Heavy Ion Performance of HL-LHC (from LS2)

mainly Pb-Pb (but also p-Pb)

John Jowett

Thanks for collaboration and contributions to:

Michaela Schaumann

S. Gilardoni, D. Manglunki (+LIU-Ions team), M. Giovannozzi, P. Hermes,
A. Lechner, F. Cerutti, G.E.Steele (+FLUKA, BLM/quench teams),

R. de Maria, T. Mertens, S. Redaelli (+collimation team),

Valuable discussions with:

G. Arduini, F. Bordry, Oliver Brüning, L. Rossi, LHC Experiments, …

The European Strategy for Particle Physics
Update 2013

Europe's top priority should be the ***exploitation of the full potential of the LHC****, including the high-luminosity upgrade of the machine and detectors with a view to collecting* ***ten times more data than in the initial design, by around 2030****. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

Where are we with respect to LHC Project Baseline?

	Pb-Pb				p-Pb	
	Baseline	**Injection 2011**	**Collision 2011**	**Injection 2013**	**“Design” 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 $[\mu\mathrm{m.rad}]$	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	115

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

“Future upgrade, not in LHC baseline”

LHC should attain it’s Pb-Pb design luminosity for 7 *Z* TeV (×2 for ATLAS, CMS?) at 6.37 *Z* TeV in the next few weeks (the start of HL-LHC heavy ions?).

p-Pb (unofficial) upgrade design luminosity for 7 *Z* TeV was achieved at 4 *Z* TeV in 2013.

Integrated nucleon-nucleon luminosity in Run 1

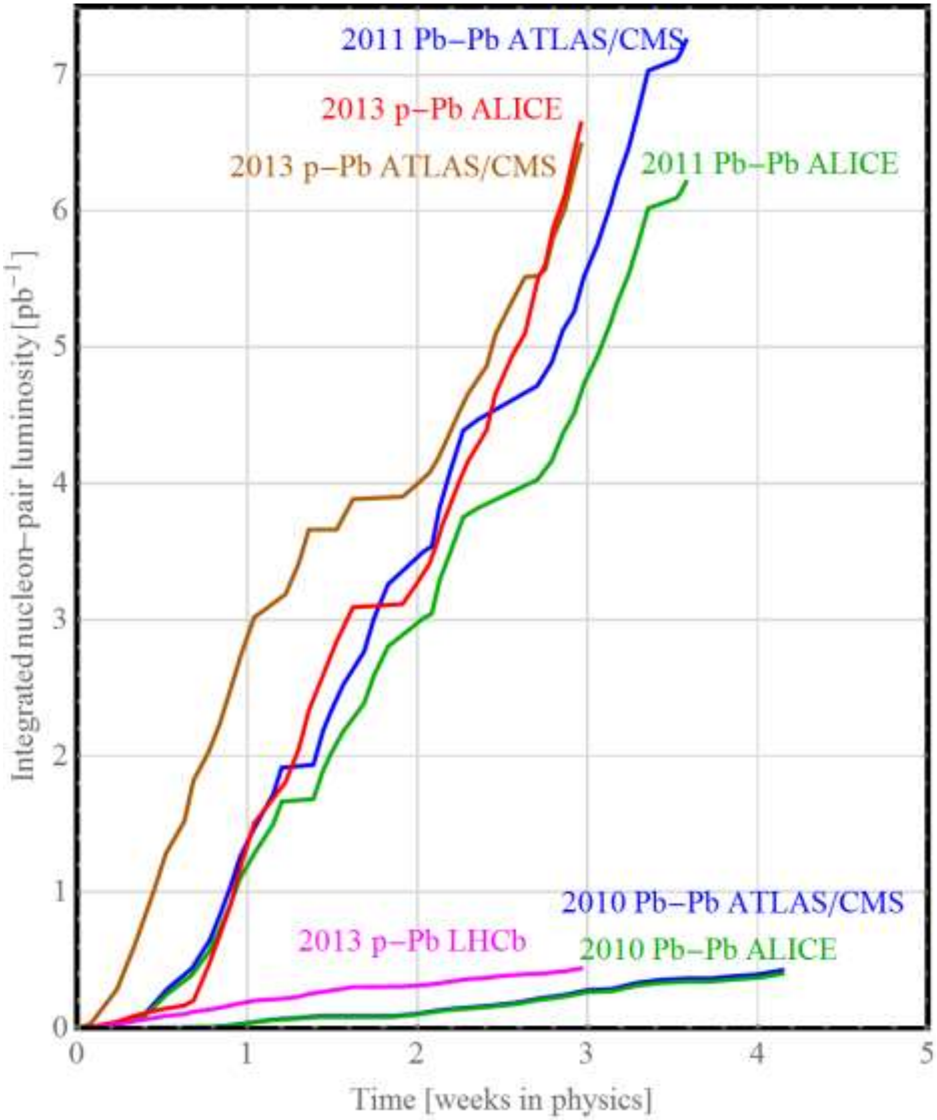
Expect to achieve LHC "first 10-year" baseline Pb-Pb luminosity goal of
1 AA nb^{-1} = 43 NN pb^{-1}
in Run 2 (=2015+2018)

Goal of the first p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs but it already provided reference data at Run 2 energy.

$$\sqrt{s_{NN}} = 5.02\ \text{TeV}$$

$$\Rightarrow E_b = \begin{cases} 6.37Z\ \text{TeV} & \text{in Pb-Pb} \\ 4\ Z\ \text{TeV} & \text{in p-Pb} \end{cases}$$

But annual 1-month runs are getting shorter and more complicated … 2015 will be 1/3 p-p reference data and include LHCb.



2012 pilot p-Pb run not shown (1 fill but major physics output)

ALICE's requested operating conditions [1]

- Maximum interaction rate of 50 kHz in Pb-Pb (ALICE upgrade in LS2)
- LoI assumed: peak luminosity of $6\times10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and an average luminosity of $2.4\times10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- The upgrade programme assumes an integrated luminosity of 10 nb^{-1} in PbPb at top energy
- In addition
  - 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.

- [1] ALICE upgrade Letter of Intent http://cds.cern.ch/record/1475243, endorsed by the LHCC on 27 Sep 2012 and approved by the Research Board on 28 Nov 2012 (http://cds.cern.ch/record/1499619/files/M-202.pdf)

Requested luminosity after LS2, updated from 2012 ALICE LoI

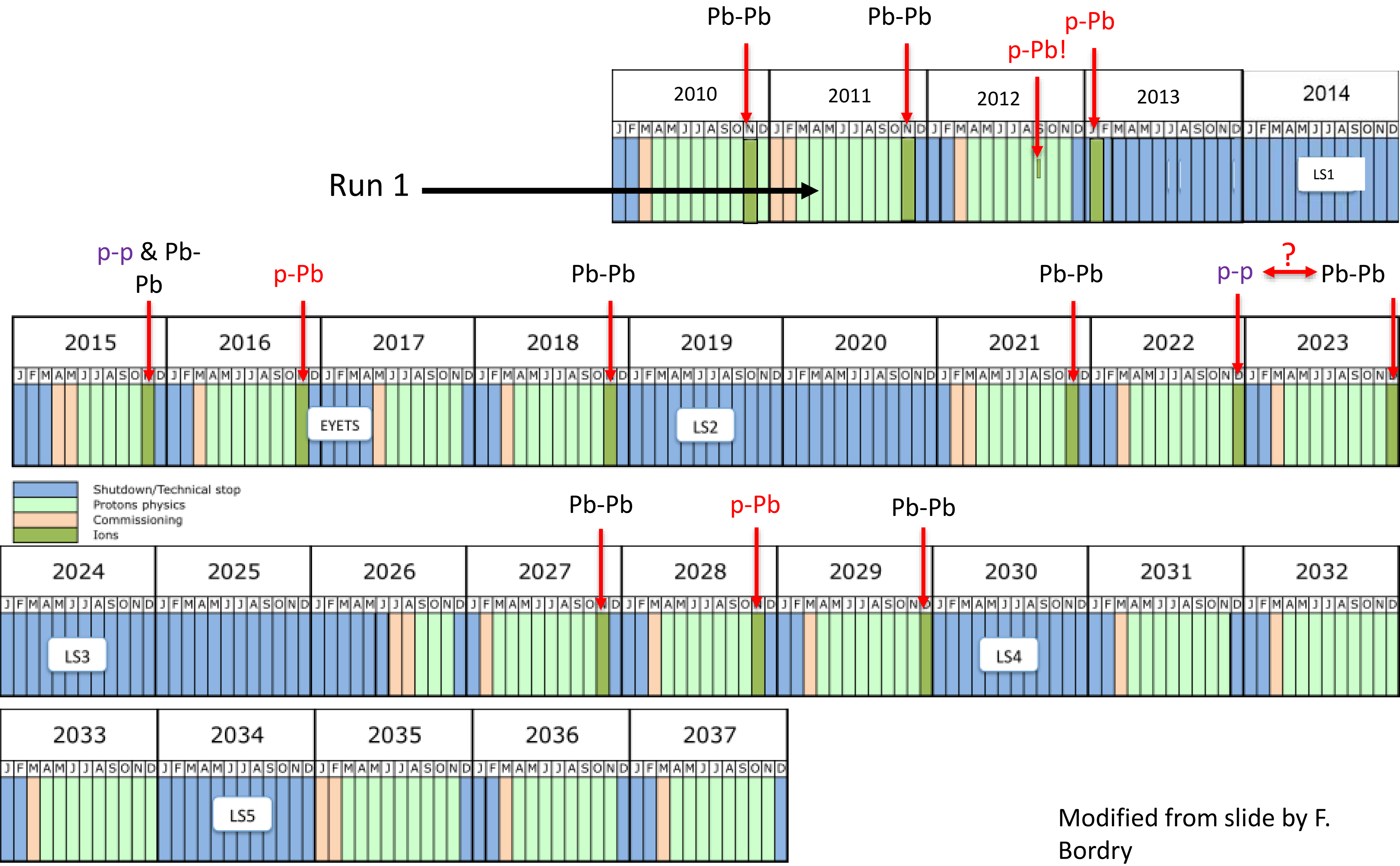
- Possible running scenario after upgrade:
  - 2021 - Pb-Pb 2.85 nb^{-1}
  - 2022 - Pb-Pb 2.85 nb^{-1}
  - 2023 - pp reference run
  - 2024,2025.6 - LS3
  - 2027 - Pb-Pb 2.85 nb^{-1}
  - 2028 - ½ Pb-Pb 1.5 nb^{-1} + ½ p-Pb 50 nb^{-1}
  - 2029 - Pb-Pb 2.85 nb^{-1}
  - 2030 LS4

We have been using the ALICE document as a reference but other experiments' requirements are broadly similar – see preceding talk by J. Wessels.

