The Future of Heavy-Ion Beams

Heavy Ions and Hidden Sectors, Louvain la Neuve – 05.12.2018

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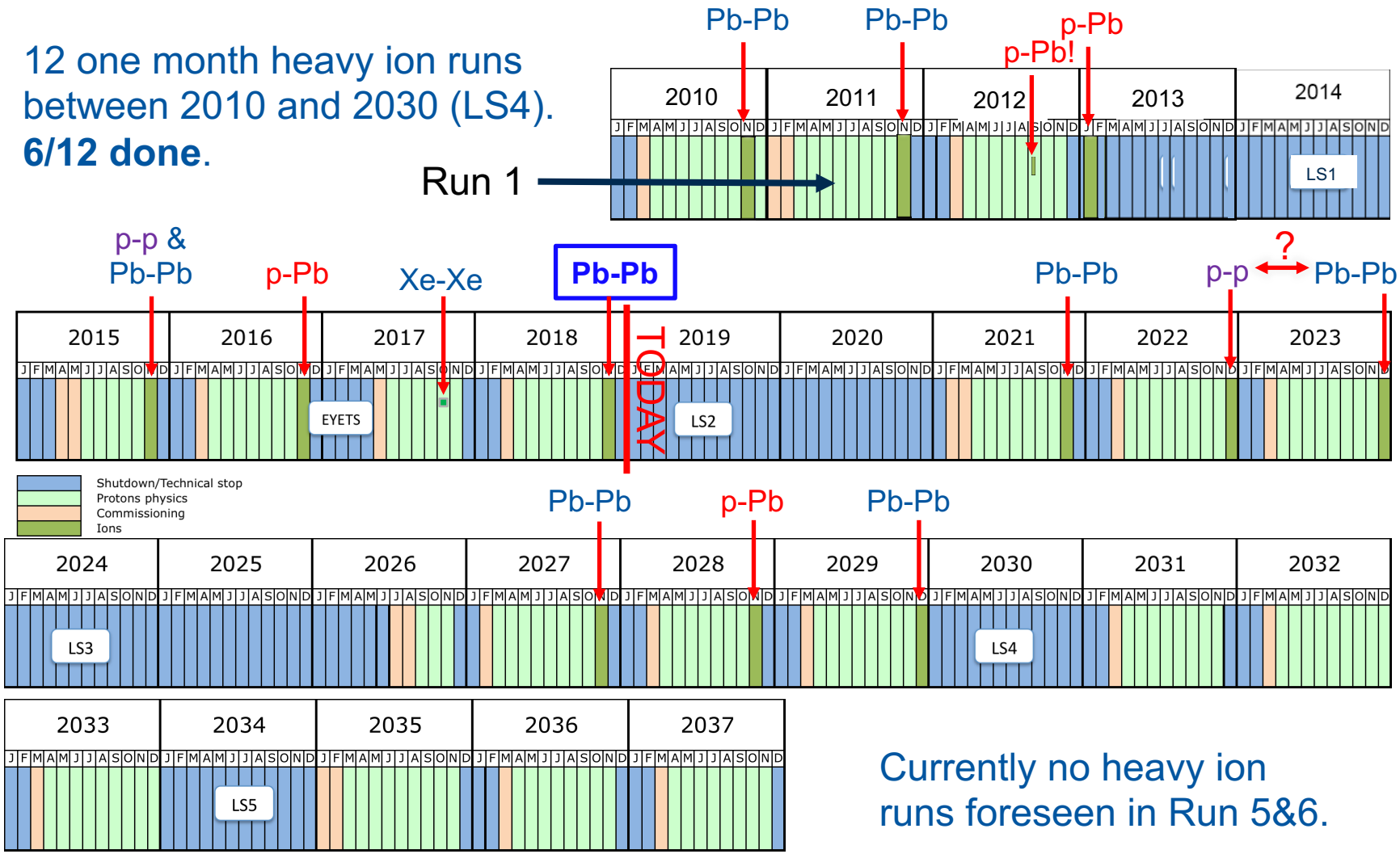
OP Group

Content

- Near Future: **Run 3 & 4**
  - Planning
  - Upgrade Status
  - Performance Estimates
- **Beyond Run 4**
  - Lighter Ions
  - HE-LHC
  - FCC

LHC Long Term Schedule (Baseline)

12 one month heavy ion runs between 2010 and 2030 (LS4).
6/12 done.



Currently no heavy ion runs foreseen in Run 5&6.

Achieved and LIU baseline (2017) Parameters

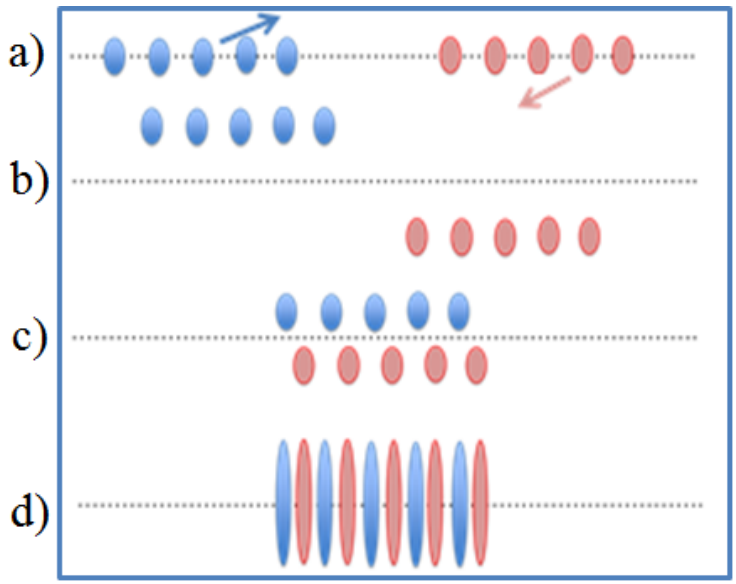
	Heavy-Ions (2018 achieved)	HL-LHC request		
Energy [TeV]	**6.37 Z**	7 Z	☹	LS2 magnet training
Particle Charge Z	**82**	82	☺	
β^* at IP 1/2/5/8 [m]	**0.5 / 0.5 / 0.5 / 1.5**	0.5 / 0.5 / 0.5 / ?	☺	
Emittance [μm]	**~2.0**	1.65	☺	
Bunch **Intensity** [10^8 ions]	**~2.3**	1.8	☺	
No. Bunches	**733**	1232	☹	Slip stacking
Bunch Spacing	**100ns → 75ns**	50ns	☹	Slip stacking
Peak **Luminosity** IP1/2/5/8 [10^{27}cm^{-2}s^{-1}]	**6.4 / 1 / 6.4 / 1**	7 / 7 / 7 / ?	😐	Luminosity levelling?

Green values are above LHC design

Some collisions in LHCb (not considered in detail yet)

SPS Momentum Slip Stacking

- Technique to obtain **effective 50/50ns bunch spacing within Pb trains**. Builds together with LEIR intensity upgrade *(already achieved)* the 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.

Luminosity

Measure of the ability of a particle accelerator to produce the required number of interactions:

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

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

$$\mathcal{L}_b = \frac{f_{\mathrm{rev}}\sqrt{\gamma^2 - 1}}{4\pi\beta^*}\frac{N_b^2}{\epsilon_n}$$

Change during fill

Dominant Effects on the Emittance

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.

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).

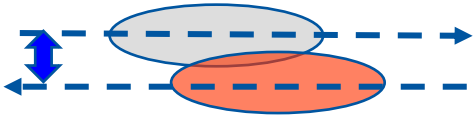
Levelling *"a la carte"*

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

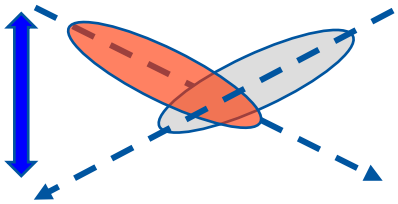
$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} F$$

Complexity

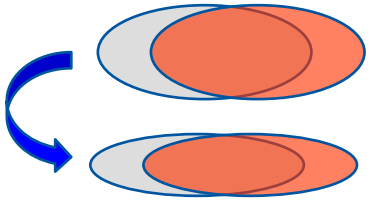
Levelling by **beam offset**



Levelling by **crossing angle**



Levelling by β* (= beam size at IP)



Each levelling technique has advantages and drawbacks!

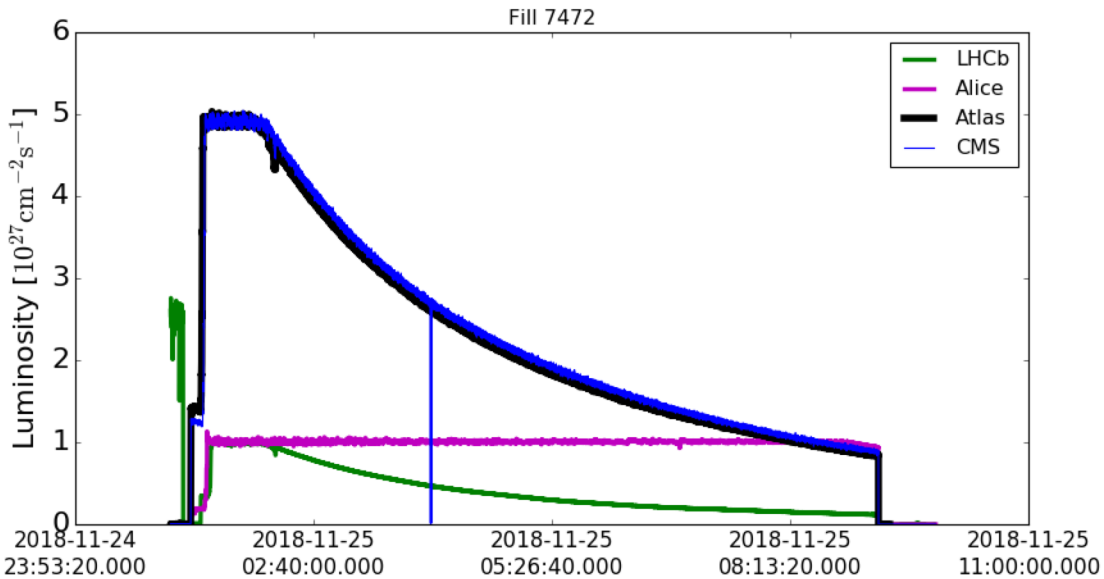
Levelling in Heavy-Ion runs

Levelling by **separation** is used in all experiments. It's performed through feedback from luminosity value.

Crossing angles can be small in HI runs because beam-beam is weak.

Due to strong burn-off smaller β* gives only small gain in luminosity.

→ Levelling by crossing angle and β* not would not be very efficient.



