

Prospects for operation with various nuclear species at LHC and HL-LHC

R. Bruce, R. Alemany, T. Argyropoulos, H. Bartosik, J.M. Jowett,
D. Kuchler, E. Mahner, R. Scrivens, N. Triantafyllou, E. Waagaard

Summarizing [LPC talk](#) and [recent paper](#)



Outline

- **Introduction: LHC ion programme**
- **Ion operation in Run 4**
- **Ion operation in Run 5**
- **Summary**



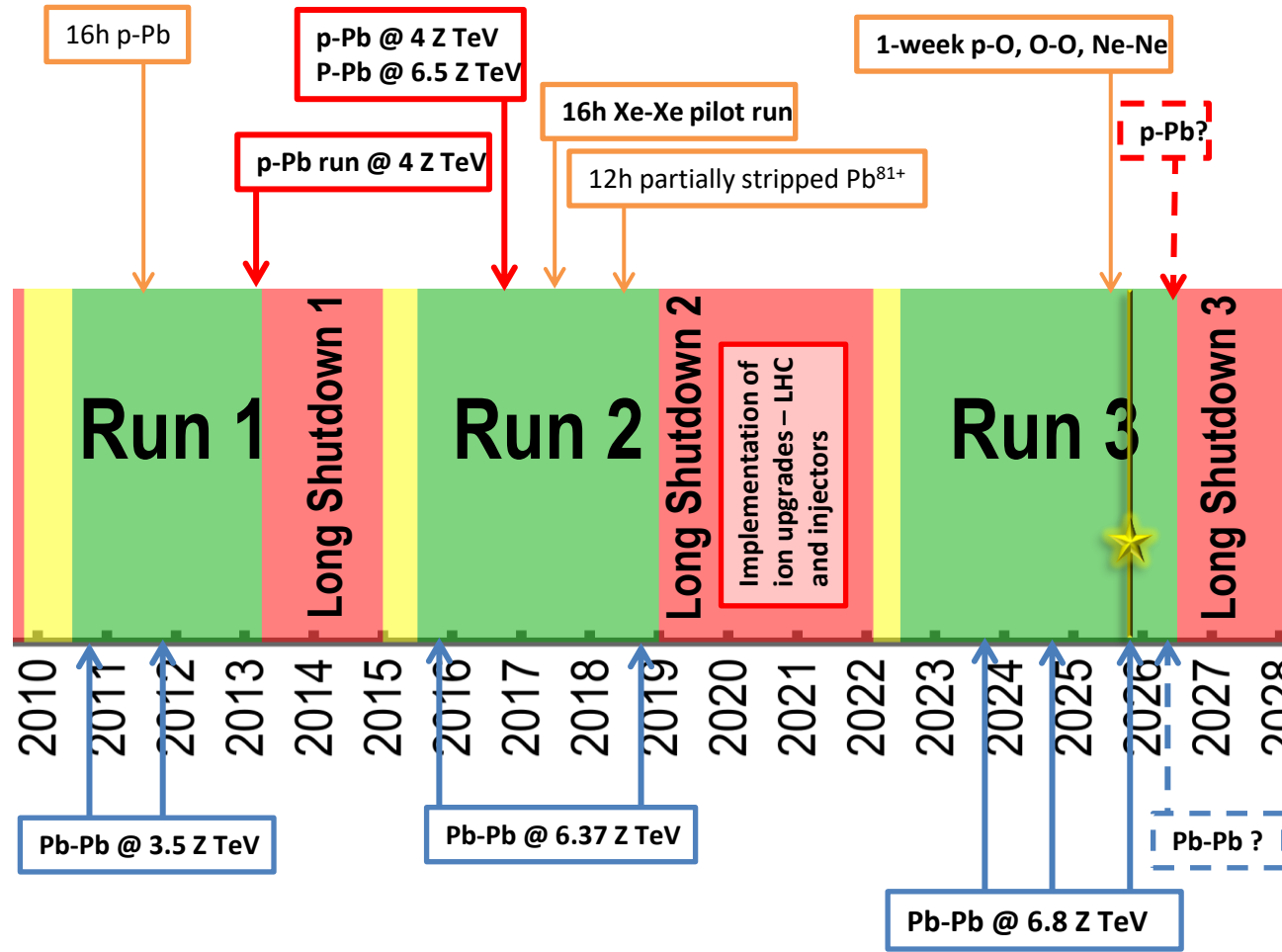
Past LHC ion runs and main achievements

LHC typically runs 1 month per year with heavy ions

- So far Pb-Pb (6 runs), p-Pb (2 runs)
- Short pilot runs in other configurations

LHC Run 3

- First Pb-Pb runs with all HL-LHC ion upgrades implemented
 - Shorter 50 ns bunch spacing from SPS, alleviation of collisional losses, ...
 - ALICE 2 upgrade allowed higher luminosity
- HL-LHC luminosity performance already reached and exceeded in Pb-Pb

