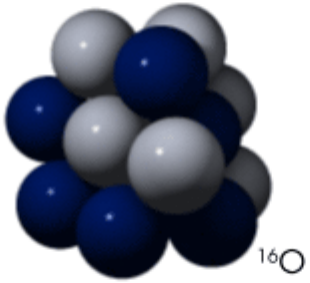
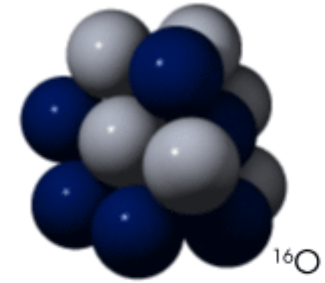


LHC machine scenario for a short oxygen run



R. Bruce, R. Alemany Fernandez, H. Bartosik, M. Jebramcik, J.M. Jowett, M. Schaumann

Outline

- Introduction
- Requests and constraints
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- Luminosity simulations and performance estimates
  - O-O
  - p-O
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- Conclusions

Introduction

- **Two previous pilot runs of LHC with *new colliding species* :**
  - p-Pb in 2012 – discoveries
  - Xe-Xe in 2017 – results at Quark Matter 2018
  - **very successful** both operationally *and* in terms of physics output

Reminder: 2017 Xe-Xe run

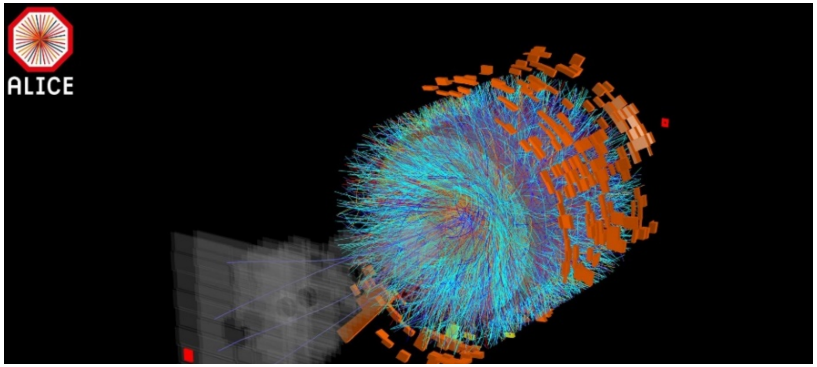

Table 1: Beam parameters at start of Stable Beams, fill 6295. Sets of three values correspond to the interaction points of ATLAS/CMS, ALICE, LHCb. Luminosity values are calculated from beam parameters.

Parameter	Fill 6295
Beam energy [Z TeV]	6.5
No. of bunches colliding	(8, 16, 8)
β^* [m]	(0.3, 10, 3)
Bunch intensity [10^8 ions]	2.87 ± 0.14
Normalized emittance (H, V) [μm]	(~1.5 / ~1.0)
Bunch length [cm]	9.1 ± 0.2
Luminosity [10^{27} cm^{-2}s^{-1}]	(0.28, 0.03, 0.04)

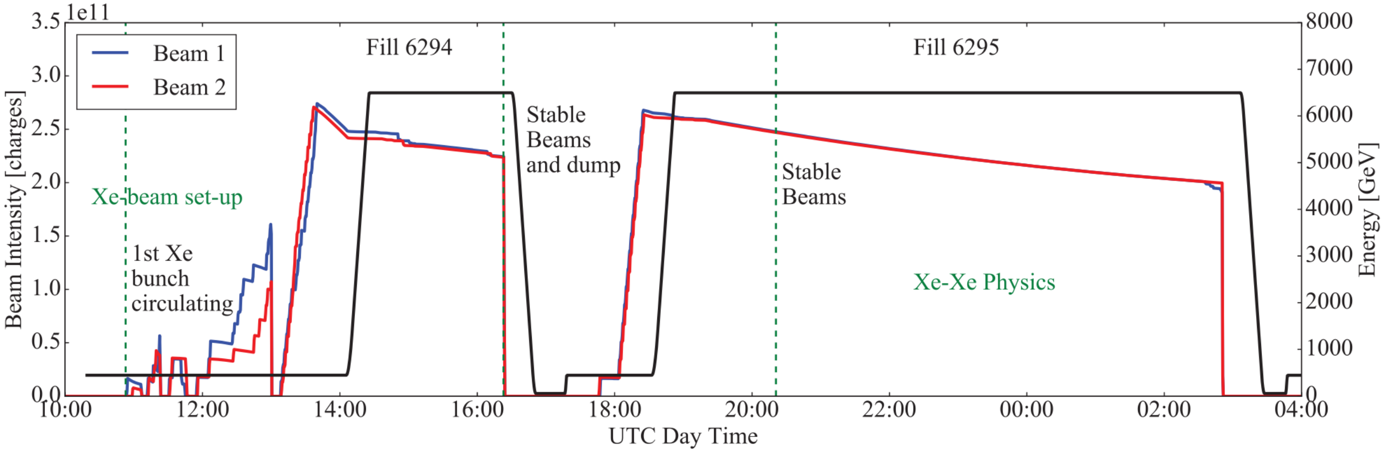

Figure 1: Evolution of the beam intensity and energy throughout the Xe–Xe run.

References at IPAC2018
https://accelconf.web.cern.ch/AccelConf/ipac2018/

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

Data on Xe-Xe data features in very large number of papers since 2018

This run used p-p optics for fast set-up ⇒ ALICE had β*=10 m so lower luminosity than ATLAS/CMS. Avoid this in future O-O run prefer to use a heavy-ion optics.

Future light-ion operation

- **HL/HE-LHC physics workshop has considered high-intensity operation with lighter species for beyond Run 4**
  - Motivation is higher nucleon-nucleon luminosity than Pb-Pb
  - See yellow report (input to European strategy)

- **Also requested pilot-like O-O and p-O run**
  - Much earlier (Run 3), a few days, low luminosity
  - Different 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

- This pilot run discussed previously at the LMC and LPC

- News since then: some updates on beam assumptions and levelling scenarios – see later

Constraints and requests for oxygen in Run 3

- **It should be a short run**, ideally not more than about a week

- **Requests for both O-O and p-O**
  - LHCb requests p in beam 1
  - No request to reverse, i.e. O-p not requested

- **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

- **Beam energy:**
  - Previously assumed same energy per charge as main Pb run (probably 7 Z TeV)
  - Some wishes from experiments for same energy per nucleon as for Pb-Pb (i.e. 5.52 Z TeV if Pb-Pb runs are done at 7 Z TeV), or at 5.02 Z TeV to match the existing pp, Pb and p-Pb datasets

Heavy-ion and pp ref energies/TeV

E_{beam} / Z	$\sqrt{s_{\mathrm{NN}}}$(pp)	$\sqrt{s_{\mathrm{NN}}}$(PbPb)	$\sqrt{s_{\mathrm{NN}}}$(XeXe)	$\sqrt{s_{\mathrm{NN}}}$(OO)	$\sqrt{s_{\mathrm{NN}}}$(pPb)	$\sqrt{s_{\mathrm{NN}}}$(pO)	Year
2.51	5.02						2015, 2017
2.76	5.52						?
3.19	6.37						?
3.5	7						?
4					5.02		2012, 13,16
5.02				5.02			??
5.52				5.52			??
6.37		5.02		6.37	8.00	9.00	2015,18, Run 3,4?
6.5			5.44		8.16		2017, 2016
7		5.52		7.00	8.79	9.90	Run 3,4?