Levelling reduces the average luminosity

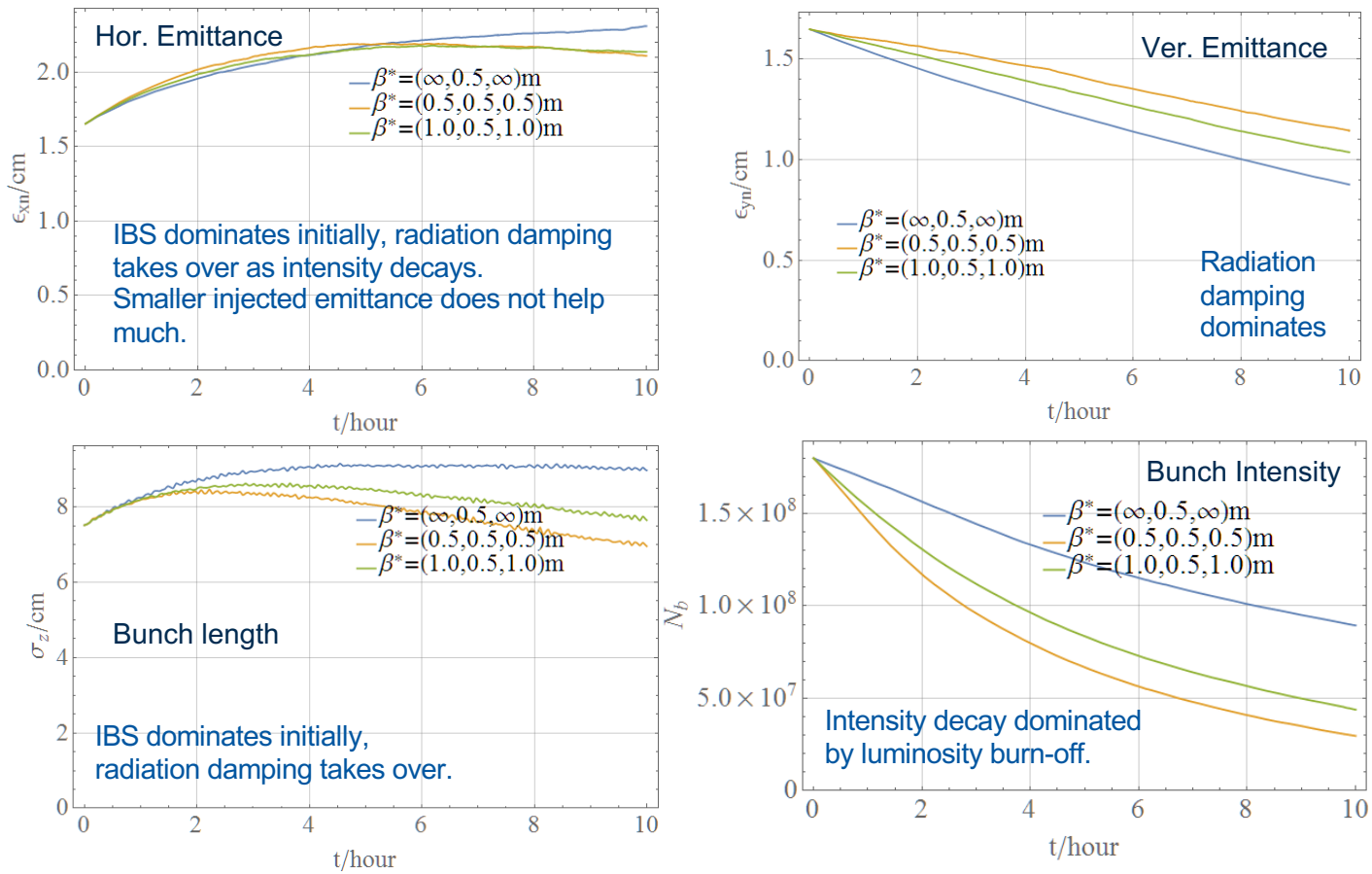
Performance Projections HL-LHC in Run 3 & 4

Three luminosity-sharing scenarios for illustration of the possibilities.
→ Equal β* scenario is nominal!

$$\beta^* = \begin{cases} (\infty, 0.5, \infty) \text{ m} & \text{(only ALICE colliding)} \\ (1.0, 0.5, 1.0) \text{ m} & \text{(ATLAS/CMS at half ALICE)} \\ (0.5, 0.5, 0.5) \text{ m} & \text{(equal)} \end{cases}$$

Pb-Pb Beam Evolution

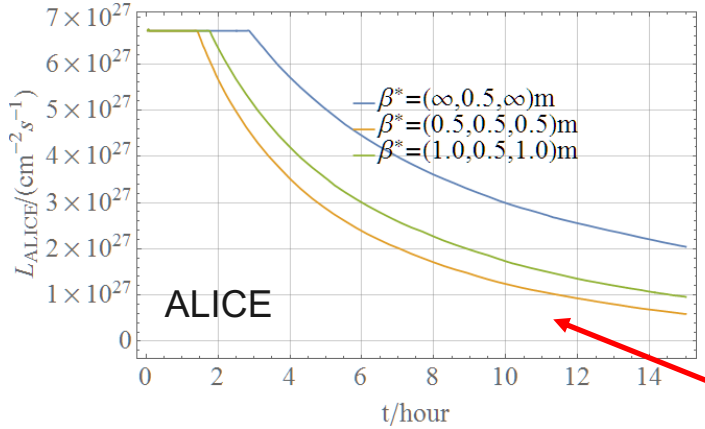
Interplay of radiation damping, IBS, luminosity burn-off couples 4 quantities: horizontal & vertical emittances, bunch length and intensity



Simulation by T. Mertens

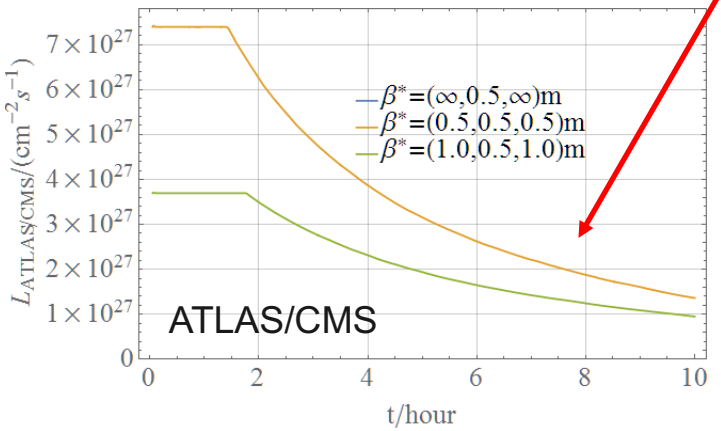
Pb-Pb Luminosity Evolution

assuming 1100 bunches colliding



ALICE, levelling at maximum acceptable rates around 50 kHz

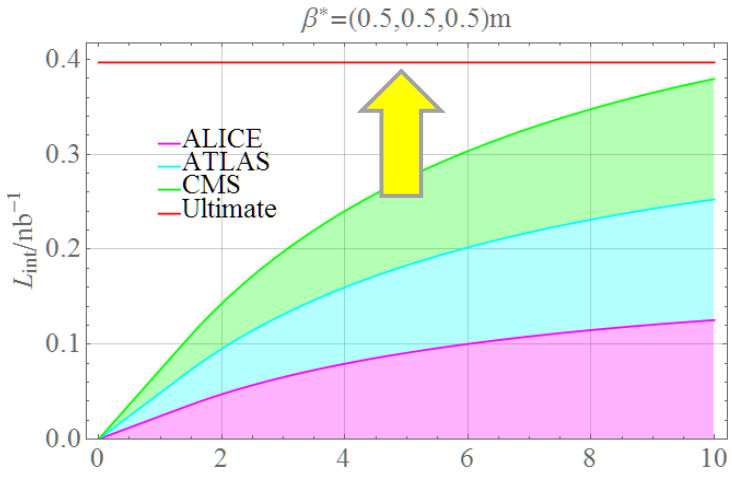
Baseline: similar luminosities in 3 experiments.

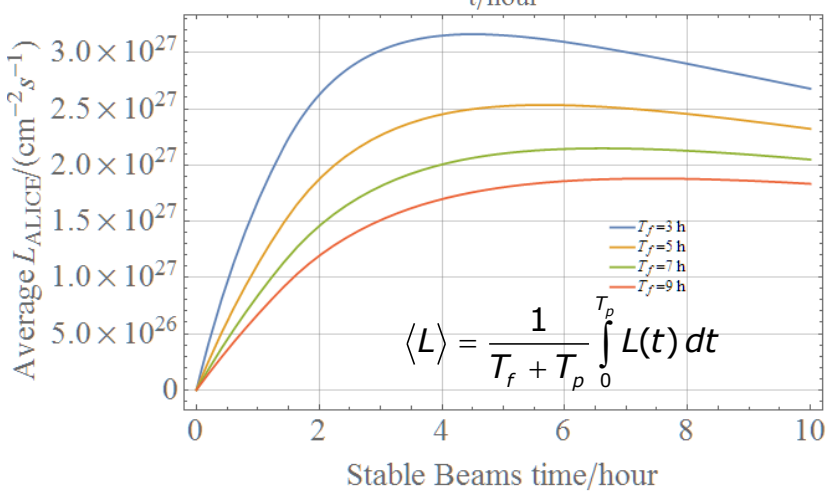


ATLAS or CMS, *assumed* levelling at similar levels to ALICE for luminosity sharing.

Pb-Pb Integrated Luminosity

For baseline scenario: $\beta^* = (0.5, 0.5, 0.5)$ m





Ultimate luminosity to share

$$L_{\text{int,max}} = \frac{k_c N_b}{\sigma_c}$$

Limited number of Pb ions to burn per fill, corresponding to 0.4nb^{-1} (~10h of collisions)

Maximize integrated luminosity:
For 3h turnaround time
→ optimum fill length is 4-5h
→ Average luminosity 3E27cm^{-2}s^{-1}

Integrated Luminosity 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

Assumptions for p-Pb

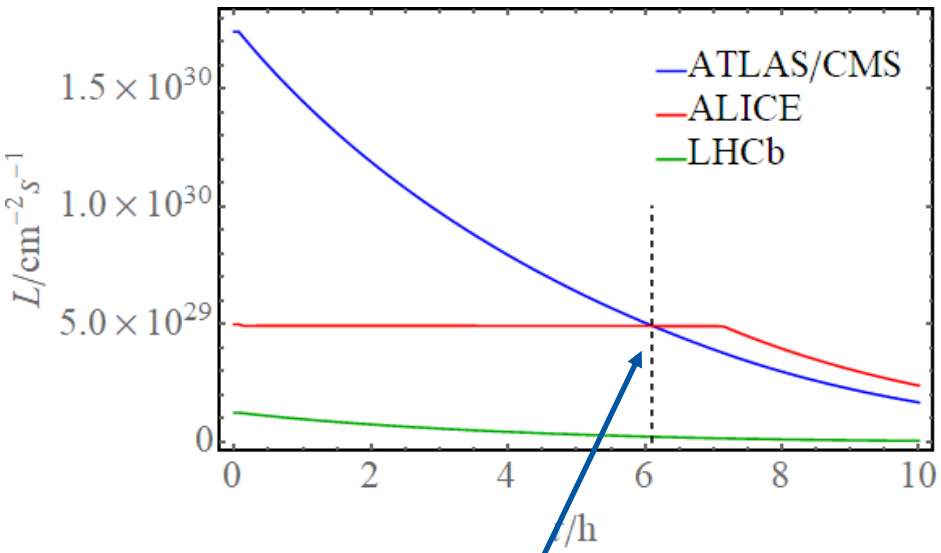
- Generally possible to replace a Pb-Pb run with a p-Pb run, if requested.
  → Split runs between p-Pb and Pb-Pb are less efficient (as in baseline for 2028) but can be handled (see 2015, 2016, …)
- Assume the **same 50ns Pb beams** and **filling scheme as for Pb-Pb.**

Parameter	Value (Pb)	Value (p)
Beam energy	7 Z TeV	7 Z TeV
Bunch intensity	1.8E8	3E10
Normalized emittance	1.65 μm	2.5 μm
Luminosity (leveled, ALICE)	5E29 cm^{-2} s^{-1}	
Luminosity (peak, ATLAS/CMS)	17.4E29 cm^{-2} s^{-1}	

p-Pb Performance Projections

- Simulations of beam parameter and luminosity evolution in ideal fill
- Further overall reduction of 5% to account for filling scheme mismatch between p and Pb

Simulation by M. Jebramcik



Note: after about 6h, the bunch intensity falls below visibility threshold of interlock BPMs → *fill is terminated*

p-Pb Integrated Luminosity per 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

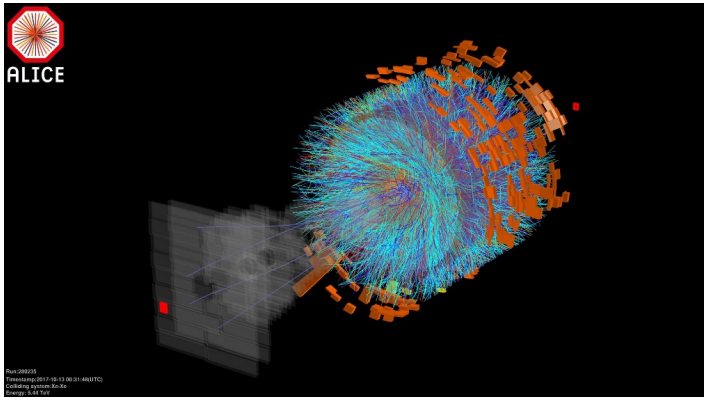
The baseline options for Run3 & 4 have been approved, but the experimental community is reviewing the detailed request.

Everything beyond LHC Run4 is a proposal and under study.

http://www.marion-isd.org/

CERN

Lighter Ions



- Operation with lighter ions is not part of the present HL-LHC baseline
- Very limited experience in LHC:
  - → 17h of low-intensity running with Xe beams in 2017
  - → Beam set up in injectors not pushed to the limits
- Significant uncertainties in estimates for future running

- 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

Papers at IPAC2018
https://ipac18.org
http://ipac2018.vrws.de/

MOPMF039 First Xenon-Xenon Collisions in the LHC

MOPMF038 Cleaning Performance of the Collimation System with Xe Beams at the Large Hadron Collider

TUPAF020 Performance of the CERN Low Energy Ion Ring (LEIR) with Xenon

TUPAF024 Impedance and Instability Studies in LEIR With Xenon

Lighter Ions from the Injectors

Experience with other species in LHC injectors for **fixed target**

→ Less stringent requirements on beam quality (emittance).

