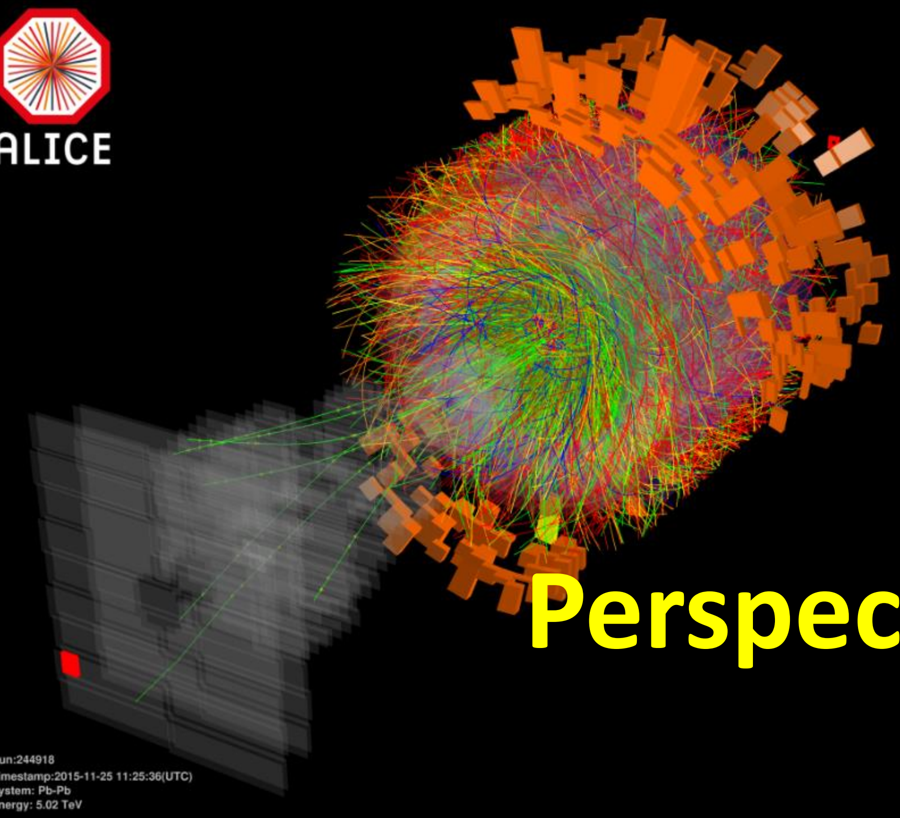
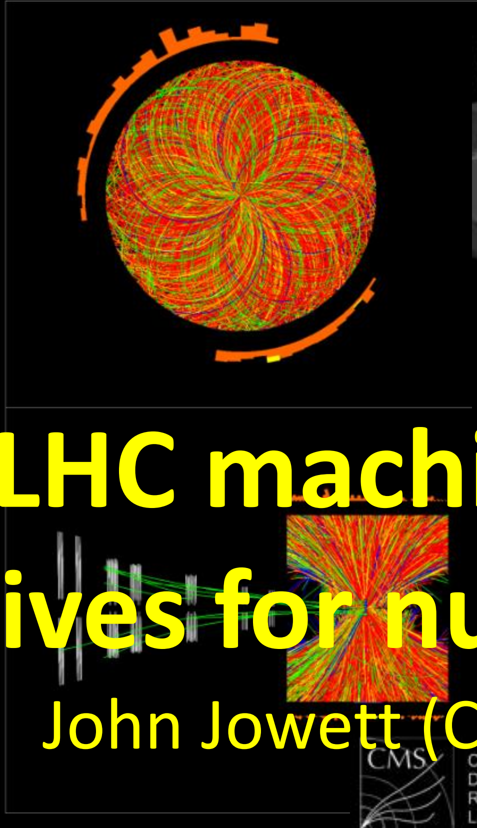
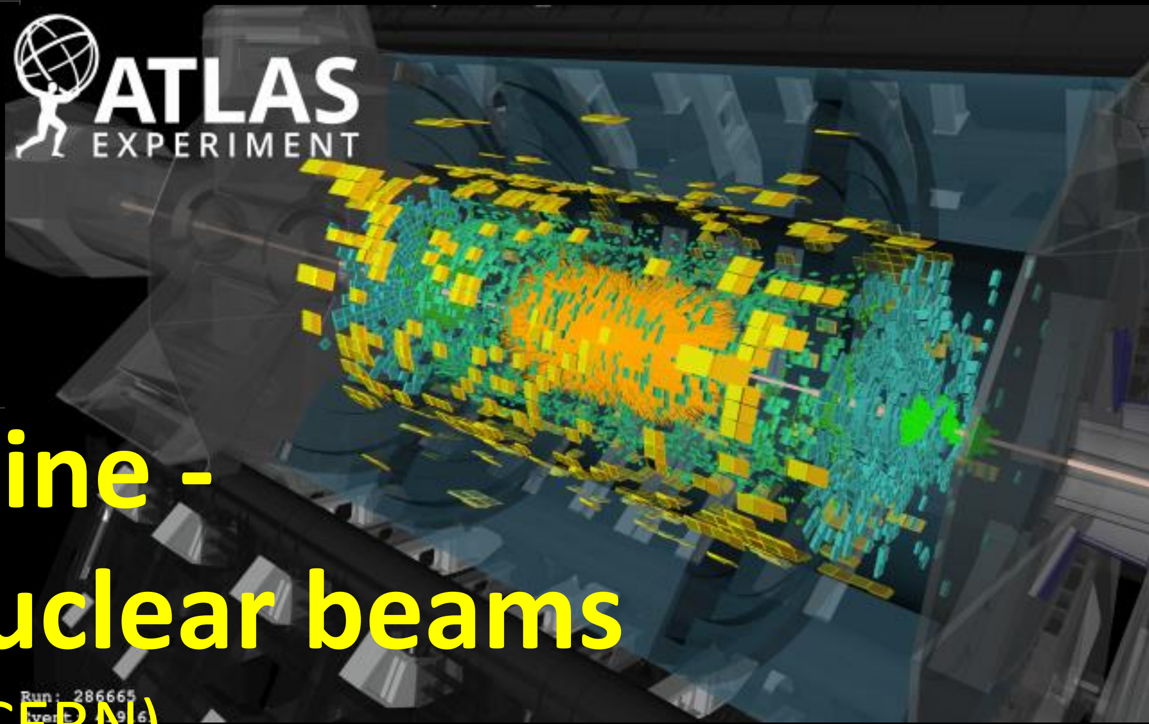


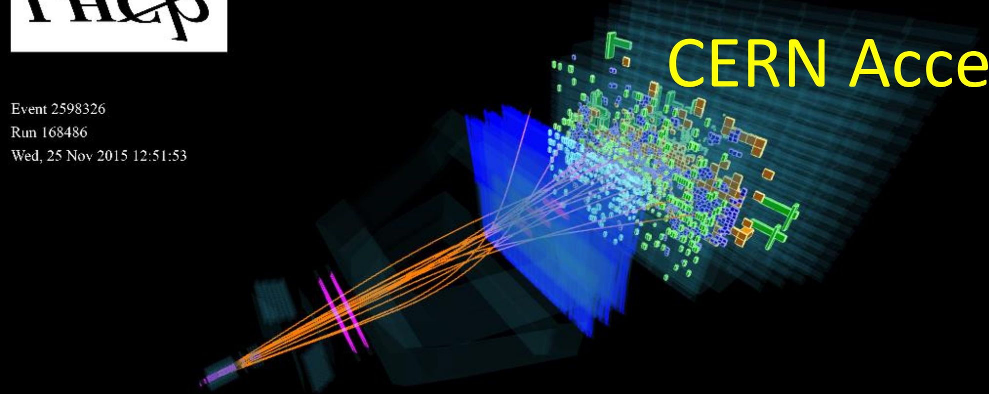


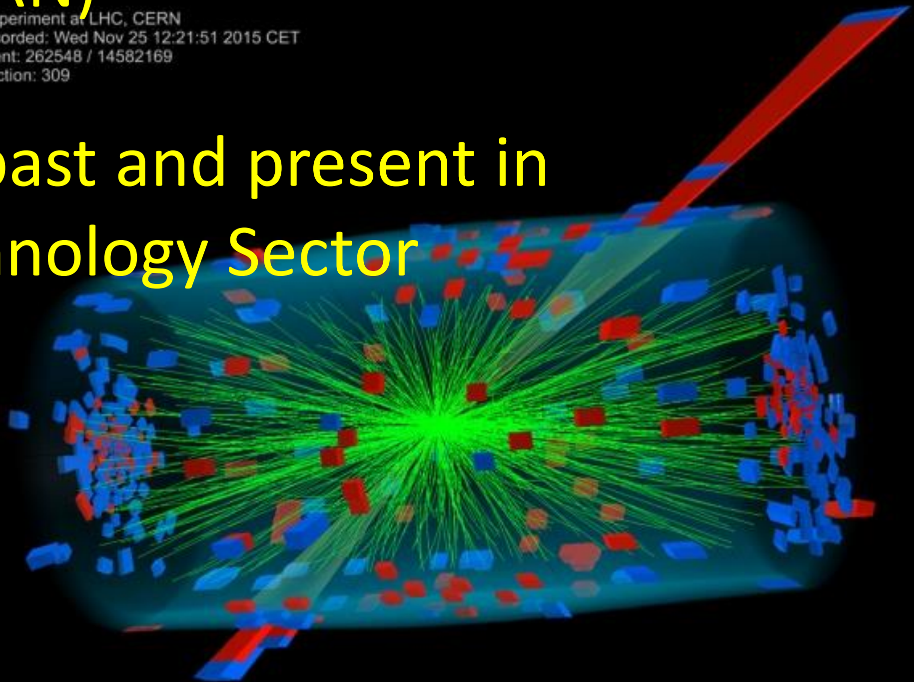


LHC machine - Perspectives for nuclear beams

John Jowett (CERN)

On behalf of many colleagues past and present in CERN Accelerator and Technology Sector





Last "Town Meeting" on 29/6/2012

Nucleus-nucleus programme status

- In ~8 weeks total Pb-Pb operation in 2010-11, the LHC has attained
  - Twice design Pb-Pb luminosity at half-design energy (scaling with E^2).
  - ~16% of the integrated luminosity goal (1 nb^{-1}) for the present phase of Pb-Pb.
- Pb-Pb in 2012 might give ~250 μb^{-1}
- Decision to go for p-Pb instead
  - Otherwise no p-Pb before 2016 or 2017
  - But this is a new, more complex and almost unprecedented mode of collider operation

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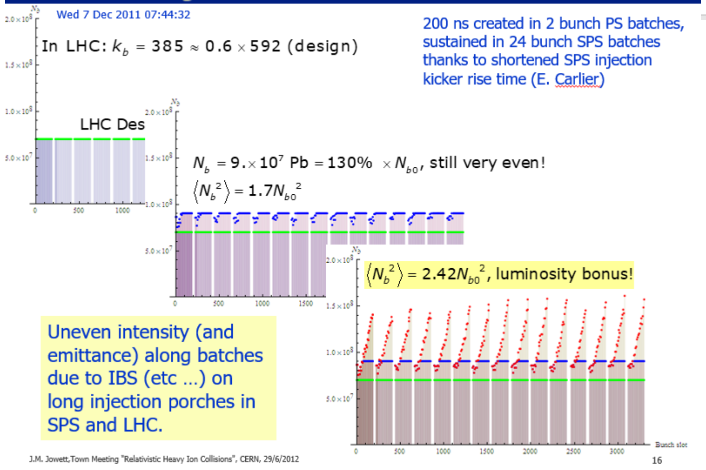
Ion Injector Chain Performance 2011



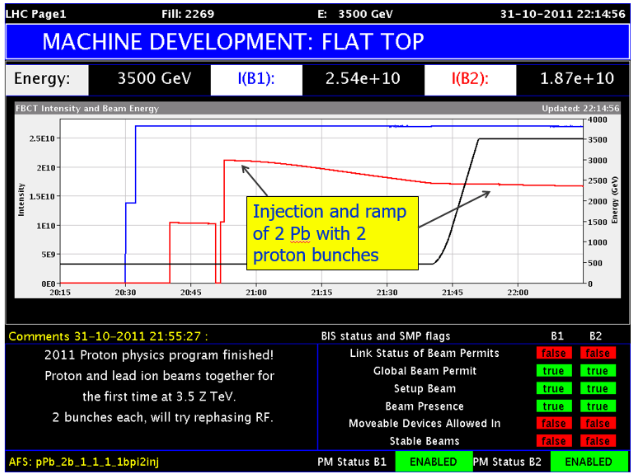
J.M. Jowett,Town Meeting "Relativistic Heavy Ion Collisions", CERN, 29/6/2012 16

p-Pb feasibility test, Part 1, 16h on 31/10/2011

- Almost unprecedented mode of collider operation
  - See pA@LHC workshop
- Several hours setup of first Pb beam of the year (timing, many details…)
- Stored 4 Pb bunches in presence of 304 p bunches (~10% nominal intensity) at injection
  - Lifetime no worse for presence of p bunches
  - Emittance blow-up, does not appear to be worse than for Pb alone
- Dumped and re-injected 4 fresh Pb
  - Still OK
- Ramped 2 Pb and 2 p bunches, good lifetime
- Re-phased RF (cogging) to move bunches 1 encounter point 9 km back to ATLAS, *no losses*

J.M. Jowett,Town Meeting "Relativistic Heavy Ion Collisions", CERN, 29/6/2012

Feasibility of p-Pb collisions?



J.M. Jowett,Town Meeting "Relativistic Heavy Ion Collisions", CERN, 29/6/2012 22

LHC Heavy-Ion Programme to 2022

2013-14		Long shutdown LS1, increase *E*
2015-16	**Pb-Pb**	Design luminosity+, ~ 250 μb^{-1}/year
2017	**p-Pb *or* Pb-Pb**	P-Pb to enhance 2015-16 data. Energy? Pb-Pb if μb^{-1} still needed
2018		LS2: install DS collimators around ALICE to protect magnets (ALICE upgrade for 6 × design luminosity)
2019	**Pb-Pb**	Beyond design luminosity … as far as we car Reduce bunch spacing?
2020	**p-Pb**	
2021	**Ar-Ar**	Intensity to be seen from injector commissioning for SPS fixed target. Demanding collimation requirements.
2022		LS3, upgrades ?? Stochastic cooling ??

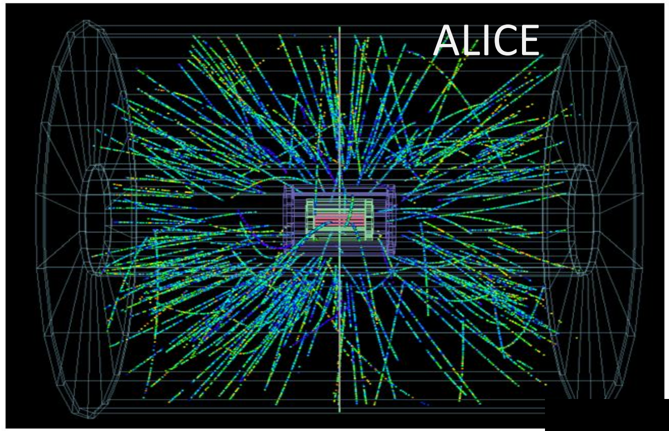
Part I - Conclusions

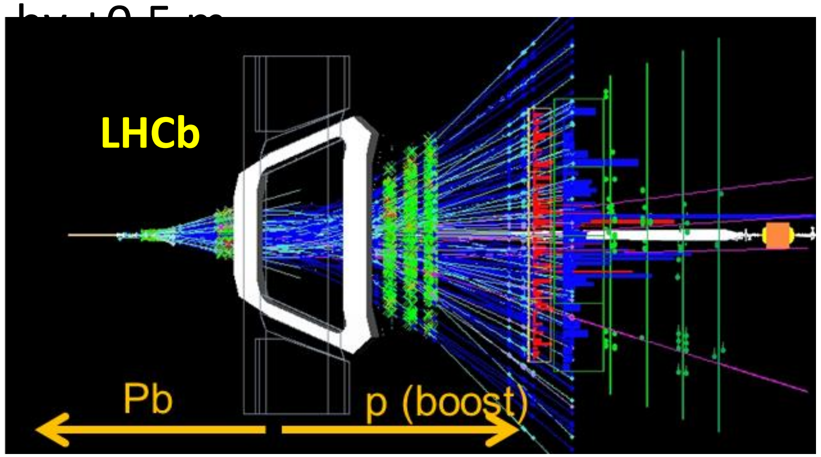
- 2011 results encouraging for future performance
  - Quench limits, strategies to help avoid them
  - Still many uncertainties
  - Still "only" design intensity in 100 ns Nominal injection scheme
- We do not yet have a clear path beyond about twice design luminosity
  - DS collimator installation for ALICE in LS2
  - Looking for solutions for more bunches in injectors

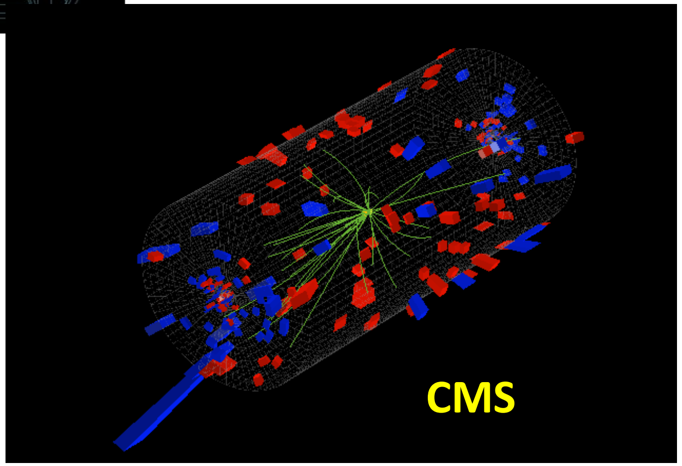
ALICE LoI emerged around time of this meeting

11 weeks later: Pilot p-Pb run, night of 13-14 September 2012

- **16:00** Starting injection, problems with ions, timing events not sent out correctly.
- 18:30 Filling Pb ions, first time in 2012
- 19:00 Start of ramp. Lost the beam on TCT position interlocks, revert collimator settings and try again ….
- QPS problems. RF problems.
- **22:52 15 p and 15 Pb bunches at 4 *Z* TeV, 8 colliding per experiment, 3 sacrificial for collimation setup**
- 23:35 Beams in collision, unsqueezed, optimising …
- 00:50 Start of loss maps to set up collimation
- **01:26 Stable beams for p-Pb Physics**
- 06:04 Adjust mode to move IP for ALICE
- 06:25 Stable beams again, IP moved by -0.5 m
- 07:55 Stable beams again, IP moved by +0.5 m
- 09:35 Beams dumped by operators