Likely to mutate into a straight p-Pb run.

- A degree of flexibility remains to redistribute Pb-Pb vs p-Pb vs p-p reference if experiments wish.
- In the following we concentrate on potential Pb-Pb luminosity in a single run.

LHC heavy-ion runs, past & future, according to ALICE 2012 LoI



Modified from slide by F. Bordry

Last presentation at HL-LHC/LARP meeting: Nov 2013

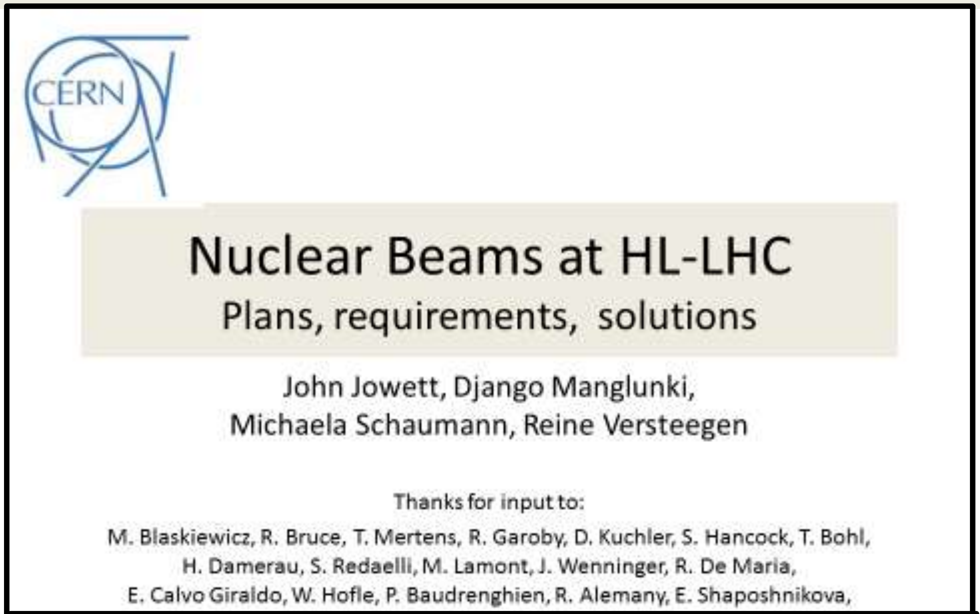
Analysis, in close collaboration with LIU project, of several plausible luminosity upgrade scenarios during 2013.

Detailed luminosity model coupling injector chain (filling of SPS from PS, intensity decay in SPS, …) and LHC luminosity evolution (CTE simulations extended to large variations along trains of intensity, IBS, luminosity burn-off, debunching, …).
[See also M. Schaumann thesis.]

Potential increases in luminosity:

- Overcome LEIR intensity limit and split bunches in PS
- SPS injection kicker upgrade
- Injection to Stable Beams efficiency
- Slip-stacking in SPS
- Stochastic cooling in collision

All scenarios fell short of ALICE request.

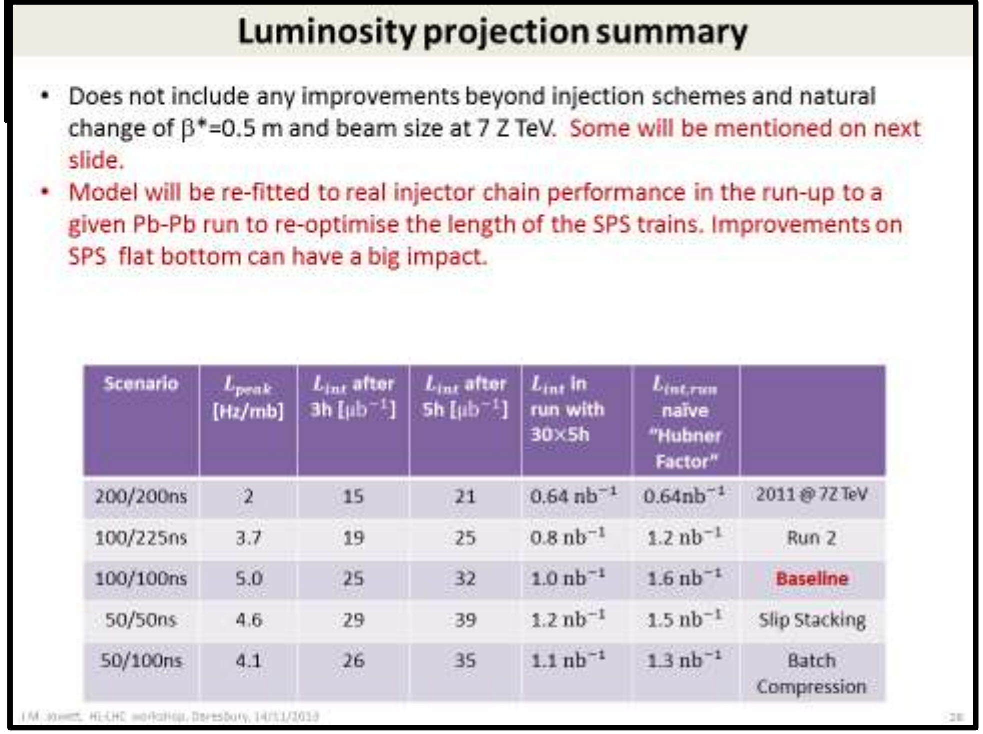


Nuclear Beams at HL-LHC

Plans, requirements, solutions

John Jowett, Django Manglunki,
Michaela Schaumann, Reine Versteegen

Thanks for input to:
M. Blaskiewicz, R. Bruce, T. Mertens, R. Garoby, D. Kuchler, S. Hancock, T. Bohl,
H. Damerau, S. Redaelli, M. Lamont, J. Wenninger, R. De Maria,
E. Calvo Giraldo, W. Hofle, P. Baudrenghien, R. Alemany, E. Shaposhnikova,



Luminosity projection summary

- 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 [μb^{-1}]	L_{int} after 5h [μb^{-1}]	L_{int} in run with 30×5h	$L_{int,run}$ naive "Hubner Factor"	
200/200ns	2	15	21	0.64 nb^{-1}	0.64nb^{-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}	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

J.M. Jowett, HL-LHC workshop, Daresbury, 14/11/2013

Parameter specification request by LIU (EDMS Note, 2015)

- Simplified scenario to make interface between LHC and injectors, **work back from ALICE request of 2.85 nb^{-1}/y**
  - 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 for illustration of the possibilities:

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

LHC Luminosity Model

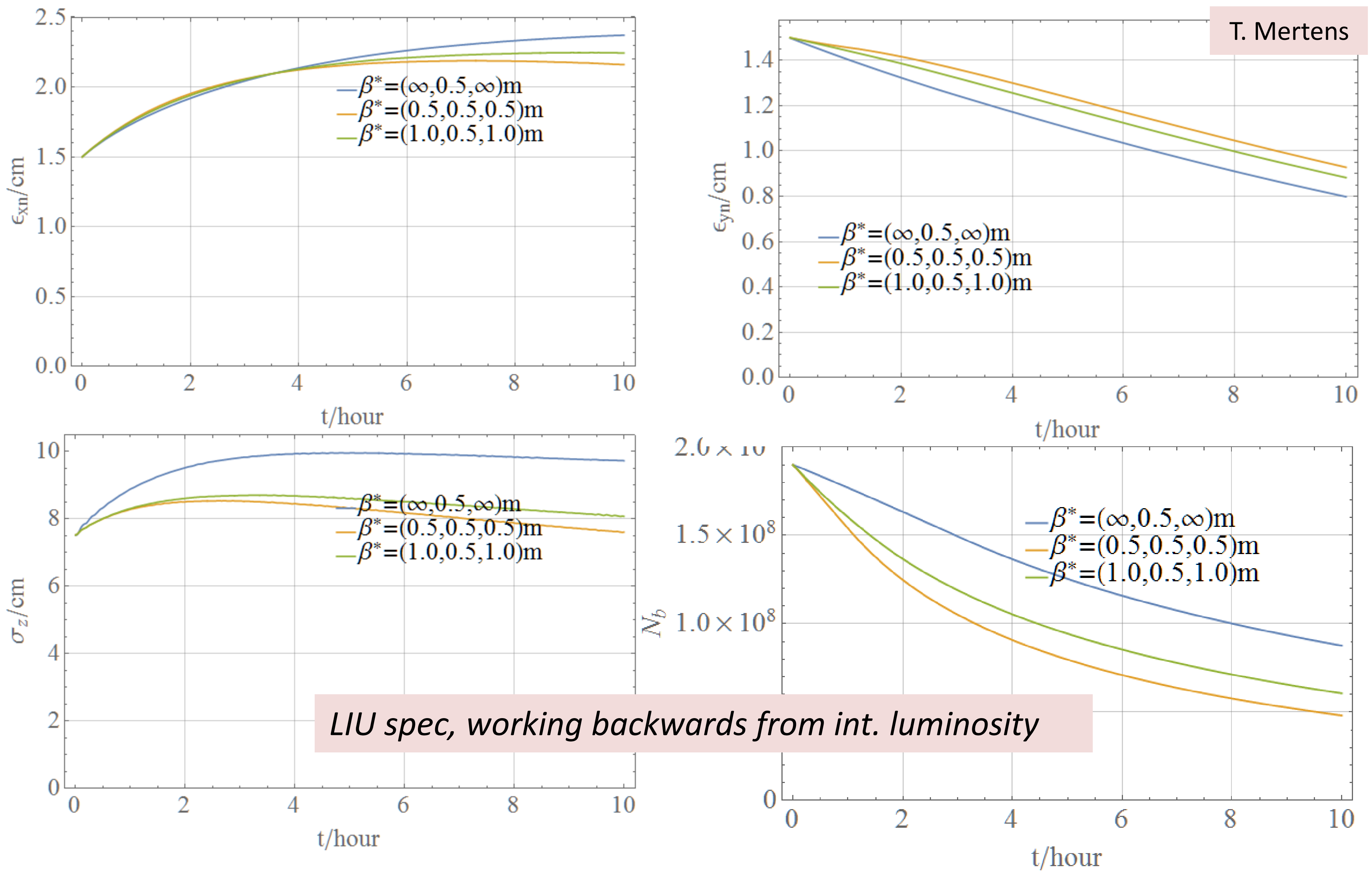
- CTE program
  - Macro-particle, macro-turn simulation of slow kinetic effects
  - Luminosity burn-off (very strong! Due to ultraperipheral "near-miss" electromagnetic interactions > 500 barn)
  - Luminosity with crossing angles (150,100,150) μrad
  - IBS with non-Gaussian longitudinal distribution
  - Debunching longitudinally (small here)
  - Synchrotron radiation damping (strong!), quantum excitation (tiny)
  - Simulates one bunch from each beam, experiencing collisions at several (different) IPs

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

LIU spec, working backwards from int. luminosity

Simulation of single colliding bunch pair



T. Mertens

LIU spec, working backwards from int. luminosity

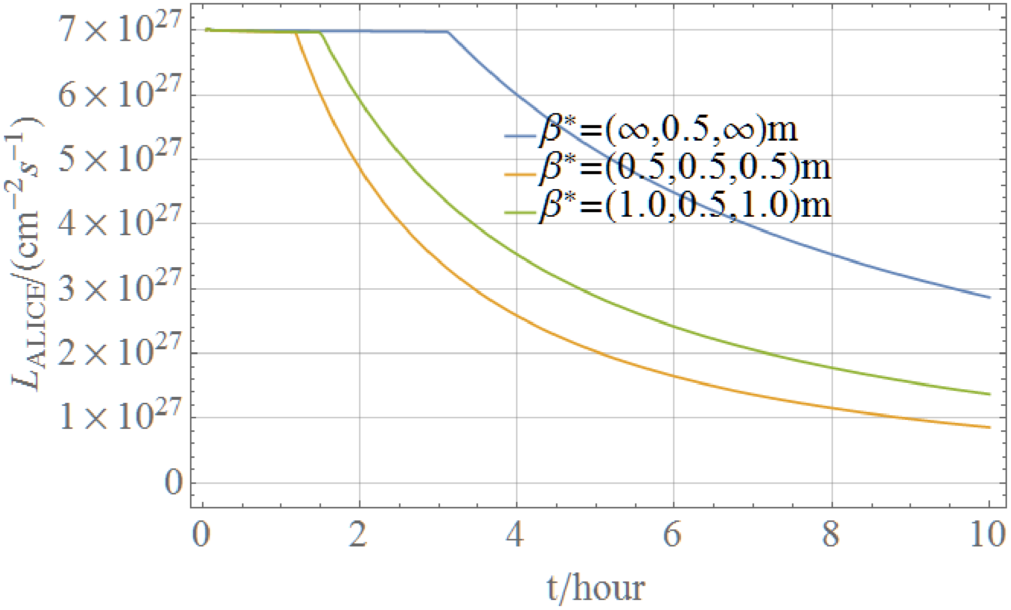
Interplay of radiation damping, IBS, luminosity burn-off couples all 4 quantities.
Different evolution according to luminosity-sharing scenario.

Filling scheme

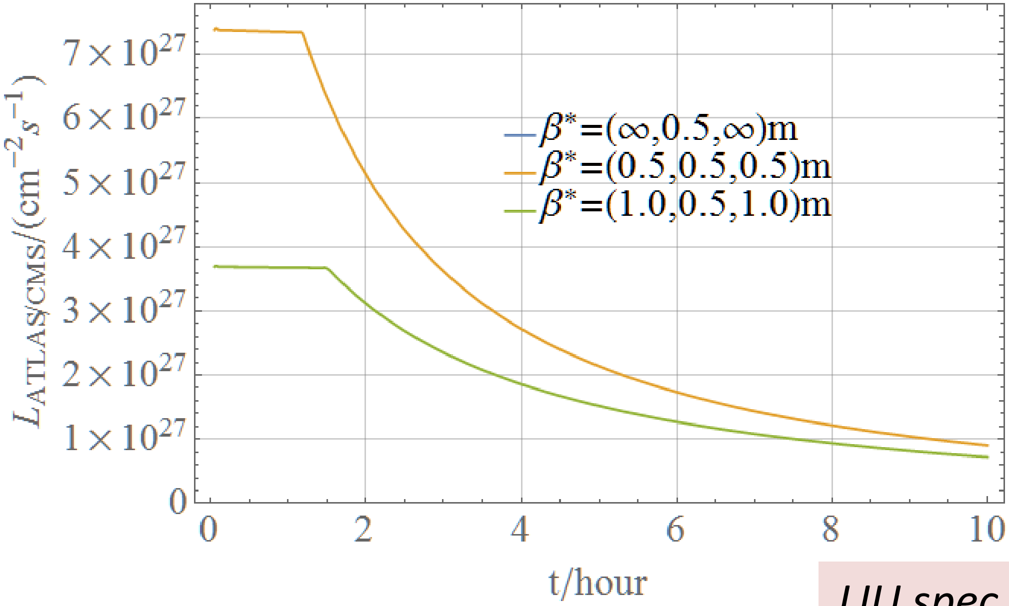
- Assume 1100 bunches colliding in ALICE, 1160 colliding in ATLAS/CMS
  - Approximation: neglect different collision histories of a few bunches, bunches all see the same burn-off
- This would need all of these:
  - LEIR intensity improvements to allow bunch splitting
  - SPS injection kicker for 100 ns rise time
  - Slip-stacking injection in SPS
  - **No intensity decay** in SPS so all bunches are the same!!!

LIU spec, working backwards from int. luminosity

Experiments' luminosities in an ideal (prolonged) fill



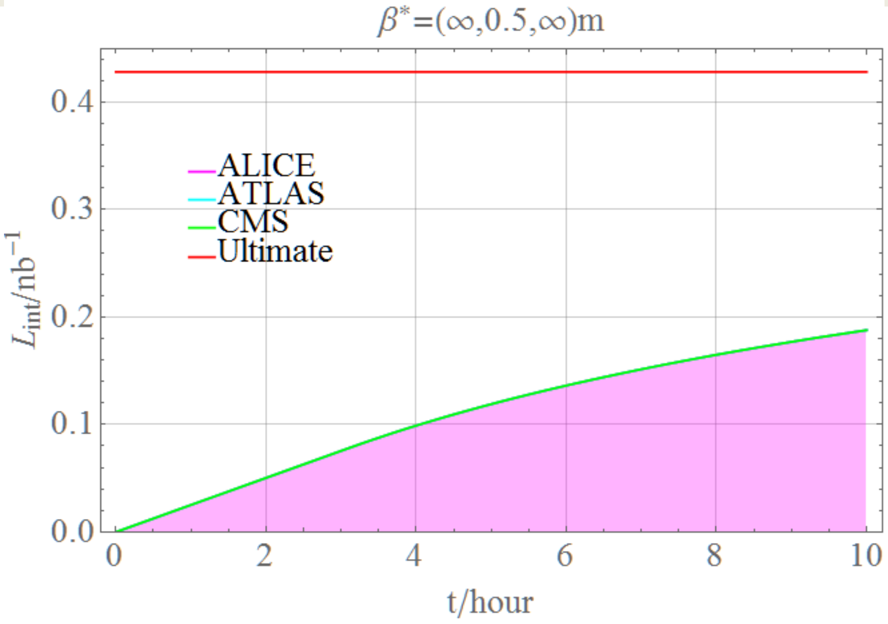
ALICE, levelling at maximum acceptable (rates around 50 kHz), assuming 1100 bunches colliding

