Heavy Ions in 2011 and Beyond

Thanks to all who contributed to the "Ions for LHC" project, now dissolved, many others involved in the 2010 operation.

Contributions to *this talk* from: R. Assmann, P. Baudrenghien, G. Bellodi, O. Berrig, T. Bohl, R. Bruce, C. Carli, E. Carlier, H. Damerau, S. Hancock, B. Holzer, D. Kuchler, D. Manglunki, T. Mertens, A. Nordt, T. Risselada, M. Sapinski, R. Steerenberg, D. Wollmann

Plan of talk

- The 2010 lead-lead run
- **The 2011 lead-lead run**
- The 2012 X-lead run
- **Critical upgrades**

THE 2010 LEAD-LEAD RUN

Lightning summary (should be a talk on this)

- Lightning commissioning plan, expounded to politely sceptical audiences at previous Chamonixes, worked.
  - Collisions within 50 hours of first injection
  - Stable beams within 4 days (… and physics)
  - Most filling schemes used once and thrown away
- The LHC worked with Pb beams
  - No rapidly decaying, invisible beams
  - No quenches, so far
- Rich/novel beam physics, much as predicted, but
  - Emittances blown-up
  - Some new losses and radiation problems

Peak luminosity in fills

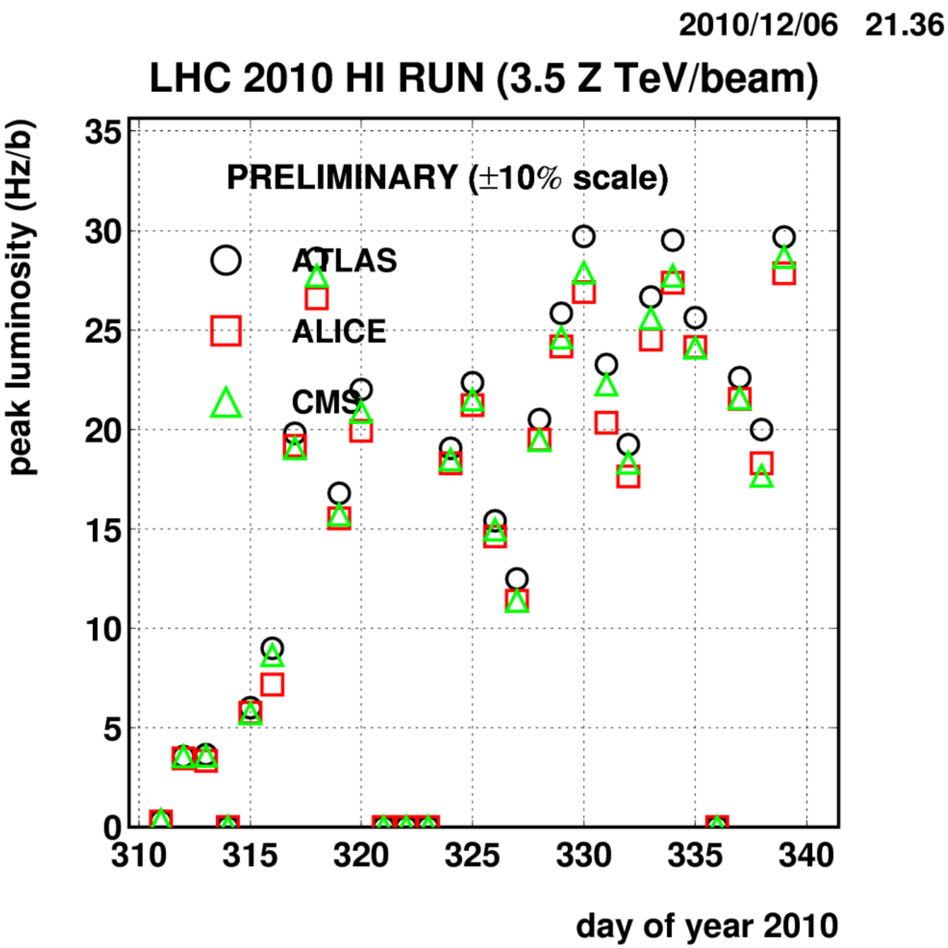
Peak performance reached very quickly.

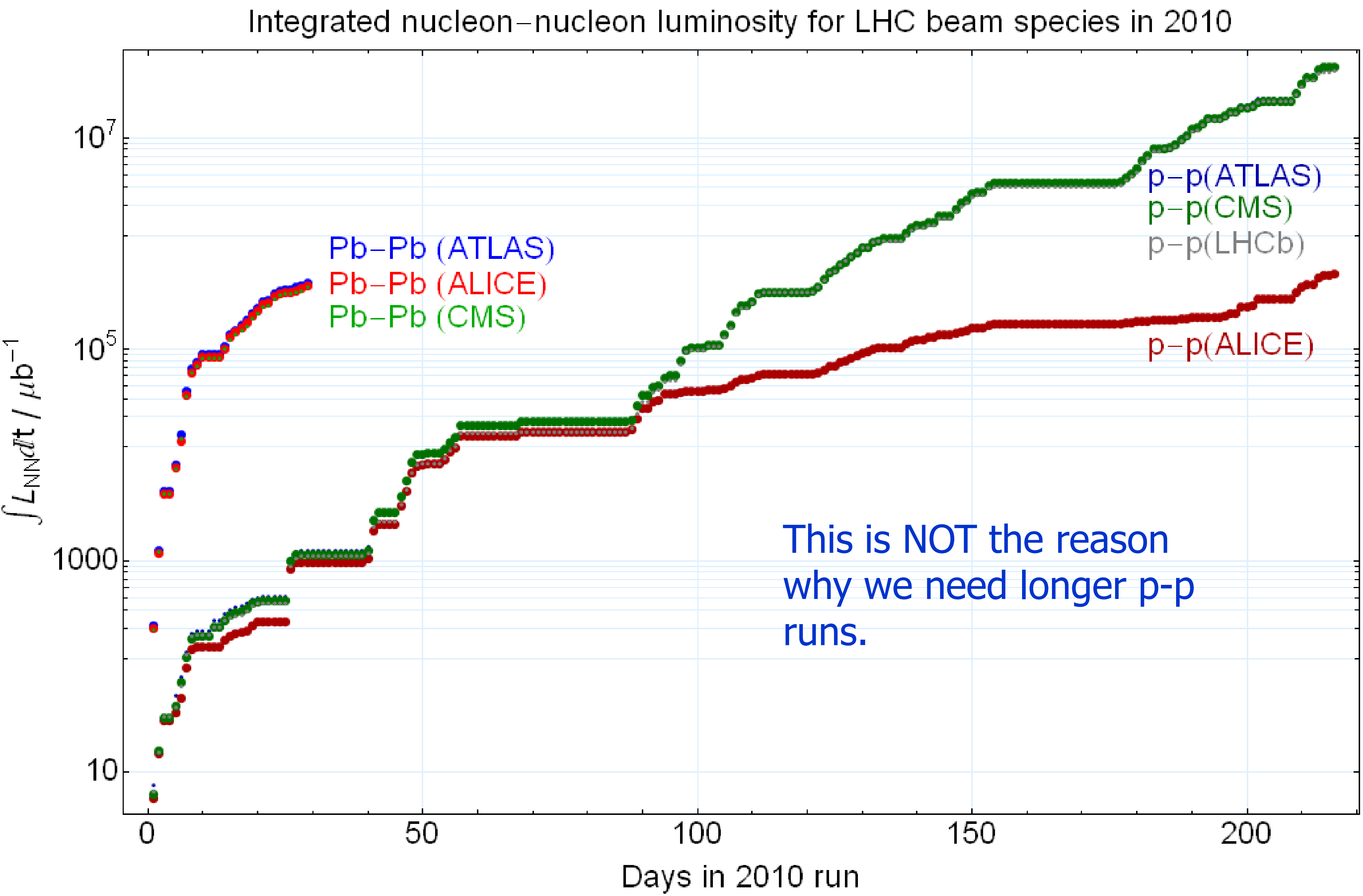
Interrupted twice by source refills (+ few days “parasitic” proton MD), some time to recover source performance.

Last few days, bunch number increased again to 137 with 8-bunch/batch from SPS.

As far as possible, we should adopt similar commissioning plan (magnetic machine as close as possible to protons, …) for every heavy ion run.

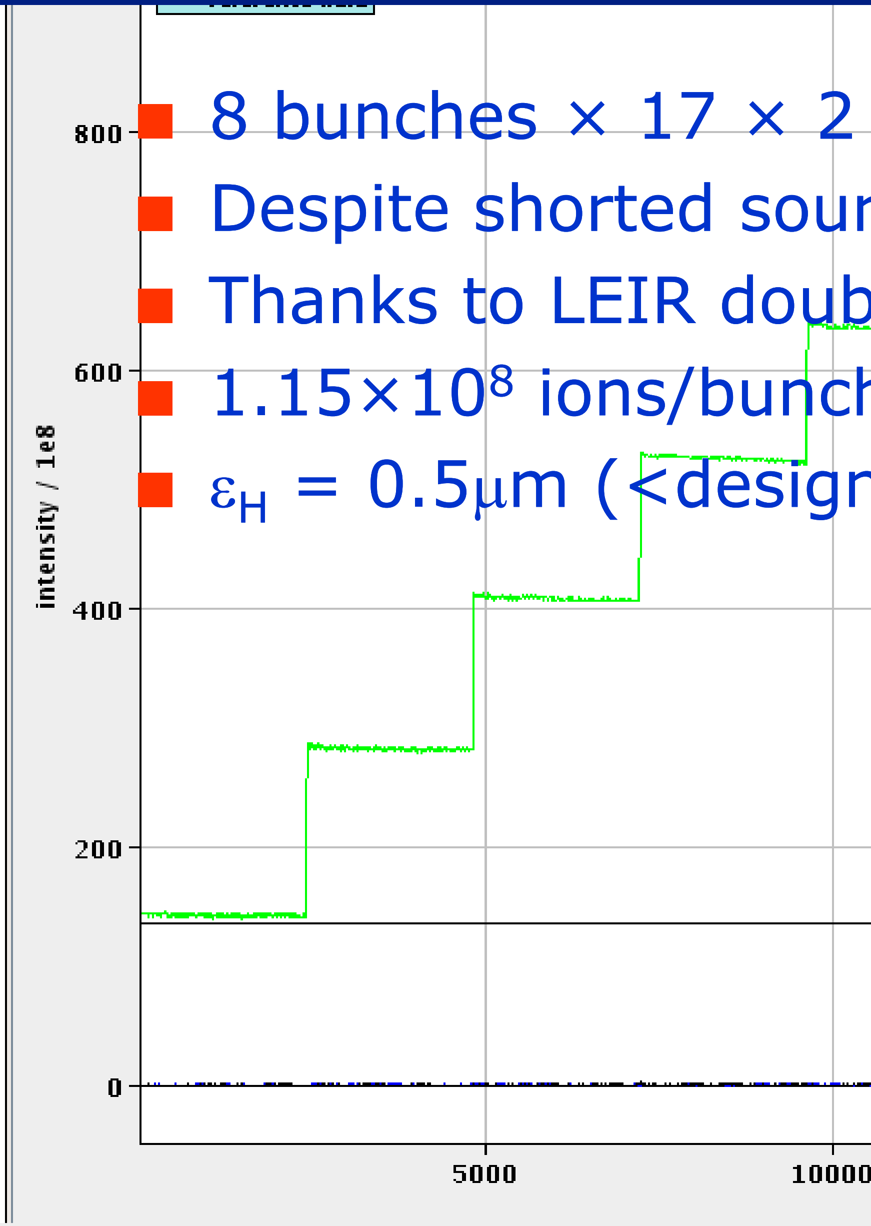
But never completely identical (even in 2010).