Historical energy jumps

$\sqrt{s_{NN}}$ is the centre-of-mass energy per colliding nucleon pair

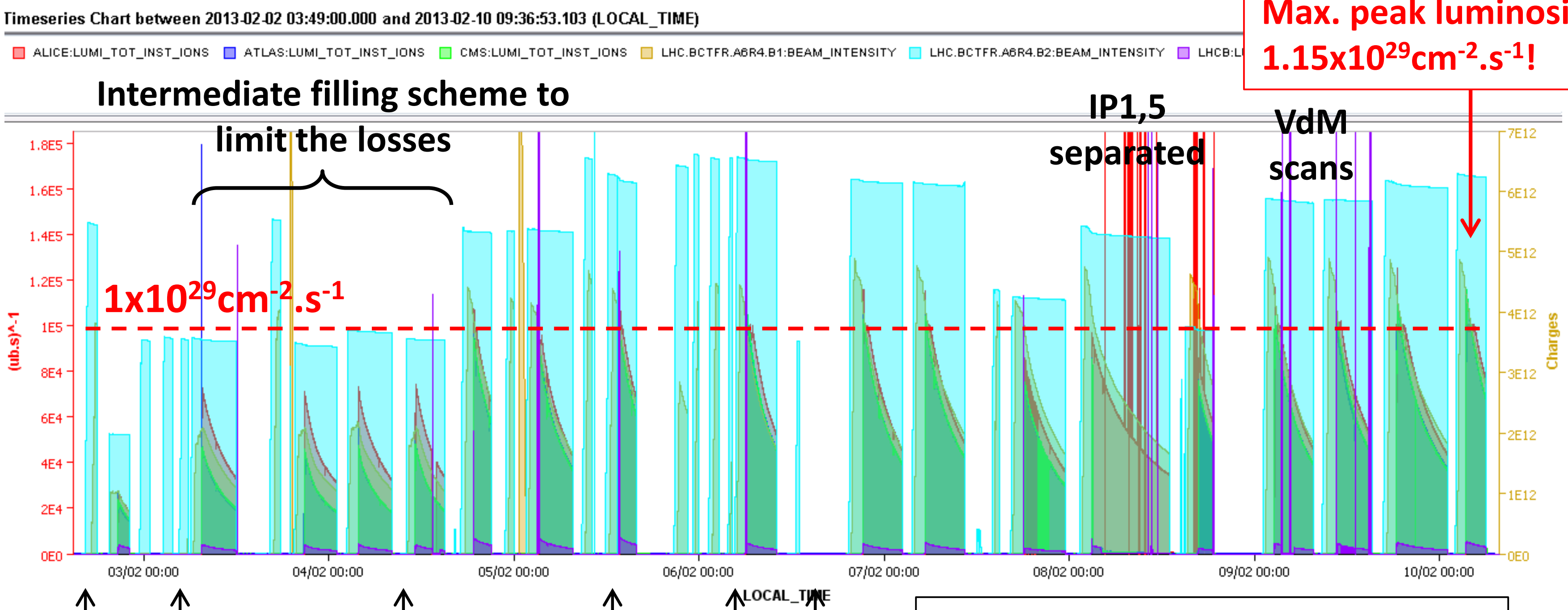
Collision type	Before	$\sqrt{s_{NN}}$ / GeV	After	$\sqrt{s_{NN}}$ / GeV	Jump
e^+e^-	any		any		2-3
pp,$\bar{p}$p	PS, AGS	7.1	ISR	52	7.3
pp,$\bar{p}$p	ISR	59	S$\bar{p}$pS	540	9.0
pp,$\bar{p}$p	S$\bar{p}$pS	540	Tevatron	1960	3.6
pp,$\bar{p}$p	Tevatron	1960	LHC (pp)	7000	3.6
DIS (e/μ)*p*	E665 (μp)	29.7	HERA (ep)	314	10.6
AA	RHIC (Au-Au)	200	LHC(Pb-Pb)	2760	13.8
(p/d)*A*	RHIC (d-Au)	200	LHC(p-Pb)	5023	25.1

This was the largest factor of increase in the energy of a given type of collision ever achieved in the history of particle accelerators - and brought new, surprising physics results.

LHC Run 1 closed with a full p-Pb run, a further factor 1000 in luminosity, … the first major upgrade of the LHC beyond its design (pp and PbPb only).

Second half of 2013 run - Luminosity production in Pb-p mode

Max. peak luminosity $1.15x10^{29}cm^{-2}.s^{-1}$!



~"Design" luminosity achieved at 4/7 design energy.

Increase of BLM monitor factor (losses end of ramp + squeeze)

Increase bandwidth of orbit feedback

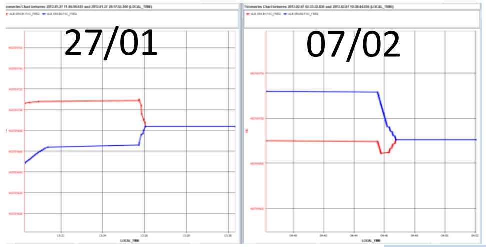
Increase of BLM monitor factor (losses during the squeeze),

Increase of BLM monitor factor (losses at the start of the ramp), rematch injection energy to the SPS

reduction of longitudinal blow-up at injection

Common frequency trimmed by -10Hz

Set the style of future Pb-Pb and p-Pb runs.

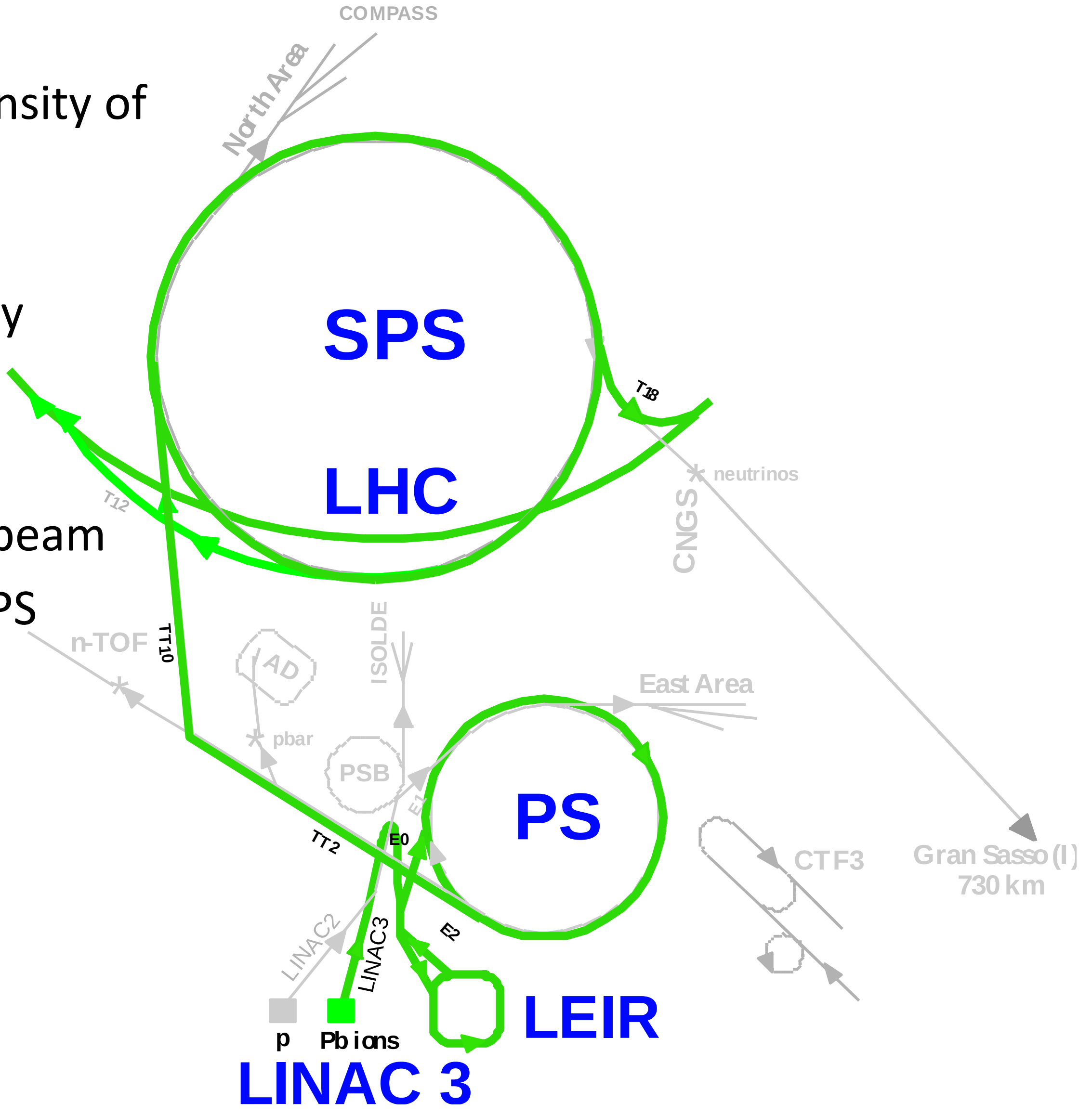


RF frequencies

R. Versteegen

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

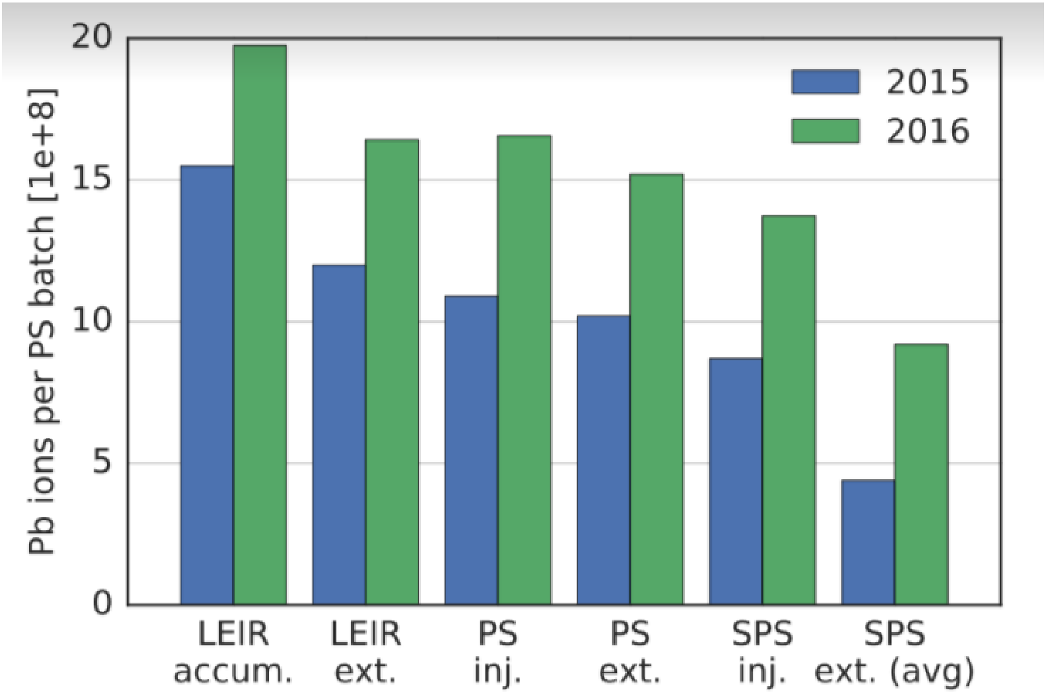


Figure 1: Comparison of operationally achieved intensities through the LHC injector chain in 2015 and 2016.

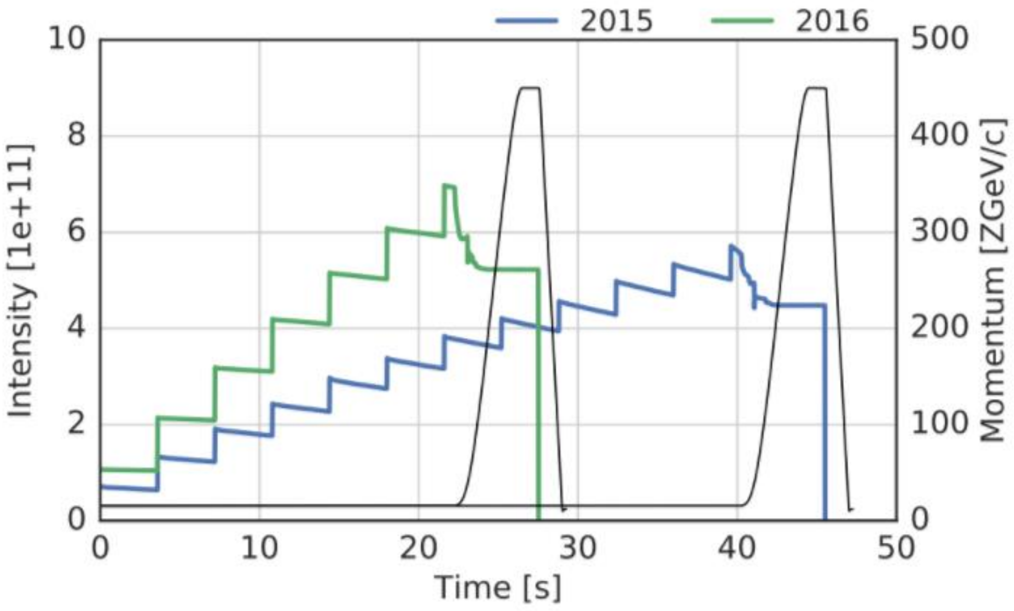


Figure 2: Typical intensity evolution along the operational Pb-ion cycles in 2016 in comparison to 2015.

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 parameters from Design Report 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ 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 $E[Z\,\mathrm{TeV}]$	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 $\sqrt{s_{\mathrm{NN}}}$ [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_{AA} [$10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1	150	0.03	0.5	116	3.6	850	6
NN lumi. L_{NN} [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	43	31	1.3	22.	24	156	177	260
Integrated lumi./expt. [$\mu\mathrm{b}^{-1}$]	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://doi.org/10.18429/JACoW-IPAC2018-TUXGBD2
TUXGBD2
+ its bibliography

The 2018 Pb-Pb run (end of next week!) should implement and exploit most of the features of the configuration for "HL-LHC" luminosity.

Nucleus-nucleus programme status

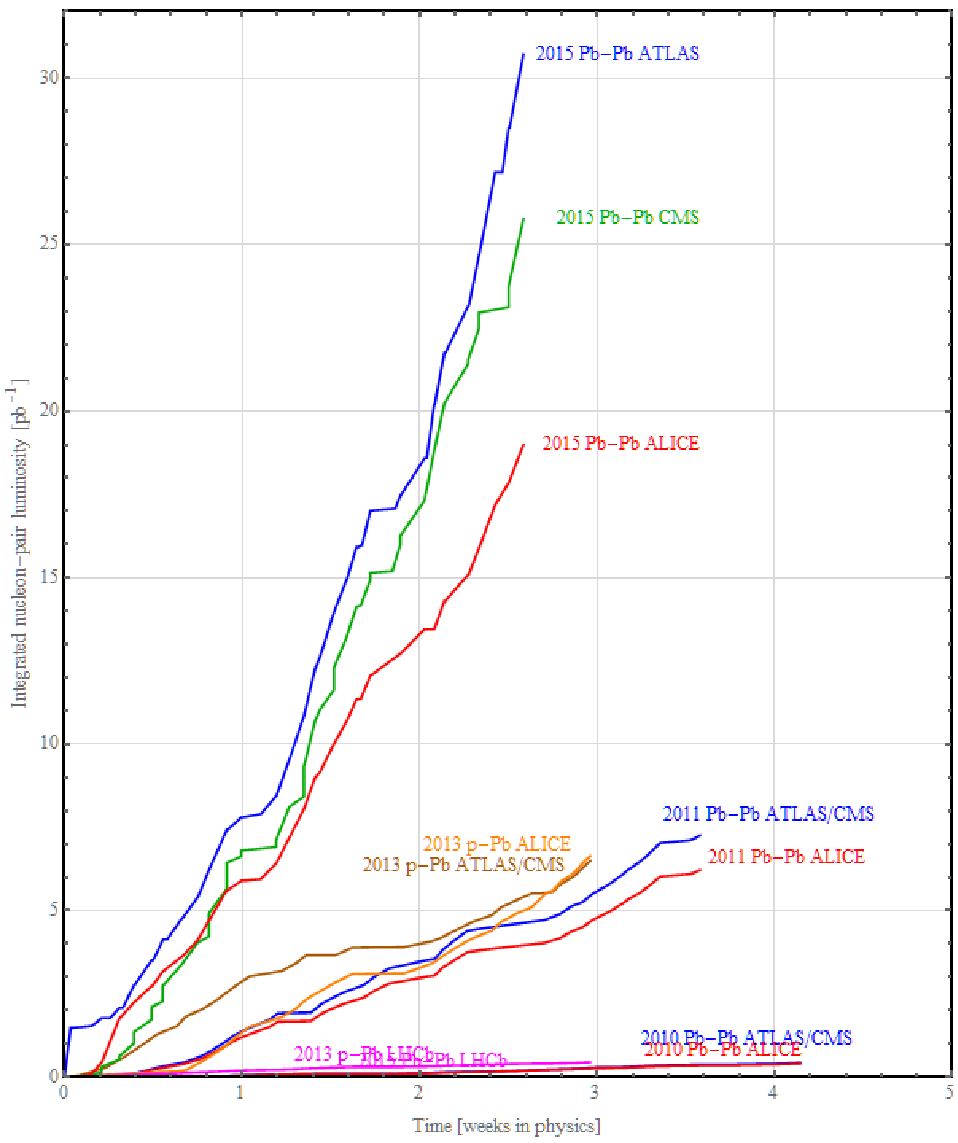
Expect to achieve LHC "first 10-year" baseline Pb-Pb luminosity goal of
1 AA nb^{-1} = 43 NN pb^{-1}
in Run 2 (=2015+2018)

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

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:

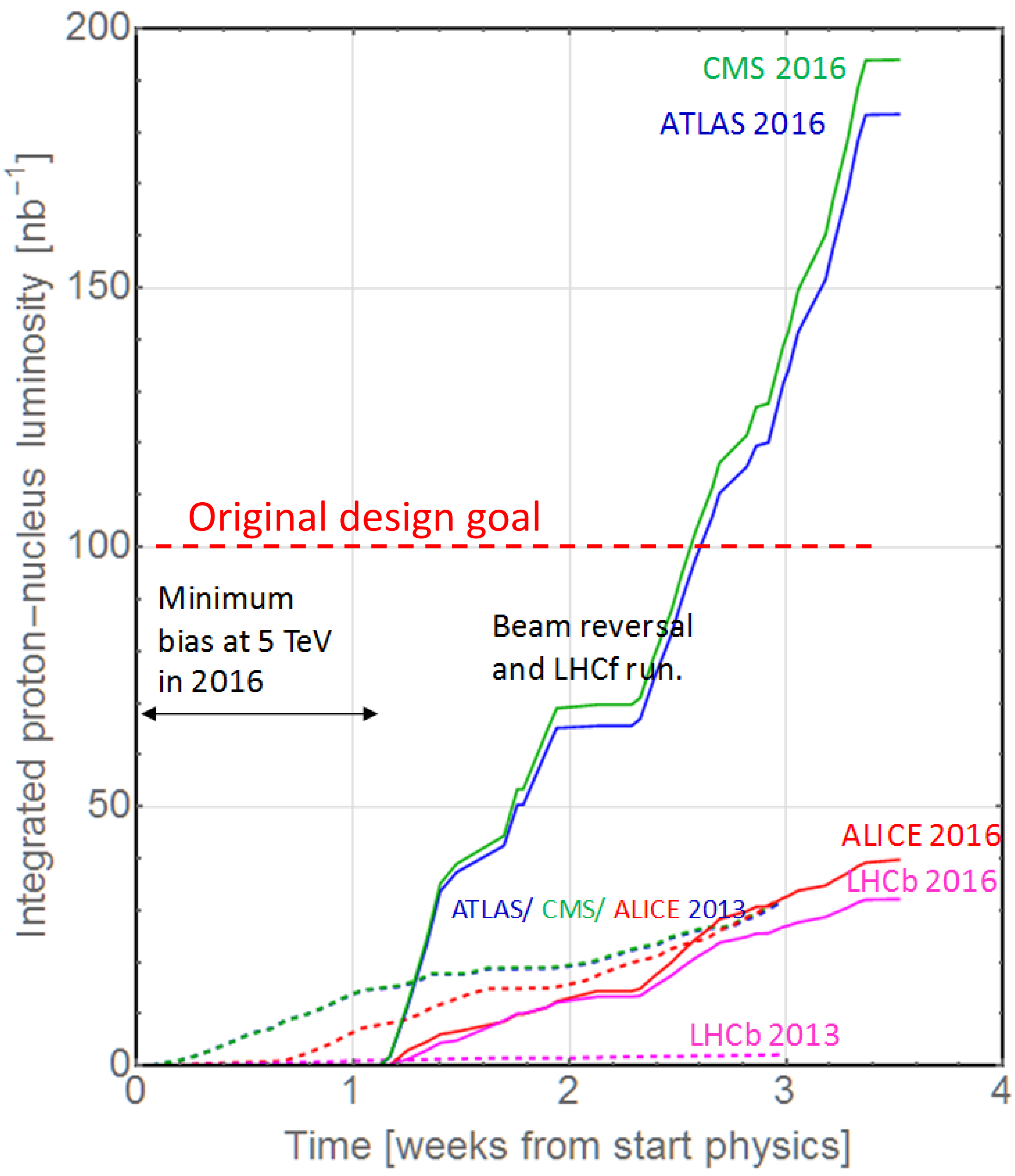
Minimum bias run at 4 Z TeV mainly for ALICE

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

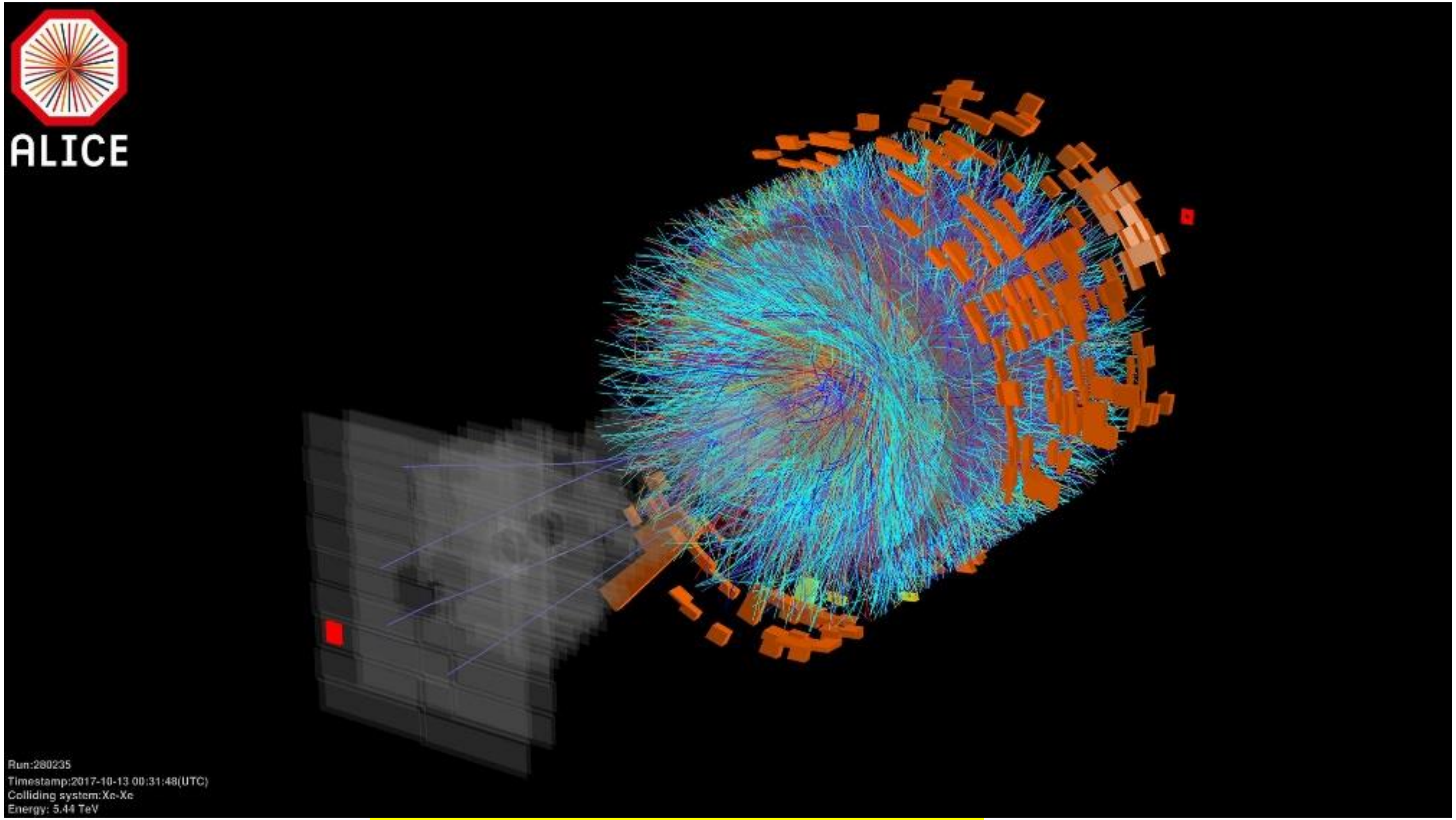
Ie, 2 new optics and 3 setups with full qualifications in 1 month.

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

Many filling schemes used for luminosity sharing.



Xe-Xe collisions in LHC, 13 October 2017 (16 h beam time total)



Future interest in lighter species

Papers at IPAC2018
http://accelconf.web.cern.ch/AccelConf/ipac2018/

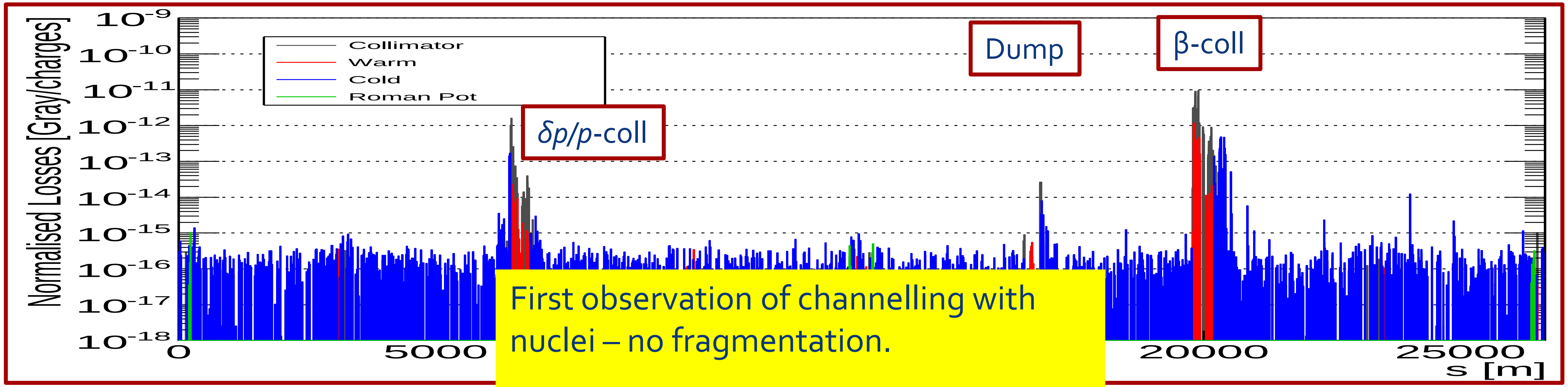
MOPMF039 M. Schaumann et al, First Xenon-Xenon Collisions in the LHC

MOPMF038 N. Fuster-Martinez et al, Cleaning Performance of the Collimation System with Xe Beams at the Large Hadron Collider

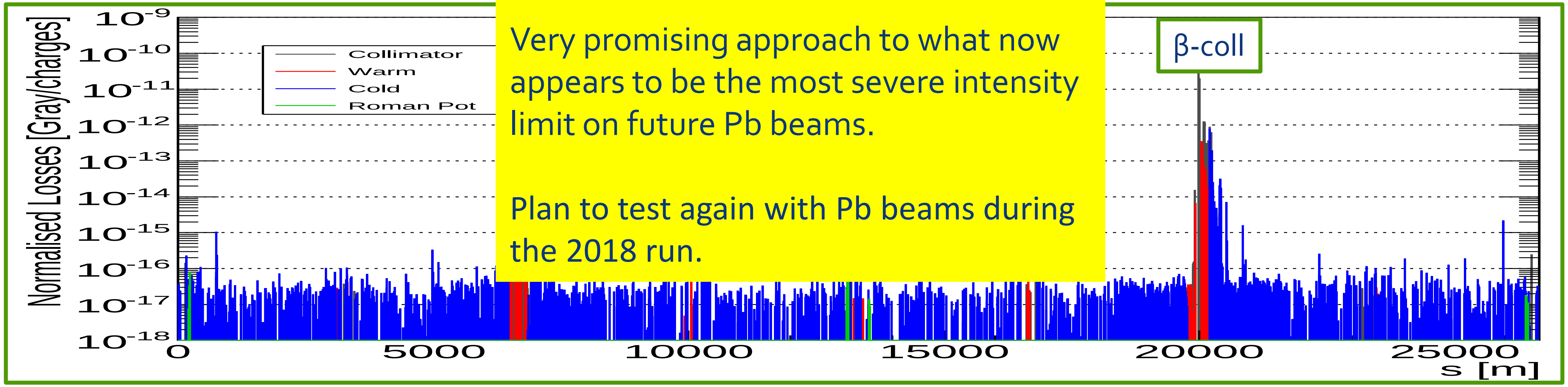
TUPAF020 R. Alemany-Fermandez et al, Performance of the CERN Low Energy Ion Ring (LEIR) with Xenon

Crystal Collimation Xenon Cleaning

Standard



Crystal



First observation of channelling with nuclei – no fragmentation.

Very promising approach to what now appears to be the most severe intensity limit on future Pb beams.

Plan to test again with Pb beams during the 2018 run.

Looking at loss maps along the ring: no dangerous peaks with crystal

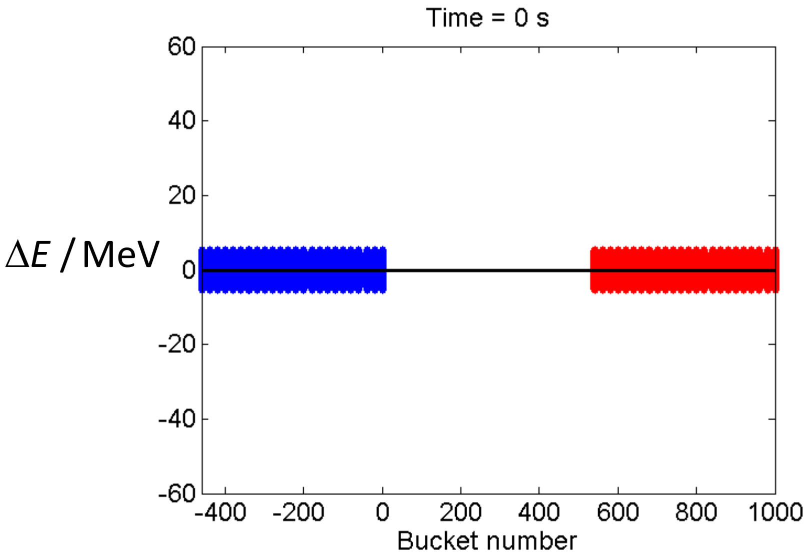
R. Rossi et al

FUTURE PERFORMANCE (RUN 3+HL-LHC) FULFILLING THE ALICE 2012 LOI

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.

SPS momentum slip stacking for 50 ns bunch spacing

- 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 (without intensity effects)
  - Longitudinal emittance blow-up (factor 2.5) at re-capture due to filamentation in large bucket
  - Bunch rotation at extraction becomes necessary for injection into LHC
  - Optimization of re-capture is crucial to keep losses <5%



H. Bartosik, Chamonix 2017

LIU baseline (Jan 2017) parameters at start of collisions

- Simplified scenario - see talk by H Bartosik, Chamonix 2017
  - All bunches are equal (consider single bunch pair simulation)
  - Initial bunch intensity (start of stable beams)

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

  - Initial emittance (start of stable beams)

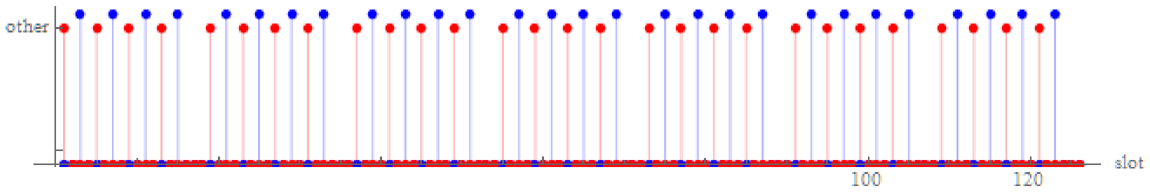
$$\varepsilon_{xn} = 1.65 \times 10^{-6}\text{m} \quad (> \text{design, some blow up from injected } 1.5 \times 10^{-6}\text{m })$$

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

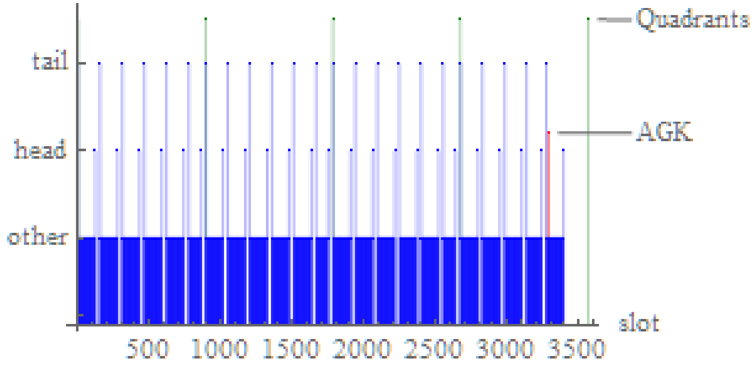
$$\beta^* = \begin{cases} (\infty, 0.5, \infty) & \text{m} \quad \text{(only ALICE colliding)} \\ (1.0, 0.5, 1.0) & \text{m} \quad \text{(ATLAS/CMS at half ALICE)} \\ (0.5, 0.5, 0.5) & \text{m} \quad \text{(equal)} \end{cases}$$

  - Some collisions in LHCb (not shown in detail)

