
CERN

Accelerators (2)

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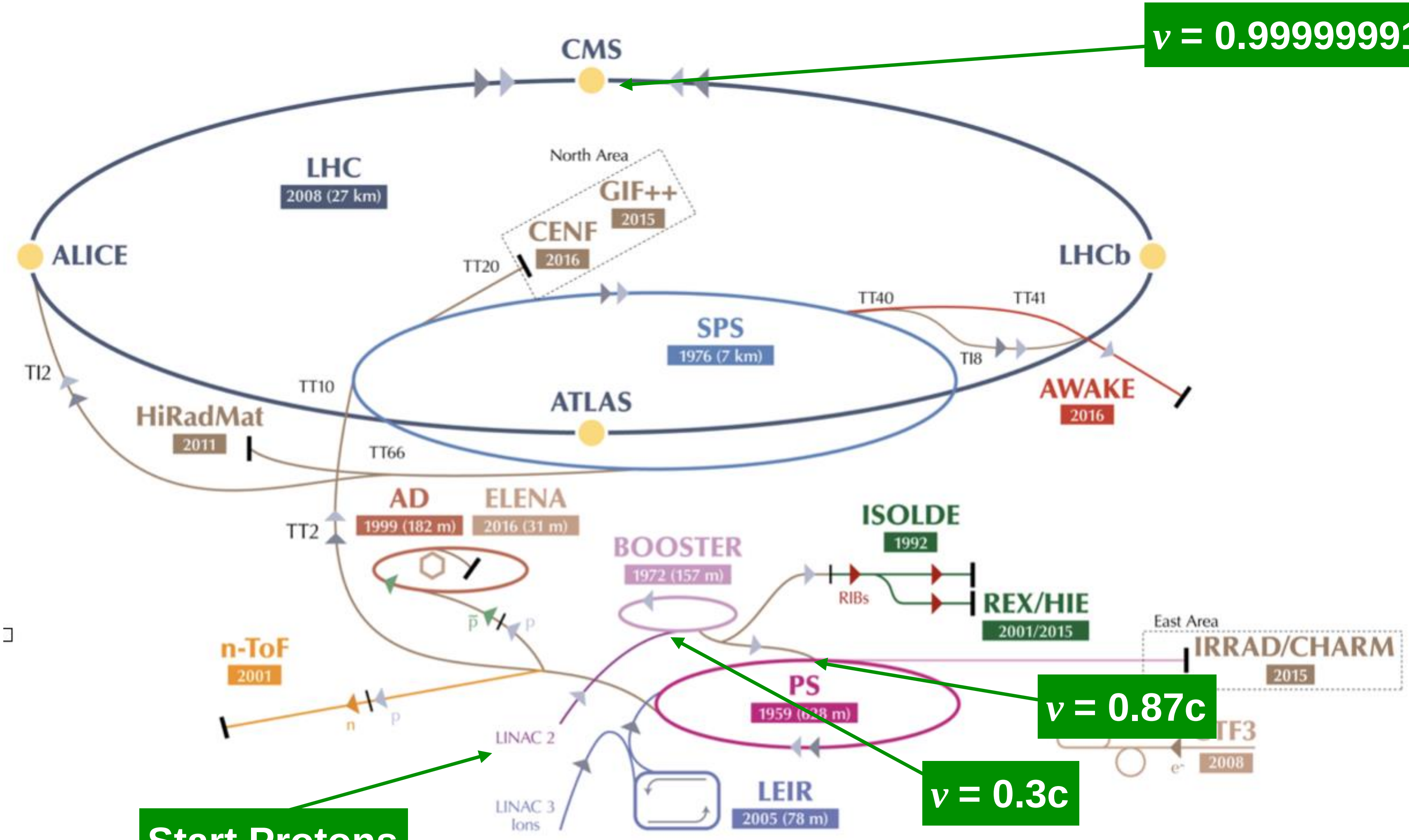
CERN BE-BI-BL

14th joint CERN-Fermilab Hadron Collider Physics Summer School
2 September 2019

Outline

- ❑ Day 1:
  - ✶ Basic accelerator concepts
  - ✶ CERN Complex
- ❑ Day 2:
  - ✶ LHC
  - ✶ HL-LHC (upgrade v2)
  - ✶ Future projects: FCC and CLIC

CERN injection Complex



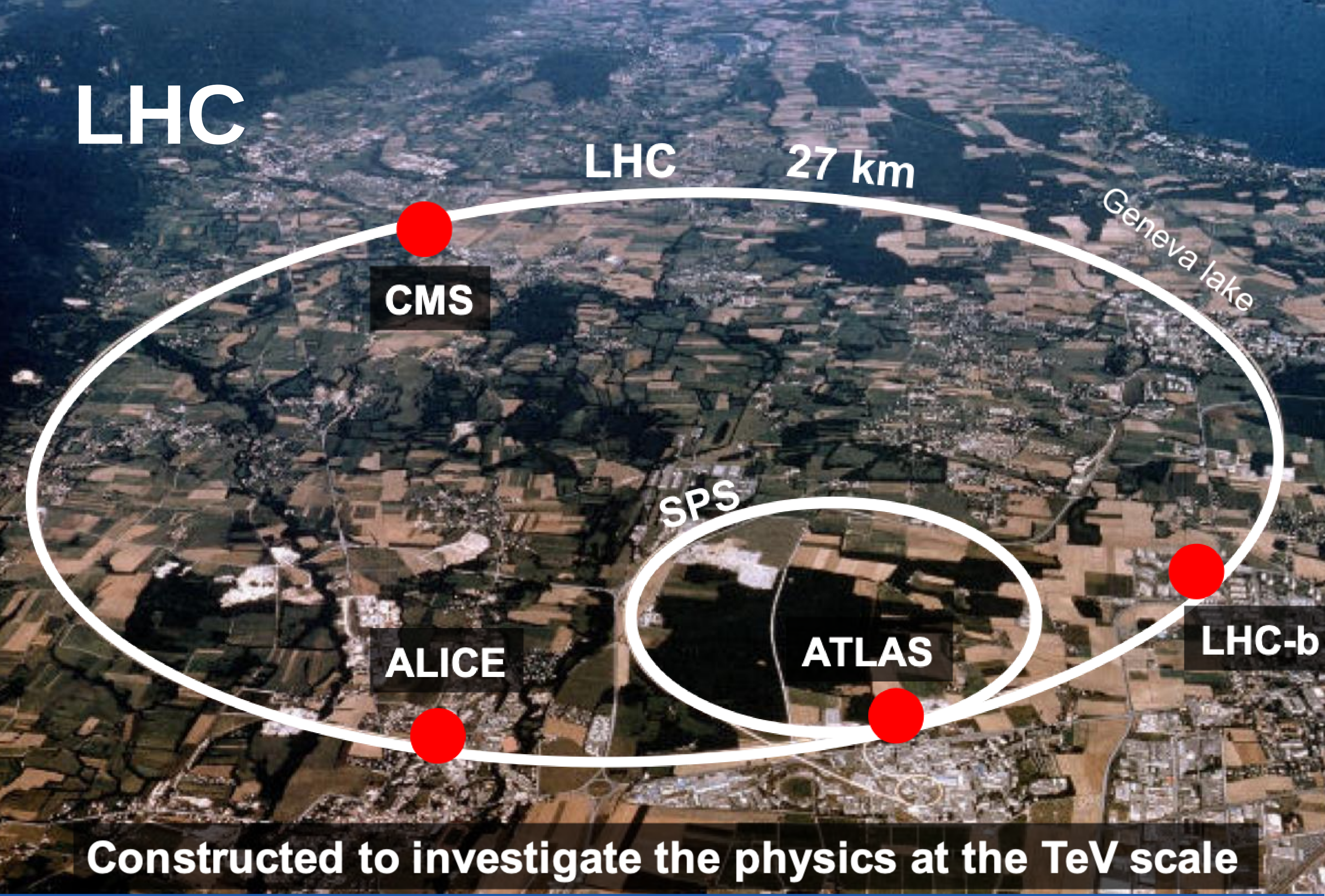
v = 0.99999991c

v = 0.87c

v = 0.3c

Start Protons

LHC



Constructed to investigate the physics at the TeV scale

LHC dipole field for 7 TeV

What is the needed dipole field to keep the protons circulating in the 27 km ring?

Magnetic rigidity $\rightarrow \; 0.3B[\mathrm{T}] \approx \dfrac{p[\mathrm{GeV}/c]}{\rho[\mathrm{m}]}$

The radius of the circumference cannot be just *27km/2π* as we need space for the detectors, RF, injection and extraction regions and collimation (so-called straight sections).
Approx. 2/3 of LHC ring are dedicated to the bending

$$\rho \approx 2.8 \text{ m} \approx \frac{0.65 \times 26.7 \text{ km}}{2\pi}$$

$$B[\mathrm{T}] \approx \frac{7000\mathrm{GeV}/\mathrm{c}}{0.3 \times 2.8 \text{ m}} = 8.33 \text{ T}$$

LHC Nominal dipole field 8.33 T

LHC super-conducting dipoles

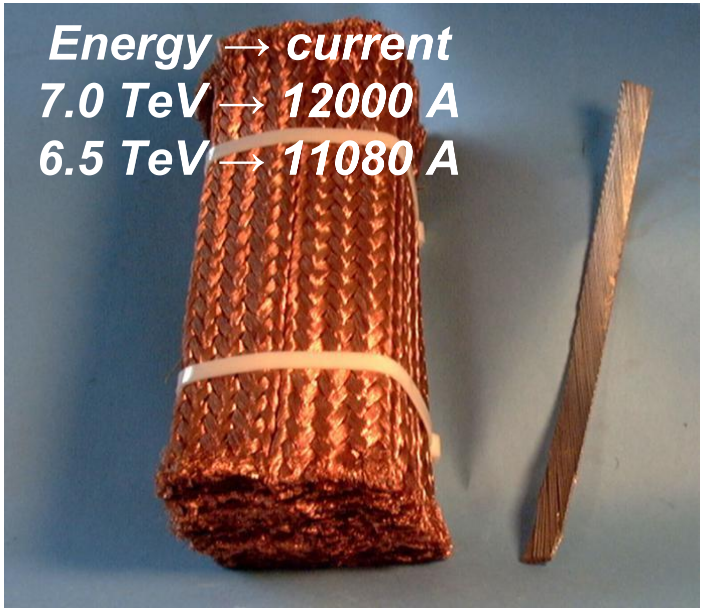
Previous machines use super-conducting magnets:

- ✴Tevatron at FNAL 1987 - 2011: proton-antiproton collider
- ✴HERA at Desy 1992 -2007: hadron-electron collider
- ✴RHIC at BNL 2000 - present : relativistic heavy-ion collider

All used NbTi cooled with He at 4.2K with a maximum B-field ~ 5 Tesla

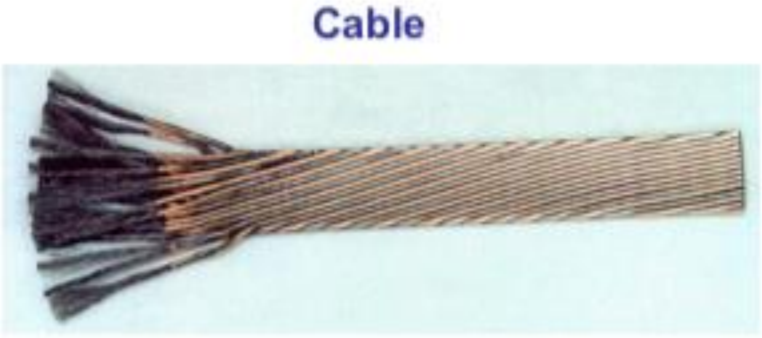
LHC also uses Nb-Ti (Cu clap) used but **to push the performance they are cooled to 1.9K using super-fluid He**.

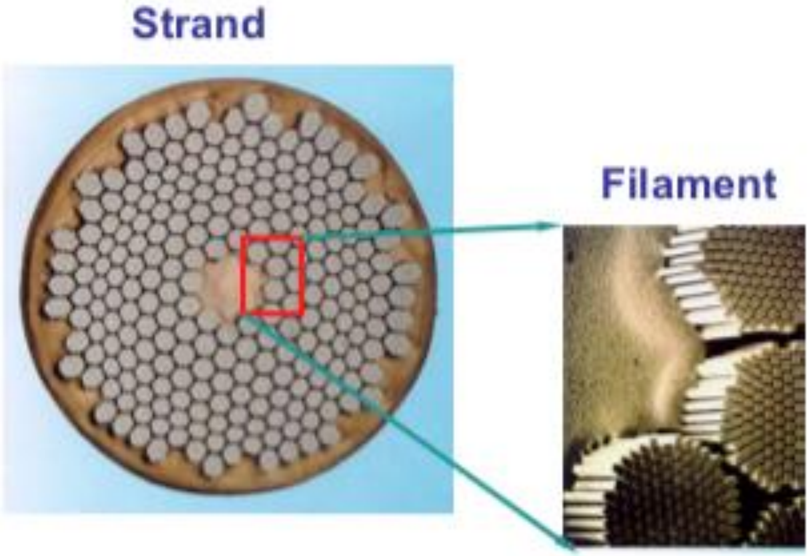
With the drawback that a **very small energy deposition** (by beam interaction in the surroundings) or **the slightest microscopic movement of the conductor** could create a **magnet quench** (loosing super-conductivity). *unless the fault was detected quickly and the current turned off.*



Energy → current
7.0 TeV → 12000 A
6.5 TeV → 11080 A

Niobium-Titanium Rutherford cable





Total superconducting cable required 1200 tonnes which translates to around 7600 km of cable.

The cable is made up of strands which is made of filaments, total length of filaments would go 5 times to the sun and back with enough left over for a few trips to the moon.

LHC cross-section

Re-use the LEP tunnel constrained the size of the magnet using the **two-in-one design**.

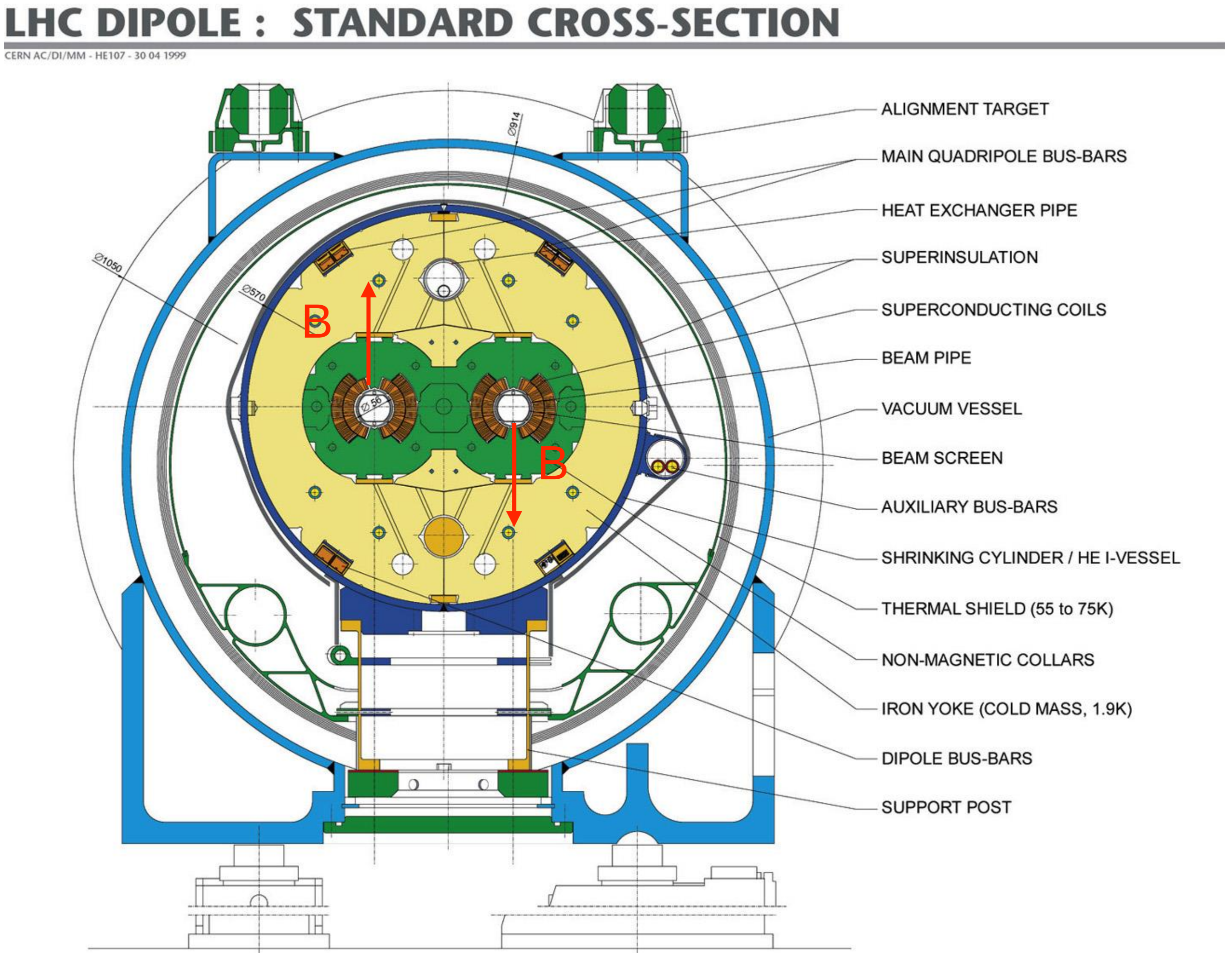
Two beam channels in a common cold mass cryostat and magnetic flux in opposite sense.

