HL-LHC performance: Update for HE-LHC and light ions

John Jowett

CERN

BASELINE HL-LHC PROGRAMME

For full details see
[presentation in October workshop](#)

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 $\sqrt{s_{NN}}$ [TeV]	5.52	8.79	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}cm^{-2}s^{-1}]	1	150	0.03	0.5	116	3.6	850	6
NN lumi. L_{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

"10-year goals"   ATLAS/CMS luminosities   "10-year goals"

- Proton-lead was not in 2004 LHC Design Report.
- "HL-LHC" for heavy-ions arguably started in 2015, with 3.5 × design luminosity.
- Luminosity limit in p-Pb not yet encountered. Can expect 500-1000 pb^{-1}/(1 month run)
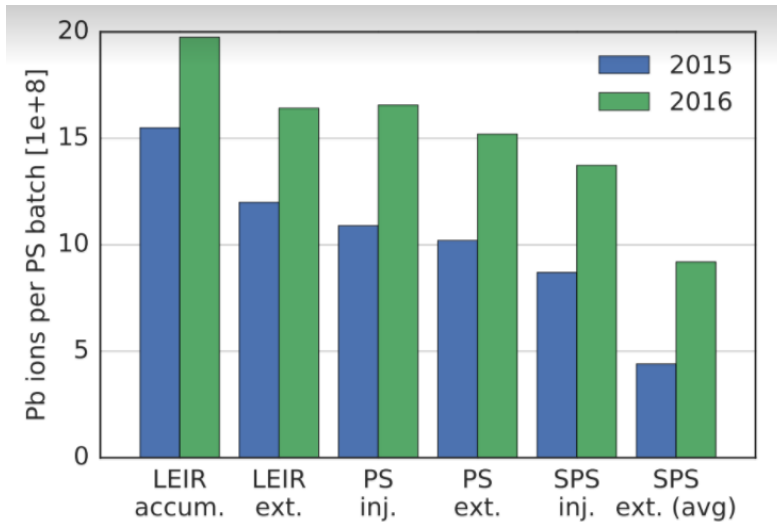
Major injector improvements since 2015

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

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.
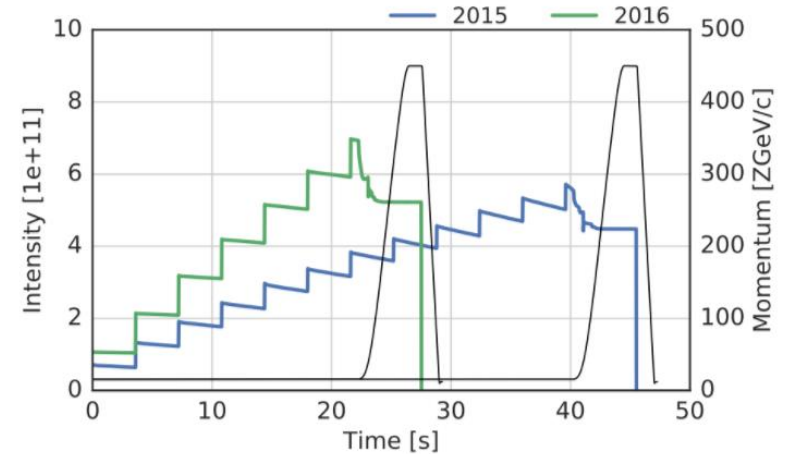

Figure 2: Typical intensity evolution along the operational Pb-ion cycles in 2016 in comparison to 2015.

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.

- Injector upgrades (major efforts in LIU project)
  - Single Pb bunch parameters already achieved with 100 ns bunch spacing, probably 75 ns in 2018
  - Last step: reduction to 50 ns by slip-stacking in SPS, to be implemented in 2021
- LHC upgrades
  - Mostly done for 2018, mitigation of losses from IPs and collimation with TCLD collimators, 11 T dipoles in LS2
- Expected to give ~ 3 nb^{-1}/0.5 pb^{-1} in Pb-Pb/p-Pb in future 1 month runs.
  - Baseline plan should fulfil ALICE 2012 LoI goals, also for ATLAS/CMS.   Can include LHCb at ~10% level.
- Possible to vary present baseline plan by switching runs between Pb-Pb and p-Pb.

LIGHTER IONS IN HL-LHC

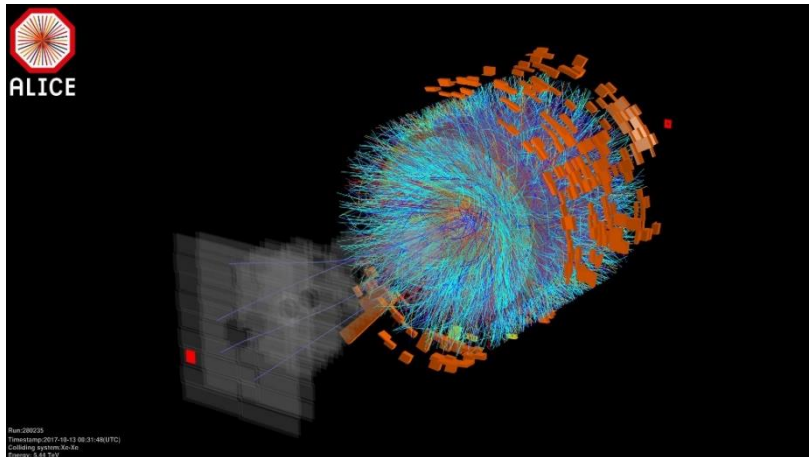# Xe-Xe collisions in LHC, 13 October 2017

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)

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
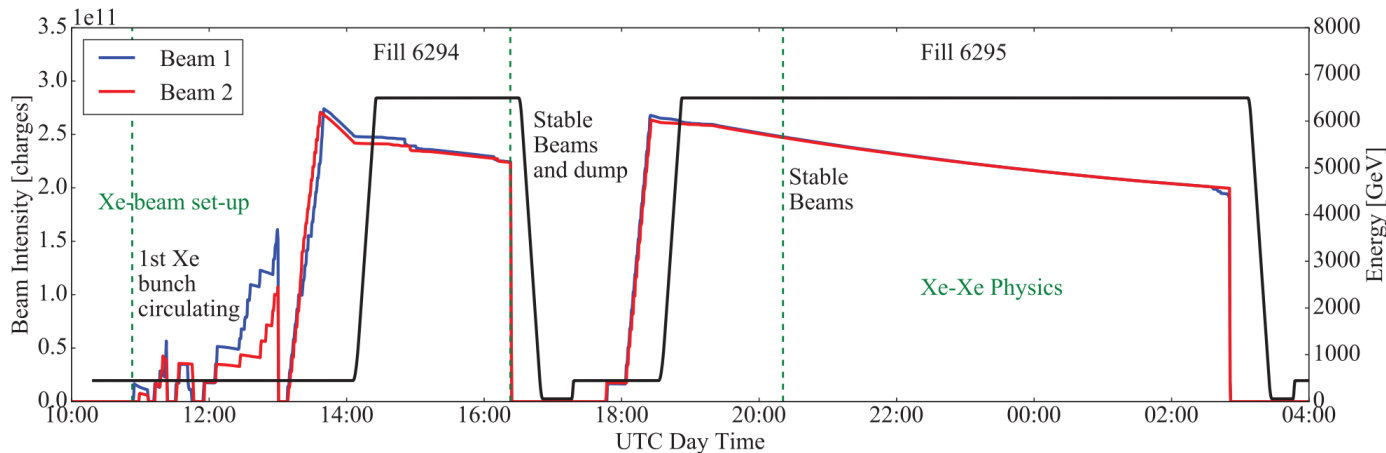
TUPAF024 Impedance and Instability Studies in LEIR With Xenon

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

Future interest in lighter species?

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).