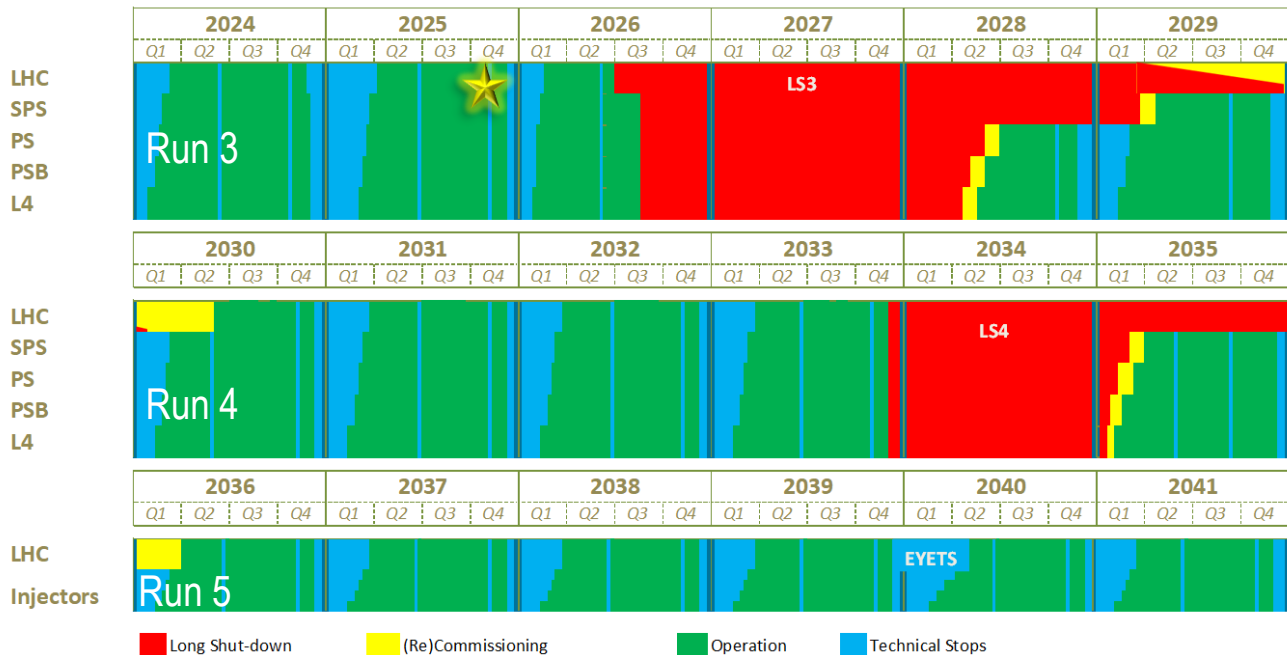




Future of LHC heavy-ion programme

- **Run 4: HL-LHC**
 - Yearly Pb-Pb and/or p-Pb operation except 2030
 - **Shorter pilot runs with other ions?**
- **Run 5**
 - **ALICE3**: new detector for significantly higher nucleon-nucleon luminosity
 - Under study, not yet approved
 - **LHC ion runs to continue**
 - if ALICE3 goes ahead
 - **Detailed program not yet decided**

Long Term Schedule for CERN Accelerator complex

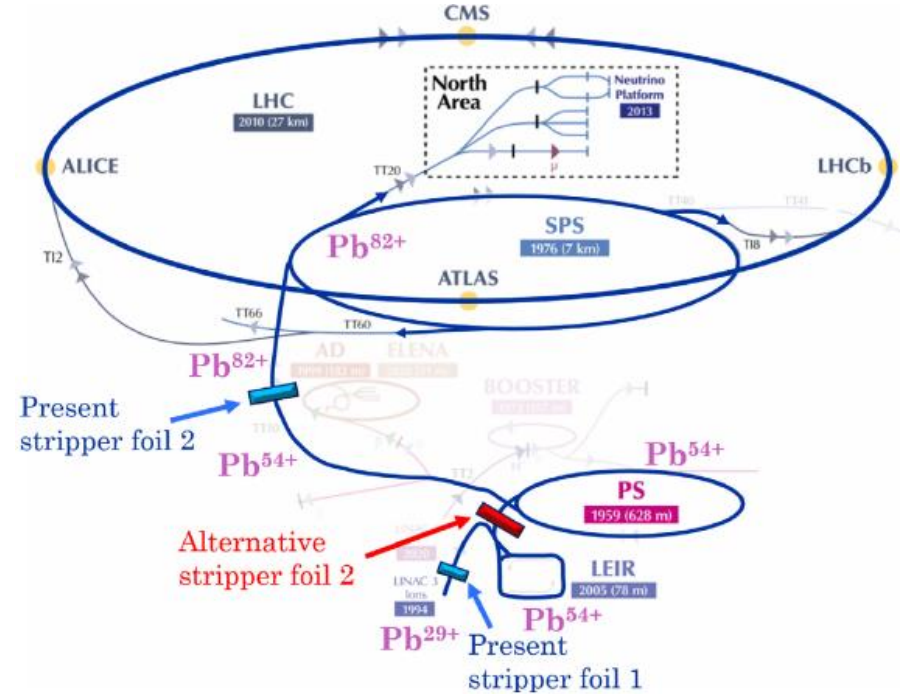


EDMS [2311633](https://cds.cern.ch/record/2311633) V 4.2



Run 4 possibilities for light ions

- **Main Run 4 program with Pb-Pb and p-Pb**
- **Potential for shorter runs with other ions**
 - Similar to the 2025 O and Ne run
 - significant uncertainty on performance
 - No formal proposal or plan yet for such a program
 - Subject to constraints from technical feasibility and scheduling in injectors and LHC






Constraints for short pilot runs in Run 4

- **Not any ion is possible**
 - Ideally test any new ion in the source before operation to minimize risks
 - Several new ions to be tested in LS3, potentially available for operation in Run 4: Kr, Mg, B
- **Typically, need significant time to switch ion species in source and the injector complex**
 - Source switching times
 - O[6 weeks] for source to switch from another ion to Pb
 - Switching Pb \rightarrow another ion is much faster: beam within days, but high uncertainty on reliability and quality
 - **A second source would make it possible to switch quickly – if this is interesting for the experiments, any expression of support could help**
 - Several days of commissioning typically needed in each machine
 - Exception: if we can use the same cycle as for the previous ion due to the same Z/A (e.g. O \rightarrow Ne)
 - **For most cases, better to separate in time light-ion run from main Pb run**



