HL-LHC and HE-LHC accelerator performance (with ions)

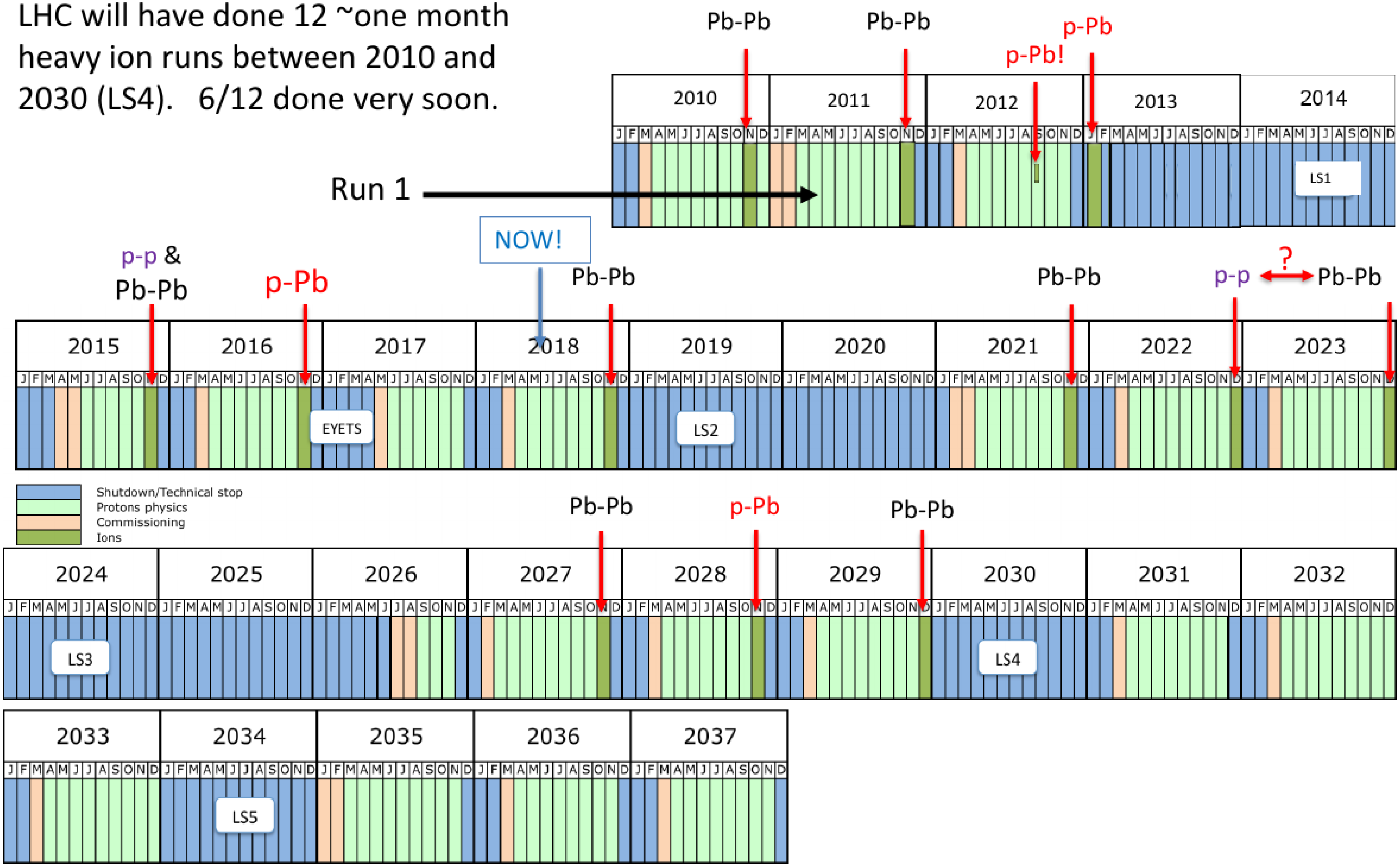
R. Bruce, M. Jebramcik, J.M. Jowett, M. Schaumann

Outline

- HL-LHC
  - Upgrades and assumptions
  - Performance with Pb-Pb
  - Performance with p-Pb
  - Performance with lighter ions
- HE-LHC
  - Performance with Pb-Pb
- Potential performance limitations from beam losses
  - Ultraperipherial collisions
  - Collimation
- Conclusions

Timeline of heavy-ion runs

LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). 6/12 done very soon.



HL-LHC: parameters and assumptions

Pb-Pb parameters

Parameter	Value	Comment
Beam energy	2.76 TeV / nucleon	*Equivalent to 7 Z TeV*
Bunch intensity	1.8E8	*Reached 2.1E8 in 2016*
Number of bunches	1232	*Requires SPS slipstacking*
Bunch spacing	50 ns	*Requires SPS slipstacking*
Normalized emittance	1.65 μm	*Reached 1.5 μm in 2016*
β*	0.5 m	*Baseline for 2018 run*
Luminosity (leveled)	6E27 cm^{-2} s^{-1}	*Assumes ALICE upgrade*

- Only remaining major LHC machine upgrade directly affecting luminosity: slipstacking in the SPS, allowing 50 ns spacing
    - Should be operational in Run 3, as well as higher beam energy
    - Other remaining upgrades are connected to beam losses – see later

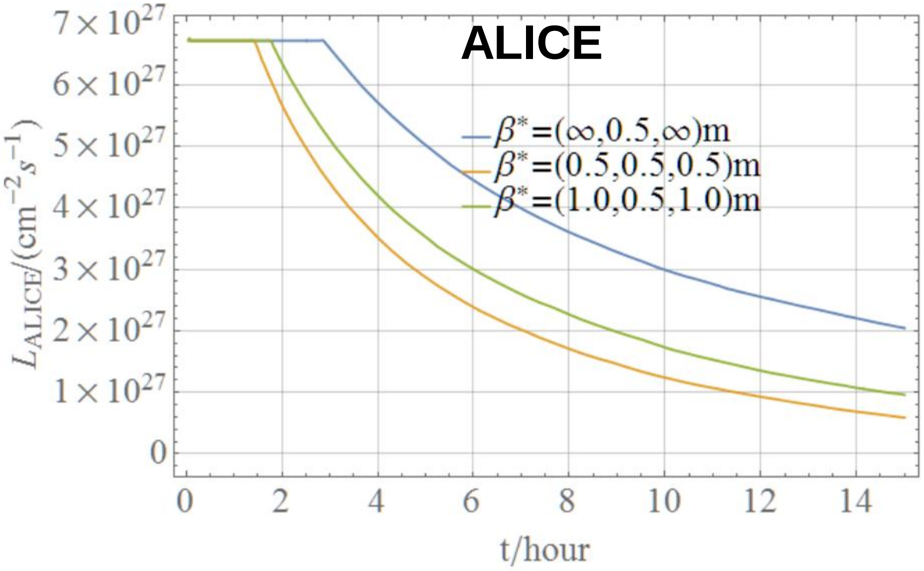
Optics compatibility with p-p operation

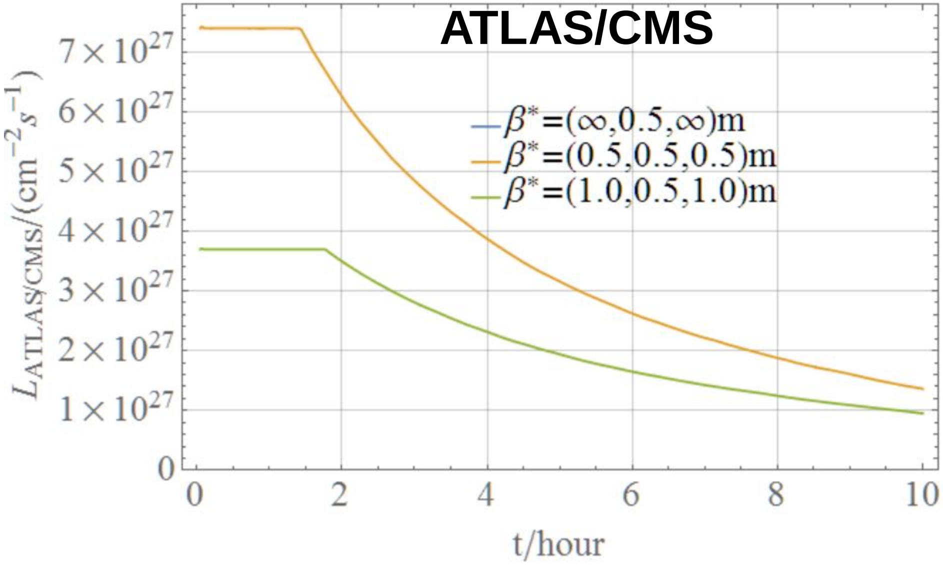
- ATS optics (achromatic telescopic squeeze) to be used for p-p operation: squeeze ATLAS / CMS to β*=15 cm
- There is no ATS optics that includes a squeeze of ALICE to similar values as ATLAS/CMS.
- However, the β*=0.5 m values assumed for heavy-ion operation do not require ATS
  - Rather little gain from lower β* in high burn-off regime
- Necessary flexibility of the optics needs to be maintained.
- A suitable optics has been designed for use in 2018.
  - Completely new ramp, squeeze, physics configuration compared to 2018 proton optics