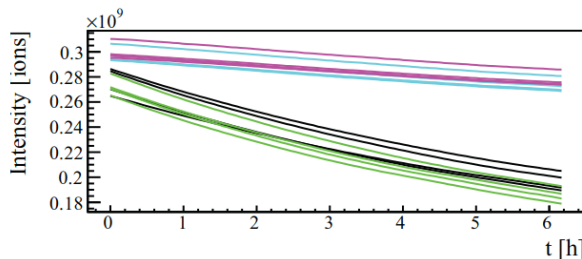| Class	IPs	$\sum_i \frac{1}{\beta_i^*}$ [m^{-1}]	τ [h]
0	-	0	87.8 ± 5.9
1 ●	2	0.10	79.2 ± 4.6
2 ●	2/8	0.43	72.1 ± 3.8
3 ●	1/2/5	6.77	17.5 ± 0.8
4 ●	1/2/5/8	7.10	16.3 ± 1.1

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.
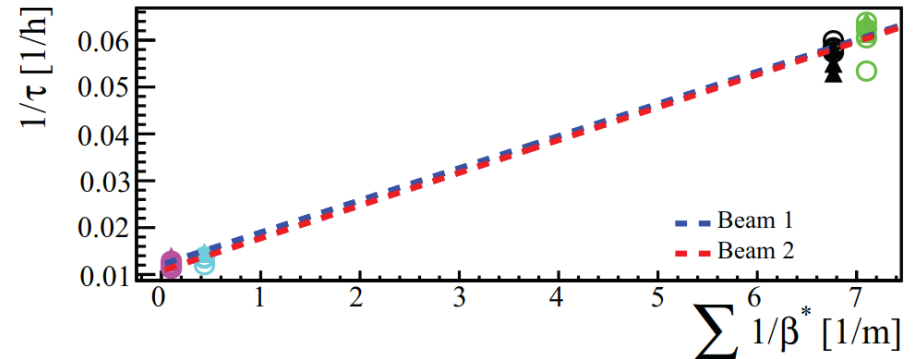

Figure 4: Relative loss rates versus $\sum_{IP} 1/\beta_{IP}^*$ during Stable Beams of fill 6295. Triangles indicate Beam 1 and circles Beam 2. The dashed lines are linear fits to obtain the non-colliding intensity lifetime.

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.

- ## 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

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

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!

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

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

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

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

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

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
$^{16}O^{8+}$	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.

Initial luminosity gain wrt Pb-Pb
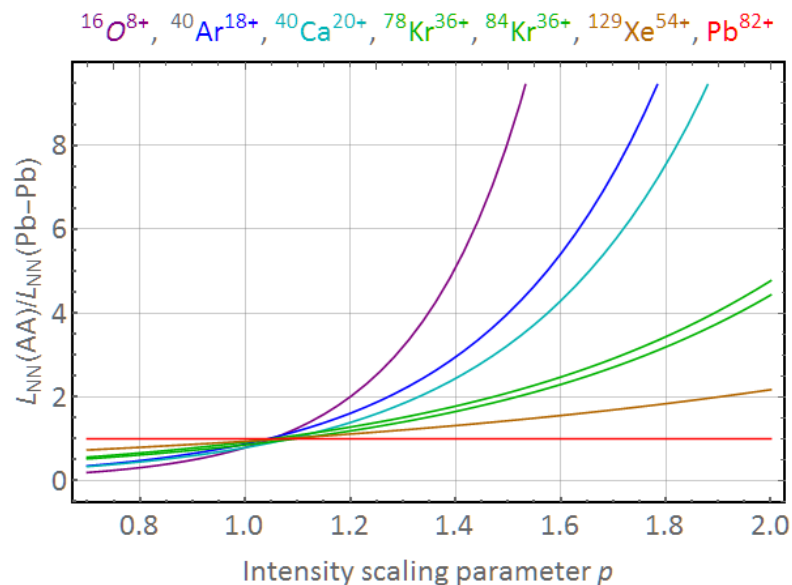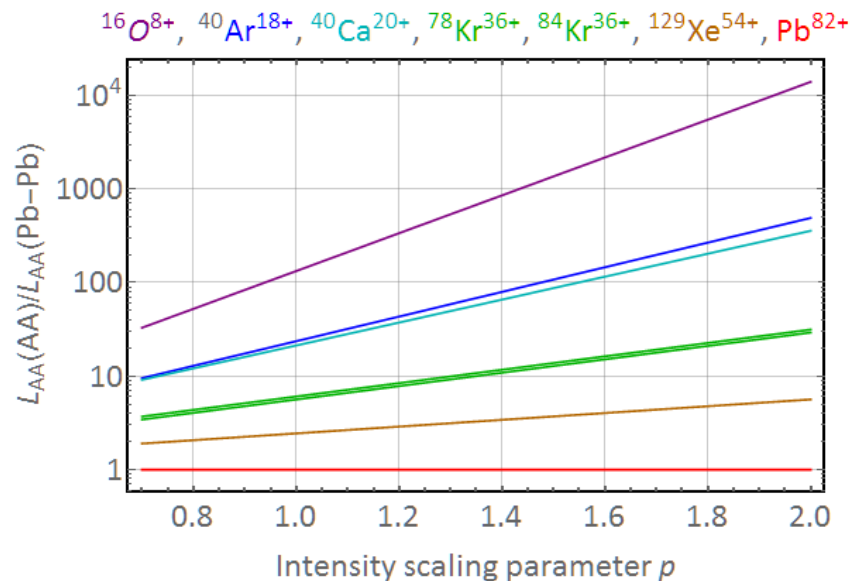
Species 2 vs species 1:

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

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.

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

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

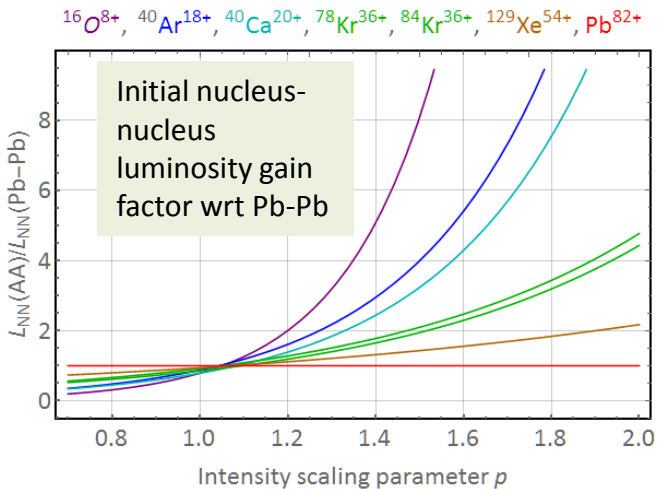# Higher nucleon-nucleon luminosity with lighter ions

Extrapolations of present experience to possible future fully-prepared "one-month run" conditions with lighter species, as *gain factors in nucleus-nucleus luminosity*.

