Prospects for the LHC Heavy-Ion Programme in the coming decade

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Thanks to

R. Alemany, F. Antinori, R. Assmann, P. Baudrenghien, G. Bellodi, R. Bruce, C. Carli, P. Giubellino, S. Hancock, D. Kuchler, S. Maury, D. Manglunki, T. Mertens, M. Solfaroli, W. Venturini, J. Wessels, D. Wollmann and many others

- Abstract
  - The first heavy-ion run of the LHC in 2010 opened up a new energy frontier in nucleus-nucleus collisions. An immediate harvest of physics results demonstrated the potential of the collider and its three heavy-ion experiments, ALICE, ATLAS and CMS. The plan for the coming decade foresees not only increasing energy and luminosity of the primary Pb-Pb collisions but also hybrid p-Pb and Ar-Ar collisions. The programme is defined by the physics requirements, the limits from beam physics and accelerator technology in the LHC and its heavy-ion injector chain, compatibility with the p-p programme and the planning of upgrades and modifications to the CERN accelerator complex.

Outline of talk

- Generalities on LHC as nucleus-nucleus collider
- The 2010 Pb-Pb run
- The 2011 Pb-Pb run
- Possible p-Pb run in 2012
- Evolution of performance
  - Limits
  - Mitigations, how and when ?
- Proposal for the years beyond 2012

LHC Ion Injector Chain

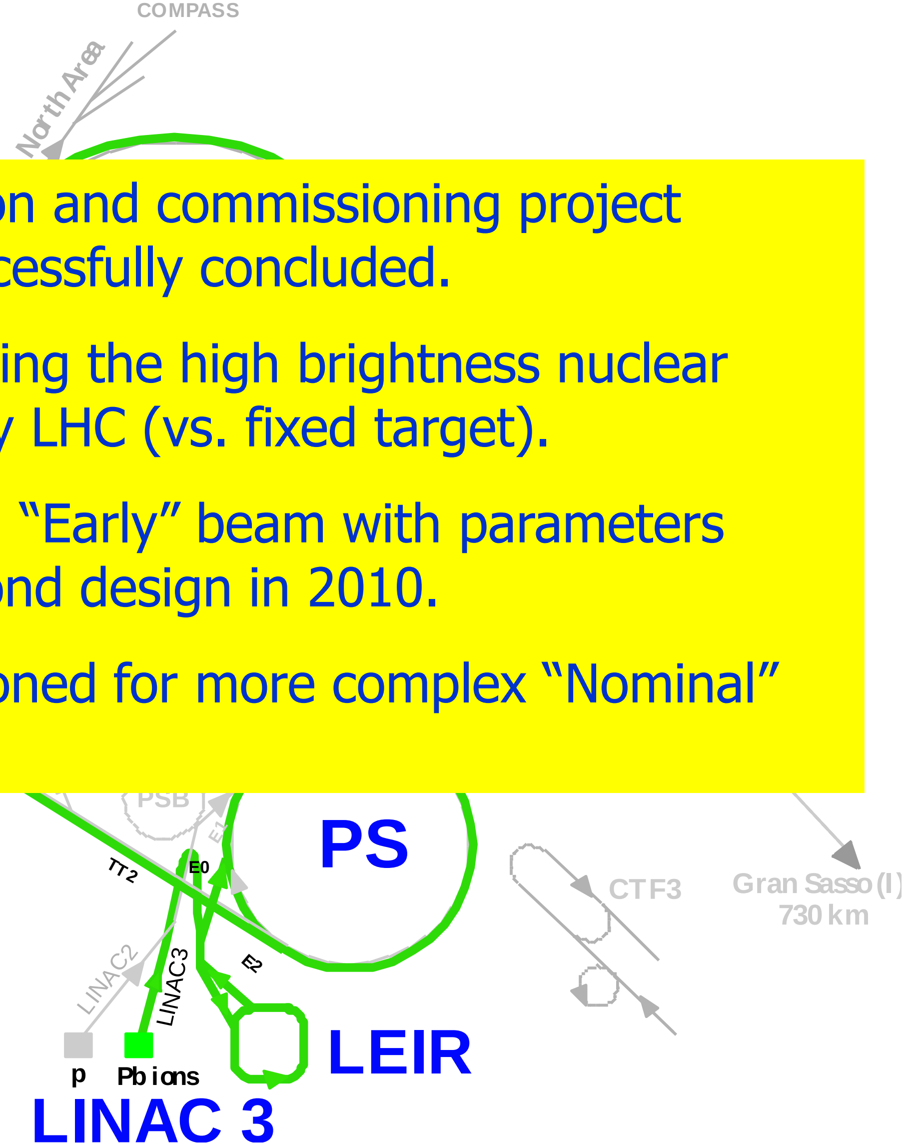
- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR ir
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and beam
  - Prepare bunch s
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC

I-LHC construction and commissioning project (2003-2010) successfully concluded.

Vital role in creating the high brightness nuclear beams needed by LHC (vs. fixed target).

Already delivered "Early" beam with parameters significantly beyond design in 2010.

Mostly commissioned for more complex "Nominal" beam.



Reference: Luminosity of a hadron collider

$$L = \frac{N^2 k_c f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_c f_0 \gamma}{4\pi\,\varepsilon_n \beta^*} F(\theta_c)$$

Hour glass factor: $F = 1 \Big/ \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$

- Parameters in luminosity
  - No. of particles per bunch N
  - No. of bunches per beam k_b
  - No. of bunches colliding at IP k_c $(k_c < k_b)$
  - Relativistic factor γ
  - Normalised emittance ε_n
  - Beta function at the IP β^*
  - Crossing angle factor F
    - Full crossing angle θ_c
    - Bunch length σ_z
    - Transverse beam size at the IP σ^*

Equal amplitude functions:

$\beta_x^* = \beta_y^* = \beta^*$,

Geometric and normalised emittance:

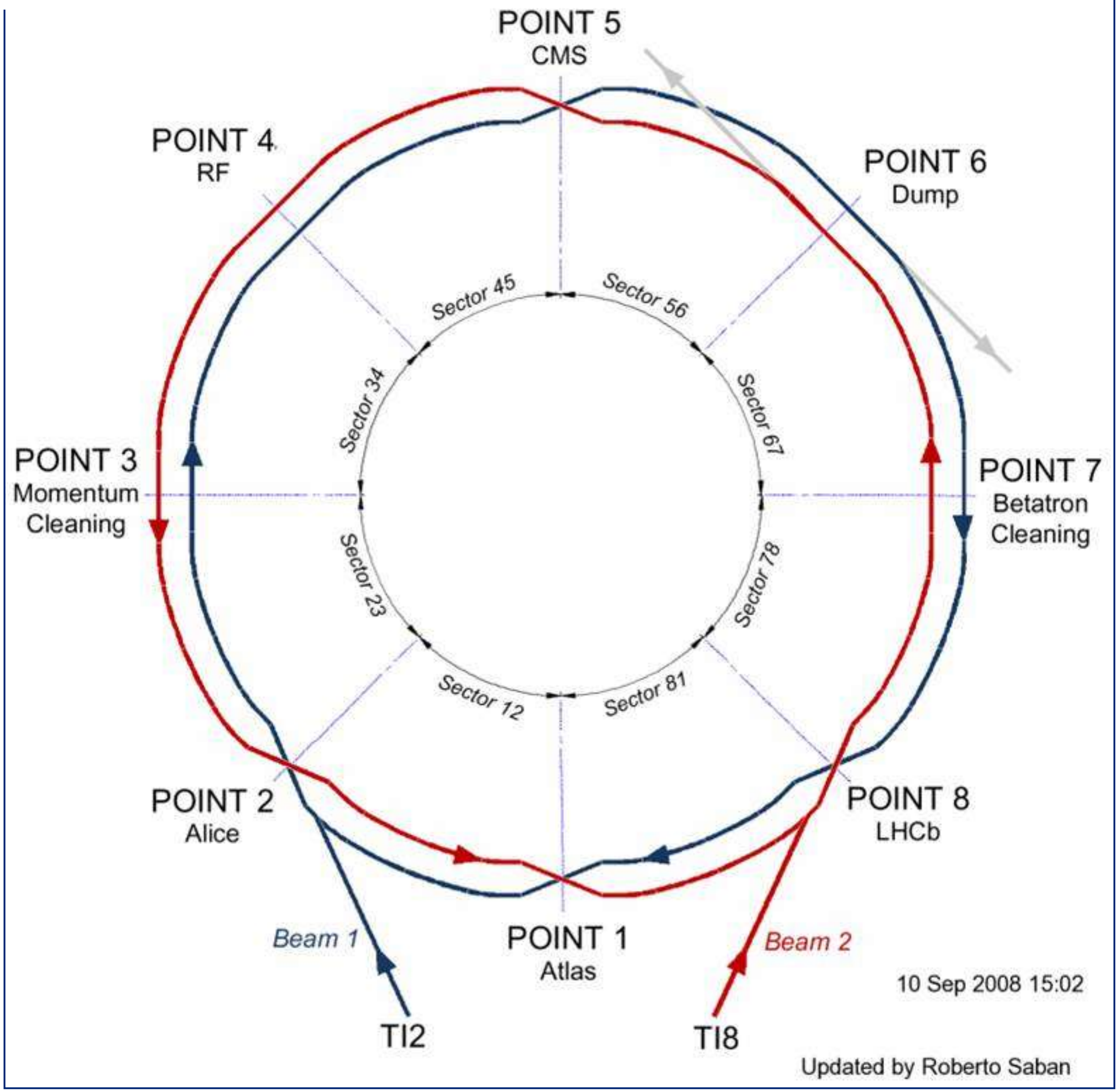
$$\varepsilon_x^* = \varepsilon_y^* = \varepsilon^* = \frac{\varepsilon_n}{\sqrt{\gamma^2 - 1}}$$

$\Rightarrow$ Round beams at IP:

$$\sigma_x^* = \sigma_y^* = \sigma^* \simeq \sqrt{\frac{\beta^* \varepsilon_n}{\gamma}}$$

(N.B. LHC uses RMS emittances.)

LHC orientation



Three large and highly capable heavy-ion physics experiments:

ALICE

ATLAS

CMS

Design Parameters for Pb-Pb (~2001)

Parameter	**Units**	**Early Beam**	**Nominal**
Energy per nucleon	TeV	2.76	2.76
Initial ion-ion Luminosity L_0	$cm^{-2}\ s^{-1}$	$\sim 5 \times 10^{25}$	1×10^{27}
No. bunches, k_b		62	592
Minimum bunch spacing	ns	1350	99.8
β^*	m	1.0	0.5 /0.55
Number of Pb ions/bunch		$\mathbf{7 \times 10^7}$	$\mathbf{7 \times 10^7}$
Transv. norm. RMS emittance	μm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	h	14, 7.5, 5.5	8, 4.5, 3

Something like this at reduced energy, higher β^*, in 2010

Probably unattainable without DS collimators (see later)

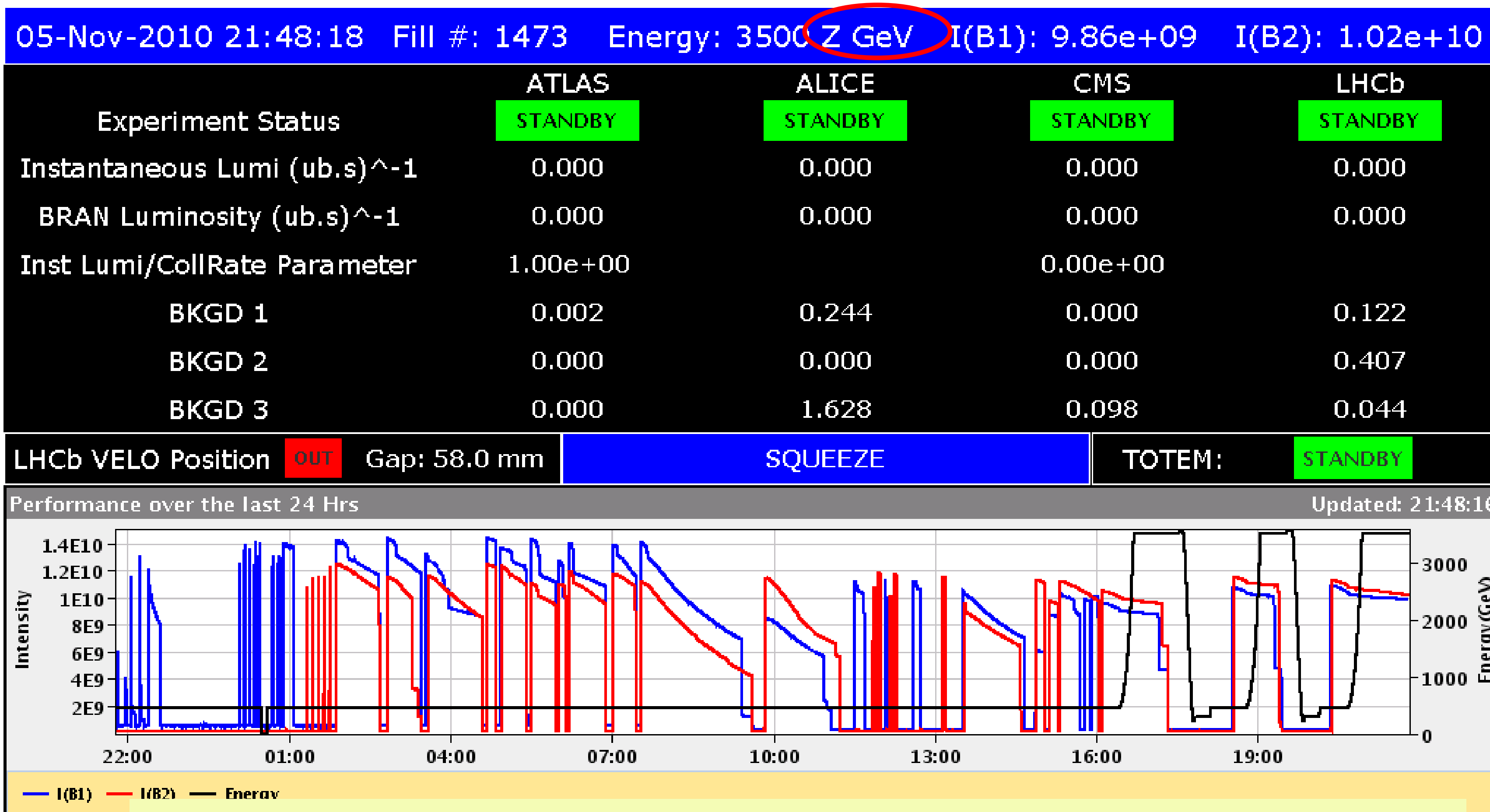
At full energy, luminosity lifetime is determined mainly by collisions ("burn-off" from ultraperipheral electromagnetic interactions) $\sigma \approx 520$ barn

THE 2010 LEAD-LEAD RUN

Commissioning in 2010

- The LHC really worked with Pb beams!
  - No rapidly decaying, invisible beams
  - No quenches, so far
- Expanded the energy frontier for laboratory nuclear collisions by a factor 13.7 (later up to 28) beyond RHIC
  - Historically: biggest energy factor ever made by any collider over its predecessor
- Rich and novel beam physics,
  - Some similarities with protons:
    - Orbits, optics, aperture
  - Many differences from protons (and RHIC heavy ions), much as predicted:
    - Nuclear processes, ultraperipheral physics in collimation and luminosity, strong IBS effects (more later)
  - Some surprises nevertheless:
    - Emittances sometimes blown-up by unexpected effects
    - Some new loss locations and radiation problems

Heavy Ion Run: first 24 h, Thu-Fri 4-5 Nov



Rapid commissioning plan exploited established proton cycle to speed through initial phase of magnetic setup (injection, ramp, squeeze) .

