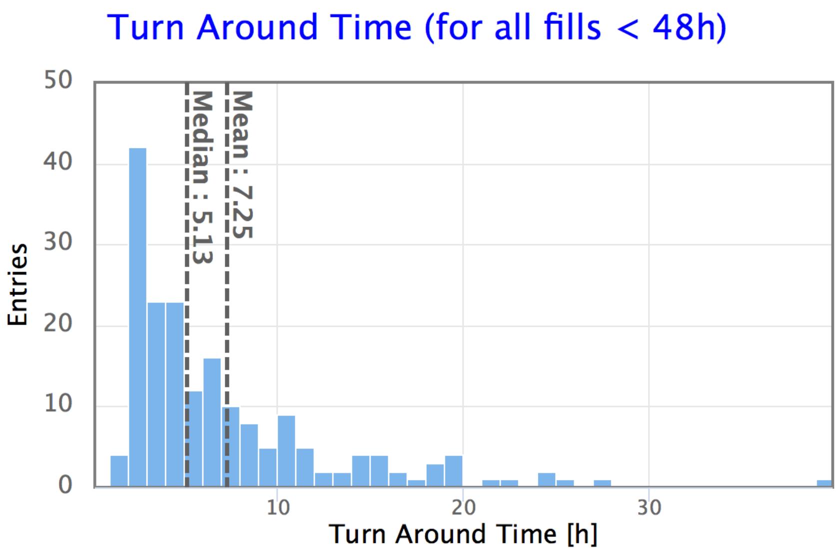
Duration in Stable Beams — Fill Length

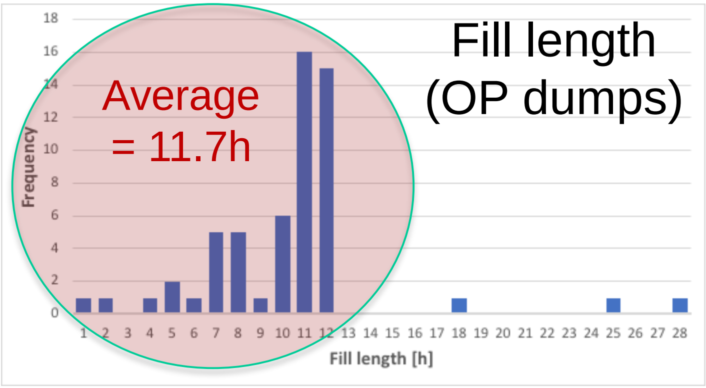
- How long should a fill be kept?





- Optimum fill length ≈10h (assuming turnaround = 5h)
- 12–13h "costs" only 1-2% for ATLAS/CMS





LHC Availability

- Careful tracking of operational efficiency, availability, downtime and fault statistics → consolidation of limiting equipment and optimizing procedures and choice of operation conditions to maximize integrated luminosity.
- LHC availability working group generates detailed reports using the *Accelerator Fault Tracker* (https://aft.cern.ch/dashboard).

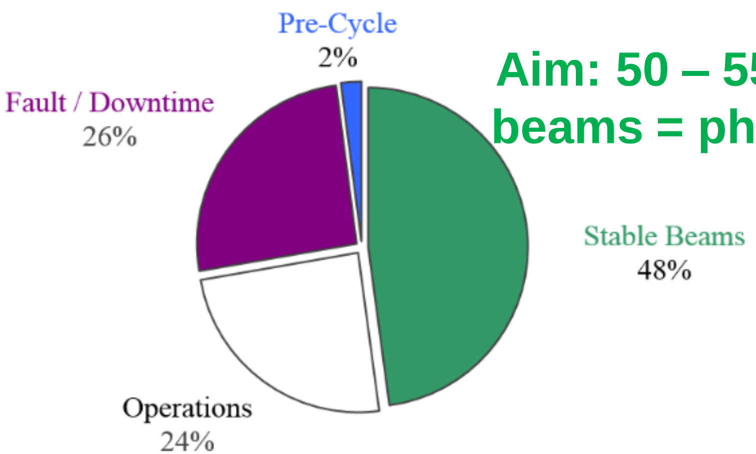


Figure 4: Machine Mode Breakdown during Physics

Aim: 50 – 55 % stable beams = physics time

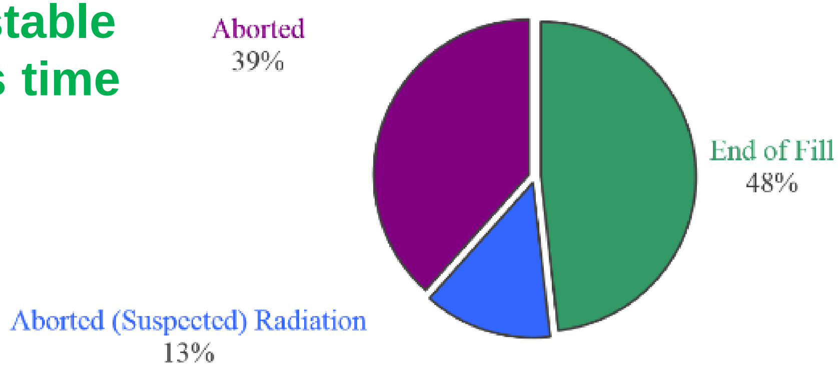


Figure 5: Beam Abort Ratio for Fills Reaching Stable Beams

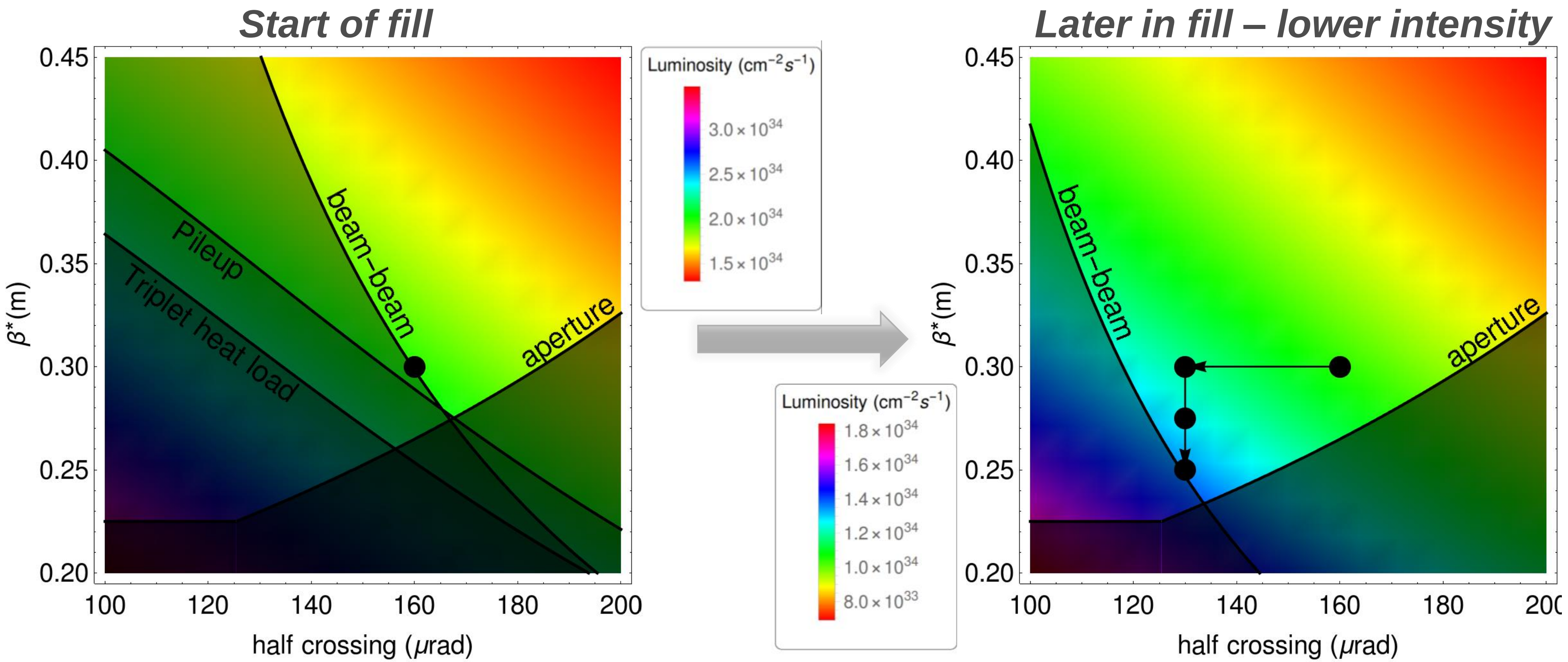
Technical Stop 1 – Technical Stop 2: ***21 June – 17 September 2018***

https://cds.cern.ch/record/2641487/files/LHC%20availabilty%202018.pdf?

Optimized running scenario

Courtesy R. Bruce

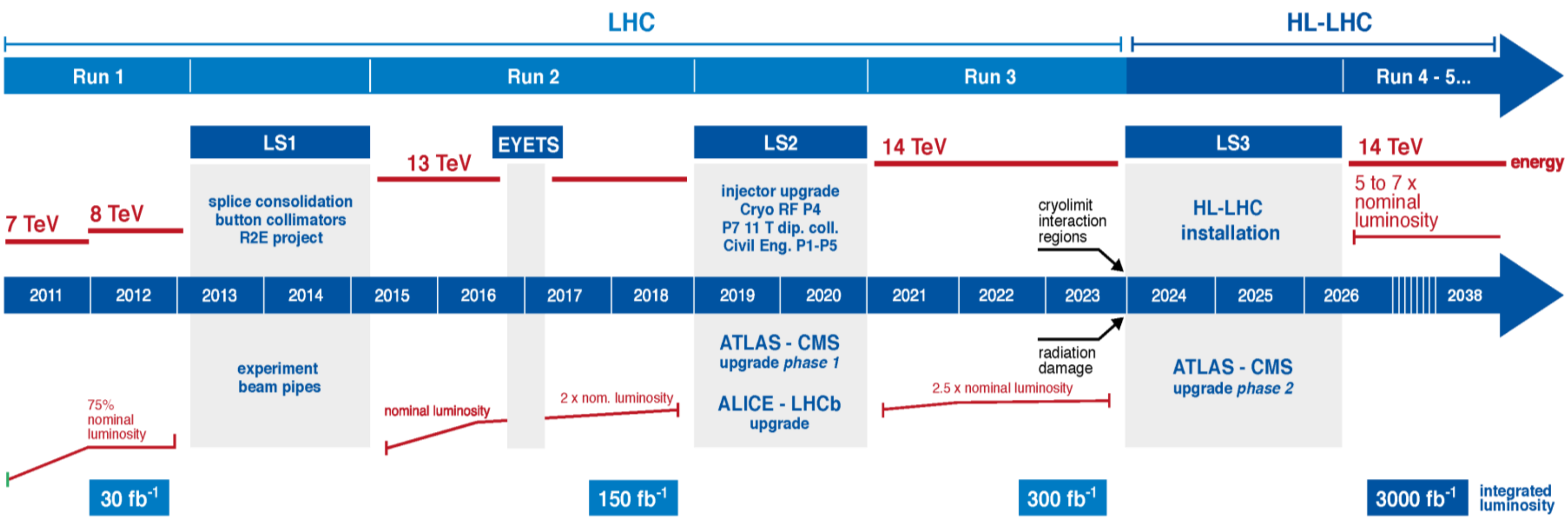
- Changing both crossing angle and β* through leveling while in stable beams
- Scenario optimized under a number of constraints