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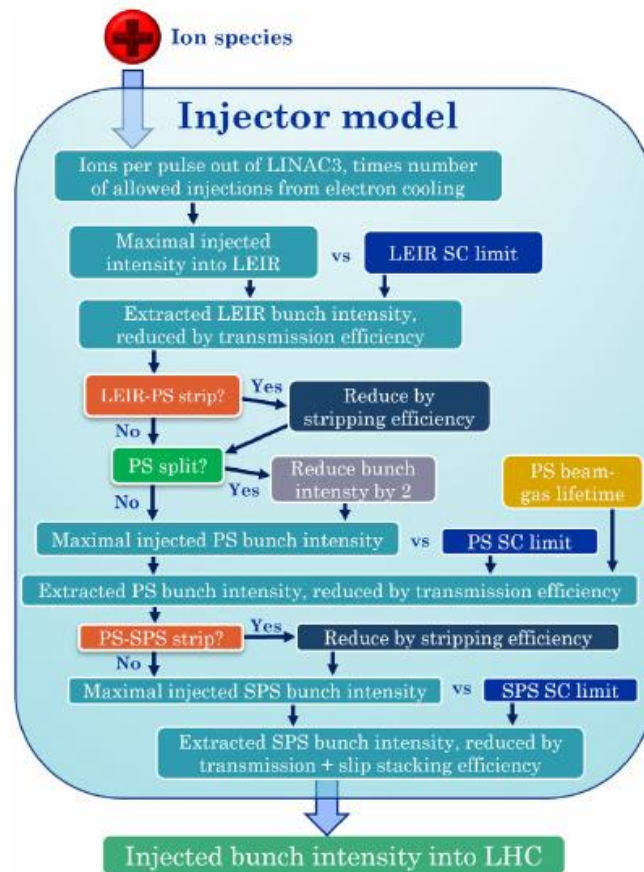
LHC ion operation in Run 5

- **Aim at significantly higher nucleon-nucleon luminosity** than HL-LHC Pb-Pb
 - New ALICE3 detector under study, letter of intent prepared - to be installed in LS4 if approved
 - **Different scope in Run 5: aim at highest luminosity** vs shorter pilot runs at low luminosity
 - Pilot runs with different ions could still be a possibility
- Many optimizations and upgrades in the injectors already gave **factor >3 higher bunch charge and factor >2 more bunches in 2024-2025 than in LHC design report (2004)**
 - **Not straight-forward to gain additional large factors in Pb-Pb luminosity with present OP scheme**
- **Different ways to further increase luminosity under study**
 - Further optimizations and upgrades to the Pb beam production scheme in the injectors
 - Use another ion species than Pb
 - Potential to achieve higher bunch intensities from the injectors, and higher NN luminosity
 - Electromagnetic cross sections in the LHC collisions scale with powers of the charge – will be less limiting
 - Could combine both ways...



Injector model

- **Need to estimate potential luminosity with other beams and ion species than Pb →**
 - Need to estimate beam properties given by the injectors
 - First rough estimate in WG5 [yellow report](#) based on fitted power law scaling
 - Detailed limitations in injectors not accounted for
- **“Injector model” developed over the last years**
 - For any ion, propagate beam through the injector chain,
 - Account for realistic production scheme (stripping, splitting, ...) and limitations in each machine depending on ion charge, mass and energy
 - Space charge, electron cooling, beam-gas losses, ...
 - Still under development - hope to add further features in the future





Studied ions and scenarios

- **Range of ion species studied**

- based on previous experience and experiments' wishes

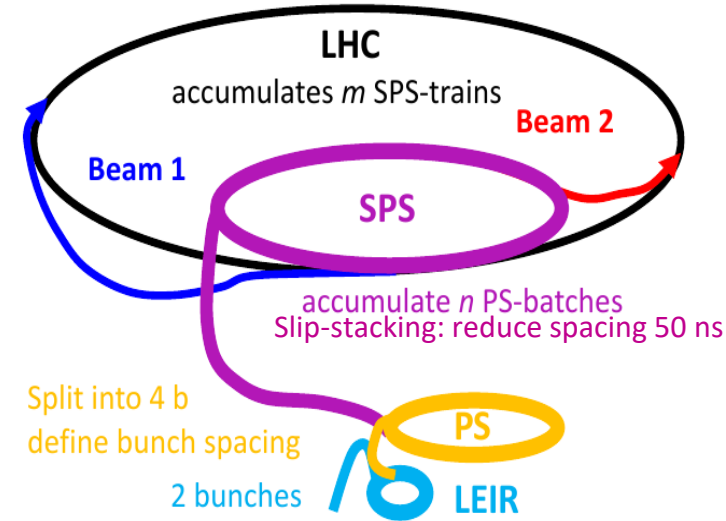
- **Range of beam production scenarios in injectors**

- 50 ns baseline
 - Same as presently used for Pb in LHC
- 50 ns, no splitting in the PS
 - Higher bunch intensity but fewer bunches and longer injection time
 - First test yesterday with Pb!
- Any of the above scenarios with optimized charge state or isotope
- Any of the above scenarios with additional electron stripping between LEIR and PS
- 25 ns spacing
 - Requires upgrade of RF system in PS
 - 40% more bunches in LHC but longer injection time
 - Consider also scheme with 6 bunches from PS instead of 4 → more bunches in LHC and faster injection time, but lower bunch intensity

Ion	Z	A
He	2	4
O	8	16
Mg	12	24
Ar	18	40
Ca	20	40
Kr	36	86
In	49	115
Xe	54	129
Pb	82	208

