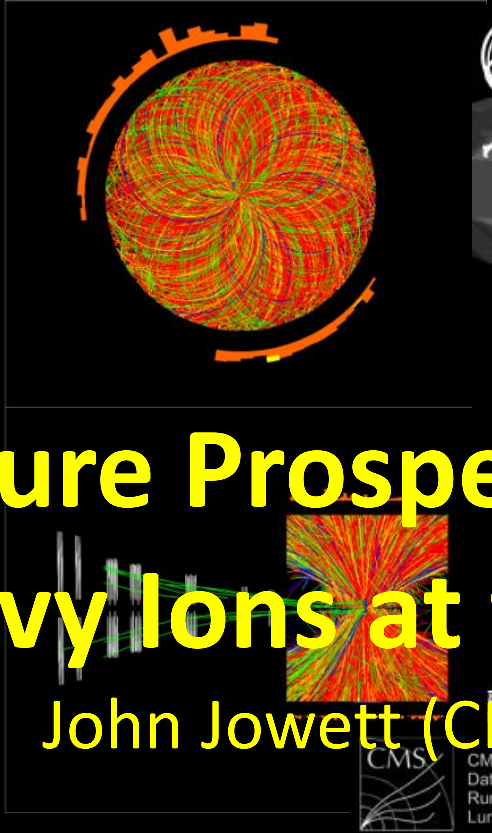
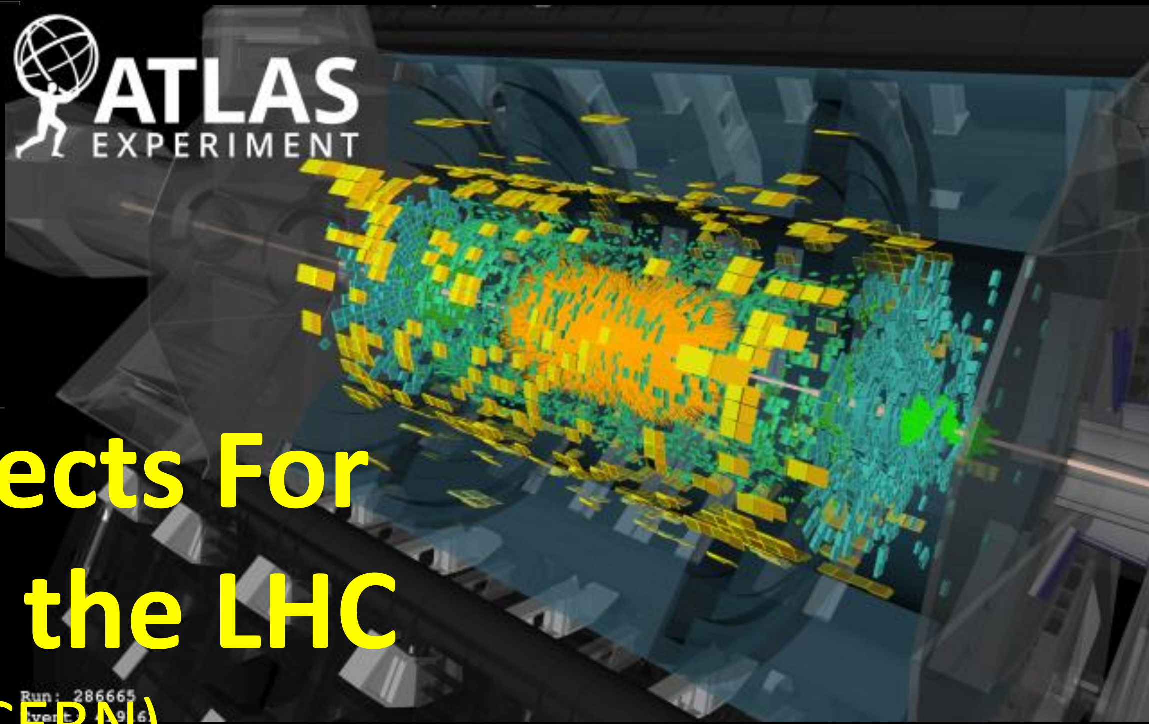
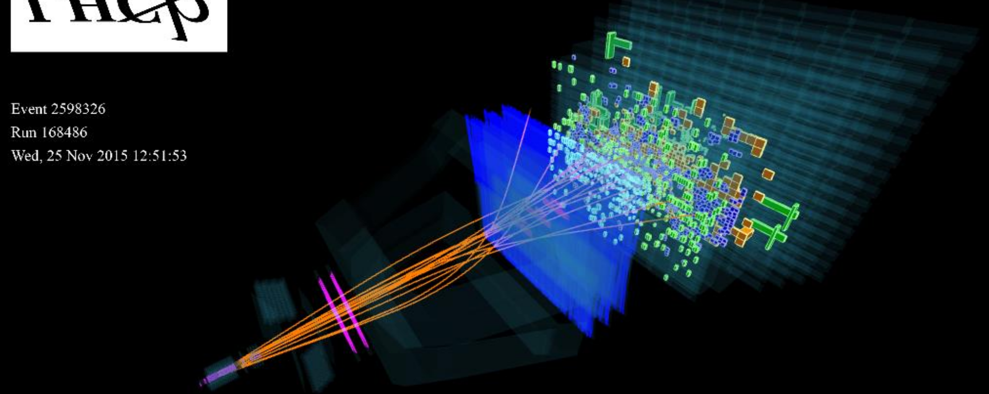
Future Prospects For Heavy Ions at the LHC

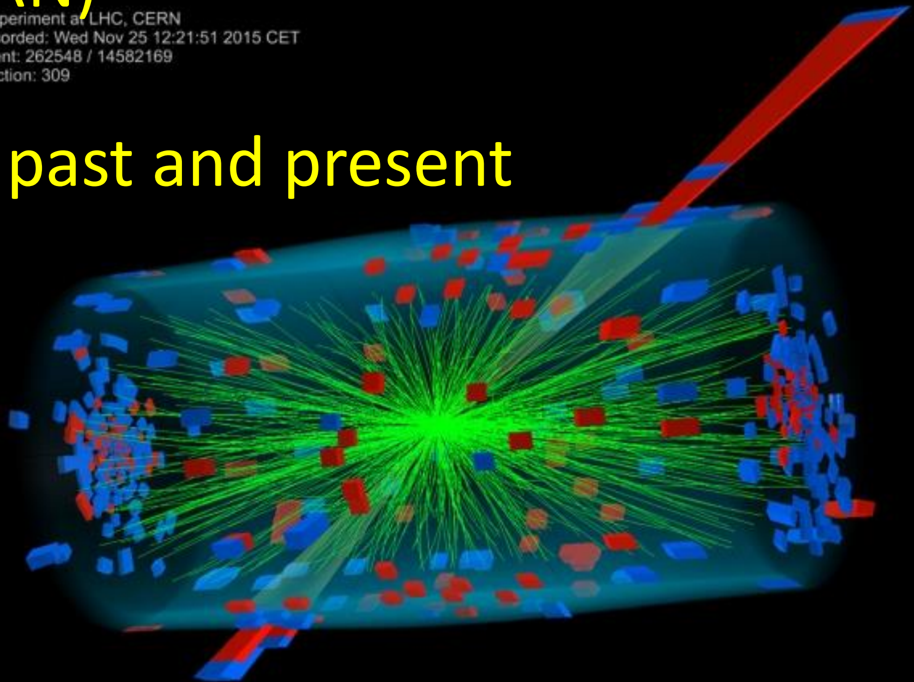
John Jowett (CERN)

On behalf of many colleagues past and present









Summary

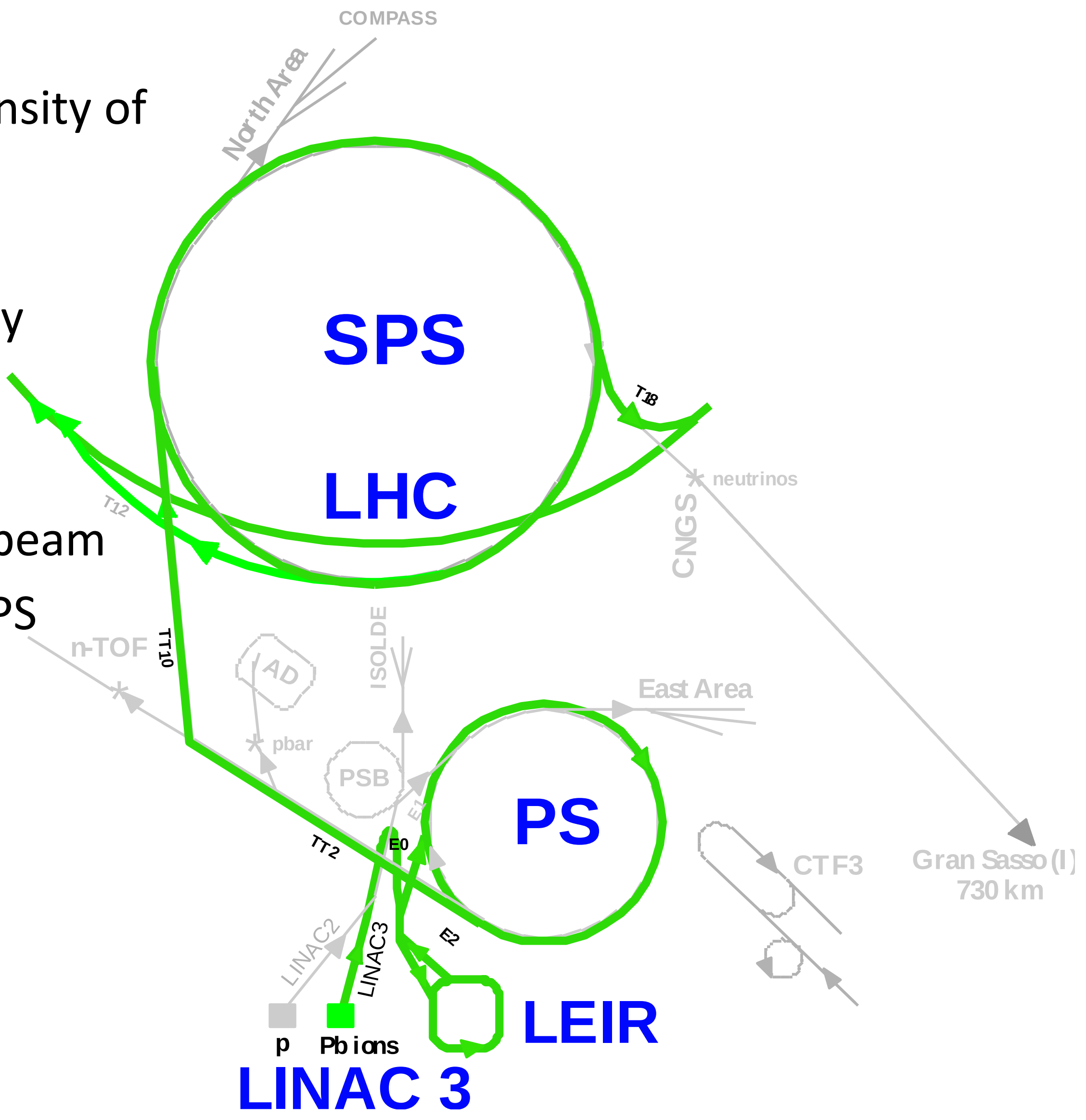
- Since its startup in 2009, the Large Hadron Collider at CERN has spent about 3 months of its operating time providing nucleus-nucleus (Pb-Pb) collisions.
- Peak Pb-Pb luminosity is now over 3 times design and integrated luminosity is expected to attain the initial design goal of 1 nb-1 in the 4th Pb-Pb run in late 2018.
- Following the demonstration of their feasibility in 2012, two one-month runs have been devoted to proton-nucleus (p-Pb) collisions in multiple conditions, with luminosity far beyond expectations.
- Recently, Xe-Xe collisions have also been demonstrated in a short run.
- All the LHC experiments now participate fully in the heavy-ion programme.
- With this experience in hand, strategies to overcome physical performance limits established, and upgrades to the LHC and its injector chain in the pipeline, it is timely to take stock of the prospects and challenges for future performance of the LHC with nuclear beams.

References in these slides

- References to International Particle Accelerator Conferences (IPAC) up to 2017 can be found at
  - http://jacow.org/index.php?n=Main.Proceedings
- References to IPAC2018 (two weeks ago) can be found in the pre-press proceedings
  - http://ipac2018.vrws.de/index.html
- except for the paper on the Xe-Xe run, temporarily available from
  - https://cernbox.cern.ch/index.php/s/3ty2G1M74MyPI9j
- Fairly comprehensive list of references on LHC heavy ion programme to date in IPAC2018 survey talk **TUXGBD2**

LHC Heavy Ion Injector Chain

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



Major injector improvements since 2015

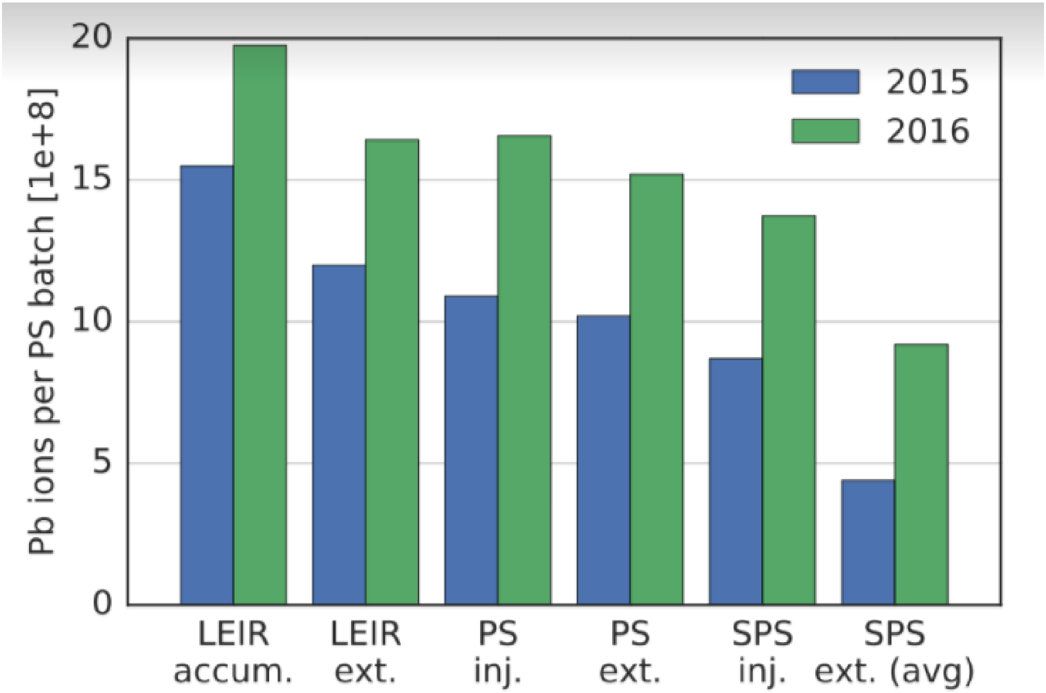


Figure 1: Comparison of operationally achieved intensities through the LHC injector chain in 2015 and 2016.

