Plans for LHC ion operation in Run 3

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Outline

- Introduction:
  - Recap of previous achievements
  - Schedule for future heavy-ion runs
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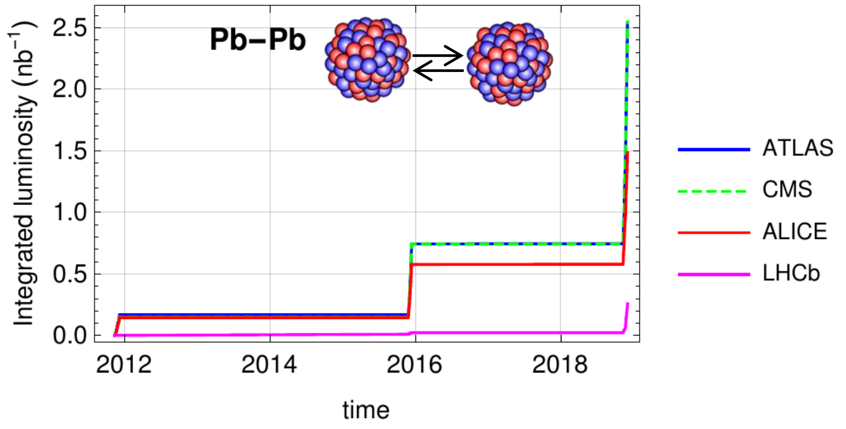
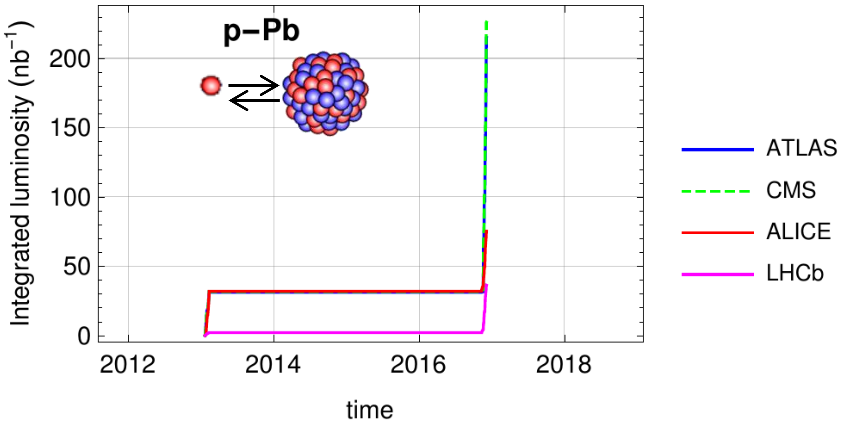
- LHC machine configuration in Run 3 for heavy-ions
  - Beam production and filling schemes
  - Expected beam parameters
  - IP configuration (optics, crossing angles, levelling…)
  - Dynamic aperture and beam stability
  - Collimation
- Performance estimates
  - Projected performance in future Pb-Pb
  - Projected performance in future p-Pb
  - Potential improvements to be further studied
- Oxygen pilot run
  - Goals and projected performance
- Conclusions

Introduction

- So far, LHC heavy-ion runs for about 1 month per year in Run 1 and Run 2
  - Production runs Pb-Pb or p-Pb
  - Pilot tests with Xe and partially stripped Pb
  - Detailed summary of Run 2: see paper by J. Jowett at Evian 2019
- Total integrated luminosity so far
  - Pb-Pb: 1.5 nb^{-1} in ALICE, 2.54 nb^{-1} in ATLAS/CMS, 0.26 nb^{-1} in LHCb
  - p-Pb: 75 nb^{-1} in ALICE, ~220 nb^{-1} in ATLAS/CMS, 36 nb^{-1} in LHCb
- Encountered limits
  - Luminosity limits from pileup at ALICE detector, and beam losses from bound-free pair production (BFPP) => levelled ALICE and LHCb at 1×10^{27} cm^{-1} s^{-2}
  - Compare: ~6×10^{27} cm^{-1} s^{-2} achieved at ATLAS/CMS
  - Several fills lost on beam dumps due to 10 Hz events; collimation efficiency





The future of heavy-ion operation

- Heavy-ion program scheduled to continue in Run 3-4 (at least)

- Tentative plan for Run 3 (from talk B. Petersen, assuming LS3 starts in 2025 – to be reviewed if LS3 shifted)
  - 2022: Pb-Pb, 1 month
  - 2023: p-Pb, 1 month
  - 2024: Pb-Pb, 2 months
  - In addition, p-p reference runs to be fitted in
  - Potential O-O and p-O pilot run to be scheduled, possibly in 2024
  - In Run 4 expect another three one-month runs => in total, 7 months before end of Run 4

EDMS: 2311633 v.1.0

Future heavy-ion runs? Detailed schedule still to be defined

Oxygen pilot run?

Requests from experiments

- WG5 in the 2018 HL-LHC / HE-LHC physics workshop dealt with heavy-ion physics
- Yellow report released with luminosity requests and 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**, $L_{int} = 500\ \mu b^{-1}$ (ALICE, ATLAS, CMS, LHCb)
- **p–O at $\sqrt{s_{NN}} = 9.9$ TeV**, $L_{int} = 200\ \mu b^{-1}$ (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 $L_{int} = 75$–$250\ nb^{-1}$

In Run 3 + Run 4

Proposal for after Run 4

- Heavy-ion operational scenario for Run 3-4: see CERN-ACC-report and EPJ Plus paper
  - Updates since then: target beam energy for Run 3 changed to 6.8 Z TeV; deferral of installation of 11T dipoles and IR7 DS collimators

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LHC beams

- In Run 3, plan to upgrade to 50 ns beams from injectors, thanks to SPS slip-stacking
  - Could get ~70% more bunches into the LHC compared to 75 ns used in 2018
  - Very good progress so far in commissioning (see talk A. Huschauer)
  - 75 ns remains available as backup in case of issues with slipstacking

- Range of 50 ns filling schemes worked out and optimized
  - Different number of LHCb collisions, with varying penalty for the other experiments

	Filling scheme	n.o. bunches	n.o. collisions at IP1/5	IP2	IP8	spacing
50 ns	1240b_1240_1200_0	1240	1240	1200	0	50 ns
50 ns	1240b_1144_1144_239	1240	1144	1144	239	50 ns
50 ns	1240b_1088_1088_398	1240	1088	1088	398	50 ns
50 ns	1240b_1032_1032_557	1240	1032	1032	557	50 ns
50 ns	1240b_976_976_716	1240	976	976	716	50 ns
75 ns backup	733b_733_702_468	733	733	702	468	75 ns

- **50 ns schemes exist with many more collisions at all IPs than with 75 ns**
- Final scheme to be selected by LHCC/LPC, variations during a run possible

Pb beam parameters at injection and collision

- Beam parameters at LHC injection provided by LIU

	LHC design	2018	Run 3
Total n.o. bunches	592	733	1240
Bunch spacing (ns)	100	75	50
N.o. bunches per injection	54	42	56
Bunch intensity (10^7 Pb ions)	7	23	19
Normalized transverse emittance (μm)	1.4	n.a.[a]	1.5

There are no reliable measurements of the 75 ns beam emittance available at LHC injection.

- Some degradation between injection and collision assumed – uncertainties apply
- Beam parameters in collision (similar to HL-LHC, but 6.8 Z TeV beam energy

	LHC design	2018	Run 3
Beam energy (Z TeV)	7	6.37	6.8
Bunch spacing (ns)	100	75	50
Total n.o. bunches	592	733	1240
Bunch intensity (10^7 Pb ions)	7	21	18
Normalized transverse emittance (μm)	1.5	2.3	1.65

IP configuration at 7 Z TeV

- Pb optics cycle will be different from the p-p optics
  - Present baseline: Optics for Run 3 similar to the 2018 Pb-Pb run

	IP1	IP2	IP5	IP8
β^* (m)	0.5	0.5	0.5	1.5
crossing plane	V	V	H	H
spectrometer half crossing (μrad)	0	$\mp$70	0	-135
external half crossing (μrad)	170	$\pm$170	170	-170
net half crossing (μrad)	170	$\pm$100	170	-305
spectrometer polarity	-	pos/neg	-	pos

- Assume offset levelling at $L=6.4\times10^{27}$ cm^{-2} s^{-1} for IP1/2/5 and $L=1.0\times10^{27}$ cm^{-2} s^{-1} at IP8
  - ALICE detector upgraded to 50 kHz max. event rate in LS2
    - Previous IR2 luminosity limit from collisional losses alleviated through new collimators installed in LS2 (see talk G. Azzopardi)
  - LHCb luminosity limited by luminosity-driven losses
  - No direct need for β*-levelling. Offset levelling provides simplicity in commissioning and validation