} Used operationally for Pb

} Potential improvements but not demonstrated, need developments



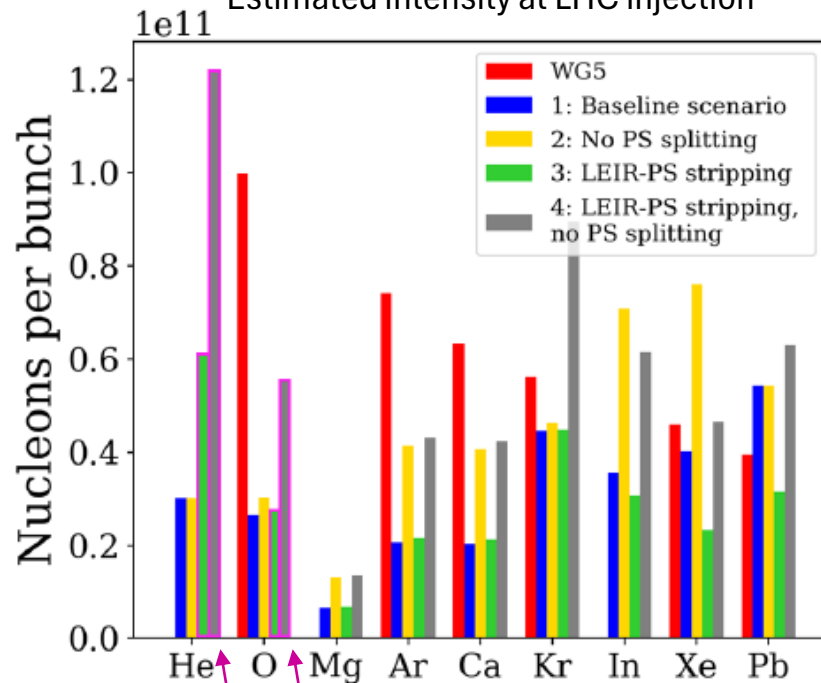


Projected intensities at LHC injection

- **Several iterations**
 - Latest version: scaling from demonstrated performance with 2024 Pb beams
 - Good agreement with 2025 oxygen beam production
- **Baseline scenario gives significantly lower bunch intensity than WG5**
 - Difference is larger for lighter ions
 - Much lower LHC luminosity to be expected than WG5
- **Main performance limitations for light ions:**
 - LEIR electron cooling time
 - Space charge at LEIR injection

From [NIMA 1083 \(171118\)](#) (2025)

Estimated intensity at LHC injection



E. Waagaard

Not feasible due to required magnetic field in PS
Inject O8+?



3 scenarios for LHC studies

- **Baseline**
 - Using the well-proven scheme for Pb, extrapolate to other ions using our best knowledge and conservative assumptions
 - Assume proven LHC performance (β^* , energy, transmission, operational efficiency)
- **Optimistic**
 - Assume scenario with no splitting in PS and best charge state; reduced β^* , crossing in LHC
 - Account for fewer bunches, longer injection in LHC, giving also additional emittance blowup and lower transmission, extra LEIR injection from improved electron cooling
 - **Has some optimism, clearly relies on assumptions that have not been proven yet**
- **25 ns**
 - Assume bunch parameters and LHC configuration as in baseline scenario, but with small additional emittance blowup and intensity loss due to longer injection time
 - Not given that the experiments can handle 25 ns
 - **Relies on assumptions that have not been proven yet and also additional hardware upgrades of the PS RF system**
- **In all scenarios, assume that luminosity levelling is no longer needed. Assume also that collimation and collisional losses are not limiting → to be studied**



LHC simulation setup

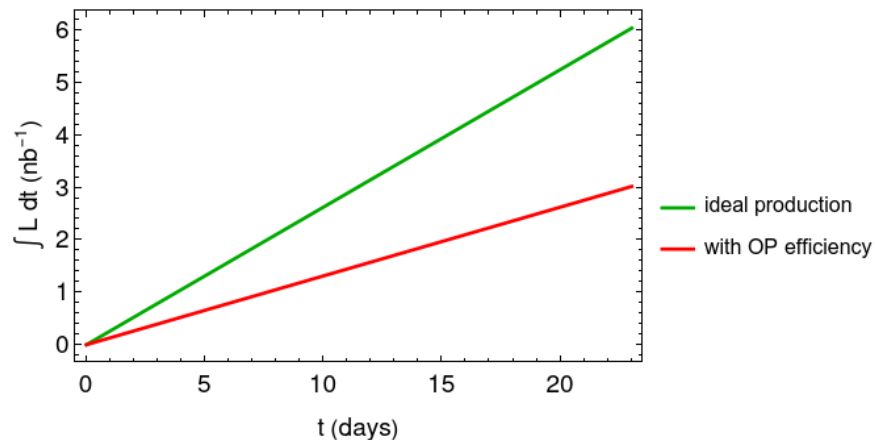
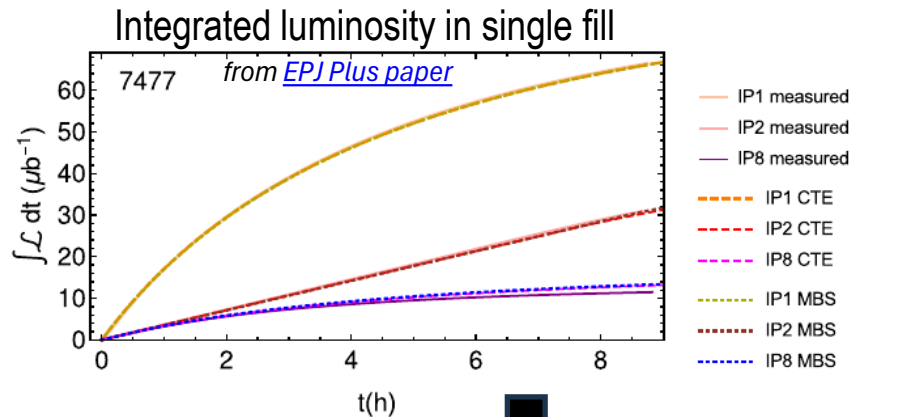
- LHC beam evolution in single fills simulated with Collider Time Evolution programme (CTE)**