Energies that have been used in heavy-ion and pp reference runs since 2012 (colours) or that might be considered for the future (black). Efficient OO/pO options for Run 3.

Operational preference for all runs in Run3 (and/or Run 4) to be made at same beam rigidity (first column).

So what oxygen levels could we get in the LHC?

Potential machine scenarios

- **How can we combine these constraints to a realistic machine scenario?**
  - To fit in about a week, **need to minimize commissioning**

- **Scenario 1**: use "EARLY" ion beam with single injections, (see talk R. Alemany) at standard Run 3 beam energy (7 Z TeV or maybe 6.37 Z TeV)
  - keep total charge per beam below $3x10^{11}$ => allows "light" machine validation
  - Reuse machine settings from previous Pb-Pb or p-p run to minimize commissioning
    - use the same optics cycle, and therefore same rigidity as in the other HI runs in Run 3
    - Pb-Pb cycle preferred – much smaller β^* in ALICE. Could use identical or similar combined ramp and squeeze to 2018

- **Scenario 2:** use "EARLY" ion beam with single injections, (see talk R. Alemany) at same energy per nucleon as Pb-Pb (probably 5.52 Z TeV)
  - keep total charge per beam below $3x10^{11}$ => allows "light" machine validation
  - Cannot reuse previous machine settings – need to commission new cycle

- **Scenario 3:** Use high intensity with trains, "NOMINAL" beam at 7 Z TeV
  - We cannot mask interlocks and need a full machine recommissioning and validation
  - We could potentially reuse the previous cycle

Needed commissioning – first estimates

Scenario 1: Assuming same energy per charge as in Pb-Pb, probably 7 Z TeV

- **O-O commissioning**
  - Recheck entire cycle: orbit, tune, Q’, coupling collisions, optics @ low beta – 3 shifts.
    - Time estimate based on the fact that optics reproducible
    - Could do it with protons
  - Clean-up the cycle with new settings (assume optics is stable !) – 1 shift.
    - Might need some additional time for BPM setup if using bunch charge around 4E10
  - Setup of injection and capture – 1 shift
  - Validation
    - 1 shift for tertiary collimators (if needed), and loss maps + asynch dump test
    - Low-intensity setup beam with bunch spacing > abort gap: do asynch dump test only at injection and collision (TBC with MP and ABT)
  - Total time 6 shifts → ~2-3 days

- **p-O commissioning**
  - Setup of injection frequencies, p-beam, cogging – 1 shift
  - Validation - 0.5 shift. Use cogging fill?
  - Sufficient with p-O (O-p not requested)
  - Total time ~2 shifts → ~0.5-1 day

- **The above estimates assume that the LHC machine and injectors are available – we could potentially lose time in case of faults**

Extra time needed in other scenarios

- **Scenario 2: For a lower beam energy: 5.52 Z TeV or 5.02 Z TeV**
  - Need to commission new machine cycle: cut existing ramp at lower energy, add new squeeze
    - Achievable β*-value to be verified
  - Needed commissioning in addition to scenario 1
    - 2-3 shifts for optics commissioning
    - 1 shift collimator alignment
    - 1 shifts for additional qualification
    - **In total 4-5 extra shifts**
  - **In addition: lower luminosity** expected => need more time for data taking. See later

- **Scenario 3: For higher intensity (>3E11 charges, "NOMINAL" beam) at 7 Z TeV**
  - Need full qualification, all interlocks active
  - Extra commissioning compared to scenario 1
    - 1 shift for collimator alignment
    - 1 shift for generation of new settings, cycle with new settings
    - 2 shifts for qualification

    } To be done for both O-O and p-O
  - **In total about 3 days more commissioning + contingency**
  - **In addition, intensity rampup needed before we arrive at top intensity**
    - Took about 3.5 days in the 2018 Pb-Pb run
  - **This scenario does not seem suitable for a 1-week run.** Could reconsider if more time is allocated.

- **Given the 1-week target, the most realistic option is to stay with the previous cycle at 7 Z TeV (scenario 1)**

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Assumptions: **O-O**

- **Consider scenarios 1 (7 Z TeV) and 2 (5.52 Z TeV)** for detailed simulations of luminosity performance

- **Expected beams from injectors** (see talk R. Alemany)
  - Significant uncertainty on achievable emittance and intensity
  - Assume same emittance as for Pb (2.1 µm)
  - Two options for intensity:
    - 3.97×10^{10} charges/bunch (4.96×10^{9} O^{8+}) can be handled in the SPS
    - We have to split these bunches in 2 to avoid SPS losses
  - Assume 7% intensity loss between injection in the LHC and collisions

- **Machine optics**
  - Scenario 1, at 7 Z TeV: identical β^*=(0.5,0.5,0.5,1.5) to 2018
  - Scenario 2, at 5.52 Z TeV: assume 0.65 m instead of 0.5 m from aperture scaling

- Crossing angles as assumed for Run 3 Pb-Pb
  - In principle no crossing needed, but removing it would cost some commissioning time. Possible optimization to be studied

Assumed parameters, O-O, scen. 1

Beam parameters	**Without SPS split**	**With SPS split**
Beam energy (Z TeV)	7	7
Beam energy per nucleon (TeV)	3.5	3.5
Number of bunches	6	12
O ions per bunch	4.6×10^{9}	2.3×10^{9}
Charges per bunch	3.7×10^{10}	1.8×10^{10}
Normalized emittance (μm)	2.1*	2.1*
Total charges per beam	2.4×10^{11}	2.4×10^{11}

*We don't know – this is a guess

IP parameters	**IP1/5**	**IP2**	**IP8**
β^* [m]	0.5	0.5	1.5
External half crossing [μrad]	170	170	-170
Total half crossing [μrad]	170	100	-305
N.o. collisions (no split, split)	4, 8	4, 8	4,8
Peak luminosity [10^{27}cm^{-2}s^{-1}] (no split, split)	21.1, 10.6	6.7*, 12.3	6.9, 3.5
Peak pileup (no split, split)	0.63, 0.18	0.20*, 0.18	0.21, 0.05