- Further push in β* and/or crossing angle for increased performance under study

Beam-beam studies for ions

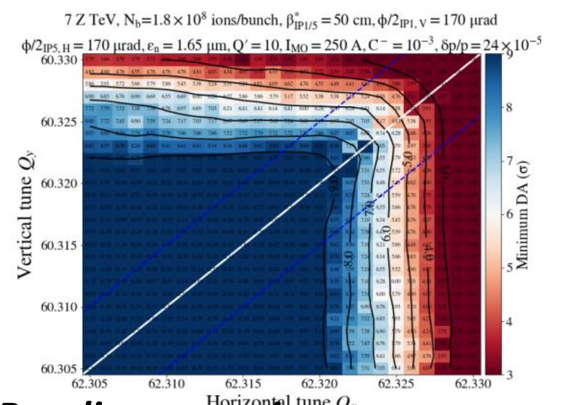
- For details: see talk S. Kostoglou at WP2 meeting

- First studies of dynamic aperture (DA) with ion beams
  - Compared to protons, beam-beam is less critical due to smaller bunch charge and larger bunch spacing
  - But magnetic errors have a larger relative contribution – dominating effect for DA

- Baseline scenario: DA > 6 σ for all seeds => OK for operation

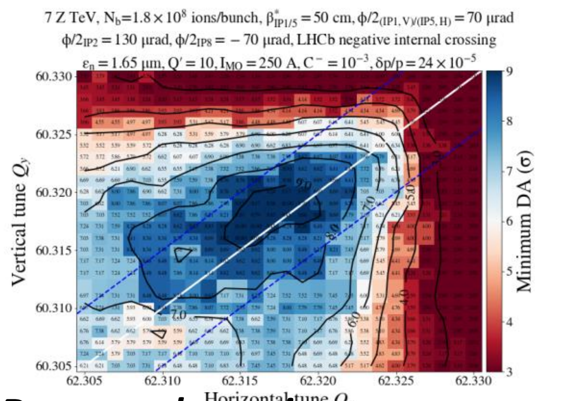
- Reduced crossing angles: OK without magnetic errors
  - With errors, worst seeds have min DA < 6 σ, but still need to include full error correction
  - Also, not clear if 6 σ criterion is well suited for ions – miss correlation between DA and beam lifetime

- To gain luminosity (see later), could potentially reduce crossing angles in future operation, but would need further studies to conclude
  - Adjust process with crossing inversion to be checked?



Baseline scenario

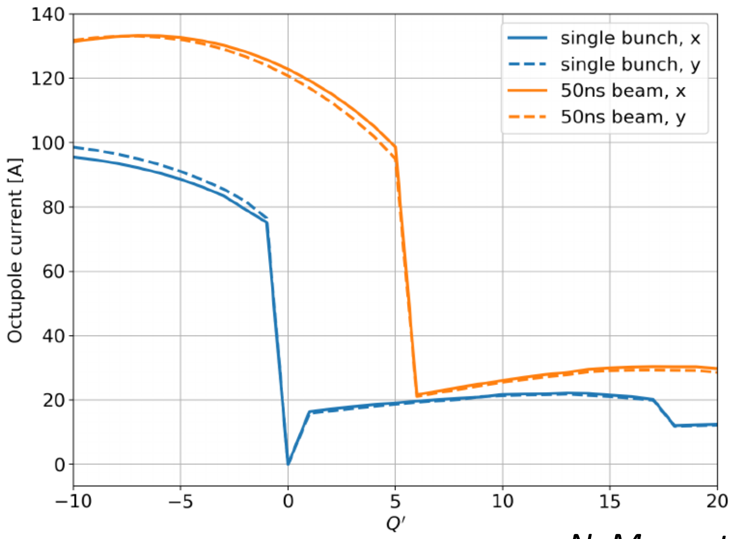
S. Kostoglou



Decreased crossing

Beam stability

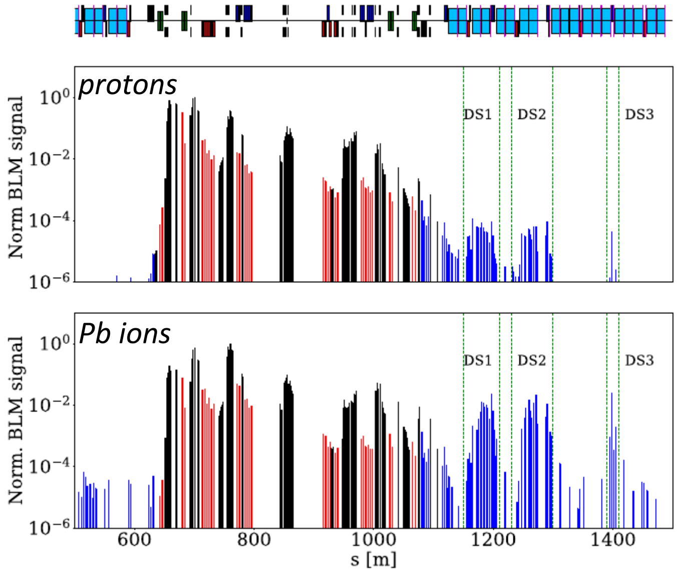
- For details, see presentation by N. Mounet in HSC meeting
- Conclusion: Pb beams can be stabilized with an octupole current of about 60A for Q'>10 (including factor 2 margin)
  - Plenty of margin w.r.t. the max current of 570 A – could give some flexibility in collimator settings if needed
  - Note: this is the worst possible scenario (LS2 upgrade, no ADT)
  - Caveat: crystal collimators still to be included in calculations, although no issues observed in 2018 MDs



N. Mounet

Collimation

- LHC collimation is ~2 orders of magnitude less efficient with Pb than with protons
  - Losses with ions risk to become limiting in Run 3 (see talk D. Mirarchi at LMC)
- Initial mitigation plan: DS collimators with 11T dipoles → postponed
- Now resorting to backup plan: crystal collimation
  - Two new crystal assemblies to be installed in 2022
  - Very good performance observed in 2018 MDs – up to factor 8 improvement with standard system in place
- If losses are really limiting, could consider staying at Run 2 energy of 6.37 Z TeV – some discussions on beam energy with experiments
  - Default option is 6.8 Z TeV unless serious issues with crystal system
  - Decision point for experiments: summer 2022



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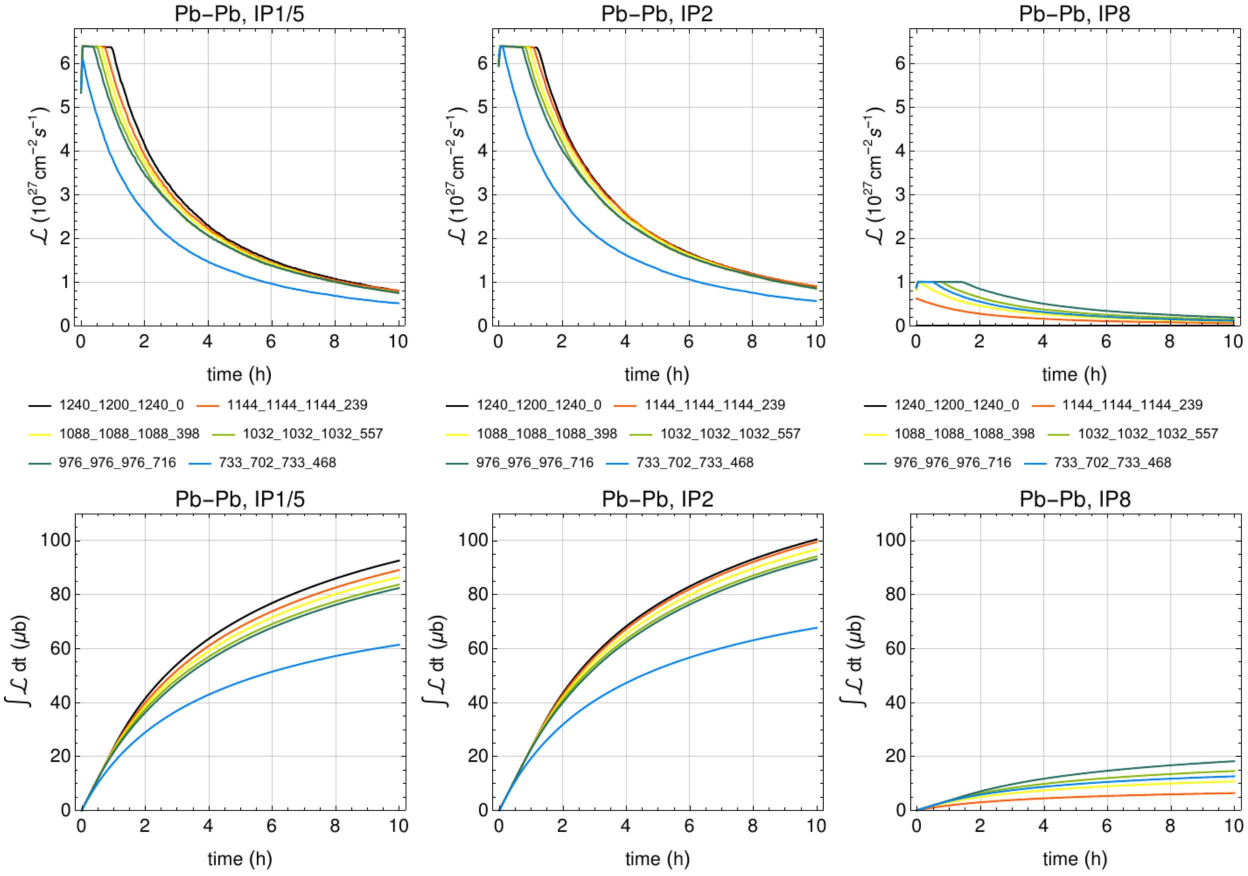
Simulations of typical Run 3 fill, **Pb-Pb**

