JAS 2019 – Ion Colliders

Heavy-Ions in the LHC

by

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With big acknowledgements to John Jowett

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Outline

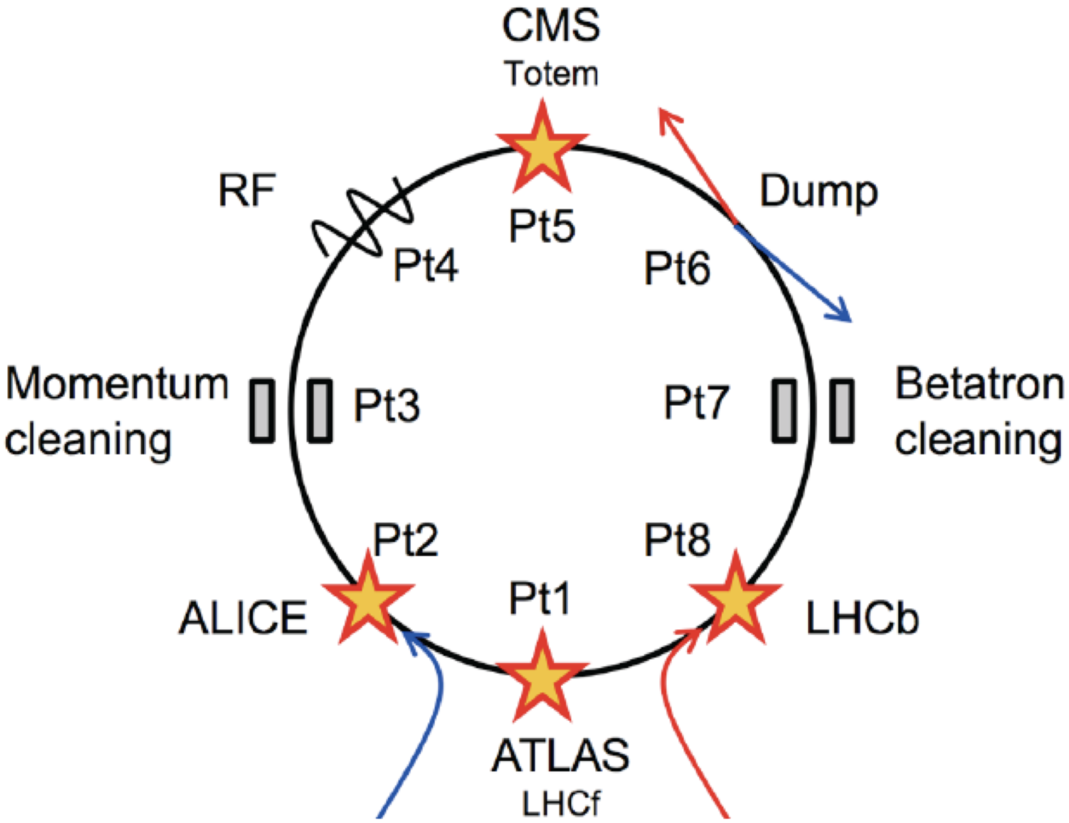
Introduction
- History and Notations
- Effects on Luminosity

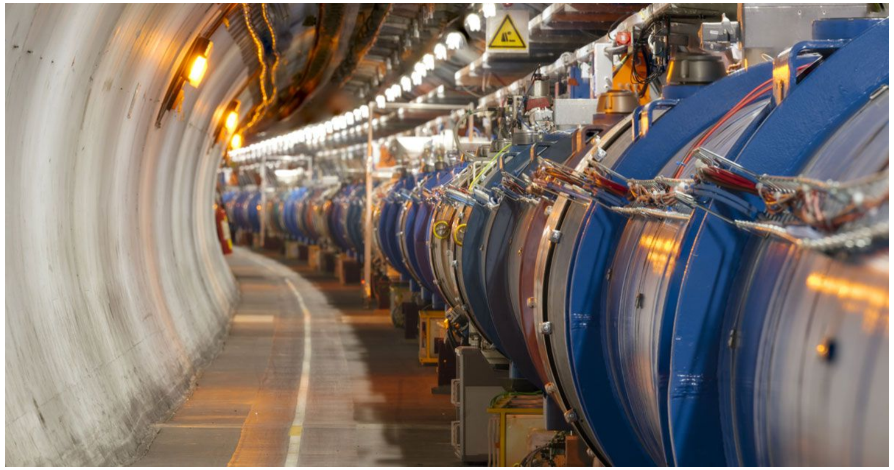
Pb-Pb Collisions
- Secondary Beams
- Getting the beams into LHC
- Beam and Luminosity Evolution
- Performance Summary

Other Operational Modes
- p-Pb collisions
- Other unforeseen, but successful operational modes

Introduction to LHC

The largest machine in the world:
The Large Hadron Collider (LHC)



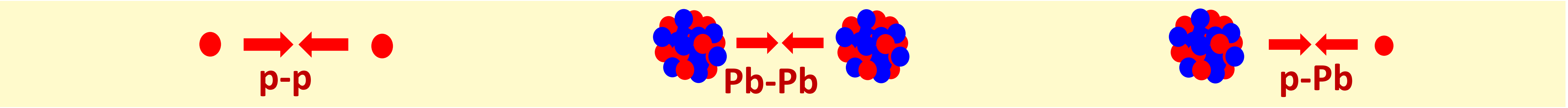


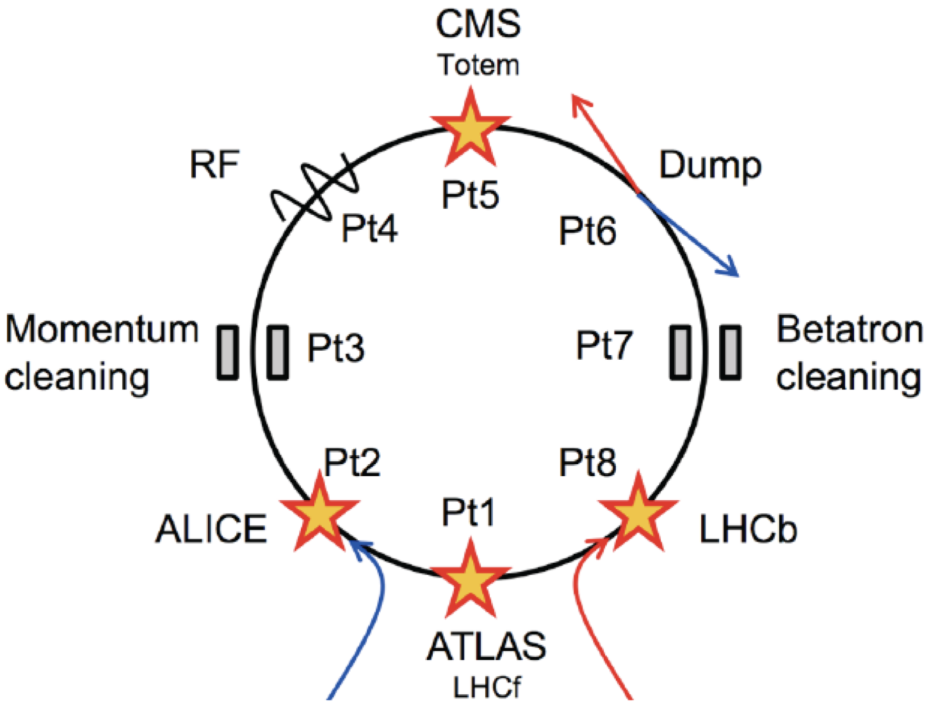
27 km circumference
100m underground

Accelerates protons and heavy-ions
to E = 6.5 Z TeV (2018).

Collides 2 counter-rotating beams
in 4 physics experiments.

Collision Modes in LHC





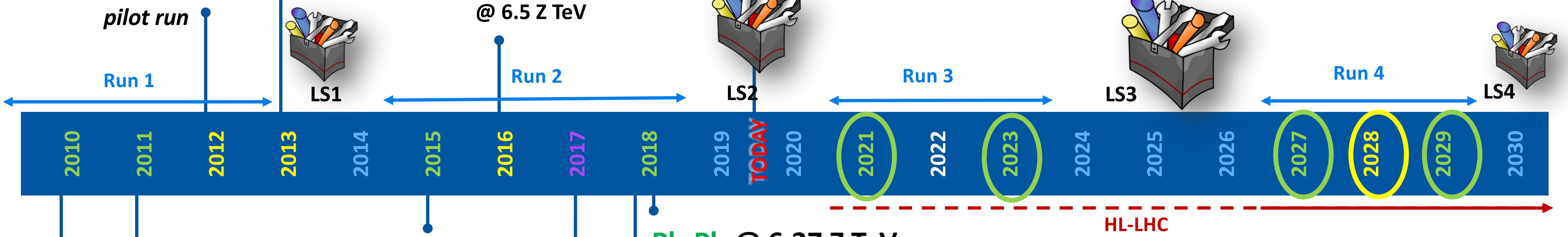
The LHC spends most of its time colliding **proton-proton (p-p)** in its 4 main experiments.

All are also highly capable heavy-ion experiments:
ALICE (IP2) and **ATLAS** (IP1) **/ CMS** (IP5)
LHCb (IP8) since 2012
also LHCf (cosmic ray physics)

1 month/year colliding **fully stripped lead** ($^{208}\mathrm{Pb}^{82+}$) or Pb ions with protons.

A short History and Future …

12 one-month heavy-ion runs between 2010 and 2030. **6/12 done**.



Upgrade: new collision mode

16h p-Pb *pilot run*

1st p-Pb high luminosity run @ 4 Z TeV

p-Pb @ 4 Z TeV @ 6.5 Z TeV

LS2 Hardware Upgrades:

- **ALICE detector upgrade to 7 x design luminosity**
- **Dispersion Suppressor collimators for BFPP losses.**
- **SPS RF (smaller bunch spacing)**

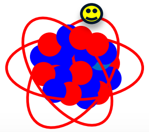
1st Pb-Pb collisions @ 3.5 Z TeV

Pb-Pb @ 3.5 Z TeV
0.5 x design luminosity

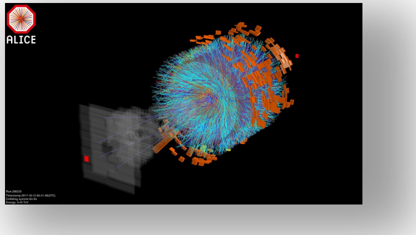
Pb-Pb @ 6.37 Z TeV
3.5 x design luminosity

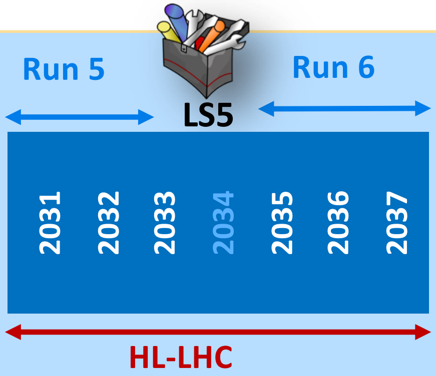
"Upgrade": new species
16h Xe-Xe operation

"Upgrade": new species
12h Pb81+ operation



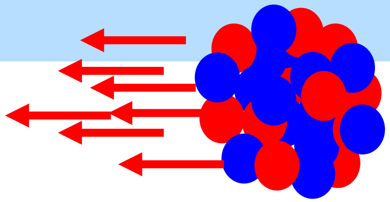
Pb-Pb @ 6.37 Z TeV
6.1 x design luminosity





Currently no heavy-ion runs foreseen in Run 5 & 6, but a revised schedule is under discussion.

Energy of ions/nuclei and nucleons



The ideal circular orbit

Lorentz Force $F_L = Q\,v\,B$

Centrifugal Force $F_{centr} = \dfrac{\gamma\, m_0\, v^2}{\rho}$

$$\underbrace{F_L = F_{centr}}$$

Magn. field *B*
Bending radius *ρ*

$$\boxed{\frac{p}{Q} = B\,\rho}$$

Beam rigidity

Energy and momentum are related via the square of the 4-momentum vector, **P** = (*E* / *c* , **p**):

$$P^2 = \frac{E^2}{c^2} - p^2 = m^2c^2$$

Operate at same beam rigidity for different species → **equivalent beam energy**:

$$\boxed{E_{ion} = E_p\,Z}$$

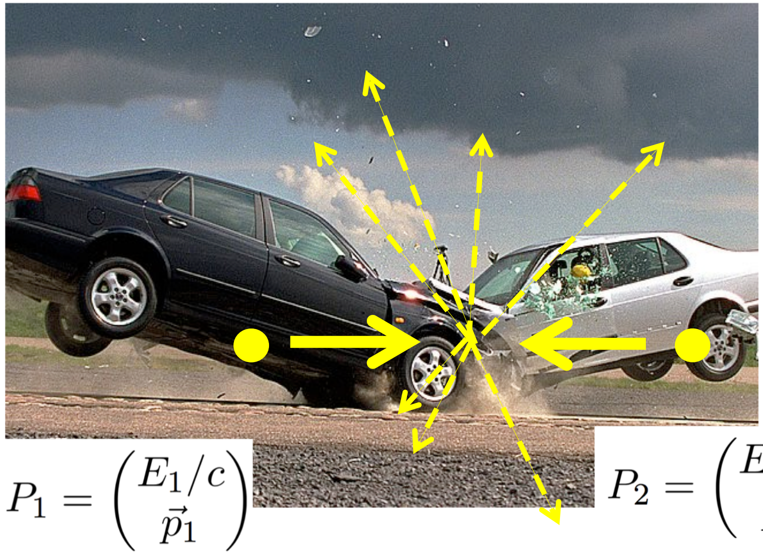
At high energy
E >> mc^2

Keep similar magnetic cycles for proton and heavy-ion operation.

$$\boxed{E \approx pc = \underbrace{7.0\,Z\,\mathrm{TeV}}_{\text{Energy per charge, relation to proton energy}} = \underbrace{2.76\,A\,\mathrm{TeV}}_{\text{Energy per nucleon}} = \underbrace{574\,\mathrm{TeV}}_{\text{Energy of the particle}}}$$

Centre-of-Mass Energy

Centre-of-Mass (CMS) energy is available for the production of new particles.



$$P_1 = \begin{pmatrix} E_1/c \\ \vec{p}_1 \end{pmatrix} \qquad P_2 = \begin{pmatrix} E_2/c \\ \vec{p}_2 \end{pmatrix}$$

$$\boxed{E = E_{beam1} + E_{beam2}}$$

From the sum of the 4-momentum vectors the **centre-of-mass energy in collision of two different species** can be calculated:

$$\boxed{\sqrt{(P_1 + P_2)^2} = \sqrt{s} \approx 2 p_p \sqrt{Z_1 Z_2}}$$

Centre-of-mass energy **per colliding nucleon pair**:

$$\boxed{\sqrt{s_{NN}} \approx 2 p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}}$$

proton momentum

LHC Pb-Pb run in 2015/18:

$$\sqrt{s} = 2 \times 6.37 \times 82\,\mathrm{TeV} > 1\,\mathrm{PeV}$$

$$\sqrt{s_{NN}} = 2 \times 6.37 \times \frac{82}{208}\,\mathrm{TeV} = 5.02\,\mathrm{TeV}$$

New energy frontier in nucleus-nucleus collisions.
Continues beyond RHIC ($\sqrt{s_{NN}} = \mathbf{0.2\ TeV}$) and previous fixed target experiments.

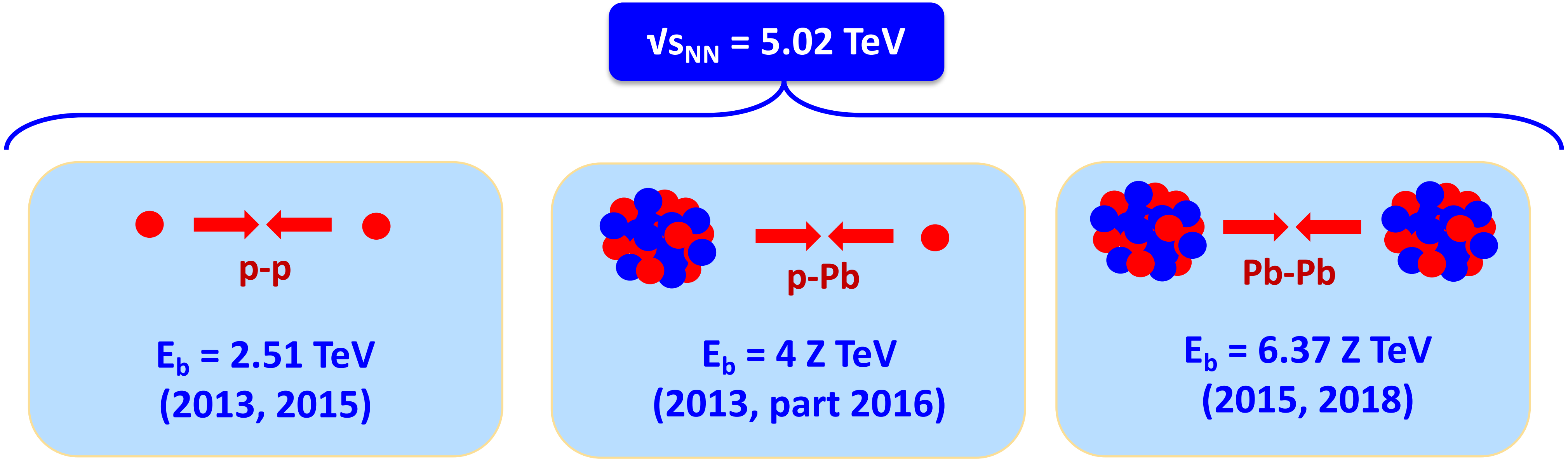
Choice of Beam Energy

particle charge

Max. beam energy achieved in p-p collisions: $E_b = 6.5\ Z$ TeV.

For Pb-Pb, **beam energy** reduction to **$E_b = 6.37\ Z$ TeV.**

→ Allows comparison of 3 collision modes at the **same center-of-mass energy $\sqrt{s_{NN}}$**



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

p-p

$E_b = 2.51$ TeV
(2013, 2015)

p-Pb

$E_b = 4\ Z$ TeV
(2013, part 2016)

Pb-Pb

$E_b = 6.37\ Z$ TeV
(2015, 2018)

p-p reference data

Special p-p runs at this energy;
different to general p-p programme

Beam Parameters

A particle bunch is characterised by its **number of particles, $N_b(t)$,** and the **normalised emittances, $\epsilon_{n,i}(t)$, in the three planes** ($i = x, y, s$).

The transverse emittances relate to the beam sizes σ_{xy}:

$$\sigma_{xy}^2 = \epsilon_{xy}\beta_{xy}$$

The beam size shrinks during acceleration by adiabatic damping. Therefore we define the so-called **normalised emittance ϵ_n,** which is constant with energy:

$$\epsilon_{n,xy} = \epsilon_{xy}\sqrt{\gamma^2 - 1} \approx \epsilon_{xy}\gamma$$

Normalized emittance in LHC
(γ@7 Z TeV, same beam size)

$$\epsilon_{n,p} = 3.75\,\mu\mathrm{m} \qquad \gamma_p = 7461$$

$$\epsilon_{n,Pb} = 1.5\,\mu\mathrm{m} \qquad \gamma_{Pb} = 2963.5$$

The rel. Lorentz factor is related to the energy as

$$E = \gamma m c^2$$

Thus, for particles in the same magnetic field

$$\gamma_{ion} = Z\frac{m_p}{m_{ion}}\gamma_p$$

Heavy-Ion vs. Proton Operation

- Some similarities with protons: aperture, optics, orbits
  → Bending ∝ Charge ($q = Ze$): $\boldsymbol{B\rho = p/q}$
- **Charge per ion bunch ~10% of proton bunch:**
  → collective effects driven by impedance or beam-beam are weak
- **Higher charge and mass: Beam dynamics and performance limits of heavy ions are quite different from those of protons.**
- Many beam dynamic effects are proportional to **high powers of $\boldsymbol{Z}$**. In same accelerator:
  → Strong Intra-beam scattering (IBS) α Z^3/A^2.
  → Radiation damping α Z^5/A^4.
  → Large event cross-sections for electromagnetic processes.

⇒ Fast intensity decay and **short luminosity lifetimes**.
⇒ **Secondary beams emerging from the interaction point** (IP).

Dominant Effects on Emittance

See lecture by **V. Kain**

Intra-Beam Scattering (IBS)

Multiple small-angle Coulomb scattering among charged particles inside their bunch.

Emittance Growth and Particle Losses

Growth rate dynamically changing with **beam properties**:

$$\alpha_{\mathrm{IBS}} \propto \frac{1}{\gamma} \boxed{\frac{N_b}{\epsilon_{n,x}\epsilon_{n,y}\epsilon_s}}$$

Dominating effect in the LHC.
Tends to reduce luminosity.

Radiation Damping

Energy loss due to synchrotron radiation emitted by charged particles bent on a circular orbit.

Emittance Shrinkage

Damping rate is **constant** for a given beam energy:

$$\alpha_{\mathrm{rad}} \propto \gamma^3$$

Starts to become noticeable at LHC energies (and above).
Tends to increase luminosity

IBS and radiation damping both depend on particle type.

Luminosity

Luminosity is a measure of the ability of a particle accelerator to produce the required number of interactions:

Luminosity

Event/Collision rate:

$$\frac{dR}{dt} = -\frac{dN}{dt} = \sigma_c \mathcal{L}$$

Reduction of beam particles with time.

Event cross-section

σ_{tot} = sum of all processes removing particles from the beam

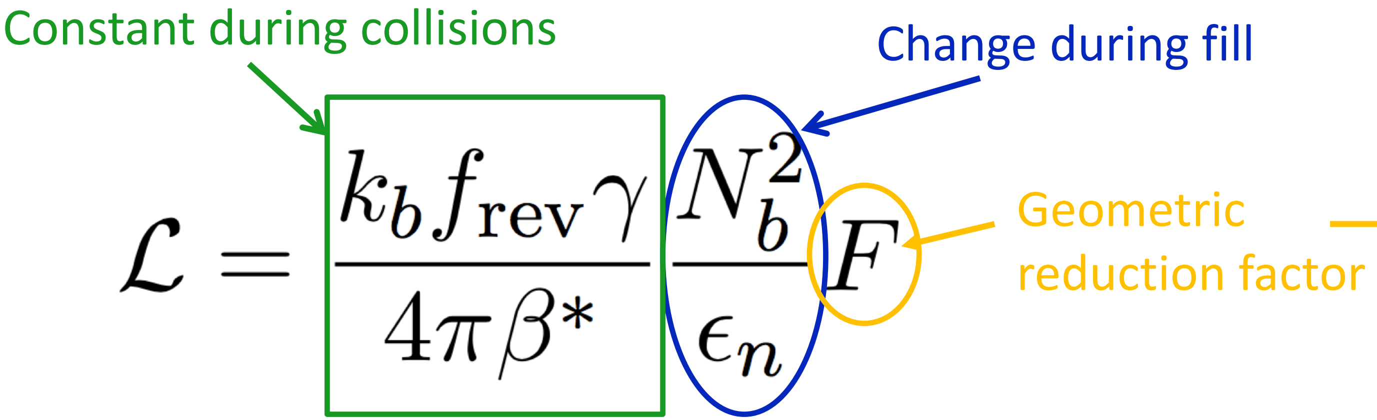
$\sigma_{\mathrm{tot}}\ (\mathrm{p}-\mathrm{p}) \sim 0.1\mathrm{b}$

$\boldsymbol{\sigma}_{\mathbf{tot}}\ (\mathbf{Pb}-\mathbf{Pb}) \sim \mathbf{500b}$, out of which $\sigma_{\mathrm{hadronic}}\ (\mathrm{Pb}-\mathrm{Pb}) \sim 8\mathrm{b}$

Luminosity

See lecture by **I. Meshkov**

For ***k_b* colliding bunches**, which are equal and round:



Constant during collisions

Change during fill

$$\mathcal{L} = \boxed{\frac{k_b f_{\mathrm{rev}} \gamma}{4\pi \beta^*}} \frac{N_b^2}{\epsilon_n} F$$

Geometric reduction factor

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

Depends on machine settings (crossing-angle θ_c, β-function at IP) and beam parameters (emittance ϵ_n, bunch length σ_z)

Beam parameters
ϵ_n , N_b, σ_z
vary bunch-by-bunch.

