Heavy Ions during HL-LHC

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Thanks for contributions:

Tom Mertens, Michaela Schaumann, Pascal Hermes

Comments from:

Gianluigi Arduini, Oliver Brüning and many others

Design Baseline and Performance Achieved

“p-Pb not part of baseline”

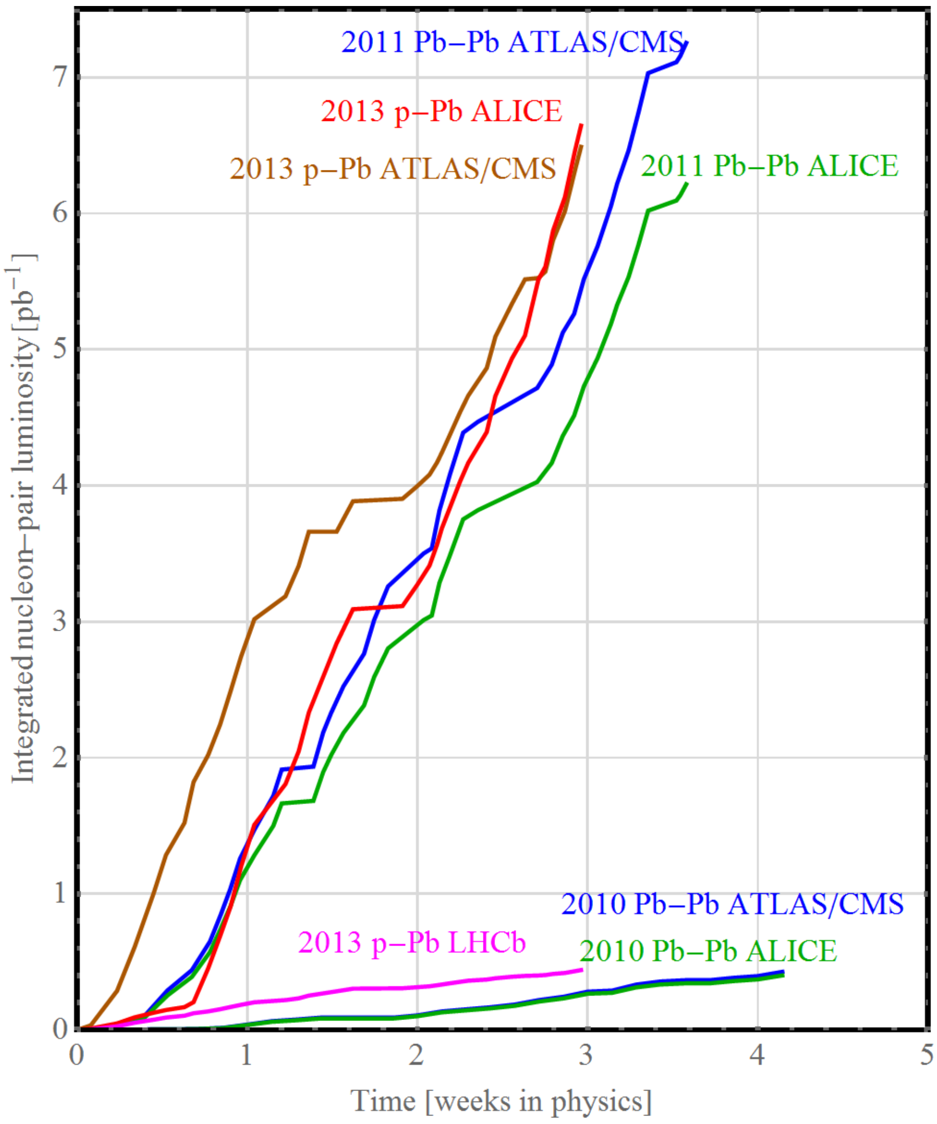
	Pb-Pb				p-Pb	
	Baseline	**Injection 2011**	**Collision 2011**	**Injection 2013**	**physics case paper**	**2013**
Beam Energy [Z GeV]	7000	450	3500	450	7000	4000
No. Ions per bunch $[10^8]$	0.7	1.24 ± 0.30	1.20 ± 0.25	1.67 ± 0.29	0.7	$\mathbf{1.40 \pm 0.27}$
Transv. normalised emittance $[\mu m.\mathrm{rad}]$	1.5	---	1.7 ± 0.2	$\mathbf{1.3 \pm 0.2}$	1.5	---
RMS bunch length $[\mathrm{cm}]$	7.94	8.1 ± 1.4	9.8 ± 0.7	8.9 ± 0.2	7.94	9.8 ± 0.1
Peak Luminosity $[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1	---	$\mathbf{0.5}$	---	115	110

$= 2 \times$ design scaled with E^2

Integrated nucleon-nucleon luminosity in Run 1

Goal of the first p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs.

Runs seem to be getting shorter …



ALICE operating conditions outlined in the LoI

- The plan is to run at a maximum interaction rate of 50 kHz in Pb-Pb.
- In the LoI we assume: peak luminosity of $6x10^{27}$ $cm^{-2}s^{-1}$ and an average luminosity of $2.4x10^{27}$ $cm^{-2}s^{-1.}$
- The upgrade program assumes an integrated luminosity of 10 nb^{-1} in PbPb at top energy
- <u>In addition</u>
  - one special PbPb run at reduced magnetic field for low-mass dileptons (O~ 3 nb^{-1})
  - one p-Pb run with about 50 nb^{-1}
  - pp reference run at 82/208 * top energy
- time horizon: to be completed by LS4 under the basic assumption of about one month LHC heavy ion operation per year.

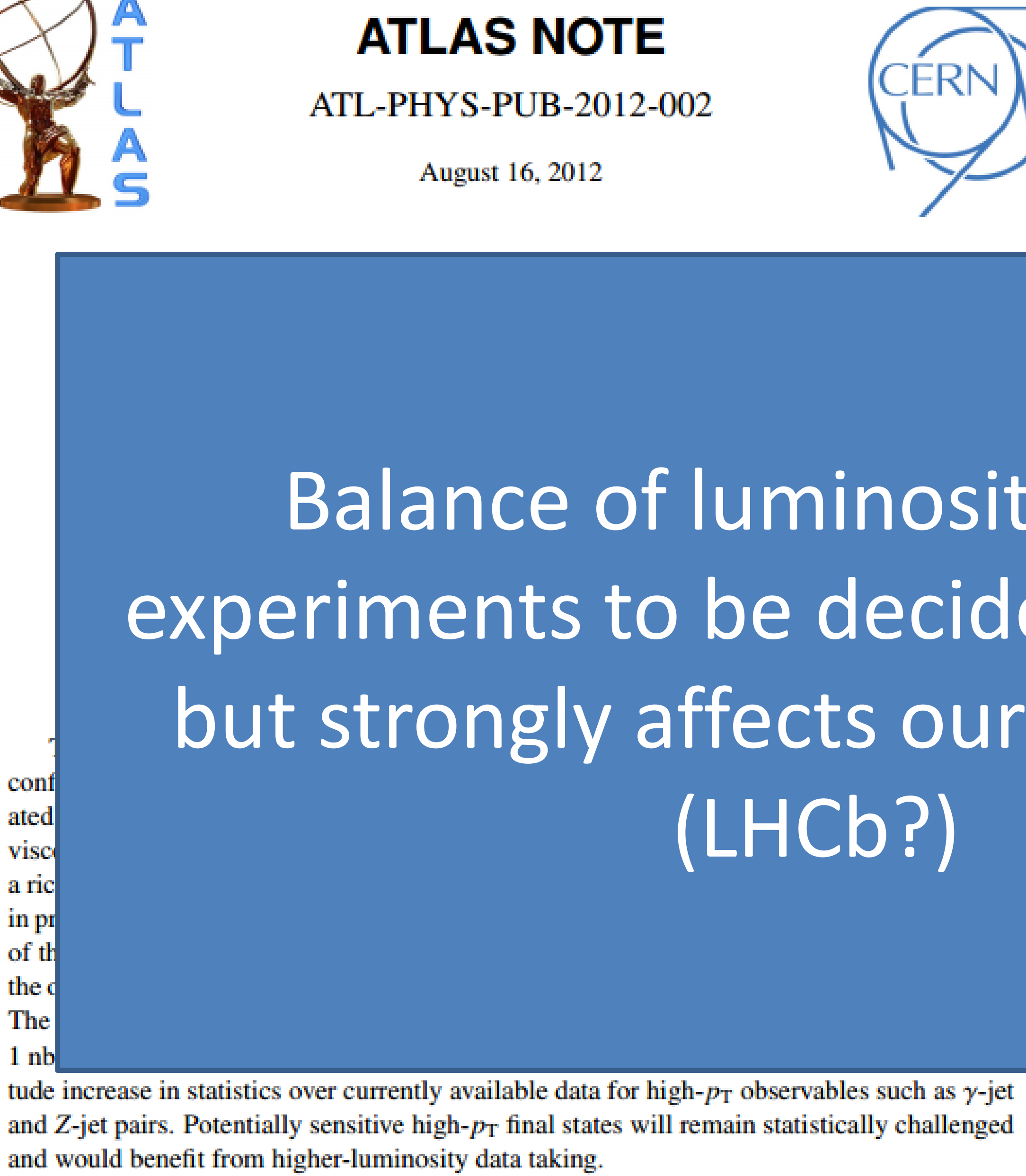
Scheduling after LS2

- Tentative plan (modulo start of Run3) as stated in the LoI of the upgrade (CERN-LHCC-2012-012)

  - Possible running scenario after upgrade:
    - 2020 – Pb–Pb 2.85 nb^{-1}
    - 2021 – Pb–Pb 2.85 nb^{-1} (low magnetic field)
    - 2022 – pp reference run

    - 2023,2024 – LS3

    - 2025 – Pb–Pb 2.85 nb^{-1}
    - 2026 – ½ Pb–Pb 1.5 nb^{-1} + ½ p–Pb 50 nb^{-1}
    - 2027 – Pb–Pb 2.85 nb^{-1}



ATLAS NOTE

ATL-PHYS-PUB-2012-002

August 16, 2012

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tude increase in statistics over currently available data for high-p_T observables such as γ-jet and Z-jet pairs. Potentially sensitive high-p_T final states will remain statistically challenged and would benefit from higher-luminosity data taking.

CMS –

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Balance of luminosity among experiments to be decided elsewhere but strongly affects our projections (LHCb?)