*levelled

Simulation setup

- Luminosity in one fill simulated with two independent simulation codes
  - CTE and MBS – see CERN-ACC-2020-0011
  - Simulates coupled beam evolution under influence of e.g. collisions, intrabeam scattering, radiation damping
  - Non-collisional lifetime of 50h assumed – possibly pessimistic, but cannot count on fully optimized machine

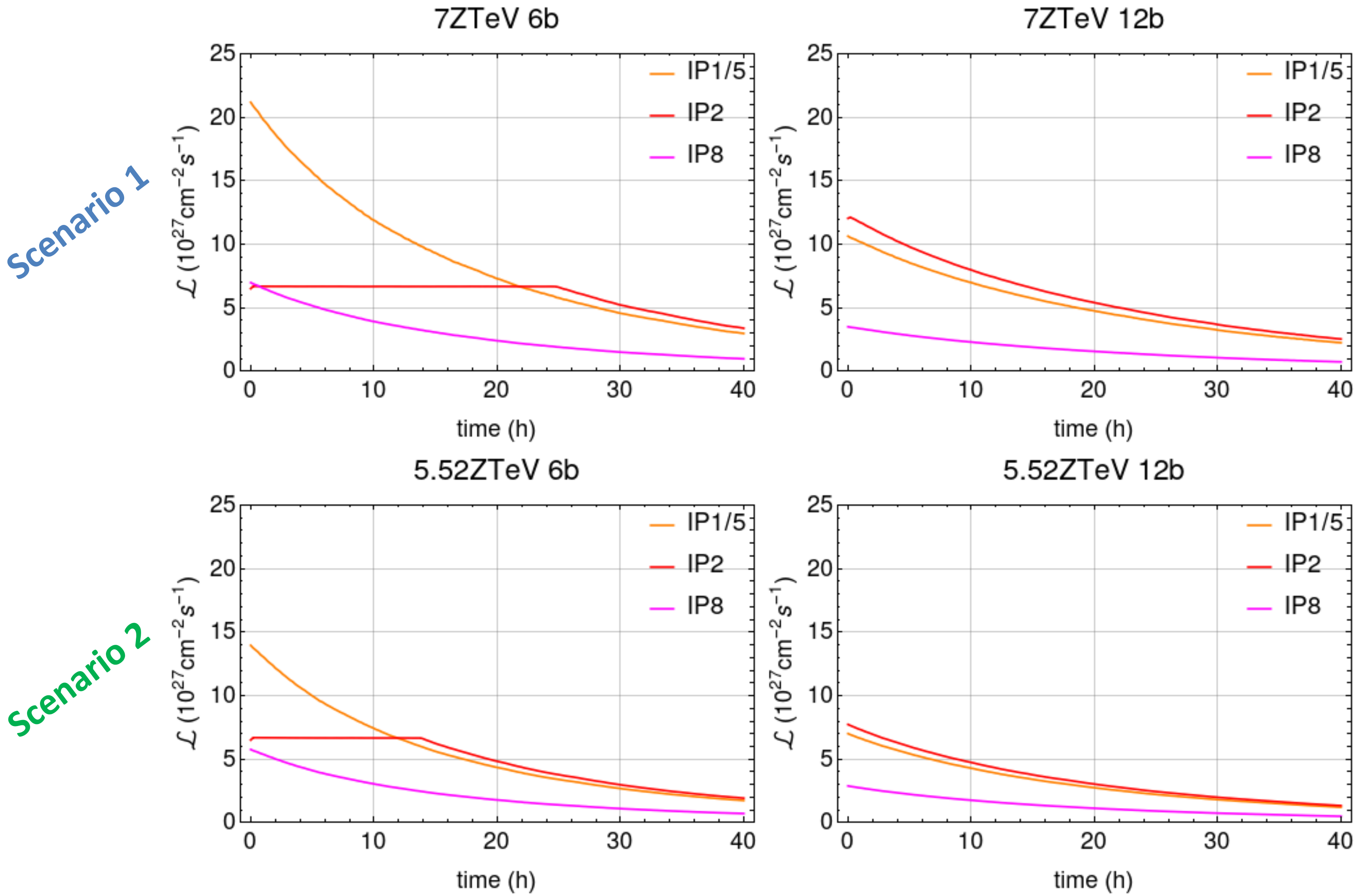
- Burnoff cross sections
  - hadronic interactions dominate for oxygen operation

	Pb-Pb	**p-Pb**	**O-O**	**p-O**
Bound-free pair production(barn)	281	0.044	**< 0.01**	**<10^{-5}**
Electromagnetic dissociation (barn)	226	0.035	**0.133**	**0.0012**
Hadronic cross section	8	2.12	**1.343***	**0.45****
Total cross section	515	2.20	**1.48**	**0.45**

