Future of heavy-ion collisions at the LHC

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With inputs from

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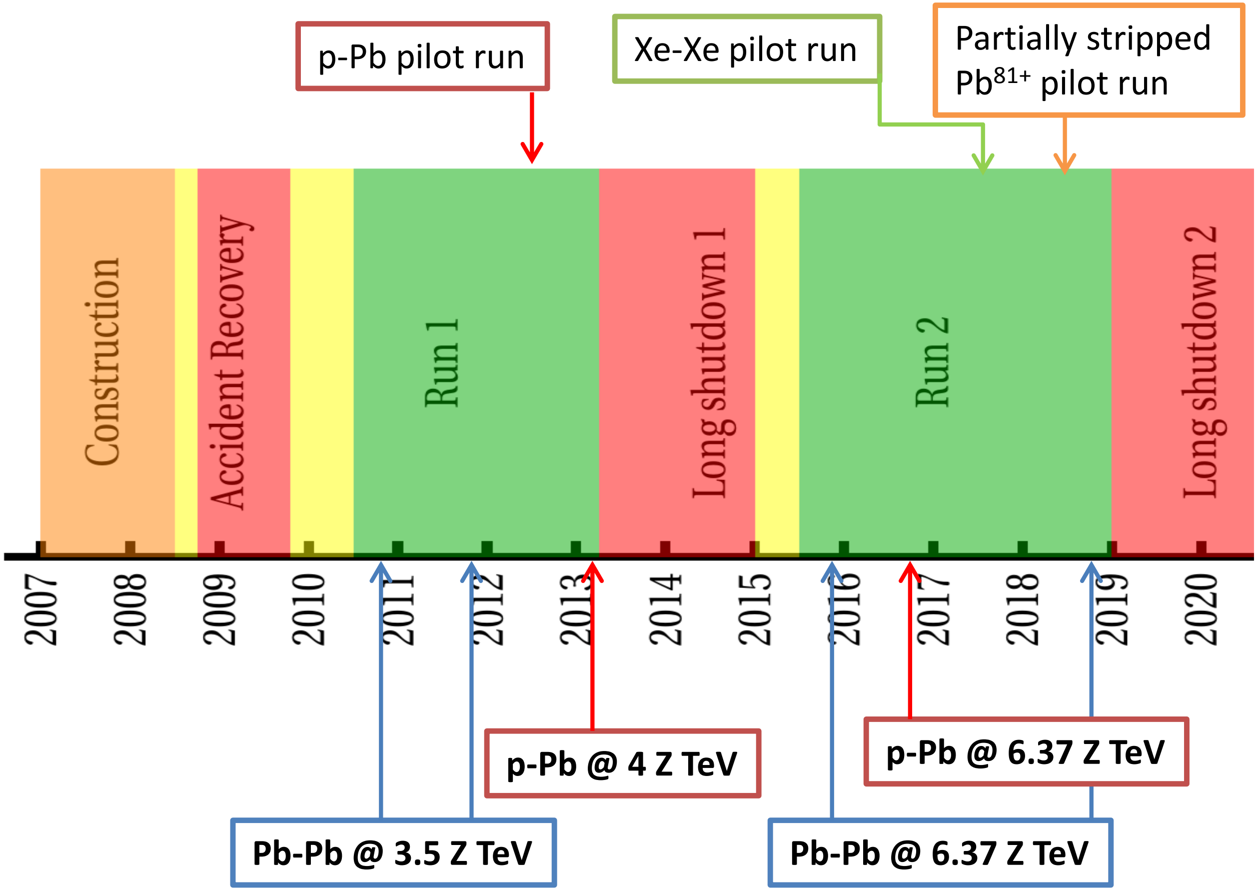
Outline

- Overview of LHC heavy-ion runs
- New future machine scenario for Run 3 and HL-LHC
  - Pb-Pb and p-Pb
- Alleviation of losses
  - Collisional beam losses
  - Collimation beam losses
- Future light-ion operation
  - Oxygen pilot run
  - High-luminosity operation with lighter species
- Summary

History of heavy-ion runs in the LHC

- Most years LHC operated 1 month per year with heavy-ion collisions
  - So far used Pb-Pb or p-Pb in regular operation
  - In total, 6 runs so far
- Did in addition very short “pilot runs” with Xe-Xe and p-Pb collisions
  - partially stripped Pb^{81+} (no collisions)



Overview of future heavy-ion operation

- Run 3 proton operation to start in early 2022
- Scheduled to continue heavy-ion operation for about one month per year in Run 3 and Run 4
  - HL-LHC to start in Run 4
  - Possibly 2-month run in 2024, before LS3
  - In the following, focus on performance in a typical one-month run, due to uncertainties in schedule
- Pilot run with oxygen beams foreseen for Run 3
- For Run 5-6: No officially approved heavy-ion program yet, but proposals for operation with lighter species under consideration

Tentative schedule, ***could well change***

★ *Guess on future heavy-ion runs – detailed schedule still to be defined*

Requests from experiments

- WG5 in the 2018 HL-LHC / HE-LHC physics workshop dealt with heavy-ion physics
- Yellow report released with proposal for extended heavy-ion running: CERN-LPCC-2018-07

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

In Run 3 + Run 4

Proposal for after Run 4

- Previous operational scenario (J. Jowett 2017) does not foresee significant luminosity at LHCb → needed to review the operational scenario to see if new request can be incorporated

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New filling schemes

- Future operation relies on Pb beams with 50 ns bunch spacing
  - Can fit more bunches in the LHC than in previous 75 ns scheme
  - New production scheme in the SPS, relying on LS2 upgrades

- HL-LHC heavy-ion running scenario presented by J. Jowett in Chamonix 2017
  - Luminosity optimized for ALICE, ATLAS, CMS
  - 50 ns filling schemes : 1232b_1232_1168_0 and 1232b_1136_1120_81

    bunches *IP1/5* *IP2* *IP8*

    ATLAS/CMS *ALICE* *LHCb*
  - 50 ns schemes do not naturally provide collisions at LHCb, and LHCb didn't have a clear request at the time
  - 75 ns naturally provides collisions at LHCb, but with significantly fewer collisions at the other experiments