Complex design.

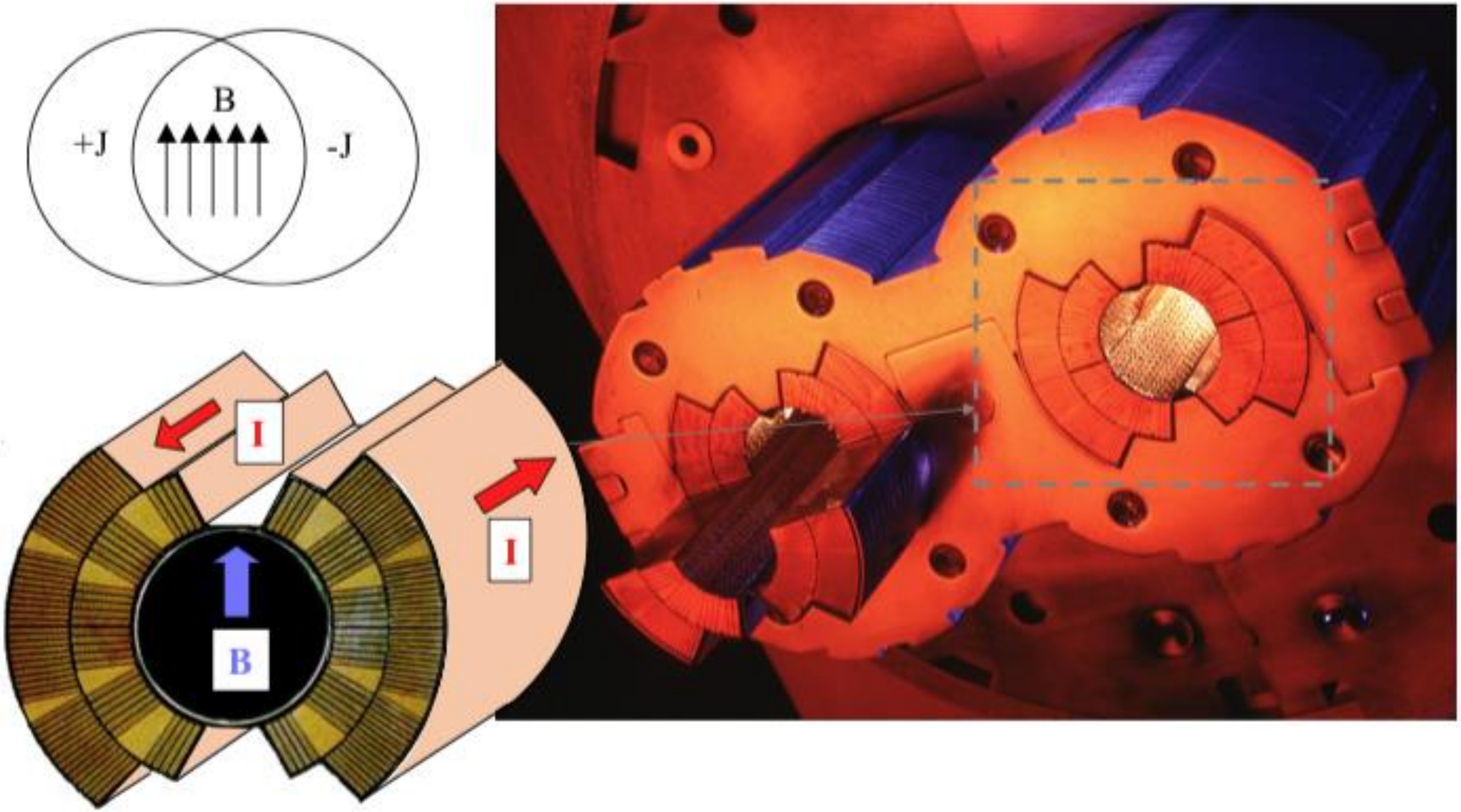
Dimensions os the dipole beam screen are:

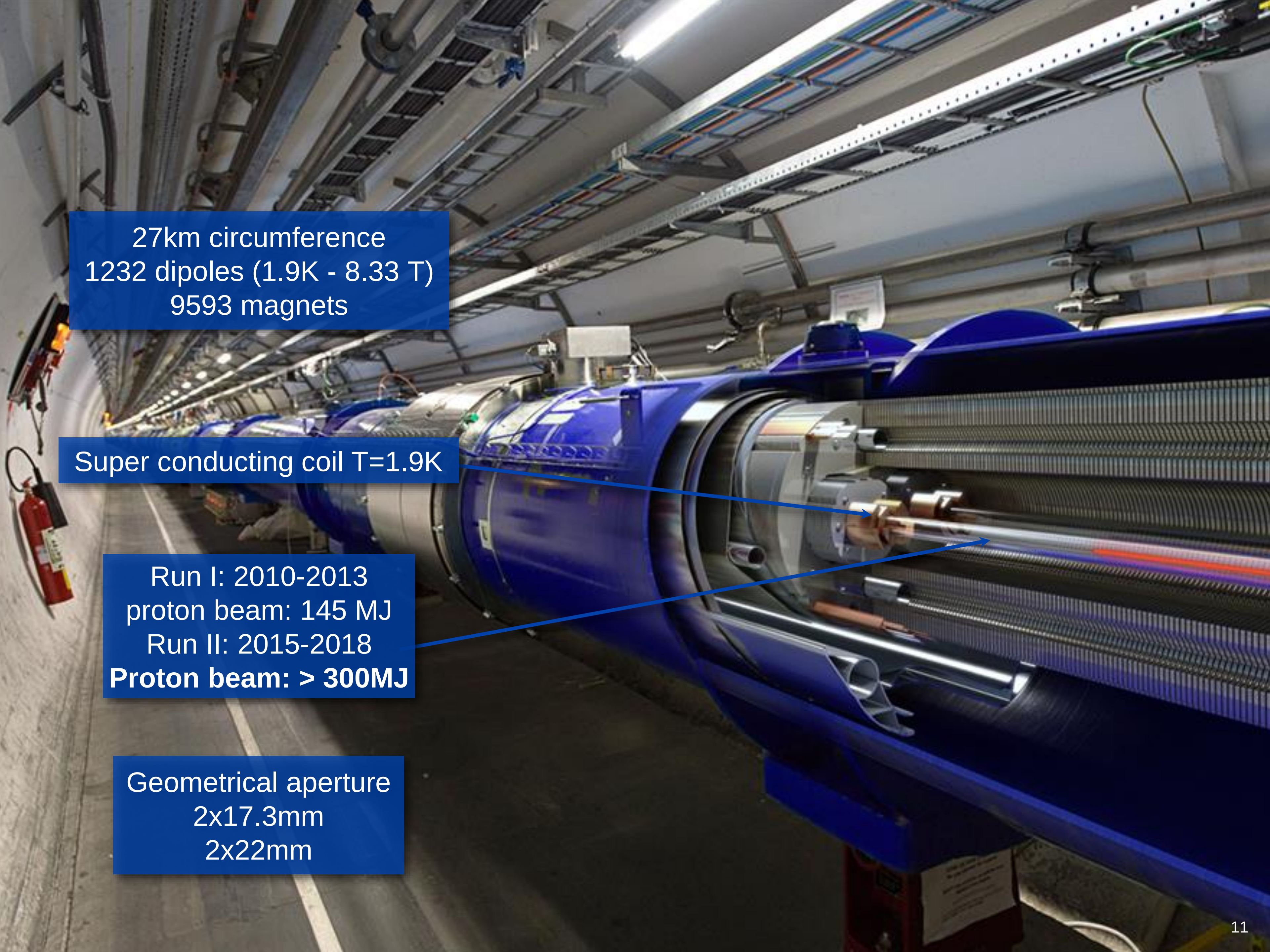
22 mm horizontal

17 mm vertical



LHC dipole





27km circumference
1232 dipoles (1.9K - 8.33 T)
9593 magnets

Super conducting coil T=1.9K

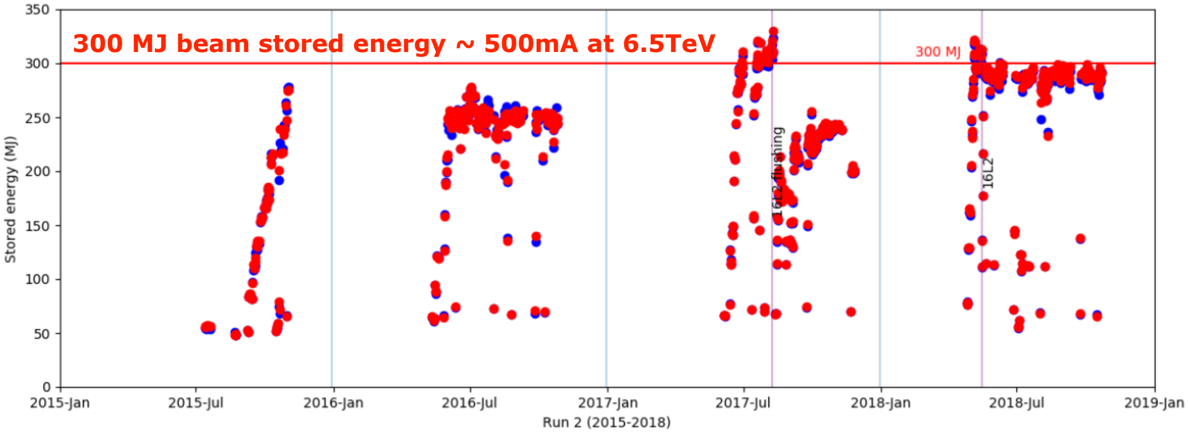
Run I: 2010-2013
proton beam: 145 MJ
Run II: 2015-2018
Proton beam: > 300MJ

Geometrical aperture
2x17.3mm
2x22mm

2018 LHC stored energy

Energy depositions **at 6.5TeV ~ 100 mJ/cm^3 risk to initiate a quench.**

During **2018** circulating beam intensities reached **~300MJ at 6.5TeV**



At 6.5 TeV with about 3e14 proton beams, a tiny fraction of beam, 0.00002%, could quench a magnet (~ 6e7protons)

A quench without damage will require ~ 10 hours of cool down time to recover the cryogenic conditions. With damage > 3 months.

SPS 2008. **400GeV** **2MJ**
J.Wenninger, CERN-BE-2009-003-OP

Beam Losses at LHC

- A tiny fraction of the full beam is enough to damage equipment
- Therefore, a very control of beam losses is mandatory to ensure safe LHC operation

Normal Losses

They can be minimised but **cannot be avoided completely**
Due to beam dynamics: particle diffusion, scattering processes, instabilities.
Due to Operational variations: orbit, tune, chromaticity changes during ramp, squeeze, collision.

Collimation *system (smallest aperture) is designed to* ***catch*** *increased* ***beam losses up to 500kW over 10sec.***

Beam Loss Measurements that extract the beam if exceed the specified max. loss rates.

Abnormal losses

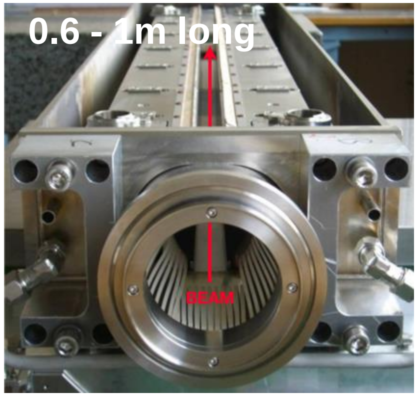
Due to failure or irregular behaviour of accelerator components.

LHC Collimation System

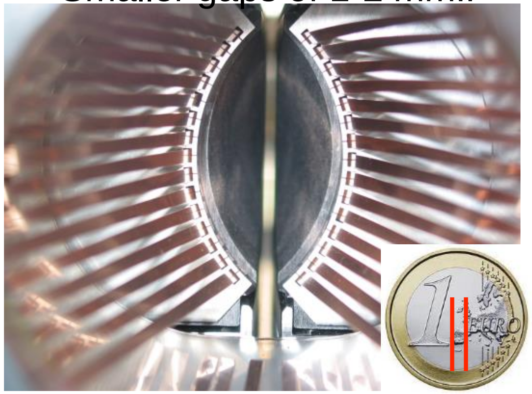
LHC Collimation system guarantees that **losses will not reach the cold region.**

Like a diaphragm in a camera, collimators are the closest elements to the circulating beam concentrating the losses in the collimation regions.

Smaller gaps of 1-2 mm!!



LHC Collimator with vacuum tank opened



Collimator Design

Two parallel jaws in a vacuum tank at different orientations.

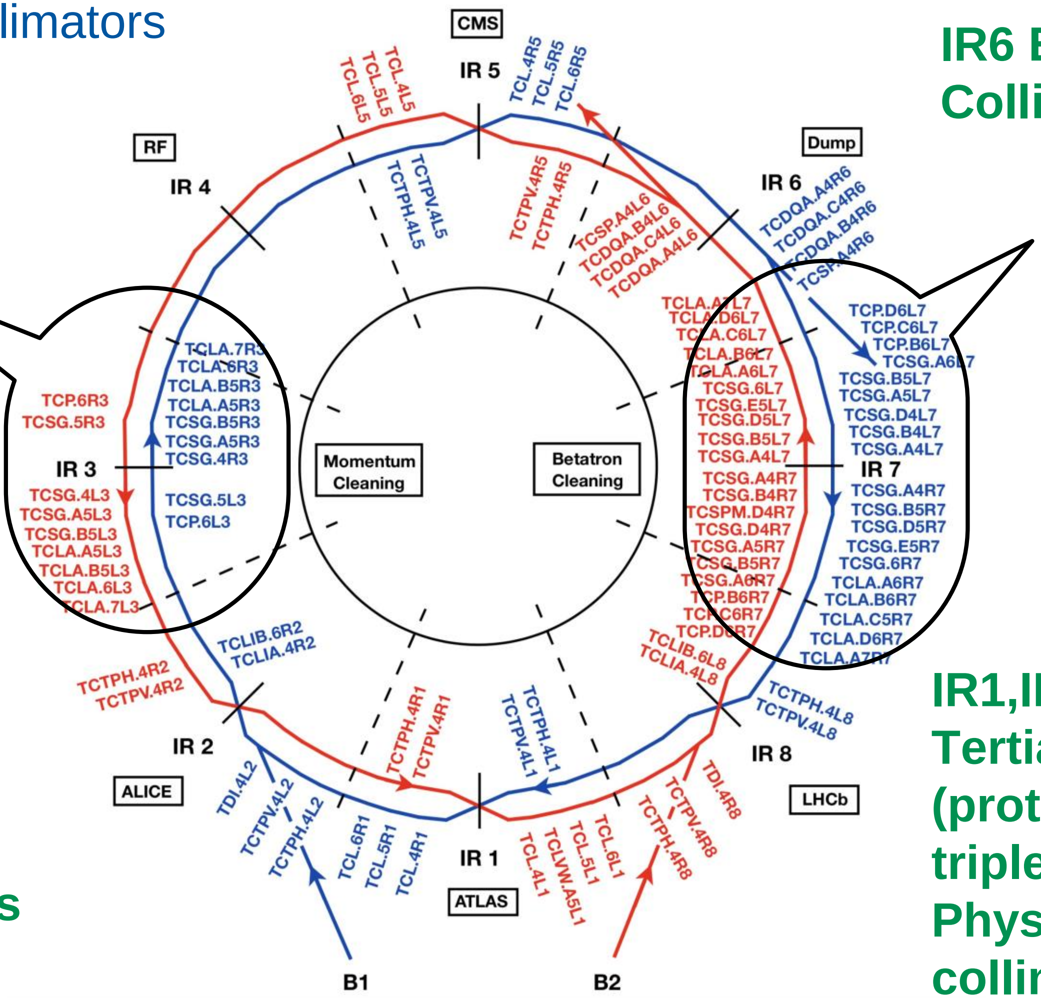
Jaw material depends on its functionality:

- ✶**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 Collimation System

108 Movable Collimators



Momentum cleaning: particles with different momentum are absorbed in this area

Main Transverse **Betatron** Beam Halo Cleaning

IR6 Extraction Collimators

IR2/IR8 Injection Protection collimators

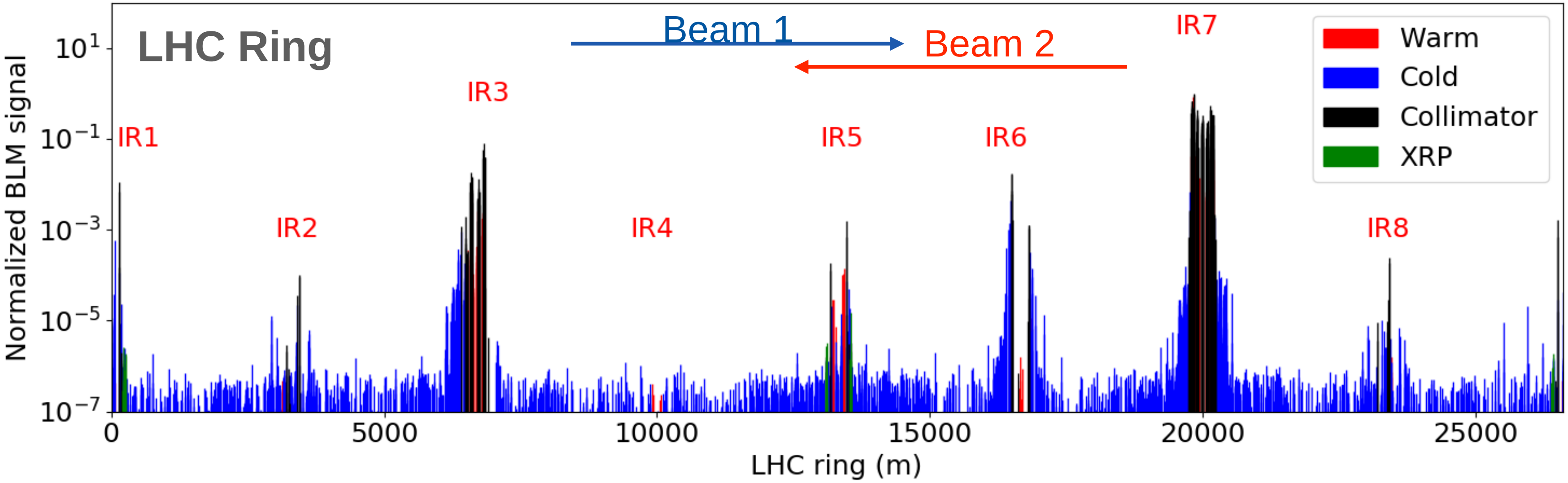
IR1,IR2,IR5,IR8 Tertiary Collimators (protecting the triplet quadrupoles) Physics Debris collimators

LHC Beam Loss Monitoring

Approximately 4000 Beam Loss Detectors distributed along the LHC covering critical locations:

- ✶Losses in the cold area: dipoles, quadrupoles, etc.
- ✶Losses at injection and extraction: transfer lines
- ✶Losses down stream each collimator.

Losses are concentrated in warm regions



LHC Beam Loss Monitors

Ionisation chamber

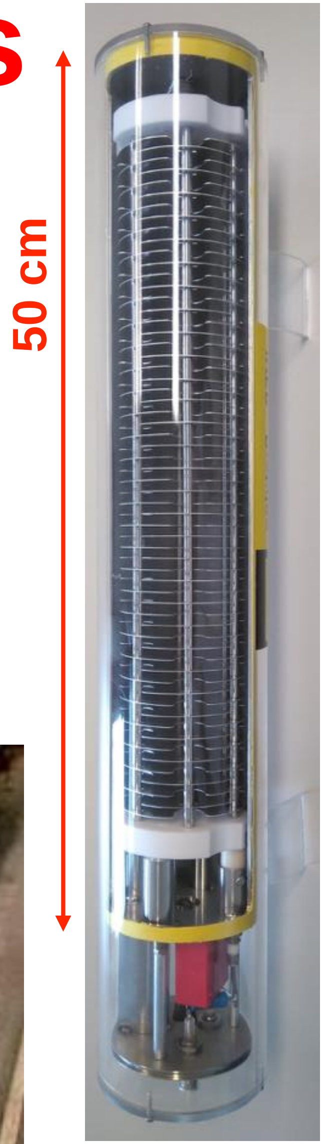
About 50cm tube with parallel aluminium electrodes plates (each 0.5 cm)
Filled with N_2 at 100mbar overpressure and HV 1.5kV
1.5L of sensitive volume

Read out

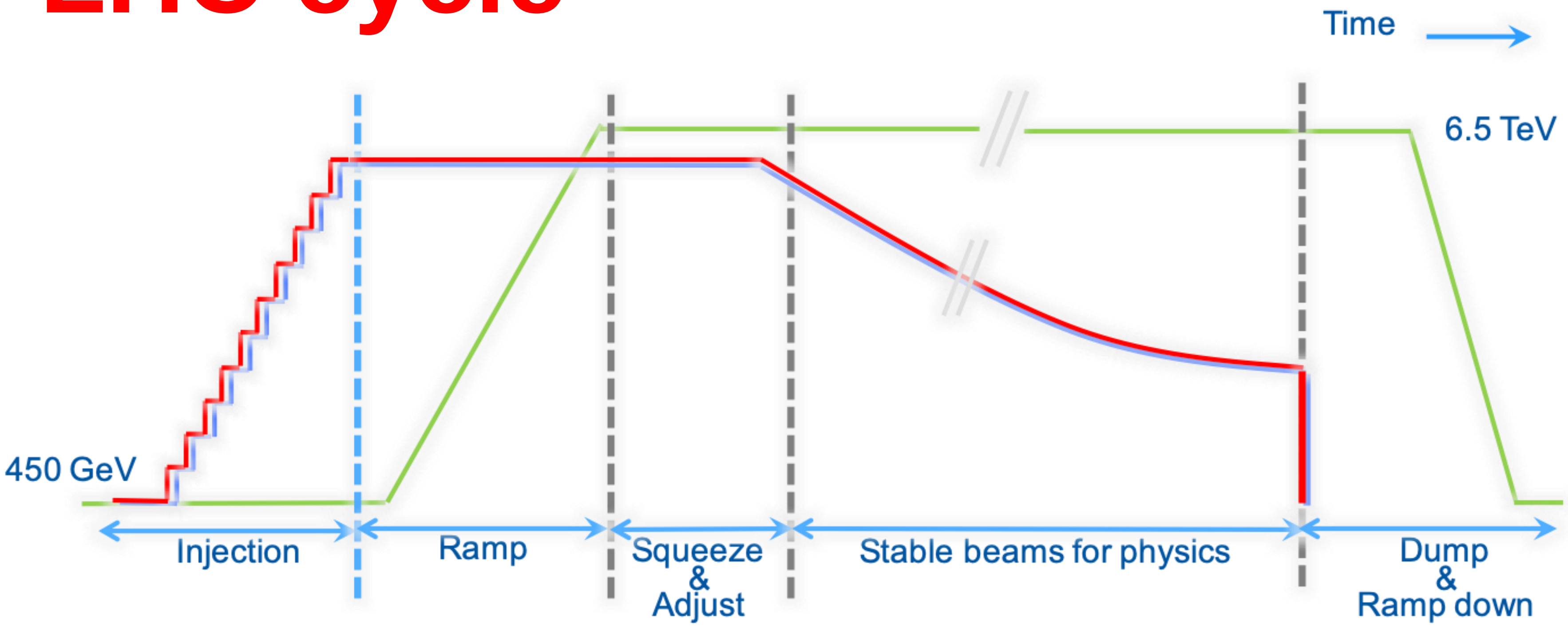
Electronics Dynamic range $>10^8$ (10 pA - 1 mA)
Measurement of Gy/s in 12 moving windows ranging **from 40 μs to 83.9 s**
Allows the setting of unique beam extraction thresholds depending on the duration of the beam loss and beam energy.

LHC turn is 89 μs

Beam extracted in ~ 3 LHC turns



LHC cycle



🟩 = Field in main magnets

🟦 = Beam 1 intensity (current)

🟥 = Beam 2 intensity (current)

The LHC is built to collide protons at 7 TeV per beam, which is **14 TeV centre of Mass**

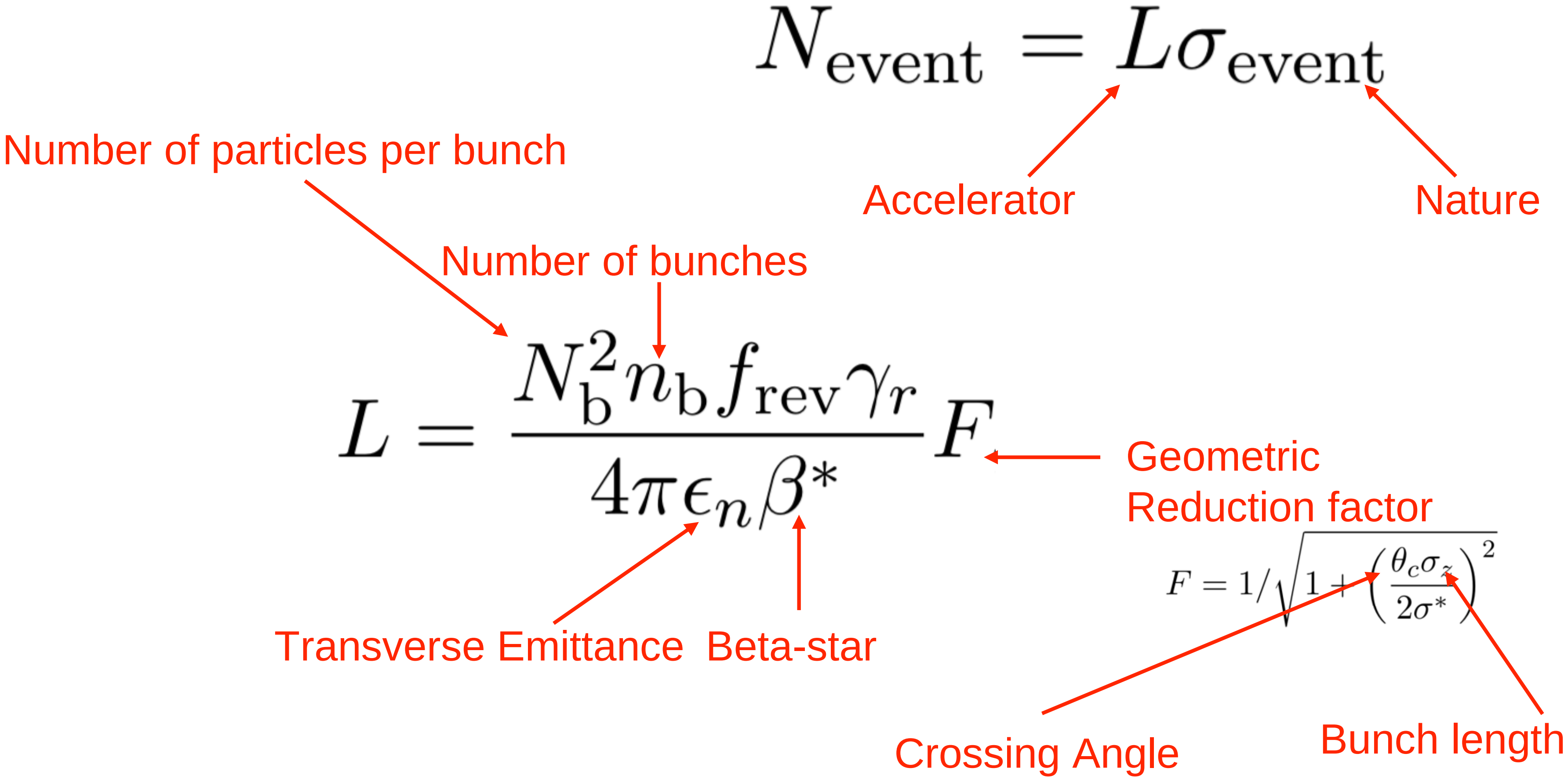
In 2012 it ran at 4 TeV per beam, 8 TeV c.o.m.

Since 2015 it runs at 6.5 TeV per beam, 13 TeV c.o.m

Luminosity

For accelerator people **this IS the quantity used to optimise the machine.**

The higher the luminosity the better.



$$N_{\text{event}} = L\sigma_{\text{event}}$$

Accelerator

Nature

Number of particles per bunch

Number of bunches

$$L = \frac{N_{\text{b}}^2 n_{\text{b}} f_{\text{rev}} \gamma_r}{4\pi\epsilon_n\beta^*}F$$

Geometric Reduction factor

$$F = 1/\sqrt{1+\left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$$

Transverse Emittance

Beta-star

Crossing Angle

Bunch length

LHC nominal parameters

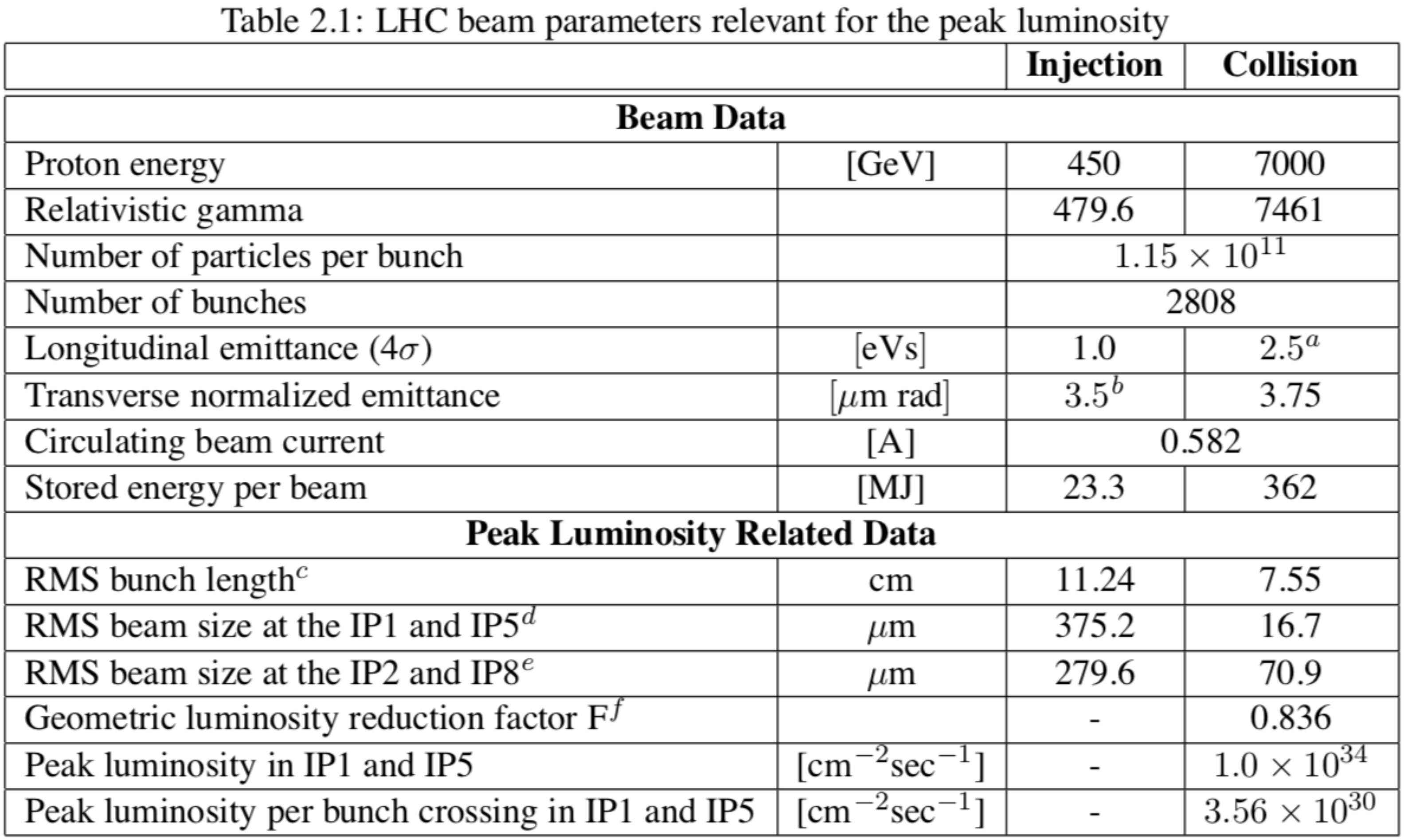


Table 2.1: LHC beam parameters relevant for the peak luminosity

		Injection	**Collision**
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5^{a}
Transverse normalized emittance	[μm rad]	3.5^{b}	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	3.56×10^{30}