* Glauber calculation by G. Contreras
** Glauber calculation by David d'Enterria

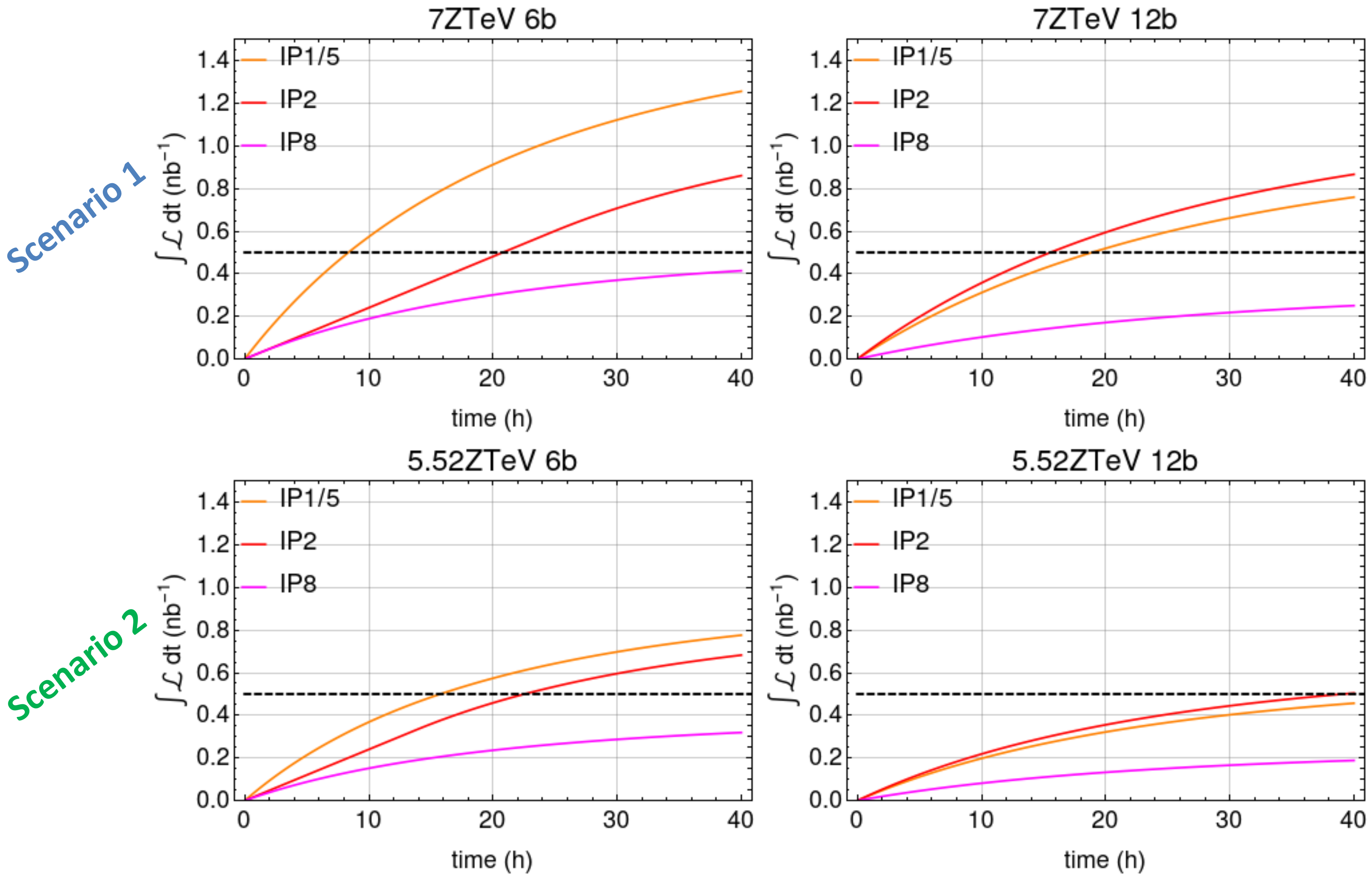
Results: O-O

Instantaneous luminosity



Results: O-O

Integrated luminosity



Observations O-O

- Scenario 1: At **7 Z TeV**, to accumulate 0.5 nb^{-1} in single, long fill:
  - ATLAS/CMS need ~8h for 6b and ~19h with 12b
  - ALICE needs ~21h with 6b and ~13h with 12b
  - LHCb: Could reach ~0.3 nb^{-1} in single long fill of ~20h
  - Of course, the fill might be dumped earlier, and we make a second fill

- Scenario 2: At **5.52 Z TeV**, to accumulate 0.5 nb^{-1} :
  - ATLAS/CMS need ~16h for 6b and >40h for 12b
  - ALICE needs ~22h with 6b and ~39h with 12b

- Clear risk that we need significantly longer running time if we go for 5.52 Z TeV, which comes on top of the additional commissioning
  - Need >1 day longer running than at 7 Z TeV if we're forced to use the 12-bunch scheme

Assumptions: **p-O**

- Consider scenarios 1 (**7 Z TeV)** and 2 (**5.52 Z TeV)** for detailed simulations of luminosity performance

- For **LHCf,** where **pileup = 0.02 is requested**: need to split beam in more bunches to make luminosity goal feasible
  - Assume 36 bunches, with 24 colliding at each IP
  - Level LHCf at 1.2×10^{28} $cm^{-2}s^{-1}$: expect just below 40h to reach 1.5 nb^{-1}
  - Upper intensity limit on both O and p beams given by max allowed total intensity of 3E11 charges
  - Need ~10% margin at injection, since we cannot control the intensity better shot-by-shot
  - Assume 7% intensity loss between injection in the LHC and collisions

- Same machine optics and crossing angles as for O-O

Assumed parameters, p-O, scen. 1

Beam parameters	**Protons**	**Oxygen**
Beam energy (Z TeV)	7	7
Beam energy per nucleon (TeV)	7	3.5
Number of bunches	36	36
Particles per bunch	7×10^9	8.7×10^8
Charges per bunch	7×10^9	7×10^9
Normalized emittance (μm)	2.5	2.1*
Total charges per beam	2.5×10^{11}	2.5×10^{11}

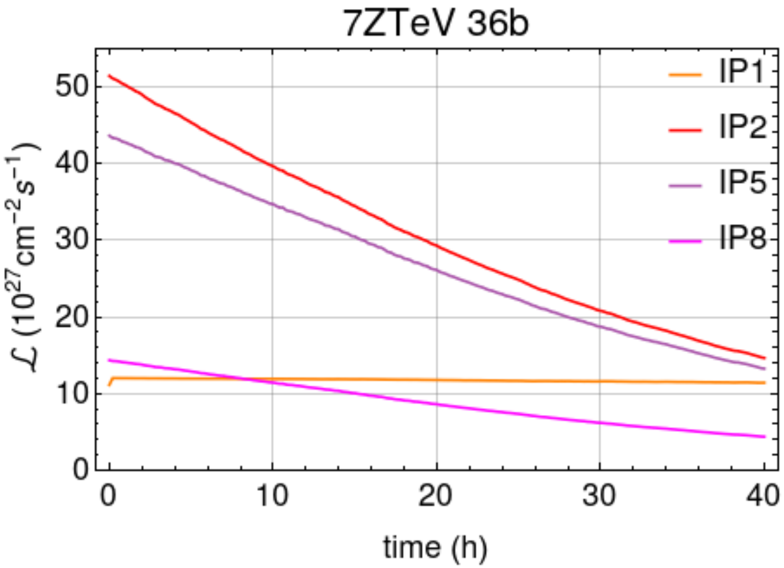
*We don't know – this is a guess

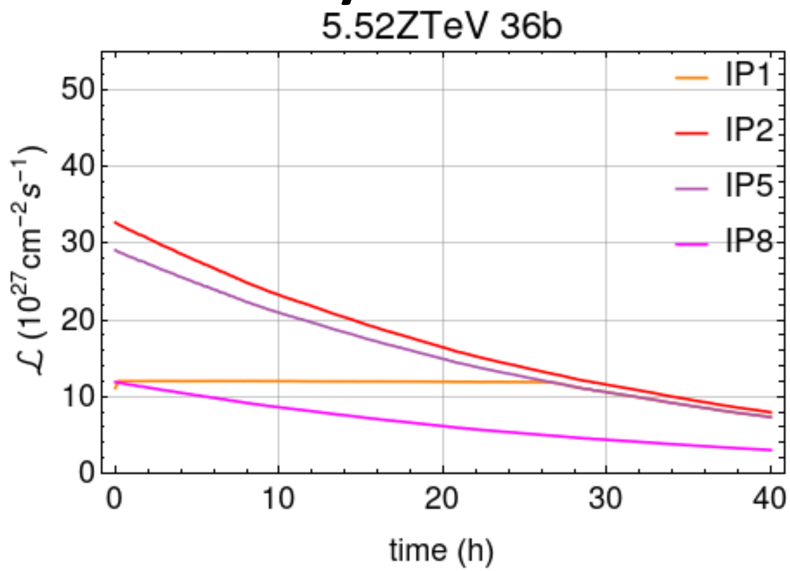
IP parameters	**IP1/5**	**IP2**	**IP8**
β^* [m]	0.5	0.5	1.5
External half crossing [μrad]	170	170	-170
Total half crossing [μrad]	170	100	-305
N.o. collisions	24	24	24
Peak luminosity [$10^{27}cm^{-2}s^{-1}$]	45 (12*)	53	15
Peak pileup (no split, split)	0.075 (0.02*)	0.08	0.025