Collision crossing angles and collimation conditions different.

Beam :

Inj., Ci

& Capt

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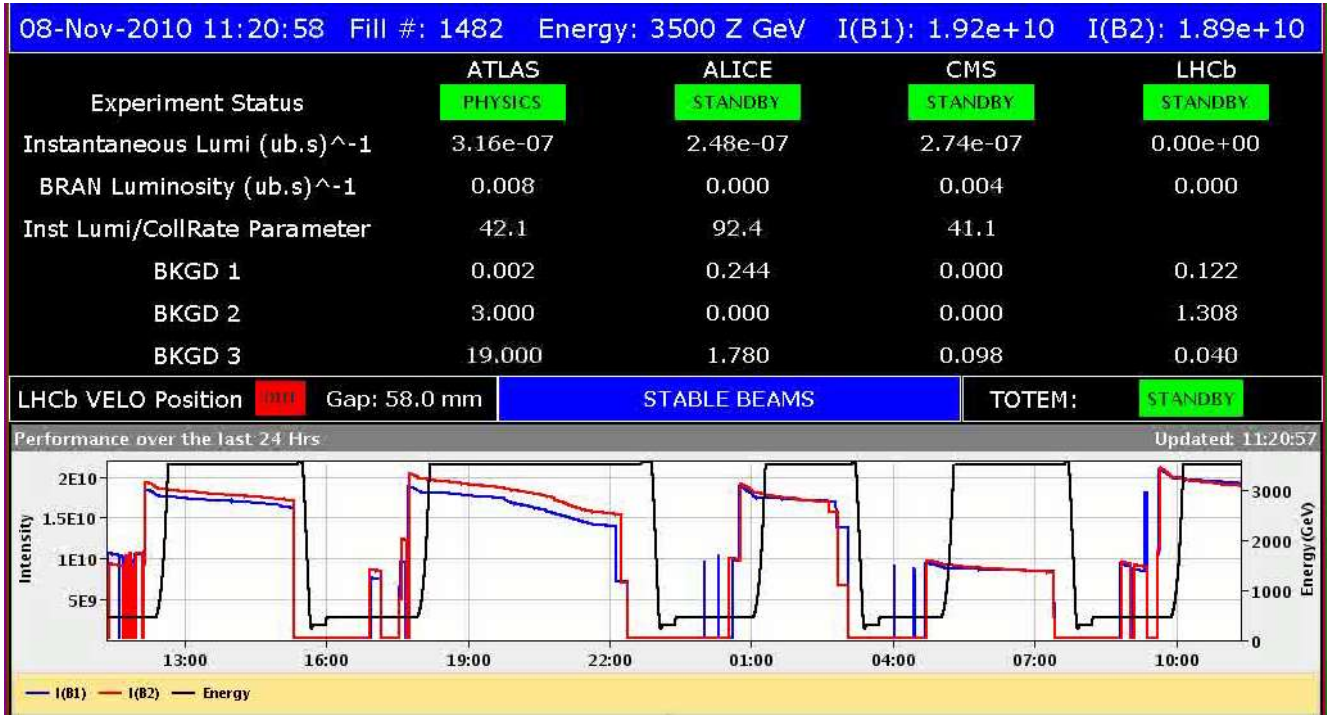
Monday morning: First Stable Beams for Pb-Pb



First stable beam with 2 bunches/beam (1 colliding)

Later same day, 5 bunches/beam, then increased on each fill: 17, 69, 121

Factor 100 in peak luminosity within 6 days.

Many interesting new RF manipulations in LHC in first 2 weeks.

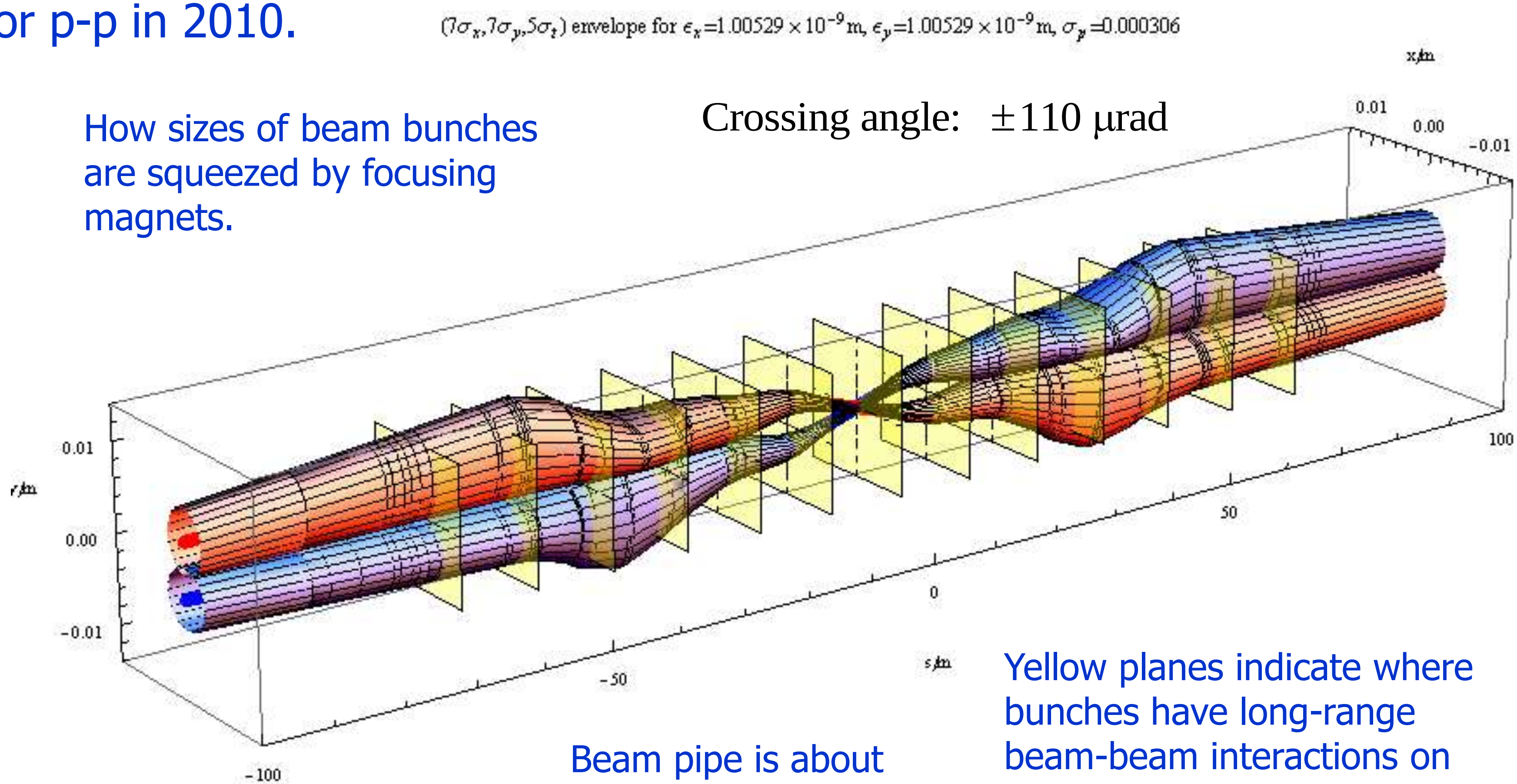
Ion injectors exceeded design intensity/bunch by 70%.

Beam envelopes around ALICE experiment

Collision conditions
for p-p in 2010.

How sizes of beam bunches are squeezed by focusing magnets.

Crossing angle: $\pm 110\ \mu$rad



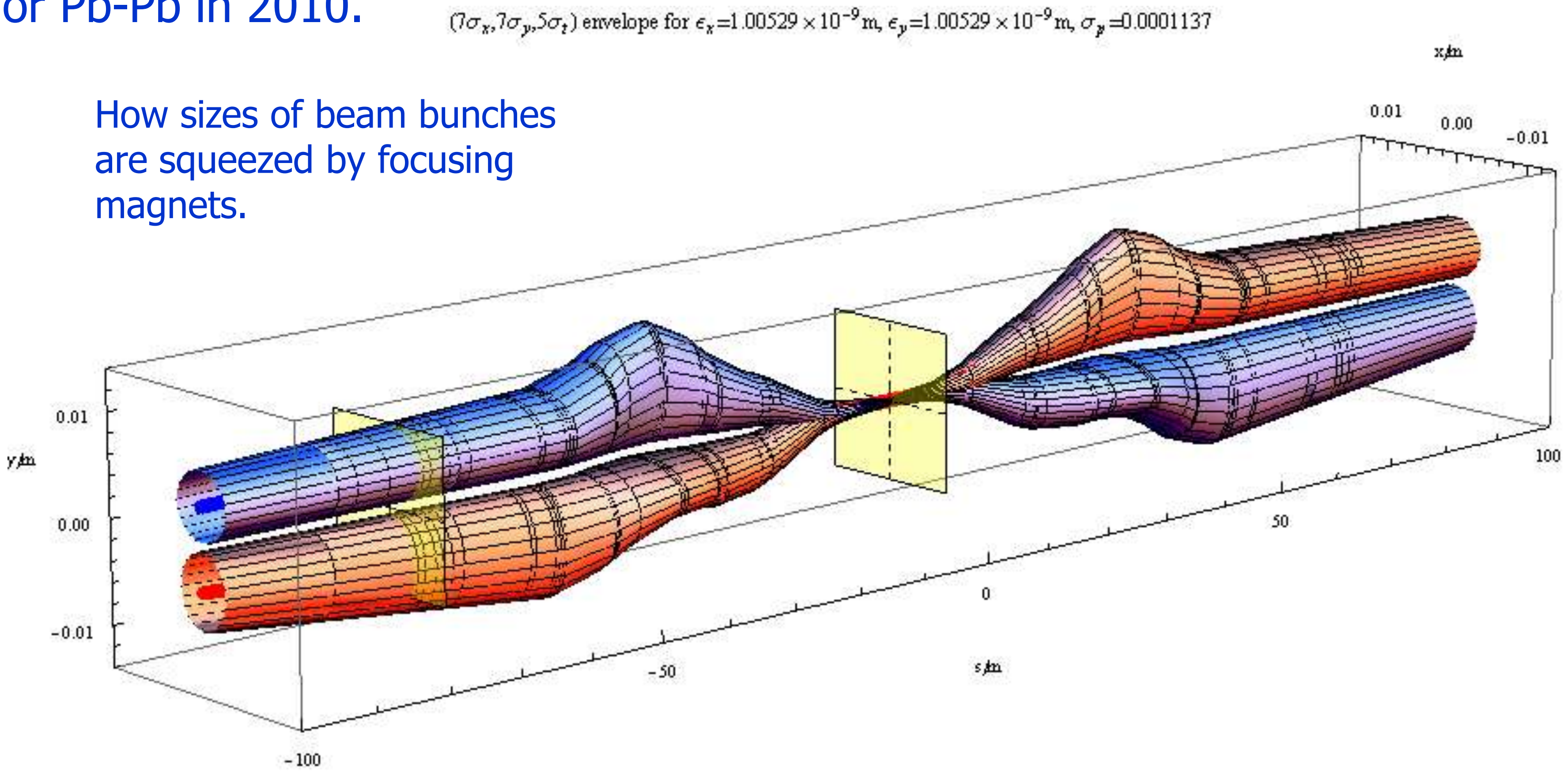
Beam pipe is about twice transverse size of box.

Yellow planes indicate where bunches have long-range beam-beam interactions on their way in and out of the collision point (75 ns bunch spacing).

Beam envelopes around ALICE experiment

Collision conditions
for Pb-Pb in 2010.

How sizes of beam bunches are squeezed by focusing magnets.