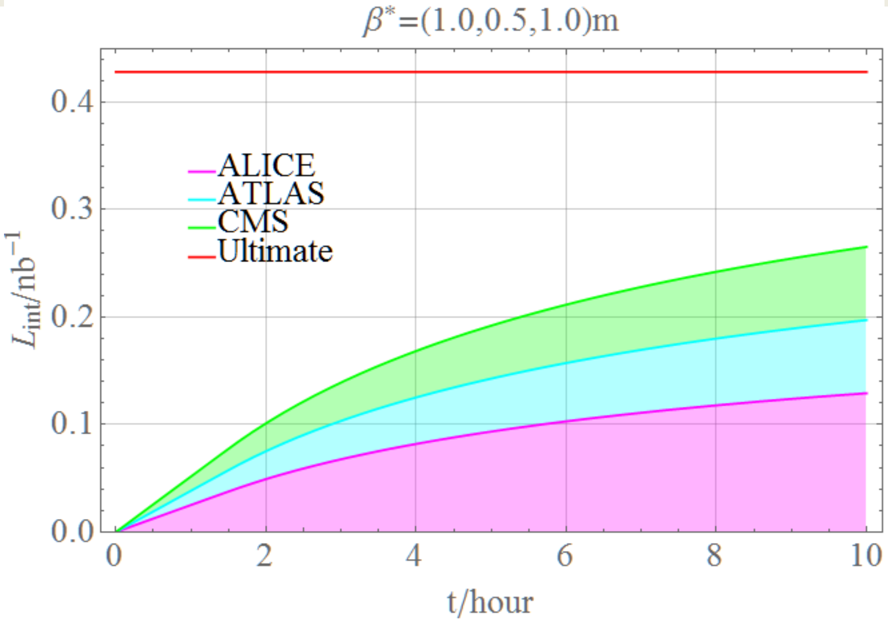


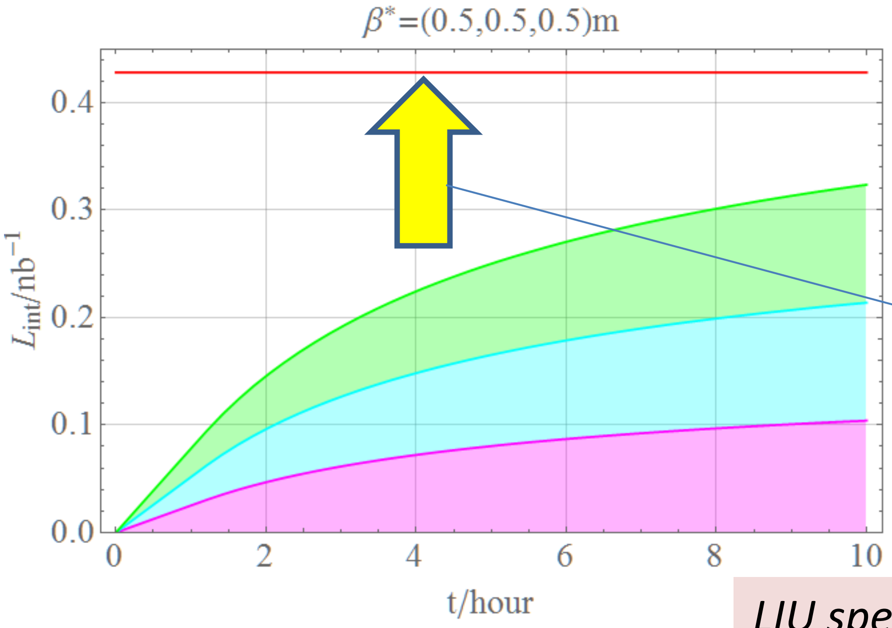
ATLAS or CMS, *assumed* levelling at corresponding levels to ALICE (not strictly necessary, assumption)

LIU spec, working backwards from int. luminosity

Integrated luminosity in fill







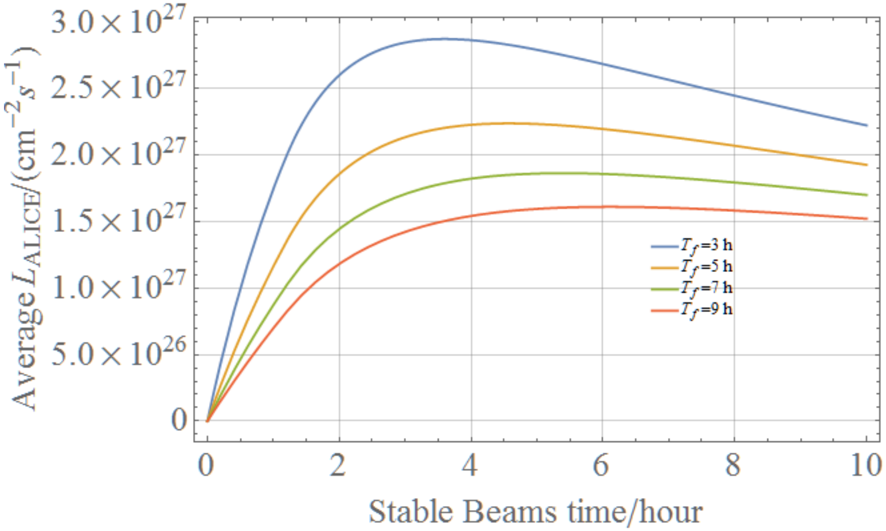
Ultimate luminosity to share

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

Potential for a stochastic cooling system

LIU spec, working backwards from int. luminosity

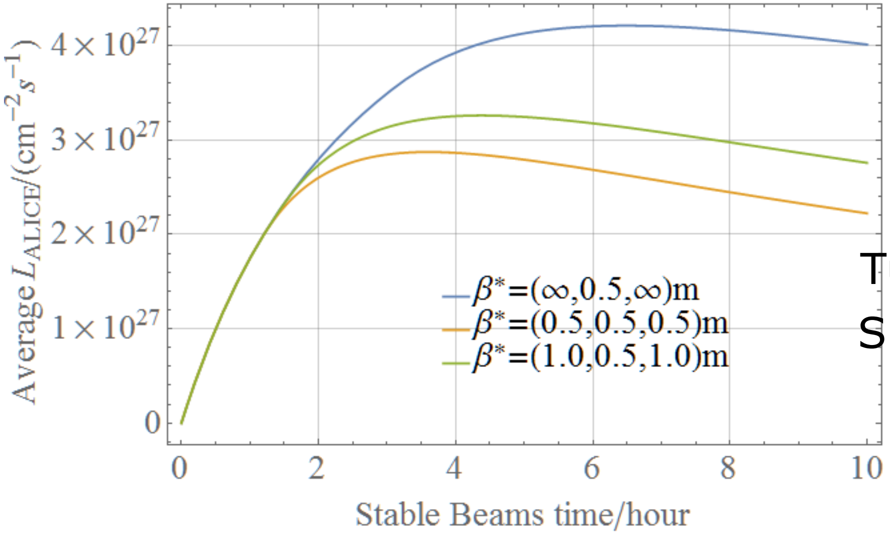
Effect of turn-around time on average luminosity