* For IP1 levelled to 0.02 pileup

Results: **p-O**

Instantaneous luminosity

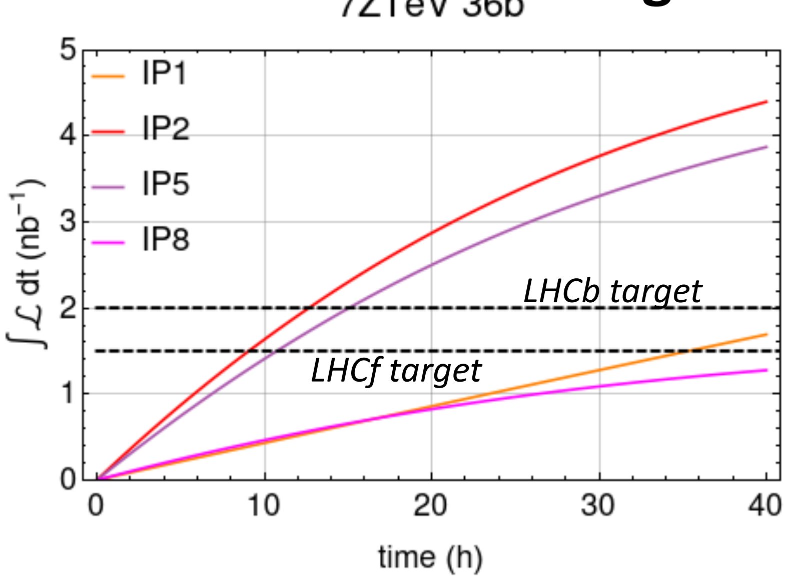


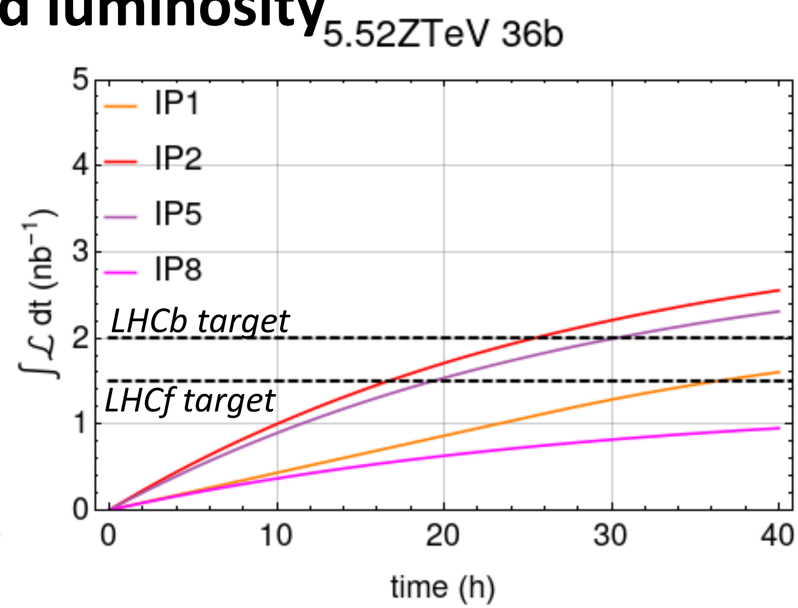


Scenario 1

Scenario 2

Integrated luminosity





Observations p-O

- **Need ~36h** in stable beams **to give 1.5 nb^{-1} to LHCf** at pileup=0.02

- **Scenario 1:** At 7 Z TeV, **LHCb target of 2 nb^{-1} can be reached in 3 fills of about 15-16h each** (optimum fill length for IP8) **+ turnaround**
  - Total time needed: 2.5 days without contingency
  - Future study: Can we optimize the filling scheme further to give more collisions to LHCf and LHCb?
  - In those 3 fills CMS and ALICE could hope for some 6-7 nb^{-1}
  - LHCf would be at about 2 nb^{-1}
  - Still might need some additional contingency

- **Scenario 2:** At 5.52 Z TeV, LHCb needs an additional ~15h of stable beams to reach 2 nb^{-1} (need to add some hours for turnaround)

First thoughts on tentative schedule

For scenario 1: Same beam energy as in Pb-Pb, probably 7 Z TeV

- O-O commissioning: 2-3 days
- O-O physics run: 1 day
  - Goal: above 0.5 nb^{-1} in ALICE, ATLAS, CMS.
- p-O commissioning: 0.5 – 1 day
- p-O physics run: 2.5-3 days
  - Goal: above 1.5 nb^{-1} in LHCf and 2 nb^{-1} in LHCb
- **Total: ~6-8 days**
  - Less physics time would still be useful

For scenario 2 (5.52 ZTeV):

- add 2-3 days of commissioning and 1-2 days of physics

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Uncertainties and complications

- Large uncertainty on emittance and bunch intensity from injectors
  - Presented performance could go in both directions