HL-LHC High Luminosity LHC Upgrade

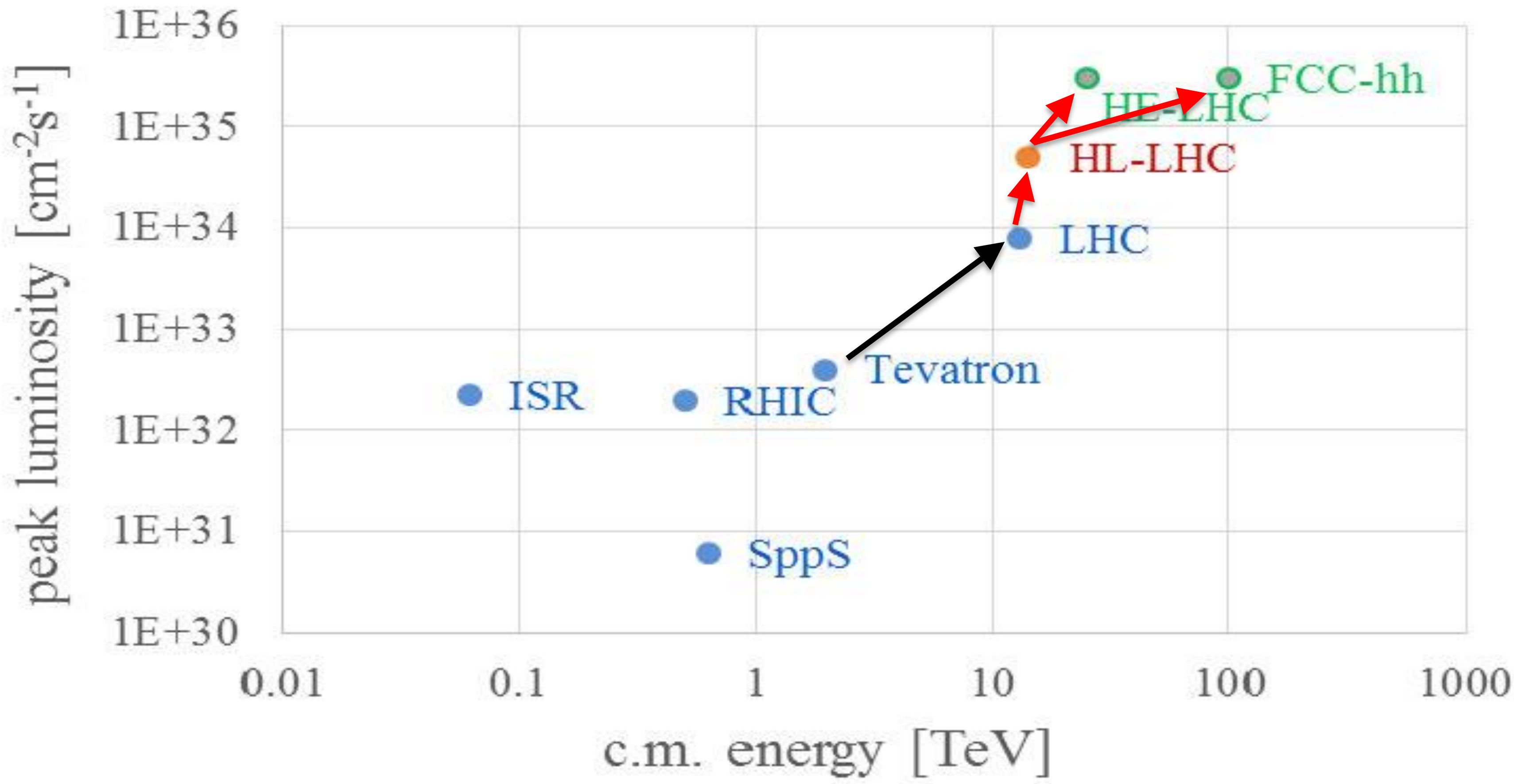
LHC / HL-LHC Plan

- HL-LHC: start with Run 4 (for protons)
- total integrated luminosity of 3000 fb^{-1} in around 10-12 years
  → 10 x luminosity of the first 10 years of LHC operation
- an integrated luminosity of ~250 fb^{-1} per year



Luminosity and Energy Reach

- Further pushing the limits

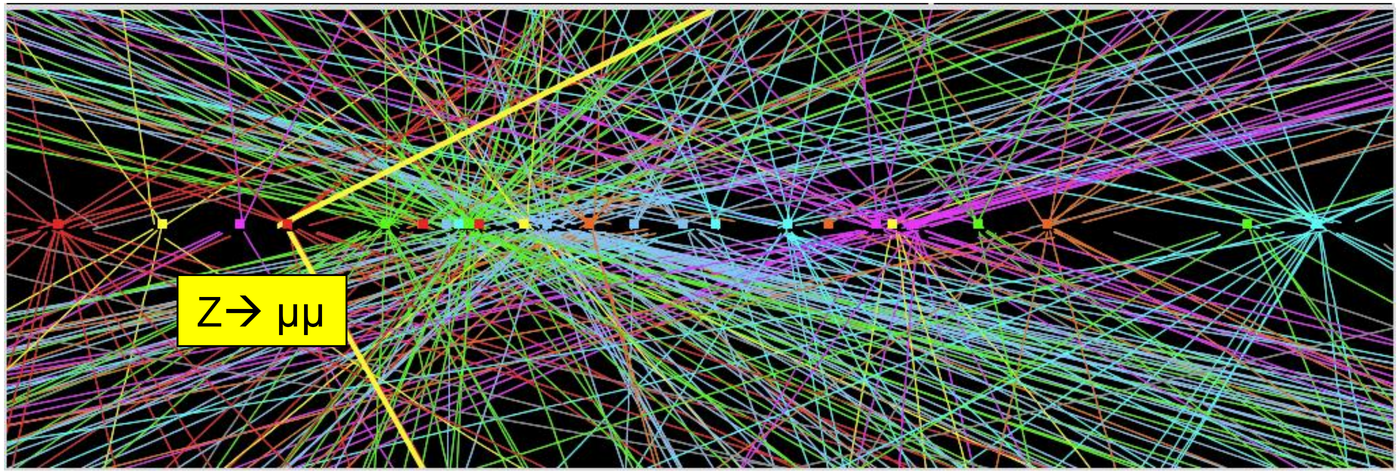


- Stored Beam power: HL-LHC > 500 MJ / beam → damage potential

HL-LHC Measures

Increase luminosity by	HL-LHC Measure
doubling bunch intensities (1.1→2.2x10^{11}) small beam emittance (2.5 μm)	Injector complex Upgrade LIU
minimizing beam size (β* 25 → 15 cm);	Wide aperture triplet magnets (Nb3Sn)
compensating for 'F'	Crab Cavities
improving machine Efficiency	Minimize number of unscheduled beam aborts etc. (e.g. remove electronics from the tunnel)

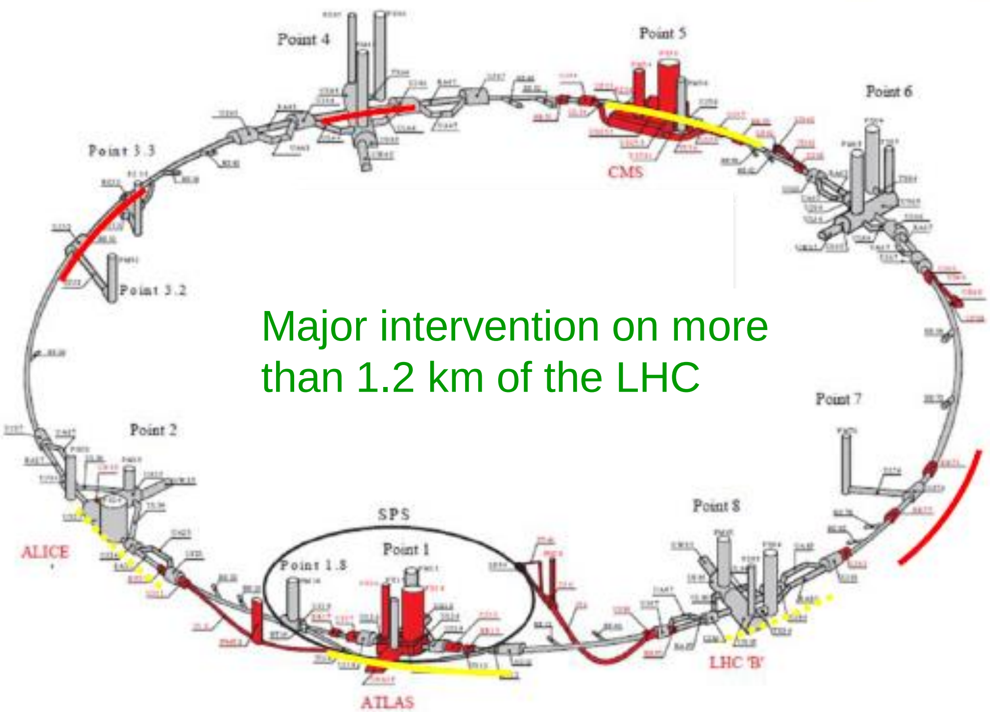
- "Virtual" luminosity: 2.4 x 10^{35} $cm^{-2}s^{-1}$
- Pile-up ≤ 140 → peak instantaneous luminosity of 5x10^{34} $cm^{-2}s^{-1}$
  - → Luminosity levelling (beta*, crossing angle & crab cavity)



Z→ μμ event from 2012 data with 25 reconstructed vertices

HL-LHC: What will be changed ?