LHC Run II Challenges

Energy

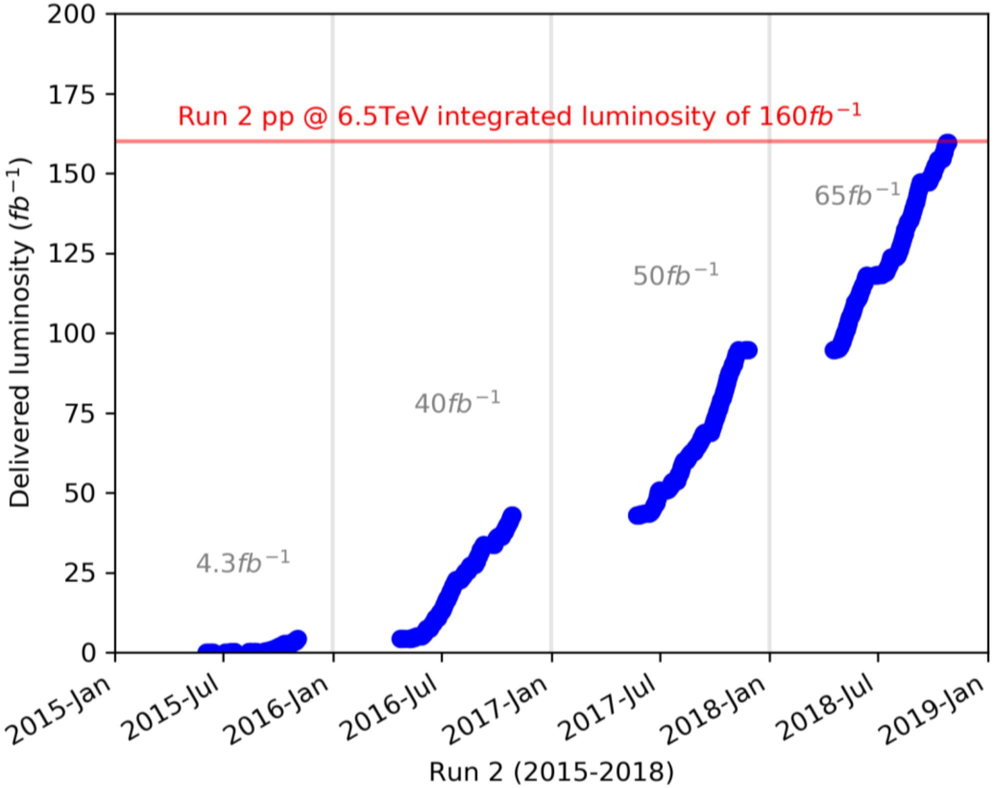
- Lower quench margins
- Lower tolerance to beam loss
- Hardware closer to maximum (beam dumps, power converters etc.)

25 ns

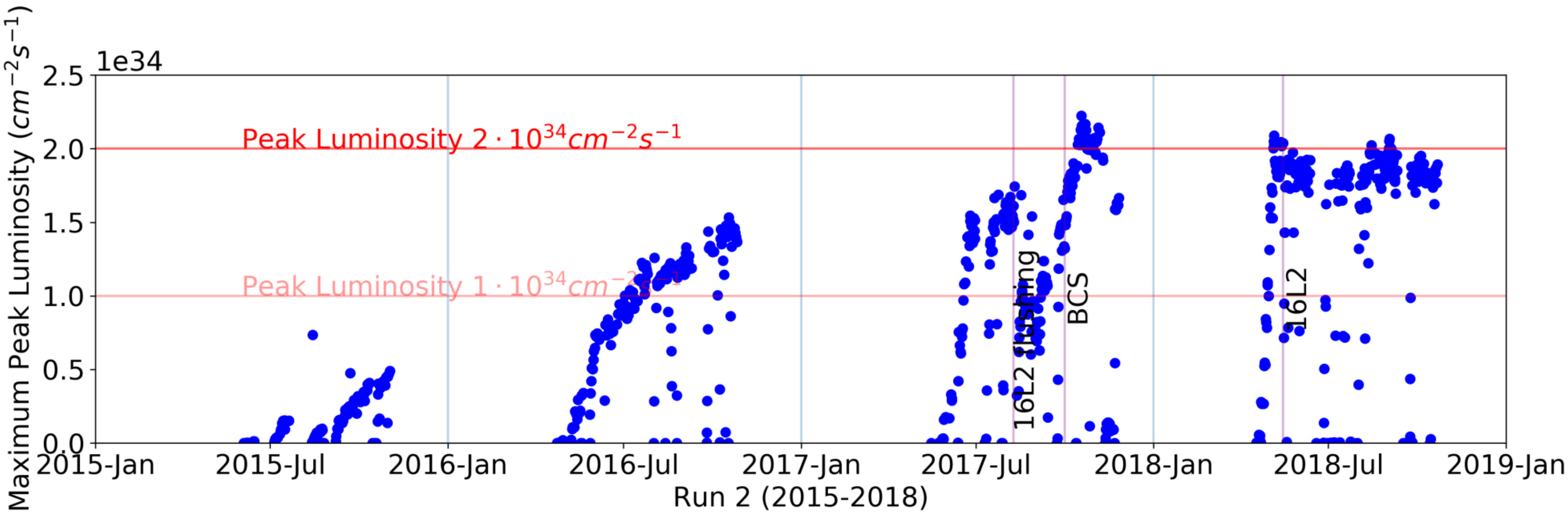
- Electron-cloud
- UFOs
- More long range collisions
- Larger crossing angle, higher beta*
- Higher total beam current
- Higher intensity per injection

Smaller Beta-star

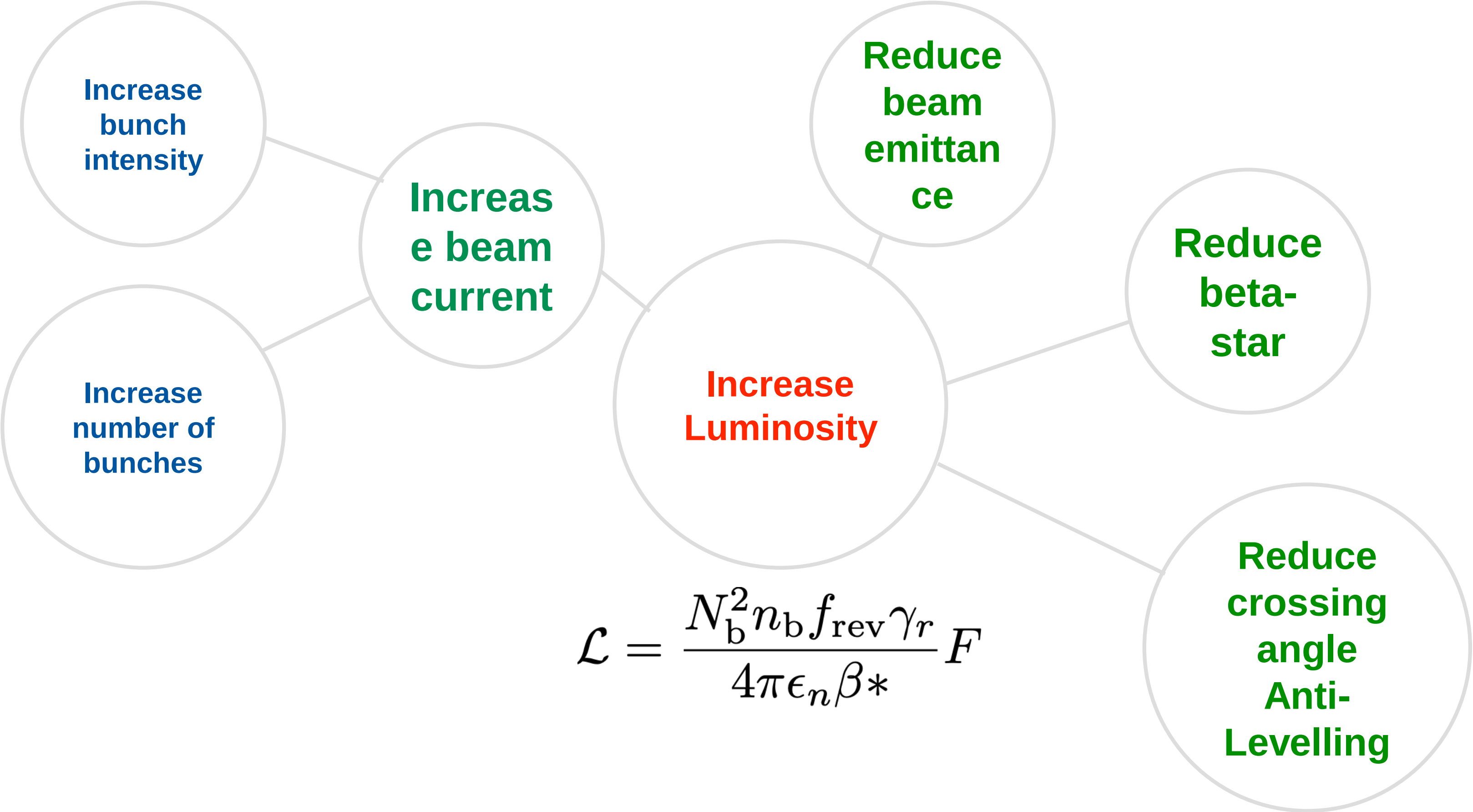
- Smaller machine aperture
- Tighter collimator settings
- Higher beam losses



Peak luminosity



How the increase of peak luminosity was achieved?



Increase bunch intensity

Increase number of bunches

Increase beam current

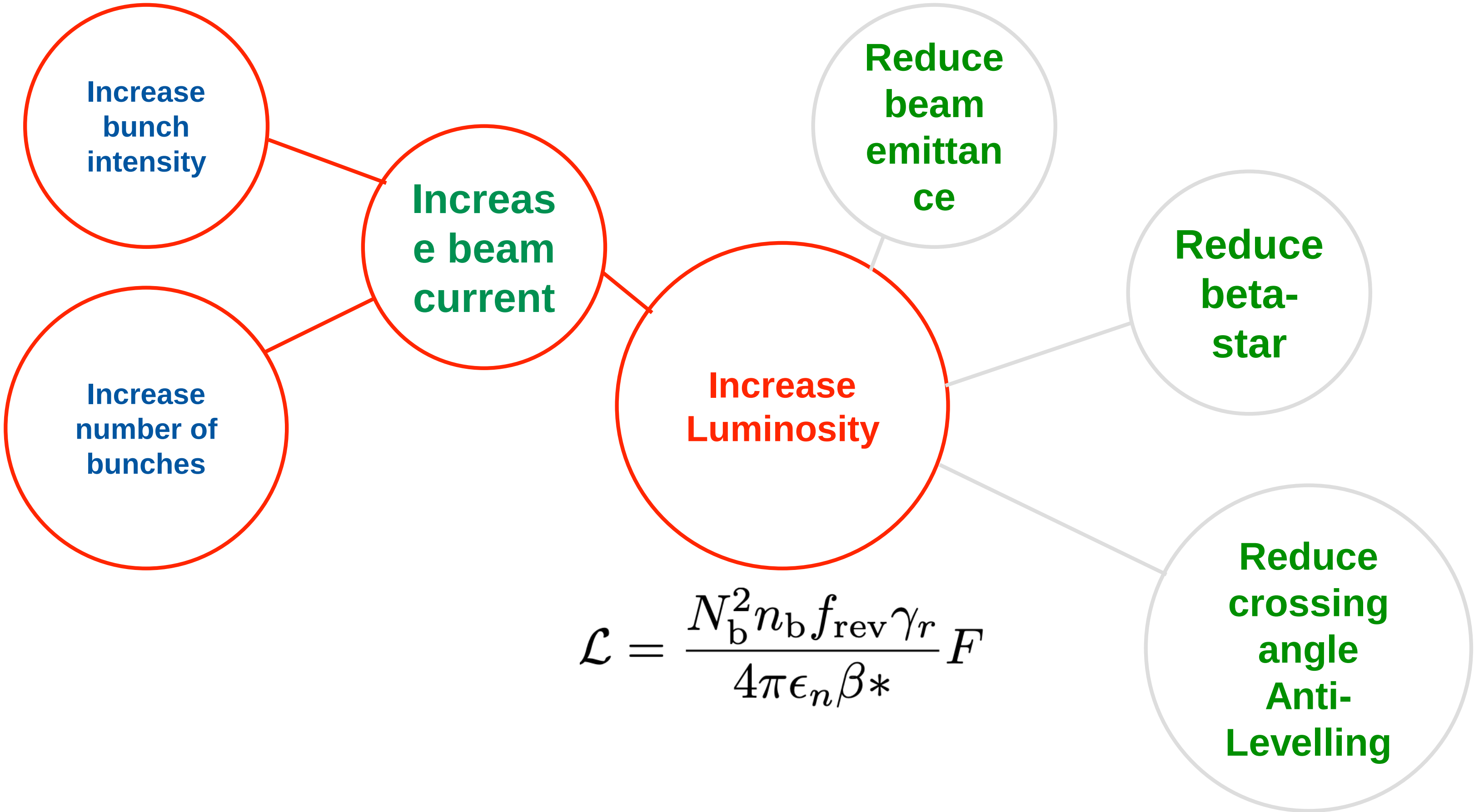
Reduce beam emittance

Increase Luminosity

Reduce beta-star

Reduce crossing angle Anti-Levelling

$$\mathcal{L} = \frac{N_{\mathrm{b}}^{2} n_{\mathrm{b}} f_{\mathrm{rev}} \gamma_{r}}{4\pi \epsilon_{n} \beta *} F$$



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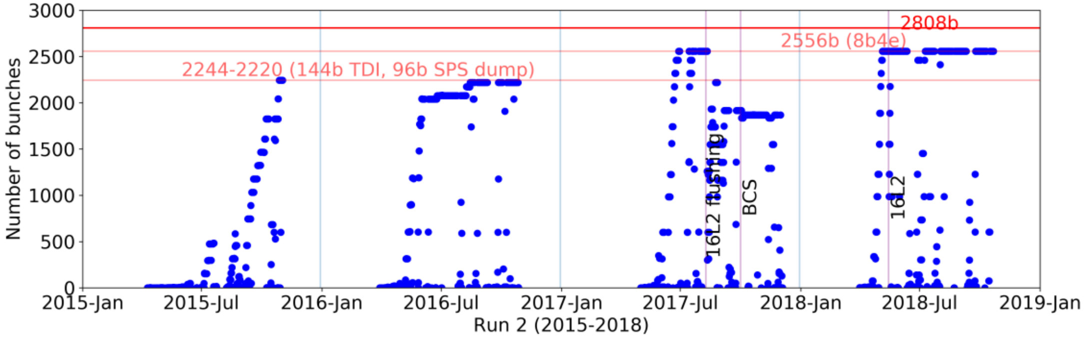
Increase of beam current

Number of bunches

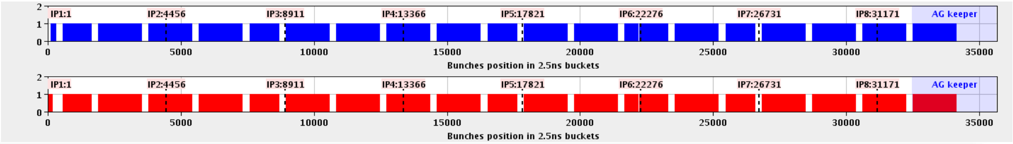
Early 2015 went from 50ns bunch spacing to 25ns.