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

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

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

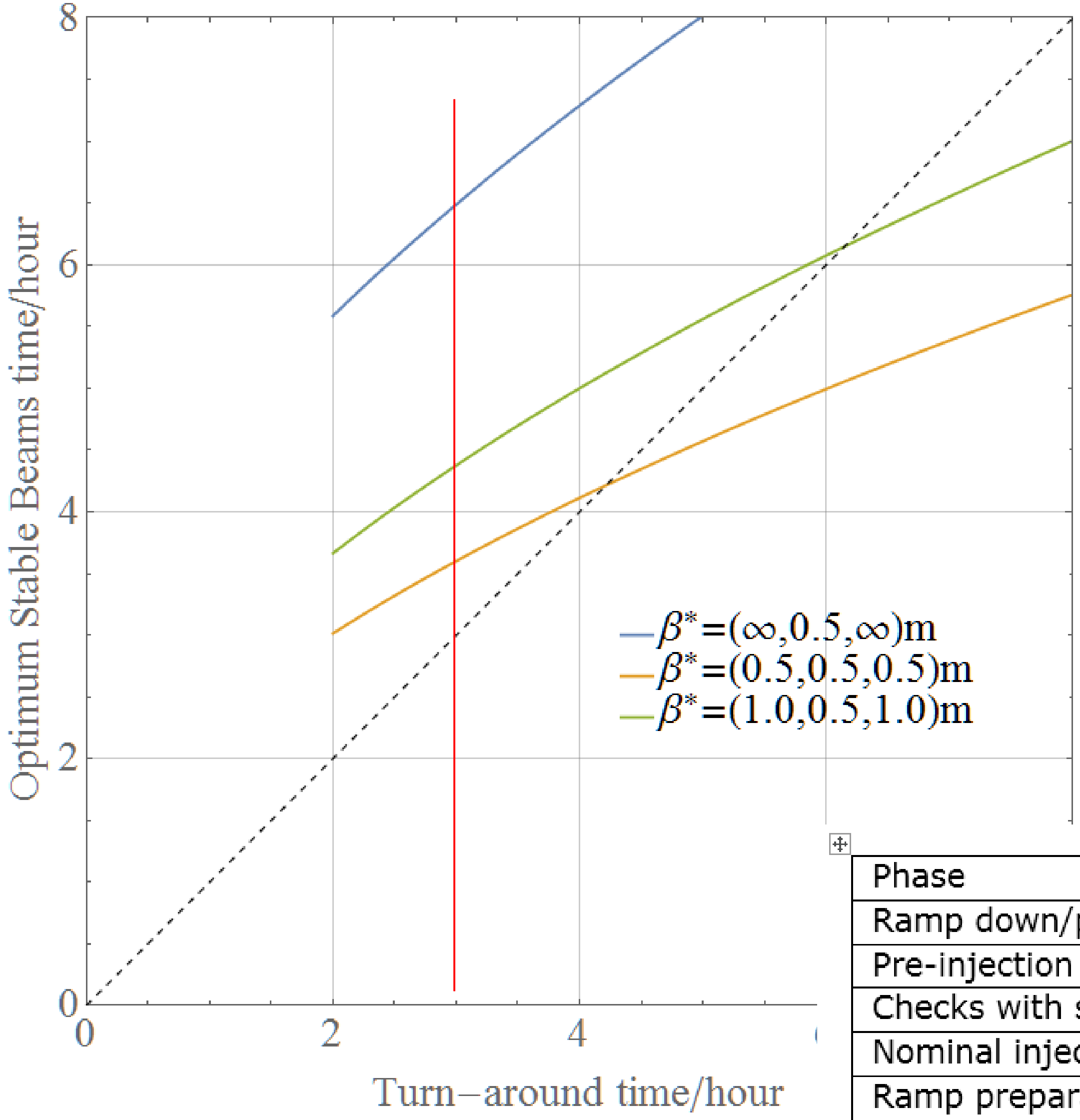


Turn around time =3 h

Shown for each luminosity sharing scenario

LIU spec, working backwards from int. luminosity

Optimum time spent in Stable Beams



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

LIU spec, working backwards from int. luminosity

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

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

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

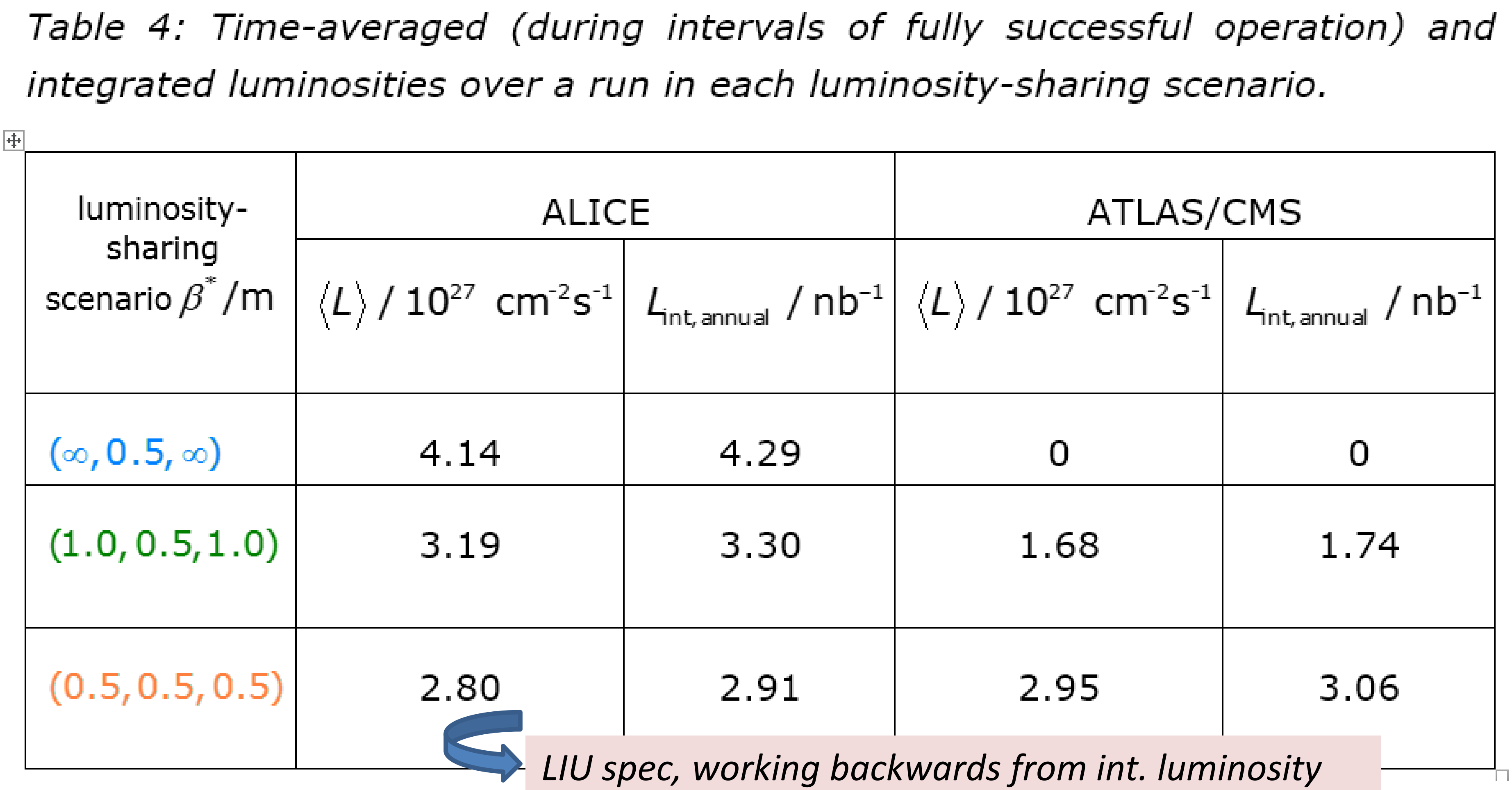


Table 4: Time-averaged (during intervals of fully successful operation) and integrated luminosities over a run in each luminosity-sharing scenario.

luminosity-sharing scenario β^* /m	ALICE		ATLAS/CMS	
	$\langle L \rangle$ / 10^{27} cm^{-2}s^{-1}	$L_{\text{int, annual}}$ / nb^{-1}	$\langle L \rangle$ / 10^{27} cm^{-2}s^{-1}	$L_{\text{int, annual}}$ / 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

LIU spec, working backwards from int. luminosity

Required parameters at injection

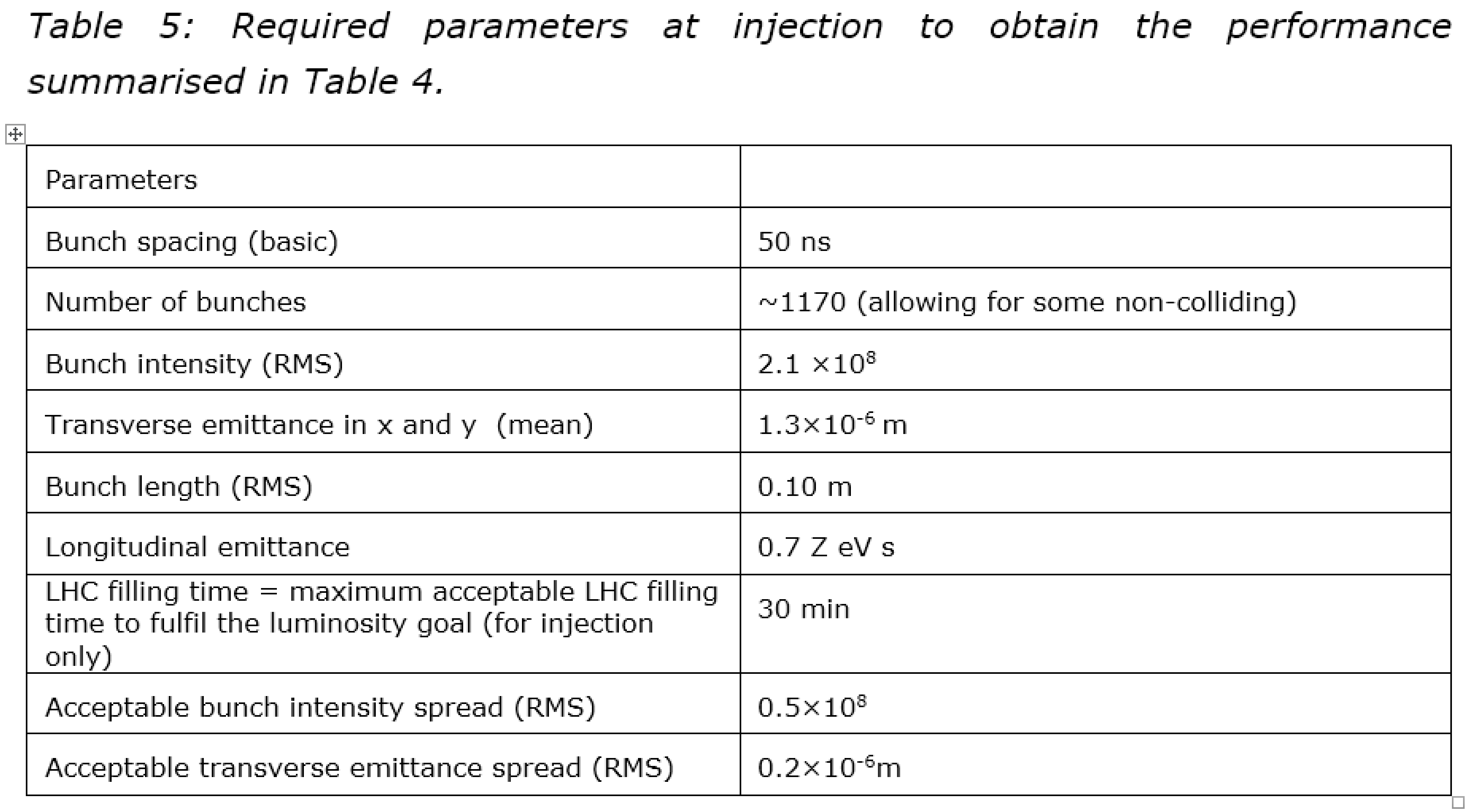


Table 5: Required parameters at injection to obtain the performance summarised in Table 4.