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

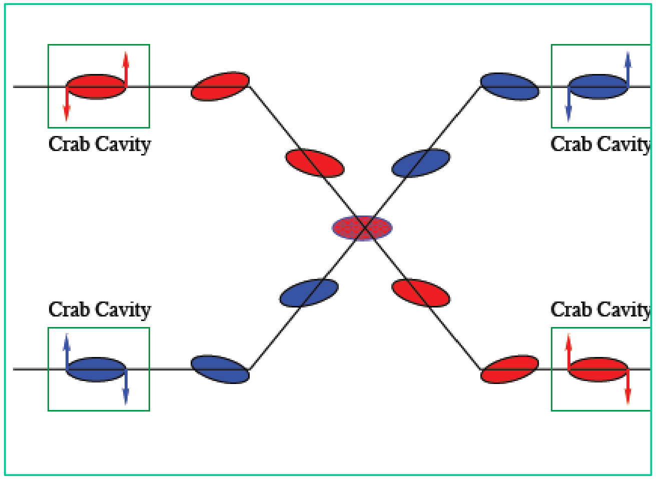


HL-LHC Parameters

Protons per bunch	2.2 x 10^{11}
Number of bunches	2750
Normalized emittance	2.5 micron
Beta*	15 cm
Crossing angle	590 microrad
Geometric reduction factor	0.305
"Virtual" luminosity	2.4 x 10^{35} $cm^{-2}s^{-1}$
Levelled luminosity	5 x 10^{34} $cm^{-2}s^{-1}$
Levelled <pile-up>	140

Crab Cavities for LH-LHC

- Reduces the effect of geometrical reduction factor
- Independent for each IP
- Kick head and tail of the bunch in opposite directions
- Already installed and tested in the SPS!



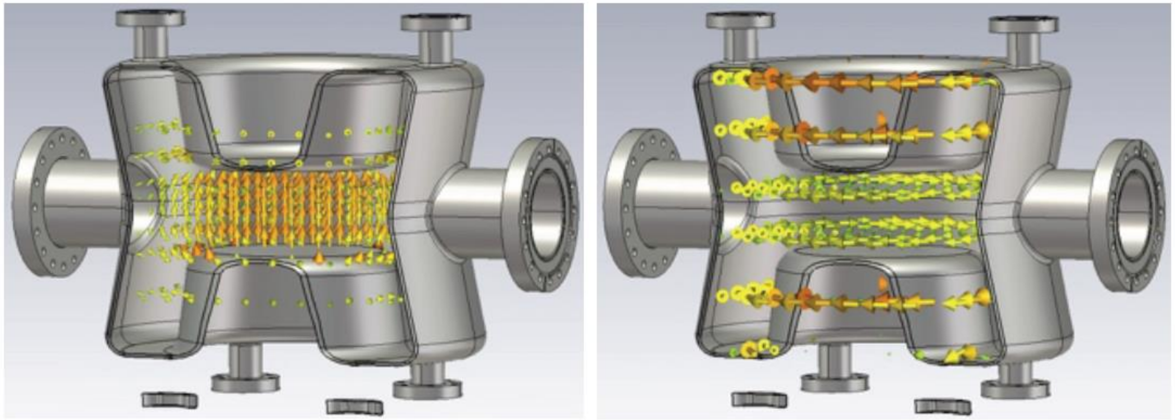
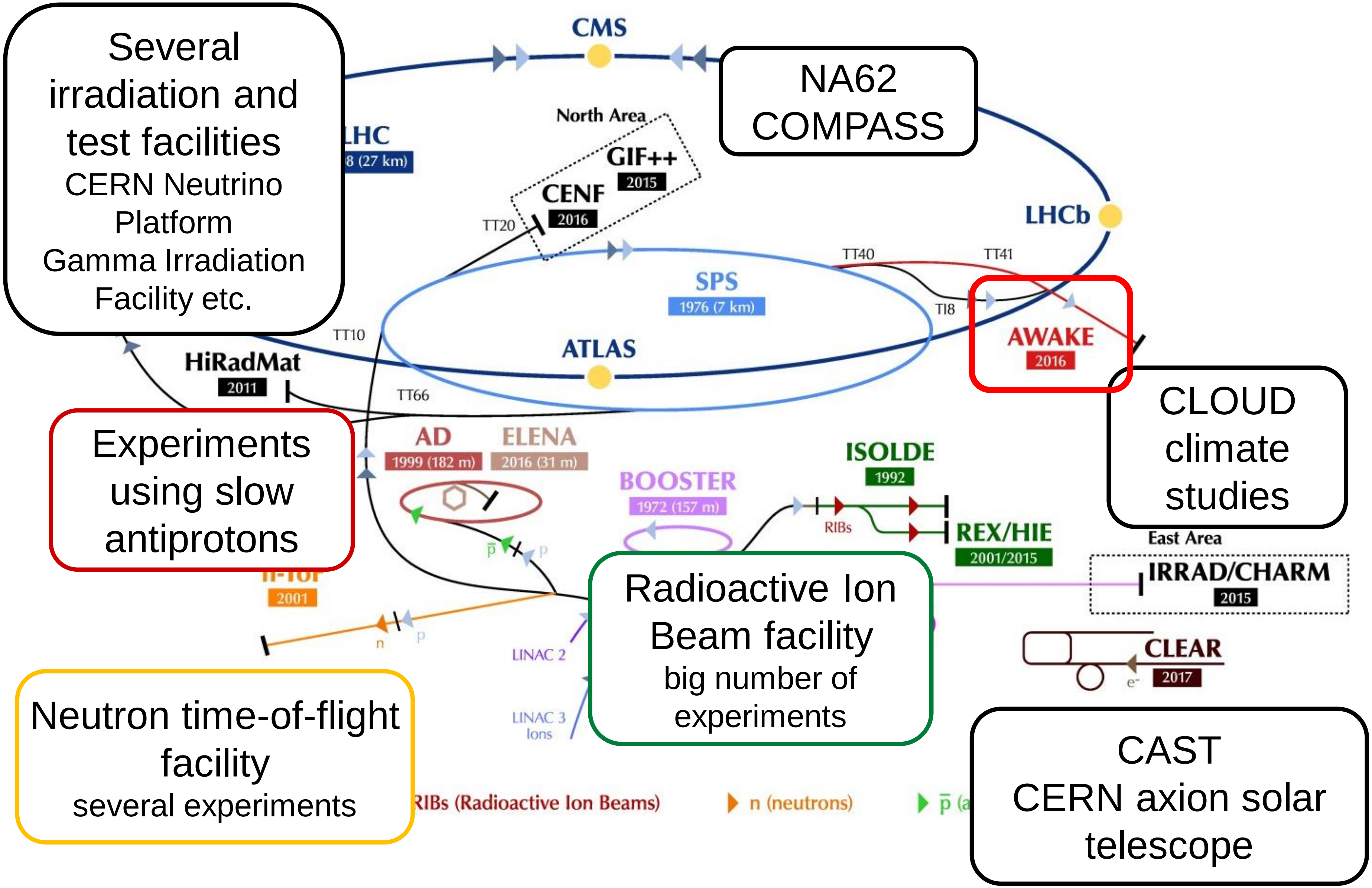


Figure 4. Electric (left) and magnetic (right) field distributions inside the DQWCC.

Small and Beautiful: The non-LHC Universe

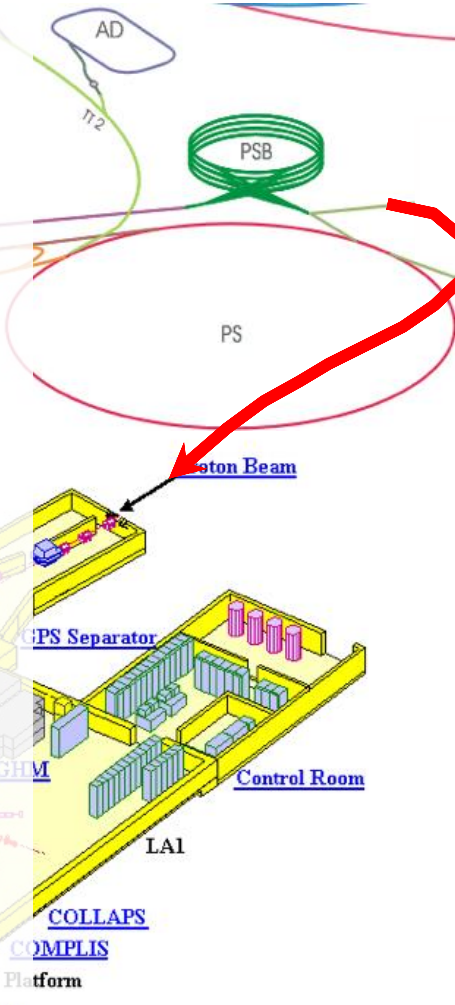
What else is there at CERN, other than the LHC?



