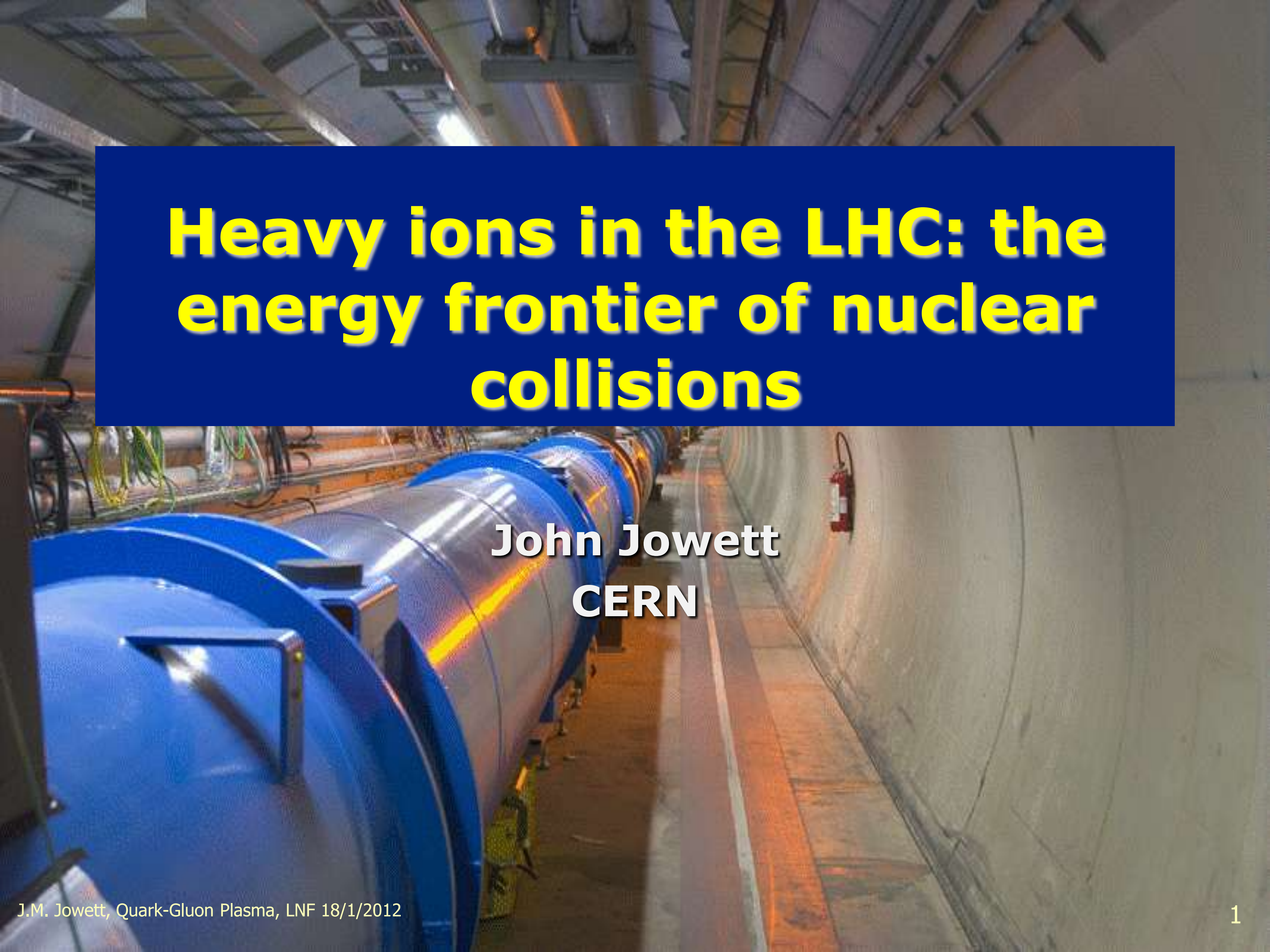


Heavy ions in the LHC: the energy frontier of nuclear collisions

John Jowett
CERN

Thanks to many colleagues:

R. Alemany-Fernandez, R. Assmann, P. Baudrenghien, G. Bellodi, H.H. Braun, R. Bruce, C. Carli, M. Giovannozzi, M. Gresham, S. Hancock, D. Kuchler, M. Lamont, S. Maury, D. Manglunki, T. Mertens, S. Passinelli, R. Tomas, M. Schaumann, K. Schindl, M. Solfaroli, W. Venturini, R. Versteegen, J. Wenninger, D. Wollmann

and many others including

many groups working on LHC,

LHC Physics coordinators,

ALICE, ATLAS, CMS experiments, RHIC colleagues, …

Outline of talk

- The LHC as a nucleus-nucleus collider
  - Design
  - Beam physics limiting performance
- The 2010 Pb-Pb run
- The 2011 Pb-Pb run
- The LHC as a proton-nucleus collider
  - The RHIC experience, concerns
  - Feasibility test in 2011
  - Possible p-Pb run in 2012
- The LHC heavy-ion future beyond 2012
  - Limits, mitigations, how and when ?

THE LHC AS A NUCLEUS-NUCLEUS COLLIDER

The LHC Programme

- LHC spends most of its time colliding p-p
  - World’s dominant particle physics programme with 4 large experiments ATLAS, CMS, ALICE, LHCb plus other smaller ones
- About one month per year colliding heavy ions in ALICE (specialised experiment) and ATLAS, CMS (general purpose experiments)
  - This is nevertheless one of the world’s largest physics communities and programmes
  - Continues beyond RHIC at Brookhaven and previous fixed target facilities (SPS, AGS, …).

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 collliding 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:

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

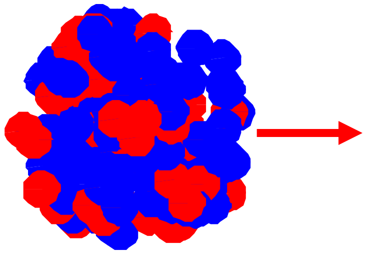
$\Rightarrow$ Round beams at IP:

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

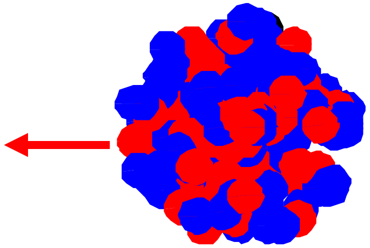
(N.B. LHC uses RMS emittances.)

On Luminosity with Heavy Ions

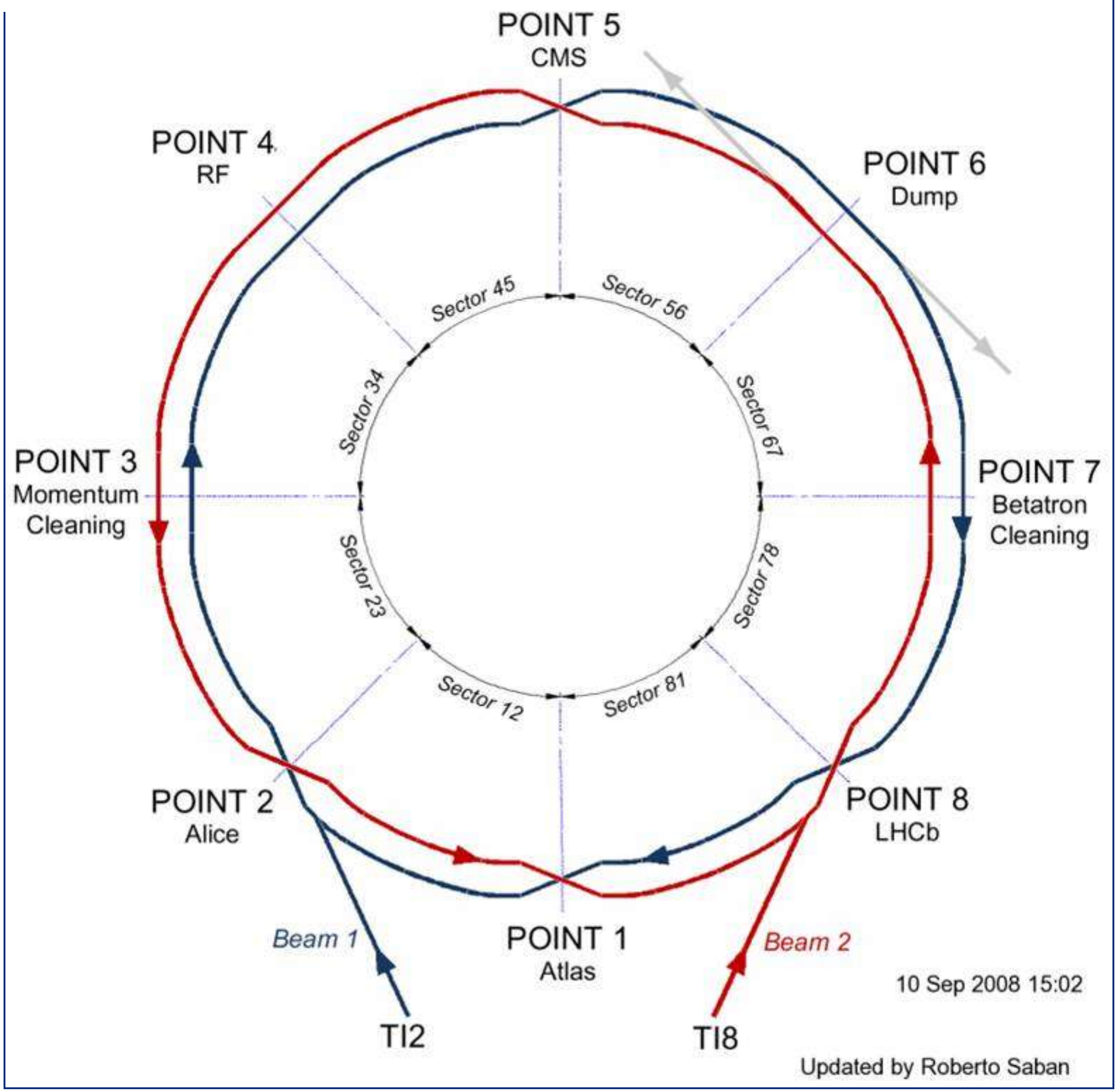
- Luminosities quoted for lead ions may seem low compared to pp or e^+e^-
- But comparisons should be made on the basis of nucleon pair luminosities



$$L = 1.0 \times 10^{27} \text{ (Pb)(Pb) cm}^{-2}\text{s}^{-1}$$
$$= 4.3 \times 10^{31} \text{ (nucleon)(nucleon) cm}^{-2}\text{s}^{-1}$$



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

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

LHC Ion Injector Chain

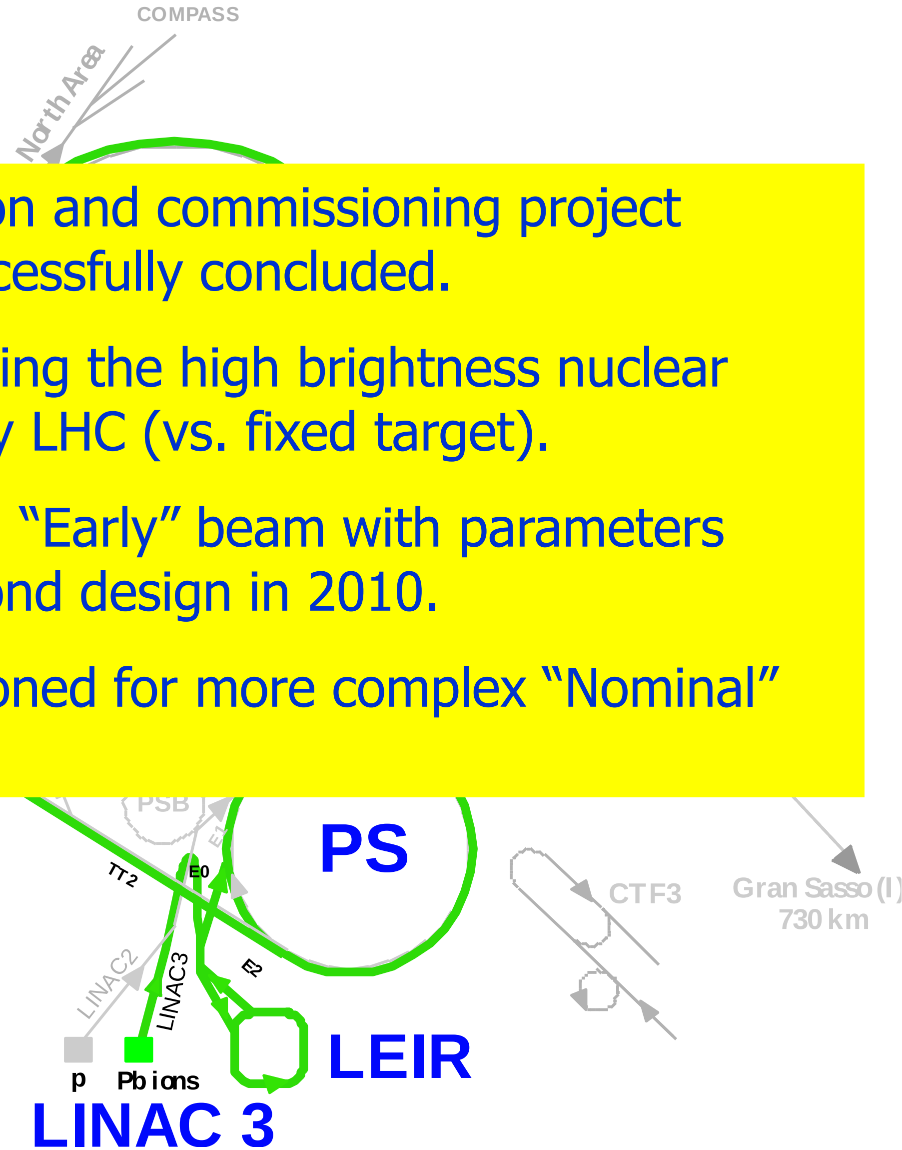
- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR ir
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and beam
  - Prepare bunch s
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC

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).

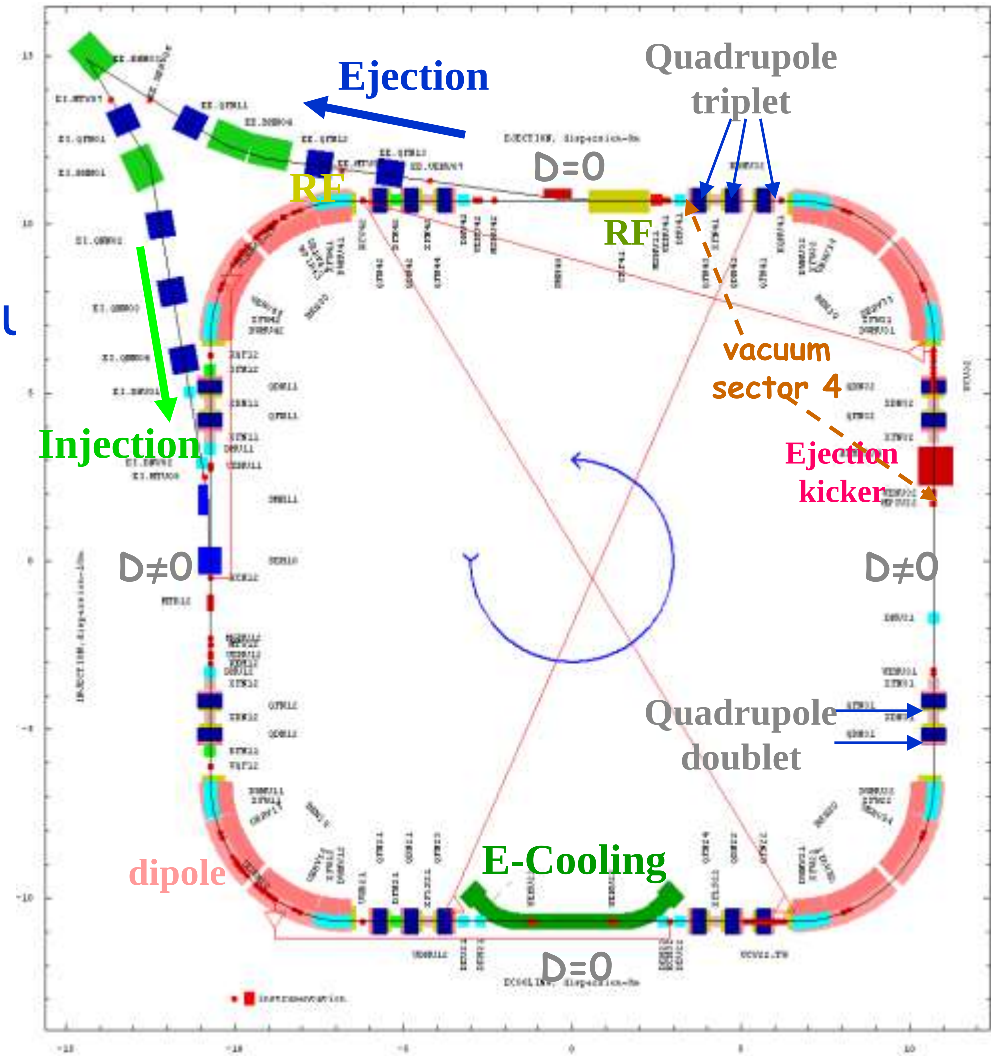
Already delivered "Early" beam with parameters significantly beyond design in 2010.

Mostly commissioned for more complex "Nominal" beam.



