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

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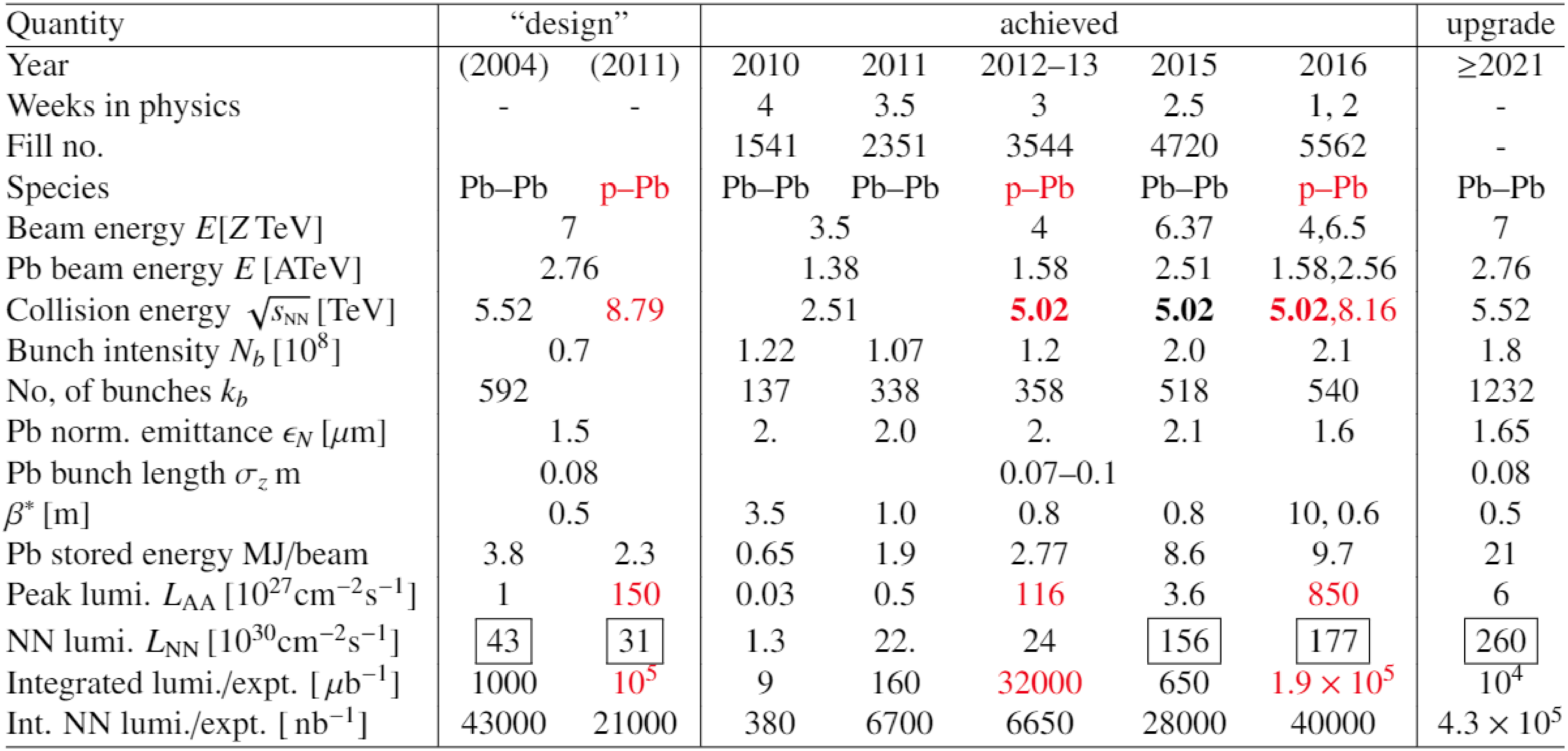
In this version of the slides, the section on performance with light ions has been improved since the presentation on 18/6/2018.

BASELINE HL-LHC PROGRAMME

For full details see
[presentation in October workshop]

HL-LHC Heavy Ion Status: Pb-Pb and p-Pb



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	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} [$10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1	150	0.03	0.5	116	3.6	850	6
NN lumi. L_{NN} [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	$\boxed{43}$	$\boxed{31}$	1.3	22.	24	$\boxed{156}$	$\boxed{177}$	$\boxed{260}$
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

"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

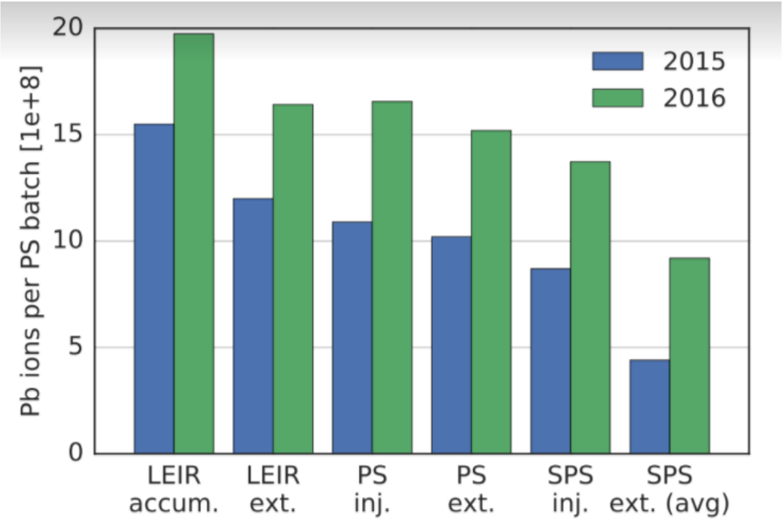


Figure 1: Comparison of operationally achieved intensities through the LHC injector chain in 2015 and 2016.

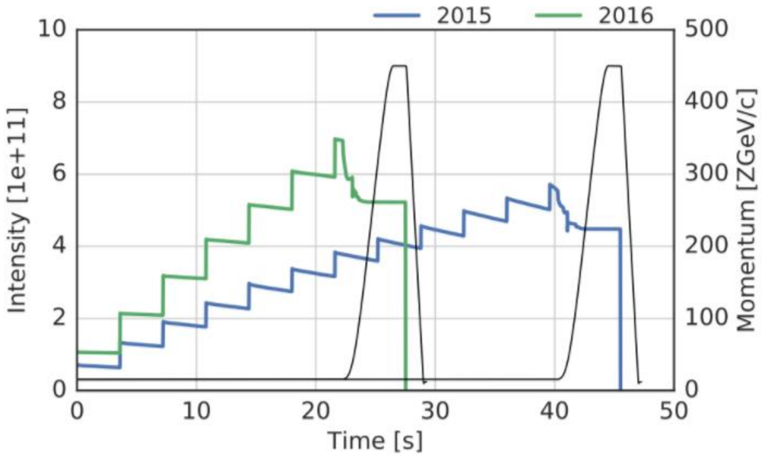


Figure 2: Typical intensity evolution along the operational Pb-ion cycles in 2016 in comparison to 2015.

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.

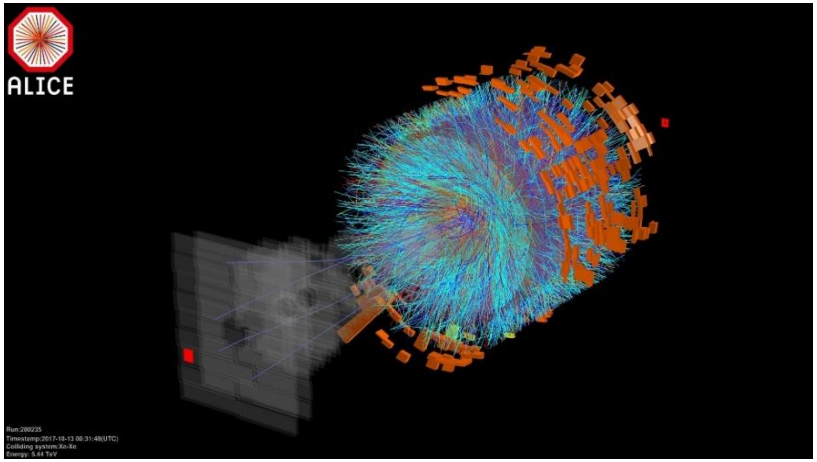
Baseline Pb-Pb and p-Pb for Runs 3-4

- 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

This section has been improved since the presentation on 18/6/2018.

Xe-Xe collisions in LHC, 13 October 2017



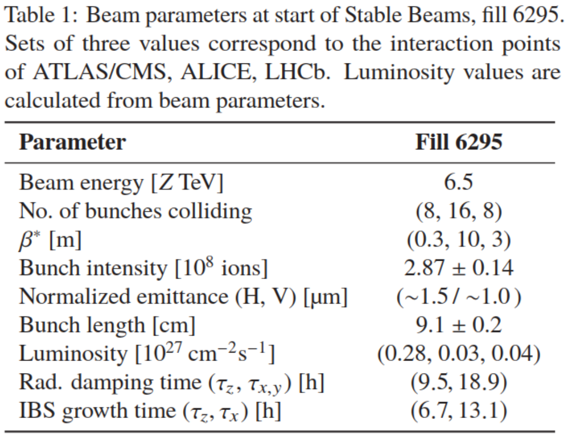


Table 1: Beam parameters at start of Stable Beams, fill 6295. Sets of three values correspond to the interaction points of ATLAS/CMS, ALICE, LHCb. Luminosity values are calculated from beam parameters.