ISOLDE — Isotope mass Separator On-Line facility

ISOLDE — Isotope mass Separator On-Line facility

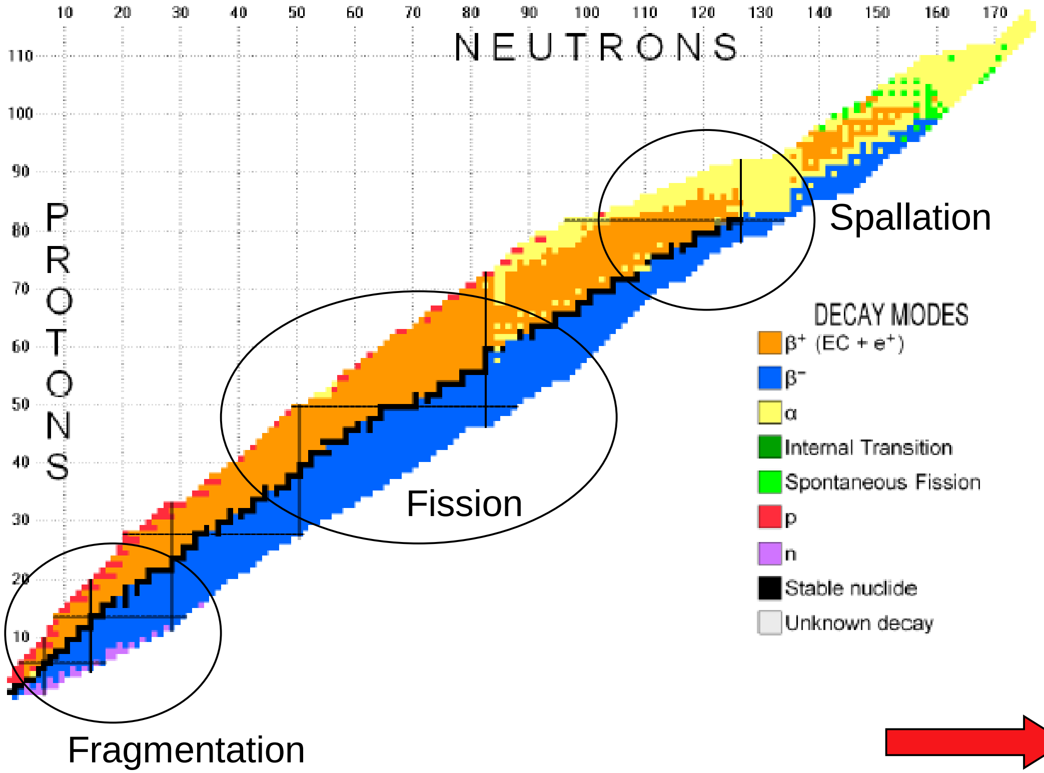
- Large variety of radioactive ion beams
  - largest range of isotopes worldwide: over 1300 isotopes of more than 70 elements
- weak interactions and nuclear and atomic physics, e.g.: nuclear shapes, lifetimes, beta-decay & EW interactions
- solid state physics and material science, e.g.: implantation of radioisotopes in semi-conductors
- astrophysics, e.g.: triple-alpha to 12C rate (star formation), nuclear processes occurring during supernovae
- biological systems, medical applications, e.g.: detoxification of mercury in bacteria, sensitive diagnostics

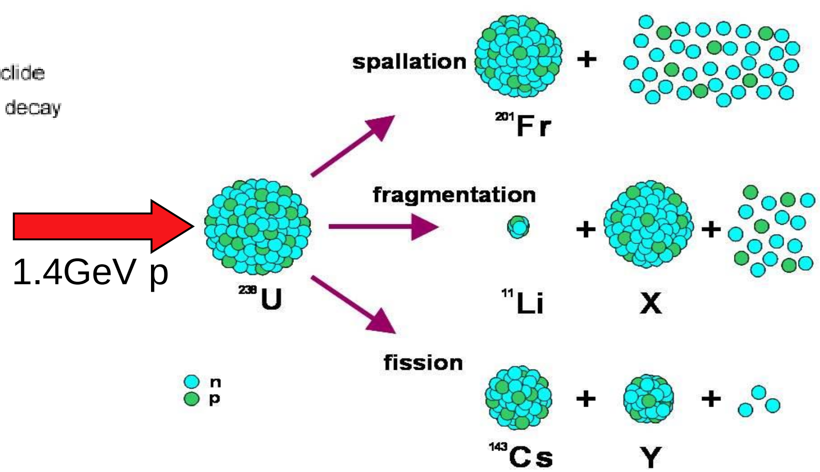


- ≈500 users, small experiments, about 60 experiments per year
- 66% of CERNs protons go to ISOLDE (<0.03% go to LHC)
- 51 years of physics at ISOLDE!

Nuclear Physics at ISOLDE

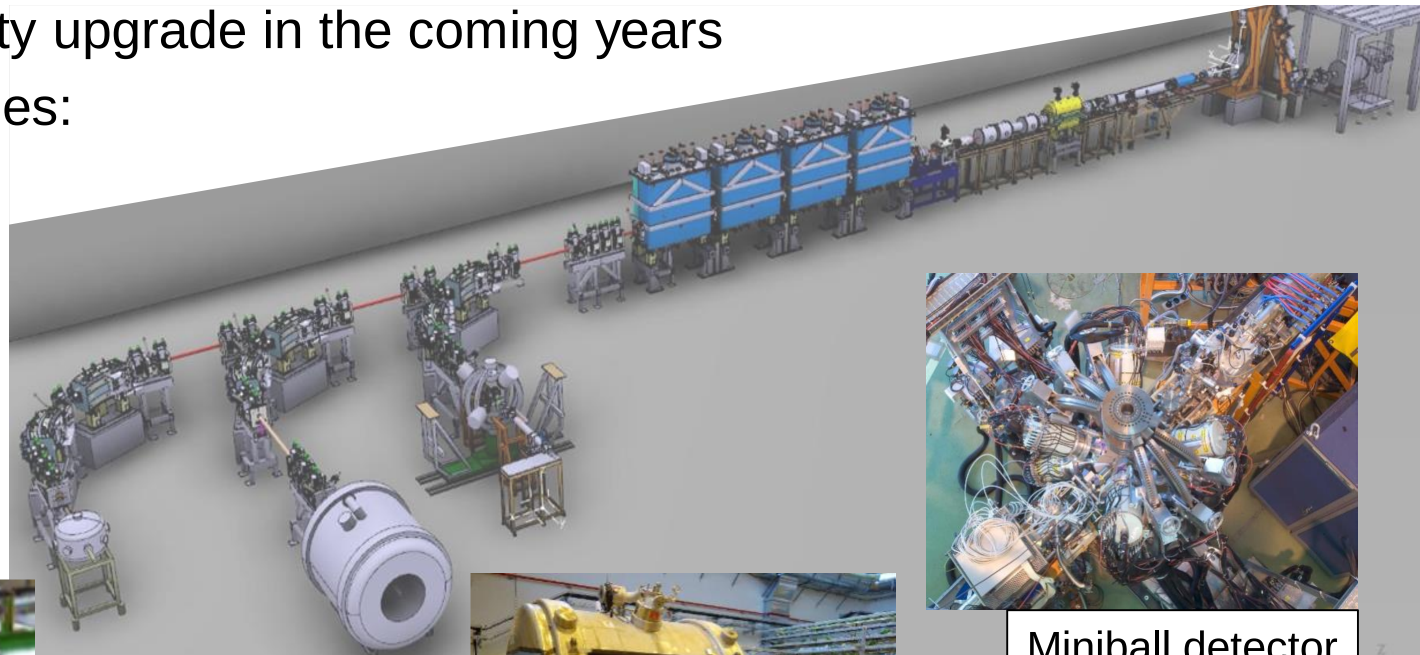
- How to create radioisotopes that do not exist on earth?





HIE-ISOLDE: High Energy and Intensity upgrade

- Superconducting linear accelerator (HIE-linac) to increase the energy from 2.8 MeV per nucleon to 10 MeV/u in summer 2018.
- Upgrade in stages:
  - first HIE-ISOLDE beams in 2015
  - intensity upgrade in the coming years
- 3 beamlines:



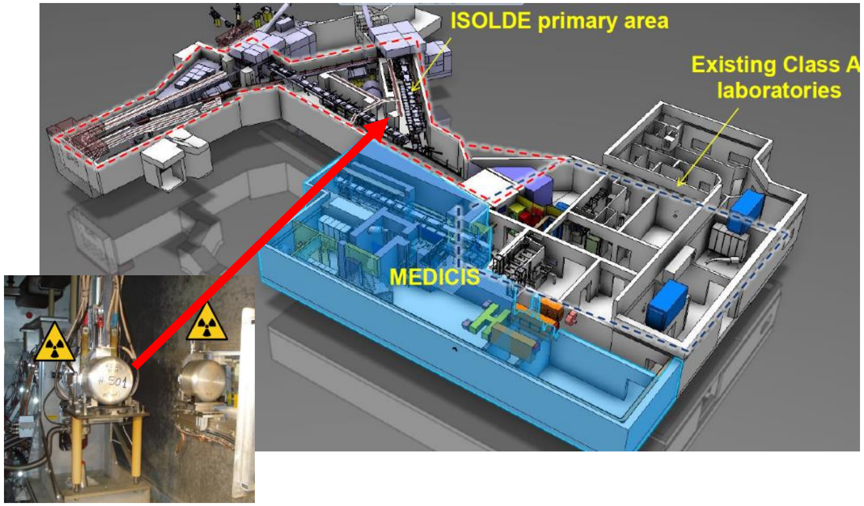
Miniball detector

Scattering chamber

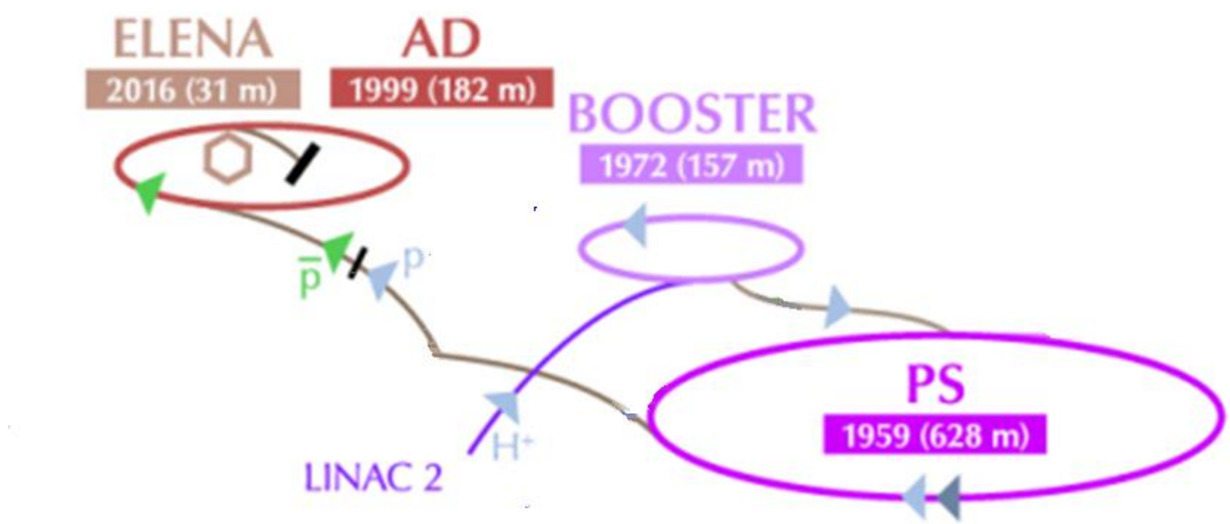
Superconducting solenoid

Medical Isotopes Collected from ISOLDE

- Fundamental studies in cancer research
- Produce and test unconventional radioisotopes for the development of new imaging and therapy protocols
- Isotopes produced at ISOLDE / MEDICIS are mainly to be delivered to hospitals and research centres in Switzerland and Europe.
- The first batch produced in the new facility (December 2017) was Terbium ^{155}Tb, which is considered a promising radioisotope for diagnosing prostate cancer, as early results have recently shown.