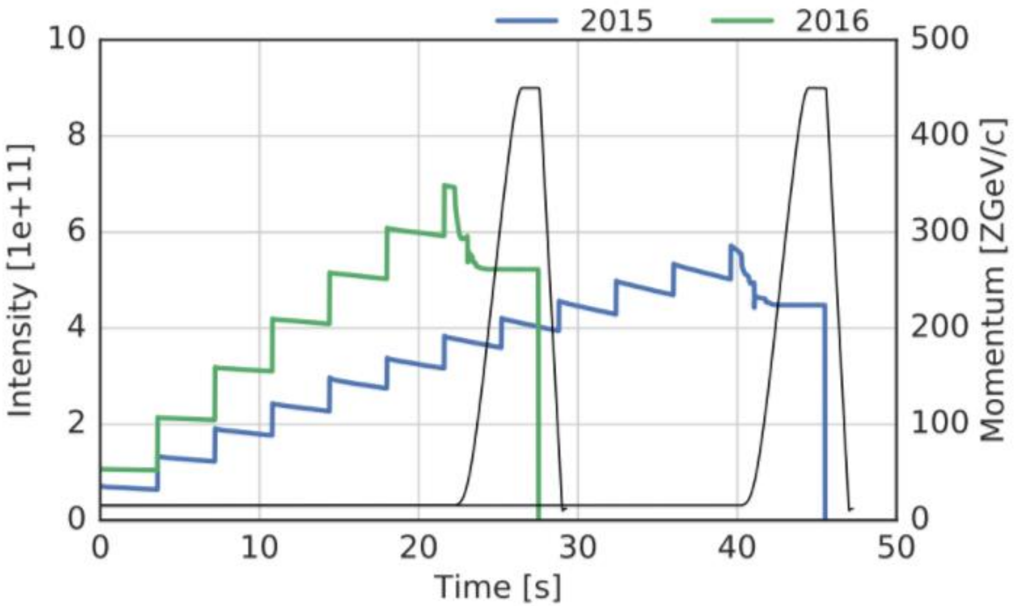


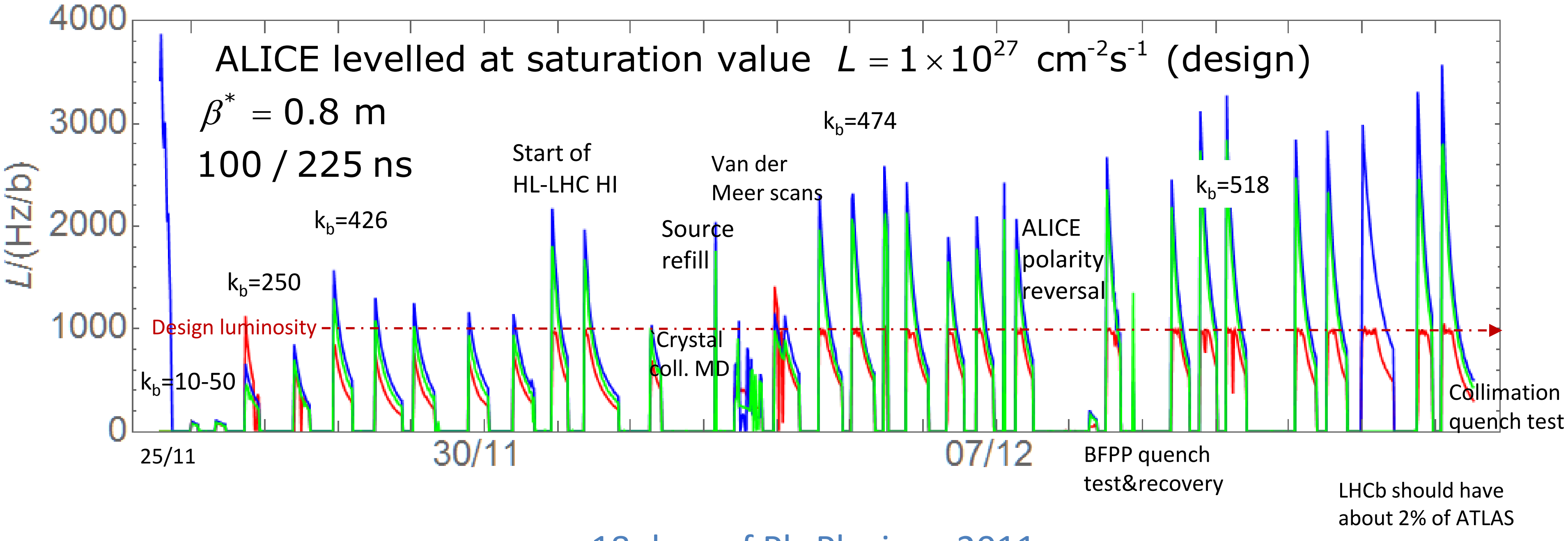
Figure 2: Typical intensity evolution along the operational Pb-ion cycles in 2016 in comparison to 2015.

H. Bartosik *et al.*, "The LHC Injectors Upgrade (LIU) Project at CERN: Ion Injector Chain," *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, paper TUPVA020, pp. 2089–2092.

Improvements in upstream injectors allowed re-introduction of bunch-splitting in PS to stay below single-bunch limit in SPS (which remains the main intensity bottleneck).

NB we will take advantage of these gains in Pb-Pb for the *first time* in 2018.

Pb-Pb peak luminosity at 3×design in 2015



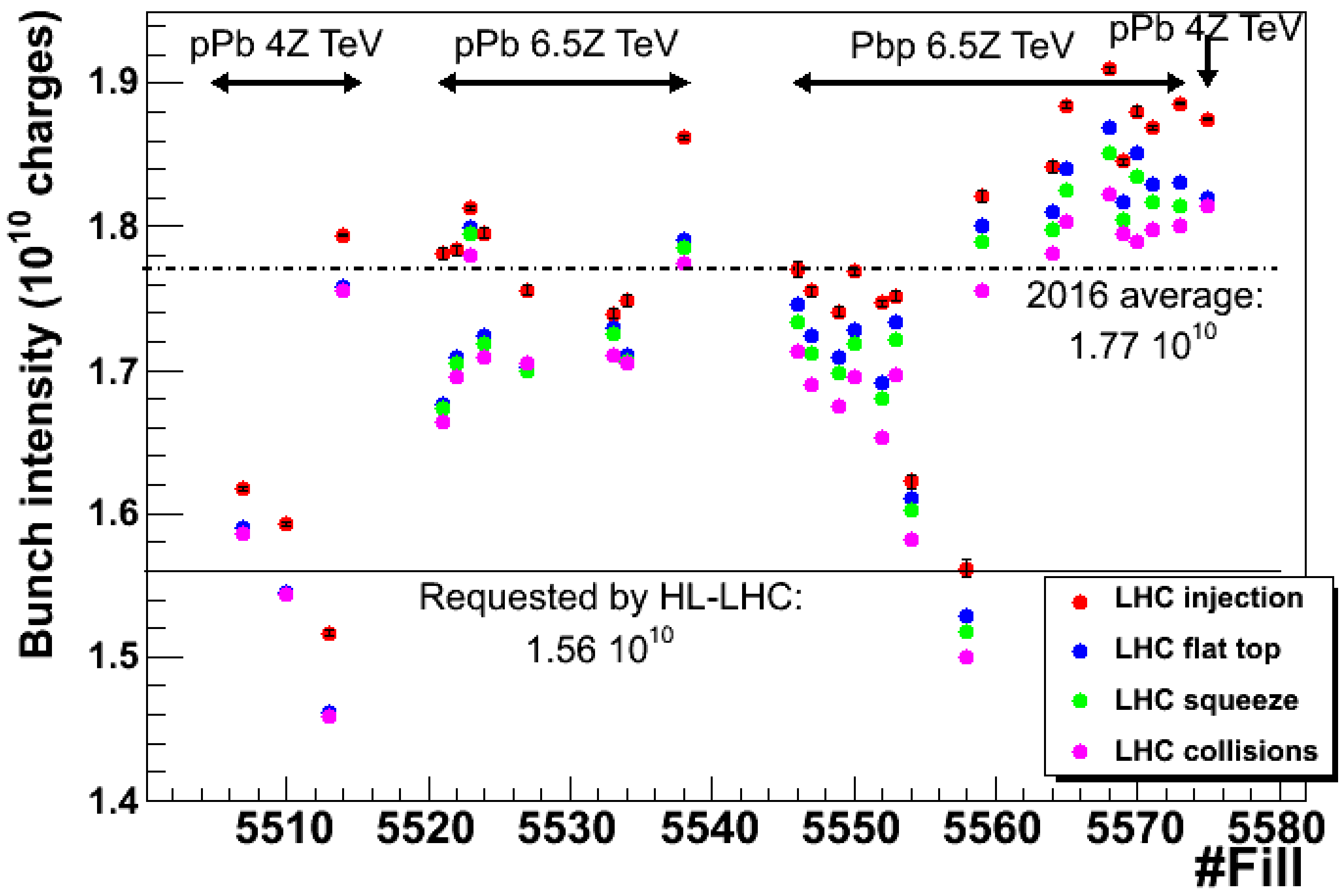
Heavy-ion runs of LHC are very short but very complex.
Experiments have many requests for changes of conditions.

This run was preceded by a week of equivalent energy p-p collisions to provide reference data.

Completely different from classical operation of Tevatron or LHC p-p.

25/11

Pb bunch intensity in LHC during 2016 p-Pb run



R. Alemany, M. Schaumann

UPC processes at the collision point

$$\text{BFPP: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^{+},$$
$$\sigma = 281\text{ b}, \quad \delta = 0.01235$$

$$\text{EMD1: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{207}\text{Pb}^{82+} + n,$$
$$\sigma = 96\text{ b}, \quad \delta = -0.00485$$

$$\text{EMD2: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{206}\text{Pb}^{82+} + 2n,$$
$$\sigma = 29\text{ b}, \quad \delta = -0.00970$$

Strong luminosity burn-off of beam intensity.

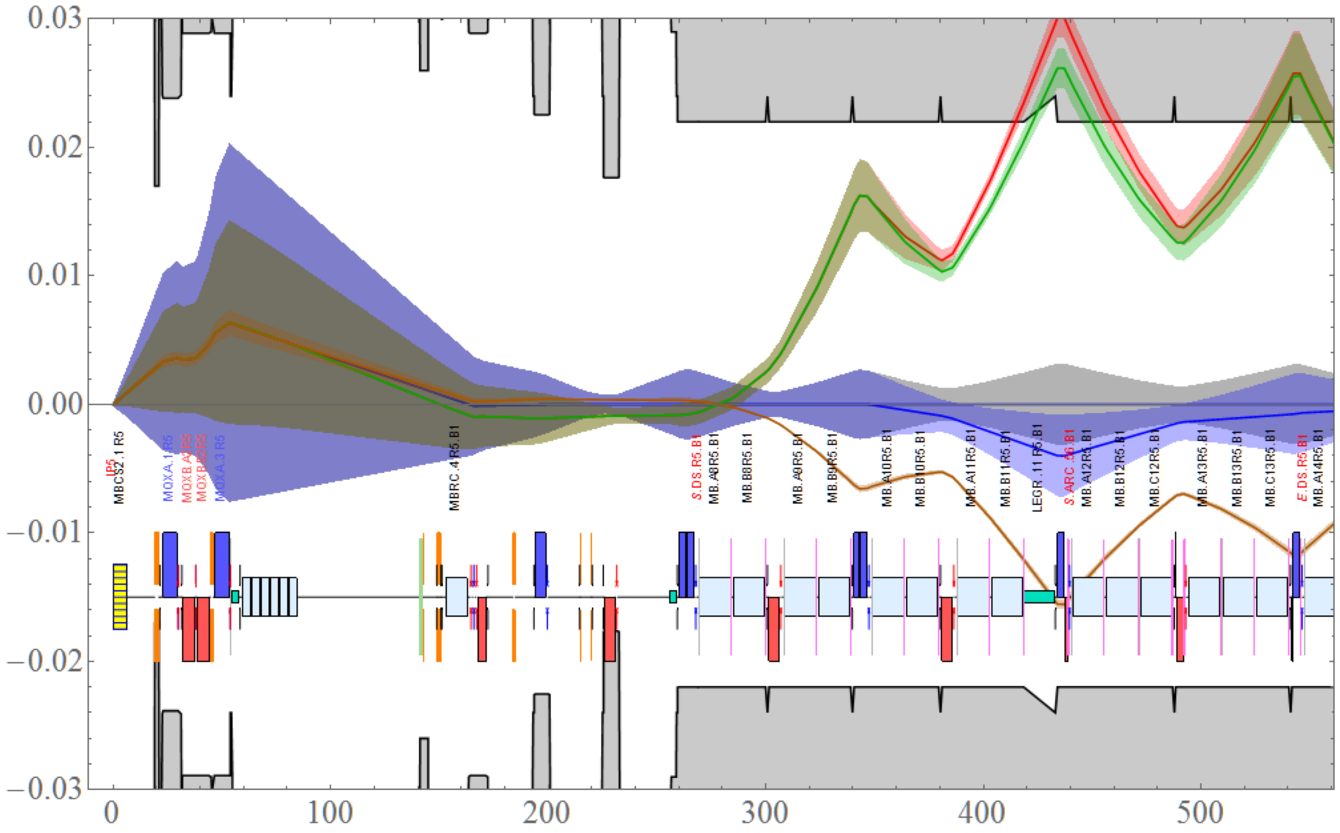
Each of these makes a secondary beam emerging from the IP with rigidity change that may quench bending magnets.

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

Discussed for LHC since Chamonix 2003 … see several references.

Hadronic cross section is 7.7 b (so luminosity debris contains much less power).

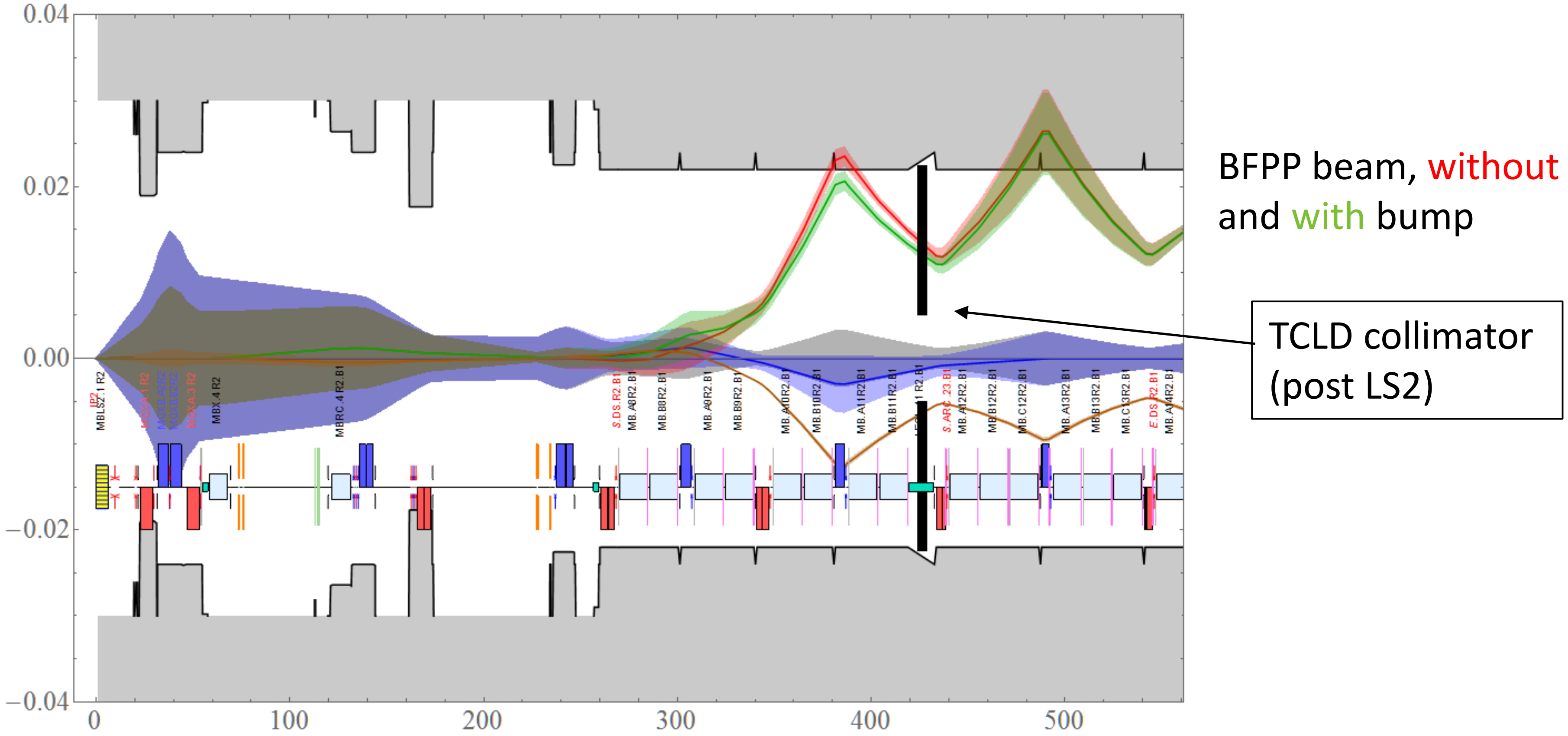
Orbit bumps mitigate BFPP for CMS (or ATLAS)



BFPP beam, without and with bump

- Primary loss location close to the connection cryostat - details slightly optics-dependent (If necessary, bumps should avoid quenches at the start of physics
- Extra BLMs were specifically added for heavy-ion operation in loss region
- Variations of bump possible, uses moderate fraction of available corrector strengths
- We applied bumps like these with ~ 3 mm amplitude around CMS and ATLAS from the beginning of the 2015 run