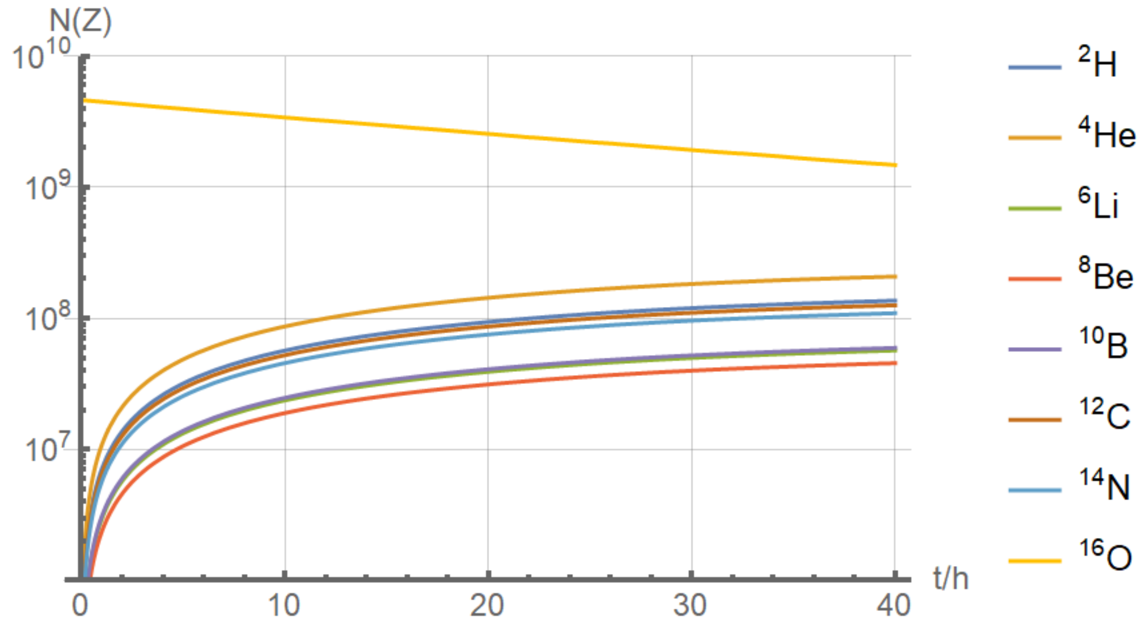
- Assuming a good machine availability – any major fault in the LHC or the injectors would cause additional delays

- Oxygen beam transmutation effect under study – could potentially pollute the collisions

Transmutation of O beam

- Electromagnetic dissociation and hadronic interactions in collisions can create nuclei with *A=2Z,* like initial $^{16}O^{8+}$ and with small momentum recoil.
- Rigidity shift is small so they can potentially stay in beam.

	δ (%) from mass only
^{2}H	0.737309
^{4}He	0.0969224
^{6}Li	0.283998
^{8}Be	0.0981555
^{10}B	0.161249
^{12}C	0.0318025
^{14}N	0.0537726
^{16}O	0.



Very(!) preliminary estimates of upper limit based on: EMD cross sections (RELDIS), rough approximations for hadronic contributions, luminosity evolution data.

Collimation system can remove some but not all of these nuclei.

Potential pollution of few % of O beam population by lighter nuclei, esp 14N,.

Collisions between, eg, C-O difficult to distinguish from peripheral OO events.

J.M. Jowett, S. Klein, E. Pshenichnov, A. Dainese, R. Bruce

Conclusions

- Studied various **options for a short LHC run, of about 1 week, with O-O and p-O**
  - **Motivated both by physics interest and for studying the machine performance** in view of future light-ion operation
  - Most efficient option is to **re-use the machine cycle of the previous Pb-Pb run at the same beam energy (**possibly **7 Z TeV), using pilot beams** with single injections (below 3×10^{11} charges per beam)

- For this option, estimated **~2.5-4 days of commissioning and 3.5-4 days of running** to reach luminosity goals
  - Assuming good machine availability – any long faults will extend the schedule
  - Large uncertainties on beam parameters apply – performance and hence needed time directly affected

- If we run at lower energy, e.g. **at 5.52 Z TeV, expect some 3-5 days more total time**

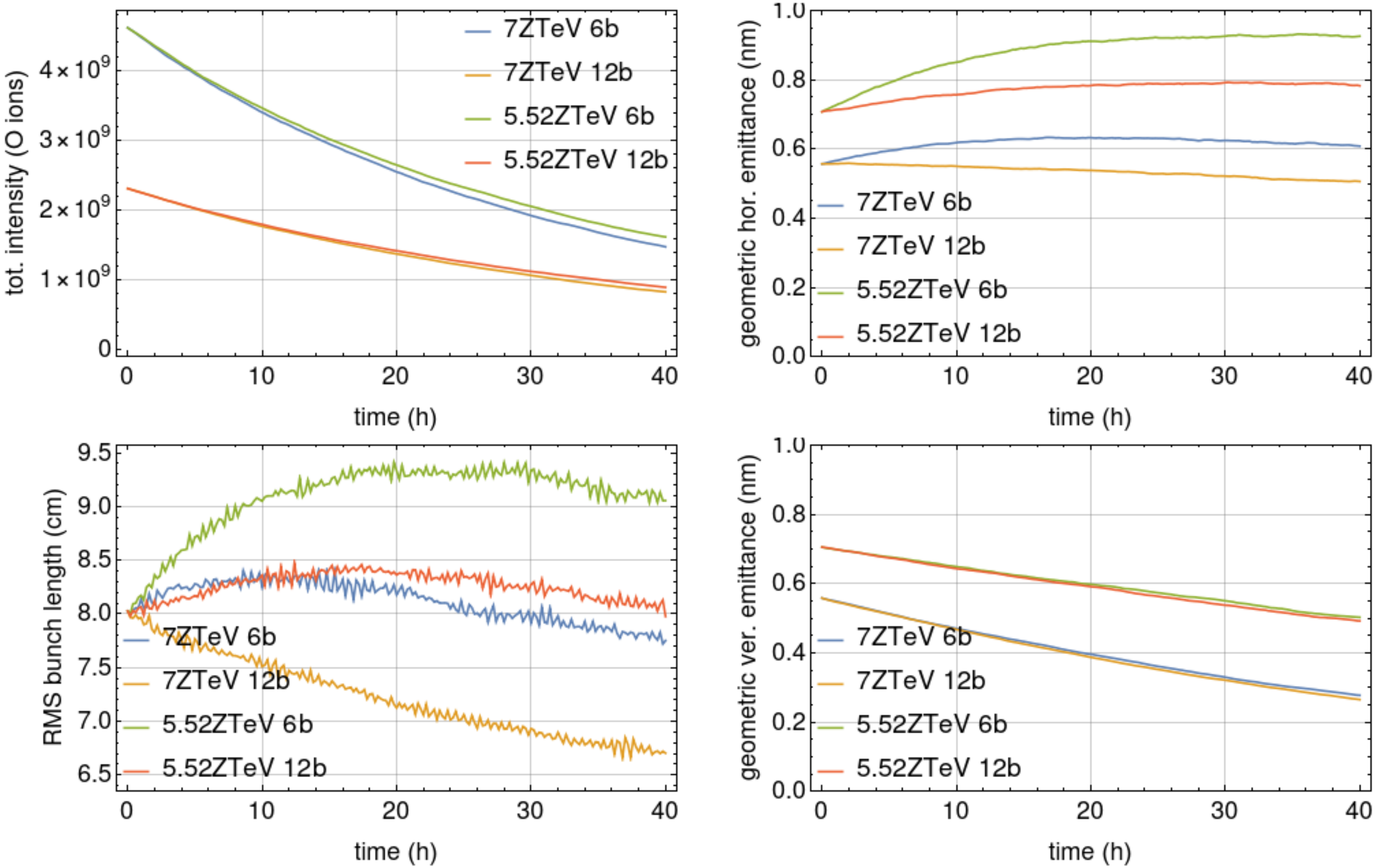
- Points for further study
  - Optimization of filling schemes
  - Oxygen beam transmutation effect

Thanks for the attention!
Questions?

