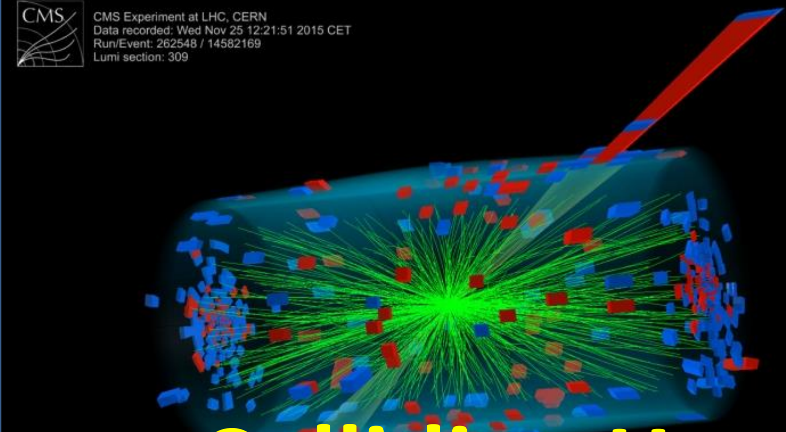
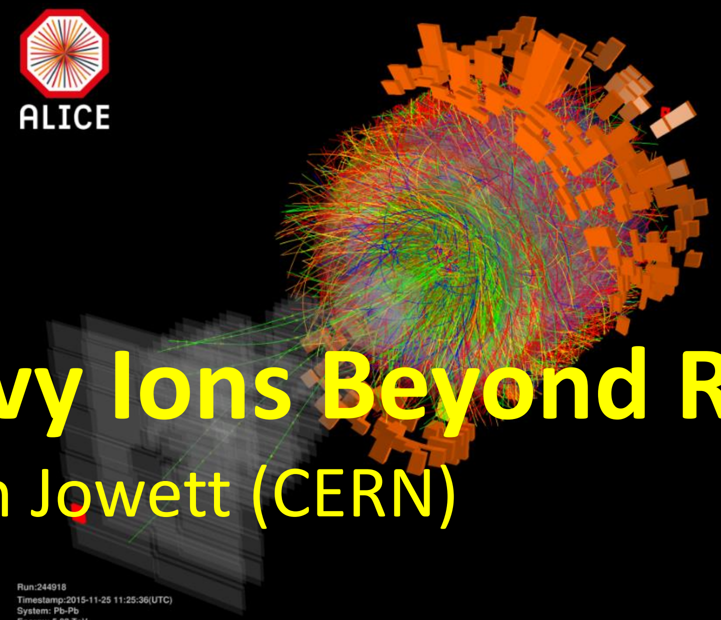
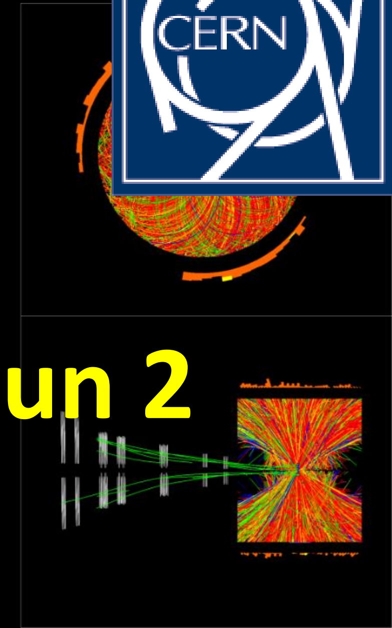
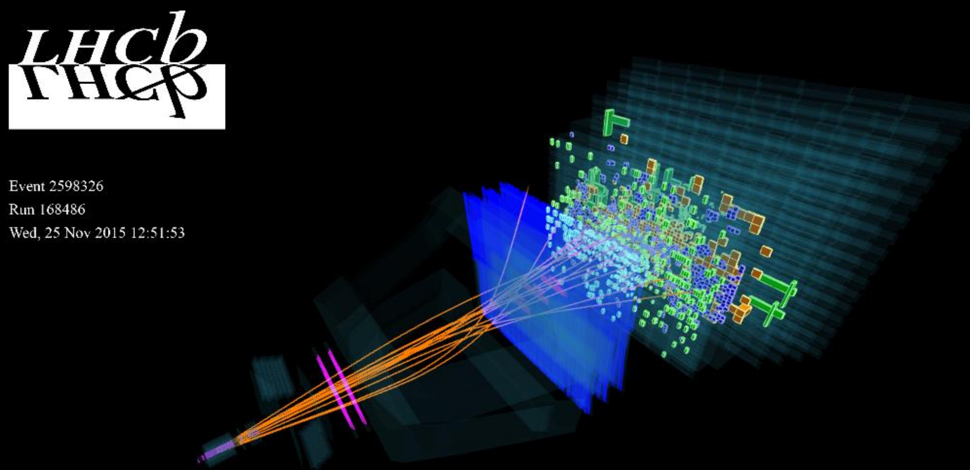


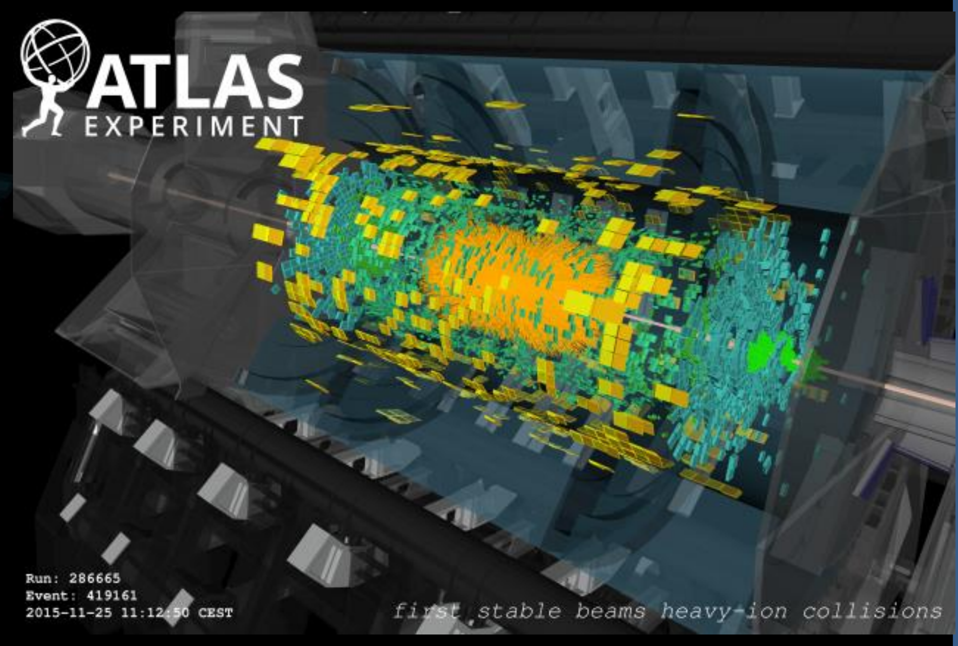




Colliding Heavy Ions Beyond Run 2

John Jowett (CERN)





Plan of talk

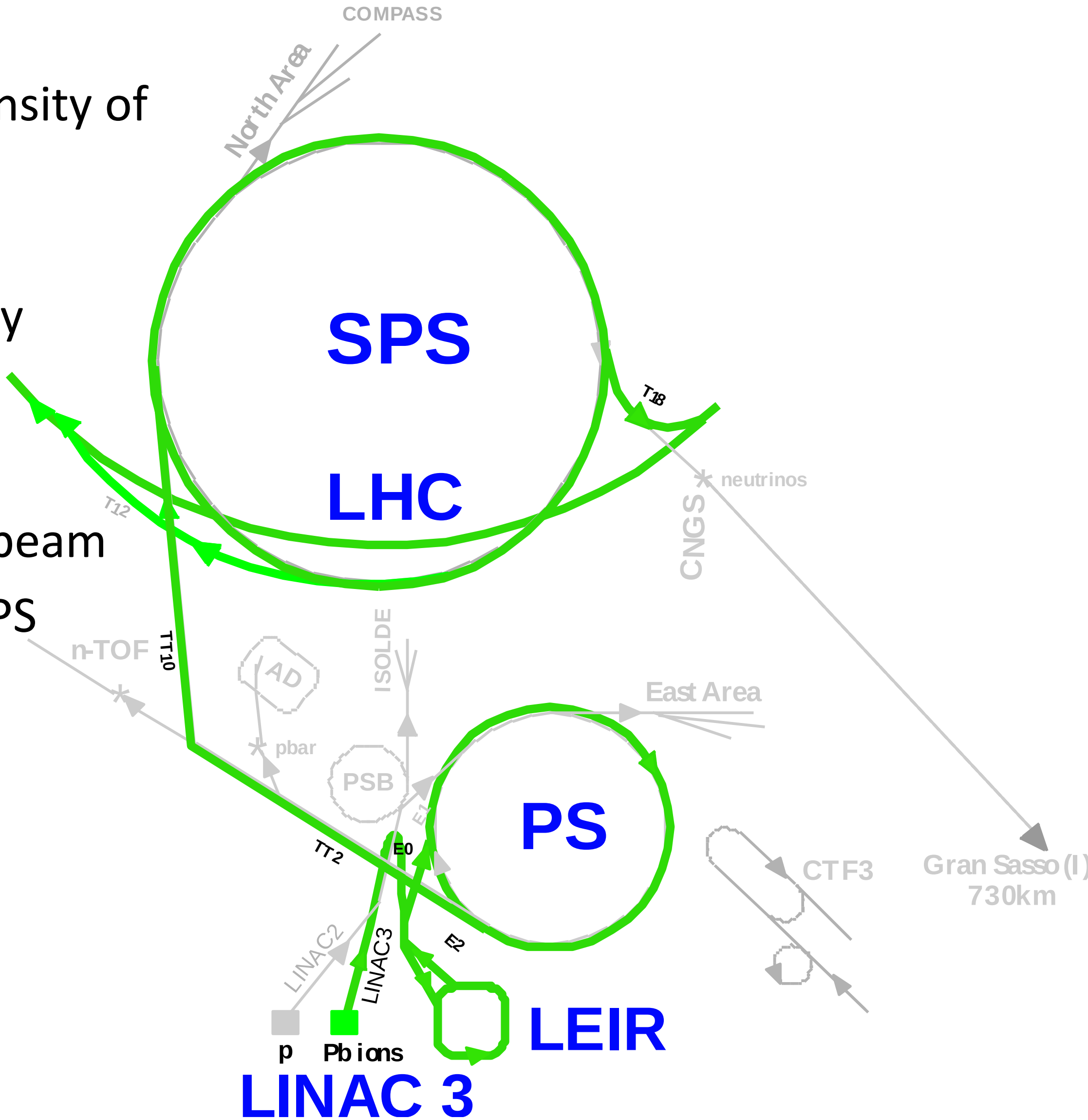
- LHC heavy-ion design parameters and initial goals
- Upgrades (=beyond design) implemented in Run 1 and Run 2
  - p-Pb
  - Pb-Pb peak luminosity
  - Xe-Xe
- Upgrades for Run 3
  - Baseline goals from ALICE 2012 Letter of Intent
  - Prospects for achieving baseline by Run 4
    - Injector upgrades
    - Upgrades in LHC, TCLDs, possible limits
- Possible variations and options
    - Higher p-Pb luminosity
    - Colliding lighter nuclei
    - Implications for LHeC e-Pb

LHC heavy-ion design parameters and initial goals

- LHC Design Report Chapter 32 (early 2004) foresaw only Pb-Pb collisions.
- I-LHC Project to provide heavy-ion injectors (ECR source, Linac3, LEIR, …)
- Peak luminosity ~matched to ALICE detector.
- Integrated luminosity goal of 1 nb^{-1} Pb-Pb in two experiments for first “10 years” (what we now call Run 1 + Run2).
  - Pb-Pb runs only in 2010, 2011, 2015, 2018

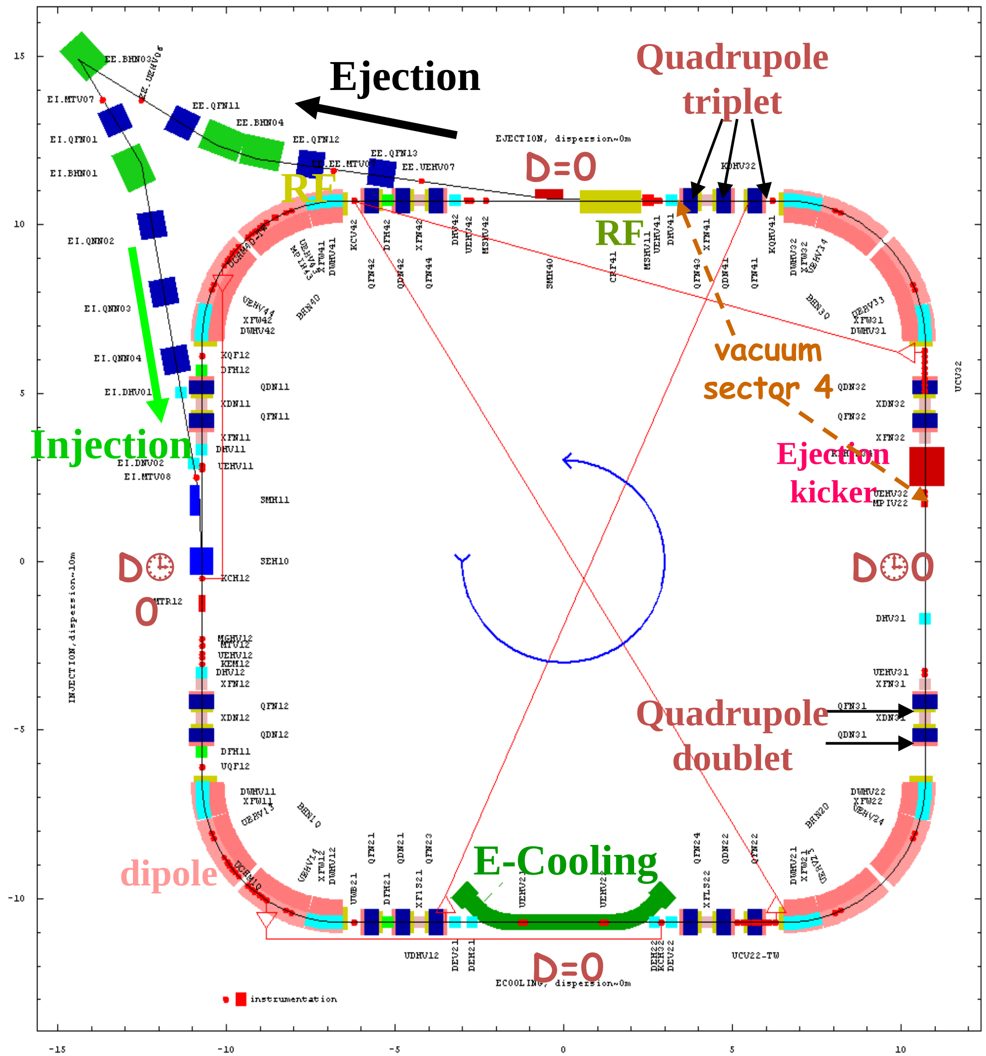
LHC Ion Injector Chain

- 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



LEIR (Low-Energy Ion Ring)