Orbit bumps alone are not effective for ALICE



- IR2 has different quadrupole polarity and dispersion from IR1/IR5
- Primary BFPP loss location is further upstream from connection cryostat
- Solution is to modify connection cryostat to include a collimator to absorb the BFPP beam – **to be ready for LS2 installation**
- With levelled luminosity in ALICE, quenches were not seen in 2015

Nucleus-nucleus programme status

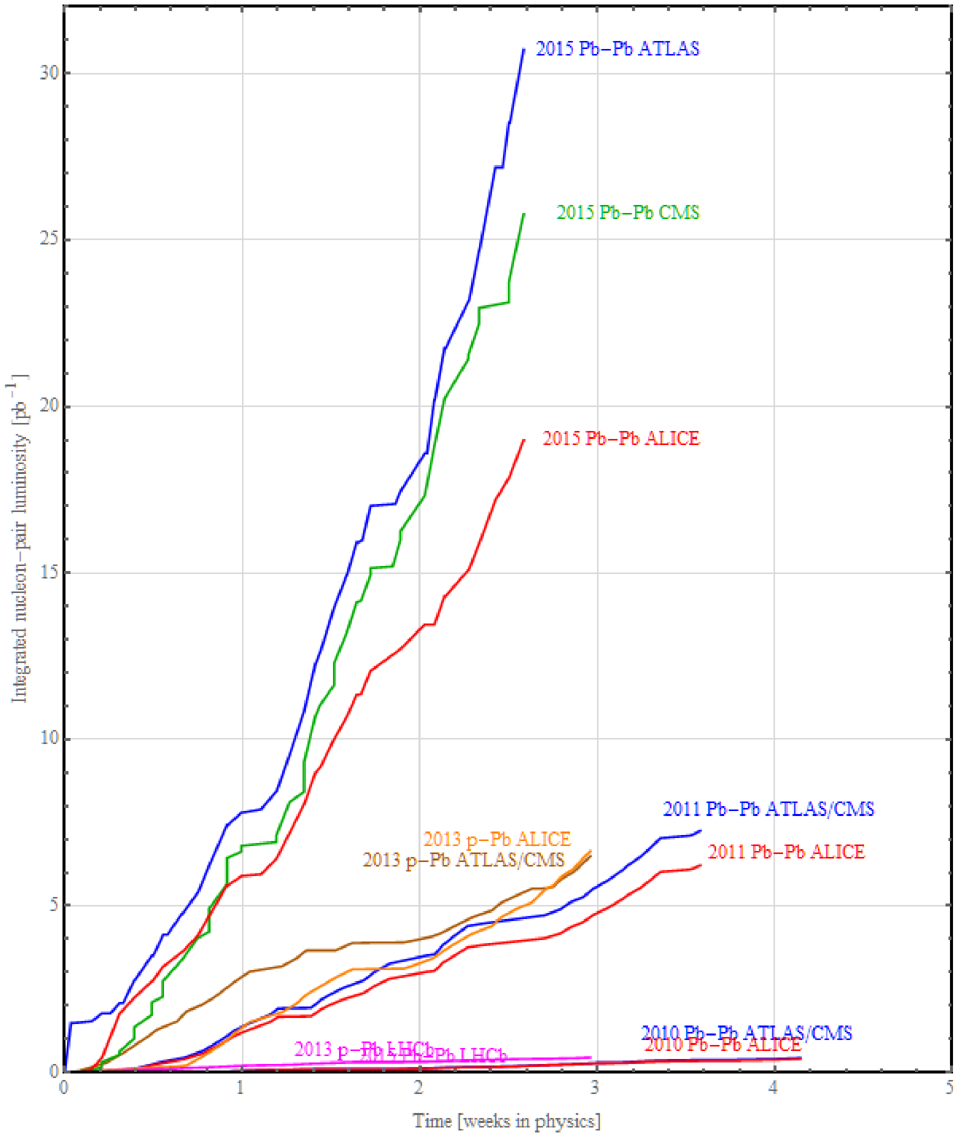
Expect to achieve LHC “first 10-year” baseline Pb-Pb luminosity goal of
1 AA nb^{-1} = 43 NN pb^{-1}
in Run 2 (=2015+2018)

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

Equivalent energy runs

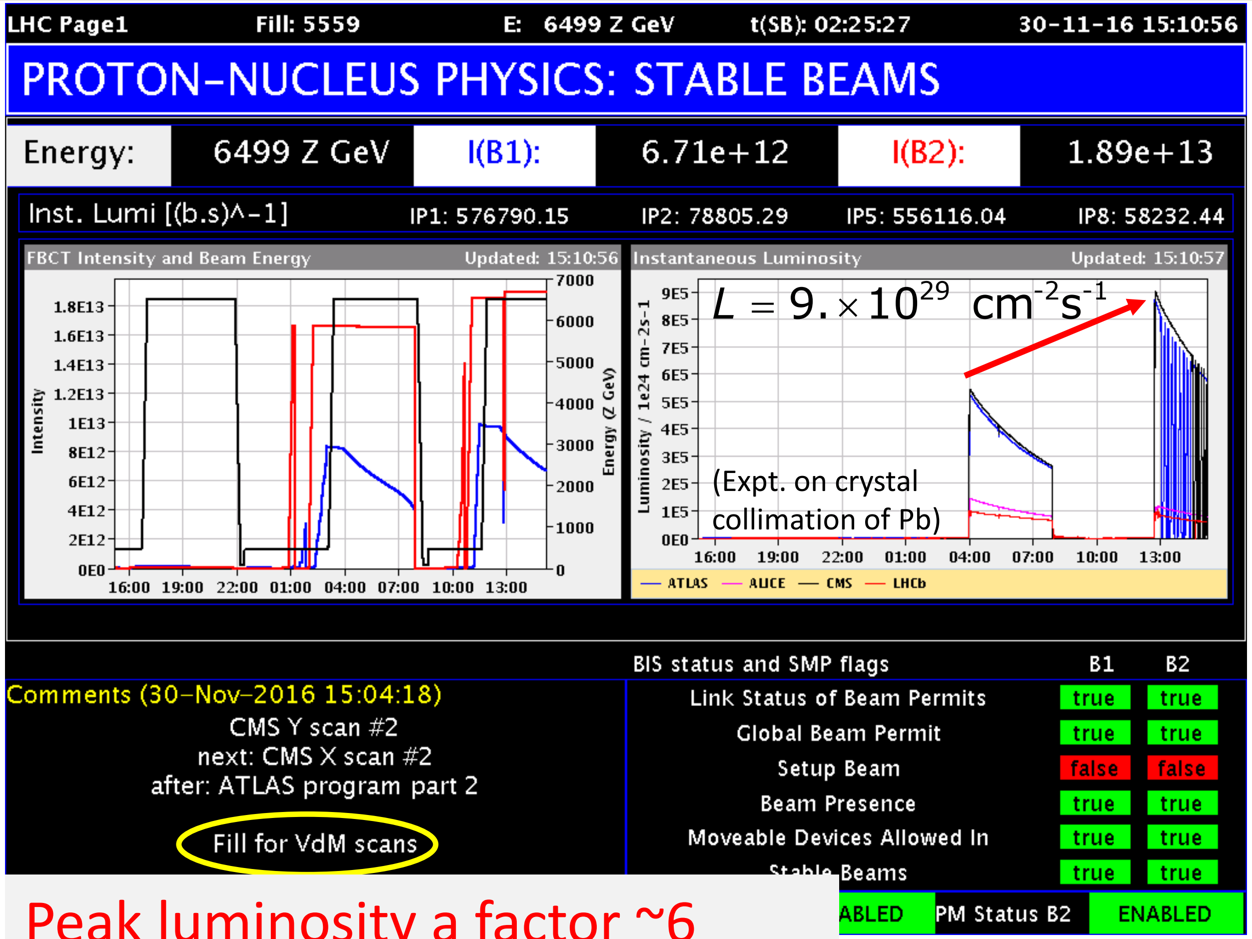
$$\sqrt{s_{NN}} = 5.02\ \text{TeV}\quad (\sqrt{s}=1.045\ \text{PeV})$$

$$\Rightarrow E_b = \begin{cases} 6.37Z\ \text{TeV} & \text{in Pb-Pb} \\ 4\ Z\ \text{TeV} & \text{in p-Pb} \\ 2.51\ \text{TeV} & \text{in p-p} \end{cases}$$



2012 pilot p-Pb run not shown

Record Pb-p luminosity in ATLAS/CMS at 8.16 TeV



Peak luminosity a factor ~6 beyond original "design" value
(J. Phys. G 39 (2012) 015010)

Could have gone higher still by further increase of p intensity but limited at present by Pb beam luminosity debris in magnets of Sector 12.

Common BPMs and moving encounters had constrained charge of p and Pb bunches to be similar.

Increase in p intensity to ~3×10^{10}/bunch
enabled by new synchronous orbit mode of beam position monitors (R. Alemany, J. Wenninger, beam instrumentation group …)

Pb intensity to ~2.1×10^{8}/bunch

25% increase in ATLAS/CMS from filling scheme

IPAC2017 TUPVA014

Goals of 2016 p-Pb run surpassed

$\sqrt{s_{NN}}$	Experiments	Primary goal	Achieved	Additional achieved
5 TeV p-Pb (Beam energy 4 Z TeV)	ALICE (priority)	700 M min bias events	**780 M**	
	ATLAS, CMS			>0.4 /nb min bias
	LHCb			SMOG p-He etc
8 TeV p-Pb *or* Pb-p (Beam energy 6.5 Z TeV)	ATLAS, CMS	100 /nb	**194,183 /nb**	
8 TeV p-Pb	ALICE, LHCb	10 /nb	**14,13 /nb**	
	LHCf	9-12 h @ 10^{28} cm^{-2}s^{-1}	**9.5 h** @ 10^{28} cm^{-2}s^{-1}	Min bias ATLAS, CMS, ALICE
8 TeV Pb-p	ALICE, LHCb	10 /nb	**25,19 /nb**	

Note: ALICE and LHCb are asymmetric experiments, with different coverage according to beam direction.

Reminder: first 1 month p-Pb/Pb-p run at 5 TeV in 2013 gave 31/nb to ALICE, ATLAS, CMS and 2/nb to LHCb.

Proton-nucleus programme status

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

Complex 2016 run plan determined after Chamonix 2016:

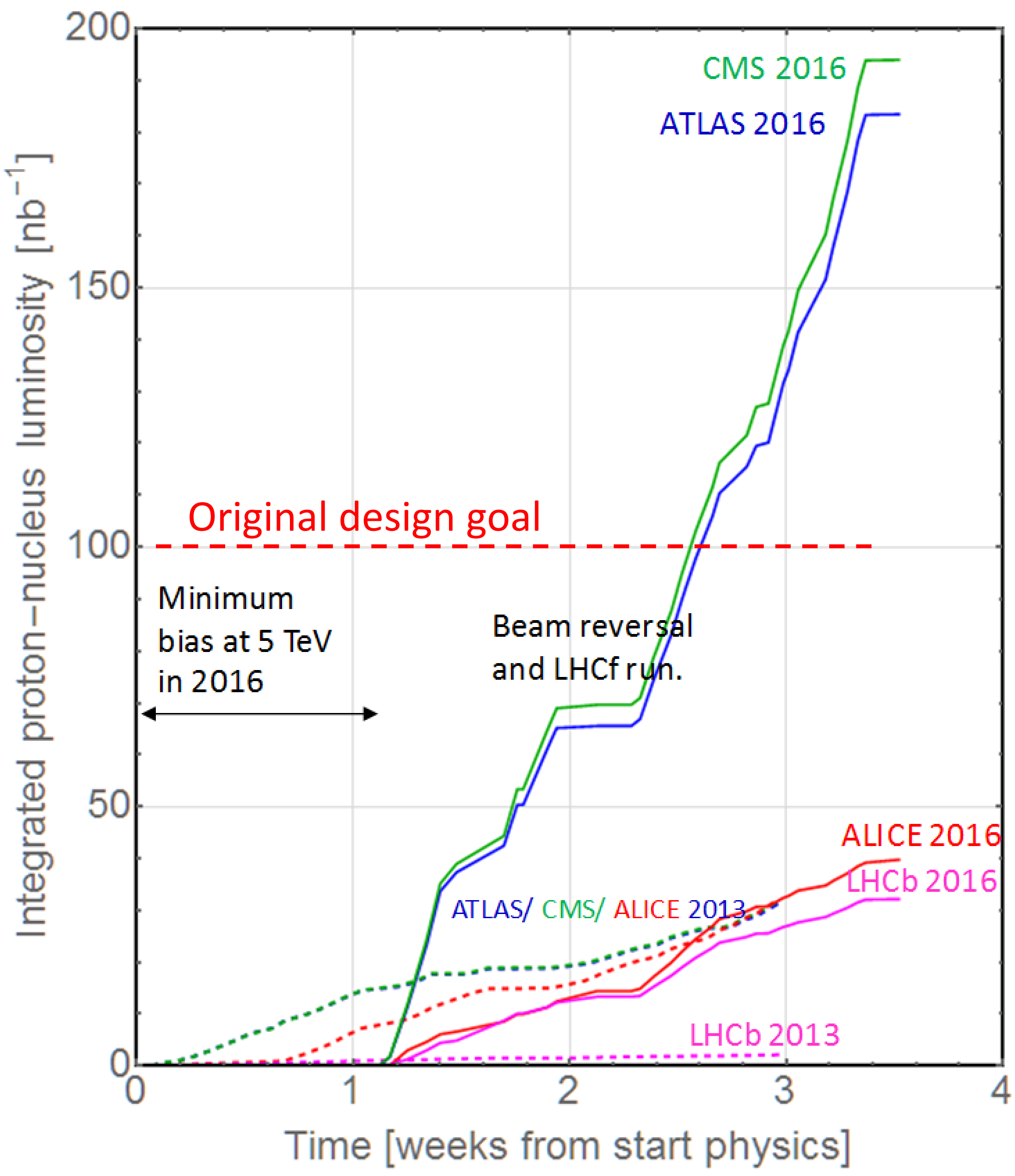
Minimum bias run at 4 Z TeV mainly for ALICE

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

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

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

Many filling schemes used for luminosity sharing.



FUTURE PERFORMANCE (HL-LHC)

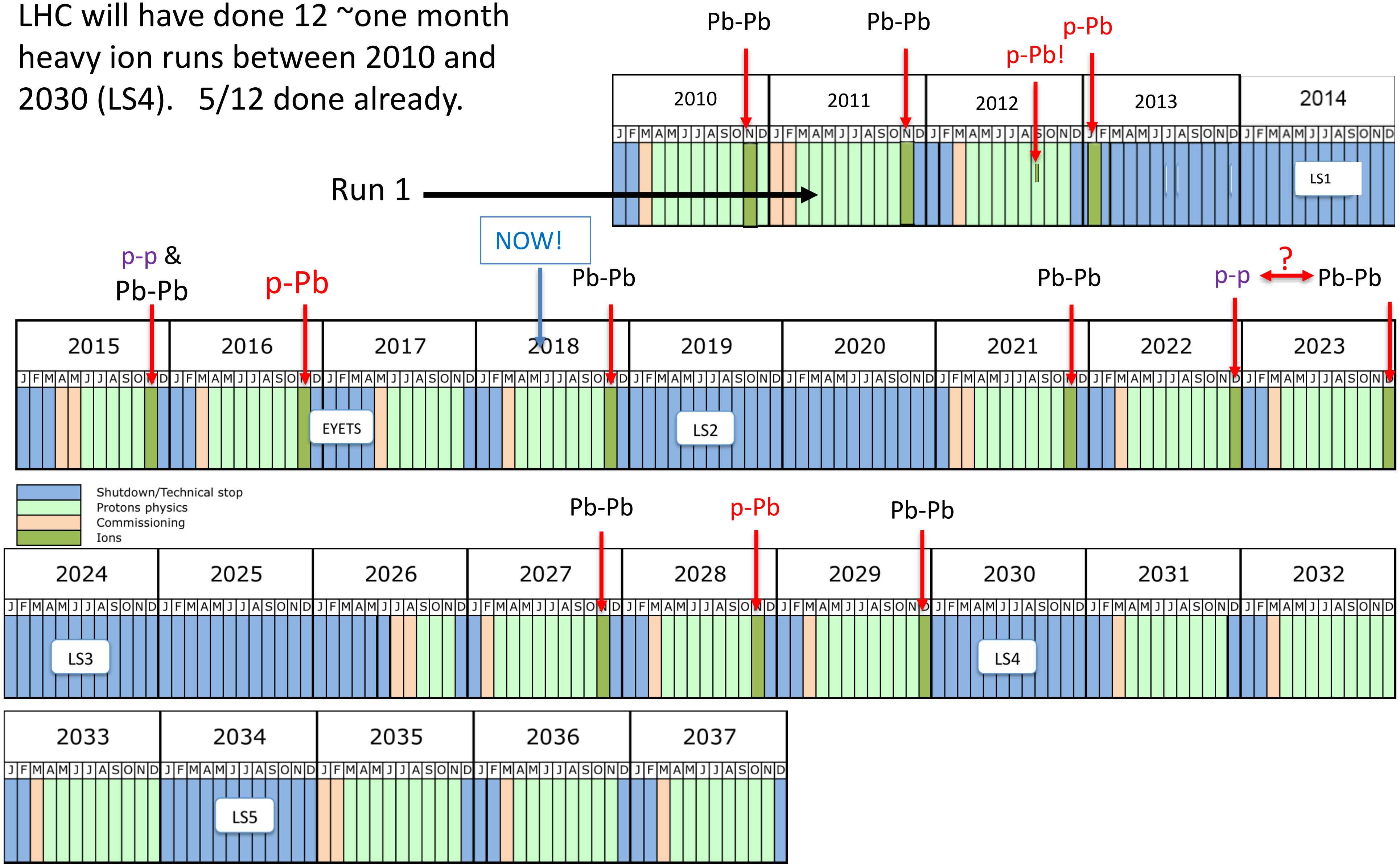
For more details on the HL-LHC projections see HL-HE-LHC workshop 30/10/2017

https://indico.cern.ch/event/647676/contributions/2721132/

and other recent talks.