- First goal for new operational scenario: find new 50 ns schemes with more collisions at LHCb, keeping a high number of collisions at ALICE,ATLAS,CMS
  - Updated abort gap keeper: can now fit 1240 bunches

New filling schemes

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

- Different options considered with different number of LHCb collisions, with varying penalty for the other experiments
- **50 ns schemes found:**
  - **With more collisions at all IPs than in previous scheme** 1232b_1136_1120_81
  - **With many more collisions at all IPs than with 75 ns**
- Final scheme to be selected by LHCC/LPC, variations during a run possible

Run 3 machine scenario

- Foreseen Pb beam parameters in collision

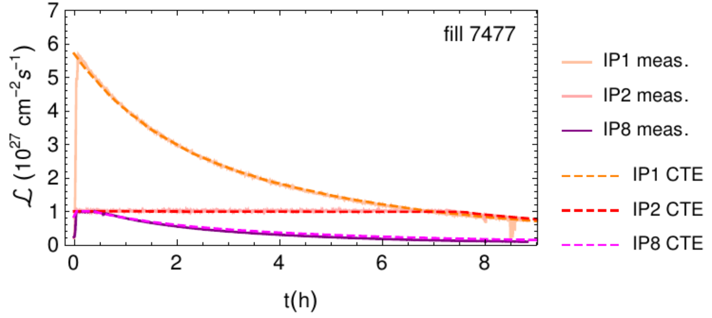
	LHC design	2018	HL-LHC and Run 3
Beam energy (Z TeV)	7	6.37	7
Total no. of bunches	592	733	1240
Bunch spacing (ns)	100	75	50
Bunch intensity (10^7 Pb ions)	7	21	18
Stored beam energy (MJ)	3.8	12.9	20.5
Total beam current (mA)	6.12	22.7	33.0
Normalized transverse emittance (μm)	1.5	2.3	1.65
Longitudinal emittance (eVs/charge)	2.5	2.33	2.42
RMS energy spread (10^{-4})	1.1	1.06	1.02
RMS bunch length (cm)	7.94	8.24	8.24

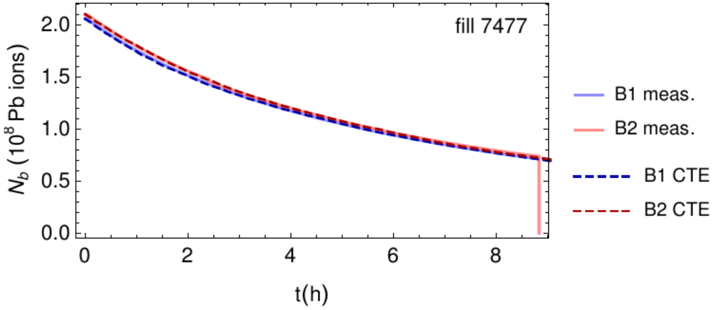
	IP1	IP2	IP5	IP8
β^* (m)	0.5	0.5	0.5	1.5
crossing plane	V	V	H	H
spectrometer half crossing (μrad)	0	$\mp$70	0	-135
external half crossing (μrad)	170	$\pm$170	170	-170
net half crossing (μrad)	170	$\pm$100	170	-305
spectrometer polarity	-	pos/neg	-	pos

- Pb optics cycle will be different from the HL-LHC p-p optics
- Optics for Run 3/HL-LHC similar to the 2018 Pb-Pb run
- In Pb-Pb, 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

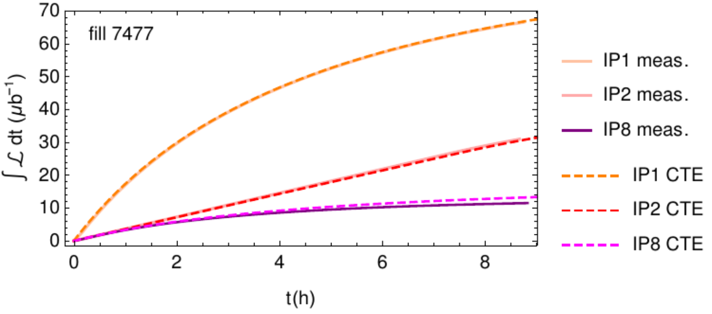
Simulation models of luminosity performance

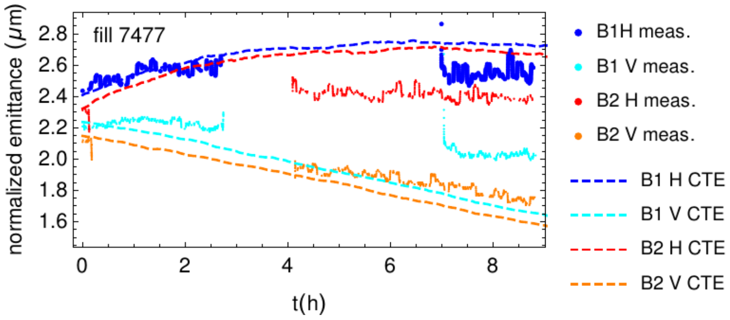
- Updated and improved existing simulation tools for beam evolution (account of filling scheme, non-collisional losses, IBS coupling, emittance blowup….)
- Used two different simulation codes (Collider Time Evolution – CTE, MultiBunch Simulation – MBS)
- Performed extensive benchmark on 2018 data – found excellent agreement in the simulation of single fills with given starting conditions taken from beam data