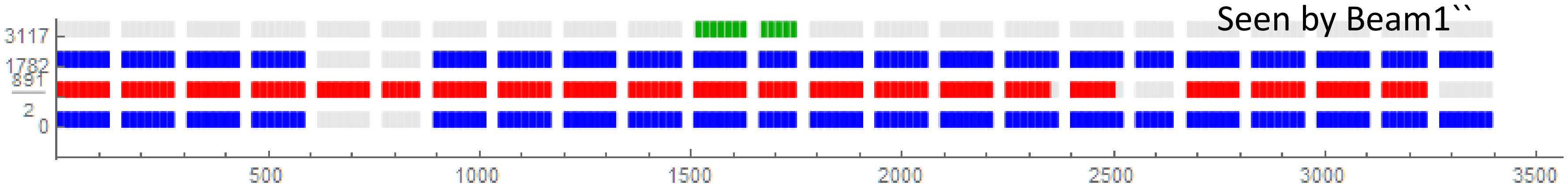
Filling scheme example for HL-LHC

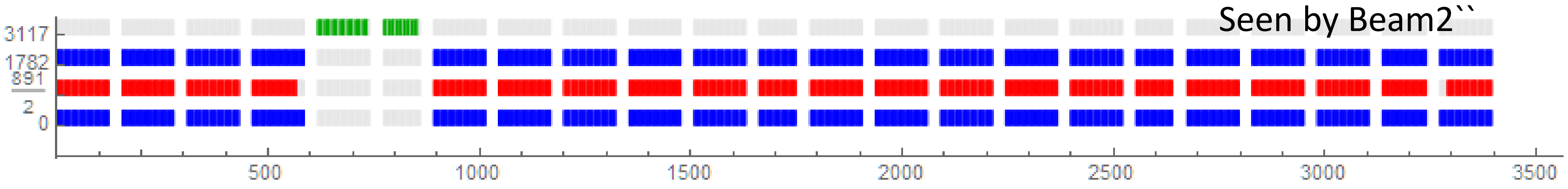


56 bunch SPS train
after slip-stacking



Displace two trains in Beam 2 to
make collisions in LHCb





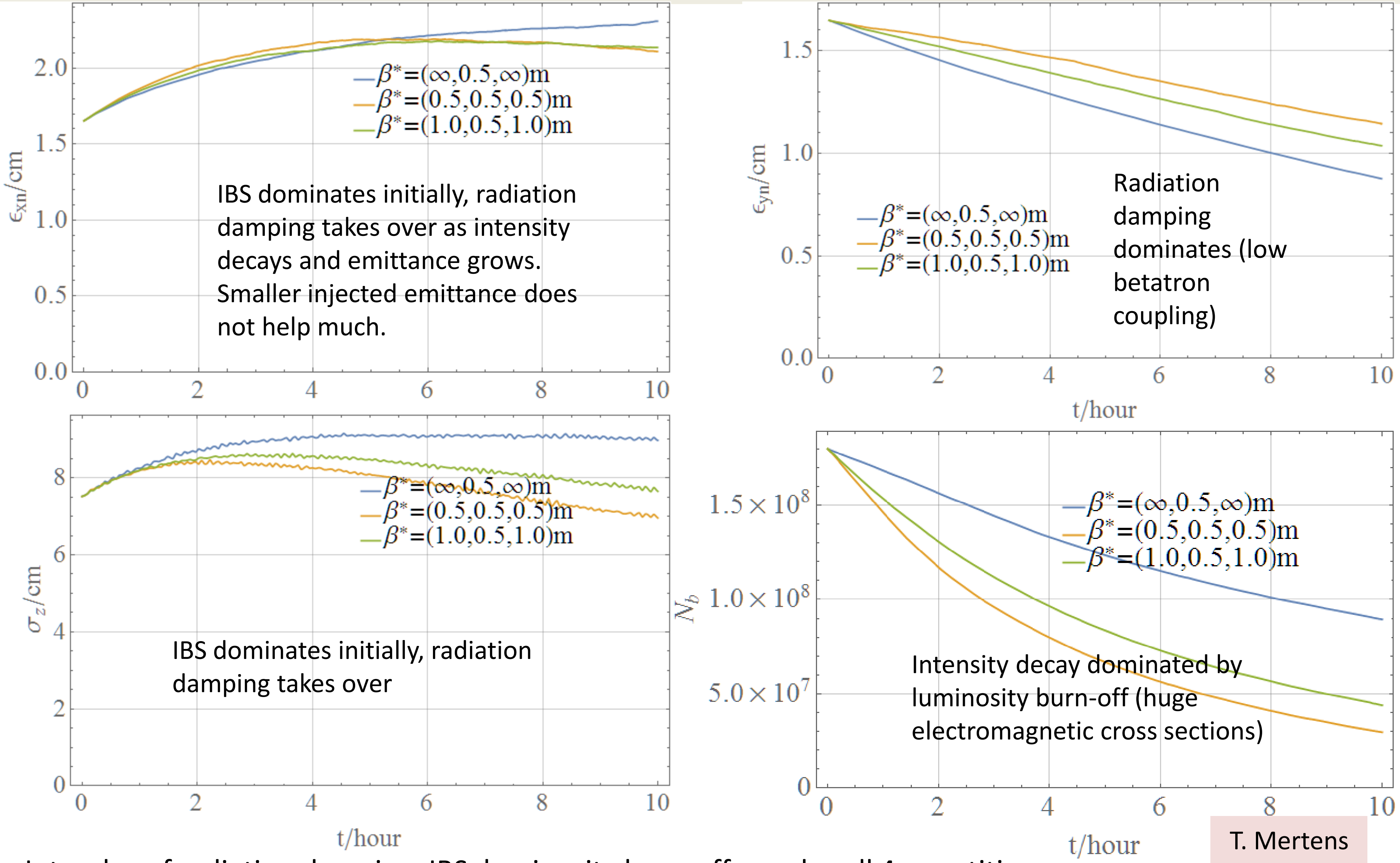
23 injections of 56-bunch trains give total of 1232 in each beam.
1136 bunch pairs collide in ATLAS CMS, 1120 in ALICE, 81 in LHCb (longer lifetime).

Optics compatibility with p-p operation

- ATS optics will be used for p-p operation
- The $\beta^*=0.5$ m values assumed for heavy-ion operation do not require ATS
  - Rather little gain from low β^* in high burn-off regime
- However to minimise set-up we can use essentially the same squeeze as ATS (telescopic part of squeeze has not started yet)
  - Interaction region squeeze sequences
  - Must add a squeeze of ALICE as usual
- Necessary functionality is included in ATS optics design
  - (Might consider further squeezing later.)

We will use this optics in 2018! Completely new optics cycle compared with p-p optics has (almost) been commissioned.

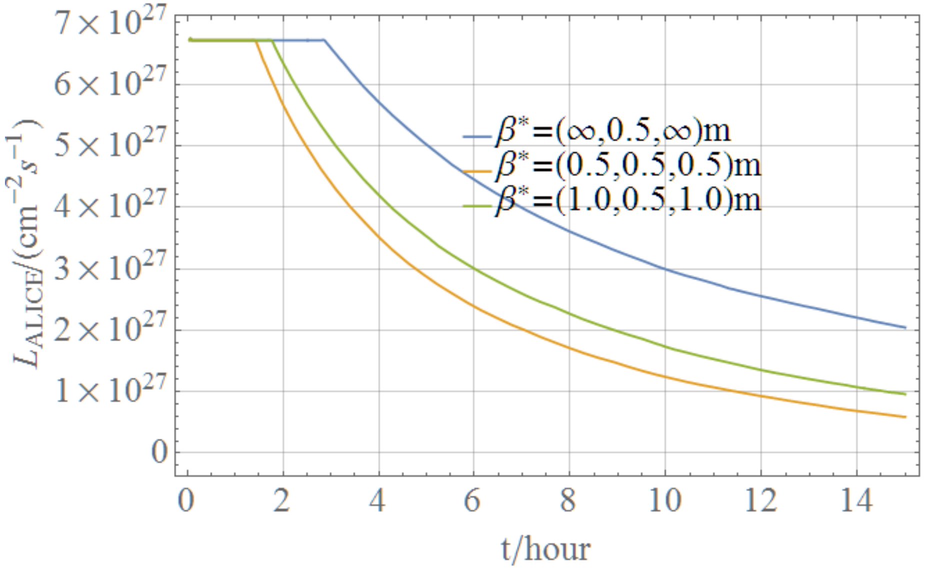
CTE Simulation of (most typical) colliding bunch pair



T. Mertens

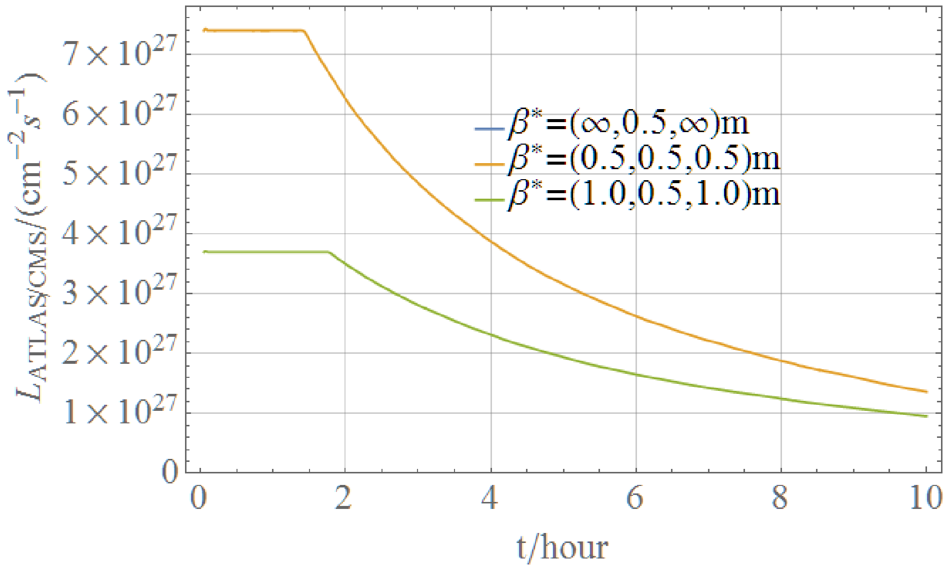
Interplay of radiation damping, IBS, luminosity burn-off couples all 4 quantities.
Different evolution according to luminosity-sharing scenario.
(Does not include additional emittance growth usually seen in operation.)

Luminosities in an ideal (prolonged) fill



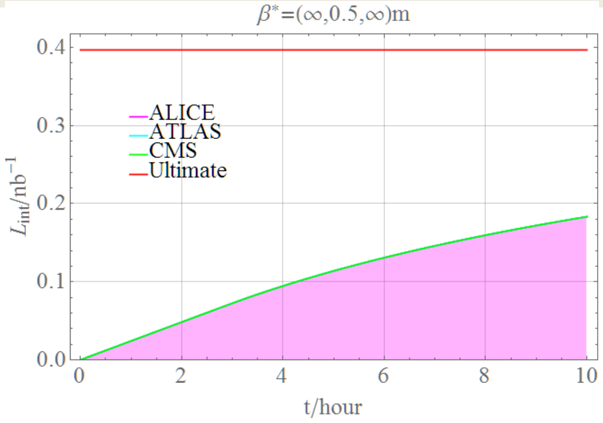
ALICE, levelling at maximum acceptable (rates around 50 kHz), assuming 1100 bunches colliding

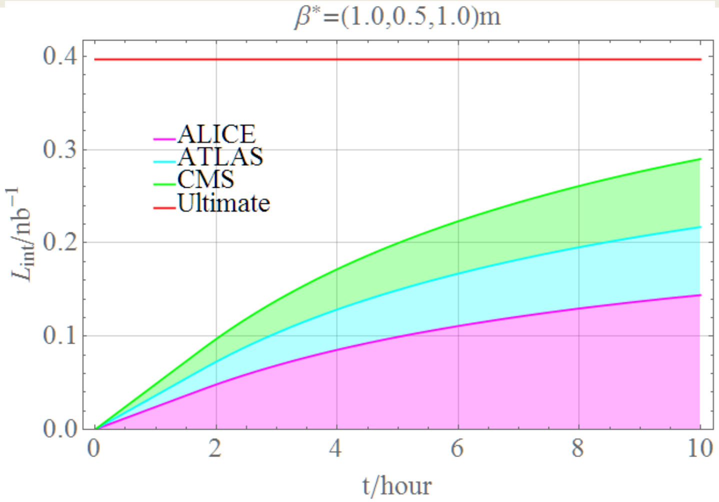
Baseline is the orange scenario with similar luminosities in 3 experiments.

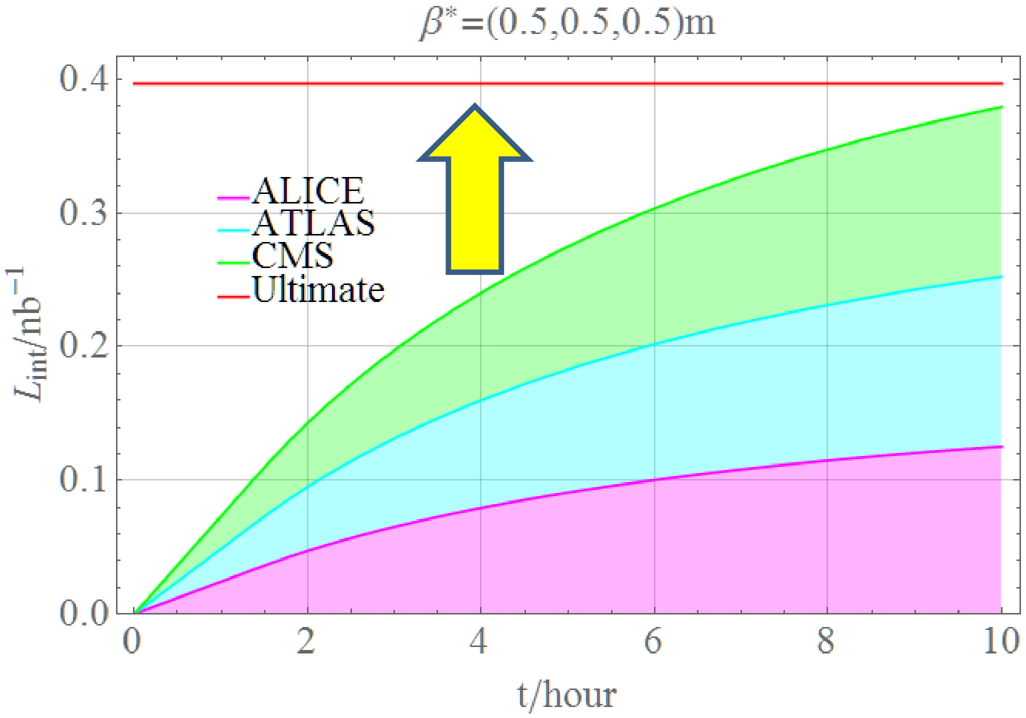


ATLAS or CMS, *assumed* levelling at similar levels to ALICE (not strictly necessary, just an assumption to simplify presentation).

Integrated luminosity in prolonged fills





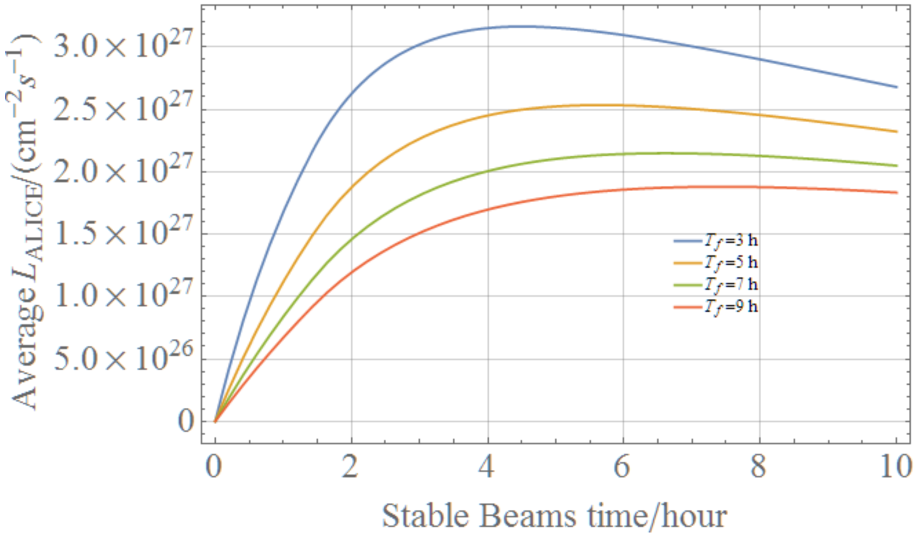


Ultimate luminosity to share

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

Fraction obtained is the luminous efficiency.

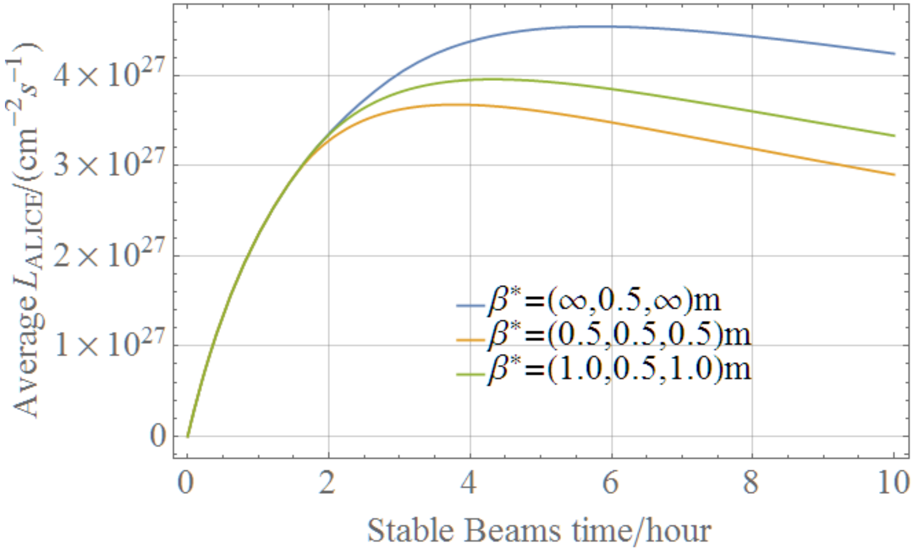
Effect of turn-around time on average luminosity



$$\langle L\rangle = \frac{1}{T_f + T_p}\int_0^{T_p} L(t)\,dt$$

$\beta^* = (0.5, 0.5, 0.5)$m (equal)

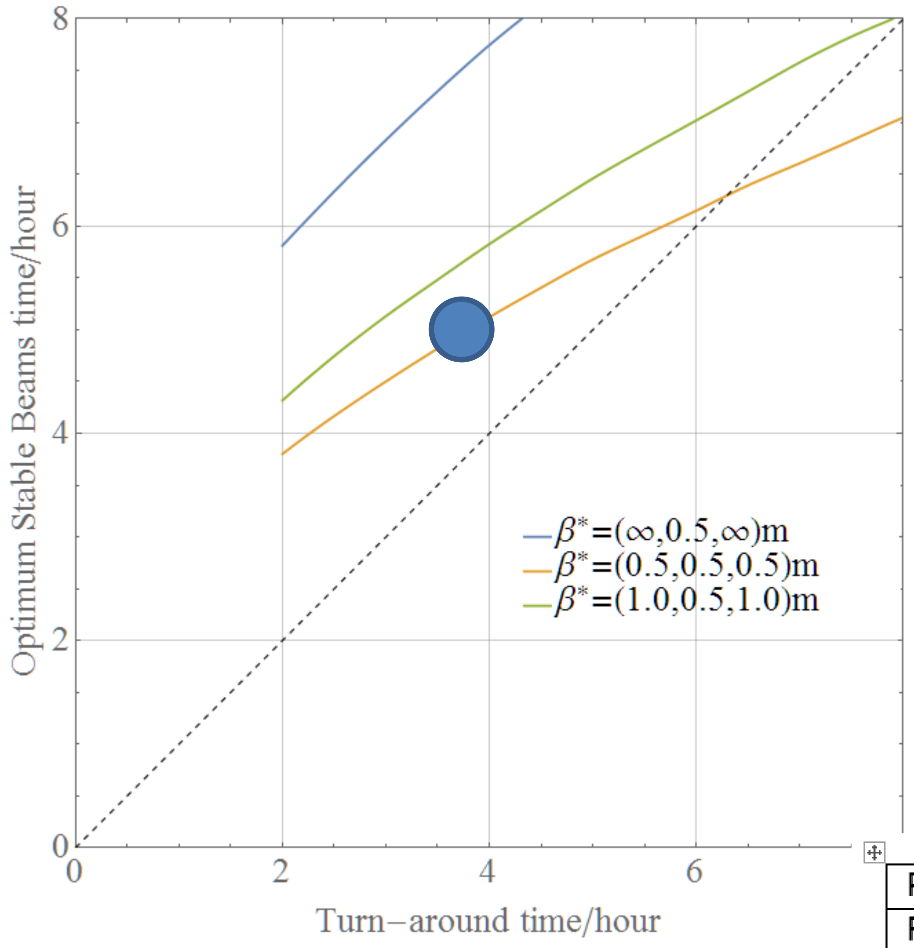
Turn around time =(3,5,7,9) h



Turn around time =3 h

Shown for each luminosity sharing scenario

Optimum time spent in Stable Beams



Assumes the operators know that the next turn-around time will be the same value.