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



Design Parameters for Pb-Pb (~2001)

Parameter	Units	Early Beam	Nominal
Energy per nucleon	TeV	2.76	2.76
Initial ion-ion Luminosity L_0	cm^{-2} s^{-1}	~ 5 $\times 10^{25}$	1 $\times 10^{27}$
No. bunches, k_b		62	592
Minimum bunch spacing	ns	1350	99.8
β^*	m	1.0	0.5 /0.55
Number of Pb ions/bunch		7 $\times 10^7$	7 $\times 10^7$
Transv. norm. RMS emittance	μm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	h	14, 7.5, 5.5	8, 4.5, 3

Something like this at reduced energy, higher β^*, in 2010

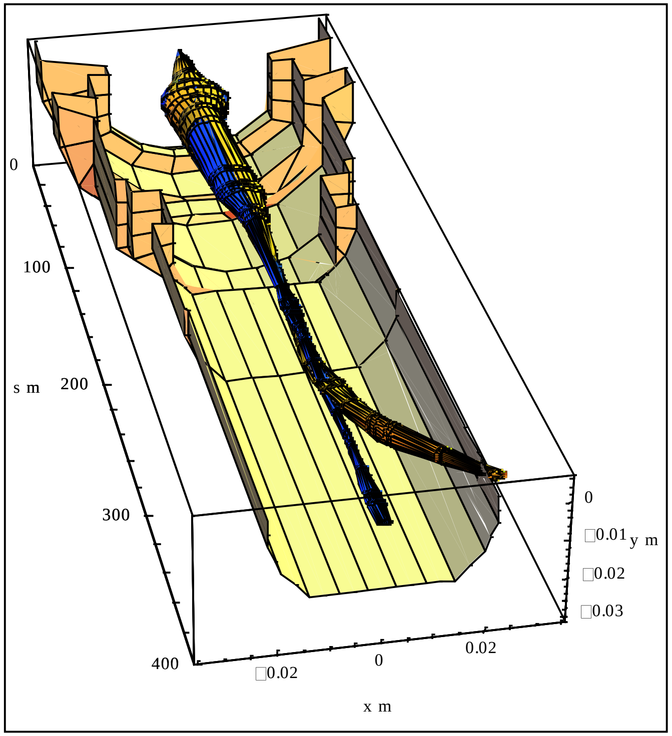
At full energy, luminosity lifetime is determined mainly by collisions ("burn-off" from ultraperipheral electromagnetic interactions) $\sigma \approx 520$ barn

Contributing factors in Run 1 and Run 2

- Optimism about commissioning time, beam instrumentation, etc, was well-founded
- Injectors gave higher bunch intensities
- Reductions of injection kicker rise times in SPS and LHC allowed denser bunch filling schemes
- Good control of non-collisional beam lifetimes reduced concerns about collimation losses and allowed higher dump thresholds on beam-loss monitors
- Strategies to control secondary beams emerging from collision point were implemented to eliminate the luminosity limit expected from bound-free pair production (BFPP) for ATLAS and CMS
- LHC magnet quench limits shown to be higher than originally expected
- Simultaneous injection and acceleration of equal-rigidity p and Pb beams shown to be feasible (unlike at RHIC), RF cogging implemented to collide them

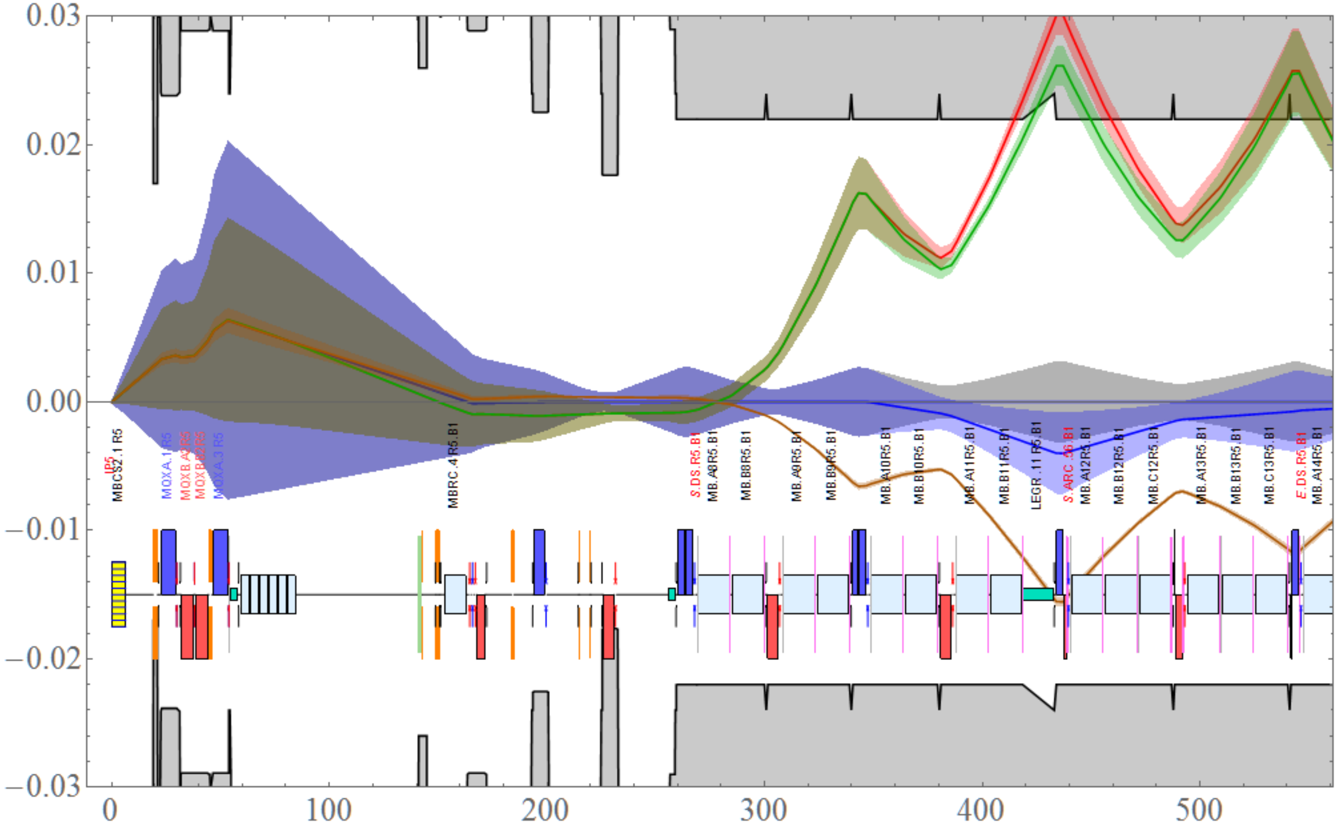
- Long-standing concern (S. Klein 2001) about losses from bound-free pair production limiting luminosity below design

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



Secondary Pb^{81+} beam (25 W at design luminosity) emerging from IP and impinging on beam screen.
Hadronic shower into superconducting coils can quench magnet.

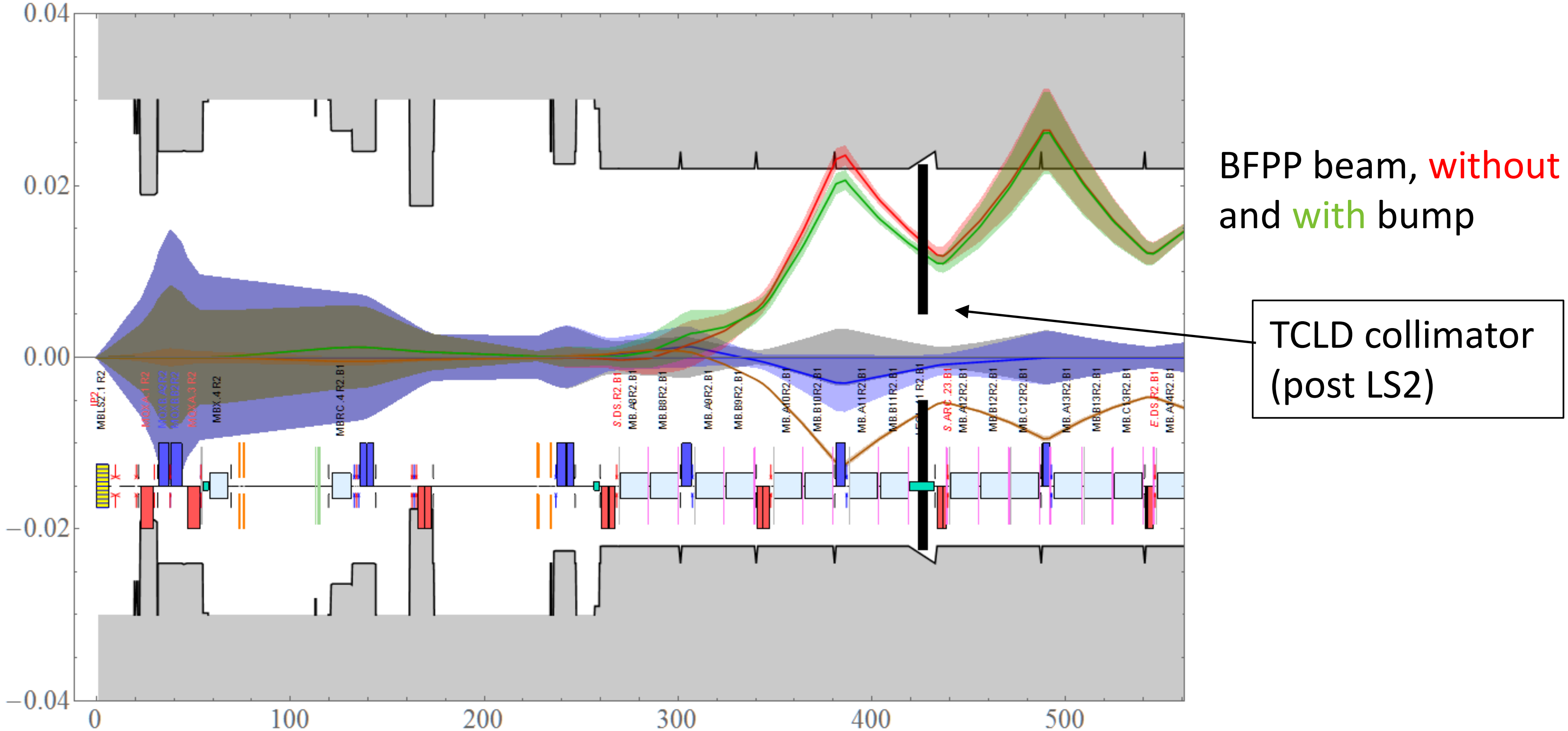
Orbit bumps mitigate BFPP for CMS (or ATLAS)



BFPP beam, without and with bump

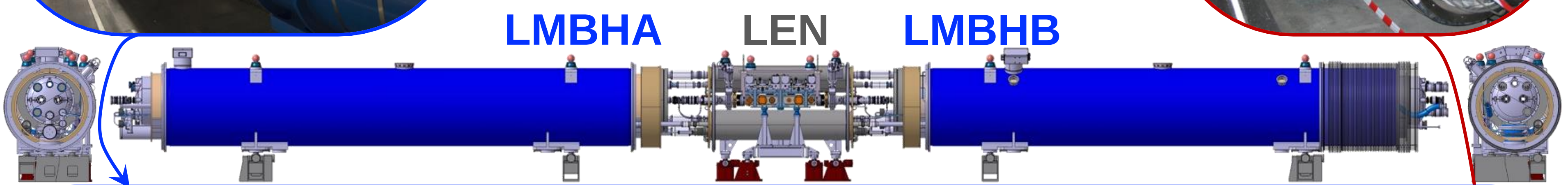
- Primary loss location close to the connection cryostat - details slightly optics-dependent (If necessary, bumps should avoid quenches at the start of physics
- Extra BLMs were specifically added for heavy-ion operation in loss region
- Variations of bump possible, uses moderate fraction of available 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 – **design advancing now to be ready for LS2 installation**
- With levelled luminosity in ALICE, quenches were not seen in 2015

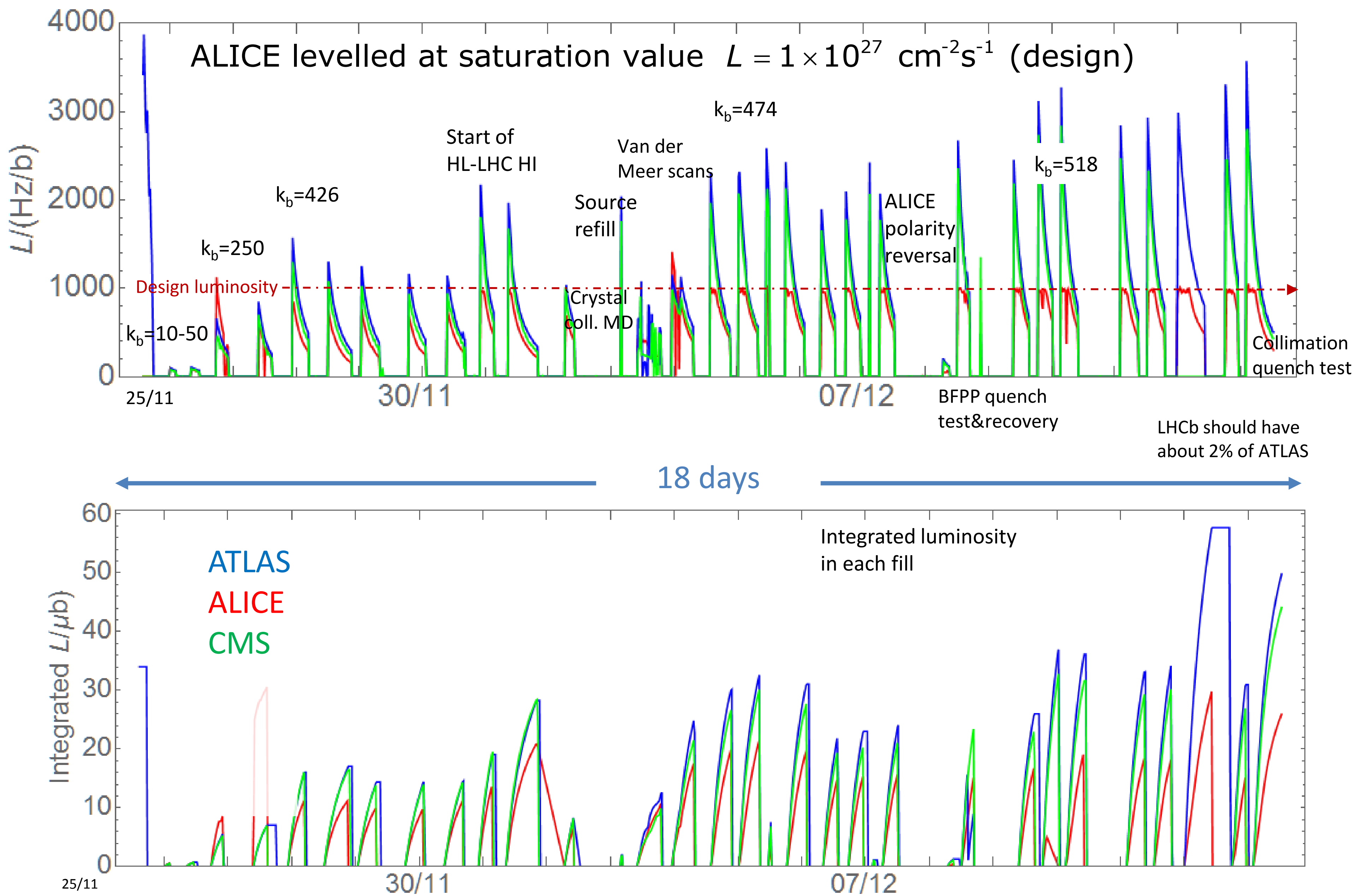
Scope of WP11



- **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** (1 with RRP conductor, ~~and 1 with PIT conductor~~)
- **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