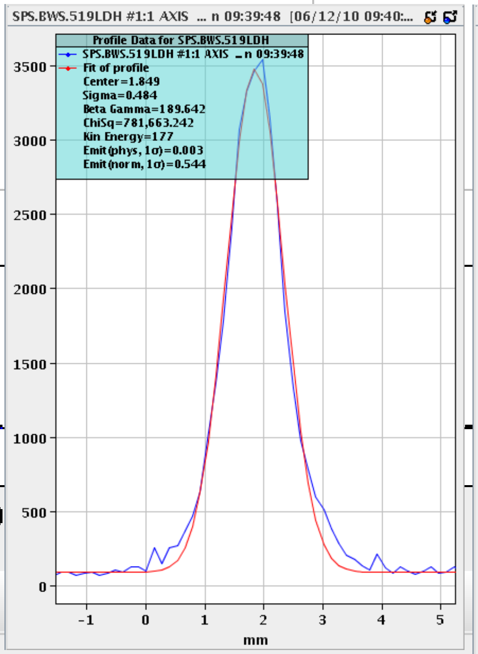


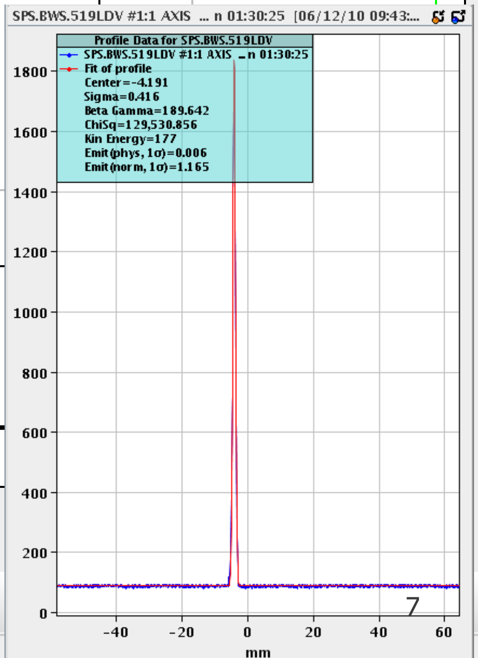

Integrated nucleon−nucleon luminosity for LHC beam species in 2010
Pb−Pb (ATLAS)
Pb−Pb (ALICE)
Pb−Pb (CMS)
p−p(ATLAS)
p−p(CMS)
p−p(LHCb)
p−p(ALICE)
This is NOT the reason why we need longer p-p runs.
$\int L_{NN} dt$ / μb^{-1}
10^7
10^5
1000
10
0
50
100
150
200
Days in 2010 run

Injectors for last LHC ion fill of the year

- 8 bunches × 17 × 2 from SPS to LHC
- Despite shorted source intermediate electrode
- Thanks to LEIR double injection
- 1.15×10^{8} ions/bunch (64% above design)
- ε_H = 0.5μm (<design/2) ; ε_V = 1.1μm (<design)







Beam instrumentation

- Major concern in some people's minds
  - BPMs intensity threshold – no problem
  - Emittance: harder than protons
    - WS: Wire scanner at low energy and intensity – best absolute calibration
    - BSRT: synchrotron light appeared in ramp (world first!), only bunch-by-bunch – typical large spread in emittance set in at injection
    - Beam-gas ionisation (BGI) commissioned during ion run, provides continuous monitoring of average emittance, some calibration questions still being resolved

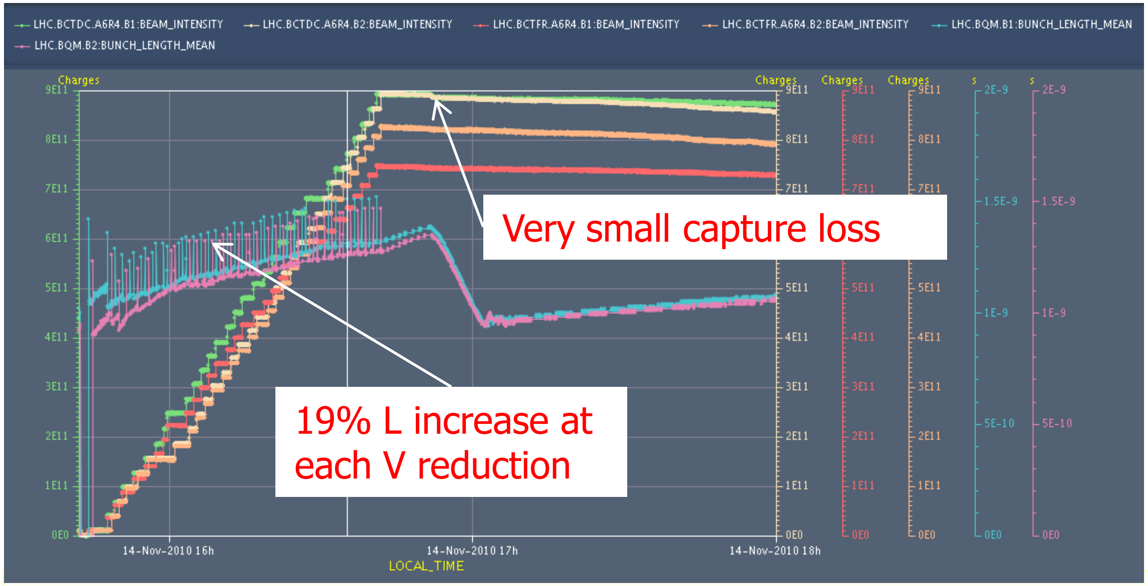
Performance limits so far

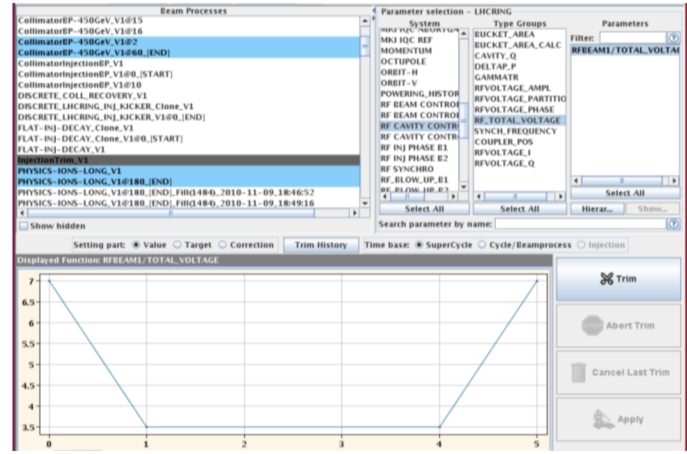
- IBS
  - Simulation comparison – transform to superposed bunches
- Hump
- Vacuum ?
  - not much to say from the vacuum side During the run with ions, pressures were recovering all around the ring (following the run with protons) and the only pressure rise observed with ions are in the injections at the TDI and linked to losses.
-
- Losses in squeeze
  - Larger emittances – must watch this.

P. Baudrenghien et al

12-13 Nov

- 7 MV at flat bottom with voltage reduction to 3.5 MV at each injection





The higher (7 MV) voltage on the long flat bottom reduces the lengthening caused by IBS. There is no more loss at start ramp. No more debunching on flat bottom.

However, the RF modulation creates ghost bunches : We have debunching at each voltage reduction followed by recapture in nearby buckets when the voltage returns to 7 MV

The 7 MV voltage is linearly reduced to 3.5 MV in 1 s just before injection, kept at 3.5 MV for the 3 seconds following the injection, then raised back to 7 MV in 1 s

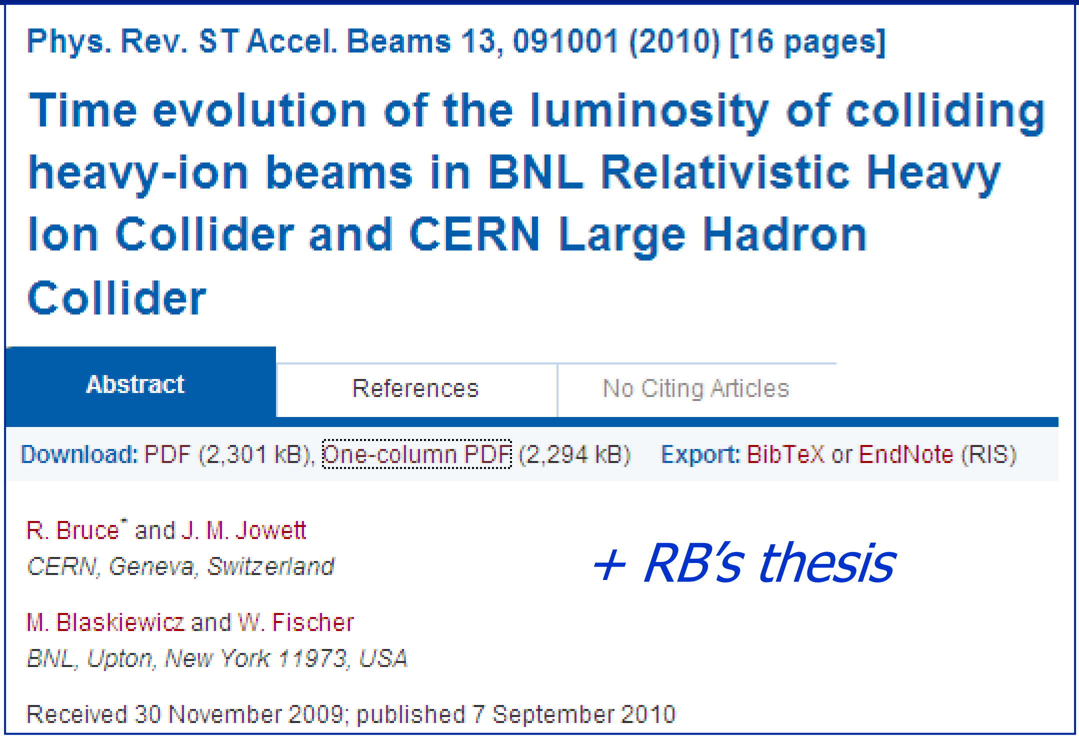
Later moved to constant large voltage to avoid ghost bunches.

Luminosity evolution models

Luminosity models, extensively benchmarked on many RHIC fills.

Systems of ODEs or simulation “CTE”. CTE includes:

- IBS, various methods beyond Gaussian approximation, predicts debunching effects
- Luminosity burn-off (BFPP, EMD, inelastic nuclear, etc.)
- Synchrotron radiation damping etc
- Also used now to simulate injection and analyse fills


Phys. Rev. ST Accel. Beams 13, 091001 (2010) [16 pages]

Time evolution of the luminosity of colliding heavy-ion beams in BNL Relativistic Heavy Ion Collider and CERN Large Hadron Collider

Abstract | References | No Citing Articles

Download: PDF (2,301 kB), One-column PDF (2,294 kB) Export: BibTeX or EndNote (RIS)

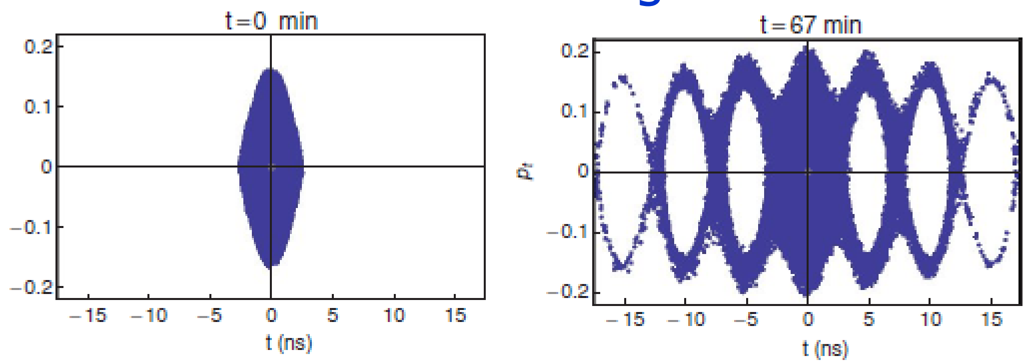
R. Bruce* and J. M. Jowett
CERN, Geneva, Switzerland