Break-down of the minimum turn-around time as for p-p

Phase	Duration [min]
Ramp down/pre-cycle	60
Pre-injection checks and preparation	15
Checks with set-up beam	15
Nominal injection sequence	45
Ramp preparation	5
Ramp	25
Squeeze/Adjust	40
Total	200

Integrated luminosity in annual Pb-Pb run

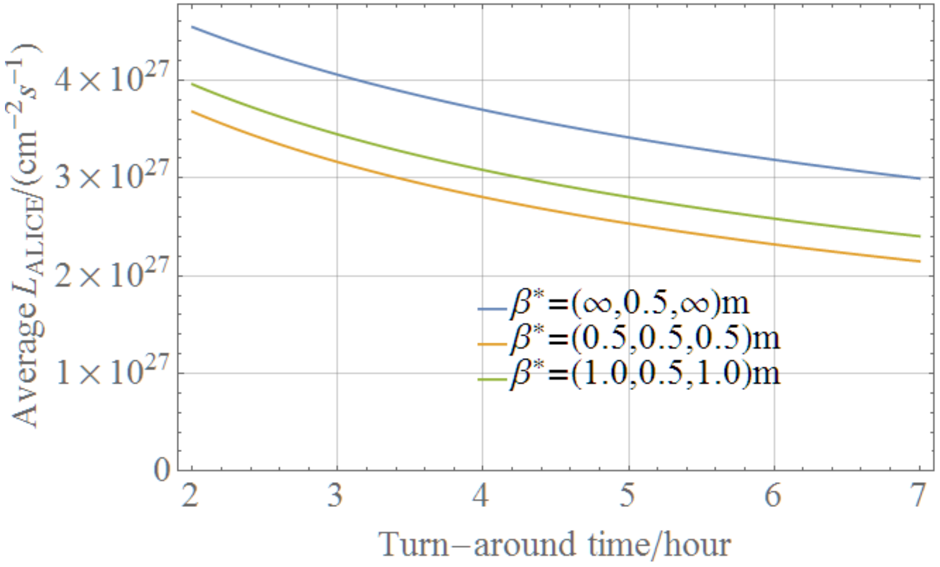
$\beta^* = (0.5, 0.5, 0.5)$ m scenario

$$L_{\text{int,annual}} = \eta \langle L \rangle T_{\text{run}}$$
$$= (50\%)(3.0 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1})(24\ \text{day})$$
$$\approx 3.1\ \text{nb}^{-1}\ \text{(c.f. target of 2.85 nb}^{-1})$$

where we (pessimistically!) assume an operational efficiency $\eta = 50\%$ and $T_{\text{run}} = 24$ day (i.e., no p-p reference run or similar).

Implies about 35 ideal fills (start-up absorbed in efficiency).

$\approx 12\ \text{nb}^{-1}$ in the 4 Pb-Pb runs foreseen after LS2.

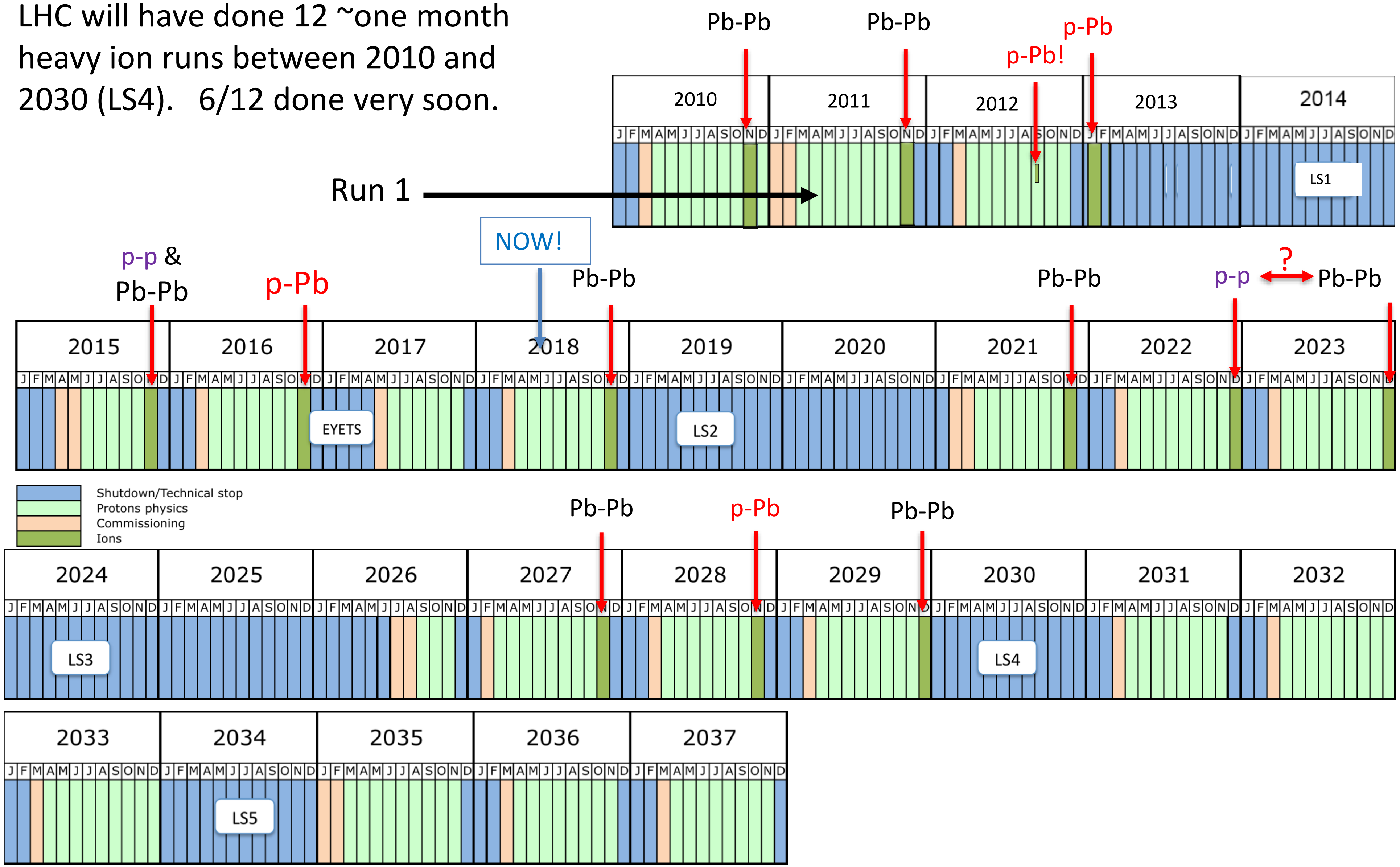


Operation efficiency in last Pb-Pb run in 2015 was 62%. Even higher in 2016 p-Pb.

Similar analysis for p-Pb suggests ~ 1 pb^{-1} is possible in a full one-month run.

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). 6/12 done very soon.



UPC processes at the collision point

BFPP: $^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{208}Pb^{81+} + e^{+},$

$\sigma = 281 \text{ b}, \quad \delta = 0.01235$

EMD1: $^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{207}Pb^{82+} + n\ ,$

$\sigma = 96 \text{ b}, \quad \delta = -0.00485$

EMD2: $^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{206}Pb^{82+} + 2n\ ,$

$\sigma = 29 \text{ b}, \quad \delta = -0.00970$

Strong luminosity burn-off of beam intensity.

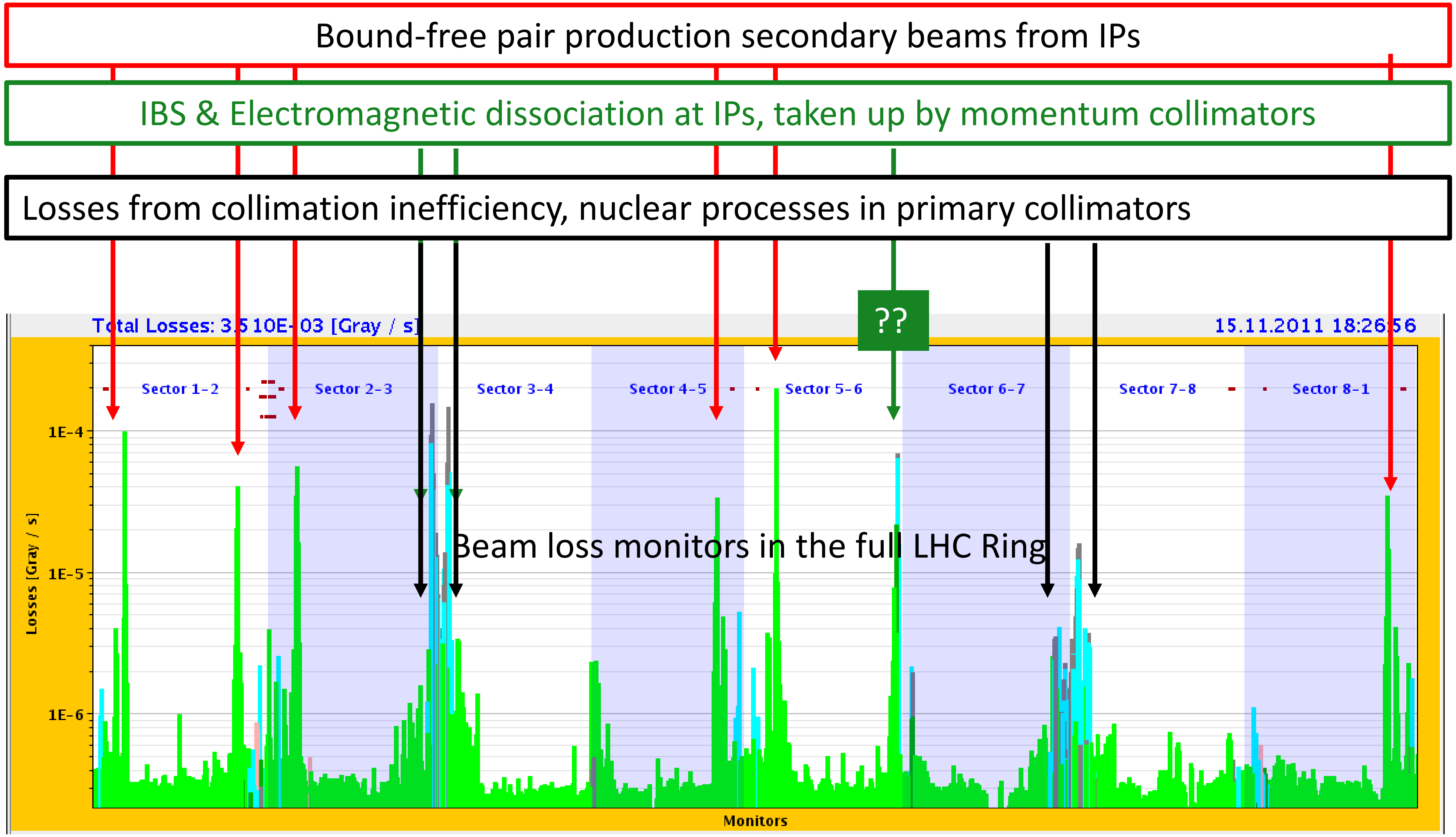
Each of these makes a secondary beam emerging from the IP with rigidity change that may quench bending magnets.

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

Discussed for LHC since Chamonix 2003 … see several references.

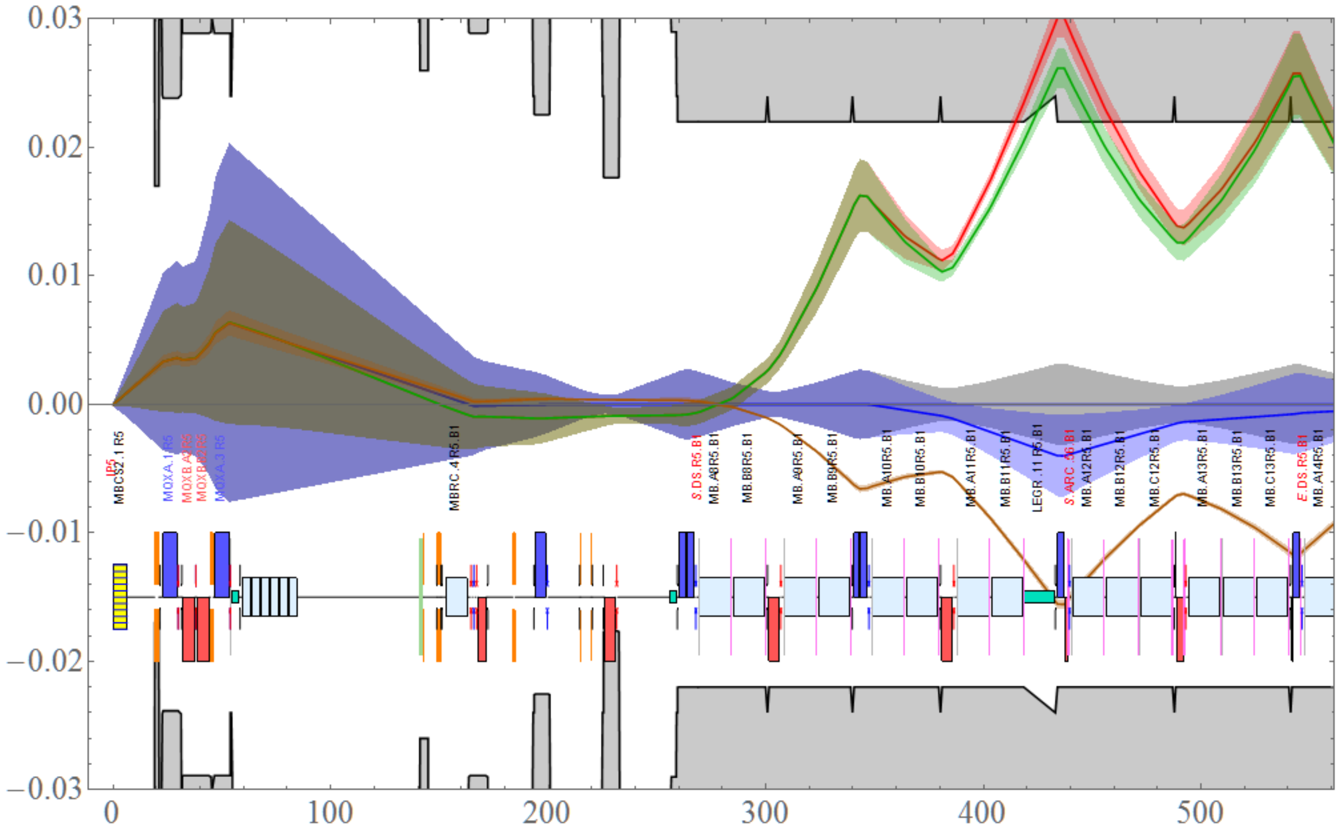
Hadronic cross section is 7.7 b (so luminosity debris contains much less power).

Steady-state losses during Pb-Pb Collisions in 2011



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

Orbit bumps mitigate BFPP for CMS (or ATLAS)