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.

LIU spec, working backwards from int. luminosity

Comparison with “realistic” injection scenarios

CASE	A	B	C	D	E
Description	Request HL-LHC (working backwards …)	LIU baseline, LEIR limit solved, slip stacking.	~~LIU Baseline and new SPS ion injection kicker~~	LIU baseline B with bunch intensity increased even more to reach C performance	HL-LHC operation without LIU Ion upgrade (2015 injection), no bunch splitting
Bunch spacing (basic)	50 ns	50 ns	~~50 ns~~	50 ns	100/225 ns
Number of bunches	~1200	820	~~1200~~	820	420
Bunch intensity (RMS)	2.1×10^{8}	1.55×10^{8}	~~1.55×10^{8}~~	1.75×10^{8}	2.2×10^{8}
Needed LEIR intensity upgrade	+90%	+40%	~~+40%~~	+60%	+0%
Normalised emittance (x and y) (mean)	1.3×10^{-6} m	1.1×10^{-6} m	~~1.1×10^{-6} m~~	1.1×10^{-6} m	1.1×10^{-6} m
Bunch length (RMS)	0.10 m	0.1 m	~~0.1 m~~	0.1 m	0.1 m
Longitudinal emittance	0.7 Z eV s	0.7 Z eV s	~~0.7 Z eV s~~	0.7 Z eV s	0.7 Z eV s
LHC filling time	30 min	1 hour	~~1 hour~~	1 hour	40 min
Acceptable bunch intensity spread (RMS)	0.5×10^{8}	0.5×10^{8}	~~0.5×10^{8}~~	0.5×10^{8}	1×10^{8}
Acceptable transverse emittance spread (RMS)	0.2×10^{-6}m	0.2×10^{-6}m	~~0.2×10^{-6}m~~	0.2×10^{-6}m	0.2×10^{-6}m

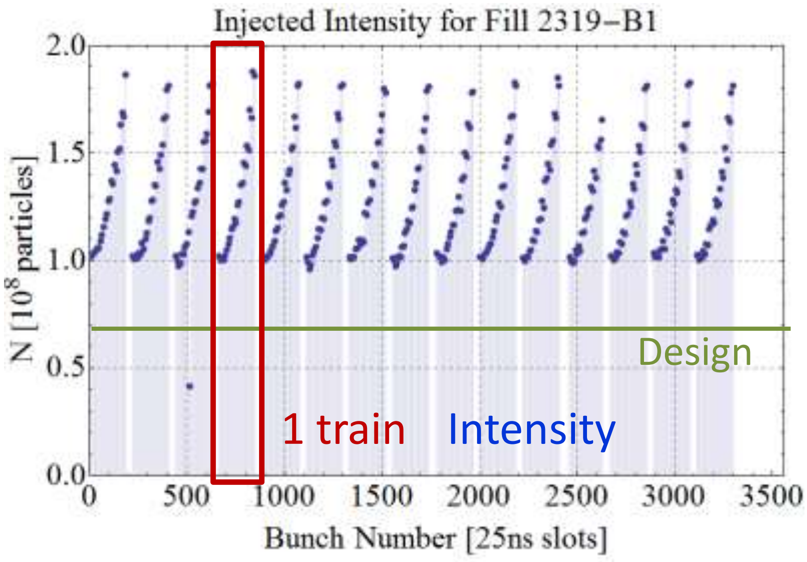
Update HL-LHC performance estimates given at RLIUP Workshop (Oct 2013) with these cases with loss margins from injection to collision.

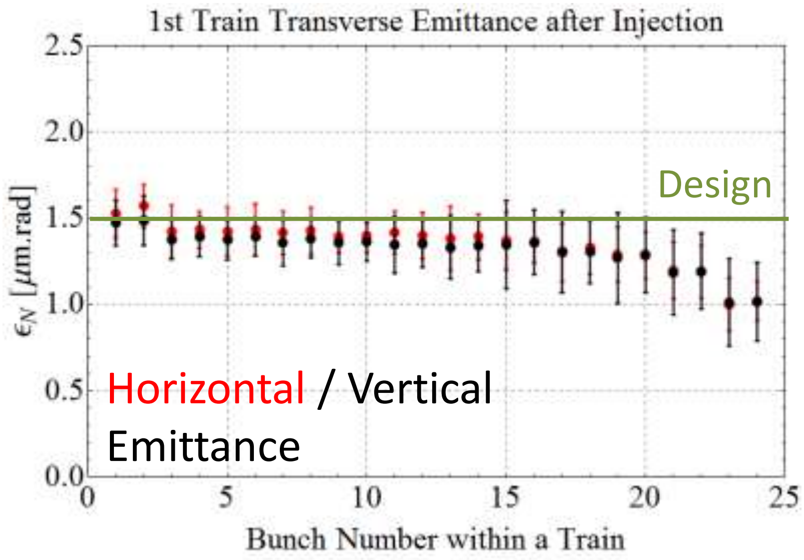
(Case D changed since 15 October meeting.)

N.B. 100/100 ns 2013 “baseline” (= E improved by kicker) might remain best choice if LEIR limit remains or if slip-stacking in SPS is not successful.

Bunch-by-Bunch Differences after Injection in the LHC

E = 450 Z GeV



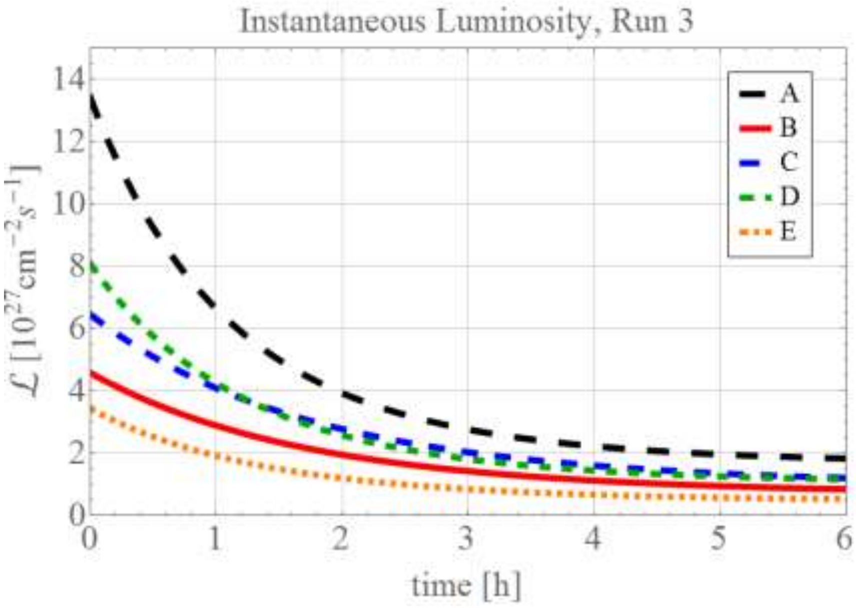


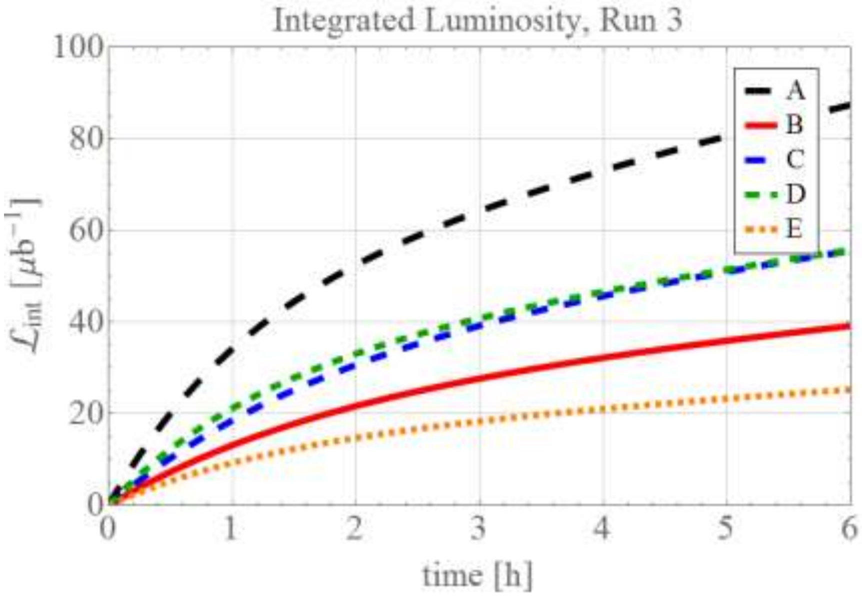
- Structure within a train (1st to last bunch):
    - increase: - intensity
      - bunch length
    - decrease: emittance.
- IBS, space charge, RF noise … at the injection plateau of the SPS:
    - while waiting for the 12 injections from the PS to construct a LHC train.
- First injections sit longer at low energy
  → strong IBS,
  → emittance growth and particle losses.

Realistic upgrade scenario comparison

- Realistic luminosity model (Michaela Schaumann’s thesis) as at 2013 HL-LHC/LARP, applied to this (slightly different) set of scenarios
  - Luminosity evolution simulated with full luminosity model (extreme burn-off, IBS, radiation damping, etc.) differently for bunches with varying parameters along trains
  - Sensitive to fit parameters describing SPS intensity decay
  - More realistic relation of integrated luminosity to individual fills (no fill-length optimization)
  - LHCb not included, no levelling in optimistic cases (A,D)
  - Large error bars on absolute values remain, as always, but we can make comparisons
  - (Nevertheless most elaborate model in current use!)