Simulated HL-LHC performance

T. Mertens

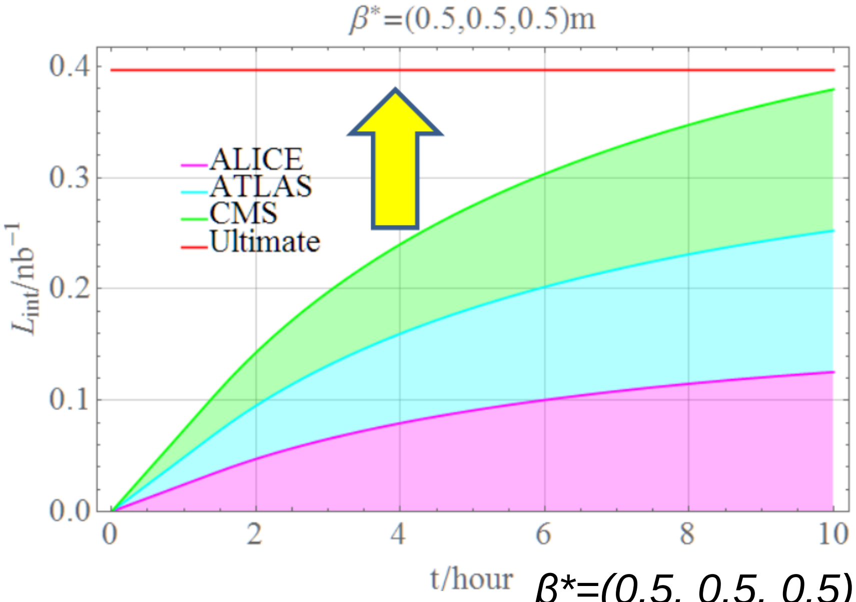
- Assuming HL-LHC beam parameters
- Simulations of beam parameter evolution and luminosity in ideal fill kept forever



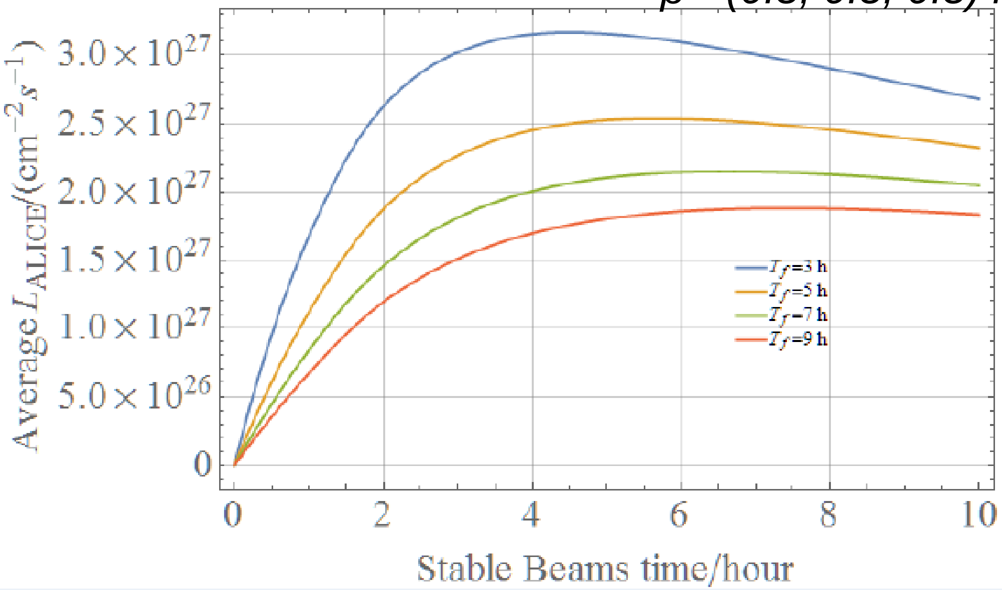


Integrated luminosity per fill

- Limited number of Pb ions to burn per fill – 0.4 nb^{-1}
- Approaching this limit after about 10 h
- Maximize integrated luminosity
  - For 3h turnaround, optimum fill length is about 4-5 h
  - Assuming average luminosity of 3E27 $cm^{-2}\ s^{-1}$



β=(0.5, 0.5, 0.5) m*



Integrated luminosity per Pb-Pb run

- For a 24-day run, with 3 experiments at β*=0.5 m, assuming (pessimistically) an operational efficiency of 50% and average luminosity of 3E27 $\text{cm}^{-2}\,\text{s}^{-1}$, the total luminosity is

$$L_{int,annual} = (50\%)(3.0 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1})(24\ \text{day}) \approx \mathbf{3.1\ nb^{-1}}$$

(c.f. target of 2.85 nb^{-1})

→ **12 nb^{-1}** in the 4 Pb-Pb runs foreseen after LS2

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Assumptions for p-Pb

- It is generally possible to replace a Pb-Pb run with a p-Pb run, if requested
  - Split runs between p-Pb and Pb-Pb are less efficient (as in baseline for 2028) but can be handled (see 2015, 2016, …)
- Assume the same 50 ns Pb beams and filling scheme as for Pb-Pb and that proton beams can beams can be constructed to match it.

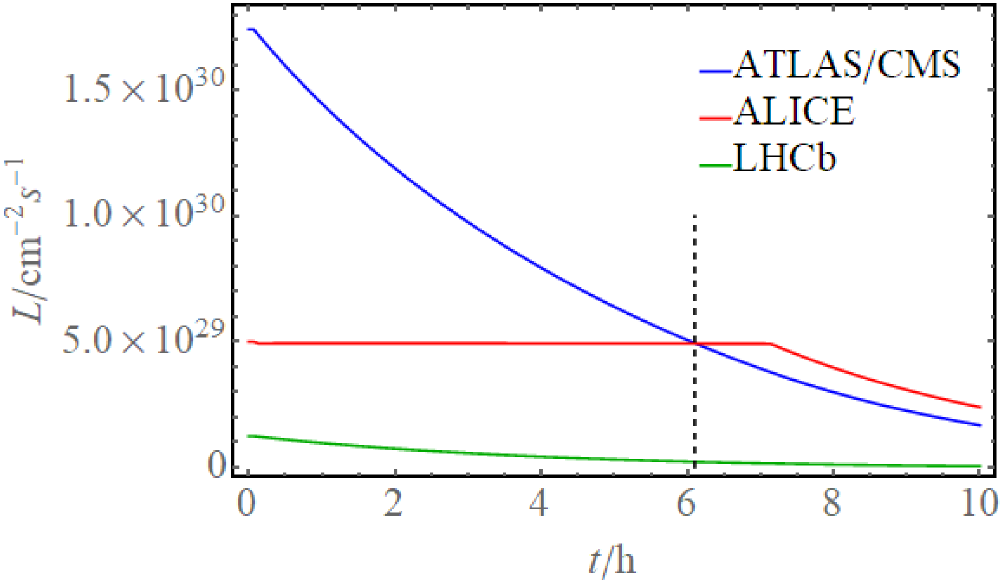
p-Pb parameters

Parameter	Value (Pb)	Value (p)
Beam energy	7 Z TeV	7 Z TeV
Bunch intensity	1.8E8	*3E10*
Number of bunches	1232	
Bunch spacing	50 ns	
Normalized emittance	1.65 μm	*2.5 μm*
β*	0.5 m	
Luminosity (leveled, ALICE)	5E29 cm^{-2} s^{-1}	
Luminosity (peak, ATLAS/CMS)	17.4E29 cm^{-2} s^{-1}	

Simulated performance for p-Pb

- Simulations of beam parameter evolution in ideal fill
- Note: after about 6h, the bunch intensity falls below visibility threshold of interlock BPMs → fills terminated
- Further overall reduction of 5% to account for filling scheme mismatch between p and Pb

Simulation by M. Jebramcik



Integrated luminosity per p-Pb run

- Assuming
  - a turnaround time of 2.5 h (optimistic!)
  - operational efficiency of 50%,
  - and fill length of 6.1 h,
- The total luminosity in 1 month of p-Pb running is estimated to
  - 714 nb^{-1} for ATLAS/CMS
  - 346 nb^{-1} for ALICE

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Assumptions on lighter ions

- Operation with lighter ions is not part of the present HL-LHC baseline
- Very limited experience – so far only about 17h of low-intensity running with Xe beams in 2017
  - Beam set up in injectors not pushed to the limits
- Significant uncertainties in estimates for future running
- Potential for significantly higher nucleon-nucleon luminosity
  - Higher bunch charge possible in the injector chain - expect dependence on ion charge (limitations due to space charge, intrabeam scattering…)
  - Lower cross sections for ultraperipheral collisions (BFPP etc) => slower burnoff and longer fills, more ions left for usable luminosity

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

Beam parameters for lighter ions

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

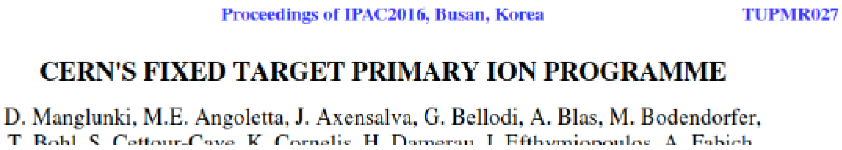
Postulate simple form for bunch intensity dependence on species charge only

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

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

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

Treat results only as tentative and indicative only!