Motivation

- Predictions of Pb-Pb luminosity beyond LS2 have been given elsewhere (JMJ et al at RLIUP workshop 2013)
  - https://indico.cern.ch/event/260492/ + write-up + various papers, thesis of M. Schaumann, etc.
  - Based on empirical data from 2011 and 2013 Pb beams and incorporating all expectations for improvement
  - Very detailed luminosity model for initially injected beams and their evolution
  - Optimising injection into SPS for maximum luminosity in LHC
  - Close collaboration with LIU heavy-ion
  - Best realistic estimates of integrated luminosity do not fulfil ALICE request
- Request from LIU to specify injected beam parameters in LHC that would fulfil ALICE request for Pb-Pb

Tentative *ideal* parameter specification

- Highly simplified scenario: assume
  - All bunches are equal (consider single bunch pair simulation)
  - Initial bunch intensity (start of stable beams)

$$N_b = 1.9 \times 10^8 \quad \text{(c.f. design } 0.7 \times 10^8 \text{ , 2013 maximum } 2.2 \times 10^8 \text{)}$$

  - Initial emittance (start of stable beams)

$$\varepsilon_{xn} = 1.5 \times 10^{-6} \quad \text{(= design, typical in operation so far)}$$

  - Other bunch parameters as Design Report nominal
  - Three luminosity-sharing scenarios

$$\beta^* = \begin{cases} (\infty, 0.5, \infty) & \text{m} \quad \text{(only ALICE colliding)} \\ (1.0, 0.5, 1.0) & \text{m} \quad \text{(ATLAS/CMS at half ALICE)} \\ (0.5, 0.5, 0.5) & \text{m} \quad \text{(equal)} \end{cases}$$

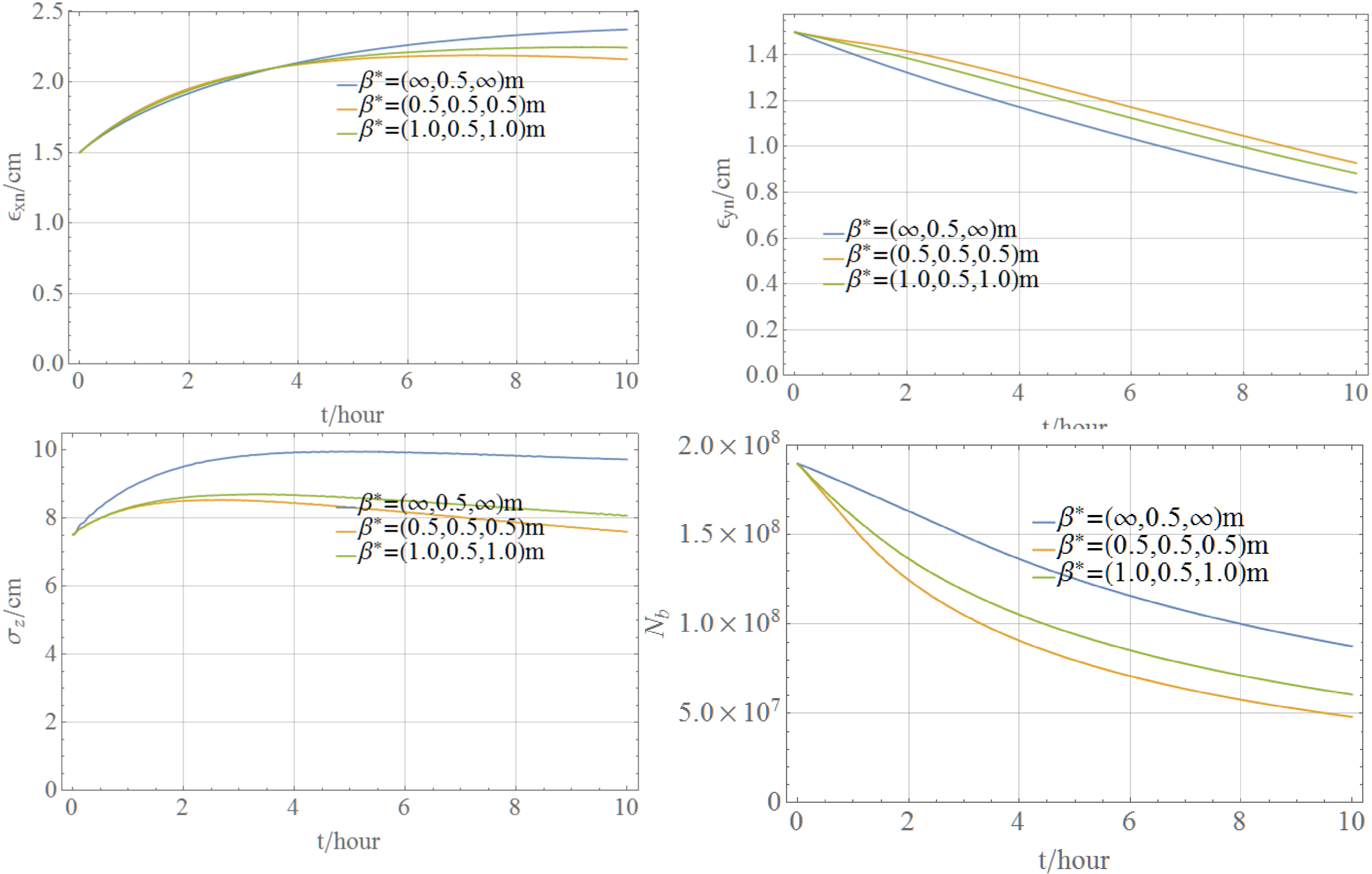
Simulation

- CTE program (many runs by Tom Mertens)
  - Macro-particle, macro-turn simulation, slow kinetic effects
  - Luminosity burn-off (very strong!)
  - Luminosity with crossing angles (150,100,150) µrad
  - IBS with non-Gaussian longitudinal distribution
  - Debunching longitudinally (small here)
  - Synchrotron radiation damping (strong!), quantum excitation (tiny)
  - Simulates one bunch from each beam, experiencing collisions at 3 IPs
- The realistic luminosity model (RLIUP etc, not today) combines simulations of varying bunch parameters along trains from SPS

Required parameters at start of collisions

Parameters	
Bunch spacing (basic)	50 ns
Number of bunches	1100
Number of colliding pairs (ATLAS, ALICE, CMS)	1160,1100,1160
Bunch intensity (RMS)	1.9×10^{8}
Transverse emittance in x and y (mean)	1.5×10^{-6} m
Bunch length (RMS)	0.075 m
Half-crossing angles (ATLAS,ALICE,CMS)	(170,100,170) μrad

Simulation of single colliding bunch pair

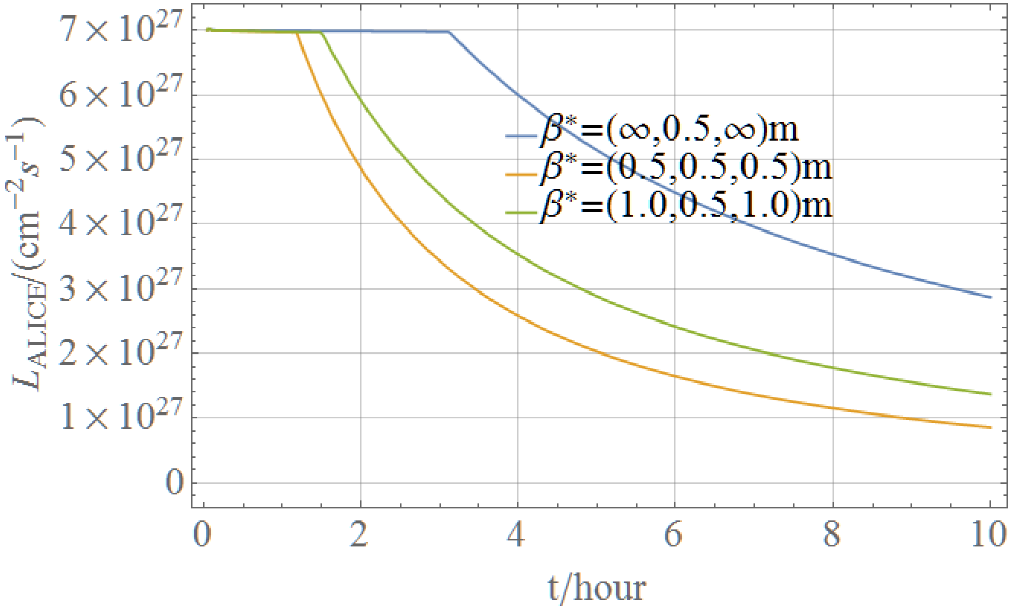


Interplay of radiation damping, IBS, luminosity burn-off couples all 4 quantities.
Different evolution according to luminosity-sharing scenario.

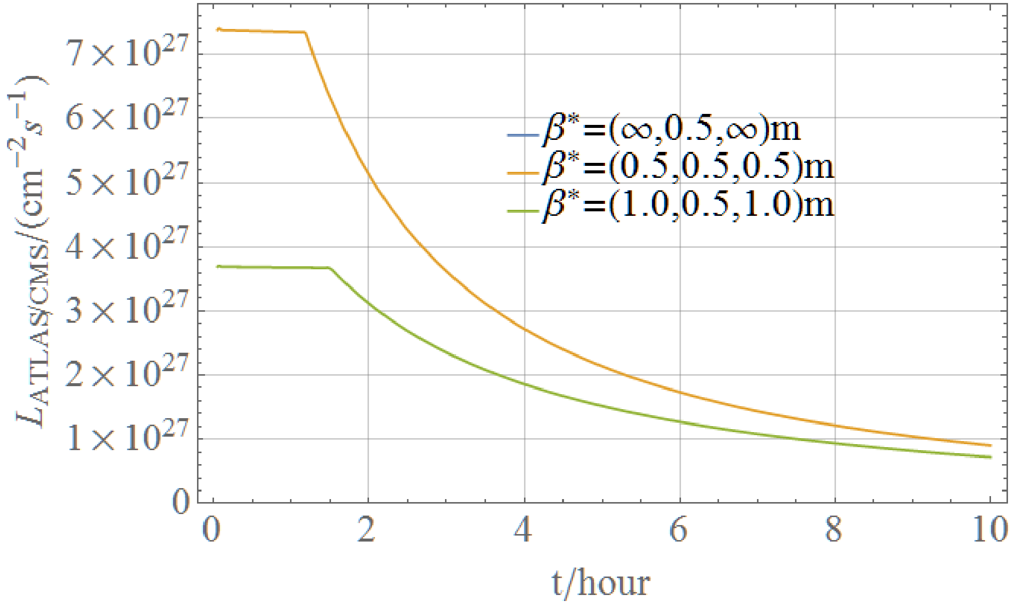
Filling scheme

- Assume 1100 bunches colliding in ALICE, 1160 colliding in ATLAS/CMS
  - Approximation: neglect different collision histories of a few bunches, bunches all see the same burn-off
- Estimate based on
  - Recent LIU baseline (50 ns basic spacing in LHC)
  - LEIR improvements to allow bunch splitting
  - SPS injection kicker for 100 ns rise time
  - Slip-stacking injection in SPS
  - Assumed no intensity decay in SPS so all bunches are the same!!!
- Filling schemes with fewer bunches would require larger single bunch intensities – limits in injectors, faster IBS in LHC, … 50 ns is essential (can we consider 25 ns?)