CTE simulation vs measurements of fill 7477, Pb-Pb @6.37 Z TeV, 2018

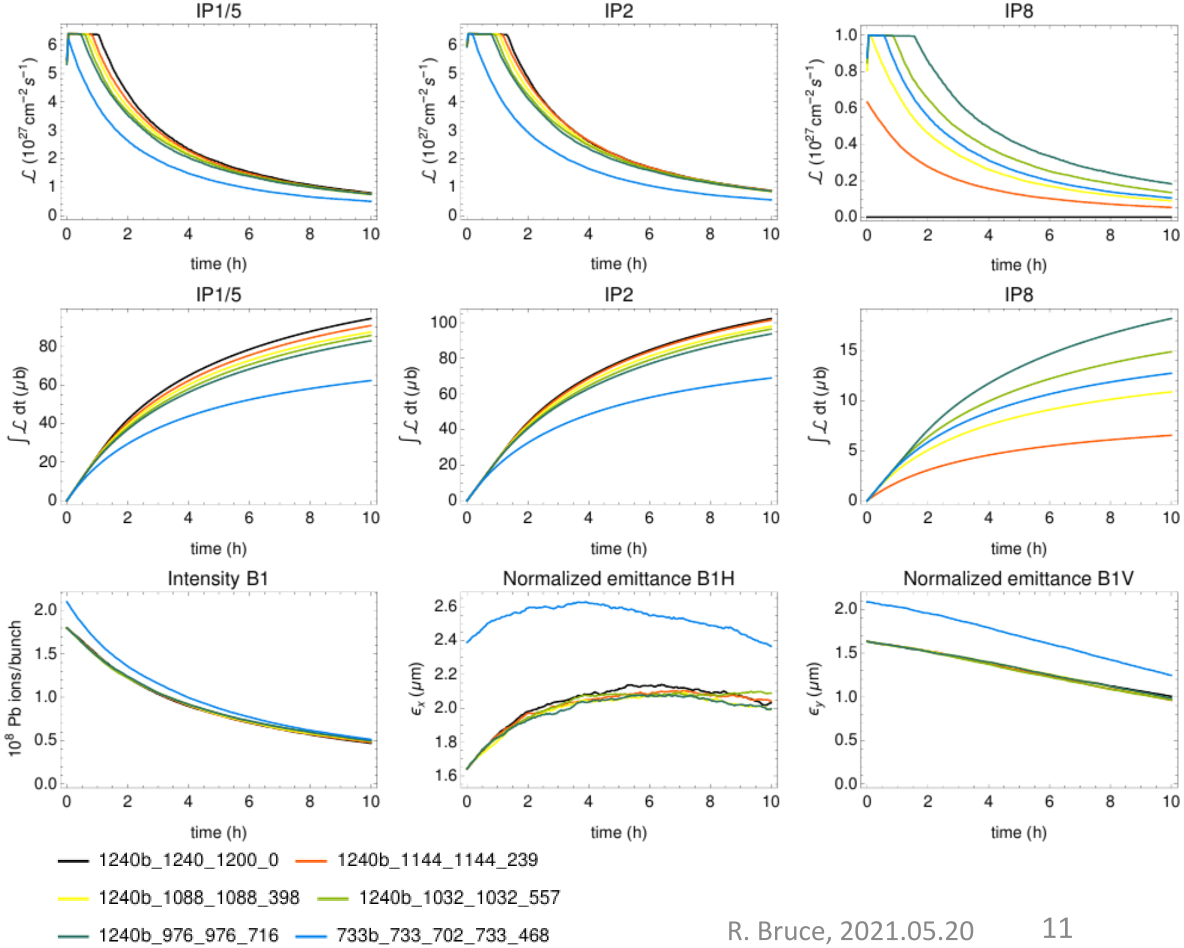




Simulation of a typical future Pb-Pb fill

- Simulated the beam evolution during a typical fill in Run 3 and HL-LHC for all considered filling schemes

- The simulated evolution, together with the assumed turnaround time of 200 min, allows determining the optimal fill length and the time-averaged luminosity <*L*>



Predicted **Pb-Pb** data in 1-month run

- From <*L*> calculate the integrated luminosity in a 1-month run
- Assuming 24 days of physics operation, 50% operational efficiency

Filling scheme	$\mathcal{L}_{tot}$ IP1/5	$\mathcal{L}_{tot}$ IP2	$\mathcal{L}_{tot}$ IP8 (nb^{-1})
1240b_1240_1200_0	2.5 [2.5]	2.7 [2.8]	0 [0]
1240b_1144_1144_239	2.4 [2.4]	2.7 [2.7]	0.18 [0.21]
1240b_1088_1088_398	2.4 [2.3]	2.6 [2.7]	0.30 [0.34]
1240b_1032_1032_557	2.3 [2.2]	2.5 [2.6]	0.39 [0.44]
1240b_976_976_716	2.2 [2.1]	2.5 [2.5]	0.46 [0.50]
733b_733_702_468	1.7 [1.7]	1.9 [1.9]	0.35 [0.36]

CTE [MBS]

- Depending on filling scheme, could expect 2.5-2.7/nb at ALICE in a typical 1-month run when 50 ns LIU beams become available, slightly less at ATLAS/CMS
  - With 75 ns scheme used in 2018, expect 25-30% loss in performance
  - Some 50 ns schemes give higher luminosity than 75 ns everywhere - always better to use 50 ns if available
  - Up to about 0.5/nb at LHCb in the most aggressive filling scheme (giving less to the other experiments)
  - Would need about 5 runs to reach targets (13/nb, 2/nb) although no filling scheme does it simultaneously at all IPs
  - Uncertainties apply on operational efficiency, beam conditions etc

Predicted p-Pb data in a 1-month run

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

Filling scheme	$\mathcal{L}_{tot}$ IP1/5	$\mathcal{L}_{tot}$ IP2	$\mathcal{L}_{tot}$ IP8
1240b_1240_1200_0	677 [705]	306 [313]	0 [0]
1240b_1144_1144_239	634 [647]	309 [316]	45 [52]
1240b_1088_1088_398	605 [613]	308 [317]	73 [85]
1240b_1032_1032_557	583 [580]	311 [319]	103 [119]
1240b_976_976_716	558 [547]	312 [320]	135 [152]
733b_733_702_468	415 [431]	287 [294]	86 [88]

- Proton filling schemes (50 ns) not yet studied in detail – using for now the Pb filling scheme, but applying a 5% penalty on the calculated luminosity
- With 50 ns, get some ~300/nb at ALICE, ~550-700/nb at ATLAS/CMS – could reach targets in 2 runs
  - up to ~150/nb at LHCb – still a factor 2 short of target in 2 runs
- Lose 20-40% at IP1/2/5 with 75 ns backup scheme