- Simulated all considered filling schemes for Run 3-4, E=6.8 Z TeV
- Using projected LIU beam parameters – might not be achieved immediately at the start of Run 3

Simulations using **Collider Time Evolution (CTE):** particle tracking simulation using one-turn map

- Ref: 2010 PRSTAB paper, T. Mertens MSc thesis, M. Schaumann PhD thesis, 2021 EPJ Plus paper
- Successfully benchmarked with 2018 data and other code (MBS, Ref: M. Jebramcik PhD thesis, 2021 EPJ Plus paper)



Integrated luminosity in a 1-month run

- From the single fill, calculate optimum fill time, and average luminosity

- Estimate luminosity in a typical 1-month ion run as

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

- Assumptions
  - 200 min turnaround time (detailed estimate from J. Jowett, Chamonix 2017)
  - Operational efficiency η assumed to be either (see LIU specification document)
    - 62% as in LIU specification
      - Could be challenging – feasibility needs to be demonstrated for future higher beam intensities
    - 50% as for Run 3 and HL-LHC protons
  - T_{run}=24 days of physics available after initial commissioning

Projected 1-month performance, **Pb-Pb**

Integrated 1-month luminosity **in nb^{-1}**	IP1/5	IP2	IP8
1240_1200_1240_0	2.5, 3.1	2.7, 3.3	0., 0.
1144_1144_1144_239	2.4, 3.	2.6, 3.3	0.17, 0.22
1088_1088_1088_398	2.3, 2.9	2.6, 3.2	0.29, 0.36
1032_1032_1032_557	2.2, 2.8	2.5, 3.1	0.38, 0.48
976_976_976_716	2.2, 2.7	2.4, 3.	0.46, 0.57
733_702_733_468	1.7, 2.1	1.9, 2.3	0.34, 0.42

50 ns (first five rows); *75 ns backup* (last row)

50% OP eff. (first value) *62% OP eff.* (second value)

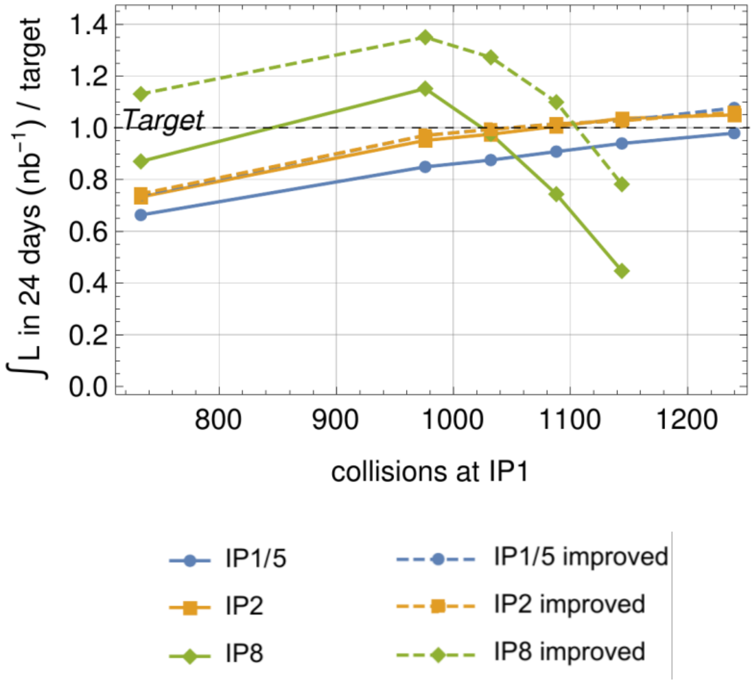
- The two last 50 ns schemes give higher luminosity than 75 ns at all experiments
  - **Always better to use 50 ns if available and with reasonable intensity**
- Lose about 1-3% at 6.8 Z TeV compared to previous numbers at 7 Z TeV
  - If stepping back to 6.37 Z TeV, would lose about 5-8%
- Assuming five Pb-Pb runs until the end of Run 4 => each month, need 2.6 nb^{-1} at IP1/2/5, 0.4 nb^{-1} at IP8
  - Experiments' requests are satisfied with 62% OP efficiency
  - We're about 10% short of requests with 50% OP efficiency

Potential performance improvements: Pb-Pb

- Recent studies (talk at WP2 meeting): Changing β*, crossing angles, levelling targets gives handle to increase luminosity
  - E.g. to reach targets if OP efficiency would be lower than 62%, or if beam parameters from the injectors are short of the LIU values

- Need further studies to verify feasibility
  - Detailed aperture measurements with beam to verify β*-reach in IR2 and IR8
  - Check optics feasibility of smaller β* in *all* IPs
    - Discussions with S. Fartoukh, R. De Maria
  - Check beam-beam for feasibility of smaller crossing angle
    - Possibly need beam studies
    - Discussions with S. Kostoglou, G. Sterbini
  - For levelling target at IP8, need to study energy deposition and quench limit
    - Discussions with FLUKA team

- Will likely not have all answers for 2022 => propose to start with baseline configuration in 2022, and explore possibilities for performance increase in later runs



Example of improved configuration: 100 urad net crossing at all IPs, β=0.45 m at IP1/2/5, β*=1m at IP8: reach target with 50% OP efficiency*

Assumptions for performance estimates: p-Pb

- For p-Pb, new filling schemes developed recently with realistic proton train structure
  - Note: previously using approximations without detailed filling schemes worked out
  - Considered both 50 ns and 25 ns proton beams
    - Possibly need further studies (instrumentation, beam-beam…) to verify impact of 50 ns ion beam and 25 ns p beam
  - For details: see talk at WP2 meeting

- Baseline assumptions, used for simulations
  - ALICE levelled at $L=5\times10^{29}$ cm^{-2} s^{-1}, following upgrade, the other experiments not levelled
  - Assuming a proton beam with 3E10 p/bunch, and 2.5 μm emittance

- Could revise some of these assumptions to gain in performance

Projected 1-month performance, p-Pb

Integrated 1-month luminosity **in nb^{-1}**

		IP1/5	IP2	IP8
50 ns p	1232 Pb_1320 p_765_762_733	474., 588.	329., 408.	149., 185.
	1232 Pb_1320 p_848_820_553	517., 641.	329., 407.	111., 137.
	1232 Pb_1320 p_901_843_432	542., 672.	327., 406.	85.4, 106.
25 ns p	1232 Pb_2520 p_1092_793_755	628., 778.	314., 389.	143., 177.
	1232 Pb_2520 p_900_926_897	529., 656.	325., 403.	173., 215.