Machine parameters
θ_c, β^*
are individually set for the requirements of each experiments.

Number of colliding bunches k_b per IP depends on filling pattern.

LHC Heavy-Ion runs are complicated!
4 experiments with sometimes very different requests and conditions, luminosity sharing, …

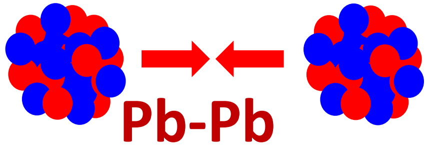
Nucleon-Nucleon Luminosity

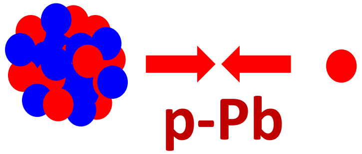
See lecture by **I. Meshkov**

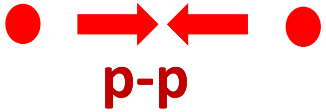
The nucleus-nucleus luminosities for collisions of different species or asymmetric collisions (e.g. p-Pb) are very different and may seem low compared to p-p.

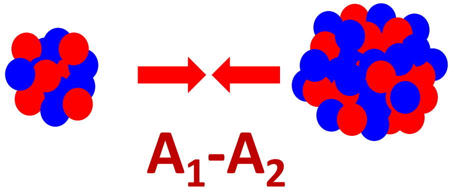
In order to make a meaningful comparison one has to look at the **nucleon-nucleon luminosity**:

$$\boxed{\mathcal{L}_{NN} = A_1 A_2 \mathcal{L}}$$









Example LHC Pb-Pb design luminosity:

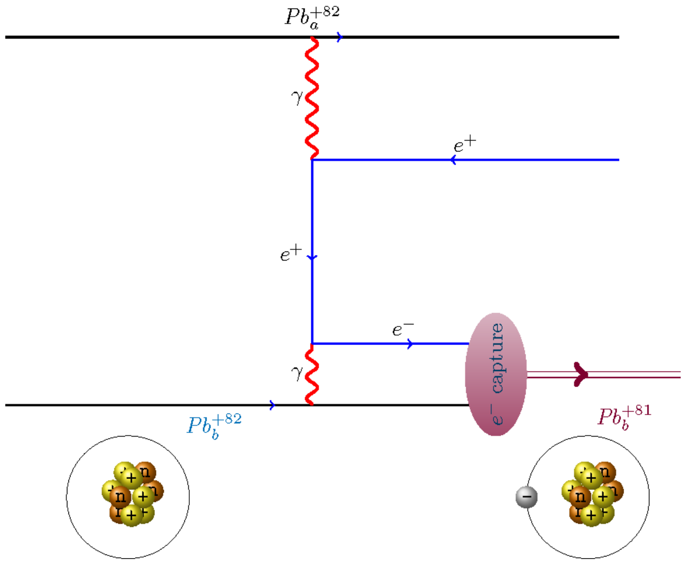
$$\begin{aligned}\mathcal{L} &= 1.0 \times 10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}\ (\mathrm{Pb}-\mathrm{Pb}) \\ &= 4.3 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}\ (\mathrm{nucleon}-\mathrm{nucleon})\end{aligned}$$

Interaction Cross-sections

Event rate: $$\frac{dR}{dt} = -\frac{dN}{dt} = \boxed{\sigma_c}\mathcal{L}$$

Bound-free pair production (BFPP)

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \rightarrow ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + \mathrm{e}^{+}$$

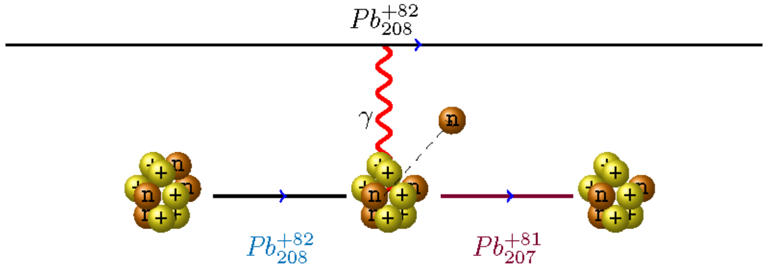


These **ultraperipheral interactions** have large interaction cross-sections in Pb-Pb collisions and are the main contribution to **fast luminosity burn-off** and **short beam lifetime**:

Electromagnetic dissociation (EMD)

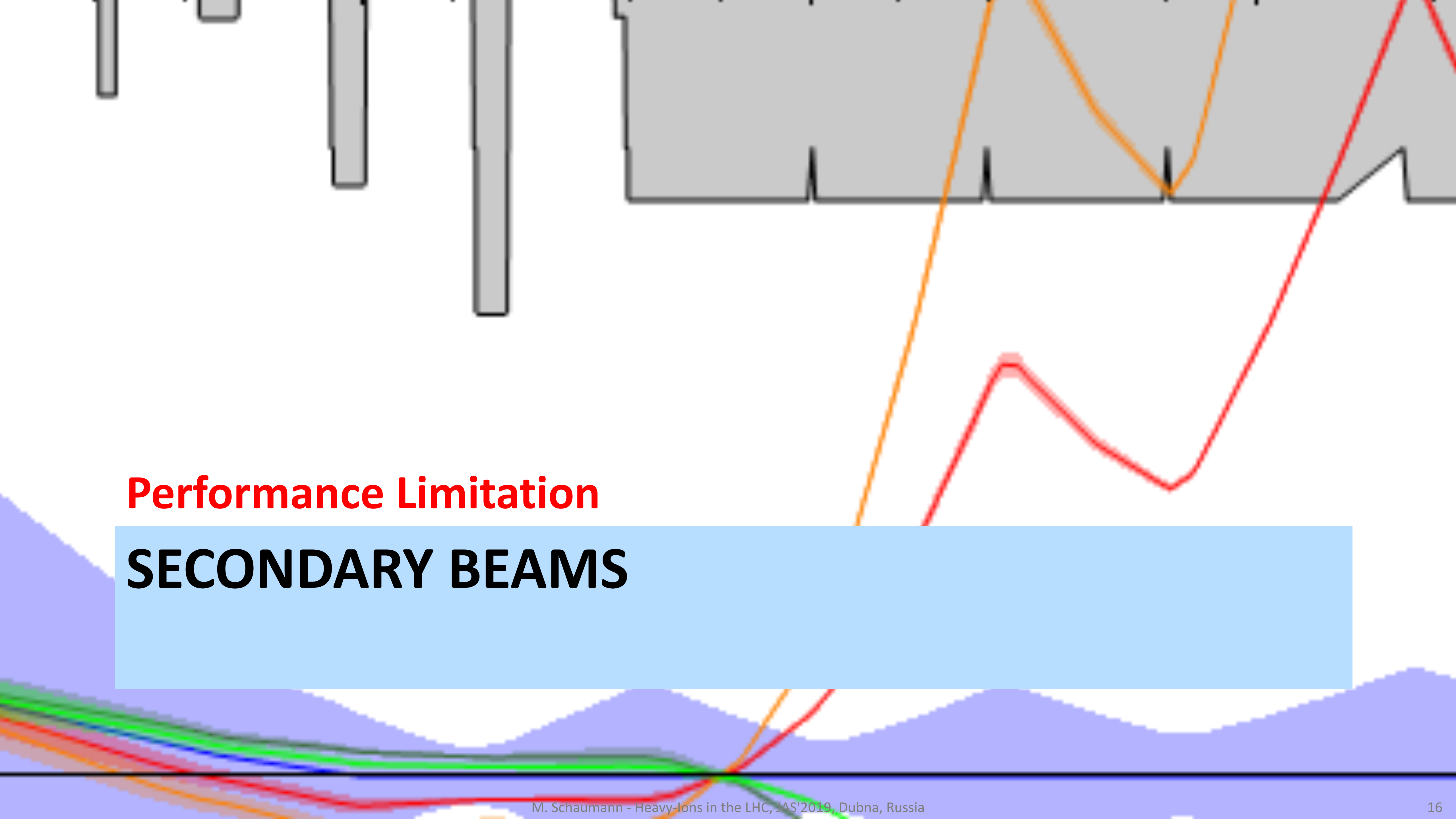
$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \rightarrow ^{208}\mathrm{Pb}^{82+} + ^{207}\mathrm{Pb}^{82+} + \mathrm{n}$$

…and higher orders



$$\begin{aligned} \sigma_{c,tot} &= \sigma_{BFPP} + \sigma_{EMD} + \sigma_{hadron} \\ &\approx 281\,\mathrm{b} + 226\,\mathrm{b} + 8\,\mathrm{b} \\ &= 515\,\mathrm{b} \end{aligned}$$

@ 7 *Z* TeV



Performance Limitation

SECONDARY BEAMS

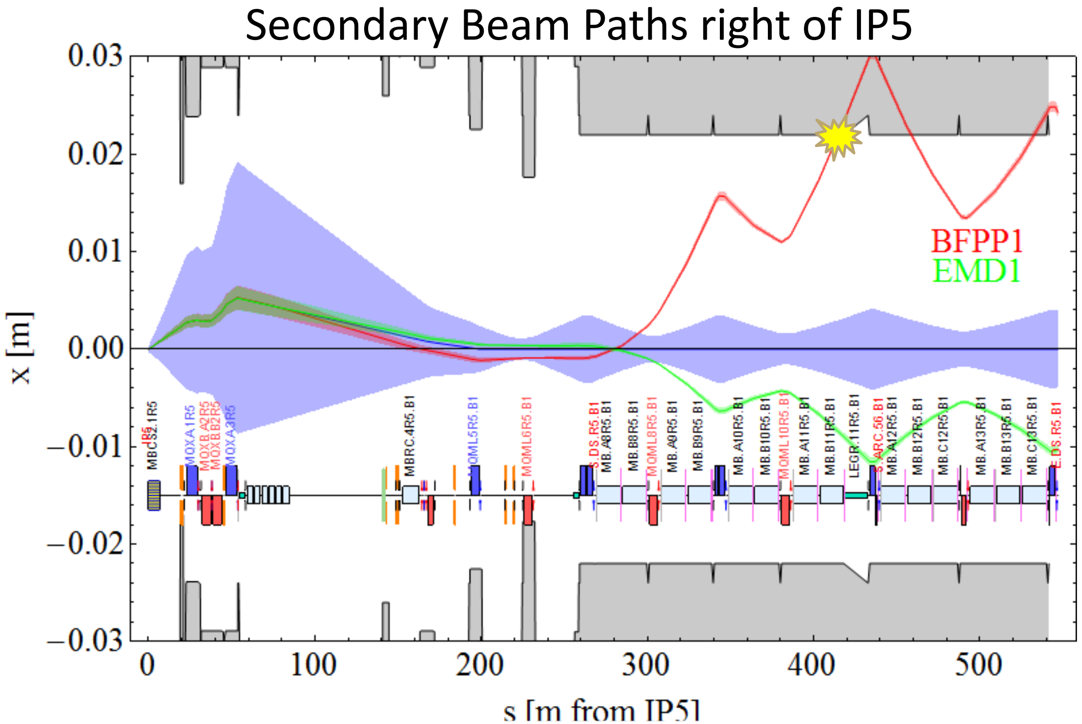
Secondary Beams Created in the Collision

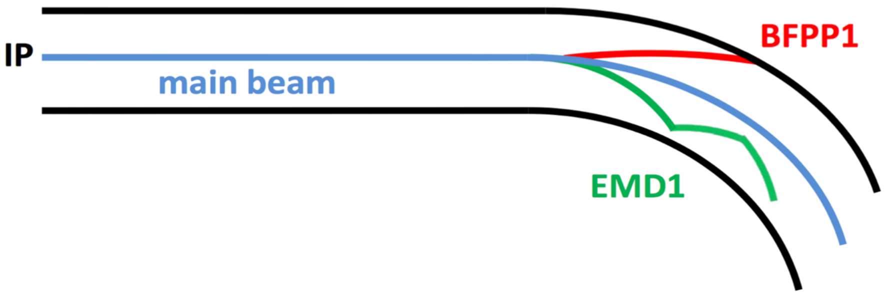
These reactions **change the charge-to-mass ratio of the ions**,
which **changes bending** in (main) dipoles: $\boldsymbol{B\rho = p/q}$

Main: **208-Pb-82+**

BFPP: **208-Pb-81+**
EMD: **207-Pb-82+**

Intense secondary beams are produced that impact in a superconducting magnet downstream from the IP.





Secondary beams with rigidity change

$$B\rho(1+\delta)$$

where

$$\delta = \frac{1 + \Delta m / m_{Pb}}{1 + \Delta Q / Q} - 1$$

<u>**Luminosity limit,**</u>
if deposited power exceeds quench limit.

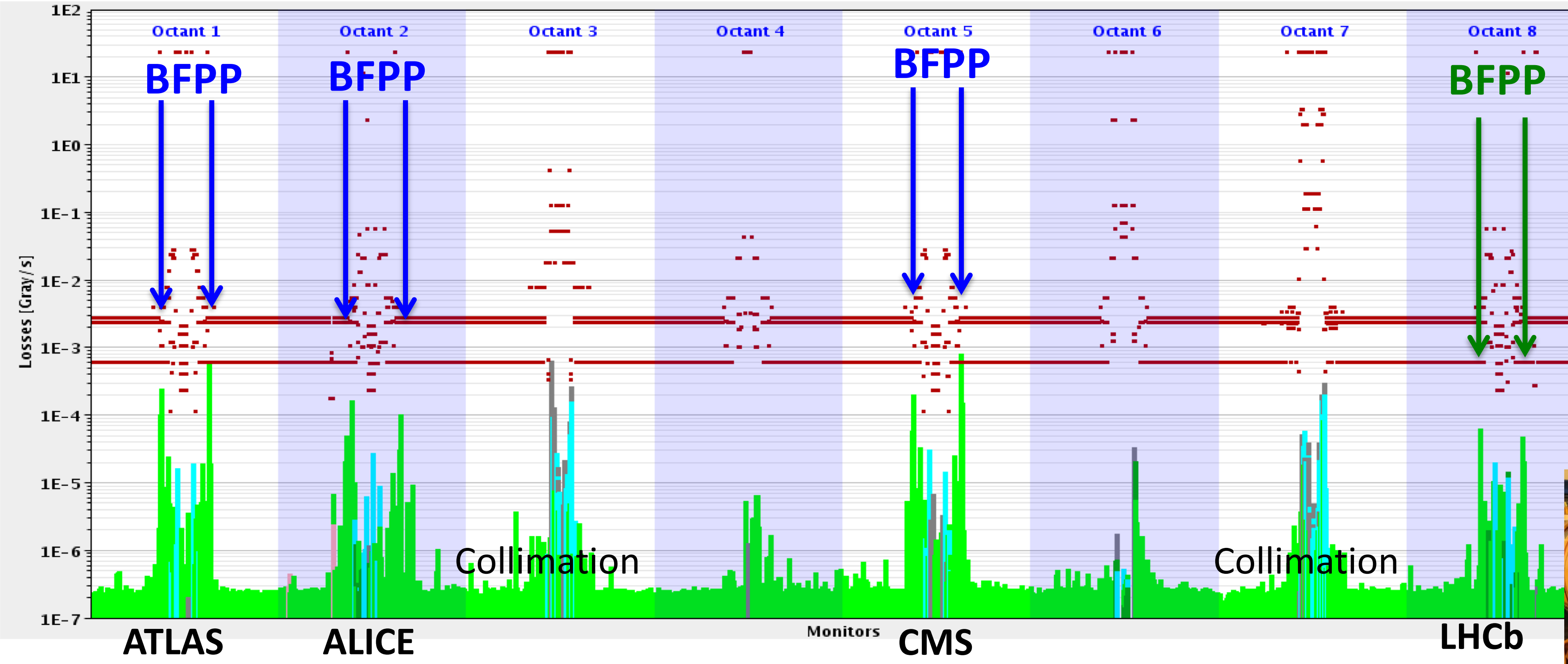
Loss Pattern around the Ring

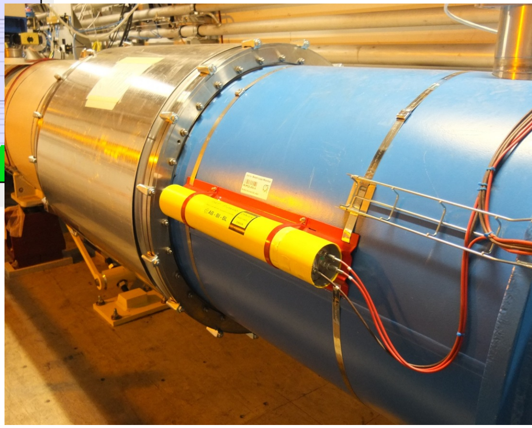
Direct limit of luminosity

Beam loss spikes around all IPs where ions collide …

Deposit power >140W → exceeds quench limit of the superconducting magnets.

Luminosity limit found at $L \approx 2.3 \times 10^{27} cm^{-2} s^{-1}$ (≅50W into magnet)



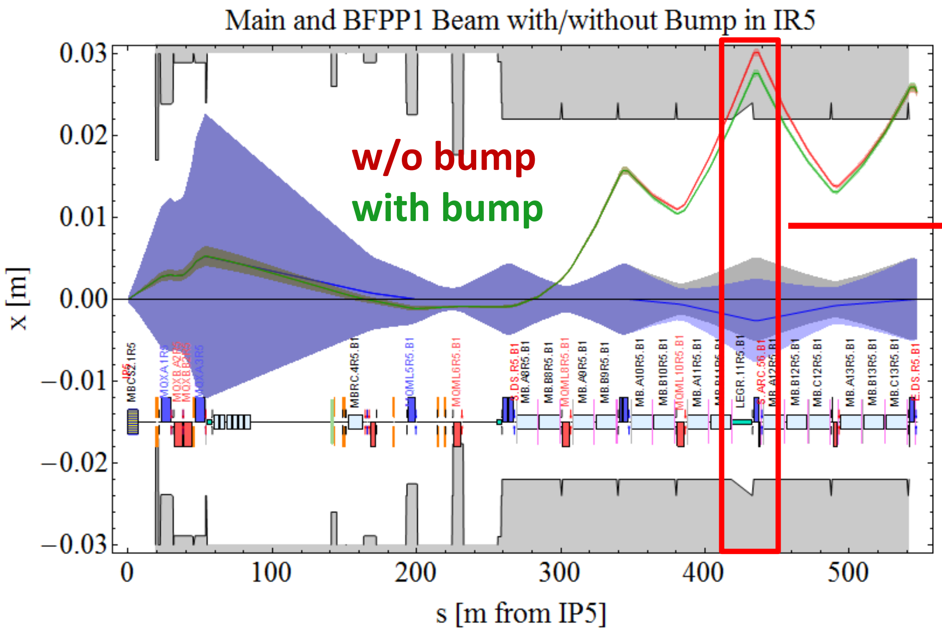


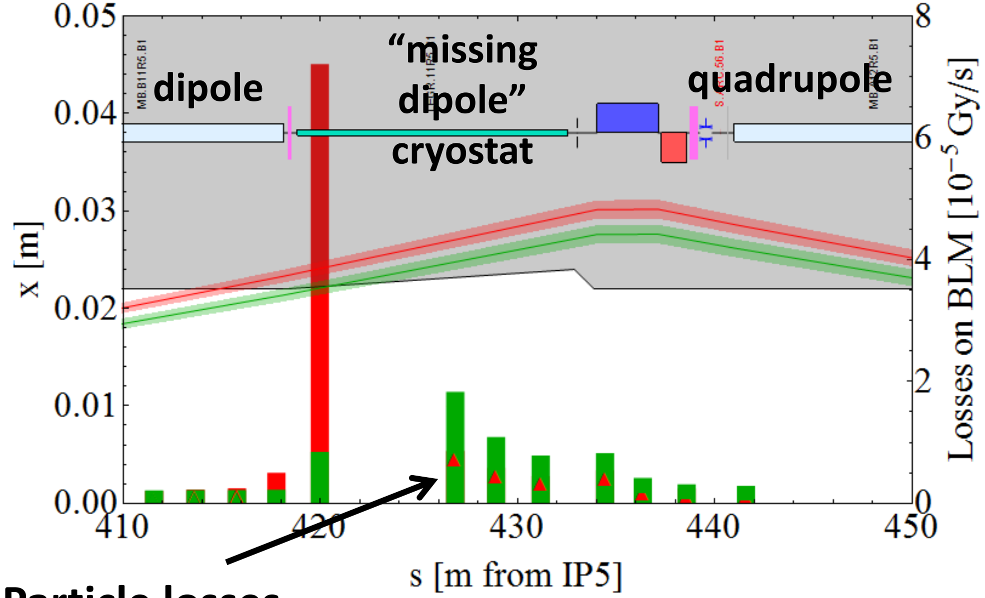
Beam **L**oss **M**onitors all around LHC circumference

Heavy-Ion collimation discussed in detail in lecture by **R.Bruce**

Quench Risk Mitigation with Orbit Bumps

Orbit bumps are used to move the secondary beam losses to a less vulnerable location in order to reduce risk of quench.





Particle losses

Careful setup of bumps in beginning of the run to achieve desired loss displacement.

Technique operationally used in ATLAS/CMS since 2015.

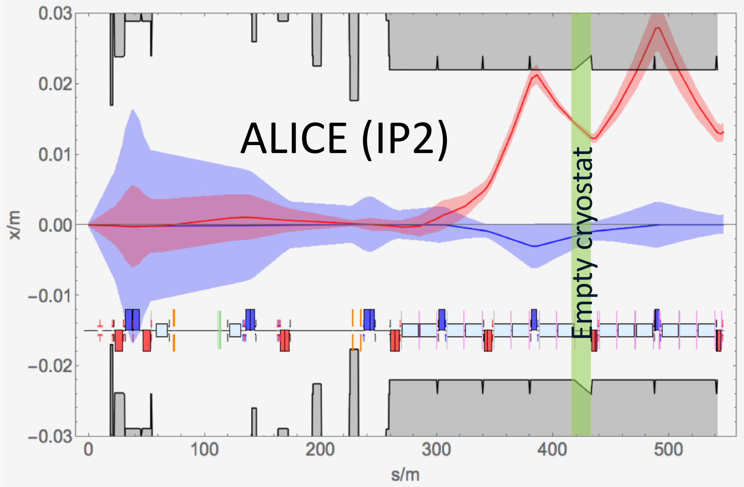
Allowed record luminosity of L > 6 x 10^{27} cm^{-2} s^{-1} in 2018.