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)

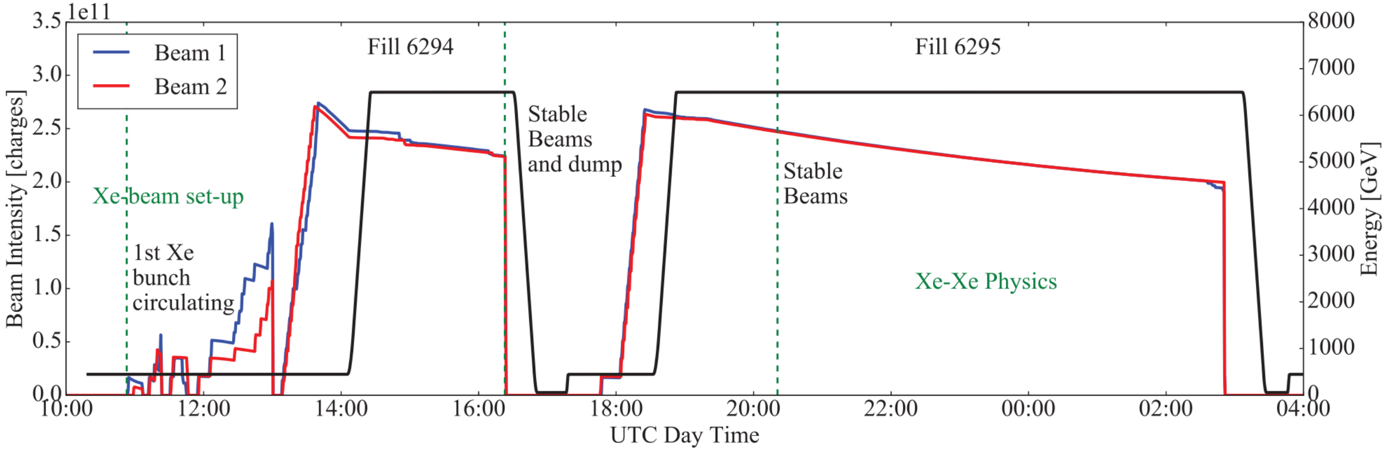


Figure 1: Evolution of the beam intensity and energy throughout the Xe–Xe run.

Future interest in lighter species?

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

MOPMF039 First Xenon-Xenon Collisions in the LHC

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

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

TUPAF024 Impedance and Instability Studies in LEIR With Xenon

Xe lifetime analysis

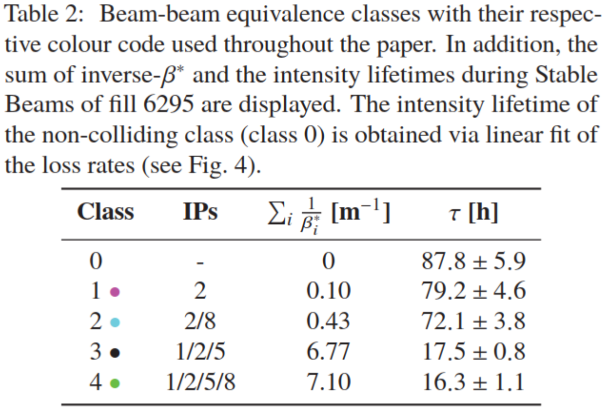


Table 2: Beam-beam equivalence classes with their respective colour code used throughout the paper. In addition, the sum of inverse-β^* and the intensity lifetimes during Stable Beams of fill 6295 are displayed. The intensity lifetime of the non-colliding class (class 0) is obtained via linear fit of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

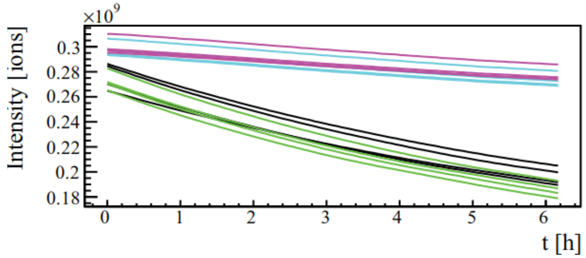


Figure 3: Bunch-intensity evolution of Beam 1 during fill 6295 after declaration of Stable Beams. The colour of each class is listed in Table 2.

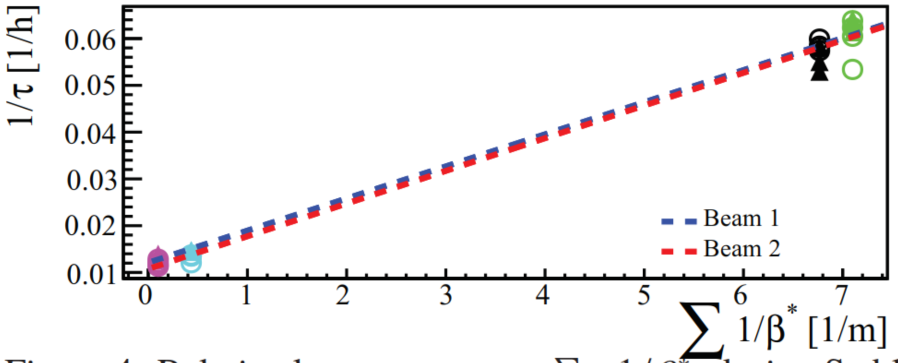


Figure 4: Relative loss rates versus $\sum_{\mathrm{IP}} 1/\beta^*_{\mathrm{IP}}$ during Stable Beams of fill 6295. Triangles indicate Beam 1 and circles Beam 2. The dashed lines are linear fits to obtain the non-colliding intensity lifetime.

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.

Bunch intensity at SPS extraction for various species

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

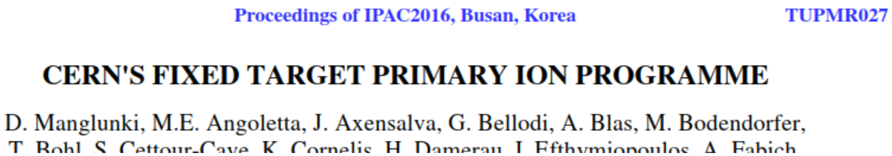
Postulate simple form for bunch intensity dependence on species charge only

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

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

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

Treat results only as tentative and indicative only!



Proceedings of IPAC2016, Busan, Korea TUPMR027

CERN'S FIXED TARGET PRIMARY ION PROGRAMME

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

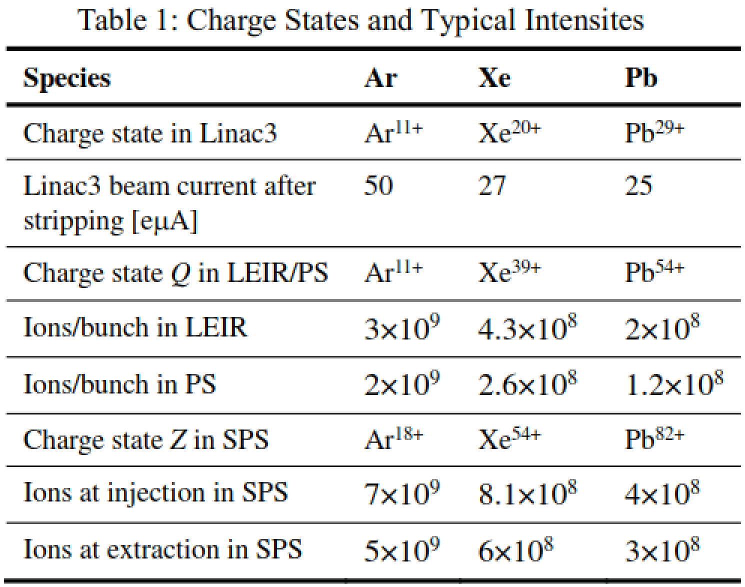


Table 1: Charge States and Typical Intensites

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

UPC cross sections determining intensity burn-off

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

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.