LHC heavy-ion runs, past & baseline future
+ species choices according to ALICE 2012 LoI (under review in HL-LHC workshop) `

LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). 5/12 done already.



LIU baseline (Jan 2017) parameters at start of collisions

- Simplified scenario -
  - See injectors upgrade paper H. Bartosik et al, IPAC2017
  - All bunches are equal (consider single bunch pair simulation)
  - Initial bunch intensity (start of stable beams)

$$\langle N_b \rangle = 1.8 \times 10^8 \quad = 95\% \;\times\; 1.9 \times 10^8 \text{ injected} \quad (\text{c.f. design } 0.7 \times 10^8)$$

  - Initial emittance (start of stable beams)

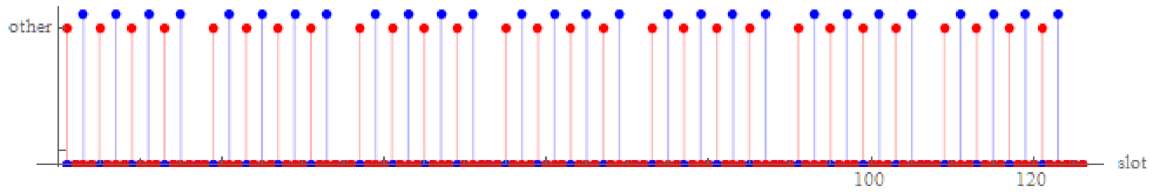
$$\varepsilon_{xn} = 1.65 \times 10^{-6}\text{m} \quad (> \text{design, some blow up from injected } 1.5 \times 10^{-6}\text{m})$$

  - Crossing angles 170, 100, 170 μrad, operation at 7*Z* TeV
  - Other bunch parameters as Design Report nominal
  - Three luminosity-sharing scenarios, to illustrate possibilities (equal β* scenario is nominal!):

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

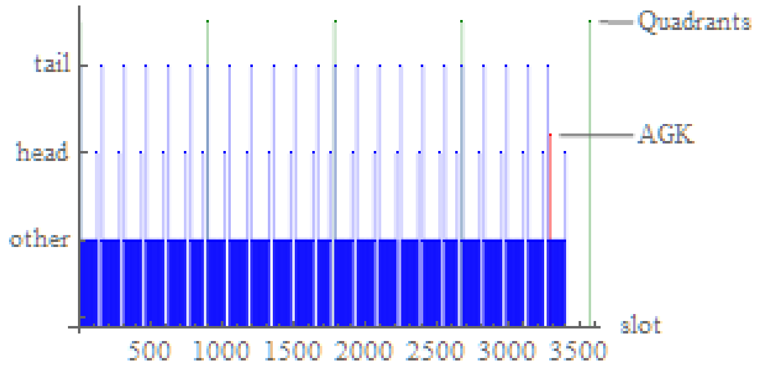
  - Some collisions in LHCb (not shown in detail)

Filling scheme with some collisions in LHCb

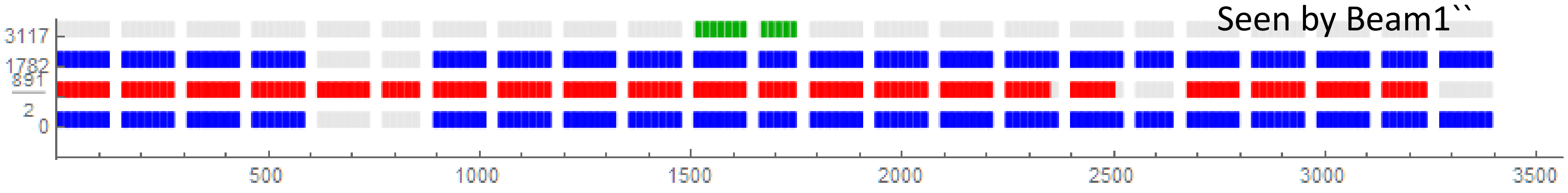


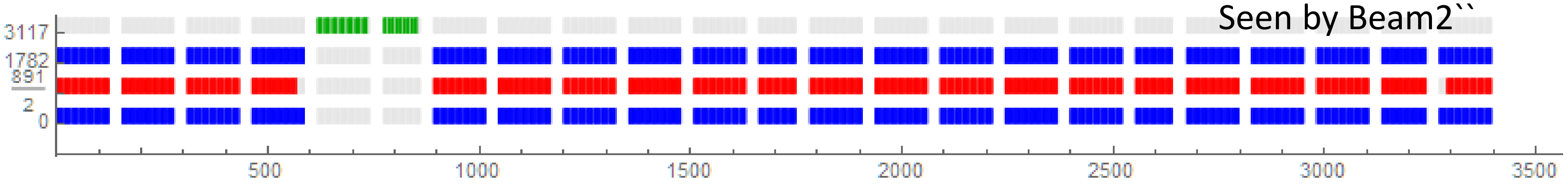
56 bunch SPS train after slip-stacking

Slip-stacking in SPS is somewhat uncertain, hope to implement in 2021 but 75 ns scheme has been proposed as a fallback (although we may use it already in 2018).



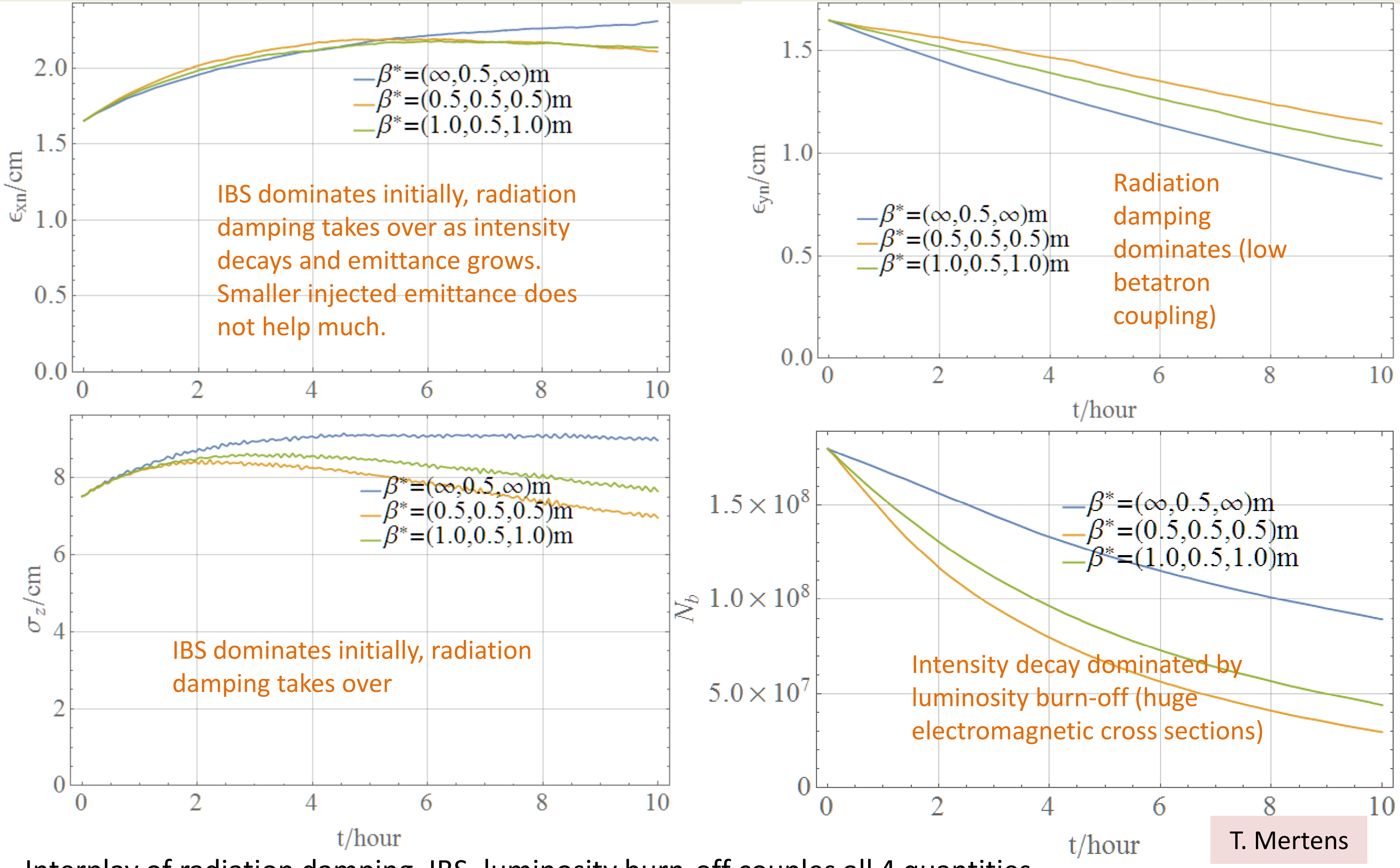
Displace two trains in Beam 2 to make collisions in LHCb (assumption while waiting for specification).





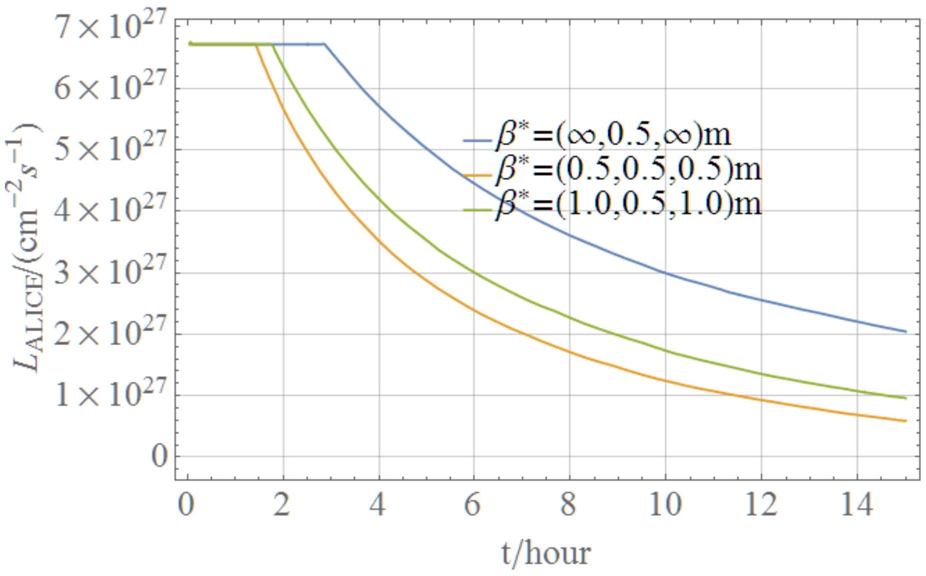
23 injections of 56-bunch trains give total of 1232 in each beam.
1136 bunch pairs collide in ATLAS CMS, 1120 in ALICE, 81 in LHCb (longer lifetime).

CTE Simulation of (most typical) colliding bunch pair

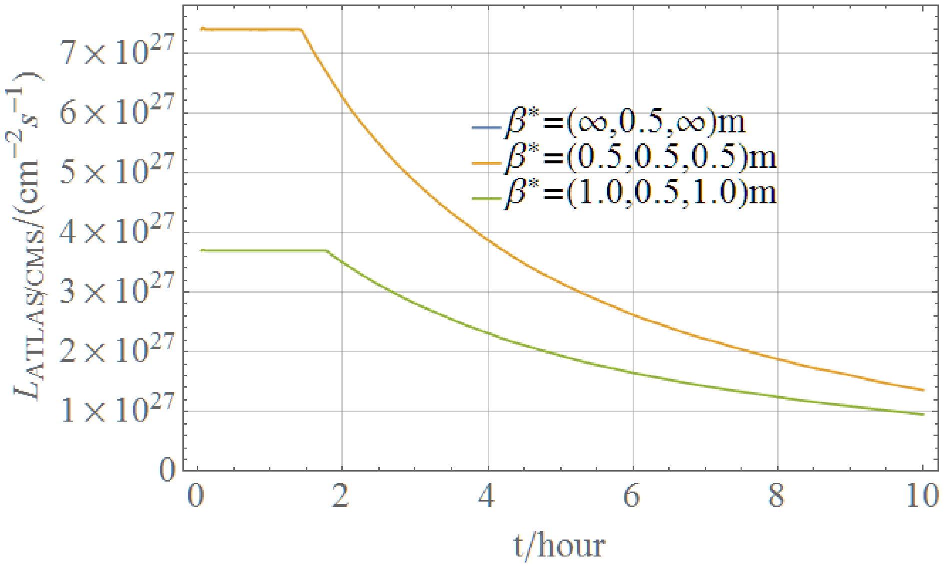


Interplay of radiation damping, IBS, luminosity burn-off couples all 4 quantities.
Different evolution according to luminosity-sharing scenario.
(Does not include additional emittance growth usually seen in operation.)

Experiments' luminosities in an ideal (prolonged) fill

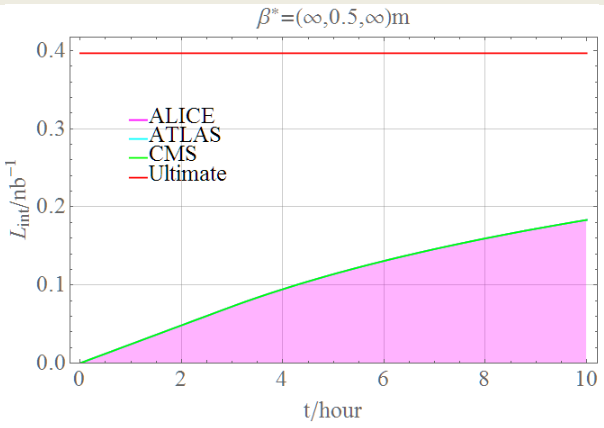


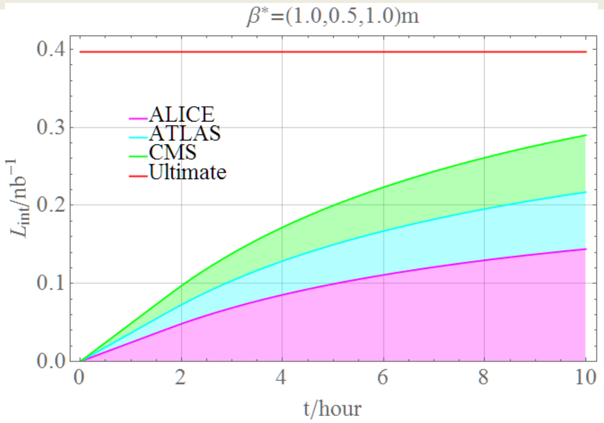
ALICE, levelling at maximum acceptable (rates around 50 kHz), assuming 1100 bunches colliding

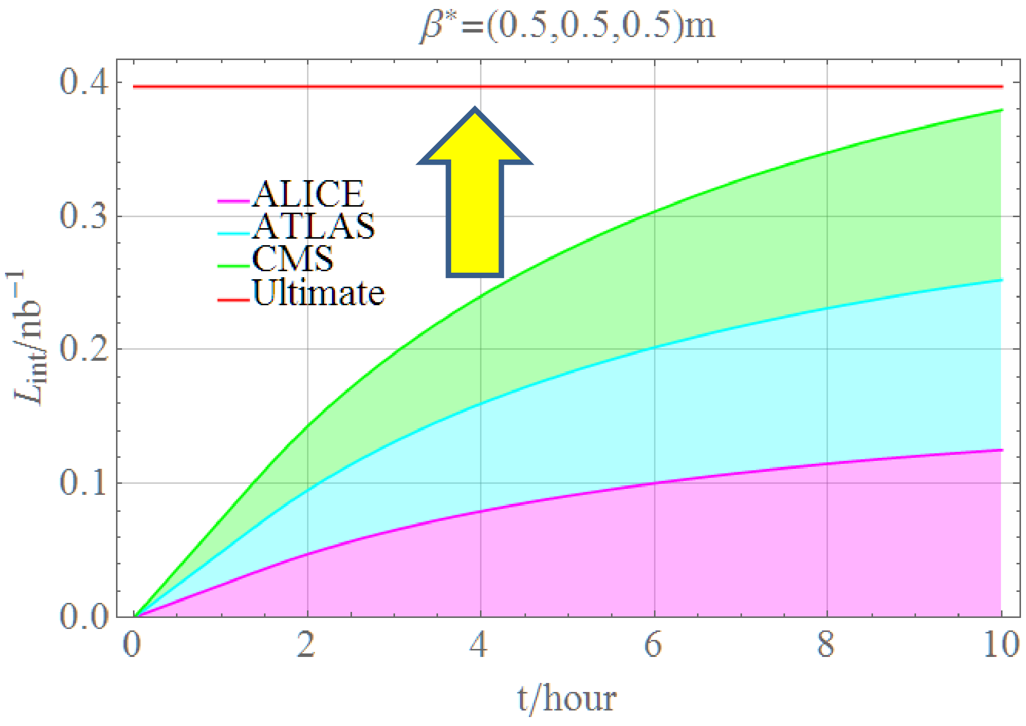


ATLAS or CMS, *assumed* levelling at slightly higher levels than ALICE

Integrated luminosity in prolonged fills







Ultimate luminosity to share

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

Fraction obtained is the luminous efficiency.