Experiments' luminosities in an ideal (prolonged) fill

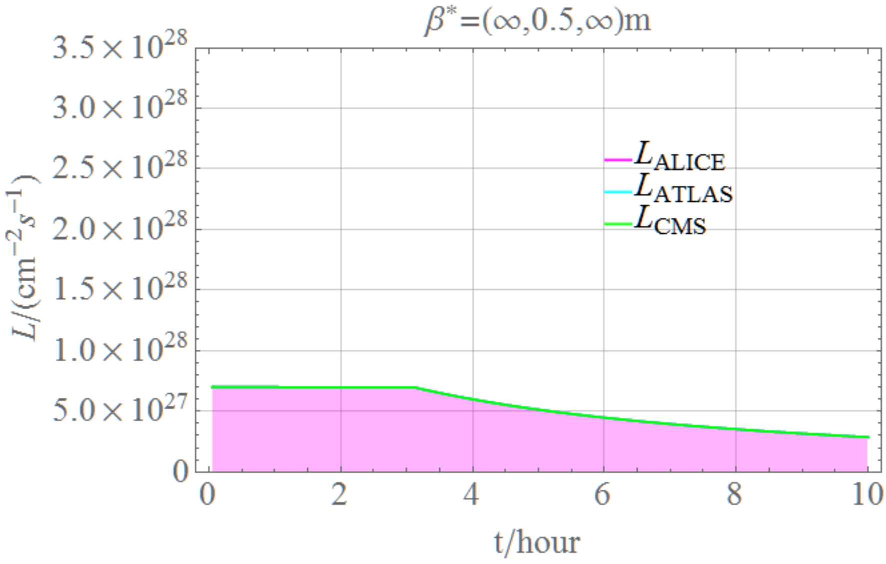


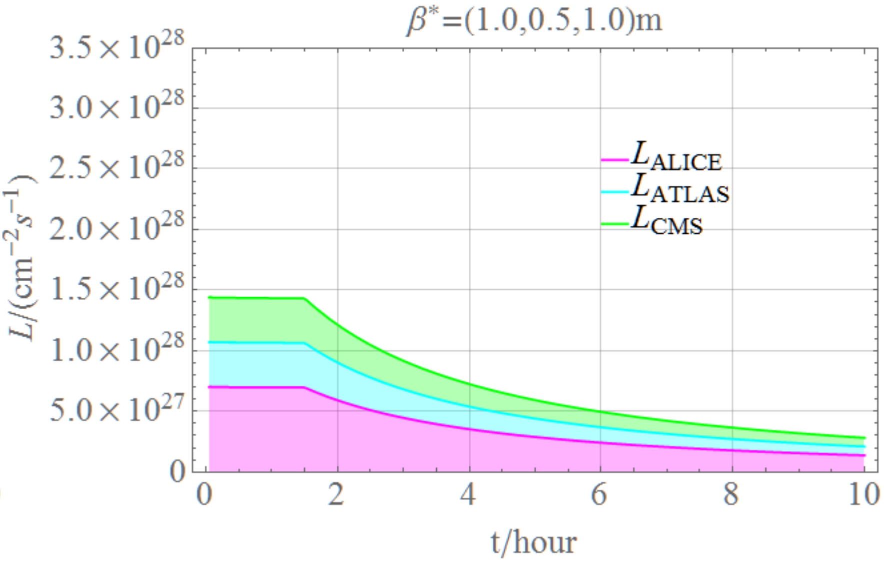
ALICE, levelling at maximum acceptable (rates around 50 kHz), assuming 1100 bunches colliding

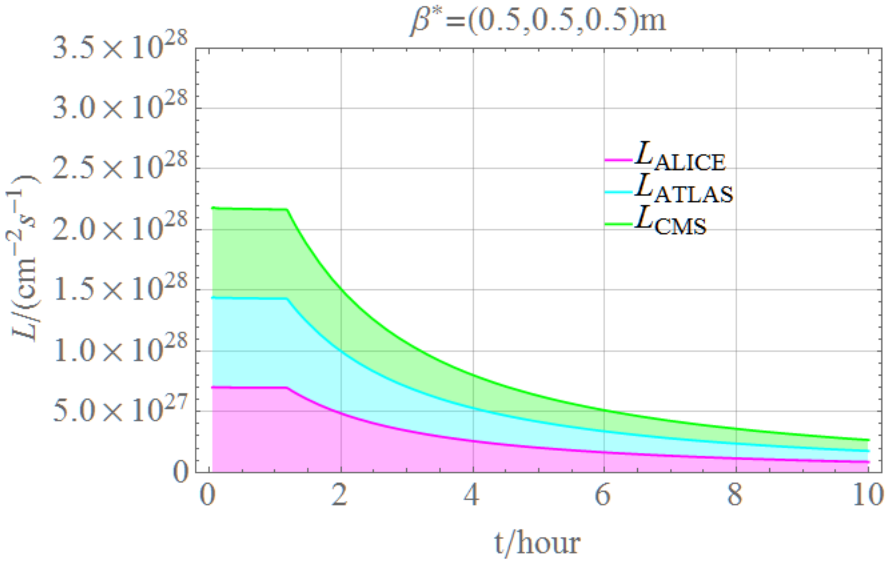


ATLAS or CMS, *assumed* levelling at corresponding levels to ALICE (not strictly necessary, assumption)

Luminosity sharing in the 3 scenarios


β^*=(∞,0.5,∞)m


β^*=(1.0,0.5,1.0)m

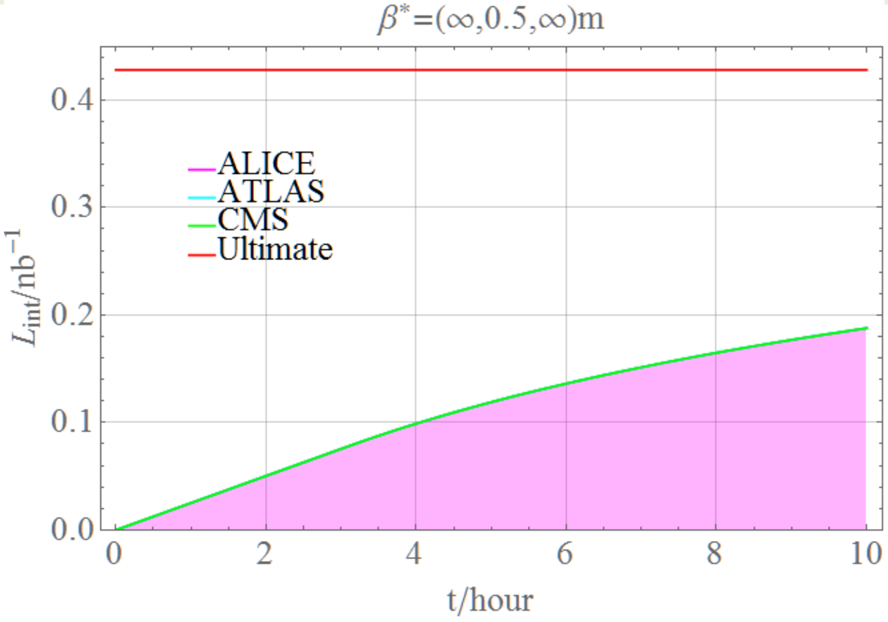

β^*=(0.5,0.5,0.5)m

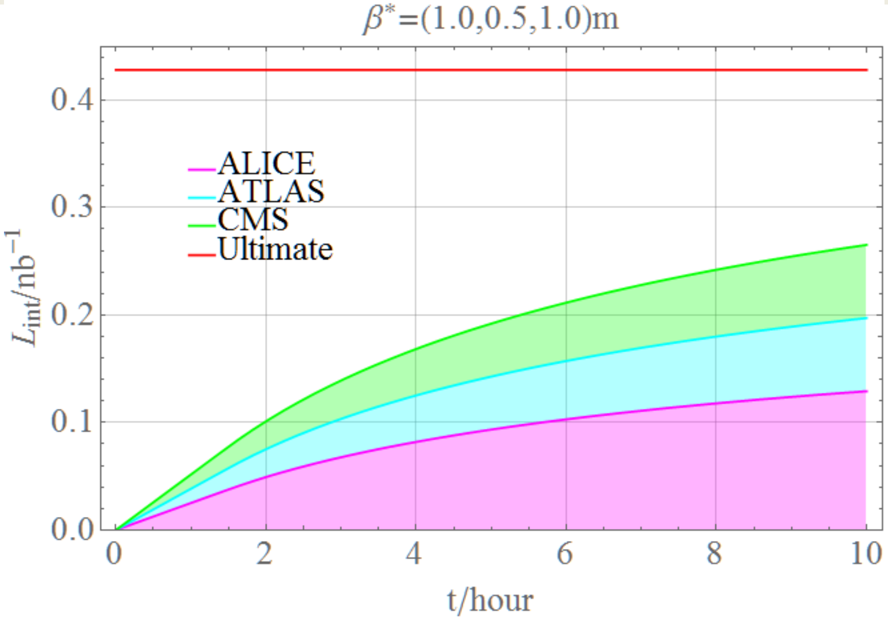
Equal (maximum) luminosity scenario gives the maximum summed over all experiments.