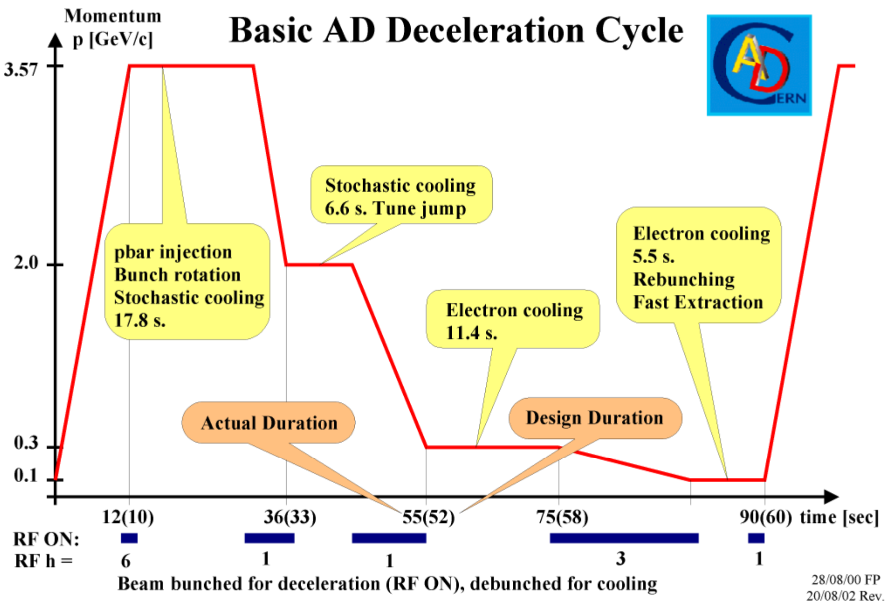


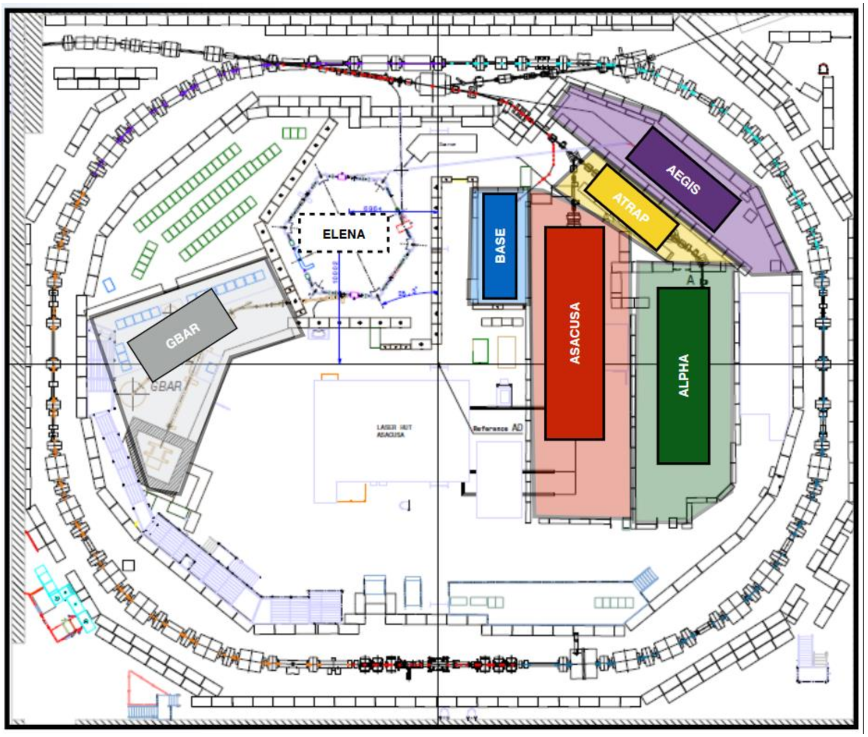
Antiproton Decelerator



AD – Antiproton Decelerator

- PS protons at 26 GeV/c on target
- Antiprotons captured at 3.57 GeV/c
- Deceleration and cooling
- Extraction of 2-4 10^7 antiprotons at 100 MeV/c (5.3 MeV) every ~100s for

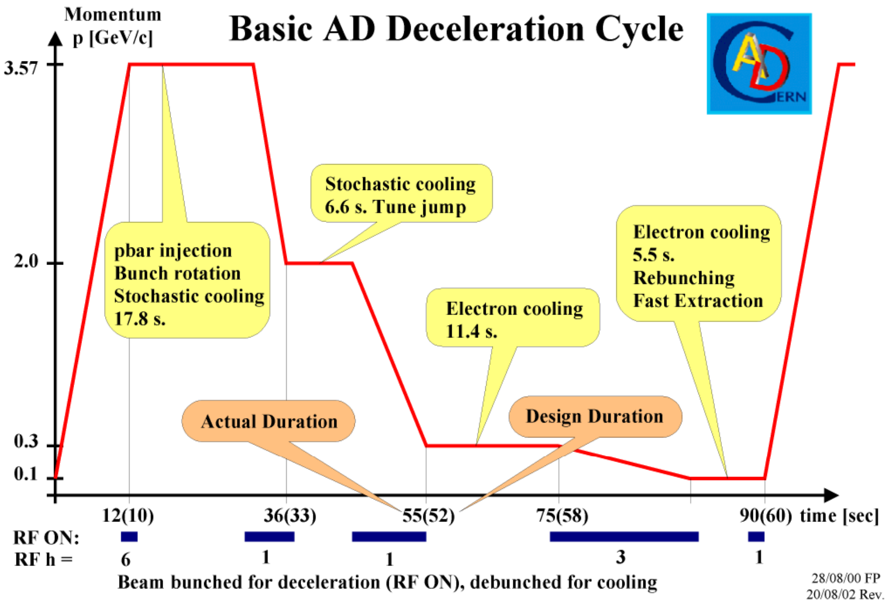


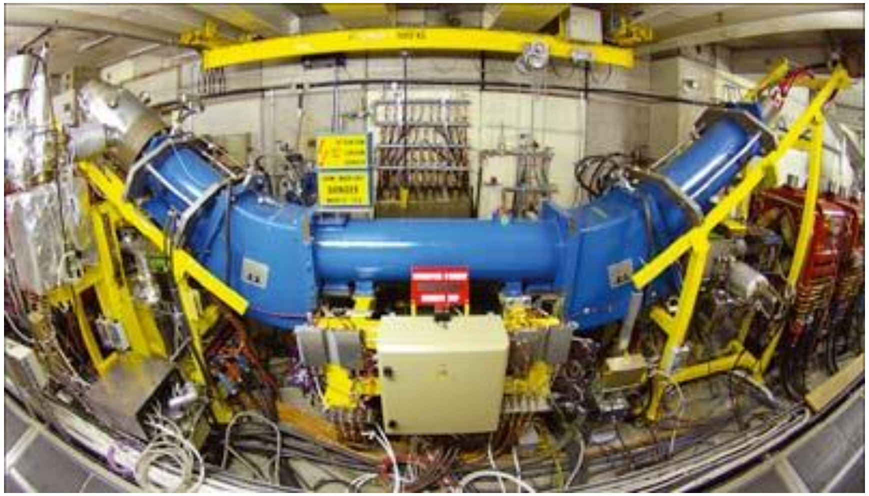


AD – Antiproton Decelerator

Stochastic Cooling

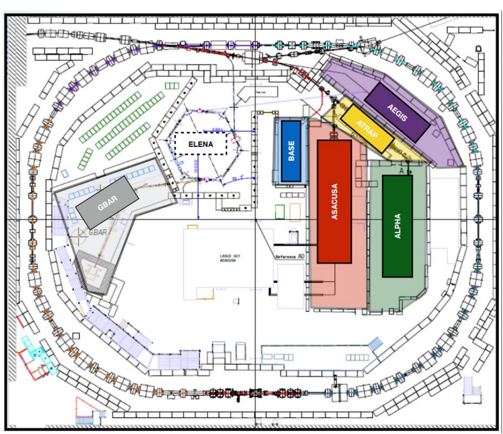
- Invented at CERN by Simon van der Meer
  → discovery W, Z bosons
  → Nobel Prize 1984
- Cooling power decreases with decreasing energy
  → Electron Cooling