Pb-Pb peak luminosity 3×design in 2015



Integrated nucleon-nucleon luminosity in Run 1 + 2015

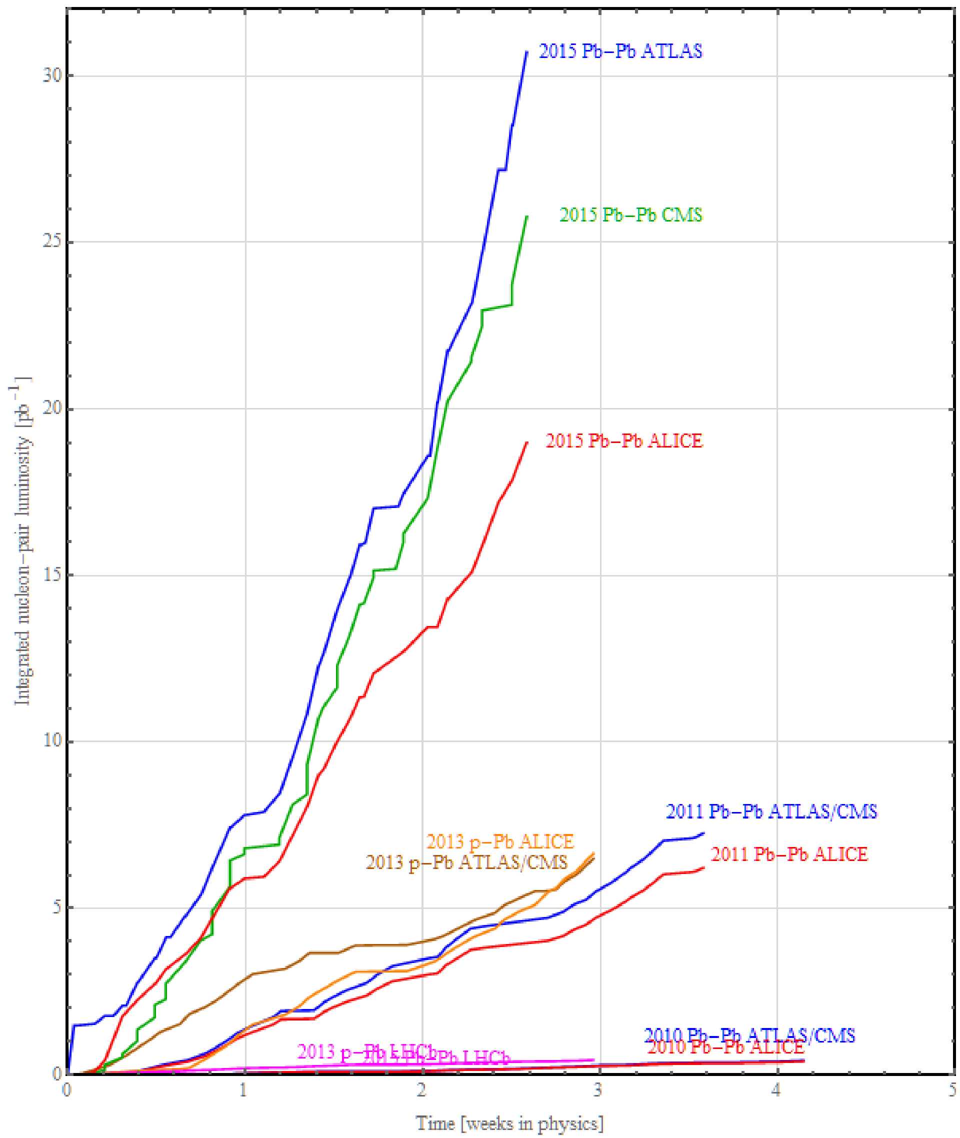
Expect to achieve LHC "first 10-year" baseline Pb-Pb luminosity goal of 1 AA nb^{-1} = 43 NN pb^{-1} in Run 2 (=2015+2018)

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.

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

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

But annual 1-month runs are getting shorter and more complicated … 2015 included p-p reference data and included LHCb.



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:

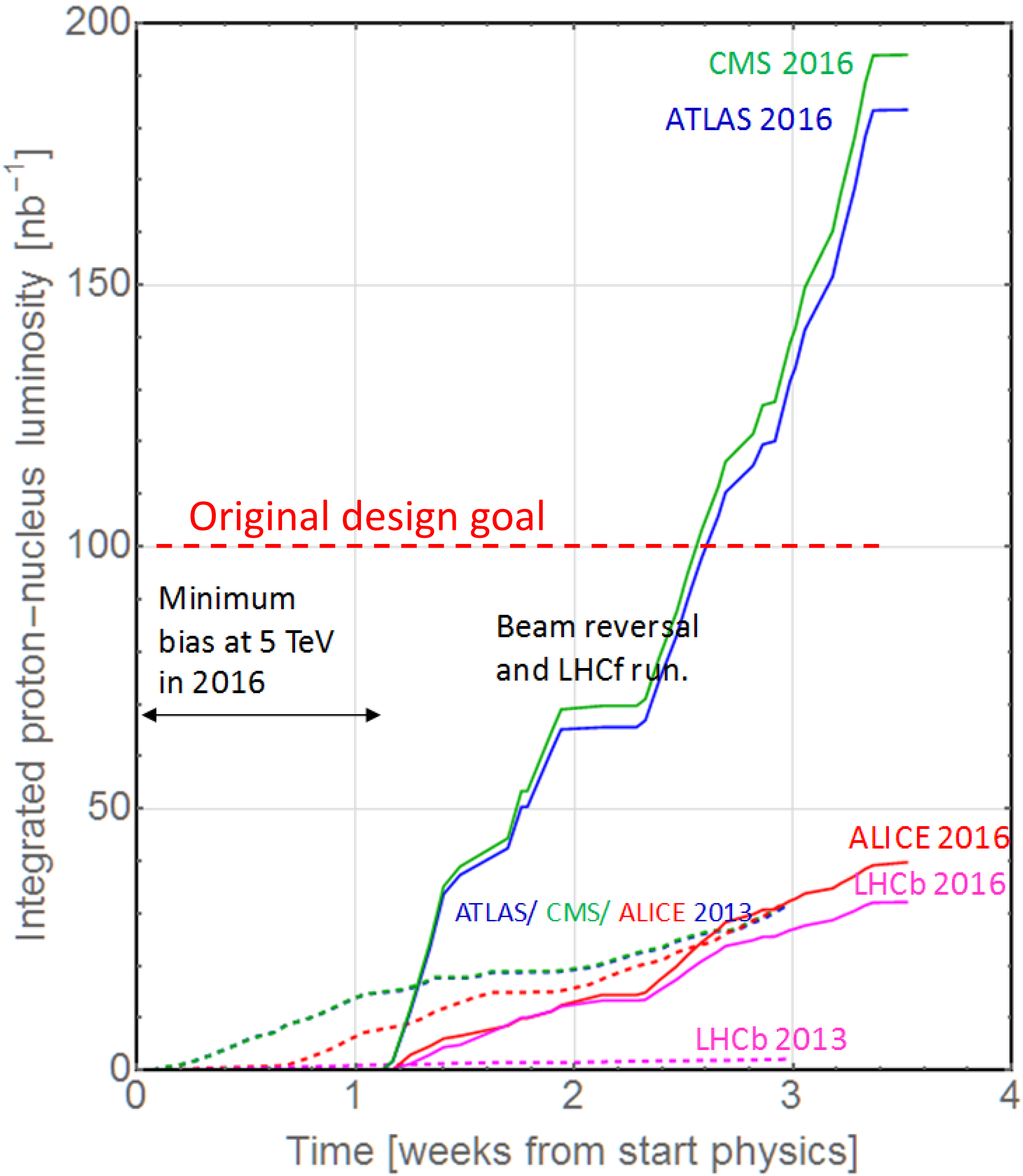
Minimum bias run at 4 Z TeV mainly for ALICE

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

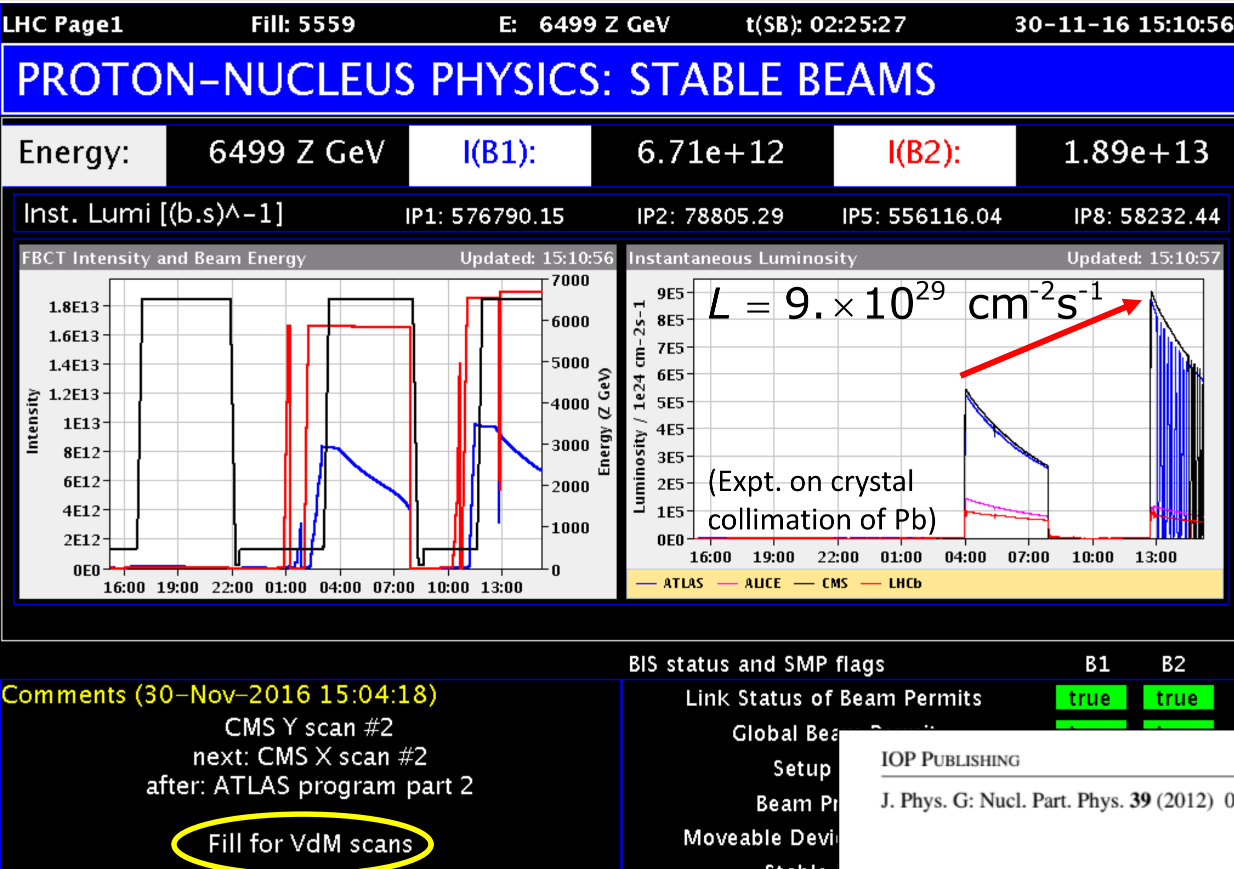
Ie, 2 new optics and 3 setups with full qualifications in 1 month.

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

Many filling schemes used for luminosity sharing.



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



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

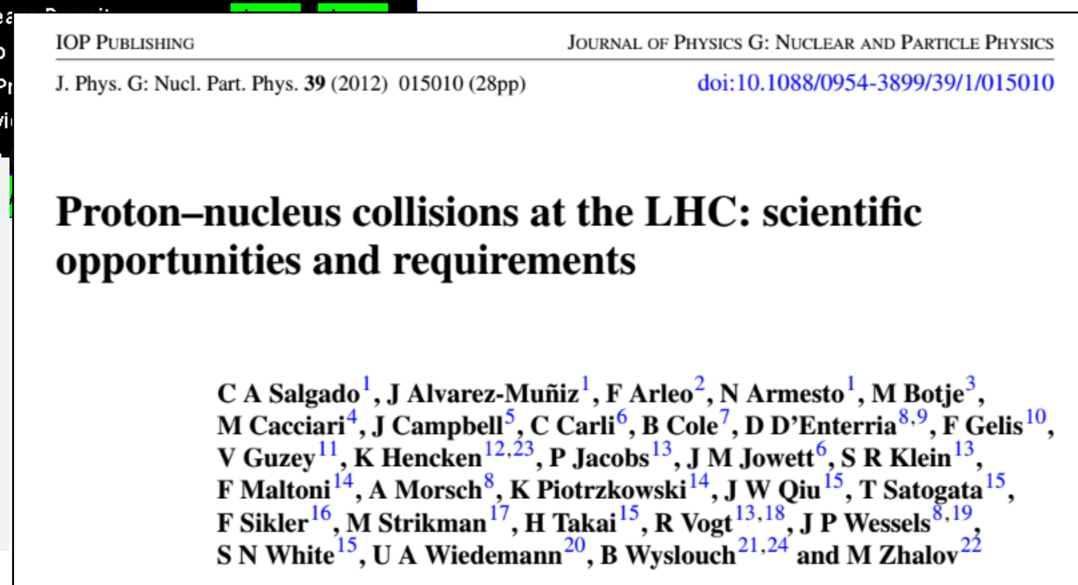
Pb intensity to ~2.1×10^{8}/bunch

25% increase in ATLAS/CMS from filling scheme

Peak luminosity a factor 7.8 beyond original "design" value

(J. Phys. G 39 (2012) 015010)

Could have gone higher still by further increase of p intensity but limited by Pb beam luminosity debris in magnets of Sector 12 (faulty magnet).