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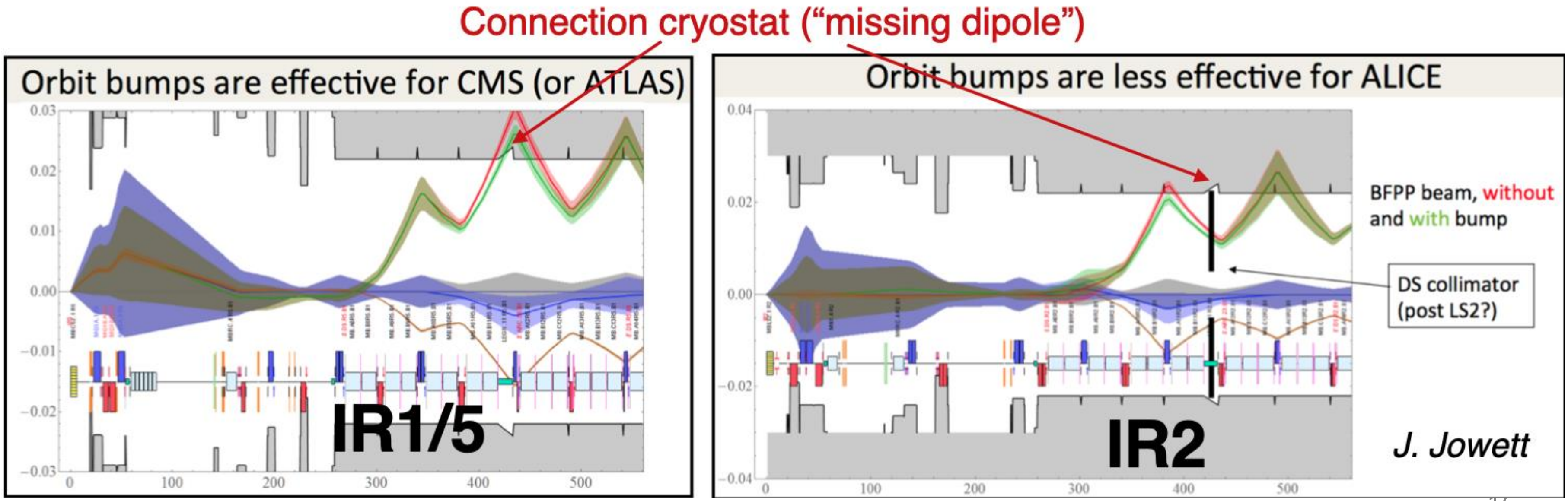
Mitigation of beam losses

- The higher luminosity and beam intensity in future heavy-ion runs are challenging for the machine
- Potential risk of magnet quenches from beam losses
  - Collisional losses, proportional to luminosity
  - Losses on collimators, proportional to beam intensity (and 1/lifetime)
- Program put in place to alleviate these losses

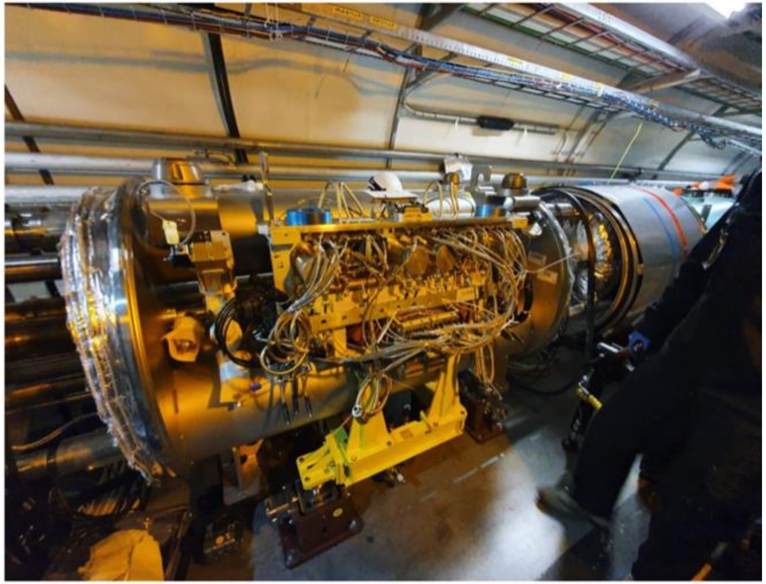
Alleviation of collisional losses

- Reminder: ultra-peripheral electromagnetic interactions create secondary beams with changed charge-to-mass ratio, e.g. Pb^{81+} from bound-free pair production
- Orbit bumps successfully deployed in IR1/5 already in run 2 to steer losses into empty connection cryostat
  - By now, a well-established operational procedure
- In IR2, bumps alone do not work
  - Need new TCLD collimator in combination with orbit bump