Example 2017

144 bunches SPS batch (max 2556b)

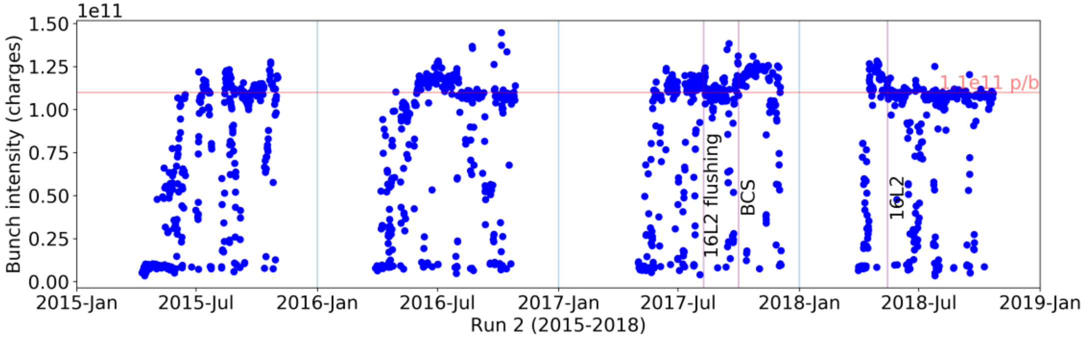
Based on 48 PS batch x 3

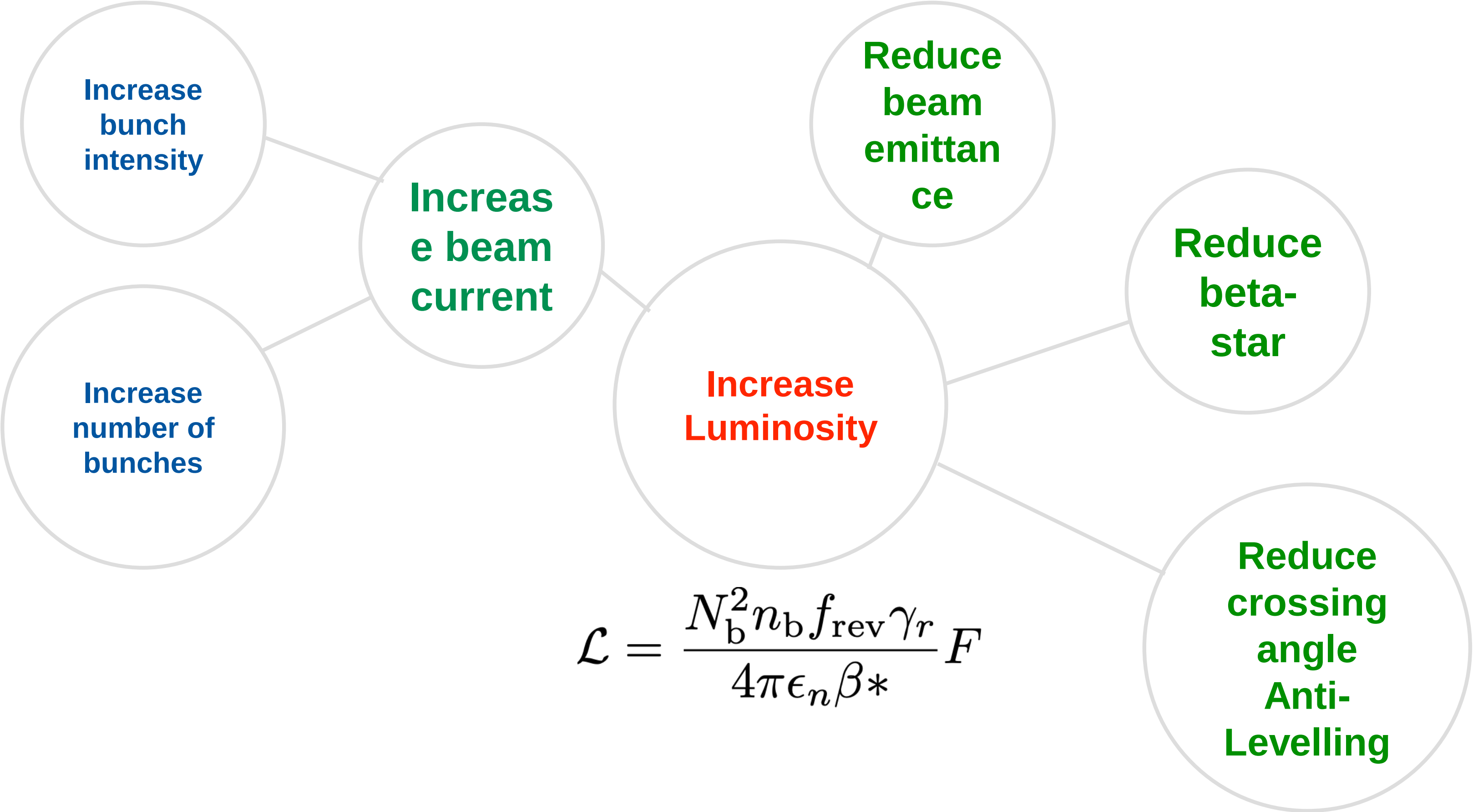


Number of protons/bunch

Average 1.1e11p/b in 2018

Peak ~ 1.5e11p/b





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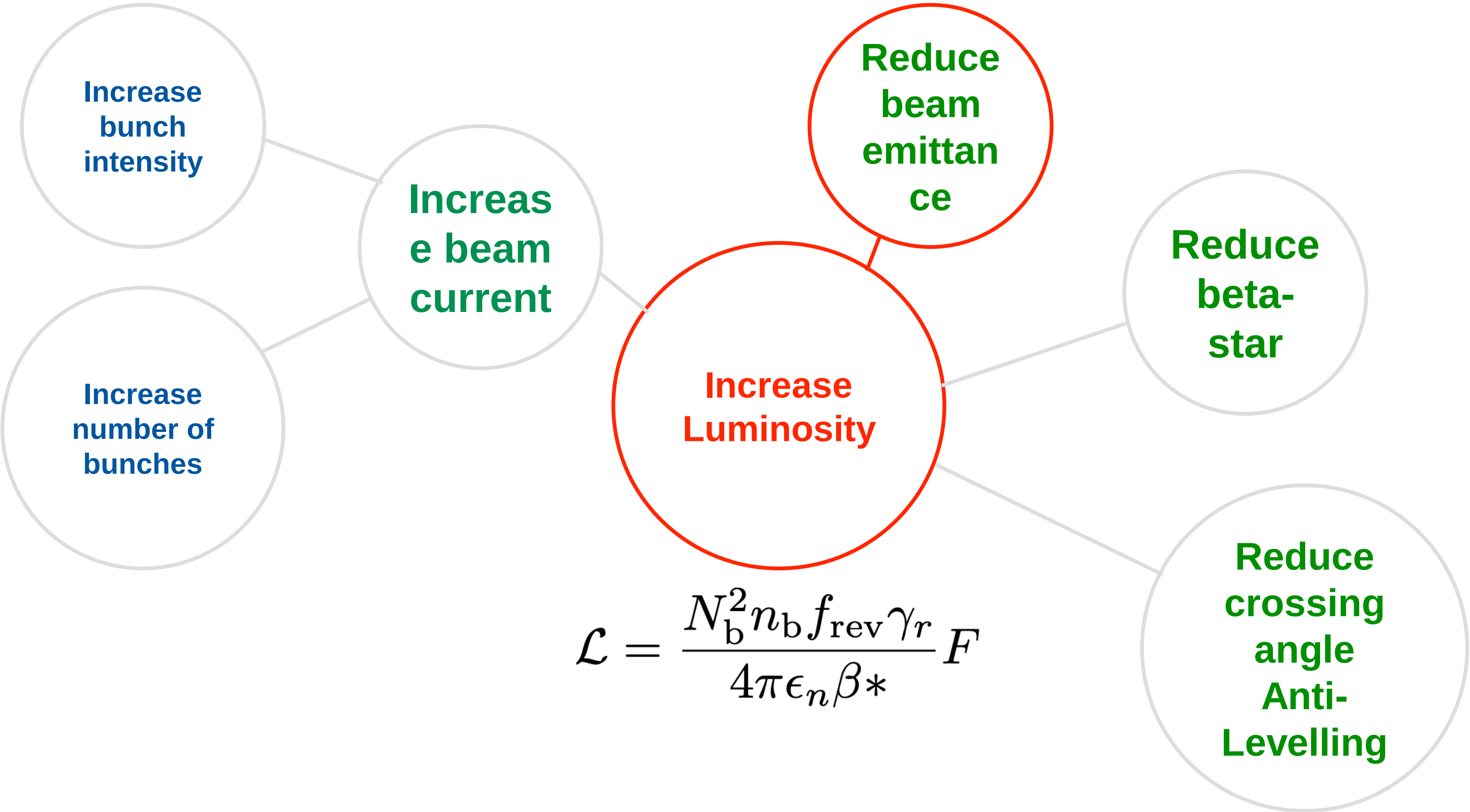

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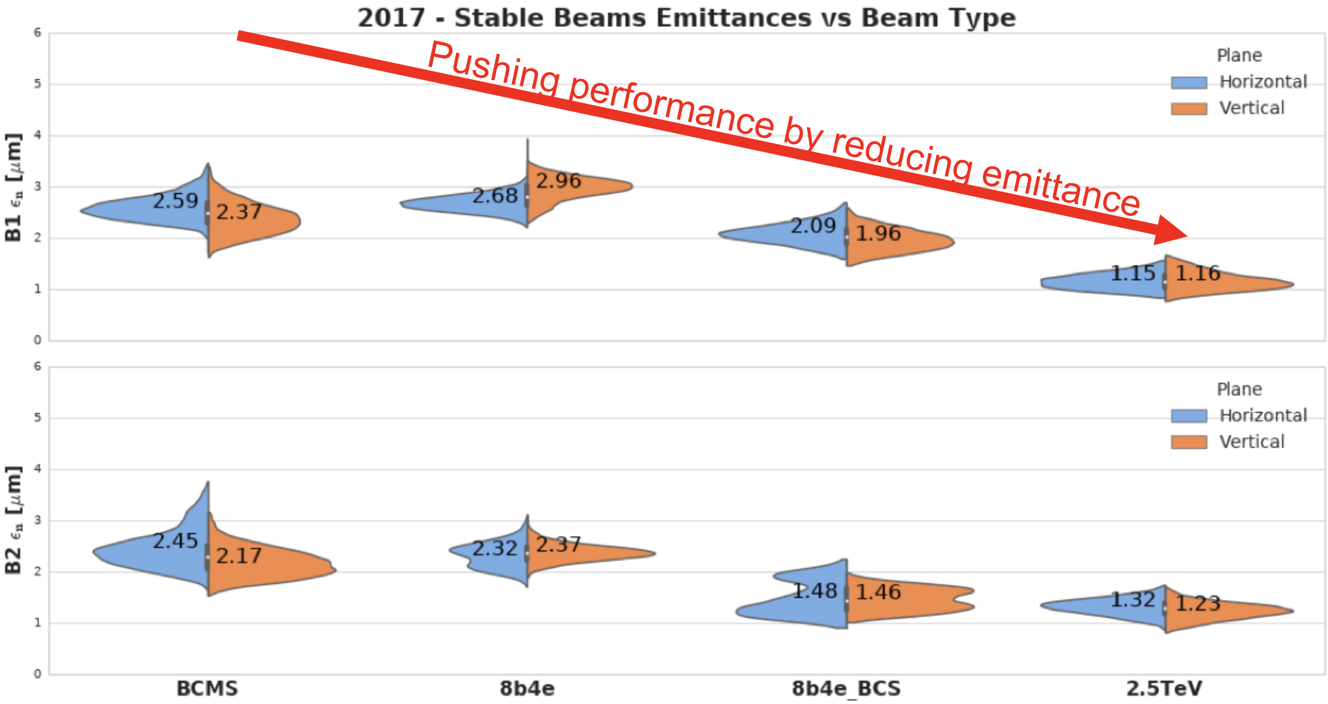
Reduction of beam emittance

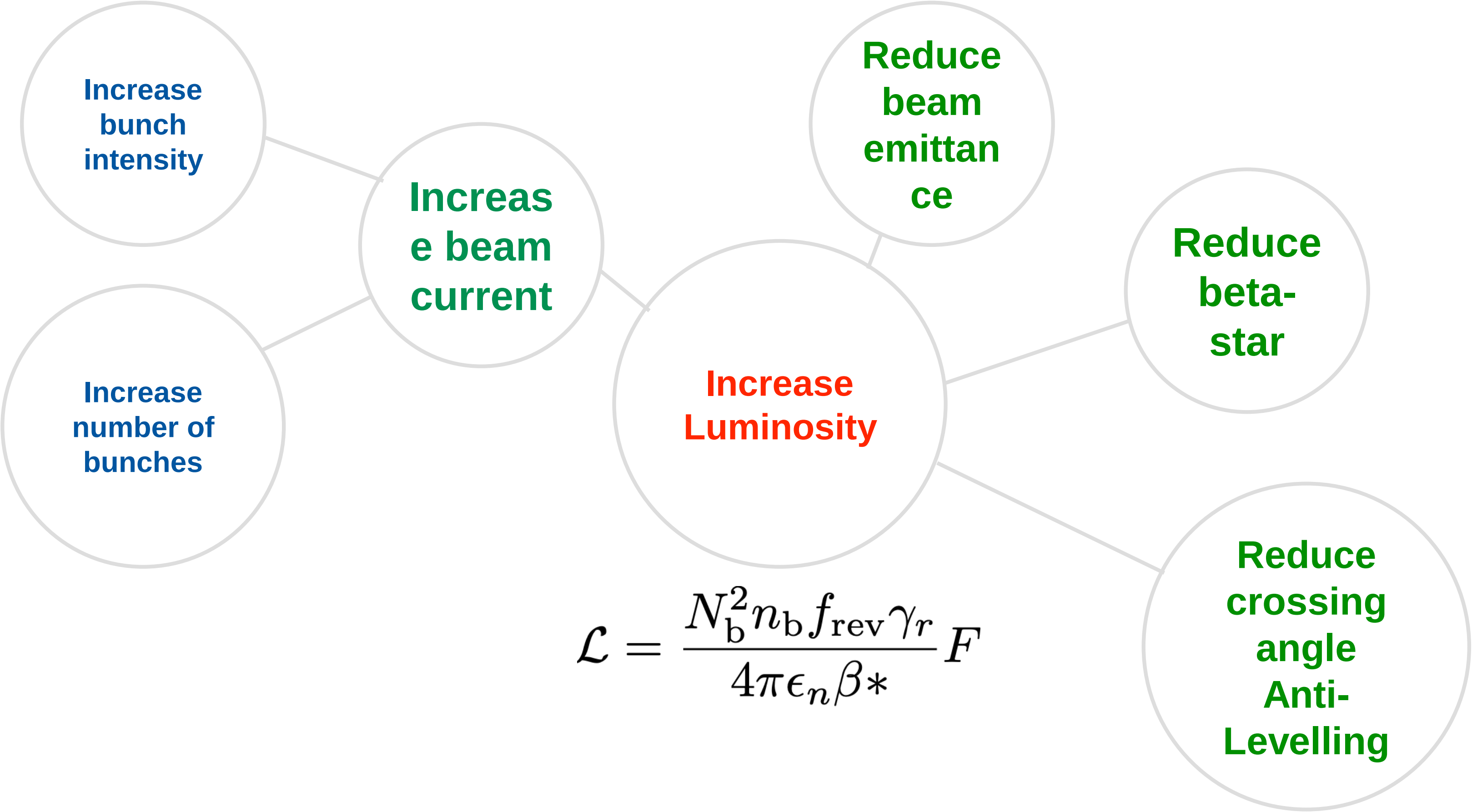
Different bunch splitting and merging in PS gives a **push on beam brightness** (reduction of emittance)



Pushing performance by reducing emittance

Higher peak luminosity *at the cost of* ***higher pile-up*** *due to reduced number of bunches*