Postulate simple form for bunch intensity dependence on species charge only

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

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

$$L_{NN} = A^2 L_{AA}$$

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

Initial nucleus-nucleus luminosity gain factor wrt Pb-Pb

Approximate integrated nucleus-nucleus luminosity gain factor wrt Pb-Pb
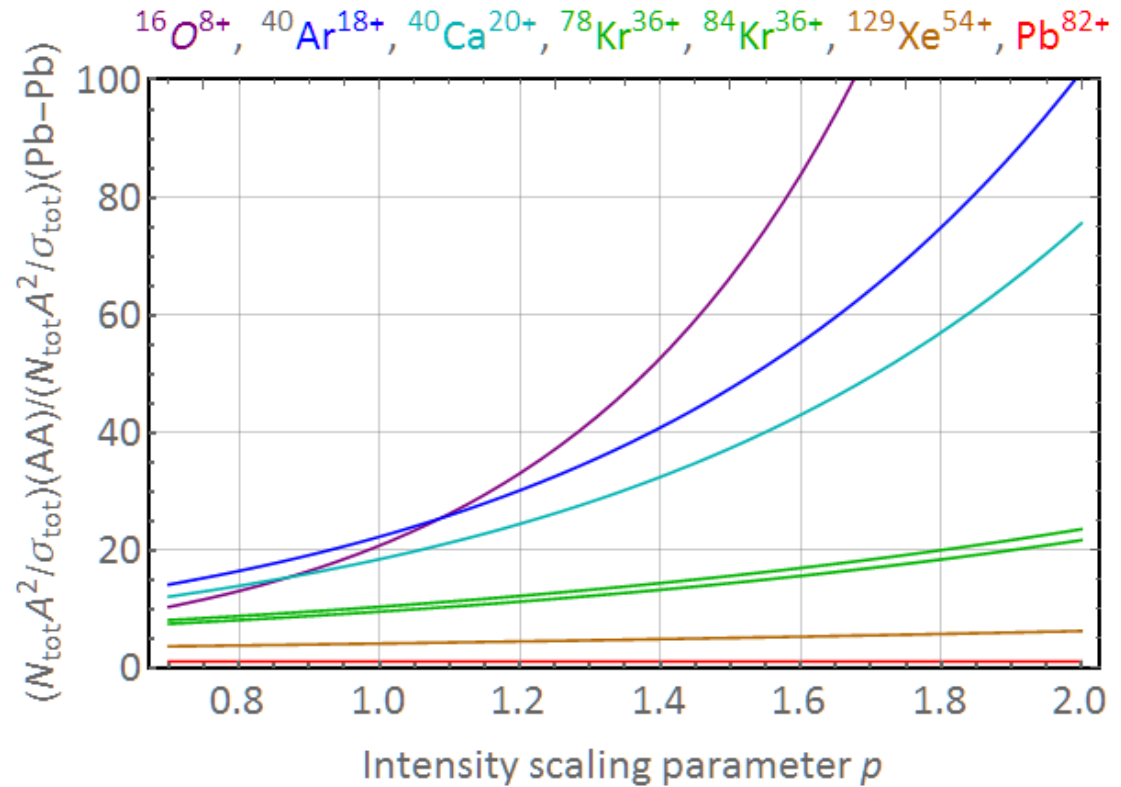

- Preliminary estimates for a range of the scaling factor *p*.   *p* = 1.5 seems reasonable.
- Detailed operational cycles to be worked out.
- Longer fills from smaller UPC cross-sections.   Plus: more luminosity events are hadronic.
- Possible limits from collimation losses, radio-protection in Linac3/LEIR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

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.

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

y-axis: $(N_{tot}A^2/\sigma_{tot})(AA)/(N_{tot}A^2/\sigma_{tot})(Pb-Pb)$

x-axis: Intensity scaling parameter p

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}
$^{16}O^{8+}$	1.48	3760.	7.	1.57×10^{30}	4.02×10^{32}	47.6	0.000332	0.143	0.534	-0.063
$^{40}Ar^{18+}$	3.85	3390.	6.3	3.11×10^{29}	4.97×10^{32}	41.3	0.0431	0.0588	3.99	-0.0252
$^{40}Ca^{20+}$	4.18	3760.	7.	2.52×10^{29}	4.03×10^{32}	42.2	0.0812	0.0526	4.53	-0.0252
$^{78}Kr^{36+}$	17.1	3470.	6.46	7.77×10^{28}	4.73×10^{32}	18.6	2.76	0.0286	19.6	-0.0129
$^{84}Kr^{36+}$	18.3	3220.	6.	7.77×10^{28}	5.48×10^{32}	17.4	2.76	0.0286	21.1	-0.012
$^{129}Xe^{54+}$	72.5	3150.	5.86	3.45×10^{28}	5.74×10^{32}	6.57	31.4	0.0189	55.6	-0.00782
Pb^{82+}	508.	2960.	5.52	1.5×10^{28}	6.47×10^{32}	1.43	385.	0.0123	155.	-0.00484

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}
$^{16}O^{8+}$	1.48	3760.	7.	1.57×10^{30}	4.02×10^{32}	47.6	0.000332	0.143	0.534	-0.063
$^{40}Ar^{18+}$	3.85	3390.	6.3	3.11×10^{29}	4.97×10^{32}	41.3	0.0431	0.0588	3.99	-0.0252
$^{40}Ca^{20+}$	4.18	3760.	7.	2.52×10^{29}	4.03×10^{32}	42.2	0.0812	0.0526	4.53	-0.0252
$^{78}Kr^{36+}$	17.1	3470.	6.46	7.77×10^{28}	4.73×10^{32}	18.6	2.76	0.0286	19.6	-0.0129
$^{84}Kr^{36+}$	18.3	3220.	6.	7.77×10^{28}	5.48×10^{32}	17.4	2.76	0.0286	21.1	-0.012
$^{129}Xe^{54+}$	72.5	3150.	5.86	3.45×10^{28}	5.74×10^{32}	6.57	31.4	0.0189	55.6	-0.00782
Pb^{82+}	508.	2960.	5.52	1.5×10^{28}	6.47×10^{32}	1.43	385.	0.0123	155.	-0.00484

Pb-Pb needs to be levelled!

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.
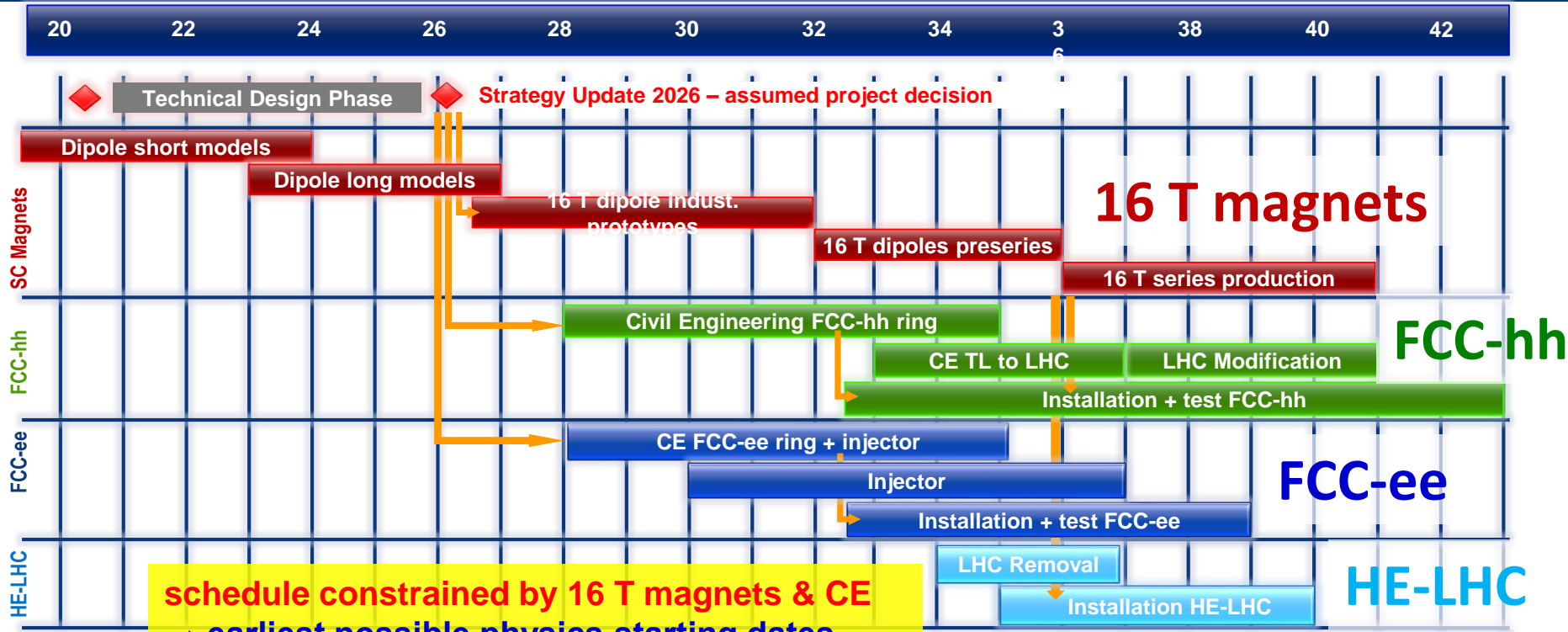 - The dramatic improvements in transmitted intensity in 2015-16 were the result of many detailed studies and improvements.