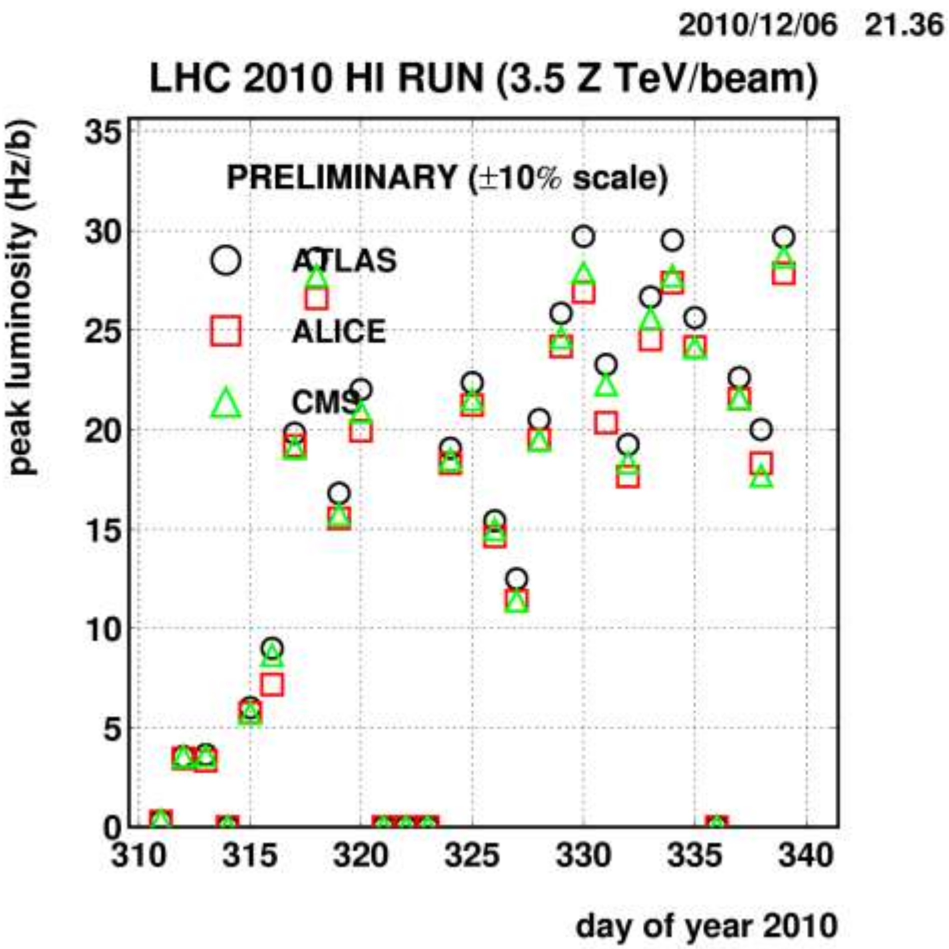
Zero crossing angle at IP (external crossing angle compensates ALICE spectrometer magnet bump).

Beam pipe is about twice transverse size of box.

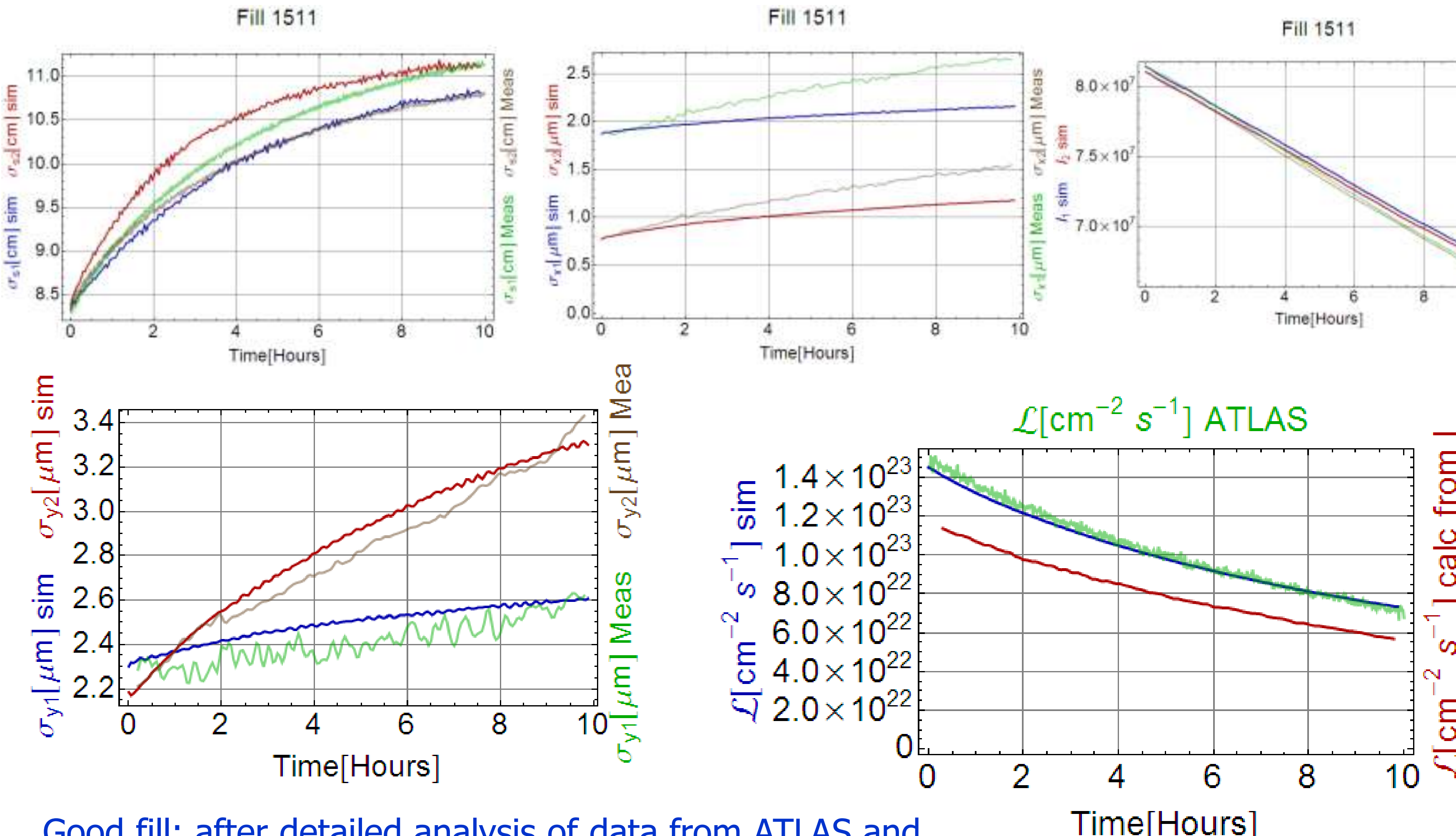
Peak luminosity in fills

Interrupted twice by source refills (+ few days "parasitic" proton MD), some time to recover source performance (improvements for 2011).

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



Understanding luminosity/bunch

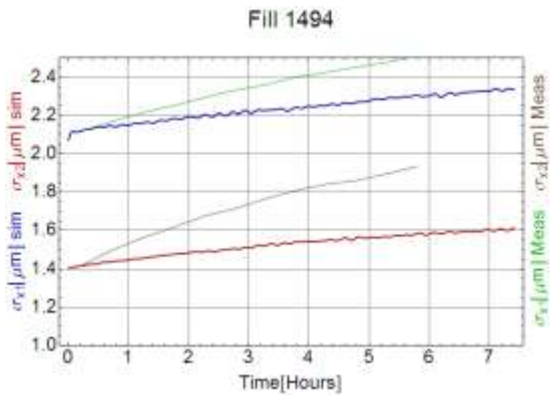


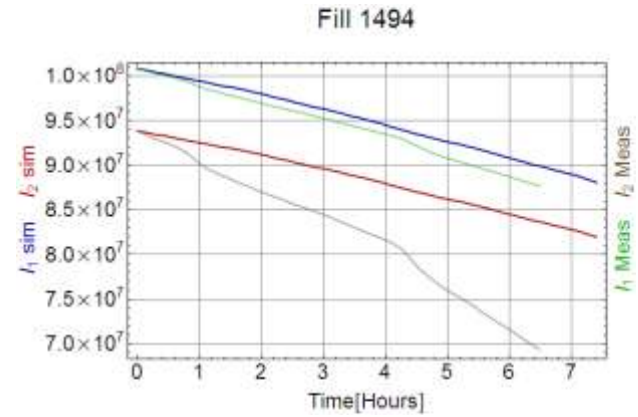
Good fill: after detailed analysis of data from ATLAS and machine instrumentation, there is good agreement with simulation model (non-gaussian IBS, emittance growth, debunching from RF bucket, luminosity burn-off, etc.). Parameters of two beams evolve separately.

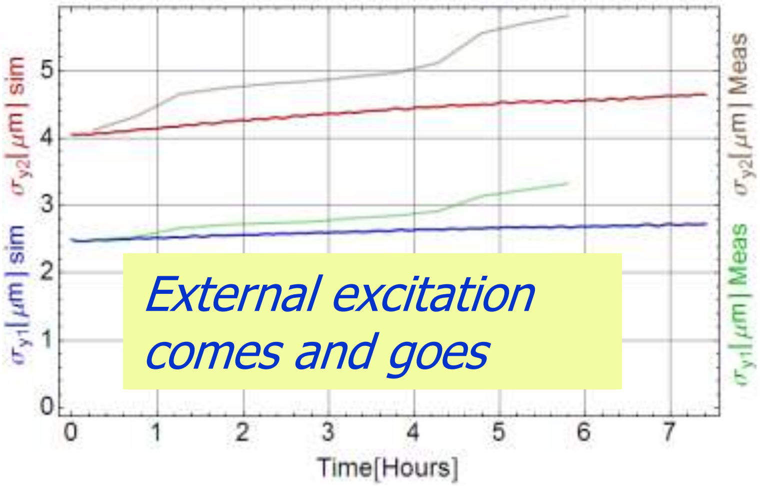
Simulations by T. Mertens, based on earlier work by R. Bruce, JMJ, M. Blaskiewicz, W. Fischer.

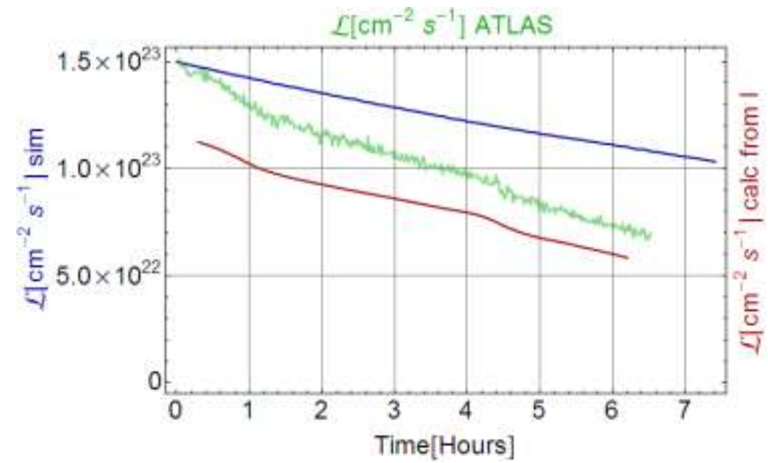
Phys. Rev. ST Accel. Beams 13, 091001 (2010)