50% OP eff. *62% OP eff.*

- Assuming two p-Pb runs until the end of Run 4, we can satisfy requests by ALICE/ATLAS/CMS, but we're about a factor 2 short of LHCb request
  - In one month, would need 600 nb^{-1} at IP1/5, 300 nb^{-1} at IP2/8
- Potential mitigation found to satisfy all experiments: Increase proton bunch intensities to 1.3×10^{11}
  - Need to verify feasibility of strong p beam vs weak Pb beam: Beam instrumentation, beam-beam …
  - See talk at WP2 meeting

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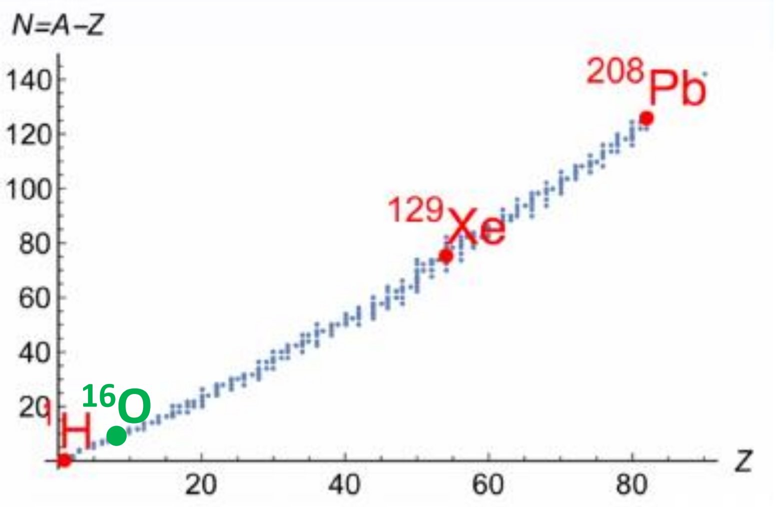
Oxygen pilot run: when, why, how

- **Proposal for pilot O-O and p-O run in Run 3 – possibly in 2024**

- Motivations:
  - Physics interest from experiments
  - Study limitations and performance, in view of proposed Run 5 high-intensity operation with lighter ions

- Target: about one week, low luminosity
  - Most efficient option is to re-use the machine cycle of the previous Pb-Pb run at the same rigidity, **using pilot beams** with single injections (staying below 3×10^{11} charges per beam)

- Studied performance for two beam energies:
  - 7 Z TeV, for highest energy → need to update for 6.8 Z TeV
  - 5.52 Z TeV, for same energy per nucleon as in main Pb-Pb runs



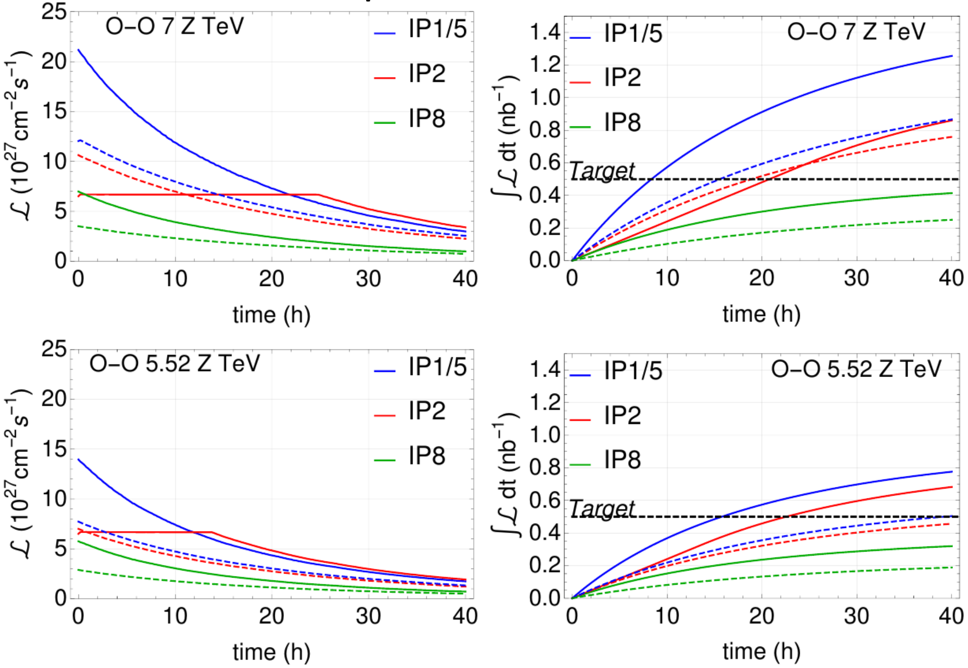
Wish list from experiments:

- O-O: ~0.5/nb for soft physics program, ~2/nb equivalent to 2010 PbPb run for hard-probes
- p-O: LHCb would like 2/nb, LHCf would like ~1.5/nb
- LHCf requests low pileup of 0.02 in p-O (update: previously 0.01)
- ALICE wants low pileup of 0.1-0.2

Performance with oxygen

- Simulations show we can reach
  - O-O targets in about a day, with 1-2 fills
  - p-O targets in about 2.5 days
- Caveat: Large uncertainties apply!
  - We have never produced these beams for LHC
  - Very sensitive to downtime and faults
- Adding time for commissioning and some contingency, could maybe fit the whole run in about 6-8 days at highest energy if re-using Pb cycle
  - At lower energy, need more commissioning time due to new cycle, and we get lower luminosity
- Oxygen run seems a priori feasible and compatible with targets, but will certainly also be challenging
- Some work still remains: optimize machine configuration, update performance estimates, study transmutation effect
- More details: See IPAC'21 paper

Simulated performance O-O



Dashed lines: 12 bunches with 2.3×10^9 O/bunch ,
Solid lines: 6 bunches with 4.6×10^9 O/bunch

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Conclusions

- Heavy-ion operation will continue in Run 3 with yearly 1-month runs
  - 2-month run foreseen in 2024 at end of Run 3
  - If LS3 is shifted, heavy-ion run schedule to be reviewed – impact on ion luminosity only if there is a change in allocated time
- Baseline machine scenario for Run 3 worked out in detail, relying on
  - New 50 ns beams using slip-stacking in SPS (backup: 75 ns)
  - New crystal collimators, dispersion suppressor collimators in IR2
  - Reaching full HL-LHC performance already in Run 3
  - Detailed schedule and scenario for p-p reference runs to be studied
- Estimated performance for typical 1-month run:
  - Pb-Pb: 2.2-2.8 nb^{-1} in ATLAS/ALICE/CMS, up to ~0.5 nb^{-1} in LHCb
    - Could envisage to increase luminosity further through β^*, crossing angle, levelling targets - need further feasibility studies
  - p-Pb: 470–630 nb^{-1} at ATLAS/CMS, ~320 nb^{-1} at ALICE, up to 170 nb^{-1} at LHCb
    - About factor 2 short of LHCb target, could be mitigated with higher p intensity – need further feasibility studies
- Propose to start in 2022 with baseline scenario and study potential improvements for later runs
- Scenario for 1-week oxygen pilot run worked out
  - Re-use existing Pb cycle, setup beam intensity
  - potential to reach experiment’s targets in 6-8 days, but large uncertainties apply

Thanks for the attention!

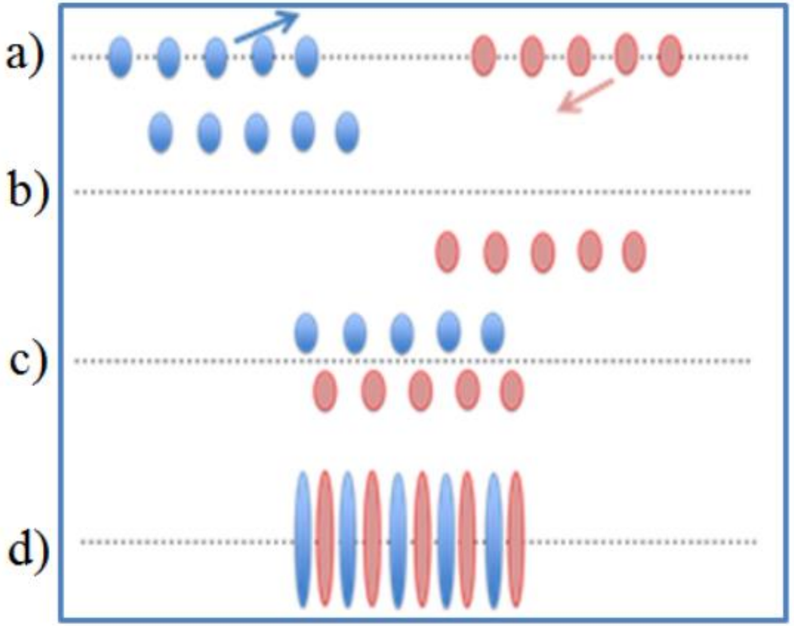
Backup

Beam production in injectors

- Significant improvement on Pb intensity already achieved over Run 1-2 following big efforts on the injector side
  - In 2018: achieved 3 times higher bunch intensity and 24% more bunches than in the LHC design report

- Only remaining intensity upgrade for HL-LHC: SPS slip-stacking
  - Interleave 100 ns bunch trains in the SPS through RF manipulations to achieve a 50 ns bunch structure
  - Result: 70% more bunches than in 2018 (had 75 ns spacing)
  - Relies on SPS RF upgrade done in LS2 – planned to be used already in Run 3, making full HL-LHC intensity available