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).

HE-LHC

| 20 | 22 | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 | 40 | 42 |

◆ Technical Design Phase ◆ Strategy Update 2026 – assumed project decision

SC Magnets
- Dipole short models
- Dipole long models
- 16 T dipole indust. prototypes
- 16 T dipoles preseries
- 16 T series production

16 T magnets

FCC-hh
- Civil Engineering FCC-hh ring
- CE TL to LHC
- LHC Modification
- Installation + test FCC-hh

FCC-hh

FCC-ee
- CE FCC-ee ring + injector
- Injector
- Installation + test FCC-ee

FCC-ee

HE-LHC
- LHC Removal
- Installation HE-LHC

HE-LHC

schedule constrained by 16 T magnets & CE
→ earliest possible physics starting dates
- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

Summary

- We take a first look at the performance of the HE-LHC as a heavy-ion collider, based on the beams foreseen to be available during the high-luminosity heavy-ion phase of the LHC that will start in 2021.

- Like the FCC, the HE-LHC benefits from the faster radiation damping of heavy ions but beam losses due to collimation and ultraperipheral collisions at the interactions points have different consequences.

So far, *zero* FTEs have been available to work on heavy ions at HE-LHC.
Little participation in HE-LHC working groups.

This is just a first look, based on experience with LHC and the studies for FCC.

See talk on FCC as a nucleus-nucleus collider given at FCC Week 2018.

Assumptions for first look at Pb-Pb operation

- Similar Pb beam as projected for HL-LHC

- Simplified scenario - see talks by JMJ and H Bartosik at LHC Performance Workshop, Chamonix 2017
  https://indico.cern.ch/event/580313/contributions/2359517/
- https://indico.cern.ch/event/580313/contributions/2359507/

  - All bunches are equal (consider single bunch pair simulation)
  - Initial bunch intensity (start of stable beams, slightly improved over HL-LHC)

    $$\langle N_b \rangle = 2 \times 10^8$$

  - Initial emittance (start of stable beams)

    $$\varepsilon_{xn} = 1.5 \times 10^{-6} \text{m}$$

  - Other bunch parameters as LHC nominal, scaled with HE-LHC energy

$$E \approx pc = \underbrace{13.5Z \text{ TeV}}_{\substack{\text{Energy per charge,} \\ \text{relation to proton energy}}} = \underbrace{5.32A \text{ TeV}}_{\text{Energy per nucleon}}$$

Centre-of-mass energy for nucleon pairs in collision
$$\sqrt{s_{NN}} \approx 10.64 \text{ TeV}$$

- Simulation with Collider-Time-Evolution (CTE) program
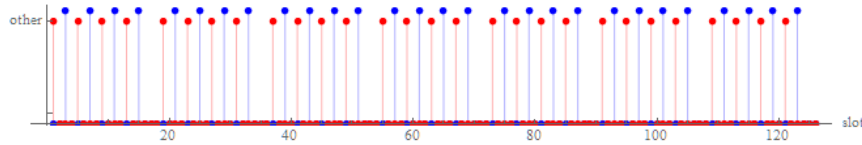
56 bunch SPS train
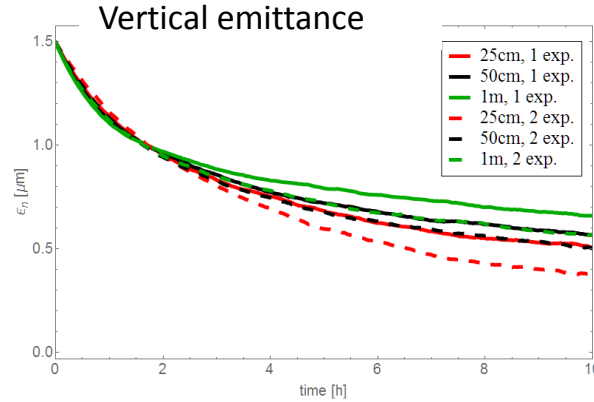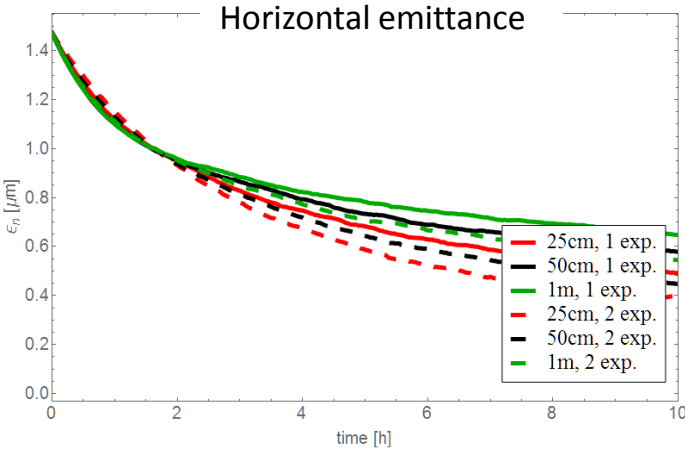after slip-stacking in SPS
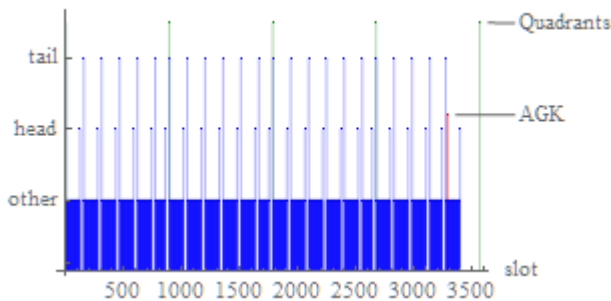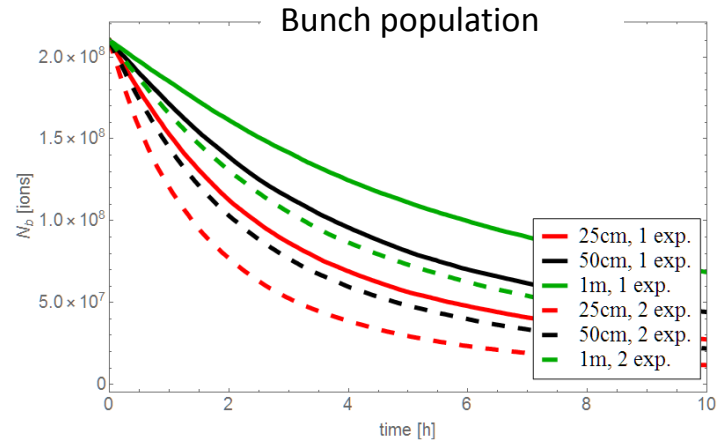
Two beams are identical, maximal
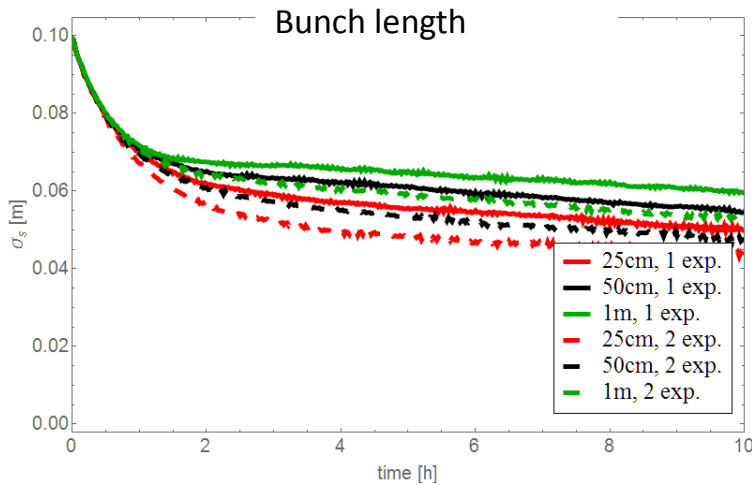filling with quadrant symmetry
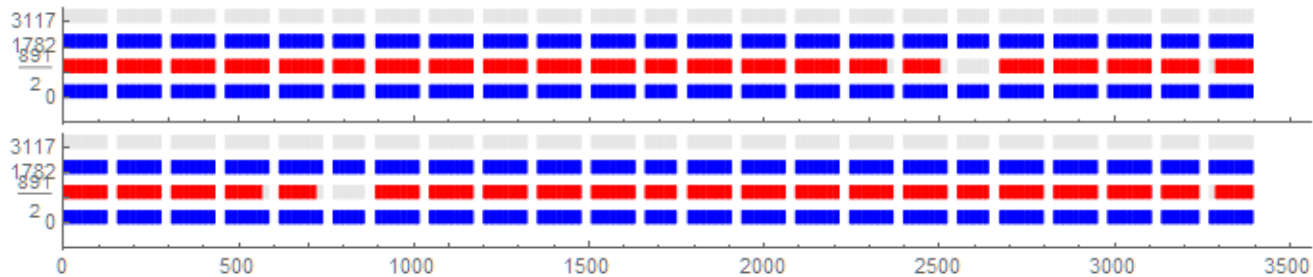
23 injections of 56-bunch trains give total of 1232 in each beam.
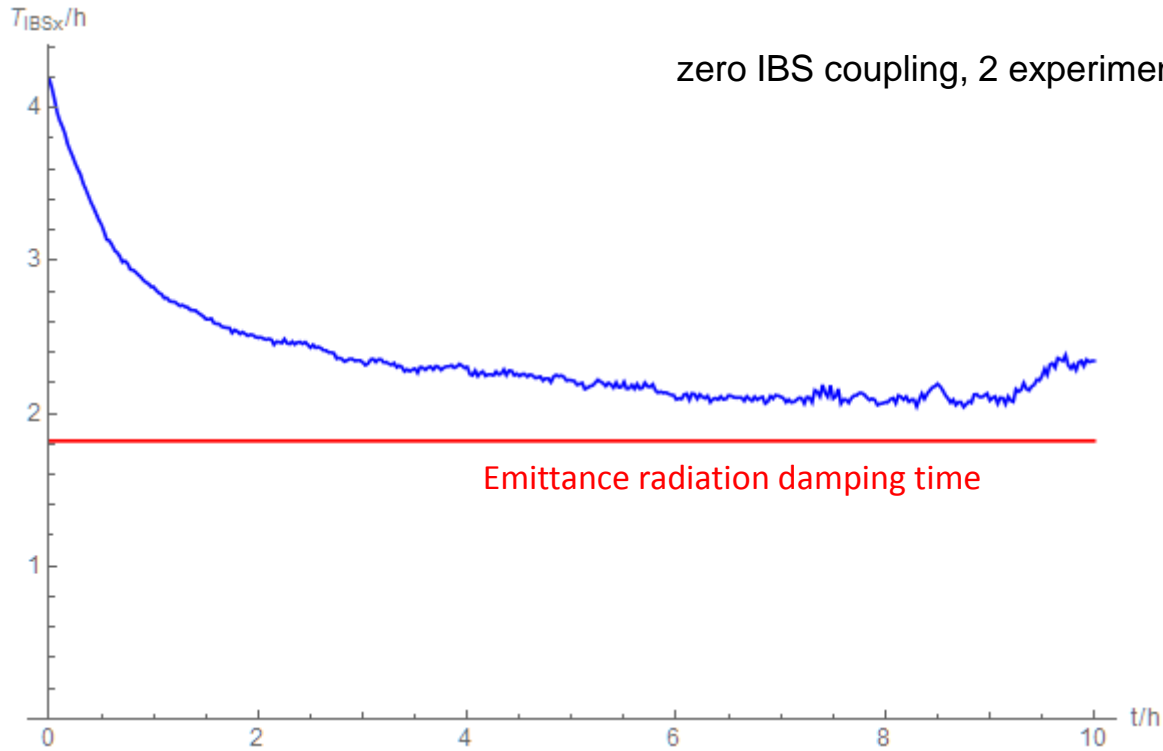1232 bunch pairs collide in ATLAS CMS, 1168 in ALICE, 0 in LHCb.