Not all species (e.g. Cu) work well in the **ion source**.

→ Noble gases are favourable.

→ The presented list is only an example of species of interest.

Bunch intensity is expected to show **dependence on ion charge**

→ Limitations due to space charge, intrabeam scattering…

→ Higher bunch charges for lighter ions.

Proceedings of IPAC2016, Busan, Korea TUPMR027

CERN'S FIXED TARGET PRIMARY ION PROGRAMME

D. Manglunki, M.E. Angoletta, J. Axensalva, G. Bellodi, A. Blas, M. Bodendorfer, T. Bohl, S. Cettour-Cave, K. Cornelis, H. Damerau, I. Efthymiopoulos, A. Fabich

Table 1: Charge States and Typical Intensites

Species	Ar	Xe	Pb
Charge state in Linac3	Ar^{11+}	Xe^{20+}	Pb^{29+}
Linac3 beam current after stripping [eμA]	50	27	25
Charge state Q in LEIR/PS	Ar^{11+}	Xe^{39+}	Pb^{54+}
Ions/bunch in LEIR	3×10^9	4.3×10^8	2×10^8
Ions/bunch in PS	2×10^9	2.6×10^8	1.2×10^8
Charge state Z in SPS	Ar^{18+}	Xe^{54+}	Pb^{82+}
Ions at injection in SPS	7×10^9	8.1×10^8	4×10^8
Ions at extraction in SPS	5×10^9	6×10^8	3×10^8

Preliminary Performance Estimates

Postulate simple form for bunch intensity dependence on species charge only

$$N_b(Z,A) = N_b(82,208)\left(\frac{Z}{82}\right)^{-p}$$

$$\text{where } p = \begin{cases} 1.9 & \text{fixed target experience} \\ 0.75 & \text{Xe run vs best Pb} \end{cases}$$

Highly simplified scaling to project future luminosity performance as a function of *p.*

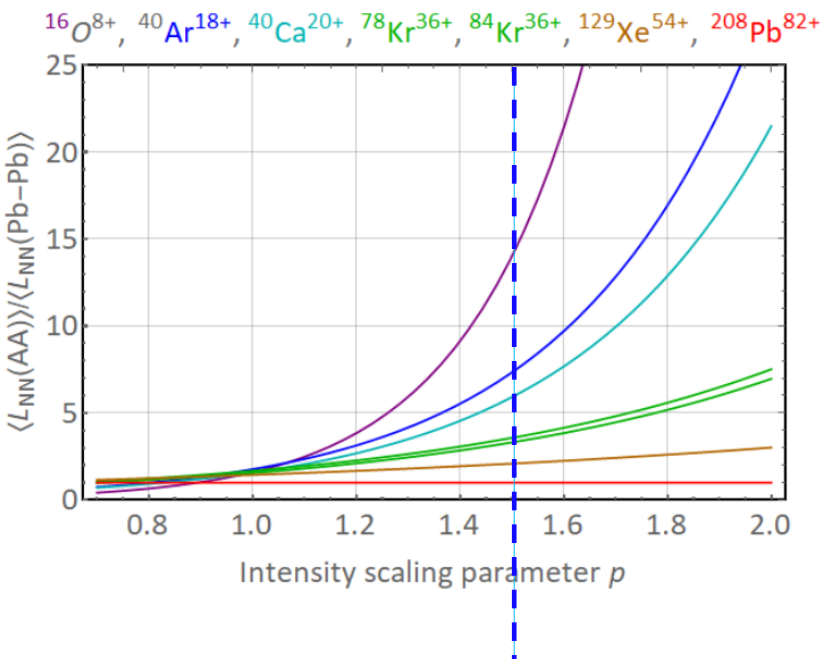
p=1.5 seems reasonable.

Assume that other quantities, like geometric beam size, filling scheme, other loss rates, etc, are equal.

Results are only tentative and indicative!

Time-averaged luminosity ratio

- Showing ratio of time-averaged luminosity to Pb-Pb
- Analytical calculation with burn-off only – not full simulation
- Assuming 2.5 h turnaround time, 3 experiments with full luminosity
- Results have large uncertainties!
- Possible limits from collimation losses, radio-protection in Linac3/LEIR (lightest species), etc, are still to be properly analysed species-by-species. *(see talk by R. Bruce)*



Nucleon-nucleon luminosity in 1-month run: **gains** ranging up to a **factor ~13 for lightest considered ion (O) at p=1.5**

Plausible Parameters (p=1.5)

strength of IBS emittance growth

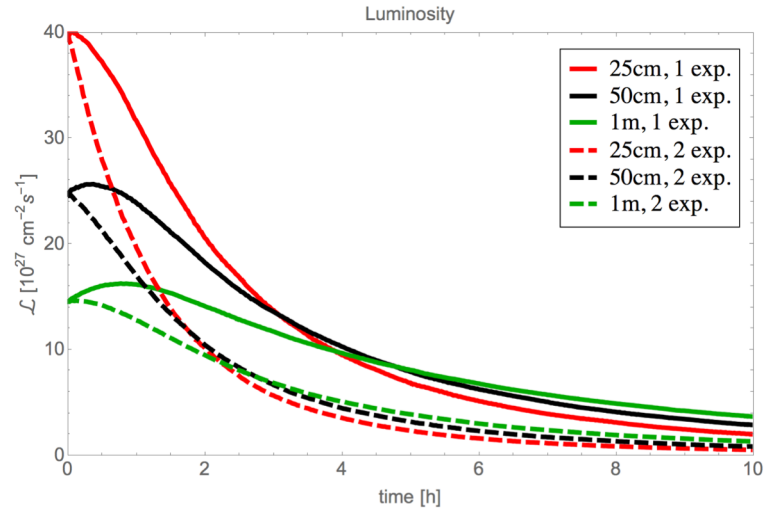
Stored energy

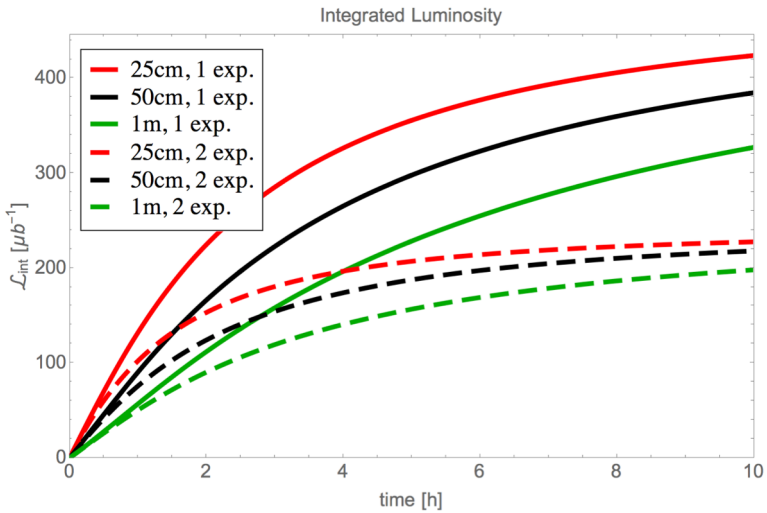
	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{84}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
γ	3760.	3390.	3760.	3470.	3220.	3150.	2960.
$\sqrt{s_{NN}}$ /TeV	7.	6.3	7.	6.46	6.	5.86	5.52
σ_{had} /b	1.41	2.6	2.6	4.06	4.26	5.67	7.8
σ_{tot} /b	1.48	3.85	4.18	17.1	18.3	72.5	508.
N_b	6.24×10^{9}	1.85×10^{9}	1.58×10^{9}	6.53×10^{8}	6.53×10^{8}	3.56×10^{8}	1.9×10^{8}
ϵ_{xn} /μm	2.	1.8	2.	1.85	1.71	1.67	1.58
f_{IBS} /(m Hz)	0.0662	0.0894	0.105	0.13	0.12	0.144	0.167
W_b /MJ	68.9	45.9	43.6	32.5	32.5	26.5	21.5
L_{AA0} /cm^{-2}s^{-1}	1.46×10^{31}	1.29×10^{30}	9.38×10^{29}	1.61×10^{29}	1.61×10^{29}	4.76×10^{28}	1.36×10^{28}
L_{NN0} /cm^{-2}s^{-1}	3.75×10^{33}	2.06×10^{33}	1.5×10^{33}	9.79×10^{32}	1.14×10^{33}	7.93×10^{32}	5.88×10^{32}
P_{BFPP} /W	0.0031	0.179	0.303	5.72	5.72	43.4	350.
P_{EMD1} /W	4.98	16.5	16.9	40.5	43.7	76.7	141.
τ_{L0} /h	16.4	21.3	23.	13.5	12.7	5.87	1.57
T_{opt} /h	9.04	10.3	10.7	8.23	7.96	5.42	2.8
$\langle L_{AA}\rangle$ /cm^{-2}s^{-1}	8.99×10^{30}	8.34×10^{29}	6.17×10^{29}	9.46×10^{28}	9.32×10^{28}	2.23×10^{28}	3.8×10^{27}
$\langle L_{NN}\rangle$ /cm^{-2}s^{-1}	2.3×10^{33}	1.33×10^{33}	9.87×10^{32}	5.76×10^{32}	6.57×10^{32}	3.71×10^{32}	1.64×10^{32}
$\int_{month} L_{AA}\, dt$ /nb^{-1}	11700.	1080.	799.	123.	121.	28.9	4.92
$\int_{month} L_{NN}\, dt$ /pb^{-1}	2980.	1730.	1280.	746.	852.	481.	213.
R_{had} /kHz	20700.	3340.	2440.	653.	686.	270.	106.
μ	1.64	0.266	0.194	0.0518	0.0544	0.0215	0.00842

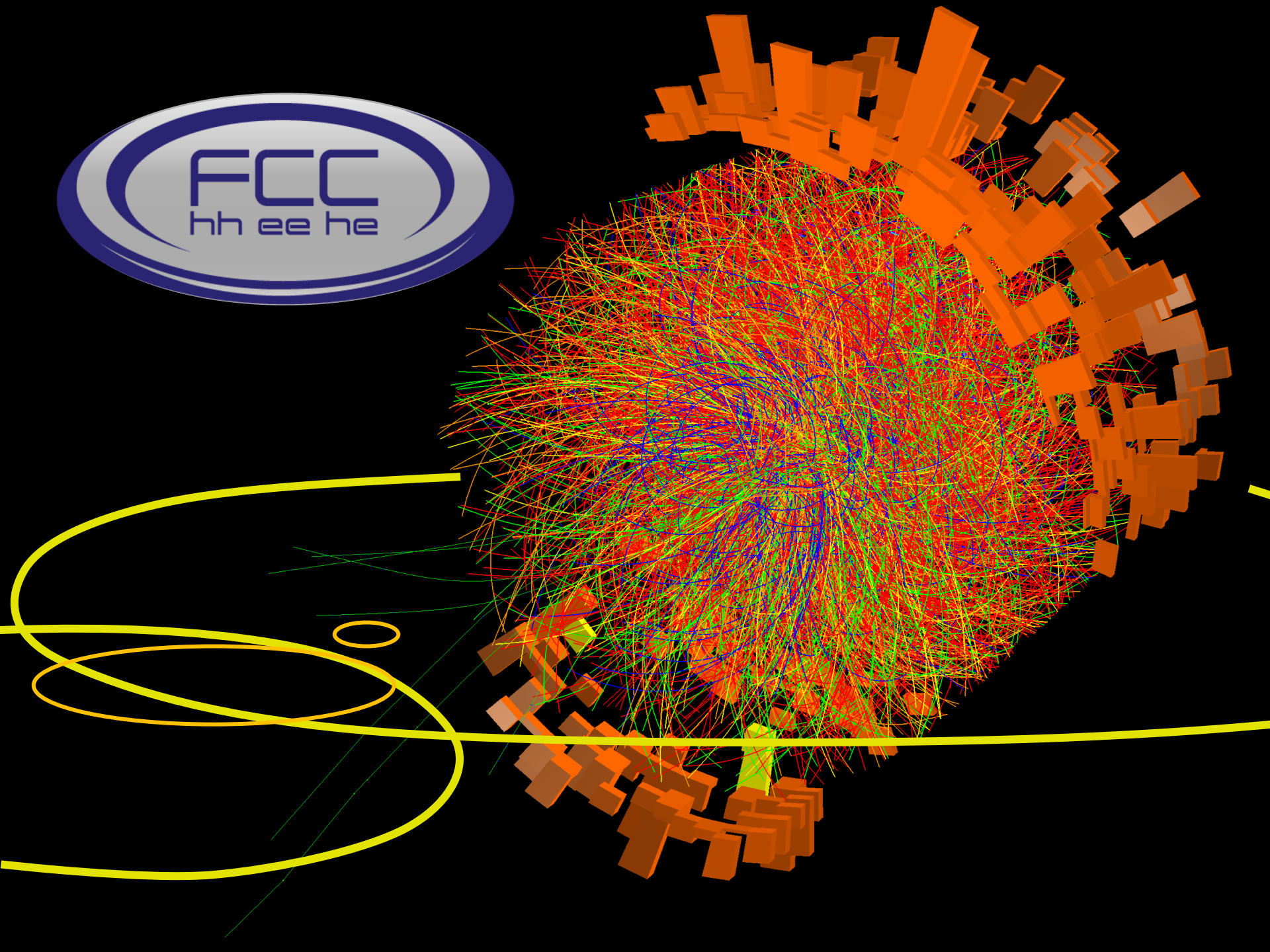
Overestimates integrated luminosity for Pb-Pb wrt official values.
No luminosity levelling. High event rates! Pileup μ ~1.