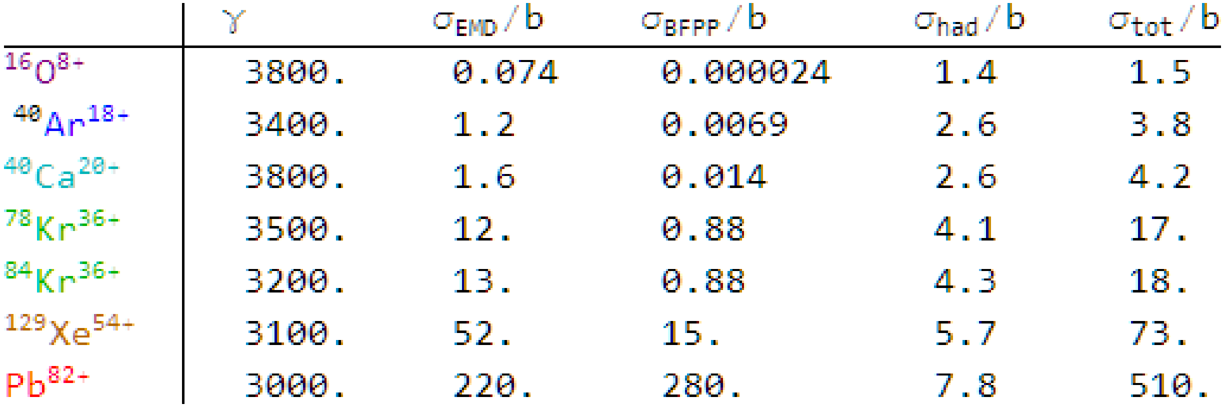
$$\sigma_{\text{EMD1}} \approx (3.42\ \mu b)\frac{(A-Z)Z^3}{A^{2/3}}\log\left(2\gamma^2 - 1\right),$$

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

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

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
$^{16}\text{O}^{8+}$	3800.	0.074	0.000024	1.4	1.5
$^{40}\text{Ar}^{18+}$	3400.	1.2	0.0069	2.6	3.8
$^{40}\text{Ca}^{20+}$	3800.	1.6	0.014	2.6	4.2
$^{78}\text{Kr}^{36+}$	3500.	12.	0.88	4.1	17.
$^{84}\text{Kr}^{36+}$	3200.	13.	0.88	4.3	18.
$^{129}\text{Xe}^{54+}$	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:

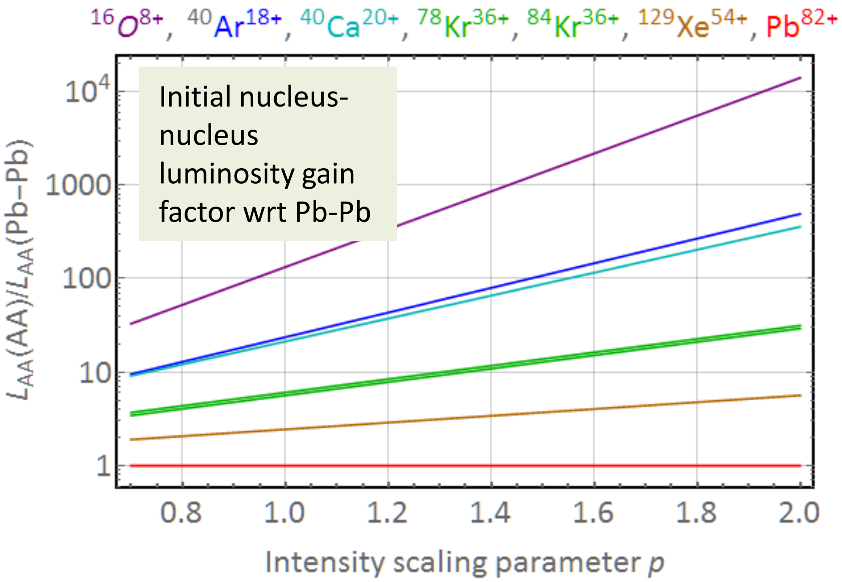
Beam size at IP: $\frac{\sigma_2^*}{\sigma_1^*} = \frac{\sqrt{A_2}\sqrt{Z_1}}{\sqrt{A_1}\sqrt{Z_2}}$

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

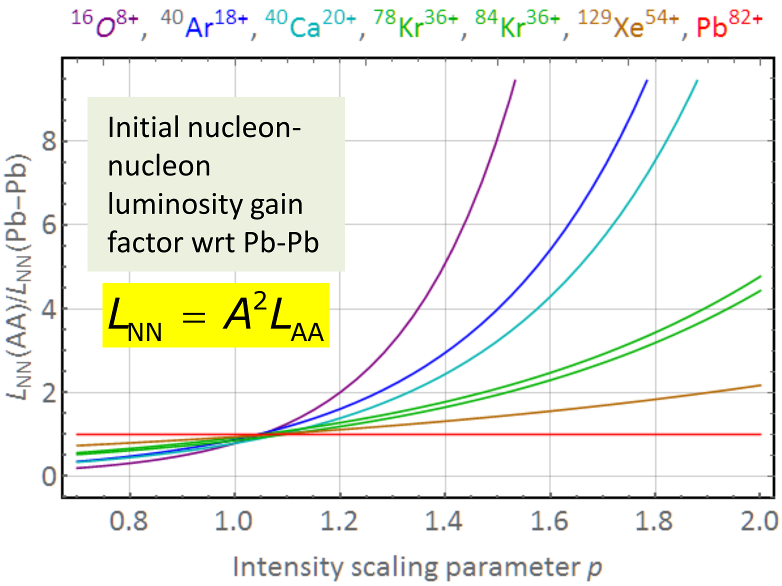
Initial NN luminosity $\frac{L_2}{L_1} = \frac{A_2 Z_1^{-1+2p}}{A_1 Z_2^{-1+2p}}$

This assumes no luminosity levelling.

Formulas for integrated luminosity gains are much messier.



Initial nucleus-nucleus luminosity gain factor wrt Pb-Pb



Initial nucleon-nucleon luminosity gain factor wrt Pb-Pb

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

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.

Time-averaged nucleon-nucleon luminosity wrt Pb-Pb

Simplified scenario:

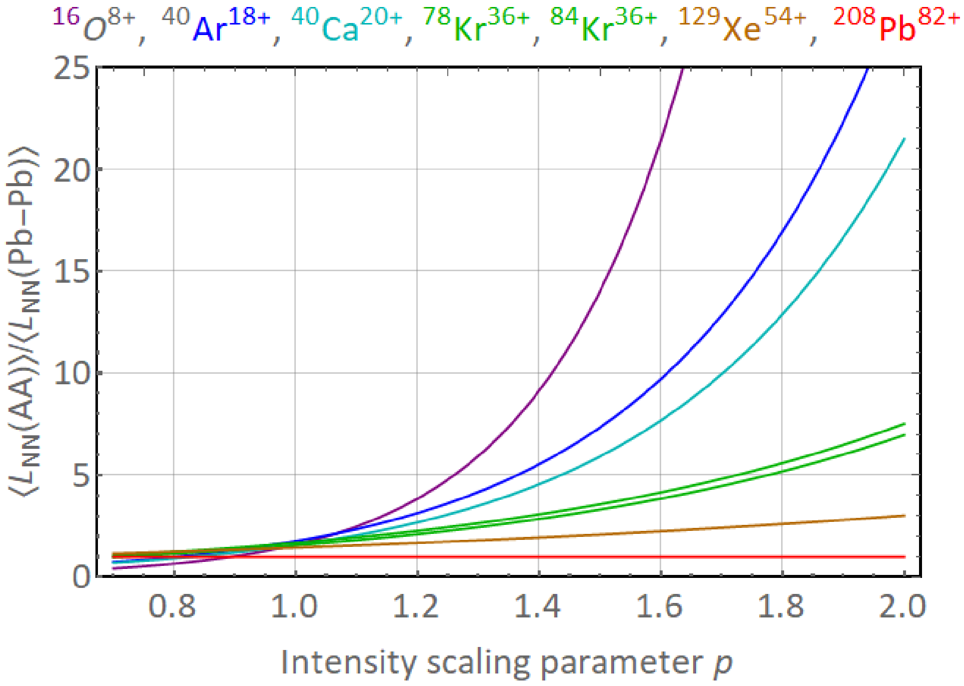
Fill lengths optimized for 2.5 h turn-around (dump to next Stable Beams).