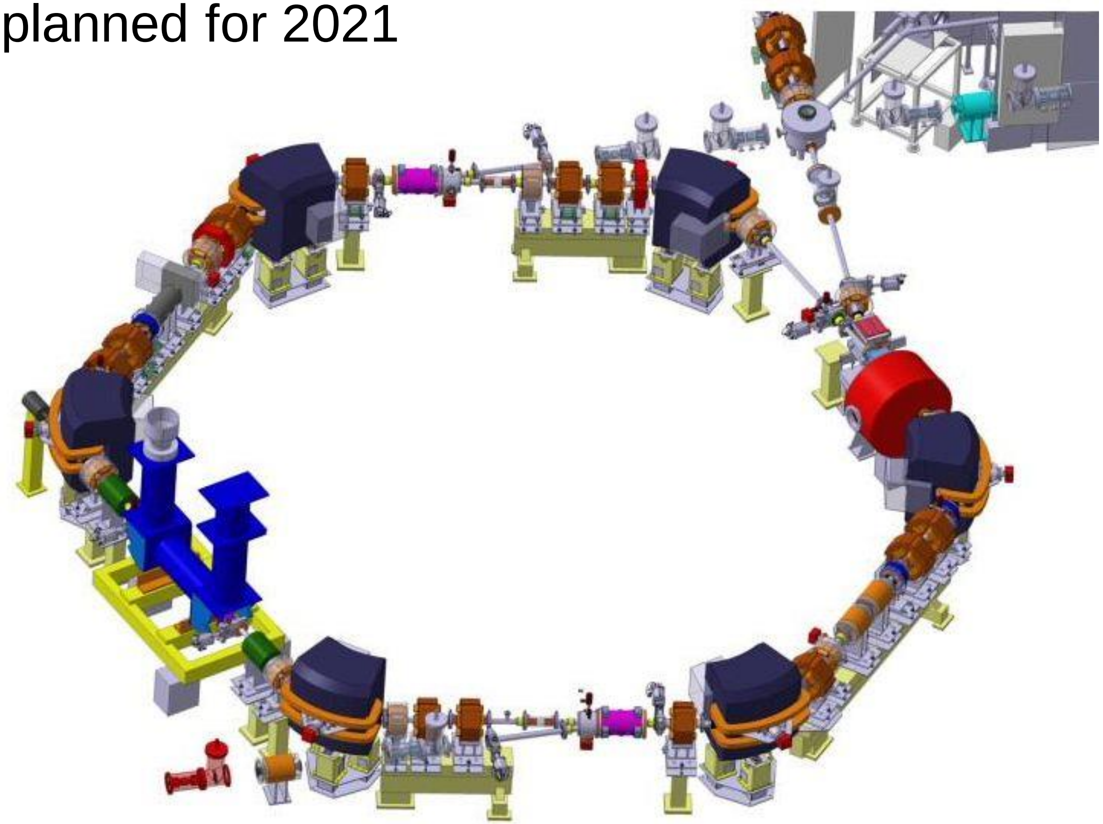




ELENA

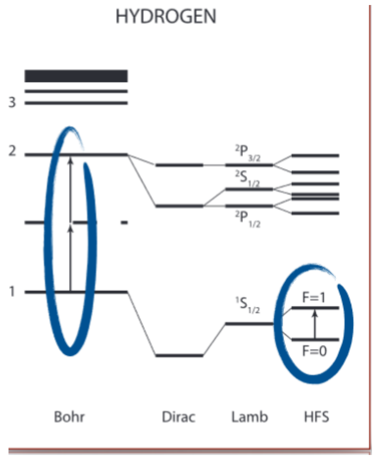
- Deceleration from 5.3 MeV to 100 keV
- Improve capture efficiency of experiments - new types of experiments (GBAR) become possible
- Currently being commissioned
- Delivery of antiprotons planned for 2021

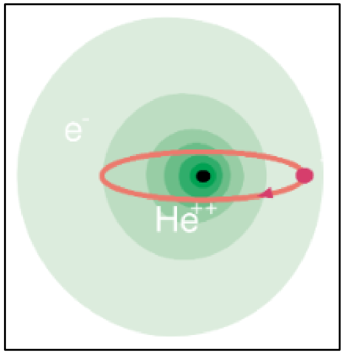




Aim of AD Experiments

- Main goals: compare Hydrogen to Antihydrogen
  - Comparison of hydrogen and antihydrogen atomic spectra: CPT symmetry test to 10^{-13} using mK atoms / antiatoms
  - Gravity for antimatter?
- Secondary goals: compare proton and antiproton (CPT symmetry), evaluate radiation-therapy potential of antiprotons, …



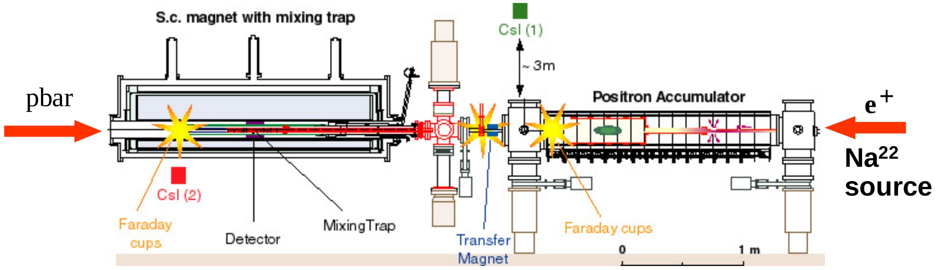


Spectroscopy on antihydrogen and more exotic objects

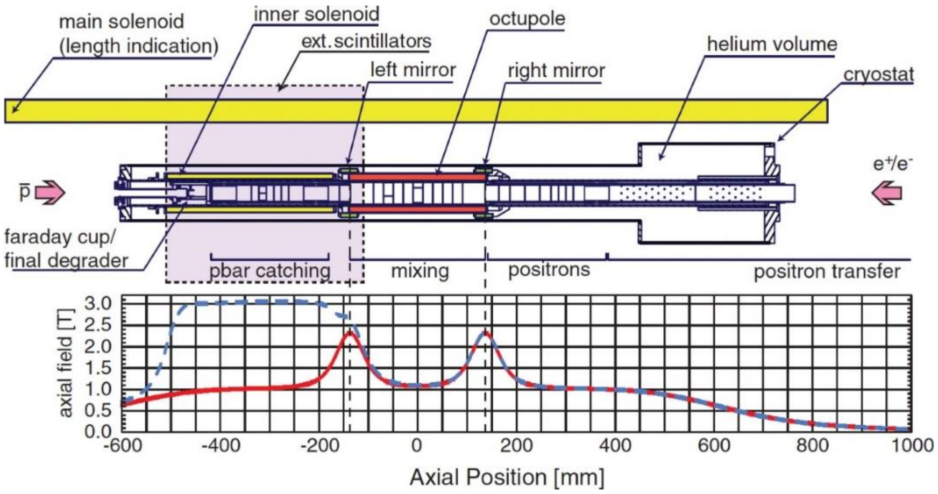
Gravitational Experiments

Experiments at the Forefront of Ion and Atom Trapping

- Performance of ion and atom traps:
  - BASE – ion trap:
    - lifetime for trapped antiprotons > 10 years
    - vacuum ≤ 2 10^{-18} mbar



  - ALPHA – use the magnetic moment to trap atoms:
    - very weak trapping force
    - lifetime of trapped antihydrogen ≥ 1 day
    - accumulation of several 100 antihydrogen atoms with 1 day of stacking



Fields of Interest / Collaboration Options AD Experiments

- Atom Physics
- Laser Spectroscopy
- Cryogenics
- Vacuum technology

- Quantum computing / surface ion traps

- Material Science
  - Nanostructures
  - Precision mechanics in the µm range
  - Thin film surface coatings

- RF technology in the µm wavelength range
- Low noise cryogenic electrical amplifiers

- Potential New Developments:
  - Development of (tunable) cavities:
    - 25.4 GHz
    - 203 GHz
  - Portable cryogenic ion trap for antiprotons
  - Low noise cryogenic electrical amplifiers in the temperature range:
    - 4-10 K
    - 100 mK

Summary

- LHC from operational viewpoint: Luminosity, luminosity, …
- How to increase / decrease instantaneous luminosity
- How to increase integrated luminosity
- 2018 proton physics
- High luminosity upgrade of the LHC

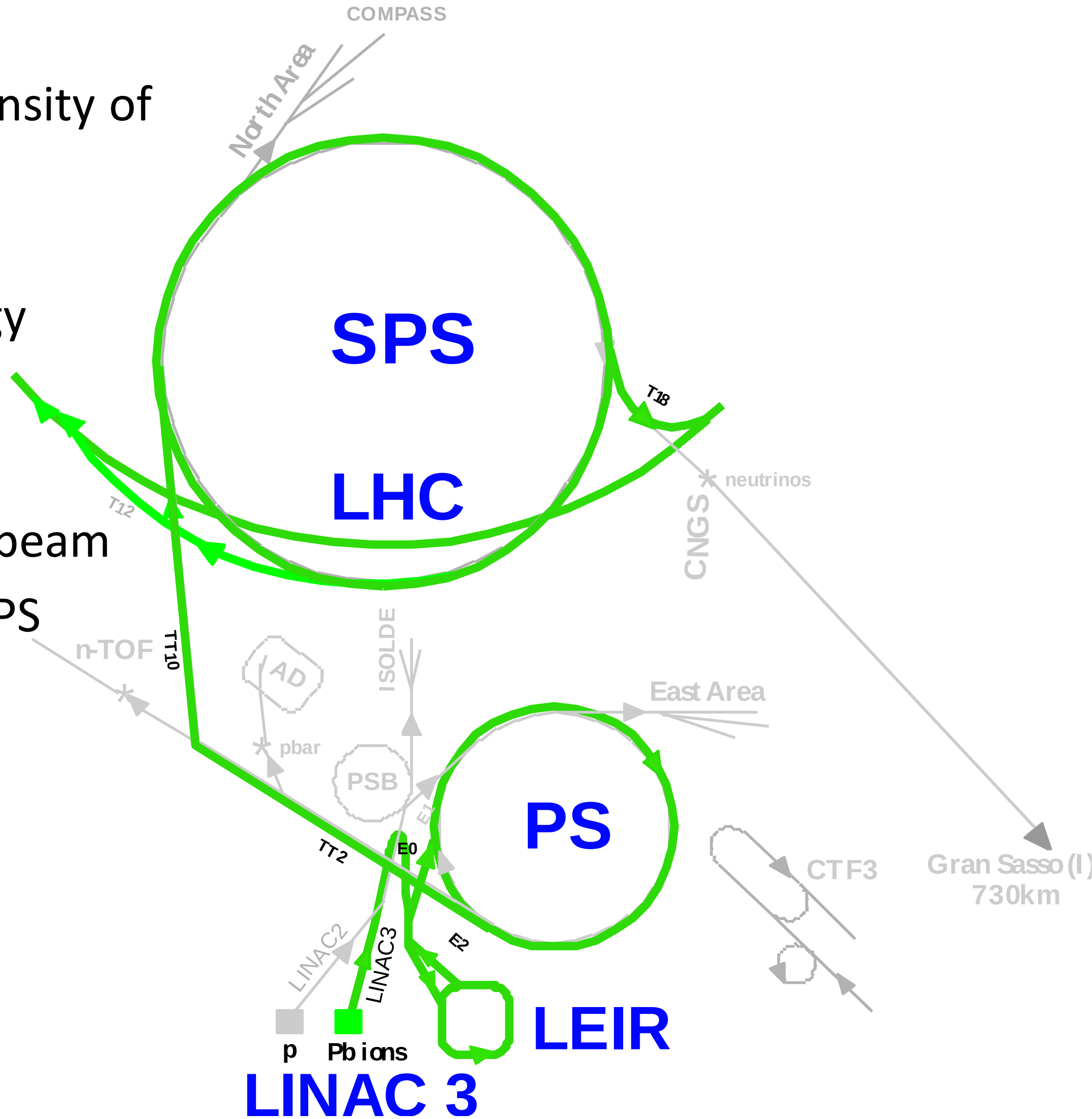
- Outside the LHC
  - ISOLDE – versatile tool from nuclear physics to medical research
  - Antiproton Decelerator – antimatter for fundamental research