BFPP Mitigation around ALICE & LHCb

Due to different optics around **ALICE** and **LHCb, bump technique does not work.**

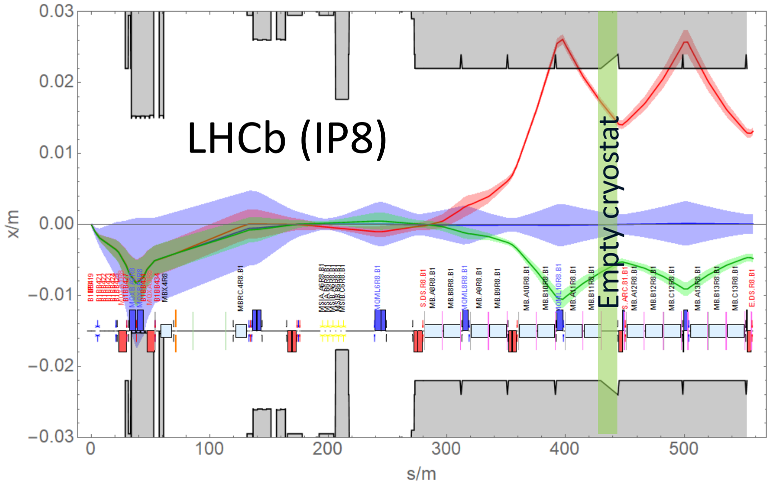
ALICE

- Peak luminosity limited by detector saturation to **1 x 10^{27}cm^{-2}s^{-1}**.
- Bump to distribute losses over two cells.



LHCb

- **No mitigation implemented.**
- 75ns bunch scheme provides many more collisions in LHCb.
- Peak luminosity levelled **1 x 10^{27}cm^{-2}s^{-1}**

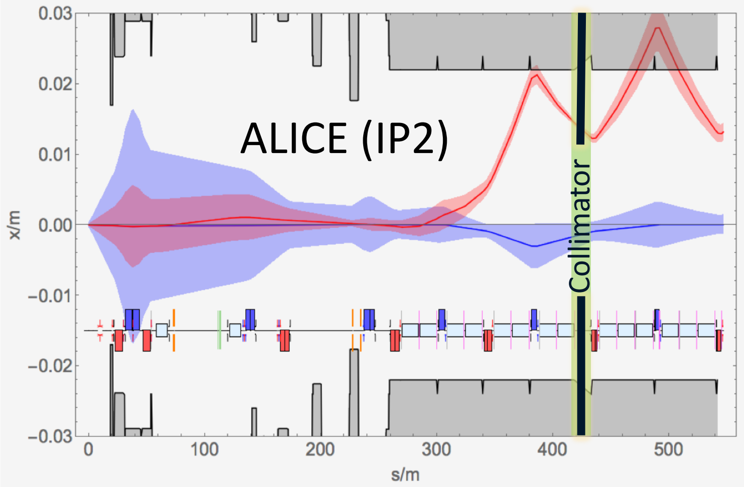


BFPP Mitigation around ALICE & LHCb – LS2 Upgrade

Due to different optics around **ALICE** and **LHCb, bump technique does not work.**

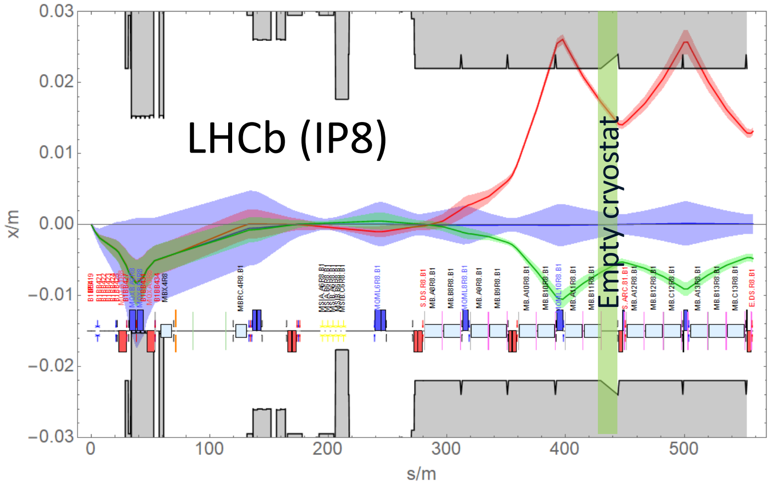
ALICE

- Currently implementing upgrade
- Will allow to go to **~7 x 10^{27}cm^{-2}s^{-1}**
- Installation of **collimator in the empty cryostat** location + orbit bump.

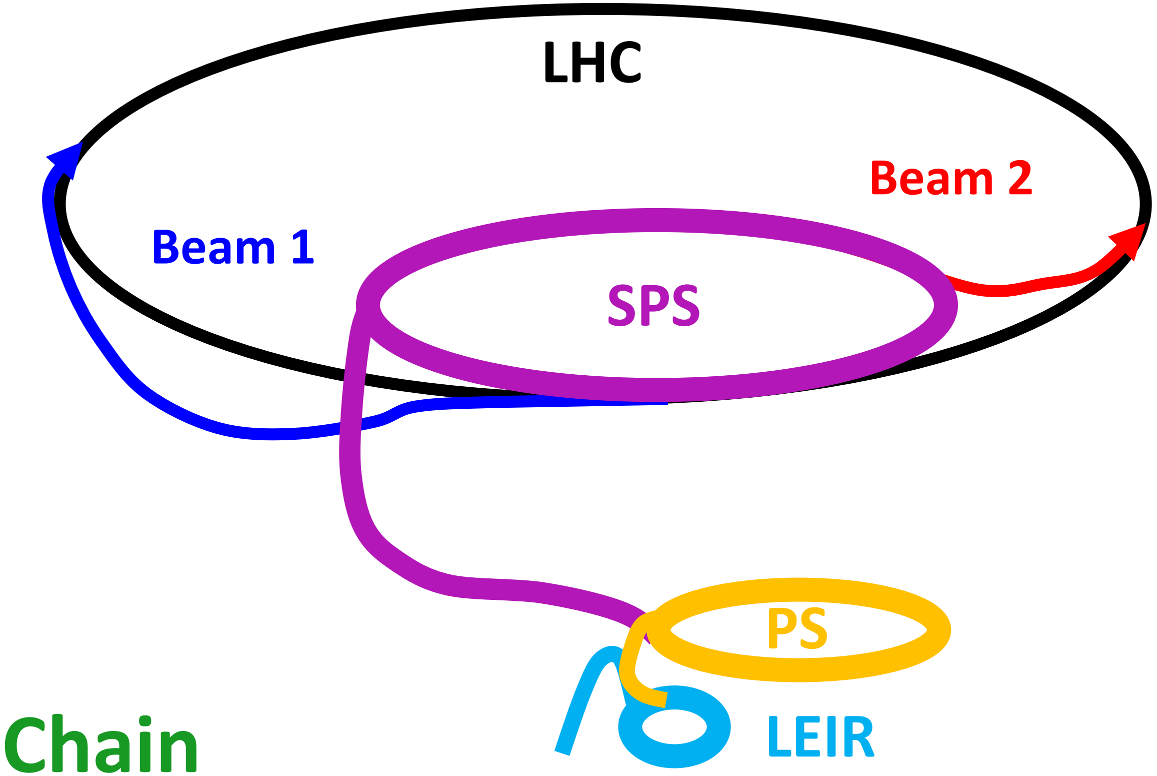


LHCb

- **No mitigation foreseen.**
- 75ns bunch scheme provides many more collisions in LHCb.
- Peak luminosity levelled **1 x 10^{27}cm^{-2}s^{-1}**



More about secondary beams & their treatment discussed in lecture by **F. Cerutti**



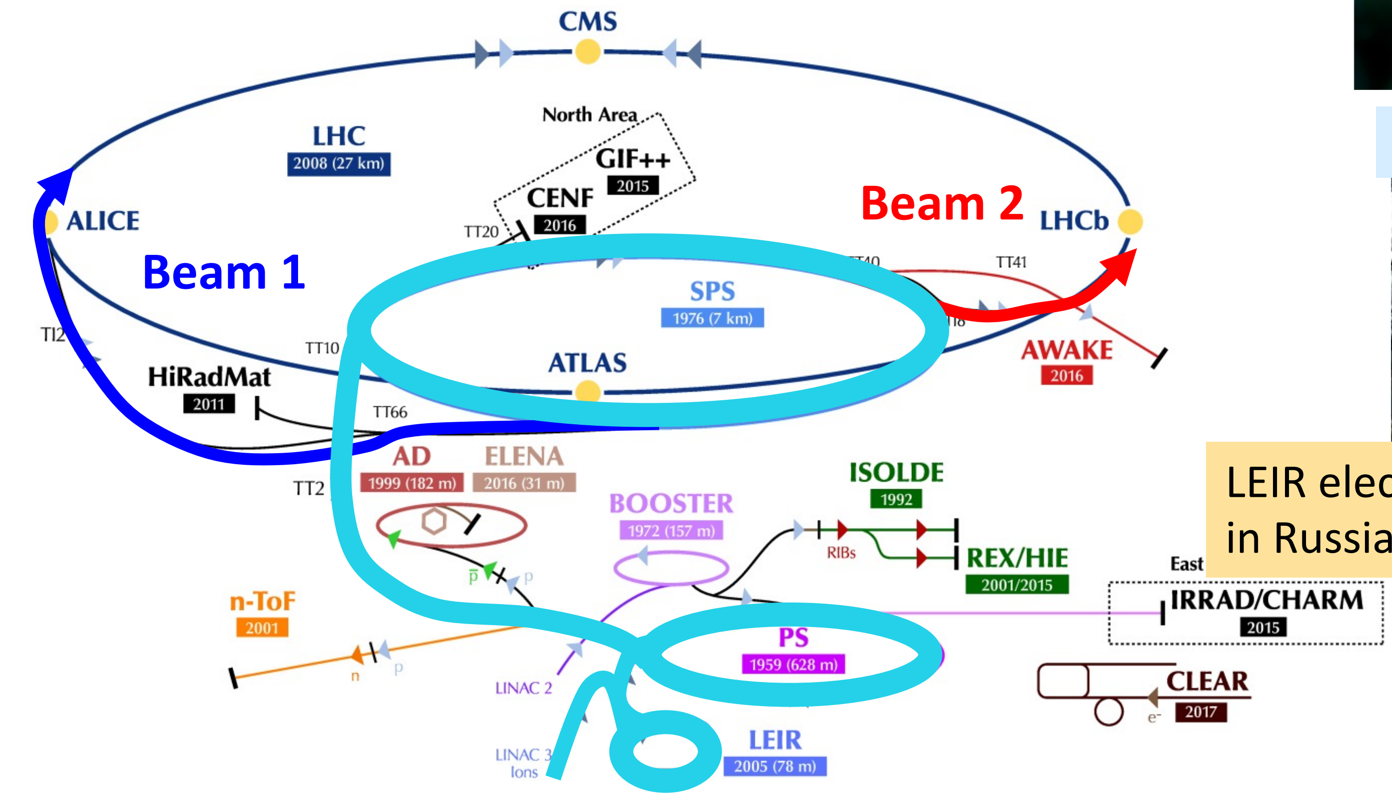
Importance of the Injector Chain

GETTING IONS INTO THE LHC

How Ions get into the LHC

The CERN accelerator complex

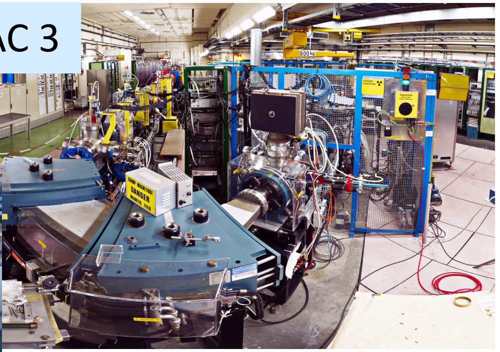
Complexe des accélérateurs du CERN



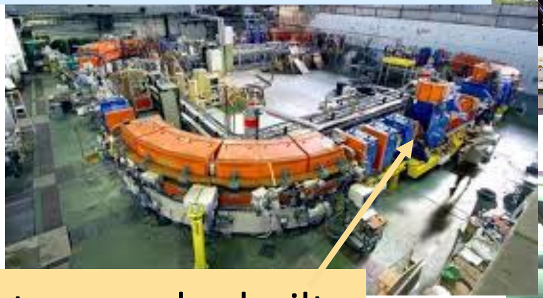
▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ p̄ (antiprotons) ▶ e⁻ (electrons)

LHC - Large Hadron Collider // **SPS** - Super Proton Synchrotron // **PS** - Proton Synchrotron // **AD** - Antiproton Decelerator // **CLEAR** - CERN Linear Electron Accelerator for Research // **AWAKE** - Advanced WAKefield Experiment // **ISOLDE** - Isotope Separator OnLine // **REX/HIE** - Radioactive EXperiment/High Intensity and Energy ISOLDE // **LEIR** - Low Energy Ion Ring // **LINAC** - LINear ACcelerator // **n-ToF** - Neutrons Time Of Flight // **HiRadMat** - High-Radiation to Materials // **CHARM** - Cern High energy AcceleRator Mixed field facility // **IRRAD** - proton IRRADiation facility // **GIF++** - Gamma Irradiation Facility // **CENF** - CErn Neutrino platForm

D. Küchler holding the source of Pb

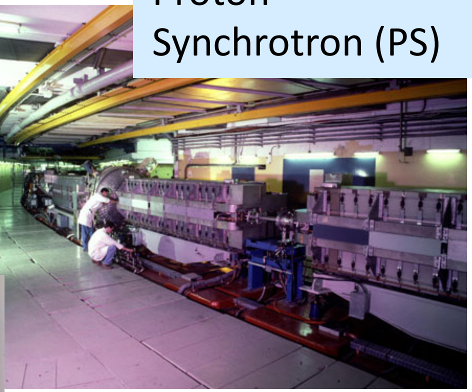


LINAC 3

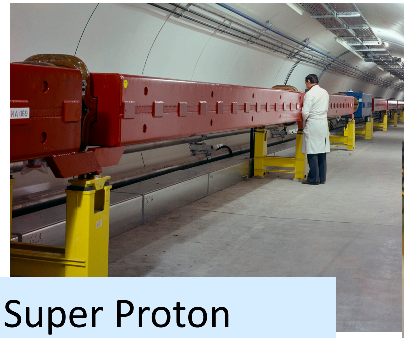


Low Energy Ion Ring (LEIR)

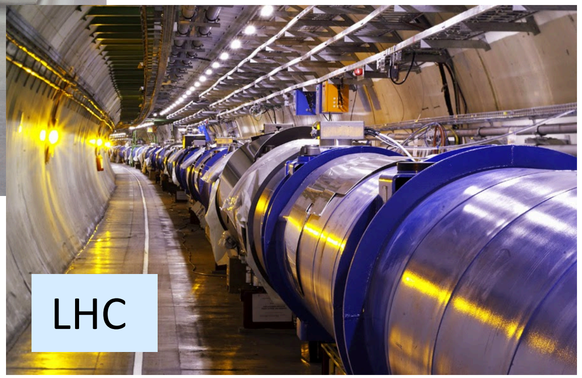
LEIR electron cooler built in Russia, at BINP



Proton Synchrotron (PS)

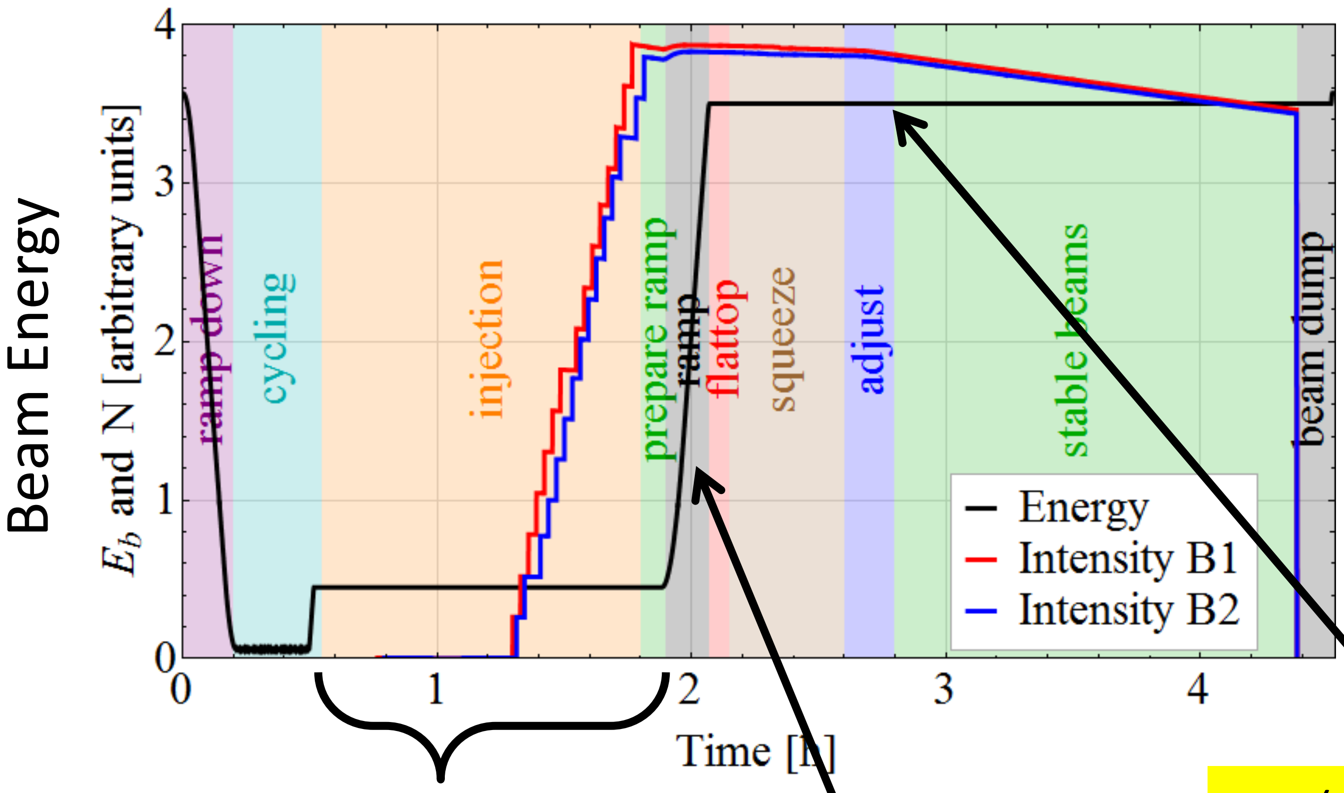


Super Proton Synchrotron (SPS)



LHC

Accelerator Cycle (Fill)



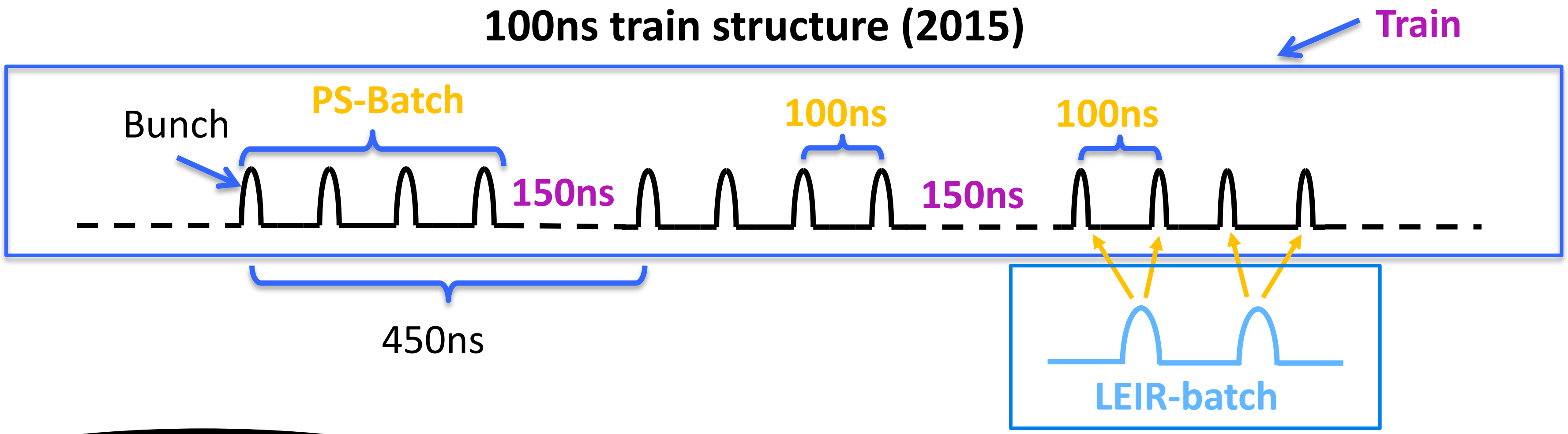
Low energy injection plateau:
Accumulation of beam

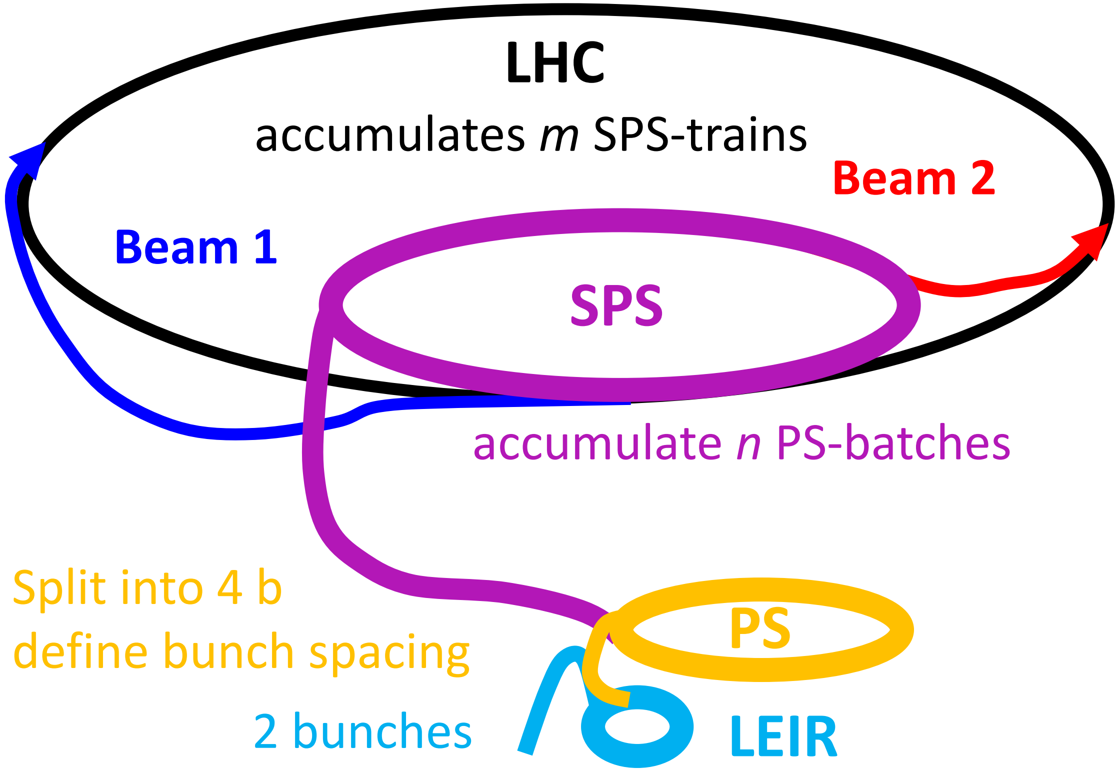
Acceleration

Top (max) Energy:
Store & Collide (LHC)

Injector cycles (e.g. PS or SPS) are analogous except: collisions → extraction

Filling Pattern: Production of Beam in the Injectors


100ns train structure (2015)



Filling scheme: How bunches are placed in the LHC defines which bunches collide where.