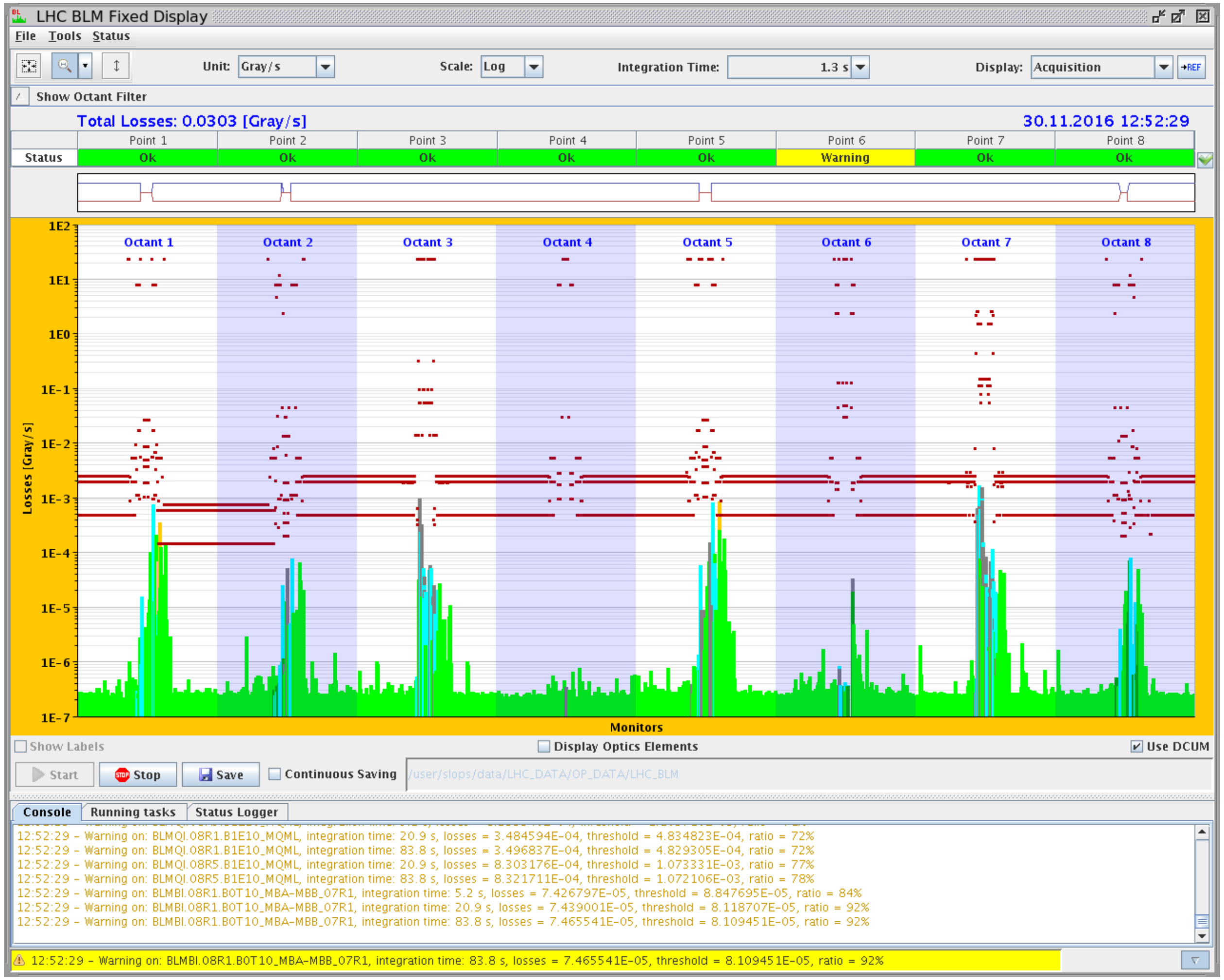

IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **39** (2012) 015010 (28pp) doi:10.1088/0954-3899/39/1/015010

Proton–nucleus collisions at the LHC: scientific opportunities and requirements

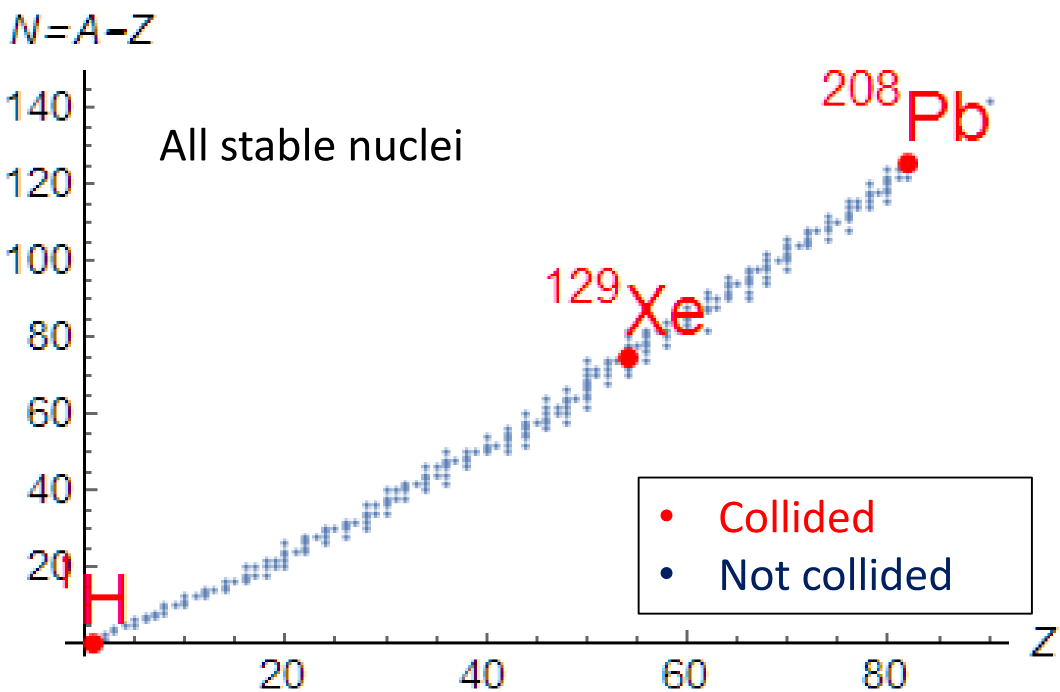
C A Salgado[1], J Alvarez-Muñiz[1], F Arleo[2], N Armesto[1], M Botje[3], M Cacciari[4], J Campbell[5], C Carli[6], B Cole[7], D D'Enterria[8,9], F Gelis[10], V Guzey[11], K Hencken[12,23], P Jacobs[13], J M Jowett[6], S R Klein[13], F Maltoni[14], A Morsch[8], K Piotrzkowski[14], J W Qiu[15], T Satogata[15], F Sikler[16], M Strikman[17], H Takai[15], R Vogt[13,18], J P Wessels[8,19], S N White[15], U A Wiedemann[20], B Wyslouch[21,24] and M Zhalov[22]

Peak luminosity limited by Pb luminosity debris



- BLMs over 92% of threshold in Sector 12, Pb beam luminosity debris, right of IP1
- Similar losses right of IP5
- Discussion with Machine Protection, decided not to change thresholds at this stage, limit p intensity, manually limit luminosity at start of fill for last few days.

Xe-Xe run, 12 October 2017



$^{129}Xe^{54+}$,

$m_{129Xe} = 120.047\ \mathrm{GeV}/c^2 \approx m_H$

$E_b = 6.5Z\ \mathrm{TeV} = 2.72A\ \mathrm{TeV} = 351\ \mathrm{TeV}$

$\sqrt{s_{NN}} = 5.44\ \mathrm{TeV}$

16 h scheduled for set-up and physics, low luminosity, 16 bunches

~ 3 μb^{-1} delivered to ATLAS/CMS

Fraction of μb^{-1} to ALICE/LHCb

- Heavy-ion injectors can produce high-intensity, high-brightness Xe beams for LHC physics.
- Longer luminosity lifetimes than for Pb.
- Preliminary data consistent with predicted cross-sections for UPCs.
- Beam-cleaning and collimation efficiency to be understood.
- [Successful test of crystal collimation of Xe.]

Upgrades for Run 3

- Upgrades for heavy-ion injectors within LIU project
  - Ion source, Linac3, LEIR, PS will deliver trains of high-intensity bunches at 100 ns spacing
  - Spacing will be reduced to 50 ns in SPS by slip-stacking (new procedure to implement in busy time immediately after LS2)
- Upgrades in LHC
  - TCLD collimators in IR2 to absorb BFPP losses for ALICE
  - TCLD collimators in IR7 to reduce collimation losses
    - Perhaps the biggest remaining uncertainty in LHC, potential for crystal collimation to help further

ALICE's request from 2012 Letter of Intent

- Maximum interaction rate of 50 kHz in Pb-Pb (ALICE upgrade in LS2)
- LoI assumed: peak luminosity of 6×10^{27} $cm^{-2}s^{-1}$ and an average luminosity of 2.4×10^{27} $cm^{-2}s^{-1}$.
- The upgrade programme assumes an integrated luminosity of 10 nb^{-1} in PbPb at top energy
- In addition
  - one special Pb-Pb run at reduced magnetic field for low-mass dileptons (O~ 3 nb^{-1})
  - one p-Pb run with about 50 nb^{-1}
  - p-p reference run at 82/208 × top energy
- Time horizon: to be completed by LS4 under the basic assumption of about one month LHC heavy ion operation per operating year.
- [1] ALICE upgrade Letter of Intent http://cds.cern.ch/record/1475243, endorsed by the LHCC on 27 Sep 2012 and approved by the Research Board on 28 Nov 2012 (http://cds.cern.ch/record/1499619/files/M-202.pdf)

Requested luminosity after LS2, adapted from 2012 ALICE LoI

- Possible running scenario after upgrade:
  - 2021 - Pb-Pb 2.85 nb^{-1}
  - 2022 - Pb-Pb 2.85 nb^{-1}
  - 2023 - pp reference run
  - 2024,2025.6 - LS3
  - 2027 - Pb-Pb 2.85 nb^{-1}
  - 2028 - ½ Pb-Pb 1.5 nb^{-1} + ½ p-Pb 50 nb^{-1} ←
  - 2029 - Pb-Pb 2.85 nb^{-1}
  - 2030 LS4

Easy modifications:

exchange Pb-Pb for p-Pb or p-p ref, most years

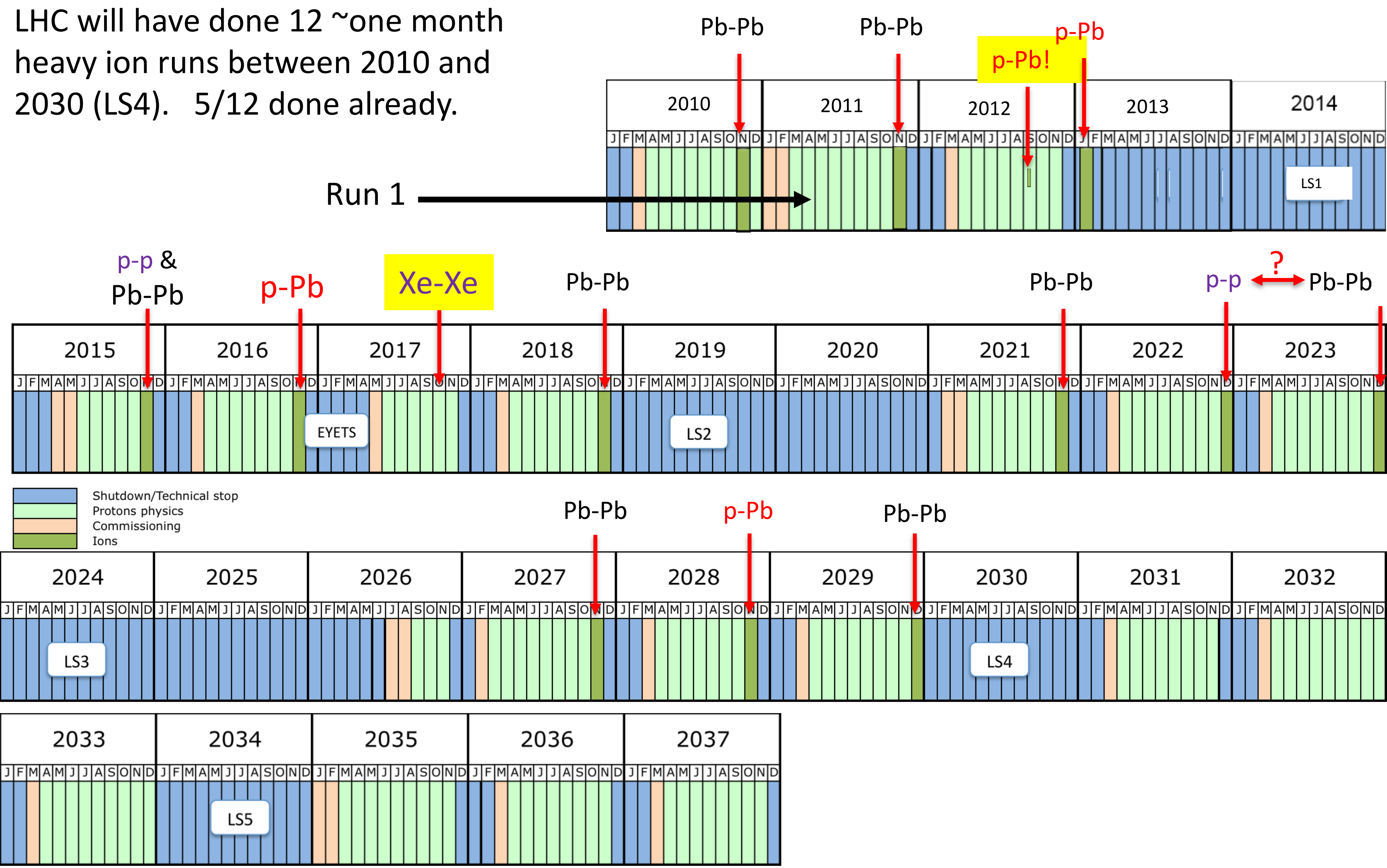
Requiring more preparation:

exchange Pb-Pb for other species, like Ar-Ar

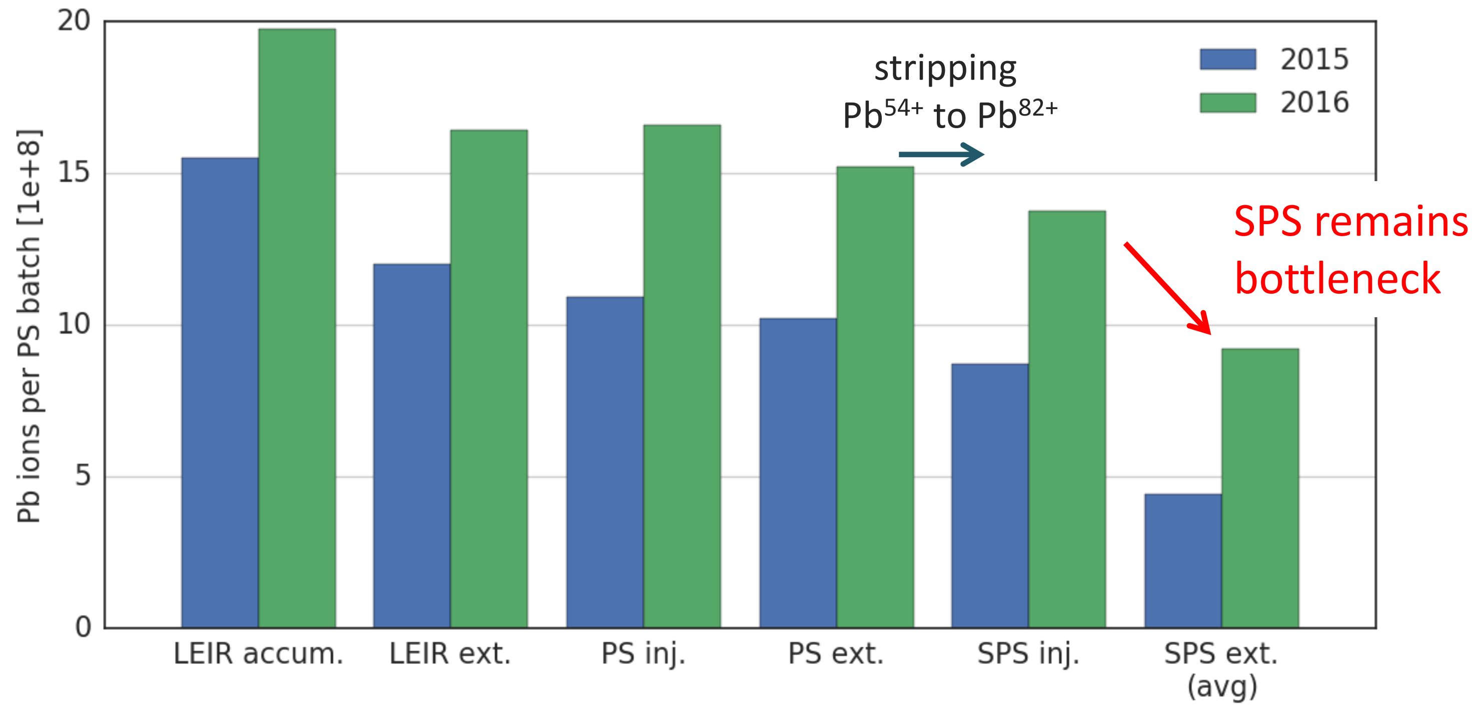
N.B. In general, it takes ~few months to change species in the heavy-ion injectors.

LHC heavy-ion runs, past & approved future
+ species choices according to ALICE 2012 LoI (some variations possible)

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



Achieved performance 2015/16

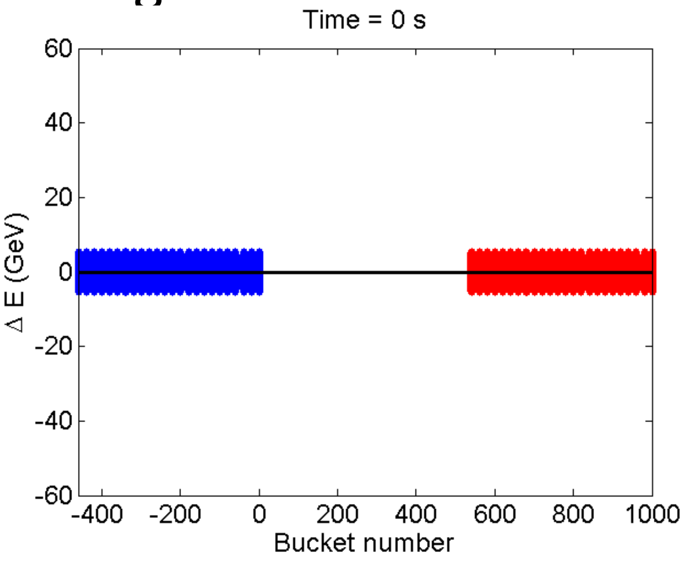


- Excellent performance in 2016 thanks to extended MD period in the injectors
  - Significantly higher intensity from Linac3 and out of LEIR
  - Improved transmission between machines
  - About twice intensity per PS batch at SPS extraction

H. Bartosik, Chamonix 2017

SPS momentum slip stacking

- Feasibility relies on
  - Large bandwidth of SPS 200 MHz travelling wave cavities
  - Low ion intensity (no need for feed-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)

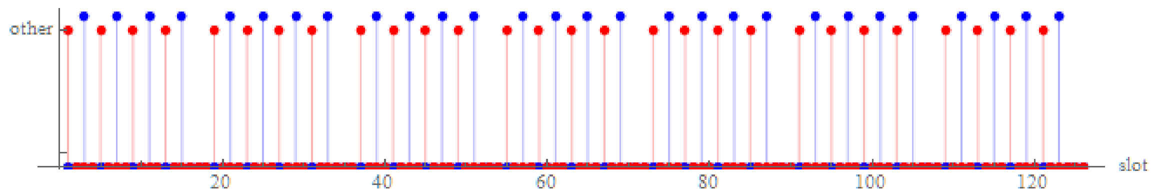
    $\langle N_b \rangle = 1.8 \times 10^8 \;\; = 95\% \; \times \; 1.9 \times 10^8$ injected (c.f. design 0.7×10^8)
  - Initial emittance (start of stable beams)

    $\varepsilon_{xn} = 1.65 \times 10^{-6}\text{m}$ (> 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!):

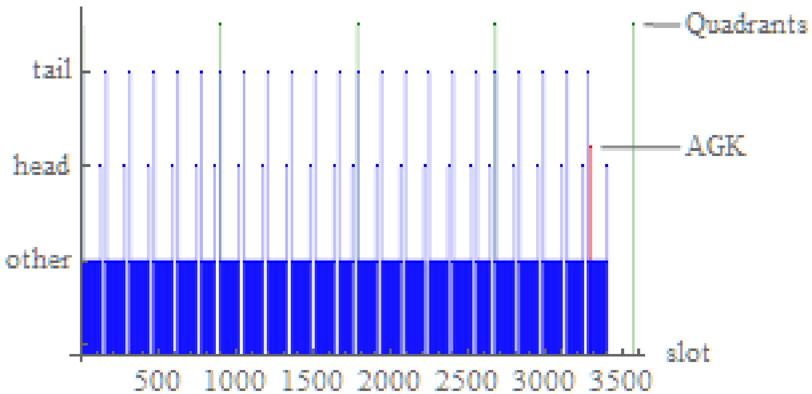
$$\beta^* = \begin{cases} (\infty, 0.5, \infty) & \text{m} \quad \text{(only ALICE colliding)} \\ (1.0, 0.5, 1.0) & \text{m} \quad \text{(ATLAS/CMS at half ALICE)} \\ (0.5, 0.5, 0.5) & \text{m} \quad \text{(equal)} \end{cases}$$

  - Some collisions in LHCb (not shown in detail)

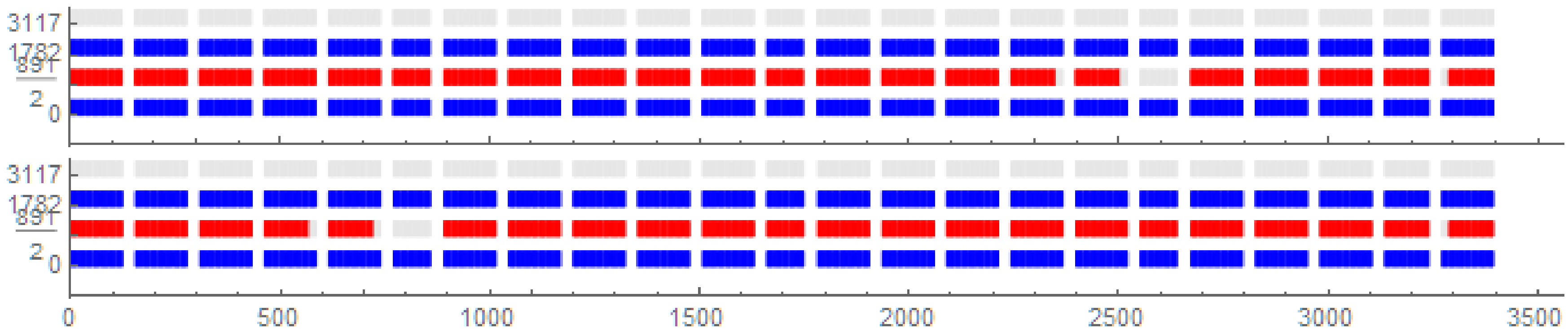
Filling scheme for HL-LHC Pb-Pb (LIU TDR baseline)



56 bunch SPS train
after slip-stacking in SPS

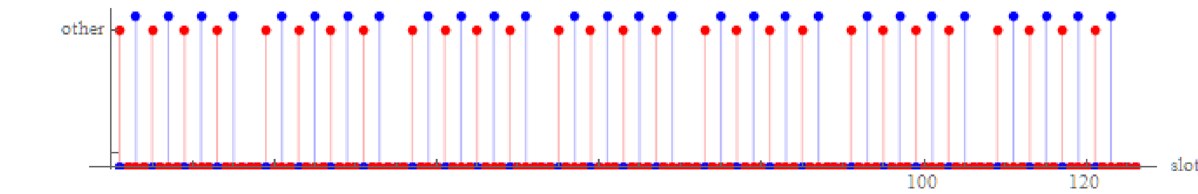


Two beams are identical, maximal filling with quadrant symmetry

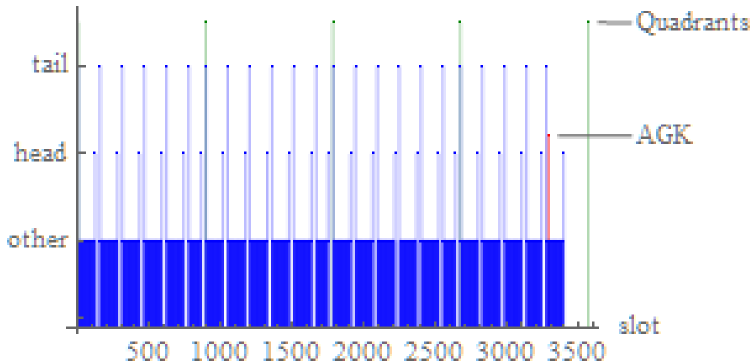


23 injections of 56-bunch trains give total of 1232 in each beam.
1232 bunch pairs collide in ATLAS CMS, 1168 in ALICE, 0 in LHCb.

Some collisions in LHCb (assumption!)