N. Karastathis, S. Papadopoulou et al., LMC 29/11/2017



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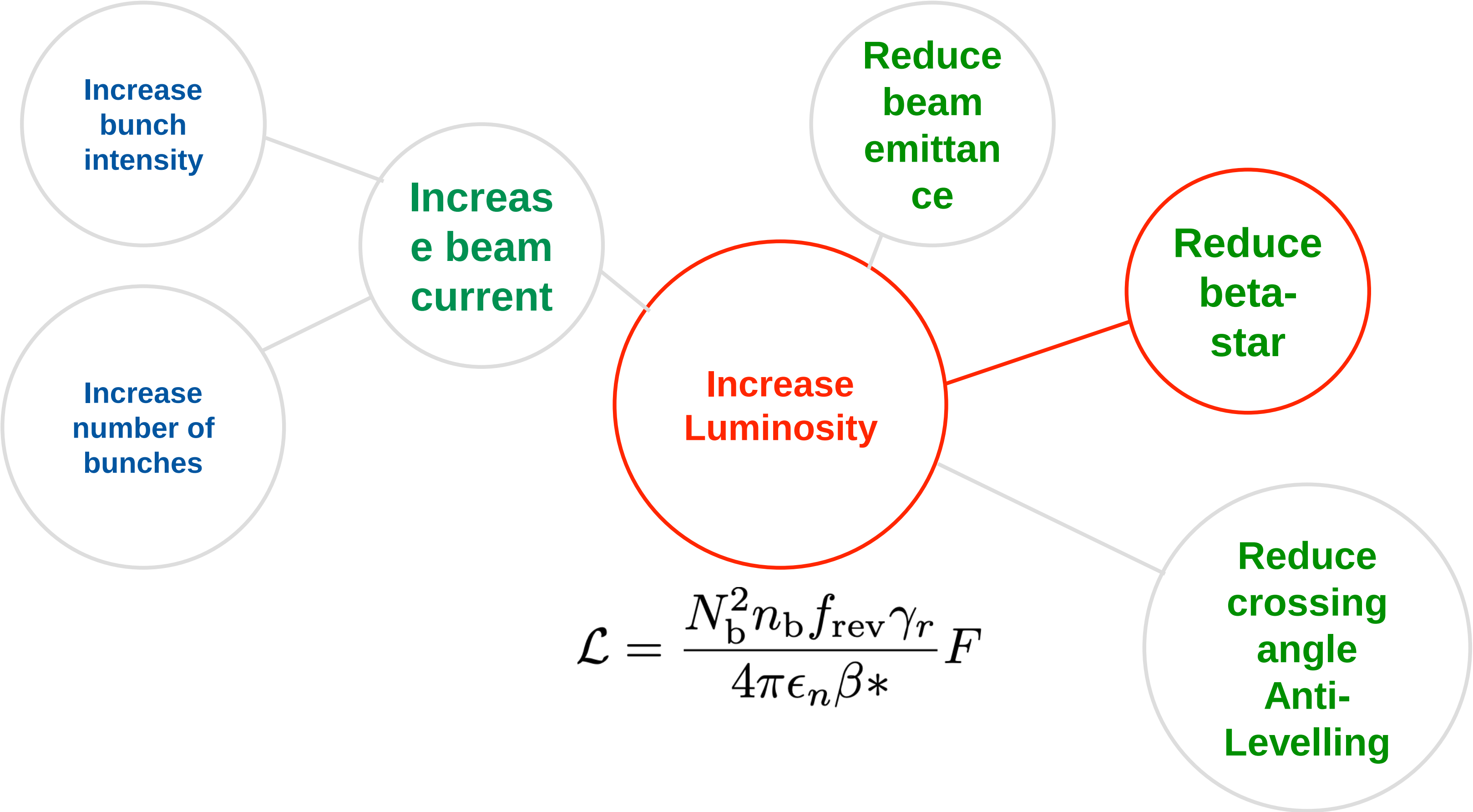

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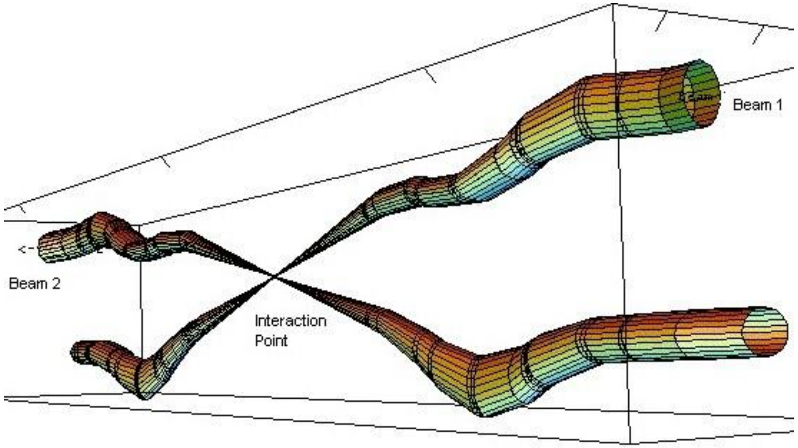
Beta-star

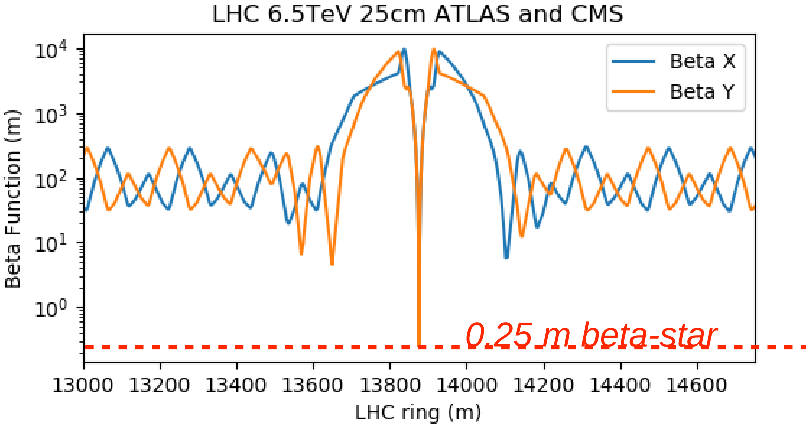
Reduction of beta-star in ATLAS/CMS over Run 2:

- *2015:* **80cm**
- *2016:* **40 cm**
  First time below Nominal values
- *2017:* **40cm → 30cm**
- *2018:* **Dynamic squeeze in Stable Beams: 30cm → 27 cm → 25 cm**

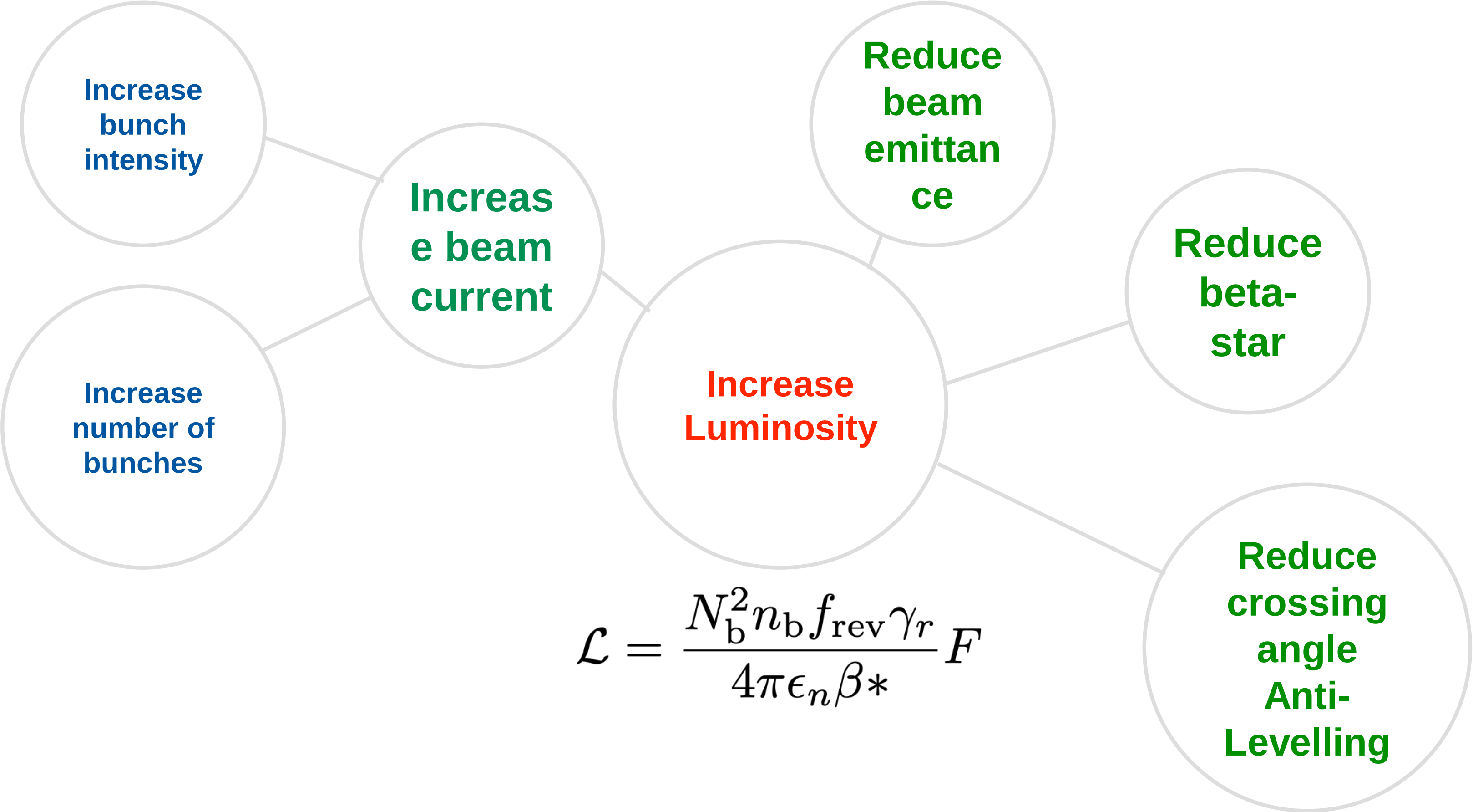


Reduction was possible thanks to the ATS optics (Achromatic Telescopic Squeeze)

Use neighbouring arcs to distribute the change of optics


LHC 6.5TeV 25cm ATLAS and CMS

0.25 m beta-star



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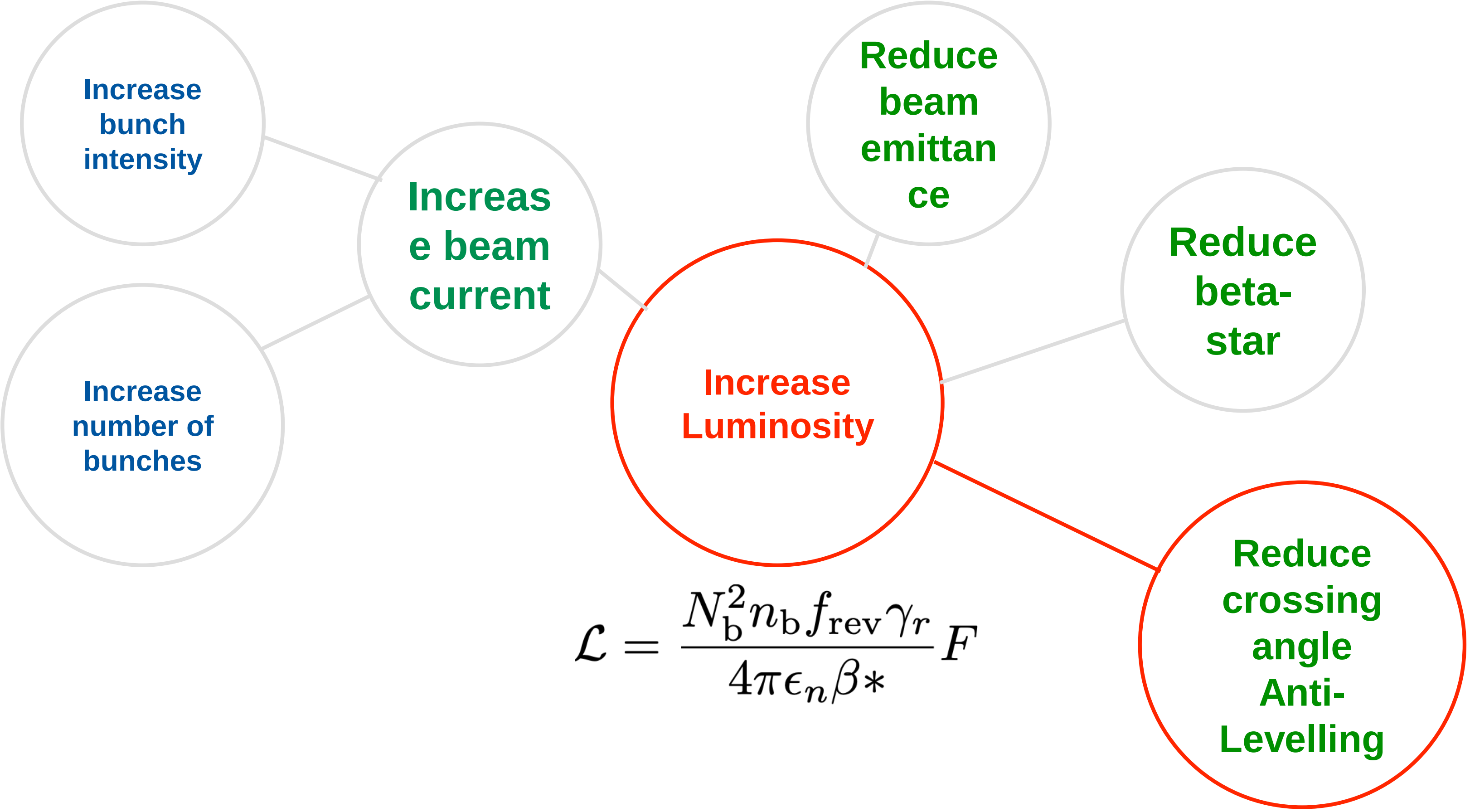

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Luminosity Levelling at LHC

Separation Levelling

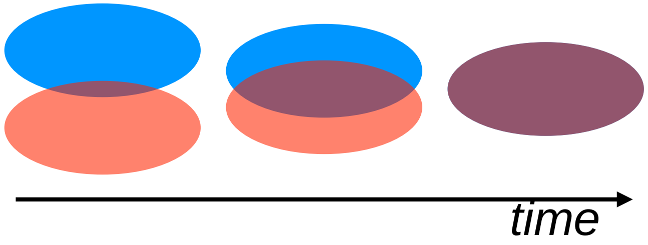
- ➞*Adding a small transverse offset (local orbit bump) to the beams.*
- ➞*It is the simplest way of implementing the levelling*

Crossing angle levelling

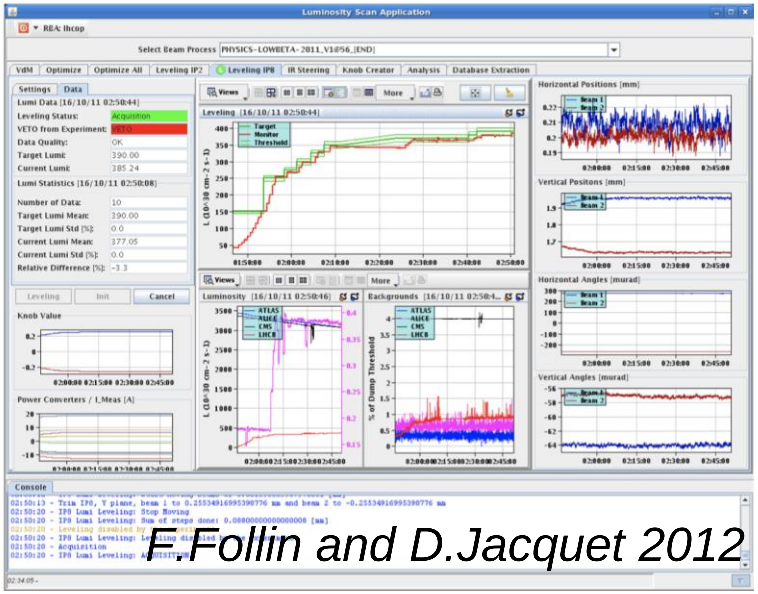
- ➞*Modification of large local orbit bump*
- ➞*Requires changes on the Orbit Feedback (Reference)*
- ➞*Requires collimator movement to protect triplet aperture*

Separation Levelling

Levelling by separation is implemented at LHC since 2011. **Trim of a small local orbit bump to separate or merge the two beams.** Initially done manually by operators and automatised in 2012.



The model/feedback converts the step size from beam size to millimetres and uses the LSA knobs to trim the new values.



Select Beam Process PHYSICS-LOWBETA-2011_V1@56_[END]

Lumi Data [16/10/11 02:50:44]

- Leveling Status: Acquisition
- VETO from Experiment: VETO
- Data Quality: OK
- Target Lumi: 390.00
- Current Lumi: 385.24

Lumi Statistics [16/10/11 02:50:08]

- Number of Data: 10
- Target Lumi Mean: 390.00
- Target Lumi Std [%]: 0.0
- Current Lumi Mean: 377.05
- Current Lumi Std [%]: 0.0
- Relative Difference [%]: -3.3

```
02:50:13 - Trim IP8, Y plane, beam 1 to 0.25534916995390776 mm and beam 2 to -0.25534916995390776 mm
02:50:20 - IP8 Lumi Leveling: Stop Moving
02:50:20 - IP8 Lumi Leveling: Sum of steps done: 0.0080000000000000008 [mm]
02:50:20 - Leveling disabled by
02:50:20 - IP8 Lumi Leveling:
02:50:20 - Acquisition
02:50:20 - IP8 Lumi Leveling:
```

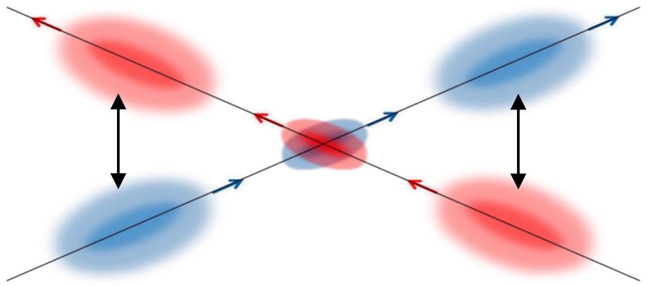
F.Follin and D.Jacquet 2012

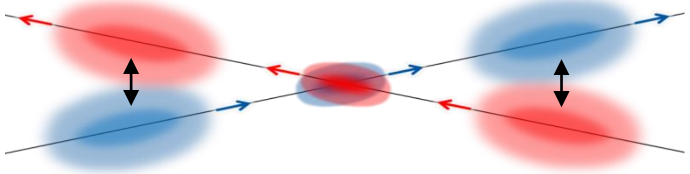
Experiments request/configure several parameters: target luminosity, levelling step, etc. and publish their measurement of peak luminosity.