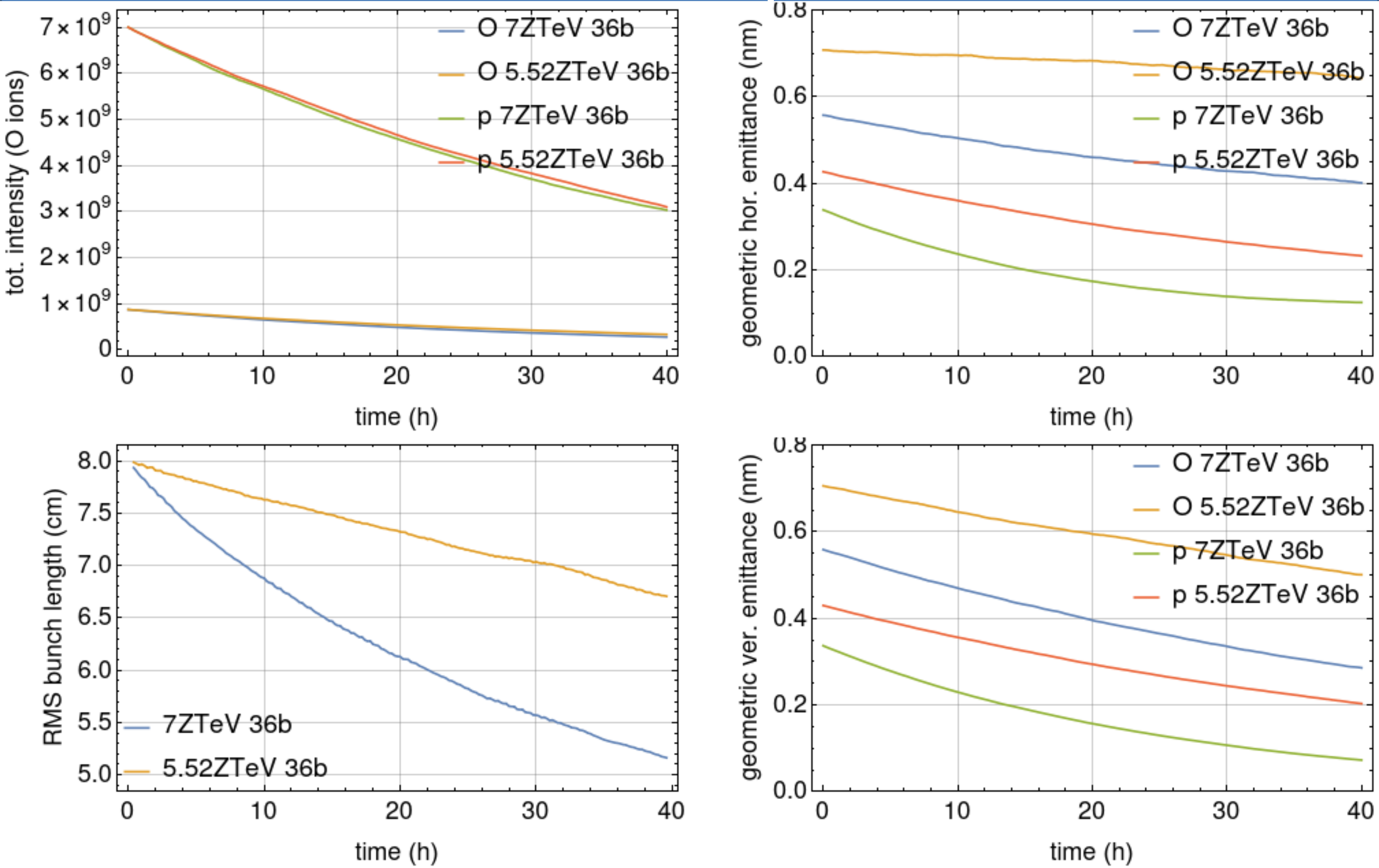
Backup

Results: O-O

Beam evolution



Results: p-O



tot. intensity (O ions)
7×10^9
6×10^9
5×10^9
4×10^9
3×10^9
2×10^9
1×10^9
0
O 7ZTeV 36b
O 5.52ZTeV 36b
p 7ZTeV 36b
p 5.52ZTeV 36b
time (h)
geometric hor. emittance (nm)
RMS bunch length (cm)
7ZTeV 36b
5.52ZTeV 36b
geometric ver. emittance (nm)

O beam transmutation

- Broad spectrum of fragments created in nuclear collisions. Usually fragments cannot stay in the ring due to their charge-to-mass ratio

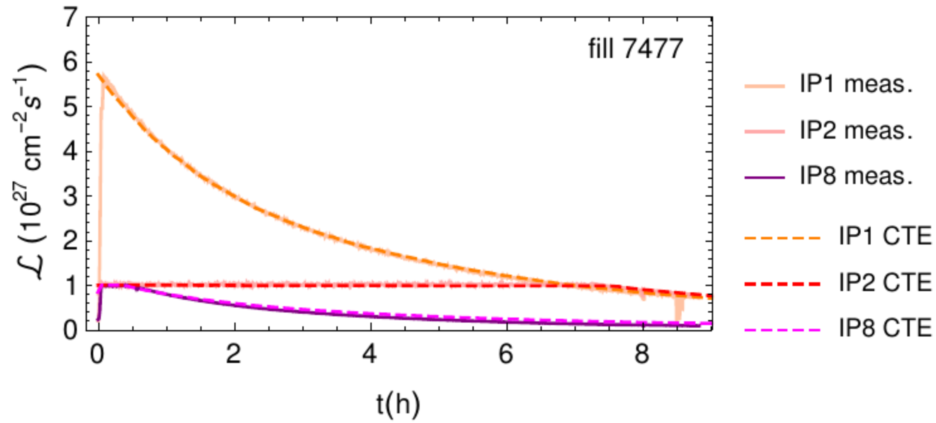
- New effect recently predicted: Nuclear breakup in oxygen collisions create fragments with the same charge-to-mass ratio as the main 16O8+ ions, e.g. $^{4}He^{2+}$, $^{6}C^{12}$, $^{14}N^{7+}$