M. Blaskiewicz and W. Fischer
BNL, Upton, New York 11973, USA

Received 30 November 2009; published 7 September 2010

+ RB’s thesis

RHIC longitudinal IBS

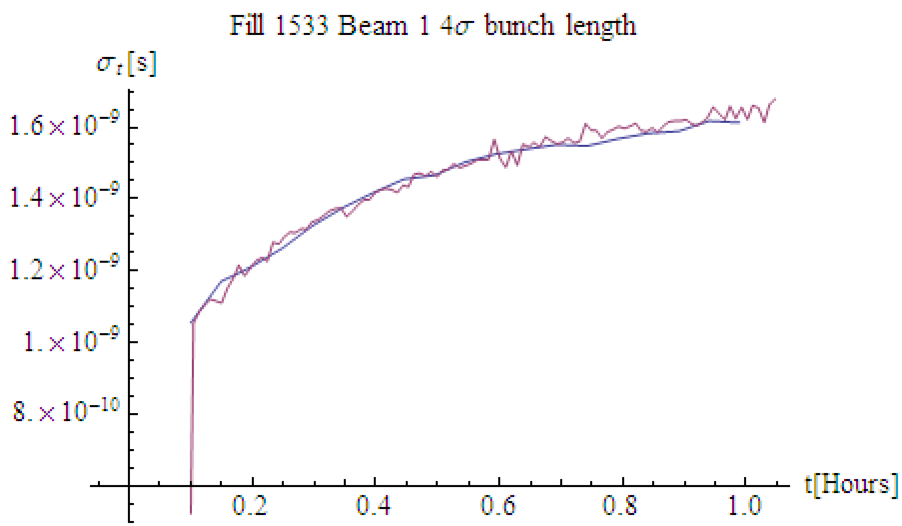


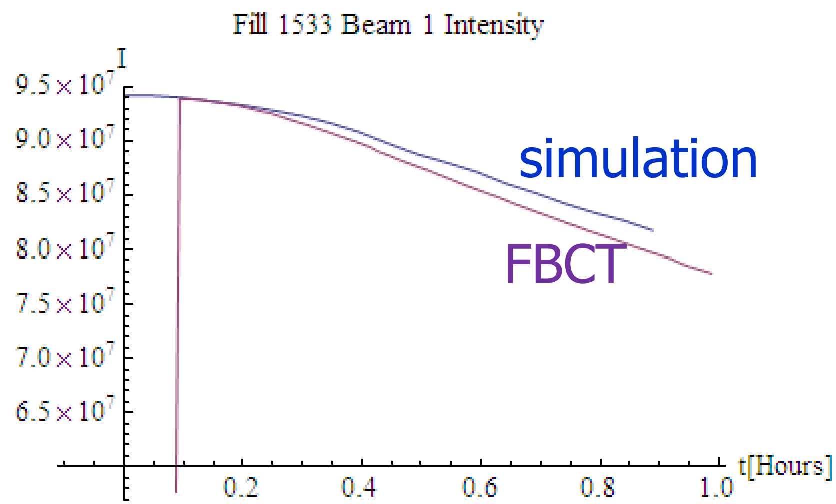
Injection plateau fill data vs. simulation

- Beam instrumentation gives us:
  - Bunch length bunch-by-bunch
  - BSRT beam size bunch-by-bunch at physics only, (almost) nothing at injection
  - Wire scanners: emittance at low intensity/energy
    - Best absolute, use to calibrate BGI (linear fit)
  - BGI: average beam size over all bunches
    - Calibration questions, threshold intensity, …
    - Fit simulation of single bunch evolution to average of bunches accumulated over ~ 1 h injection FORMULA
    - Never quite know the initial emittance

Tom Mertens

Fill 1533: 1st bunch longitudinal





Moving averages over 50 s (50 data points)

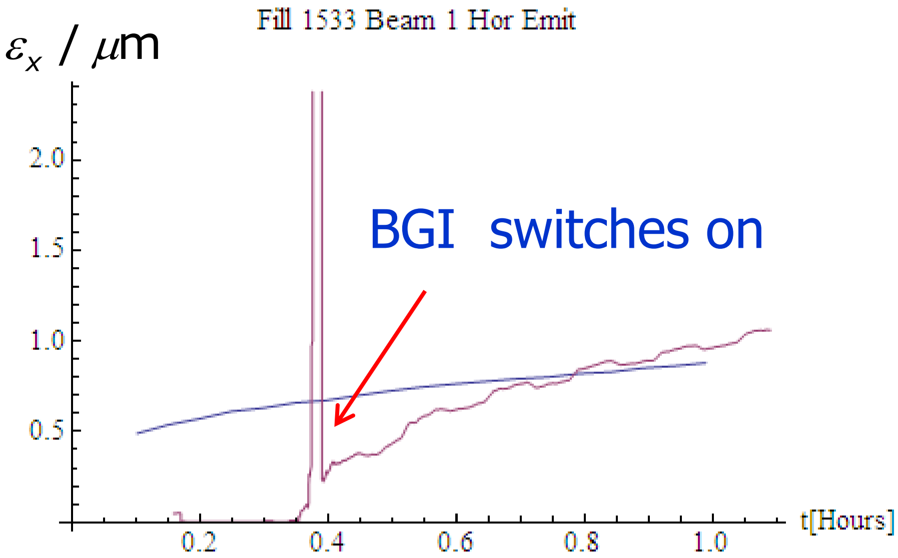
Initial longitudinal emittance chosen to fit initial bunch length and RF voltage 7 MV.

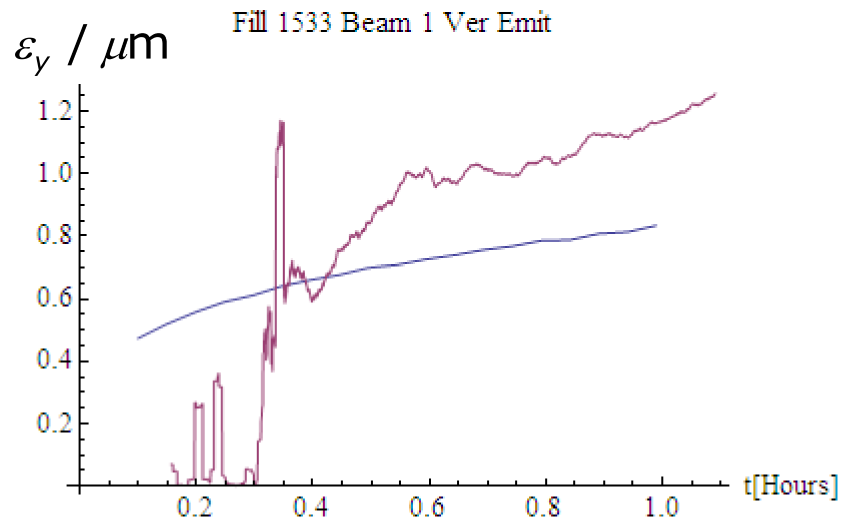
Transverse emittance chosen to fit initial IBS growth rate.

Debunching and bunch lengthening from IBS are predicted very well.

Tom Mertens

Fill 1533: transverse emittances





Plausible initial emittance from fit to longitudinal growth.

BGI calibration via WS ?

Possible other source of vertical emittance growth.

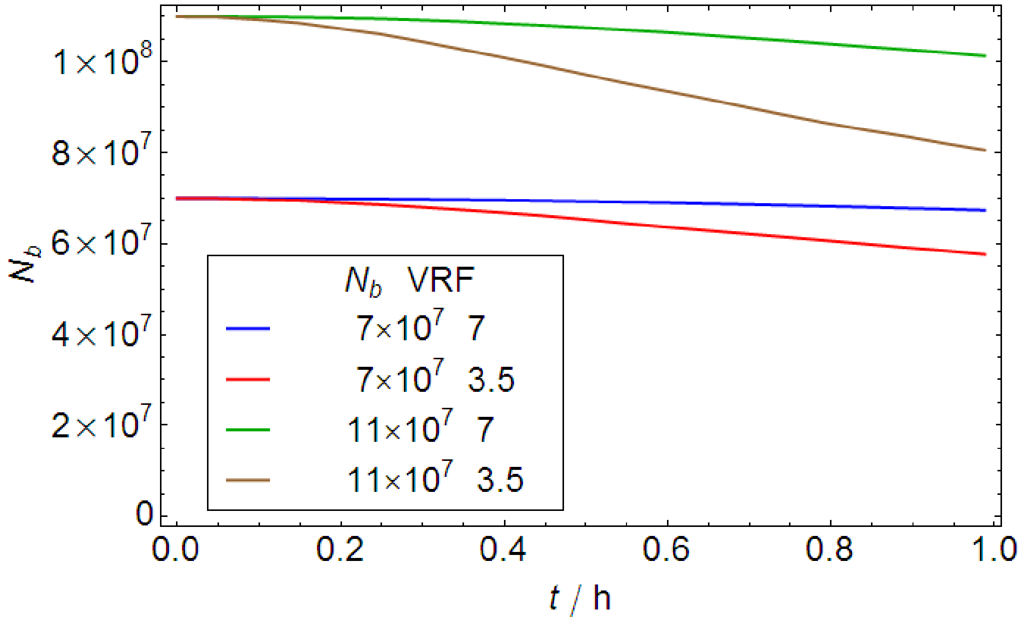
Periodic variation (~ 5 min) of horizontal emittance superposed on growth ?? Feature of all fills.

Work continues to resolve these questions.
Will also do luminosity analysis with these tools.

Tom Mertens

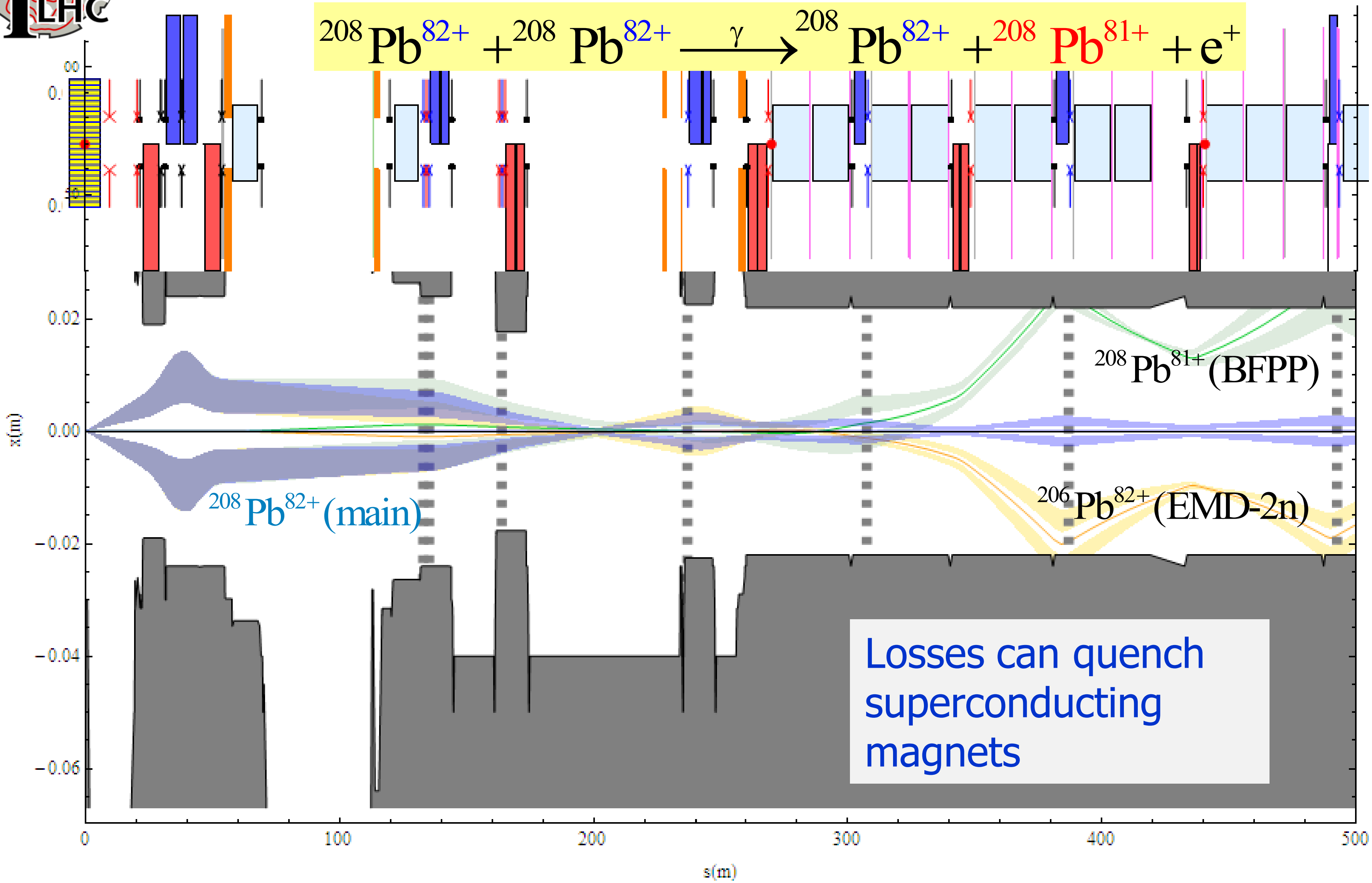
Other results

- Simulations reproduce effects of changing RF voltage on IBS and debunching rates
- Will/should be applied to protons in LHC, Pb in SPS, as well …