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

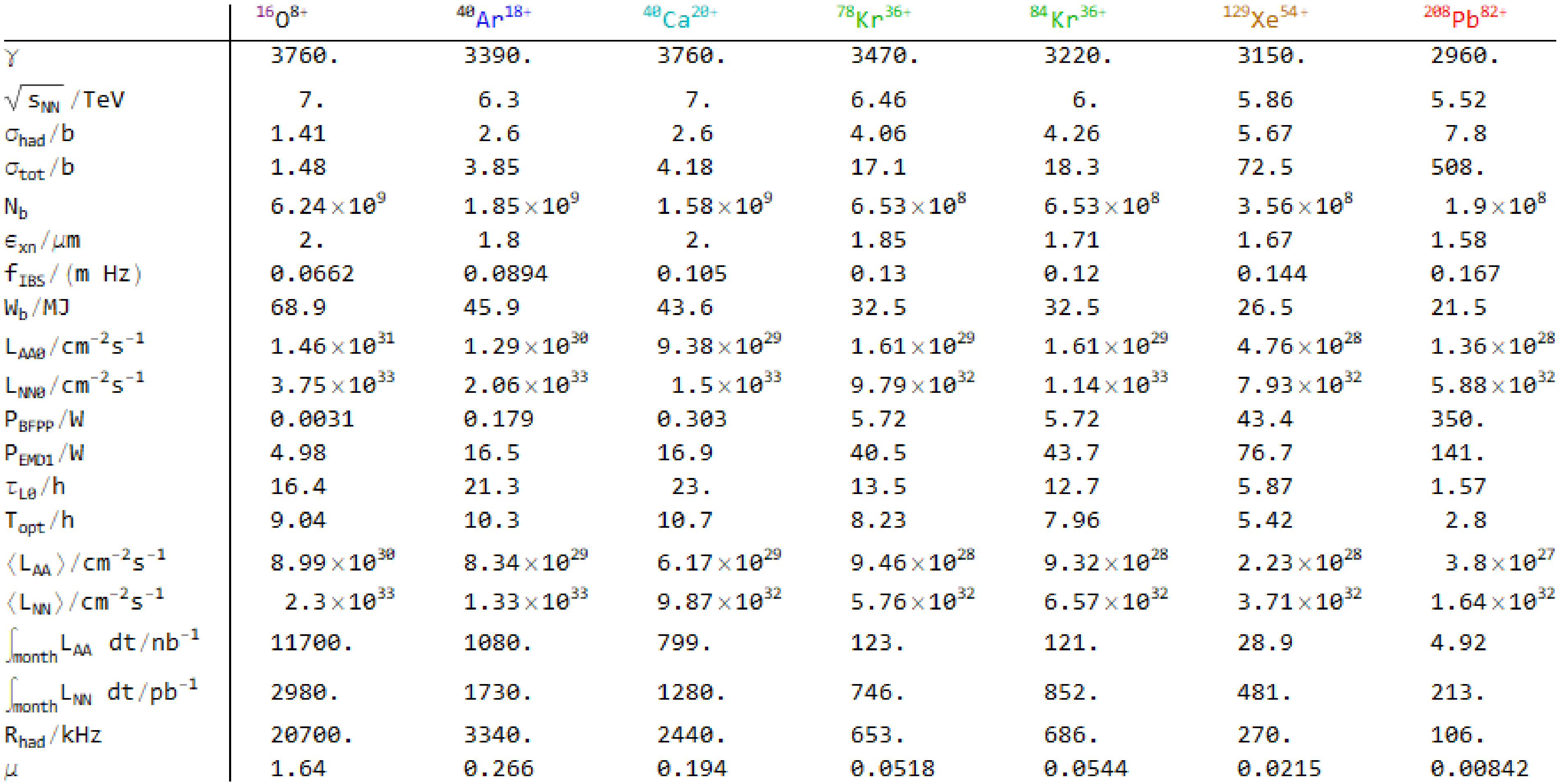
Stored energy in beam W_b is identical in this case ⇒ Collimation risks ~ comparable.

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)



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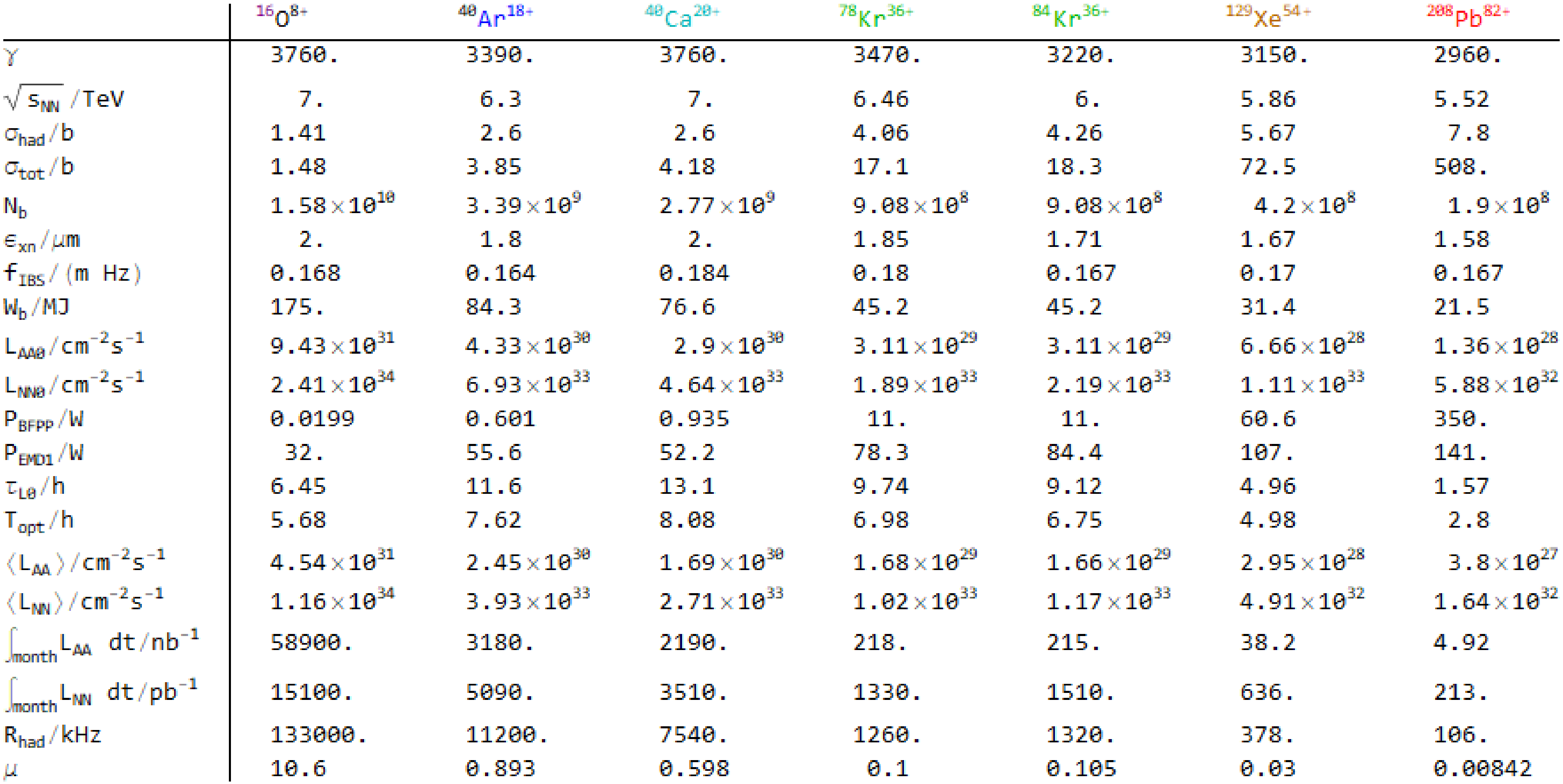
$\sqrt{s_{NN}}$ /TeV	7.	6.3	7.	6.46	6.	5.86	5.52
σ_{had}/b	1.41	2.6	2.6	4.06	4.26	5.67	7.8
σ_{tot}/b	1.48	3.85	4.18	17.1	18.3	72.5	508.
N_b	6.24×10^{9}	1.85×10^{9}	1.58×10^{9}	6.53×10^{8}	6.53×10^{8}	3.56×10^{8}	1.9×10^{8}
$\epsilon_{xn}/\mu m$	2.	1.8	2.	1.85	1.71	1.67	1.58
f_{IBS}/(m Hz)	0.0662	0.0894	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 ⇒ 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)



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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
$L_{AA0}/\mathrm{cm}^{-2}\mathrm{s}^{-1}$	9.43×10^{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}
$L_{NN0}/\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.41×10^{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
$\langle L_{AA}\rangle/\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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}
$\langle L_{NN}\rangle/\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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}
$\int_{month} L_{AA}\,dt/\mathrm{nb}^{-1}$	58900.	3180.	2190.	218.	215.	38.2	4.92
$\int_{month} L_{NN}\,dt/\mathrm{pb}^{-1}$	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, needs 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