TCLD collimators installed in IR2

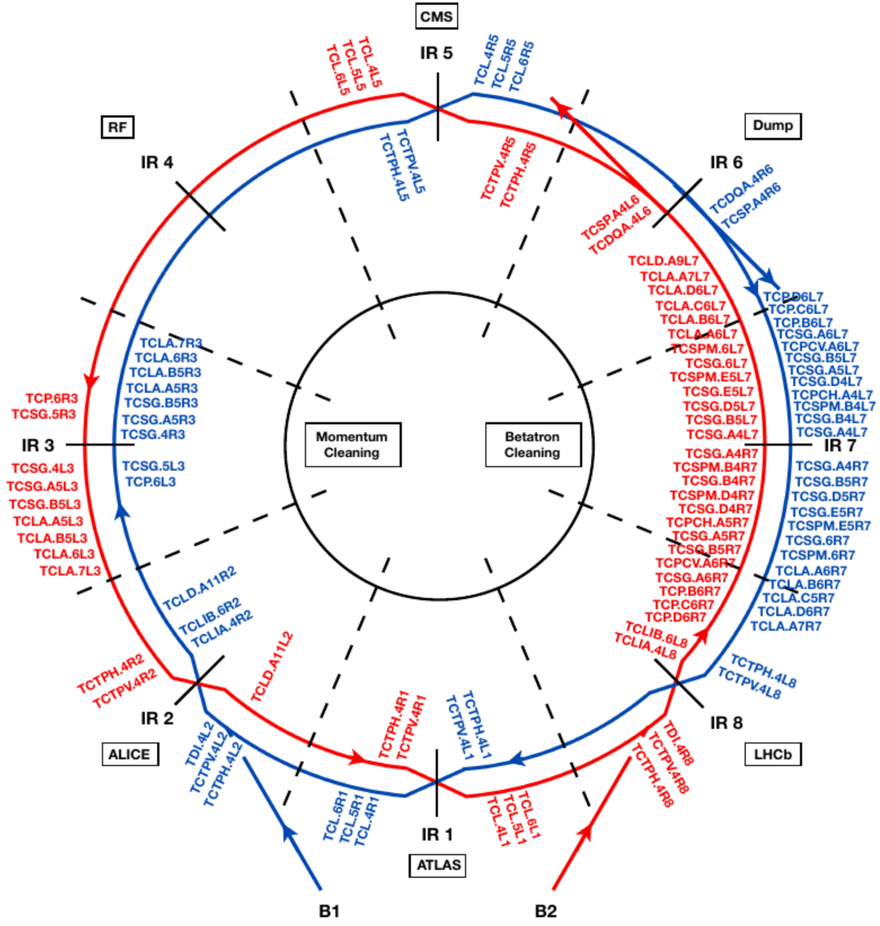
- In 2020, one TCLD successfully installed per side of IR2



- Foreseen alleviation measures have been deployed – **green light for high-luminosity operation at ALICE!**

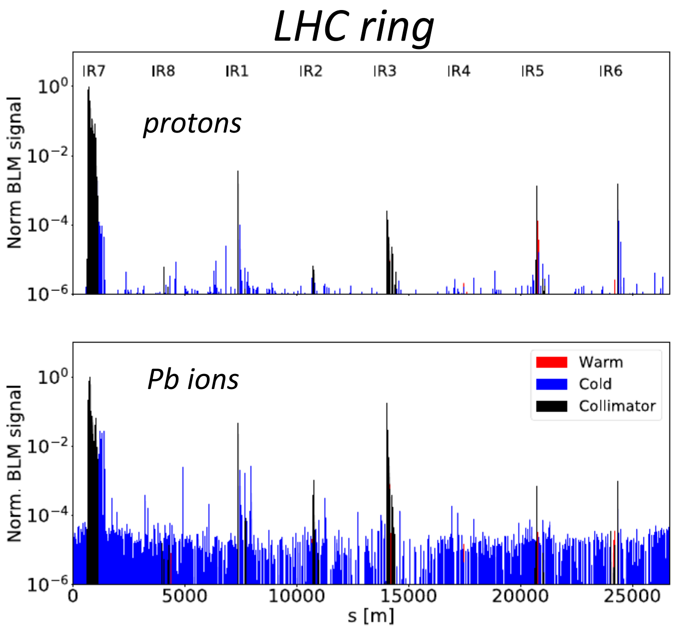
Collimation losses

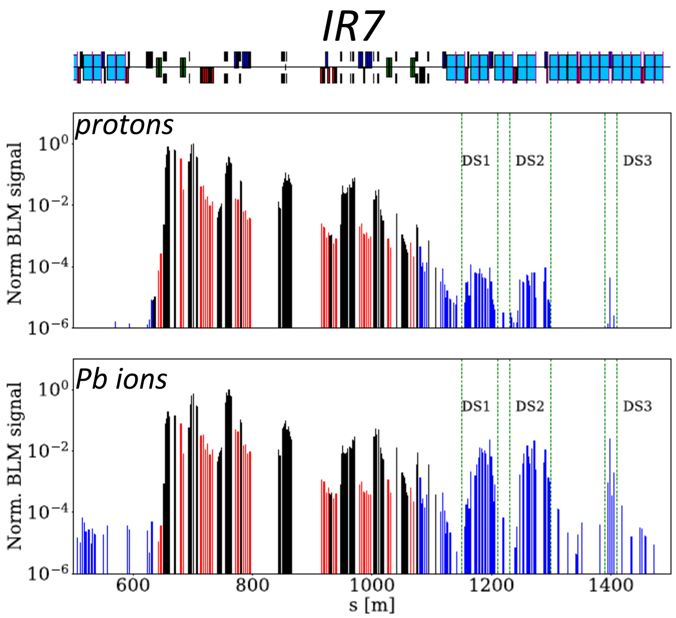
- Any regular or irregular losses should be first intercepted by the collimation system, protecting the machine from damage and quenches
  - Around 100 collimators installed, most in IR7 (betatron cleaning) and IR3 (momentum cleaning)
- Pb stored beam energy will increase from 12.9 MJ (2018) to 20.5 MJ (Run 3)
  - A loss of a given (small) fraction of the beam causes a higher absolute loss and leakage to the superconducting magnets



LHC collimation with heavy ions

- The same collimation system is used for proton and Pb operation
  - LHC collimation is ~2 orders of magnitude less efficient with Pb than with protons
  - Risk for limitations in Pb runs in spite of much lower stored beam energy – demonstrated by quench test with beam and scaling of observed losses in 2018





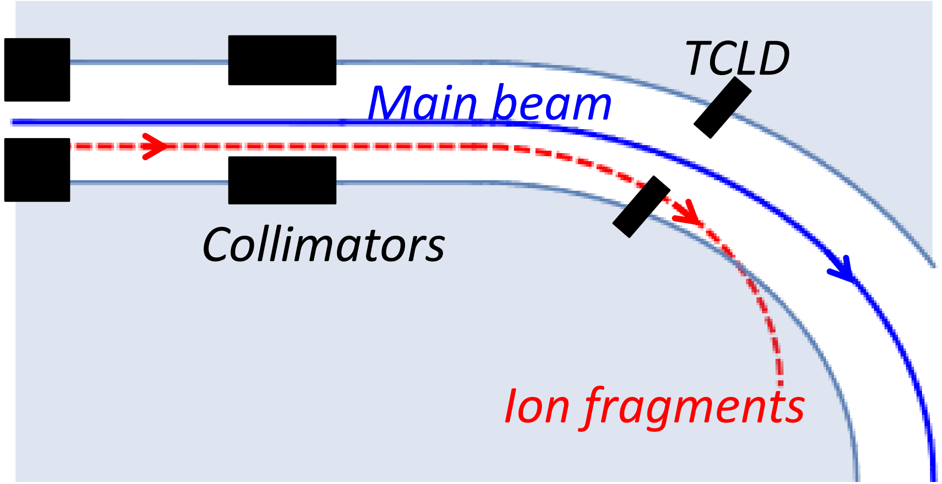
N. Fuster Martinez, P. Hermes

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
  - Limiting losses caused by ion fragments with wrong charge-to-mass ratio scattering out of primary collimator