HE-LHC: Pb-Pb Performance

- Assuming HL-LHC beams
  → upper limit of 0.4 nb^{-1} per fill
- Stronger radiation damping than in LHC due to higher energy
- No leveling assumed, 1-2 active experiments
- ***The gain in integrated luminosity for HE-LHC over HL-LHC is fairly small*** and is strongly affected by turnaround time.
- Detailed numbers to be worked out.
- Likely limits from beam losses (*see talk of R. Bruce)*



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General Parameters

	LHC achieved	HL-LHC baseline	FCC-hh baseline	FCC-hh ultimate
Circumference	26.66 km		**97.75 km**	
Beam Energy [Z TeV]	6.37	7	**50**	
β-function at the IP [m]	0.5	0.5	**1.1**	**0.3**
No. Ions per bunch [1e8]	2.4	1.8	**2.0**	
Transv. normalised emittance [μm.rad]	~2	1.65	**1.5**	
Bunch spacing [ns]	75	50	**100**	**50**
Number of bunches	733	1256	**2760**	**5400**
Stored energy/beam [MJ]	14	21	**362**	**709**
Stored energy/beam at Injection [MJ]	0.7	1.5	**24**	**47**

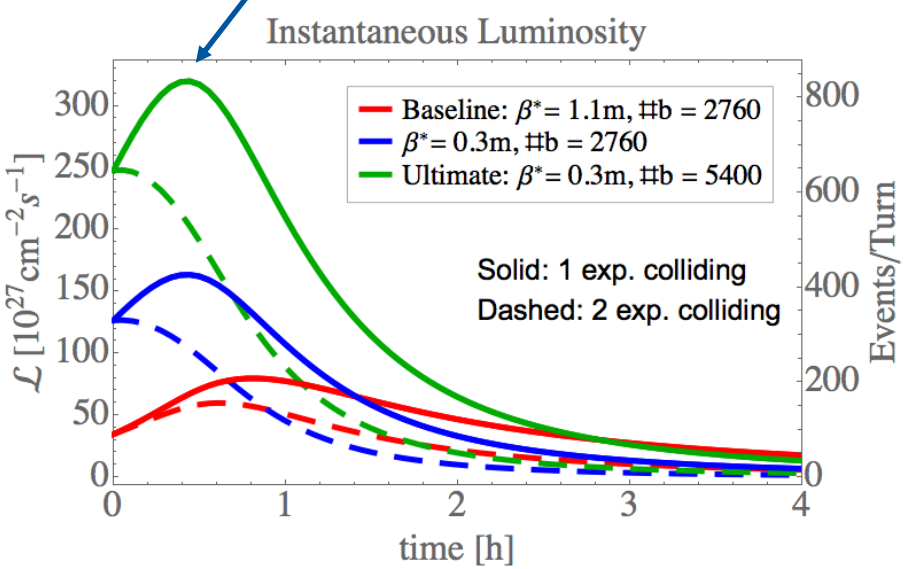
LHC experience

30% larger beam size as protons

more than 10x smaller as for protons

Pb-Pb Luminosity Evolution

Rise of luminosity at start of fill:
Strong radiation damping decreases emittance rapidly until IBS kicks in.

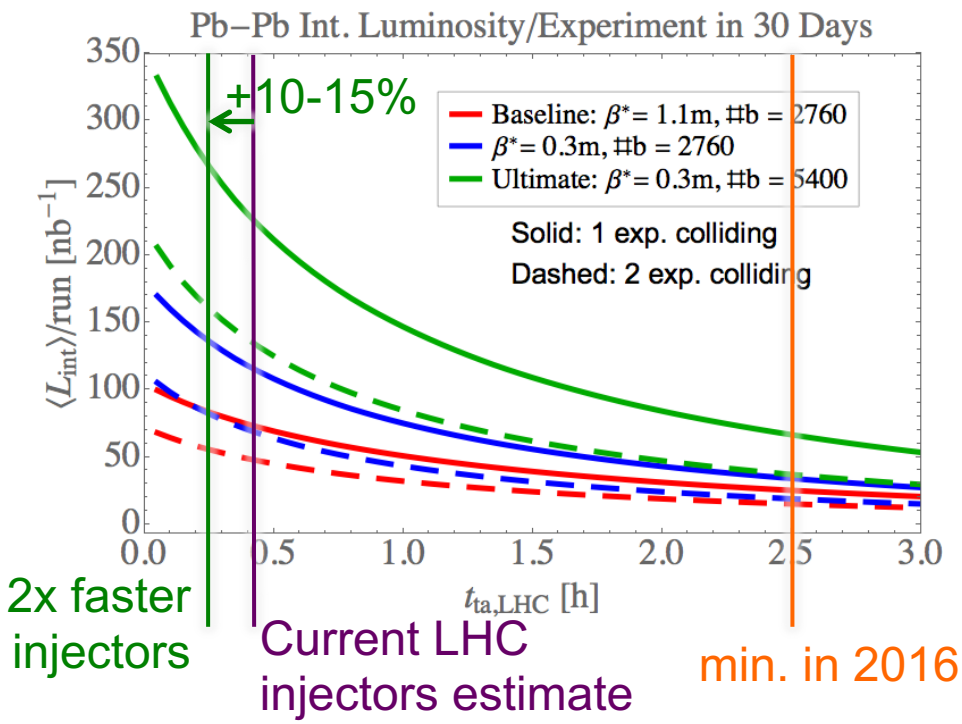


Scenarios:

- Baseline and Ultimate
- 1 (solid) and 2 (dashed) experiments in collisions in **main IPs**

The available total integrated luminosity is shared.

Pb-Pb Integrated Luminosity per Run



Considers:

- **Particle losses on FCC injection plateau** of already circulating trains.
- **Optimum turn around**
- **Optimum time in collision** for each scenario

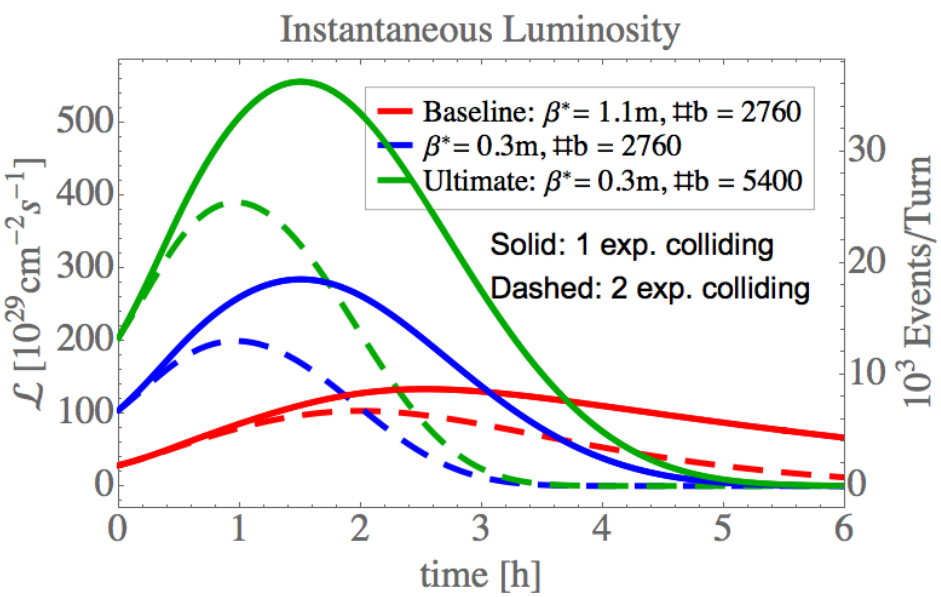
Neglects:

- **Down time** due to failures

Including a **performance efficiency factor** of 50%

	Baseline:	Ultimate:
1 exp. L_{int}/run:	**35nb^{-1}**	**110nb^{-1}**
2 exp. L_{int}/run:	**23nb^{-1}**	**65nb^{-1}**

p-Pb Luminosity Evolution



Same color code as for Pb-Pb

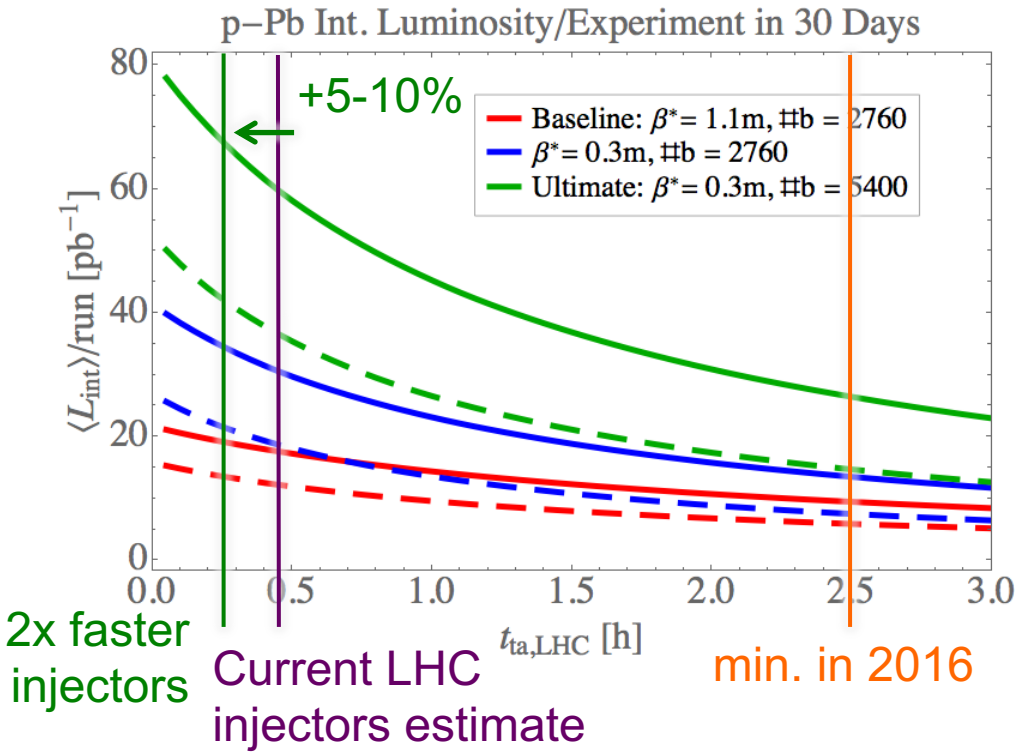
Assumed:

- same Pb-beam as in Pb-Pb
- p-beam with the same number of charges and geometrical emittance as Pb-beam.

Longer luminosity lifetime, because for 82-Pb charges only 1-p is burned-off.