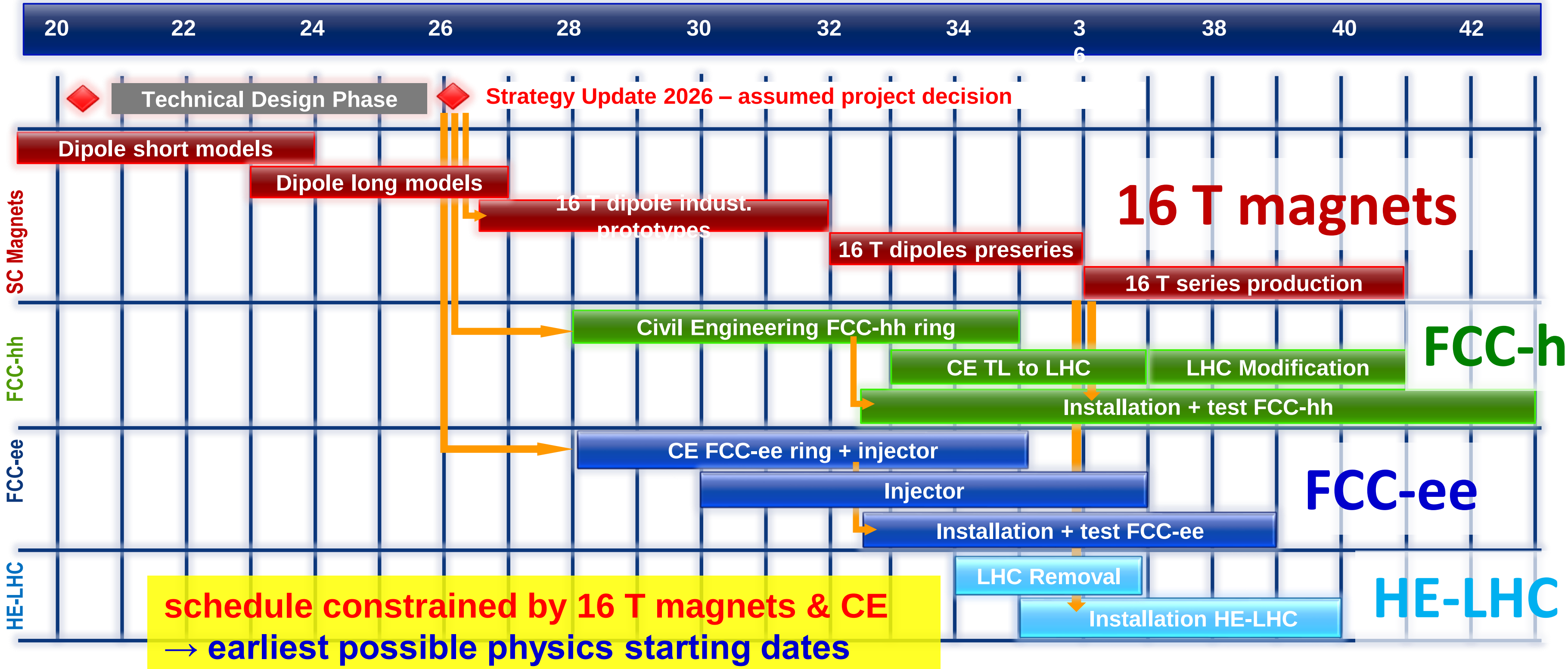
- Collimation is more complicated, needs careful study
  - See first measurements with Xe vs. Pb in MOPMF038 paper in IPAC2018
  - Simulations done for Ar, Xe (by Pascal Hermes) have not yet included effects of DS collimators in IR7.
  - May need new hardware in LHC
  - Crystal collimation (also tested 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

Technical Schedule for each of the 3 options



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)

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

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

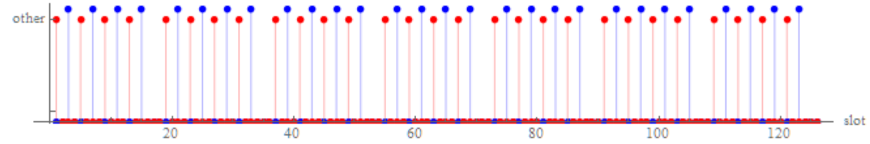
$$E \approx pc = \underbrace{13.5Z\ \mathrm{TeV}}_{\substack{\text{Energy per charge,}\\ \text{relation to proton energy}}} = \underbrace{5.32A\ \mathrm{TeV}}_{\text{Energy per nucleon}}$$

Centre-of-mass energy for nucleon pairs in collision

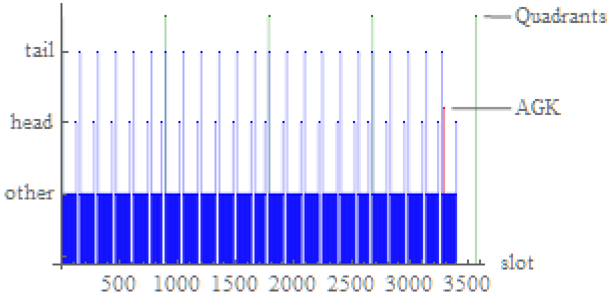
$$\sqrt{s_{NN}} \approx 10.64\ \mathrm{TeV}$$

- Simulation with Collider-Time-Evolution (CTE) program

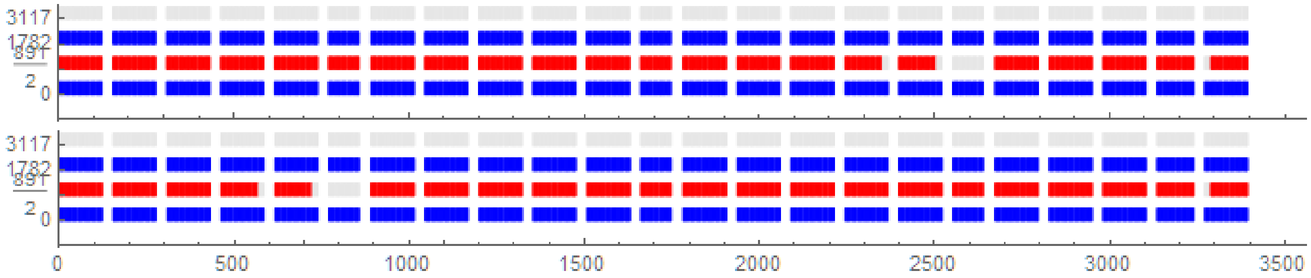
Filling scheme for HL-LHC Pb-Pb (LIU TDR baseline)



56 bunch SPS train
after slip-stacking in SPS

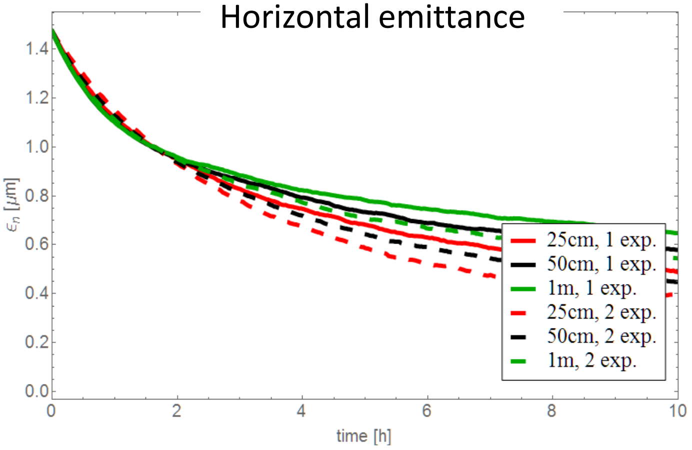


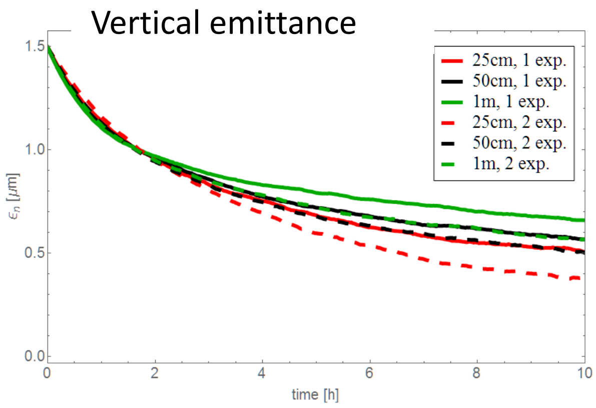
Two beams are identical, maximal
filling with quadrant symmetry



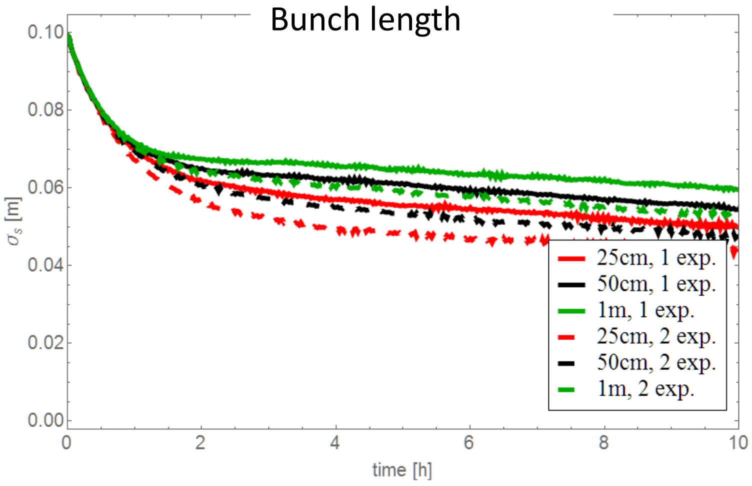
23 injections of 56-bunch trains give total of 1232 in each beam.
1232 bunch pairs collide in ATLAS CMS, 1168 in ALICE, 0 in LHCb.