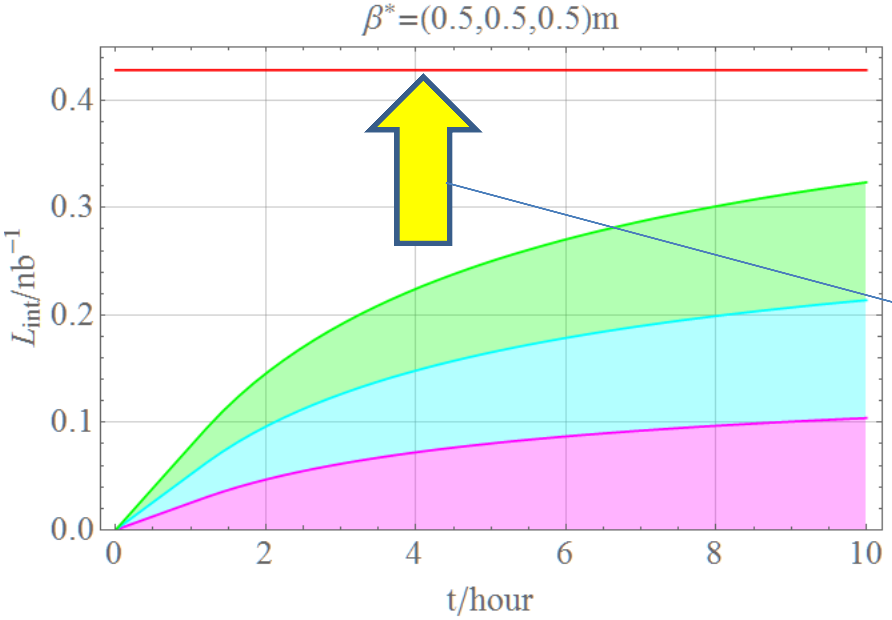
Other scenarios give more to ALICE.

(This is the same information as the last slide, just summed over experiments).

Integrated luminosity in fill







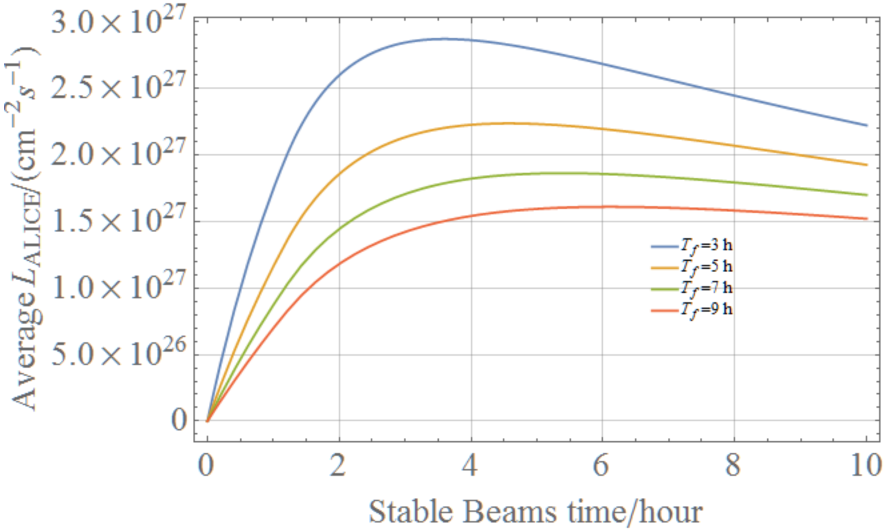
Ultimate luminosity to share

$$L_{\text{int,max}} = \frac{k_c N_b}{\sigma_c}$$

Potential for a stochastic cooling system

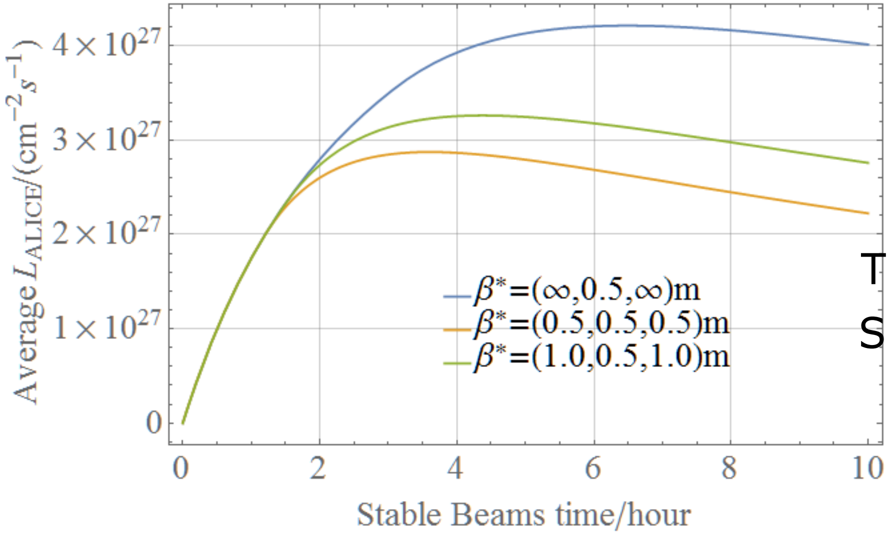
Effect of turn-around time on average luminosity

$$\langle L\rangle = \frac{1}{T_f + T_p}\int_0^{T_p} L(t)\,dt$$



$\beta^* = (0.5,0.5,0.5)\mathrm{m}$ (equal)

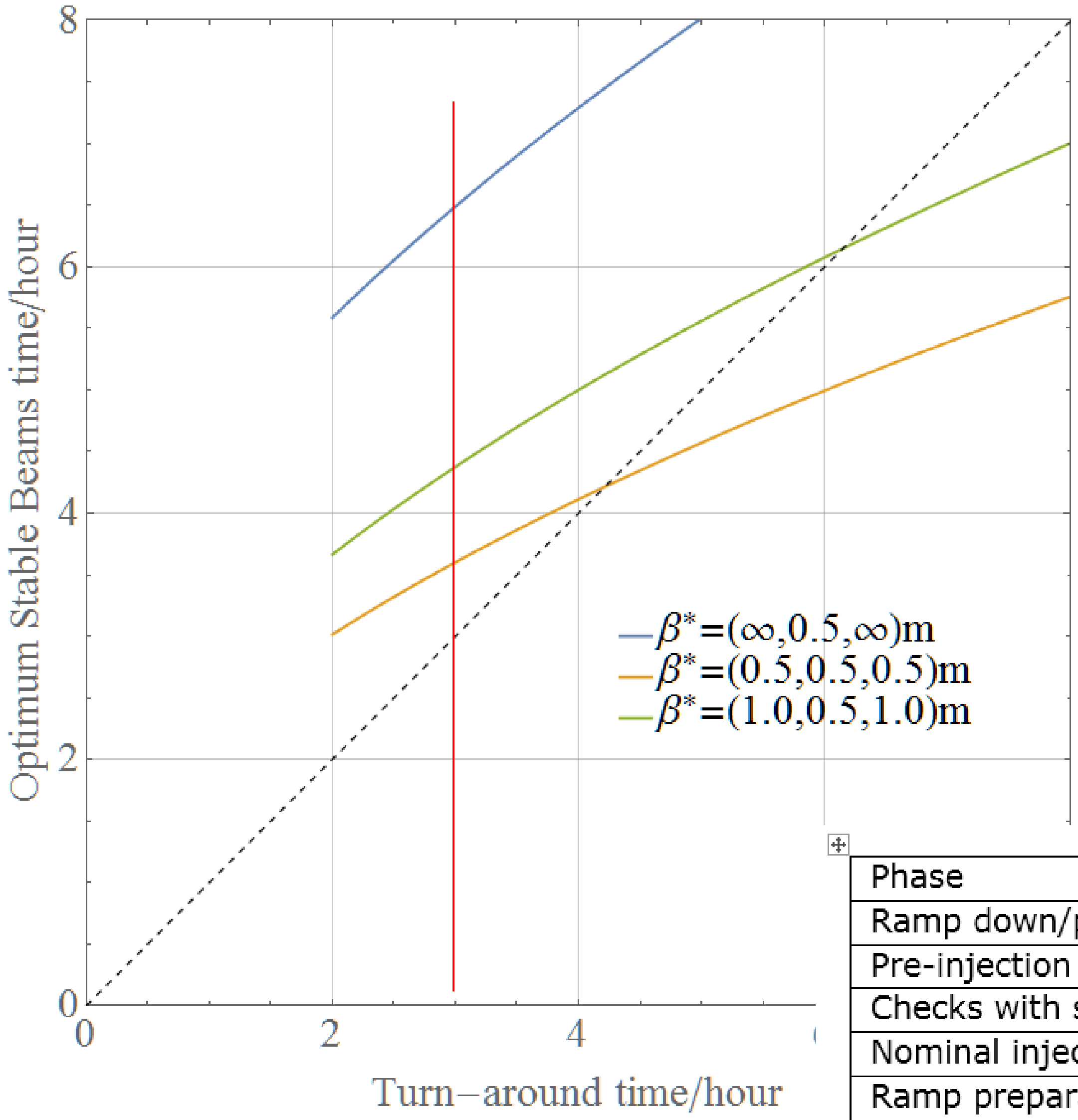
Turn around time =(3,5,7,9) h



Turn around time =3 h

Shown for each luminosity sharing scenario

Optimum time spent in Stable Beams



Assumes the operators know that the next turn-around time will be the same value.

Break-down of the minimum turn-around time as for p-p

Phase	Duration [min]
Ramp down/pre-cycle	60
Pre-injection checks and preparation	15
Checks with set-up beam	15
Nominal injection sequence	30
Ramp preparation	5
Ramp	25
Squeeze/Adjust	40
Total	190

Integrated luminosity in annual Pb-Pb run

$$L_{\mathrm{int,annual}} = \eta \langle L \rangle T_{\mathrm{run}}$$

where we assume an operation efficiency $\eta =$ 50% (c.f. 35% in 2011) and $T_{\mathrm{run}} = 24$ day.