Proceedings of IPAC2016, Busan, Korea TUPMR027

CERN'S FIXED TARGET PRIMARY ION PROGRAMME

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

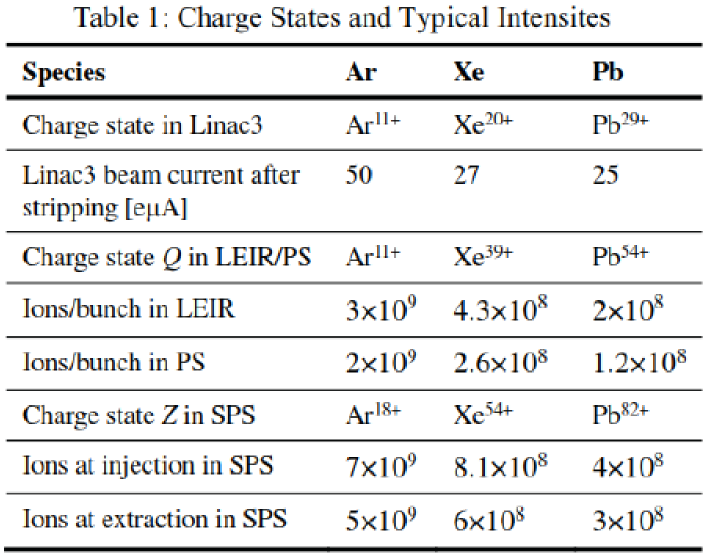


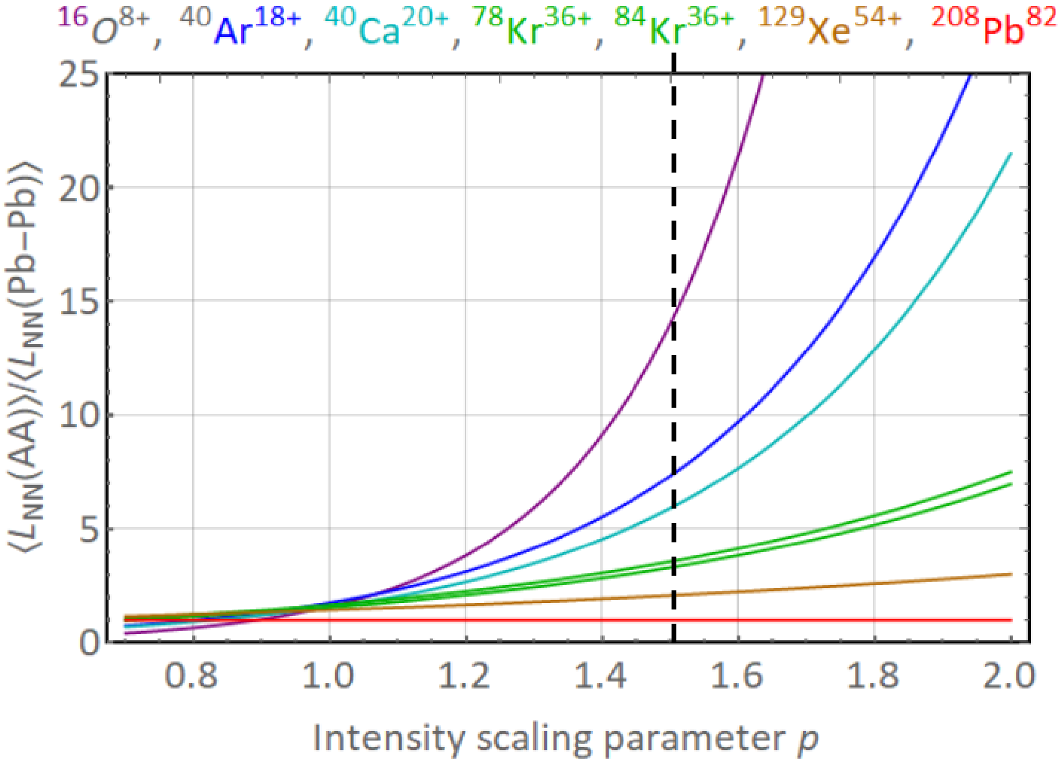
Table 1: Charge States and Typical Intensites

Species	Ar	Xe	Pb
Charge state in Linac3	Ar^{11+}	Xe^{20+}	Pb^{29+}
Linac3 beam current after stripping [eμA]	50	27	25
Charge state Q in LEIR/PS	Ar^{11+}	Xe^{39+}	Pb^{54+}
Ions/bunch in LEIR	3×10^9	4.3×10^8	2×10^8
Ions/bunch in PS	2×10^9	2.6×10^8	1.2×10^8
Charge state Z in SPS	Ar^{18+}	Xe^{54+}	Pb^{82+}
Ions at injection in SPS	7×10^9	8.1×10^8	4×10^8
Ions at extraction in SPS	5×10^9	6×10^8	3×10^8

Study range of p-values
p=1.5 seems reasonable

Time-averaged luminosity ratio

- Showing ratio of time-averaged luminosity to Pb-Pb
- Analytical calculation with burnoff only –
  not full simulation
- Assuming 2.5 h turnaround time, 3 experiments with full luminosity
- Nucleon-nucleon luminosity in 1-month run: gains ranging up to a factor ~13 for lightest considered ion (O) at p=1.5



- The dramatic improvements in transmitted Pb intensity in 2015-16 were the result of many detailed studies and improvements
- Results have large uncertainties!

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Assumptions

- HE-LHC could start physics running around 2040, using higher-field magnets
- Assuming Pb beams as in Run 3 / HL-LHC

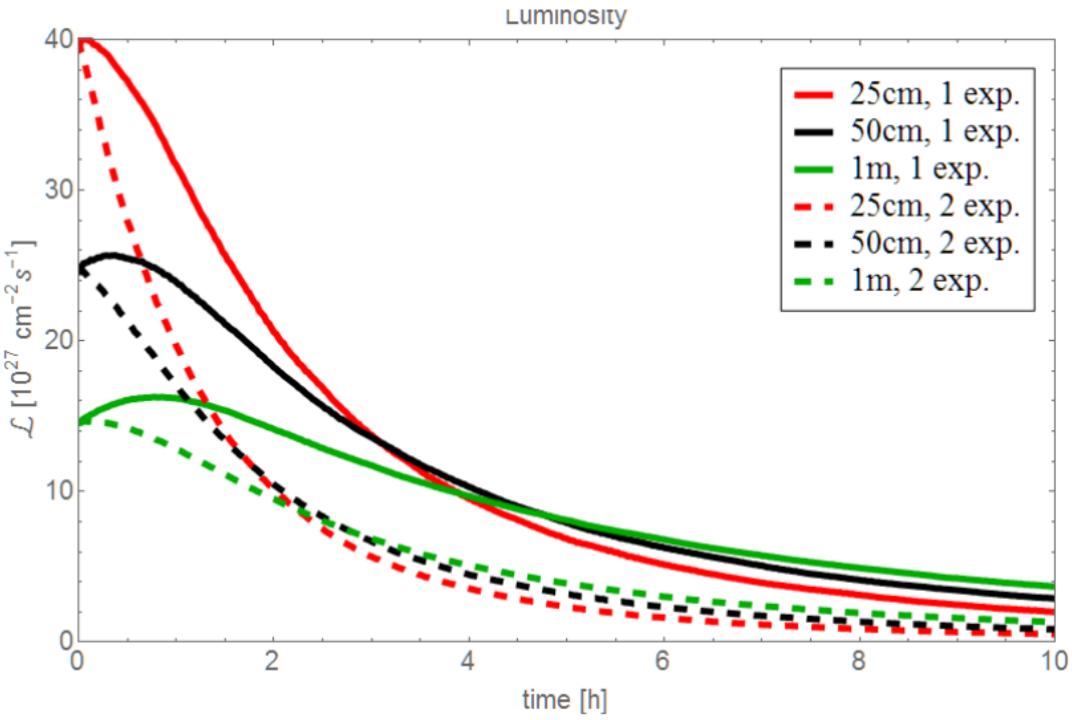
Pb-Pb parameters

Parameter	Value
Beam energy	5.32 TeV / nucleon
Bunch intensity	2E8
Number of bunches	1232
Bunch spacing	50 ns
Normalized emittance	1.5 μm
β*	0.25 m – 1 m
Peak luminosity	14E27 - 40E27 $cm^{-2}\,s^{-1}$

(13.5 Z TeV)

Simulated performance: Pb-Pb in HE-LHC

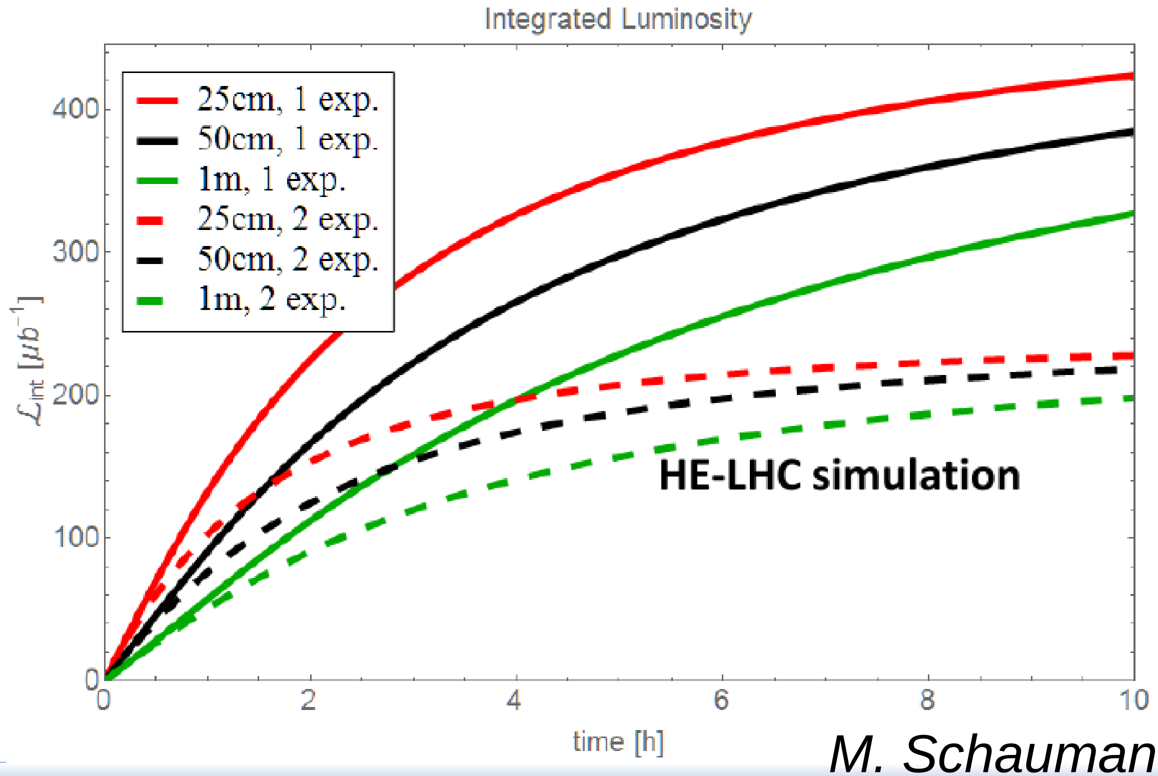
- Simulated beam and luminosity evolution in ideal fill kept forever
- Stronger radiation damping than in LHC due to higher energy
- No leveling assumed, 1-2 active experiments



M. Schaumann

Integrated luminosity performance

- Assuming HL-LHC beams => upper limit of 0.4 nb^{-1} per fill
- The gain in integrated luminosity for HE-LHC over HL-LHC is fairly small and is strongly affected by turn-around time.
  - Detailed numbers to be worked out.
  - Likely limits from beam losses – see later