Done for ALICE and LHCb regularly. ATLAS and CMS from 2017

Crossing Angle Anti-Levelling

Crossing angles at the colliding IRs are necessary to decrease the Beam Beam force. As intensity decrease over time the initial Beam Beam separation can be reduced.Smaller crossing angles provide more luminosity.

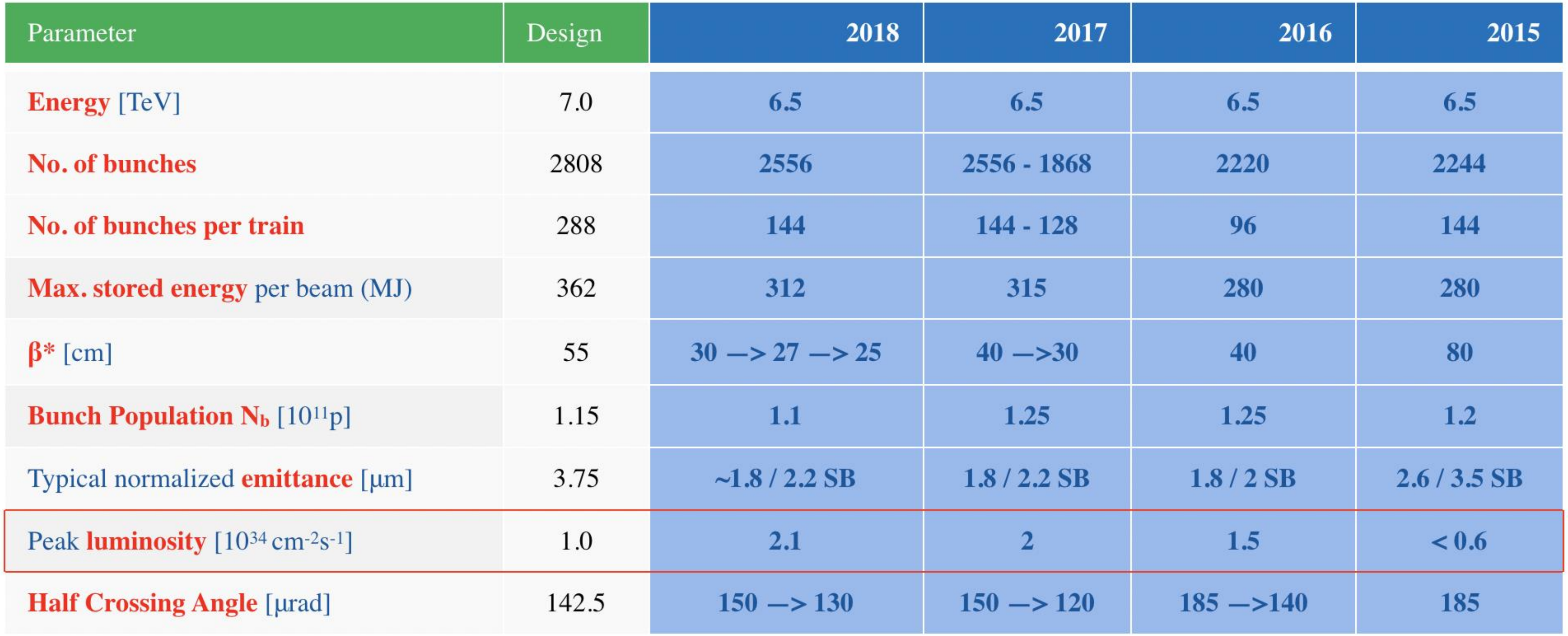




Implementation is more complex. The orbit needs to be controlled during change Feedback must be ON. Triplet aperture needs to be protected.

During 2018 LHC was operating with levelling by crossing.

Summary LHC



Parameter	Design	2018	2017	2016	2015
Energy [TeV]	7.0	6.5	6.5	6.5	6.5
No. of bunches	2808	2556	2556 - 1868	2220	2244
No. of bunches per train	288	144	144 - 128	96	144
Max. stored energy per beam (MJ)	362	312	315	280	280
β* [cm]	55	30 —> 27 —> 25	40 —>30	40	80
Bunch Population N_b [10^{11}p]	1.15	1.1	1.25	1.25	1.2
Typical normalized **emittance** [µm]	3.75	~1.8 / 2.2 SB	1.8 / 2.2 SB	1.8 / 2 SB	2.6 / 3.5 SB
Peak **luminosity** [10^{34} cm^{-2}s^{-1}]	1.0	2.1	2	1.5	< 0.6
Half Crossing Angle [µrad]	142.5	150 —> 130	150 —> 120	185 —>140	185

160fb-1 for proton-proton Run 2 and a rich physics program

Outline

- Day 1:
  - Basic accelerator concepts
  - CERN Complex
- Day 2:
  - LHC
  - HL-LHC (upgrade v2)
  - Future projects: FCC and CLIC

HL-LHC

The main goal is to increase luminosity by a factor of 5 to 10 in order to observe rare physics processes.

250 fb^{-1} per year ← 2 x LHC 4 years of Run II

3000 fb^{-1} in 12 years

This will be accomplished with a series of upgrades

Injectors Upgrade (LIU)

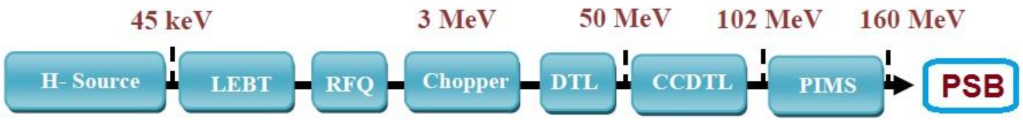
Higher brightness beams
More intensity less emittance

LHC Upgrade

Increase of luminosity

HL-LHC established as project in summer 2010
Described in HL-LHC book and the HL-LHC design report

LIU

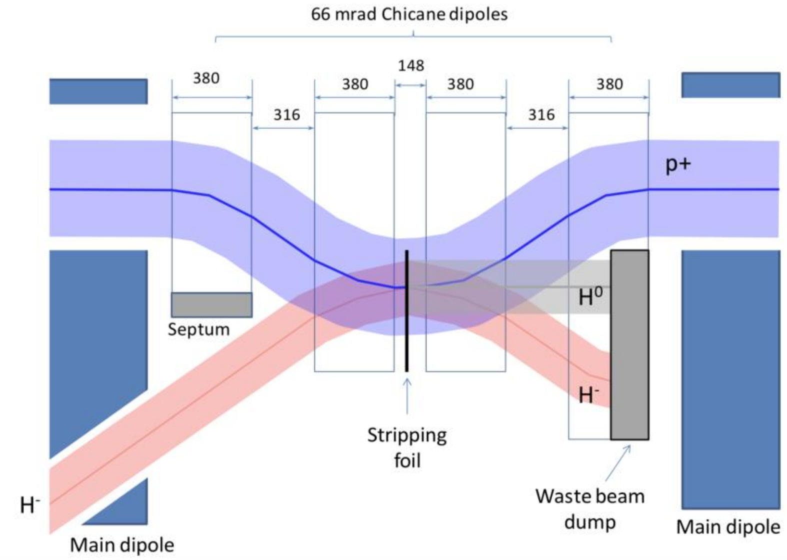


2019-2020 Linac 4 (160 MeV) will replace Linac 2 (50MeV) as injector to PS Booster as part of the LHC injectors upgrade for HL-LHC.

Factor 2 brightness ≅ charge density

Acceleration of H- ions with 2 weak bounded electrons to 160MeV and injection to the PSB after passage by carbon thin foil.

In the PS Booster during following turns interleave again a stream of H- with the circulating protons. Electrons will be stripped again with thin foil.



PS will receive beam at 2 GeV (instead of 1.4GeV)

SPS upgrade to reduce machine impedance (instability). New 200MHz RF system and Carbon coating of vacuum chambers to reduce e-cloud.

HI-LHC Upgrade

- LHC Upgrade of IR ATLAS/CMS inner triplets (quadrupoles)
- Upgrade of Collimation System
- Crab cavities for beam rotation
- 11 Tesla magnet + connection cryostat
- Cold powering
- Machine protection
- …

HL-LHC Collimators

Study of more robust materials for collimation and reduce impedance.

During LS2

Replacement of existing primary collimators and 8 secondary collimators with higher-ele

Addition of 4 collimators in the dispersion suppression region

→ shorter magnets 11T Dipole 11-m (Nb_3Sn technology)

Impact of 288 proton bunches on copper-allow (left) and MoGr (right)

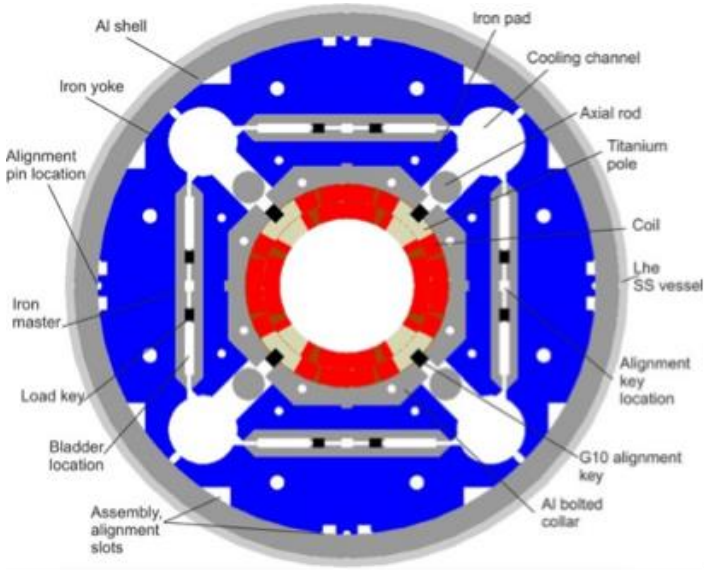
IR ATLAS/CMS

HL-LHC baseline smaller beta-star 15 cm

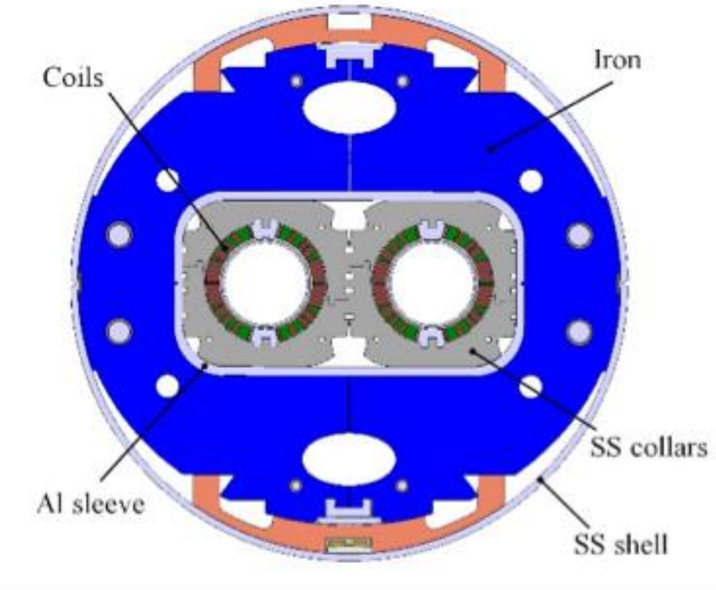
Replace 1.2 km of the 27 km LHC ring

Super conductive large aperture triplet quadrupoles with use of novel Nb3Sn magnet technology

Super conductive separation/recombination dipoles D2 with B field same direction.

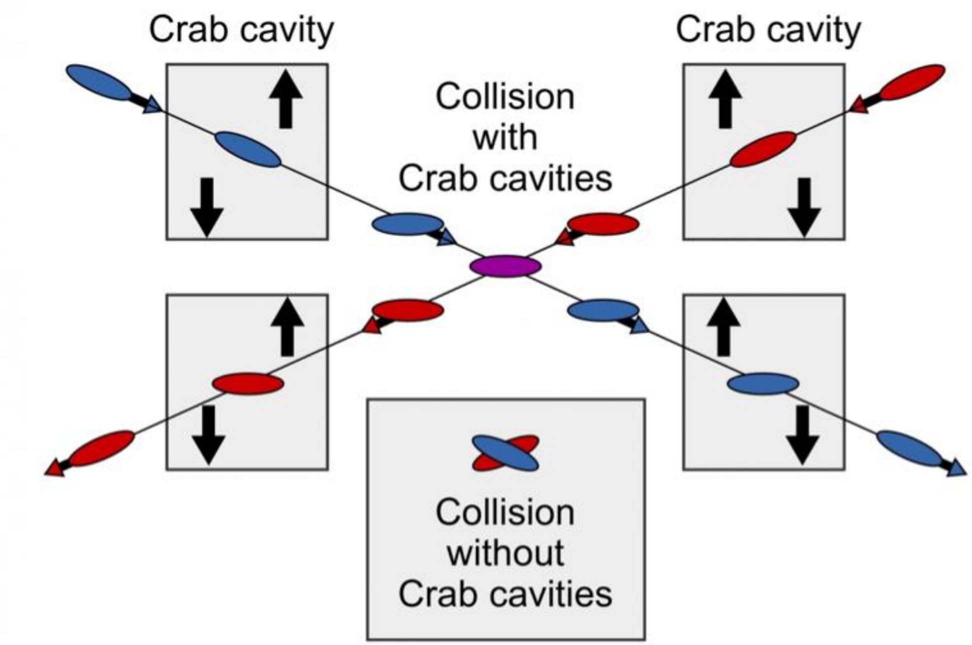


Triplet [G. Ambrosio, P. Ferracin et al.]



D2 [P. Fabbricatore, S. Farinon, et al.]