Not-quite-understanding luminosity/bunch





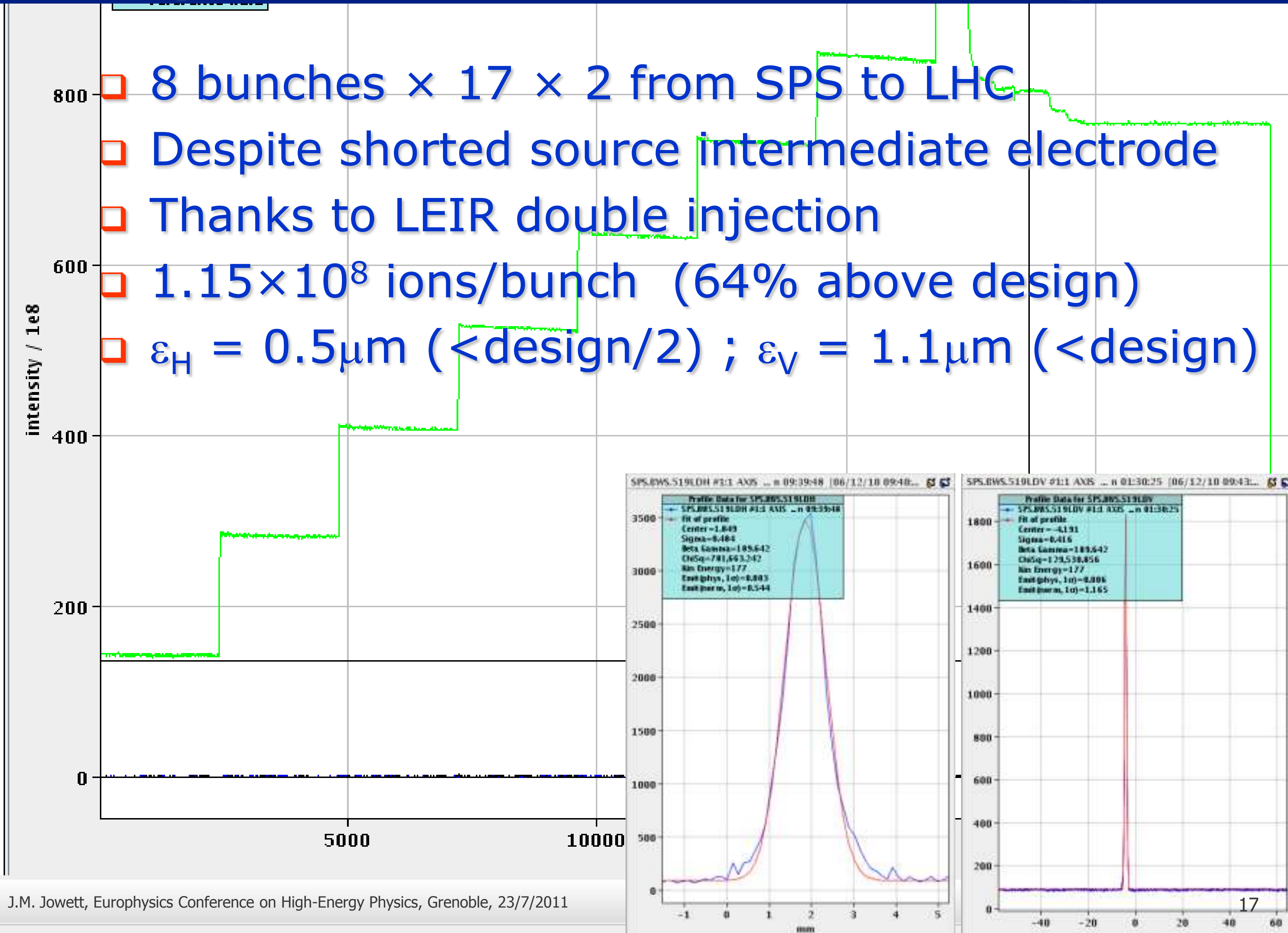


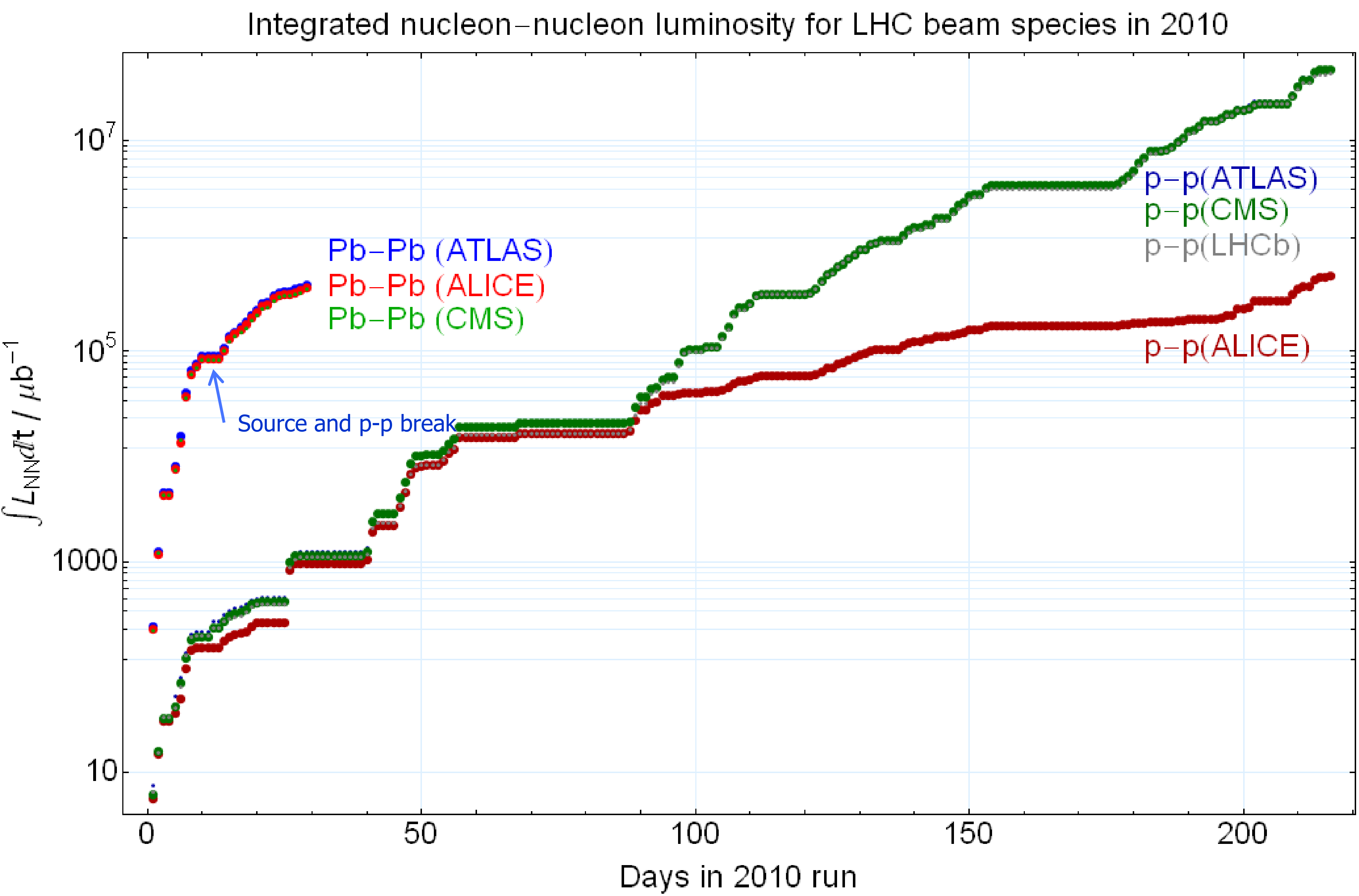


"Hump-influenced" fill: similar analysis and simulation show the influence of an unknown intermittent excitation, mainly Beam 2 vertical

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)
- $\varepsilon_H = 0.5\mu m$ (<design/2) ; $\varepsilon_V = 1.1\mu m$ (<design)





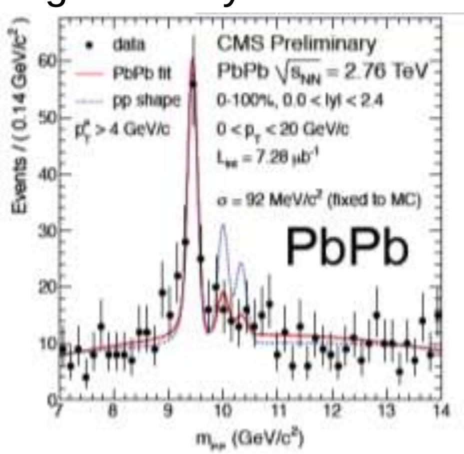
Integrated nucleon−nucleon luminosity for LHC beam species in 2010
$\int L_{\mathrm{NN}} dt \;/\; \mu b^{-1}$
10^7
10^5
1000
10
0
50
100
150
200
Days in 2010 run
Pb−Pb (ATLAS)
Pb−Pb (ALICE)
Pb−Pb (CMS)
Source and p-p break
p−p(ATLAS)
p−p(CMS)
p−p(LHCb)
p−p(ALICE)

QUARK MATTER 2011
23-28 May 2011 – Annecy, France

- Most important conference series for ultra-relativistic AA collisions
- First edition after start of LHC
  - > 800 participants

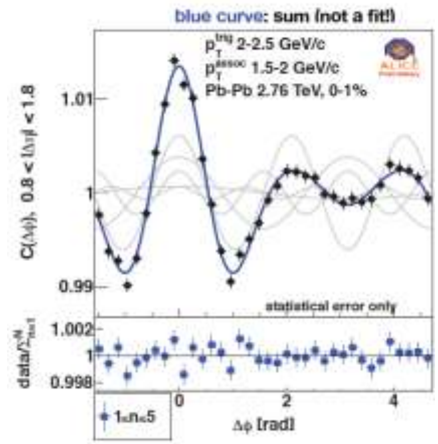
→ First, rich LHC harvest, a few examples…

- <u>Quarkonium suppression</u>
  - e.g: Υ family



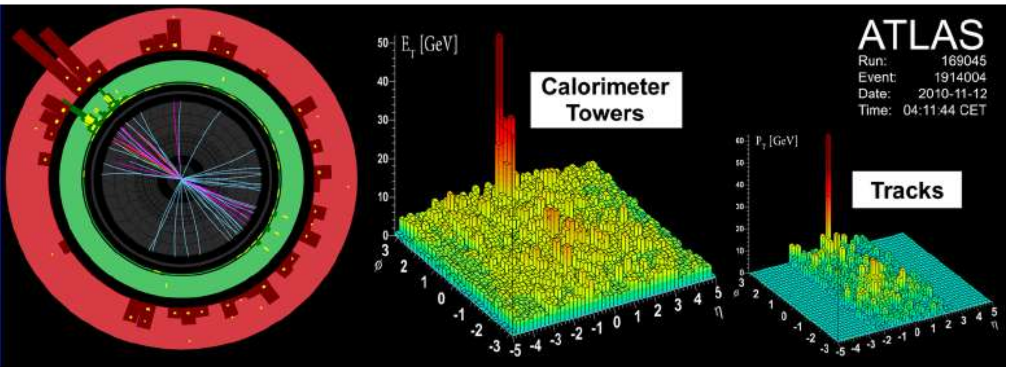
  - measurement of detailed suppression pattern will give information on QGP temperature, evolution

- <u>Long-range η correlations</u>



  - Explanations invoking response of QGP medium to propagating partons were proposed at RHIC (“ridge”, “Mach cone”)
  - Fourier analysis of new data suggests very natural alternative explanation in terms of almost ideal hydrodynamic response of QGP to initial state fluctuations

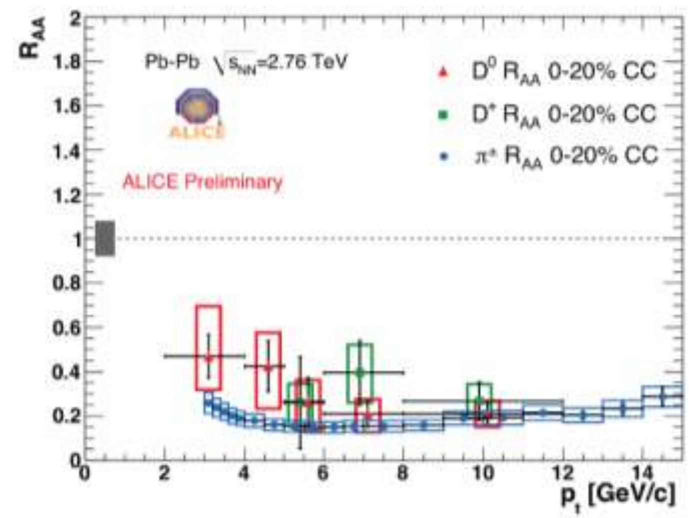
- Suppression of di-jet production



  – recoiling high energy jets strongly quenched in QGP

  (but no visible angular decorrelation in azimuth!)

- Heavy flavour energy loss
  – suppression with respect to scaled pp



  – D almost as strongly suppressed as π

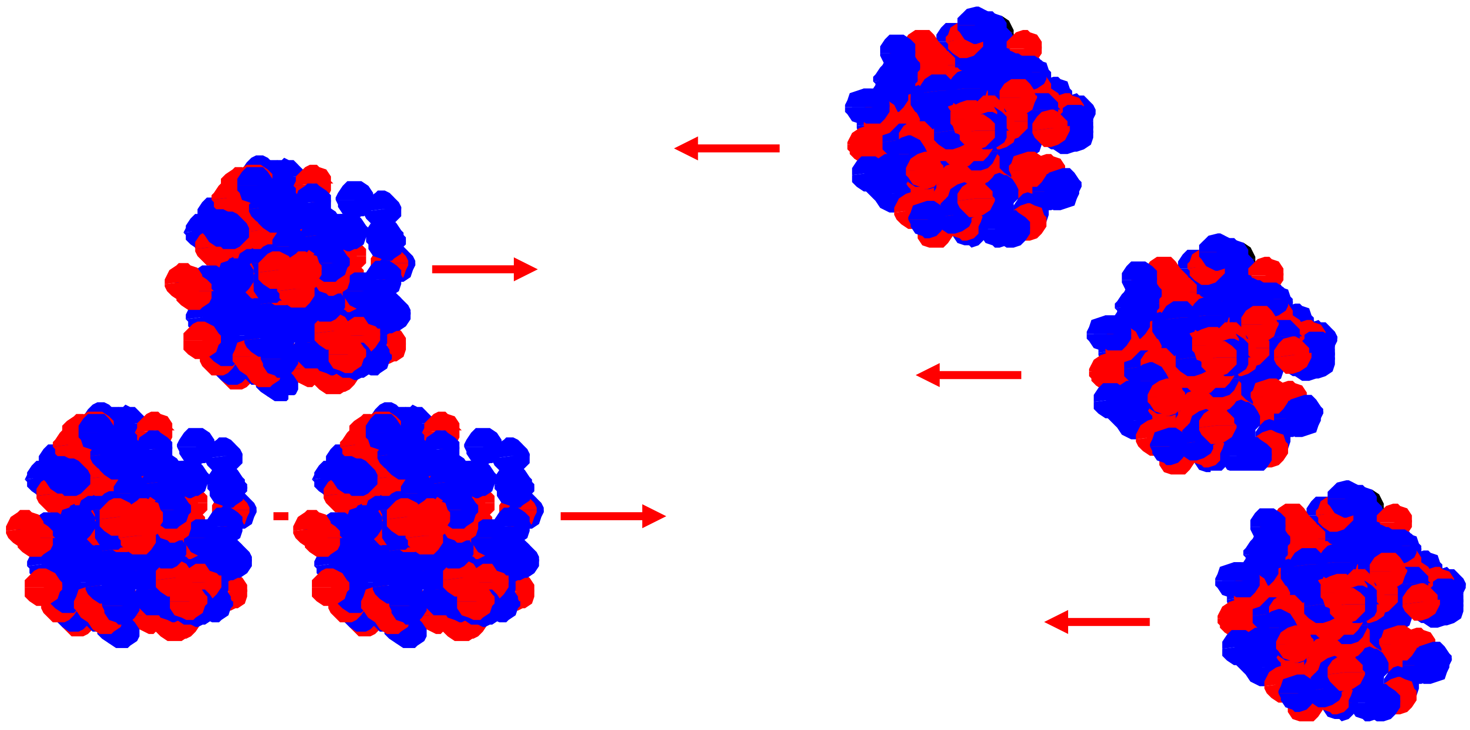
  → information on dependence of energy loss in QGP on mass and colour charge of propagating parton

→ Start of new hard probes era for ultra-relativistic A-A collisions

- Much more about physics in plenary talks at this conference:
- 17:30 Monday, Experiment, F. Antinori,
- 18:00 Monday, Theory, C. Salgado

General assumptions for future years

- In a typical running year of LHC, a heavy-ion run will take place in the last few weeks before the end-of-year stop/shutdown.
  - Radiological cool-down benefit
  - No time cost to restore p-p conditions
- The beam conditions chosen for this run will not affect the preceding p-p run
  - Essentially free choice according to HI physics needs and feasibility
  - Nevertheless choose them (e.g., same beam rigidity) to exploit established operational conditions for rapid, efficient commissioning, c.f., 2010