Consider optics as in V0.2 physics configuration but also some additional cases with higher β*.
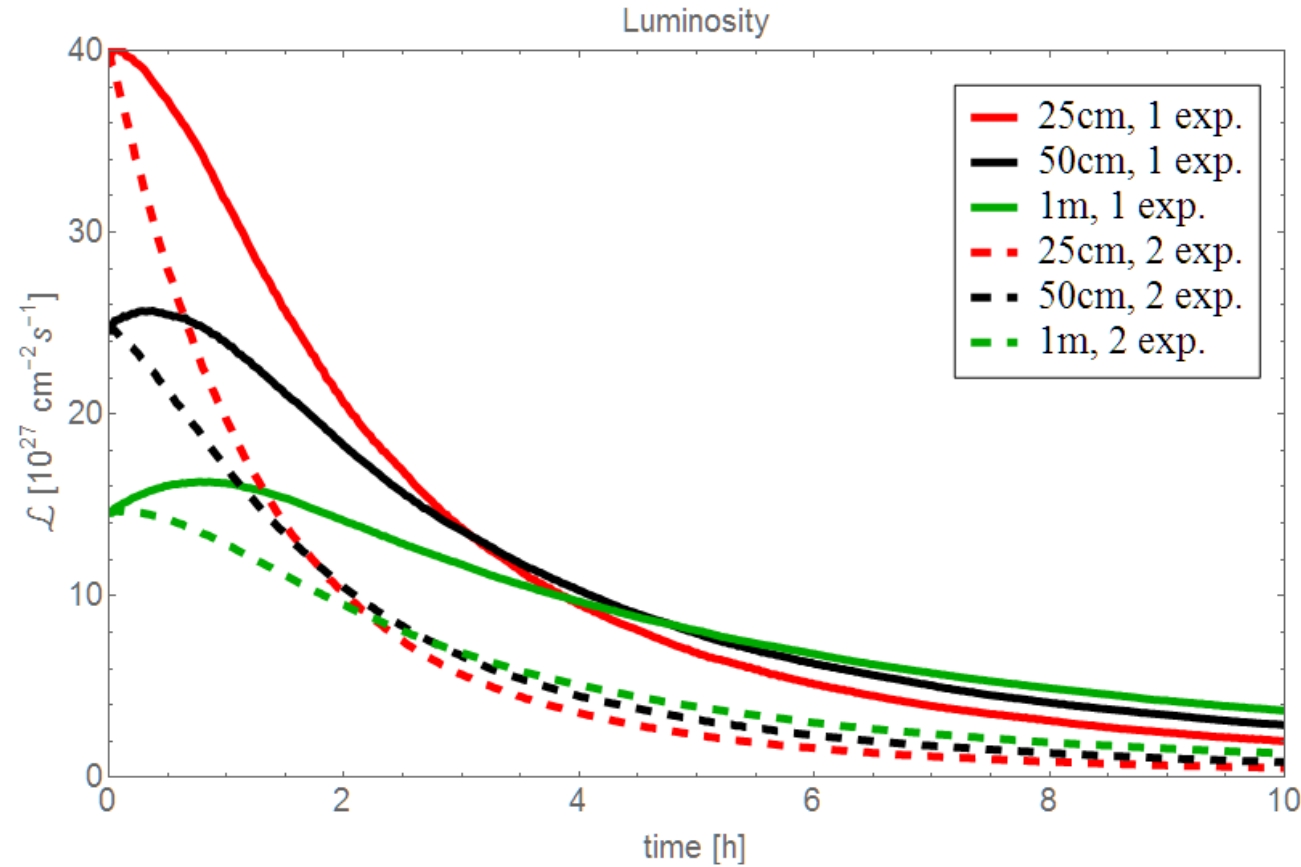
Michaela Schaumann

T_{IBSx}/h

zero IBS coupling, 2 experiments and 25cm beta*

Regime of balance between particle losses, radiation damping and intra-beam scattering.