LEIR (Low-Energy Ion Ring)

- Prepares beams for LHC using electron cooling
- circumference 25p m (1/8 PS)
- Multiturn injection into horizontal+vertical+longitudinal phase planes
- Fast Electron Cooling : Electron current from 0.5 to 0.6 A with variable density
- Dynamic vacuum (NEG, Au-coated collimators, scrubbing)



LHC Pb Injector Chain: Design Parameters for luminosity 10^{27} cm^{-2} s^{-1}

	ECR Source →	Linac 3 → (4)	LEIR →	PS → (13,12,8)	SPS → (12)	LHC
Output energy	**2.5 KeV/n**	**4.2 MeV/n**	**72.2 MeV/n**	**5.9 GeV/n**	**177 GeV/n**	**2.76 TeV/n**
^{208}Pb charge state	**27+**	**27+ → 54+**	**54+**	**54+ → 82+**	**82+**	**82+**
Output Bρ [Tm]		2.28 → 1.14	4.80	86.7 → 57.1	1500	23350
bunches/ring			2 (1/8 of PS)	4 (or 4x2)[4]	52,48,32	592
ions/pulse	$9\ 10^{9}$	$1.15\ 10^{9}$ [1])	$9\ 10^{8}$	$4.8\ 10^{8}$	$\leq 4.7\ 10^{9}$	$4.1\ 10^{10}$
ions/LHC bunch	**$9\ 10^{9}$**	**$1.15\ 10^{9}$**	**$2.25\ 10^{8}$**	**$1.2\ 10^{8}$**	**$9\ 10^{7}$**	**$7\ 10^{7}$**
bunch spacing [ns]				100 (or 95/5)[4]	100	100
ε*(nor. rms) [μm][2]	**~0.10**	**0.25**	**0.7**	**1.0**	**1.2**	**1.5**
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	**~10'fill/ring**
ε_{long} per LHC bunch[3]			0.025 eVs/n	0.05	0.4	1 eVs/n
total bunch length [ns]			200	3.9	1.65	1

Stripping foil

[1] 50 eμA_e x 200 μs Linac3 output after stripping

[2] Same physical emittance as protons,

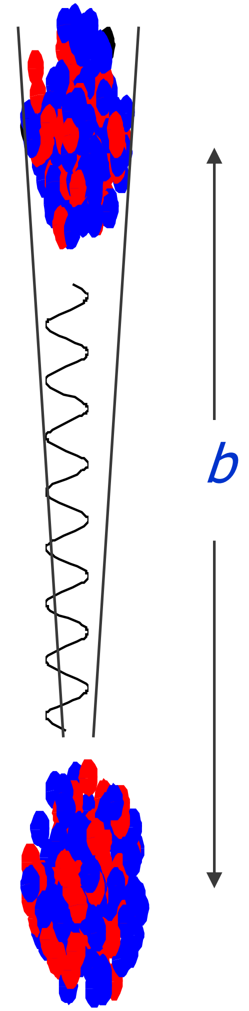
$$\varepsilon^* \equiv \varepsilon_n = \sqrt{\gamma^2 - 1}\,\varepsilon_{x,y} \text{ is } \sim \text{invariant in ramp.}$$

BEAM PHYSICS LIMITING PERFORMANCE

Ultra-Peripheral Collisions

- Electromagnetic interactions in encounters which are not close enough to overlap nuclear densities
  - Extremely Lorentz-contracted Coulomb fields (equivalent quasi-real photons in Fermi-Weizsacker-Williams method)
  - In this sense, LHC is a $\gamma\gamma$ collider.
  - Frequency spectrum of FWW photons depends on impact parameter, *b*.

$$\gamma_{\text{target}} = 2\gamma^2 - 1 \approx 1.7 \times 10^7$$



$$\text{Coupling } Z\alpha = \frac{82}{137} \approx 1$$

Pair Production in Heavy Ion Collisions

Racah formula (1937) for free pair production in heavy-ion collisions

$$Z_1 + Z_2 \rightarrow Z_1 + e^- + e^+ + Z_2$$

$$\sigma_{PP} = \frac{Z_1^{\,2} Z_2^{\,2} \alpha^2 r_e^2}{\pi}\left[\frac{224}{27}\log(2\gamma_{CM})^3 + \cdots\right] \approx \begin{cases} 1.7\times 10^4\,\text{b for Au-Au RHIC} \\ 2.\times 10^4\,\text{b for Pb-Pb LHC} \end{cases}$$

Cross section for Bound-Free Pair Production (BFPP) (several authors)

$$Z_1 + Z_2 \rightarrow \left(Z_1 + e^-\right)_{1s_{1/2},\ldots} + e^+ + Z_2$$

has very different dependence on ion charges (and energy)

$$\sigma_{PP} \propto Z_1^{\,5} Z_2^{\,2}\left[A\log\gamma_{CM} + B\right]$$

$$\propto Z^7\left[A\log\gamma_{CM} + B\right] \text{ for } Z_1 = Z_2$$

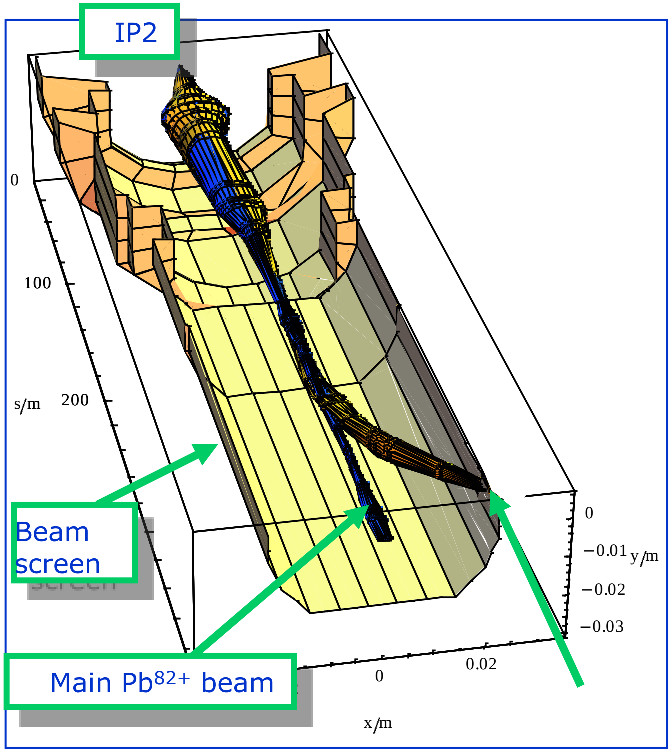
$$\approx \begin{cases} 0.2\text{ b for Cu-Cu RHIC} \\ 114\text{ b for Au-Au RHIC} \\ 281\text{ b for Pb-Pb LHC} \end{cases}$$

We use BFPP values from Meier et al, Phys. Rev. A, **63**, 032713 (2001), includes detailed calculations for Pb-Pb at LHC energy

BFPP can limit luminosity in heavy-ion colliders, S. Klein, NIM A **459** (2001) 51

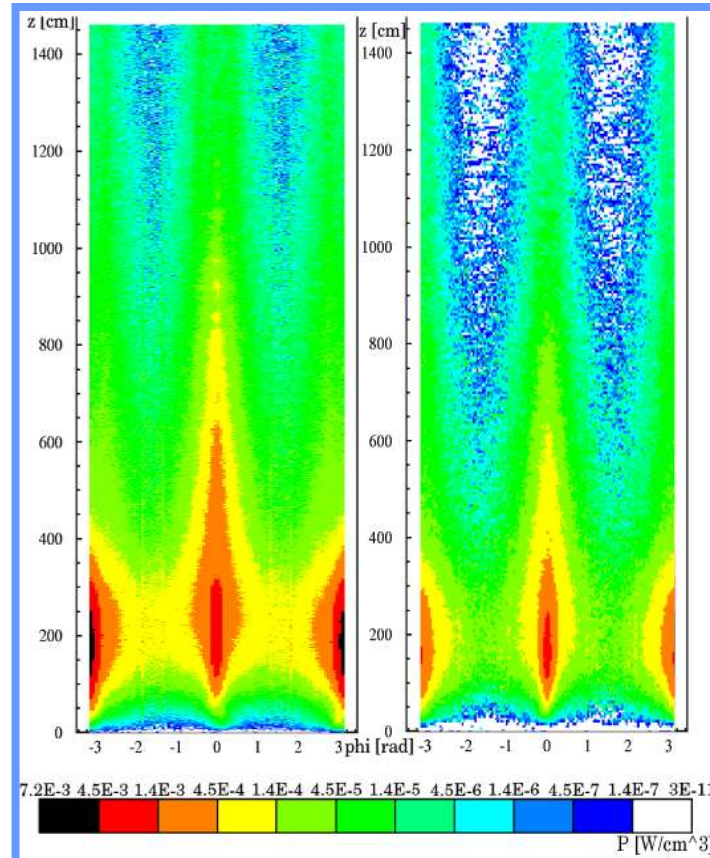
Luminosity Limit from bound-free pair production

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



Secondary Pb^{81+} beam (25 W at design luminosity) emerging from IP and impinging on beam screen.

Hadronic shower into superconducting coils can quench magnet.



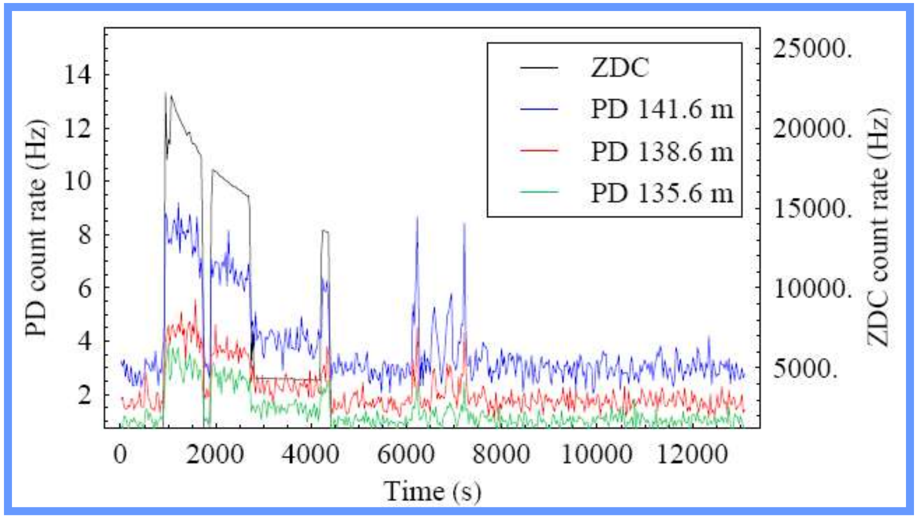
Distinct EMD process (similar rates) does not form spot on beam pipe

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\mathrm{GDR}} {}^{208}\mathrm{Pb}^{82+} + {}^{207}\mathrm{Pb}^{82+} + n$$

Test of LHC methodology at RHIC

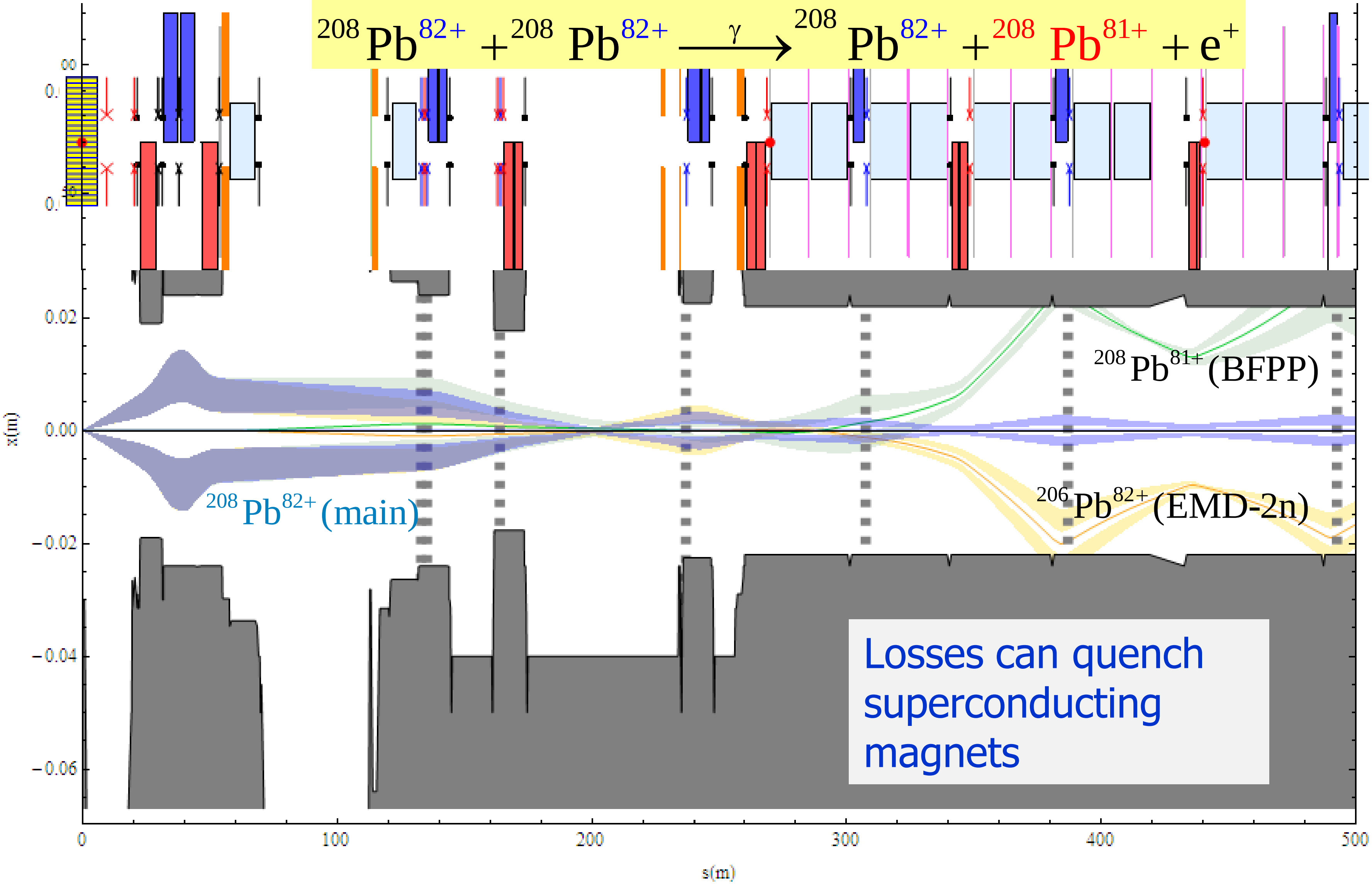
- Parasitic measurement during RHIC Cu-Cu run in 2005
  - Loss monitors setup as for LHC
  - Just visible signal!
- Compared predictions and shower calculations as for LHC
  - Reasonable agreement
- *R. Bruce et al, Phys. Rev. Letters 99:144801, 2007*
- We still need to find quench limit in LHC!

View towards PHENIX



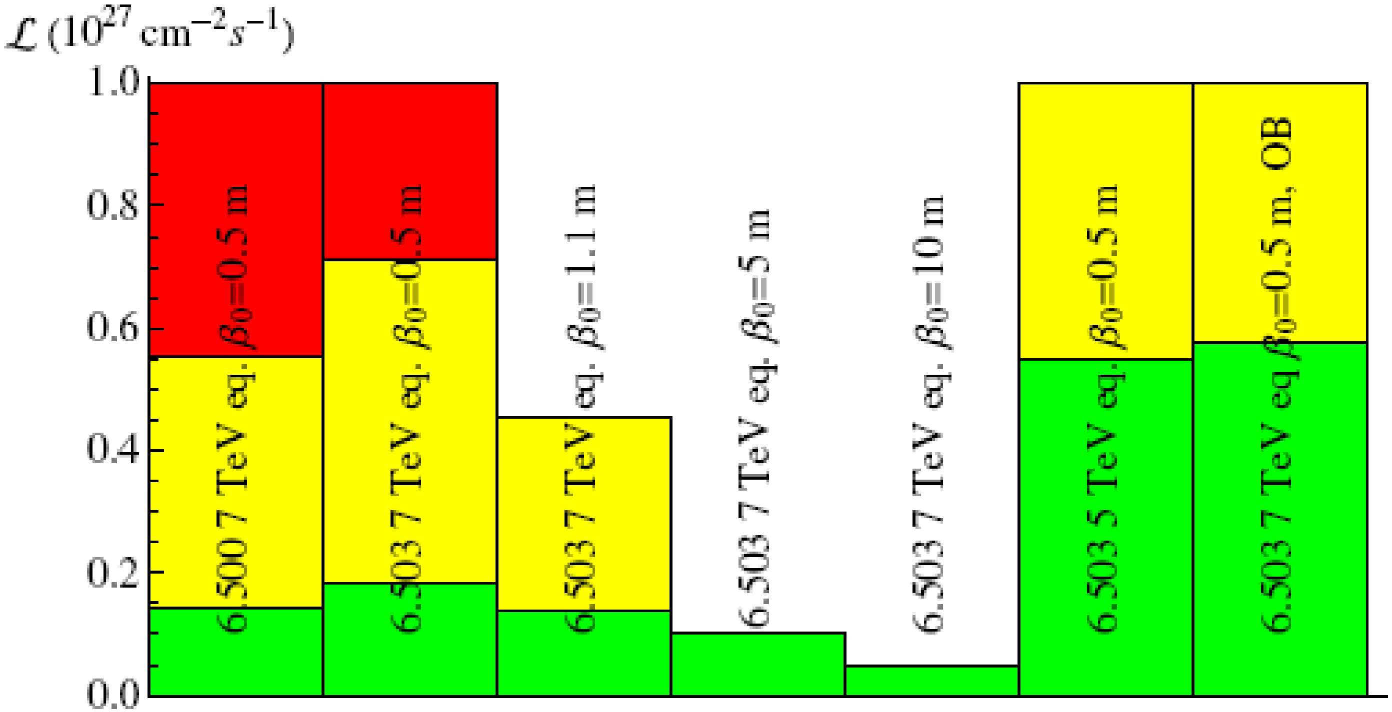
Main and secondary Pb beams from ALICE IP

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



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.