- Simulate beam blowup and losses at injection plateau to evolution in collision including burnoff, intrabeam scattering, radiation damping, collimation
- Benchmarked with LHC Pb data – gives excellent agreement for known starting conditions

- Single fill luminosity extrapolated to total data in typical 1-month run (24 days for physics)**

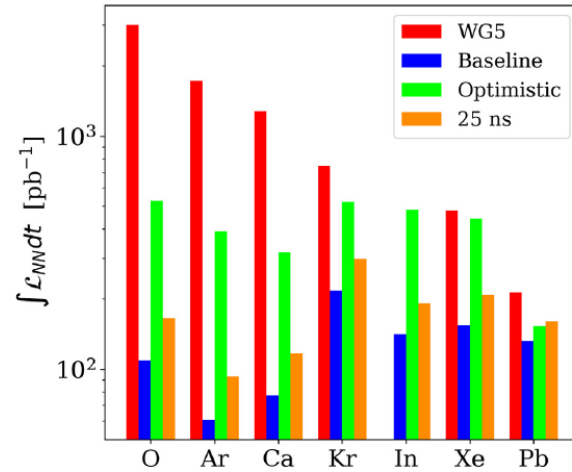
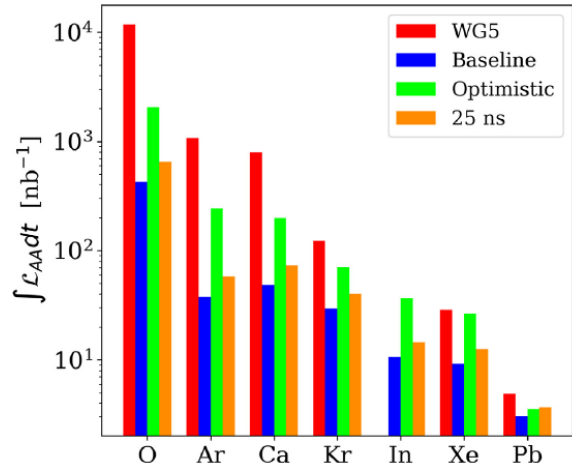
- Calculate optimal fill time, calculate total production in ideal conditions, reduce results by assumed operational efficiency factor

$$\mathcal{L}_{\text{tot}} = \mathcal{L}_{\text{avg}}(T_{f,\text{opt}}) \times T_{\text{run}} \times \eta$$





Projected one-month luminosity



From [NIMA 1083 \(171118\)](#) (2025)

- Even in optimistic scenario, we get **significantly lower luminosity than in WG5 for most considered ions**
- No single “winner” ion stands out – no clear trend as function of ion mass
- Optimistic scenario gives best performance
- 25 ns: gives moderate gain over baseline scenario
 - Combine with other improvement strategies?
- **Both optimistic and 25 ns scenarios rely on assumptions that have not been proven yet**



Projected one-month luminosity

	One-month $\int \mathcal{L}_{AA} dt$ [nb ⁻¹]				One-month $\int \mathcal{L}_{NN} dt$ [pb ⁻¹]			
	WG5	Baseline	Optimistic	25 ns	WG5	Baseline	Optimistic	25 ns
O	11 700	428.1	2070.4	648.6	2995.2	109.6	530.0	166.0
Ar	1080	38.0	244.7	58.3	1728.0	60.8	391.4	93.2
Ca	799	48.4	199.3	73.3	1278.4	77.5	318.9	117.2
Kr	123	29.4	70.9	40.3	748.3	217.5	524.5	298.2
In	–	10.7	36.7	14.5	–	141.5	485.2	192.1
Xe	28.9	9.3	26.6	12.6	480.9	154.3	443.4	209.7
Pb	4.92	3.0	3.5	3.7	212.9	131.8	153.5	160.2

- **Note: Pb-Pb baseline gives higher integrated luminosity than previous studies for HL-LHC**
 - Assuming higher bunch charge as demonstrated in 2024-2025
 - No luminosity levelling assumed
- **Baseline scenario: up to 64% gain in NN luminosity (for Kr) compared to Pb**
- **Optimistic scenario**
 - Up to a factor ~4 gain in NN-luminosity per ion and compared to Pb-Pb baseline
 - WG5 had gain ratio of 14 compared to Pb-Pb (for O)
- **25 ns:**
 - 20-50% gain in NN luminosity for each ion
 - Factor ~2.3 gain for the best case compared to Pb-Pb baseline



Evolution of predictions

- Over the years, the **predicted luminosity has evolved**, following improvements of the modelling and accounting for the progress in operation
- **Work is ongoing - results likely to evolve further in the future**
 - Several parts of modelling still missing: interplay between intrabeam scattering and space-charge, space-charge tune shift dependent transmissions instead of hard cut-off
 - LHC limitations on beam intensity and luminosity not yet studied in detail for new ions



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Summary

- **In Run 3 and Run 4**
 - LHC will continue operation with Pb-Pb and/or p-Pb for about 1 month per year
 - HL-LHC performance established and significantly surpassed in 2024
 - Potential for shorter “pilot runs” with other ions as for Xe in 2017 and O/Ne in 2025?
- **Beyond Run 4**
 - LHC ion runs approved
 - Aiming at significantly higher NN luminosity
 - Investigating alternative ion species and beam production schemes
 - Potential also for shorter “pilot runs” with different ions
- **Performance studies for beyond Run 4**
 - Injector model developed to estimate achievable intensity for a range of ions
 - LHC simulations to study luminosity
 - Potential to reach up to factor ~ 4 higher NN luminosity with alternative ions and production schemes
 - Relies on optimistic assumptions, still to be proven
- **Studies will continue**
 - Important to gather further information and improve the models – simulations and experimentally
 - Expect valuable information from 2025 oxygen run and updated results
- **More information in [recent paper](#)**