HL-LHC Crab-cavities


Crab cavity

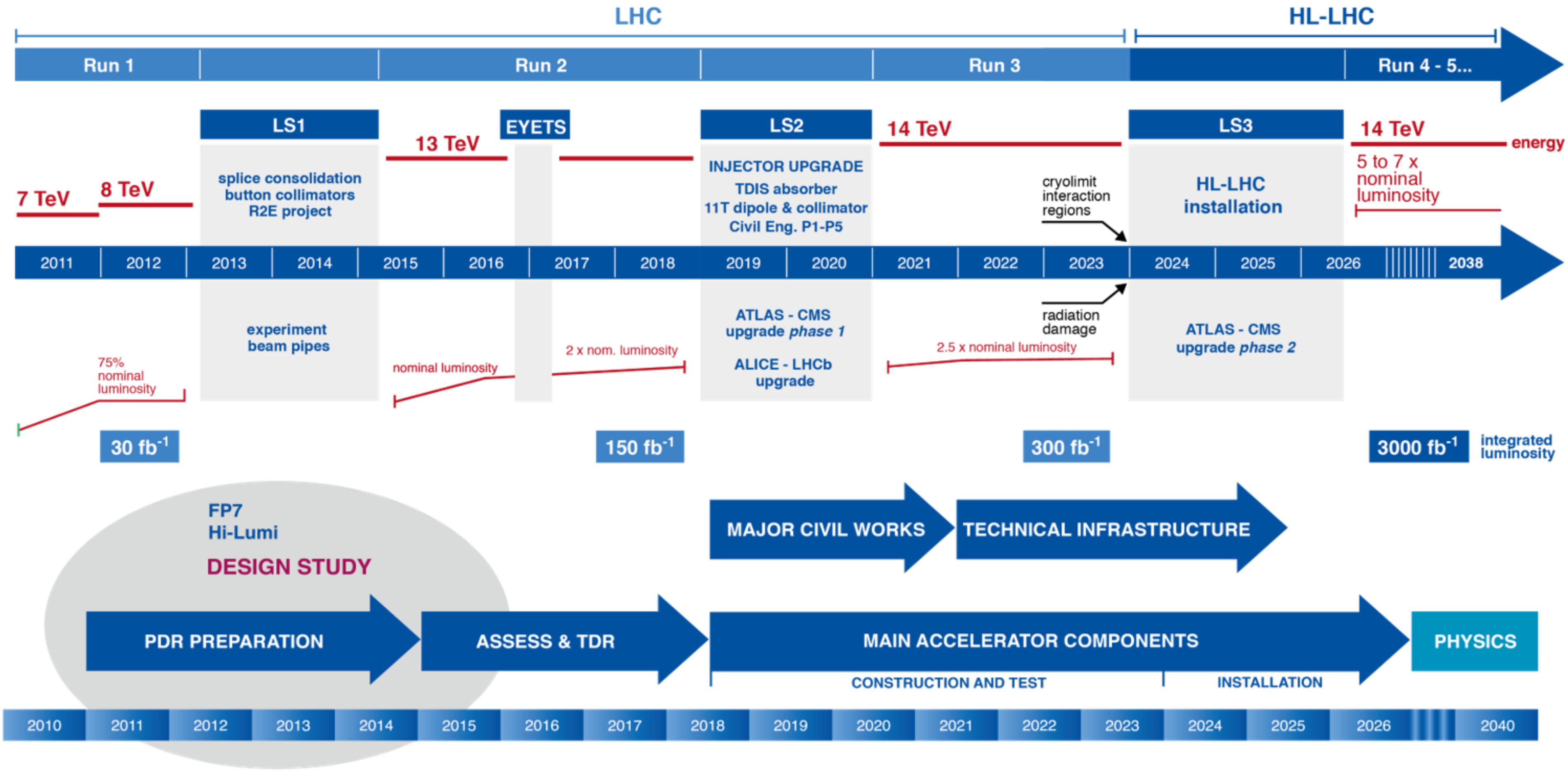
Crab cavity

Collision
with
Crab cavities

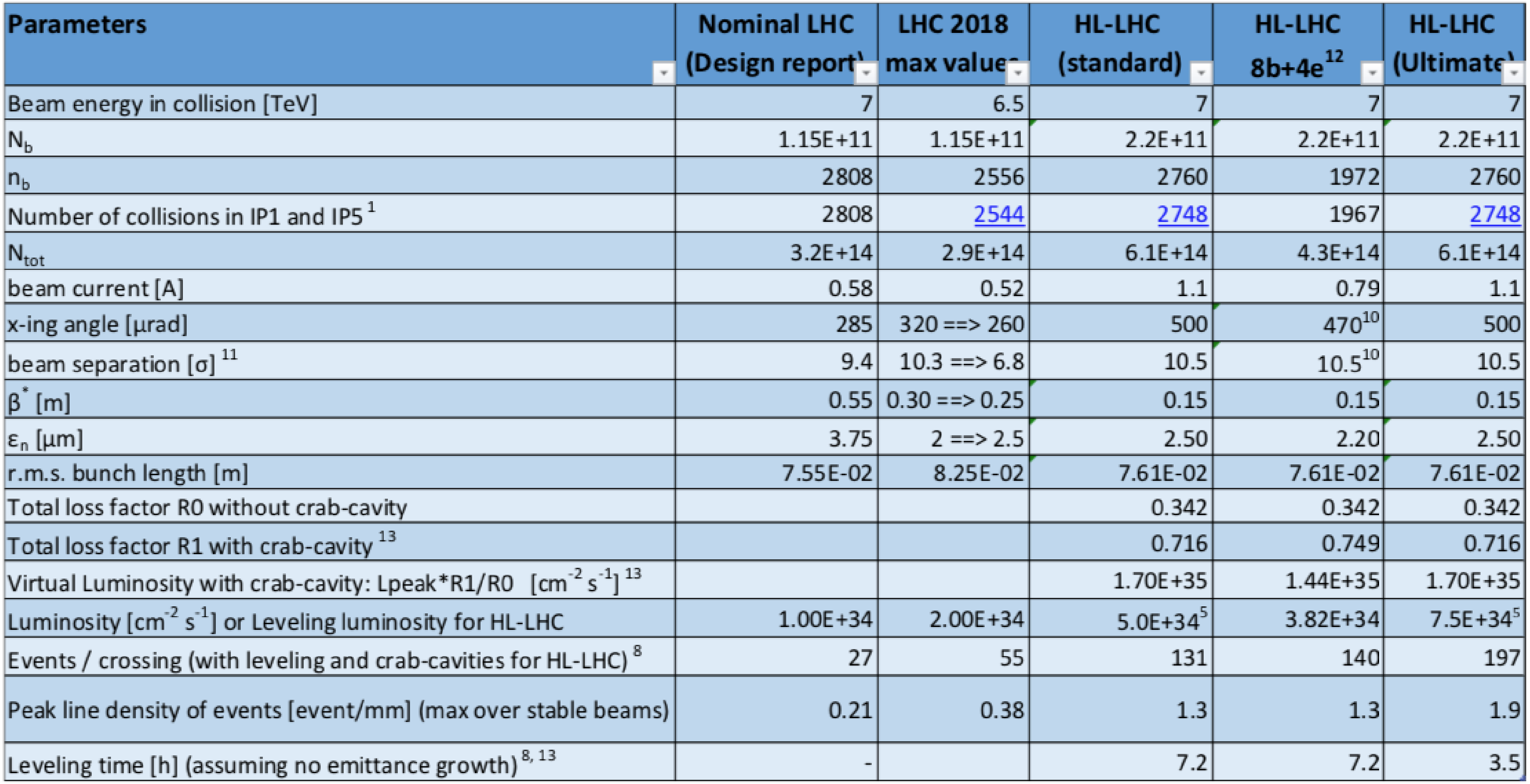
Collision
without
Crab cavities

Crab cavities will reduce the effect of the geometrical factor on the luminosity

HL-LHC timeline



HL-LHC parameter table



Parameters	Nominal LHC (Design report)	LHC 2018 max value	HL-LHC (standard)	HL-LHC 8b+4e[12]	HL-LHC (Ultimate)
Beam energy in collision [TeV]	7	6.5	7	7	7
N_b	1.15E+11	1.15E+11	2.2E+11	2.2E+11	2.2E+11
n_b	2808	2556	2760	1972	2760
Number of collisions in IP1 and IP5 [1]	2808	2544	2748	1967	2748
N_{tot}	3.2E+14	2.9E+14	6.1E+14	4.3E+14	6.1E+14
beam current [A]	0.58	0.52	1.1	0.79	1.1
x-ing angle [μrad]	285	320 ==> 260	500	470[10]	500
beam separation [σ] [11]	9.4	10.3 ==> 6.8	10.5	10.5[10]	10.5
β^* [m]	0.55	0.30 ==> 0.25	0.15	0.15	0.15
ε_n [μm]	3.75	2 ==> 2.5	2.50	2.20	2.50
r.m.s. bunch length [m]	7.55E-02	8.25E-02	7.61E-02	7.61E-02	7.61E-02
Total loss factor R0 without crab-cavity			0.342	0.342	0.342
Total loss factor R1 with crab-cavity [13]			0.716	0.749	0.716
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2} s^{-1}$] [13]			1.70E+35	1.44E+35	1.70E+35
Luminosity [$cm^{-2} s^{-1}$] or Leveling luminosity for HL-LHC	1.00E+34	2.00E+34	5.0E+34[5]	3.82E+34	7.5E+34[5]
Events / crossing (with leveling and crab-cavities for HL-LHC) [8]	27	55	131	140	197
Peak line density of events [event/mm] (max over stable beams)	0.21	0.38	1.3	1.3	1.9
Leveling time [h] (assuming no emittance growth) [8, 13]	-		7.2	7.2	3.5

Proj. leader L. Rossi talk [8th annual collaboration meeting]() **October 2018**

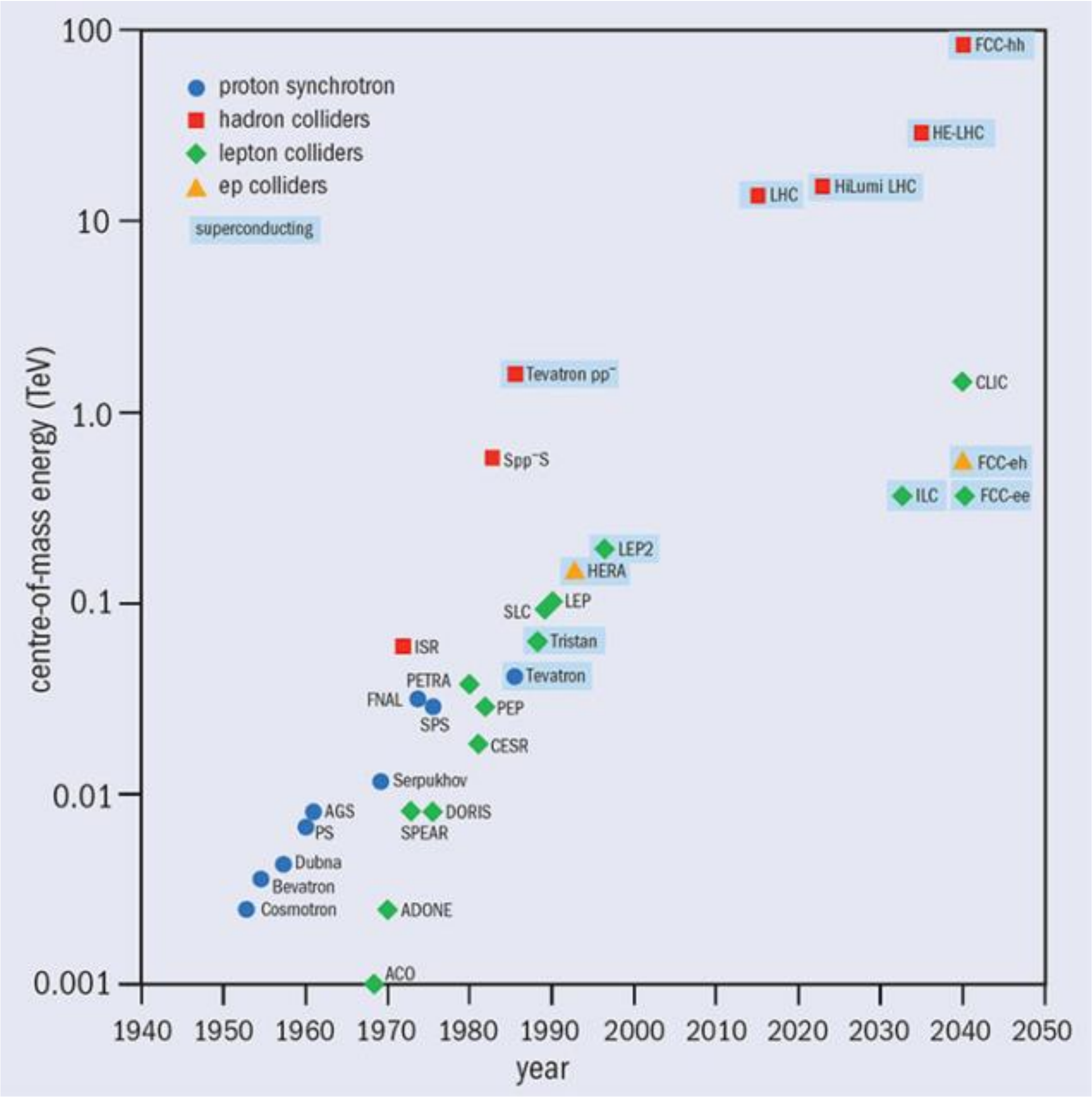
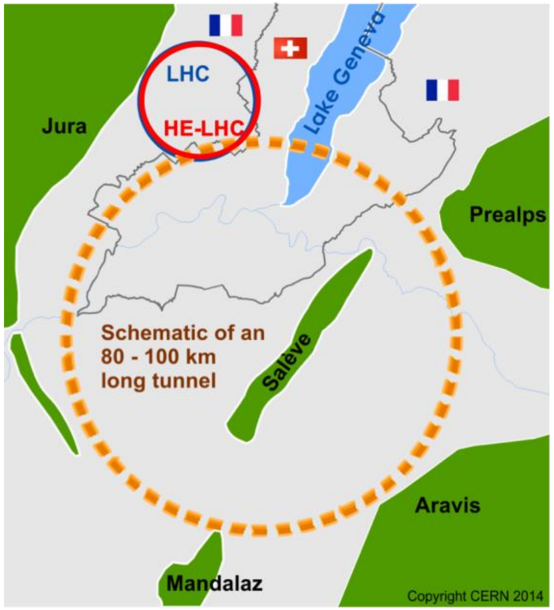


Image credit L.Rossi, P Lebrun

Future Circular Collider (FCC)



Study of a hadron **collider** with a **centre-of-mass energy of the order of 100 TeV** in a new tunnel of **80-100 km circumference**

Start as *e+e-* collider FCC-ee → Higgs Factory

Ecom of 90 - 365 GeV

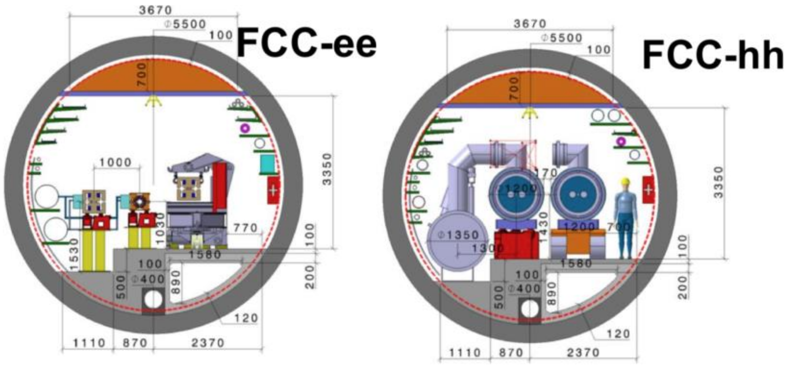
Luminosity ~ 17 x 10^{34} cm-2s-1

Beta-star ~ 1 mm

Second stage *pp* collider FCC-hh → Energy frontier

Ecom of 50 - 100 TeV **16 T ⇒ 100 TeV *pp* in 100 km**

Luminosity ~ 3 x 10^{34} cm-2s-1

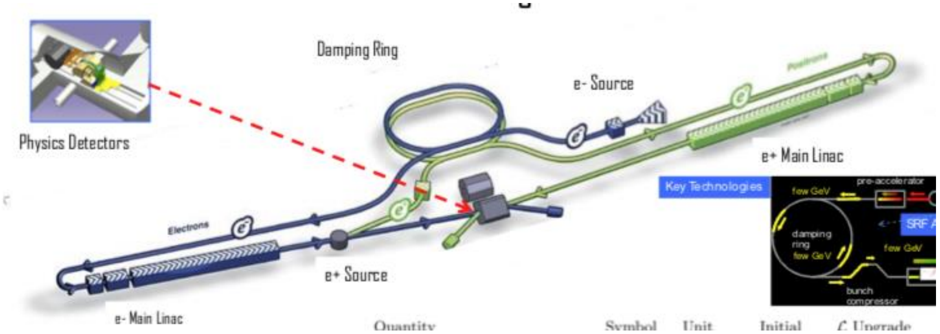


[FCC-Condeptual Design Reports]

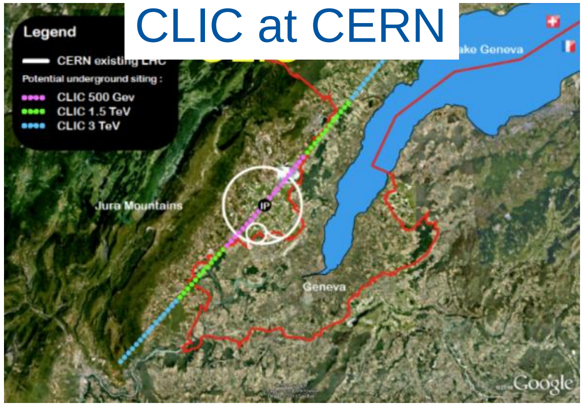
Linear Colliders ILC/CLIC

Two linear accelerators facing each other

ILC in Japan



CLIC at CERN



Both propose a staged implementation of e+e- collider

Ecom = 0.25 - 1 TeV
Luminosity 1.35 x 10^{34} $cm^{-2}s^{-1}$

Ecom = 0.5 TeV - 3 TeV
Luminosity 1.3 - 5.9 x 10^{34} $cm^{-2}s^{-1}$

More about ILC: https://ilchome.web.cern.ch

More about CLIC: https://clic.cern

Thank you!