Pb-Pb parameters from 2010 to HL-LHC upgrade

Table 1: Representative simplified beam parameters at the start of the highest luminosity physics fills, in conditions that lasted for > 5 days, in each annual Pb-Pb and p–Pb run [12–16]. The original design values for Pb–Pb [4] and p-Pb [17] and future upgrade Pb–Pb goals are also shown (in these columns the integrated luminosity goal is to be attained over the 4 P–Pb runs in the 10-year periods before and after 2020). Peak and integrated luminosities are averages for ATLAS and CMS (ALICE being levelled). The smaller luminosities delivered to LHCb from 2013–2016 and in the minimum-bias part of the run in 2016 are not shown. Emittance and bunch length are RMS values. Single bunch parameters for p-Pb or Pb-p runs are generally for Pb. The series of runs with $\sqrt{s_{\rm NN}}$ = 5.02 TeV also included p–p reference runs, not shown here. Design and record achieved nucleon-pair luminosities are boxed for easy comparison. The upgrade value is reduced by a factor ≃ 3 from its potential value by levelling.

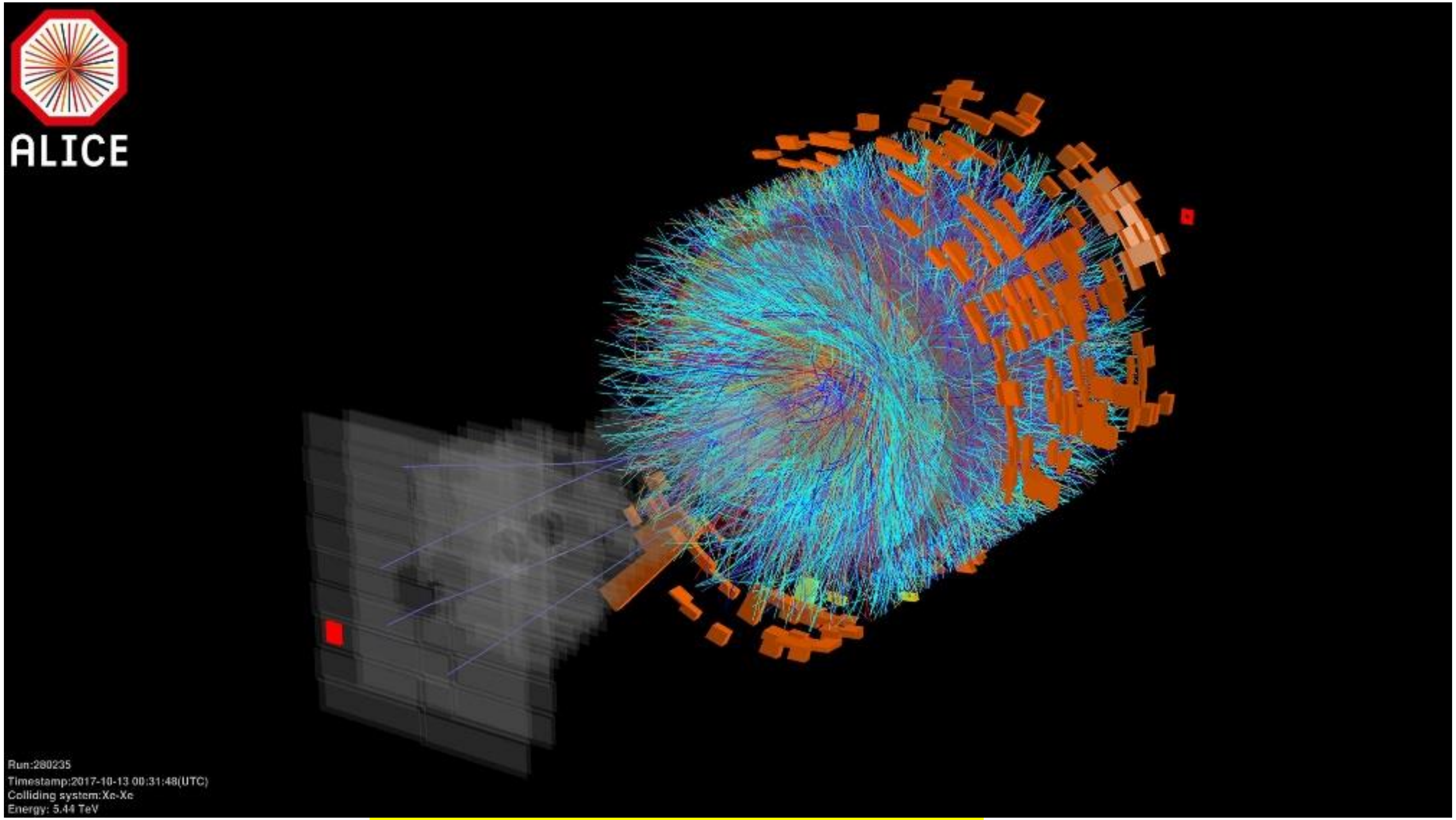
Quantity	"design"		achieved					upgrade
Year	(2004)	(2011)	2010	2011	2012–13	2015	2016	≥2021
Weeks in physics	-	-	4	3.5	3	2.5	1, 2	-
Fill no.			1541	2351	3544	4720	5562	-
Species	Pb–Pb	p–Pb	Pb–Pb	Pb–Pb	p–Pb	Pb–Pb	p–Pb	Pb–Pb
Beam energy E[Z TeV]	7		3.5		4	6.37	4,6.5	7
Pb beam energy E [ATeV]	2.76		1.38		1.58	2.51	1.58,2.56	2.76
Collision energy $\sqrt{s_{\rm NN}}$ [TeV]	5.52		2.51		**5.02**	**5.02**	**5.02**,8.16	5.52
Bunch intensity N_b [10^8]	0.7		1.22	1.07	1.2	2.0	2.1	1.8
No, of bunches k_b	592		137	338	358	518	540	1232
Pb norm. emittance ϵ_N [μm]	1.5		2.	2.0	2.	2.1	1.6	1.65
Pb bunch length σ_z m	0.08				0.07–0.1			0.08
β^* [m]	0.5		3.5	1.0	0.8	0.8	10, 0.6	0.5
Pb stored energy MJ/beam	3.8	2.3	0.65	1.9	2.77	8.6	9.7	21
Peak lumi. $L_{\rm AA}$ [10^{27}cm^{-2}s^{-1}]	1	150	0.03	0.5	116	3.6	850	6
NN lumi. $L_{\rm NN}$ [10^{30}cm^{-2}s^{-1}]	43	31	1.3	22.	24	156	177	260
Integrated lumi./expt. [μb^{-1}]	1000	10^5	9	160	32000	650	1.9×10^5	10^4
Int. NN lumi./expt. [nb^{-1}]	43000	21000	380	6700	6650	28000	40000	4.3×10^5

Levelled,
could be ~15.

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

TUXGBD2
+ its bibliography

Xe-Xe collisions in LHC, 13 October 2017



Future interest in lighter species?

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

Duration of Xe run

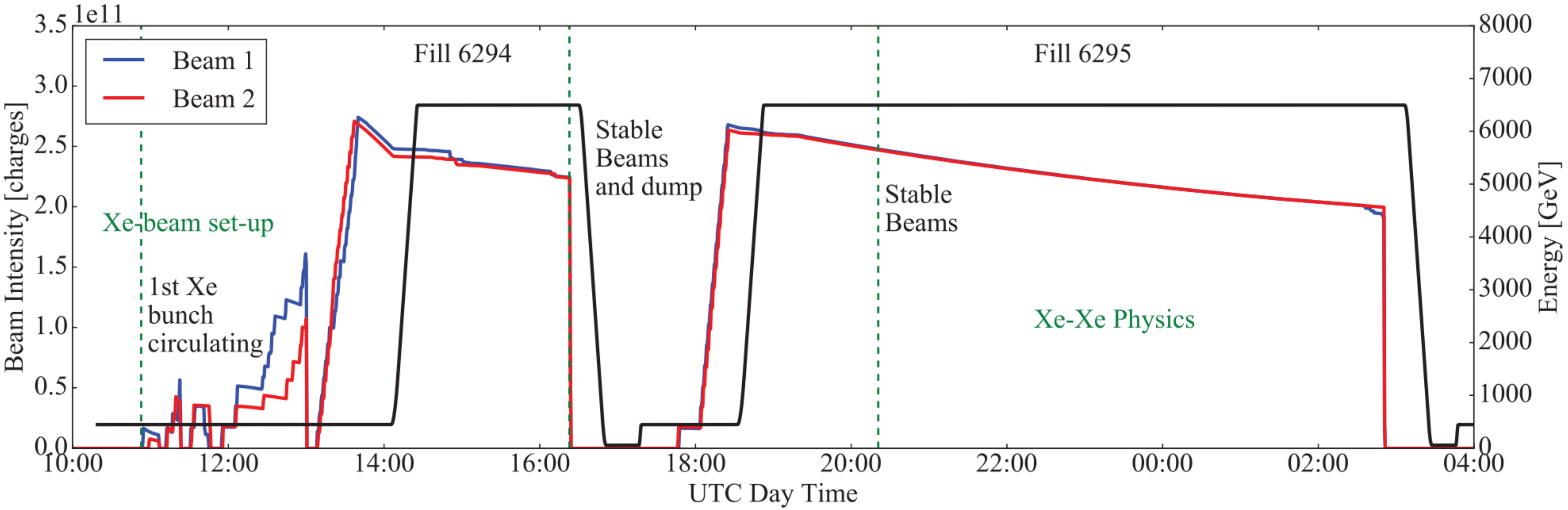


Figure 1: Evolution of the beam intensity and energy throughout the Xe–Xe run.

Beam intensity roughly as expected.

See discussion of cross-sections later.

Table 1: Beam parameters at start of Stable Beams, fill 6295. Sets of three values correspond to the interaction points of ATLAS/CMS, ALICE, LHCb. Luminosity values are calculated from beam parameters.

Parameter	**Fill 6295**
Beam energy [Z TeV]	6.5
No. of bunches colliding	(8, 16, 8)
β^* [m]	(0.3, 10, 3)
Bunch intensity [10^8 ions]	2.87 ± 0.14
Normalized emittance (H, V) [μm]	(~1.5 / ~1.0)
Bunch length [cm]	9.1 ± 0.2
Luminosity [10^{27} cm^{-2}s^{-1}]	(0.28, 0.03, 0.04)
Rad. damping time (τ_z, $\tau_{x,y}$) [h]	(9.5, 18.9)
IBS growth time (τ_z, τ_x) [h]	(6.7, 13.1)

Xe lifetime analysis

Table 2: Beam-beam equivalence classes with their respective colour code used throughout the paper. In addition, the sum of inverse-β^* and the intensity lifetimes during Stable Beams of fill 6295 are displayed. The intensity lifetime of the non-colliding class (class 0) is obtained via linear fit of the loss rates (see Fig. 4).

Class	IPs	$\sum_i \frac{1}{\beta_i^*}$ [m^{-1}]	τ [h]
0	-	0	87.8 ± 5.9
1 •	2	0.10	79.2 ± 4.6
2 •	2/8	0.43	72.1 ± 3.8
3 •	1/2/5	6.77	17.5 ± 0.8
4 •	1/2/5/8	7.10	16.3 ± 1.1

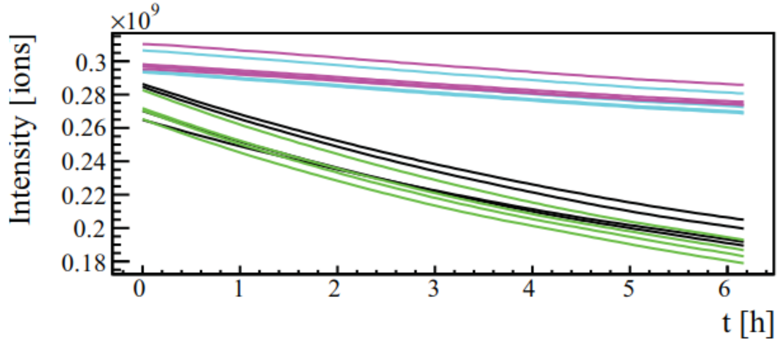


Figure 3: Bunch-intensity evolution of Beam 1 during fill 6295 after declaration of Stable Beams. The colour of each class is listed in Table 2.

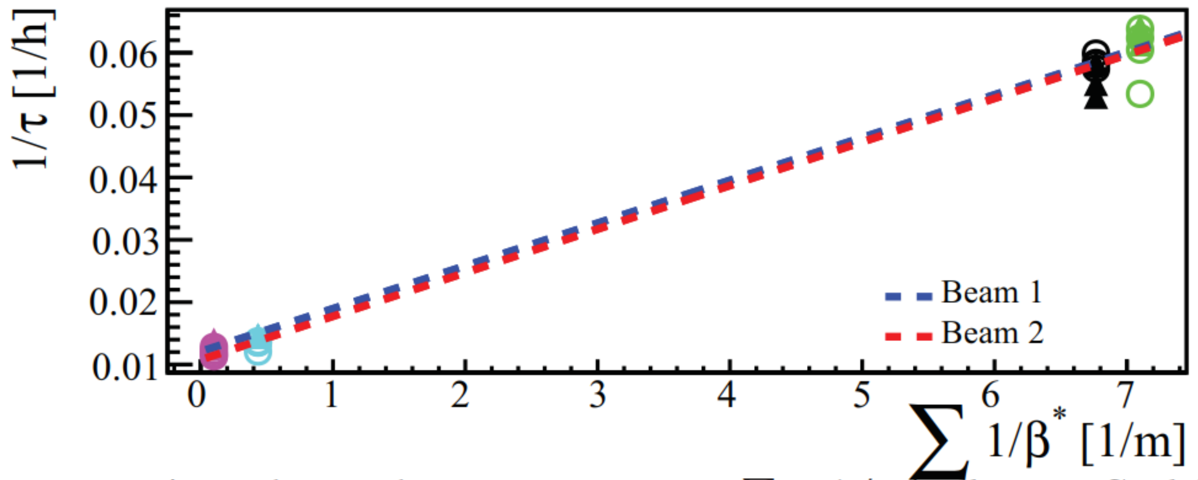


Figure 4: Relative loss rates versus $\sum_{IP} 1/\beta^*_{IP}$ during Stable Beams of fill 6295. Triangles indicate Beam 1 and circles Beam 2. The dashed lines are linear fits to obtain the non-colliding intensity lifetime.

Shows that beam intensity decay was dominated by luminosity burn-off (other effects on 100 h time scale).
Luminosity lifetime ~agrees with p=0.75 value (later in this talk).