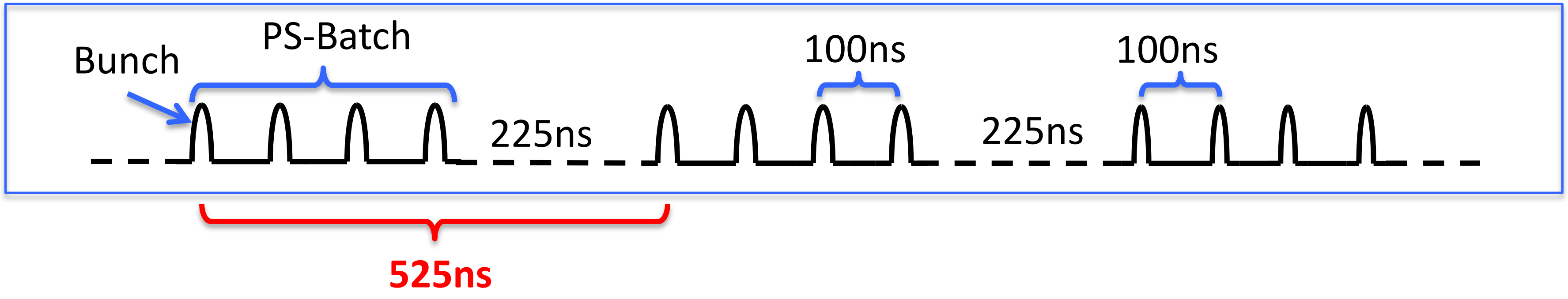
Due to symmetry and detector position not all bunches collide in each experiment.

Play with:
- Number of PS-batches per SPS-train
- Position of SPS-trains in LHC
- *(Separation levelling)*

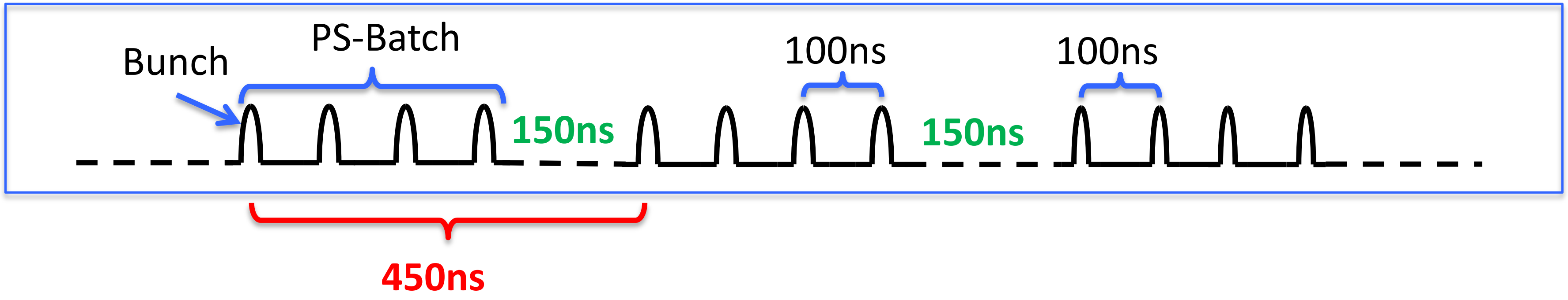
to get fair luminosity sharing.

Filling Pattern: design → 100ns → 75ns

Design train structure



100ns train structure (2015)



75ns train structure (2018)

Reduction of PS-batch spacing by 30% (!)

Thanks to improvement of SPS injection kicker rise time

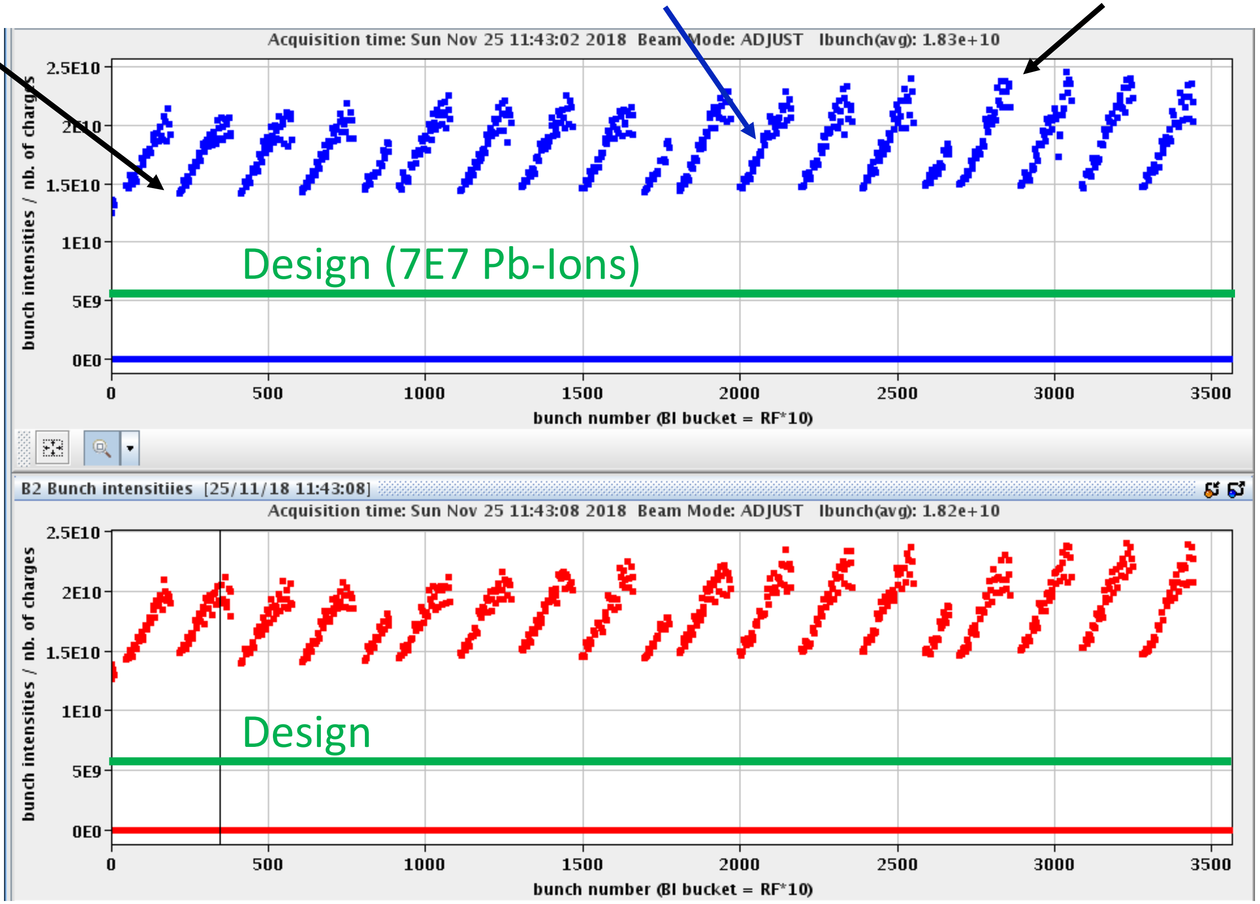
Bunch intensity >3x design

Improvement of performance throughout injector chain

New 3-bunch scheme with reduced bunch spacing out of LEIR and no splitting in PS.

→ more bunches
→ Higher bunch intensity

LHC Pb-Pb Bunch Intensities



min. 1.8E8 Pb-Ions

mean 2.2E8 Pb-Ions

max. 3E8 Pb-Ions

Design (7E7 Pb-Ions)

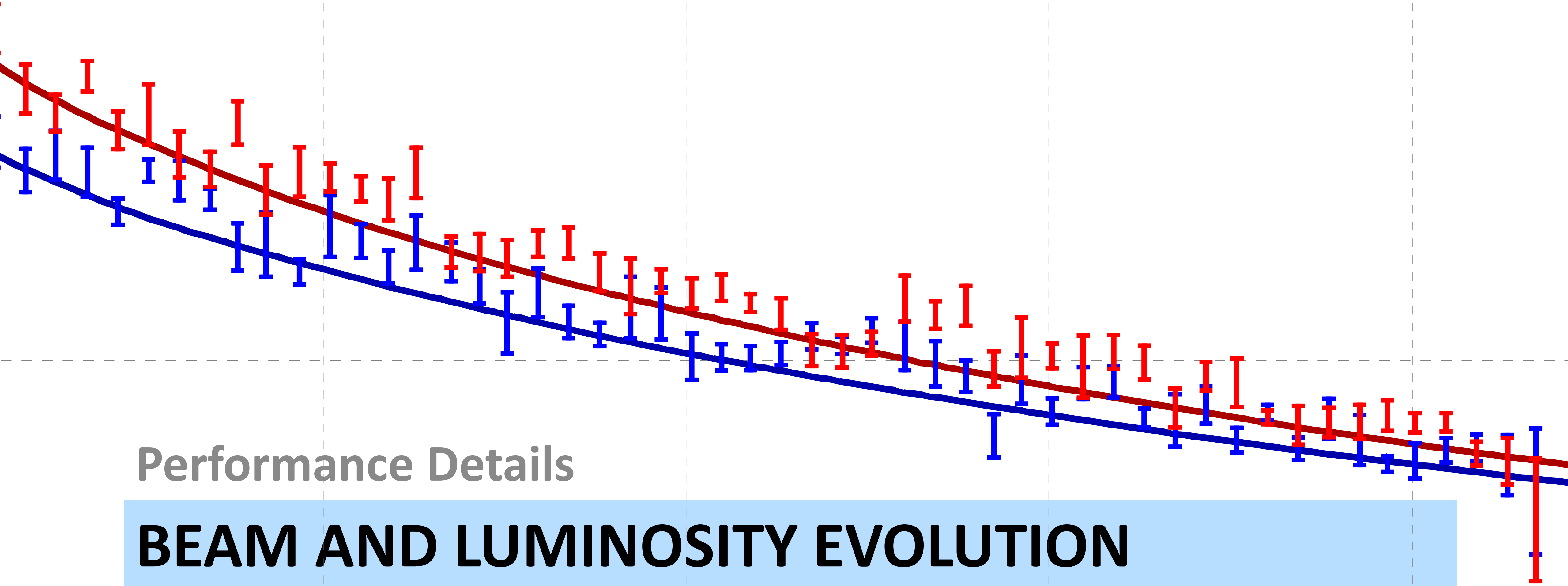
Design

Screenshot from 2018 operation: bunch intensities at top energy just before collisions

- Injectors provided **intensities far above the design**.

- Typical structure:
  - Along bunch train, due to losses at the SPS injection plateau.
  - Along the beam, similar losses in the LHC.

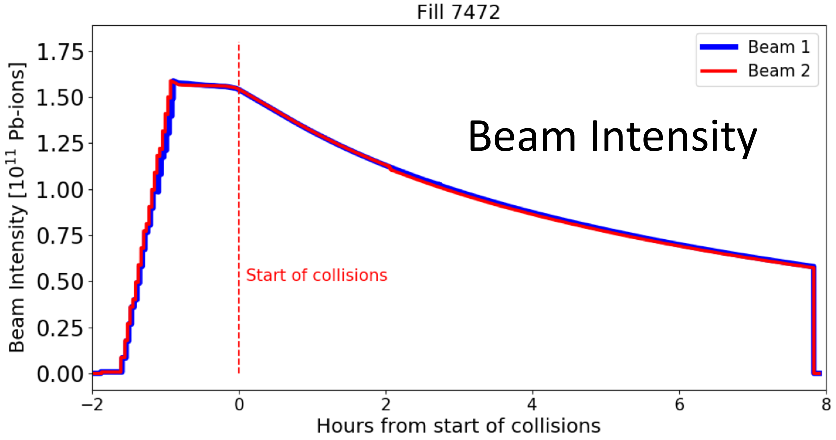
- Max. total number of bunches per beam: 733



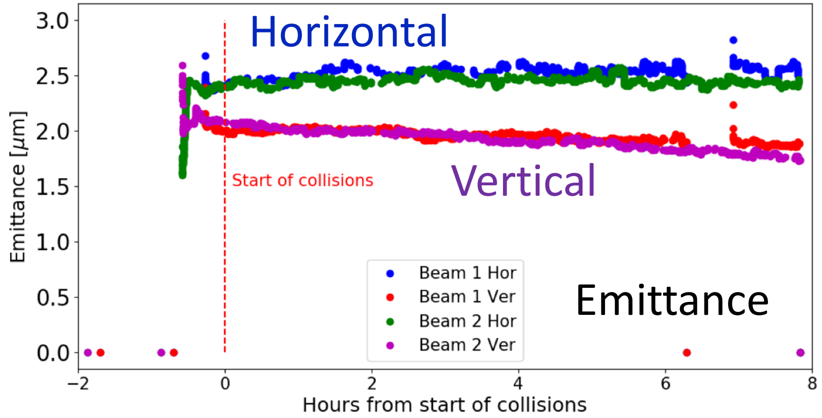
Performance Details

BEAM AND LUMINOSITY EVOLUTION

Intensity and Emittance Evolution

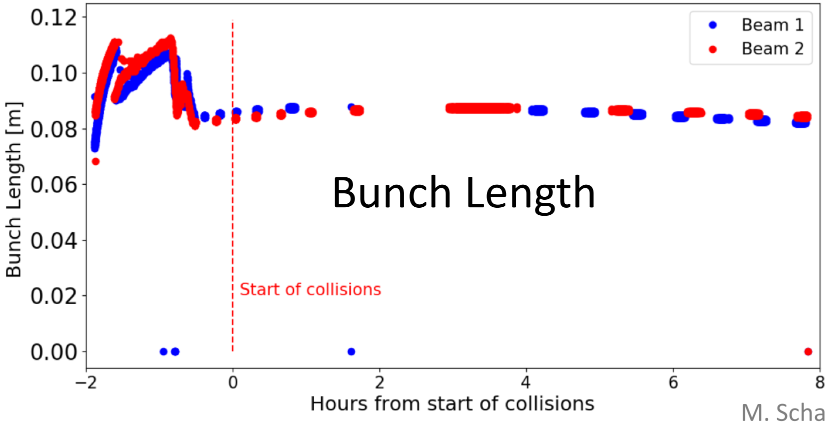


Beam intensity decay **dominated by burn-off** (losses from production of collisions)



IBS counteracts radiation damping in horizontal plane

In vertical, IBS is negligible
→ **rad. damping leads to shrinkage**



Bunch length similar behavior to horizontal emittance

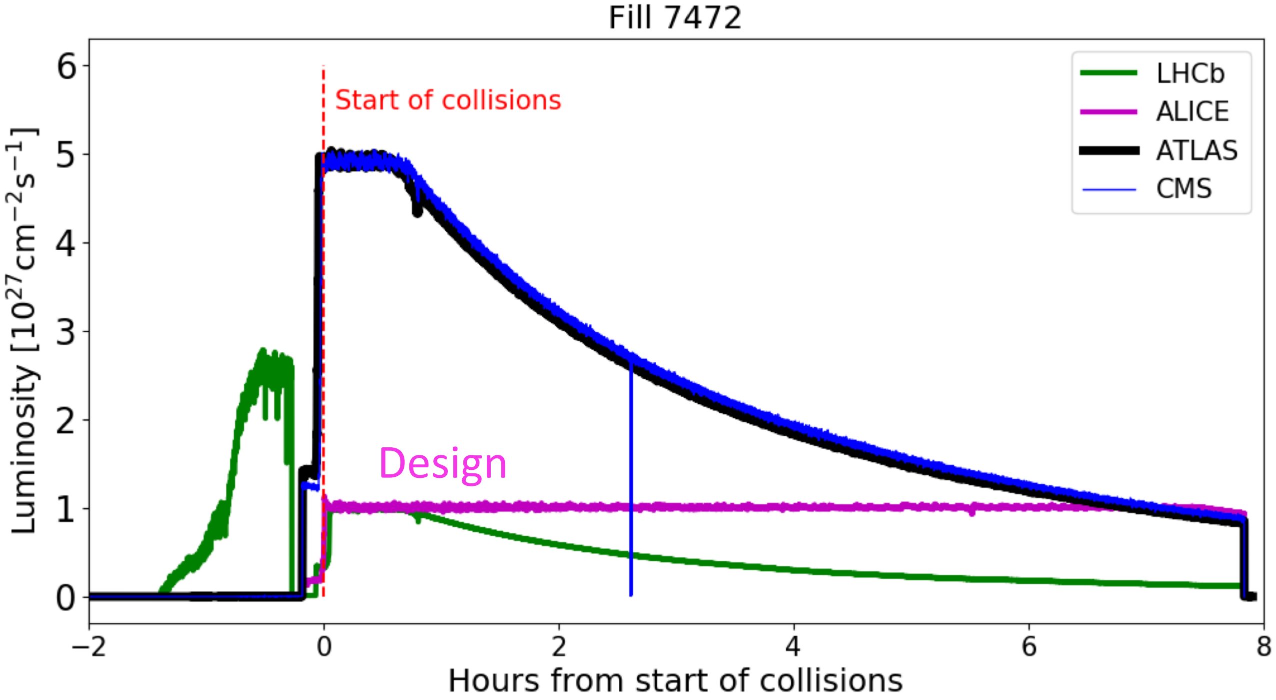
Typical Luminosity Evolution in 2018

Each experiment has individual requirements: max. Luminosity, β^*, crossing-angle, …
→ Separated machine setup per IP, luminosity levelling, *luminosity sharing*

ATLAS & **CMS:**
- β^*= 0.5m, $\theta_c = 170\mu$rad
- Short levelling period
- **Record: 6.1 x 10^{27}cm^{-2}s^{-1}** peak luminosity

ALICE:
- β^*= 0.5m, $\theta_c = 60\mu$rad
- Levelled to design saturation level most of the time in physics.
- **Upgrade to ~7 x 10^{27}cm^{-2}s^{-1} in LS2.**

LHCb:
- β^*= 1.5m, $\theta_c = 250\mu$rad
- Also levelled to design value

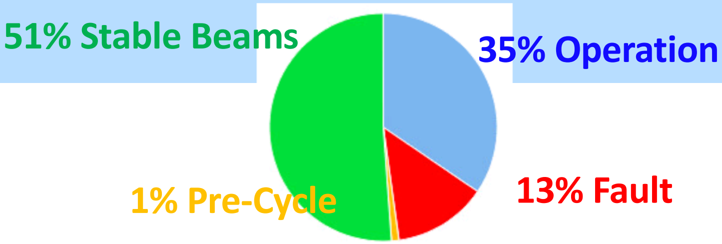


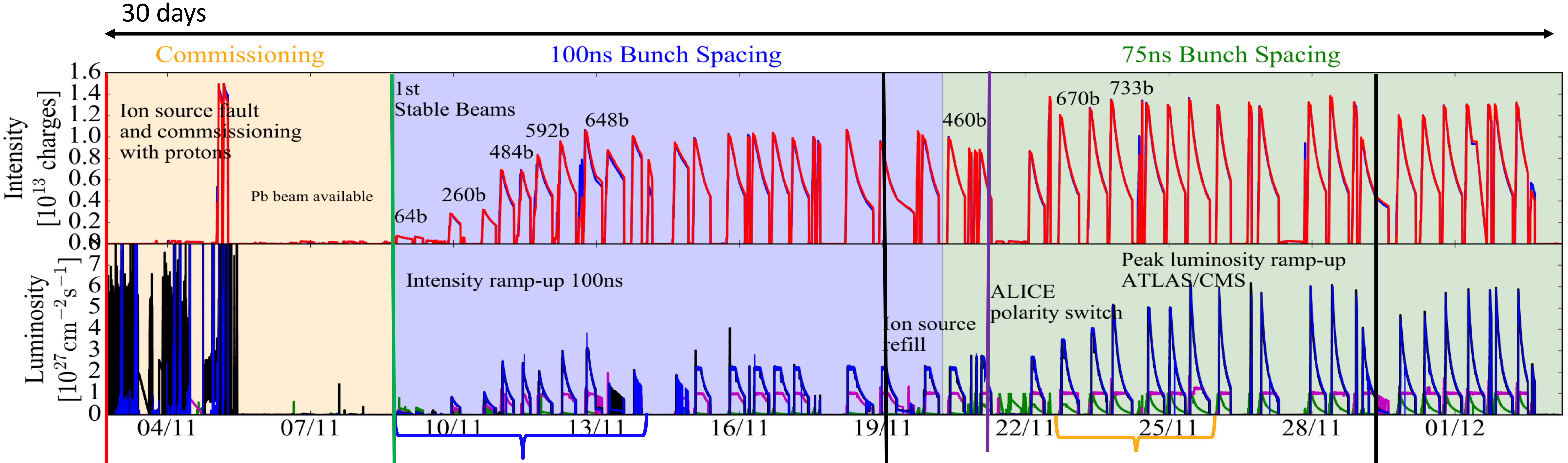
*LHC **Pb-Pb design luminosity** was chosen to be the detector saturation value of the ALICE experiment.*

A (typical) LHC Ion Run

Overview of the 2018 Pb-Pb run

Availability
87%





Ion source fault
no ions available

Intensity ramp-up 100ns beams

1st Pb-Pb
Stable Beams

1st source refill

New Record Peak luminosity in every fill up to 6.1 x 10^{27}cm^{-2}s^{-1}

ALICE polarity switch

2nd source refill

Status LHC → HL-LHC

Most of HL-LHC performance demonstrated!