M. Schaumann

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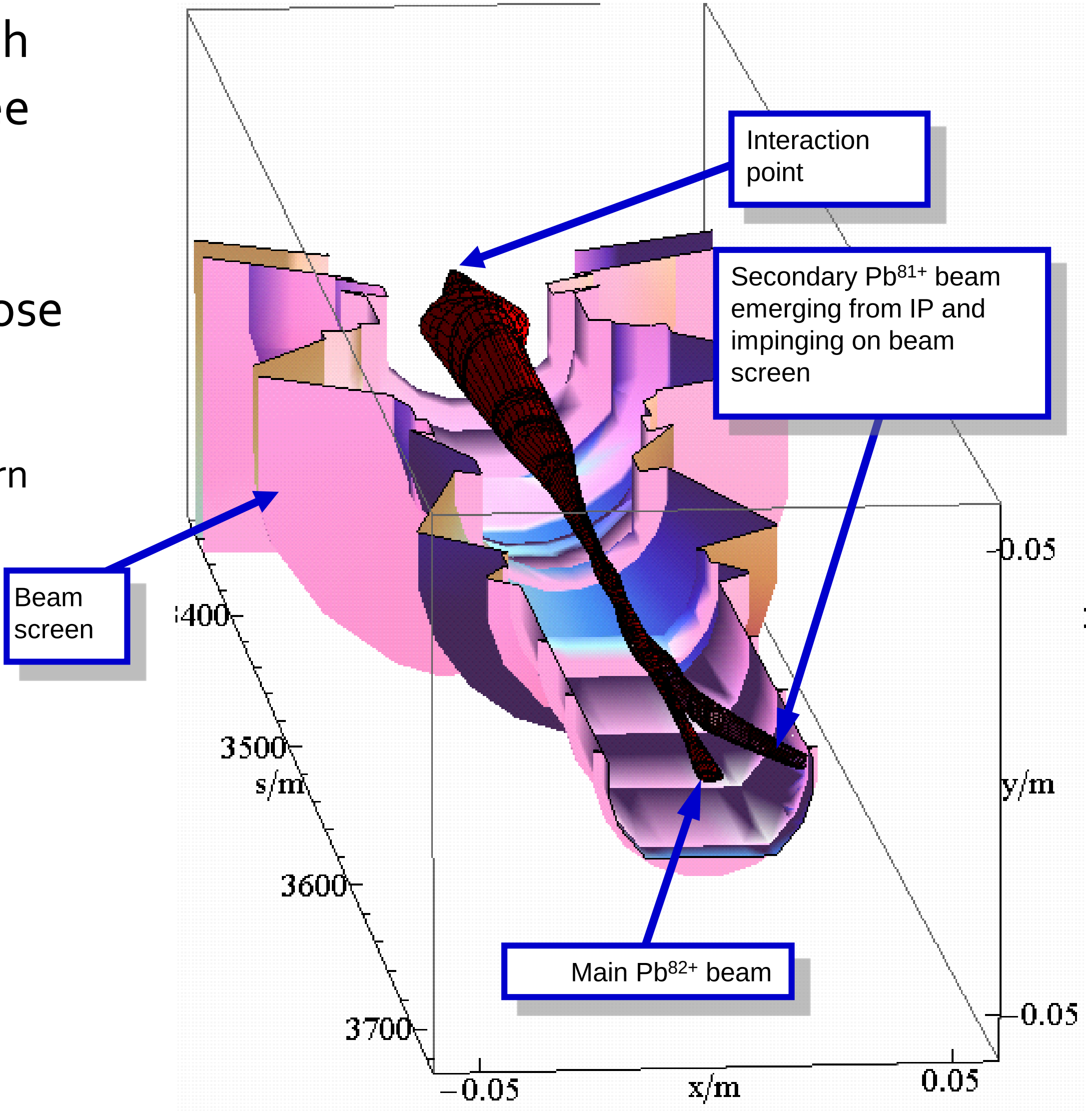
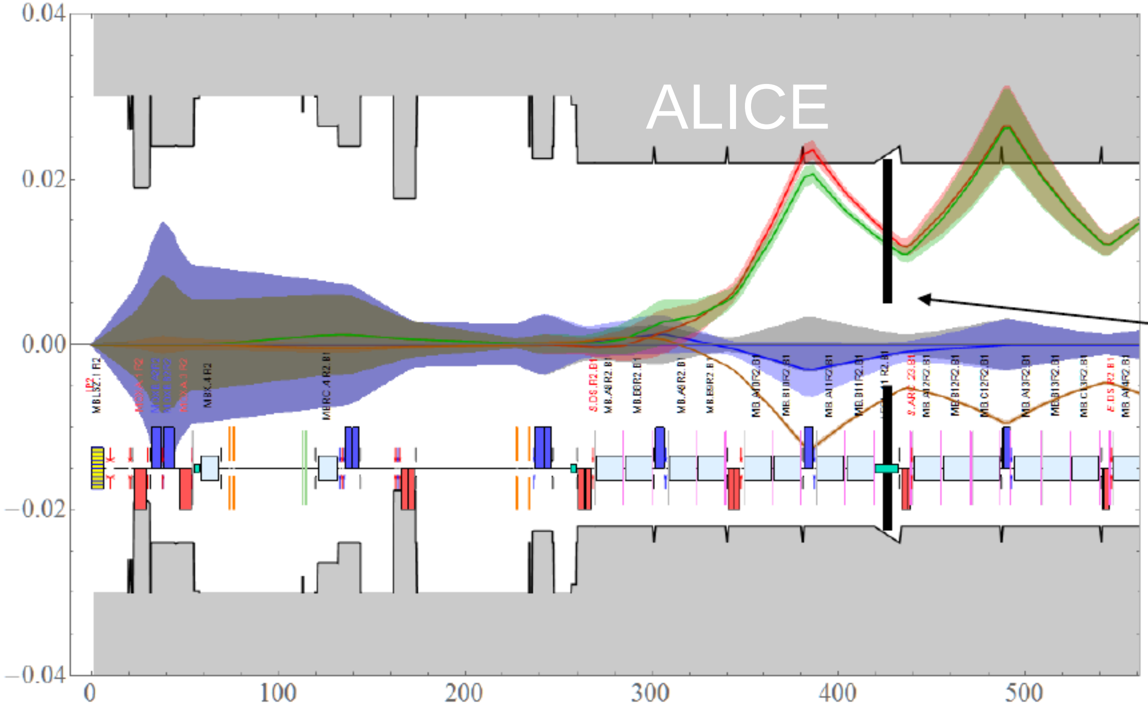
Ultraperipheral collisions

- Ultraperipheral interactions with largest cross section: bound-free pair production (BFPP – pick up one electron) and 1-neutron electromagnetic dissociation (lose 1 neutron)
  - BFPP most limiting – about 280 barn cross section
- Secondary beams with wrong charge-to-mass ratio => bent wrongly by dipoles and lost on aperture => risk for magnet quenches



Alleviation in HL-LHC

- In ATLAS and CMS, use orbit bump to steer losses to empty connection cryostat
- In ALICE, use orbit bump to steer losses on new collimator, to be installed in LS2



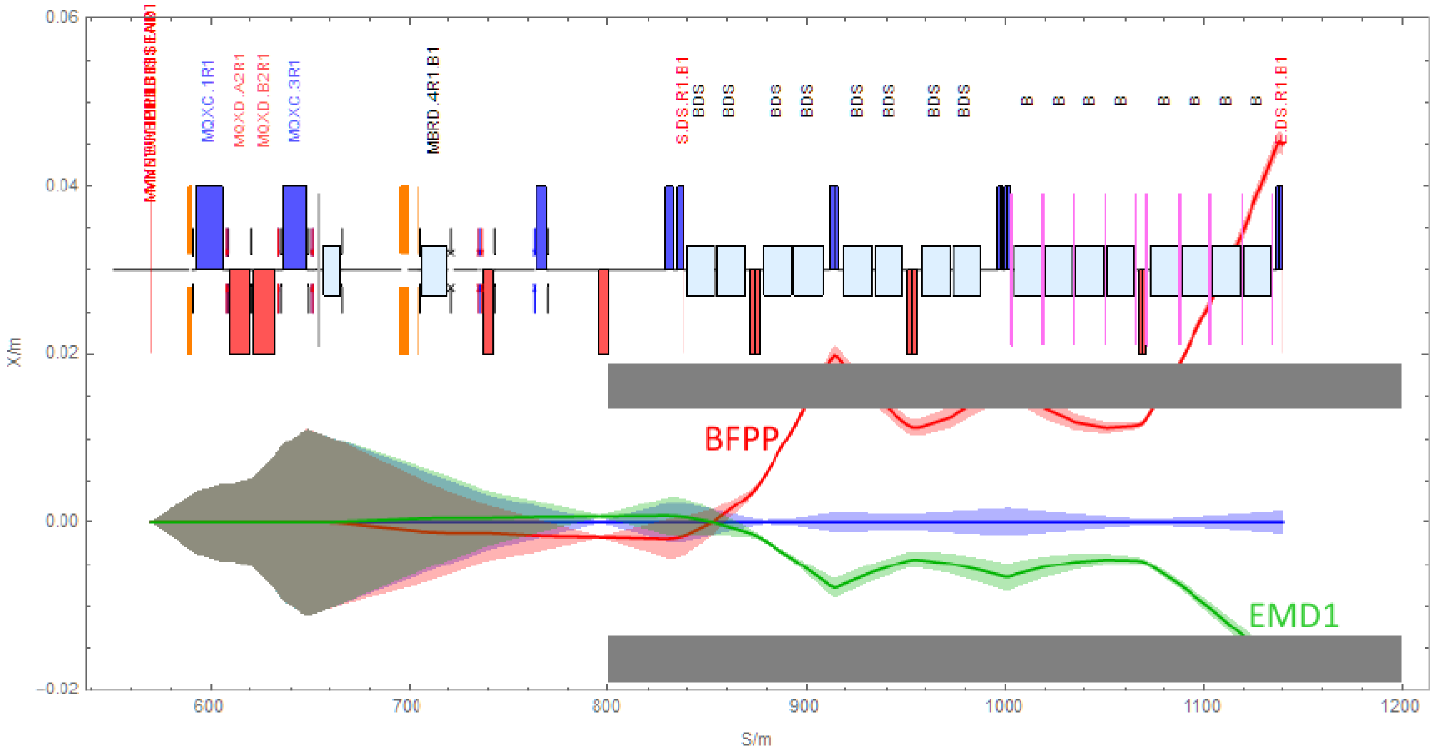
BFPP beam, without and with bump

TCLD collimator (post LS2)