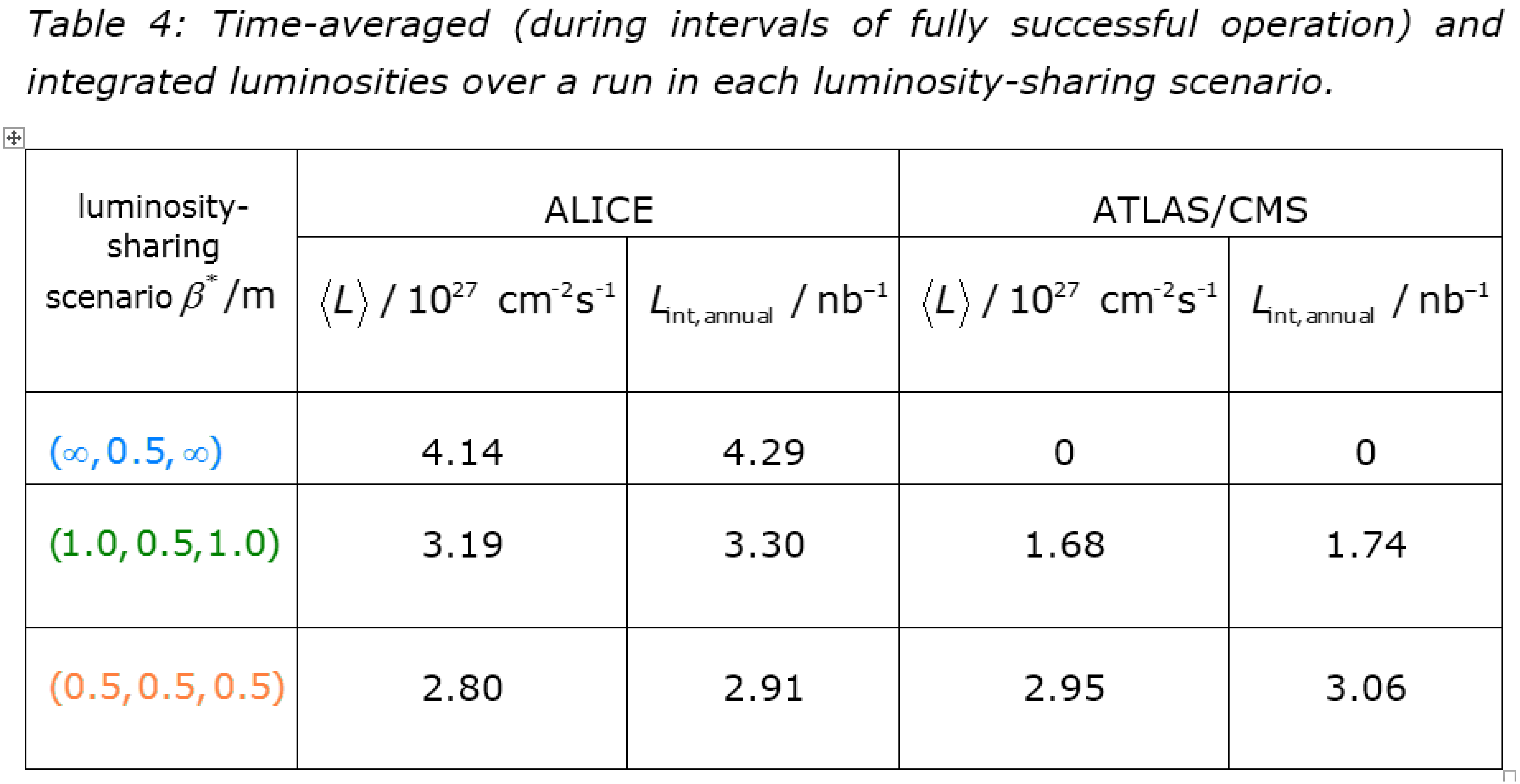


Table 4: Time-averaged (during intervals of fully successful operation) and integrated luminosities over a run in each luminosity-sharing scenario.

luminosity-sharing scenario β^* /m	ALICE		ATLAS/CMS	
	$\langle L \rangle / 10^{27}\ \mathrm{cm^{-2}s^{-1}}$	$L_{\mathrm{int,annual}} / \mathrm{nb^{-1}}$	$\langle L \rangle / 10^{27}\ \mathrm{cm^{-2}s^{-1}}$	$L_{\mathrm{int,annual}} / \mathrm{nb^{-1}}$
$(\infty, 0.5, \infty)$	4.14	4.29	0	0
$(1.0, 0.5, 1.0)$	3.19	3.30	1.68	1.74
$(0.5, 0.5, 0.5)$	2.80	2.91	2.95	3.06

Required parameters at injection

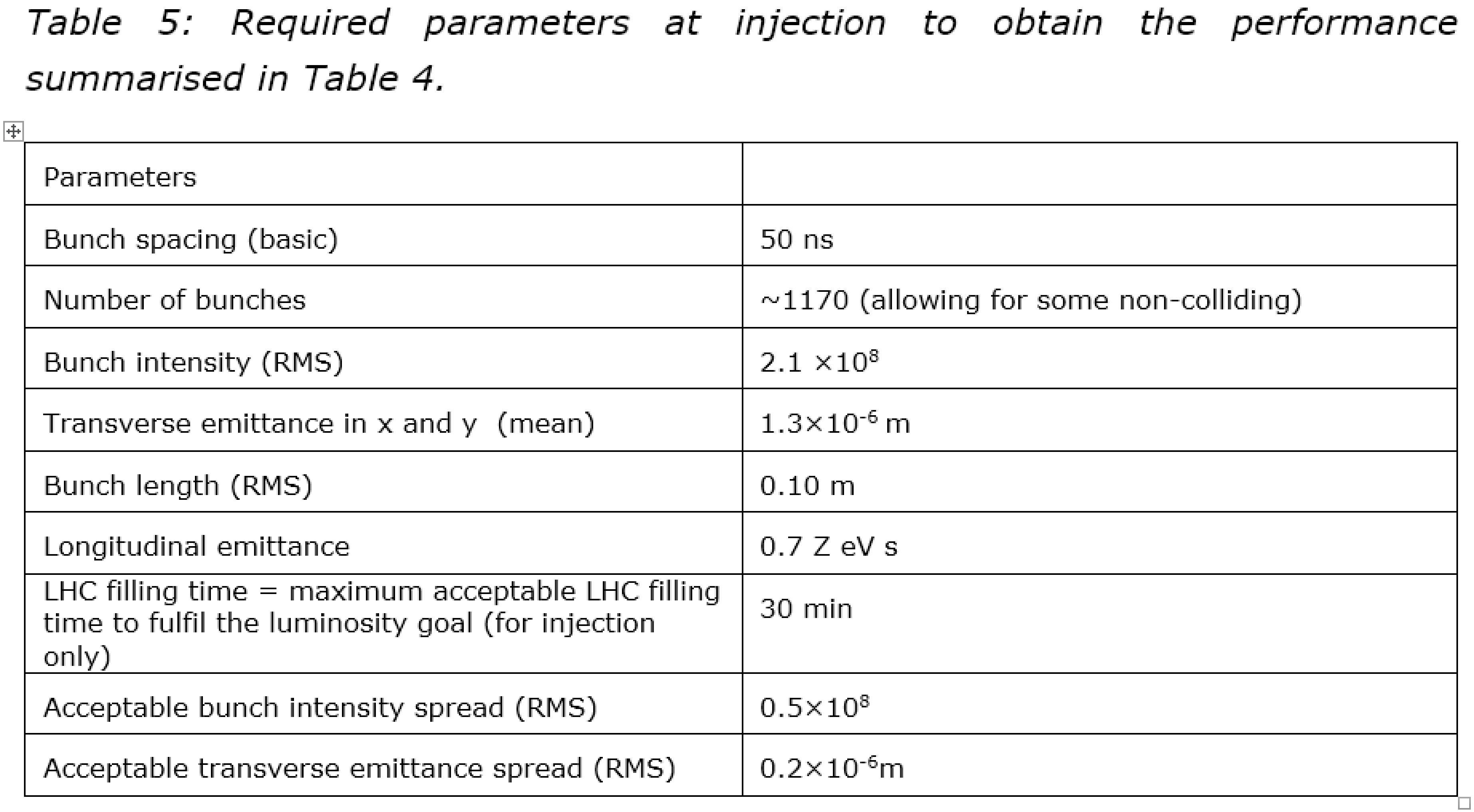


Table 5: Required parameters at injection to obtain the performance summarised in Table 4.

Parameters	
Bunch spacing (basic)	50 ns
Number of bunches	~1170 (allowing for some non-colliding)
Bunch intensity (RMS)	2.1×10^{8}
Transverse emittance in x and y (mean)	1.3×10^{-6} m
Bunch length (RMS)	0.10 m
Longitudinal emittance	0.7 Z eV s
LHC filling time = maximum acceptable LHC filling time to fulfil the luminosity goal (for injection only)	30 min
Acceptable bunch intensity spread (RMS)	0.5×10^{8}
Acceptable transverse emittance spread (RMS)	0.2×10^{-6}m

Margins on intensity and emittance from injection to collision (see RLIUP for past runs), also roughly comparable to assumptions for protons.

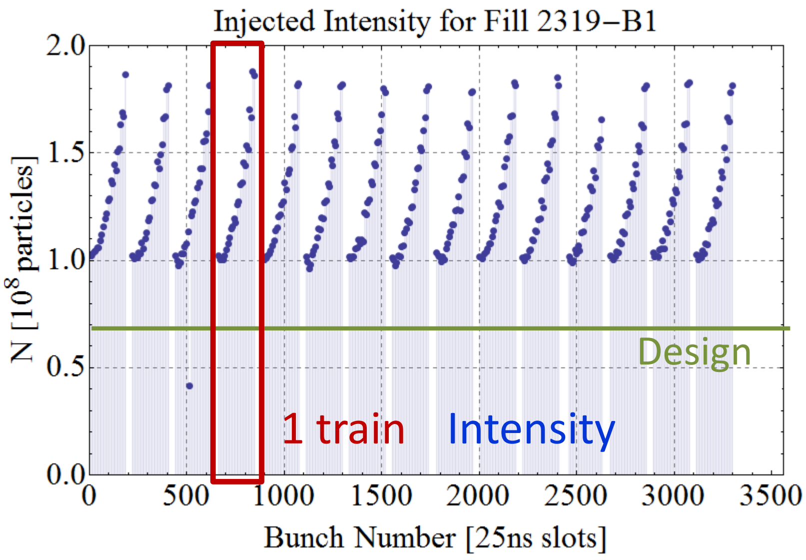
Reminder of realistic projections

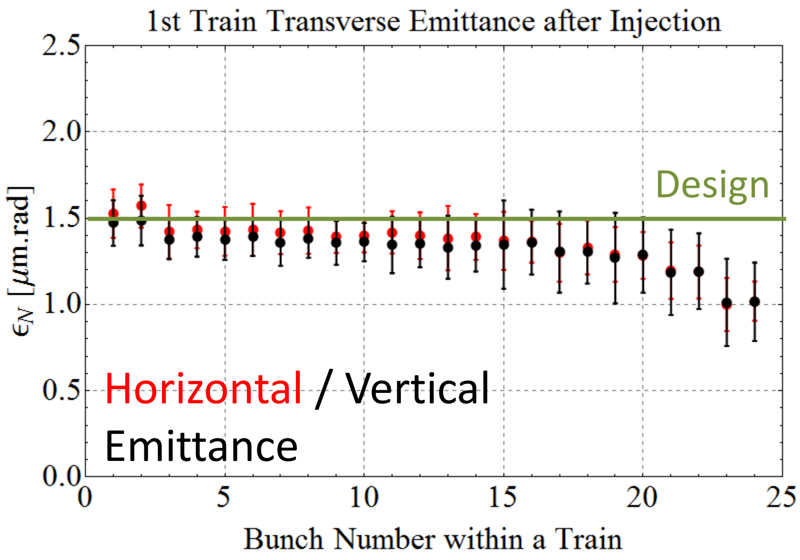
- These numbers were computed backwards from the requested integrated luminosity.