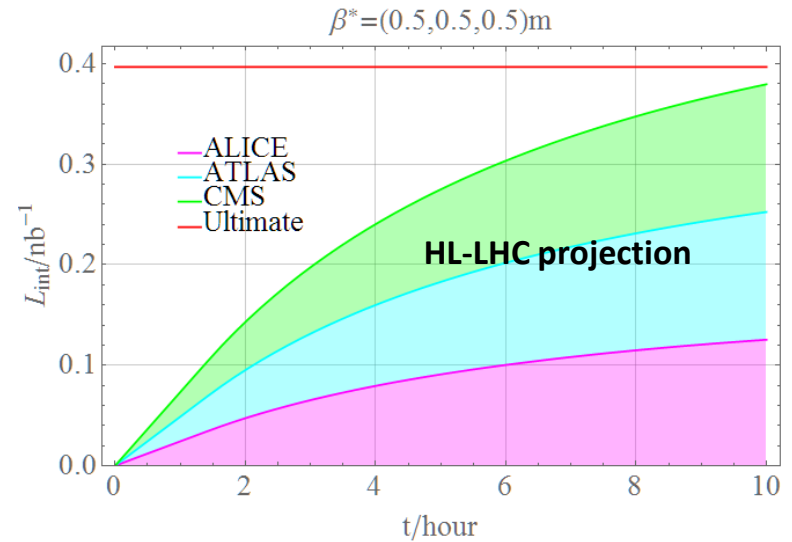IBS evaluated in simulation with CTE program (includes non-Gaussian longitudinal distribution).

Emittance radiation damping time
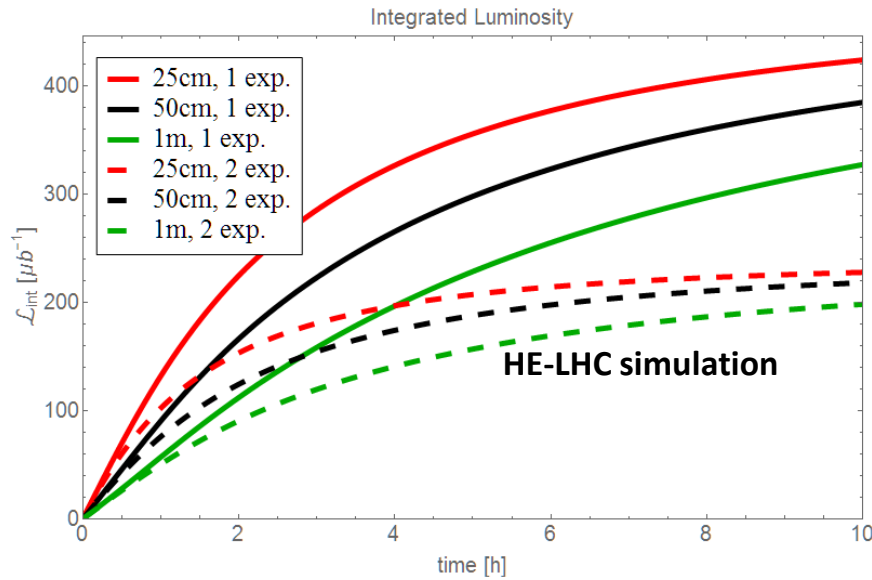
t/h

Michaela Schaumann

Luminosity evolution in a fill

Consider optics as in V0.2 physics configuration but also some additional cases with higher β*.

Ultimate luminosity to share per fill

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

The gain in integrated luminosity over HL-LHC is fairly small and is strongly affected by turn-around time – not surprising since we are assuming essentially the same injected beam.

HL-LHC projections are for 3.85 nb^{-1} per one-month run
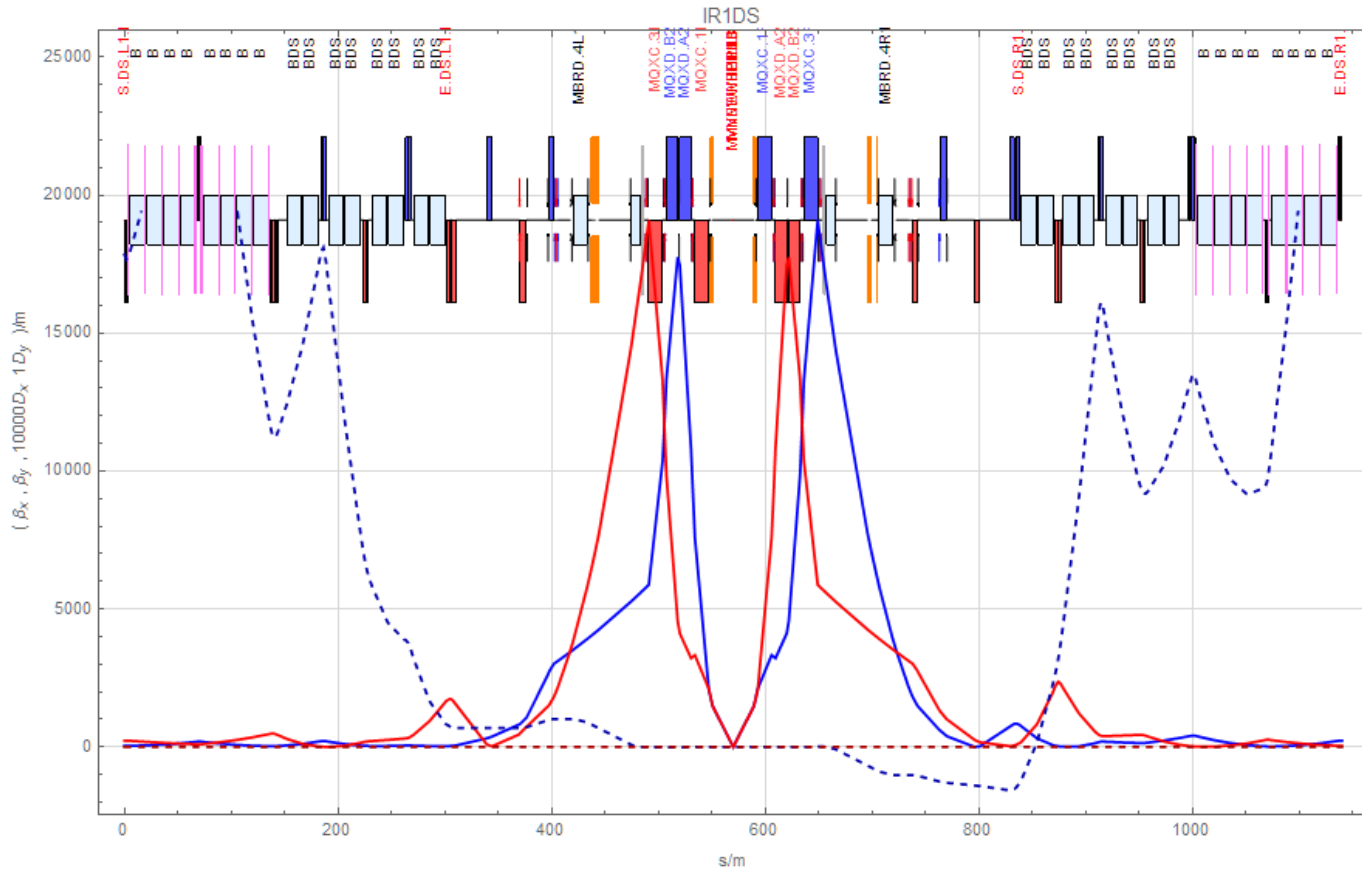
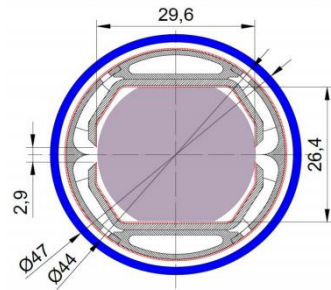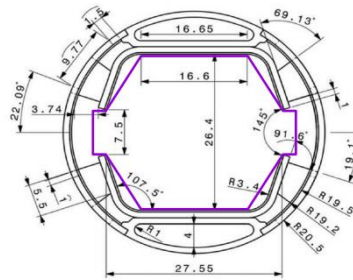Weaker focussing in arcs and DS than LHC.