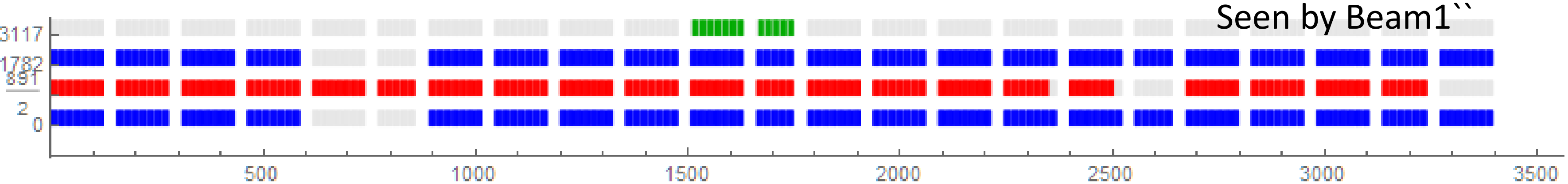


56 bunch SPS train after slip-stacking

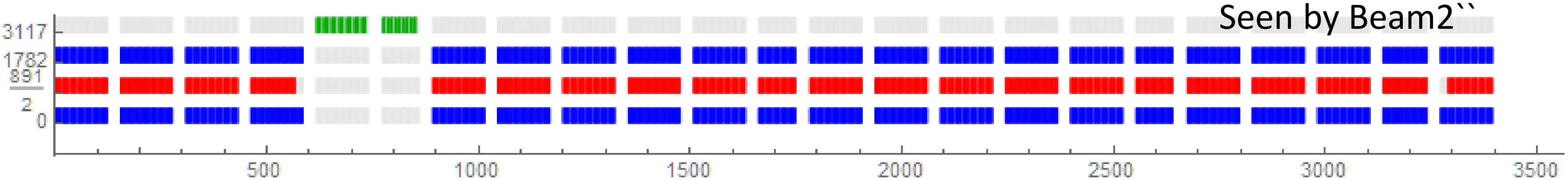


Displace two trains in Beam 2 to make collisions in LHCb

Seen by Beam1``



Seen by Beam2``



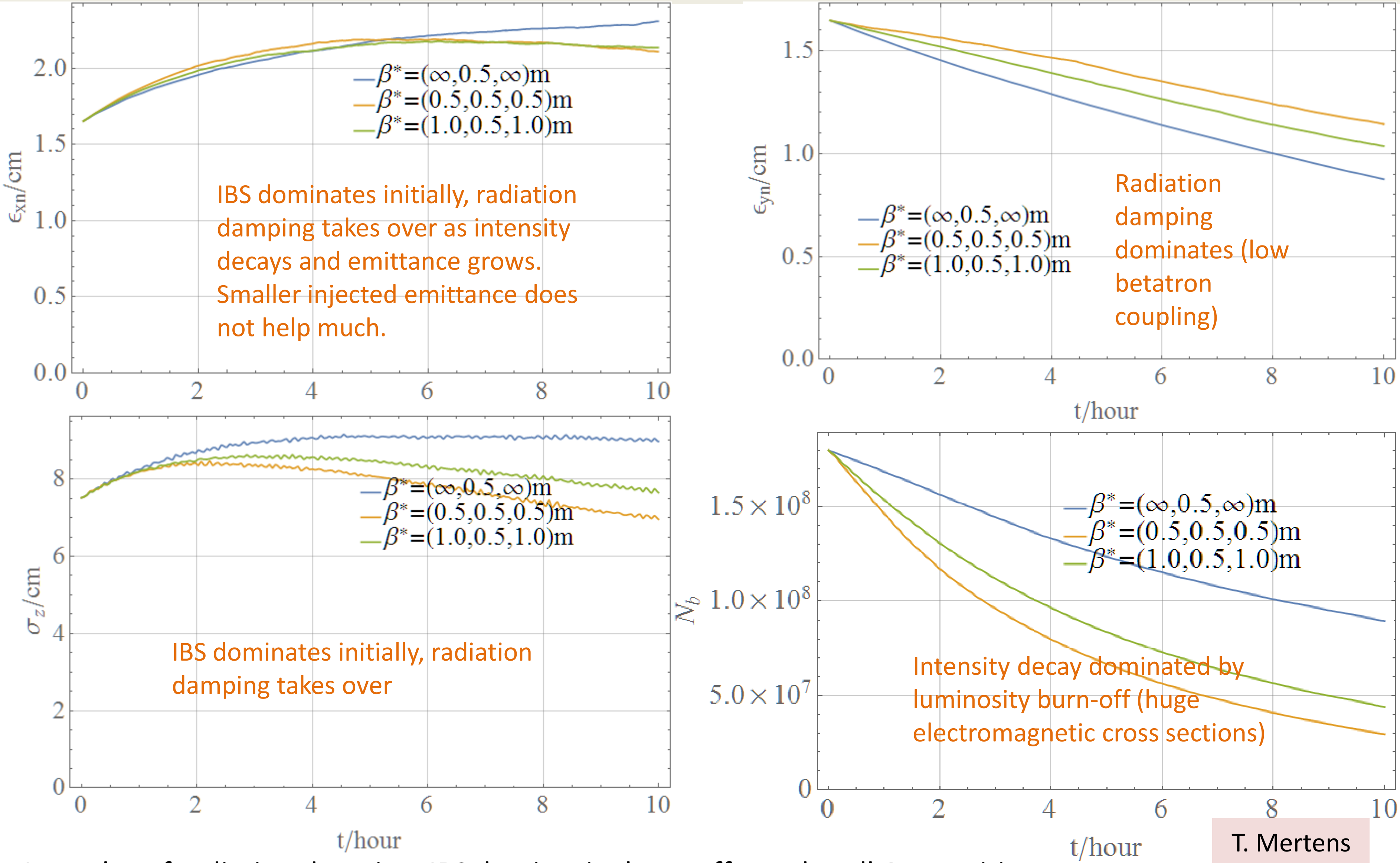
23 injections of 56-bunch trains give total of 1232 in each beam.

1136 bunch pairs collide in ATLAS CMS, 1120 in ALICE, 81 in LHCb (longer lifetime).

Optics compatibility with p-p operation

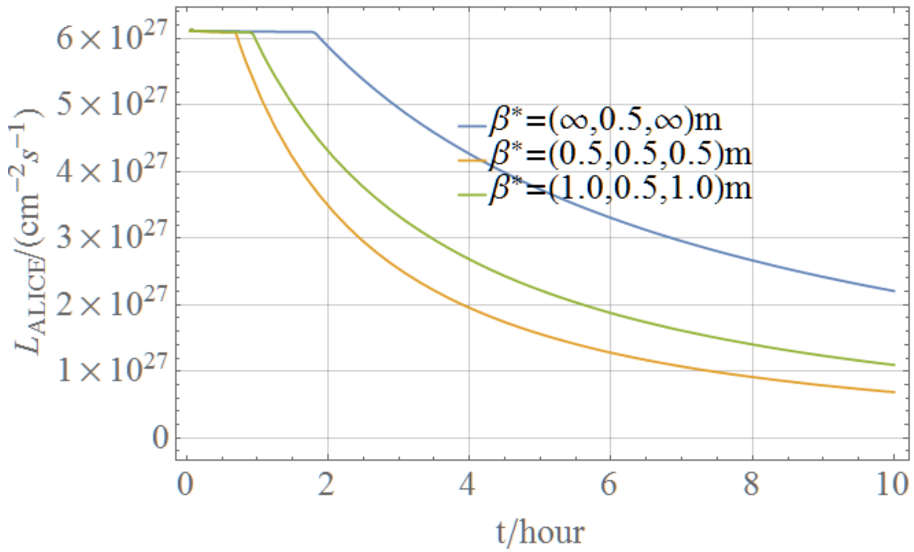
- ATS optics will be used for p-p operation
- The β*=0.5 m values assumed for heavy-ion operation do not require ATS
  - Rather little gain from low β* in high burn-off regime
- However to minimise set-up we can use essentially the same squeeze as ATS (telescopic part of squeeze has not started yet)
  - 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.)

CTE Simulation of (most typical) colliding bunch pair



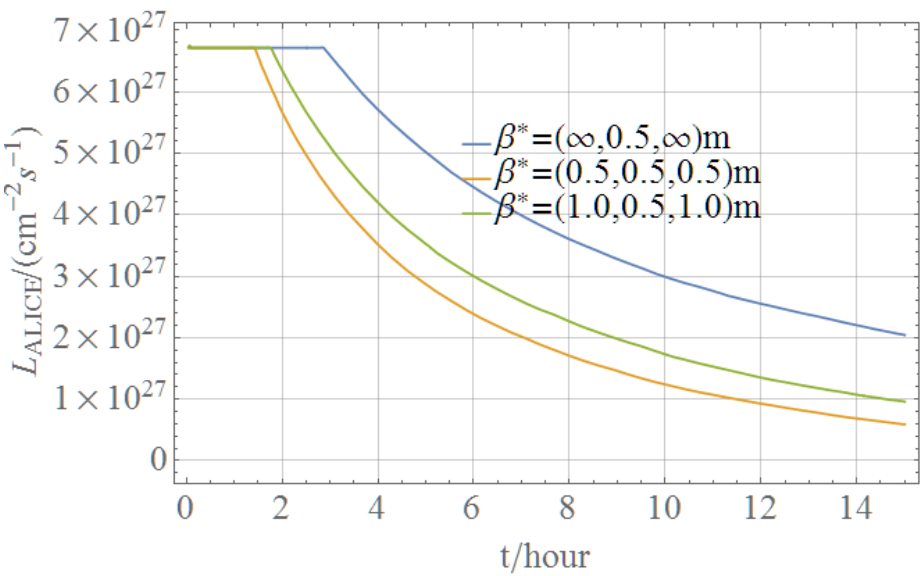
Interplay of radiation damping, IBS, luminosity burn-off couples all 4 quantities.
Different evolution according to luminosity-sharing scenario.
(Does not include additional emittance growth usually seen in operation.)

ALICE luminosities in an ideal (prolonged) fill



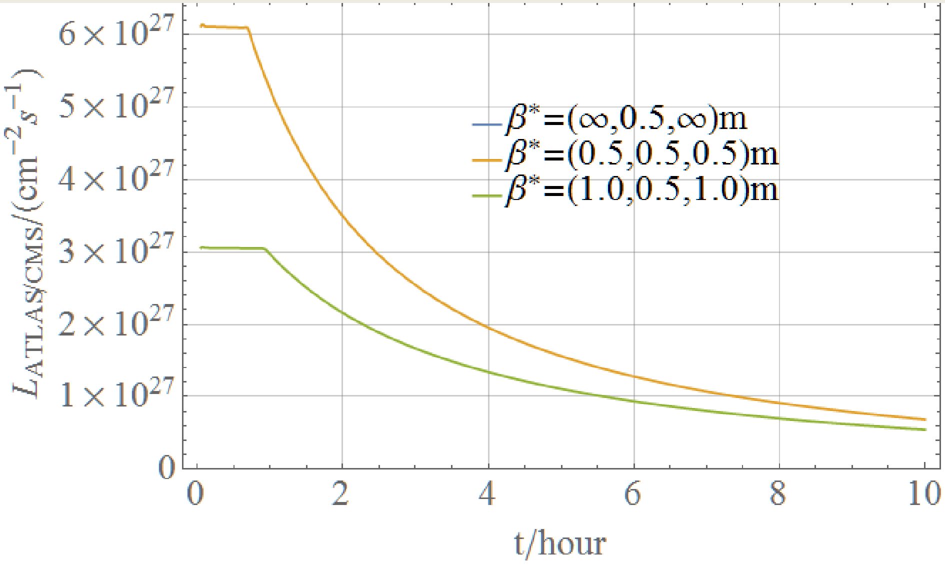
ALICE, levelling at maximum acceptable (rates around 50 kHz), assuming 1100 bunches colliding

LIU baseline with TDR parameters from **Chamonix 2016**



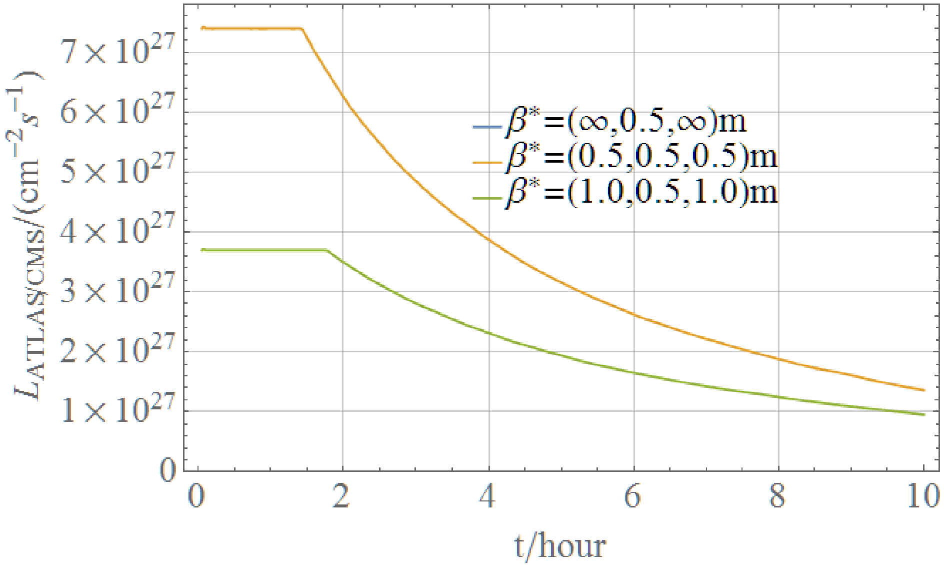
New LIU baseline parameters **(Chamonix 2017),** levelling at higher initial value.

ATLAS/CMS luminosities in an ideal (prolonged) fill



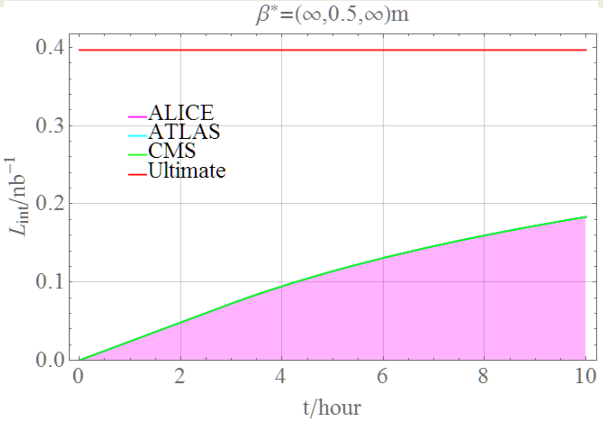
ATLAS or CMS, *assumed* levelling at similar levels to ALICE (not strictly necessary, just an assumption to simplify presentation).

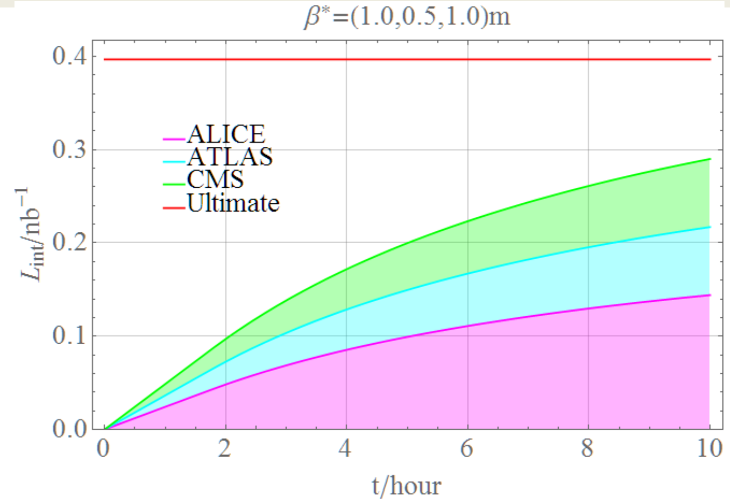
LIU baseline with TDR parameters from **Chamonix 2016**

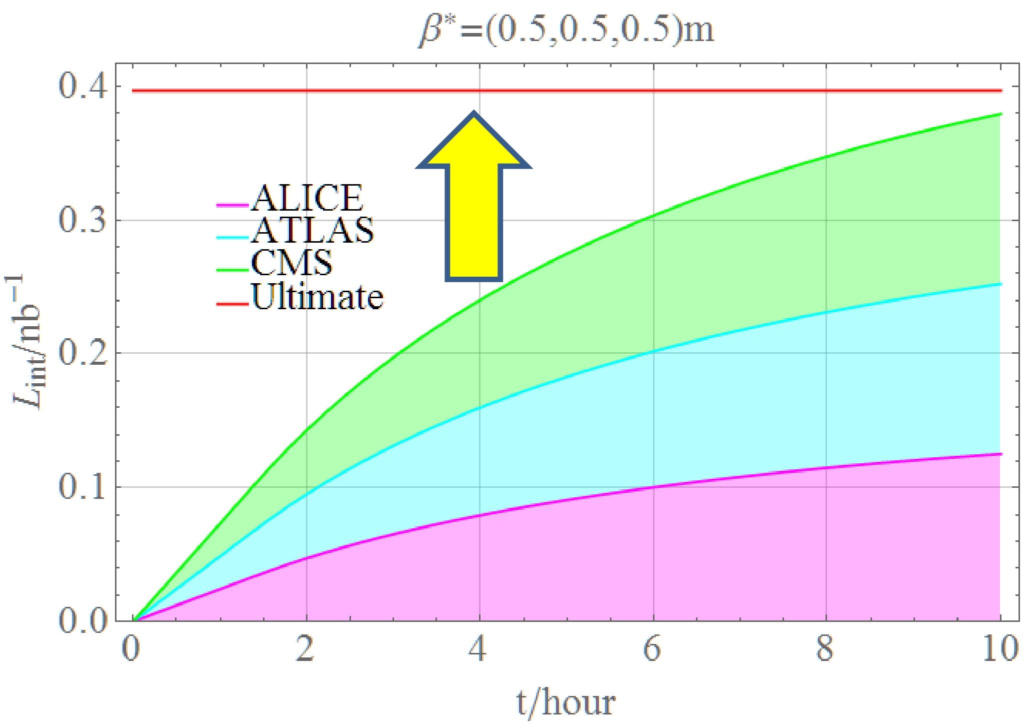


New LIU baseline parameters **(Chamonix 2017),** levelling at higher initial value.