- Very good progress with SPS commissioning in 2021
  - Slip-stacking gymnastics demonstrated, but some work still needed to achieve LIU intensity at SPS extraction
  - Good hope to have operational slip-stacking in 2022
  - More details: see talk A. Huhschauer (yesterday)



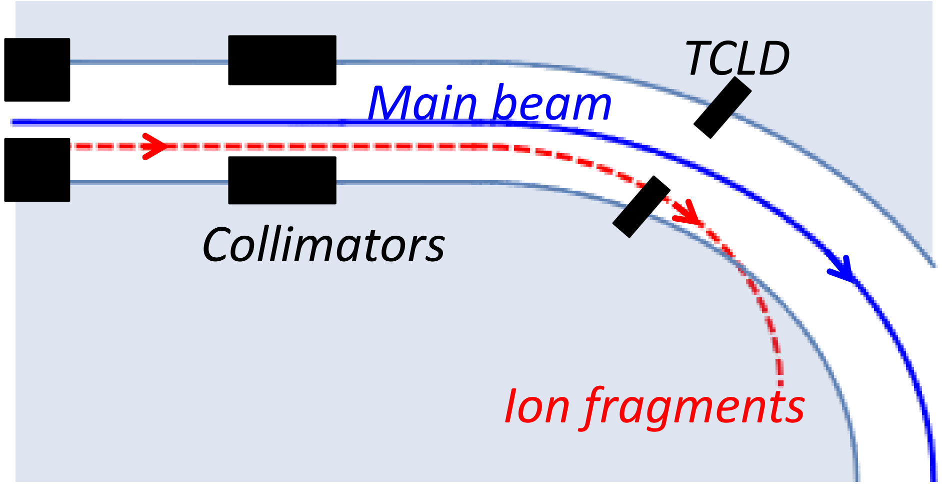
From LIU technical design report, vol. 2

Alleviation of collimation losses

- Original plan from HL-LHC project, to alleviate problems with losses due to higher Pb intensity: install new collimators (TCLDs) to safely intercept losses in cold region after first dipoles

- To make space, replace standard main dipole (8.33 T) by two shorter and stronger 11T magnets

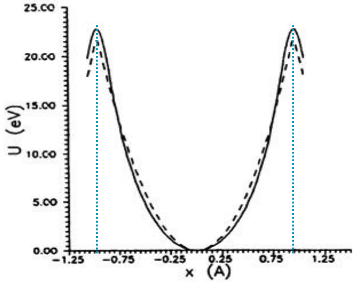
- Decision in 2020: Installation of TCLD + 11T dipoles postponed, due to performance degradation observed with 11T magnets
  - **Now we fall back to the backup plan with crystal collimation**

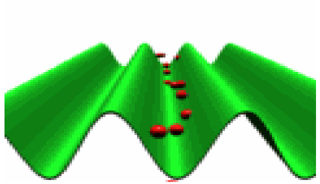


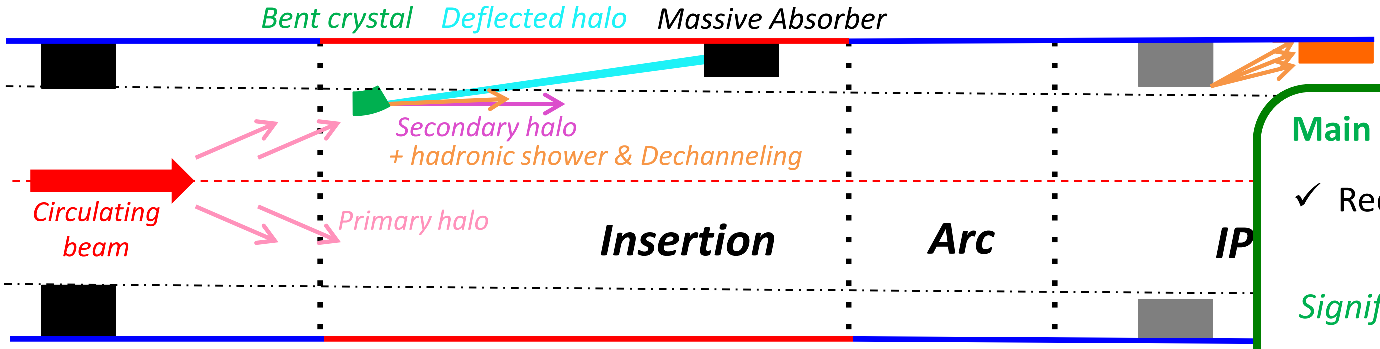
15.66 m long 11 T Dipole Full Assembly with Collimator

Principles of crystal collimation

- Charged particles can get **trapped** in the potential well generated by adjacent **crystalline planes**
- Particles are forced to oscillate in relatively empty space: **reduced interaction rate**
- **Bent crystals** can efficiently **steer halo particles**: equivalent magnetic field of **hundreds of Tesla** onto massive absorber







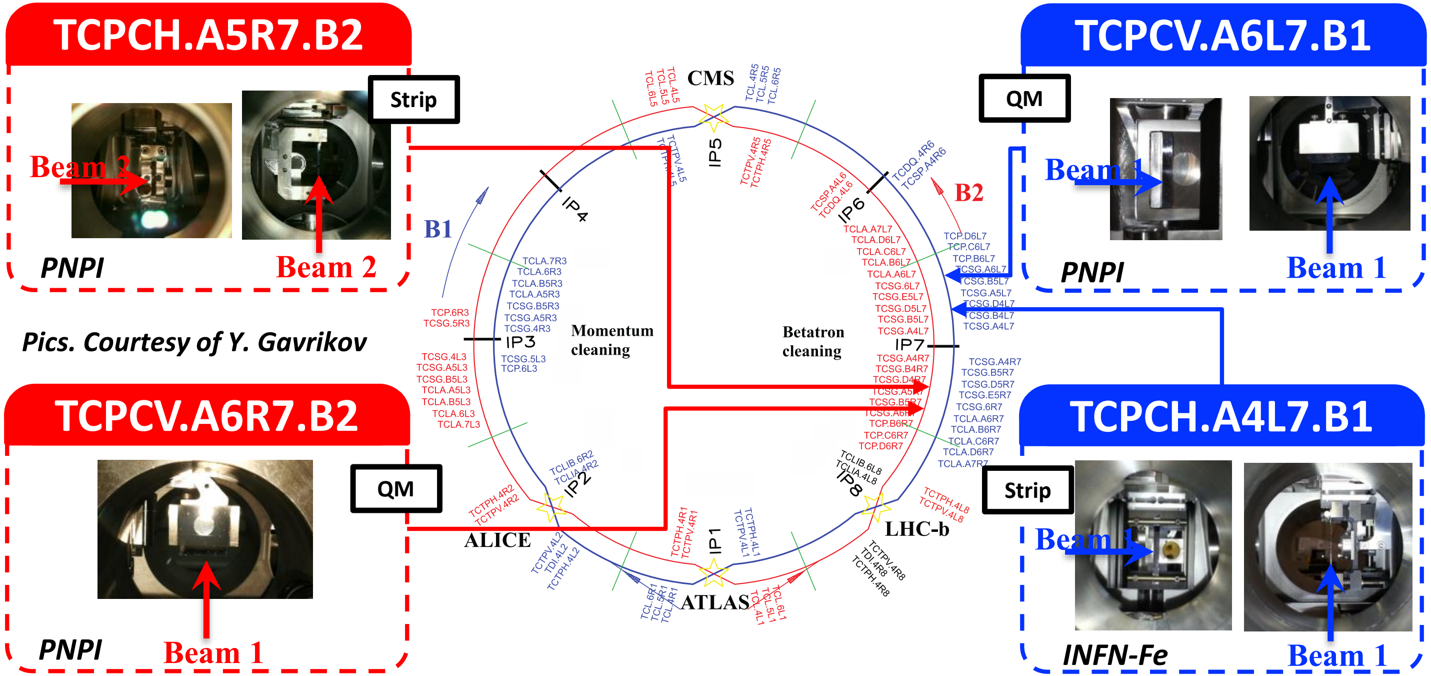
Main promise:

✓ Reduced **fragmentation of ions**

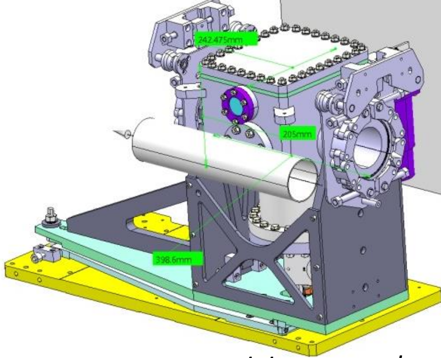
Significant cleaning improvement

LHC crystal installation

- **Four Si crystals** installed in the LHC 2015-2018: two per beam, one per plane