THE 2011 LEAD-LEAD RUN

Physics conditions

- Number of bunches affects bunch intensity
  - Injectors, Early or Nominal operation
- Optics and orbits
  - Take over ATLAS and CMS β^* from pp
    - Possibly reduce crossing angles ? Quick in 2010.
  - Squeeze ALICE to same value $\beta^*= 1.5$ m
    - 2 days setup
    - Crossing angles in ALICE
    - Zero-degree calorimeter (ZDC) preferences
- TCTVs (tertiary collimators in IR) open in IR2
  - Pending replacement for 2012 run

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
- Some 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
- Inject up to 15 times into SPS
  – Work on SPS injection kicker should give gap of 200 ns (E. Carlier)
  – Batches of up to 30 bunches to LHC – can optimise the length, 200 ns spacing, ~300 bunches
- Potential to retain higher bunch intensity (70% beyond design) already realised with Early scheme
- Decide between schemes in late Aug/early Sept

Predictions for Pb-Pb at 3.5 Z TeV/beam

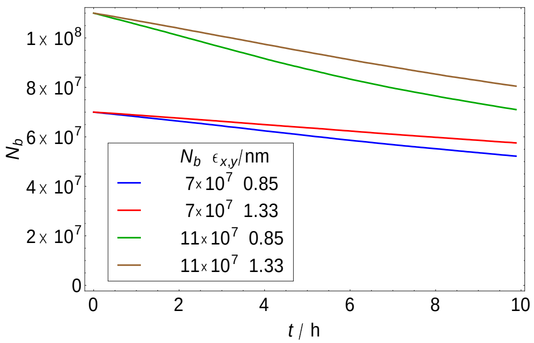
- Luminosity factors w.r.t. 2010
  - 1.5/3.5 from β*
  - 2-2.5 from bunch number and intensity

$$L = 1 - 1.5 \times 10^{26}\ \mathrm{cm^{-2}s^{-1}}$$

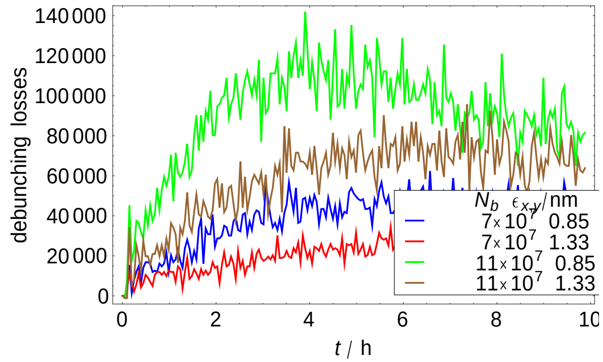
$$\text{Integrated luminosity 30-50 } \mu\mathrm{b}^{-1}$$

- Very sensitive to lost time in short run
- Some prospects for doing better eg, β*=1 m ?

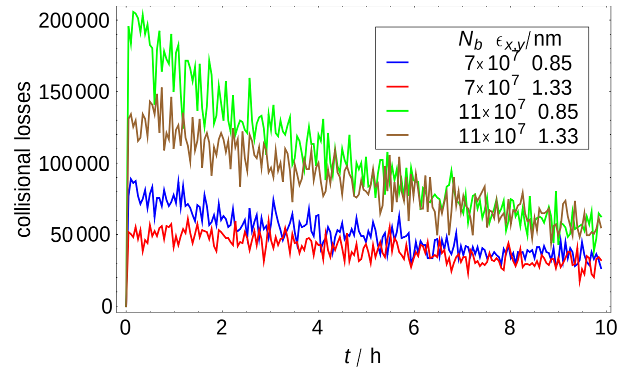
2011 Luminosity evolution



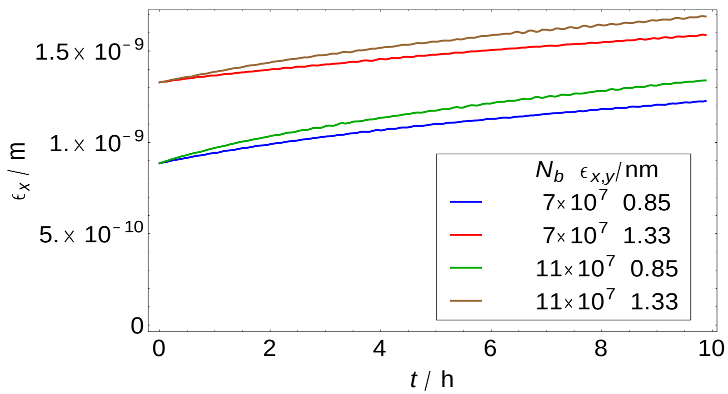
Single bunch intensity



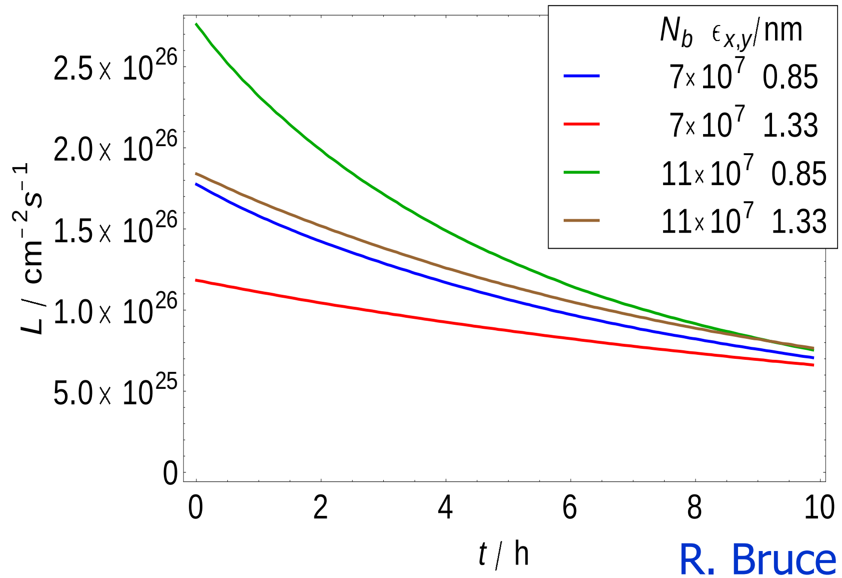
Debunching from IBS



Luminosity burn-off

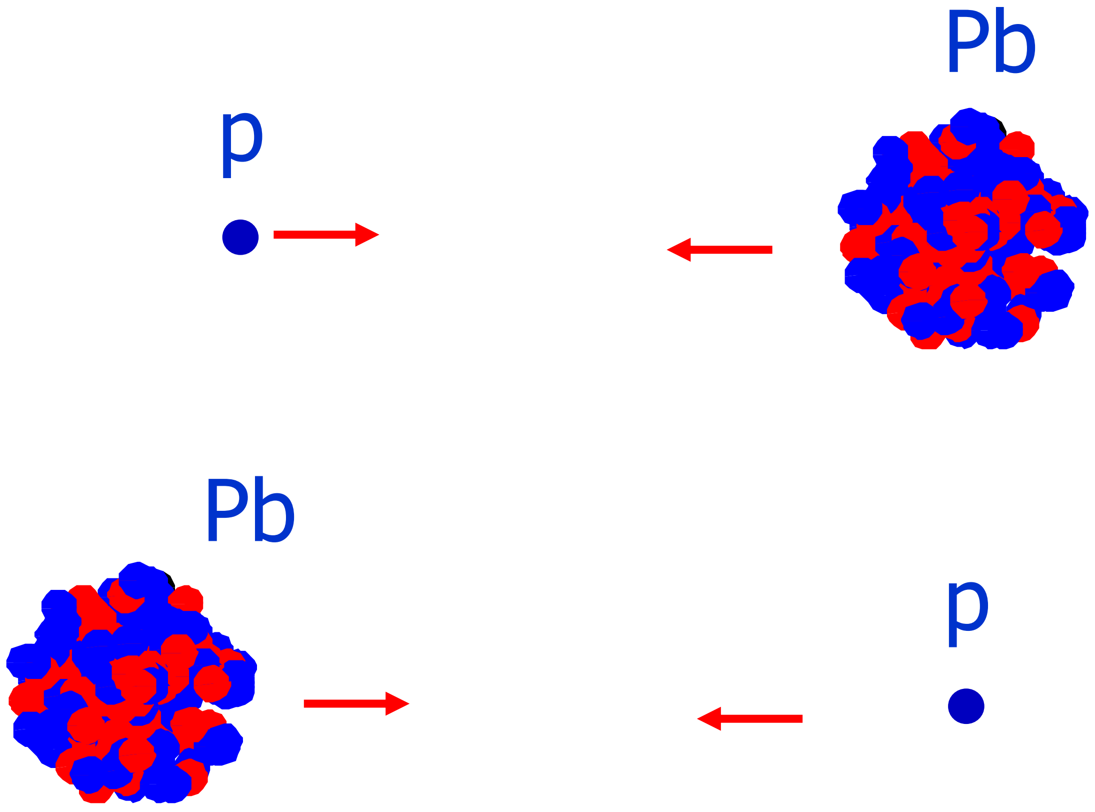


Emittance



R. Bruce

Realistic choice between blue (Nominal) and brown (Intermediate) filling cases. Blow-up may be worse than this.



THE (POSSIBLE) 2012 PROTON-LEAD RUN

2012

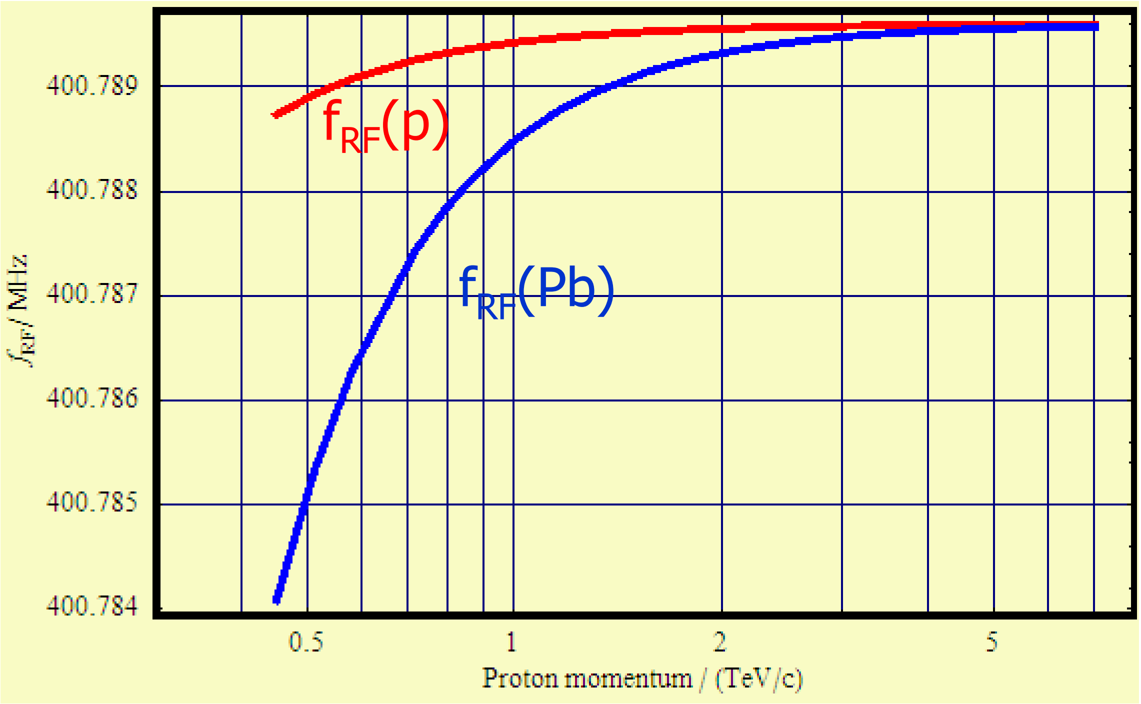
- EITHER physics with Pb-Pb, maximum luminosity, OR physics with p-Pb (and Pb-p) Nominal beam
  - For ALICE, choice depends on sufficient integrated luminosity with Pb-Pb in 2011
  - Also depends on success of feasibility test.
- HI run should be at end of run
  - Avoids interrupting high luminosity p-p
  - Benefit from radiological cool-down
  - Start source, Linac3, LEIR, PS, SPS in good time

RF Frequency for p and Pb

RF frequency $$f_{\mathrm{RF}} = \frac{h_{\mathrm{RF}}}{T\left(p_{\mathrm{p}}, m, Q\right)}$$

where the harmonic number $h_{\mathrm{RF}} \in \mathbb{Z}$, $h_{\mathrm{RF}} = 35640$ in LHC

RF frequencies needed to keep p or Pb on stable central orbit of constant length *C* are different at low energy.



No problem in terms of hardware as LHC has independent RF systems in each ring.