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]
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Collimation of heavy ions

- LHC proton collimation principle:
  - Errant protons encounter primary collimator and are diffractively scattered to larger betatron oscillation amplitude, cleaned by secondary collimators
- Collimation of heavy ions is very different from protons
  - Nuclear interactions (hadronic fragmentation, EM dissociation) in primary collimator material.
  - Staged collimation principle does not work.
  - Single stage system, reduced collimation efficiency

Collimation system cleans beam halo

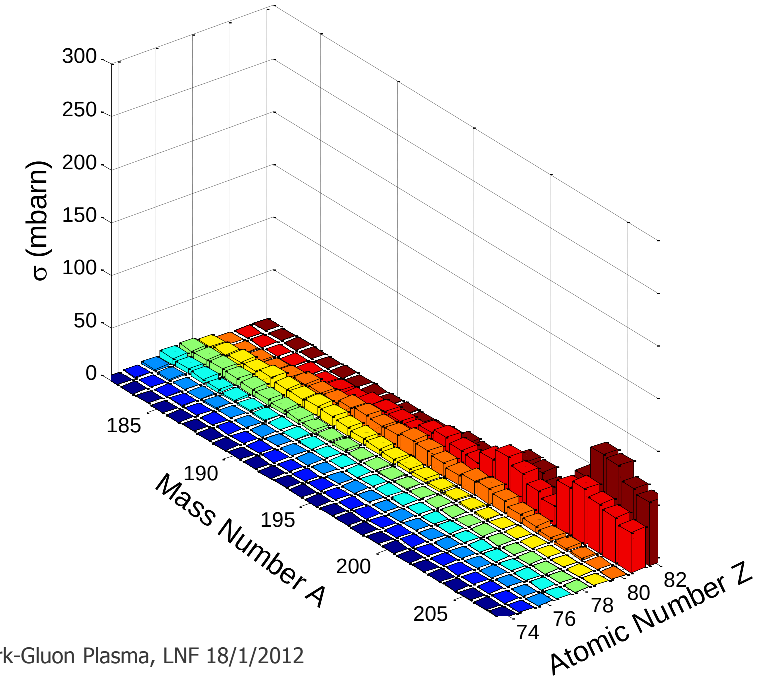
LHC design (primarily for p beam) principle: diffractive scattering of errant particles on primary collimator towards absorption in secondary collimators

Nuclear physics different for heavy ions!

Hadronic fragmentation:

Large variety of daughter nuclei, specific cross sections

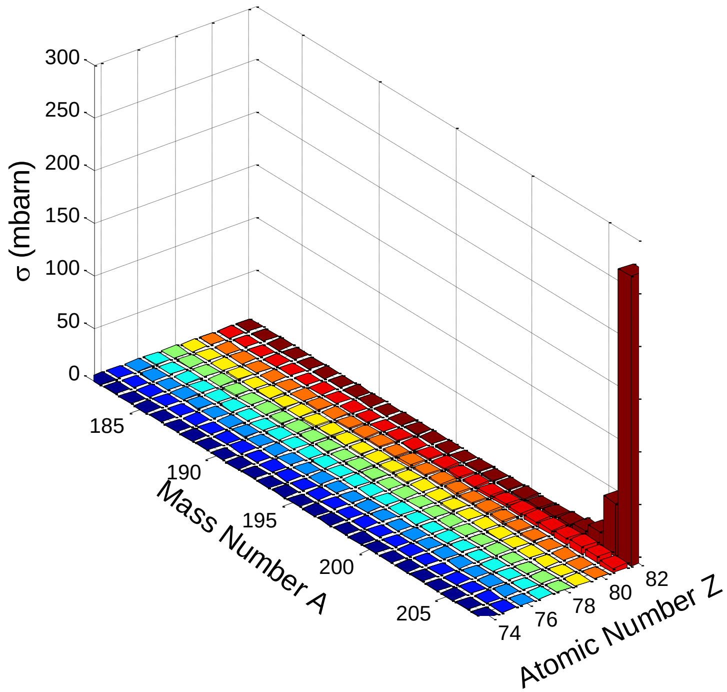
Hadronic Fragmentation cross sections for ^{208}Pb on ^{12}C



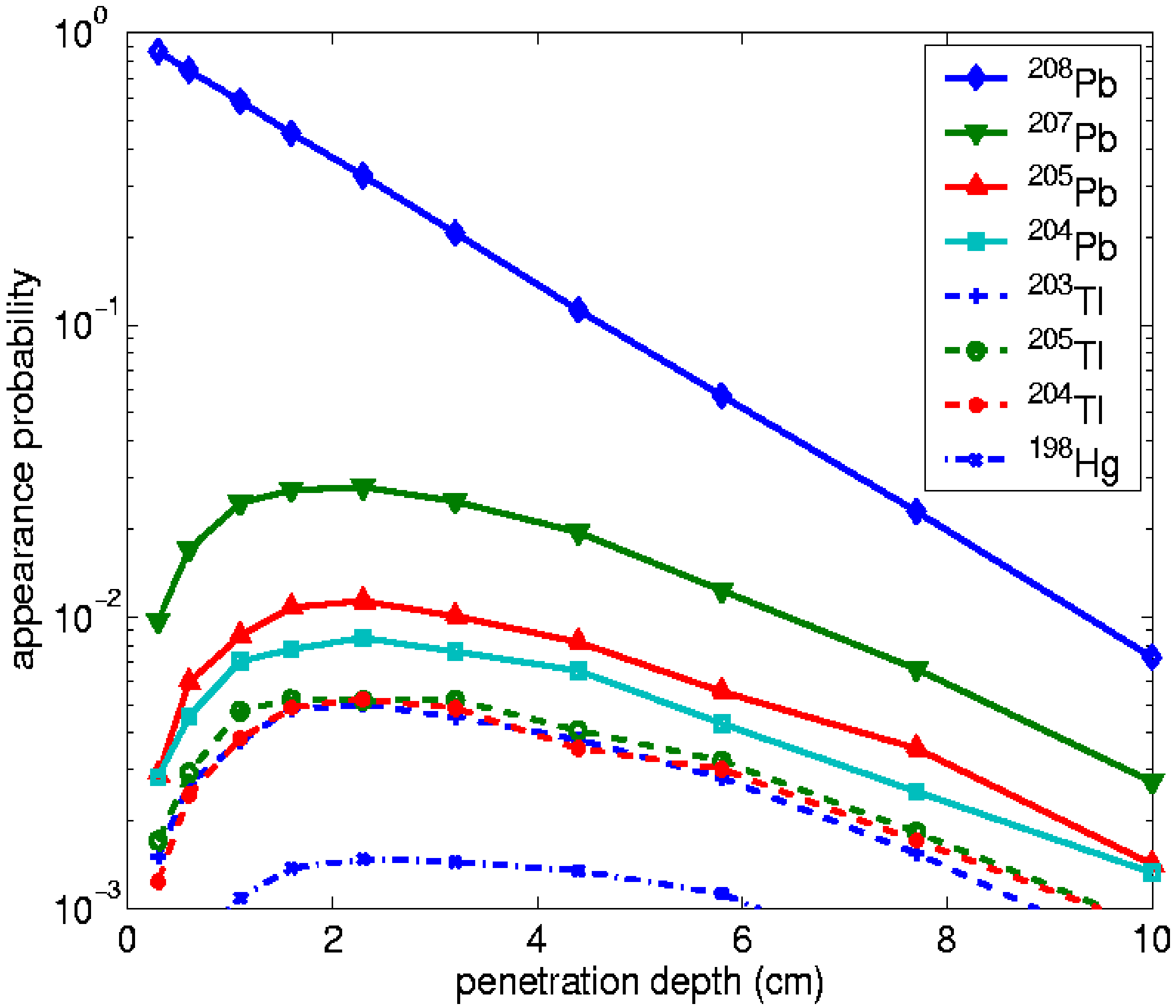
Electromagnetic dissociation:

Mainly loss of 1 (59%) or 2 (11%) neutrons → ^{207}Pb, ^{206}Pb

Electromagnetic Dissociation cross sections for ^{208}Pb on ^{12}C



Cleaning efficiency



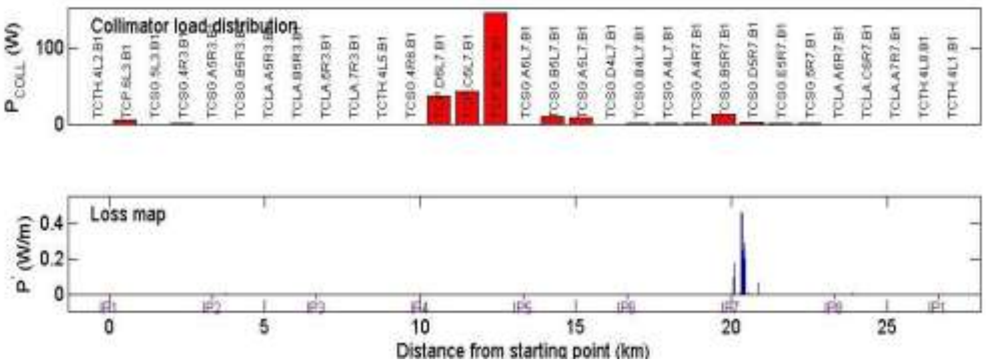
Collimators tend to put fragments on trajectories with large effective momentum errors (Z/A) and small betatron amplitude – but the secondary collimators are designed to cut *betatron* amplitudes

The probability to convert a ^{208}Pb nucleus into a neighboring nucleus. Impact on graphite at LHC collision energy.

From Hans Braun

Beam1, betatron collimation E=3.5 Z TeV, β^* =3.5m, 12min lifetime

TCP IR7	5.7 σ	TCP IR3	12 σ
TCSG IR7	8.5 σ	TCSG IR3	15.6 σ
TCLA IR7	17.7 σ	TCLA IR3	17.6 σ
		TCTs	15 σ



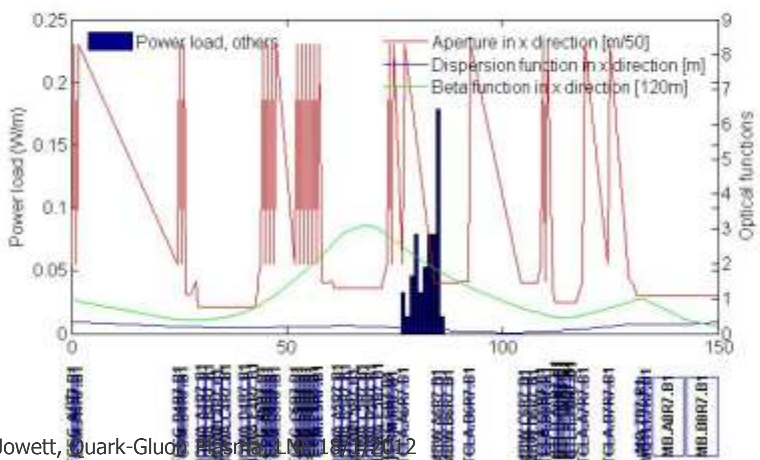
Σ aperture hits/Σ collimator hits= η= 0.033

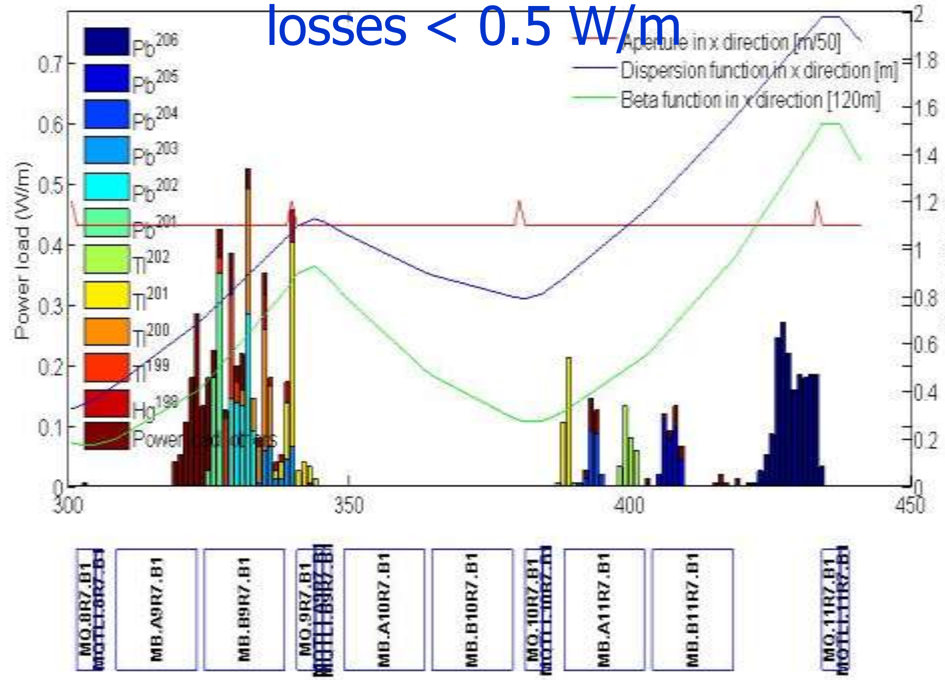
Isotopic loss map, DS.R7

losses < 0.5 W/m

Max load on TCP.B6L7.B1=122W

Some losses before DS





From G. Bellodi

Other limits on performance

- Total bunch charge is near lower limits of visibility on beam instrumentation, particularly the beam position monitors
  - Must always inject close to nominal bunch current and not lose too much!
  - Rely on ionization profile monitors more than with protons ,etc
- Intra-beam scattering (IBS)
  - Multiple Coulomb scattering within bunches is significant but less so than at RHIC where it dominates luminosity decay
- Vacuum effects (losses, emittance growth, electron cloud …) should not be significant

Synchrotron Radiation

- LHC is the first *proton* storage ring in which synchrotron radiation plays a noticeable role, (mainly as a heat load on the cryogenic system)
- At full energy, it will be the first *heavy ion* storage ring in which synchrotron radiation has significant effects on beam dynamics.
  - Surprisingly, perhaps, some of these effects are stronger for lead ions than for protons.
  - Nucleus radiates coherently:

Synchrotron radiation loss per turn

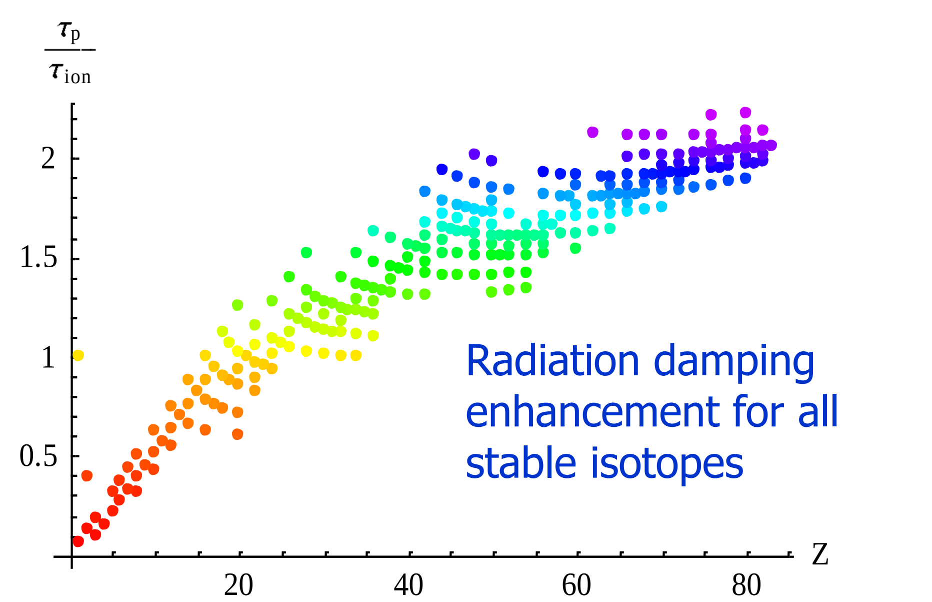
$$U = \frac{4}{3}\frac{\pi r_{\text{ion}} E_{\text{ion}}^{4}}{c^{6} m_{\text{ion}}^{3} \rho} = \frac{4}{3}\frac{\pi Z^{2} r_{p} E_{\text{ion}}^{4}}{c^{6} A^{4} m_{p}^{3} \rho}, \qquad E_{\text{ion}} = \frac{Z}{A} E_{p}$$

Synchrotron Radiation from lead

- Nuclear charge radiates *coherently* at relevant wavelengths (~ nm)
- Scaling with respect to protons *in same ring, same magnetic field*
  - Radiation damping for Pb is twice as fast as for protons
    - Many very soft photons
    - Critical energy in visible spectrum
- This is fast enough to overcome IBS at full energy and intensity