Higher D_x and also different matching from LHC.
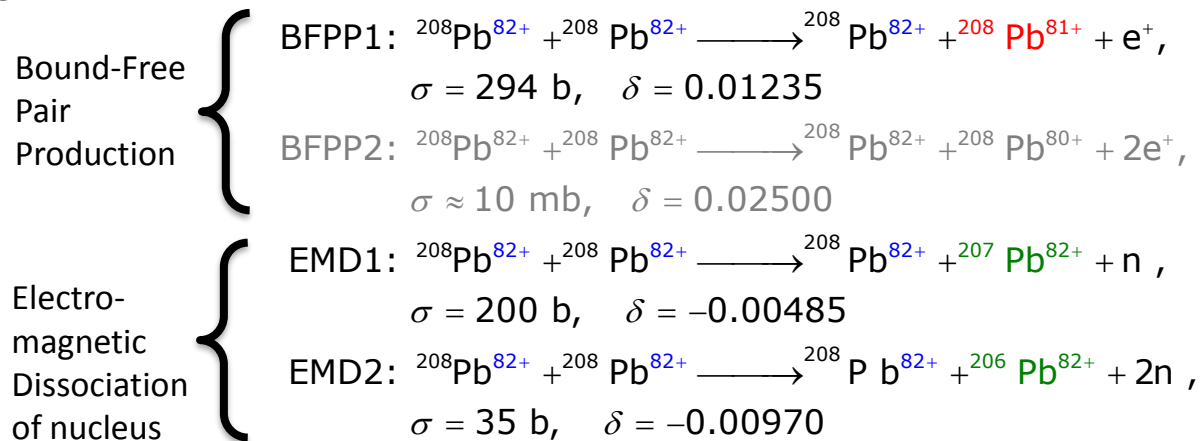
Aperture available

C. Garion, FCC Week 2016

I. Bellafont, EuroCirCol meeting Oct. 2017

HE-LHC Review Meeting   Dec 11, 2017   12

γ-γ and γ-A processes in Pb-Pb collisions

Nuclei are surrounded by intense EM fields: collisions of almost-real photons in Fermi-Weizsacker-Williams picture.

Ultra-peripheral electromagnetic interactions dominate the total cross-section during Pb-Pb collisions.

Bound-Free Pair Production
$$\text{BFPP1: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^+,$$
$$\sigma = 294 \text{ b}, \quad \delta = 0.01235$$

$$\text{BFPP2: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{80+} + 2e^+,$$
$$\sigma \approx 10 \text{ mb}, \quad \delta = 0.02500$$

Electro-magnetic Dissociation of nucleus
$$\text{EMD1: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{207}\text{Pb}^{82+} + n,$$
$$\sigma = 200 \text{ b}, \quad \delta = -0.00485$$

$$\text{EMD2: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{P b}^{82+} + {}^{206}\text{Pb}^{82+} + 2n,$$
$$\sigma = 35 \text{ b}, \quad \delta = -0.00970$$

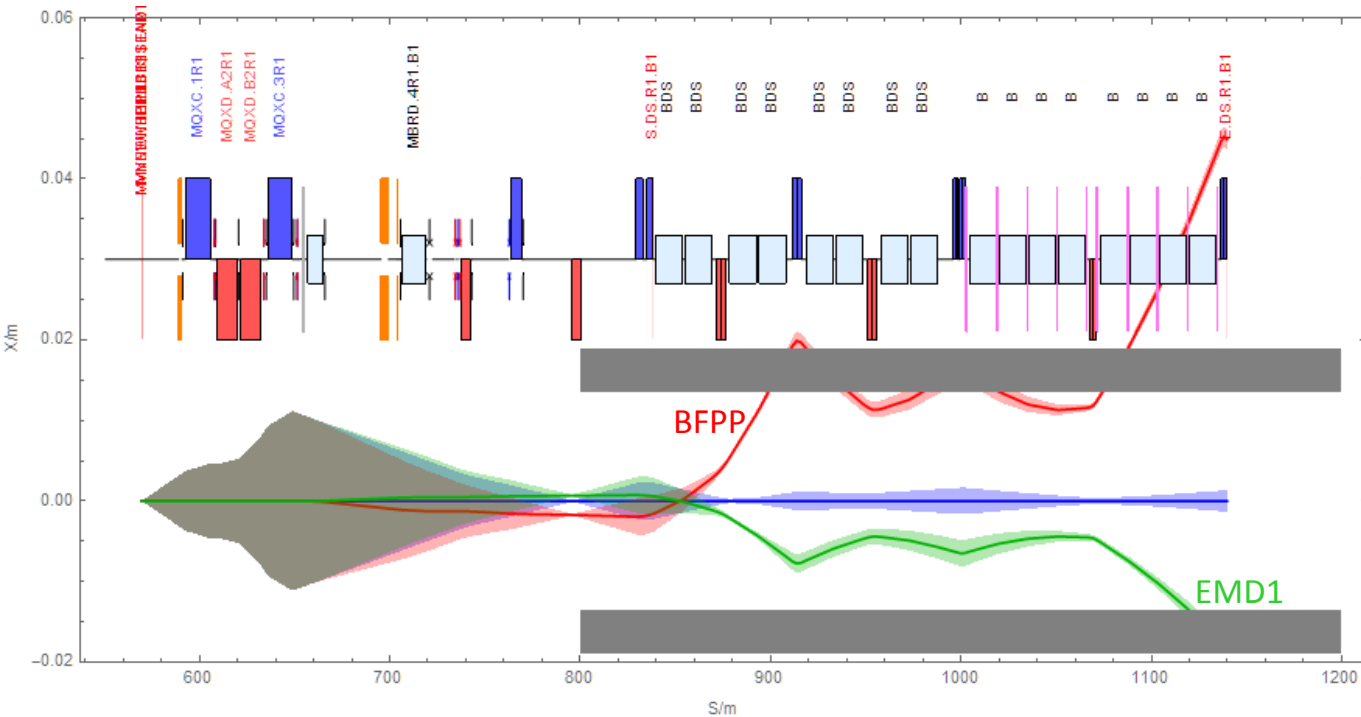Hadronic cross section is 8 b (so much less power in debris).

Each of these makes a secondary beam emerging from the IP.

Effects now familiar in Pb-Pb at LHC

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

Secondary beams from IP in Pb-Pb

Consequences of small beam pipe and weaker focussing:

Impact point of BFPP beam is not near the missing magnet slot in the DS and the solutions adopted for LHC will not work.

May help with EMD1 beam.

Can the matching be changed?

Secondary beam has few 100 W power.

Can the first 3 dipole magnets be moved closer to the IP to make a space for collimators?
Scheme used for earlier proposal for DS collimators in LHC – would not need >22 T dipoles … talk by JMJ at 2009 LHC Collimation Review https://indico.cern.ch/event/55195/

Another solution is to only collide nuclei with low enough Z. Acceptable for the physics programme ?

Conclusions for HE-LHC

- A first look at Pb-Pb collisions in HE-LHC suggests that integrated luminosity can be somewhat more than at HL-LHC (assuming similar injected beams)
  - Fills short, cycling and turn-around times are critical
  - Physics interest should come mainly from energy
- BFPP and EMD losses from IP may be unmanageable because of small beam pipe and weak focussing
  - Alternative layouts for the dispersion suppressors to install collimators under study.
  - Otherwise, limit colliding species to lighter nuclei, eg, Xe ?
- Heavy-ion operation of HE-LHC requires serious study:
  - BFPP and EMD losses from IPs, mitigations, solutions
  - Collimation and cleaning inefficiency
  - Best choice of colliding species for physics and machine ?
  - Injection, operational cycle
 - Hybrid proton-nucleus collisions, p-Pb, etc.