Potential to increase p intensity as already done at LHC in 2016.

p-Pb Integrated Luminosity per Run



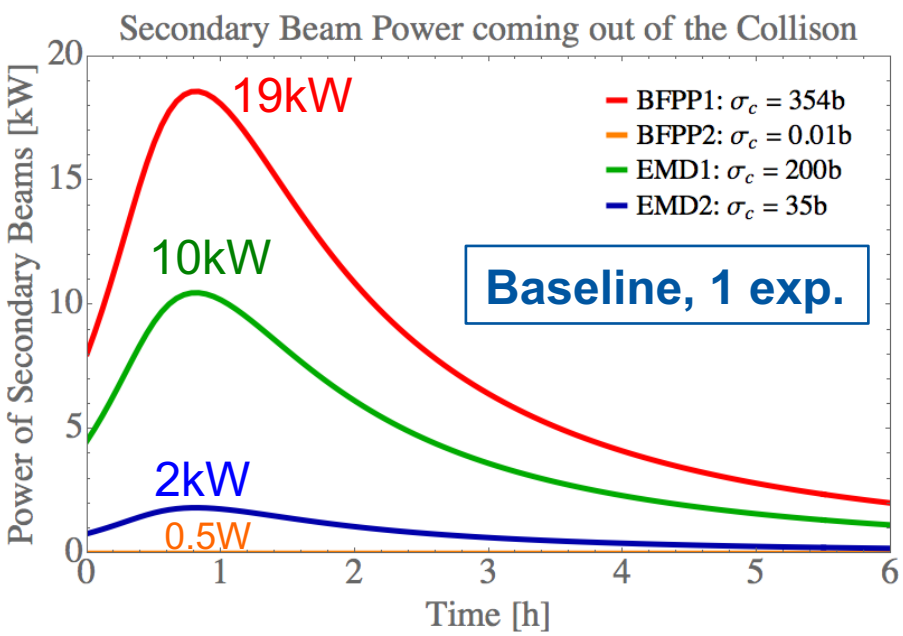
Including a **performance efficiency factor** of 50%

	Baseline:	Ultimate:
1 exp. L_{int}/run:	**8pb^{-1}**	**29pb^{-1}**
2 exp. L_{int}/run:	**6pb^{-1}**	**18pb^{-1}**

Secondary Beam Power

$P = \sigma_c L E \approx$ ***19kW*** (Baseline, 1 exp.)
75kW (Ultimate, 1 exp.)

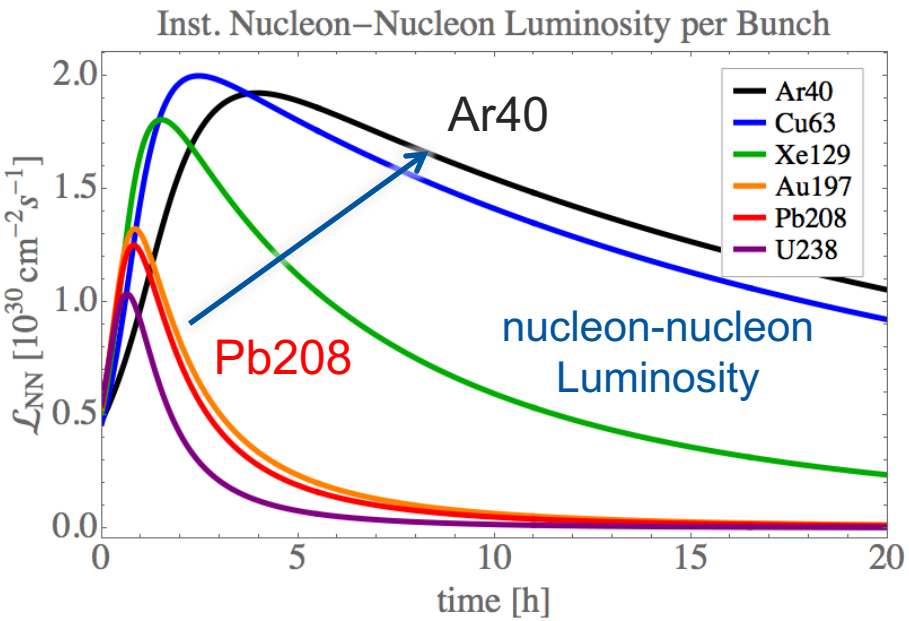
Continuous and very **localised** losses



nominal LHC: ***P ≈ 26W***
2018 Pb-Pb run: P ≈ 160W
→ mitigation methods are already required, long-term damage expected

Special collimators are required to absorb those beams and **enable** the FCC **to run with heavy ions.** (see talk of R. Bruce)

Other Ion Species

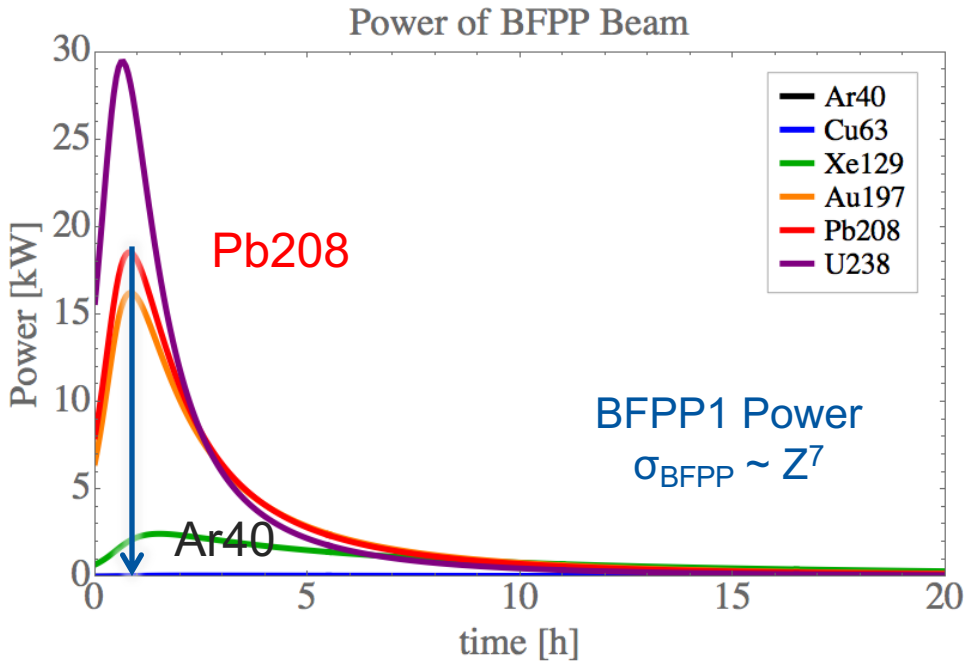


- ✧ Assume same number of charges per bunch for each species.
- ✧ **Increased luminosity lifetime**, more particles available for hadronic interactions.

$$N_{\text{hadronic}} = \sigma_h \int L\,dt \propto \frac{\sigma_h}{\sigma_h + \sigma_{\text{BFPP}} + \sigma_{\text{EMD}}} N_{tot} \propto Z^{-(6\text{--}8)}$$

Other Ion Species

✧ **Reduced secondary beam power** emerging from collision point.



Worth considering small Z reduction from Pb!

Summary

- Options and performance estimates for near and far future heavy-ion beams have been presented.
  - Based on Pb-beam parameters assumed for LHC Injector Upgrade (LIU) to fulfill ALICE LoI of 2012.
  - Most features were already implemented for 2018 Pb-Pb run.
  - Greatest remaining uncertainties: collimation in LHC, slip-stacking in SPS.
- The current HL-LHC planning does not include other species than Pb.
  - The feasibility of runs with lighter species has been demonstrated with Xe-Xe in 2017.
  - First considerations for lighter ions give hope for substantially higher integrated nucleon-nucleon luminosity than with Pb-Pb, however still with large uncertainties. More studies and experience are needed.
  - Scope for special short runs (O-O, p-O, …) at small cost in LHC time and within certain limits of intensity and scheduling.

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Heavy Ions in the LHC at the End of Run2

- 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)
- Since 2013 all 4 experiments have participated in heavy-ion data taking.
- The 2018 Pb-Pb run *(finished on Monday)* fulfilled the *"initial 10 years"* LHC design **goal of 1 nb^{-1} Pb-Pb luminosity for ALICE, ATLAS and CMS**
  - Delivered Luminosity to LHCb increased by 2 orders of magnitude compared to 2015 (first Pb-Pb data taking for LHCb)

Schedule Proposal

A. Dainese & J.F. Grosse-Oetringhaus @ WG5 HI: general meeting on Yellow Report overview, 30.10.2018 https://indico.cern.ch/event/758181/

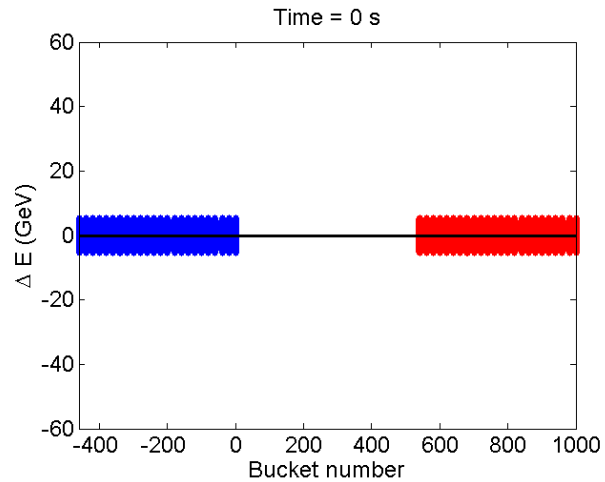
Revised schedule proposal (2 longer runs in 2022 and 2028)

Year	Systems, time, L_{int}	Total per Run (3, 4, 5)
2021	Pb-Pb, 3 weeks, 2.3/nb pp 5.5, 1week, 3/pb @ ALICE, 350/pb ATLAS, CMS	**Pb-Pb, 6.2/nb** pp 5.5, "half L_{int} target" p-Pb 8.8, 1/pb ATLAS,CMS, 0.5/pb ALICE, 0.25/pb LHCb pp 8.8, "half L_{int} target" O-O p-O
2022 (extended from 4 to 6 weeks)	p-O + O-O 7 TeV, 1 week, few 100/μb (after EYETS?) Pb-Pb, 5 weeks, 3.9/nb	
2023	pp 8.8 TeV, few days p-Pb 8.8 TeV, 3.x weeks	
LS3	ATLAS/CMS upgrades, ALICE: ITS3? FoCal?	
2027	Pb-Pb, 3 weeks, 2.3/nb pp 5.5, 1week, 3/pb @ ALICE, 350/pb ATLAS, CMS	**Pb-Pb, 6.8/nb** pp 5.5, "half L_{int} target" p-Pb, 0.6/pb ATLAS,CMS, 0.3/pb ALICE, 0.25/pb LHCb pp 8.8 "half L_{int} target"
2028 (extended from 4 to 6 weeks)	Pb-Pb, 2 weeks, 1.5/nb p-Pb 8.8 TeV, 3.x weeks pp 8.8 TeV, few days	
2029	Pb-Pb, 4 weeks, 3/nb	
LS4	LHCb upgrade? ALICE faster?	
2031	"LightA-LightA", 3 weeks, 6.3 TeV, pp, 1 week	"LightA-LightA": e.g. Ar-Ar (A=40), L_{NN} equiv 6-18 x Pb-Pb 13/nb Kr-Kr (A=78), L_{NN} equiv 1.5-5 x Pb-Pb 13/nb
2032	"LightA-LightA", 4 weeks	
2033	"LightA-LightA", 4 weeks	

Optics compatibility with p-p operation

- **ATS optics** (achromatic telescopic squeeze) to be used for p-p operation: squeeze ATLAS / CMS to $\beta^*=15$ cm
- There is no ATS optics that includes a squeeze of ALICE to similar values as ATLAS/CMS.
- However, the $\beta^*=0.5$ m values assumed for heavy-ion operation do not require ATS
  - Rather little gain from lower β^* in high burn-off regime
- Necessary flexibility of the optics needs to be maintained.
- **$\beta^*=0.5$ m has been used in 2018.**
  - Completely new ramp, squeeze, physics configuration compared to 2018 proton optics

Slip Stacking Feasibility



- **Feasibility relies on**
  - Large bandwidth of SPS 200 MHz travelling wave cavities.
  - Low ion intensity (no need for feed-back, feed-forward, …).
  - Independent cavity control (SPS LLRF upgrade in LS2).