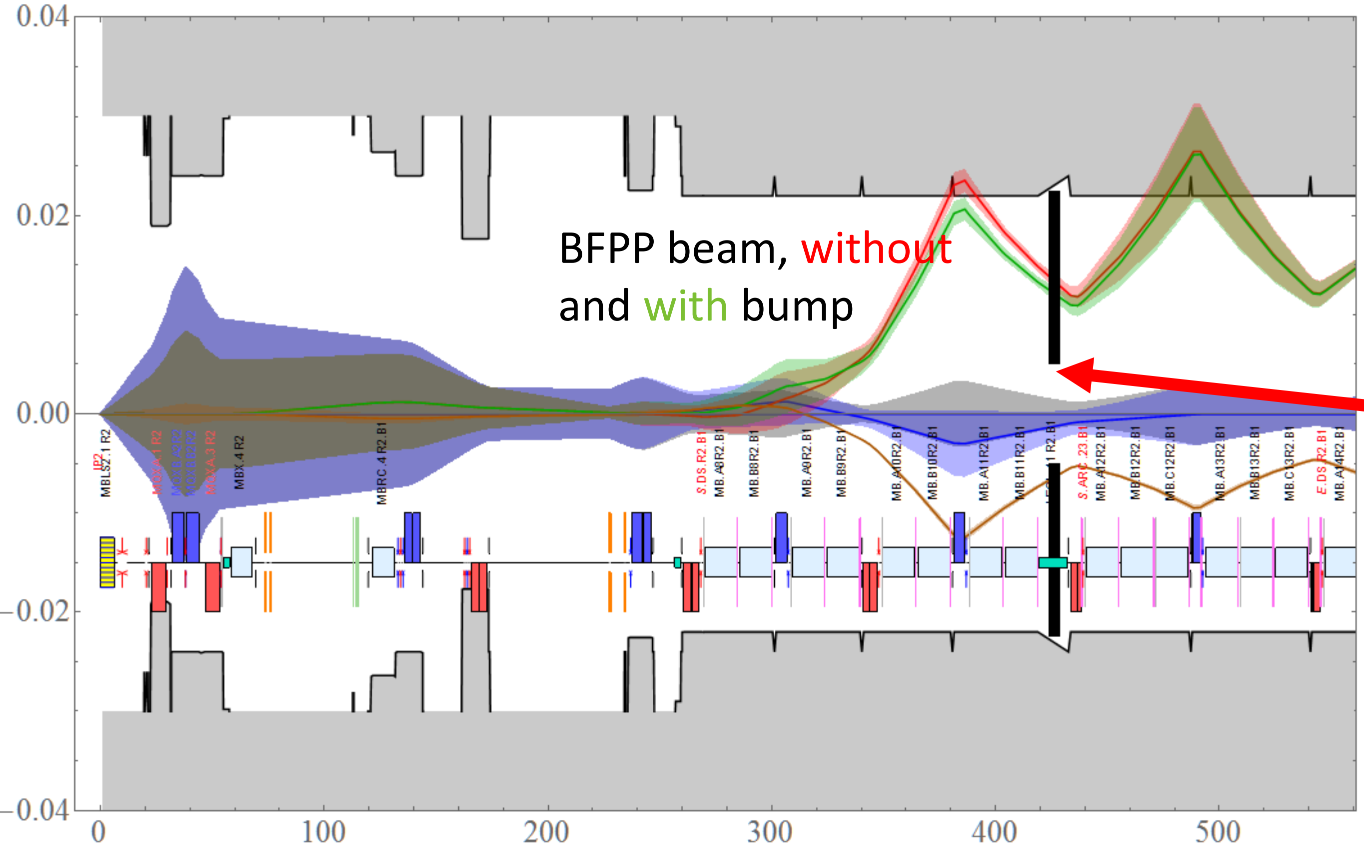


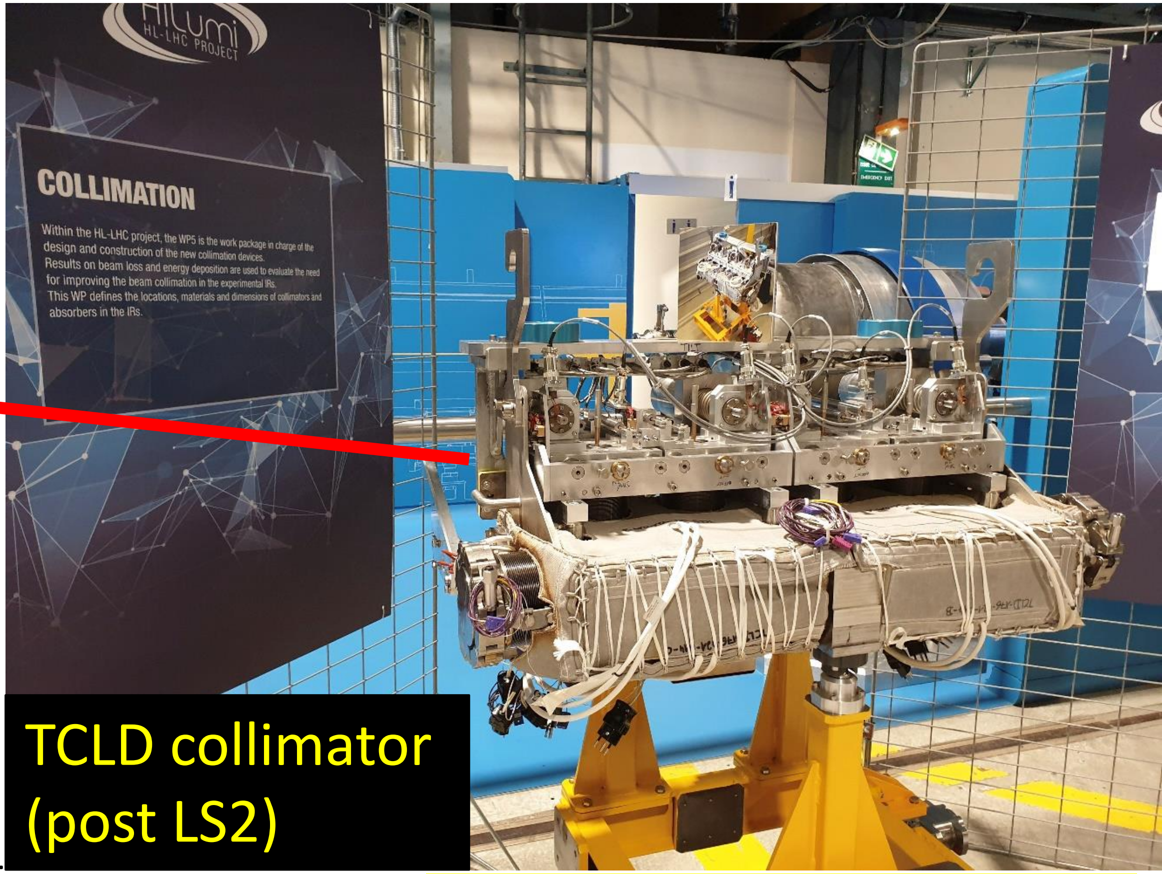
BFPP beam, without and with bump

Plan to test this strategy further to fully validate the nominal HL-LHC levelled luminosity at ATLAS/CMS during the 2018 run (no further mitigation upgrades are planned for these experiments).

- 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





TCLD collimator (post LS2)

- 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
- **TCLDs should allow luminosity increase for upgraded ALICE to run at at 50 kHz**

Also during LS2, further TCLD collimators will be installed between 11 T magnets in IR7 to improve Pb collimation (first application of Nb_3Sn superconductors in an operating accelerator).

BEYOND HL-LHC BASELINE: LIGHTER NUCLEI

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!
For Pb-Pb they are a bit more optimistic than HL-LHC baseline.

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, J. 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

Don't go too low in Z with this!
Not everything in the periodic table will work well in the ion source.

UPC cross sections determining intensity burn-off

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

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

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

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

List of species are examples that are of interest.

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

Noble 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
$^{16}O^{8+}$	3800.	0.074	0.000024	1.4	1.5
$^{40}Ar^{18+}$	3400.	1.2	0.0069	2.6	3.8
$^{40}Ca^{20+}$	3800.	1.6	0.014	2.6	4.2
$^{78}Kr^{36+}$	3500.	12.	0.88	4.1	17.
$^{84}Kr^{36+}$	3200.	13.	0.88	4.3	18.
$^{129}Xe^{54+}$	3100.	52.	15.	5.7	73.
Pb^{82+}	3000.	220.	280.	7.8	510.

Higher nucleon-nucleon luminosity with lighter ions

- Extrapolations of present experience to possible future fully-prepared "one-month run" conditions with lighter species.
- Preliminary estimates for a range of the scaling factor *p*. $p = 1.5$ seems reasonable.
- Detailed operational cycles to be worked out.
- Longer fills from smaller UPC cross-sections. Plus: more luminosity events are hadronic.
- Possible limits from collimation losses, radio-protection in Linac3/LEIR (lightest species), etc, are still to be properly analysed on species-by-species basis.

Higher nucleon-nucleon luminosity with lighter ions

- Extrapolations of present experience to possible future fully-prepared "one-month run" conditions with lighter species.
  - No discussion of calendar here.
- Simplified comparatives estimates for a range of the scaling factor p. p = 1.5 seems reasonable.
- Detailed operational cycles to be worked out.
- Longer fills from smaller UPC cross-sections. Plus: more luminosity events are hadronic.
- Possible limits from collimation losses, radio-protection in Linac3/LEIR (lightest species), etc, are still to be properly analysed on species-by-species basis.

Time-averaged nucleon-nucleon luminosity wrt Pb-Pb

Simplified scenario:

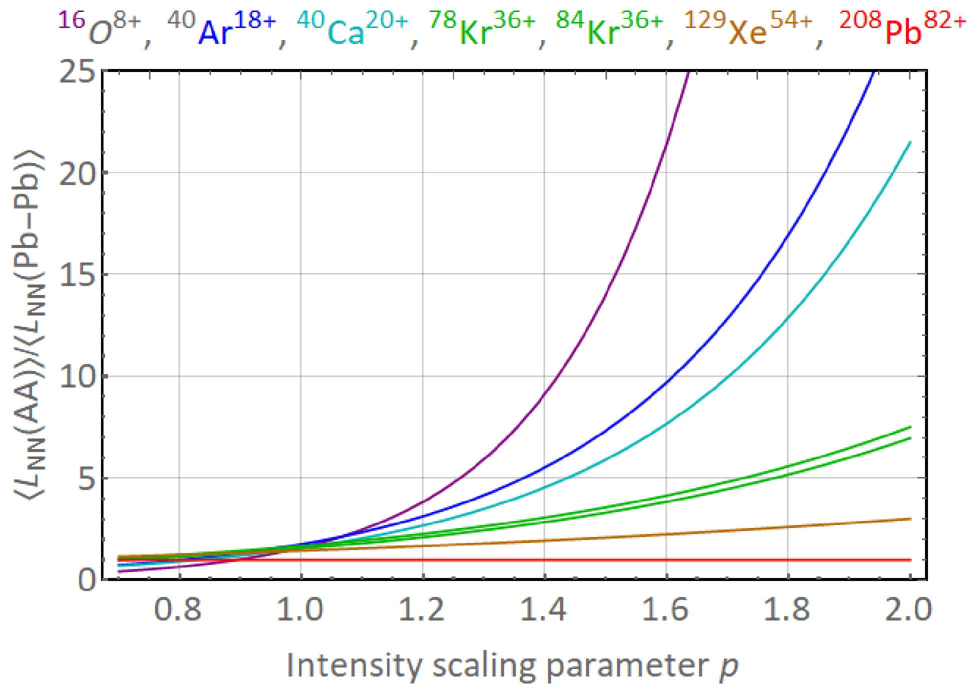
Fill lengths optimized for 2.5 h turn-around (dump to next Stable Beams).

Analytical estimates assuming beam losses dominated by luminosity burn-off (no simulations of other physics as for canonical Pb-Pb projections).

Assume 3 experiments taking full luminosity - **no levelling of any experiment!**

Overall operational efficiency factor 50% (standard HL-LHC assumption).

Gives reasonable indication of potential increase in integrated NN-luminosity from lighter species.



Pessimistic "no-gain" scaling (p=1)

	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{84}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
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	1.95×10^9	8.66×10^8	7.79×10^8	4.33×10^8	4.33×10^8	2.89×10^8	1.9×10^8
$\epsilon_{xn}/\mu m$	2.	1.8	2.	1.85	1.71	1.67	1.58
f_{IBS}/(m Hz)	0.0207	0.0419	0.0517	0.086	0.0798	0.117	0.167
W_b/MJ	21.5	21.5	21.5	21.5	21.5	21.5	21.5
$L_{AA0}/cm^{-2}s^{-1}$	1.43×10^{30}	2.82×10^{29}	2.29×10^{29}	7.06×10^{28}	7.06×10^{28}	3.14×10^{28}	1.36×10^{28}
$L_{NN0}/cm^{-2}s^{-1}$	3.66×10^{32}	4.52×10^{32}	3.66×10^{32}	4.3×10^{32}	4.98×10^{32}	5.22×10^{32}	5.88×10^{32}
P_{BFPP}/W	0.000302	0.0392	0.0738	2.51	2.51	28.6	350.
P_{EMD1}/W	0.485	3.63	4.12	17.8	19.2	50.5	141.
τ_{L0}/h	52.4	45.4	46.5	20.4	19.1	7.23	1.57
T_{opt}/h	16.2	15.1	15.2	10.1	9.78	6.01	2.8
$\langle L_{AA}\rangle/cm^{-2}s^{-1}$	1.07×10^{30}	2.08×10^{29}	1.69×10^{29}	4.54×10^{28}	4.48×10^{28}	1.57×10^{28}	3.8×10^{27}
$\langle L_{NN}\rangle/cm^{-2}s^{-1}$	2.74×10^{32}	3.33×10^{32}	2.7×10^{32}	2.76×10^{32}	3.16×10^{32}	2.6×10^{32}	1.64×10^{32}
$\int_{month} L_{AA}\,dt/nb^{-1}$	1390.	269.	219.	58.8	58.1	20.3	4.92
$\int_{month} L_{NN}\,dt/pb^{-1}$	356.	431.	350.	358.	410.	338.	213.
R_{had}/kHz	2020.	734.	595.	286.	301.	178.	106.
μ	0.16	0.0583	0.0472	0.0227	0.0239	0.0141	0.00842

Stored energy in beam W_b is identical in this case $\Rightarrow$ Collimation risks ~ comparable.
f_{IBS} indicates strength of IBS emittance growth – all cases better than Pb.
Overestimates integrated luminosity for Pb-Pb wrt official values (since no levelling, etc).
Initial event rates are high! Much longer fills.

Plausible scaling (p=1.5)

	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{84}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
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

Stored energy in beam W_b increased in this case $\Rightarrow$ Collimation risks higher

f_{IBS} indicates strength of IBS emittance growth – still better than Pb.

NB still no luminosity levelling, etc. High event rates! Some pileup μ ~1. Fills still longer.

Optimistic scaling (p=1.9)

	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{84}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
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	1.58×10^{10}	3.39×10^{9}	2.77×10^{9}	9.08×10^{8}	9.08×10^{8}	4.2×10^{8}	1.9×10^{8}
ϵ_{xn} /μm	2.	1.8	2.	1.85	1.71	1.67	1.58
f_{IBS} /(m Hz)	0.168	0.164	0.184	0.18	0.167	0.17	0.167
W_b /MJ	175.	84.3	76.6	45.2	45.2	31.4	21.5
L_{AA0} /$cm^{-2}s^{-1}$	9.4[illegible]$\times10^{31}$	4.33×10^{30}	2.9×10^{30}	3.11×10^{29}	3.11×10^{29}	6.66×10^{28}	1.36×10^{28}
L_{NN0} /$cm^{-2}s^{-1}$	2.4[illegible]$\times10^{34}$	6.93×10^{33}	4.64×10^{33}	1.89×10^{33}	2.19×10^{33}	1.11×10^{33}	5.88×10^{32}
P_{BFPP} /W	0.0199	0.601	0.935	11.	11.	60.6	350.
P_{EMD1} /W	32.	55.6	52.2	78.3	84.4	107.	141.
τ_{L0} /h	6.45	11.6	13.1	9.74	9.12	4.96	1.57
T_{opt} /h	5.68	7.62	8.08	6.98	6.75	4.98	2.8
$\langle L_{AA}\rangle$ /$cm^{-2}s^{-1}$	4.54×10^{31}	2.45×10^{30}	1.69×10^{30}	1.68×10^{29}	1.66×10^{29}	2.95×10^{28}	3.8×10^{27}
$\langle L_{NN}\rangle$ /$cm^{-2}s^{-1}$	1.16×10^{34}	3.93×10^{33}	2.71×10^{33}	1.02×10^{33}	1.17×10^{33}	4.91×10^{32}	1.64×10^{32}
$\int_{month} L_{AA}\,dt$ /nb^{-1}	53900.	3180.	2190.	218.	215.	38.2	4.92
$\int_{month} L_{NN}\,dt$ /pb^{-1}	15100.	5090.	3510.	1330.	1510.	636.	213.
R_{had} /kHz	133000.	11200.	7540.	1260.	1320.	378.	106.
μ	10.6	0.893	0.598	0.1	0.105	0.03	0.00842

Stored energy in beam W_b several times Pb $\Rightarrow$ Collimation risks higher, may need new solutions

f_{IBS} indicates strength of IBS emittance growth – comparable to Pb.

NB still no luminosity levelling, etc. High event rates! Some pileup μ ~1. Fills still longer.

Caveats about lighter species

- Collimation is more complicated, needs careful study
  - See first measurements with Xe vs. Pb in MOPMF038 paper in IPAC2018
  - Simulations done for Ar, Xe (by Pascal Hermes) have not yet included effects of DS collimators in IR7.
    - Planned for study (N. Fuster-Martinez)
  - Crystal collimation (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 Pb intensity in 2015-16 were the result of many detailed studies and improvements.

Special runs with other species

- The 2012 p-Pb run and the 2017 Xe-Xe run used a special rapid-commissioning strategy to go from scratch to physics delivery in a 16 h shift.
  - Limits on total stored energy in beam to avoid lengthy validation.
  - May have to use the operational p-p optics (not so good for ALICE)
- Other short runs can be envisaged within these constraints
- Example of current interest
  - O-O run: needs to be separated in time from Pb-Pb to allow lengthy switchover of ion source and injector chain.   Springtime of a typical year?
  - Could be followed by short p-O run of interest for cosmic ray physics

Conclusions

- It has been possible to rapidly recommission the LHC in multiple new heavy-ion configurations very efficiently and substantially exceed design performance.
- The baseline performance goals for Pb-Pb integrated luminosity from the ALICE LoI of 2012 appear to be within reach by end of Run 4
  - Most features 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.
- Scope for special short runs (O-O,p-O, …) at small cost in LHC time and within certain limits of intensity and scheduling.

BACKUP SLIDES

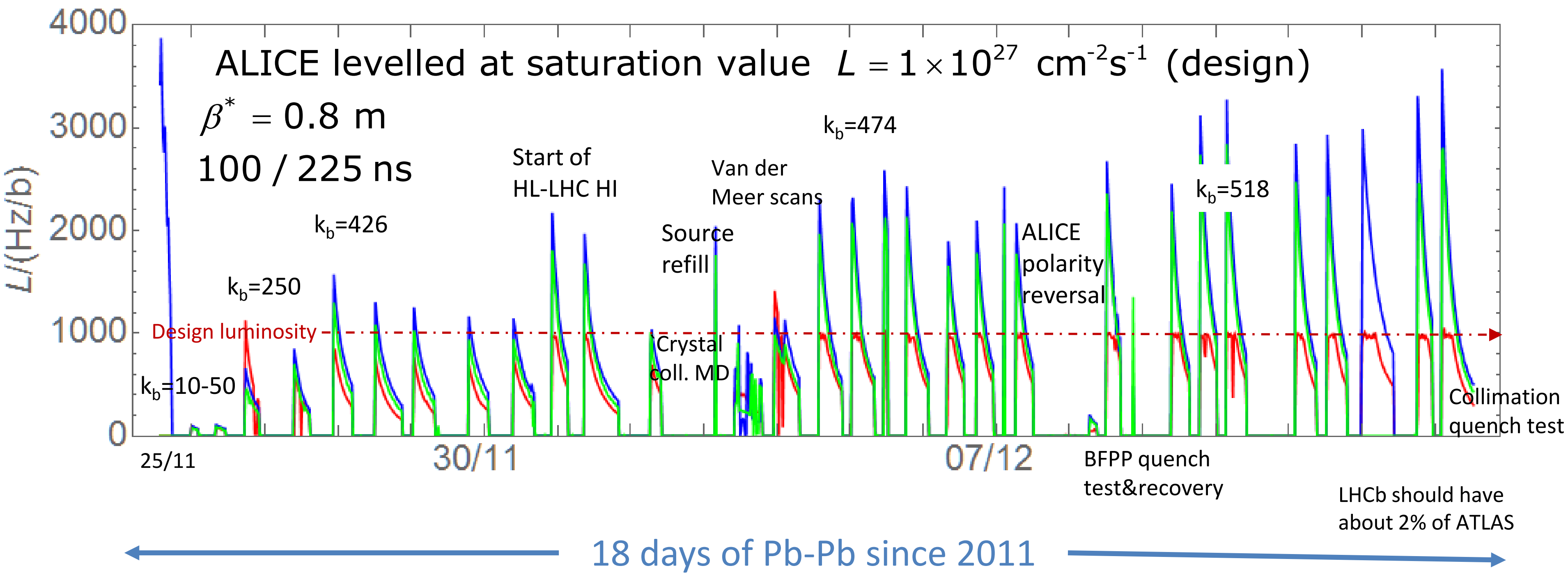
References in these slides

- 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://accelconf.web.cern.ch/AccelConf/ipac2018/
- Fairly comprehensive list of references on LHC heavy ion programme to date in IPAC2018 survey talk **TUXGBD2**

Summary (from QM2018)

- 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.