Analysis by Marc Jebramcik, Michaela Schaumann. See IPAC2018 paper.

Bunch intensity at SPS extraction for various species

- Experience with other species in LHC injectors for fixed target
  - Less stringent requirements on beam quality (emittance)

Postulate simple form for bunch intensity dependence on species charge only

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

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

Use this highly simplified scaling to project future luminosity performance as a function of *p.*
Assume that other quantities (like geometric beam size), filling scheme, other loss rates, etc, are equal.

Treat results only as tentative and indicative only!

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

UPC cross sections determining intensity burn-off

$$\frac{dN}{dt} = -(\sigma_{\text{had}} + \sigma_{\text{EMD}} + \sigma_{\text{BFPP}})L - \frac{N}{\tau_{\text{other}}}, \qquad L = \frac{N^2 f_0}{4\pi\beta^* \varepsilon_{xn} k_c}$$

$$\sigma_{\text{EMD1}} \approx (3.42\ \mu b)\frac{(A-Z)Z^3}{A^{2/3}}\log(2\gamma^2 - 1),$$

$$\sigma_{\text{EMD}} \approx 1.95\ \sigma_{\text{EMD1}} \quad \text{(total for all EMD channels)}$$

$$\sigma_{\text{BFPP}} \approx Z^7(A\log(2\gamma^2 - 1) + B)$$

List of species are examples that are of interest.

Some species (e.g., Cu) are difficult to produce in the ECR heavy ion source.

Nobles gases are particularly favourable.

Cross section scalings from papers by G. Baur et al, S. Klein, I. Pshenichnov, ….

Pb is worse in this respect because of high BFPP and EMD cross-sections.
Makes short fills, more time spend refilling, ramping, etc.

	γ	σ_{EMD} / b	σ_{BFPP} / b	σ_{had} / b	σ_{tot} / b
Ar^{18+}	3385.68	1.23986	0.00687652	2.59872	3.84546
$^{40}Ca^{20+}$	3761.95	1.56538	0.0143771	2.59872	4.17848
$^{78}Kr^{36+}$	3472.8	12.1684	0.880194	4.05616	17.1048
$^{84}Kr^{36+}$	3224.79	13.121	0.880194	4.26159	18.2628
$^{129}Xe^{54+}$	3148.78	51.8349	15.0389	5.67256	72.5464
Pb^{82+}	2963.54	220.156	280.	7.8	507.956

Scaling formulas, initial nucleon-nucleon luminosity gain wrt Pb-Pb

Species 2 vs species 1:

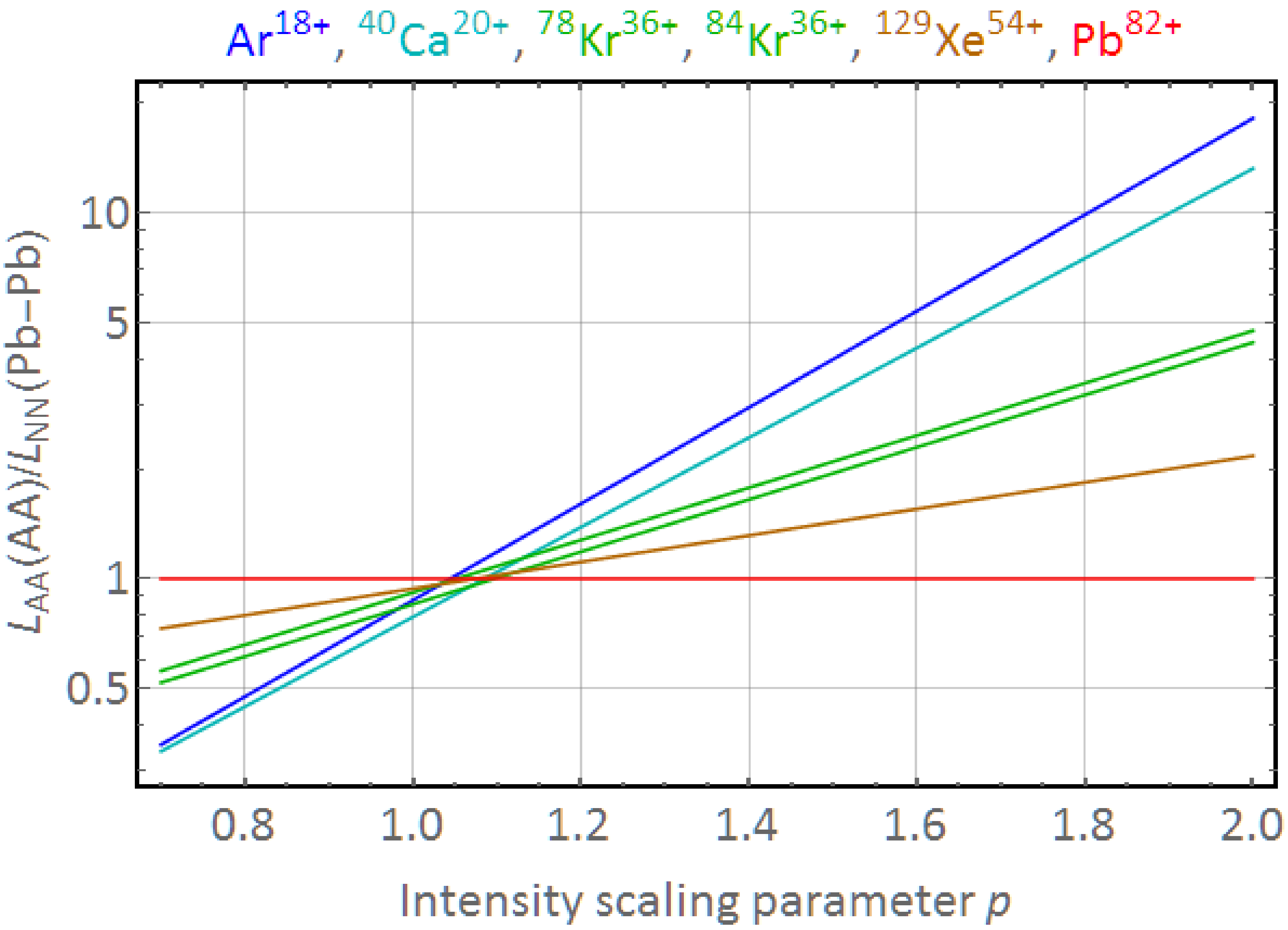
Beam size at IP: $\frac{\sigma_2^*}{\sigma_1^*} = \frac{\sqrt{A_2}\sqrt{Z_1}}{\sqrt{A_1}\sqrt{Z_2}}$

Initial luminosity $\frac{L_2}{L_1} = \frac{A_1 Z_1^{-1+2p}}{A_2 Z_2^{-1+2p}}$

Initial NN luminosity $\frac{L_2}{L_1} = \frac{A_2 Z_1^{-1+2p}}{A_1 Z_2^{-1+2p}}$

This assumes no luminosity levelling.

Formulas for integrated luminosity gains are much messier.

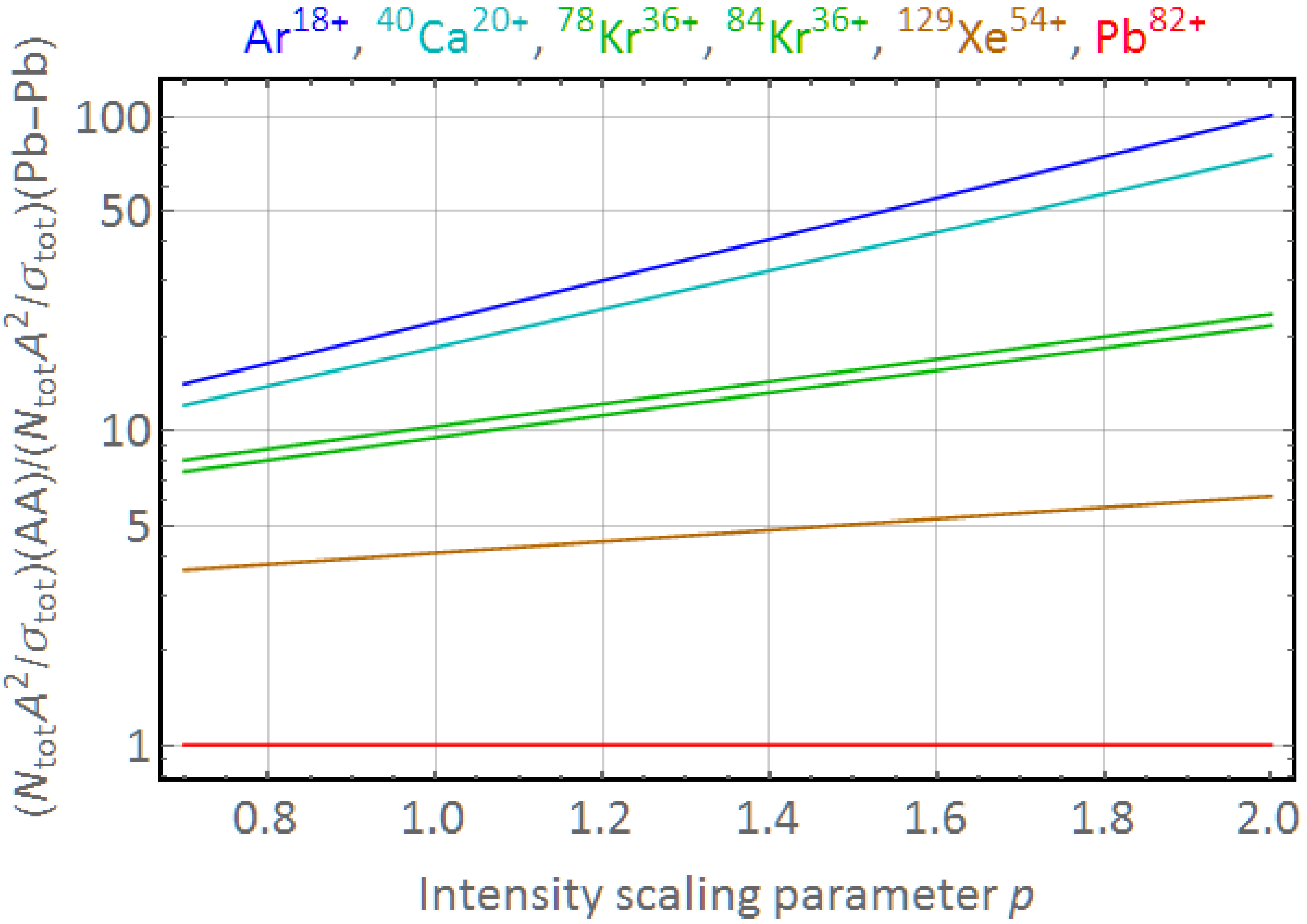


Gains in ULTIMATE integrated nucleon-nucleon luminosity PER FILL wrt Pb-Pb

This would be on the assumption that a fill would be kept forever until one beam was exhausted (and other loss mechanisms are neglected). Real gain/fill will be less.

In reality, one also gains from longer luminosity lifetime and less time spent refilling the machine.

We will try to quantify this better in future.



“HL-LHC” initial parameters for various species

p=1, no gain in L_{NN} scenario

	σ_{tot} / b	γ	$\sqrt{s_{NN}}$ / TeV	L_{AA0} / $cm^{-2}s^{-1}$	L_{NN0} / $cm^{-2}s^{-1}$	τ_{L0} / h	P_{BFPP} / W	δ_{BFPP}	P_{EMD1} / W	δ_{EMD1}
Ar^{18+}	3.84546	3385.68	6.3	3.10723×10^{29}	4.97156×10^{32}	41.3172	0.0431343	0.0588235	3.98835	-0.0252118
$^{40}Ca^{20+}$	4.17848	3761.95	7.	2.51691×10^{29}	4.02706×10^{32}	42.2482	0.0811666	0.0526316	4.53203	-0.0252124
$^{78}Kr^{36+}$	17.1048	3472.8	6.46154	7.76874×10^{28}	4.7265×10^{32}	18.5761	2.76083	0.0285714	19.5732	-0.0129303
$^{84}Kr^{36+}$	18.2628	3224.79	6.	7.76886×10^{28}	5.48171×10^{32}	17.3979	2.76087	0.0285714	21.1057	-0.0120068
$^{129}Xe^{54+}$	72.5464	3148.78	5.86047	3.45172×10^{28}	5.744×10^{32}	6.57173	31.438	0.0188679	55.568	-0.0078159
Pb^{82+}	507.956	2963.54	5.51923	1.49595×10^{28}	6.47208×10^{32}	1.42616	385.21	0.0123457	155.323	-0.00484426

p=1.5, fairly optimistic scenario

	σ_{tot} / b	γ	$\sqrt{s_{NN}}$ / TeV	L_{AA0} / $cm^{-2}s^{-1}$	L_{NN0} / $cm^{-2}s^{-1}$	τ_{L0} / h	P_{BFPP} / W	δ_{BFPP}	P_{EMD1} / W	δ_{EMD1}
$^{40}Ar^{18+}$	3.84546	3385.68	6.3	1.41551×10^{30}	2.26482×10^{33}	19.358	0.196501	0.0588235	18.1691	-0.0252118
$^{40}Ca^{20+}$	4.17848	3761.95	7.	1.03193×10^{30}	1.65109×10^{33}	20.8649	0.332783	0.0526316	18.5813	-0.0252124
$^{78}Kr^{36+}$	17.1048	3472.8	6.46154	1.76955×10^{29}	1.07659×10^{33}	12.3083	6.28857	0.0285714	44.5833	-0.0129303
$^{84}Kr^{36+}$	18.2628	3224.79	6.	1.76957×10^{29}	1.24861×10^{33}	11.5277	6.28866	0.0285714	48.0741	-0.0120068
$^{129}Xe^{54+}$	72.5464	3148.78	5.86047	5.2415×10^{28}	8.72237×10^{32}	5.33298	47.7392	0.0188679	84.381	-0.0078159
Pb^{82+}	507.956	2963.54	5.51923	1.49595×10^{28}	6.47208×10^{32}	1.42616	385.21	0.0123457	155.323	-0.00484426

Lifetime gains could give another factor 2-4 in integrated luminosity.

Going beyond this would give EMD1 secondary beams impinging closer to the IP. Levelling or new TCLDs?

Caveats about lighter species

- Collimation is more complicated, needs careful study
  - See first measurements with Xe vs. Pb in MOPMF038 paper in IPAC2018
  - May need new hardware in LHC
  - Crystal collimation (also tested with Xe) may be a solution for the future (Pb also)
  - It takes time to change species in the injector chain, therefore it is hard to gain experience.
  - The dramatic improvements in transmitted intensity in 2015-16 were the result of many detailed studies and improvements.