Distorting the Closed Orbit

- Additional degree of freedom: adjust length of closed orbits to compensate different speeds of species.
  - Done by adjusting RF frequency

$$T\left(p_{\mathrm{p}}, m, Q\right) = \frac{C}{c}\sqrt{1 + \left(\frac{mc}{Qp_{\mathrm{p}}}\right)^2}\,(1 + \eta\delta)$$

where $\delta = \dfrac{(p - Qp_{\mathrm{p}})}{Qp_{\mathrm{p}}}$ is a fractional momentum deviation and

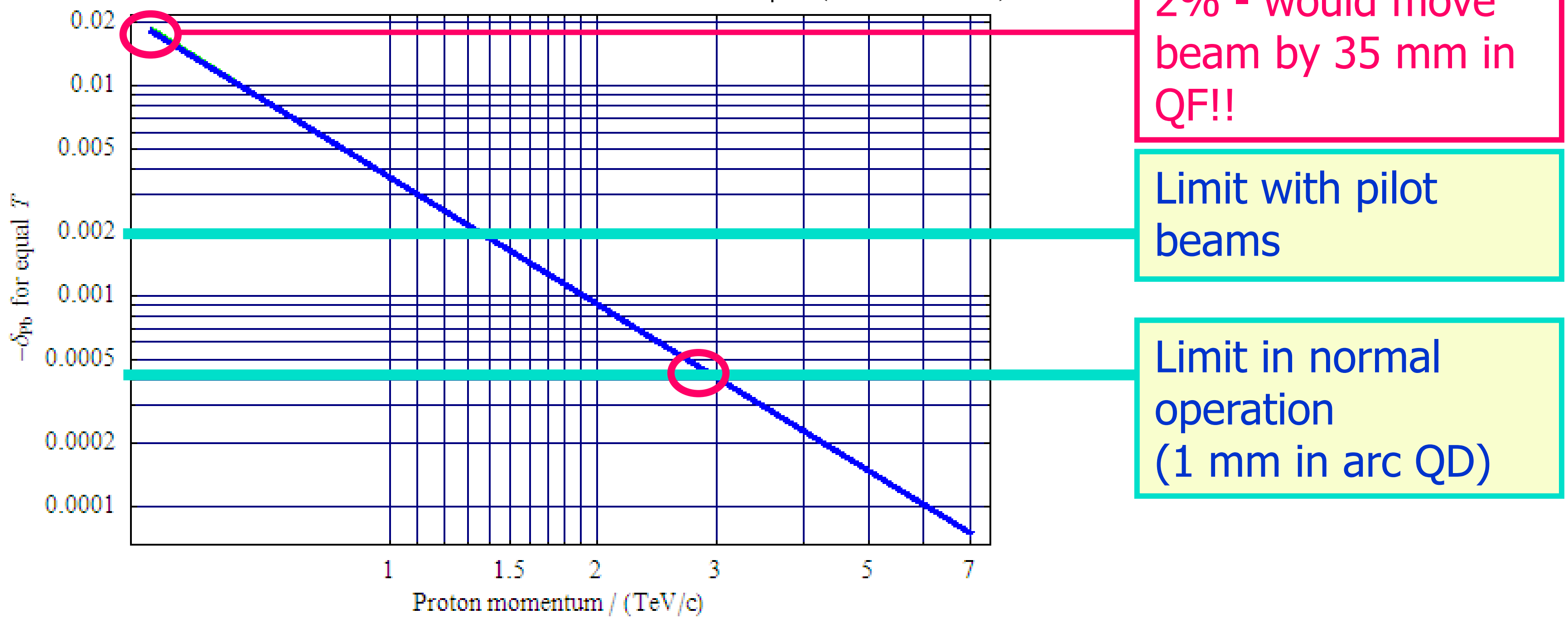
the phase-slip factor $\eta = \dfrac{1}{{\gamma_T}^2} - \dfrac{1}{\gamma^2}$, $\quad \gamma = \sqrt{1 + \left(\dfrac{Qp_{\mathrm{p}}}{mc}\right)^2}$, $\quad \gamma_T = 55.8$ for LHC optics.

Moves beam on to off-momentum orbit, longer for $\delta > 0$.

Horizontal offset given by dispersion: $\Delta x = D_x\left(s\right)\delta$.

Momentum offset required through ramp

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



Revolution frequencies must be equal for collisions at top energy

Lower limit on energy of p-Pb collisions, E=2.7 Z TeV

Below this energy, RF frequencies must be unequal for injection, ramp.

Moving long-range beam-beam encounters may be a problem (cf RHIC).

Preparation and Feasibility test in 2011

- Review of all LHC systems done - basically OK
- Tests in August
  - Injection into ring with wrong RF frequency (Machine Protection)
  - Ramp with independent radial loops
  - RF rephasing to move collision point
- Tests in October MD
  - Injection of 100 ns p beam (to match Pb)
  - Commission Pb injection
  - Inject Pb against p
- During 1st week of physics (Pb ramp available)
  - Ramp p and Pb together
- If successful, can do p-Pb in 2012 !

Accessible energies and CM rapidities

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

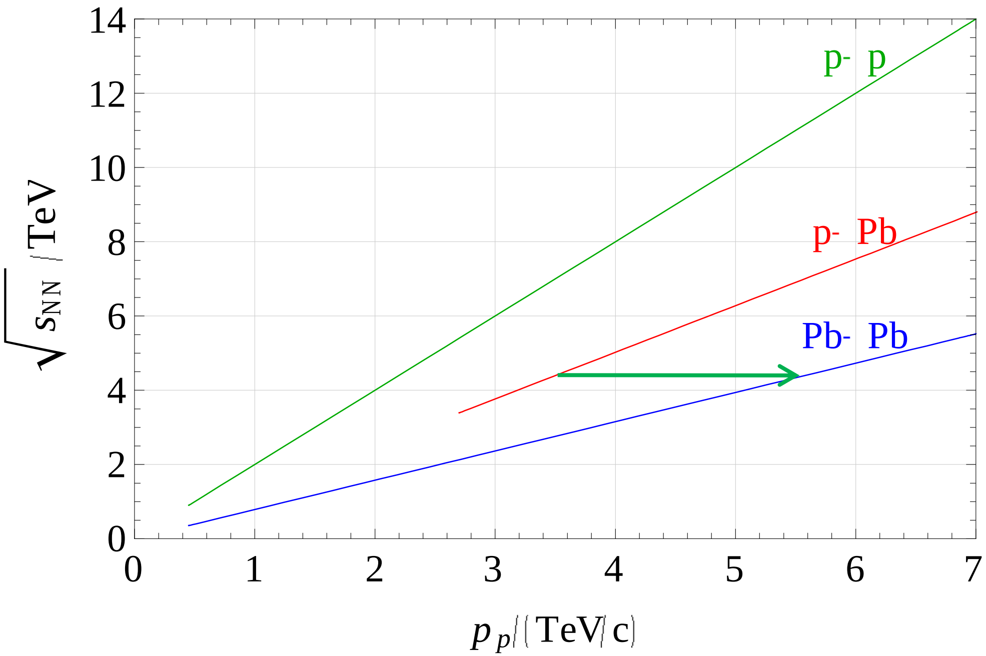
Relations between these numbers are a simple consequence of the two-in-one magnet design

	p-p	Pb-Pb	p-Pb
$E\,/\,\mathrm{TeV}$	0.45-7	287-574	(2.7-7,287-574)
$E_N\,/\,\mathrm{TeV}$	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

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

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



Potential Performance (if it works ...)

Assume Pb ion bunch with nominal intensity $N_{\mathrm{Pb}} = 7 \times 10^7$,
proton bunch with 10% nominal intensity $N_p = 1.15 \times 10^{10}$,
nominal emittances (equal geometric beam sizes).

With Pb ion nominal bunch structure in both beams, $\beta^* = 0.5$ m,
peak $L = 1.5 \times 10^{29}$ cm^{-2}s^{-1}, in p+Pb collisions at $7\,Z$ TeV.

At 3.5 Z TeV, $\beta^* = 1.5$ m, peak $L \approx 3 \times 10^{28}$ cm^{-2}s^{-1}.

Luminosity burn-off much less than Pb-Pb:

BFPP flux of $^{208}\mathrm{Pb}^{81+}$ from IP reduced to 1.5% of Pb-Pb value
(BFPP flux of neutral H atoms to ZDC is tiny!)
EMD also less

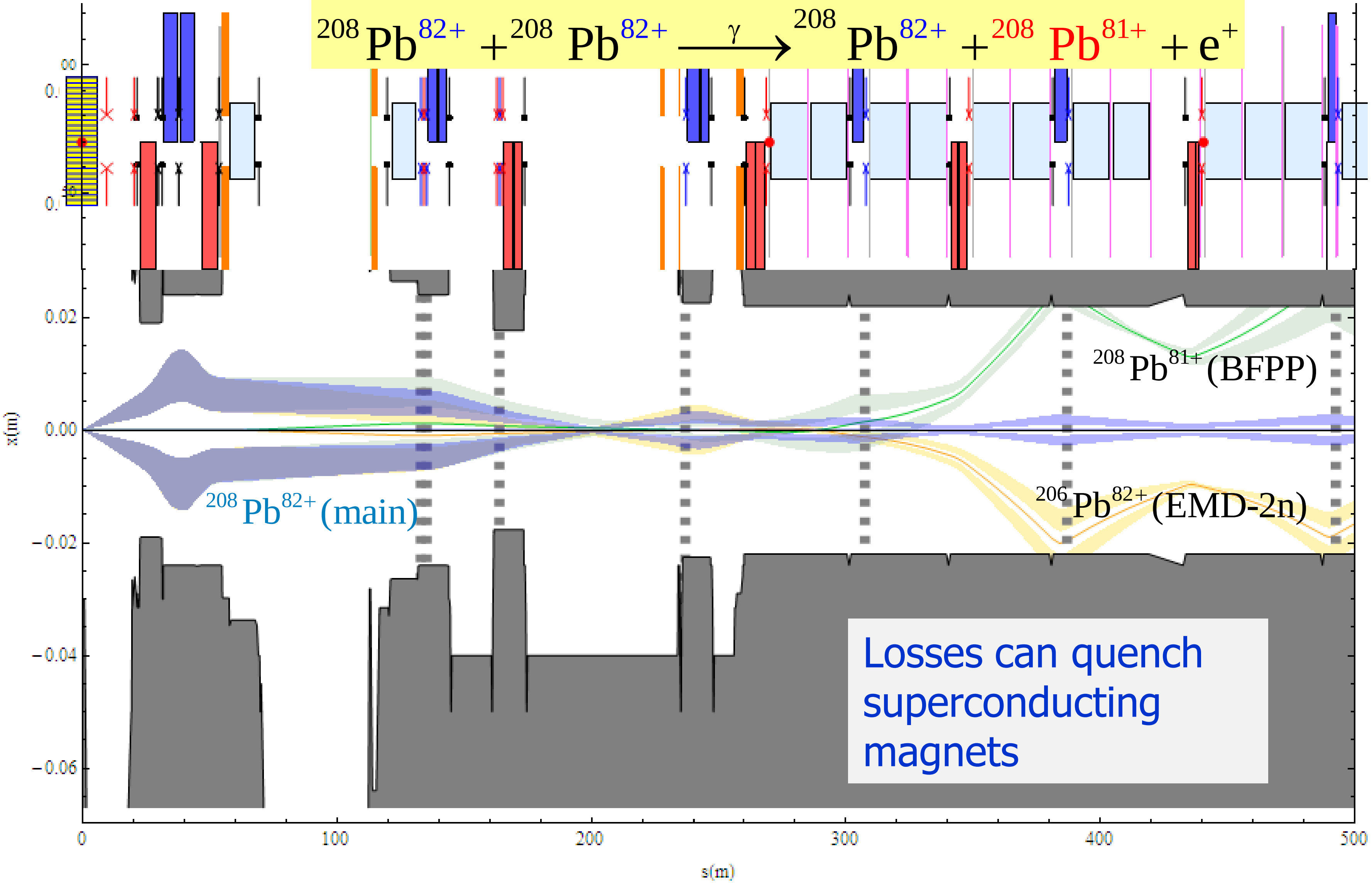
BEYOND 2012 …

Main performance limits

- IBS
  - Slow blow-up of emittances, debunching from RF bucket
  - Countered by radiation damping at 7 Z TeV
- Collision products from IP
  - Ultraperipheral EM processes, BFPP, EMD
  - Quench magnets
- Collimation inefficiency
  - Nuclear interactions with collimator material
  - Very different from protons
  - *Much* less efficient collimation
  - Losses can quench magnets, cause radiation problems

Main and secondary Pb beams from ALICE IP

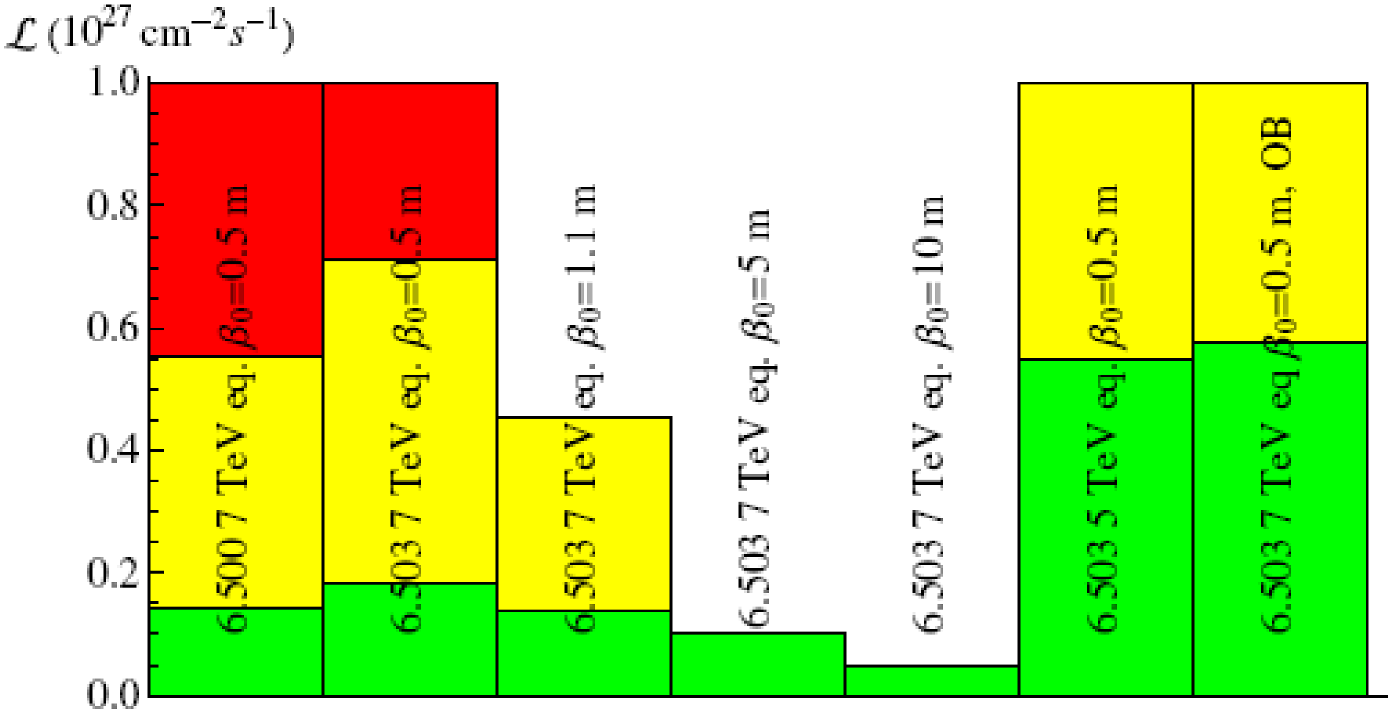
$$^{208}Pb^{82+} + {}^{208}Pb^{82+} \xrightarrow{\gamma} {}^{208}Pb^{82+} + {}^{208}Pb^{81+} + e^{+}$$