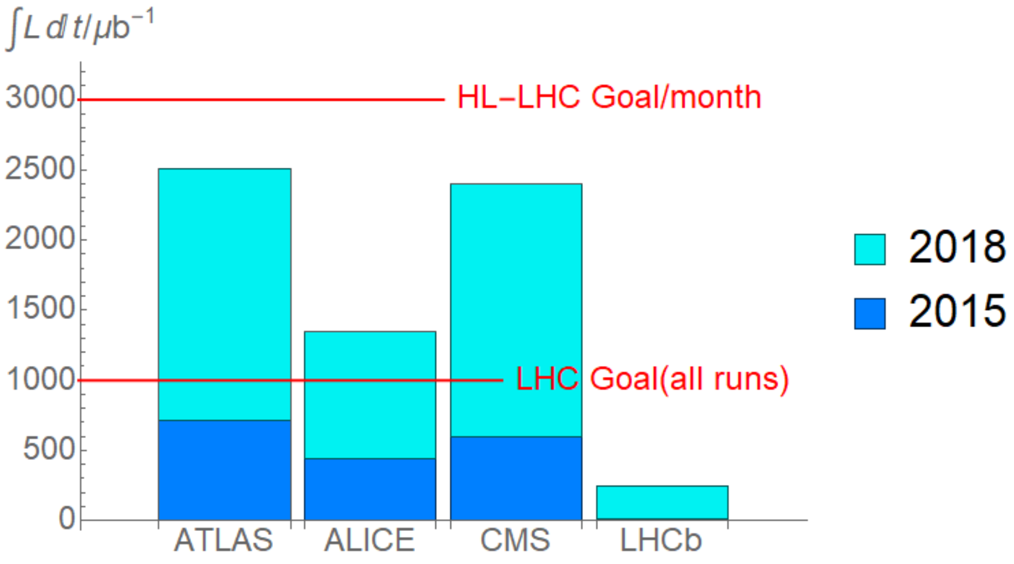
	Pb-Pb (Design)	Pb-Pb (2018 achieved)	”HL-LHC” Pb-Pb (after LS2)	Upgrade Status	
Energy [TeV]	7 Z	6.37 Z	7 Z	🔴	Magnet training
β^* at IP (1/2/5,8) [m]	(0.5, -)	**(0.5, 1.5)**	(0.5, 1.5)	🟢	
Emittance [μm]	1.5	~2	1.65	🟢	
Bunch Intensity [10^8 ions]	0.7	**2.2**	1.8	🟢	
No. Bunches	592	**733**	1232	🔴	SPS RF Upgrade (slip-stacking)
Bunch Spacing	100ns	100ns → **75ns**	50ns	🔴	
Peak Luminosity at IP1/2/5/8 [10^{27}cm^{-2}s^{-1}]	- / 1 / 1 / -	**6.1 / 1 / 6.1 / 1**	7 / 7 / 7 / ?	🟡	Lumi levelling

Green values reached & exceeded LHC design

Some collisions in LHCb (not considered in detail yet)

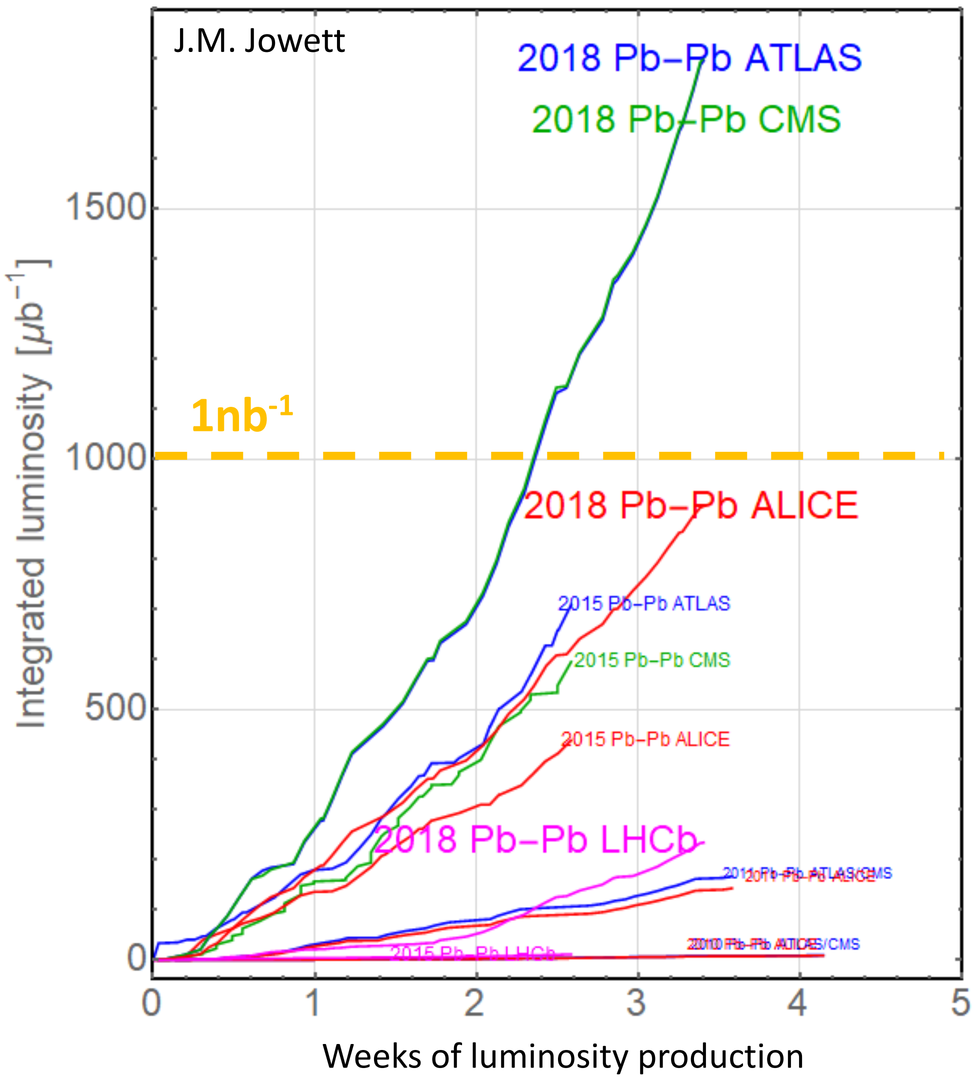
Delivered Luminosity: Pb-Pb

LHC design goal of 1nb^{-1} in Pb-Pb luminosity already exceeded.



Future performance estimate from 2021:

3 nb^{-1}/run → 12 nb^{-1} in 4 more Pb-Pb runs



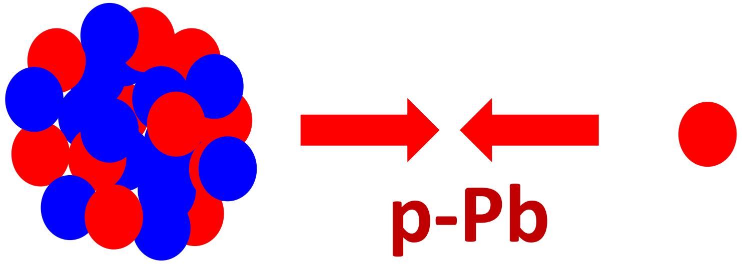
LHC has operated in 5 different modes, but was designed only for 2:

- Design: **p-p, Pb-Pb**
- Upgrade: **p-Pb**, **Xe-Xe** (pilot run)**, Pb81+** (MD in July)

Few hours runs with new particle types showed that the LHC is highly flexible and well under control.

Demonstrating Flexibility

COLLISION MODE UPGRADES



PROTON-LEAD

Storing and Colliding Different Species

Revolution time and RF frequency depend on particle's mass *m*, charge *Q=Ze*:

$$T(p_p, m, Z) = \frac{C}{c}\sqrt{1+\left(\frac{mc}{Zp_p}\right)^2}$$

$$f_{RF} = \frac{h_{RF}}{T(p_p, m, Z)}$$

where harmonic number h_{RF} = 35640 in LHC

Relation between momenta is fixed by two-in-one magnet design: $p_{Pb} = Zp_p$ → $T_p \neq T_{Pb}$ → $f_{RF,p} \neq f_{RF.Pb}$
But in order for bunches to meet repeatedly and create collisions we need: $T_p = T_{Pb}$ → $f_{RF,p} = f_{RF.Pb}$

→ Use **length of closed orbit *C*** to compensate for speed difference.
Done by **adjusting RF frequency** → **moving to (slightly) off-momentum orbit**

$$T(p_p, m, Z) = \frac{C}{c}\sqrt{1+\left(\frac{mc}{Zp_p}\right)^2}(1+\eta\delta)$$

→ Pb is slower, need smaller orbit length → move inward, $\delta < 0$
→ Protons are faster, need longer orbit length → move outward, $\delta > 0$

momentum of offset orbit

$$\delta = \frac{p - Zp_p}{Zp_p}$$

Fractional momentum difference

$$\eta = \frac{1}{\gamma_T} - \frac{1}{\gamma}$$

Phase-slip factor, $\gamma_T = 55.8$ for LHC optics

Horizontal offset given by dispersion: $\Delta x = D_x(s)\delta$

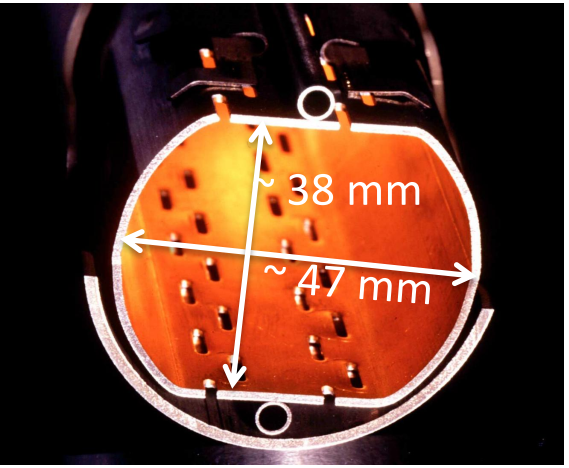
Momentum Offset required through Ramp

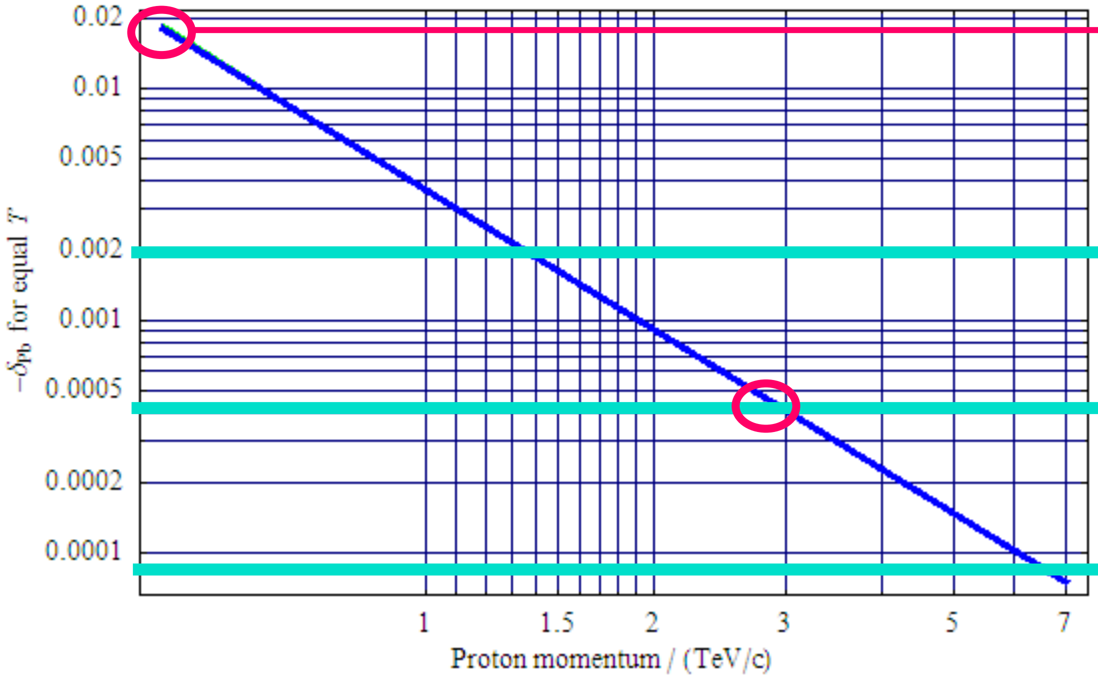
Minimize needed aperture → take average f_{RF} of both beams and share required momentum offset:

$$\delta_p = -\delta_{Pb} = \frac{c^2\gamma_T^2}{4p_p^2}\left(\frac{m_{Pb}^2}{Z^2} - m_p^2\right)$$

Horizontal offset given by dispersion:

$$\Delta x = D_x(s)\delta$$





2% - would move beam by 35 mm in QF!!

D_x (Quadrupole) ≈ 2m

Limit with pilot beams

Limit in normal operation (1 mm in arc QD)

~500μm offset from central orbit at 6.5 Z TeV

Revolution frequencies must be equal for collisions at top energy.

Lower limit on beam energy for p-Pb collisions, *E*=2.7 Z TeV.

RF frequencies must be unequal for injection, ramp!

Un-equal Frequency Injection and Ramp

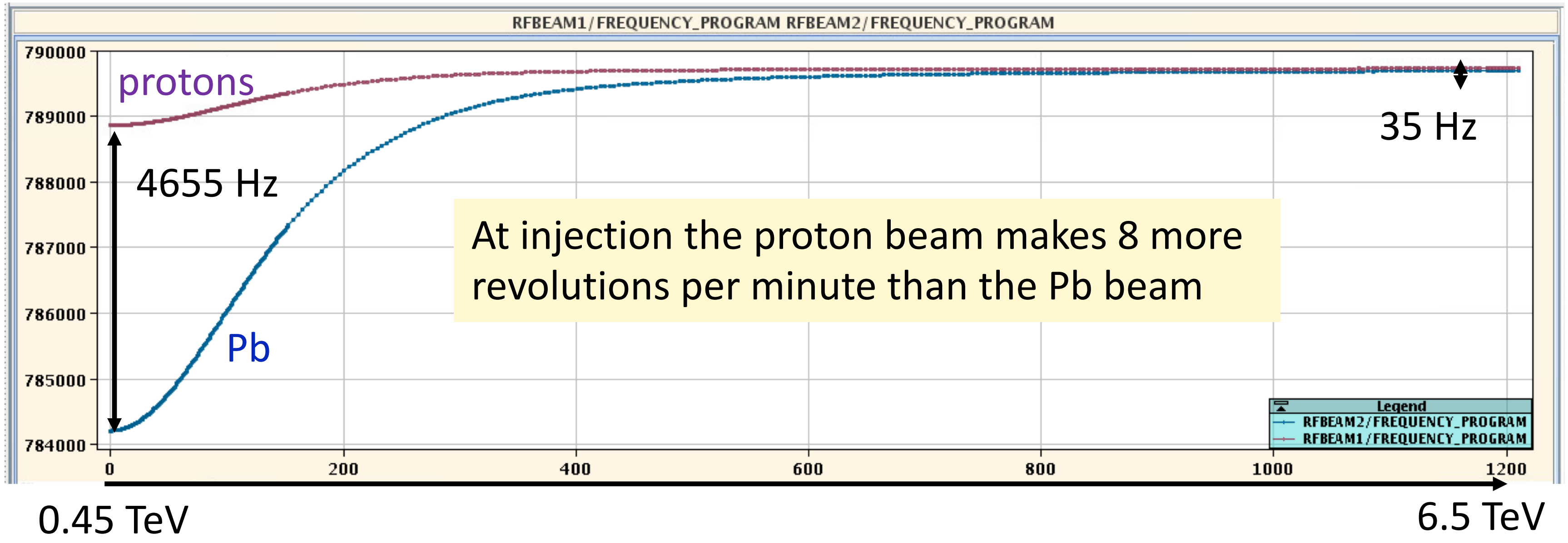
Both beams **circulate on the central orbit**, but with **un-equal frequencies**.

→ Arrive at different times in the IP – **missing synchronization for collisions** in every turn.

→ At injection and during energy ramp beams are always **kept separated** to avoid collisions anyway.

When being accelerated, the speeds of the two species approach each other.

RF frequency program during p-Pb energy ramp

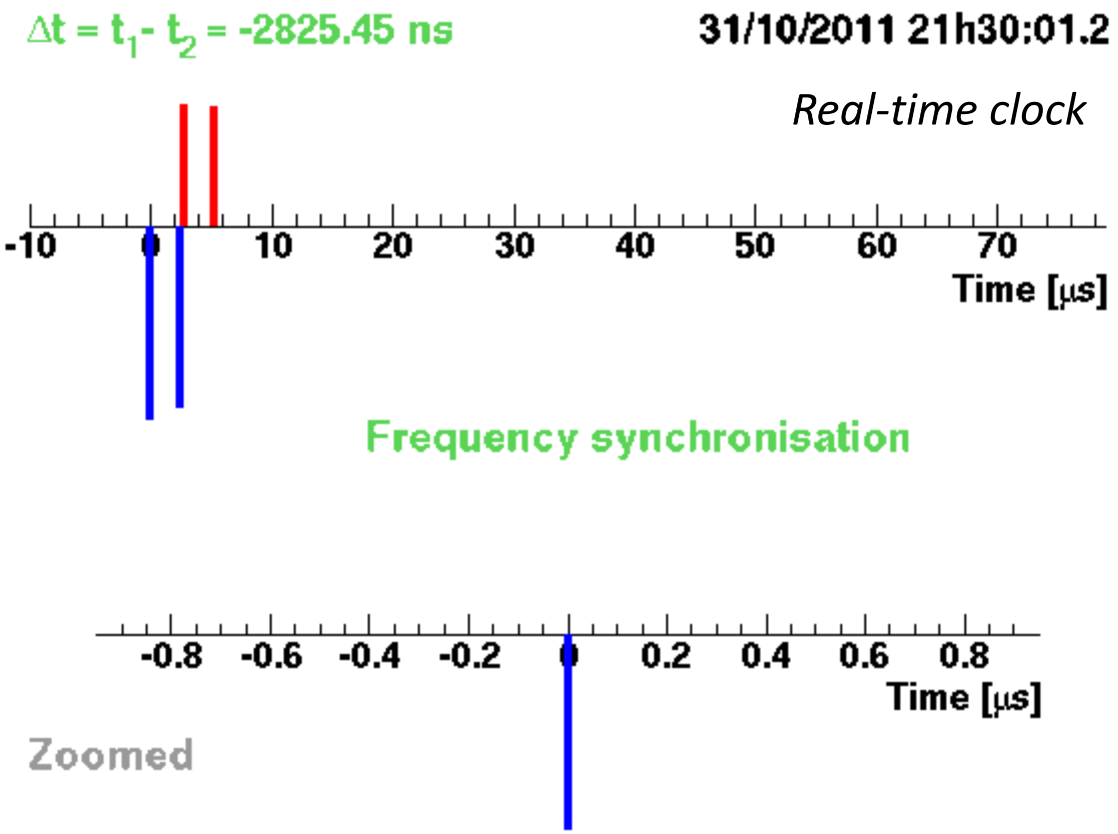


At injection the proton beam makes 8 more revolutions per minute than the Pb beam

Top Energy: Cogging and Collisions

At top energy (min. 2.7 Z TeV):

- **Equalize revolution frequencies** for collisions → move beams to off-momentum orbit.
- **Cogging**: RF re-phasing to re-establish synchronization of bunch arrival times in IP (see video).
- Squeeze and Collide



RF cogging by Philippe Baudrenghien

Video shows the difference in arrival time of the bunches at IP1, taking Beam 1 (blue) as reference.

Timing data from BPTX beam position monitor during first cogging exercise in LHC (now its done faster), video by Thilo Pauly (ATLAS)

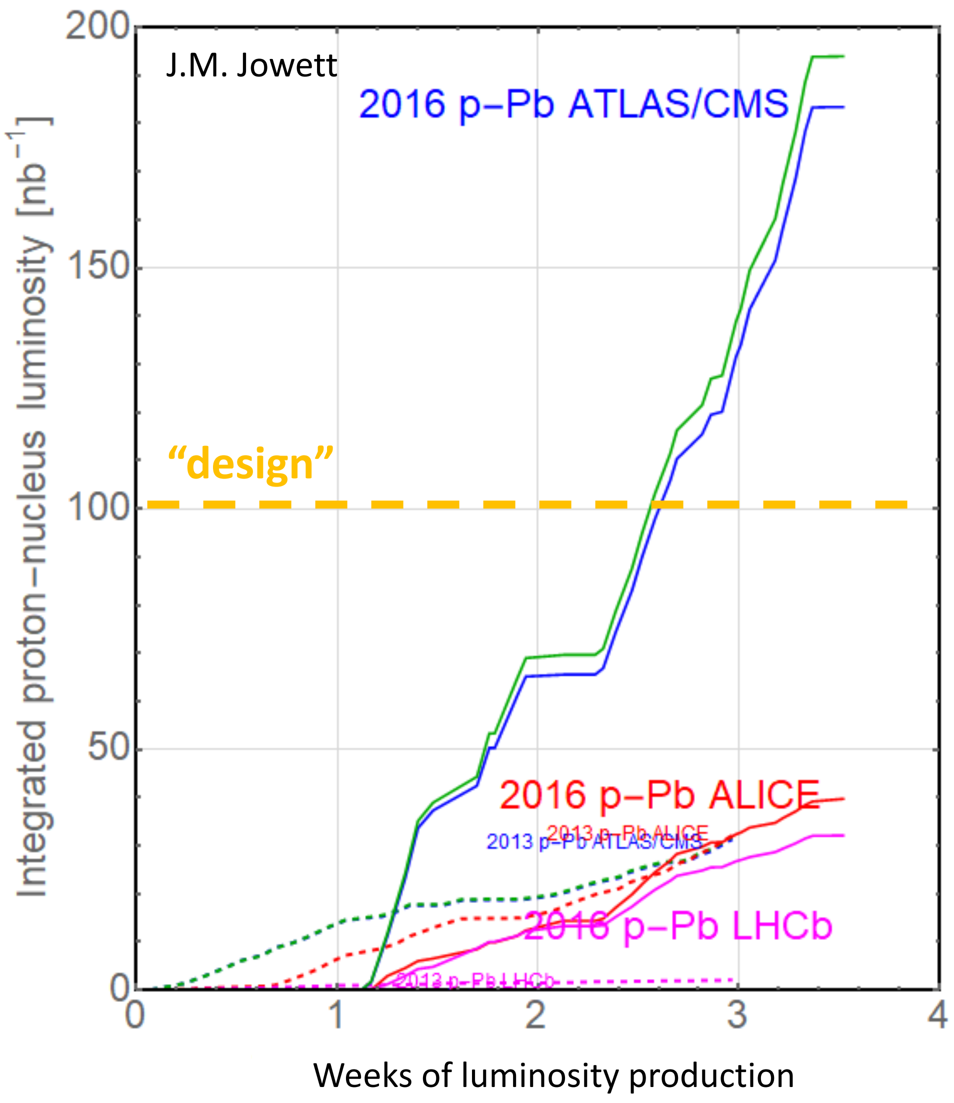
History and Performance of p-Pb Collisions at LHC

Long considered desirable by experiments but never included in LHC baseline design.