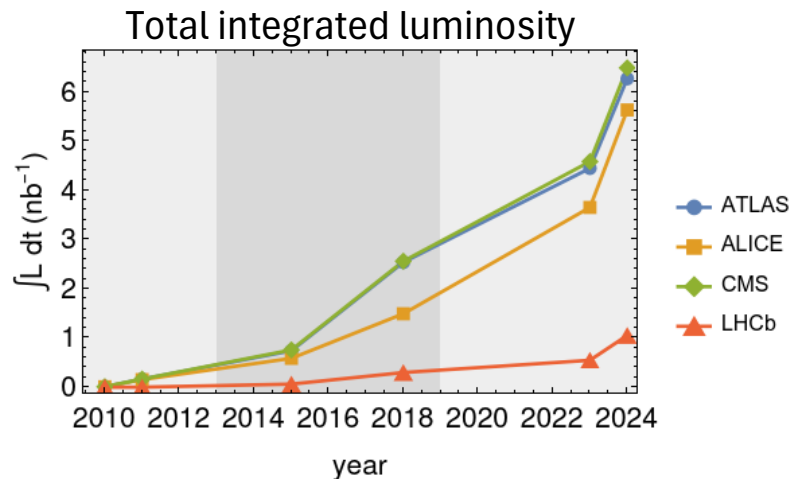
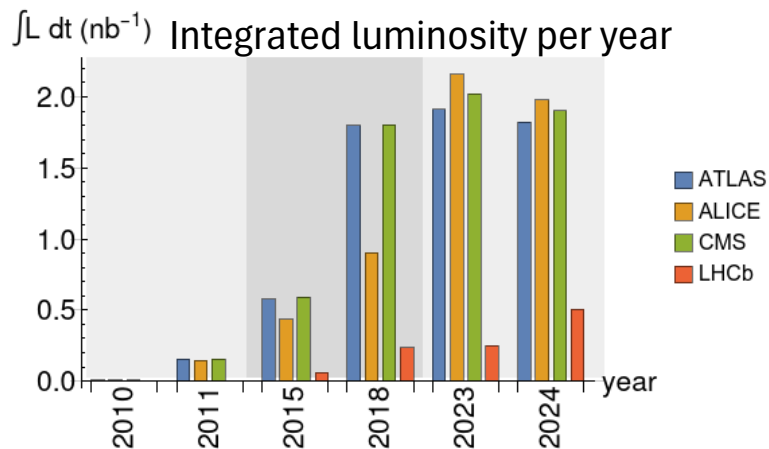
Thanks for the attention!



Backup



Integrated luminosity so far



ALICE2 and HL-LHC upgrades in LS2 allowed higher luminosity from 2023

- **2024 was the by far best run so far**
 - Half of the time allocated compared to 2023

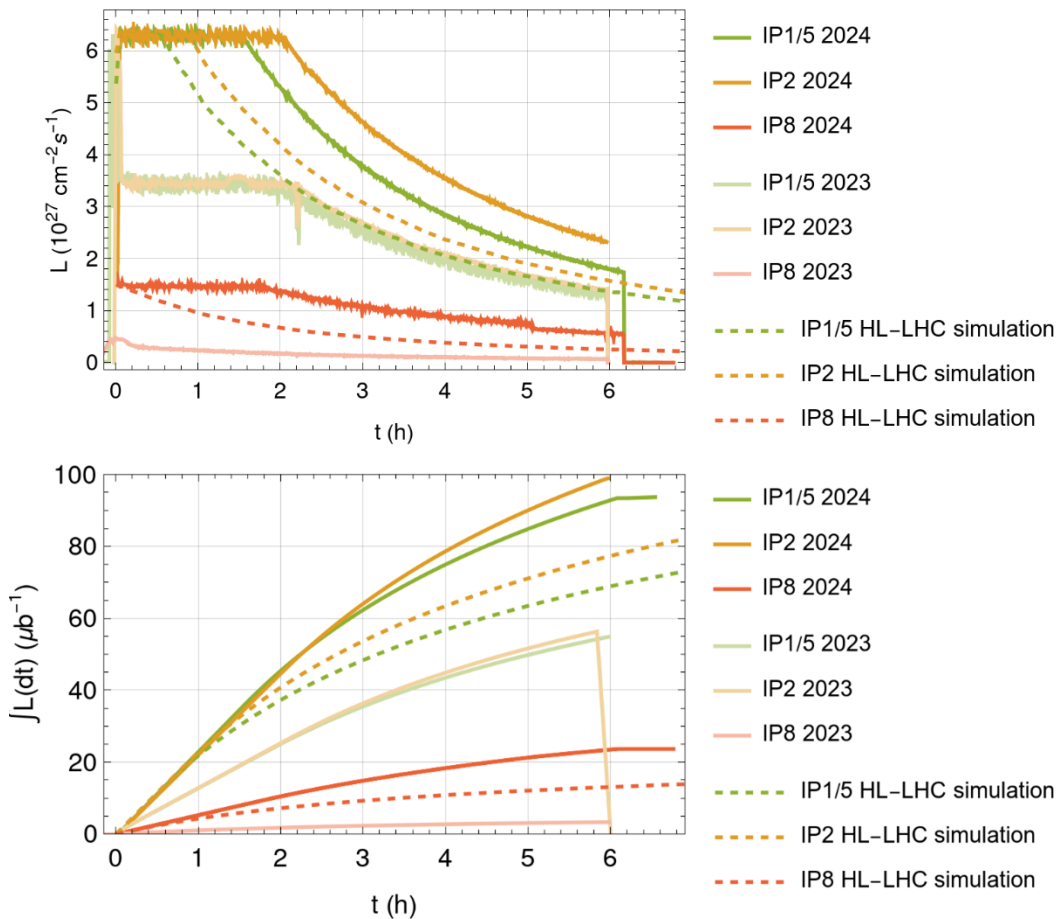
- **Total integrated Pb-Pb luminosity**
 - ATLAS: 6.3 nb^{-1}
 - ALICE: 5.6 nb^{-1}
 - CMS: 6.5 nb^{-1}
 - LHCb: 1.05 nb^{-1}