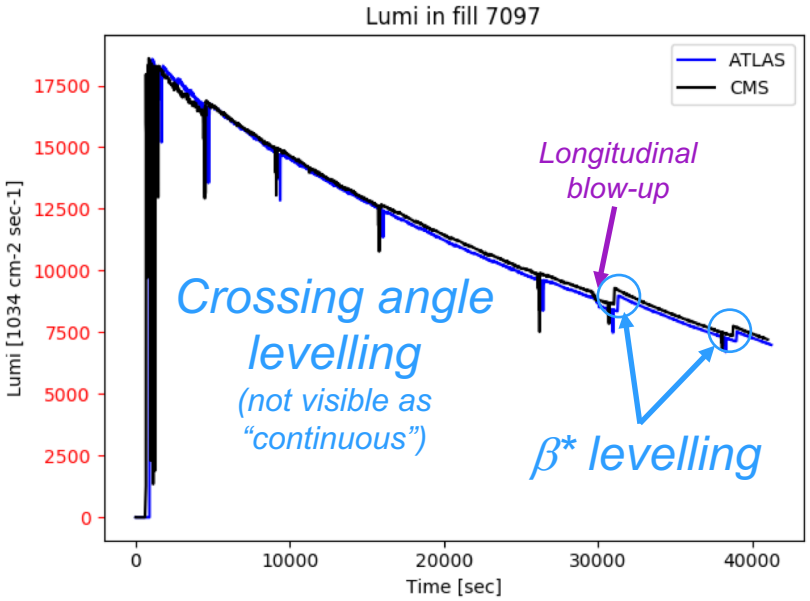
- **Macroparticle simulations show**
  - Proof of principle (with intensity effects).
  - *Longitudinal emittance blow-up* (factor 2.5) at re-capture due to filamentation in large bucket with current SPS impedance mode.
  - *Bunches will be hollow* in longitudinal phase space.
  - Might need bunch rotation at SPS extraction to fit LHC bucket.
  - Optimization of re-capture is crucial to keep losses <5%.

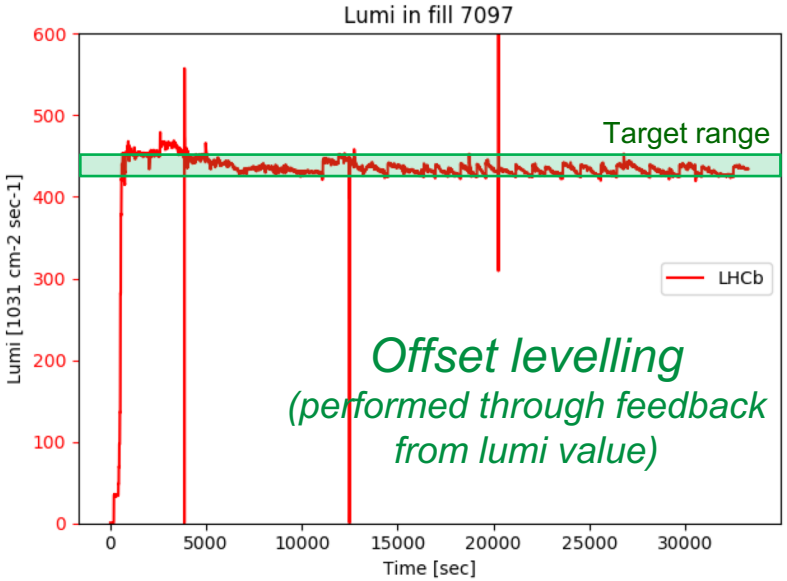
T. Argyropoulos

Levelling in 2018

All three levelling techniques have been used in **proton** operation (only separation levelling for ions so far):

- **Crossing angle** levelling is used for ATLAS and CMS throughout the fill in a "continuous" way.
- **β*** levelling is used to enhance luminosity at lower intensity (low pile up). This technique will be central to operation from Run 3 on.
- Levelling by **separation** is used in LHCb and ALICE since the beginning of LHC operation. It's performed through feedback from luminosity value.





FCC Beam Evolution Studies

- Time evolution of beam parameters obtained from numerical solution of a **system of four coupled differential equations**
  - dN/dt, $d\varepsilon_{xy}/dt$, $d\sigma_s/dt$.
  - Includes luminosity burn-off, intra-beam scattering (IBS) and synchrotron radiation damping

- Pb damps ~2x faster than protons.
  - radiation damping times for Pb ~0.5h

- Initial IBS is weak, but damping is very fast.
  - → Fast emittance decrease at the beginning of the fill until IBS starts to counteract the damping.

Beam Evolution

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

Intra-beam scattering (IBS)

Radiation Damping

Scattering during the collision

$$\frac{1}{\epsilon_x}\frac{d\epsilon_x}{dt} = \alpha_{\mathrm{IBS},x}(N_b,\epsilon_x,\epsilon_y,\epsilon_s) - \alpha_{\mathrm{rad},x} + \alpha_{\mathrm{coll},x}(N_b,\epsilon_x,\epsilon_y,\epsilon_s) + \ldots$$

$$\frac{1}{\epsilon_y}\frac{d\epsilon_y}{dt} = \alpha_{\mathrm{IBS},y}(N_b,\epsilon_x,\epsilon_y,\epsilon_s) - \alpha_{\mathrm{rad},y} + \alpha_{\mathrm{coll},y}(N_b,\epsilon_x,\epsilon_y,\epsilon_s) + \ldots$$

$$\frac{1}{\epsilon_s}\frac{d\epsilon_s}{dt} = \alpha_{\mathrm{IBS},s}(N_b,\epsilon_x,\epsilon_y,\epsilon_s) - \alpha_{\mathrm{rad},s} + \ldots$$

Many other, less important, effects.

$$\frac{1}{N_b}\frac{dN_b}{dt} = -\frac{\sigma_{\mathrm{c,tot}}\mathcal{L}}{N_b} - 1/\tau_{\mathrm{IBS},N}(N_b,\epsilon_x,\epsilon_y,\epsilon_s) - 1/\tau_{\mathrm{clean}} - \ldots$$

Luminosity burn-off

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.

Dominant Effects on the Emittance

Intra-Beam Scattering Growth Rates

A. Piwinski's formalism

$$\alpha_{\mathrm{IBS},s} = \left\langle A_{\mathrm{p}} \frac{\sigma_h^2}{\sigma_p^2} f(a,b,q) \right\rangle$$

$$\alpha_{\mathrm{IBS},x} = \left\langle A_{\mathrm{p}} \left[f\left(\frac{1}{a}, \frac{b}{a}, \frac{q}{a}\right) + \frac{D_x^2 \sigma_h^2}{\sigma_x^2} f(a,b,q) \right] \right\rangle$$

$$\alpha_{\mathrm{IBS},y} = \left\langle A_{\mathrm{p}} \left[f\left(\frac{1}{b}, \frac{a}{b}, \frac{q}{b}\right) + \frac{D_y^2 \sigma_h^2}{\sigma_y^2} f(a,b,q) \right] \right\rangle$$

Complicated Integral, to be solved numerically

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

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

Dynamic change with beam parameters

Dependency on lattice and beam parameters

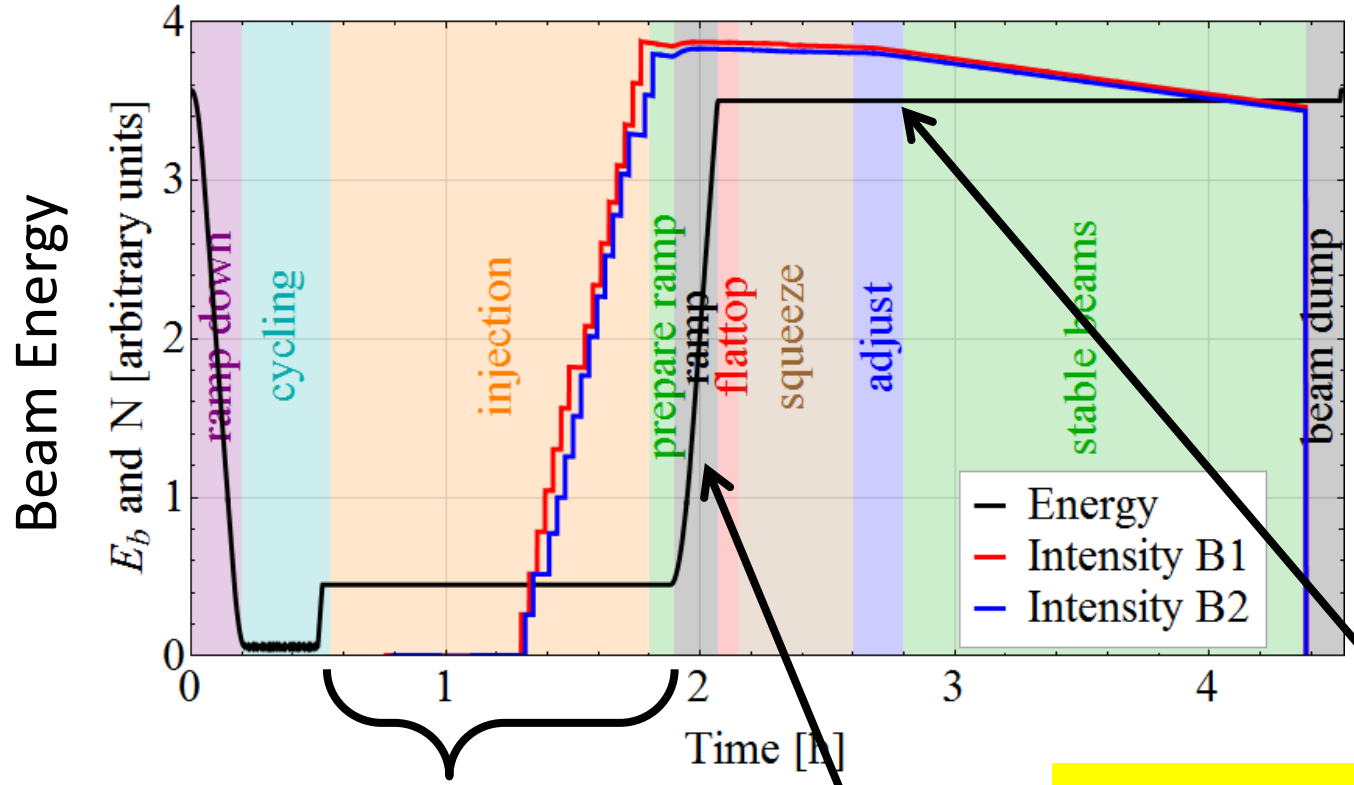
$$\frac{1}{\sigma_h^2} = \frac{1}{\sigma_p^2} + \frac{D_x^2}{\sigma_x^2} + \frac{D_y^2}{\sigma_y^2}$$

$$a = \frac{\sigma_h \beta_x}{\gamma \sigma_x}, \quad b = \frac{\sigma_h \beta_y}{\gamma \sigma_y}, \quad q = \sigma_h \beta_{\mathrm{rel}} \sqrt{\frac{2d}{r_0}}$$

$$P^2 = a^2 + (1-a^2)u^2$$

$$Q^2 = b^2 + (1-b^2)u^2.$$

Accelerator Cycle (Fill)

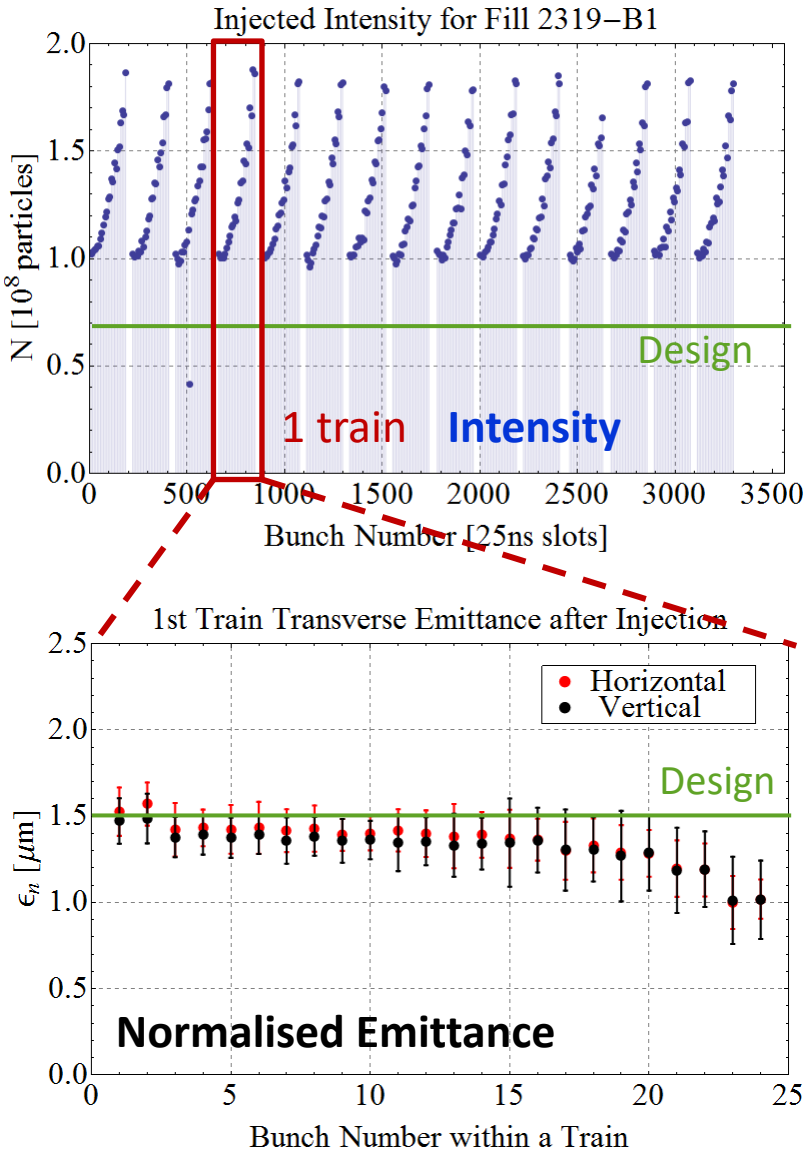


Low energy injection plateau: Accumulation of beam

Acceleration

Top (max) Energy: Extraction (PS, SPS…) Store & Collide (LHC)