2005: First estimates
2011: Preparation of LHC + feasibility test
2012: Physics case document + Pilot-run (one night)
2013: 1st full physics runs
2016: 2nd run with multiple collision conditions

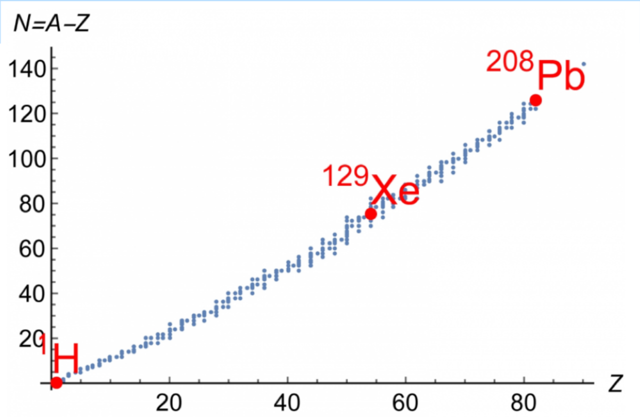
	ATLAS/CMS	ALICE	LHCb
2016	190 nb^{-1}	40 nb^{-1}	30 nb^{-1}
Total	222 nb^{-1}	72 nb^{-1}	35 nb^{-1}

Future performance estimate:
~700 nb^{-1}/run (ATLAS/CMS)
~350 nb^{-1}/run (ALICE levelled)

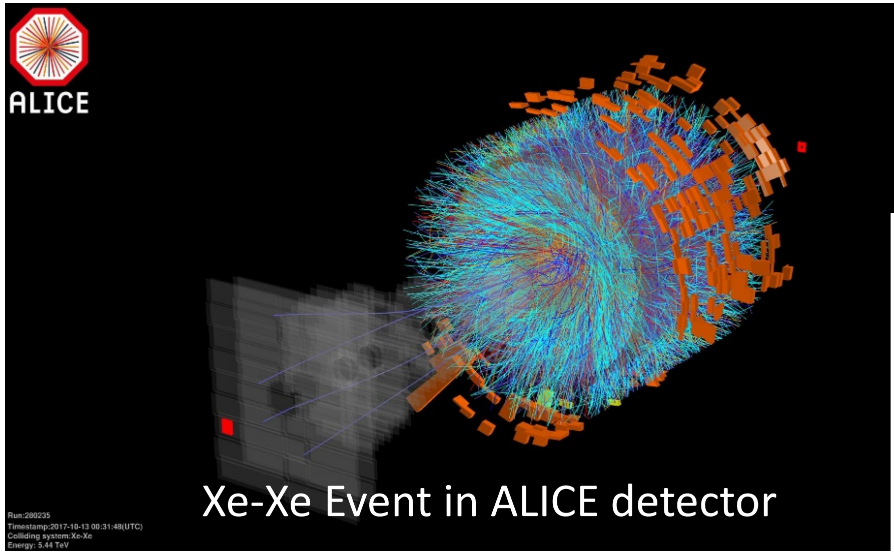


UNFORESEEN OPERATIONAL MODES

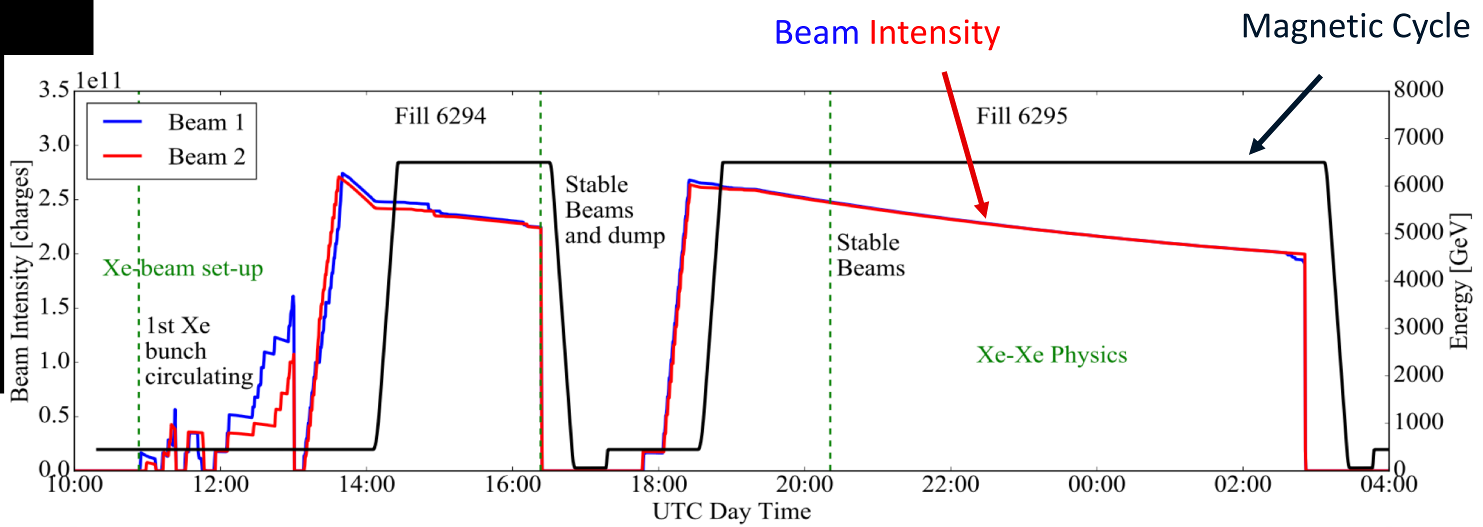
Xe-Xe Collisions



- Lighter ions are not part of the present HL-LHC baseline.
  - ➢ Potential for higher nucleon-nucleon luminosities (smaller el.mag. cross-sections)
- 17h of low-intensity running with Xe beams in 2017.
  - ➢ Demonstrated the feasibility to operate with other species.
  - ➢ Great physics outcome fed the interest in lighter ions for HL-LHC era



Xe-Xe Event in ALICE detector



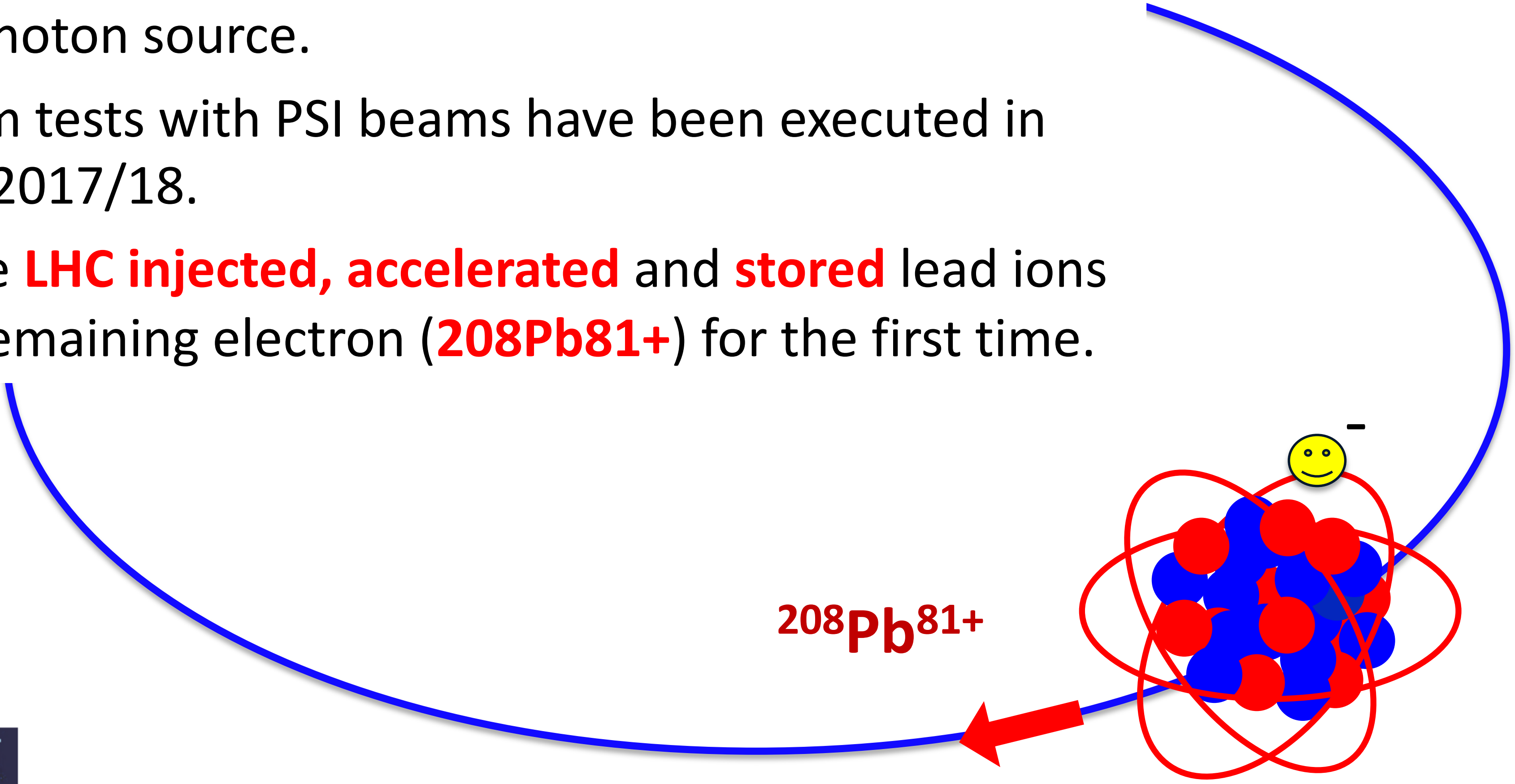
Total period of LHC Xe-Xe Operations

18 hours

Partially Stripped Ions

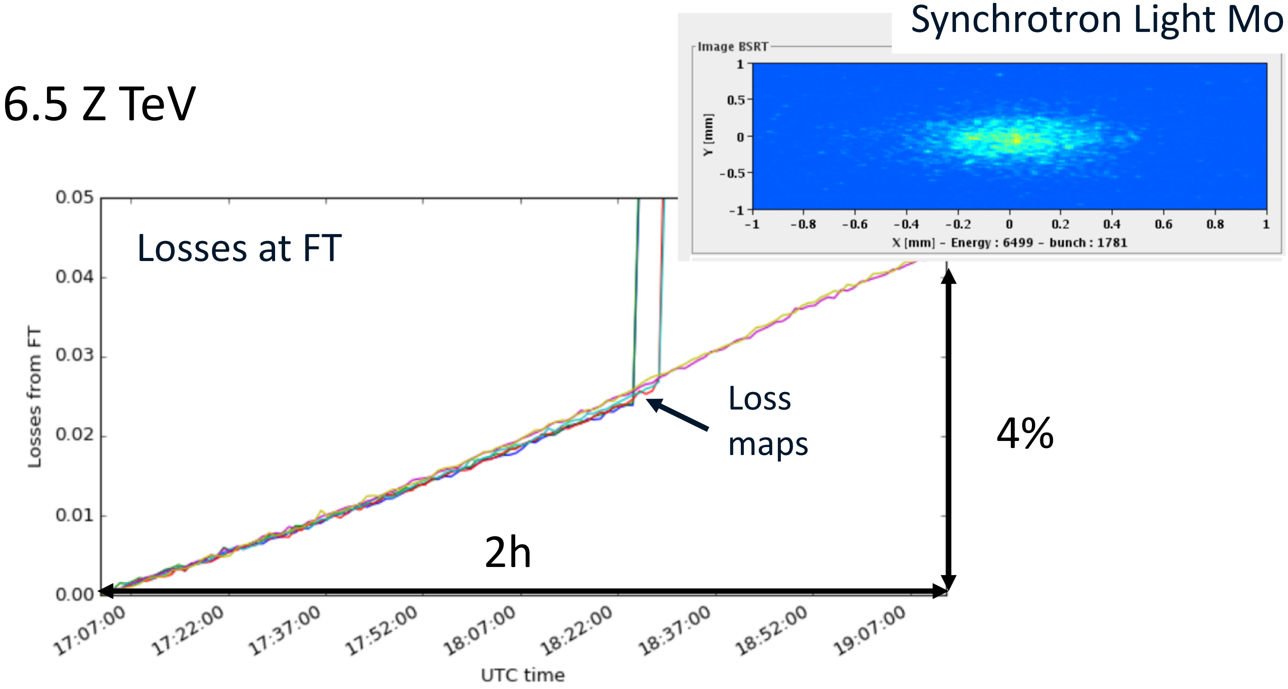
Physics Beyond Colliders

- The **Gamma Factory** initiative proposes to use **partially stripped ion (PSI)** beams as drivers of a new type, high intensity photon source.
- Initial beam tests with PSI beams have been executed in the SPS in 2017/18.
- In 2018 the **LHC injected, accelerated** and **stored** lead ions with one remaining electron (**208Pb81+**) for the first time.

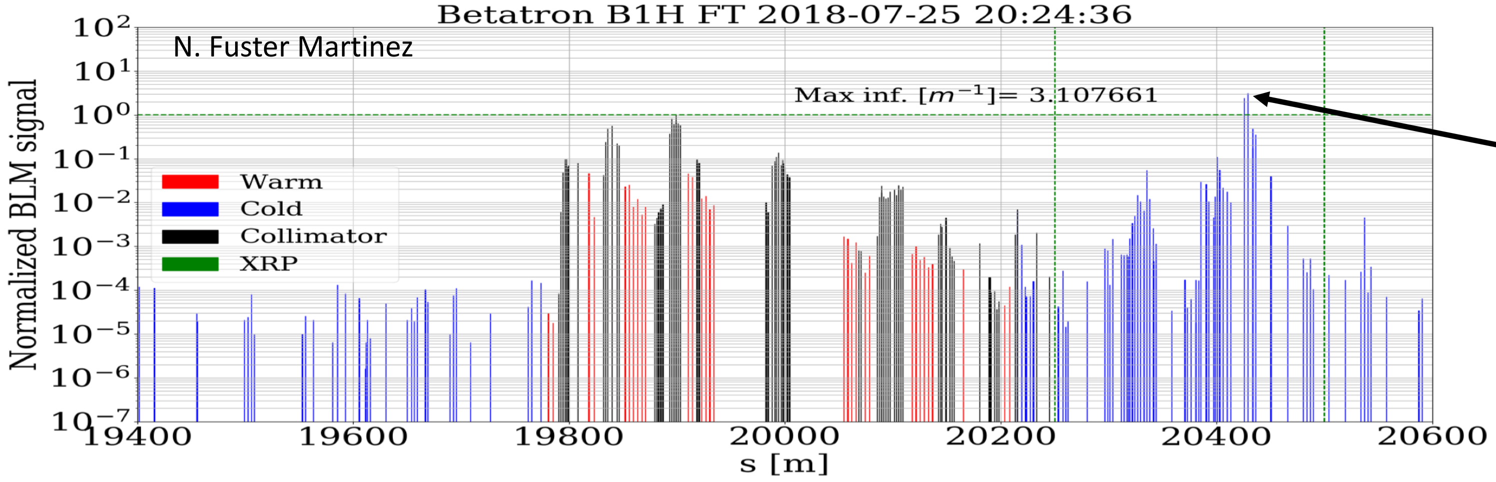


Partially Stripped Ions

A few Pb81+ bunches circulated at 6.5 Z TeV with **beam lifetimes of ~40 hours**.

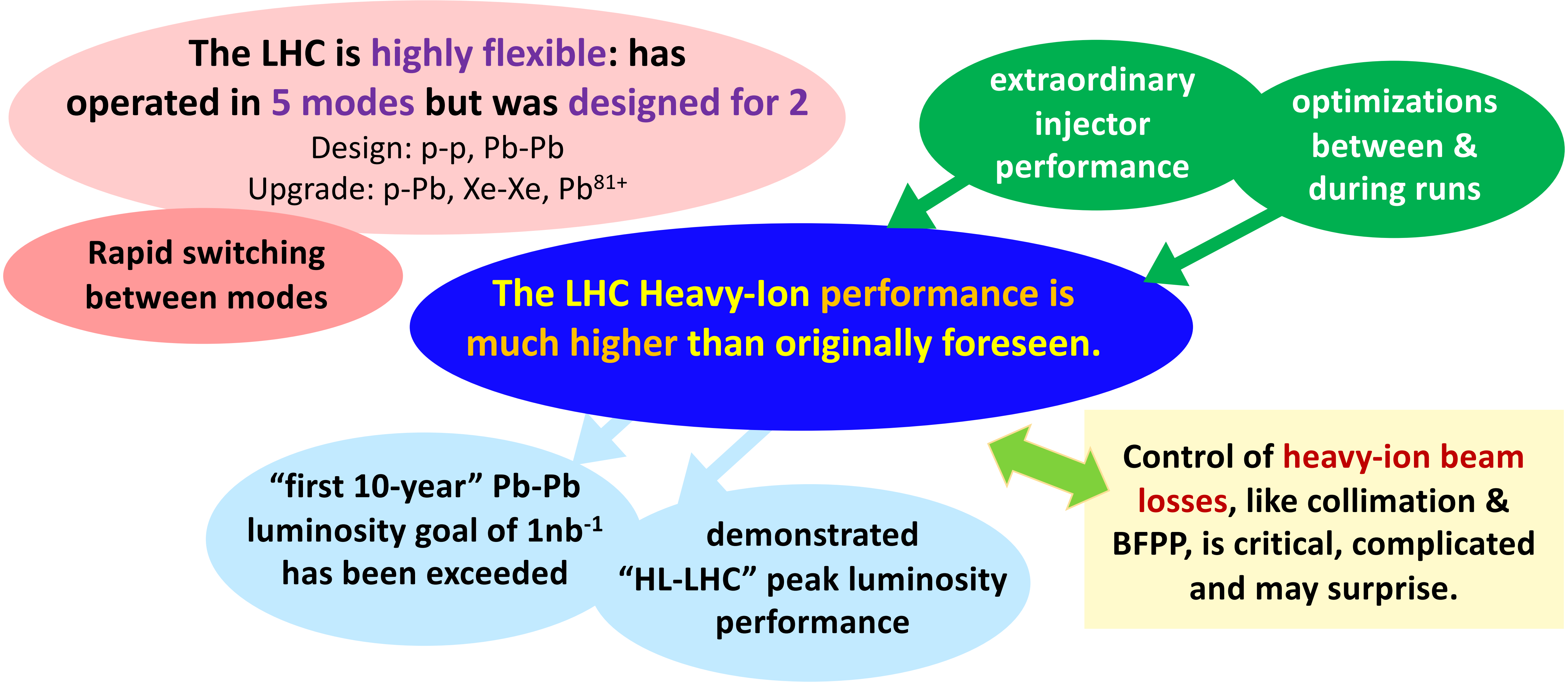


Worst collimation cleaning efficiency ever observed. Introduces **dominant limit of the beam intensity.**



Electrons are stripped off at first interaction with collimators leading to a change of rigidity outside acceptance:
→ Pb82+ lost in cell 11R7.

Take home message …



The LHC is highly flexible: has operated in 5 modes but was designed for 2

Design: p-p, Pb-Pb

Upgrade: p-Pb, Xe-Xe, Pb^{81+}

Rapid switching between modes

extraordinary injector performance

optimizations between & during runs

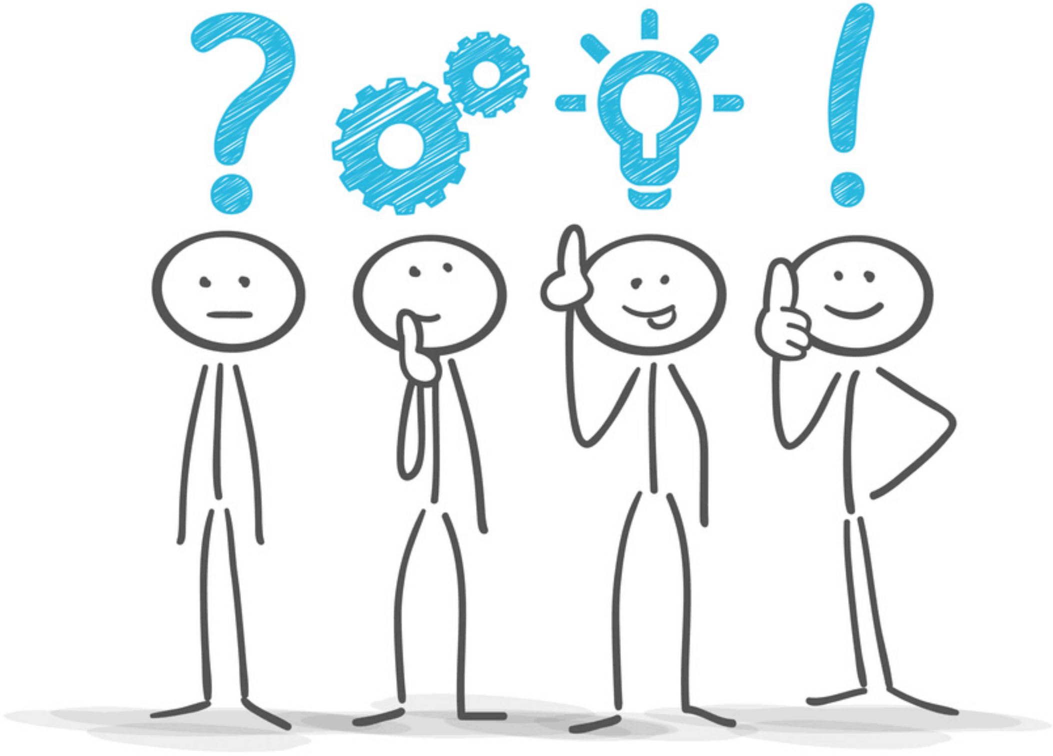
The LHC Heavy-Ion performance is much higher than originally foreseen.

“first 10-year” Pb-Pb luminosity goal of 1nb^{-1} has been exceeded

demonstrated “HL-LHC” peak luminosity performance

Control of heavy-ion beam losses, like collimation & BFPP, is critical, complicated and may surprise.

Heavy ions will come back to the LHC end of 2021 after the injector and LHC hardware upgrades with the “HL-LHC” configuration.



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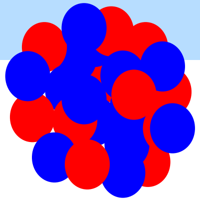
Everything clear! Hmm ….

Mass of ions/nuclei



In general an ion is described by

charge ***Qe***
(Lorenz-Invariant or rest) mass ***m***
nucleon number ("mass number") ***A***.

Mainly collide **fully-stripped ions**, bare nuclei → ***$Q = Z$*** (charge or proton number)

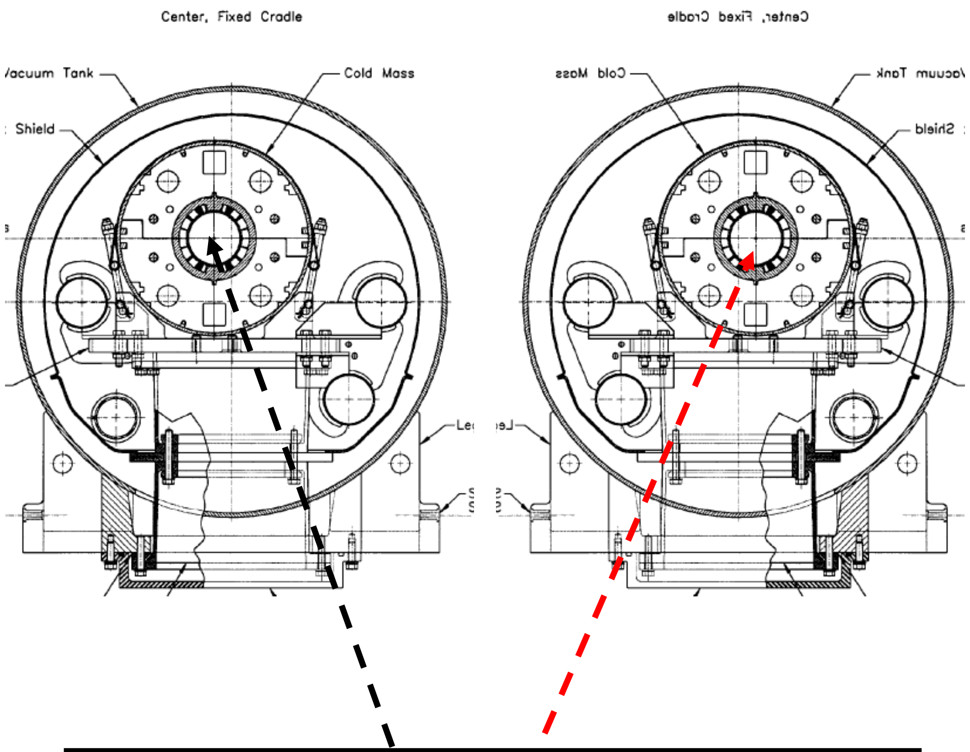
in LHC we use **^{208}Pb^{82+}** with
Z = 82
A = 208

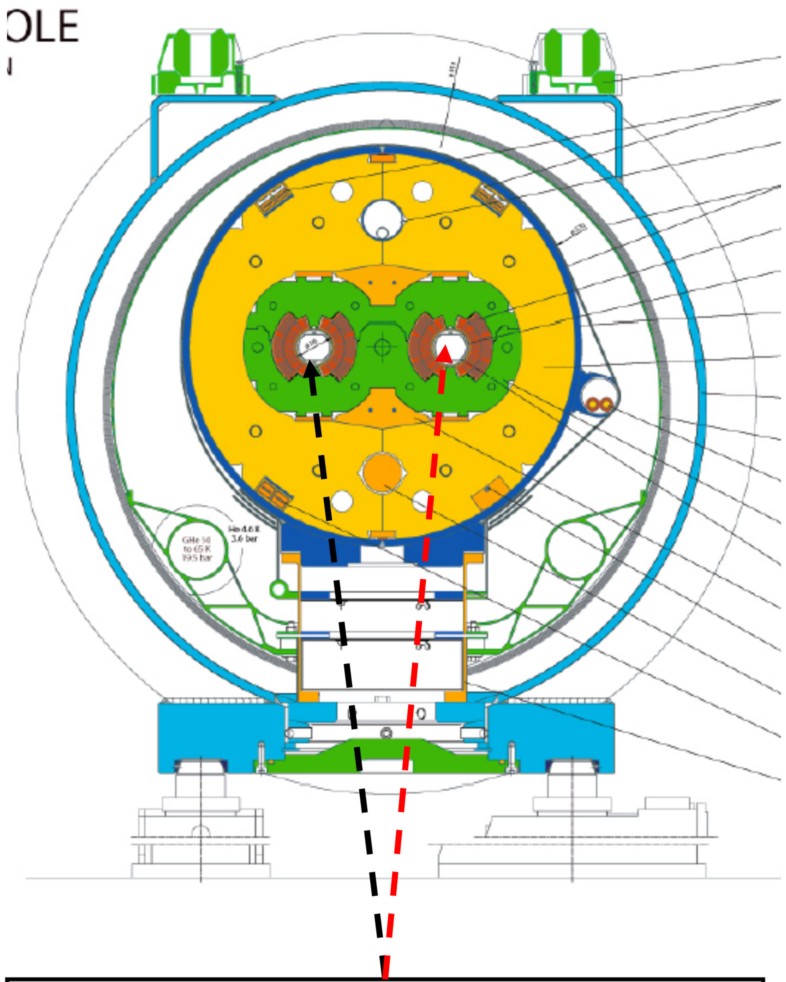
$$m_{208\text{-}Pb\text{-}82+} = 207.976652071\text{u} - 82m_e$$
$$= (193.729 - 82 \times 0.000511)\ \text{GeV} / c^2$$
$$= 193.687\ \text{GeV} / c^2$$

N.B. $208m_p = 195.161$ GeV / c^2 is a poor approximation!
For this species the binding energy of the 82 electrons < 1 MeV.