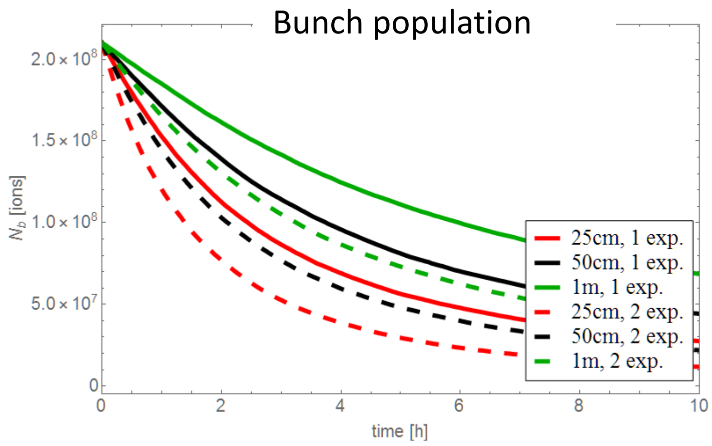
Beam parameter evolution in simulated Pb-Pb fill


Horizontal emittance


Vertical emittance

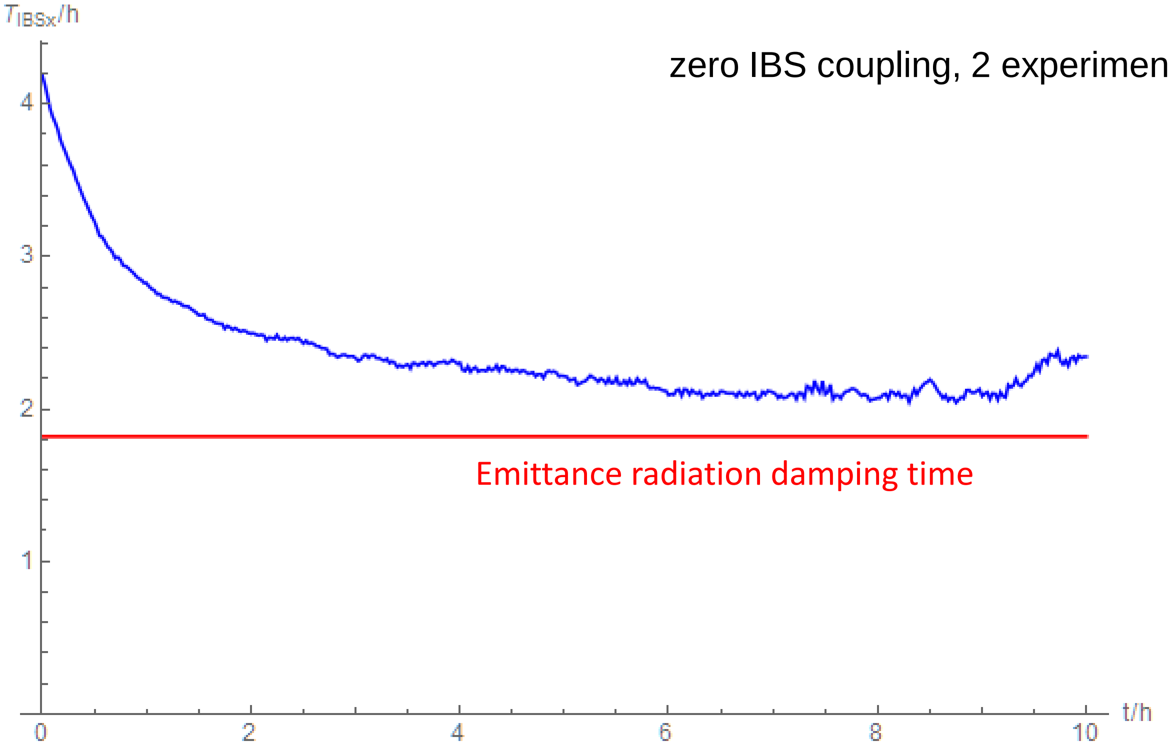
Consider optics as in V0.2 physics configuration but also some additional cases with higher β*.