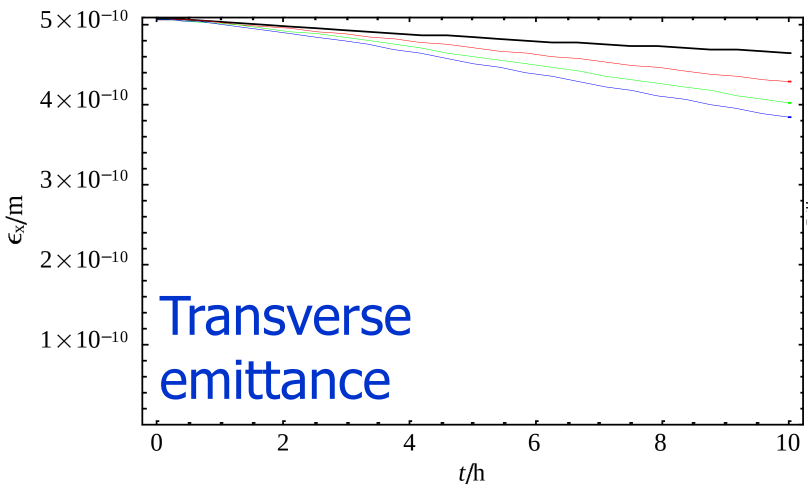
$$\frac{U_{\text{ion}}}{U_{\text{p}}} \simeq \frac{Z^6}{A^4} \simeq 162, \qquad \frac{u^c_{\text{ion}}}{u^c_{\text{p}}} \simeq \frac{Z^3}{A^3} \simeq 0.061,$$

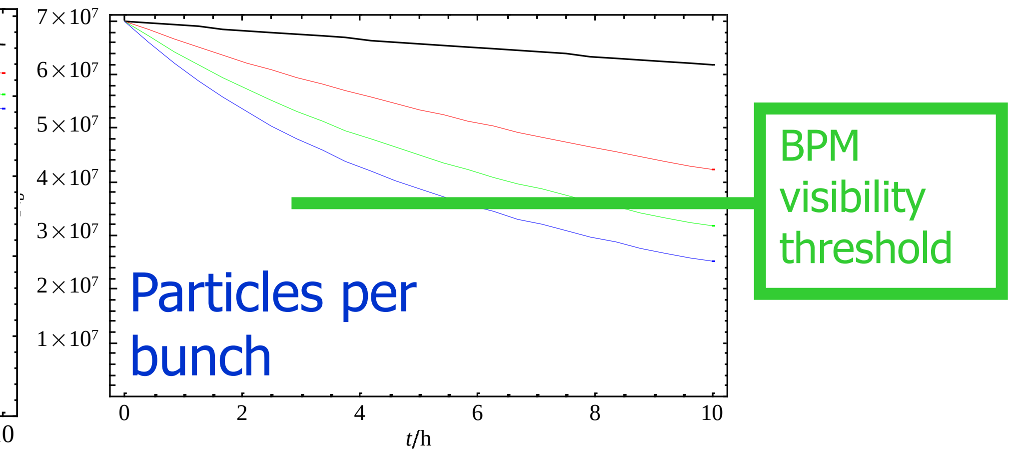
$$\frac{N_{\text{ion}}}{N_{\text{p}}} \simeq \frac{Z^3}{A} \simeq 2651, \qquad \frac{\tau_{\text{ion}}}{\tau_{\text{p}}} \simeq \frac{A^4}{Z^5} \simeq 0.5$$



Lead is (almost) best, deuteron is worst.

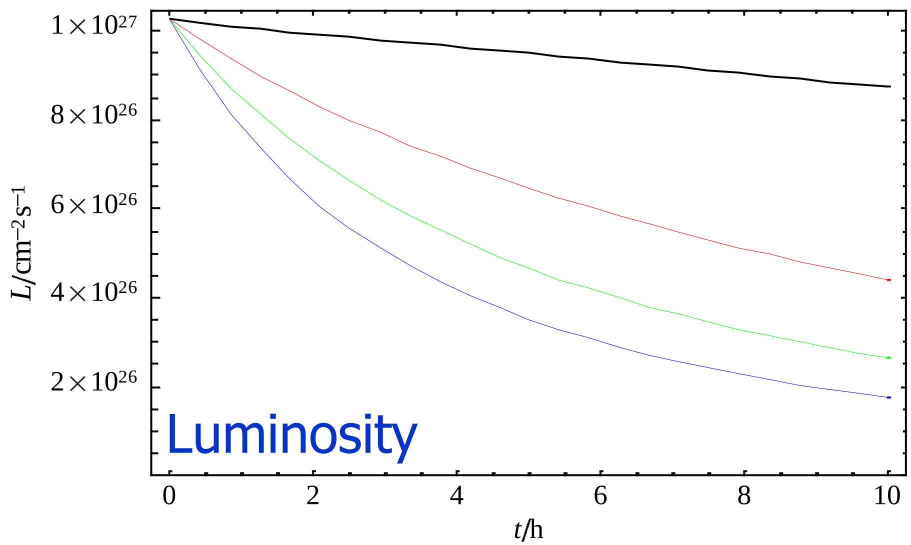
Luminosity evolution: Nominal scheme (old expectations)





No. of experiments: $n_{exp} = 0, 1, 2, 3$

An "ideal" fill, starting from design parameters giving nominal luminosity.



Increasing number of experiments reduces beam and luminosity lifetime.

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 commissioning plan (1)

ACTION	No. OF BUNCHES/BEAM	TIME ESTIMATE (in shift)	COMMENT	Beam1	Beam2	GROUP	PERSON RESP	SLOT
LHCb switch off		till noon	ACCESS and recovery	OK	OK			THU M
Check with protons after access	protons	1 h	Calibrate BCTs	OK	OK	OP		THU M
			Injection of high intensity proton bunch	OK	OK			
			Injection of low intensity proton bunch	OK	OK			
			switch injector chain to ions	OK	OK			
Injection and circulating beams	1 (non colliding)	1	Injection of Ions (to establish the reference orbit)	OK	OK	OP		THU A
			Rough BI check	OK	OK	BI	JJG	
			Resteering of transfer lines (if needed)	OK	OK	ABT	BG	
			RF capture (at -5 kHz frequency shift)	OK	OK	RF	PB	
			check injection oscillation	OK	OK	OP		
			check 450 GeV dump ok	OK	OK	ABT	BG	
450 Z GeV commissioning (BI setup)	1 (non colliding)	0.5	Wire-scanner for 1 beam	OK	OK	BI	JJG	THU N
			BGI				JJG	THU N
450 Z GeV optics checks with two beams	1 (non colliding)	0.5	beta-beating. >0.4 nominal bunch intensity	OK	OK	ABP	RT	THU N
Collimation	1 (non colliding)	1	Collimation check	OK	OK	COLL	SR, RA, DW	FRI M
			Loss maps	OK	OK			
LBDS	1 (non colliding)	0.25	Asynchronous beam dump	OK	OK	ABT	BG	FRI A
Ramp	1 (non colliding)	1	Blowup off - TFB off - OFB on - QFB on - Collimators ramp if no issues at injection	OK	OK	OP, COLL	RA	FRI A
			Collimator check, NO squeeze, loss maps	OK	OK	OP, ABP	RT	
			check 3.5 TeV dump ok	OK	OK	ABT	BG	

Heavy ion commissioning plan (2)

RAMP and SQUEEZE	1 (non colliding)	0.5	Ramp THEN squeeze, optics check	OK	OK	COLL	RA, DW, GV, GB	FRI N
LBDS	1 (non colliding)	0.25	Asynchronous beam dump	OK	OK	ABT	BG	FRI N
Setup for collisions	2 (colliding)	2	Squeeze, find collision, and transition to zero real crossing angle in ALICE, CMS & ATLAS. LHCb separated, squeezed.	OK!!	OK!!	OP		SAT M,A
			Collimation setup.	OK	OK	COLL	RA, RB, DW,	
Collimation	2 (colliding)	1	Loss maps	OK	OK	OP	GB	SAT N
LBDS	2 (colliding)	0.25	Asynchronous dump	OK	OK	ABT	BG	SUN M
First collisions + PHYSICS	2 colliding	1 or 2	Ramp with two beams, squeeze, checks, Stable beams.	OK!!	OK!!			SUN M
Increase intensity (1)	17	1 or 2	Increase bunch number to 17 (16 colliding in IP1,2,5 + 1 probe)	OK	OK			
Increase intensity (1.5)	69	1	New scheme, 65 or 66 collisions/turn	OK	OK			*WED A*
Increase intensity (2)	121	1	Increase bunch number to 128	OK	OK			
Physics	121		Parasitic measurements during physics (luminosity evolution, BFPP, etc, ...) to test models and prepare future runs	OK	OK			

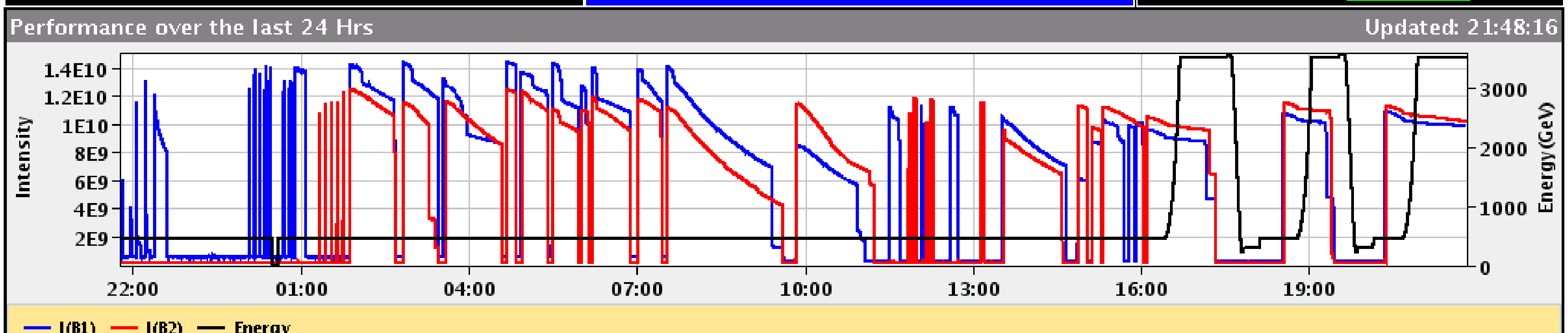
Last updated: 16/11/2010 11:56

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

05-Nov-2010 21:48:18 Fill #: 1473 Energy: 3500 Z GeV I(B1): 9.86e+09 I(B2): 1.02e+10

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Lumi (ub.s)^-1	0.000	0.000	0.000	0.000
BRAN Luminosity (ub.s)^-1	0.000	0.000	0.000	0.000
Inst Lumi/CollRate Parameter	1.00e+00		0.00e+00	
BKGD 1	0.002	0.244	0.000	0.122
BKGD 2	0.000	0.000	0.000	0.407
BKGD 3	0.000	1.628	0.098	0.044

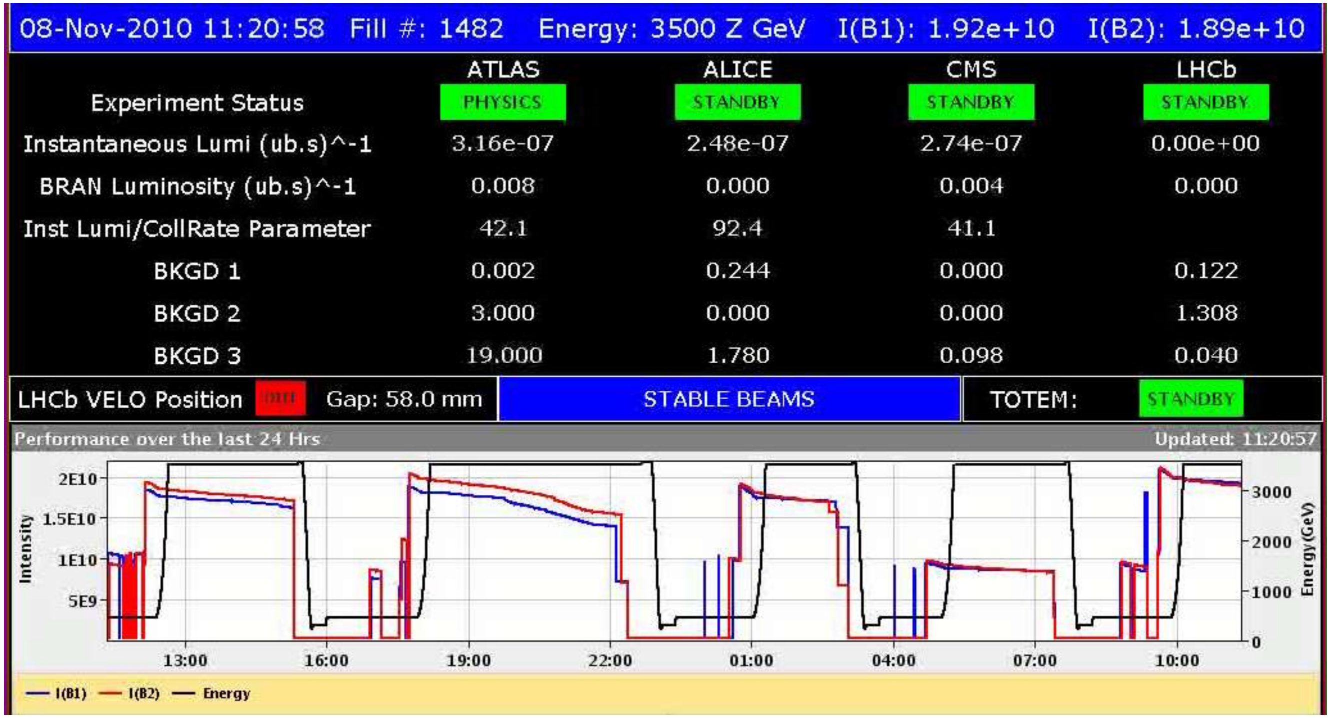
LHCb VELO Position OUT Gap: 58.0 mm SQUEEZE TOTEM: STANDBY



Beam :
Inj., Ci
& Capt
ks

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.

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.

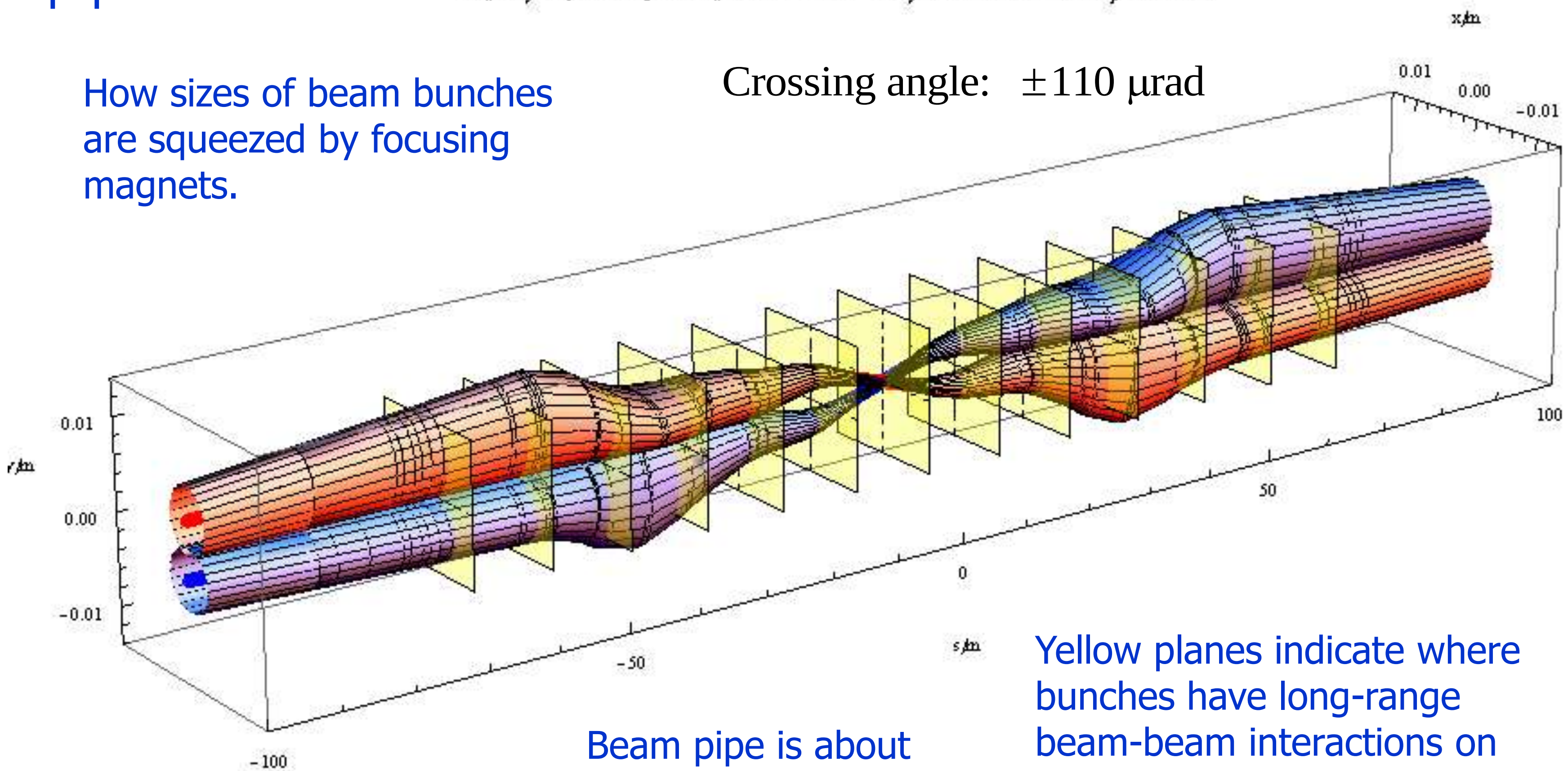
Ion injectors exceeded design intensity/bunch by 70%.