1u = 931.49410242(28) MeV

Critical difference between RHIC and LHC

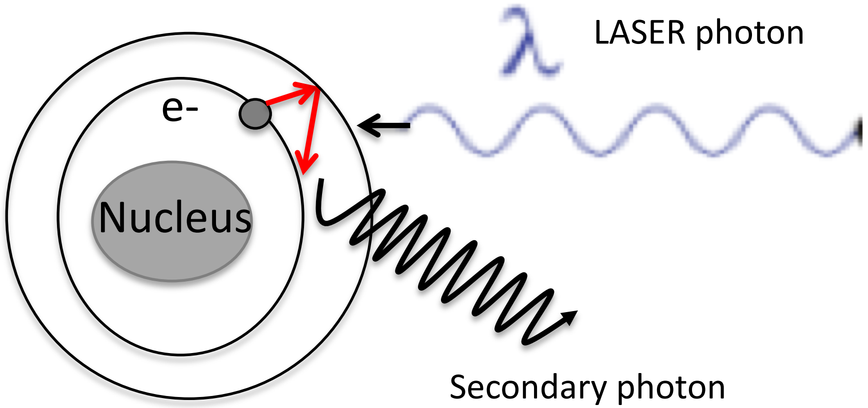




RHIC: Independent bending field for the two beams – they abandoned equal-rigidity and switched to equal-frequency d-Au.

LHC: Identical bending field in both apertures of
two-in-one dipole – no choice

The Idea of a Gamma Factory



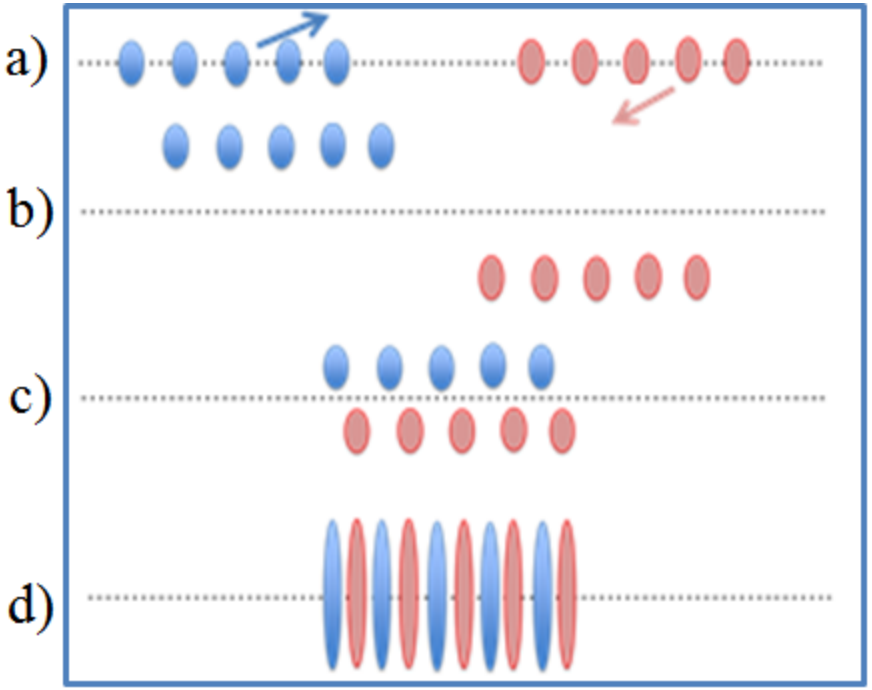
1.) Resonant absorption of the laser photons by the Partially Stripped Ion (PSI) beam.

2.) Followed by a spontaneous atomic-transition emissions of secondary photons.

LASER photon strongly boosted by $(2\gamma_{rel})^2$ → For LHC energy, photon energy exceeds those reachable for FEL at high light intensity.

Slip-Stacking

- Technique to obtain **effective 50/50ns bunch spacing within Pb trains**. Builds together with LEIR intensity upgrade the new LIU baseline option.
- The SPS is filled with 2 ”super-batches” of 6 x 4-bunch-PS-batches with a bunch spacing of 100ns.
- The 2 super-batches are captured by two independently controlled 200MHz cavity systems.



a) Decelerate first super-batch, accelerate second super-batch.

b) Batches are allowed to slip until they interleave.

c) Bring back to same energy.

a) Recapture at an average RF frequency.

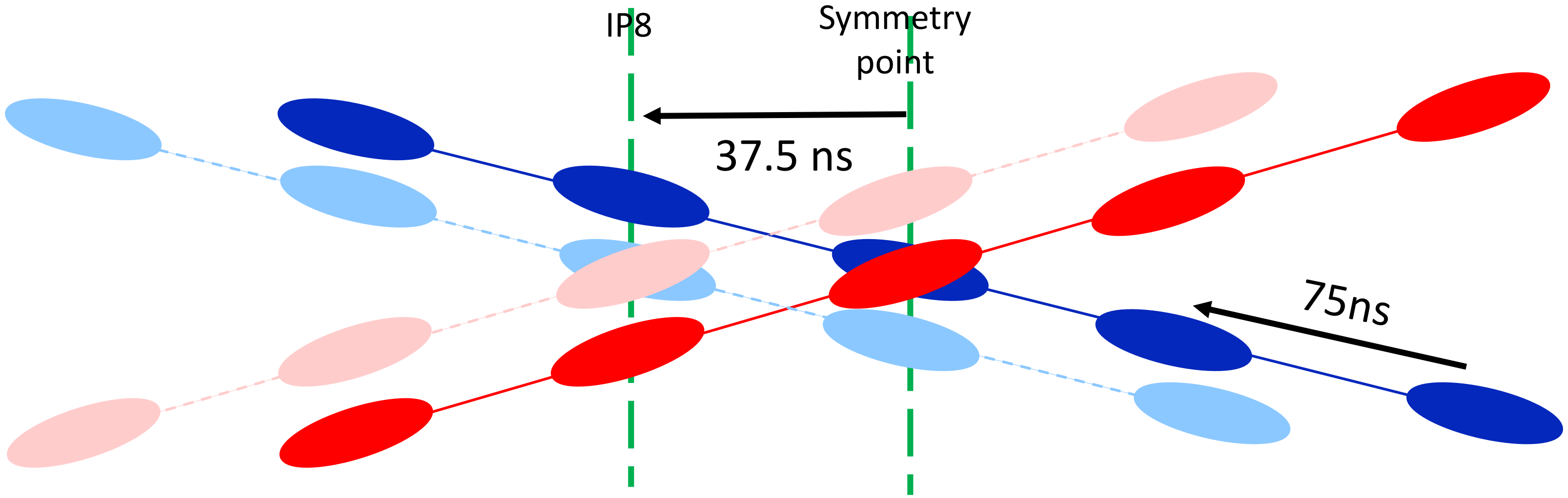
Collisions in LHCb

LHCb interaction point is displaced by **15 buckets (=37.5ns)** with respect to symmetry point.

In order to have a collision in LHCb a long-range (LR) beam-beam encounter is required at a distance of 37.5ns or 11.25m away from the symmetry point.

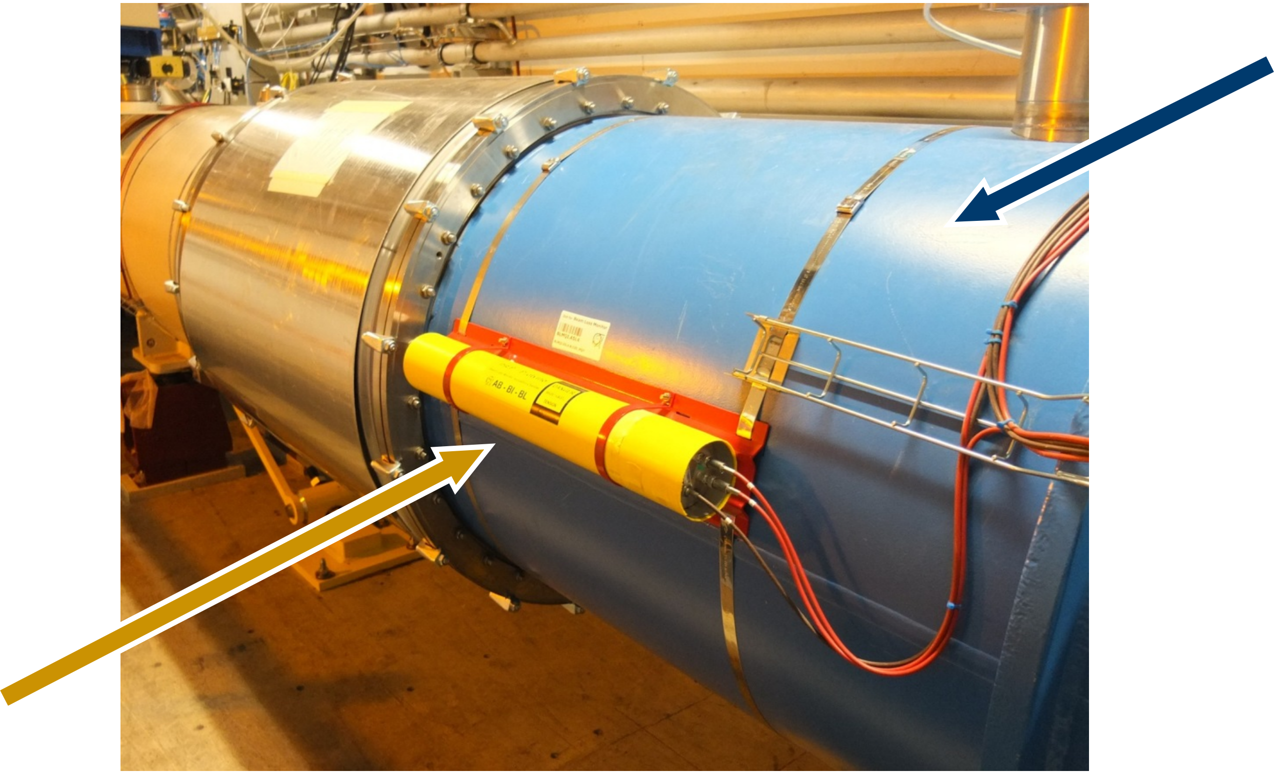
Long-range beam-beam encounters occur at ***s = n x ½ bunch spacing:***

25ns bunch spacing → LR @ 12.5ns, 25ns, **37.5ns** … → **collisions in LHCb**
50ns bunch spacing → LR @ 25ns, 50ns … → need to displace a train of bunches to create collisions
75ns bunch spacing → LR @ **37.5ns**, 75ns … → **collisions in LHCb**
100ns bunch spacing → LR @ 50ns, 100ns … → need to displace a train of bunches to create collisions

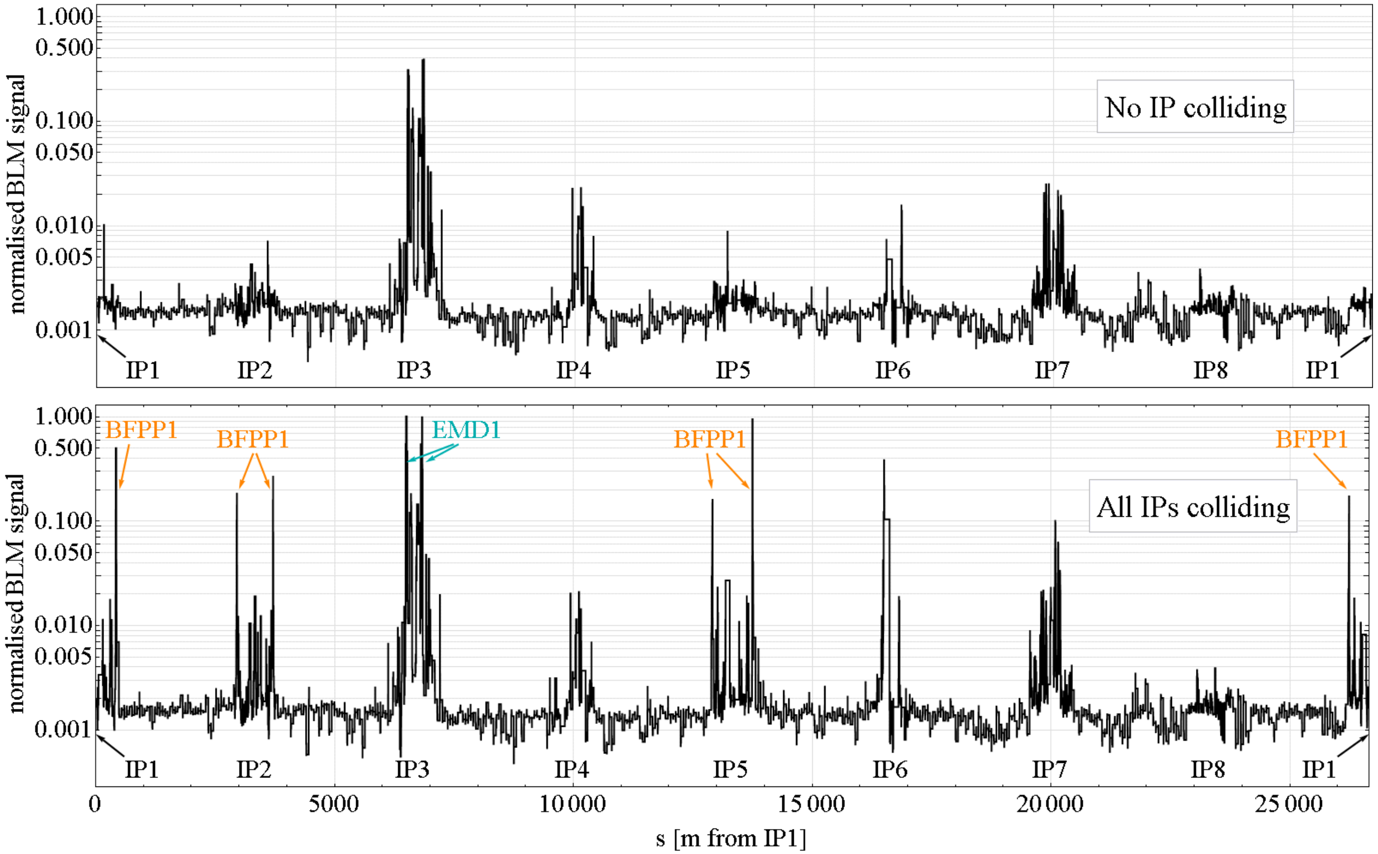


BLM-System

The **Beam Loss Monitor (BLM) System** measures secondary particles from beam losses all around LHC circumference.



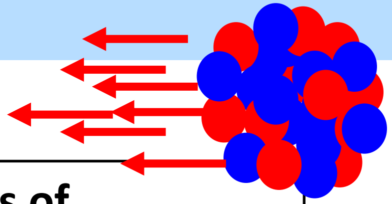
Particle Losses around the Ring



Before collisions

IP1, IP2, IP5 colliding

Notations – Energy of ions/nuclei and nucleons



Nucleus of
- charge Ze
- (rest) mass m
- nucleon number A

Energy and momentum are related via the square of the 4-momentum vector, **P** = (*E* / *c* , **p**),

$$P^2 = \frac{E^2}{c^2} - p^2 = m^2c^2$$

where *m* is the Lorentz-invariant mass (rest mass) of the nucleus.

Traditionally, in low-energy ion accelerators, the kinetic energy per nucleon is quoted in parameter lists:

$$E_{kin} = \frac{\sqrt{p^2c^2 + m^2c^4} - mc^2}{A} \approx \frac{E}{A} \qquad \text{at high energy}$$

but this quantity does not appear in any equation of motion!

At LHC (highly relativistic case) we use:

$$\boxed{E \approx pc = \underbrace{7.0\,Z\,\mathrm{TeV}}_{\substack{\text{Energy per charge,}\\ \text{relation to proton energy}}} = \underbrace{2.76\,A\,\mathrm{TeV}}_{\text{Energy per nucleon}} = \underbrace{574\,\mathrm{TeV}}_{\text{Energy of the particle}}}$$

Derive Center-of-Mass Equations for Collisions of two Species

$$
\begin{aligned}
(P_1 + P_2)^2 &= (E_1 + E_2)^2/c^2 - (\vec{p}_1 + \vec{p}_2)^2 \\
&= E_1^2/c^2 + E_2^2/c^2 + 2E_1E_2/c^4 - \vec{p}_1^{\,2} - \vec{p}_2^{\,2} - 2p_1p_2\cos\alpha \\
&= 4p_1p_2 \\
&= 4p_p^2 Z_1 Z_2
\end{aligned}
$$

$\alpha = 180^o$

$E \approx pc$

$$\sqrt{(P_1 + P_2)^2} = \sqrt{s} = 2p_p^2\sqrt{Z_1Z_2}$$

Center-of-Mass Energy

$$\sqrt{s_{NN}} = 2p_p^2\sqrt{\frac{Z_1Z_2}{A_1A_2}}$$

Center-of-Mass Energy per nucleon

Luminosity Bunch-by-Bunch

The total luminosity in 1 experiment
is the **sum over all colliding individual bunches** of the 2 beams:

$$\mathcal{L} = \sum_{(i,j)\in\mathrm{coll.pairs}}^{k_b} \frac{N_{1,i} N_{2,j} f_{\mathrm{rev}} \sqrt{\gamma^2 - 1}}{2\pi\beta^* \sqrt{\epsilon_{x,1,i} + \epsilon_{x,2,j}} \sqrt{\epsilon_{y,1,i} + \epsilon_{y,2,j}}}$$

Integrated Luminosity Prediction per Pb-Pb run

For a **24-day** run, with **3 experiments at β*=0.5 m**, assuming (pessimistically) an **operational efficiency of 50%** and **average luminosity of 3E27 cm^{-2} s^{-1}**, the total luminosity is

$$L_{int,annual} = (50\%)(3.0 \times 10^{27}\ cm^{-2}s^{-1})(24\ day) \approx 3.1\ nb^{-1}$$

(c.f. target of 2.85 nb^{-1})

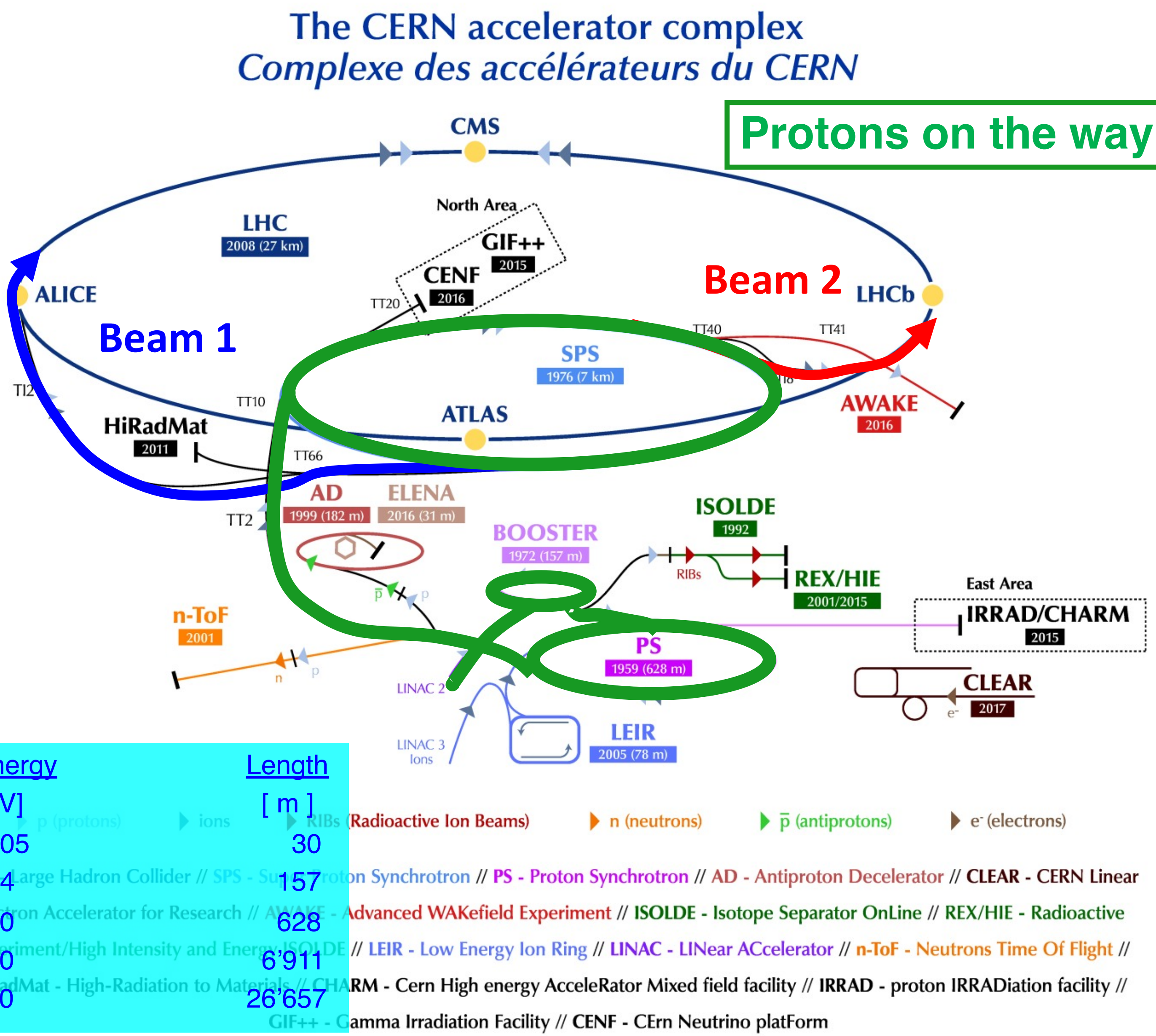
→ **12 nb^{-1}** in the 4 Pb-Pb runs
foreseen after LS2