- With these alleviations, such losses not expected to be limiting the HL-LHC performance
  - Some collisional losses observed in 2016 with p-Pb still need to be understood

BFPP in HE-LHC

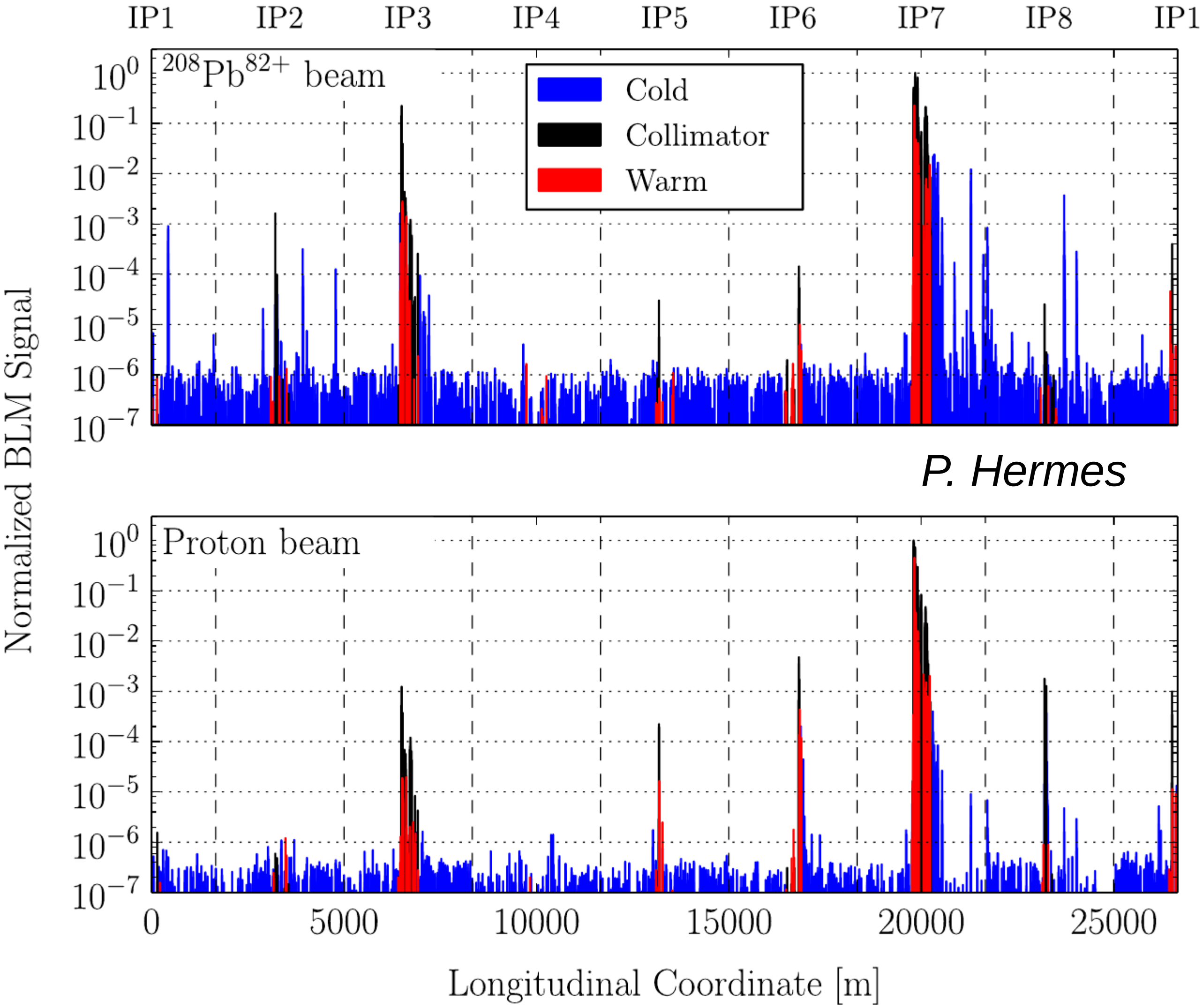
- In HE-LHC, smaller beam pipe and weaker focusing =>
  - Different impact position
  - Foreseen HL-LHC alleviations do not work
  - Further studies are needed: change optics, change layout, collide only lighter species?



Collimation

- LHC collimation much less efficient with ion beams than with protons
  - Measured leakage to cold magnets factor ~100 worse
  - Pb ion collimation more critical than p collimation, in spite of lower intensity

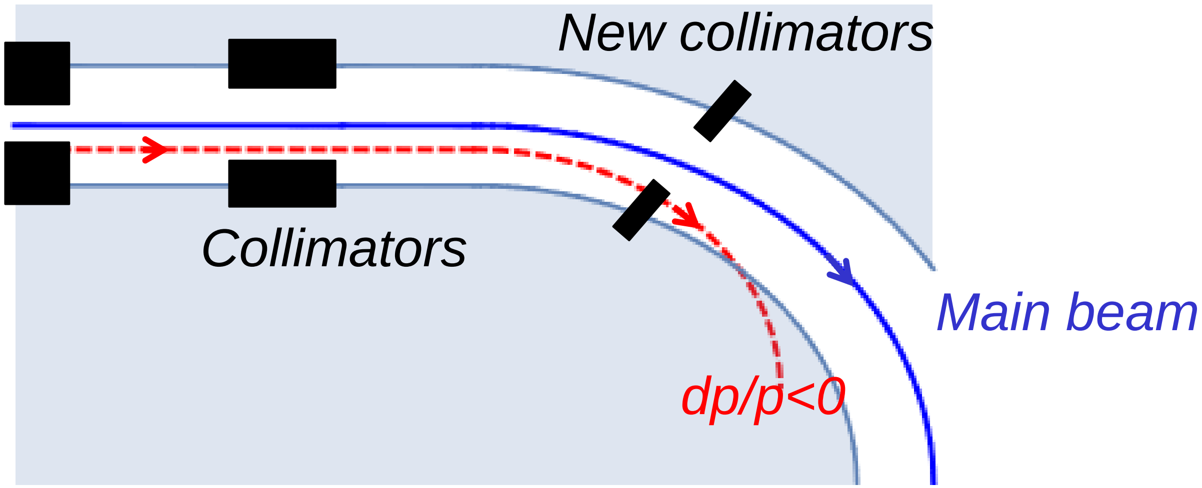
Measured beam losses around the ring



P. Hermes

Alleviation for HL-LHC

- Nuclear fragmentation of beam halo in primary collimator =>
  - Outscattered fragments with wrong magnetic rigidity
  - Pass downstream collimators in straight section, lost in dispersion suppressor in first couple of dipoles
  - Solution: install additional collimator in LS2 in the dispersion suppressor
  - Make space by replacing existing dipole by two shorter and stronger units



Collimation limitations in future runs

- Even with the new collimator, beam losses might be too high on cold magnets in HL-LHC
  - Premature dumps could limit machine availability
- Possible mitigations
  - A second new collimator
  - Optimize placement of new collimator
  - Alternative collimation scheme using bent crystals as primary collimators
- Collimation risks to impose limitations in future runs, especially for lighter ions and for HE-LHC
  - Reduced availability or reduced maximum intensity to be injected
  - Further studies needed

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Conclusions

- Performance estimated in future ion running configurations
- **HL-LHC**
  - Pb-Pb: hope for 3.1 nb^{-1} in a 1-month run (The baseline performance goals for Pb-Pb integrated luminosity from the ALICE LoI of 2012 appear to be within reach)
  - p-Pb: hope for 350 – 710 nb^{-1} in a 1-month run (24 days of physics)
  - lighter ions (not baseline): potential gain in nucleon-nucleon luminosity
  - Need slipstacking in the SPS – to be demonstrated in Run 3
- **HE-LHC:**
  - Pb-Pb: no large improvement in integrated luminosity compared to HL-LHC
- **Potential limitations from beam losses**
  - Ultraperipheral collisions: with proposed alleviations, not expected to be limiting HL-LHC, but potential major limitation for HE-LHC
  - Collimation: even with proposed alleviation, risk for reduced availability or intensity limits. Options under study