Losses can quench superconducting magnets

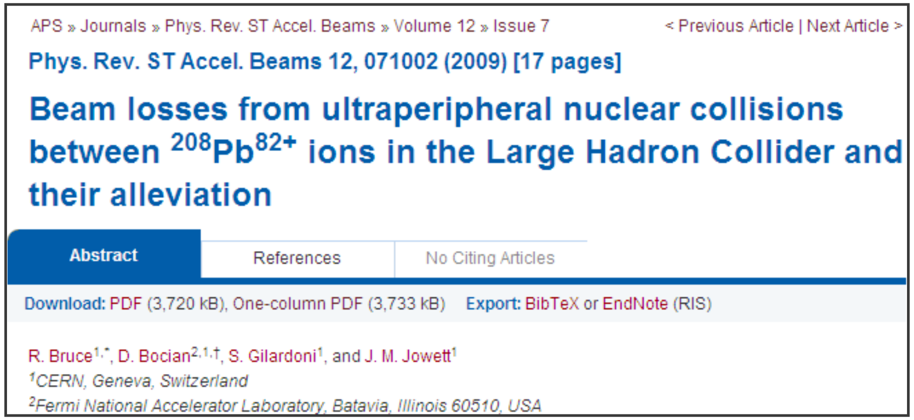
Large EM cross sections. Similar in ATLAS, CMS

Propensity to quench from BFPP



Variations of operating conditions affect luminosity limit, see paper for details.

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

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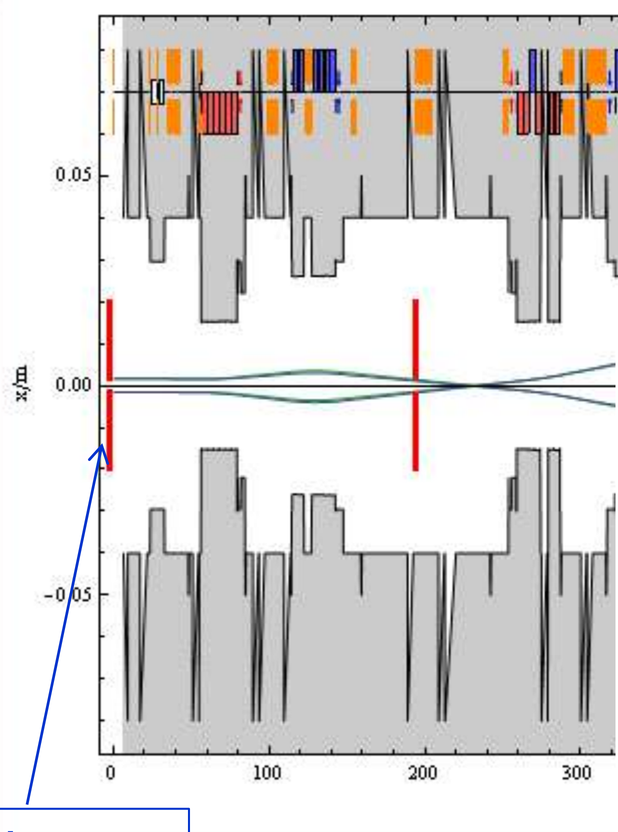
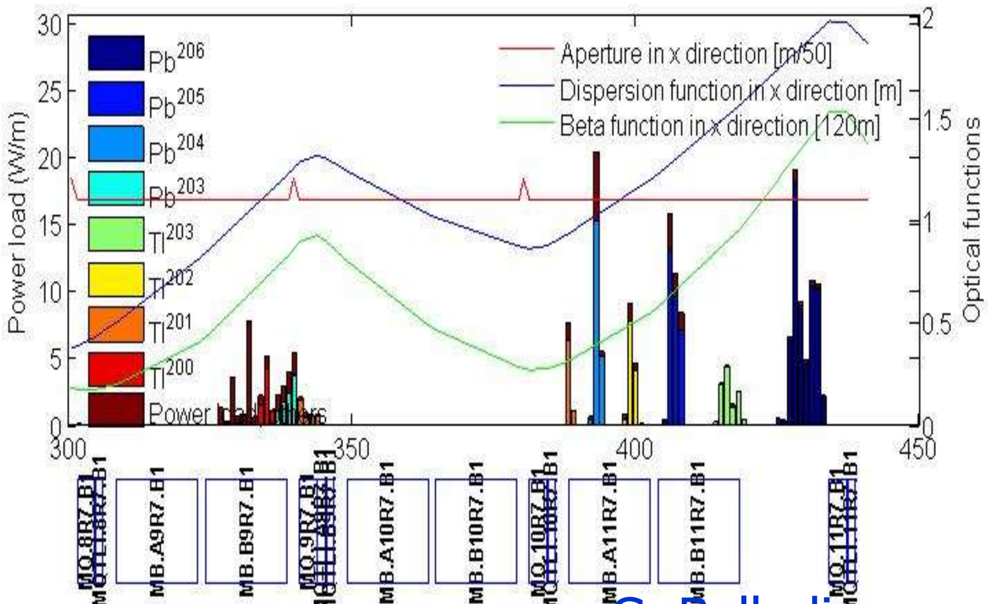
Example of ^{206}Pb created by 2-neutron EMD

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



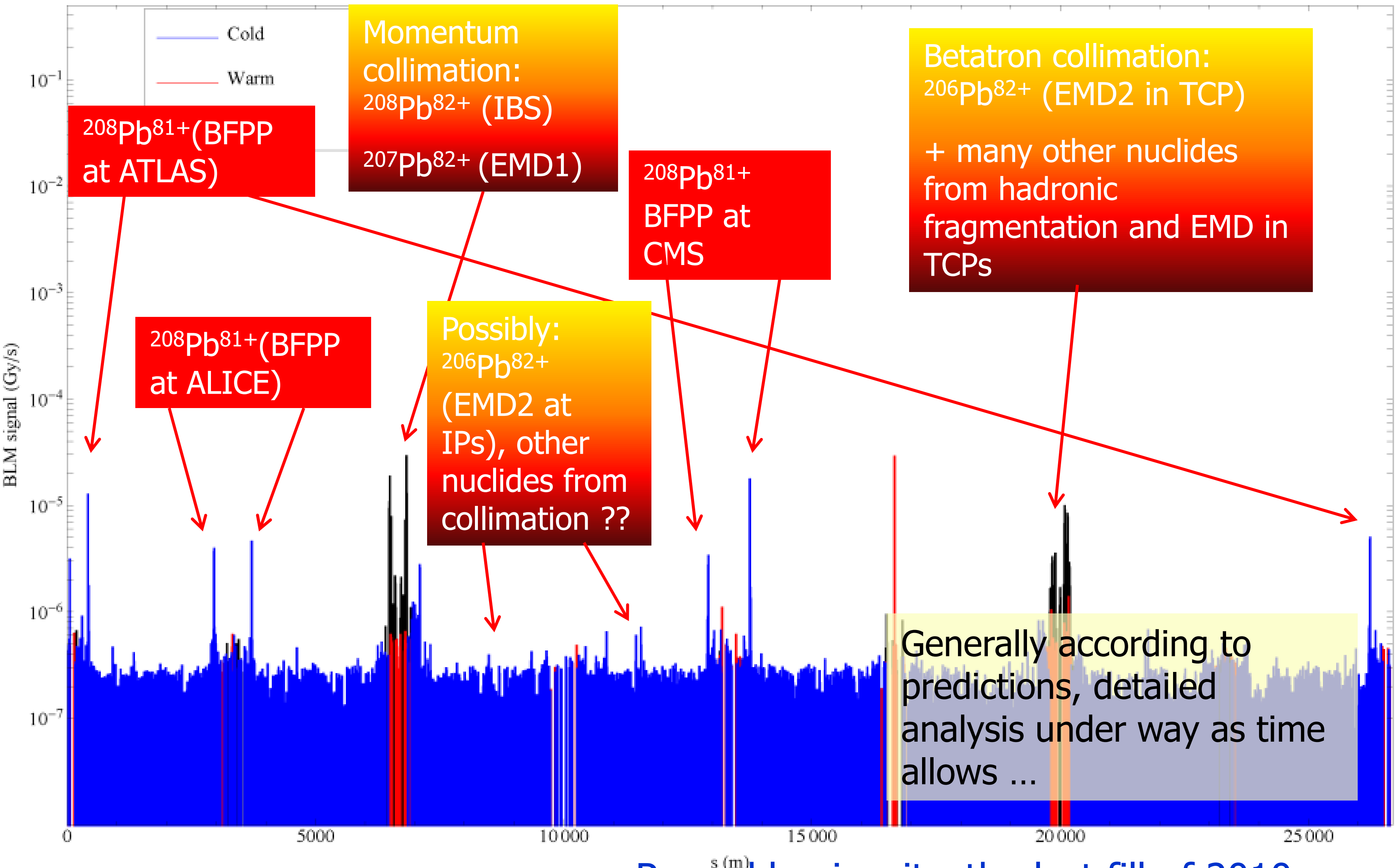
Beam pipe in IR7 of LHC



Primary collimator

G. Bellodi

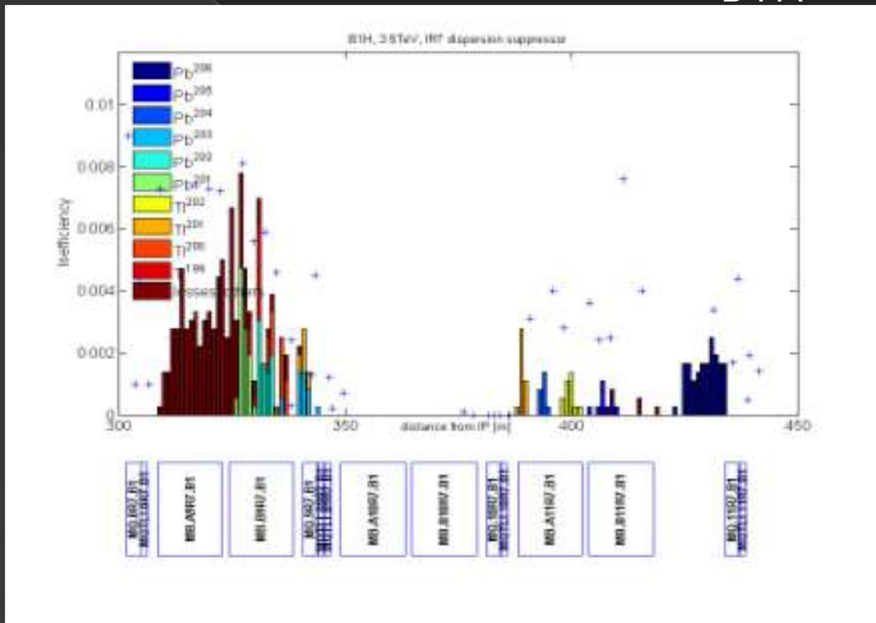
Global view of losses, Pb-Pb stable beams



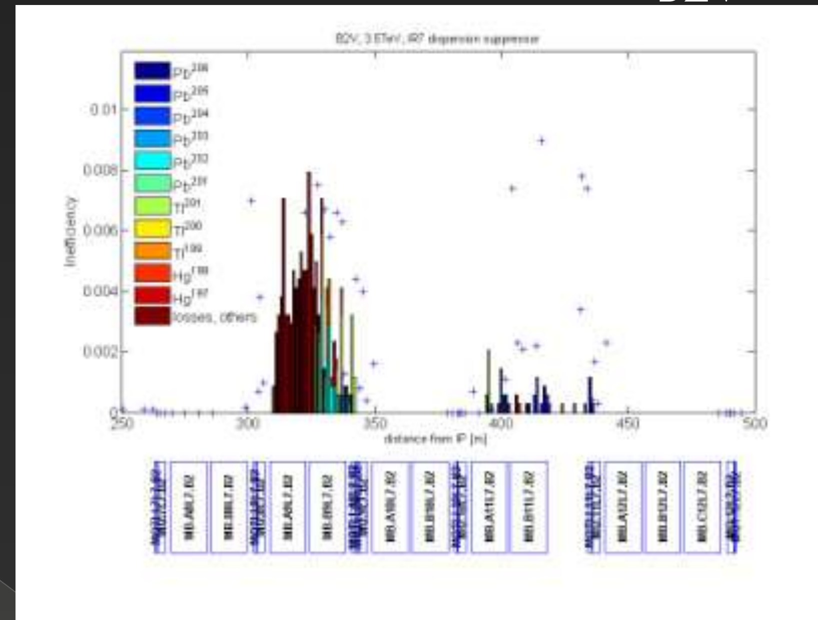
Record luminosity, the last fill of 2010