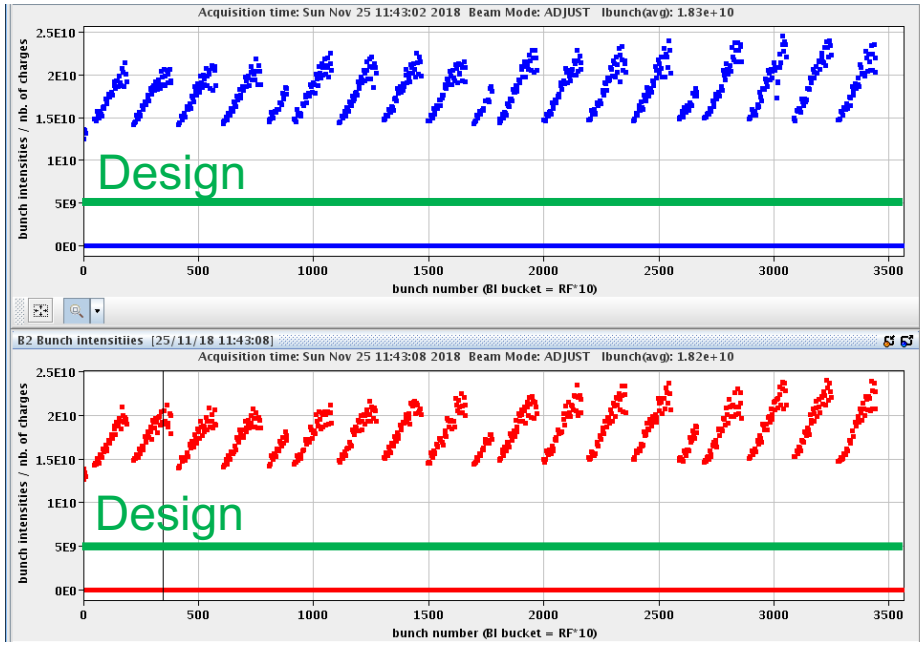
Bunch-by-Bunch Differences



- **Typical structure within a LHC Pb train**.
- From 1st to last bunch of a train:
  - Increase of intensity.
  - Decrease of emittance.

- While already circulating bunches wait **at low energy on the SPS injection plateau** for the remaining PS-injections to construct a full LHC train, **IBS and other effects lead to emittance growth and particle losses.**

LHC Pb-Pb Bunch Intensities



- 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.

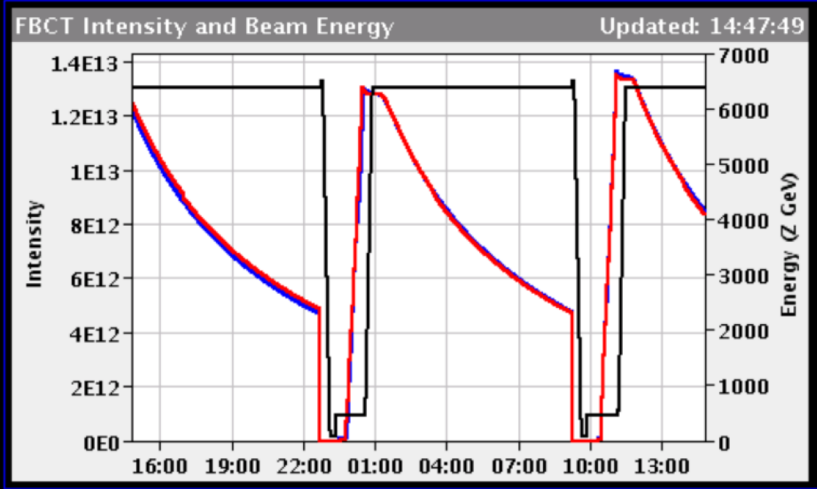
- Two types of beam used
  - 100ns bunch separation
  - 75ns bunch separation

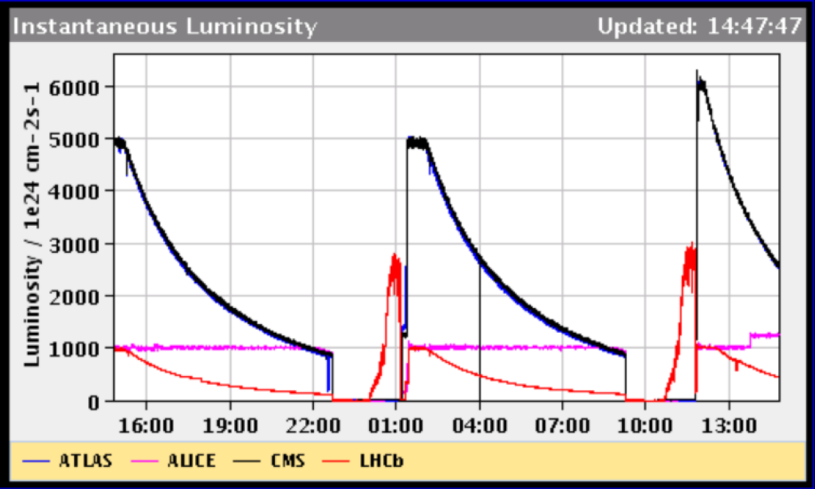
LHC Page1 | Fill: 7473 | E: 6369 Z GeV | t(SB): 02:58:43 | 25-11-18 14:47:49

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





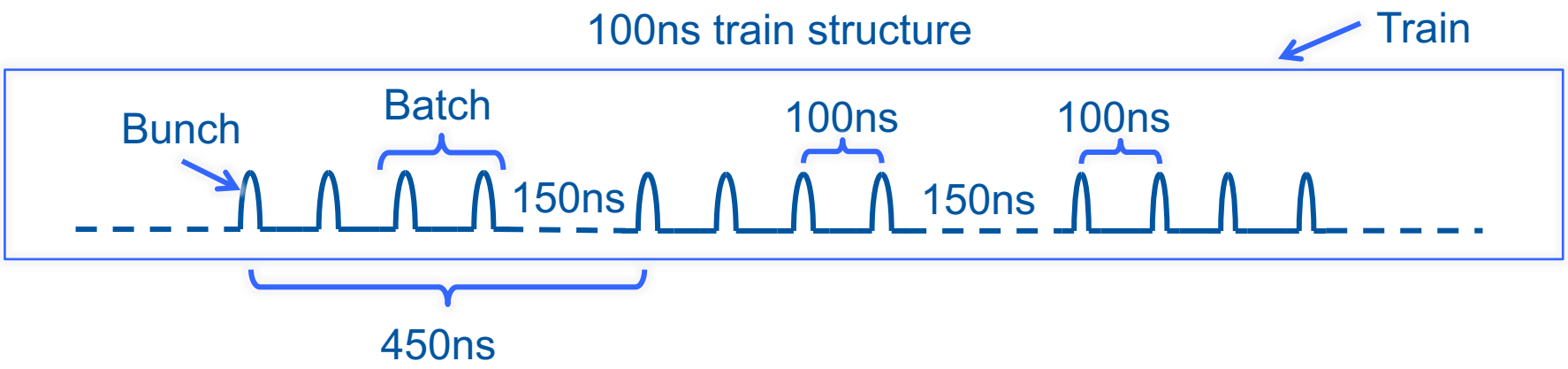
Comments (25-Nov-2018 09:41:52)

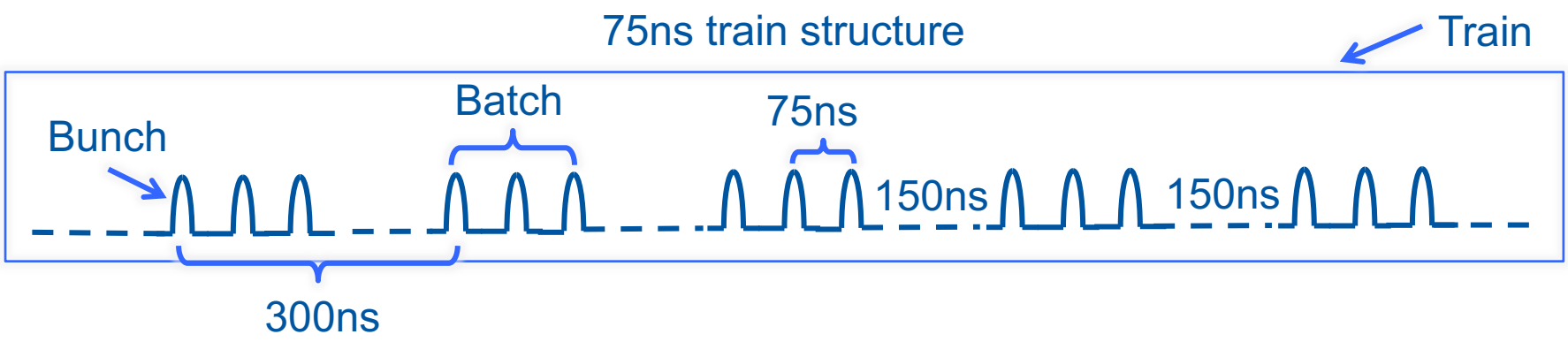
Re-fill for physics with 733Pb.

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

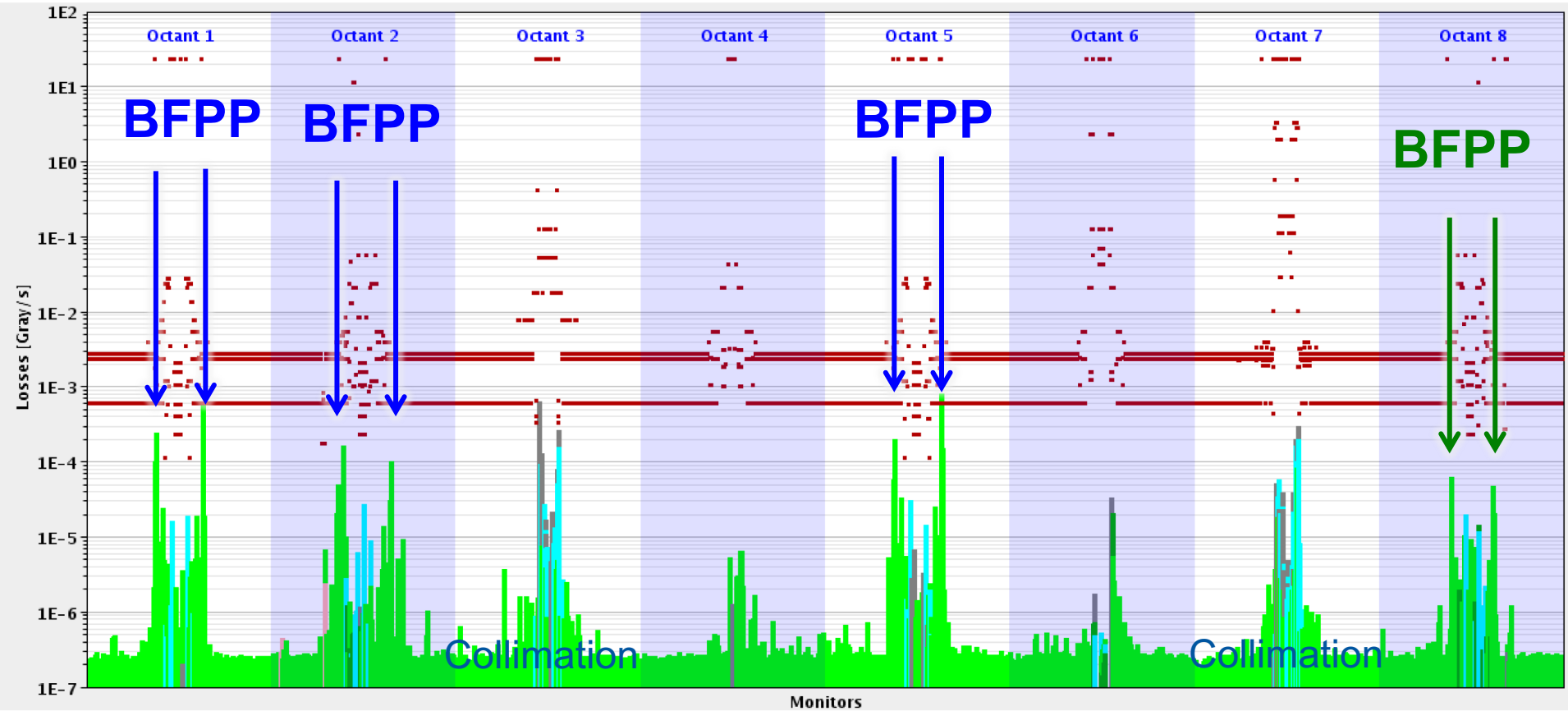
100ns vs. 75ns Beams





Loss Pattern around the Ring

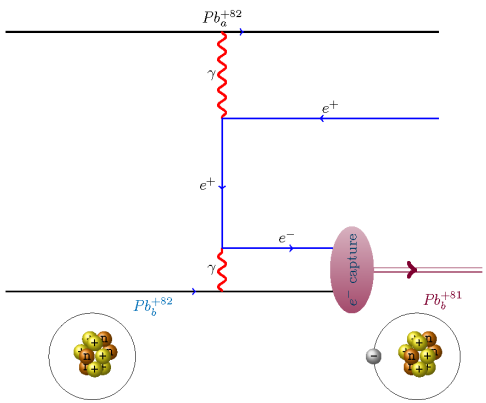
Loss spikes around all IPs where ions collide …