- Realistic estimates, given the known performance of the injectors and known expectations for future improvements were given at RLIUP and still stand.

Bunch-by-Bunch Differences after Injection in the LHC

E = 450 Z GeV





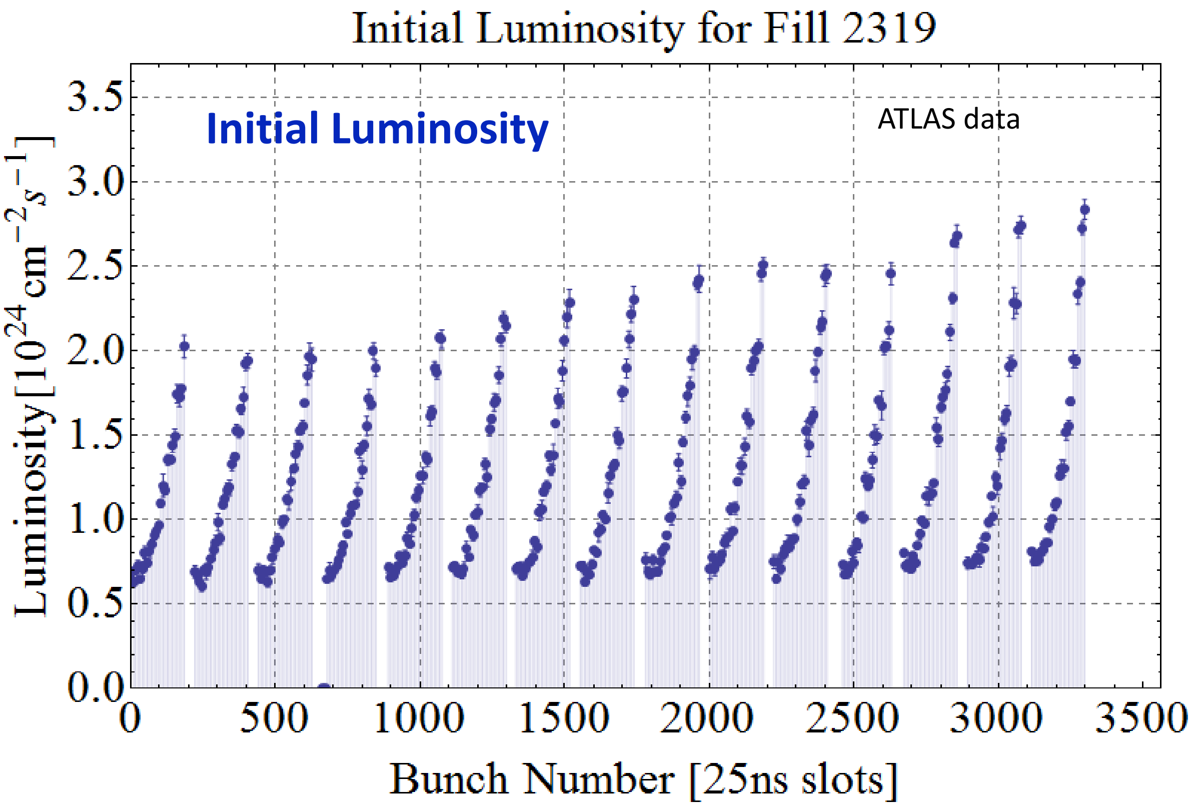
- Structure within a train (1st to last bunch):
  - increase: - intensity
    - bunch length
  - decrease: emittance.

- IBS, space charge, RF noise … at the injection plateau of the SPS:
  - while waiting for the 12 injections from the PS to construct a LHC train.

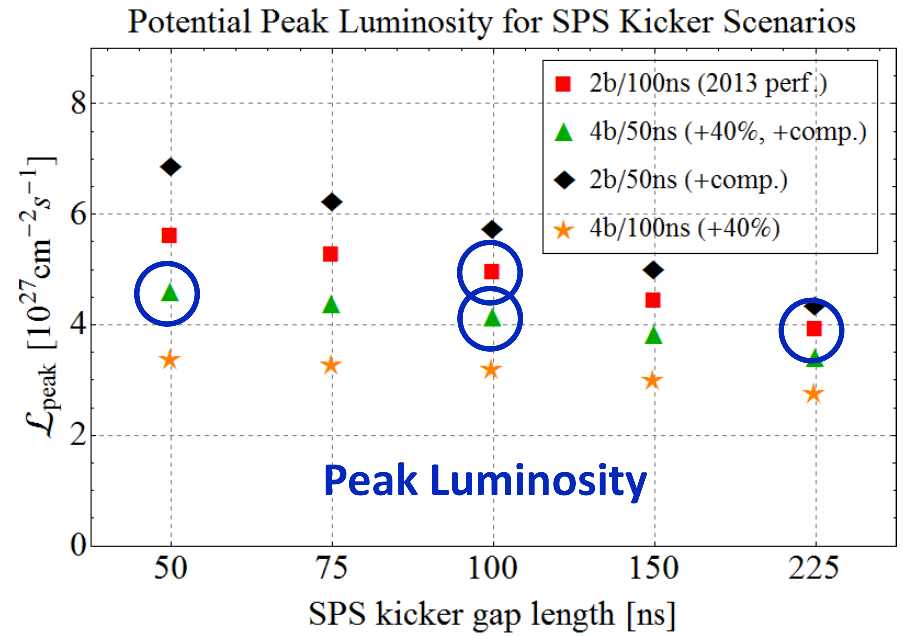
- First injections sit longer at low energy
  → strong IBS,
  → emittance growth and particle losses.

Bunch-by-Bunch Luminosity

E = 3.5Z TeV

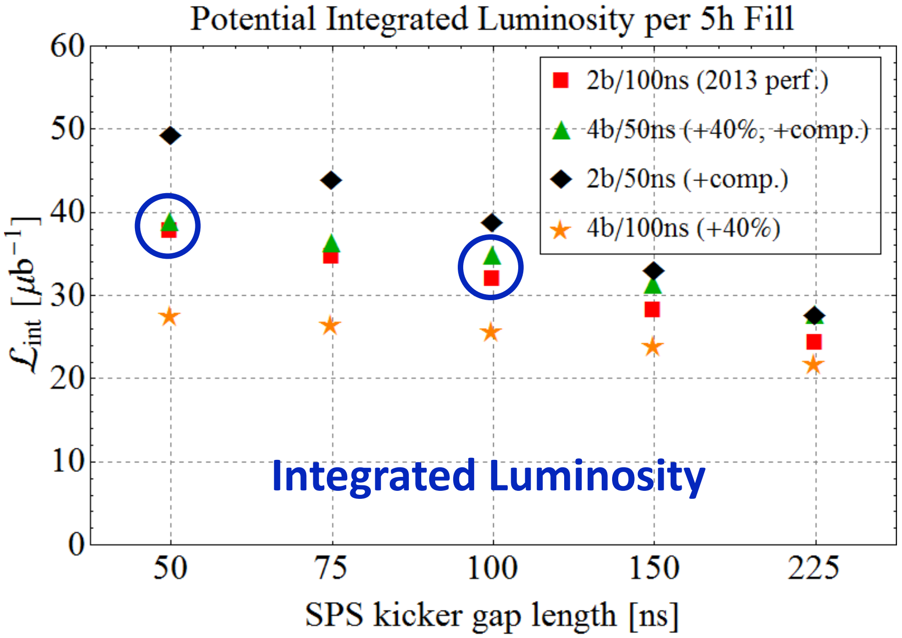


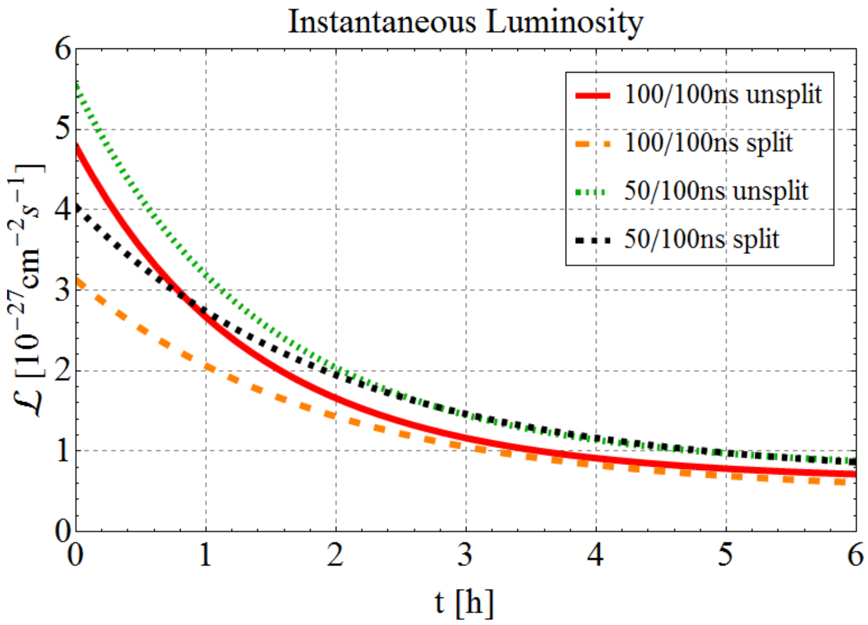
Estimates for after LS2 from RLIUP (realistic)



Peak luminosity higher for 100ns PS spacing with unsplit bunches.
→ Higher brightness bunches decay faster.
→ Higher integrated luminosity for 50ns PS spacing with split bunches.