Integrated luminosity in prolonged fills





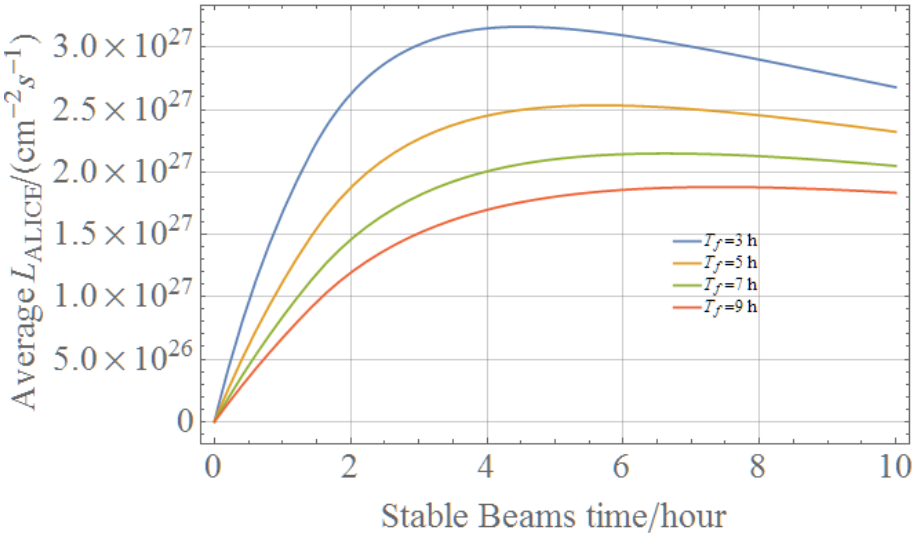


Ultimate luminosity to share

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

Fraction obtained is the luminous efficiency.

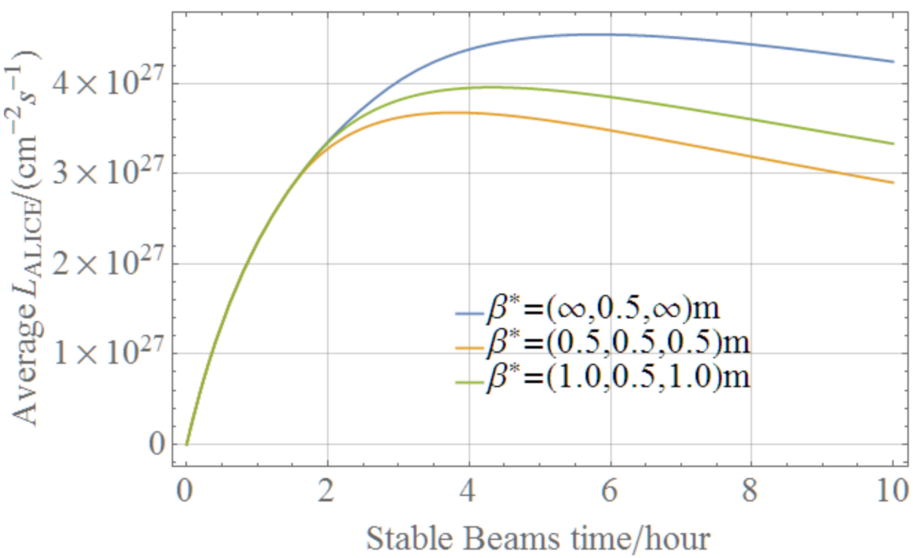
Effect of turn-around time on average luminosity



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

β^* = (0.5,0.5,0.5)m (equal)

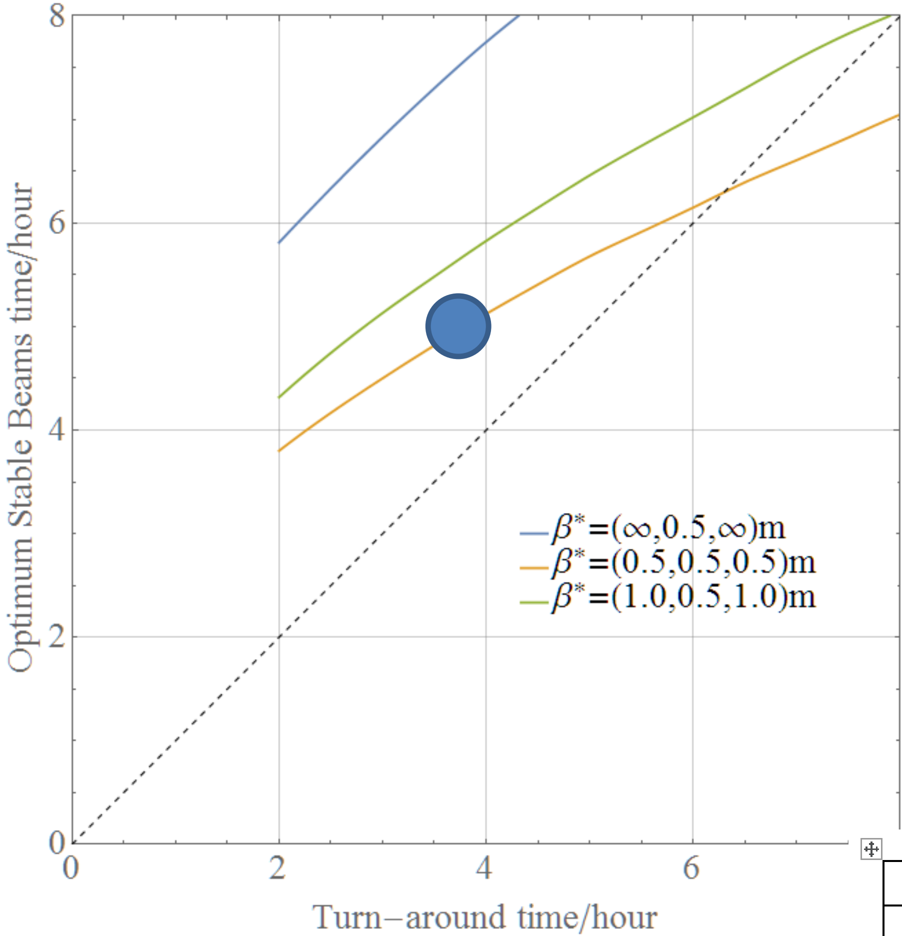
Turn around time =(3,5,7,9) h



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

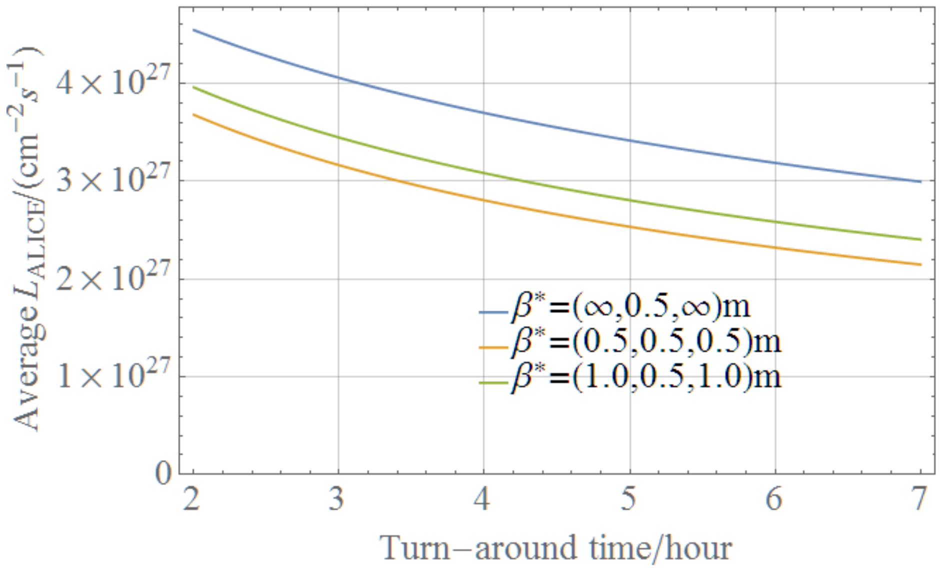
$$L_{\text{int,annual}} = \eta \langle L \rangle T_{\text{run}}$$
$$= (50\%)(3.0 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1})(24\ \text{day})$$
$$\approx 3.1\ \text{nb}^{-1}\ \text{(c.f. target of } 2.85\ \text{nb}^{-1})$$

where we (pessimistically!) assume an operation 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.



What if slip-stacking in SPS does not work?

- About half the number of bunches
- Average bunch intensity higher
- Less, if any, levelling
- Shorter lifetime
- About 60-70% of the integrated luminosity

- This would fall short of the ALICE LoI goals.
- Possible mitigations?
  - See talk by H Bartosik at Chamonix 2017

Higher luminosity p-Pb

- Recall: we had to stop increasing p intensity in 2016 so peak luminosity could be higher still
- Reasonable to hope for ~500-1000 nb^{-1} in any future 1-month p-Pb run at full energy with HL-Pb beams
  - Baseline request is 50 nb^{-1} in 2 weeks in 2028
- Would this be of interest ?

Lighter nuclei

- First Xe-Xe pilot run being analysed but has demonstrated potential

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, J.A. Ferreira Somoza, A. Findlay, P. Freyermuth, S. Gilardoni, S.B. Hancock, E.B. Holzer, S. Jensen, V. Kain, D. Küchler, A.M. Lombardi, A.I. Michet, M. O'Neil, S. Pasinelli, R. Scrivens, R. Steerenberg, G. Tranquille, CERN, Geneva, Switzerland

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

c.f. $N_b = 3.3\times10^8$ in 2017 Xe-Xe run

Assuming $N_b = 2\times10^9$ in future Ar-Ar run

$$\Rightarrow L_{NN} \approx 2\times10^{30} A^2 \text{ cm}^{-2}\text{s}^{-1}$$

$$\approx 5\times L_{NN}(\text{Pb-Pb at HL-LHC})$$

With longer beam-lifetimes (much lower UPC cross-sections), fewer turn-arounds, ~an order of magnitude in integrated nucleon-nucleon luminosity appears feasible. Collimation??

- e-Pb performance in 2012 CDR was based on LHC Design Pb beams – now upgraded with HL-Pb beams

Future Circular Collider Study
FCC-he Baseline Parameters

Oliver Brüning[1], John Jowett[1], Max Klein[2], Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool

CERN-ACC-2017-0019, April 2017

parameter [unit]	LHeC (HL-LHC)
E_{Pb} [PeV]	0.574
E_e [GeV]	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8
bunch spacing [ns]	50
no. of bunches	1200
ions per bunch [10^8]	1.8
$\gamma\epsilon_A$ [μm]	1.5
electrons per bunch [10^9]	4.67
electron current [mA]	15
IP beta function β_A^* [cm]	7
hourglass factor H_{geom}	0.9
pinch factor H_{b-b}	1.3
bunch filling H_{coll}	0.8
luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	7

Peak luminosity increase by an order of magnitude since CDR.

Summary

- LHC heavy-ion programme is already well into the "HL" regime
- Nucleus-nucleus (Pb-Pb) programme:
  - Peak luminosity was >3 × design in 2015
  - Expect to exceed 1 nb^{-1} integrated luminosity design goal (for 2 experiments) in 2018 in ALICE, ATLAS, CMS
  - now expected to reach 10 nb^{-1}++ goals set out in ALICE 2012 Letter of Intent with similar in ATLAS/CMS (+ fraction for LHCb?).
- Proton-nucleus (p-Pb) programme:
  - Peak luminosity was ~8 × "design" in 2016
  - Attained almost twice the 0.1 pb^{-1} integrated luminosity "design" goal in 2 experiments (+ several other physics data-sets for 5 experiments including large minimum-bias data set for ALICE)
  - Clear path to higher integrated luminosity in 3, possibly 4, experiments
- Short low-luminosity runs with new beams are feasible
  - See p-Pb (2012), Xe-Xe (2017)

Questions for the workshop

- Does the present baseline need any changes?
  - Luminosity sharing – request of LHCb to be clarified in any case.
- More p-Pb ?
  - HL request already ~fulfilled but could be much more.
- Should we consider lighter nuclei any further?
  - Optimum species? Ar?
  - Luminosity requirements?
  - Interest in hybrid collisions, eg, p-Ar ?
  - Short, low-luminosity runs (eg, p-O or p-N for cosmic ray studies) are feasible, mainly question of scheduling and preparation of beams in injectors

Acknowledgements

- LHC heavy-ion team (present and past)
  - M. Schaumann, T. Mertens, R. Alemany-Fernandez, H. Bartosik, for material in this talk
- LHC Injectors Upgrade (LIU) project
- HL-LHC Project
- Many, many, colleagues working on LHC and injectors

BACKUP SLIDES

LHC Pb Injector Chain:
Design Parameters for luminosity 10^{27} cm^{-2} s^{-1}

	ECR Source →	Linac 3 → (4)	LEIR →	PS → (13,12,8)	SPS → (12)	LHC
Output energy	**2.5 KeV/n**	**4.2 MeV/n**	**72.2 MeV/n**	**5.9 GeV/n**	**177 GeV/n**	**2.76 TeV/n**
^{208}Pb charge state	**27+**	**27+ → 54+**	**54+**	**54+ → 82+**	**82+**	**82+**
Output Bρ [Tm]		2.28 → 1.14	4.80	86.7 → 57.1	1500	23350
bunches/ring			2 (1/8 of PS)	4 (or 4x2)[4]	52,48,32	592
ions/pulse	$9\ 10^9$	$1.15\ 10^9$ [1])	$9\ 10^8$	$4.8\ 10^8$	$\leq 4.7\ 10^9$	$4.1\ 10^{10}$
ions/LHC bunch	**$9\ 10^9$**	**$1.15\ 10^9$**	**$2.25\ 10^8$**	**$1.2\ 10^8$**	**$9\ 10^7$**	**$7\ 10^7$**
bunch spacing [ns]				100 (or 95/5)[4]	100	100
ε*(nor. rms) [μm][2]	**~0.10**	**0.25**	**0.7**	**1.0**	**1.2**	**1.5**
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	**~10'fill/ring**
ε_{long} per LHC bunch[3]			0.025 eVs/n	0.05	0.4	1 eVs/n
total bunch length [ns]			200	3.9	1.65	1