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

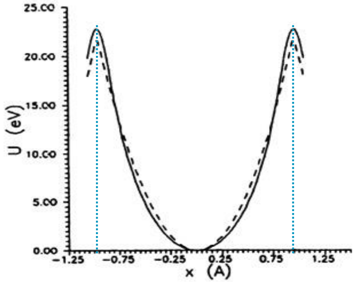
- Decision in 2020: Installation of TCLD + 11T dipoles postponed, due to performance degradation observed with 11T magnets
  - **Now we fall back to the backup plan with crystal collimation**

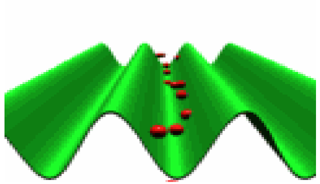


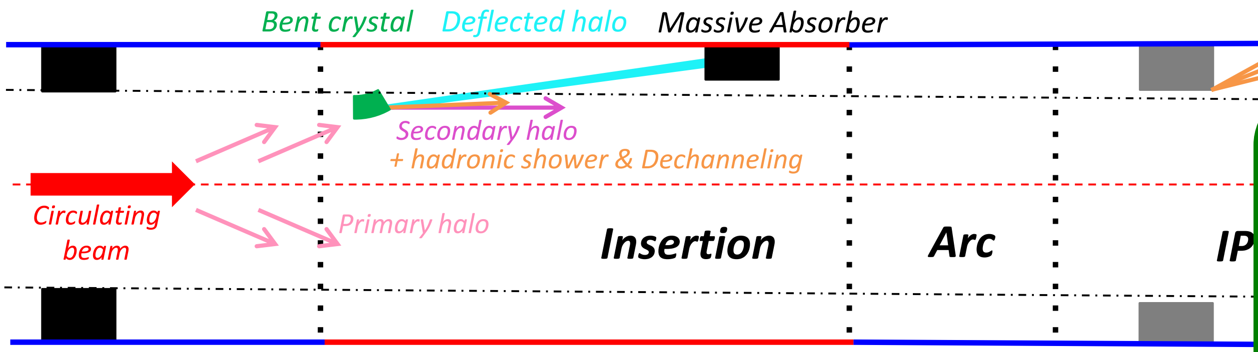
15.66 m long 11 T Dipole Full Assembly with Collimator

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

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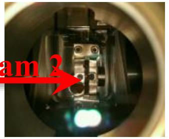

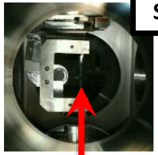

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Pics. Courtesy of Y. Gavrikov

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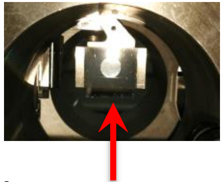

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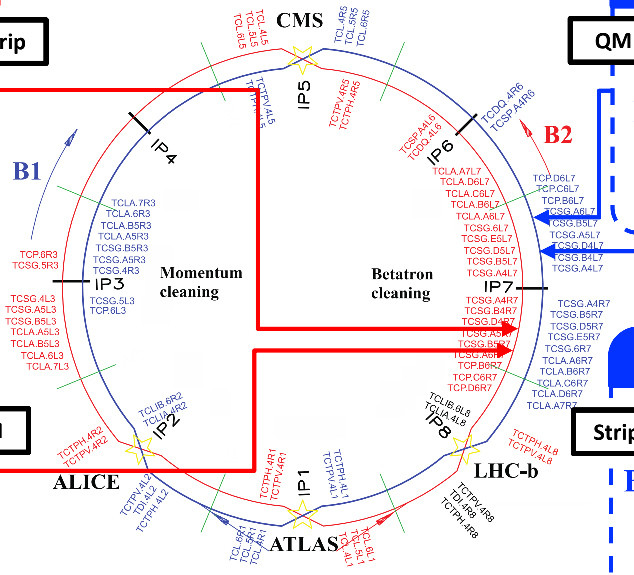

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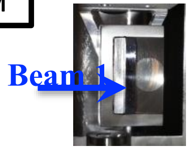

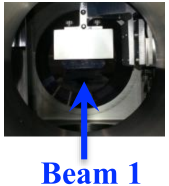

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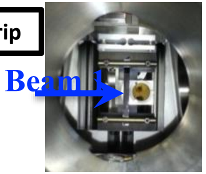
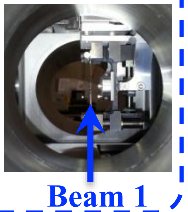
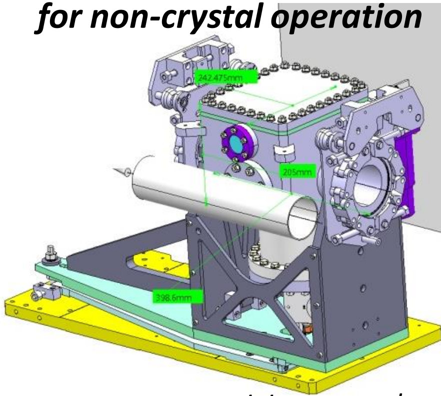