Backup

Pb-Pb parameters from Design Report to HL-LHC upgrade

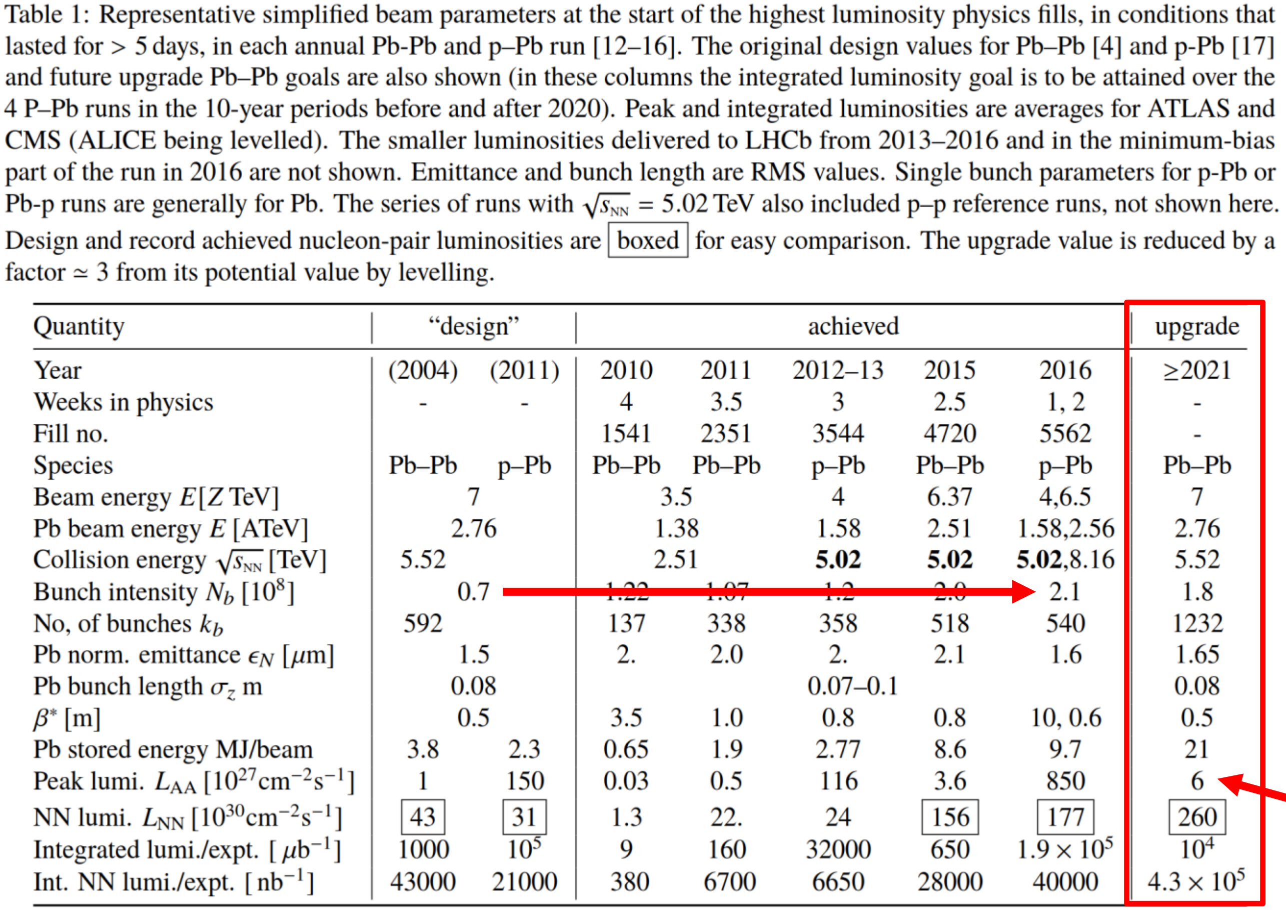


Table 1: Representative simplified beam parameters at the start of the highest luminosity physics fills, in conditions that lasted for > 5 days, in each annual Pb-Pb and p–Pb run [12–16]. The original design values for Pb–Pb [4] and p-Pb [17] and future upgrade Pb–Pb goals are also shown (in these columns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

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

Paper at IPAC2018
https://doi.org/10.18429/JACoW-IPAC2018-TUXGBD2
TUXGBD2
+ its bibliography

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

Levelled,
could be ~15.

Nucleus-nucleus programme status

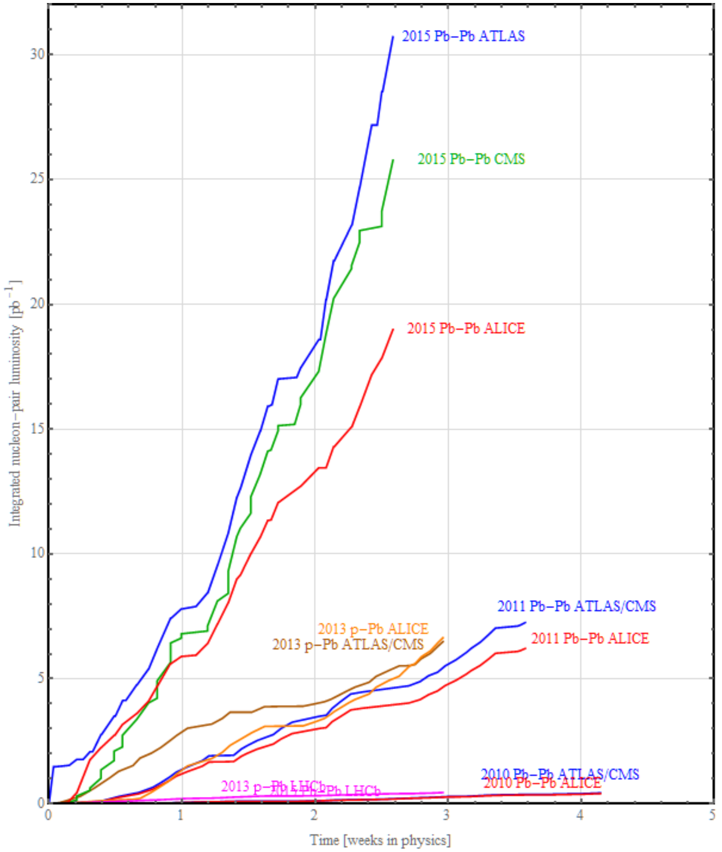
Expect to achieve LHC “first 10-year” baseline Pb-Pb luminosity goal of
1 AA $\text{nb}^{-1} = 43$ NN pb^{-1}
in Run 2 (=2015+2018)

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

Equivalent energy runs

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

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



2012 pilot p-Pb run not shown

Proton-nucleus programme status

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

Complex 2016 run plan determined after Chamonix 2016:

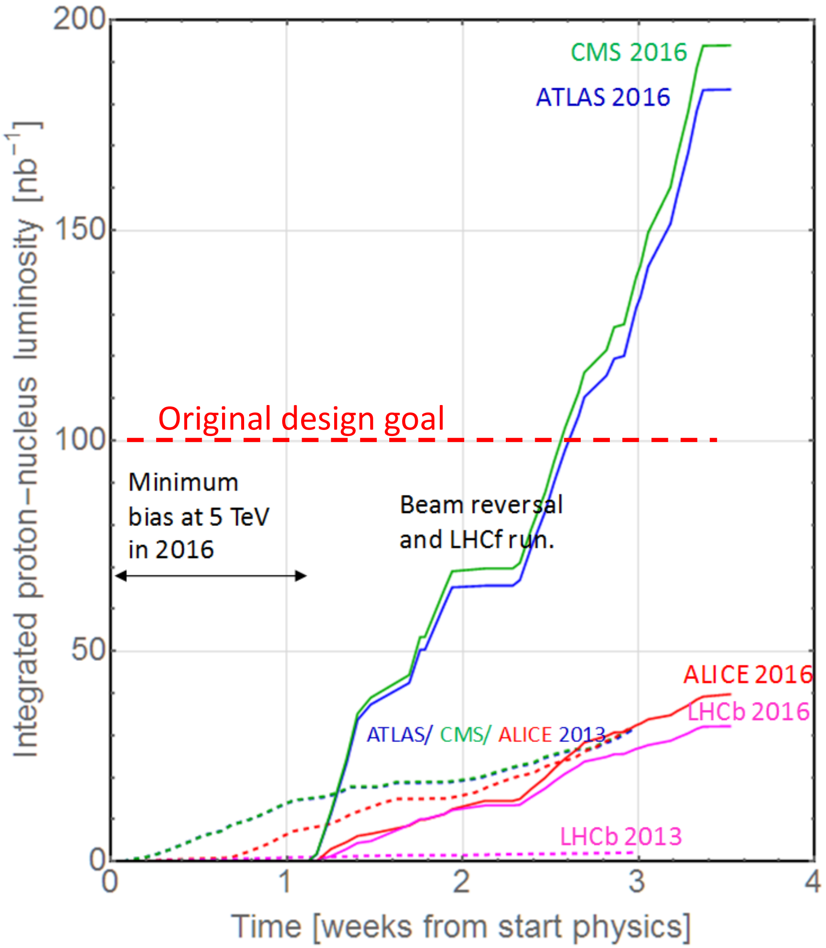
Minimum bias run at 4 Z TeV mainly for ALICE

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

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

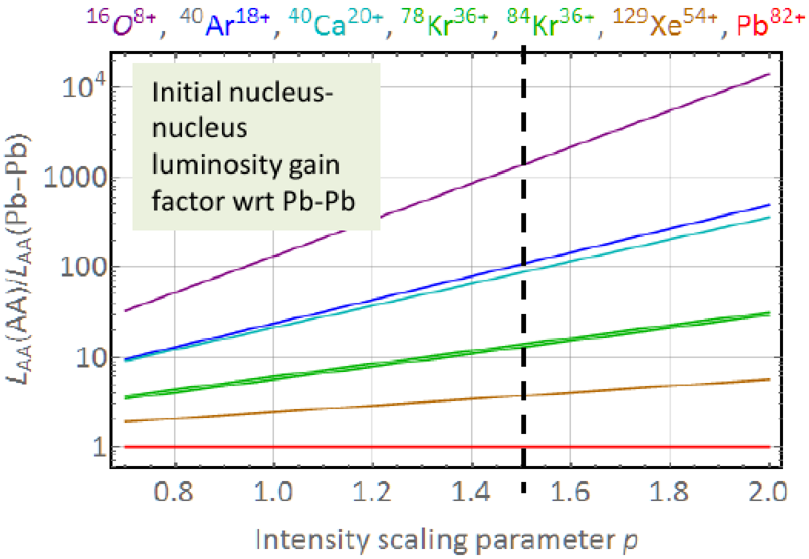
Asymmetric beams, unequal frequency ramp, cogging for collisions off-momentum, etc.

Many filling schemes used for luminosity sharing.