50/100ns split → ~1000 bunches/beam
100/100ns unsplit → ~600 bunches/beam





Luminosity projection summary (RLIUP realistic)

- Does not include any improvements beyond injection schemes and natural change of β^*=0.5 m and beam size at 7 Z TeV. Some will be mentioned on next slide.
- Model will be re-fitted to real injector chain performance in the run-up to a given Pb-Pb run to re-optimise the length of the SPS trains. Improvements on SPS flat bottom can have a big impact.

Scenario	L_{peak} [Hz/mb]	L_{int} after 3h $[\mu b^{-1}]$	L_{int} after 5h $[\mu b^{-1}]$	L_{int} in run with 30×5h	$L_{int,run}$ naïve "Hubner Factor"	
200/200ns	2	15	21	$0.64\ nb^{-1}$	$0.64 nb^{-1}$	2011 @ 7Z TeV
100/225ns	3.7	19	25	$0.8\ nb^{-1}$	$1.2\ nb^{-1}$	Run 2
100/100ns	5.0	25	32	$1.0\ nb^{-1}$	$1.6\ nb^{-1}$	**Old baseline**
50/50ns	4.6	29	39	$1.2\ nb^{-1}$	$1.5\ nb^{-1}$	Slip Stacking
50/100ns	4.1	26	35	$1.1\ nb^{-1}$	$1.3\ nb^{-1}$	Batch Compression

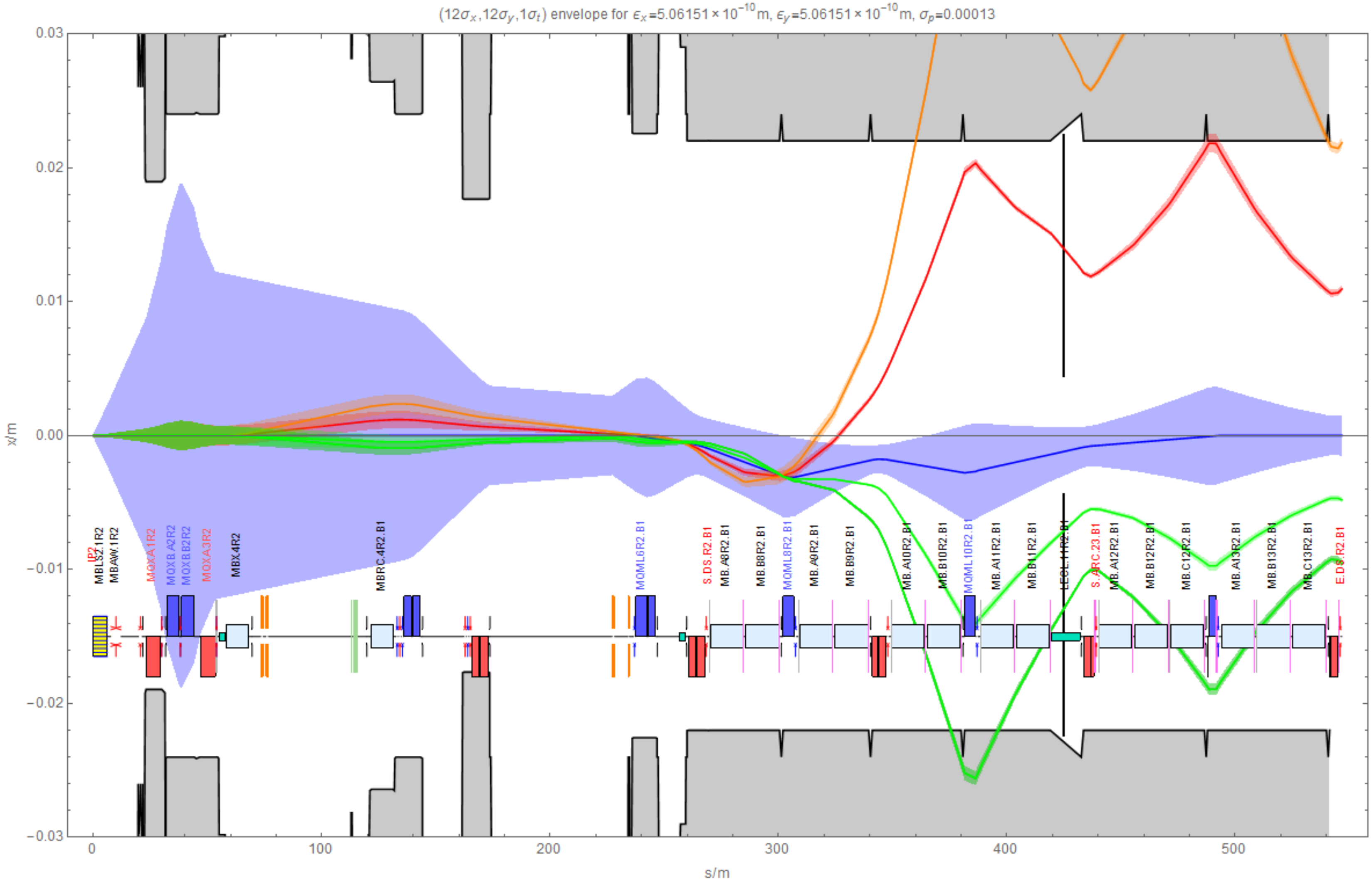
Evolution of DS Collimation for LHC

- Need for DS collimators emerged at Chamonix 2003 but too late to modify original design of cold DS regions
- DS collimators may be needed, with varying degrees of likelihood/urgency, for:
  - Pb-Pb luminosity losses (BFPP, EMD, …) around ALICE
  - Pb-Pb and p-Pb collimation losses in IR7 and IR3
  - p-p collimation losses in IR7 and IR3
  - Pb-Pb luminosity losses (BFPP, EMD, …) around ATLAS, CMS
  - p-p luminosity debris around ATLAS, CMS at HL-LHC
- Original solution (moving magnets to make space) dropped in favour of modular scheme, replacing standard MB dipole magnet with (2×11 T dipoles+TCLD) unit, applicable in all potential locations.
  - Synergy with high-field magnet development.
- Following 2013 Collimation Review:
  - First installation (2 TCLD units) foreseen for ALICE Pb-Pb in LS2, **subject to confirmation after 2015 Pb-Pb run and tests of bump mitigation techniques**
  - Further installations elsewhere in LS3, depending on experience at higher energy and luminosity, quench test results, etc

Alternative TCLD installation for IR2

- Bump mitigation as in 2011 experiment is less effective in IR2 than in IR1/IR5
  - Some effect predicted in 2009 paper, could be marginally enough, depending on true quench limit, plan to test in 2015
  - Hence IR2 was given priority for possible TCLDs
- Alternative proposed at ColUSM 1 August 2014 http://indico.cern.ch/event/333525/
- Because of the form of the dispersion function in IR2, there is a possibility that we can combine bumps and an alternative location of the TCLD in the connection cryostat (missing MB)
  - No 11 T magnets required
  - Different but apparently simpler integration
  - Significant orbit bump during luminosity operation !
  - Option to include an additional horizontal corrector beside it.

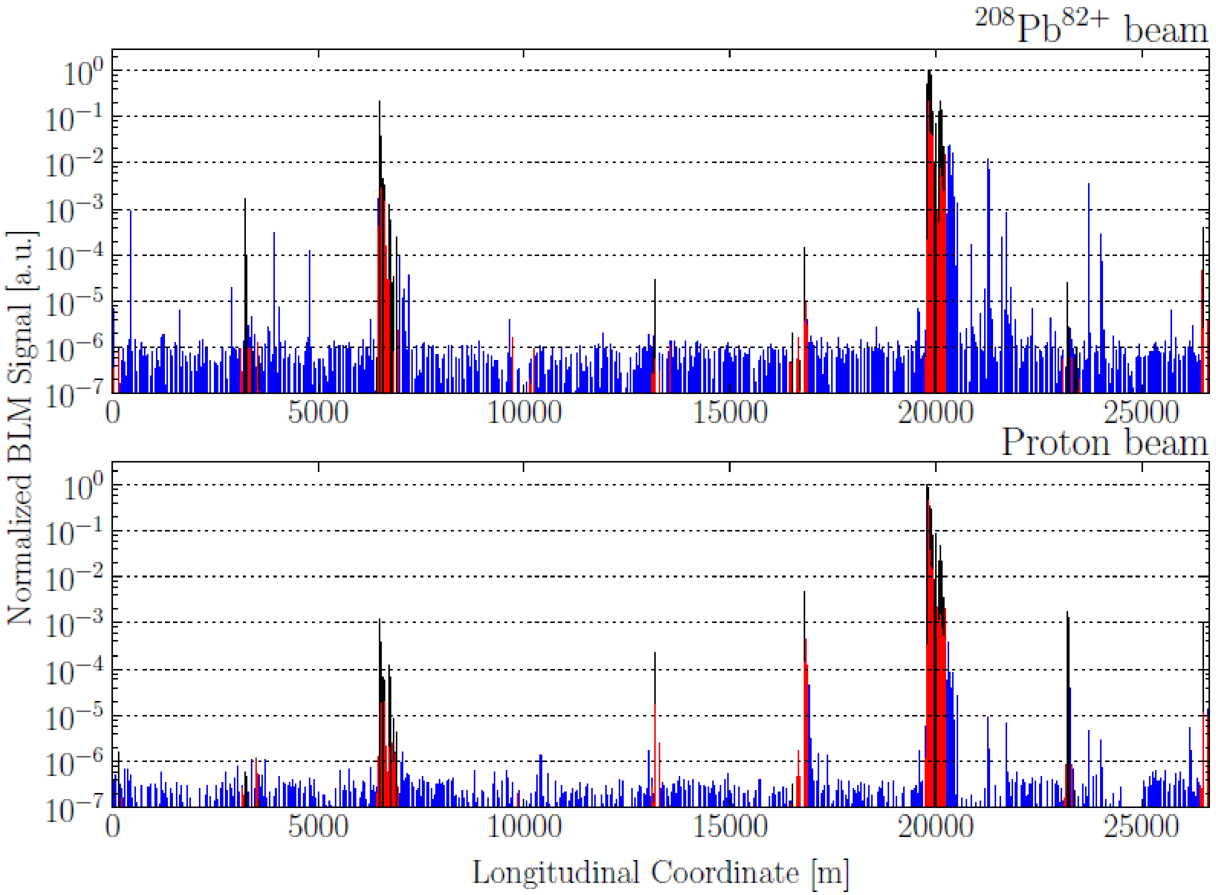
TCLD in connection cryostat at IR2



Variations of optics, bump and use of available orbit correctors studied (Tom Mertens, detailed document coming). Solution only applicable in IR2.