Bunch length


Bunch population

Michaela Schaumann

Emittance growth time from IBS and radiation damping



zero IBS coupling, 2 experiments and 25cm beta*

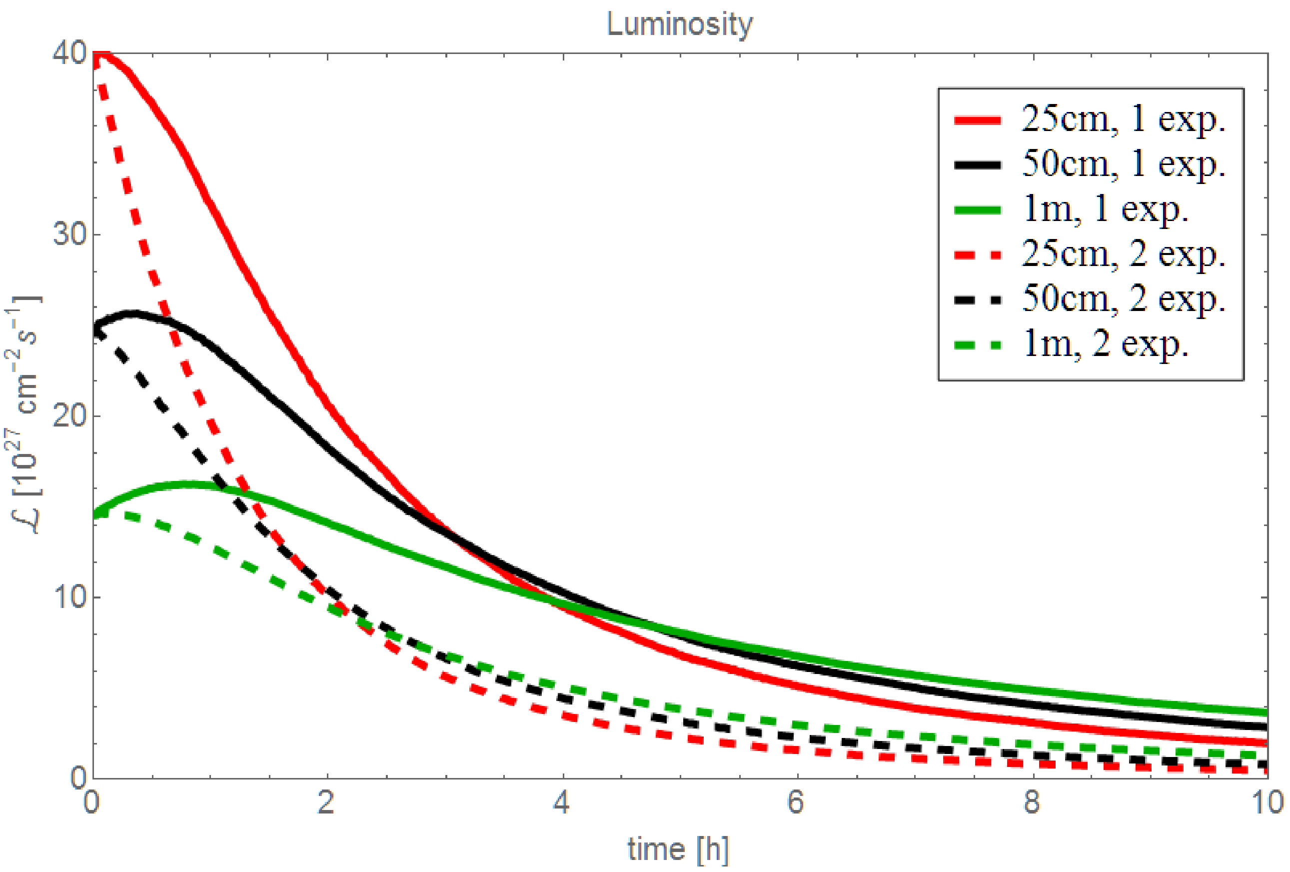
Emittance radiation damping time

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

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

Michaela Schaumann

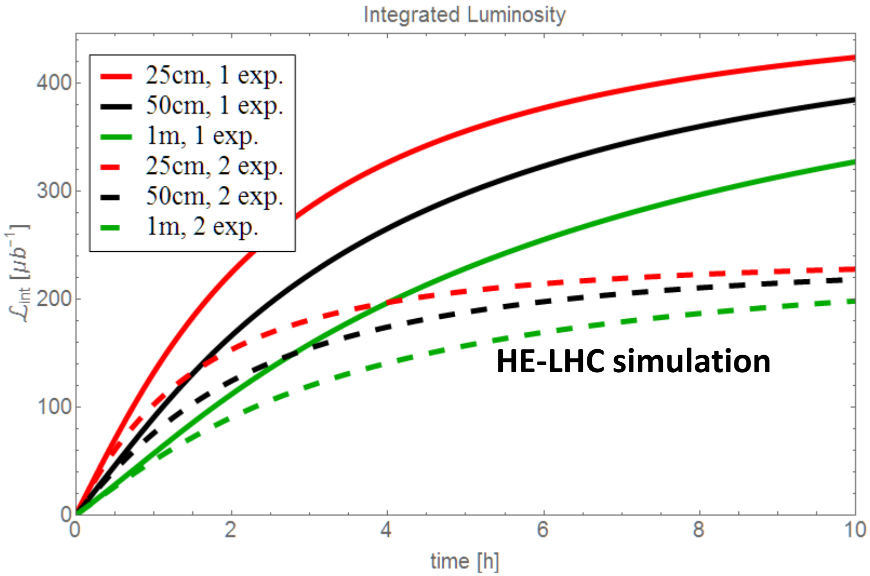
Luminosity evolution in a fill

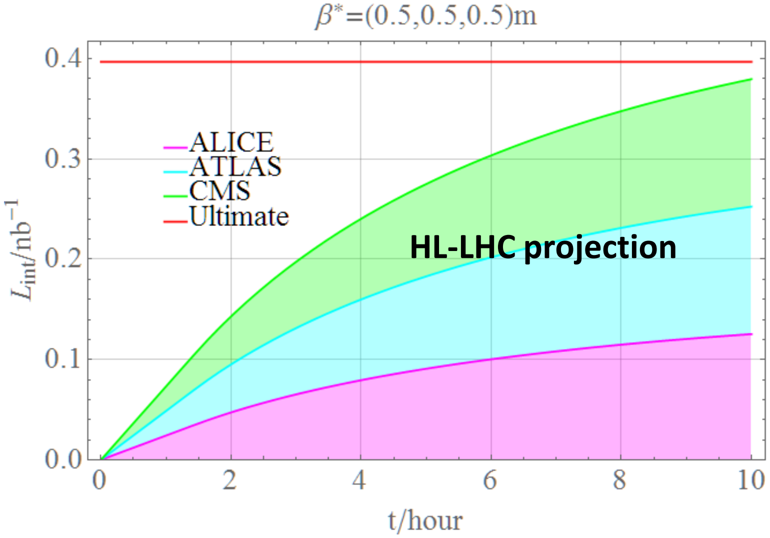


Consider optics as in V0.2 physics configuration but also some additional cases with higher β*.

Michaela Schaumann

Integrated luminosity in a fill compared with Pb-Pb at HL-LHC





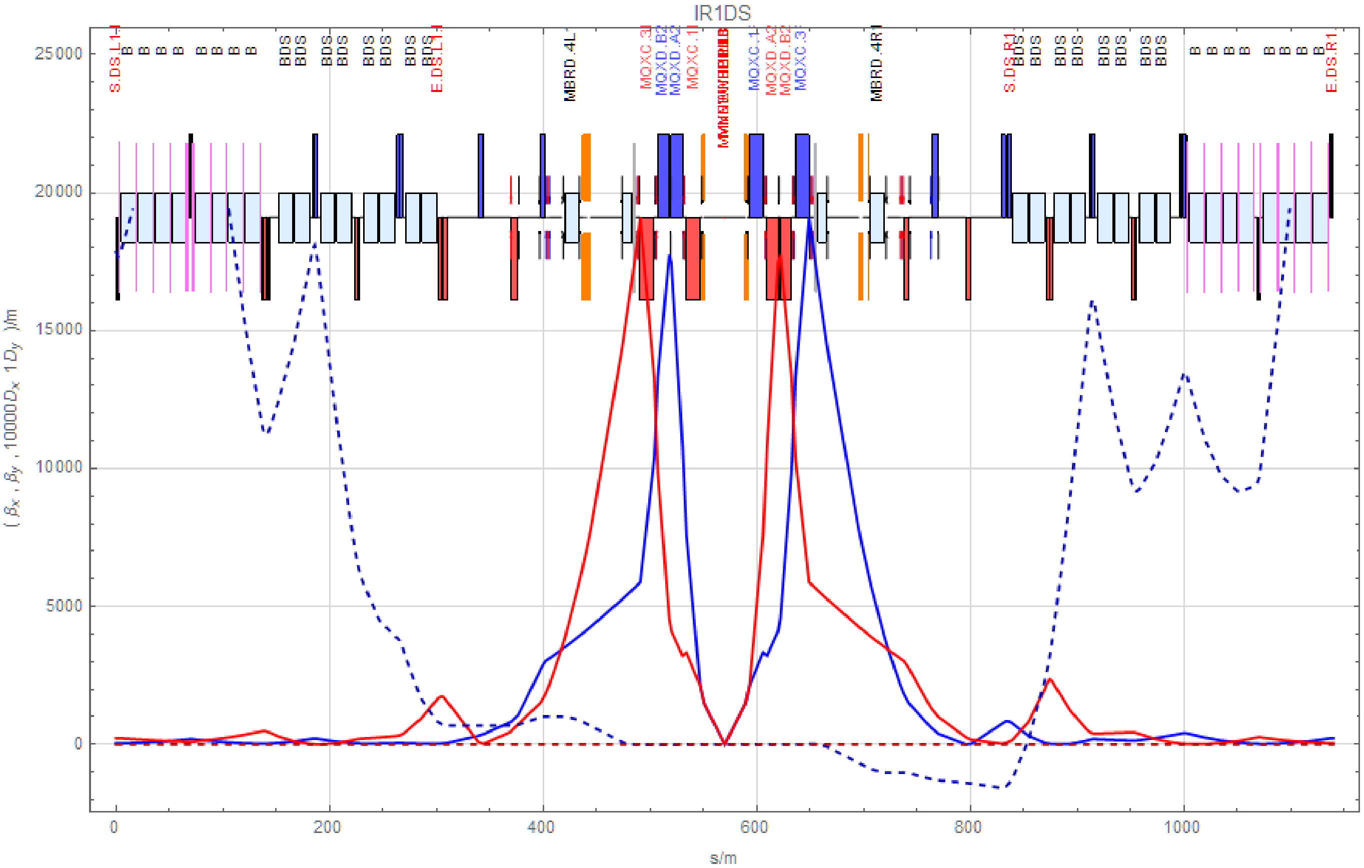
Ultimate luminosity to share per fill

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

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

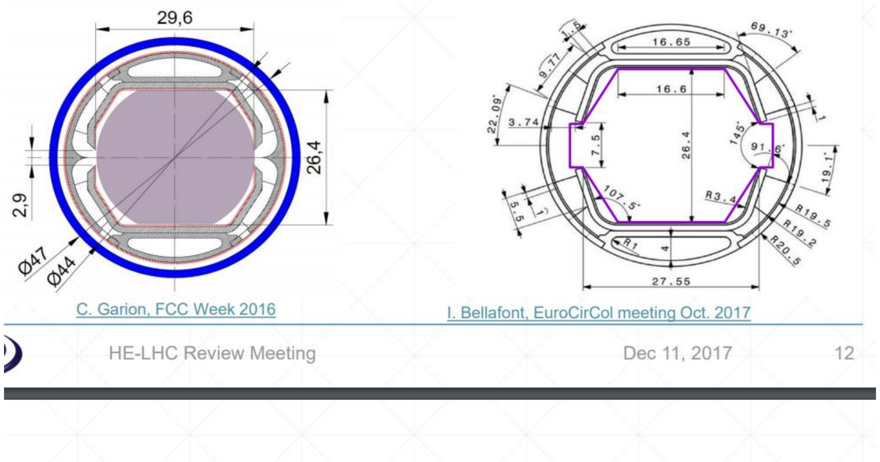
Physics optics in IR1, V0.2



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

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

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

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

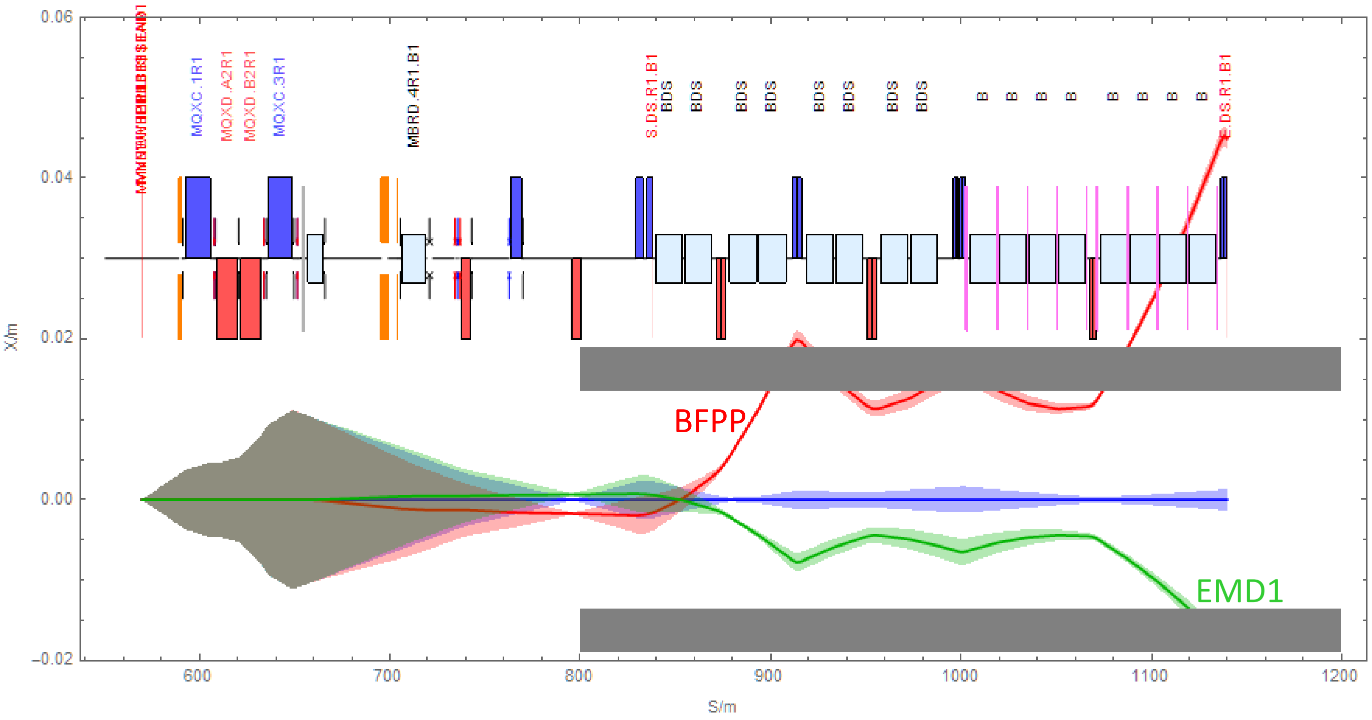
Each of these makes a secondary beam emerging from the IP.