Main and secondary Pb beams from ALICE IP

$$^{208}Pb^{82+} + {}^{208}Pb^{82+} \xrightarrow{\gamma} {}^{208}Pb^{82+} + {}^{208}Pb^{81+} + e^{+}$$

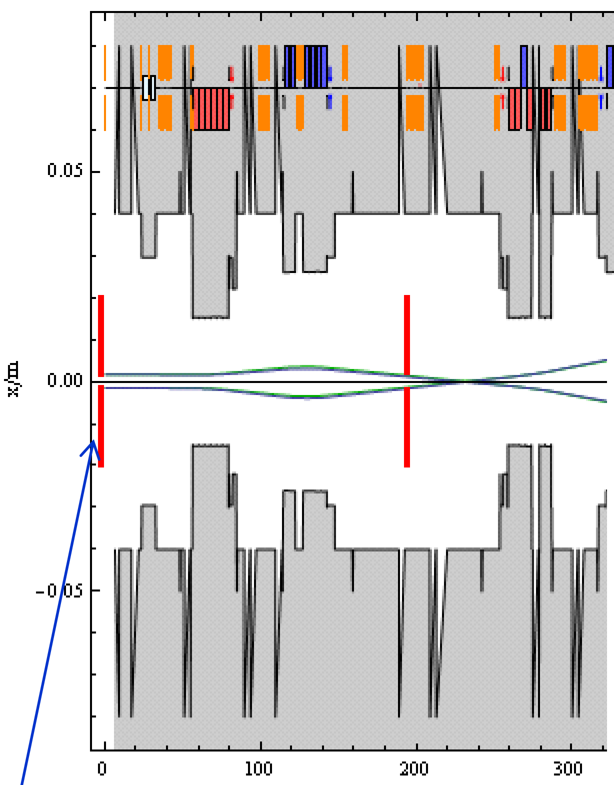


Losses can quench superconducting magnets

Large EM cross sections. Similar in ATLAS, CMS

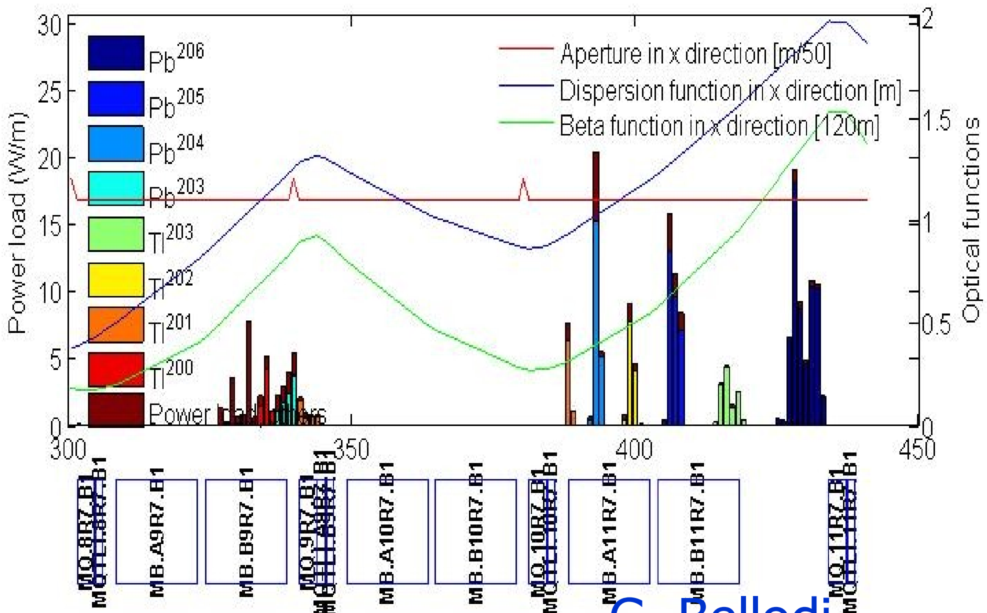
Example of ^{206}Pb created by 2-neutron EMD

- Green rays are ions that almost reach collimator
- Blue rays are ^{206}Pb rays with rigidity change



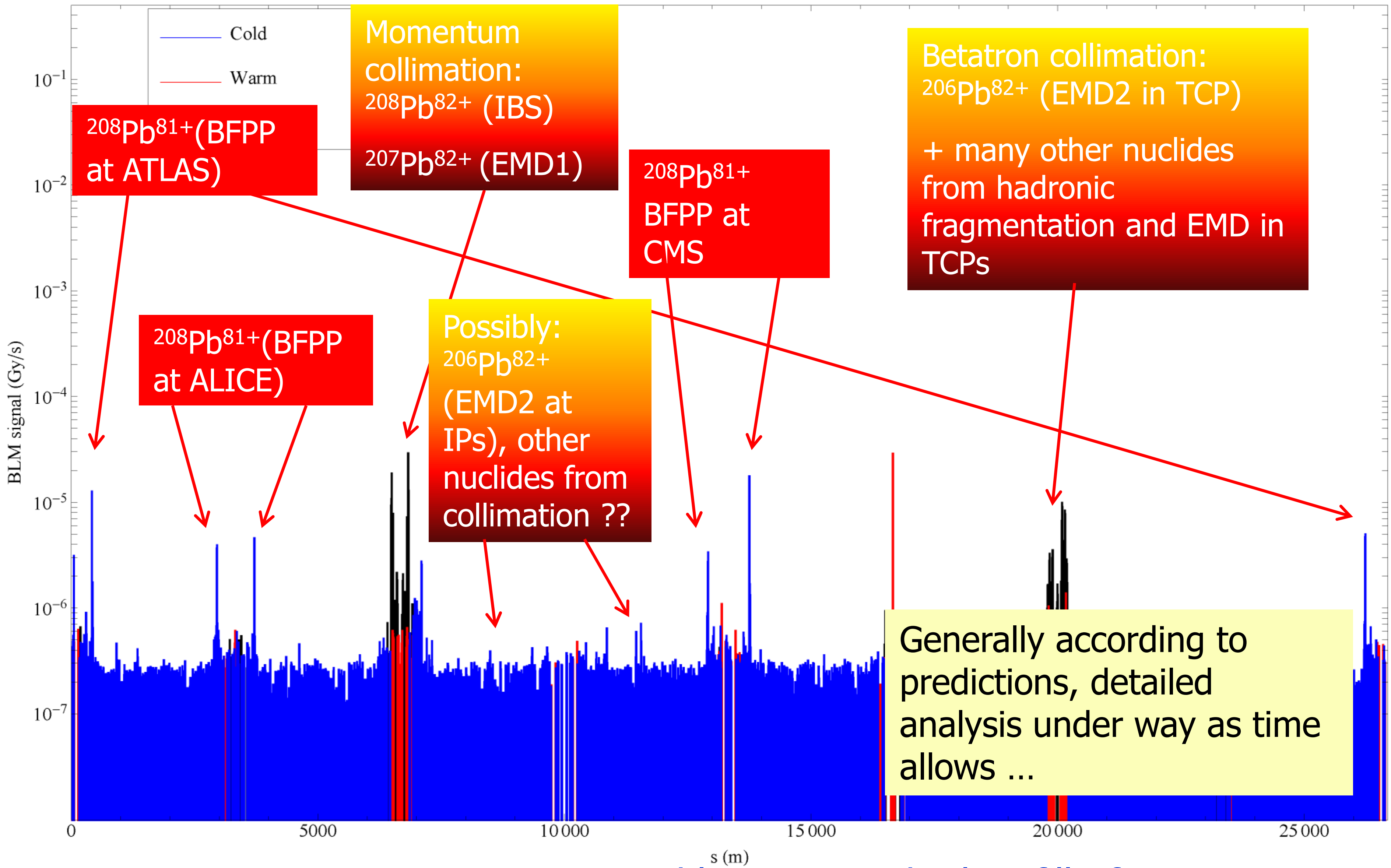
Beam pipe in IR7 of LHC

Primary collimator



G. Bellodi

Global view of losses, Pb-Pb stable beams



Record luminosity, the last fill of 2010

Intensity limit from collimation (tentative)

Table 2: Ions: Overview of measured parameters for and the results of calculating the total intensity limit. For this analyses the lowest life time of the proton runs and the lowest life time of the 2 analyzed ion runs was used. For protons this fill took place at the 26.10.2010 and had 368 bunches per beam with 150 ns bunch spacing. For ions the fill was on the 20.11.2010 with 121 bunches per beam and 500 ns bunch spacing.

	with measured proton life time	with measured ion life time
η_c [1/m]	3e-2	3e-2
BLM response	0.36	0.36
η_{corr} [1/m]	1.08e-2	1.08e-2
τ_{min} [s]	4680	5667
R_q [p/m/s] @3.5 TeV	2.4e7	-
R_q [p/m/s] @4 TeV	1.9e7	-
R_q [p/m/s] @7 TeV	7.8e6	-
BLM factor	0.33	0.33
FLUKA factor	3.5	3.5
N^q_{tot} [charges] @3.5 TeV/c	1.20e13	**1.45e13**
N^q_{tot} [ions] @3.5 TeV/c	1.47e11	1.77e11
N^q_{tot} [charges] @4 TeV/c	9.52e12	**1.152e13**
N^q_{tot} [ions] @4 TeV/c	1.16e11	1.4e11
N^q_{tot} [charges] @7 TeV/c	3.9e12	**4.73e12**
N^q_{tot} [ions] @7 TeV/c	4.76e10	5.76e10

D. Wollmann, extending method used in Evian to estimate proton intensity limit to ions.

c.f. nominal intensity for Pb

$k_b = 592, \quad N_b = 7 \times 10^7$

$\Rightarrow N_{tot} = 4.1 \times 10^{10}$

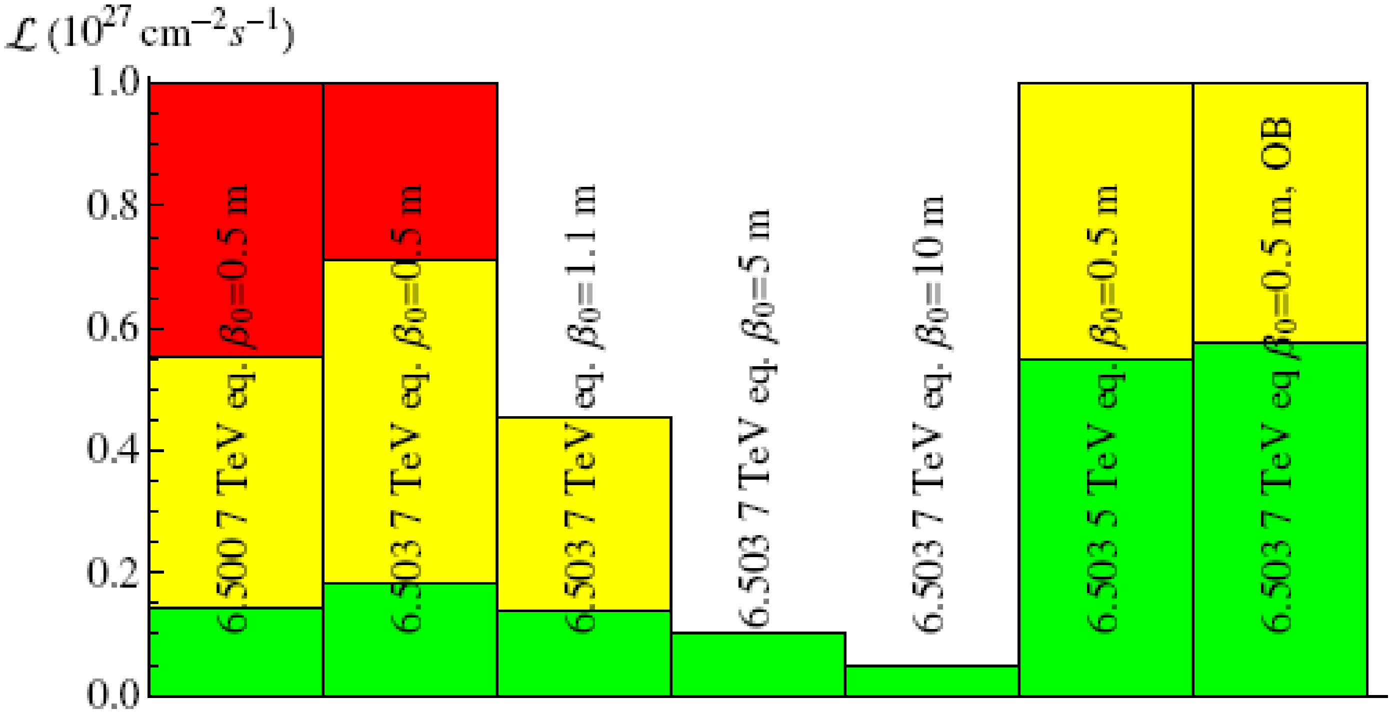
seems attainable!