Piezo-goniometer with replacement beampipe for non-crystal operation

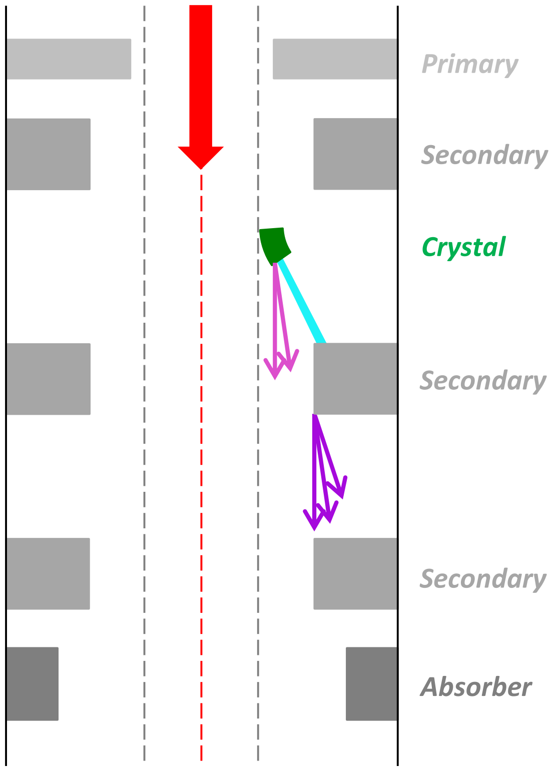


I. Lamas et al.

Assemblies with **different designs**, specific for **Machine Development activities**

Complete layout to allow thorough investigations and **operational** tests

Operational tests with crystal collimation

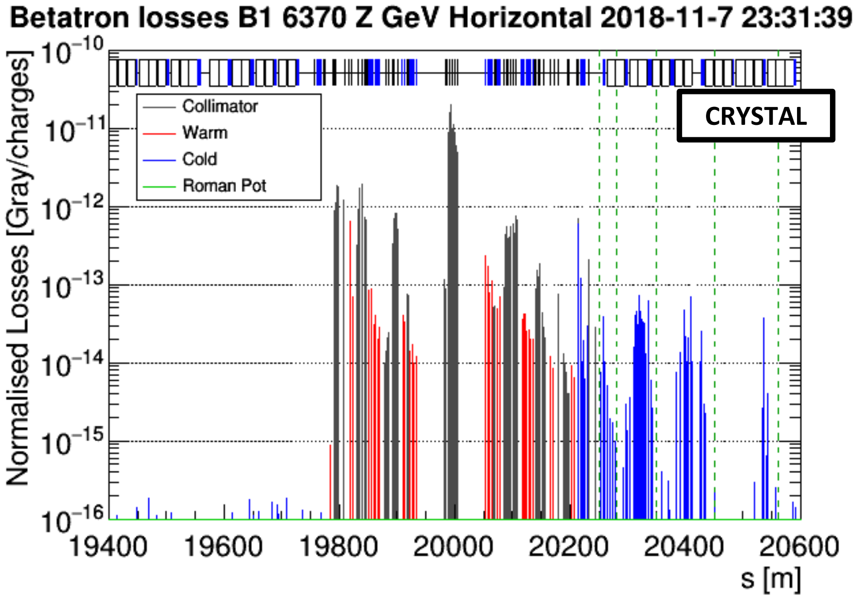


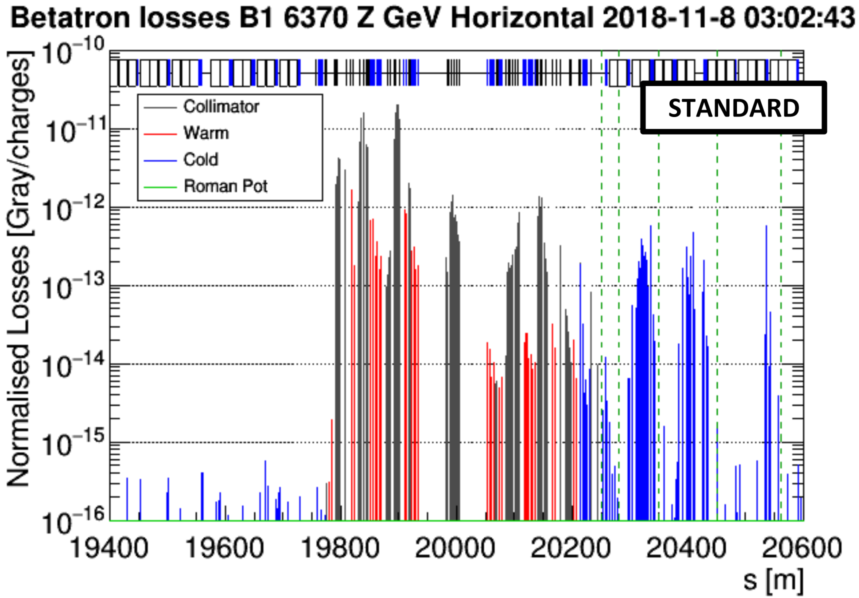
- Several LHC machine development sessions done to study crystal collimation with protons and heavy ions
- In 2018 Pb run, crystal collimators adiabatically inserted in the standard system with up to 648 bunches
  - Standard collimation system kept at nominal settings
  - Crystals set 0.25 σ tighter with respect to TCPs
  - Standard secondary collimator used as absorber for channeled halo
- These settings are a potential candidate for operational settings in the 2022 Pb run
  - In case of unexpected issues, fall back on the standard collimation system, but may need to limit intensity

Cleaning efficiency with crystals

- Beam loss pattern for Pb in IR7 studied with standard system and with crystals

M. D'Andrea





- Significant improvement observed with crystals

Achieved performance with crystals

- Global leakage ratio calculated from highest BLM reading in the whole IR7-DS with the standard versus crystal collimation system
  - Leakage ratio > 1 indicates improved cleaning efficiency with crystals
  - Improvement factor 1.5-8 observed
- Note: These are empirical figures of merit based on BLMs
  - On-going effort to verify these results in simulations

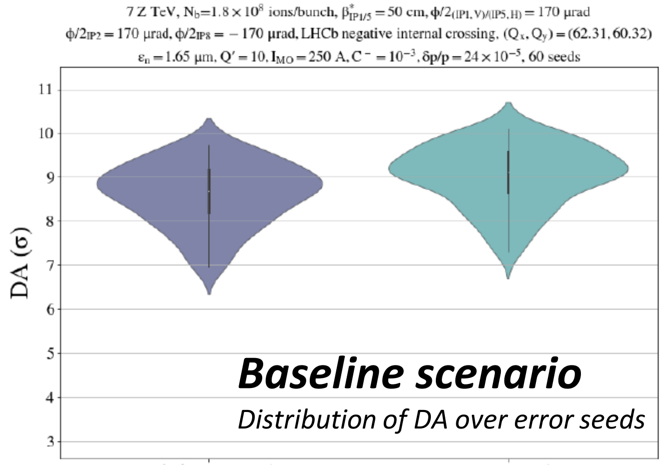
Crystal	Maximum normalized BLM signal [a.u.]		Global leakage ratio
	Standard	Crystal	
B1H	$(5.81 \pm 1.03) \cdot 10^{-13}$ Q8-9	$(7.30 \pm 0.15) \cdot 10^{-14}$ Q8-9	8.0 ± 1.4
B1V	$(1.95 \pm 0.07) \cdot 10^{-13}$ Q8-9	$(6.39 \pm 0.05) \cdot 10^{-14}$ Q12-13	3.1 ± 0.1
B2H	$(2.76 \pm 0.39) \cdot 10^{-13}$ Q12-13	$(7.89 \pm 0.78) \cdot 10^{-14}$ Q8-9	3.5 ± 0.6
B2V	$(2.25 \pm 0.01) \cdot 10^{-13}$ Q8-9	$(1.46 \pm 0.36) \cdot 10^{-13}$ Q8-9	1.5 ± 0.4