Integrated Luminosity Prediction per p-Pb run

- Assuming
  - a turnaround time of 2.5 h (optimistic!)
  - operational efficiency of 50%,
  - and optimal fill length of 6.1 h,

- The total luminosity in 1 month of p-Pb running is estimated to
  - 714 nb^{-1} for ATLAS/CMS
  - 346 nb^{-1} for ALICE

Getting protons into the LHC

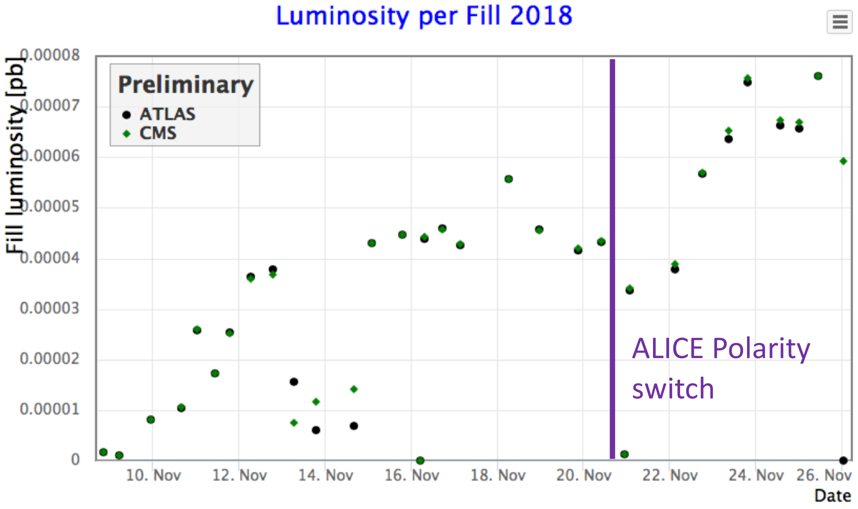


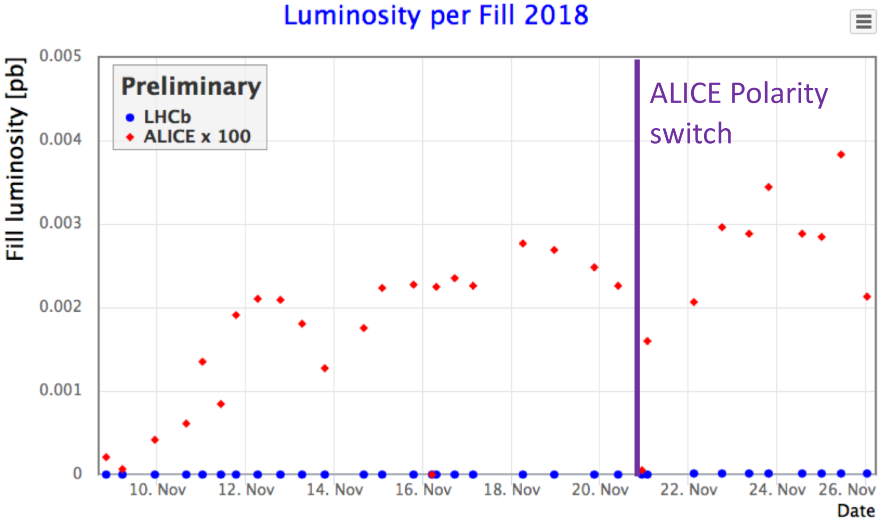
Protons on the way to LHC

	Year	Top energy [GeV]	Length [m]
Linac	1979	0.05	30
PSB	1972	1.4	157
PS	1959	26.0	628
SPS	1976	450.0	6'911
LHC	2008	7000.0	26'657

Luminosity Production

Steady increase of luminosity/fill





Increasing

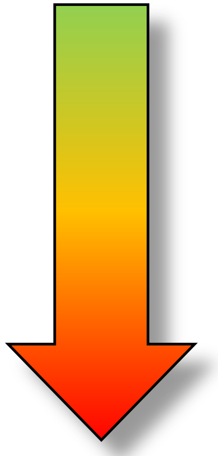
- **No. of bunches** & bunch **intensities**
- Levelling **targets** (ATLAS/CMS/LHCb)
- Levelling **time** (after solving ALICE beam size problem)

Source: http://lpc.web.cern.ch/

Levelling *“a la carte”*

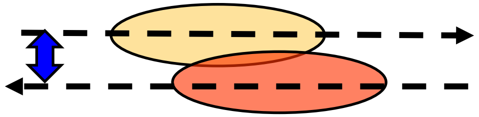
Under certain conditions and depending on the experiments request, it is desirable to adapt the luminosity dynamically with beams in collision – **luminosity levelling**

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

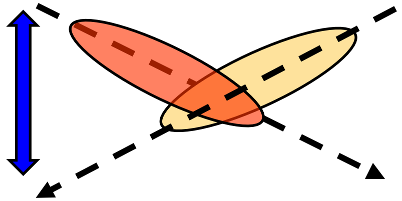


Complexity

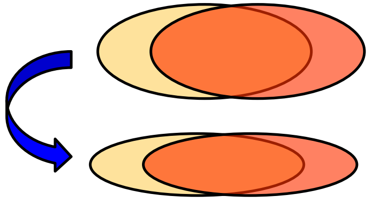
Levelling by **beam offset**

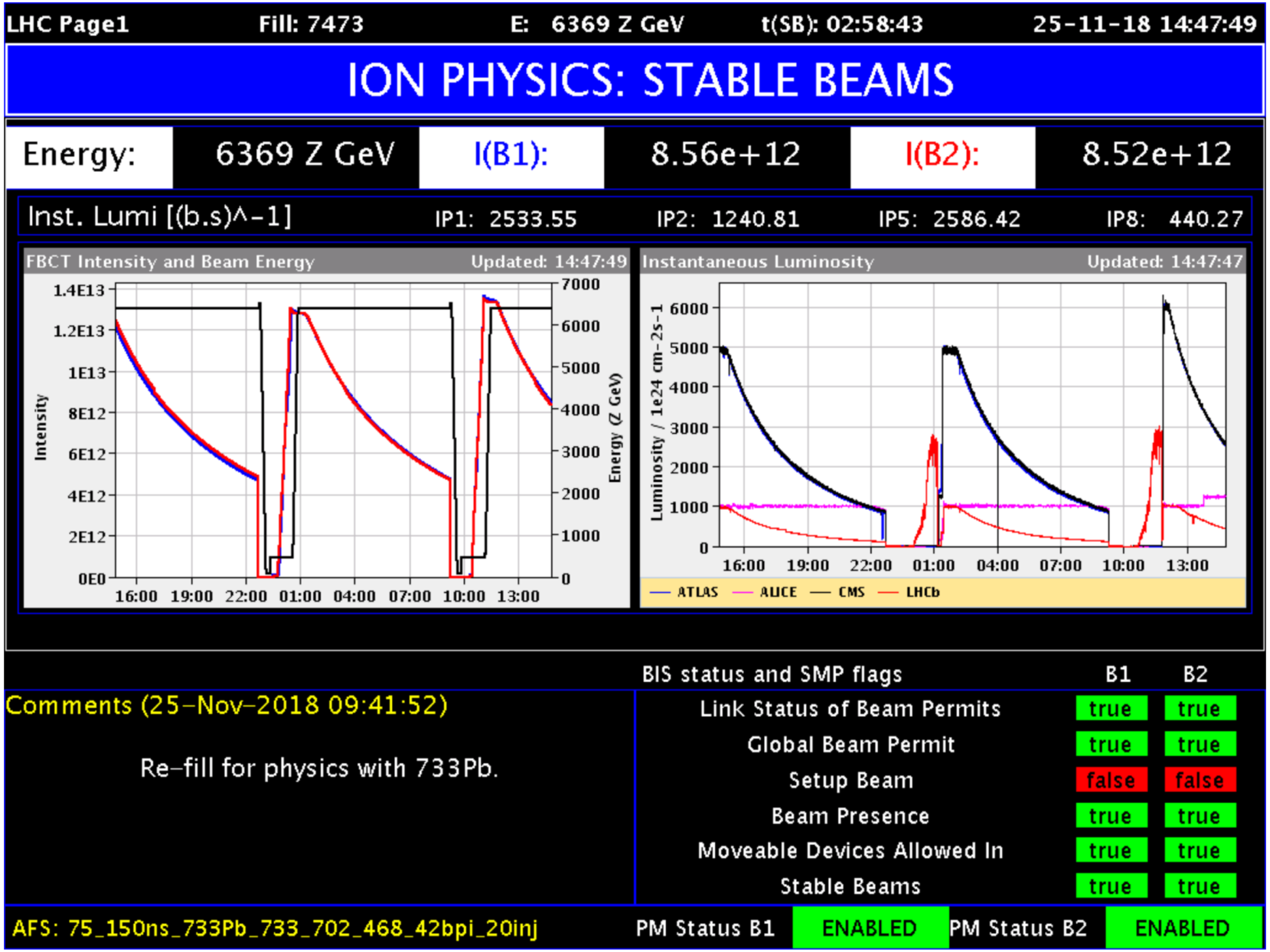


Levelling by **crossing angle**



Levelling by β* (= beam size at IP)





LHC Page1 Fill: 7473 E: 6369 Z GeV t(SB): 02:58:43 25-11-18 14:47:49

ION PHYSICS: STABLE BEAMS

Energy:	6369 Z GeV	I(B1):	8.56e+12	I(B2):	8.52e+12

Inst. Lumi [(b.s)^-1] IP1: 2533.55 IP2: 1240.81 IP5: 2586.42 IP8: 440.27

Comments (25-Nov-2018 09:41:52)

Re-fill for physics with 733Pb.

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 75_150ns_733Pb_733_702_468_42bpi_20inj PM Status B1 ENABLED PM Status B2 ENABLED

Intra-Beam Scattering

See lecture by **V. Kain**

Intra-Beam Scattering Growth Rates

A. Piwinski's formalism

$$
\begin{aligned}
\alpha_{\mathrm{IBS},s} &= \left\langle A_{\mathrm{p}} \frac{\sigma_h^2}{\sigma_p^2} f(a,b,q) \right\rangle \\
\alpha_{\mathrm{IBS},x} &= \left\langle A_{\mathrm{p}} \left[f\left(\frac{1}{a}, \frac{b}{a}, \frac{q}{a}\right) + \frac{D_x^2 \sigma_h^2}{\sigma_x^2} f(a,b,q) \right] \right\rangle \\
\alpha_{\mathrm{IBS},y} &= \left\langle A_{\mathrm{p}} \left[f\left(\frac{1}{b}, \frac{a}{b}, \frac{q}{b}\right) + \frac{D_y^2 \sigma_h^2}{\sigma_y^2} f(a,b,q) \right] \right\rangle
\end{aligned}
$$

Complicated Integral, to be evaluated numerically at each element of lattice

$$
f(a,b,q) = 8\pi \int_0^1 \left\{ 2 \ln \left[\frac{q}{2} \left(\frac{1}{P} + \frac{1}{Q} \right) \right] - 0.577\ldots \right\} \frac{1-3u^2}{PQ} \mathrm{d}u
$$

$$
\boxed{A_{\mathrm{p}} = \frac{2 r_0^2 c N_b}{64 \pi^2 \beta_{\mathrm{rel}}^3 \gamma^4 \epsilon_x \epsilon_y \sigma_s \sigma_p}}
$$

Dynamic change with beam parameters

Dependency on lattice and beam parameters

$$
\begin{aligned}
\frac{1}{\sigma_h^2} &= \frac{1}{\sigma_p^2} + \frac{D_x^2}{\sigma_x^2} + \frac{D_y^2}{\sigma_y^2} \\
a &= \frac{\sigma_h \beta_x}{\gamma \sigma_x}, \quad b = \frac{\sigma_h \beta_y}{\gamma \sigma_y}, \quad q = \sigma_h \beta_{\mathrm{rel}} \sqrt{\frac{2d}{r_0}}
\end{aligned}
$$

$$
\begin{aligned}
P^2 &= a^2 + (1-a^2)u^2 \\
Q^2 &= b^2 + (1-b^2)u^2.
\end{aligned}
$$

Radiation Damping

See lecture by **V. Kain**

The average energy loss into synchrotron radiation in a circular accelerator leads to damping of the transverse and longitudinal **emittances** like

$$A_i = A_{0,i} e^{-\alpha_{\mathrm{rad},i} t}, \text{ where } i = x, y, s.$$

Emittance radiation damping rates

$$\begin{aligned}
\alpha_{\mathrm{rad},s} &= 2E_b^3 \frac{C_\alpha}{C_{\mathrm{ring}}} \mathcal{I}_2 \left(2 + \frac{\mathcal{I}_{4,x} + \mathcal{I}_{4,y}}{\mathcal{I}_2}\right) \\
\alpha_{\mathrm{rad},x} &= 2E_b^3 \frac{C_\alpha}{C_{\mathrm{ring}}} \mathcal{I}_2 \left(1 - \frac{\mathcal{I}_{4,x}}{\mathcal{I}_2}\right) \\
\alpha_{\mathrm{rad},y} &= 2E_b^3 \frac{C_\alpha}{C_{\mathrm{ring}}} \mathcal{I}_2 \left(1 - \frac{\mathcal{I}_{4,y}}{\mathcal{I}_2}\right)
\end{aligned}$$

For an isomagnetic ring with separate function magnets and *D*

For an isomagnetic ring with separate function magnets and $D_y=0$:

$$\begin{aligned}
\mathcal{I}_2 &\approx \frac{2\pi}{\rho_0} \\
\mathcal{I}_{4,x} &\approx 2\pi \frac{D_x}{\rho_0^2} \ll \mathcal{I}_2 \\
\mathcal{I}_{4,y} &\approx 0.
\end{aligned}$$

$$\begin{aligned}
\alpha_{\mathrm{rad},s} &\approx 2E_b^3 C_\alpha \frac{4\pi}{\rho_0 C_{\mathrm{ring}}} \\
\alpha_{\mathrm{rad},x} &\approx 2E_b^3 C_\alpha \frac{2\pi}{\rho_0 C_{\mathrm{ring}}} \\
\alpha_{\mathrm{rad},y} &\approx 2E_b^3 C_\alpha \frac{2\pi}{\rho_0 C_{\mathrm{ring}}}.
\end{aligned}$$

$$C_\alpha = r_0 c / (3 (m_{\mathrm{ion}} c^2)^3)$$

Note:

1.) Independ of beam parameters.

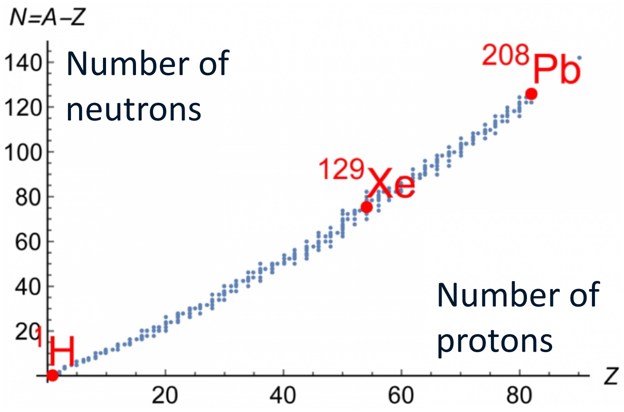
2.) Depend on Energy^3, machine size and particle type.

3.) In this approximation, longitudinal damping is twice as fast as transverse: $\alpha_{\mathrm{rad},s} = 2\alpha_{\mathrm{rad},x} = 2\alpha_{\mathrm{rad},y}$.

4.) Rad. damping for Pb 2x faster than for protons: $\alpha_{rad,xy} = 12h$

5.) Fast enough to overcome IBS at full energy and intensity

Xe-Xe Collisions



Data used to estimate future running.

Lighter ions have potential for **significantly higher nucleon-nucleon luminosity:**

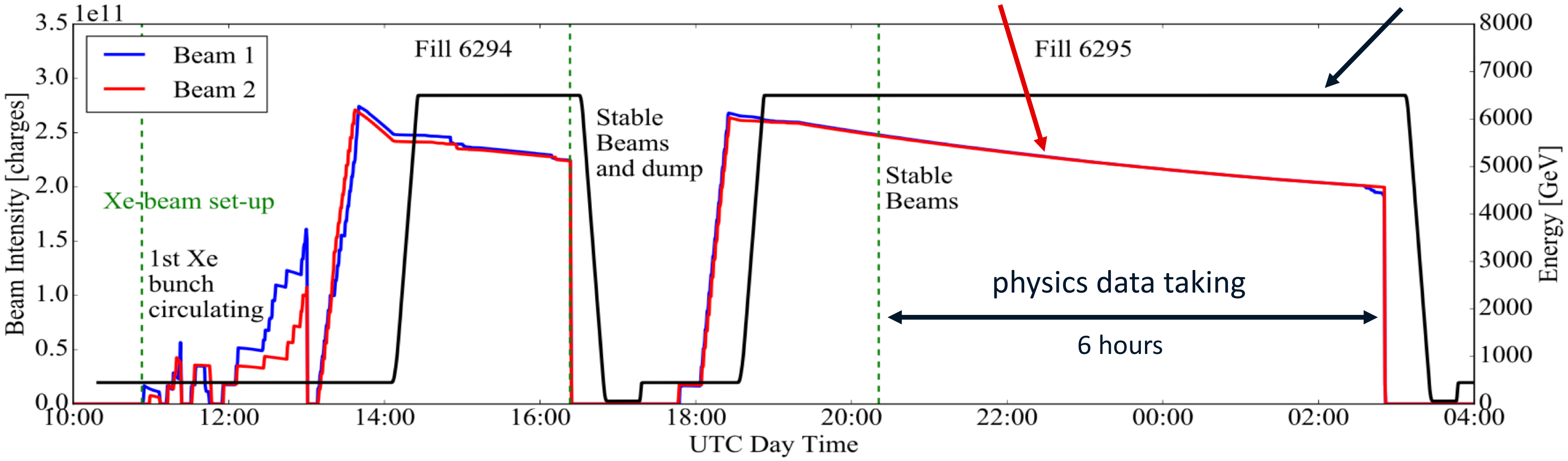
- Expect higher bunch charge in the injector chain
- Lower cross sections for ultraperipheral collisions

→ $\sigma_{BFPP} \sim Z^7$, $\sigma_{EMD} \sim Z^4$

→ Slower burn-off and longer fills, more ions left for usable luminosity

Beam Intensity

Magnetic Cycle



physics data taking

6 hours

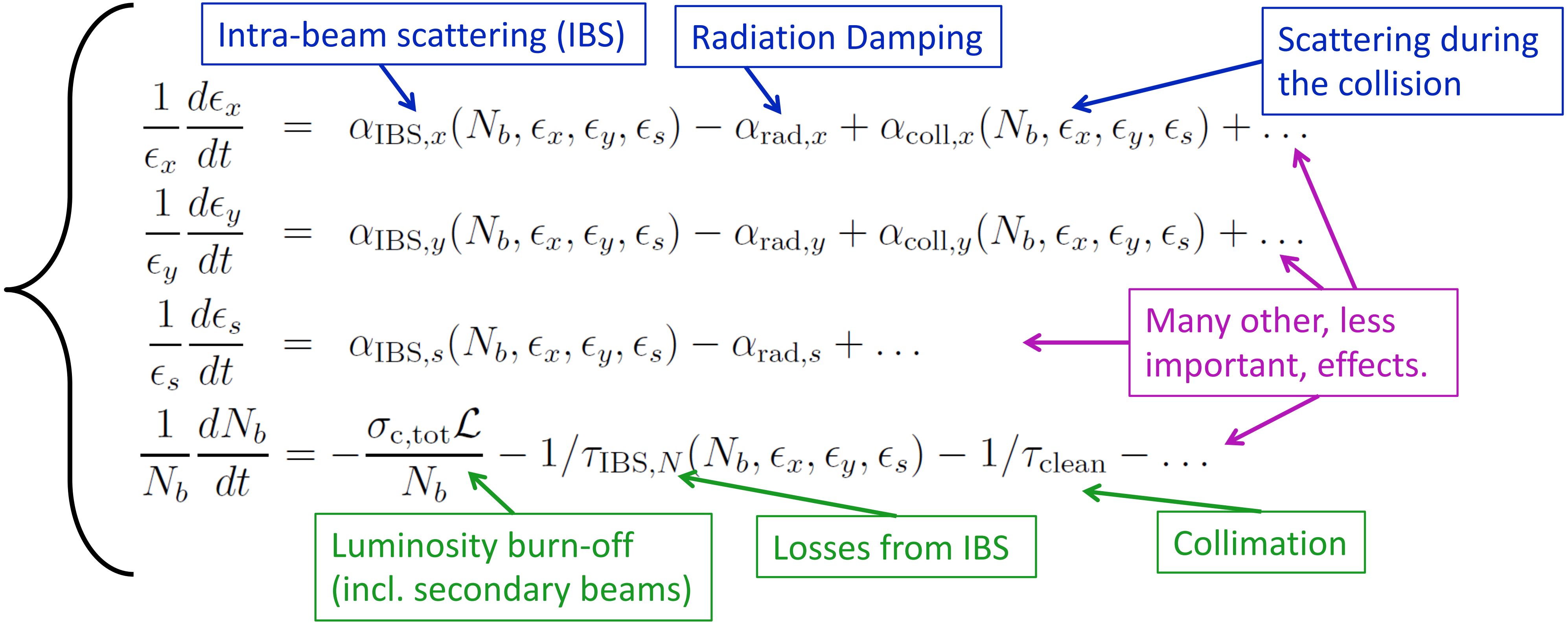
Total period of LH Xe-Xe Operations

18 hours

Beam Evolution

A particle bunch is characterised by its **number of particles, $N_b(t)$,** and the **emittances, $\epsilon_{n,i}(t)$, in the three planes** ($i = x, y, s$).

The bunch's evolution with time is defined by a system of 4 coupled differential equations:



$$
\begin{cases}
\frac{1}{\epsilon_x}\frac{d\epsilon_x}{dt} = \alpha_{\mathrm{IBS},x}(N_b, \epsilon_x, \epsilon_y, \epsilon_s) - \alpha_{\mathrm{rad},x} + \alpha_{\mathrm{coll},x}(N_b, \epsilon_x, \epsilon_y, \epsilon_s) + \ldots \\
\frac{1}{\epsilon_y}\frac{d\epsilon_y}{dt} = \alpha_{\mathrm{IBS},y}(N_b, \epsilon_x, \epsilon_y, \epsilon_s) - \alpha_{\mathrm{rad},y} + \alpha_{\mathrm{coll},y}(N_b, \epsilon_x, \epsilon_y, \epsilon_s) + \ldots \\
\frac{1}{\epsilon_s}\frac{d\epsilon_s}{dt} = \alpha_{\mathrm{IBS},s}(N_b, \epsilon_x, \epsilon_y, \epsilon_s) - \alpha_{\mathrm{rad},s} + \ldots \\
\frac{1}{N_b}\frac{dN_b}{dt} = -\frac{\sigma_{\mathrm{c,tot}}\mathcal{L}}{N_b} - 1/\tau_{\mathrm{IBS,N}}(N_b, \epsilon_x, \epsilon_y, \epsilon_s) - 1/\tau_{\mathrm{clean}} - \ldots
\end{cases}
$$

Intra-beam scattering (IBS)

Radiation Damping

Scattering during the collision

Many other, less important, effects.

Luminosity burn-off (incl. secondary beams)

Losses from IBS

Collimation

α are growth rates or inverse lifetimes, describing how fast the corresponding process changes a quantity.

The bunch's evolution is usually obtained by (numerically) solving those differential equations, or by tracking simulations.