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

Integrated nucleon-nucleon luminosity in Run 1 + 2015

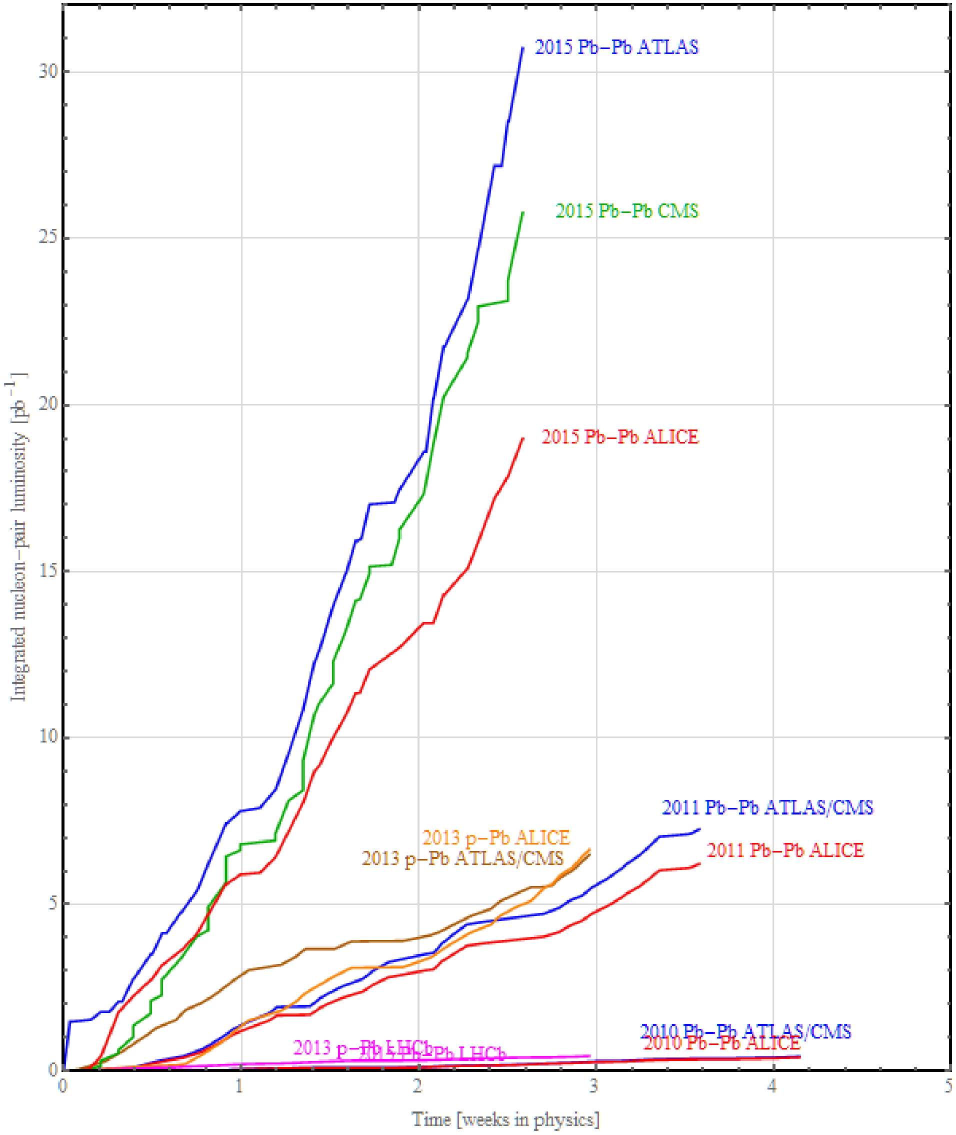
Expect to achieve LHC “first 10-year” baseline Pb-Pb luminosity goal of
1 AA nb^{-1} = 43 NN pb^{-1}
in Run 2 (=2015+2018)

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.

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

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

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:

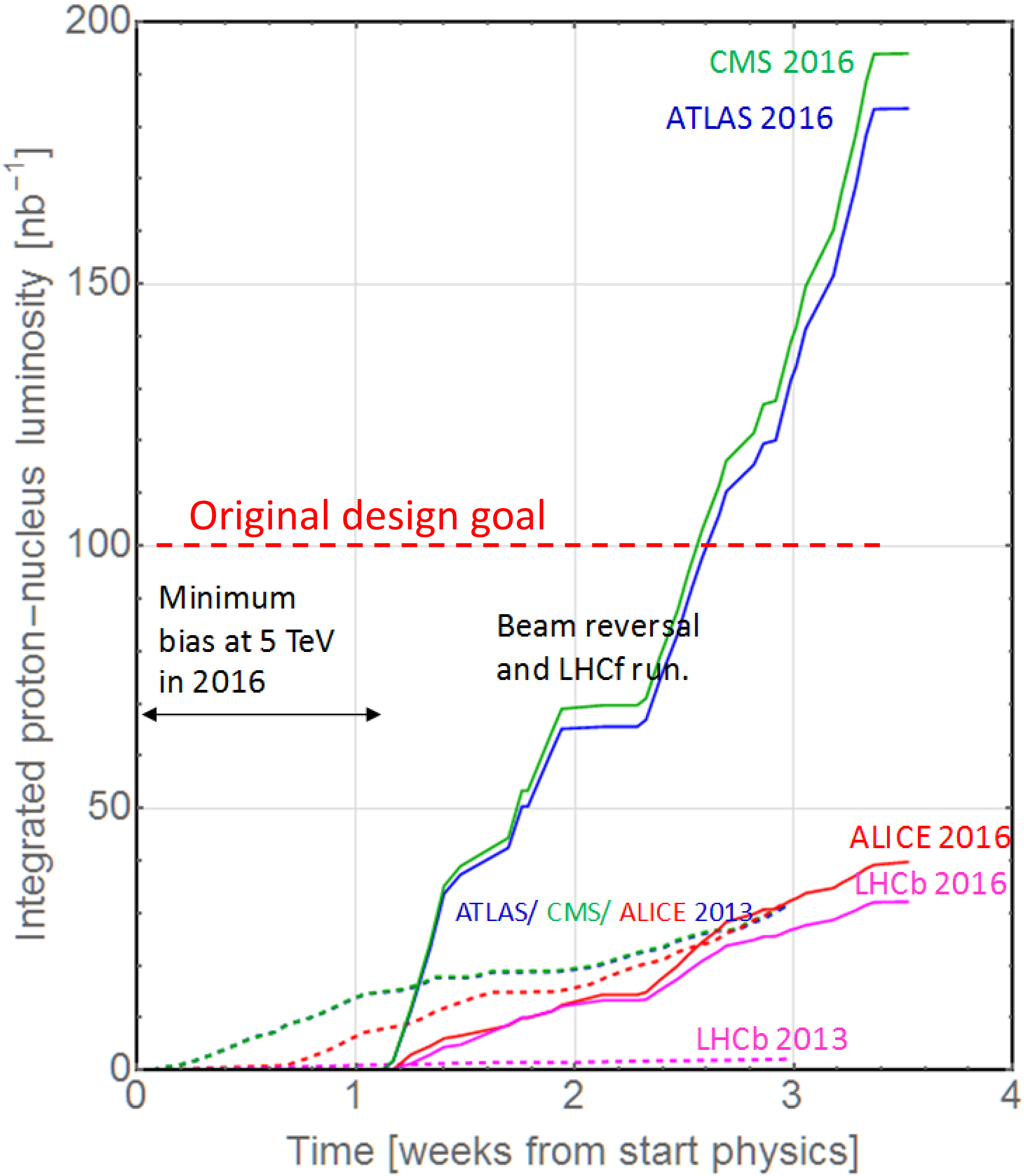
Minimum bias run at 4 Z TeV mainly for ALICE

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.



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.