2024: surpassing nominal HL-LHC performance

- Achieved **levelling time up to about 2h** in ALICE
- 2024 luminosity production in single fills **surpasses by far 2023, and even HL-LHC projections**
 - After 6h, ALICE has about 80% more data than in 2023 and 30% more than HL-LHC prediction
 - After 6h, LHCb has 80% more data than in HL-LHC prediction
 - Reason: significantly higher bunch intensity from injectors; mitigation of LHC limitations
- Plan for rest of Run 3 and Run 4: continue production as in 2024**
 - incremental improvements may be within reach, but probably not big factors

2024: fill 10400; 2023: fill 9285 (among the best fills each year)





Physics goals from yellow report

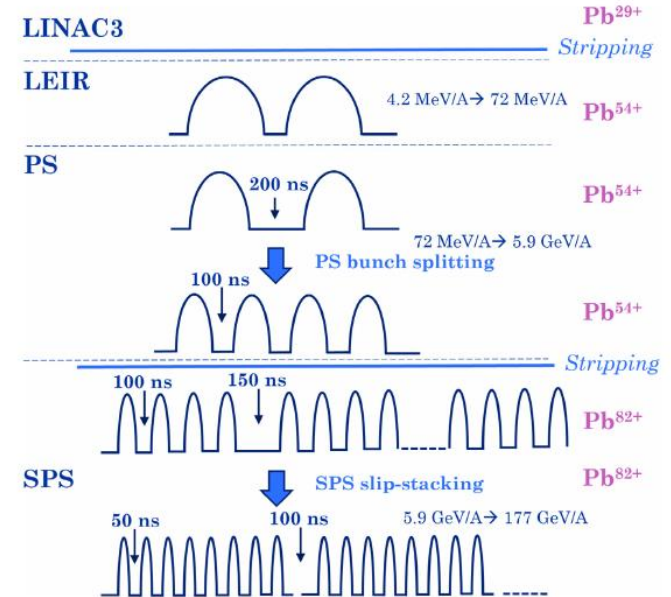
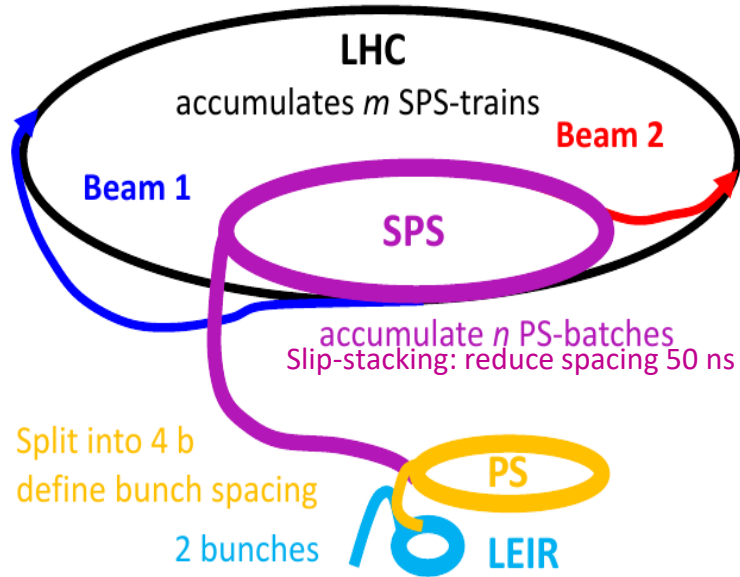
- WG5 in the 2018 HL-LHC / HE-LHC physics workshop dealt with heavy-ion physics
- Yellow report details requests for Run 3 and Run 4, as well as proposal for extended heavy-ion running: [CERN-LPCC-2018-07](#)

- **Pb-Pb at $\sqrt{s_{NN}} = 5.5$ TeV, $L_{int} = 13$ nb⁻¹ (ALICE, ATLAS, CMS), 2 nb⁻¹ (LHCb)**
- **pp at $\sqrt{s} = 5.5$ TeV, $L_{int} = 600$ pb⁻¹ (ATLAS, CMS), 6 pb⁻¹ (ALICE), 50 pb⁻¹ (LHCb)**
- **pp at $\sqrt{s} = 14$ TeV, $L_{int} = 200$ pb⁻¹ with low pileup (ALICE, ATLAS, CMS)**
- **p-Pb at $\sqrt{s_{NN}} = 8.8$ TeV, $L_{int} = 1.2$ pb⁻¹ (ATLAS, CMS), 0.6 pb⁻¹ (ALICE, LHCb)**
- **pp at $\sqrt{s} = 8.8$ TeV, $L_{int} = 200$ pb⁻¹ (ATLAS, CMS, LHCb), 3 pb⁻¹ (ALICE)**
- **O-O at $\sqrt{s_{NN}} = 7$ TeV, $L_{int} = 500$ μ b⁻¹ (ALICE, ATLAS, CMS, LHCb)**
- **p-O at $\sqrt{s_{NN}} = 9.9$ TeV, $L_{int} = 200$ μ b⁻¹ (ALICE, ATLAS, CMS, LHCb)**
- **Intermediate AA, e.g. $L_{int}^{Ar-Ar} = 3-9$ pb⁻¹ (about 3 months) gives NN luminosity equivalent to Pb-Pb with $L_{int} = 75-250$ nb⁻¹**