Ion commissioning loss maps vs simulation – Nov 2010

B1H



B2V

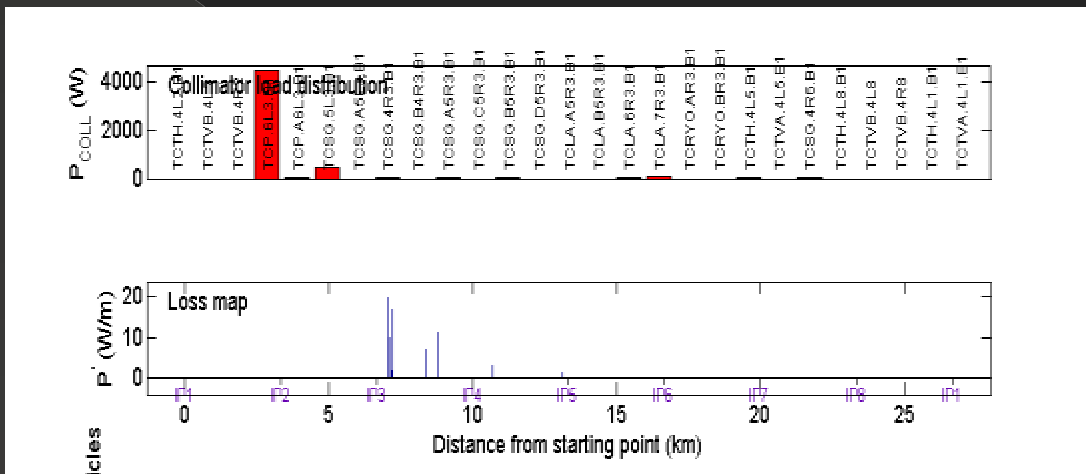


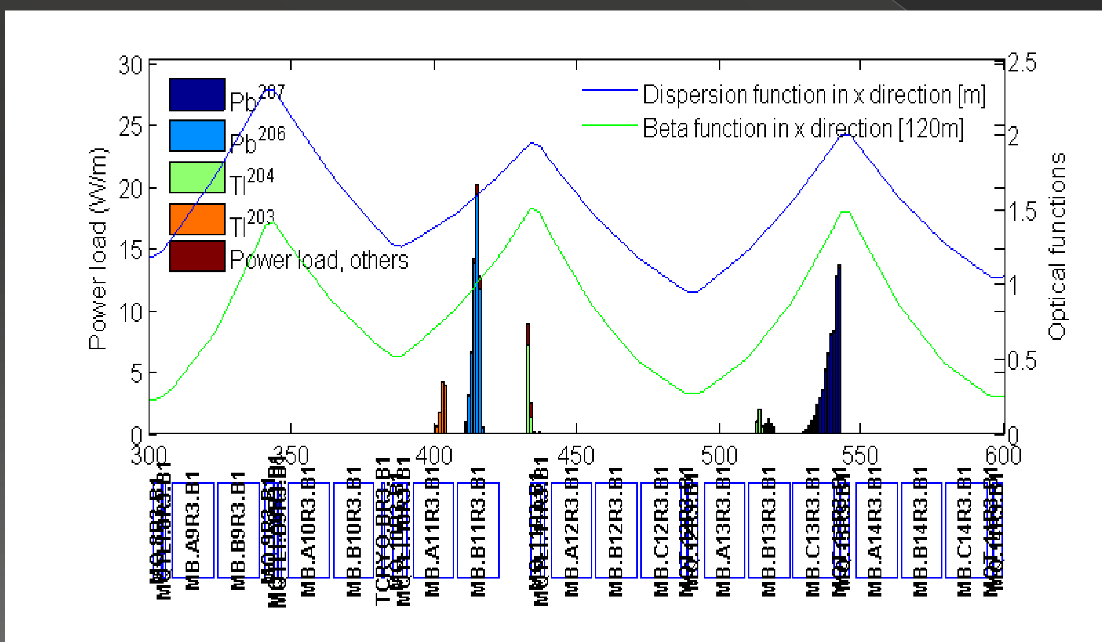
	DS	COLD	TCT
B1h	0.02	0.006	1.0×10^{-4}
B1v	0.027	0.005	0.001
B2h	0.03	0.011	8×10^{-5}
B2v	0.025	0.006	1.4×10^{-4}
B1+B2 pos. off momentum	0.045	8e-4	0.06
B1+B2 neg. off momentum	0.007	2e-4	0.005

3.5TeV eq.
Physics conditions

D Wollmann,
Evian Dec 2010

IR3 combined cleaning without TCRYOs





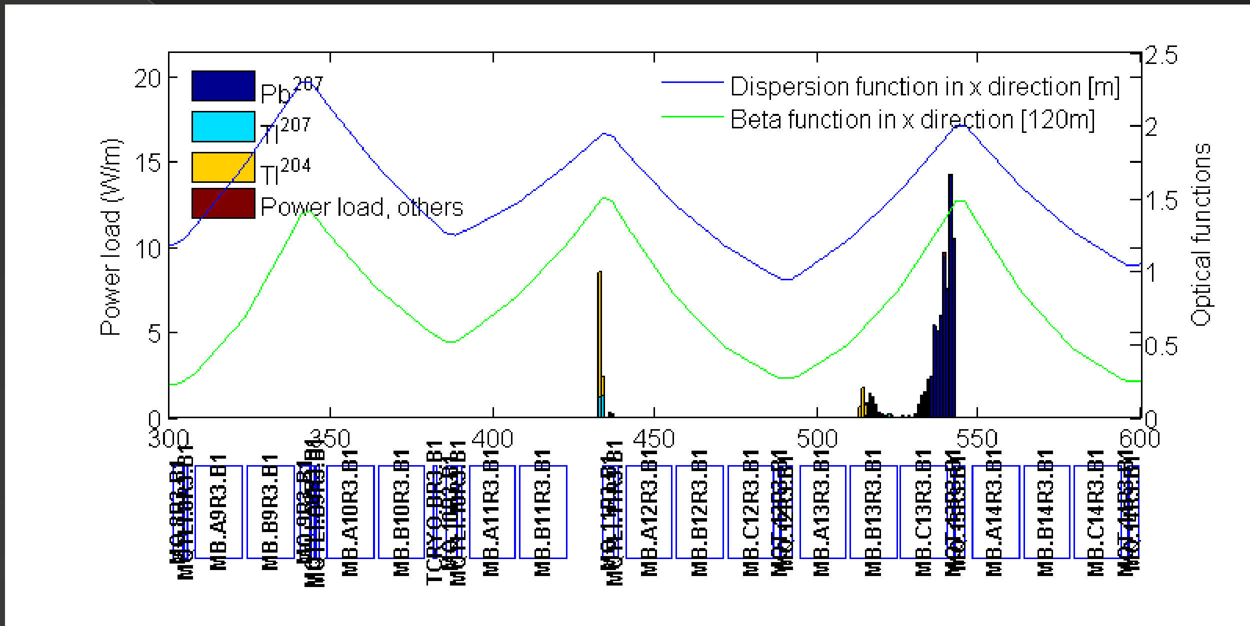
Sector	Family	Half gap
LSS7	TCP IR7	Open
	TCSG IR7	Open
	TCLA IR7	open
LSS3	TCP IR3	6
	TCSG IR3	7
	TCLA IR3	10
LSS1/2/5/8	TCTH	8.3
	TCTV	8.3

τ=12 min lifetime
$7\times10^{7}\times592= 4.14\times10^{10}$ ions
E=7 Z TeV eq.

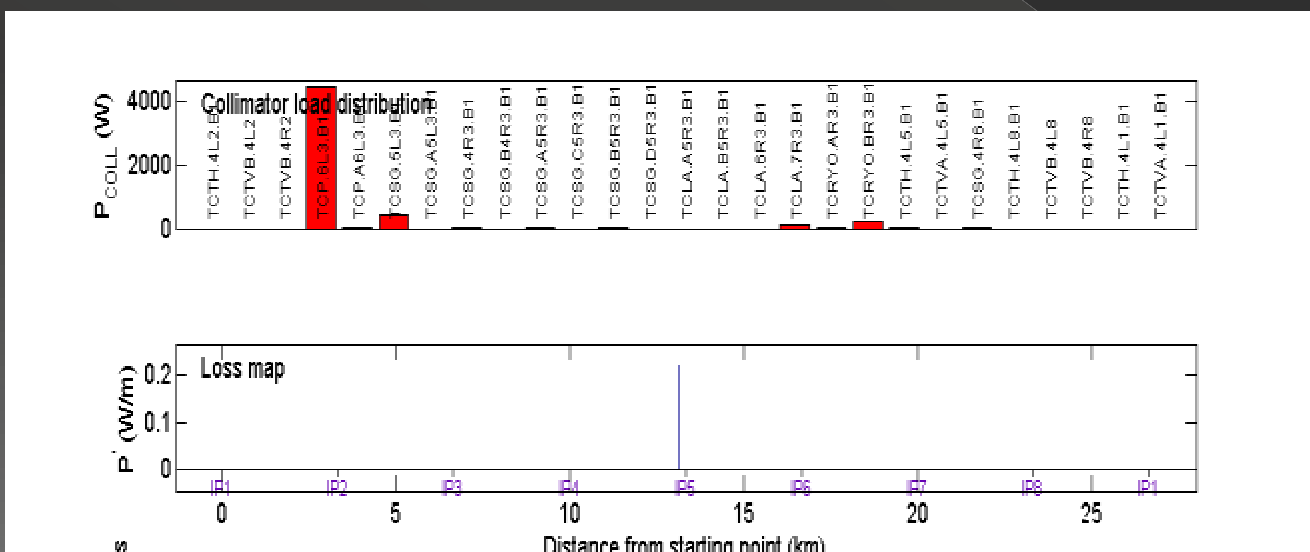
Max TCP load ~ 4500W
Peak loss in DS3 ~ 20W/m
η (local) = 0.0044

$$\eta = \frac{\sum \text{aperture hits}}{\sum \text{collimatorhits}} = 0.04$$

and with TCRYOs in



50 sigma half gap – DS already significantly cleaner



20 sigma half gap, No losses visible!

LHC Collimation Review 2011 - outcome

- http://indico.cern.ch/conferenceDisplay.py?confId=139719
- It had been proposed to add collimators in dispersion suppressors of collimation insertions to intercept losses
  - Shown to be extremely effective in simulations for p, Pb
  - Similar devices around experiments for BFPP losses
  - To make space, required moving dipole magnets, changing geometry, difficult engineering problems
  - Could be facilitated later by higher field magnets and other developments

7. Summary and response to charge

1.) Yes, collimation performance and limitations are properly analyzed and adequately addressed by the upgrade plans.

2.) On the basis of the evidence presented, the committee concludes that the nominal proton beam intensity of LHC at 7 TeV can be achieved without the installation of additional collimators in the IR3 dispersion suppression region during the LS1 shutdown. For heavy ion beams less experimental evidence exists and thus the extrapolation to full energy entails more uncertainty.

2013+2014

- Long shutdown LS1: desirable work for heavy-ion programme
  - Splices for heavy ion *energy* limit …
  - Following recent Collimation Review, there will be NO installation of dispersion suppressor collimators in LHC IR3
- Consequences
  - Risk for Pb beam intensity
    - Plan to measure limit this year
  - Luminosity may still be limited by BFPP losses around each experiment
    - Hope for DS collimators around experiments to fix that in *next* long shutdown.

2015, 2016

- Physics with Pb-Pb at end of each year
  - Nominal (or maybe even higher) *intensity* at top energy but peak *luminosity* may be limited
    - Luminosity levelling in all experiments, new regime with strong luminosity burn-off, significant radiation damping (see previous talks)

$$L \sim 5 \times 10^{26}\ \mathrm{cm^{-2}s^{-1}}$$

- This is the core period of the LHC Heavy Ion programme, devoted to maximum Pb-Pb luminosity integration

2017

- EITHER:

  Physics with p-Pb (which energy?) to enhance 2015-16 data

  OR:

  Pb-Pb collisions at top energy
  - Maximum possible luminosity
  - Scheduled at the end of the year.

2018

- Long shutdown LS2: desirable work for heavy-ion programme
  - Installation of dispersion suppressor collimators in IR2 (previously requested), to increase Pb-Pb *luminosity* limit.
    - N.B. collimator locations are different from IR3, IR7 (see diagram in Chamonix talk) with performance and integration schemes still to be studied
  - Installation of dispersion suppressor collimators in IR3 (collimation inefficiency)
  - Installation of dispersion suppressor collimators in IR7 may help Pb and Ar intensity limit (unless IR3 already sufficient)

2019-2021

- 2019: Pb-Pb collisions at top energy
  - Maximum possible luminosity should now be higher
  - Scheduled at the end of the year.
- 2020: Physics with p-Pb
- 2021: Physics with Ar-Ar collisions.
  - Already commissioned in the injectors, Ar ion beam will be ready
  - Intensity, luminosity to be seen
  - Preliminary study indicates demanding collimation requirements

2022

- General shutdown LS3
  - DS collimators for p-p luminosity debris in IR1, IR5 ?
    - Similar requirement for BFPP, so could also help with Pb-Pb luminosity limit for ATLAS, CMS.
    - To be checked whether required locations are the same.
- Other upgrades for heavy ions ?

Longer term

- Future for LHC heavy ions beyond 2021
    - See S. Bertolucci at Chamonix workshop 2011
- Would certainly require enhanced performance
- Need motivated and *timely* R&D to develop, eg:
    - DS collimator options
    - Hollow electron beam collimators ? (Fermilab)
    - Beam cooling – cf: major success of stochastic cooling at RHIC
    - Crystal collimation ?
    - Other species and sources ?
    - HE-LHC (~2×energy) would be a very favourable beam dynamics regime for heavy ion beams
        - Natural cooling from rapid radiation damping

Conclusions

- LHC heavy-ion collisions have already produced a remarkable harvest of physics
- The coming decade will see the exploration of a vastly extended energy frontier in nucleus-nucleus collisions
- p-Pb collision mode will be tested soon and, we hope, implemented in 2012
- Luminosity limits may be encountered in 2015
  - Tests in 2011 should clarify
  - No DS collimators before 2018
    - Review priorities: IR2 for ALICE luminosity, IR3/7 for intensity, IR1/5 for ATLAS/CMS luminosity
- Longer term operation requires some R&D on new concepts for higher performance

BACKUP SLIDES

Deuteron-Pb collisions

- Alternative to p-Pb, *not* currently requested
  - Smaller central rapidity shift in collisions
  - Smaller frequency differences between beams
- Interest for e-D in LHeC, possibly also medical
- Implementation
  - Second source to produce deuterons, a second RFQ, a LEBT and a switchyard (to be decided more than 5 years earlier if needed).
  - Some alternatives mooted recently (D. Kuchler)
  - Commissioning of the new source would have to be done during a long shutdown.