BACKUP SLIDES

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.
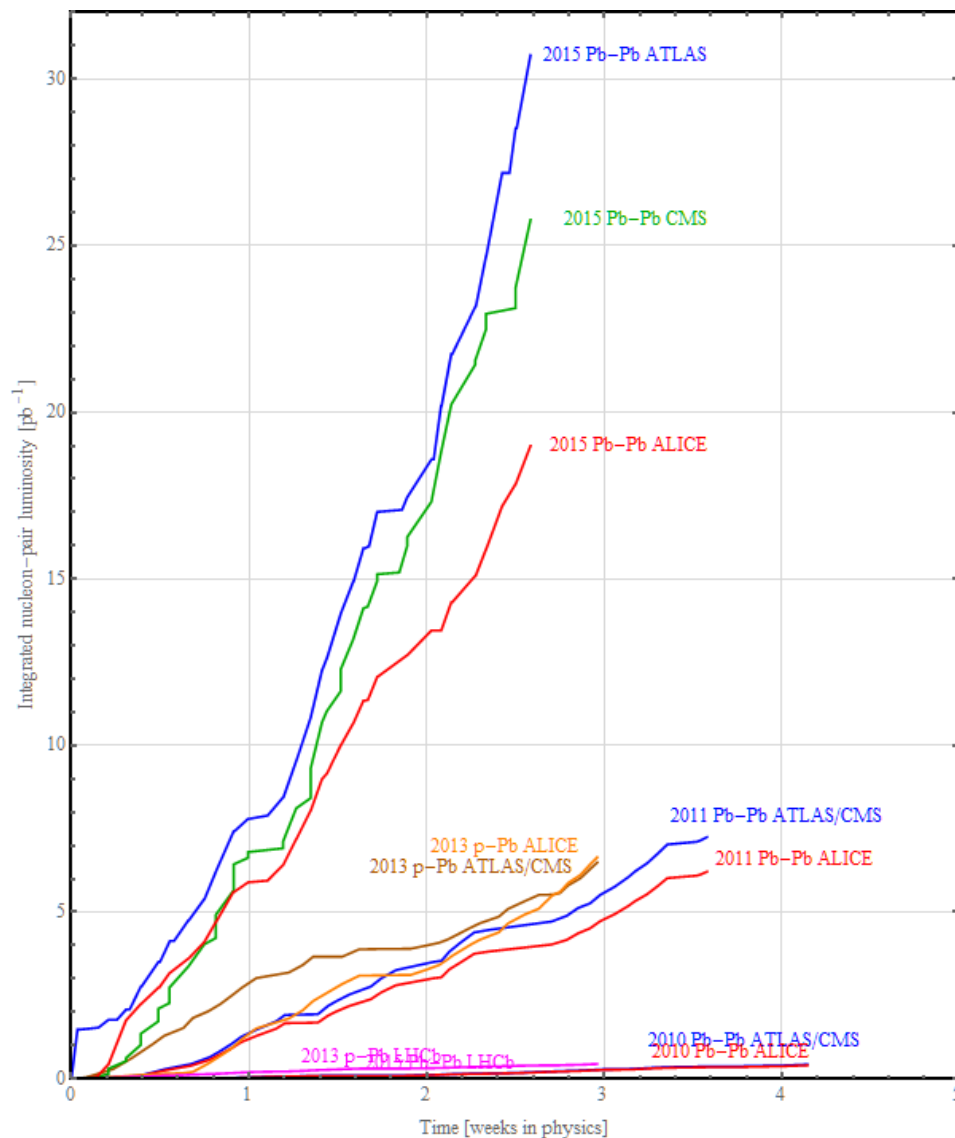
2012 pilot p-Pb run not shown

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.
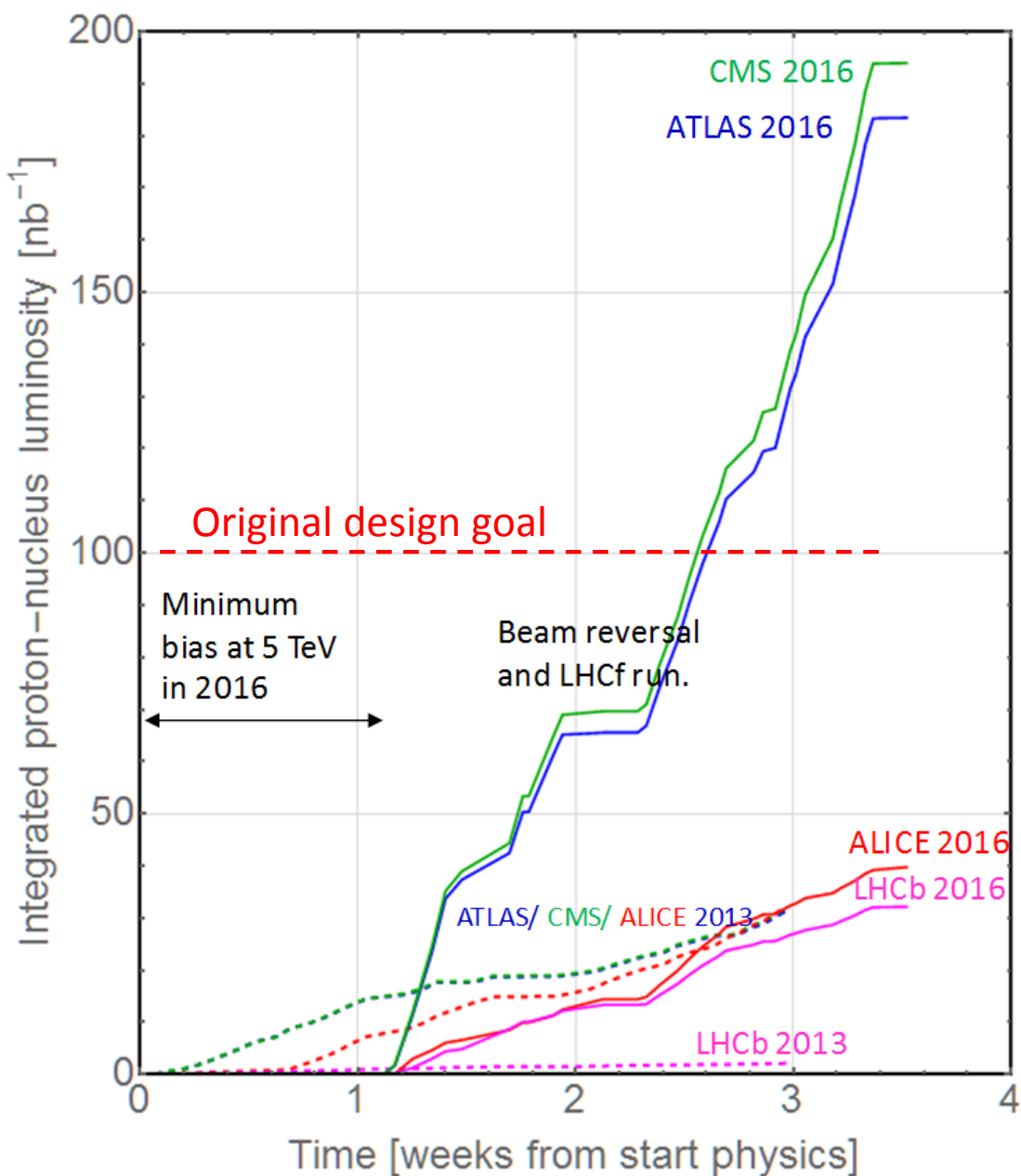
- Possible running scenario after upgrade:

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

Run 1

Pb-Pb   Pb-Pb   p-Pb!   p-Pb

2010   2011   2012   2013   2014   LS1

p-p & Pb-Pb   p-Pb   Xe-Xe   Pb-Pb   Pb-Pb   p-p   ?   Pb-Pb

2015   2016   2017   2018   2019   2020   2021   2022   2023

EYETS   LS2

Shutdown/Technical stop
Protons physics
Commissioning
Ions

Pb-Pb   p-Pb   Pb-Pb

2024   2025   2026   2027   2028   2029   2030   2031   2032

LS3   LS4

2033   2034   2035   2036   2037

LS5