Introduction

Example for measured LHC lossmap

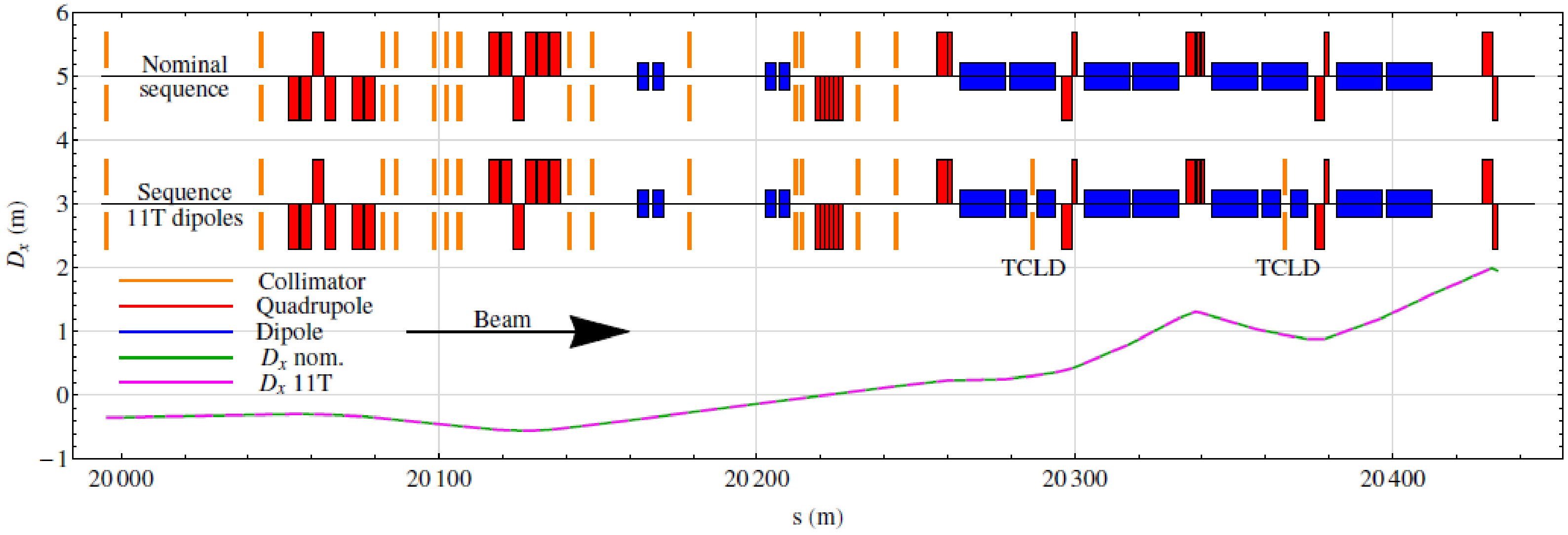


Data presented in P. Hermes et al., Proc. HB2014, MOPAB43 & R. Bruce et al., Proc. IPAC 2014, MOPRO042

Collimation of Pb beams

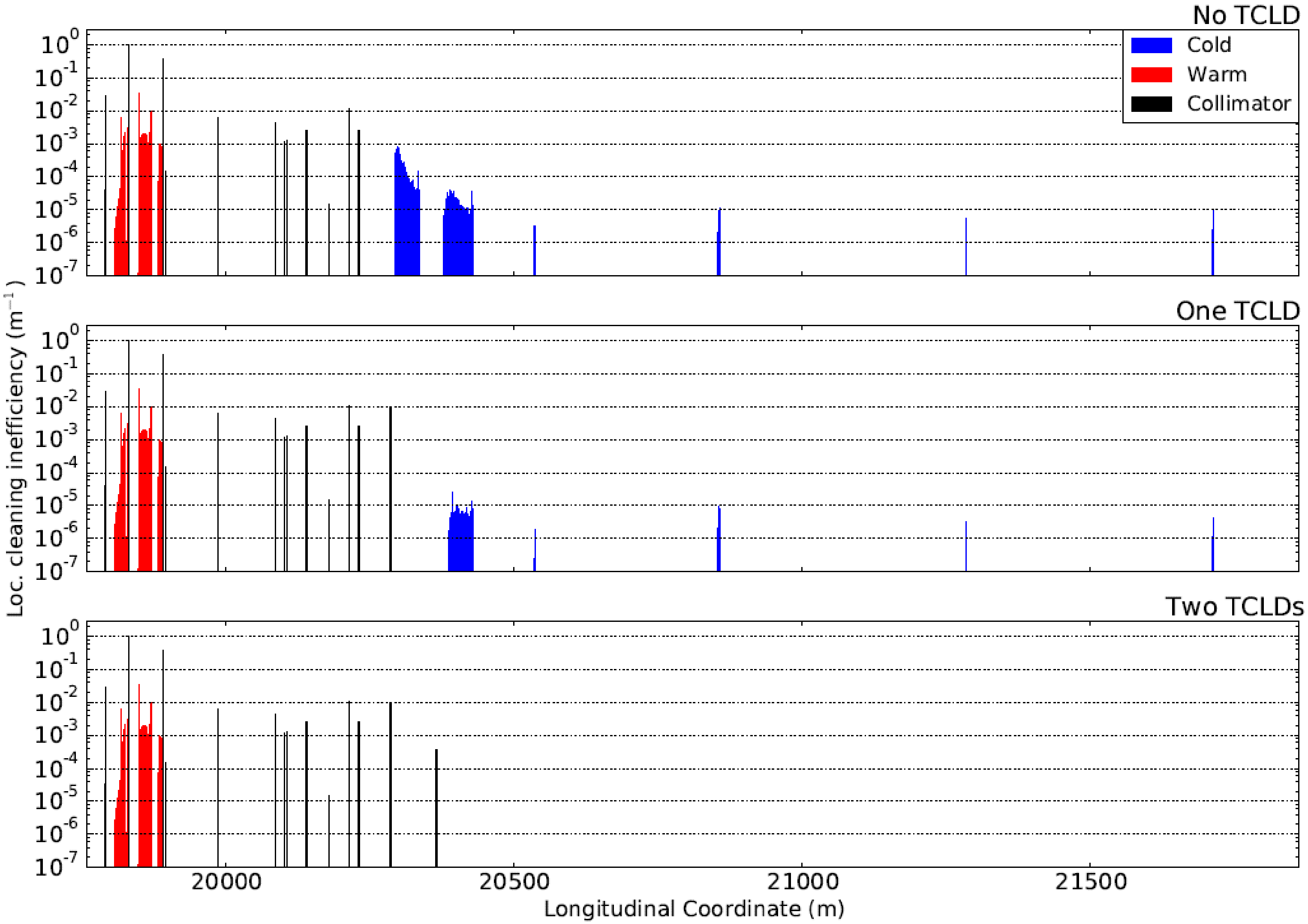
- IR7 DS is the limiting location in terms of cleaning inefficiency
- Heavy-ion cleaning performance even worse than for protons (by two orders of magnitude)
- Planned increase of ion intensity in run 3 might be limited by the ion cleaning performance
- Possible solution for better proton cleaning : TCLD collimators: replace dipole by two shorter dipoles with collimator inbetween
- Gain in cleaning efficiency for heavy-ion beams ?

TCLD concept



- Replacement of one or two DS dipoles by two shorter and stronger dipoles
- Use the freed space to install TCLD collimators
- How is the ion cleaning performance going to improve ?

Simulation Result



Relation to quench limit

Very preliminary estimate of quench limit in terms of local cleaning inefficiency with envisaged (ambitious) Pb beam parameters :

- Number of bunches $n_b = 1100$
- Nucleons per bunch $N = 208 \times 1.9 \times 10^8$
- Beam lifetime $\tau = 12 \times 60\,\mathrm{s}$
- Quench limit at $7\,Z$ TeV : $N_Q = \left(\frac{208}{82}\right) \times 7.8 \times 10^6 \,\frac{\mathrm{nuc}}{\mathrm{m}\times\mathrm{s}}$ corresponding to $5\,\mathrm{mW/cm^3}$

$$\eta_Q = \frac{\tau}{N\, n_b}\, N_Q = 3.3 \times 10^{-4}\,\mathrm{m}^{-1}$$

- Quench limit estimate[1] conservative, could be updated

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1. C. Bracco, Thesis, 2008, CERN-THESIS-2009-031

Status of DS collimators for heavy-ion operation

- The scheme with 2 TCLDs in connection cryostats seems the best option for IR2
  - Lower cost, does not depend on 11 T magnets
- May need TCLDs + 11 T magnets in IR7
- Bump mitigation (to be tested) probably adequate for IR1, IR5 (less likely to need TCLD+11 T magnets in LS3)
- Need to be confirmed by quench tests (p, Pb) and operational experience with mitigation schemes during 2015

Summary

- For LIU needs, we can propose the bunch parameters in the last table, ie, essentially nominal but with, in a mean-square sense over all bunches perhaps,

$$N_b = 2.1\times10^8 \quad \text{(c.f. design } 0.7\times10^8 \text{ , 2013 maximum } 2.2\times10^8 \text{)}$$

  - EDMS note giving functional spec
- Filling scheme should allow ~1100 colliding bunch pairs in ALICE
  - Crossing angles chosen for 50 ns basic spacing

- Integrated luminosity sharing among experiments is crucial …
- TCLD in connection cryostat is a good option for IR2
- May need TCLD + 11 T magnets in IR7

BACKUP SLIDES