INFN-Fe

Piezo-goniometer with replacement beampipe for non-crystal operation



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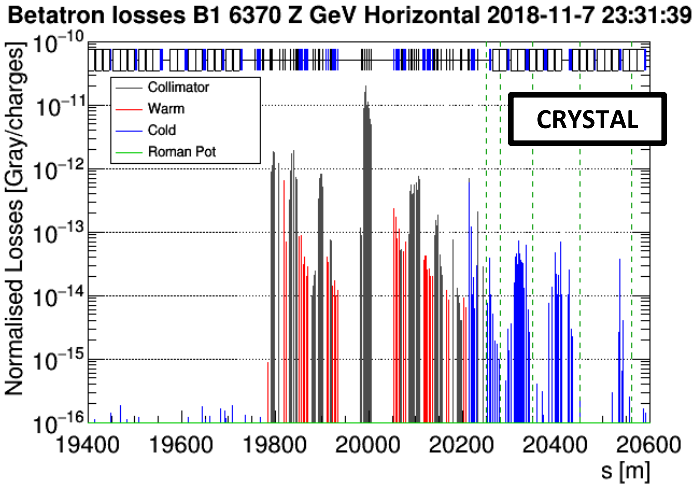
Assemblies with **different designs**, specific for **Machine Development activities**

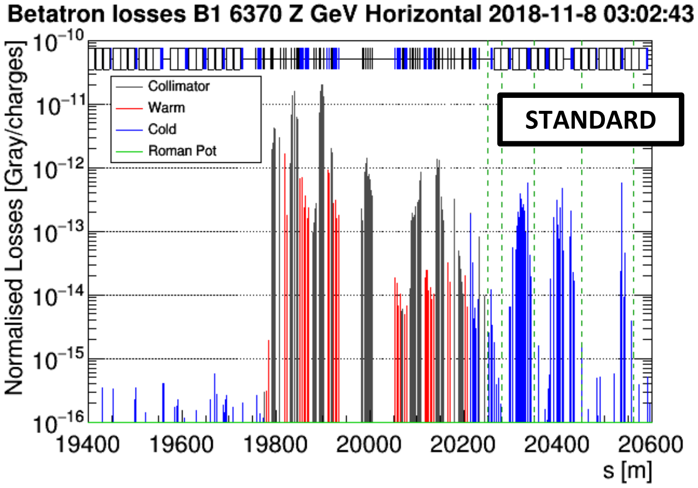
Complete layout to allow thorough investigations and **operational** tests

Cleaning efficiency with crystals

- Several beam tests performed in Run 2 with up to 648 bunches
  - Beam loss pattern for Pb in IR7 studied with standard system and with crystals

M. D'Andrea





- Significant improvement observed with crystals: factor 1.5 – 8 depending on beam and plane
- Plan to exchange the worst performing assemblies in 2021 with a new design, and the remaining two in a later year-end technical stop

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Oxygen pilot run

- **Request for a pilot-like O-O and p-O run in Run 3**
  - A few days, low luminosity
  - Discussed in a recent workshop

- Motivations
  - O-O intermediate system (as Xe-Xe since QM2018)
  - p-O requested by cosmic ray community for several years
  - Not necessarily a prelude to Run 5 light-ion physics interest
  - A pilot run would be very useful to understand limitations and performance in the injectors and LHC, in view of Run 5 high-intensity operation

- Preliminary **luminosity targets:** (from B. Petersen at LMC)
  - 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

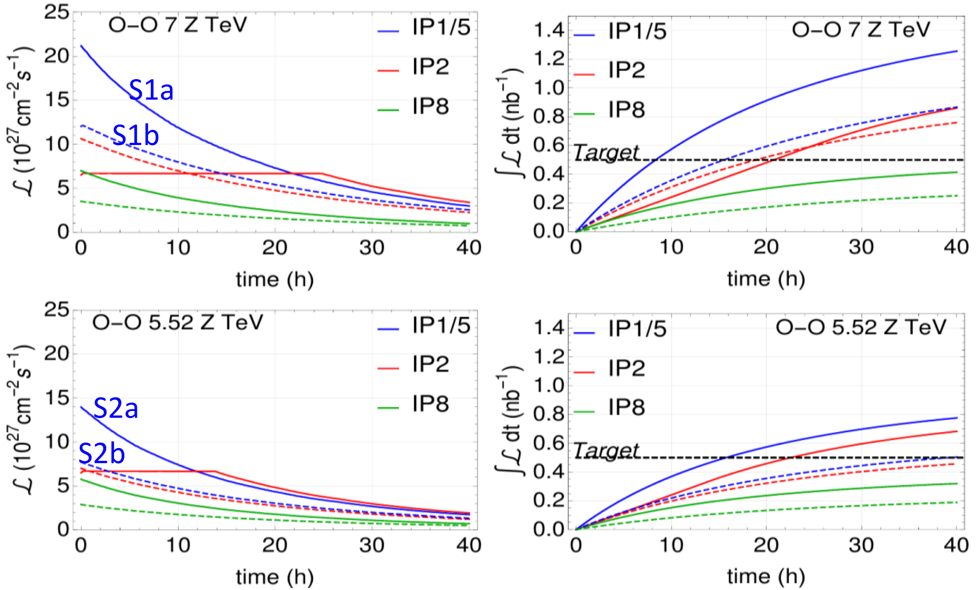
Machine scenarios for an O run

- Reuse machine settings from previous Pb-Pb run to minimize commissioning
- Given the short time, use "EARLY" ion beam with single injections
  - keep total intensity below $3x10^{11}$ charges per beam => allows "light" machine validation and fast commissioning
    - "NOMINAL" beam with train injections for higher intensity and requires longer validation
- Beams from the injectors:
  - For O-O, might get up to $5x10^9$ O/bunch, but possibly need to split in two bunches with $2.5x10^9$ O/bunch of due to space charge limitations in the SPS – limits to be quantified experimentally
  - For p-O, necessary to make many low-intensity bunches to cope with requested pileup
- Four scenarios considered (two beam energies, two bunch intensities for O-O)