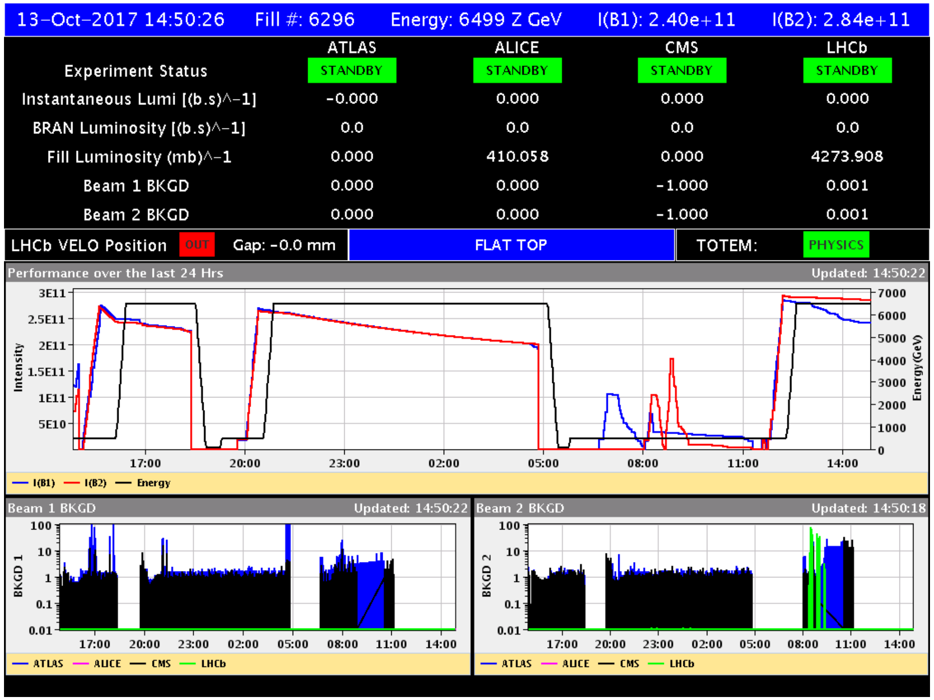
Stripping foil

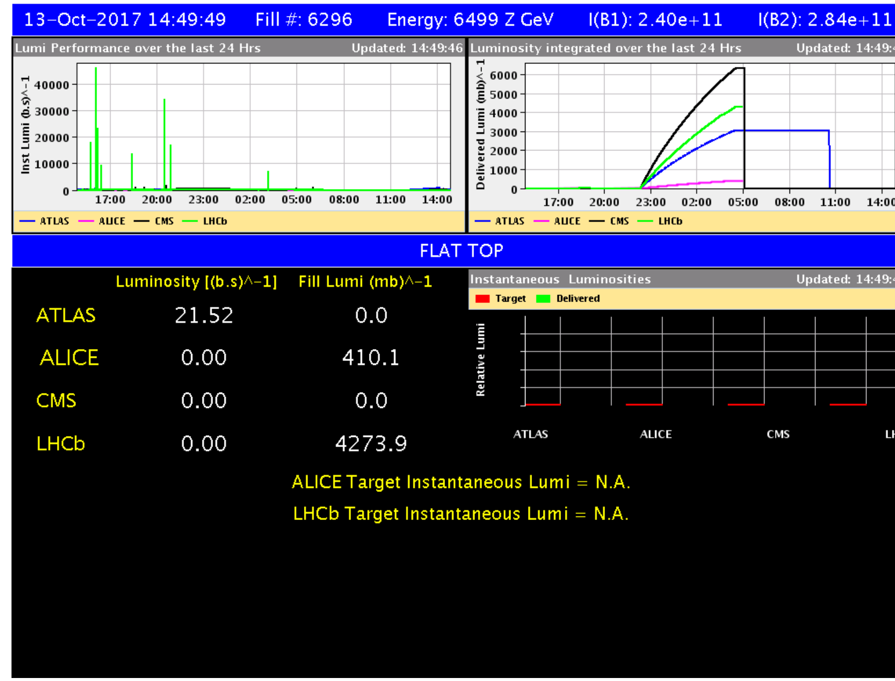
[1] 50 eμA$_e$ x 200 μs Linac3 output after stripping

[2] Same physical emittance as protons,

$$\varepsilon^* \equiv \varepsilon_n = \sqrt{\gamma^2 - 1}\,\varepsilon_{x,y}$$ is invariant in ramp.

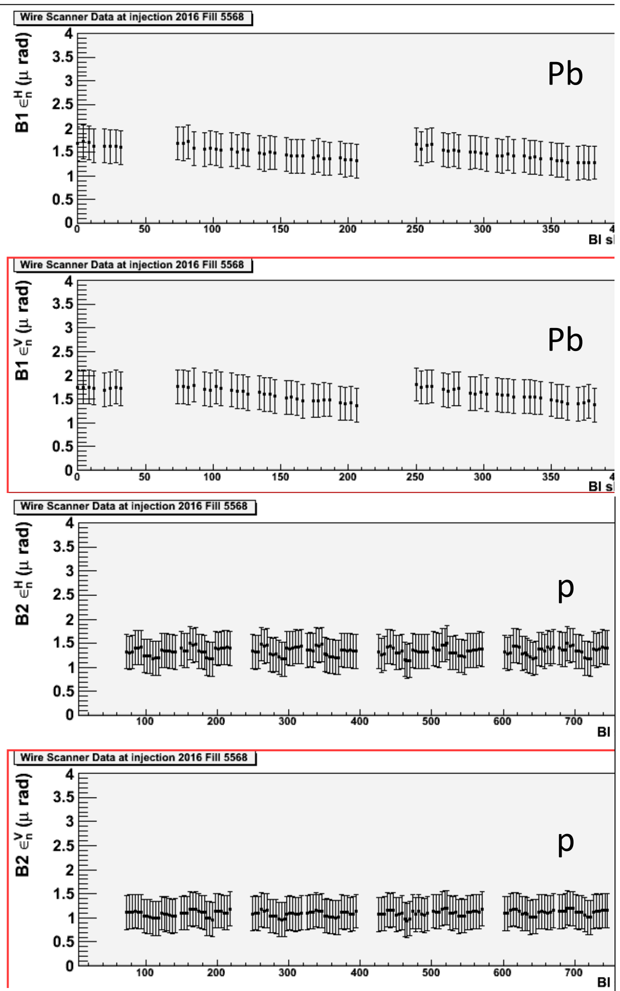
Xe-Xe run, final overview 24h



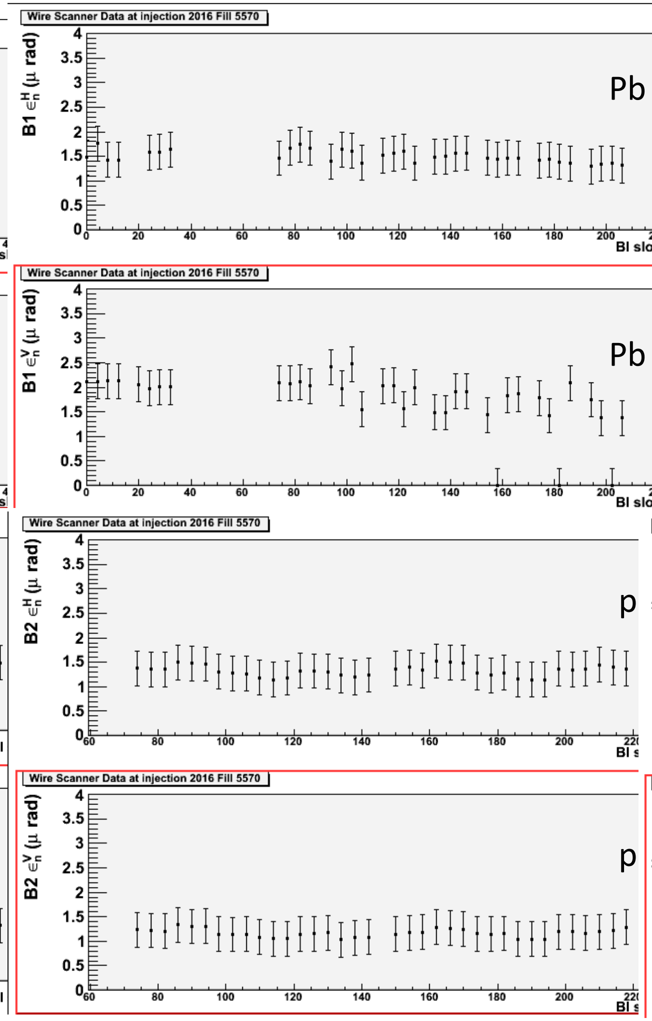


Pb wire scanner emittances at injection, 450 *Z* GeV, 2016

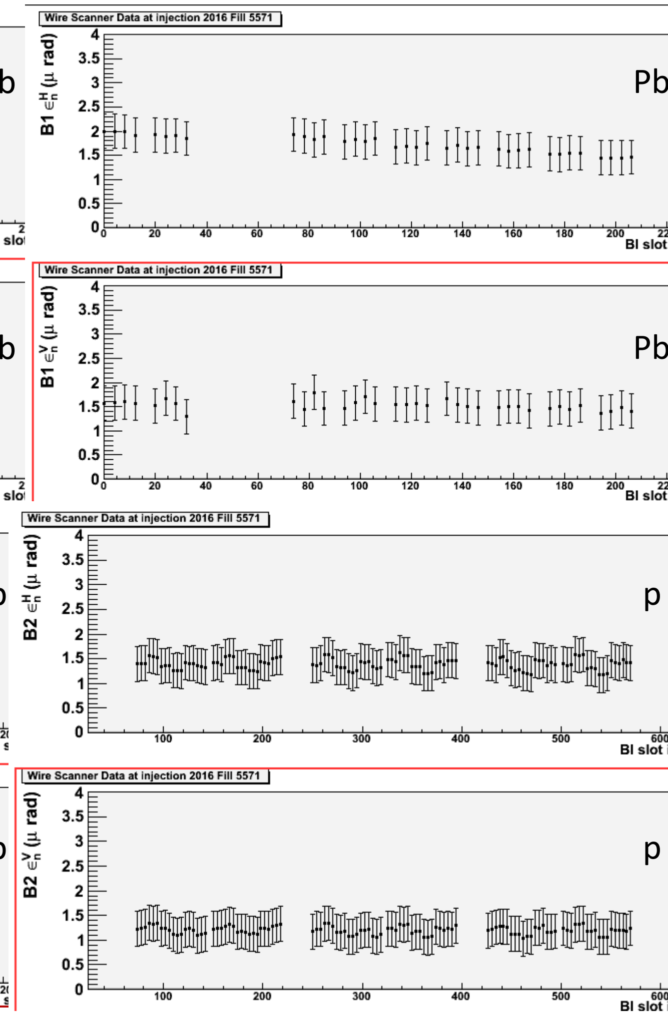
FILL 5568 Pbp @6.5 TeV



FILL 5570 Pbp @6.5 TeV

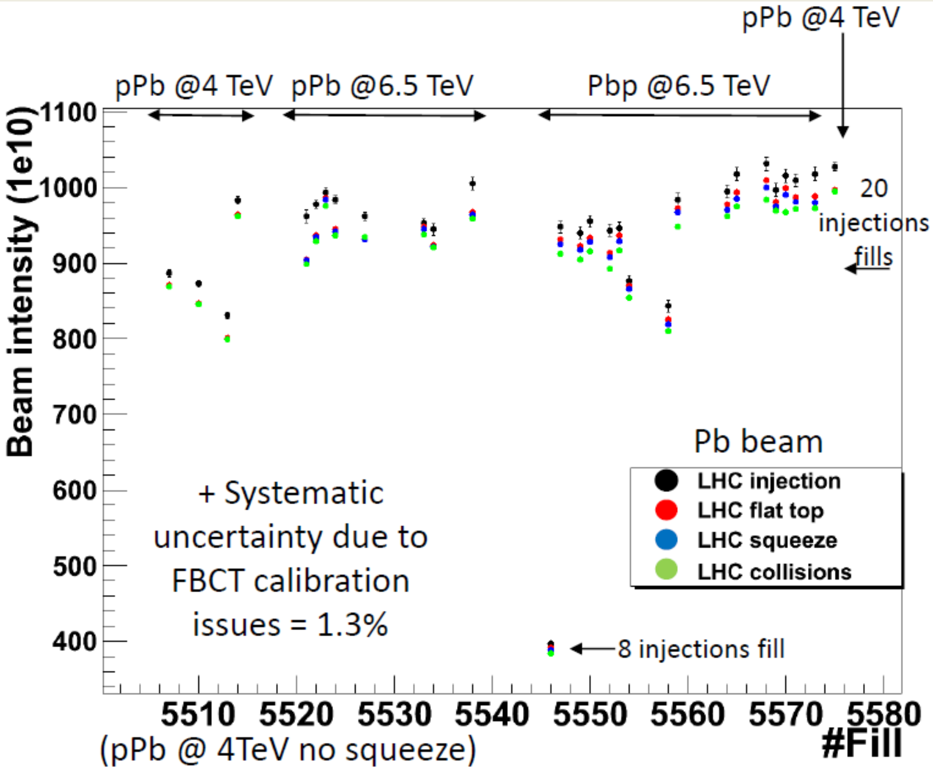


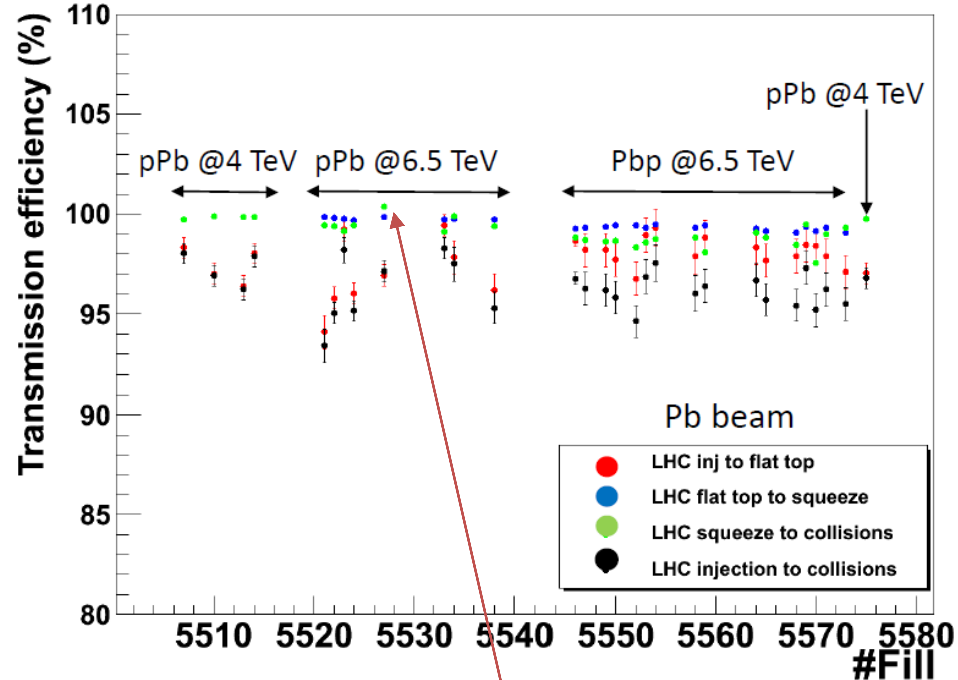
FILL 5571 Pbp @6.5 TeV



Intensity transmission: injection to collision, Pb in 2016

R. Alemany, M. Schaumann





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