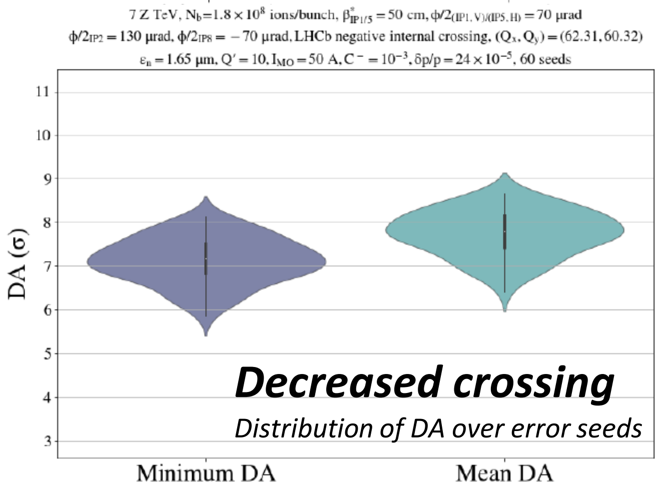
M. D'Andrea

Crystals and goniometers to be exchanged in 2021 with new design

Beam-beam studies for ions

- For details: see talk S. Kostoglou at WP2 meeting
- First studies of dynamic aperture (DA) with ion beams
  - Compared to protons, beam-beam is less critical due to smaller bunch charge and larger bunch spacing
  - But magnetic errors have a larger relative contribution – dominating effect for DA
- Large spread between different error seeds
  - Baseline scenario: DA > 6 σ for all seeds => OK for operation
  - Reduced crossing angles: worst seeds have min DA < 6 σ
    - Could potentially study intermediate angles
  - However, not clear if 6 σ criterion is well suited for ions – miss correlation between DA and beam lifetime
- Could potentially reduce crossing angles in future operation, but would need further studies, possibly with beam
  - Propose to use present baseline crossing angles in 2022, but potentially study a crossing angle reduction in future runs



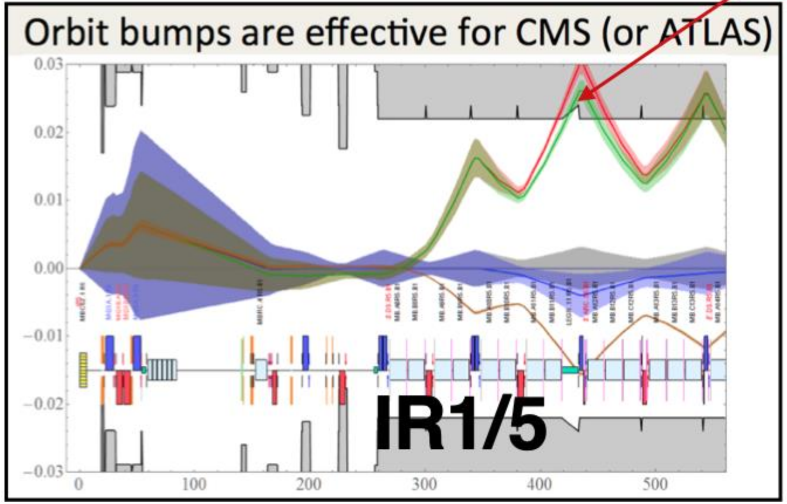


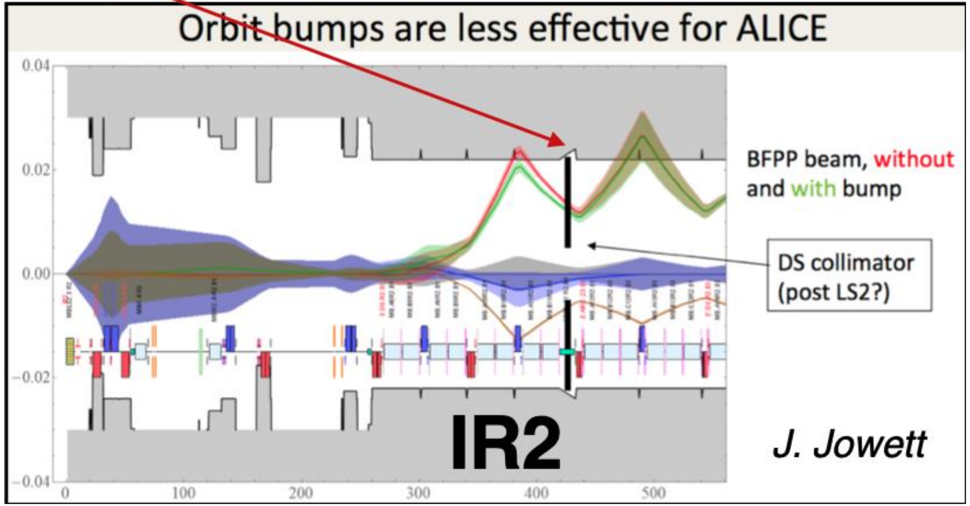
S. Kostoglou

Alleviation of collisional losses

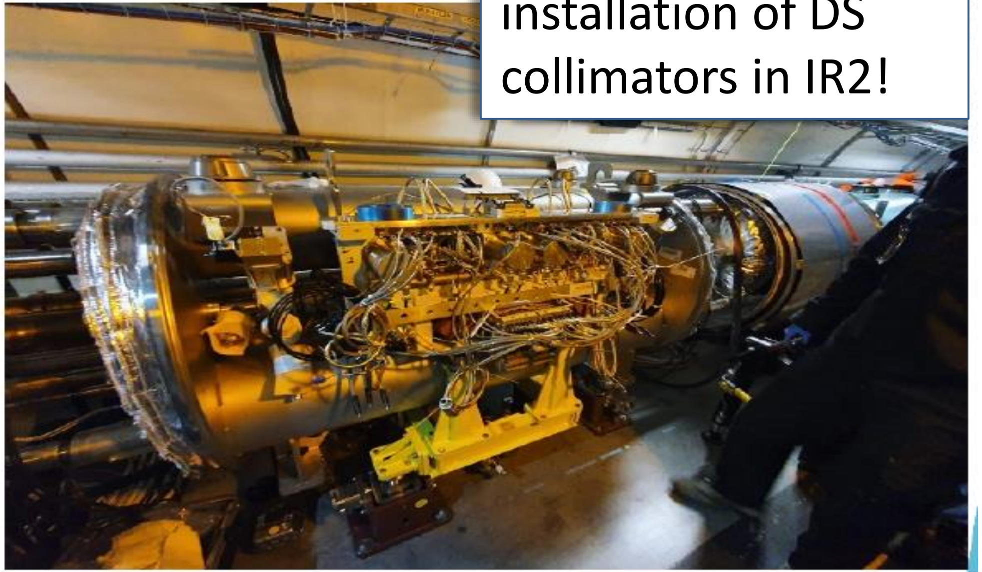
- Secondary beams created in Pb-Pb collisions with altered magnetic rigidity
  - Bound-free pair production (BFPP): electron capture => changed charge (dominant process)
  - Electromagnetic dissociation (EMD): loss of one or several nucleons => changed mass (1n and 2n dominant), and possibly charge
  - Cause localized losses in the dispersion suppressor that could quench impacted magnets => limit on luminosity
- Alleviation through orbit bumps successfully deployed in IR1/5 already in Run 2
  - Steer losses into empty connection cryostat: By now, a well-established operational procedure
- In IR2, bumps alone do not work => Run 2 luminosity was limited
  - Alleviation: Need new TCLD collimator in combination with orbit bump
  - New IR2 TCLDs successfully installed in 2020 for Run 3
- In IR8: No TCLDs, bumps alone do not work: still need to limit IP8 luminosity in Run 3

Connection cryostat ("missing dipole")



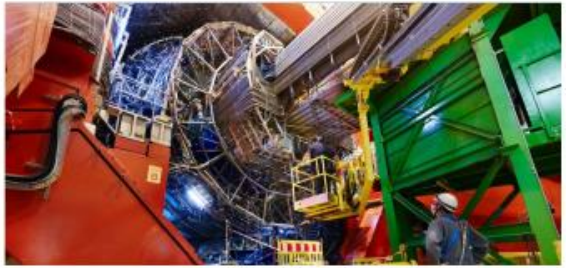


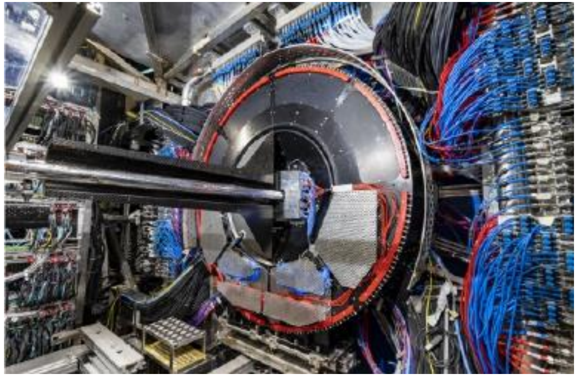
Installation of TCLDs in IR2

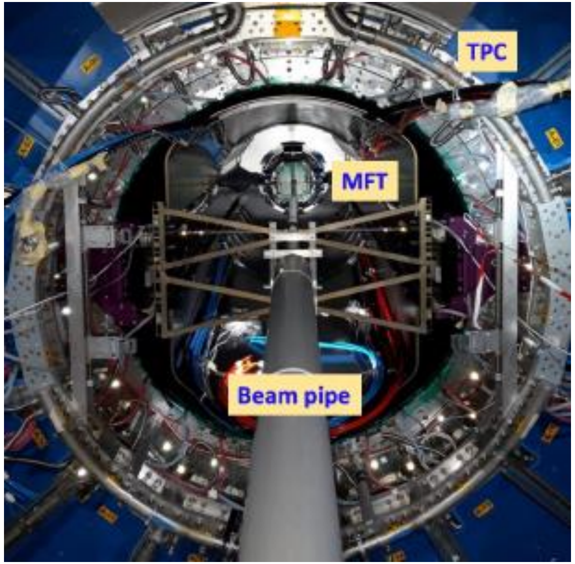


Successful LS2 installation of DS collimators in IR2!