But higher intensity may be within reach from injectors!

Luminosity limit (mainly BFPP)

- Unlike p-p, where most losses (collimation, cleaning efficiency, …) are proportional to total beam intensity, Pb-Pb collisions will ultimately be limited by losses proportional to luminosity itself
  - Quenches
  - Rapid intensity burn-off
    - A preview of HL-LHC

Propensity to quench from BFPP



Various operating conditions, see paper for details.

Elaborate chain of calculations with several uncertainties from IP to liquid He flow.

Some improvement might be possible with orbit bump method.

APS » Journals » Phys. Rev. ST Accel. Beams » Volume 12 » Issue 7 < Previous Article | Next Article >

Phys. Rev. ST Accel. Beams 12, 071002 (2009) [17 pages]

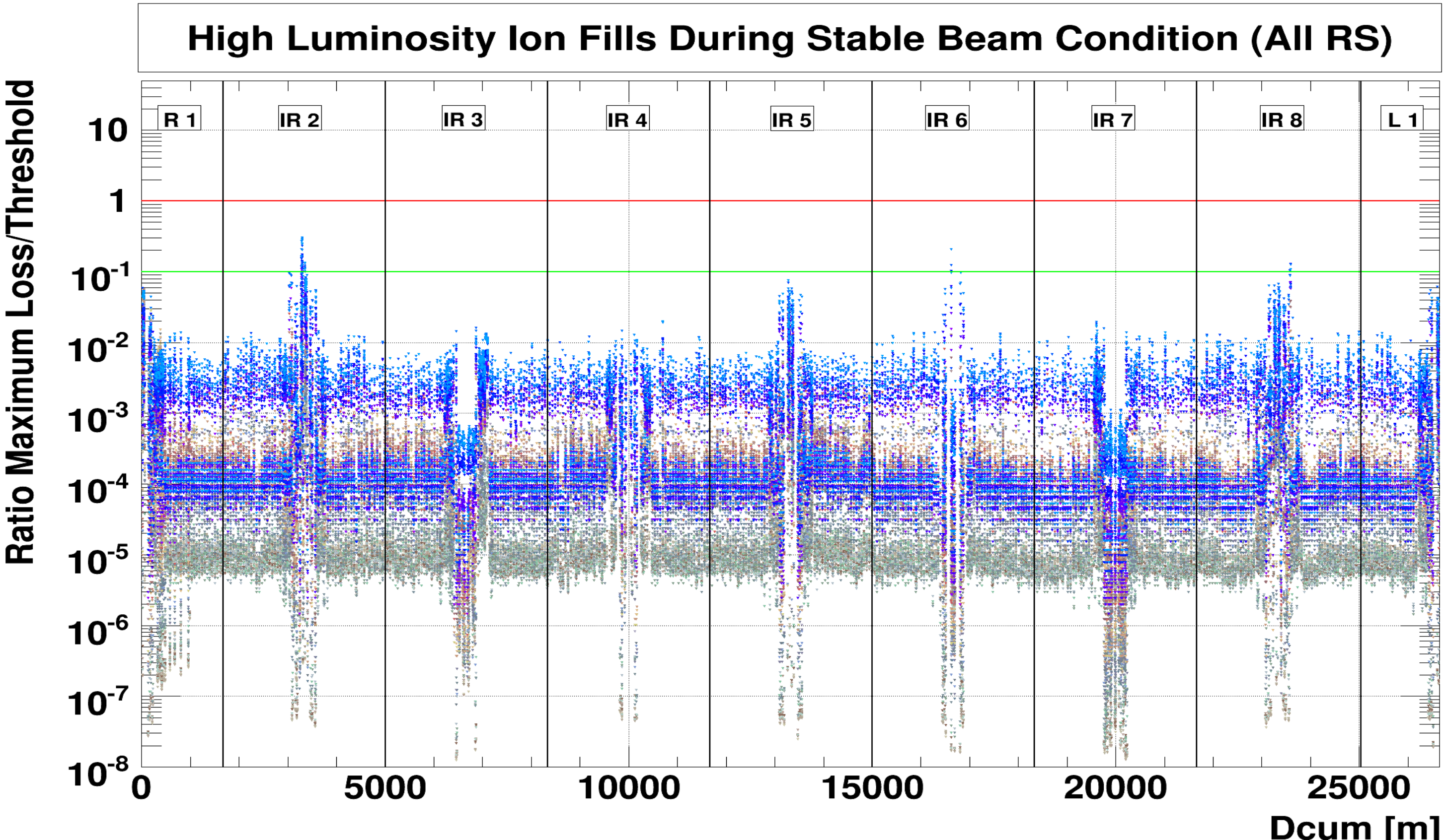
Beam losses from ultraperipheral nuclear collisions between $^{208}Pb^{82+}$ ions in the Large Hadron Collider and their alleviation

Abstract | References | No Citing Articles

Download: PDF (3,720 kB), One-column PDF (3,733 kB) Export: BibTeX or EndNote (RIS)

R. Bruce[1,*], D. Bocian[2,1,†], S. Gilardoni[1], and J. M. Jowett[1]
[1]*CERN, Geneva, Switzerland*
[2]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

Estimating luminosity limit



High lumi fills,

3.5 ZTeV.

- 40 μs integration
- …
- …
- …

1.3 s integration

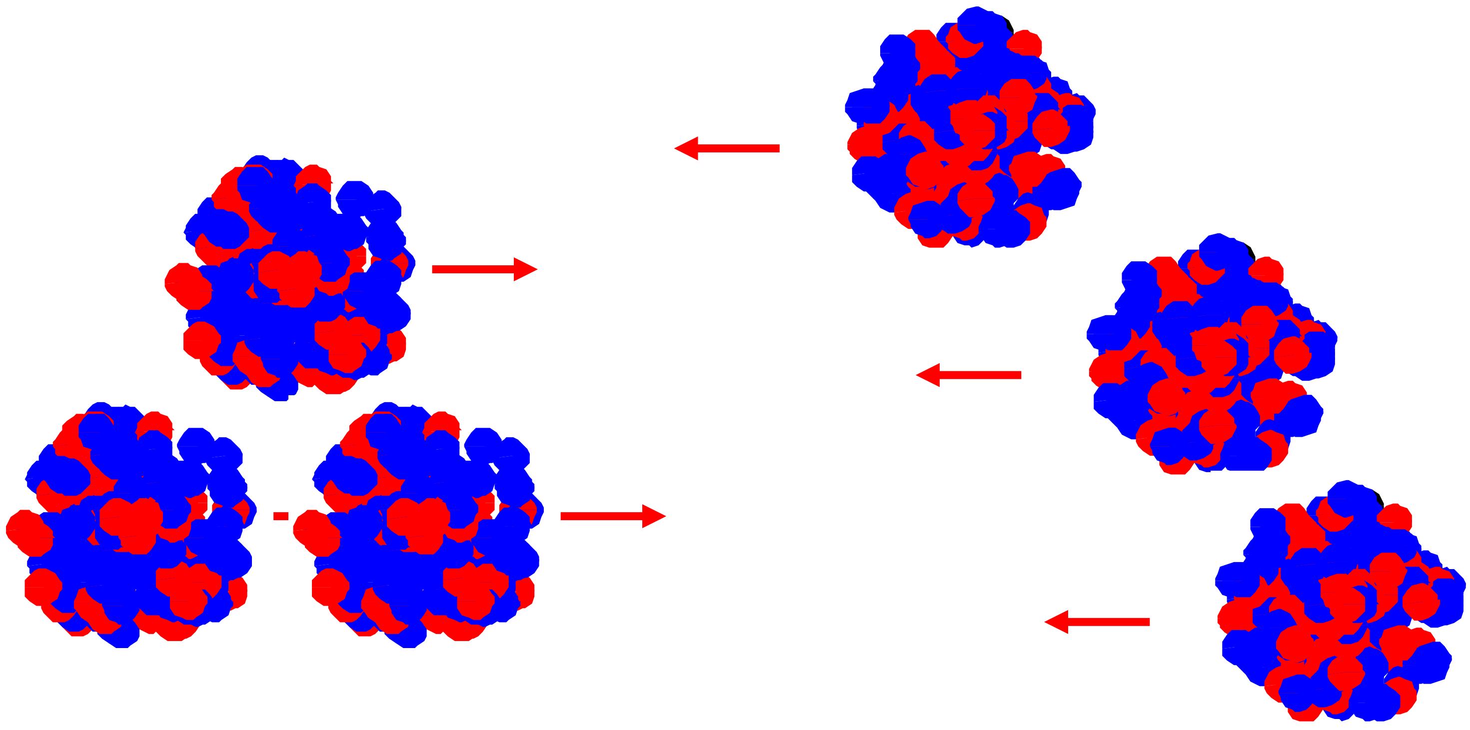
A. Nordt,
M. Sapinski,
B. Holzer

Max loss signal versus applied threshold during stable beams.

We are factor 30 short of design luminosity, factor 2 in energy.

Need factor 60 at BFPP loss points in dispersion suppressor.

Further analysis necessary – but looks comparable to predictions, depending on thresholds that are set.