Scenario	S1a	S1b	S2a	S2b
Beam energy (Z TeV)	7	7	5.52	5.52
β^* (cm), IP1;2;5;8	50;50;50;150	50;50;50;150	65;65;65;150	65;65;65;150
Net half crossing angle (μrad), IP1;2;5;8	170;100;170;305	170;100;170;305	170;100;170;305	170;100;170;305
Normalized O emittance (μm)	2.1	2.1	2.1	2.1
O beam energy per nucleon (TeV)	3.5	3.5	2.76	2.76
Number of bunches, O-O	6	12	6	12
Ions per bunch, O-O	4.6×10^9	2.3×10^9	4.6×10^9	2.3×10^9
Number of bunches, p-O	36	36	36	36
O ions per bunch, p-O	8.7×10^8	8.7×10^8	8.7×10^8	8.7×10^8
Protons per bunch, p-O	7×10^9	7×10^9	7×10^9	7×10^9

Simulated O-O performance

- Can reach 0.5 nb^{-1} in about a day of operation in most scenarios, with 1-2 fills
- Best performance at 7 Z TeV (S1a and S1b)
  - S1b is fastest overall: no levelling for pileup required at IP2 (bottleneck in S1a)
  - Slower data accumulation at IP1/5 with 12 bunches (S1b) than with 6 bunches (S1a)
  - Up to 9h more needed for S2b (slowest)



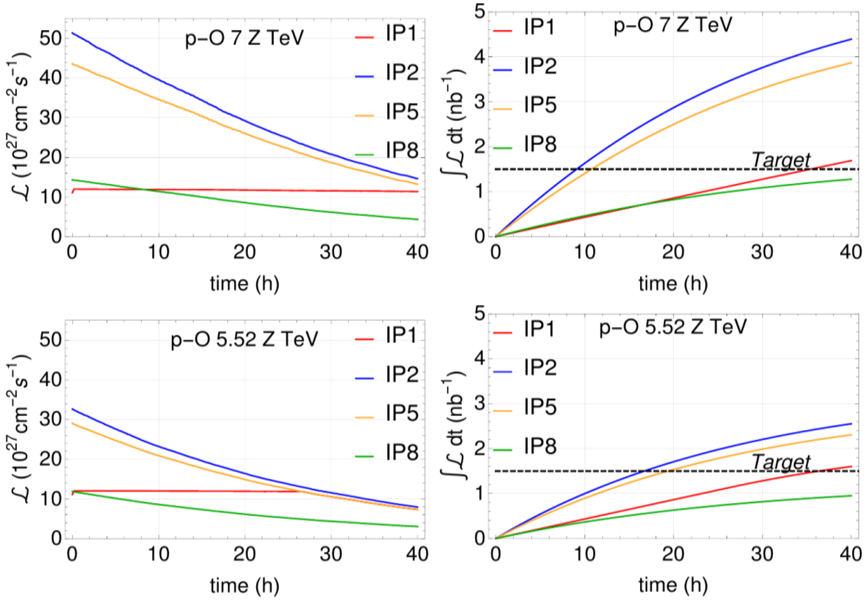
Dashed lines: 12 bunches, solid lines: 6 bunches

Number of fills and total time needed in each O-O scenario to reach 0.5 nb^{-1}, assuming a 4 h turnaround time.

Scenario	Limiting IP	Time per fill	Fills	Σ time
S1a	IP2	21 h	1	25 h
S1b	IP1/5	19 h	1	23 h
S2a	IP2	23 h	1	27 h
S2b	IP1/5	12 h	2	32 h

Simulated p-O performance

- About 36 h in collision needed to reach the IP1 target of 1.5 nb^{-1} at 7 Z TeV (S1a and S1b) due to levelling with low pileup
  - could be done in a single fill
- 3 fills with about 15-16 h each in collision needed to reach the 2 nb^{-1} target at IP8
- With turnaround time => total running time of about 2.5 days without contingency
- At 5.52 Z TeV (S2a and S2b), one additional fill with about 15~h in collision is needed to reach the IP8 target



In total, would need about 6-8 days at 7 Z TeV, for commissioning, O-O and p-O

Large uncertainties: beam parameters from injectors, faults or downtime in the LHC

High-intensity light-ion operation

- High-intensity operation with light species has been proposed for Run 5-6 by WG5
  - Motivation: higher integrated luminosity
  - First estimates of beam parameters and luminosity in WG5 report
- Now working with injector colleagues on refining the projected performance of the injector complex
  - We will probably get lower bunch intensities than initially hoped
- Updated LHC estimates underway, including the latest LHC models – will likely show a significantly lower luminosity than the previous estimates

Outline

- Overview of LHC heavy-ion runs
- New machine scenario for Run 3 and HL-LHC
  - Pb-Pb and p-Pb
- Alleviation of losses
  - Collisional beam losses
  - Collimation beam losses
- Future light-ion operation
  - Oxygen pilot run
  - High-luminosity operation with lighter species
- Summary

Summary

- **Updated future operational scenario** for Pb-Pb and p-Pb in the LHC (for Run 3 and Run 4)
  - Range of new improved filling schemes with more collisions at LHCb, only minor penalty for the others
  - New performance estimates using two updated, benchmarked and independent codes
  - For a 1-month Pb-Pb run, estimate around 2.2-2.8 nb^{-1} in ATLAS/ALICE/CMS, up to ~0.5 nb^{-1} in LHCb
    - Would need ~5 runs to reach targets (13 nb-1 at IP1/2/5 and 2 nb-1 at IP8)
  - For a 1-month p-Pb run, estimate 530–690 nb^{-1} at ATLAS and CMS, and about 310 nb^{-1} at ALICE, up to 150 nb^{-1} at LHCb
    - Potentially two runs sufficient to reach IP1/2/5 target (1200 nb-1 at IP1/5 and 600 nb-1 at IP2/8), but factor ~2 missing at LHCb
  - Uncertainties apply: operational efficiency, beam parameters…
  - Future work: study various performance enhancements

- Strategies to mitigate potentially limiting beam losses: orbit bumps, dispersion suppressor collimators (postponed), crystal collimators

- Studied various **options for a short LHC run, of about 1 week, with O-O and p-O collisions**
  - Motivated both by physics interest and for studying the machine performance in view of future light-ion operation
  - Simulations show: requested integrated luminosity could be collected in a few days**,** with 6-8 days for the total run, but large uncertainties apply (beam conditions, downtime …)

- Updated scenarios for light-ion operation for Run 5 under study

Thanks for the attention!