Instantaneous luminosity comparison

- Calculating the instantaneous luminosity ratio with respect to Pb as a function of parameter p



Species 2 vs species 1:

Beam size at IP:

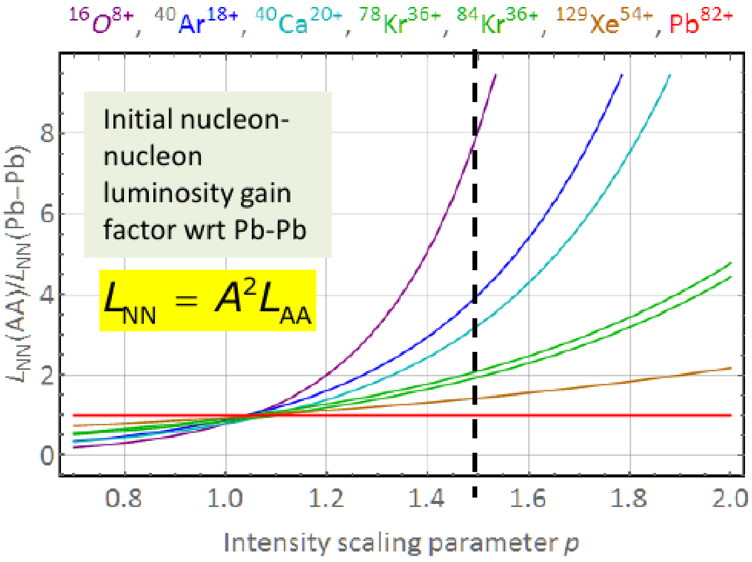
$$\frac{\sigma_2^*}{\sigma_1^*} = \frac{\sqrt{A_2}\sqrt{Z_1}}{\sqrt{A_1}\sqrt{Z_2}}$$

Initial luminosity

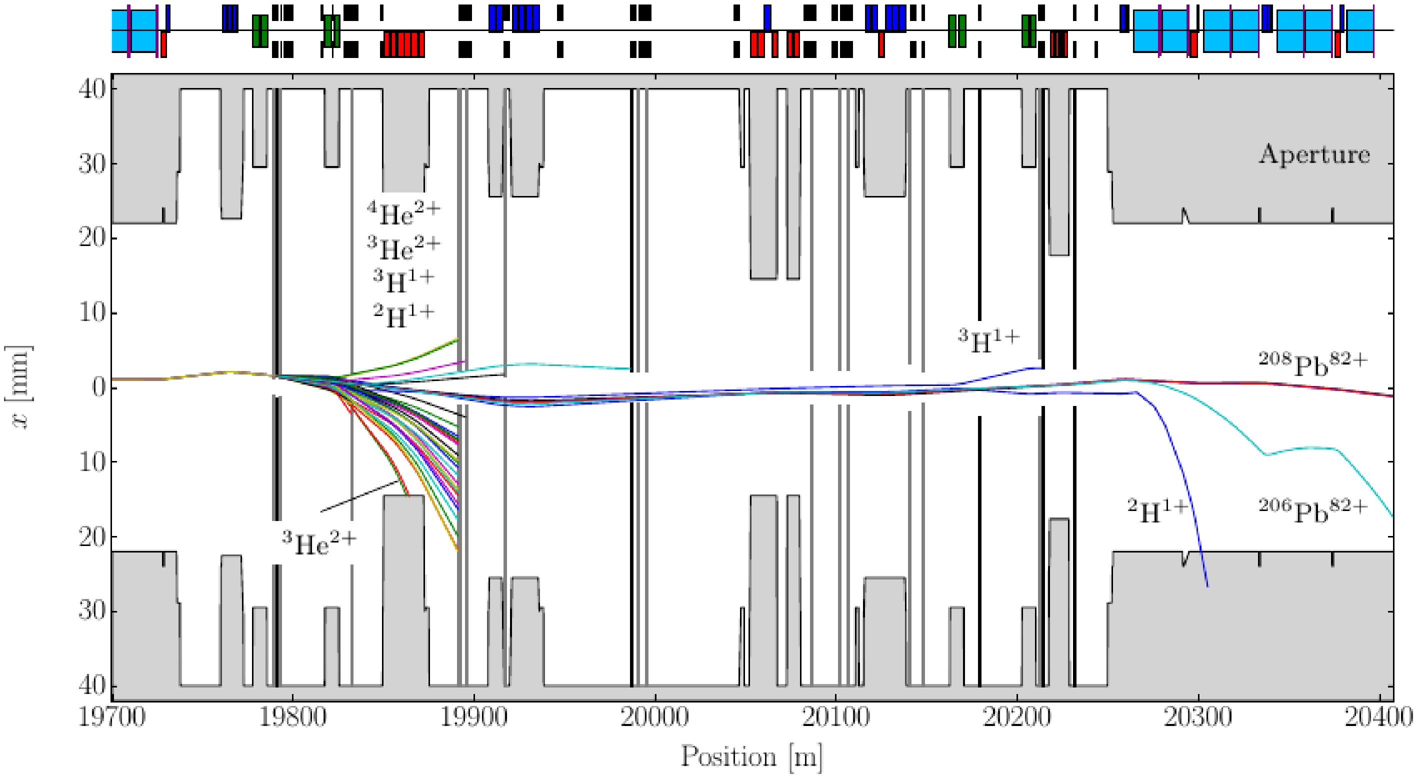
$$\frac{L_2}{L_1} = \frac{A_1 Z_1^{-1+2p}}{A_2 Z_2^{-1+2p}}$$

Initial NN luminosity

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



- Nuclear fragmentation of beam halo in primary collimator =>
  - Outscattered fragments with wrong magnetic rigidity
  - Pass downstream collimators in straight section, lost in dispersion suppressor in first couple of dipoles



Xe lifetime analysis

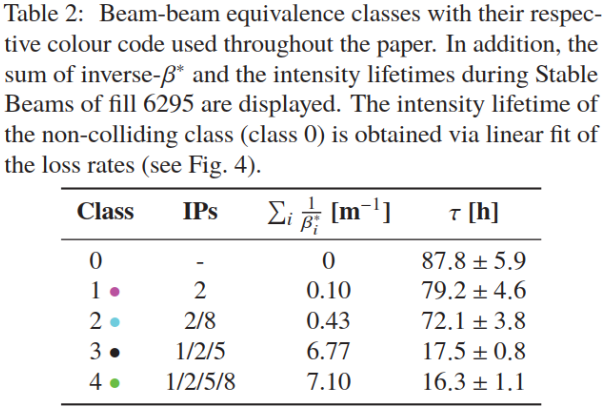


Table 2: Beam-beam equivalence classes with their respective colour code used throughout the paper. In addition, the sum of inverse-β^* and the intensity lifetimes during Stable Beams of fill 6295 are displayed. The intensity lifetime of the non-colliding class (class 0) is obtained via linear fit of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

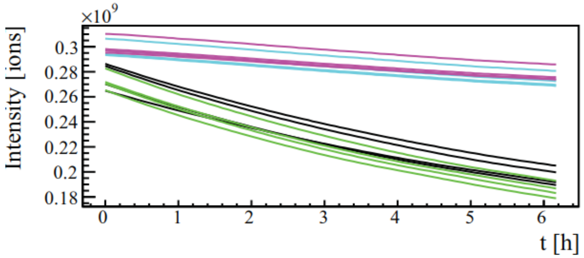


Figure 3: Bunch-intensity evolution of Beam 1 during fill 6295 after declaration of Stable Beams. The colour of each class is listed in Table 2.

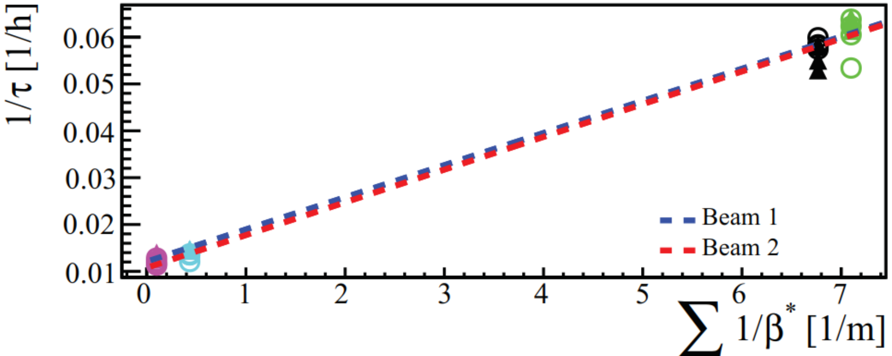


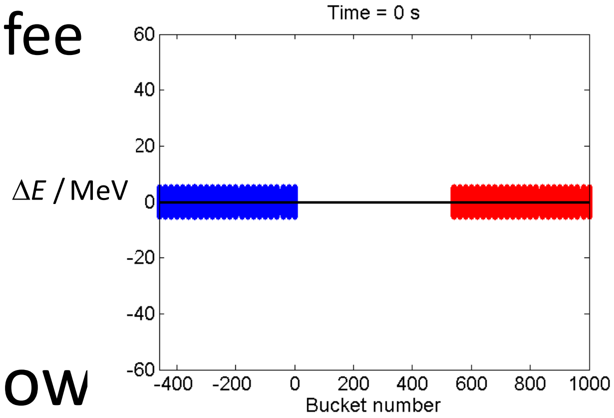
Figure 4: Relative loss rates versus $\sum_{\mathrm{IP}} 1/\beta^*_{\mathrm{IP}}$ during Stable Beams of fill 6295. Triangles indicate Beam 1 and circles Beam 2. The dashed lines are linear fits to obtain the non-colliding intensity lifetime.

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.