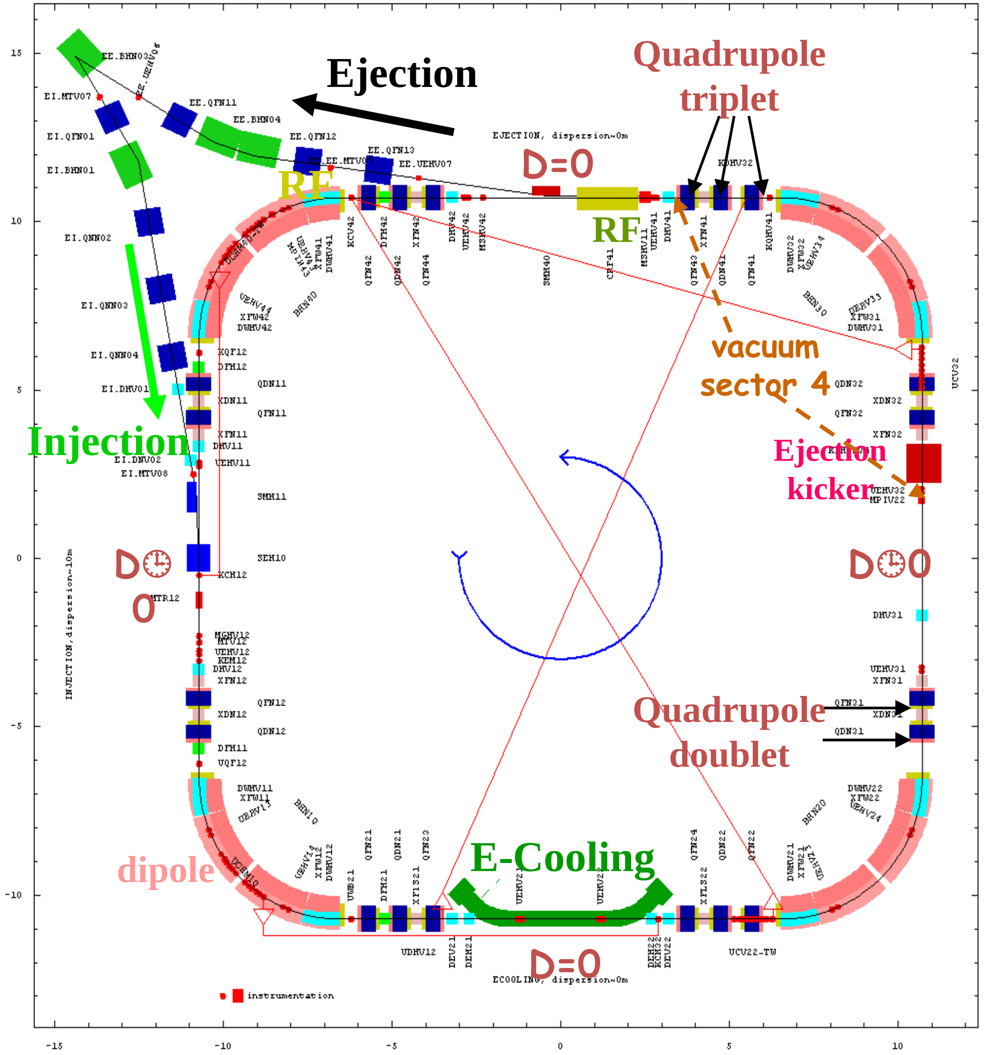
Conclusions

- It has been possible to rapidly recommission the LHC in multiple new configurations very efficiently.
- The baseline performance goals for Pb-Pb integrated luminosity from the ALICE LoI of 2012 appear to be within reach
  - Most of them already available for 2018 Pb-Pb run
  - Greatest remaining uncertainties: collimation in LHC, slip-stacking in SPS.
- We can go further with p-Pb luminosity than we did in 2016.
- The feasibility of runs with lighter species has been demonstrated with Xe-Xe in 2017.
  - There is very good hope for substantially higher integrated nucleon-nucleon luminosity than with Pb-Pb but further studies (and resources) are certainly required.
- Not discussed: it is easy to switch from Pb to O so short p-O runs (for cosmic ray physics, etc) should be feasible (using the model of p-Pb in 2012, Xe-Xe in 2017).

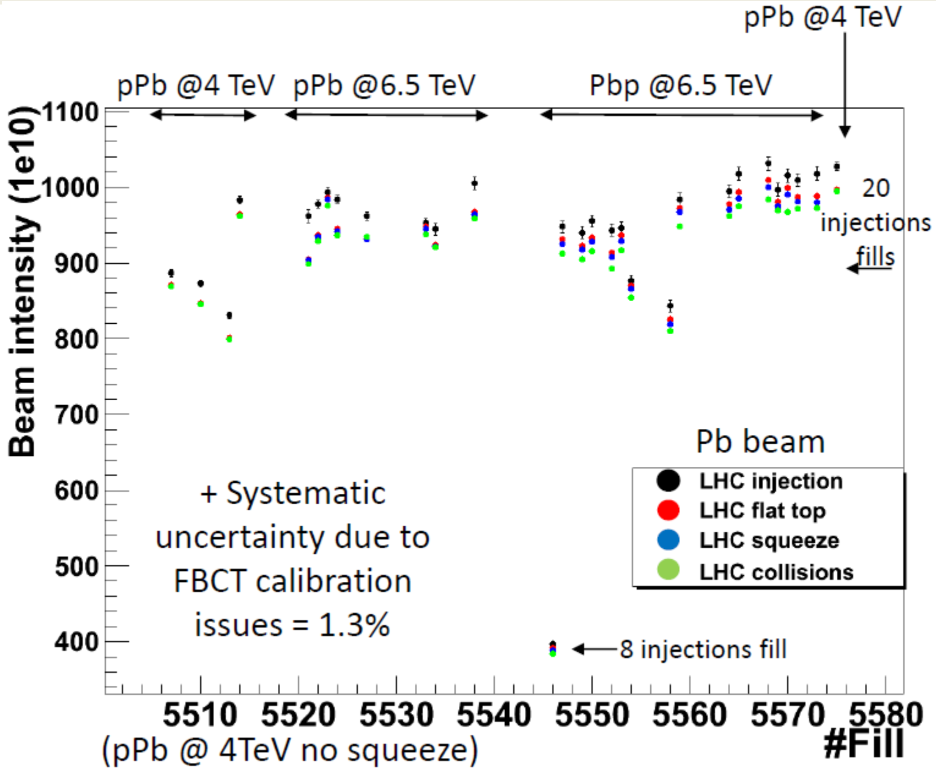
BACKUP SLIDES

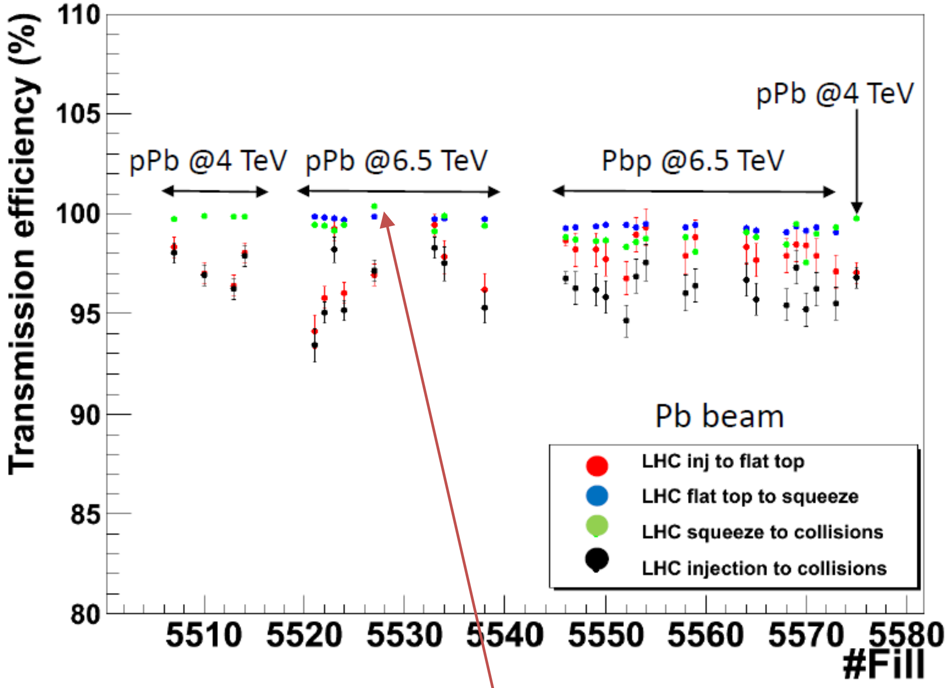
LEIR (Low-Energy Ion Ring)

- Prepares beams for LHC using electron cooling
- circumference 25p m (1/8 PS)
- 70 turn injection into horizontal+vertical+longitudinal phase planes
- Fast Electron Cooling : Electron current from 0.5 to 0.6 A with variable density
- RF capture
- Dynamic vacuum (NEG, Au-coated collimators, scrubbing)



Intensity transmission: injection to collision, Pb in 2016





Data from 2016 p-Pb run, for Pb beam only.
Expect Pb-Pb to be generally better.

Previous estimates of future Pb-Pb performance assumed 90% transmission from injection to collision.

Data justify using 95% now (previously 90%).

R. Alemany, M. Schaumann

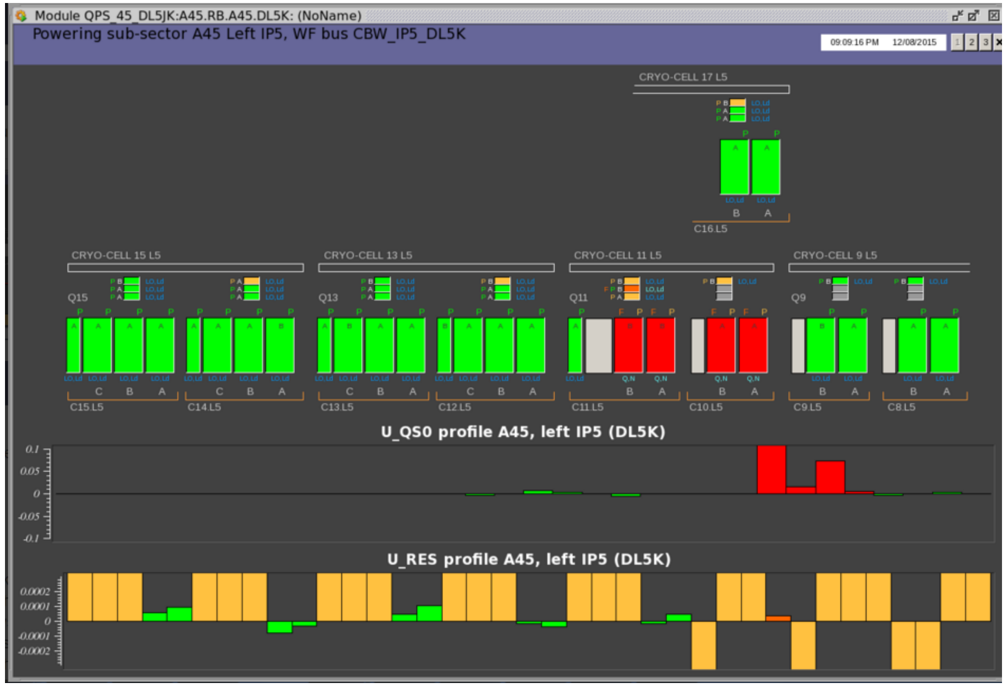
>100% due to FBCT re-calibration

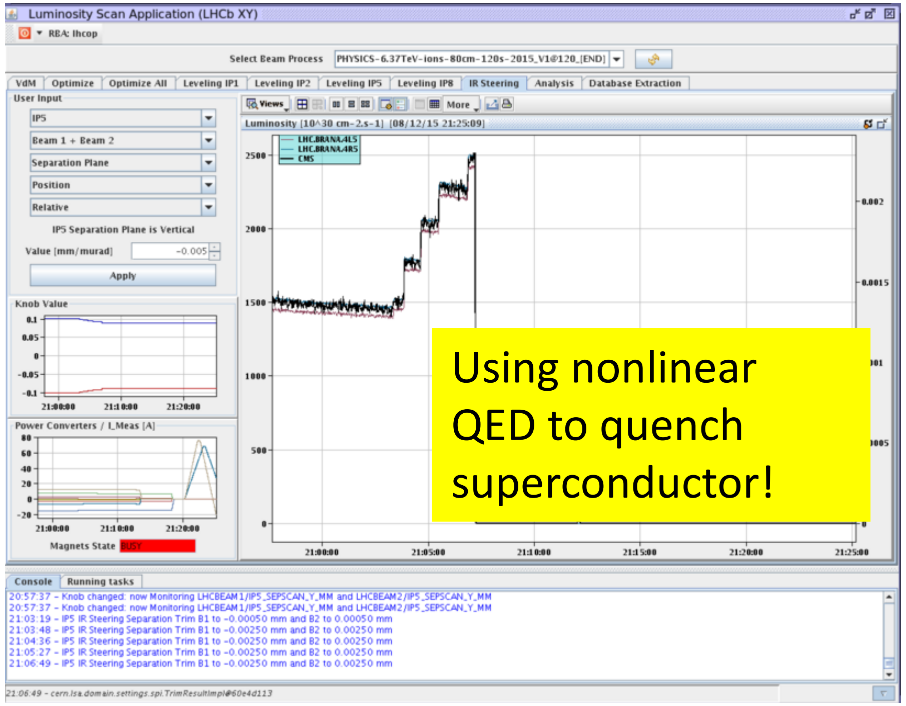
BFPP Quench MD – first luminosity quench in LHC

- BLM thresholds in BFPP loss region raised by factor 10 for one fill 8/12/2015 evening.
- Prepared as for physics fill, separated beams to achieve moderate luminosity in IP5 only.
- Changed amplitude of BFPP mitigation bump from -3 mm to +0.5 mm to bring loss point well within body of dipole magnet (it started just outside).
- Put IP5 back into collision in 5 μm steps.
- Unexpectedly quenched at luminosity value (CMS):

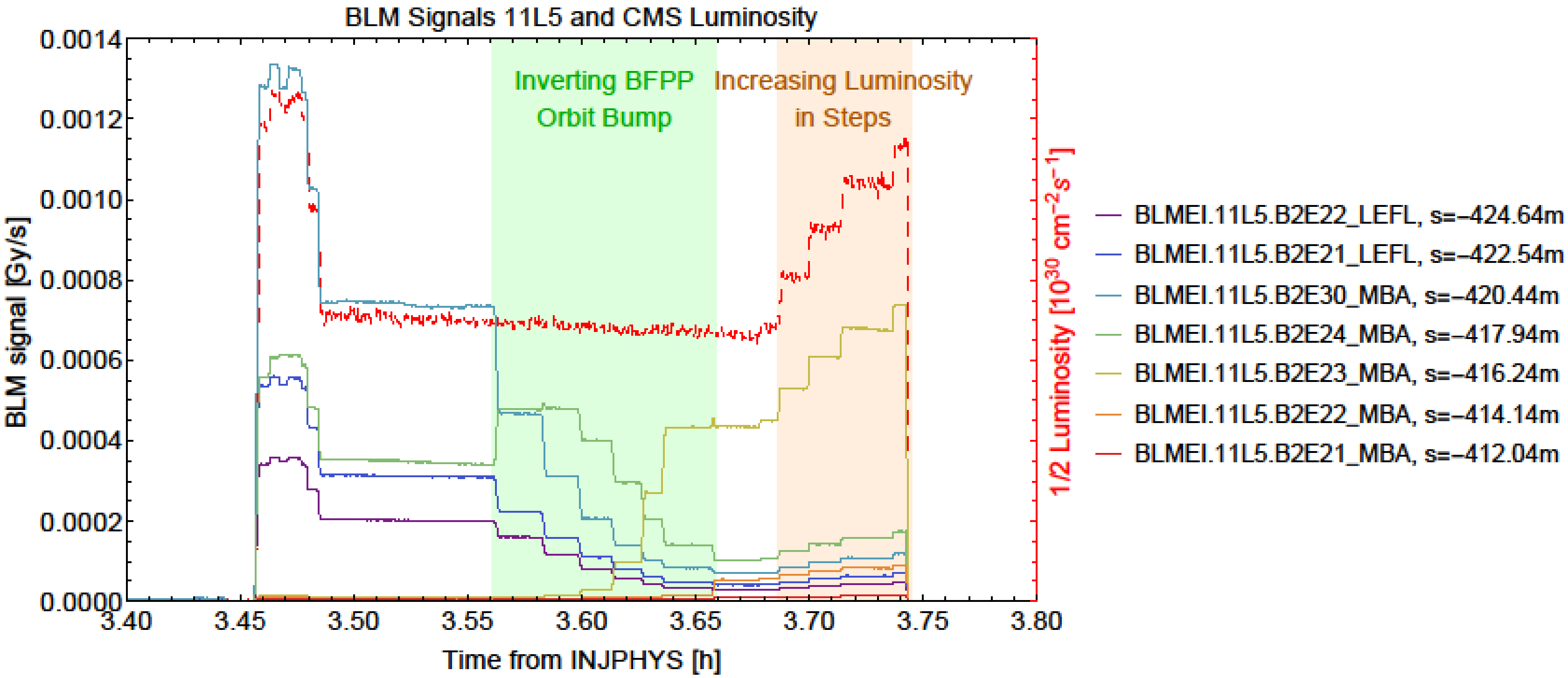
$$L \approx 2.3 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Rightarrow\quad 0.64\ \text{MHz event rate, about 45 W of power in } \text{Pb}^{81+} \text{ beam into magnet}$$



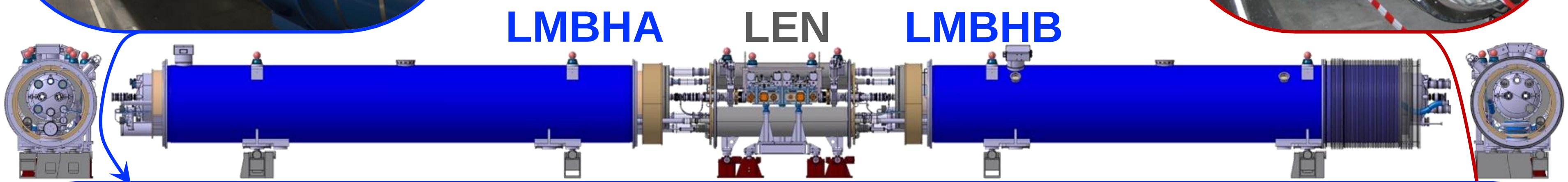


Luminosity and BLM signals during measurement



Resolved decades of uncertainty about steady-state quench level of LHC dipole magnets.
Later a second collimation quench test with Pb was also successful.