ALICE upgrade





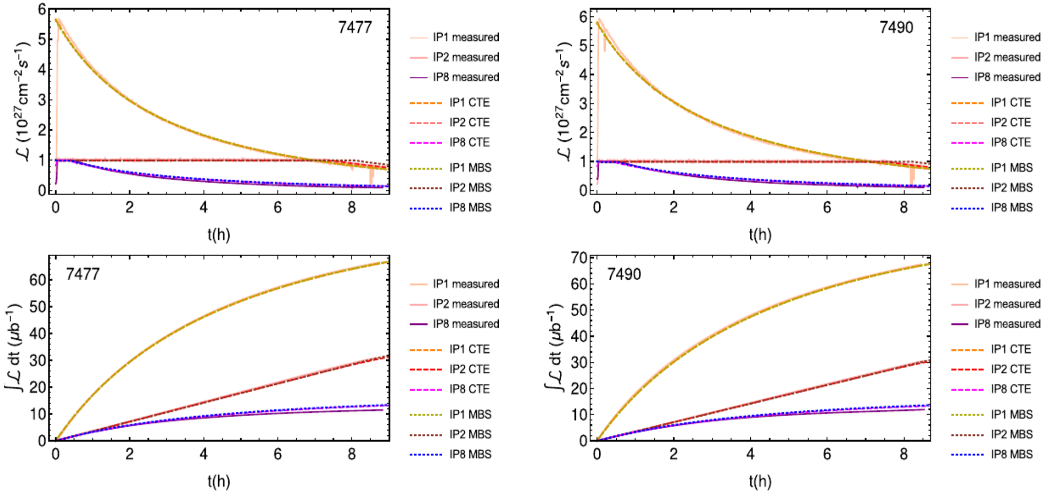


- LS2 upgrade of ALICE detector => Can now handle ~6.4 higher peak luminosity than in Run 2
- Both pileup limit and BFPP limit from Run 2 are overcome => Increase ALICE levelling target in Run 3 to 6.4×10^{27} cm^{-1} s^{-2}

Images from LHCC talk by T. Gunji

Simulation codes and benchmark

- Now estimate luminosity in typical fill in baseline scenario
- To reduce uncertainty and increase confidence, using two different codes based on different principles to simulate luminosity performance
- Collider Time Evolution (CTE): particle tracking simulation using one-turn map
  - Ref: 2010 PRSTAB paper, T. Mertens MSc thesis, M. Schaumann PhD thesis, 2021 EPJ Plus paper
- Multi-bunch simulation (MBS): Numeric solution of ODEs for all bunches in filling scheme
  - Ref: M. Jebramcik PhD thesis, 2021 EPJ Plus paper
- Extensive benchmark with 2018 Pb-Pb data
  - Excellent agreement found – for given starting conditions, integrated luminosity in single fills typically reproduced within a few percent
  - Including 100h non-collisional lifetime, from fit of non-colliding bunches



Eur. Phys. J. Plus **136,** 745 (2021): link

Example fills: 7477 and 7490
Pb-Pb, 6.37 Z TeV

733 bunches, 75 ns

Integrated luminosity in a 1-month run

- From the single fill, calculate optimum fill time, and average luminosity, assuming all fills are kept to optimal length

$$\mathcal{L}_{\mathrm{avg}}(T_{\mathrm{f}}) = \frac{\int_0^{T_{\mathrm{f}}} \mathcal{L}(t)\mathrm{d}t}{T_{\mathrm{f}} + T_{\mathrm{ta}}}$$

- Estimating luminosity in a typical 1-month ion run as

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

- Assumptions
  - 200 min turnaround time (detailed estimate from J. Jowett, Chamonix 2017)
  - η=50% operational efficiency
  - T_{run}=24 days of physics available after initial commissioning

Burnoff cross sections

	6.37 Z TeV Pb-Pb	7 Z TeV Pb-Pb	7 Z TeV p-Pb
Hadronic inelastic (b)	7.7	7.8	2.13
BFPP (b)	278	281	0.044
EMD (b)	223	226	0.035
Total(b)	509	515	2.21

- Pb-Pb intensity decay dominated by very large burnoff cross sections

- Hadronic inelastic (with the main processes to be studied by the experiments) is only 1.5% of the total cross section
  - Electromagnetic interactions dominate
  - Interesting physics program also for those

Projected 1-month performance, **Pb-Pb**

	Filling scheme	$\mathcal{L}_{tot}$ IP1/5	$\mathcal{L}_{tot}$ IP2	$\mathcal{L}_{tot}$ IP8
50 ns	1240b_1240_1200_0	2.5 [2.6]	2.7 [2.8]	0 [0]
50 ns	1240b_1144_1144_239	2.4 [2.4]	2.6 [2.7]	0.17 [0.21]
50 ns	1240b_1088_1088_398	2.3 [2.3]	2.6 [2.6]	0.29 [0.33]
50 ns	1240b_1032_1032_557	2.2 [2.2]	2.5 [2.5]	0.38 [0.43]
50 ns	1240b_976_976_716	2.2 [2.1]	2.4 [2.5]	0.45 [0.49]
75 ns backup	733b_733_702_468	1.7 [1.8]	1.9 [1.9]	0.34 [0.36]

From CTE *From MBS in []*

Integrated 1-month luminosity **in nb^{-1}**

- The two last 50 ns schemes give higher luminosity than 75 ns at all experiments
  - **Always better to use 50 ns if available and with reasonable intensity**
- Lose about 1-3% at 6.8 Z TeV compared to previous numbers at 7 Z TeV
- If stepping back to 6.37 Z TeV, would lose about 5-8%
- Assuming five Pb-Pb runs until the end of Run 4, would be about 10% short of requests from experiments
  - Note: 50 % operational efficiency might be conservative

Projected 1-month performance, p-Pb

	Filling scheme	$\mathcal{L}_{tot}$ IP1/5	$\mathcal{L}_{tot}$ IP2	$\mathcal{L}_{tot}$ IP8
50 ns p	1232Pb_1320p_765_762_733	473 [-]	329 [-]	149 [-]
	1232Pb_1320p_848_820_553	516 [-]	328 [-]	110 [-]
	1232Pb_1320p_901_843_432	542 [-]	327 [-]	85 [-]
25 ns p	1232Pb_2520p_1092_793_755	628 [-]	313 [-]	143 [-]
	1232Pb_2520p_900_926_897	528 [-]	325 [-]	173 [-]

From CTE (↑ $\mathcal{L}_{tot}$ IP1/5)

- Assuming two p-Pb runs until the end of Run 4, we can satisfy requests by ALICE/ATLAS/CMS, but we're about a factor 2 short of LHCb request
  - Note: 50 % operational efficiency might be conservative

Potential performance improvements: p-Pb

- Recent studies (talk at WP2 meeting): For p-Pb, improvements of machine configuration are possibly not enough to gain factor >2 at LHCb
  - A very pushed machine configuration with β*=0.4 m at IP1/2/5 and β*=0.5 m at IP8, combined with smaller crossing angles, gives luminosity very close to targets – might not be feasible in operation
  - Increasing proton bunch intensities to 1.3E11 gives needed improvement

- Need further studies to verify feasibility (as for Pb-Pb)
  - Specifically for p-Pb: Feasibility of strong p beam vs weak Pb beam
    - Beam instrumentation
    - Beam-beam
  - Feasibility of 25 ns p beam vs 50 ns Pb beam
    - Not strictly necessary: with nominal p intensity, can reach targets also with 50 ns
  - Leveling targets and filling schemes still to be further optimized