THE

END

LHC Ion Injector Chain

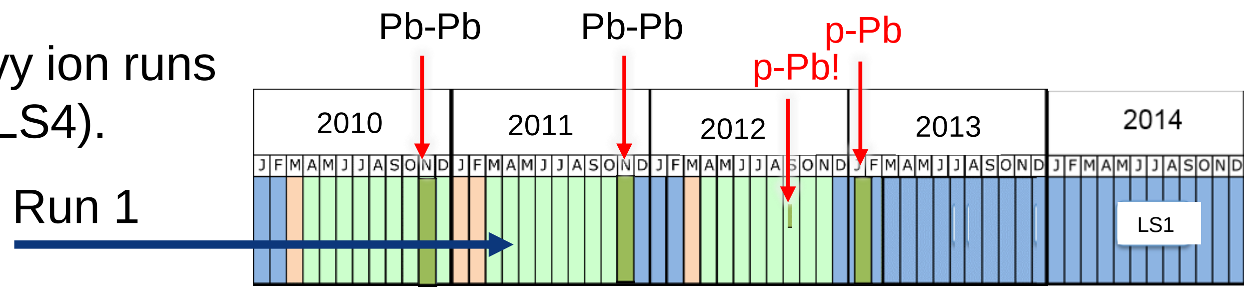
- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC

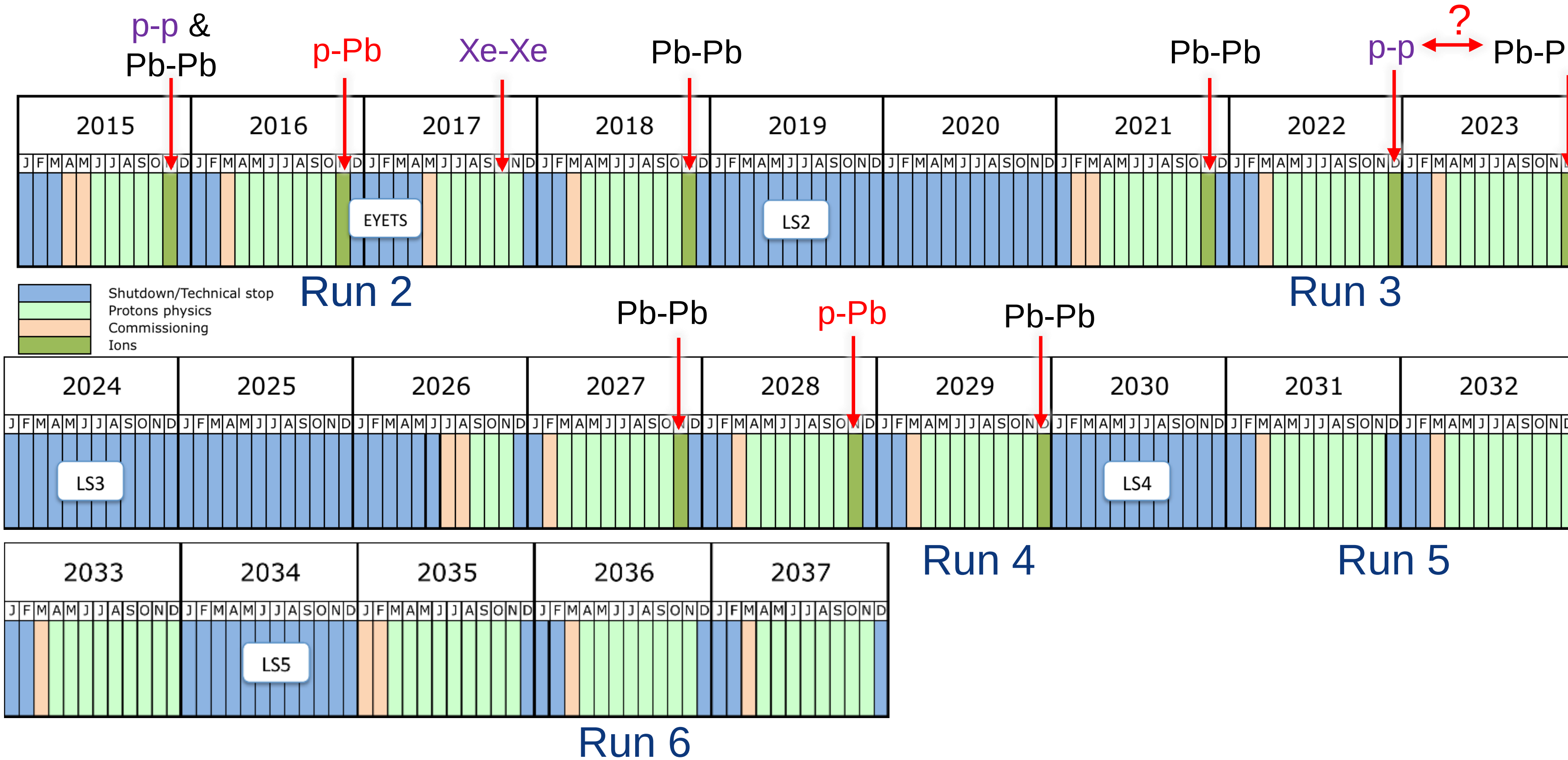


LHC heavy-ion runs, past & future

LHC :12 ~one month heavy ion runs between 2010 and 2030 (LS4).

Five done already.





Integrated nucleon-nucleon luminosity in Run 1 + 2015

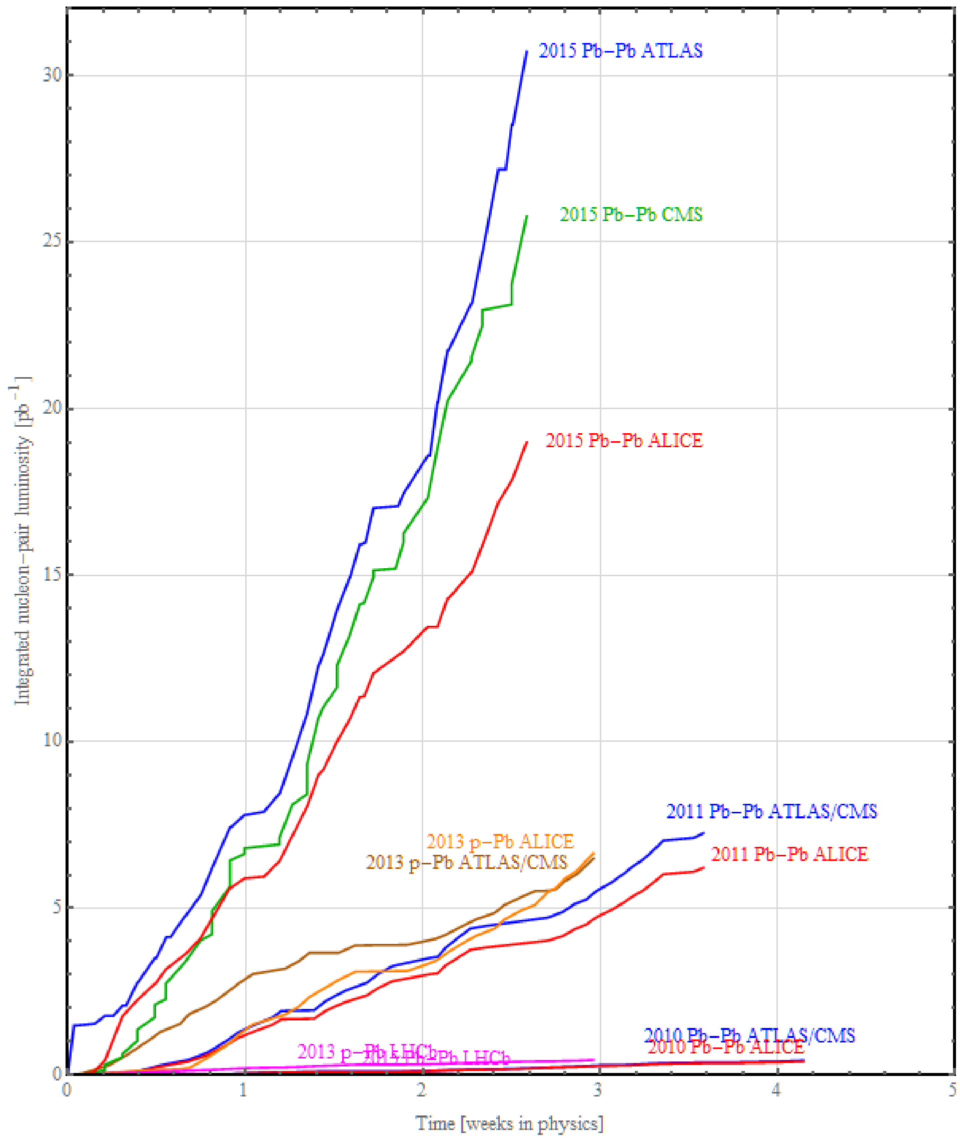
Expect to achieve LHC "first 10-year" baseline Pb-Pb luminosity goal of $1\ \mathrm{AA\ nb}^{-1} = 43\ \mathrm{NN\ pb}^{-1}$ in Run 2 (=2015+2018)

Goal of the first p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs but it already provided reference data at 2015 energy.

$$\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$$

$$\Rightarrow E_b = \begin{cases} 6.37 Z\ \mathrm{TeV} & \text{in Pb-Pb} \\ 4\ Z\ \mathrm{TeV} & \text{in p-Pb} \end{cases}$$

But annual 1-month runs are getting shorter and more complicated … 2015 included p-p reference data and included LHCb.



2012 pilot p-Pb run not shown

Proton-nucleus programme status

Feasibility and first p-Pb run at 4 Z TeV in 2012/13.