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



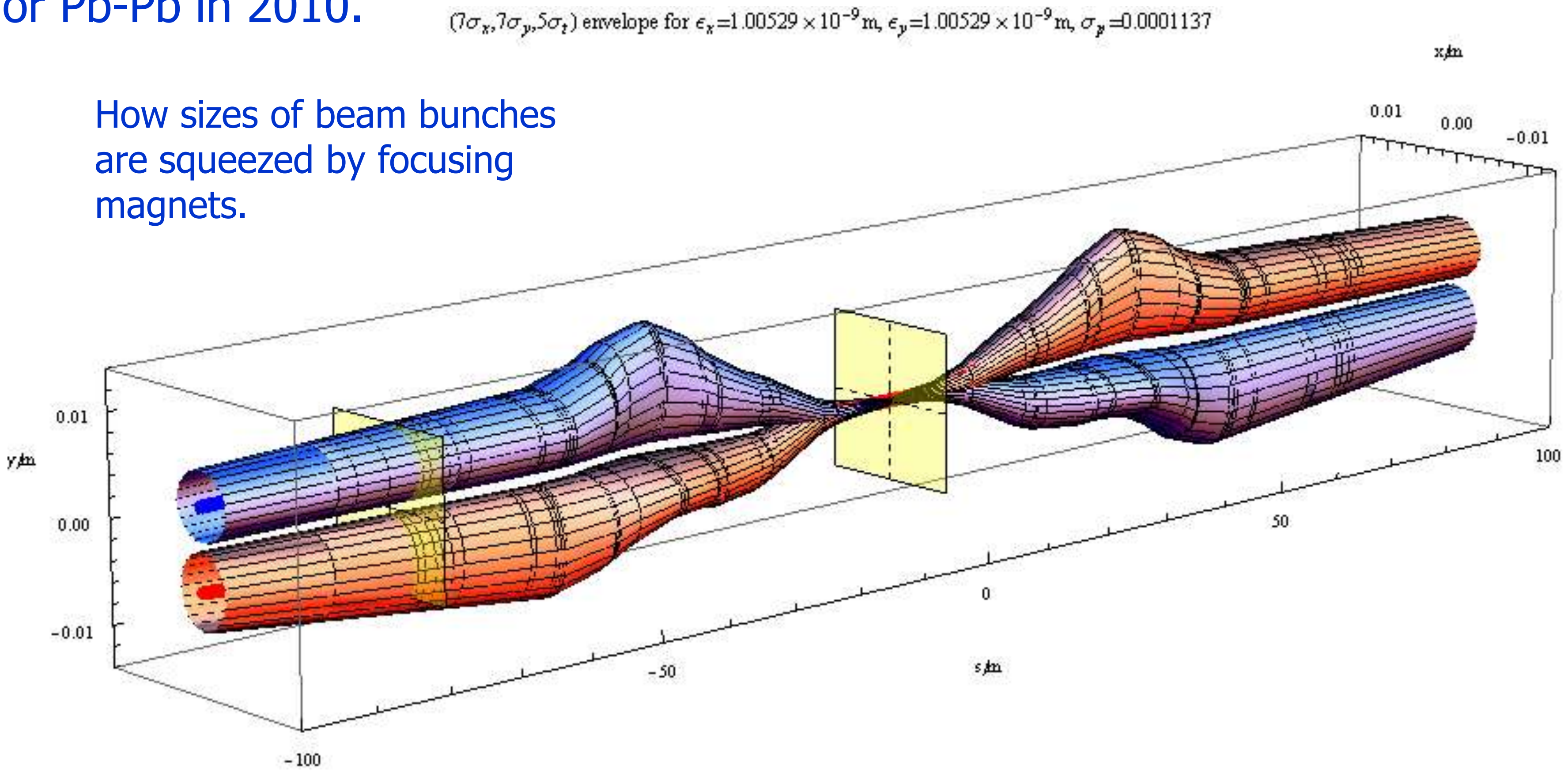
Beam pipe is about twice transverse size of box.

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.

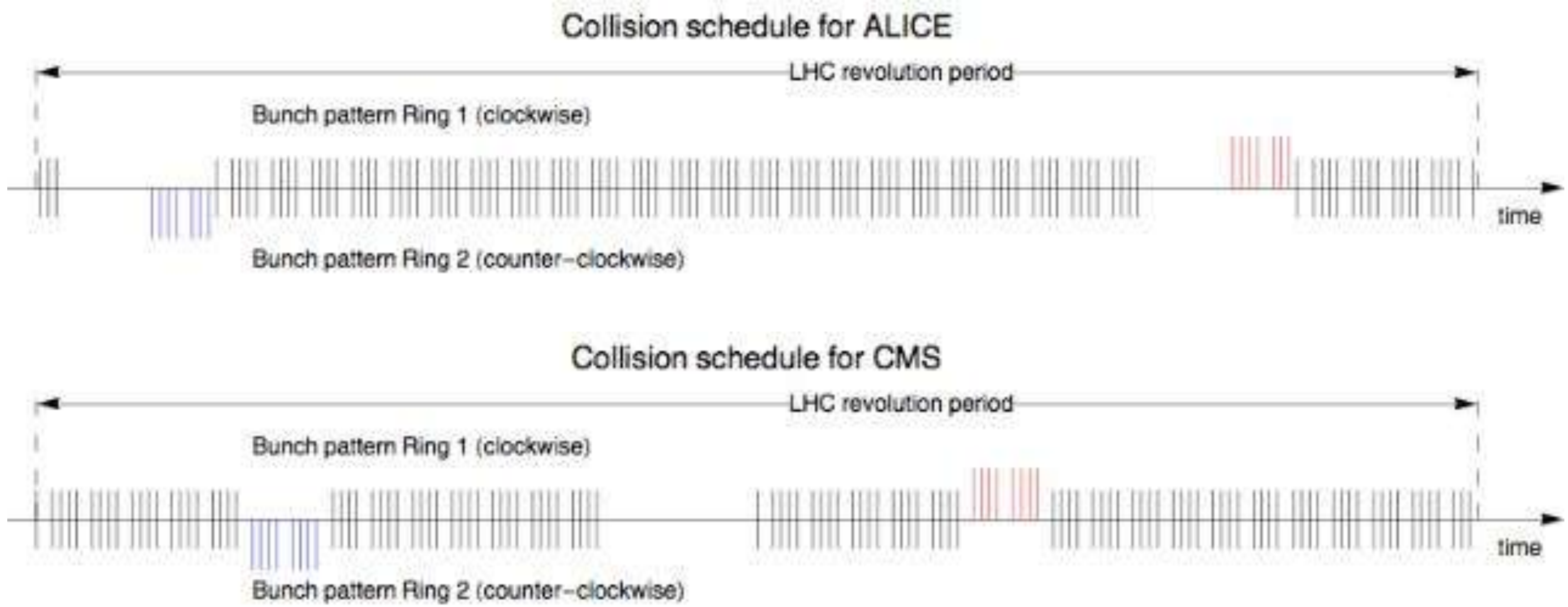


Zero crossing angle at IP (external crossing angle compensates ALICE spectrometer magnet bump).

Beam pipe is about twice transverse size of box.

Filling schemes

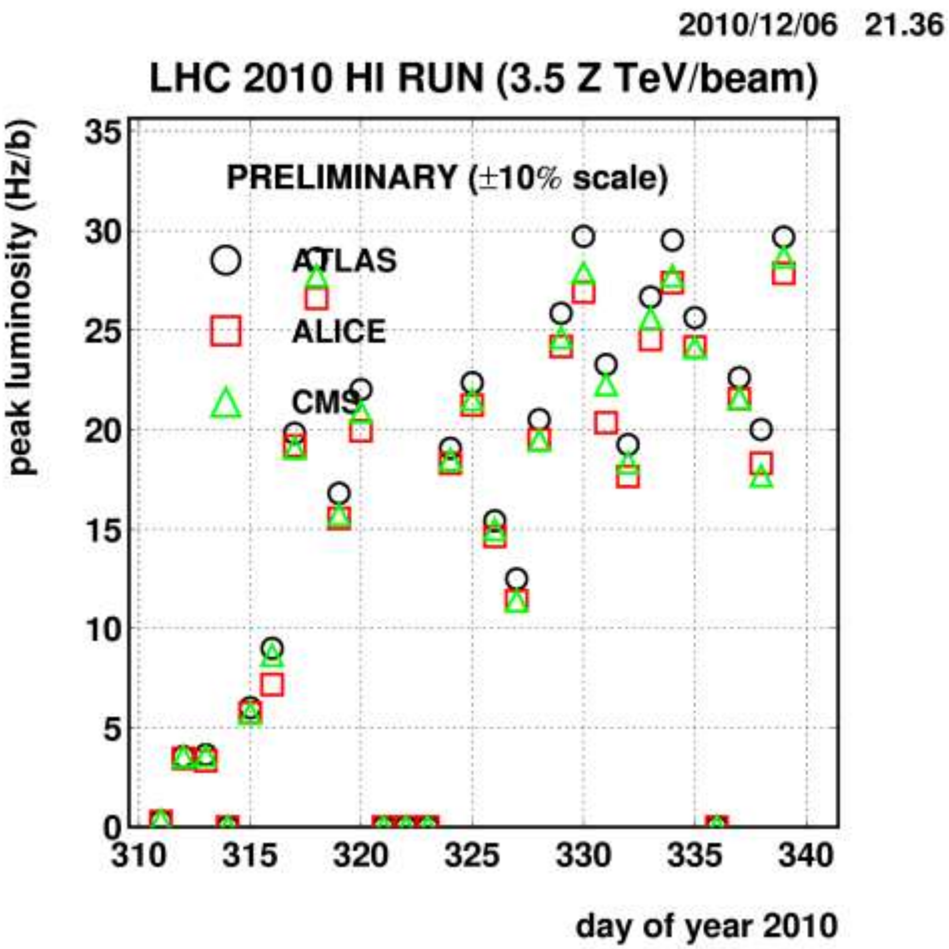
- First week: no two fills with same number of bunches
  - 2,5,17,69, then 121 per beam (475 ns basic spacing)



Peak luminosity in fills

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

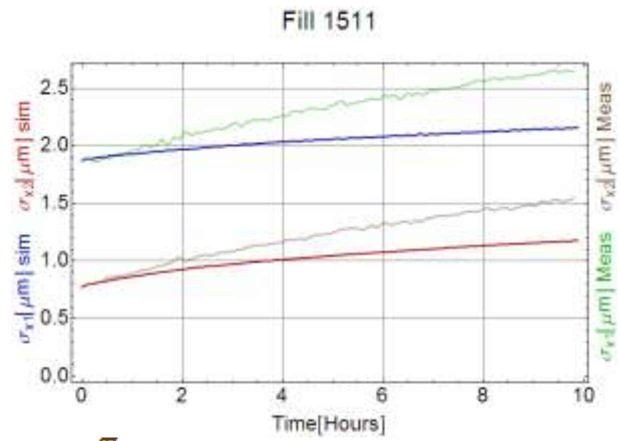
Last few days: bunch number increased again to 137 with 8-bunches/batch from SPS.

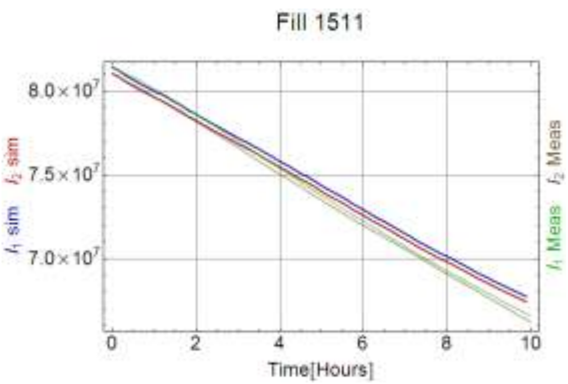


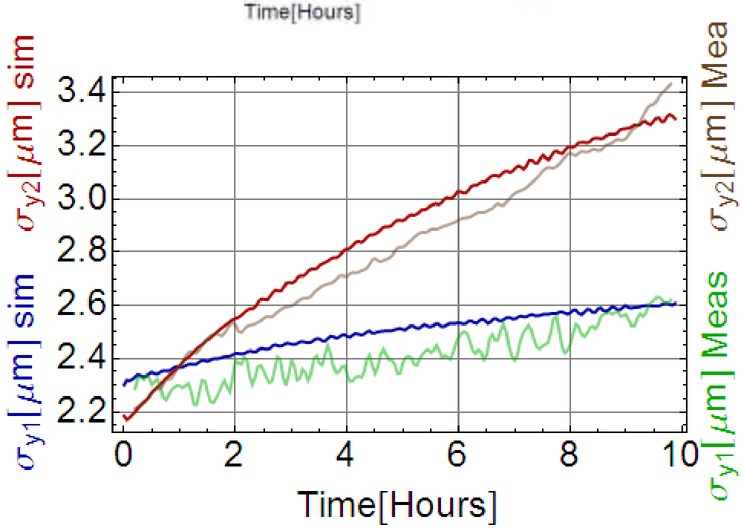
Beam instrumentation

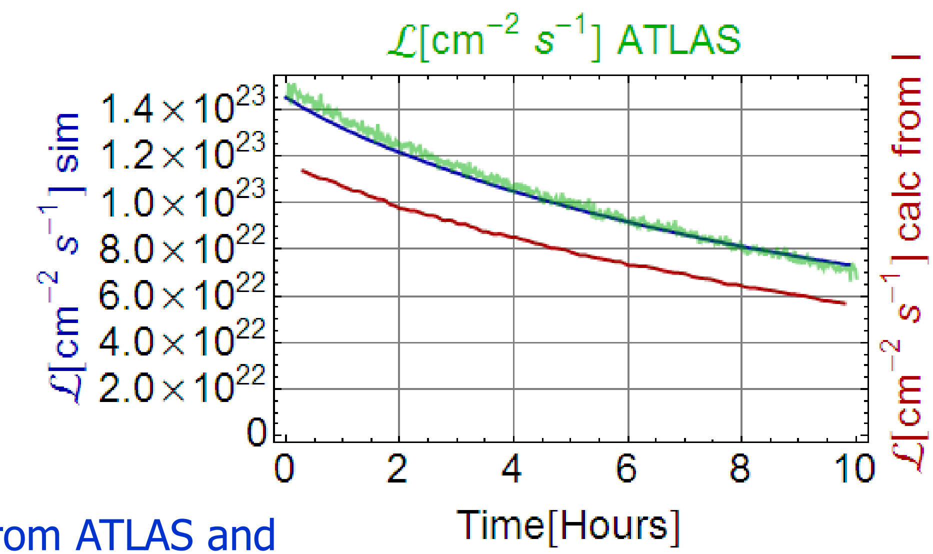
- Major concern in preceding years
  - BPMs intensity threshold – no problem
  - Emittance: harder than protons
    - WS: Wire scanner at low energy and intensity – best absolute calibration
    - BSRT: synchrotron light appeared in ramp (world first!), only bunch-by-bunch – typical large spread in emittance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

Understanding luminosity/bunch







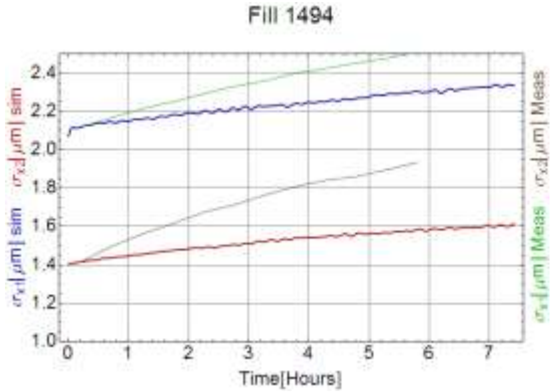


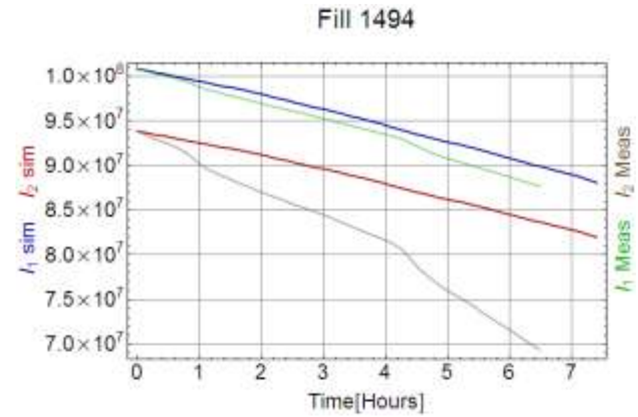
Good fill: after detailed analysis of data from ATLAS and machine instrumentation, there is good agreement with simulation model (non-gaussian IBS, emittance growth, debunching from RF bucket, luminosity burn-off, etc.). Parameters of two beams evolve separately.

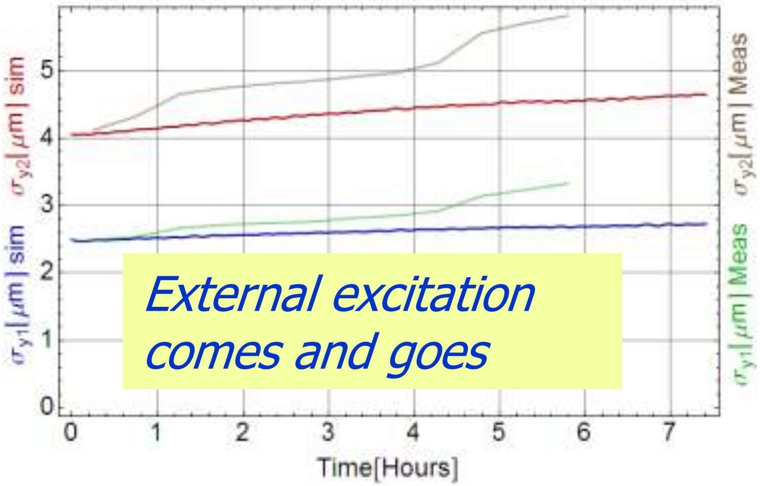
Simulations by T. Mertens, based on earlier work by R. Bruce, JMJ, M. Blaskiewicz, W. Fischer.