Secondary Beams created in the Collision

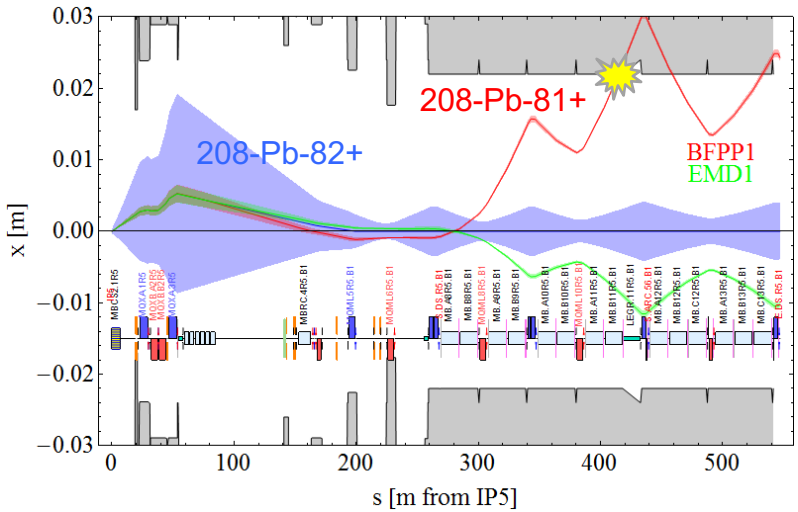
Bound-free pair production (BFPP)

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



Has large interaction cross-section (>200b) in Pb-Pb collisions and is the main contribution to fast luminosity burn-off.

Secondary beams impact in superconducting magnets downstream the interaction points.

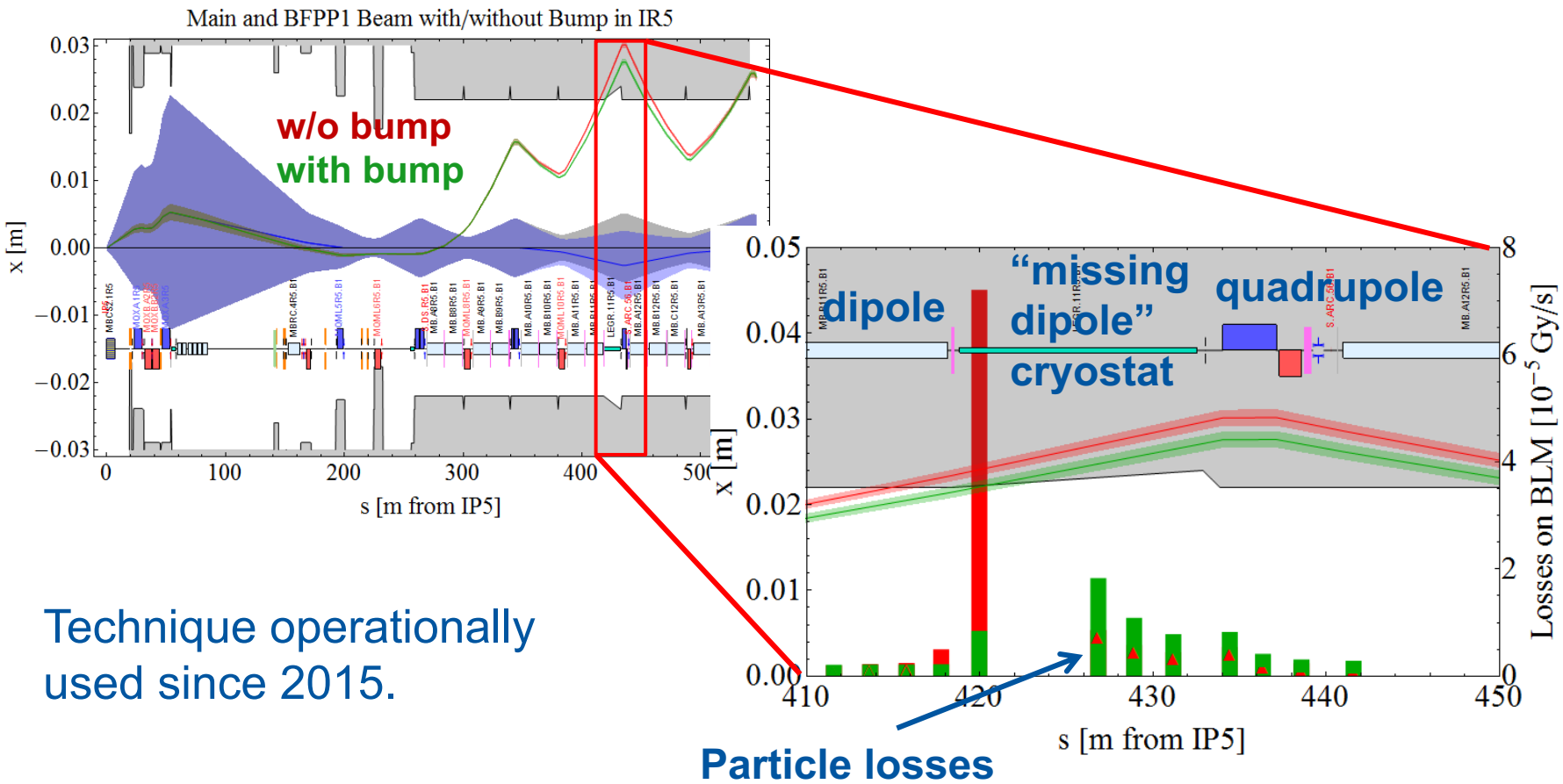


Deposited power exceeds quench limit.

Luminosity limit found at $L \approx 2.3e27 cm^{-2} s^{-1}$ (≅50W into magnet)

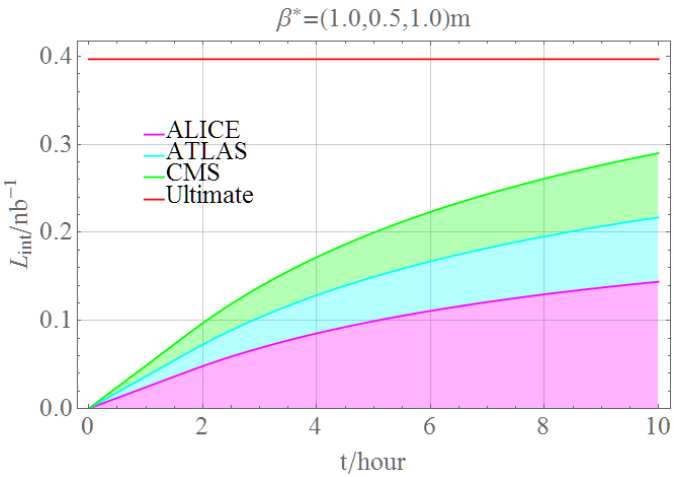
Quench Risk Mitigation with Orbit Bumps

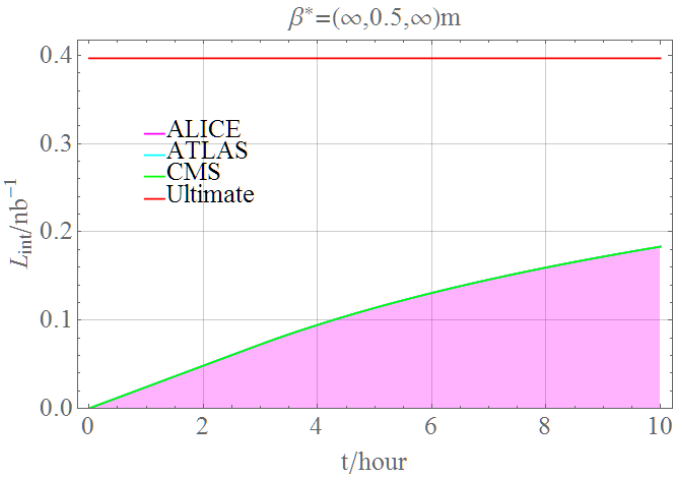
Orbit bumps are used to move the secondary beam losses to a less vulnerable location in order to reduce risk of quench.



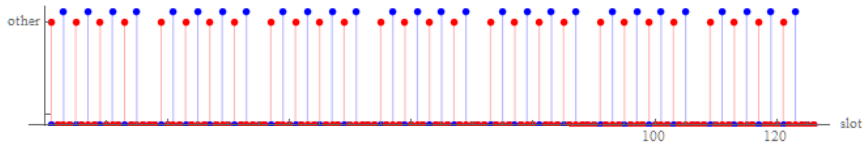
Technique operationally used since 2015.

Integrated Luminosity (Run 3 & 4, sharing options)

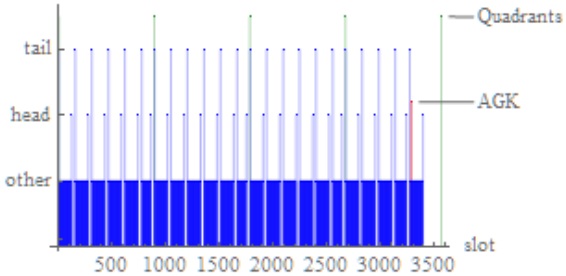




Filling scheme example for HL-LHC

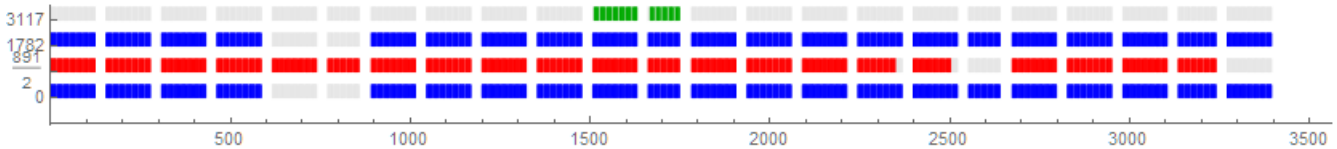


56 bunch SPS train after slip-stacking

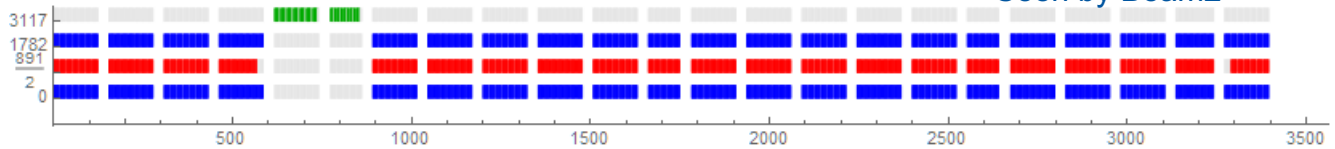


Displace two trains in Beam 2 to make collisions in LHCb

Seen by Beam1``



Seen by Beam2``



23 injections of 56-bunch trains give total of 1232 in each beam.
1136 bunch pairs collide in ATLAS CMS, 1120 in ALICE, 81 in LHCb (longer lifetime).