Pb-Pb peak luminosity at 3×design in 2015



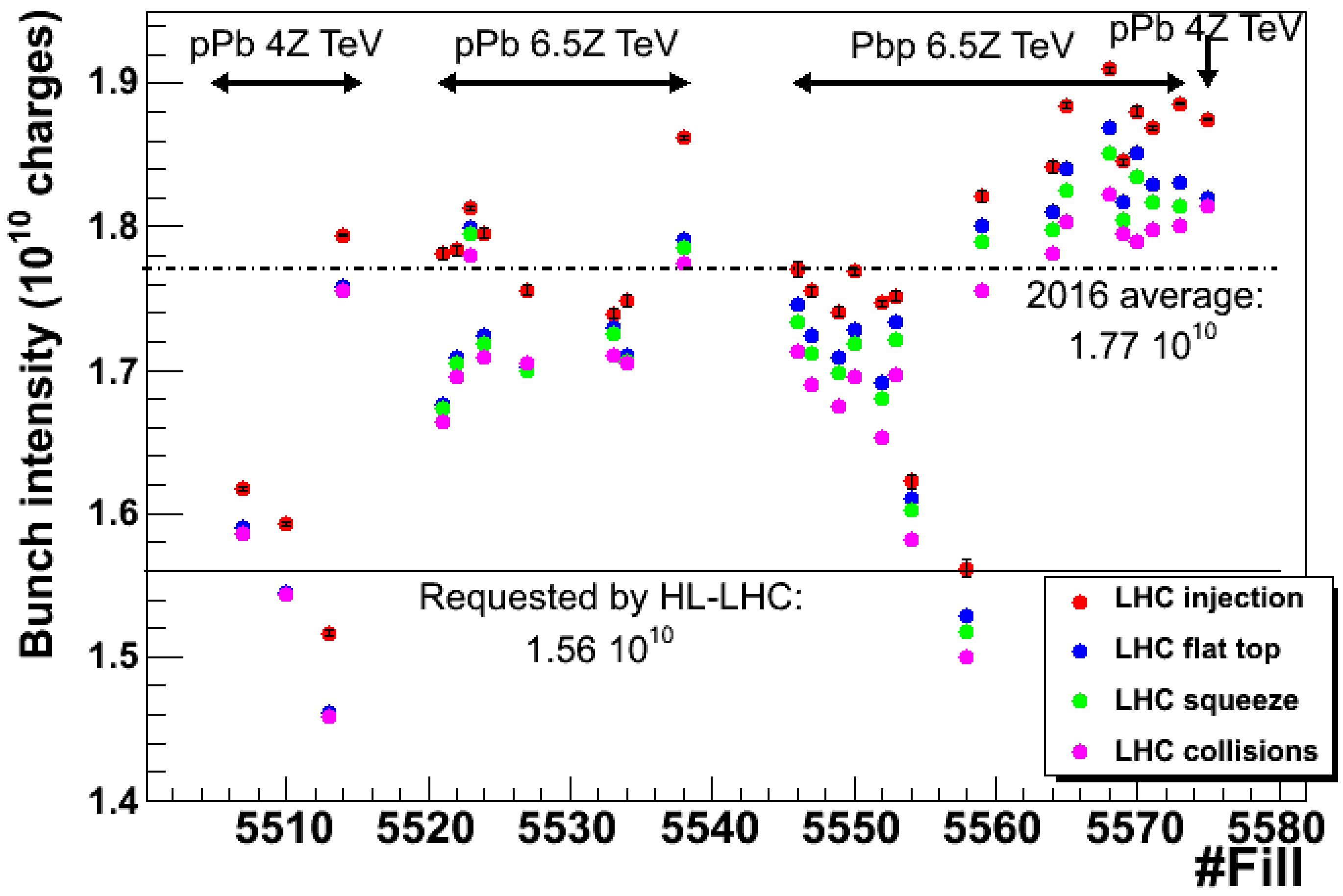
Heavy-ion runs of LHC are very short but very complex.
Experiments have many requests for changes of conditions.

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.

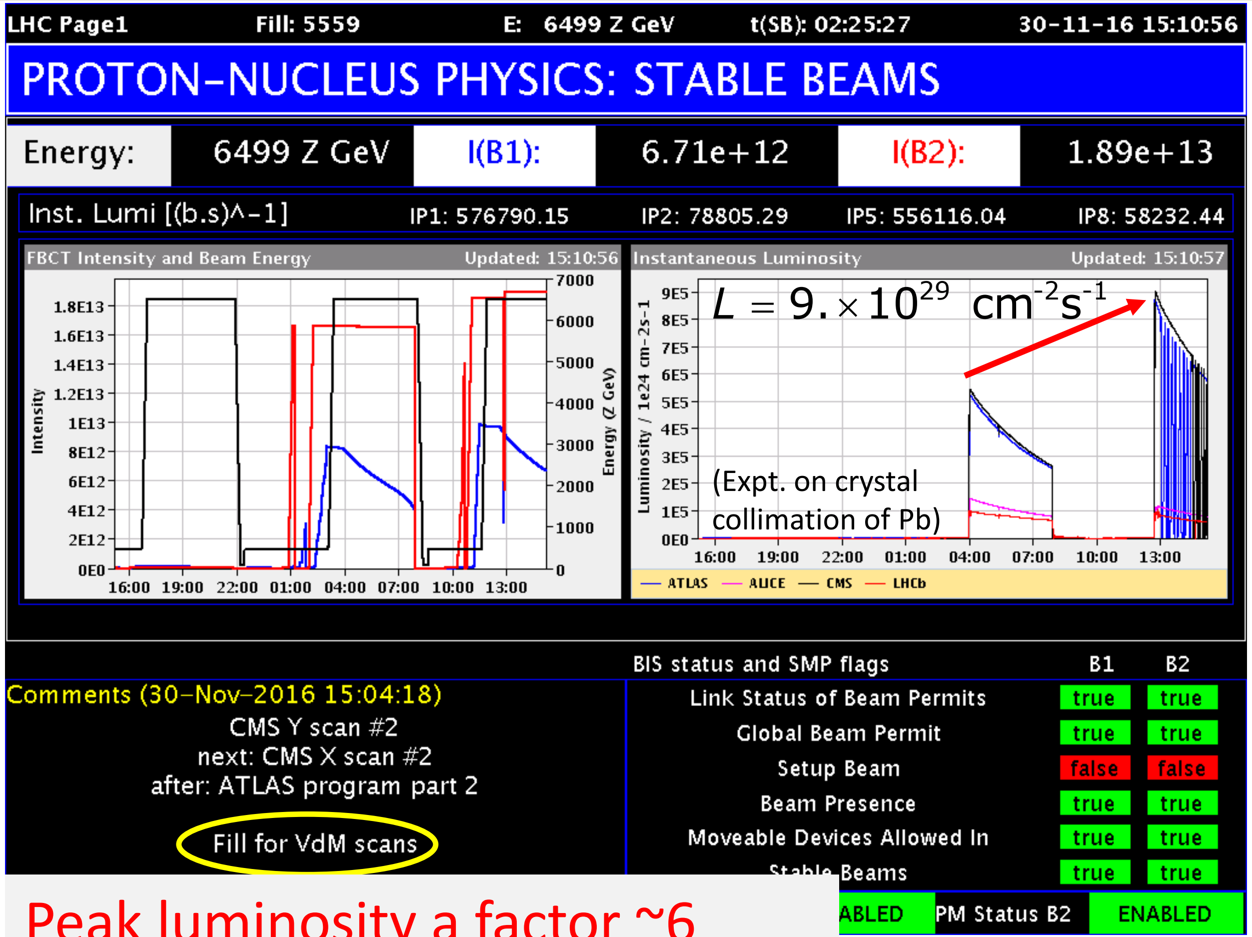
25/11

Pb bunch intensity in LHC during 2016 p-Pb run



R. Alemany, M. Schaumann

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.

Duration of Xe run

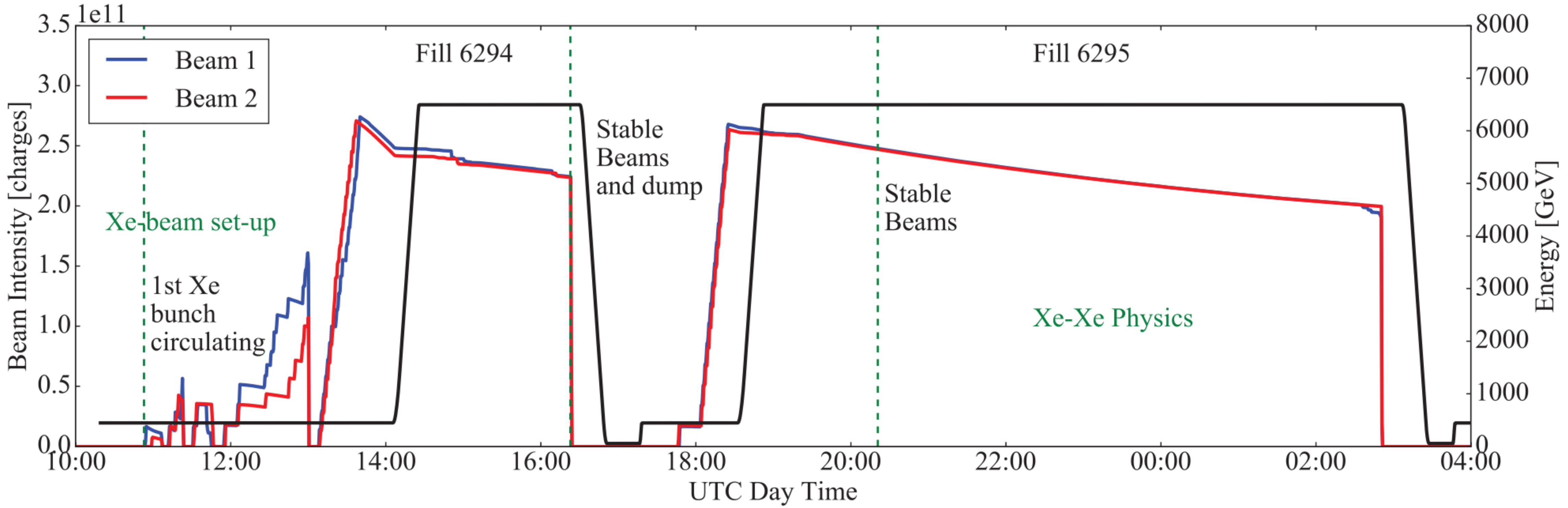


Figure 1: Evolution of the beam intensity and energy throughout the Xe–Xe run.

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

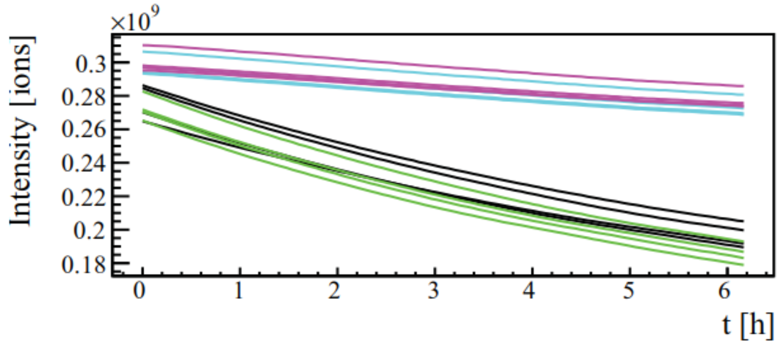


Figure 3: Bunch-intensity evolution of Beam 1 during fill 6295 after declaration of Stable Beams. The colour of each class is listed in Table 2.

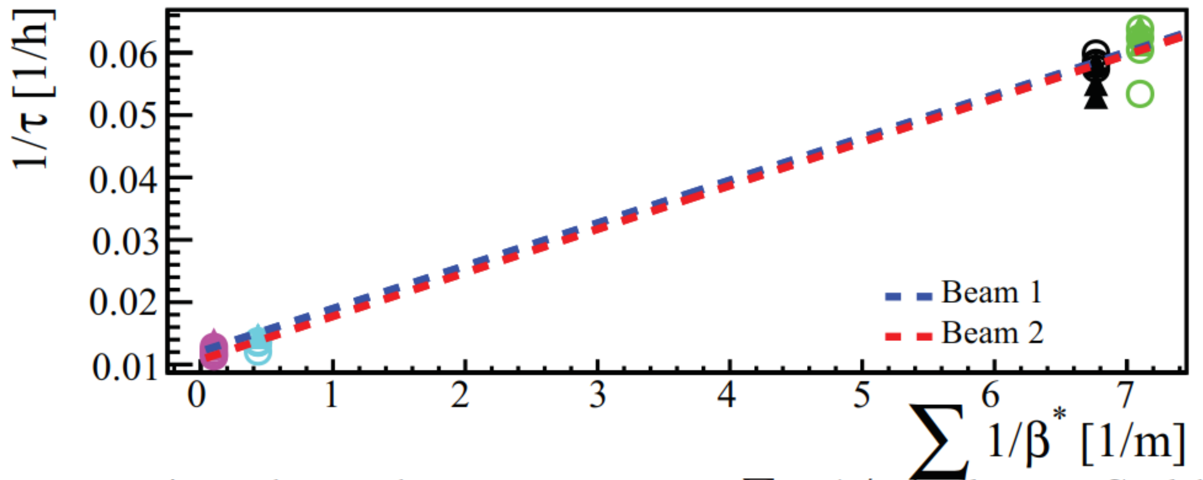


Figure 4: Relative loss rates versus $\sum_{\mathrm{IP}} 1/\beta^*_{\mathrm{IP}}$ during Stable Beams of fill 6295. Triangles indicate Beam 1 and circles Beam 2. The dashed lines are linear fits to obtain the non-colliding intensity lifetime.

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).

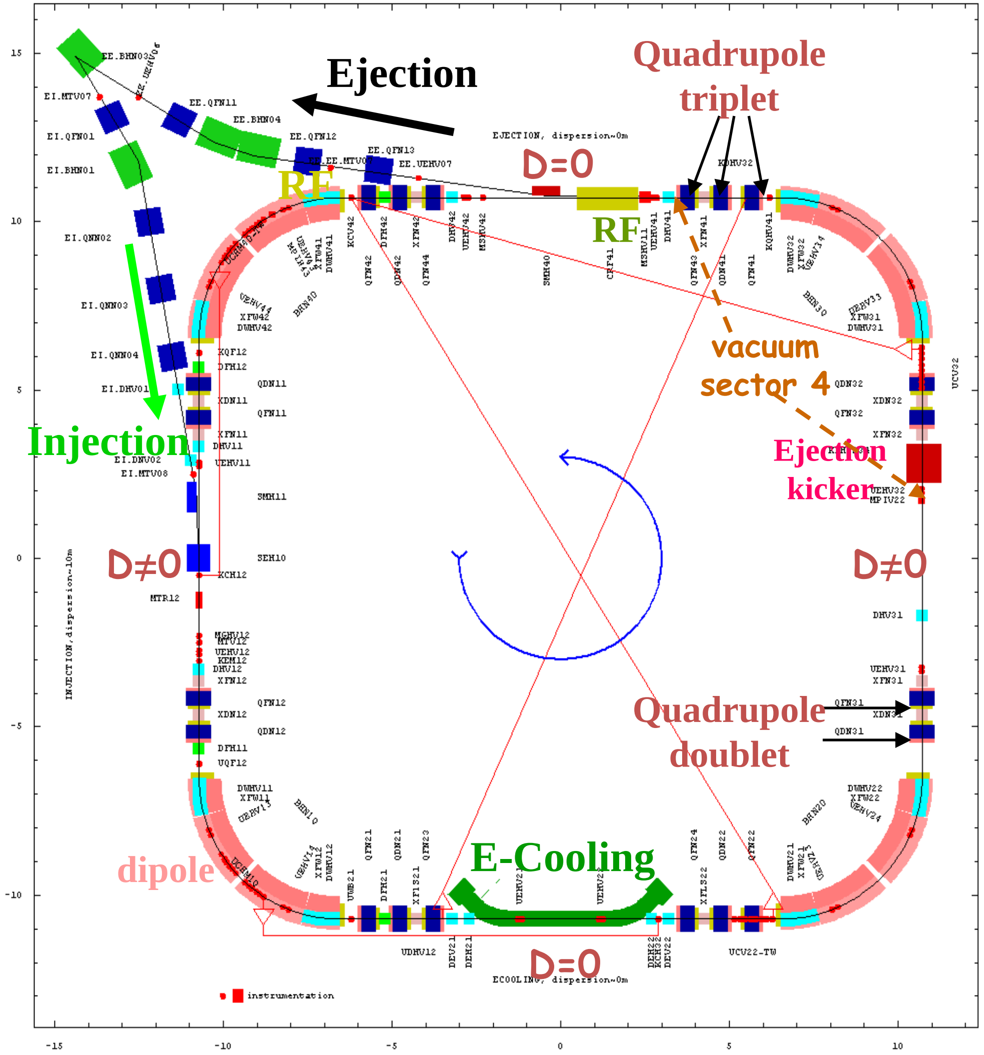
Analysis by Marc Jebramcik, Michaela Schaumann. See IPAC2018 paper.