THE 2011 LEAD-LEAD RUN

Physics conditions

- Number of bunches vs Nb
  - Injectors, Early or Nominal
  - Alternative backup 75 ns scheme
- Optics and orbits
  - Take over ATLAS and CMS β* from pp
    - Possibly reduce crossing angles ? Quick in 2010.
  - Squeeze ALICE to same value β*= 1.5 m
    - 2 days setup, unless done previously with protons
  - Crossing angles in ALICE
    - ZDC preferences
- TCTVBs open in IR2
  - Awaiting green light from Machine Protection
- Low β* in 3 IPs, as established for p-p

Nominal Filling scheme

- Nominal beam has been prepared in injectors up to PS
  - Intensity/bunch N_b close to design (but: we had better with the Early scheme in 2010)
- In LHC, 592 bunches of Nominal described in LHC Design Report reduced to 540 by present abort gap keeper requirement
- There are concerns about behaviour of beams (IBS, space-charge, …) on long (~40 s) injection plateau in SPS
  - No clear data with recent definitive RF configuration

Intermediate filling scheme

- Based on "Early" mode of operation of injectors
- Two bunches at 200 ns in PS but no splitting
  - "Can set up in an afternoon" S. Hancock
- Inject up to 15 times into SPS
  - Work on SPS injection kicker should give gap of 225 ns (E. Carlier)
  - Batches of up to 30 bunches to LHC – can optimise the length, mixture of 200 and 225 ns spacing, ~300 bunches
- Potential to retain higher bunch intensity (70% beyond design) already realised with Early scheme

Predictions for Pb-Pb at 4 Z TeV/beam

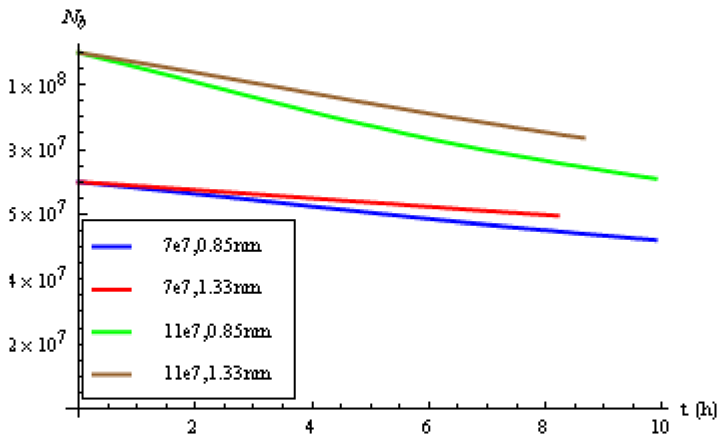
- Luminosity factors w.r.t. 2010
  - 1.5/3.5 from β*
  - 2-2.5 from bunch number and intensity

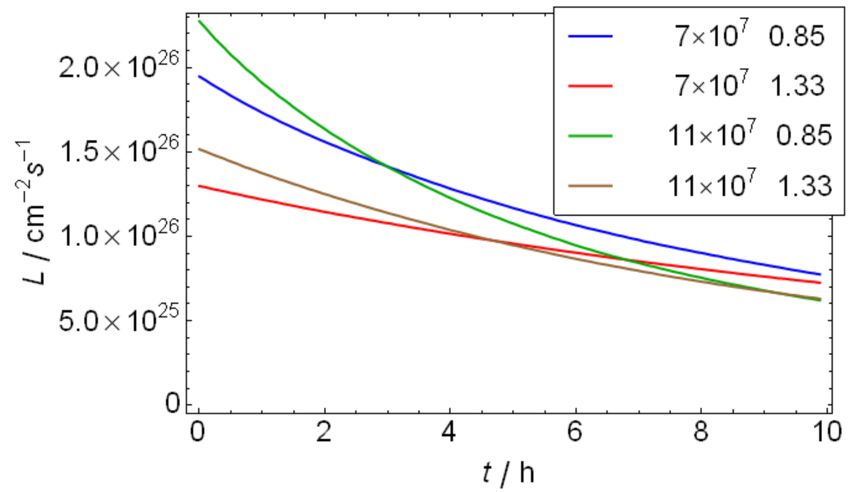
$$L = 1 - 1.4 \times 10^{26}\ \mathrm{cm^{-2}s^{-1}}$$

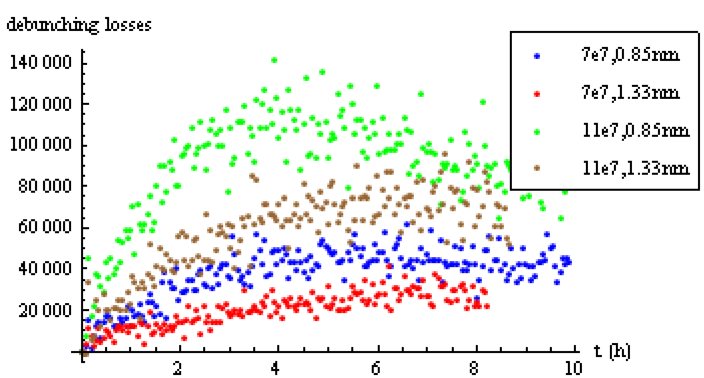
$$\text{Integrated luminosity } 30\text{-}50\ \mu\mathrm{b}^{-1}$$

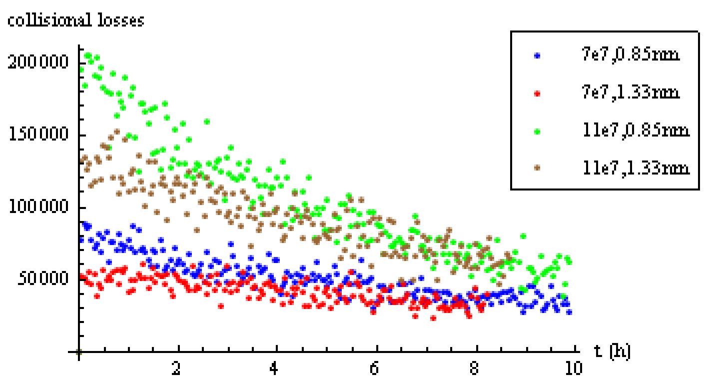
- Very sensitive to lost time in short run
- Some prospects for doing better

2011 Luminosity evolution (R. Bruce)









Luminosity burn-off

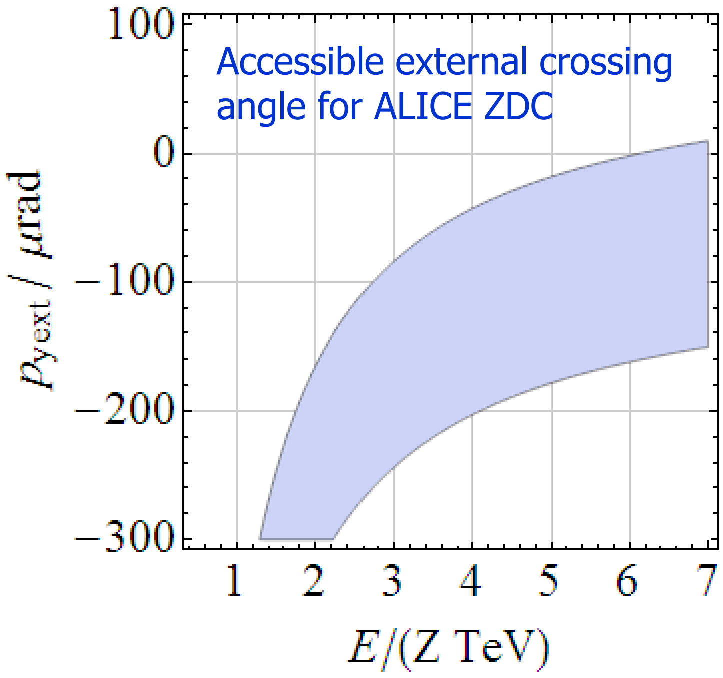
Debunching from IBS

Crossing angles for Pb-Pb physics

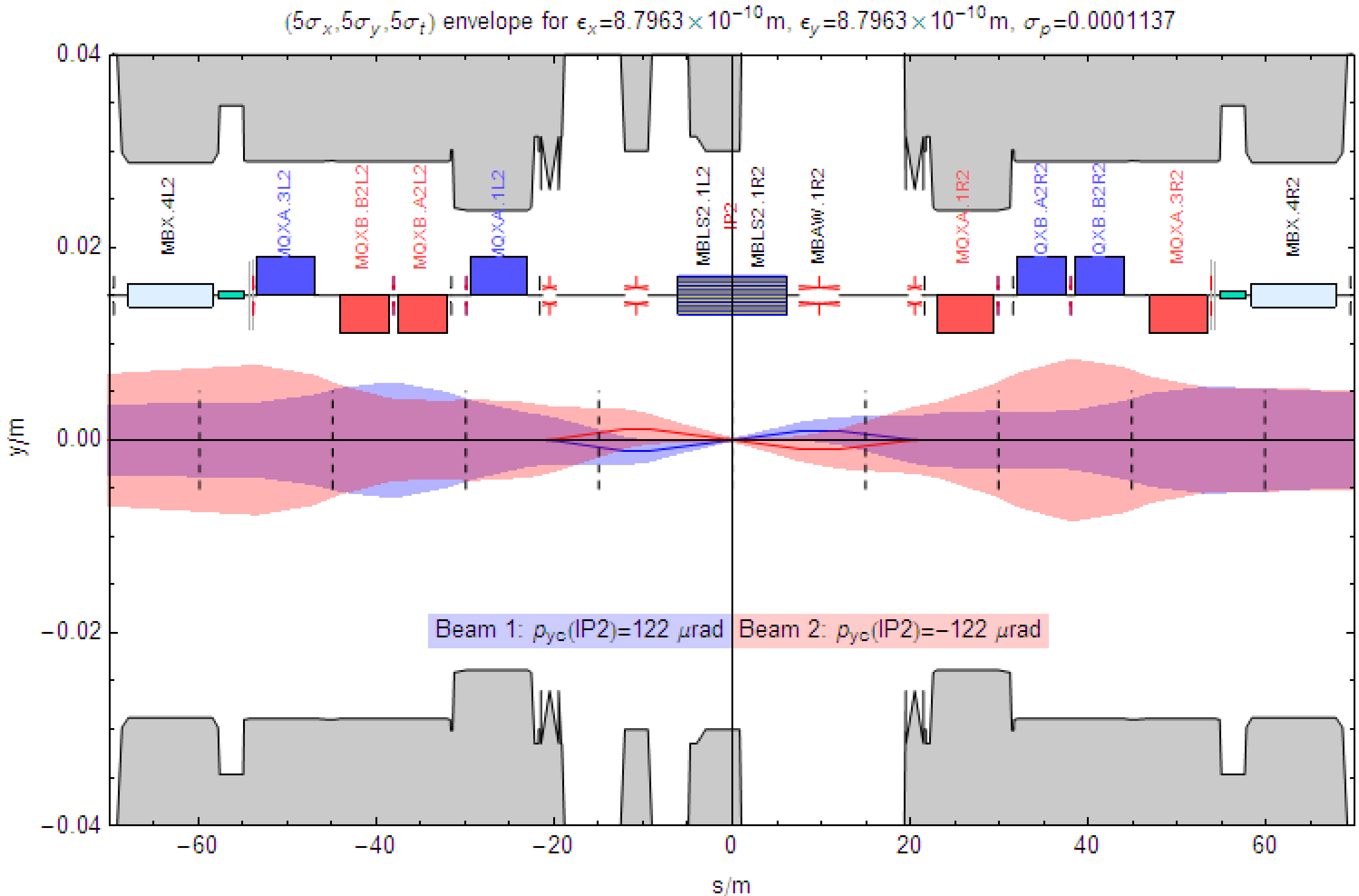
- ALICE: need to avoid shadowing of spectator neutrons to ZDC by TCTVBs
  - Hope we can keep TCTVBs fully open as last year
  - Even so, crossing angle is constrained by 28 mm gap (until the "old" TCTVs are taken out)
- ATLAS, CMS:
  - consider retaining crossing angle used in p-p (or reduce)
- LHCb: spectrometer off, injection optics and separation (as 2010)

Assuming spectrometer at full field, the half-crossing angle is:

$$p_{yc}(\mathrm{IP2}) = \frac{490\ \mu\mathrm{rad}}{E\,/\,(Z\ \mathrm{TeV})} + p_{yext}$$