Luminosity evolution in a fill (no levelling)





Despite higher initial L for D, their luminosities converge after 2 h.

Caveat: A and D possibly outside range of model fits.

(Case D changed since 15 October meeting.)

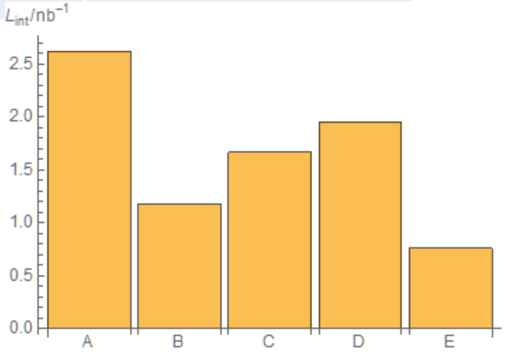
Injection scenarios with integrated luminosity/run

CASE	A	B	C	D	E
Description	Request HL-LHC (previous slides)	LIU baseline	~~LIU Baseline and new SPS ion injection kicker~~	LIU baseline with increased bunch intensity to reach C performance	HL-LHC operation without LIU Ion upgrade (2015 injection)
Bunch spacing (basic)	50 ns	50 ns	~~50 ns~~	50 ns	100/225 ns
Number of bunches	~1200	820	~~1200~~	820	420
Bunch intensity (RMS)	2.1×10^8	1.55×10^8	~~1.55×10^8~~	1.75×10^8	2.2×10^8
Needed LEIR intensity upgrade	+90%	+40%	~~+40%~~	+80%	+0%
Normalised emittance (x and y) (mean)	1.3×10^{-6} m	1.1×10^{-6} m	~~1.1×10^{-6} m~~	1.1×10^{-6} m	1.1×10^{-6} m
Bunch length (RMS)	0.10 m	0.1 m	~~0.1 m~~	0.1 m	0.1 m
Longitudinal emittance	0.7 Z eV s	0.7 Z eV s	~~0.7 Z eV s~~	0.7 Z eV s	0.7 Z eV s
LHC filling time	30 min	1 hour	~~1 hour~~	1 hour	40 min
Acceptable bunch intensity spread (RMS)	0.5×10^8	0.5×10^8	~~0.5×10^8~~	0.5×10^8	1×10^8
Acceptable transverse emittance spread (RMS)	0.2×10^{-6}m	0.2×10^{-6}m	~~0.2×10^{-6}m~~	0.2×10^{-6}m	0.2×10^{-6}m
Integrated luminosity per annual 1 month run	**2.62 nb^{-1}**	**1.17 nb^{-1}**	~~**1.67 nb^{-1}**~~	**1.67 nb^{-1}**	**0.76 nb^{-1}**

Integrated luminosity estimates based on 30 6 hour fills (similar to 2011).

No fill time optimisation as in EDMS Note (explains small difference).

Bunch numbers in LHC may be slightly over-estimated.



Integrated luminosity scenarios

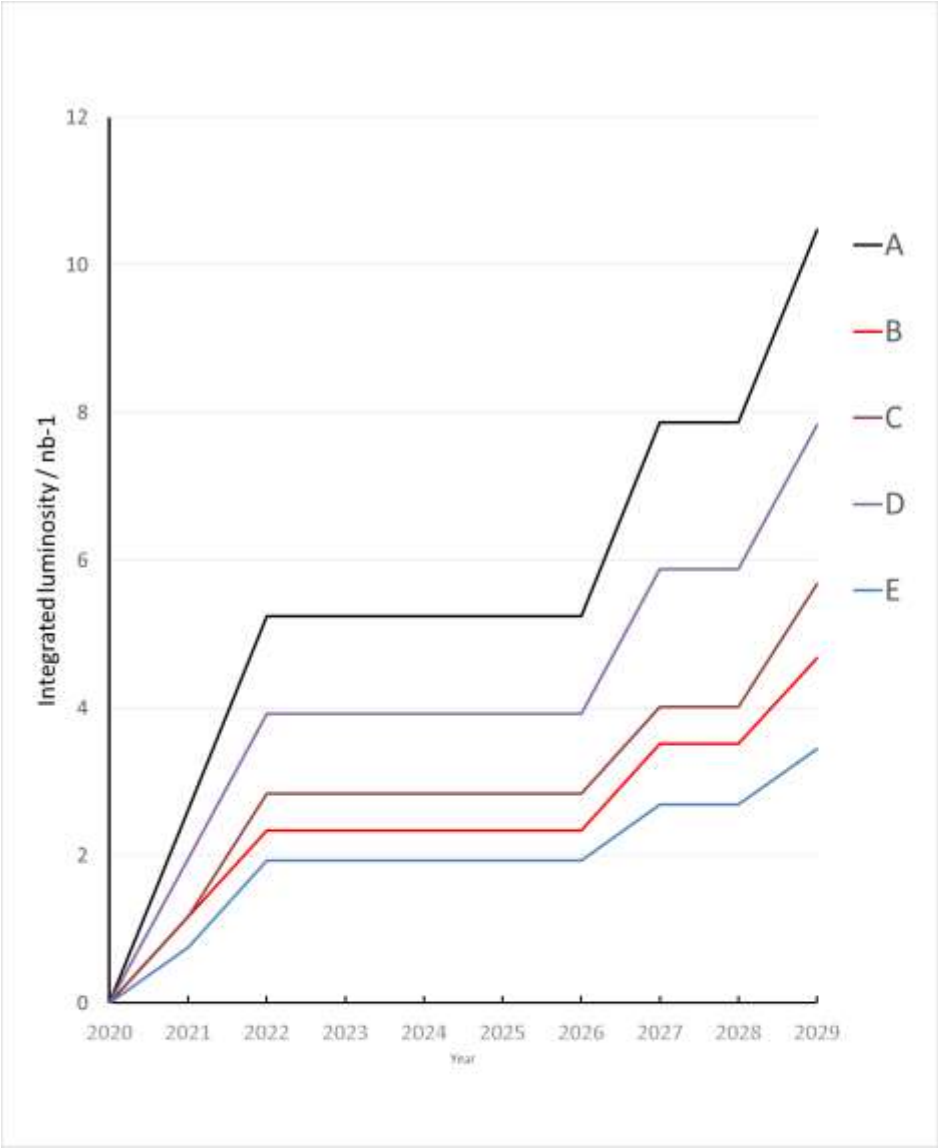
Scenario B is present LIU baseline (assuming LEIR limit solved + slip-stacking).

Scenario A is HL-LHC (experiments) request.

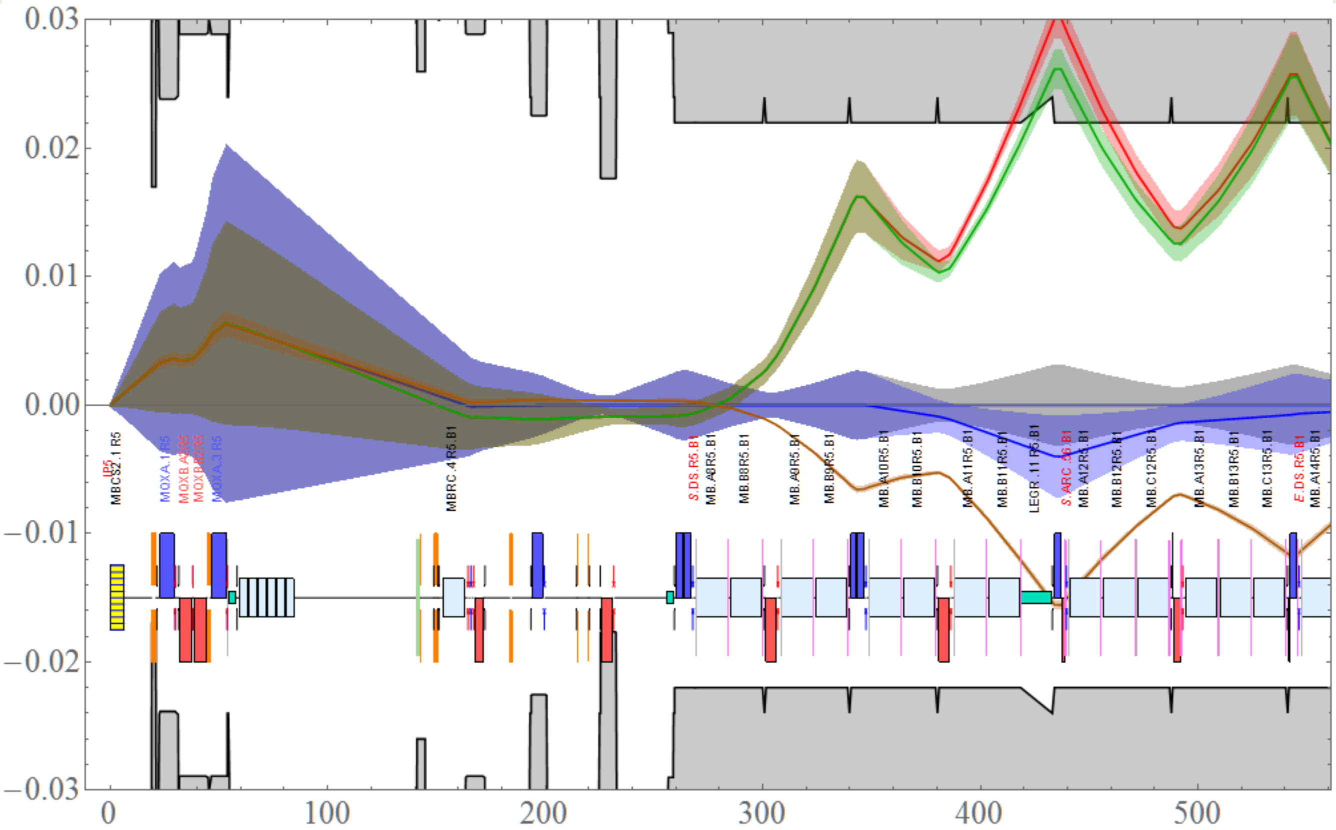
The p-p reference in 2022 could be swapped with Pb-Pb in 2021 if necessary for better radiological cooldown before LS3.