Conclusions

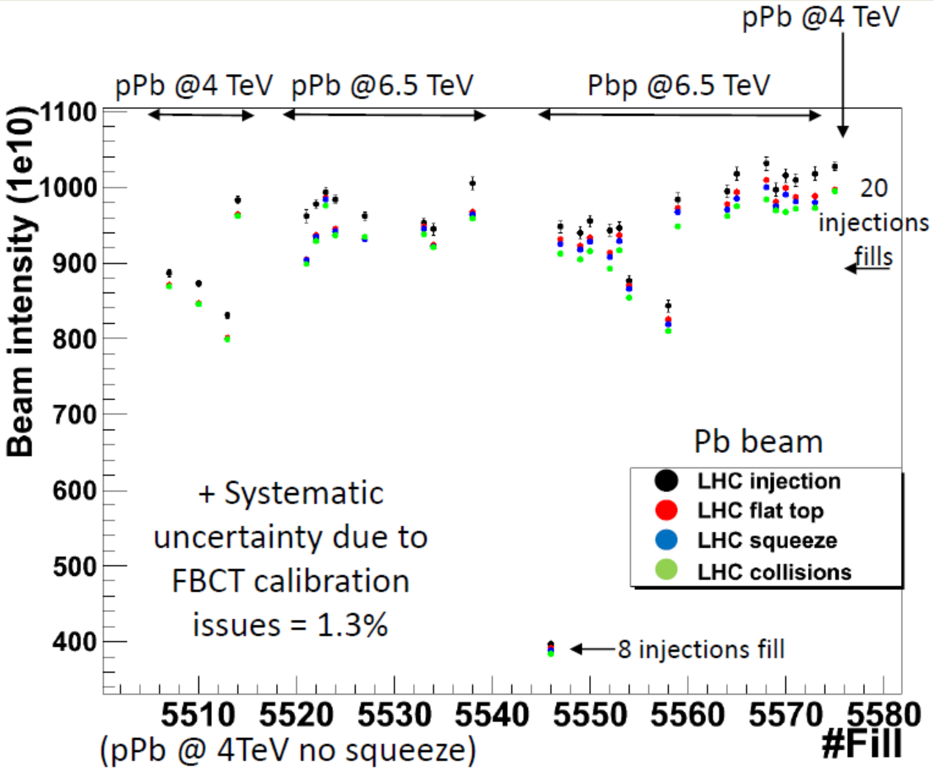
- It has been possible to rapidly recommission the LHC in multiple new configurations very efficiently.
- The baseline performance goals for Pb-Pb integrated luminosity from the ALICE LoI of 2012 appear to be within reach
  - Most of them already available for 2018 Pb-Pb run
  - Greatest remaining uncertainties: 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).

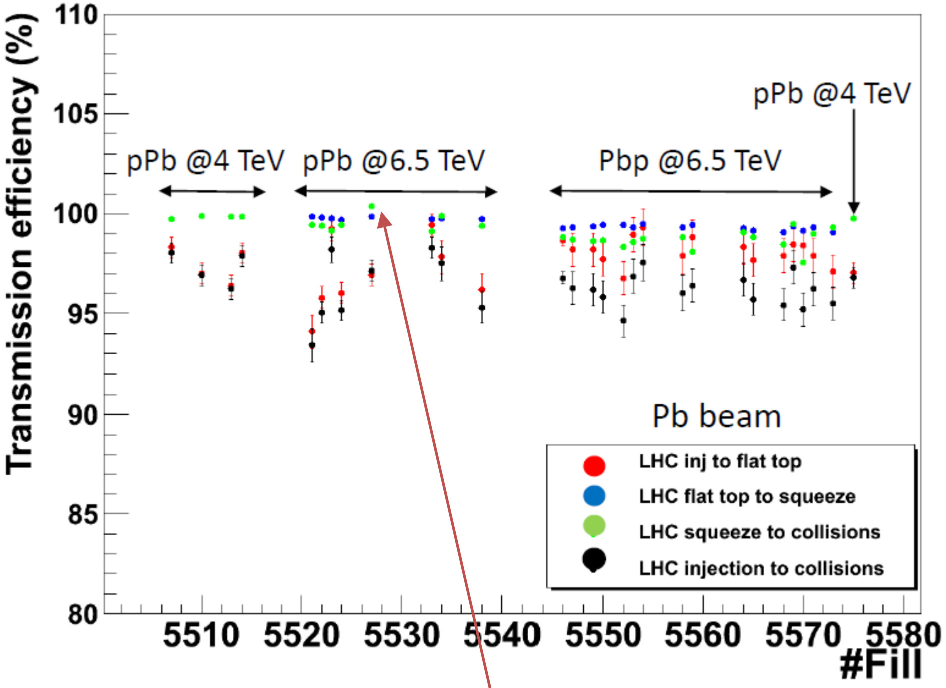
LEIR (Low-Energy Ion Ring)

- 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%).

>100% due to FBCT re-calibration

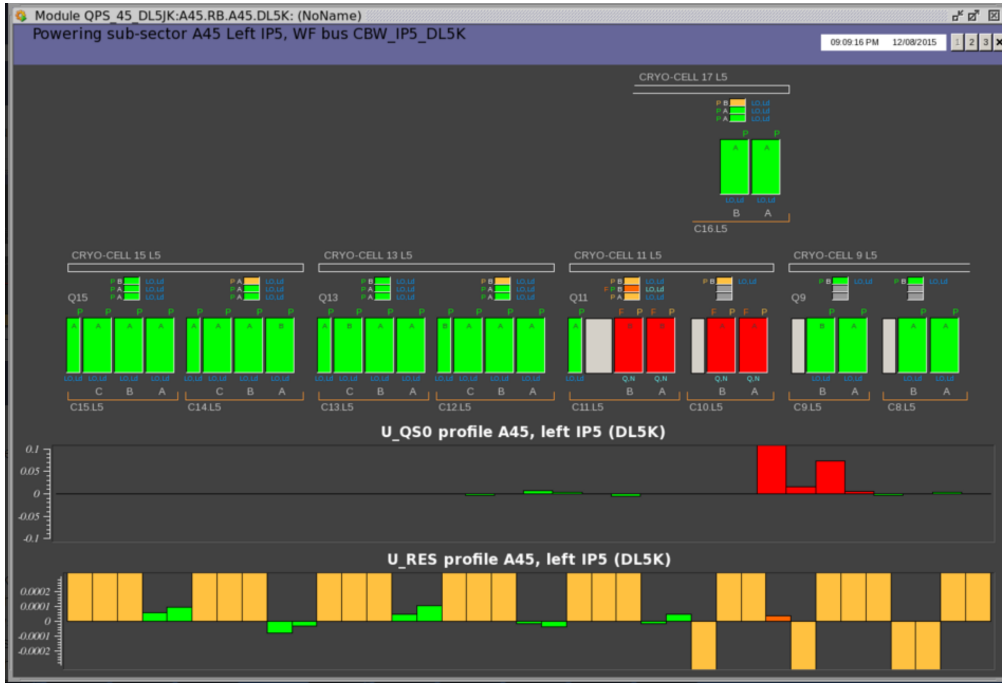
R. Alemany, M. Schaumann

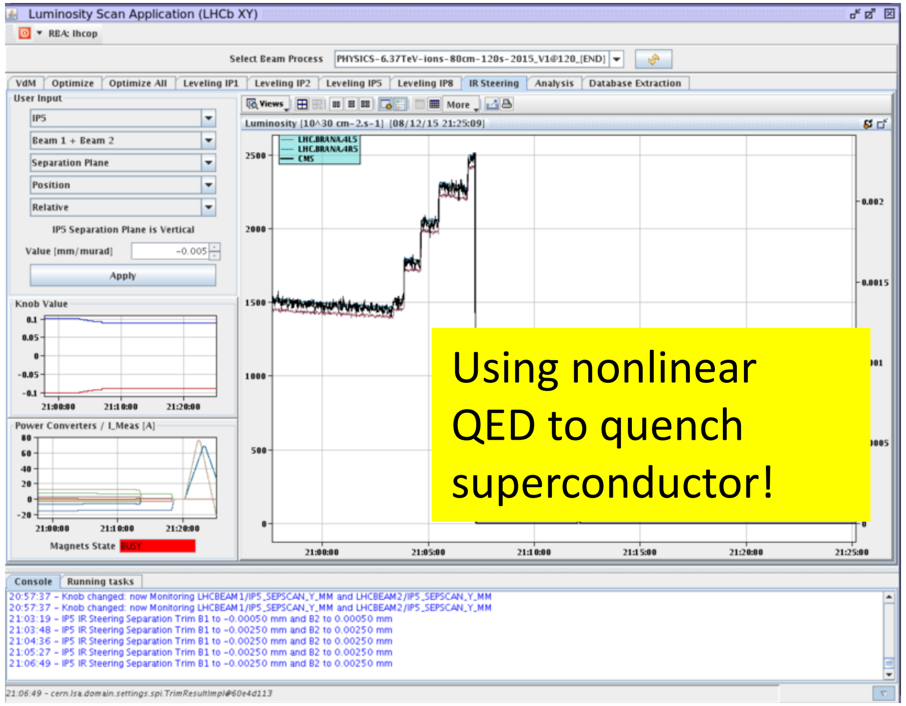
BFPP Quench MD – first luminosity quench in LHC

- 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):

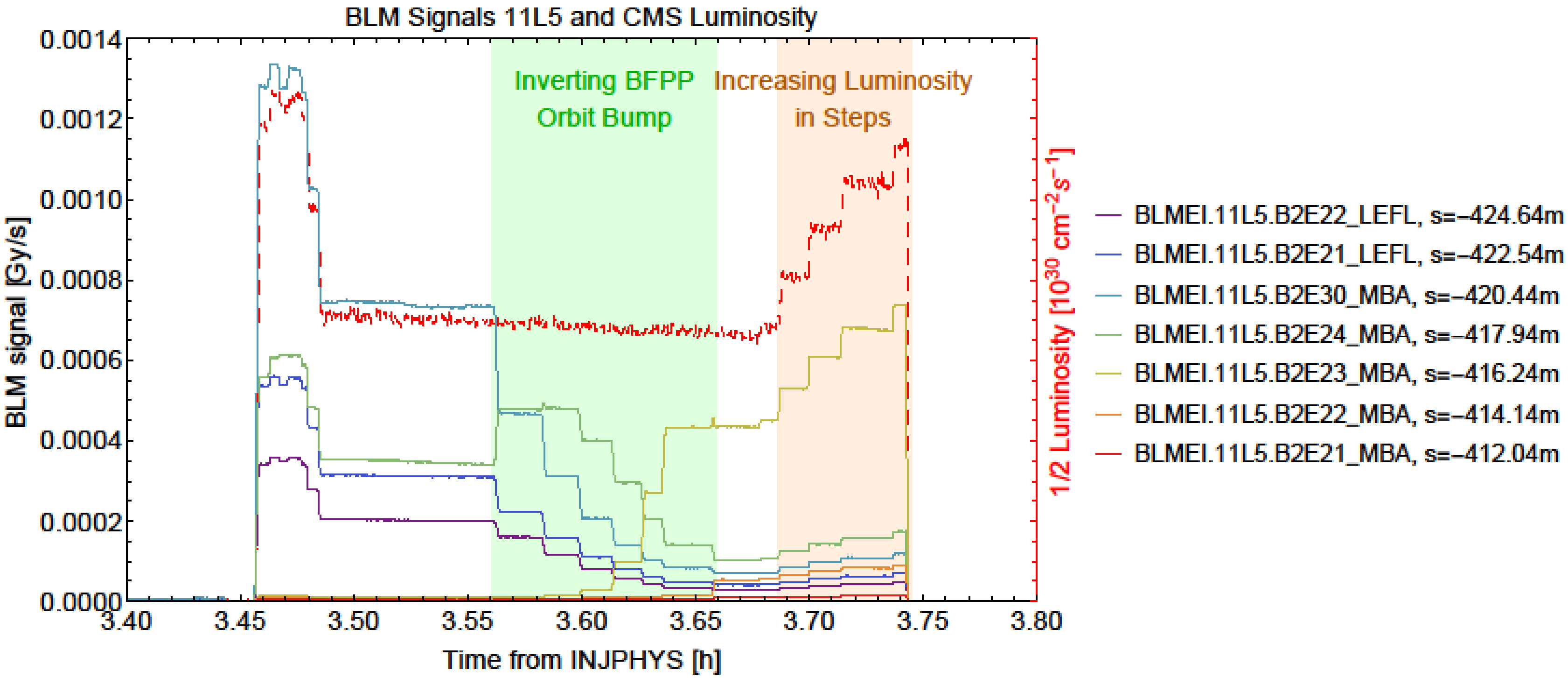
$$L \approx 2.3 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$$

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



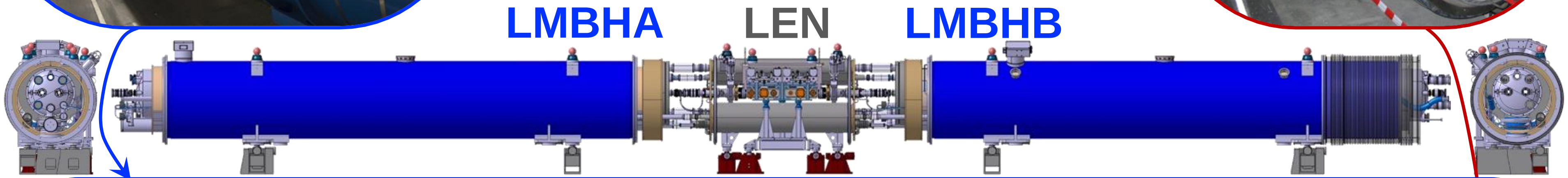


Luminosity and BLM signals during measurement



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

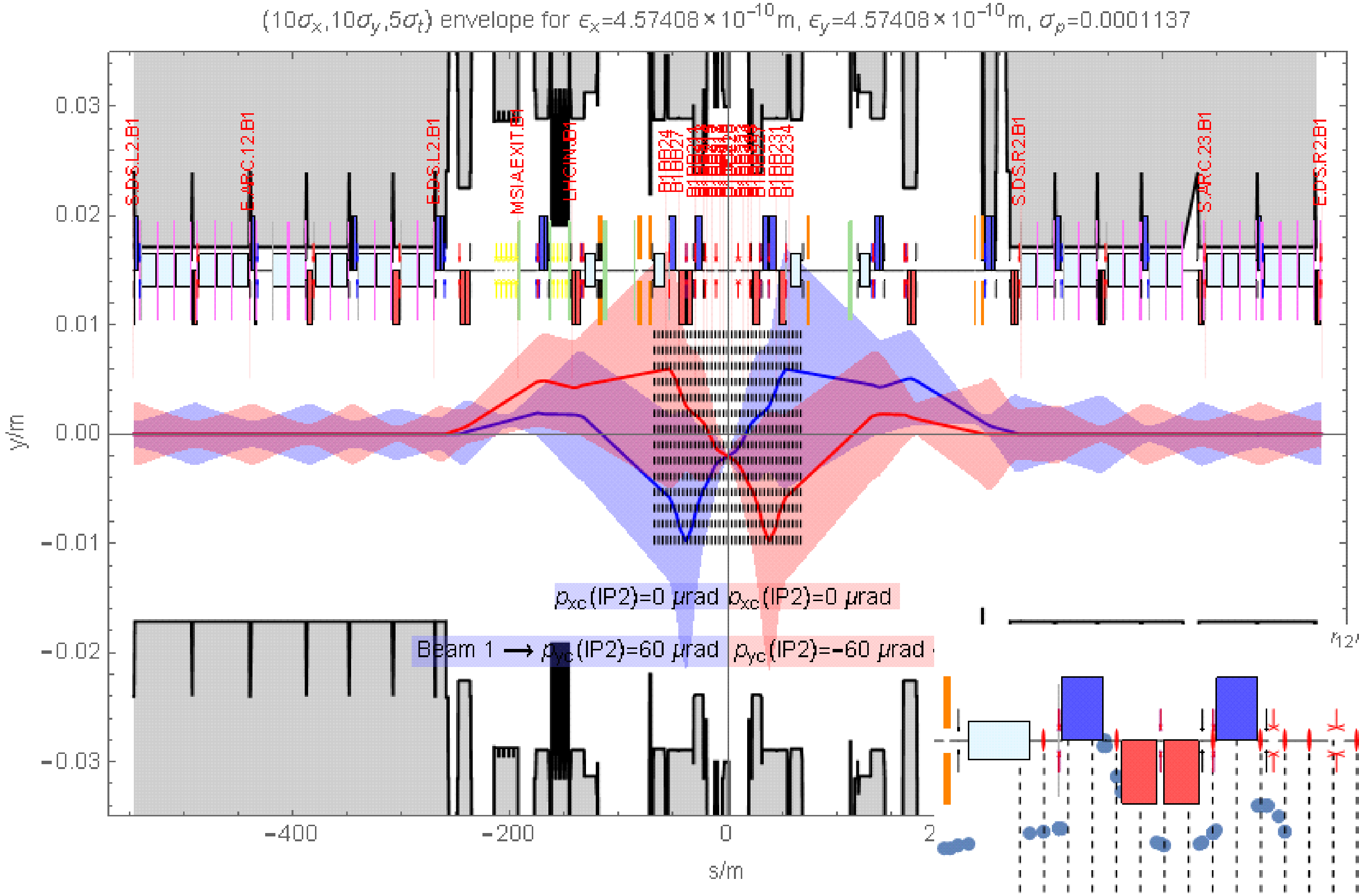
DS collimators



- **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**

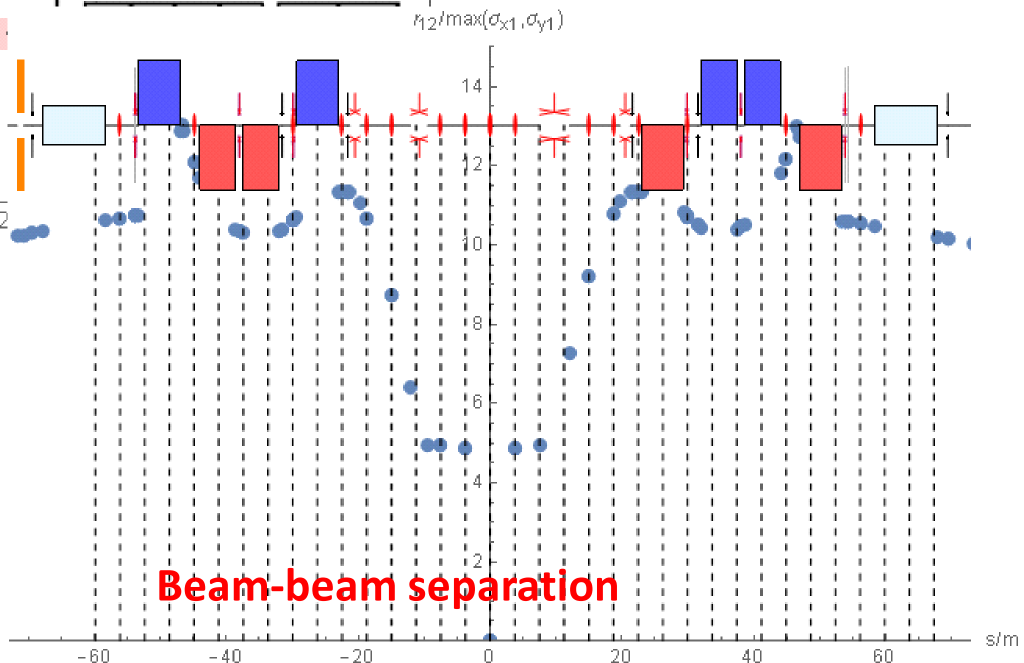
F. Savary

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.