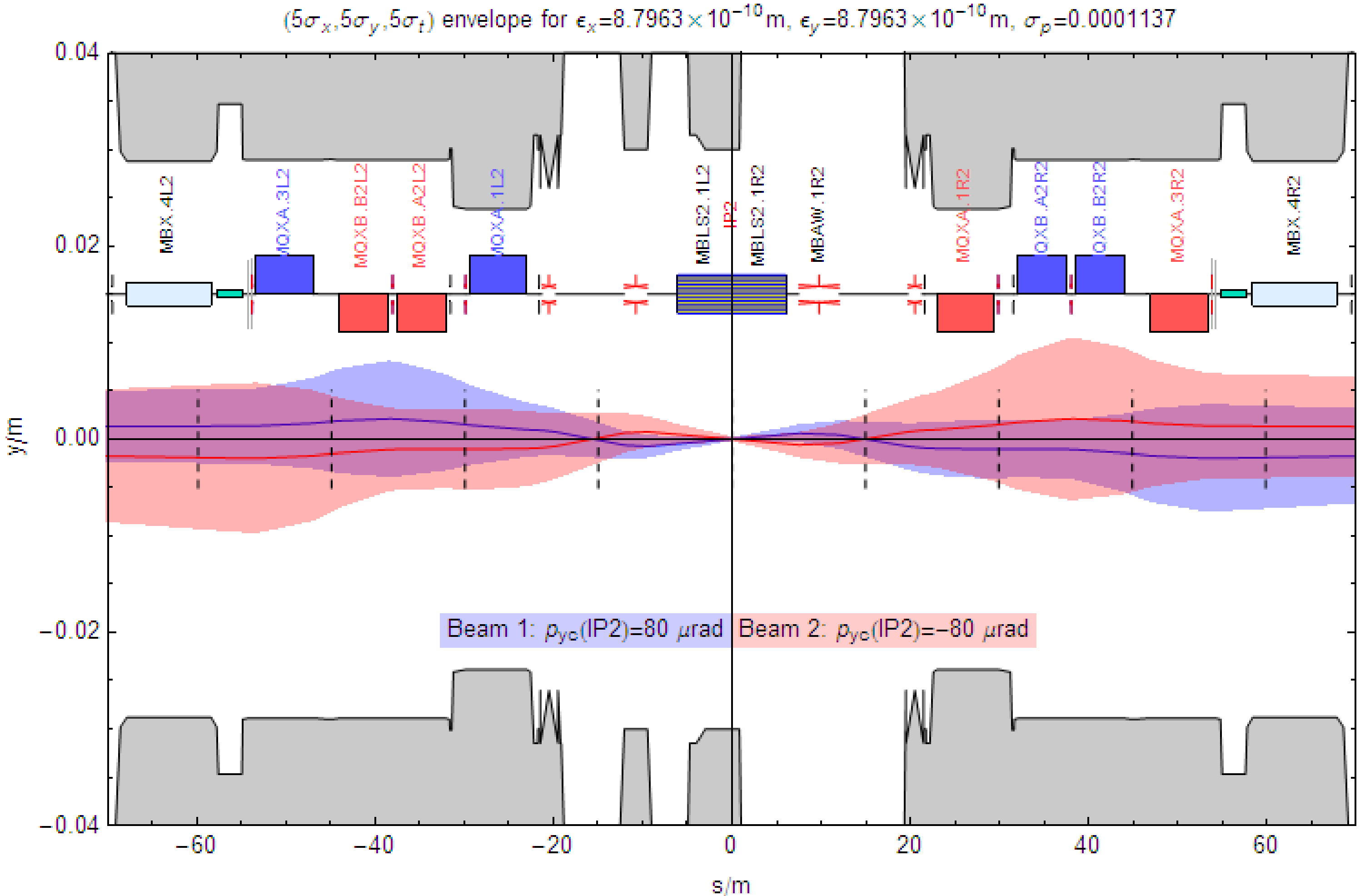


ALICE spectrometer alone (full field, 4 Z TeV)



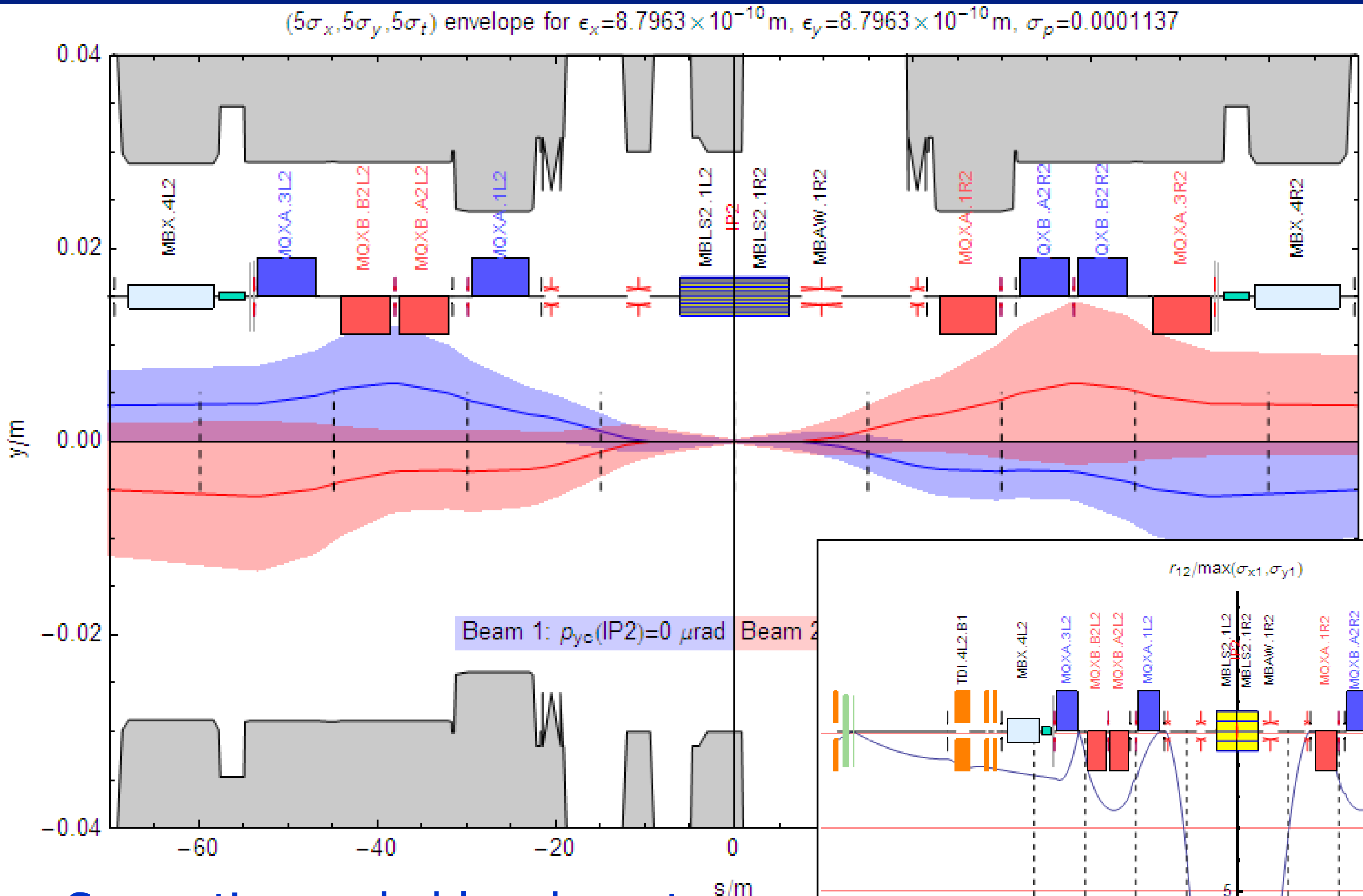
A little bump with a big lever arm

One extreme (fully open TCTVB, 4 Z TeV)



External bump partially cancels spectrometer – beams cross again, poor separation (but good aperture!)

Zero crossing angle (4 Z TeV) - ideal for ZDC

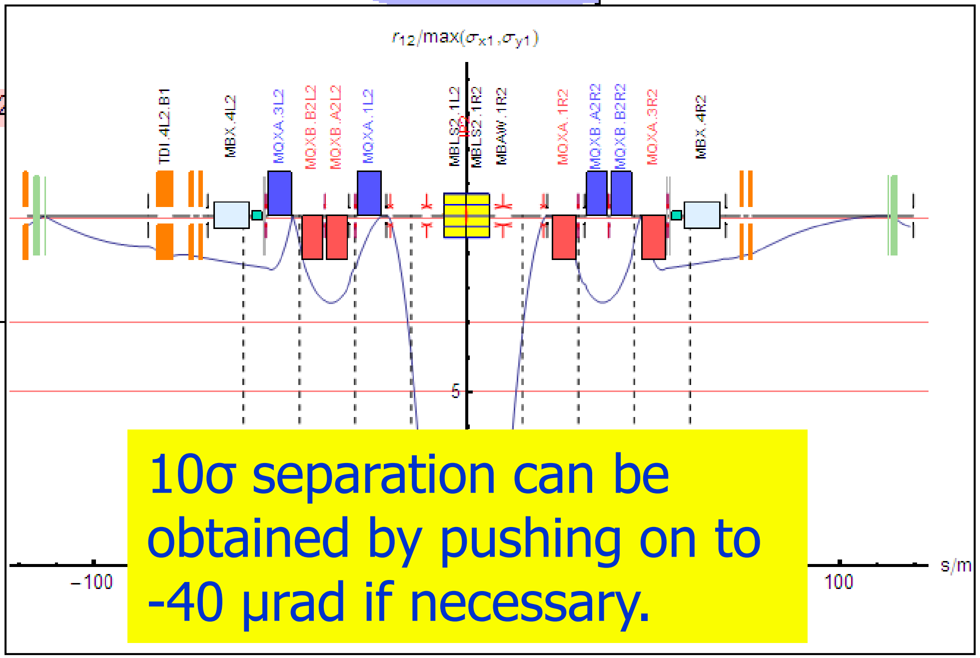


As in 2010 except that now:

$E = 4Z$ TeV,

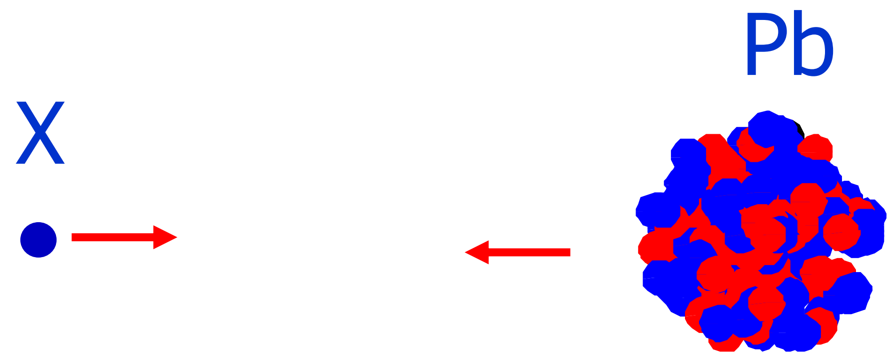
$\beta^* = 1.5$ m,

$S_b = 100c$ ns



10σ separation can be obtained by pushing on to -40 μrad if necessary.

Separation probably adequate for beam-beam at these intensities, but more comfortable at 200 ns.



THE 2012 X-LEAD RUN

Continue Pb-Pb in 2012

- Obvious possibility
  - it will still be a long way to 1 nb^{-1}

- Review further factors in luminosity obtainable between 2011 and 2012 after 2011 run

Something new: p-Pb in 2012

- Physics interest
  - C.f. deuteron-gold at RHIC
- No resources available to study so far, nevertheless:
  - pA workshop at CERN in 2005
    - http://ph-dep-th.web.cern.ch/ph-dep-th/content2/workshops/pAatLHC/pAworkshop2.html
  - Paper at EPAC 2006:

MOPLS009 Proceedings of EPAC 2006, Edinburgh, Scotland

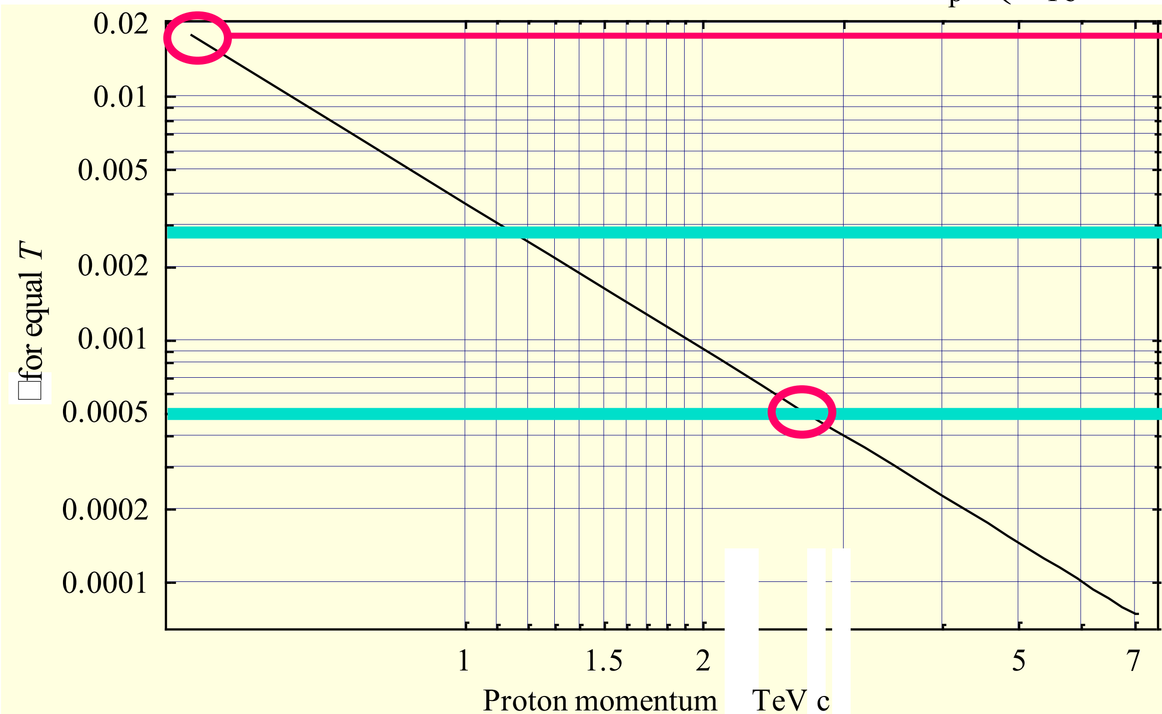
THE LHC AS A PROTON-NUCLEUS COLLIDER

J.M. Jowett, C. Carli, CERN, Geneva, Switzerland

  - Forthcoming CERN report contains accelerator chapter (approved in 2005)

Momentum offset required to equalise frequencies

Minimise aperture needed by $\delta_{\mathrm{p}} = -\delta_{\mathrm{Pb}} = \dfrac{c^2 \gamma_T^{\,2}}{4 p_{\mathrm{p}}^2}\left(\dfrac{m_{\mathrm{Pb}}^2}{Z_{\mathrm{Pb}}^2} - m_{\mathrm{p}}^2\right).$



Would move beam by 35 mm in QF!!

Limit with pilot beams

Limit in normal operation

Revolution frequencies must be equal for collisions.

⇒Lower limit on energy of p-Pb collisions, E_p ~ 2.7 TeV

Energy where RF frequencies can become equal in ramp.

Summary of key facts about p-Pb

- Modes of operation of injectors worked out
  - Some concern about 80 MHz cavities in PS
  - Priority protons in Beam 1
- 4 Z TeV gives comparison data for Pb-Pb at full energy
  - Unlikely to be another opportunity to run at this energy
- Important to resolve uncertainties regarding feasibility, Pb intensity limit from unequal revolution frequencies at injection, ramp
  - Modulation of long-range beam-beam, excitation of overlap knock-out resonances, transverse feedback, tune-control …

Accessible energies and CM rapidities

Possible range of collision energies Minimum p-Pb energy for equal revolution frequency.

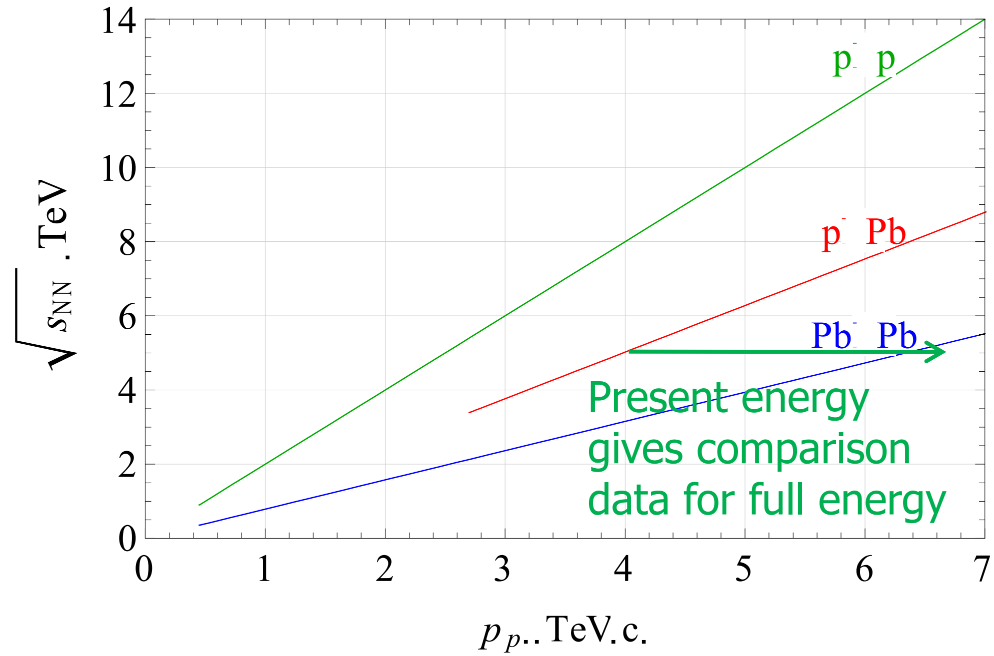
Relations between these numbers are a simple consequence of the two-in-one magnet design

	p-p	Pb-Pb	p-Pb
E/TeV	0.45-7	287-574	(2.7-7,287-574)
E_N/TeV	0.45-7	1.38-2.76	(2.7-7, 1.38-2.76)
$\sqrt{s}/\mathrm{TeV}$	7-14	73.8-1148	48.9-126.8
$\sqrt{s_{\mathrm{NN}}}/\mathrm{TeV}$	7-14	0.355-5.52	3.39-8.79
y_{CM}	0	0	-2.20
y_{NN}	0	0	+0.46

Charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p

$$\sqrt{s_{NN}} \approx 2c\, p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}},$$

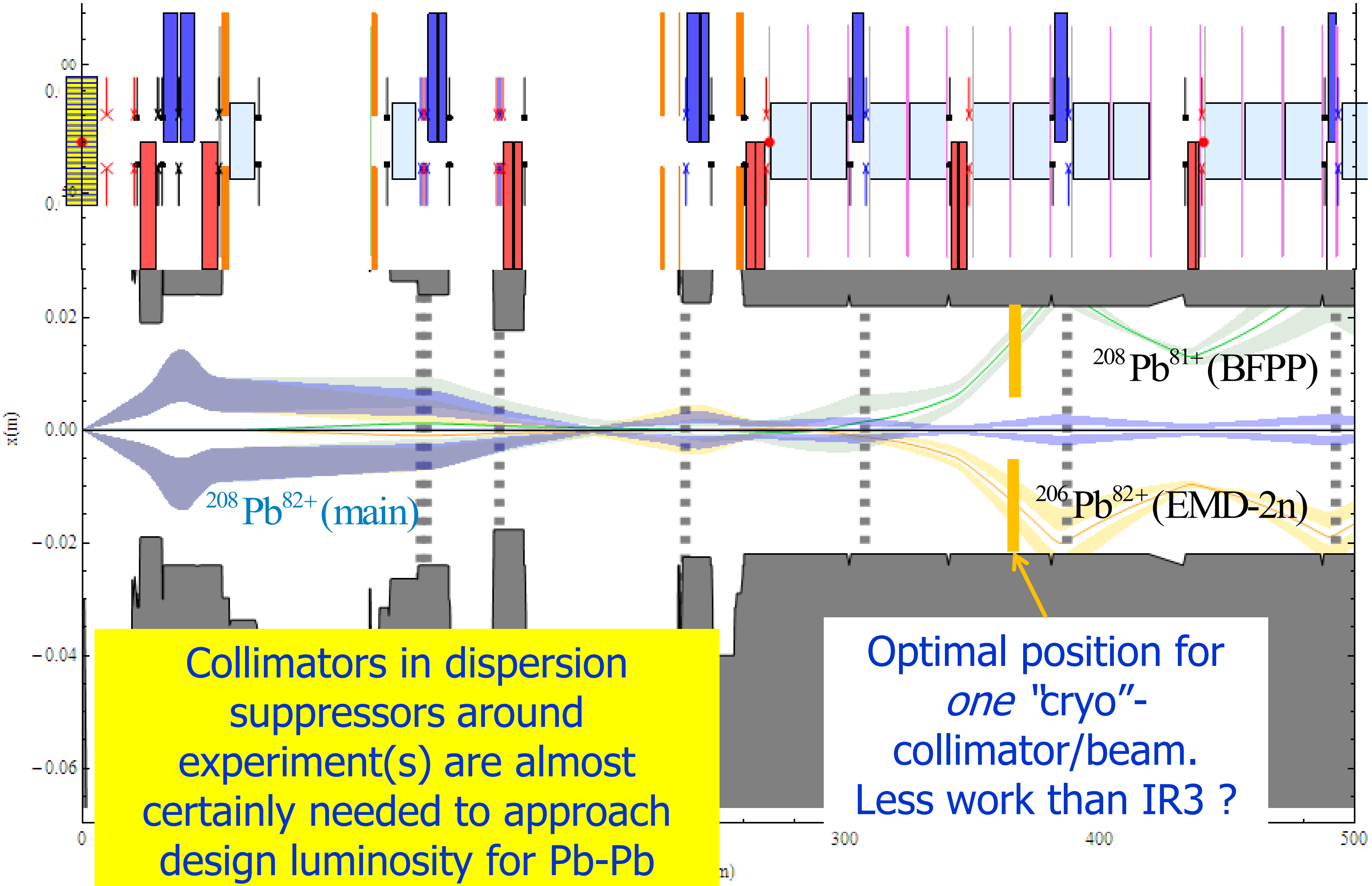
$$y_{NN} = \frac{1}{2}\log\frac{Z_1 A_2}{A_1 Z_2}$$



Testing p-Pb in 2011

- Crucial questions are related to injection and ramping
  - Effects of protons (say 10% of nominal) on one Pb bunch
  - Inject few Pb bunches against some convenient p filling scheme
  - Possible in 2011 (small LLRF upgrade needed to collide, OK in 2012)
  - Detailed planning of MD strategy needs to be done: study and overcome intensity/emittance blow-up

Main and secondary Pb beams from ALICE IP



Collimators in dispersion suppressors around experiment(s) are almost certainly needed to approach design luminosity for Pb-Pb collisions.

Optimal position for *one* "cryo"-collimator/beam. Less work than IR3 ?

Upgrades important for heavy ions

- LLRF upgrade – p-Pb collisions in 2012
  - OK
- New TCTVAs in IR2 – ZDC + triplet protection
  - Intervention to be planned
  - Then remove old TCTVBS asap
- DS collimators in IR3 – intensity limitw
  - 2013
- DS collimators in IR2 – luminosity limit
  - 2016 ?
  - Highest priority for heavy ion physics
  - If IR3 postponed, can we do this in 2012 ?
- DS collimators in IR7 – intensity limit

Long-term possibilities

- IR2 DS collimators open up possibilities for Pb-Pb luminosity beyond design in ALICE
- IR3 DS collimators also very important
  - See other presentations (eg 2009 Collimation Review)
- Lighter ions (Ar, …) made available in synergy with SPS fixed target programme
  - N.B. first indications are that Ar collimation will make heaviest demands on DS collimators

Conclusions

- The 2010 Pb-Pb run showed that the LHC can work well with heavy ions
  - Operation very efficient in beam time
- Beam physics is complex!
  - Needs more resources for study, analysis of data
- Substantial factor in luminosity possible for 2011
  - Options for filling etc, will be clarified in injector commissioning, experiments are flexible
- 2012 appears to be a good opportunity for p-Pb
  - Otherwise it will be a long time … interesting energy
  - Feasibility test in MD can be tried in 2011
- Upgrades critical to sustain performance ramp
  - Installation of DS collimators in IR2 should not be allowed to slip too far into the future

BACKUP SLIDES

•Two ovens operational

•The first oven filling lasts for around two weeks, the second for only one week (due to plasma heating of the oven)

•Oven refill takes around 36 hours

•In 2010 only the first oven was used, the second one was used as hot spare in case of problems

•In principle one can extend the period between two oven refills to three weeks, but the third week may suffer from instabilities and intensity fluctuations

•The switch between the two ovens is normally transparent to the operation, it takes several hours to bring up the second oven to operational conditions (big thermal mass)

•Mechanical movement of the oven