Assumed that 2027 run is entirely devoted to p-Pb.

Scenario C only gets the SPS kicker at end of 2021 (not baseline now).

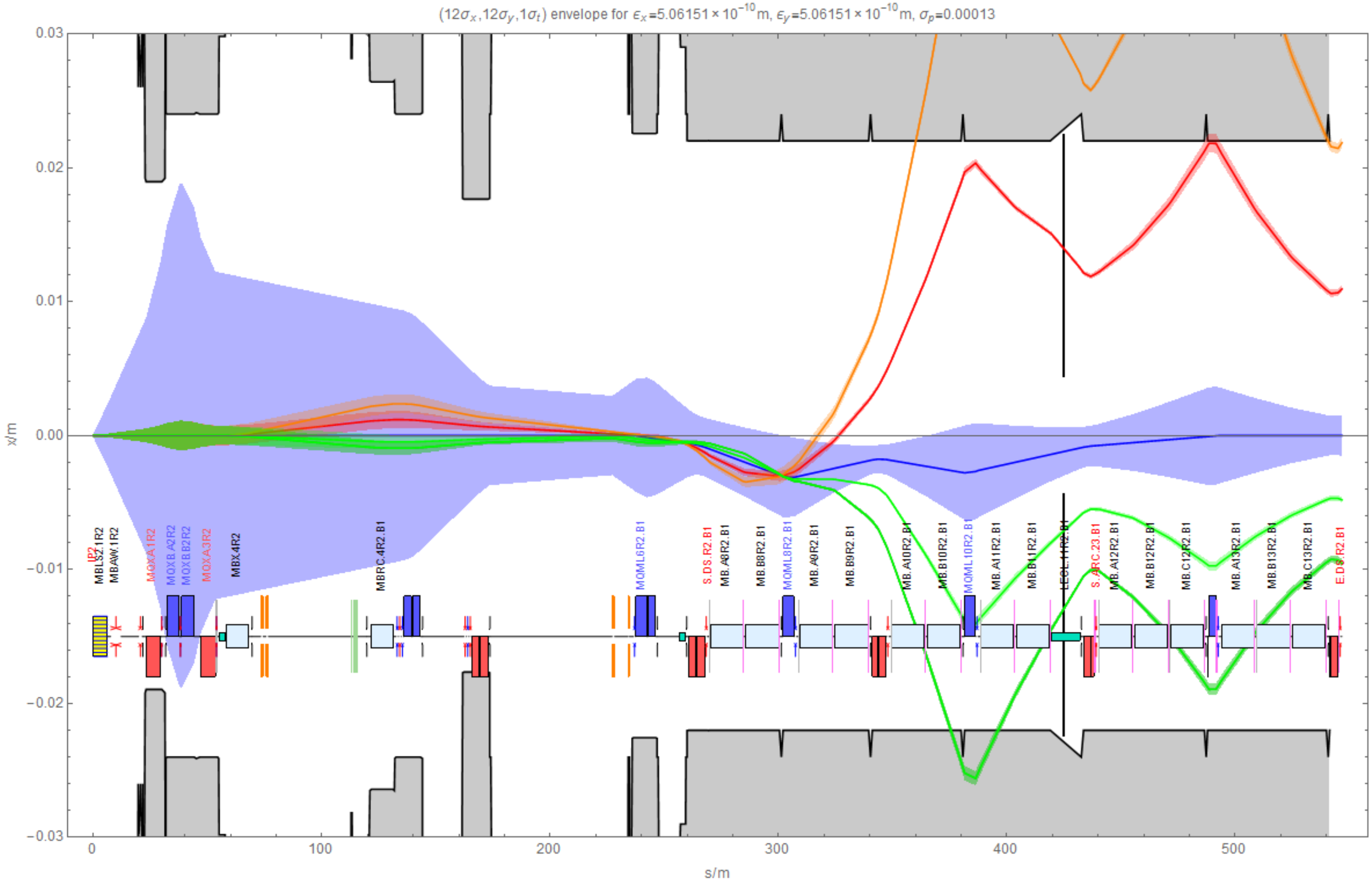


BFPP mitigation: Orbit bumps effective for CMS or ATLAS



- Primary loss location for Pb^{81+} beam close to the connection cryostat - details slightly optics-dependent (this example for a 2015 optics)
- If necessary, bumps should avoid quenches at the start of physics
- Extra BLMs were specifically added for heavy-ion operation in loss region
- Variations of bump possible, uses moderate fraction of available corrector strengths

BFPP mitigation: TCLD in connection cryostat at IR2



TCLD combined with bump is cheaper than present baseline using 11 T magnets.
There is no solution using bumps without a collimator in IR2.

BFPP power deposition in the DS next to IR2

- Existing layout:
  - For a luminosity of 6×10^{27} $cm^{-2}s^{-1}$ (HL goal of ALICE), the estimated peak power density in MB coils is ~44 mW/cm^3
  - Recent MB quench level estimates: 27-49 mW/cm^3 [1,2] (depends on the assumed cooling efficiency at the spacer between inner and out coil)
  - In addition, the dynamic heat load to the cold mass is expected to be ~100W (cooling redundancy of cooling loops may become questionable [3])
- Layout with DS collimator between two 11T dipoles:
  - In presence of a collimator the estimated peak power in the 11T magnet coils (<3 mW/cm^3) remains well below the quench level of Nb_3Sn cables (which is ~110 mW/cm^3 according to first estimates [4])
  - A similar gain is expected if the DS collimator is embedded in the connection cryostat and not between 11T dipoles (to be confirmed with simulations)
  - A good fraction of power carried by BFPP ions will be dissipated by the collimator, therefore relaxing the power load to cold mass elements

[1] B. Auchmann et al., Phys. Rev. ST Accel. Beams, 18, 061002, (2015).
[2] P.P. Granieri and R. Van Weelderen, IEEE Trans. Appl. Supercond., Vol 24 (2014).
[3] R. Van Weelderen, private communication.
[4] P.P. Granieri, “Steady-state cable quench limit of the 11T dipole”, ColUSM #35 (2014).

Slide from A. Lechner (with F. Cerutti, G. Steele)

LHCb

- LHCb participated (with low luminosity) in the 2012 and 2013 p-Pb runs
- They have recently expressed interest in taking Pb-Pb collisions (and fixed target Pb-A), now and through HL-LHC period.
- We will try to provide LHCb with Pb-Pb in 2015
  - No time or resources to study in advance.
- Possible issues (already seen in p-Pb to some extent)
  - Subtracting some luminosity from other experiments
  - Very close parasitic beam-beam encounters around ALICE
  - Reduced lifetime of some bunches triggering dumps

- Wait for 2015 experience before discussing further

Proton-lead operation

- New operating mode, no time to discuss here in detail
- Already had extreme burn-off regime in 2013
  - One sharing scenario was exploited successfully to provide >30 nb^{-1} in 3 experiments
- Integrated luminosity given by total Pb intensity
- LIU intensity upgrades are similarly beneficial for p-Pb
- LIU must maintain capability to construct proton filling schemes matching the Pb ones.

Other important topics, no time to discuss today

- Crossing scheme in ALICE
  - Small net angle for ZDC, aperture gains of TCLI, etc
  - Close encounters generated by LHCb ?
  - Possible aperture problems with low β* if detector is not raised again in LS2
- Heavy ion collimation
  - May require DS collimators + 11 T magnets in IR7
  - Quench test soon
  - Better tracking simulation (replacing ICOSIM) under development (P. Hermes)
- RF: blow-up with noise, possible 200 MHz, etc
- Beam instrumentation often limiting

Conclusions

- Extreme burn-off regime:

Ultimate integrated luminosity: $\sum_{\text{experiments}} \int_{\text{fill}} L\,dt \propto \frac{k_c N_b}{\sigma_c}$

- To approach integrated luminosity targets, for both Pb-Pb and p-Pb, LIU should do everything possible to maximise injected Pb intensity in LHC preferably by maximising number of bunches.
  - Breakthroughs in injector limits (LEIR, SPS, …) to be sought!

- Present LIU baseline (assuming LEIR 40% etc) may give 30-45% of experiments' request.
- Greater operational efficiency may help a lot (more than for p-p)
- More running time (in Run 3?) would help
- Luminosity sharing options exist

- DS collimators (with or without 11 T magnets) likely to be needed in IR2 (dynamic heat load as well as quench risk)
  - BFPP quench test on LHC in December (maybe only lower bound)
- DS collimators (with 11 T magnets) may be needed in IR7
  - IR7 collimation quench test in December
- Bump technique seems to obviate need for DS collimators in IR1 and IR5
  - Confirm in 2015 operation

- Confirmation/updates/refutation likely very soon when we get data from the first Pb-Pb run since 2011 at new energy.