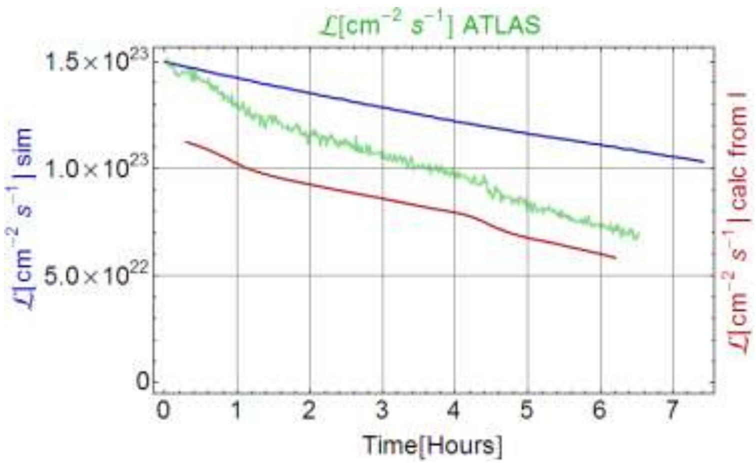
Phys. Rev. ST Accel. Beams 13, 091001 (2010)

Not-quite-understanding luminosity/bunch





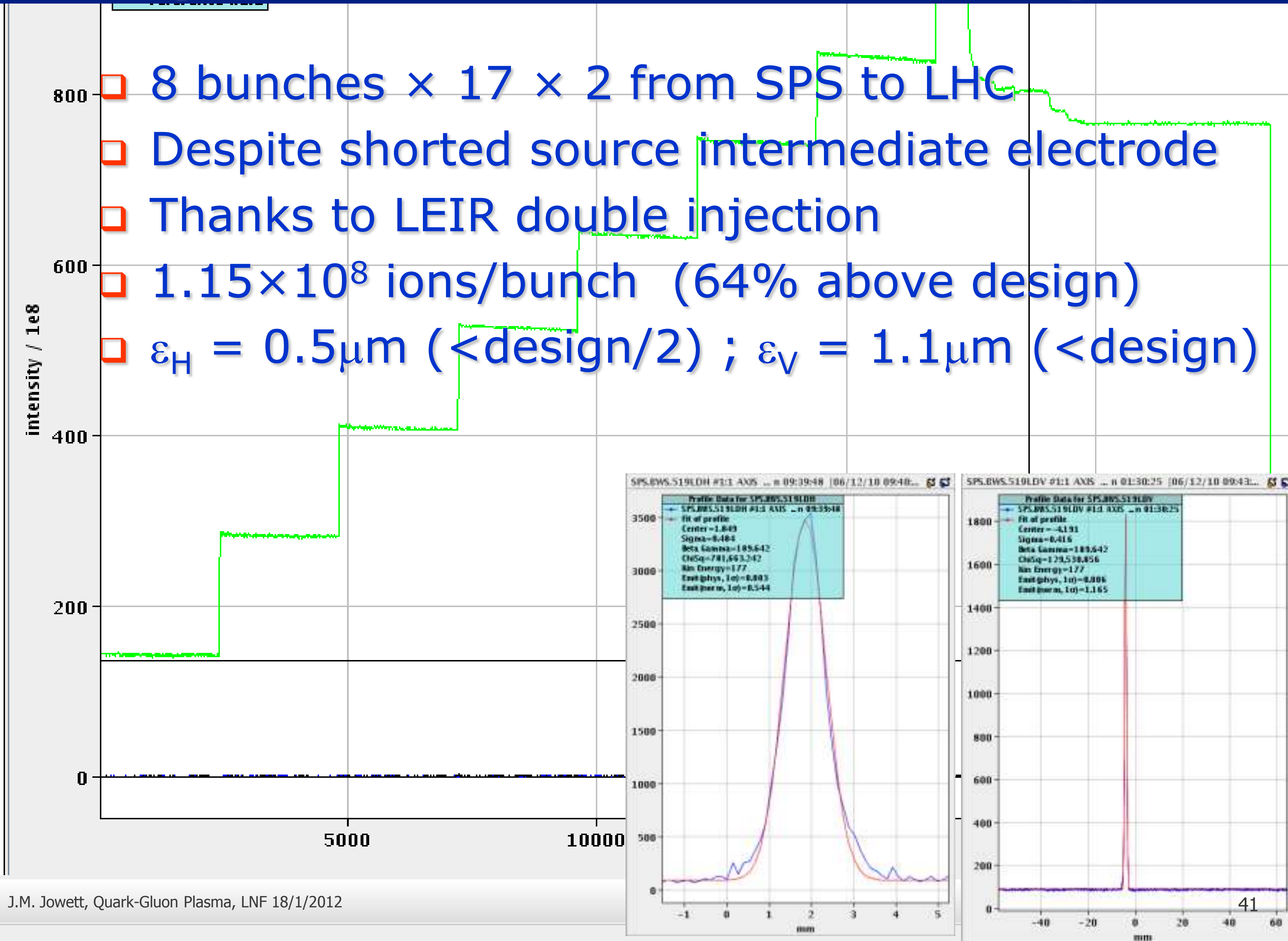




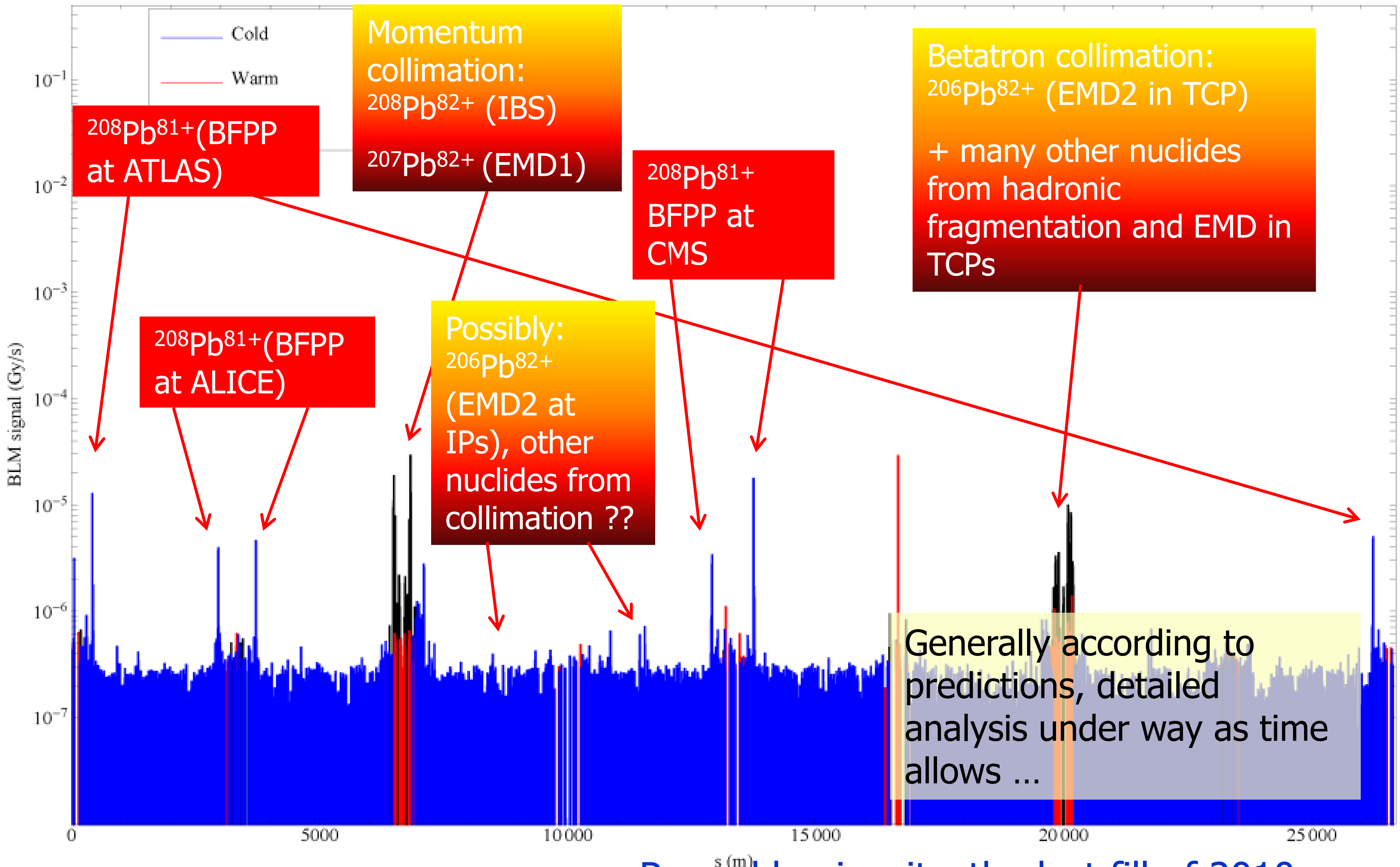
"Hump-influenced" fill: similar analysis and simulation show the influence of an unknown intermittent excitation, mainly Beam 2 vertical (origin never found, much reduced in 2011).

Injectors for last LHC ion fill of the year

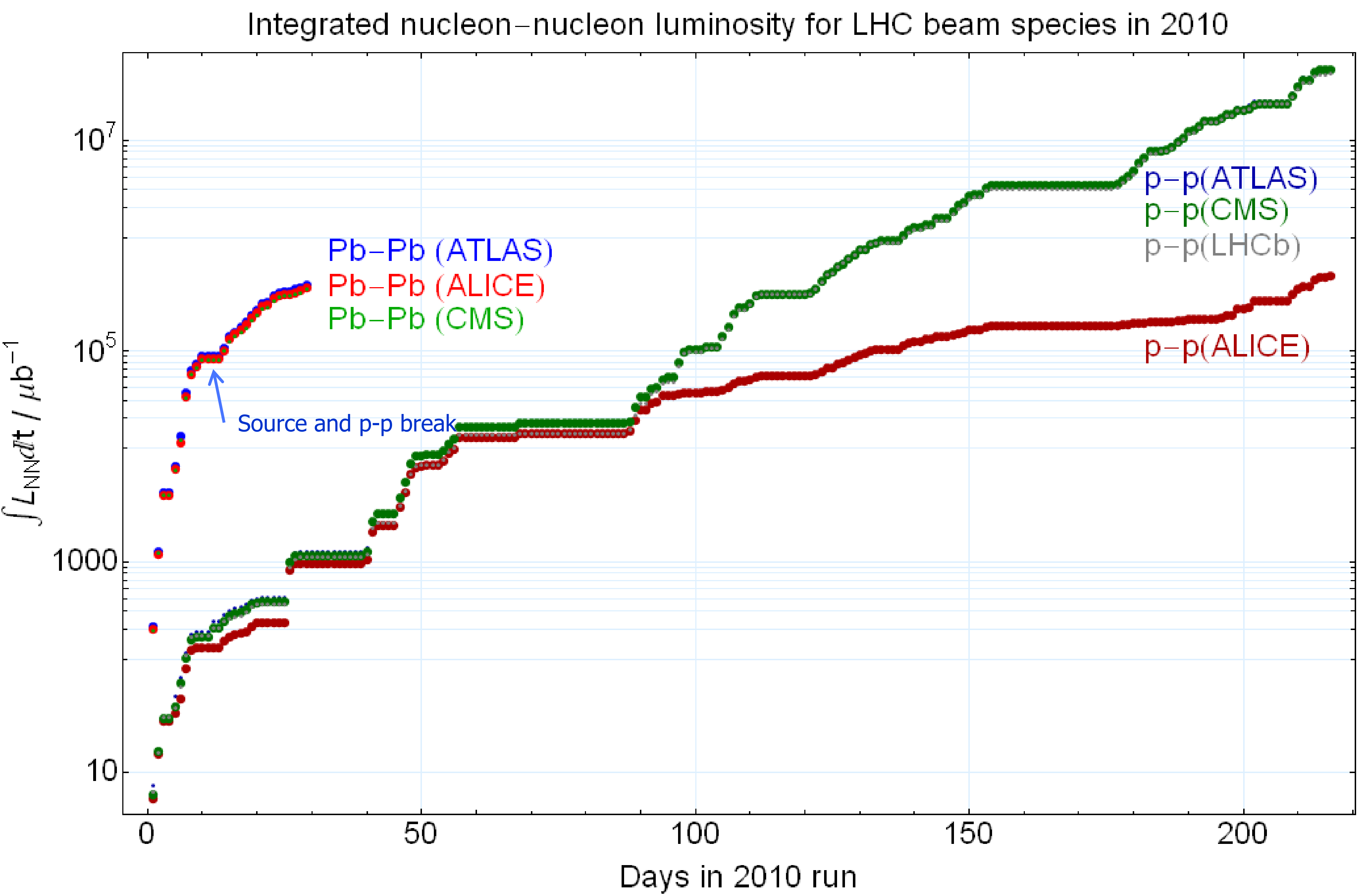
- 8 bunches × 17 × 2 from SPS to LHC
- Despite shorted source intermediate electrode
- Thanks to LEIR double injection
- 1.15×10^{8} ions/bunch (64% above design)
- $\varepsilon_H = 0.5\mu m$ (<design/2) ; $\varepsilon_V = 1.1\mu m$ (<design)



Global view of losses, Pb-Pb stable beams

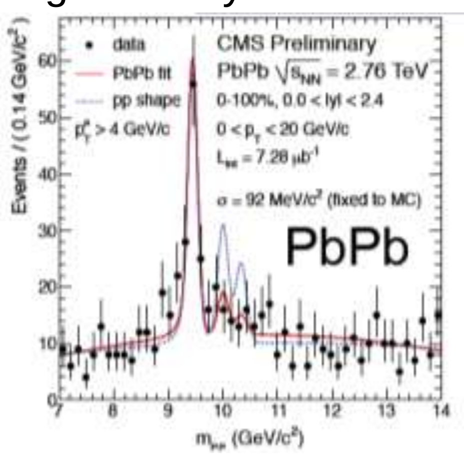


Record luminosity, the last fill of 2010


Integrated nucleon−nucleon luminosity for LHC beam species in 2010
$\int L_{NN} dt \,/\, \mu b^{-1}$
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)

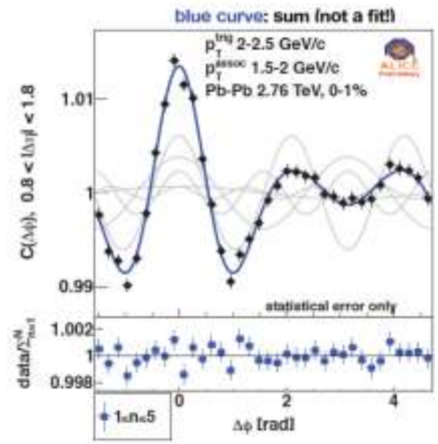
- Most important conference series for ultra-relativistic AA collisions
- First edition after start of LHC
  - > 800 participants
- → First, rich LHC harvest, a few examples…

- Quarkonium suppression
  - e.g: Υ family



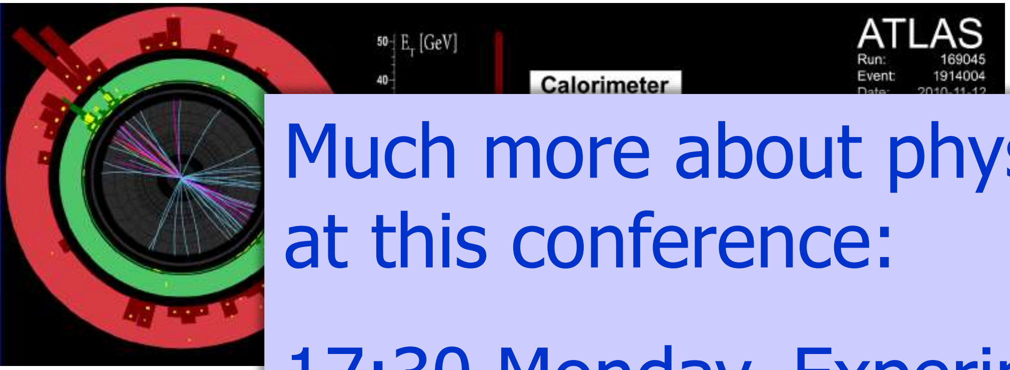
  - measurement of detailed suppression pattern will give information on QGP temperature, evolution

- Long-range η correlations



  - 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



  - reco
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    in a

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

ed as π
energy
loss in QGP on mass and colour charge of propagating parton

Much more about physics in plenary talks at this conference:

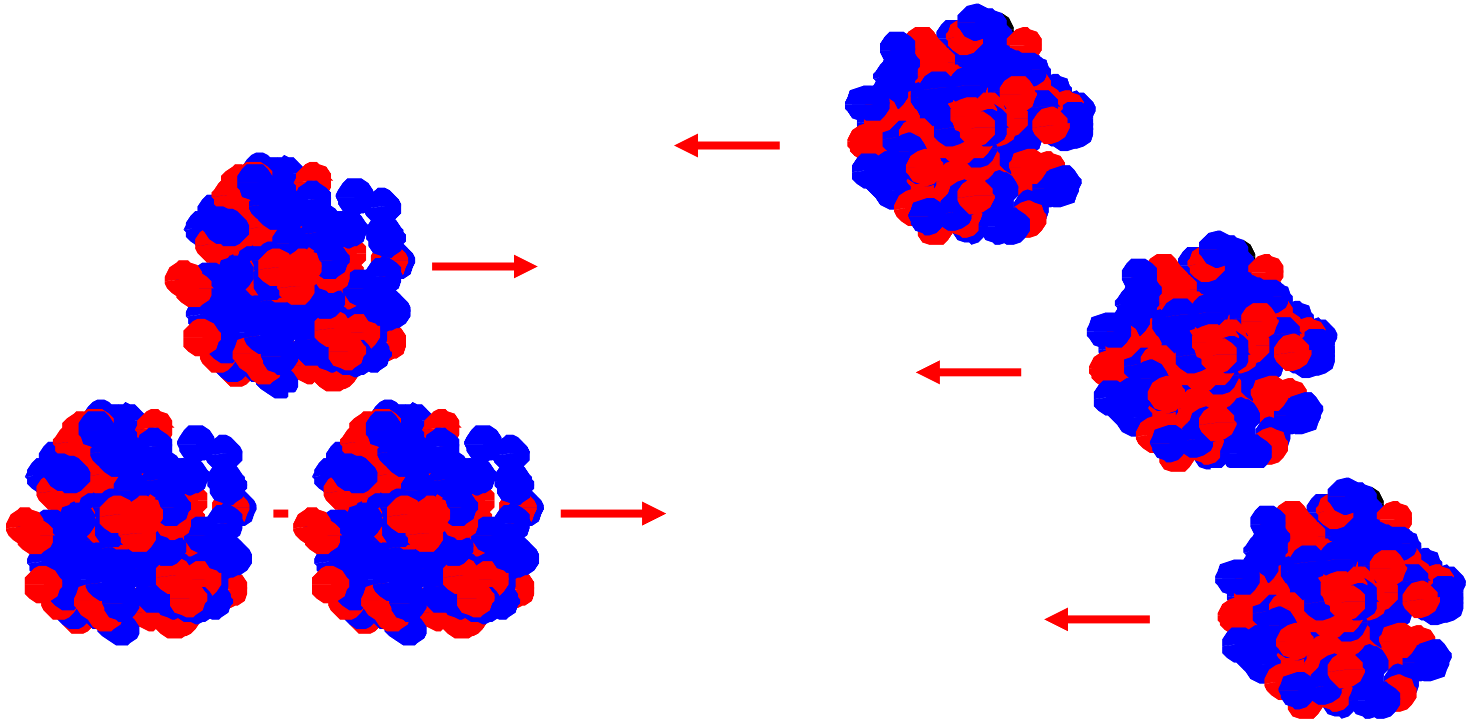
17:30 Monday, Experiment, F. Antinori,

18:00 Monday, Theory, C. Salgado

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

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

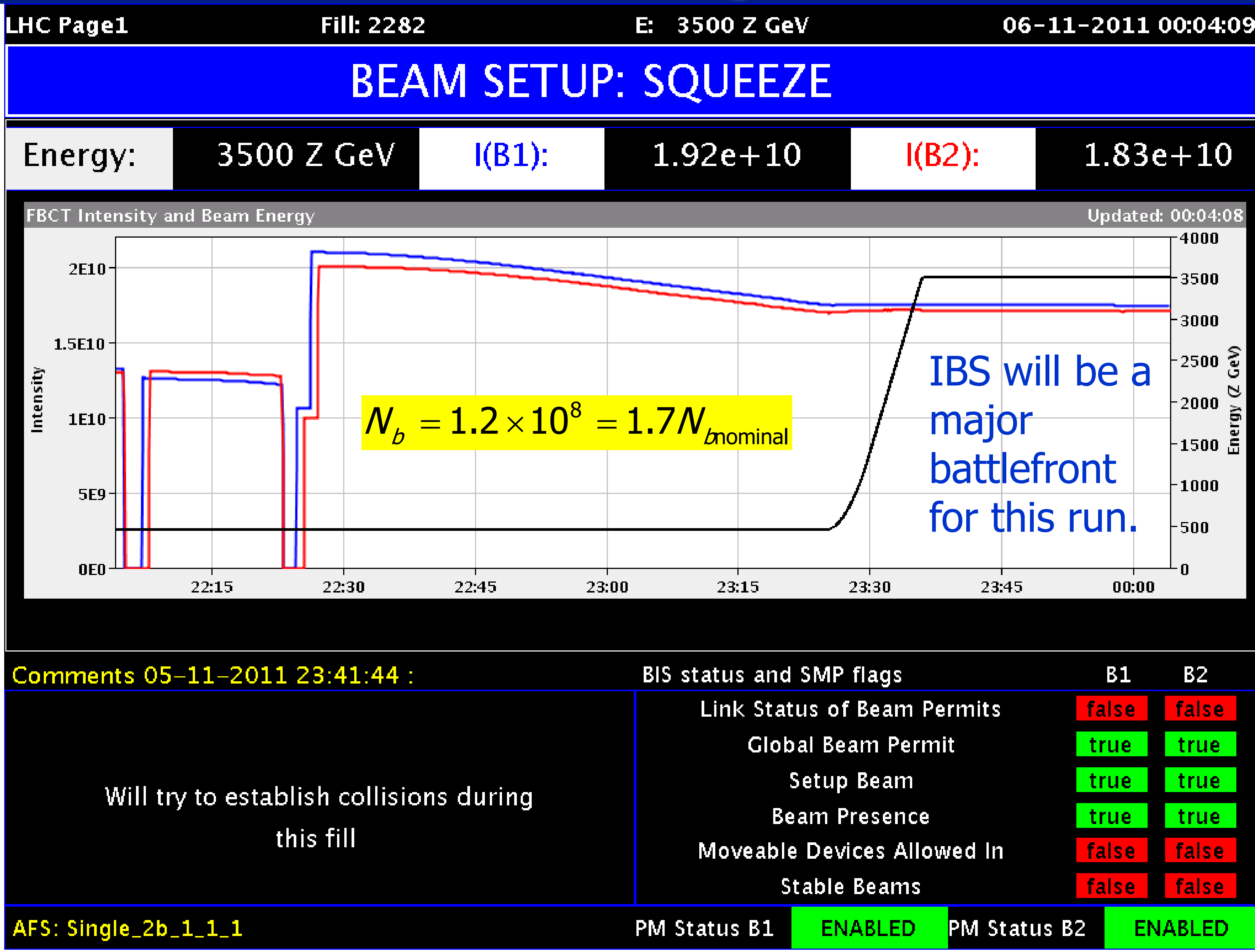


THE 2011 LEAD-LEAD RUN

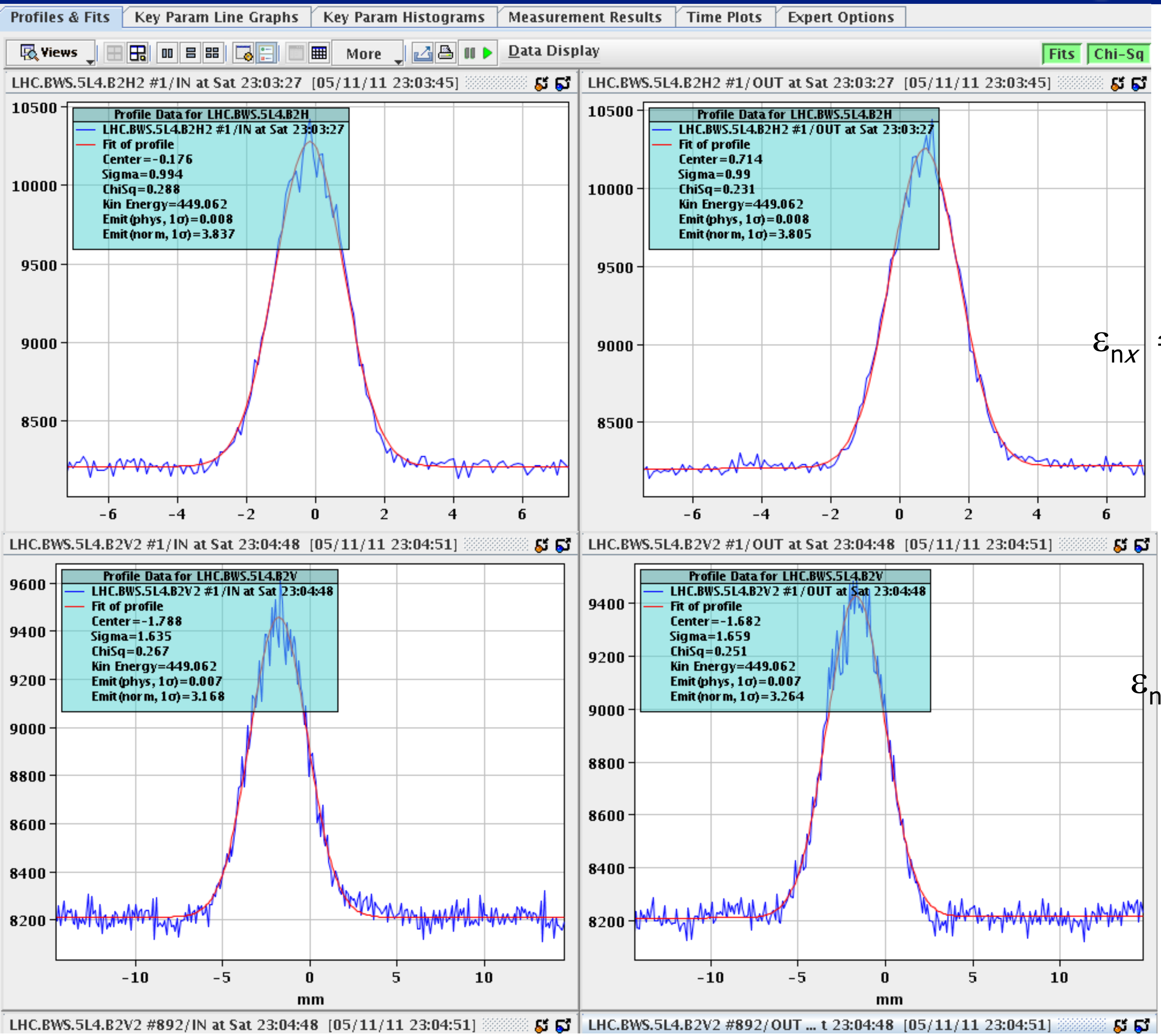
HI2011 Commissioning Status

- 5/11/2011, 09:00 meeting: Decision on ALICE physics conditions
  - Based on aperture measurements (see slides by M. Giovannozzi at that meeting)
  - $\beta^* = 1$ m
  - Crossing angle 60 μrad (external -80 μrad)
    - Limit of acceptable range for ALICE ZDC
    - Unknown aperture restriction near TCTVB.4L2 ? ?
- HI commissioning started 15:00 5/11/2011
  - Reversed polarity of ALICE solenoid, spectrometer dipole and compensators
  - ALICE BRAN converter taken out (luminosity now from ZDC)

Pb-Pb commissioning for HI2011



Emittance after 1 h at injection



$\varepsilon_{nx} \simeq 1.5\ \mu\mathrm{m}$ (approx. design)

$\varepsilon_{nx} \simeq 1.2\ \mu\mathrm{m}$ (< design)

Ramp and squeeze

- 00:20 6/11/2011 First ramp and squeeze finished
  - < 3 h after first injection
    - Established with protons previous weekend
    - Beam 2 ramp and squeeze already in p-Pb MD
  - β^*=(1,1,1,3) m, briefly held record as the most squeezed LHC optics so far …
  - Nuclear synchrotron radiation again

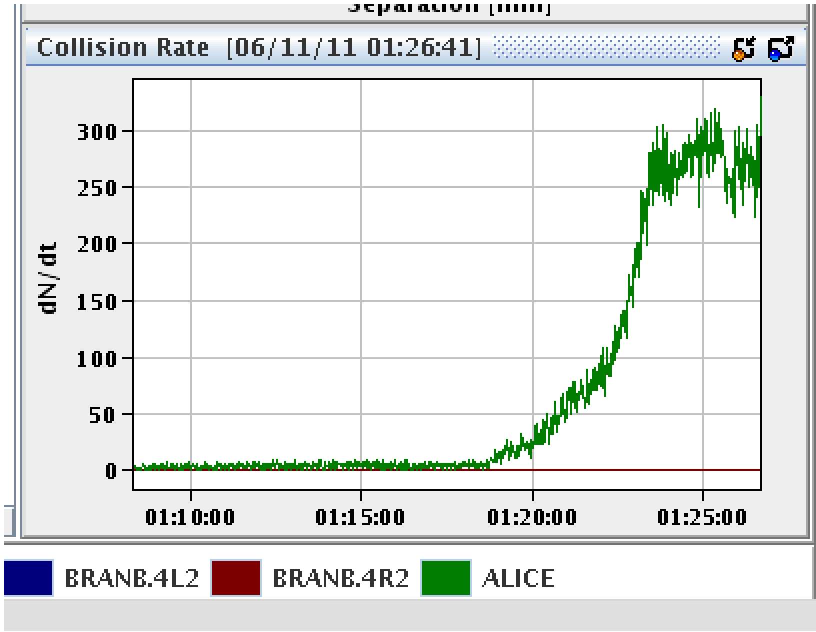
$\varepsilon_{nxy} \simeq (1.9,1.2)\ \mu m$ (Beam 2 Wire scanner)

N.B. Injected emittances are better

$\varepsilon_{nxy} \simeq (1.1,0.9)\ \mu m$

Collisions

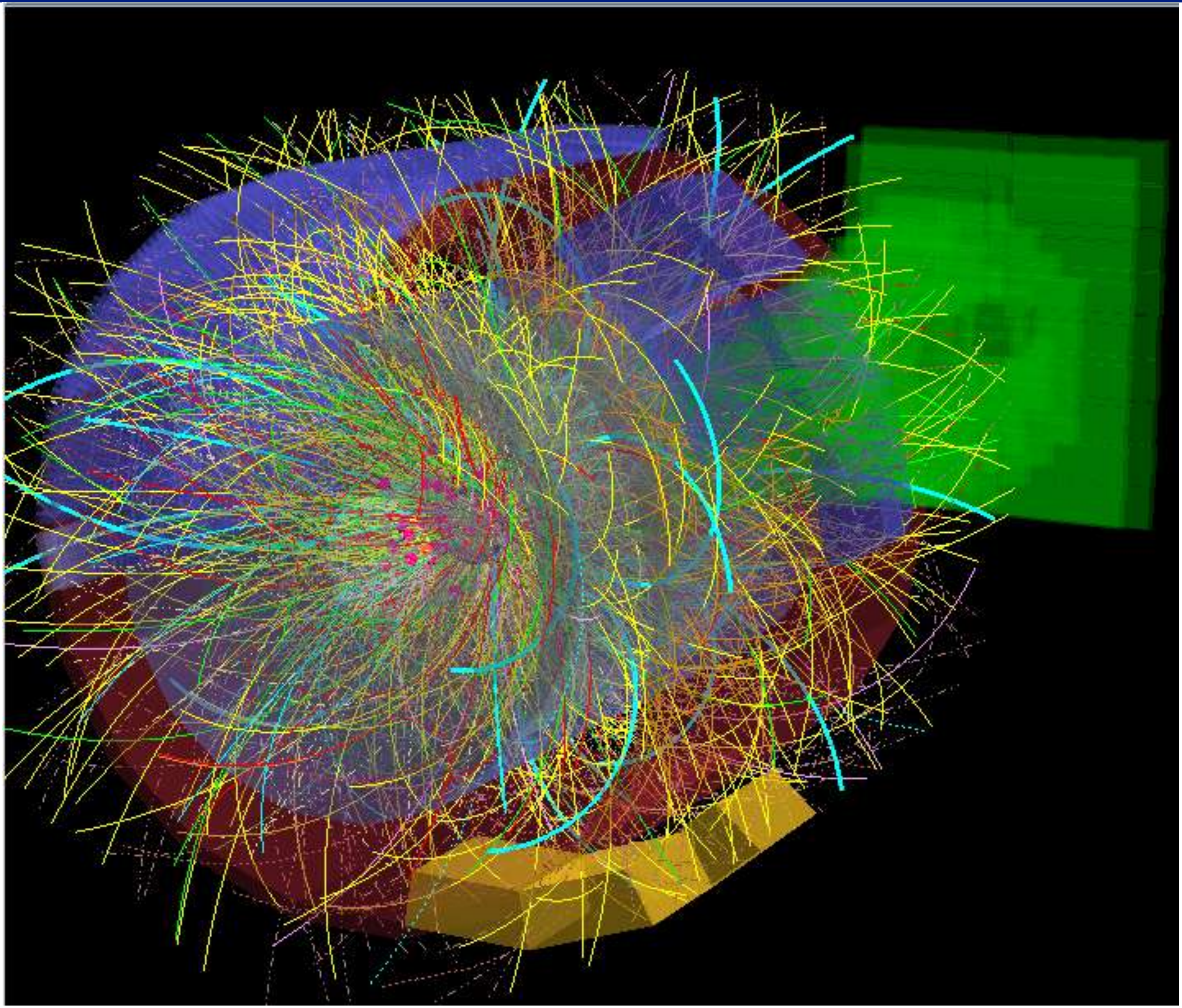
- Collisions found using neutrons in either side ALICE ZDC
  - Trims of several 100 µm
- Still using LUCID (ATLAS), HF (CMS) – lower rates
- TCTVs around ALICE fully opened
  - ZDC data OK so far (aperture worry …)