Complex 2016 run plan determined after Chamonix 2016:

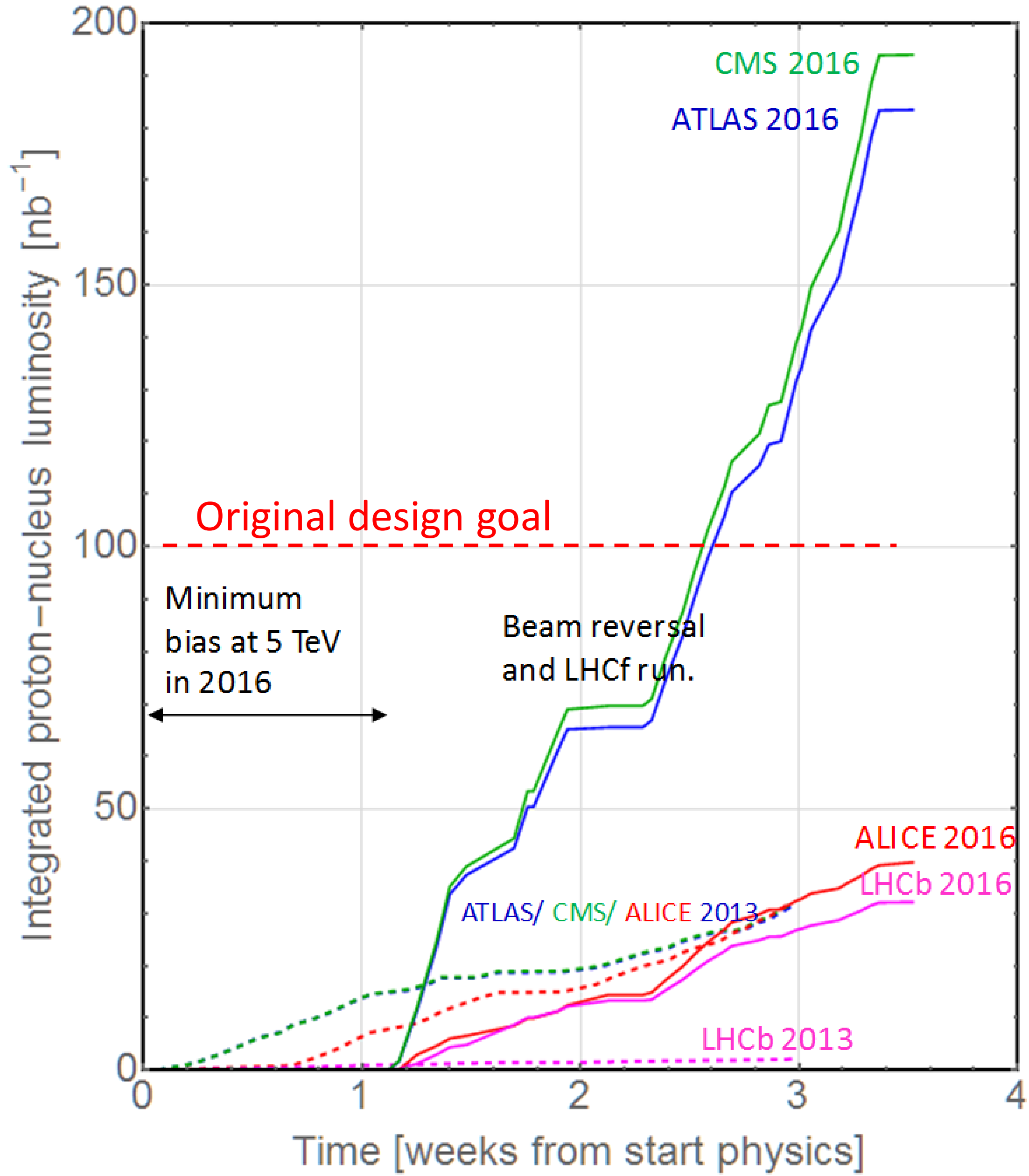
Minimum bias run at 4 Z TeV mainly for ALICE

High luminosity run for all experiments (+LHCf) at 6.5 Z TeV, with beam reversal p-Pb and Pb-p.

Ie, 2 new optics and 3 setups with full qualifications in 1 month.

Asymmetric beams, unequal frequency ramp, cogging for collisions off-momentum, etc.

Many filling schemes used for luminosity sharing.

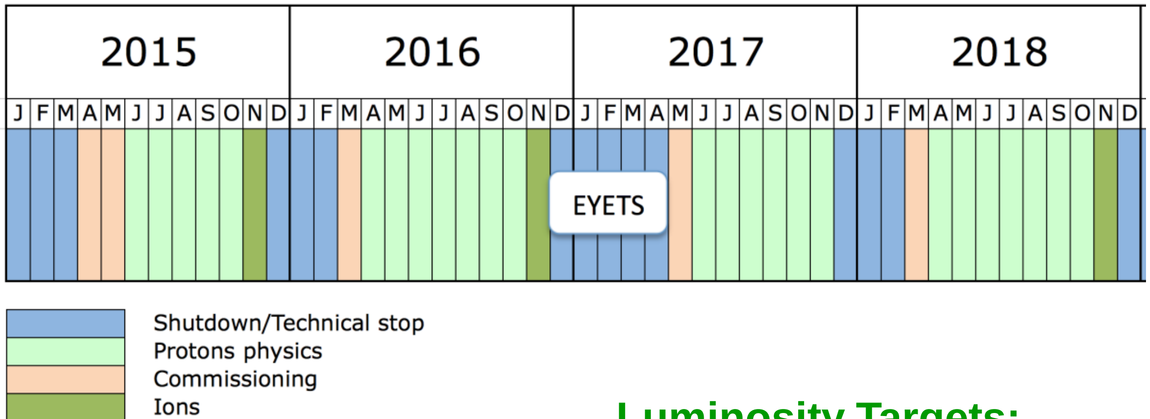


Summary

- LHC heavy-ion programme is already well into the “HL” regime
- Nucleus-nucleus (Pb-Pb) programme:
  - Peak luminosity was >3 × design in 2015
  - Expect to exceed 1 nb^{-1} integrated luminosity design goal (for 2 experiments) in 2018 in ALICE, ATLAS, CMS
  - now expected to reach 10 nb^{-1}++ goals set out in ALICE 2012 Letter of Intent with similar in ATLAS/CMS (+ fraction for LHCb?).
- Proton-nucleus (p-Pb) programme:
  - Peak luminosity was ~8 × “design” in 2016
  - Attained almost twice the 0.1 pb^{-1} integrated luminosity “design” goal in 2 experiments (+ several other physics data-sets for 5 experiments including large minimum-bias data set for ALICE)
  - Clear path to higher integrated luminosity in 3, possibly 4, experiments
- Short low-luminosity runs with new beams are feasible
  - See p-Pb (2012), Xe-Xe (2017)

LHC Run 2 and Run 3

- Schedule and integrated luminosity:

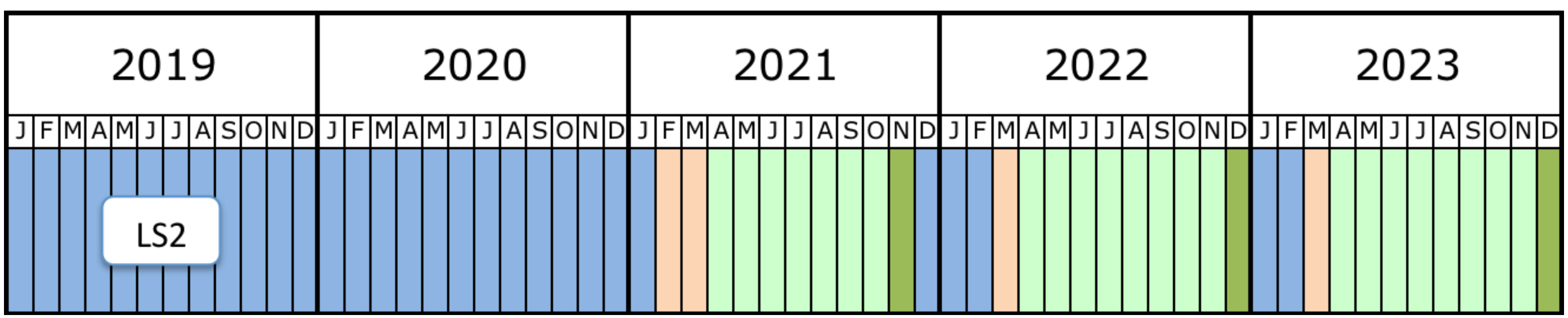


Period	**Delivered** Int. Luminosity [fb^{-1}]
Run 1	**29.2**
Run 2: 2015	4.2
Run 2: 2016	39.7
Run 2: 2017	50.2
Run 2: 2018	60
Total Run 2	**> 154**
Total Run 1 + 2	**> 183**

Luminosity Targets:

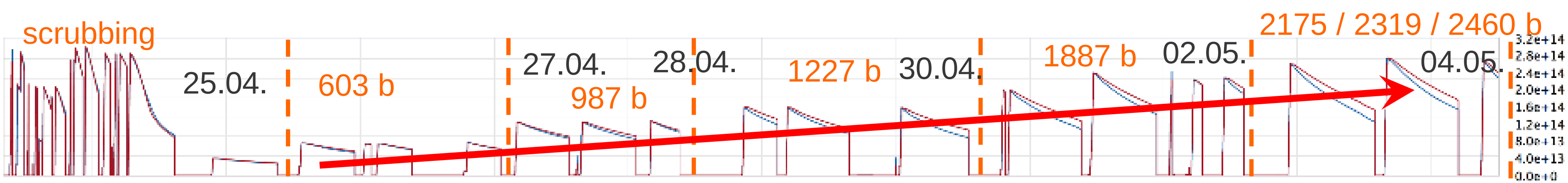
∑(Run1 + Run2) >150 fb^{-1}

∑(Run1 + Run2 + Run 3) > 300 fb^{-1}



Smooth and Fast Commissioning

- Very efficient commissioning and intensity ramp-up
  - took ≈2/3 of the time compared to 2017 and
  - reached full number of bunches ahead of 2018 schedule



Intensity ramp up plan: 3 – 12 – 72 – 300 – 600 – 900 – 1200 – 1800 – 2400 – 2550

Establish cycle
Machine Protection dominated
Intensity dominated