SPS momentum slip stacking for 50 ns bunch spacing

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

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

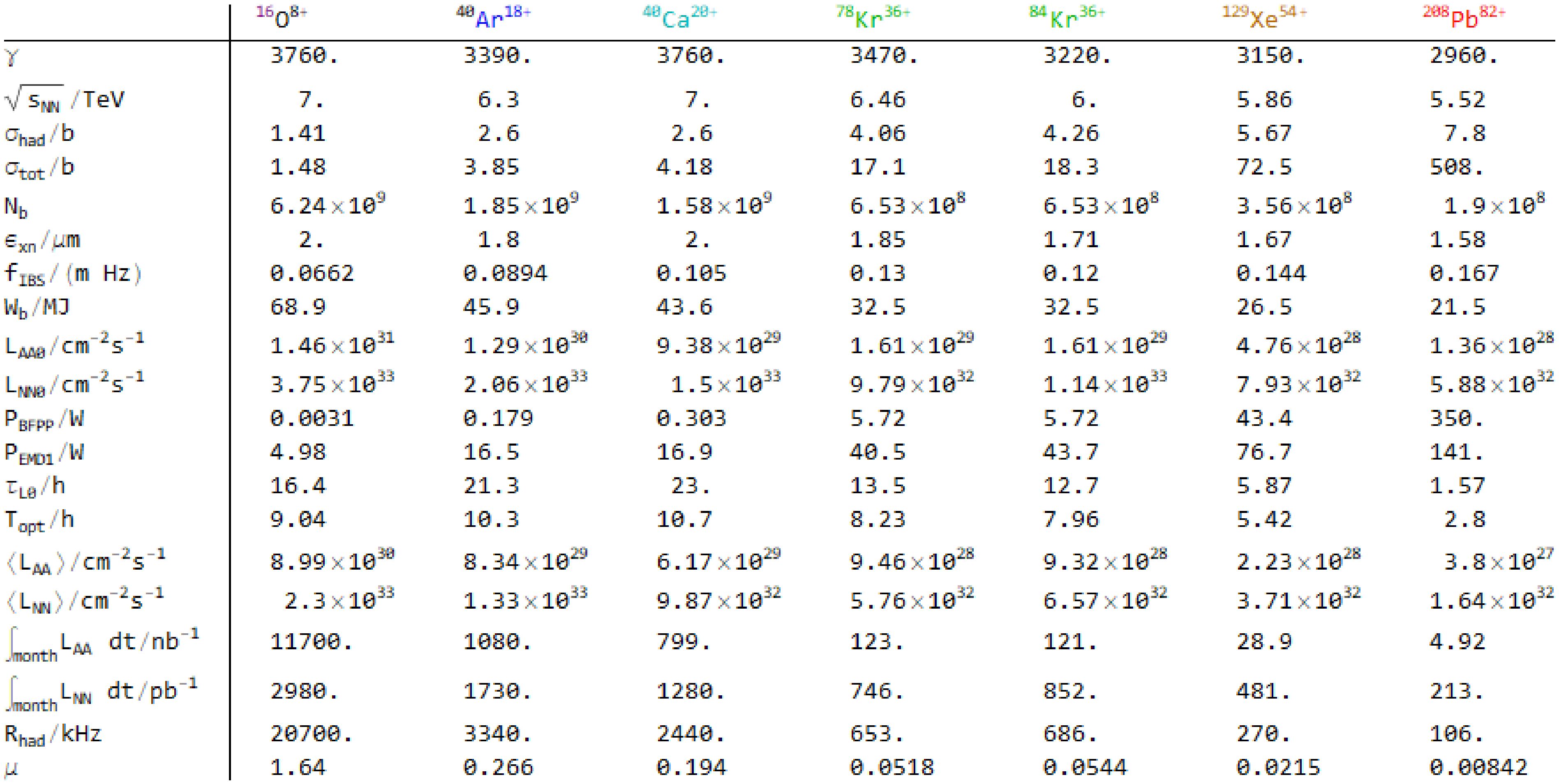
Stored energy in beam W_b is identical in this case $\Rightarrow$ Collimation risks ~ comparable.

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

Overestimates integrated luminosity for Pb-Pb wrt official values (since no levelling, etc).

Initial event rates are high! Much longer fills.

Plausible scaling (p=1.5)



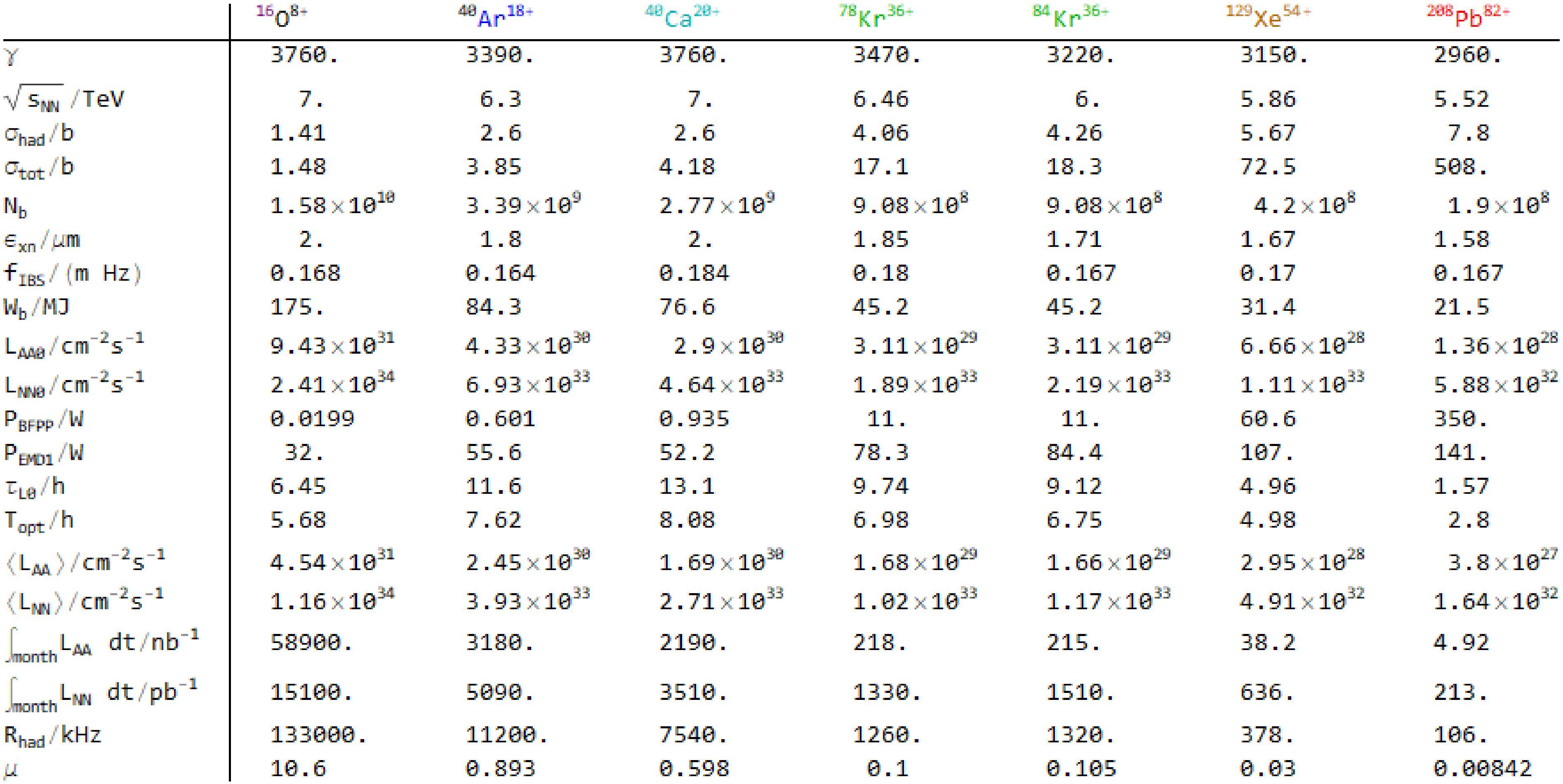
	$^{16}\mathrm{O}^{8+}$	$^{40}\mathrm{Ar}^{18+}$	$^{40}\mathrm{Ca}^{20+}$	$^{78}\mathrm{Kr}^{36+}$	$^{84}\mathrm{Kr}^{36+}$	$^{129}\mathrm{Xe}^{54+}$	$^{208}\mathrm{Pb}^{82+}$
γ	3760.	3390.	3760.	3470.	3220.	3150.	2960.
$\sqrt{s_{NN}}$ /TeV	7.	6.3	7.	6.46	6.	5.86	5.52
σ_{had}/b	1.41	2.6	2.6	4.06	4.26	5.67	7.8
σ_{tot}/b	1.48	3.85	4.18	17.1	18.3	72.5	508.
N_b	6.24×10^{9}	1.85×10^{9}	1.58×10^{9}	6.53×10^{8}	6.53×10^{8}	3.56×10^{8}	1.9×10^{8}
ϵ_{xn}/µm	2.	1.8	2.	1.85	1.71	1.67	1.58
f_{IBS}/(m Hz)	0.0662	0.0894	0.105	0.13	0.12	0.144	0.167
W_b/MJ	68.9	45.9	43.6	32.5	32.5	26.5	21.5
$L_{AA0}/\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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}
$L_{NN0}/\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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
$\langle L_{AA}\rangle/\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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}
$\langle L_{NN}\rangle/\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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}
$\int_{month} L_{AA}\, dt/\mathrm{nb}^{-1}$	11700.	1080.	799.	123.	121.	28.9	4.92
$\int_{month} L_{NN}\, dt/\mathrm{pb}^{-1}$	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)



	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{84}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
γ	3760.	3390.	3760.	3470.	3220.	3150.	2960.
$\sqrt{s_{NN}}$ /TeV	7.	6.3	7.	6.46	6.	5.86	5.52
σ_{had}/b	1.41	2.6	2.6	4.06	4.26	5.67	7.8
σ_{tot}/b	1.48	3.85	4.18	17.1	18.3	72.5	508.
N_b	1.58×10^{10}	3.39×10^{9}	2.77×10^{9}	9.08×10^{8}	9.08×10^{8}	4.2×10^{8}	1.9×10^{8}
ϵ_{xn}/μm	2.	1.8	2.	1.85	1.71	1.67	1.58
f_{IBS}/(m Hz)	0.168	0.164	0.184	0.18	0.167	0.17	0.167
W_b/MJ	175.	84.3	76.6	45.2	45.2	31.4	21.5
$L_{AA0}/cm^{-2}s^{-1}$	9.43×10^{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}
$L_{NN0}/cm^{-2}s^{-1}$	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
$\langle L_{AA}\rangle/cm^{-2}s^{-1}$	4.54×10^{31}	2.45×10^{30}	1.69×10^{30}	1.68×10^{29}	1.66×10^{29}	2.95×10^{28}	3.8×10^{27}
$\langle L_{NN}\rangle/cm^{-2}s^{-1}$	1.16×10^{34}	3.93×10^{33}	2.71×10^{33}	1.02×10^{33}	1.17×10^{33}	4.91×10^{32}	1.64×10^{32}
$\int_{month} L_{AA}\, dt/nb^{-1}$	58900.	3180.	2190.	218.	215.	38.2	4.92
$\int_{month} L_{NN}\, dt/pb^{-1}$	15100.	5090.	3510.	1330.	1510.	636.	213.
R_{had}/kHz	133000.	11200.	7540.	1260.	1320.	378.	106.
μ	10.6	0.893	0.598	0.1	0.105	0.03	0.00842

Stored energy in beam W_b several times Pb ⇒ 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.