Run 4
In Run 3 +



Present Pb production scheme





Injector limitations

- **LEIR electron cooling**
 - worse for lighter ions and lower charge states
- **Space charge**
 - worse at lower energy and higher charge
- **Beam-gas interactions**

$$\tau_{\text{cool}} = \tau_{\text{cool, Pb}} \times \left(\frac{q_{\text{Pb}}}{q} \right)^2 \frac{A}{A_{\text{Pb}}}.$$

$$\Delta Q_u = - \frac{r_0 \hat{\lambda}}{2\pi\gamma(\gamma^2 - 1)} \oint \frac{\beta_u(s)}{\sigma_u(s) (\sigma_x(s) + \sigma_y(s))} ds,$$

$$N_b \approx N_{b,\text{Pb}} \frac{q_{\text{Pb}}^2 m\gamma(\gamma^2 - 1)}{q^2 m_{\text{Pb}} \gamma_{\text{Pb}} (\gamma_{\text{Pb}}^2 - 1)}.$$

$$\tau_i = \frac{1}{\sigma n_i \beta c},$$



Baseline ion production scenario: predicted theoretical maximum bunch intensities N_b (in number of ions) and space charge limit (SCL) at the injection energies along the injector chain. In LEIR, N_b represents the total intensity at injection before capture. Two values are shown for N_b : one for **8 injections** in LEIR (achieved for Pb) and one assuming the Electron-Cooling Limit (**ECL**) from Table 3. For each ion species, the **global bottleneck** in LEIR, PS or SPS is marked in bold and underlined.

LEIR injection (accumulated intensity before capture)			PS injection		SPS injection		LHC injection		
N.o. LEIR injections	Max N_b 8 inj, ECL	SCL	Max N_b , with bunch splitting	SCL (at least)	Max N_b	SCL	Max N_b	Max charges per bunch ($ e $)	
He	1	<u>1.2E+12, 1.5E+11</u>	<u>1.45E+11</u>	<u>5.1E+10, 5.1E+10</u>	9.6E+10	<u>1.8E+10, 1.8E+10</u>	<u>1.1E+10</u>	<u>7.5E+9, 7.5E+9</u>	<u>1.5E+10</u>
O	1	<u>1.7E+11, 2.1E+10</u>	<u>3.6E+10</u>	<u>1.3E+10, 7.4E+9</u>	2.4E+10	<u>4.3E+9, 2.5E+9</u>	<u>2.8E+9</u>	<u>1.9E+9, 1.7E+9</u>	<u>1.3E+10</u>
Mg	1	<u>2.1E+10, 2.7E+9</u>	1.8E+10	<u>6.3E+9, 9.5E+8</u>	1.6E+10	<u>2.4E+9, 3.6E+8</u>	3.0E+9	<u>1.6E+9, 2.4E+8</u>	<u>2.9E+9</u>
Ar	1	<u>4.1E+10, 5.1E+9</u>	1.2E+10	<u>4.2E+9, 1.8E+9</u>	9.7E+9	<u>1.7E+9, 7.4E+8</u>	1.9E+9	<u>1.2E+9, 4.9E+8</u>	<u>8.9E+9</u>
Ca	4	<u>1.1E+10, 5.5E+9</u>	<u>5.0E+9</u>	<u>1.8E+9, 1.8E+9</u>	1.1E+10	<u>7.6E+8, 7.6E+8</u>	5.5E+9	<u>5.1E+8, 5.1E+8</u>	<u>1.0E+10</u>
Kr	3	<u>1.4E+10, 5.1E+9</u>	6.4E+9	<u>2.3E+9, 1.8E+9</u>	4.5E+9	<u>9.6E+8, 7.6E+8</u>	8.0E+8	<u>5.4E+8, 5.1E+8</u>	<u>1.8E+10</u>
In	7	<u>5.1E+9, 4.4E+9</u>	<u>3.0E+9</u>	<u>1.1E+9, 1.1E+9</u>	3.5E+9	<u>4.6E+8, 4.6E+8</u>	1.2E+9	<u>3.1E+8, 3.1E+8</u>	<u>1.5E+10</u>
Xe	6	<u>5.8E+9, 4.3E+9</u>	<u>3.1E+9</u>	<u>1.1E+9, 1.1E+9</u>	3.1E+9	<u>4.6E+8, 4.6E+8</u>	8.8E+8	<u>3.1E+8, 3.1E+8</u>	<u>1.7E+10</u>
Pb	8	<u>4.2E+9</u>	<u>2.6E+9</u>	9.8E+8	9.8E+8	3.9E+8	<u>3.9E+8</u>	2.6E+8	<u>2.1E+10</u>



Peak luminosity and rates

	\mathcal{L}_{AA} [$\text{cm}^{-2}\text{s}^{-1}$]			\mathcal{L}_{NN} [$\text{cm}^{-2}\text{s}^{-1}$]			$N_{AA,\text{had}}$ [kHz]			σ_{had} [barn]
	Baseline	Optimistic	25 ns	Baseline	Optimistic	25 ns	Baseline	Optimistic	25 ns	
O	5.8E+29	2.6E+30	9.2E+29	1.5E+32	6.6E+32	2.4E+32	819.7	3639.9	1299.35	1.41
Ar	4.8E+28	2.9E+29	7.7E+28	7.7E+31	4.6E+32	1.2E+32	124.7	751.0	199.1	2.60
Ca	5.2E+28	2.0E+29	8.2E+28	8.3E+31	3.2E+32	1.3E+32	134.0	524.9	212.1	2.60
Kr	4.6E+28	1.0E+29	6.6E+28	3.4E+32	7.5E+32	4.9E+32	198.0	441.6	286.1	4.33
In	1.8E+28	6.7E+28	2.6E+28	2.4E+32	8.8E+32	3.5E+32	93.4	349.6	138.3	5.25
Xe	1.7E+28	5.3E+28	2.6E+28	2.9E+32	8.8E+32	4.3E+32	98.2	301.6	145.2	5.67
Pb	1.1E+28	1.2E+28	1.5E+28	4.8E+32	5.2E+32	6.5E+32	86.7	94.4	117.3	7.80