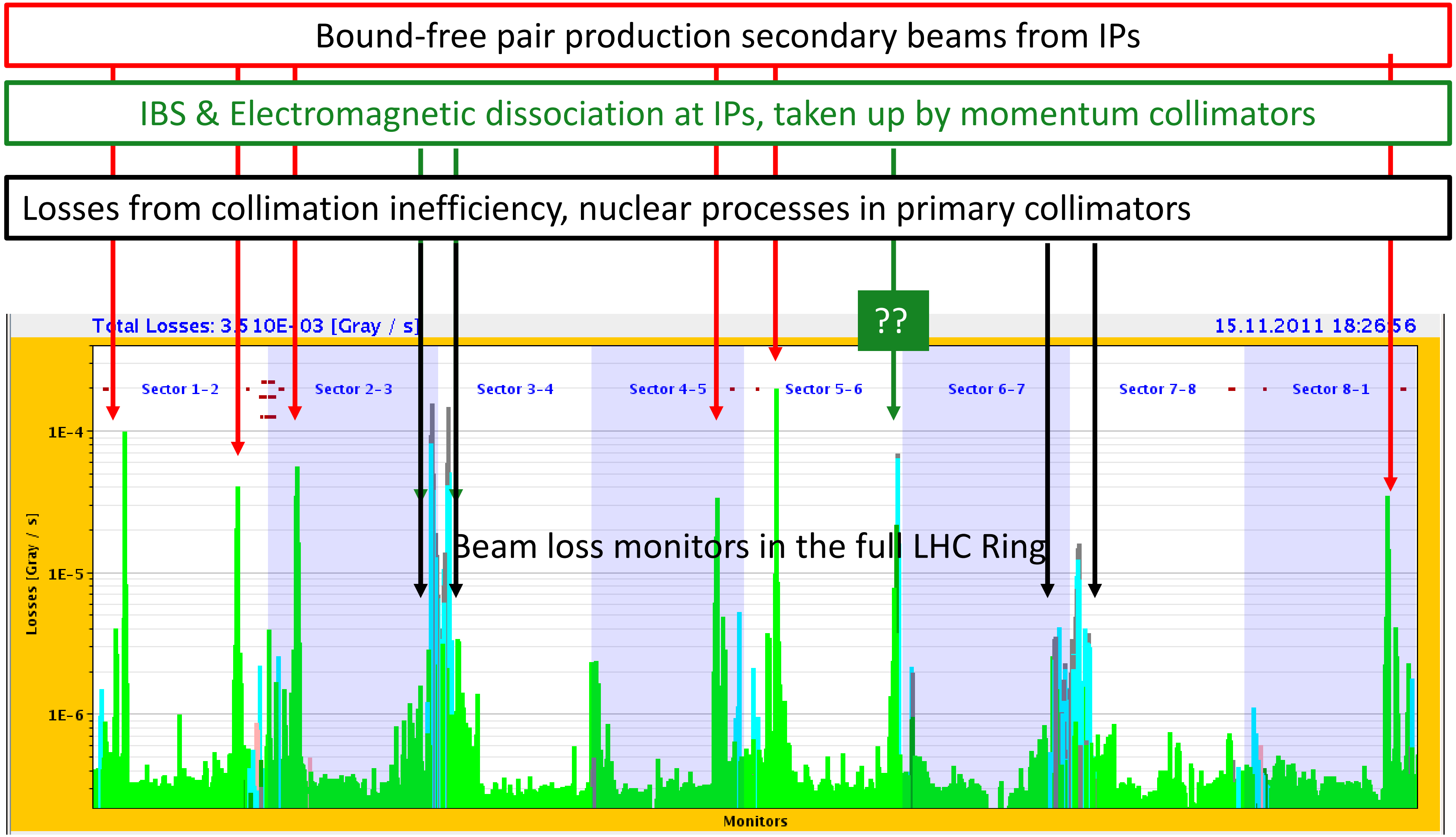
DS collimators



- **IP7**, for both proton and heavy-ion collimation losses
  - Design, fabricate, test, and install during **LS2**, around **IP7**, **two 11 T Dipole Full Assemblies** (replace the MBs MBA-B8L7 and MBB-B8R7)
  - Fabricate and test **one spare 11 T Dipole Full Assembly**
  - Plan **includes 14 magnet models**, and ~~2~~**1 full-length prototype**
)
- **IP2**, for heavy-ion secondary beams
  - Design, fabricate, and install during **LS2**, around **IP2**, **two Connection Cryostat Full Assemblies**, i.e. no 11 T Dipole magnet needed for this
  - Fabricate **one spare Connection Cryostat Full Assembly**
  - A Connection Cryostat Full Assembly contains two new connection cryostats, **LEP**, and one by-pass cryostat, **LEN**

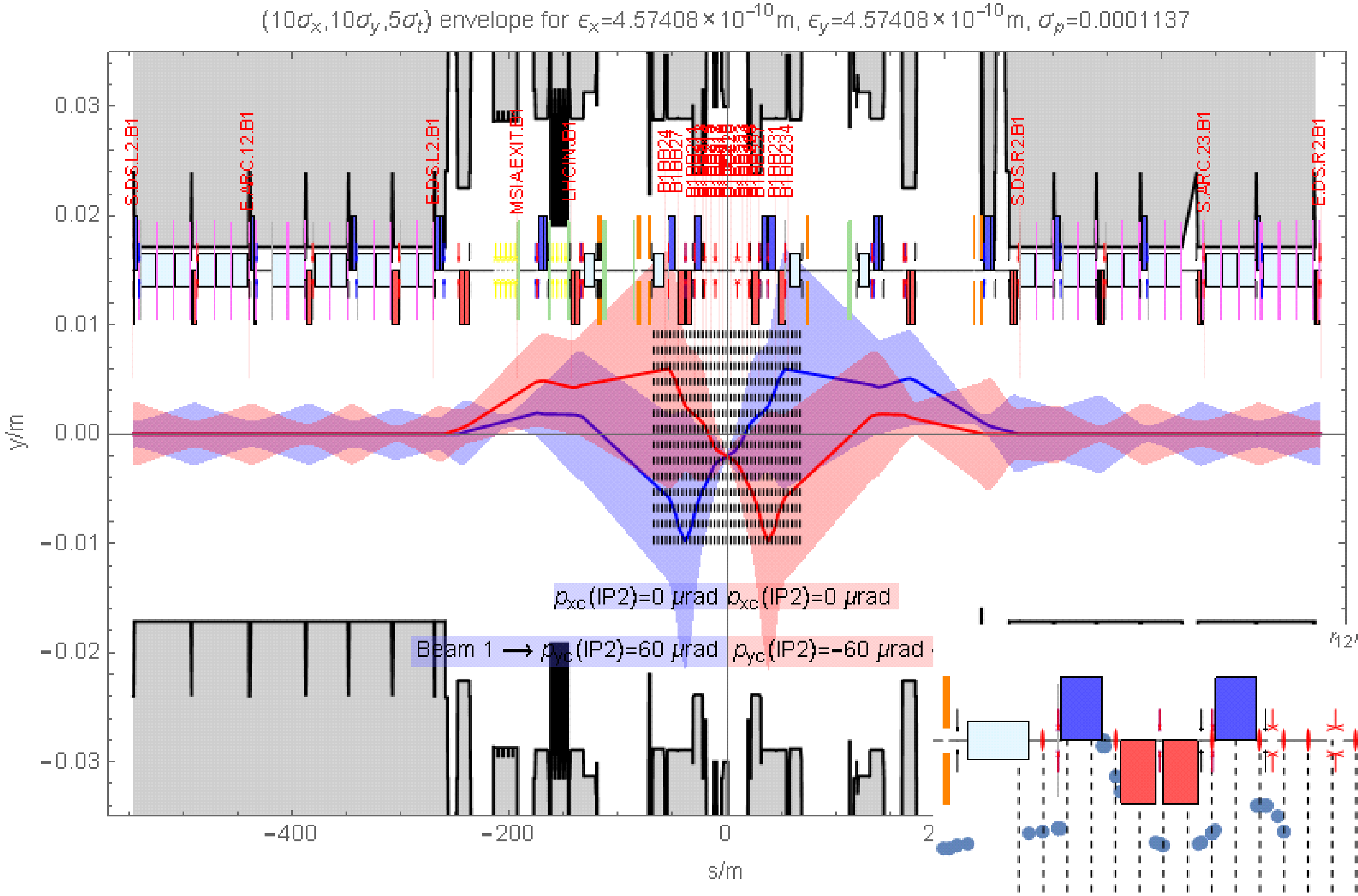
F. Savary

Steady-state losses during Pb-Pb Collisions in 2011



No time to fully discuss major topic of heavy-ion collimation in this talk.

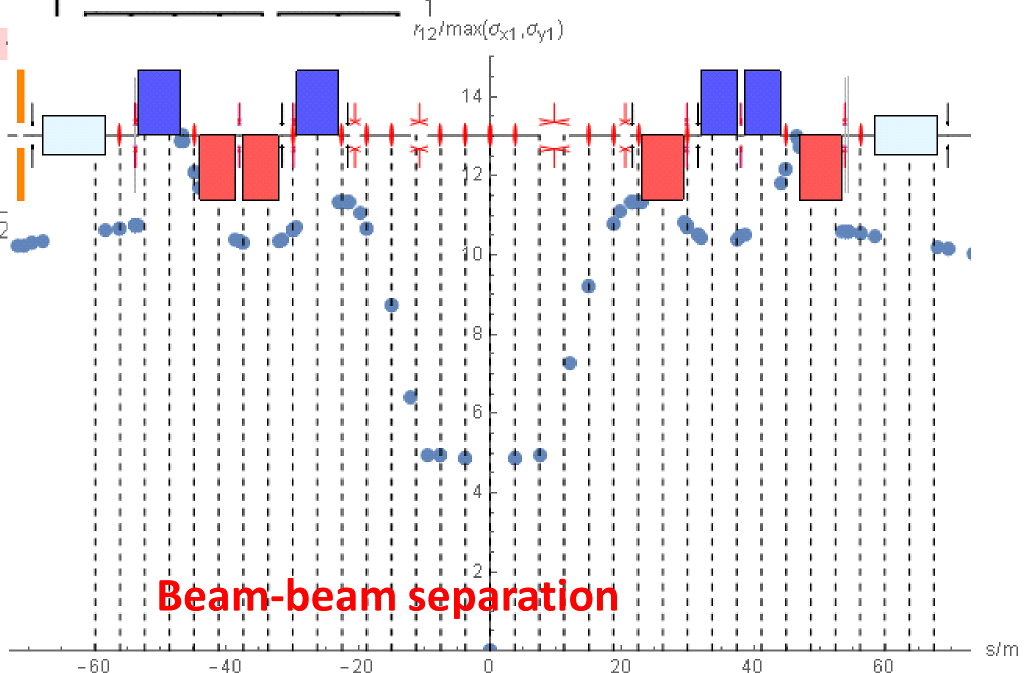
Spectrometer ON_ALICE=-7/6.37 (start of 2015 Pb-Pb run)



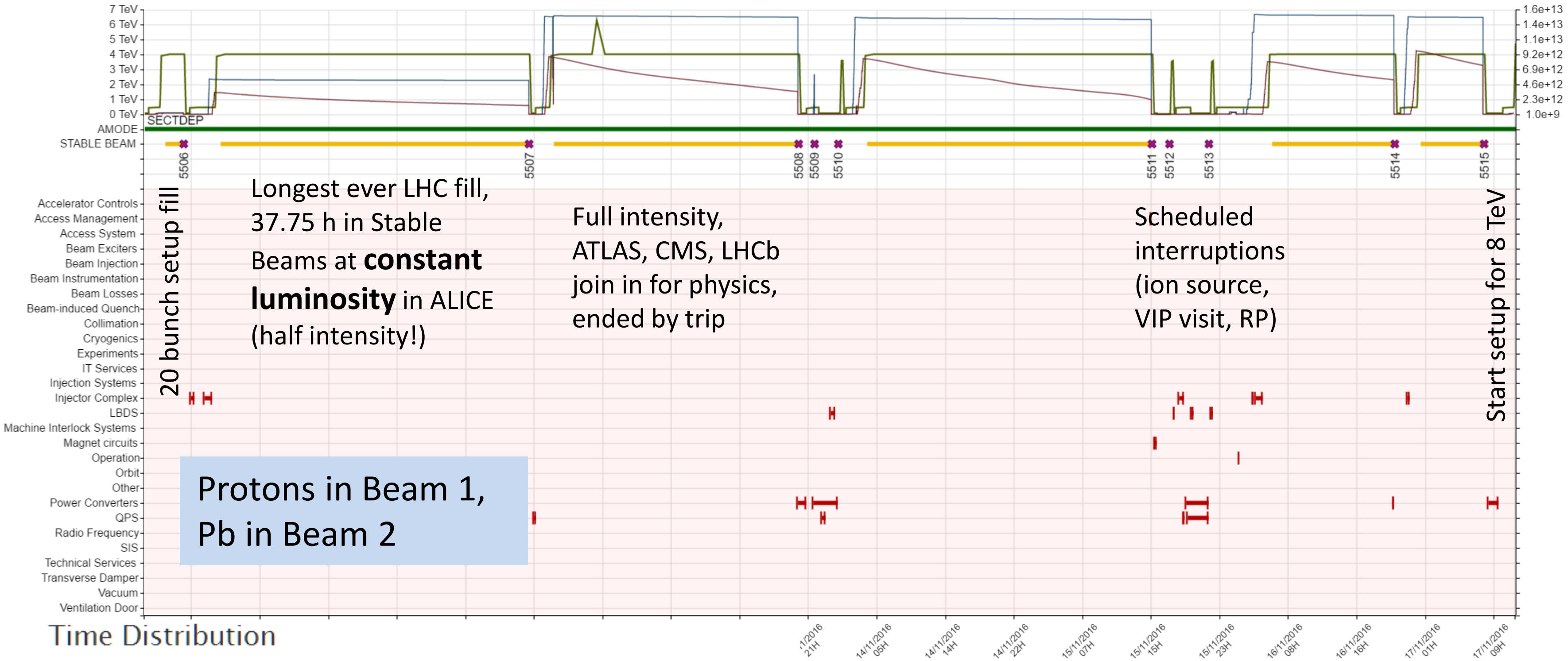
Include downward shift of IP by -2 mm (detector sank).

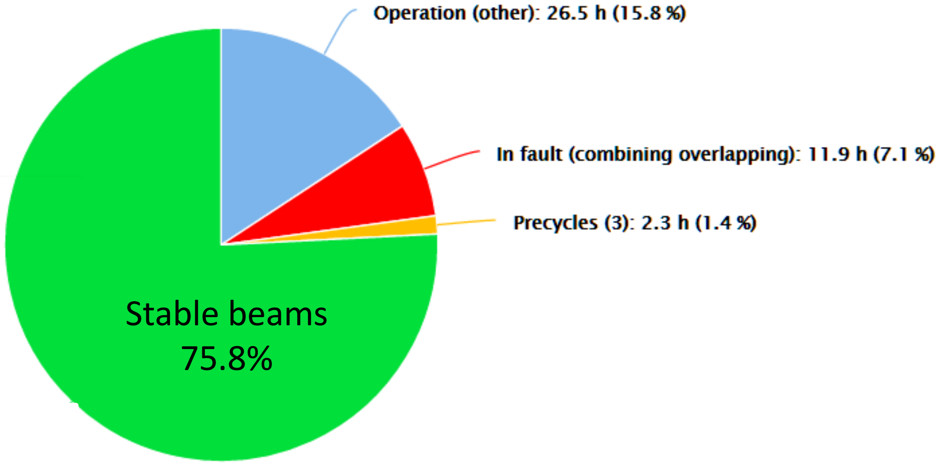
Constraints on crossing angle to allow spectator neutron cone to reach Zero Degree Calorimeters.

Spectrometer bump angle -77 µrad, external bump +137 µrad for Beam 1.



Part 1: 1 week at 5 TeV, levelled luminosity for ALICE





Fills could have been much longer still. Lifetime good enough to give bonus minimum-bias programmes to ATLAS, CMS as well as ALICE.

LHCb colliding p-He (gas).

Special conditions admittedly, but astonishing availability!