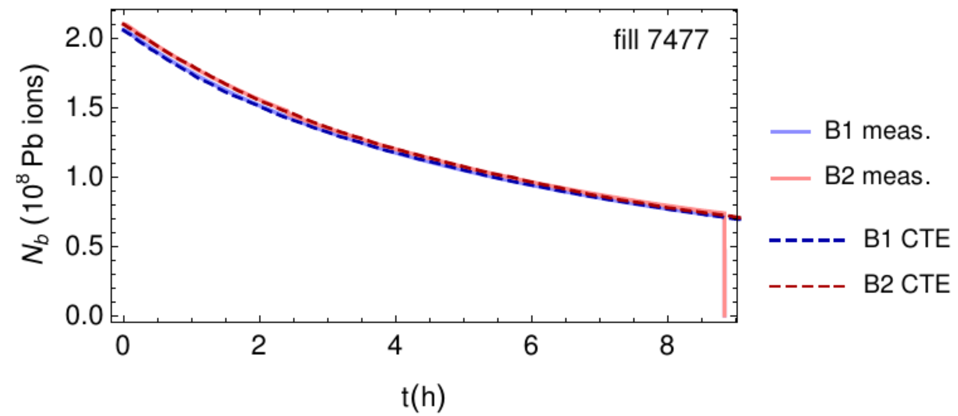
- These ions could potentially stay in the beam and pollute the collisions
  - To be investigated: are the kicks in energy and momentum from the scattering enough to make these particles impact on the aperture or collimators

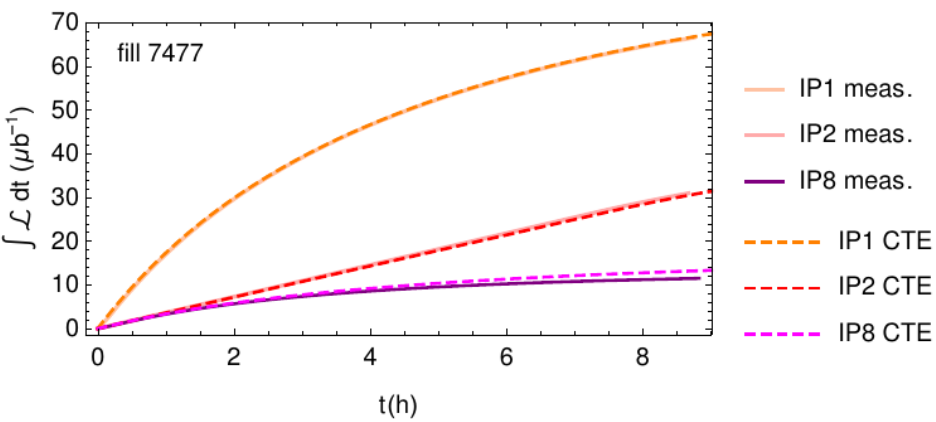
- Effect is under study and the impact is still to be quantified

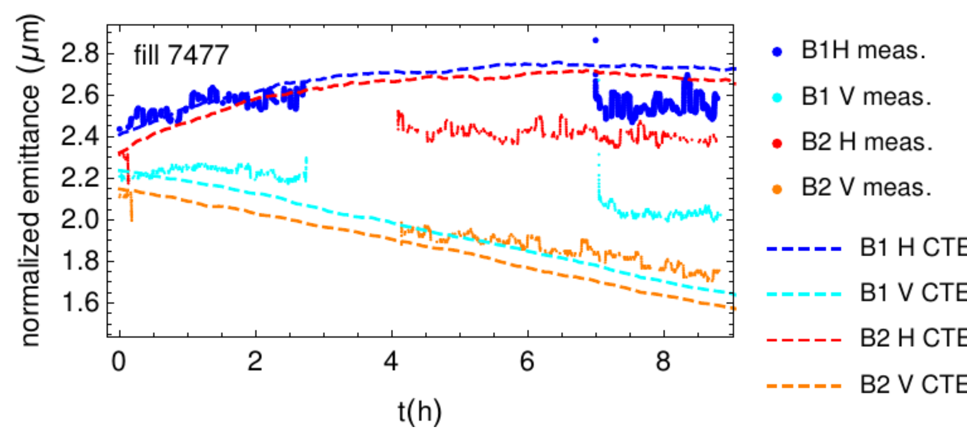
Simulation benchmark

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





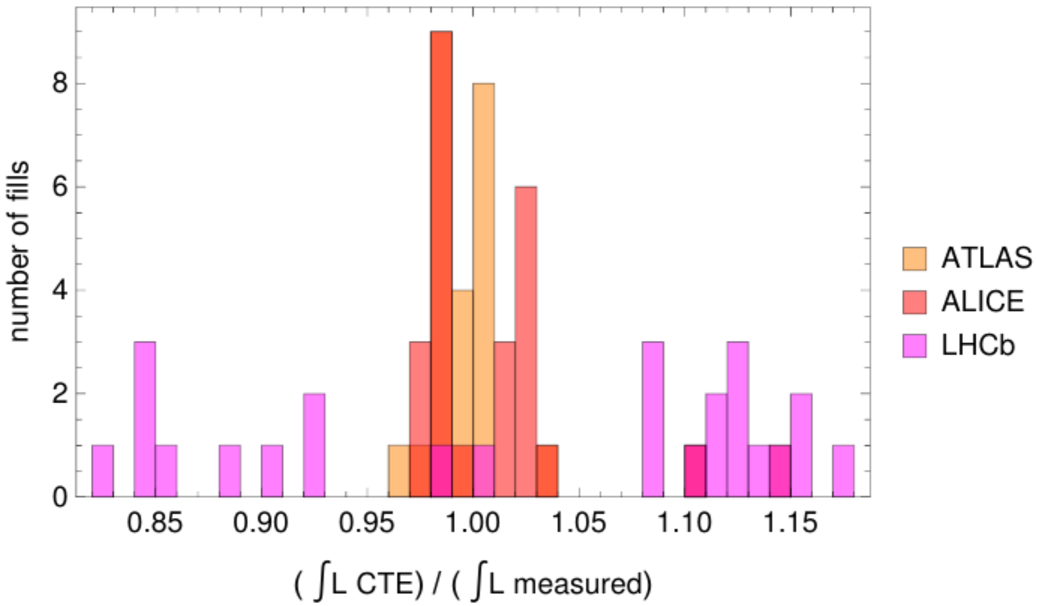




Integrated Pb-Pb luminosity per fill

- Showing ratio of simulated/measured integrated luminosity in 30 stable-beam fills from 2018

- In general very good agreement
  - Large spread at LHCb not well understood. LHCb experts have doubts on the cross sections used for calibration



Ratio Sim./Meas.

	Mean	Std. dev.
ATLAS	1.00	0.03
ALICE	1.01	0.04
LHCb	1.02	0.12