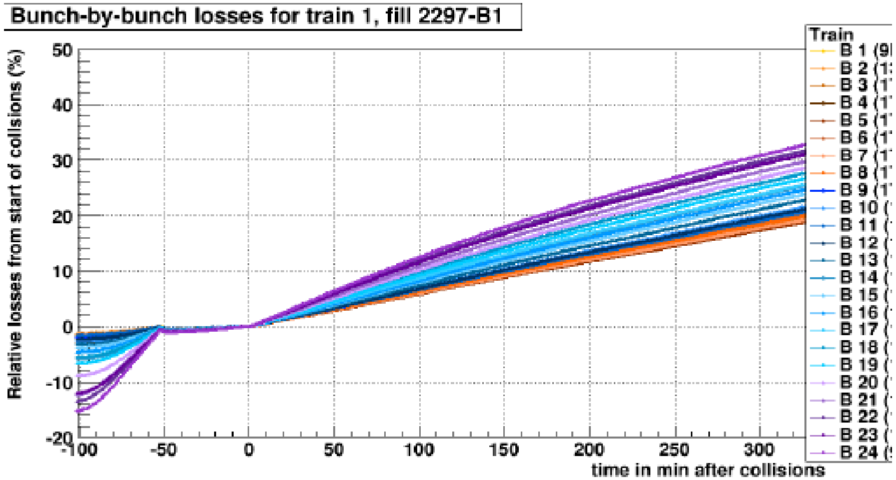
ALICE rates consistent with $L \sim 10^{24}$ cm^{-2}s^{-1} as expected for 1 bunch colliding

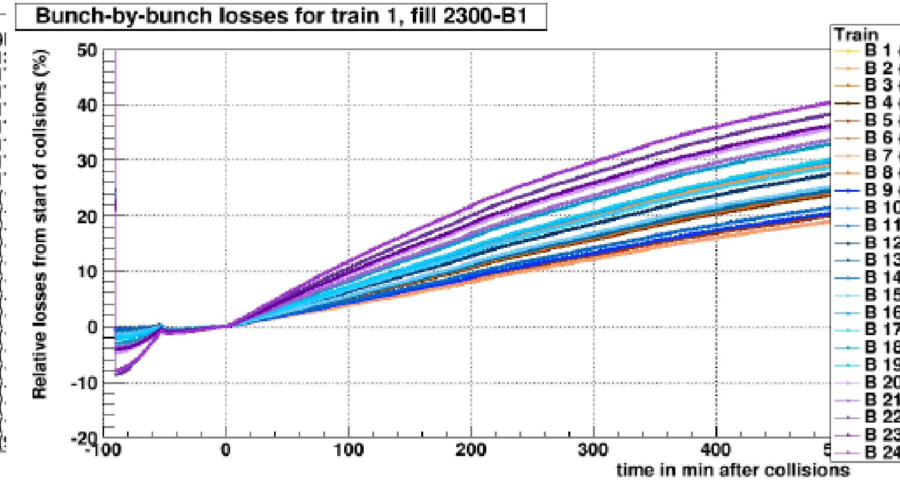
- Collisions for experiments (ADJUST mode) for 1 hour, then dumped, refilled

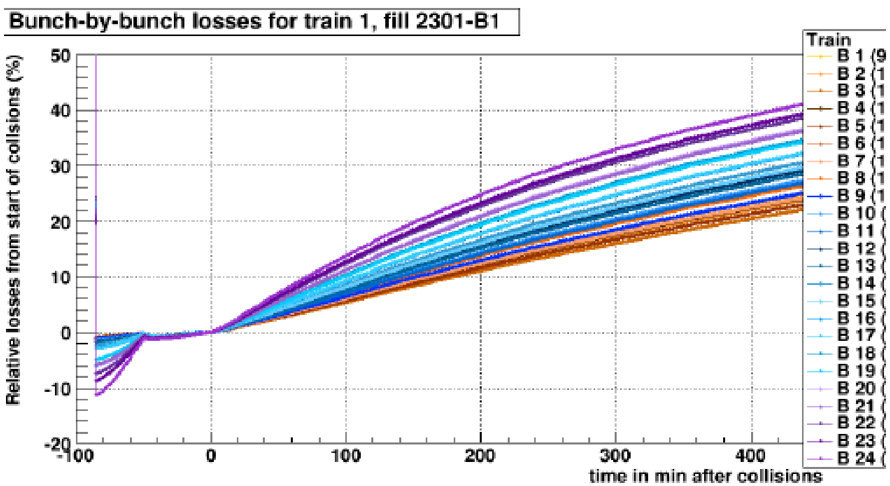
ALICE events

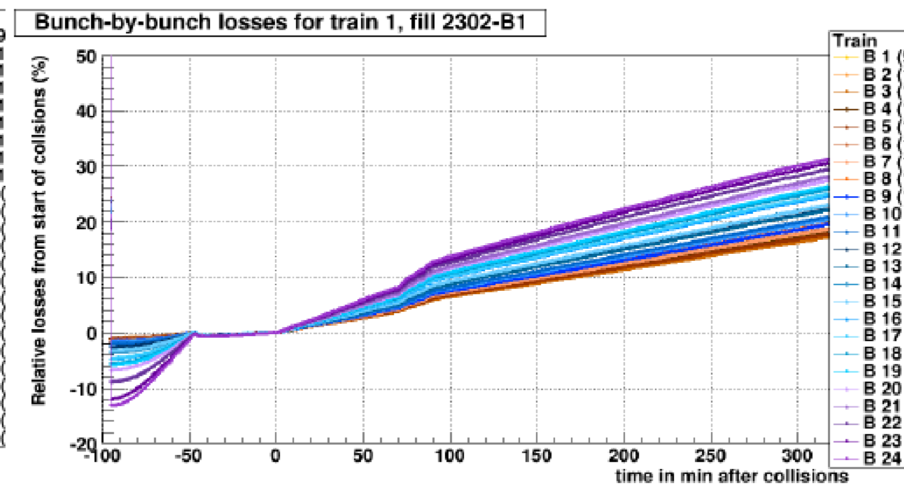


Losses B1



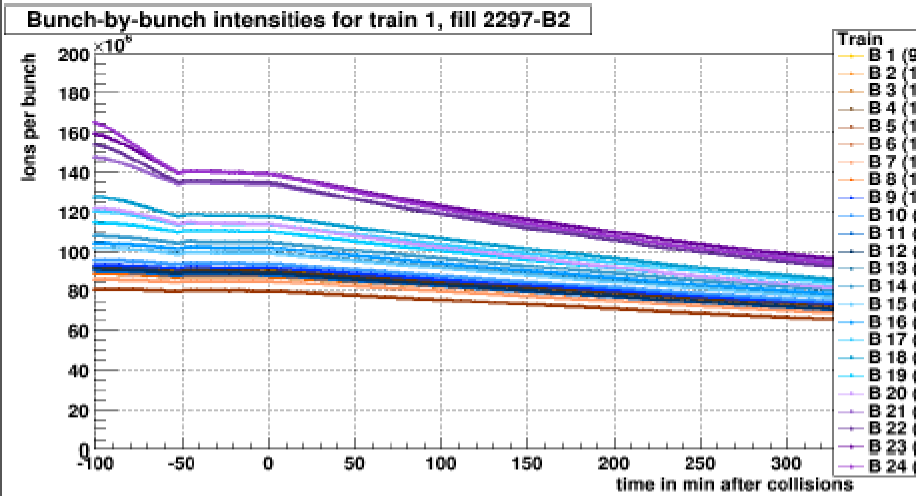


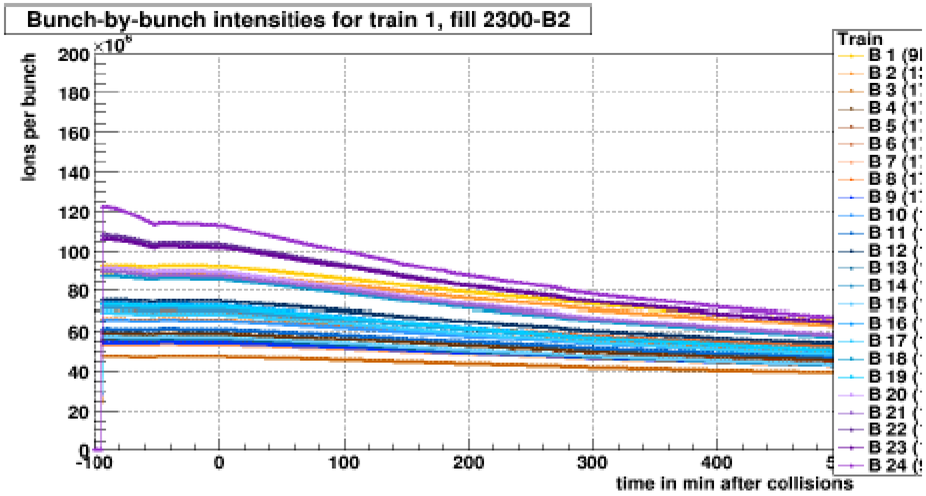


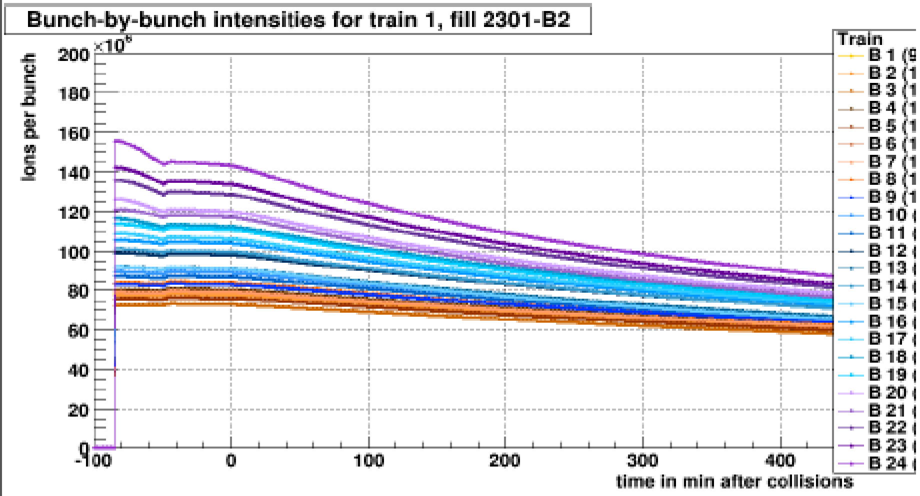


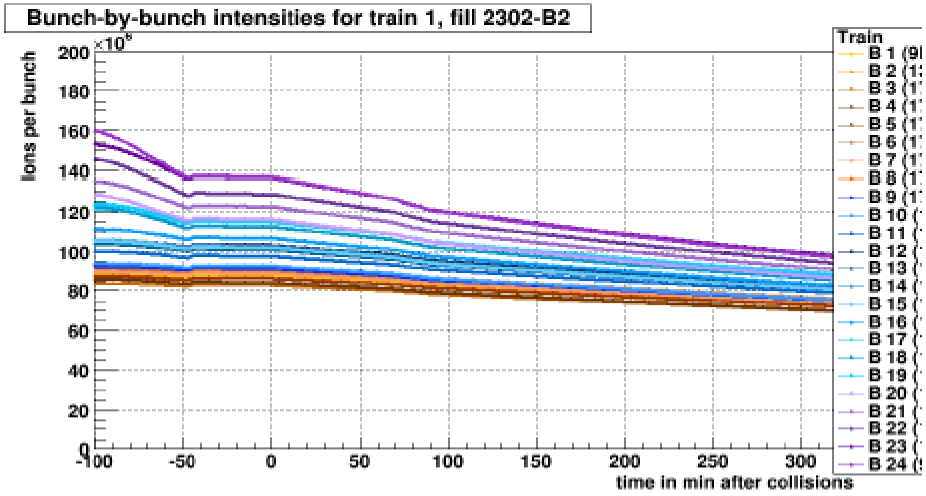
M. Schaumann

Intensity B2



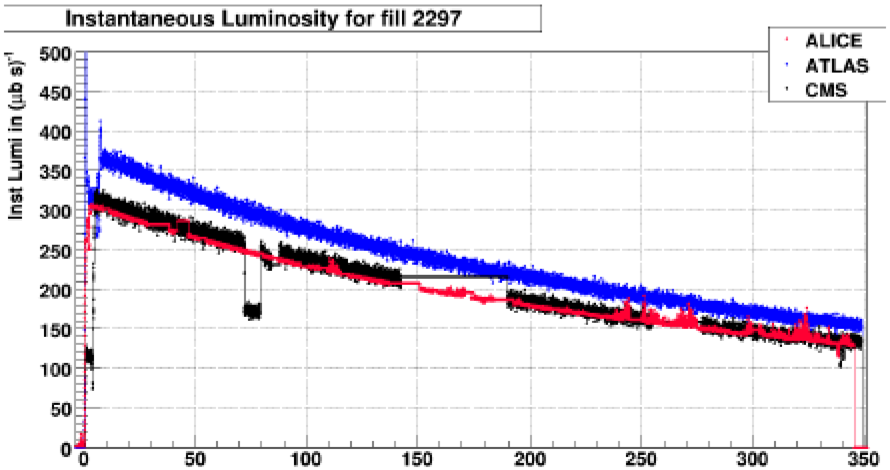


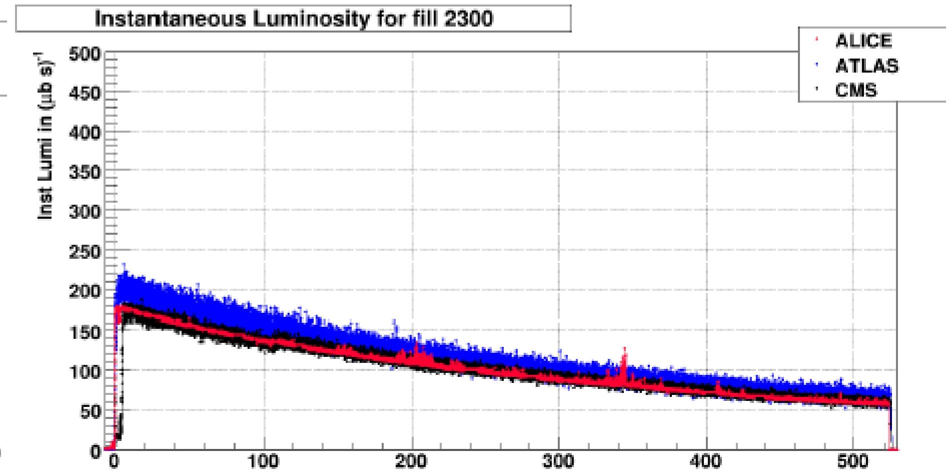


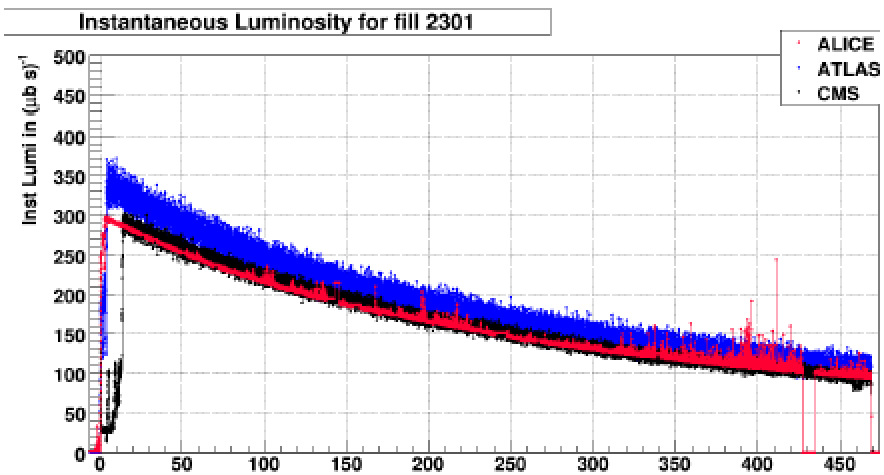


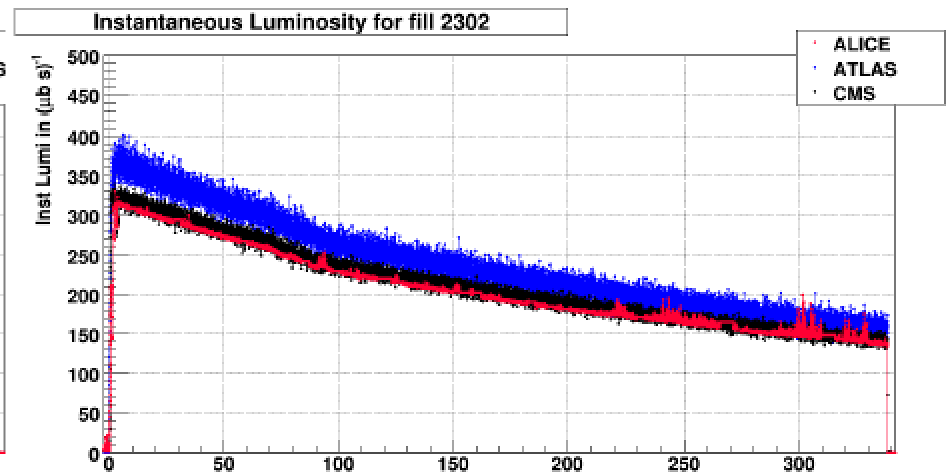
M. Schaumann

Instantaneous Luminosity







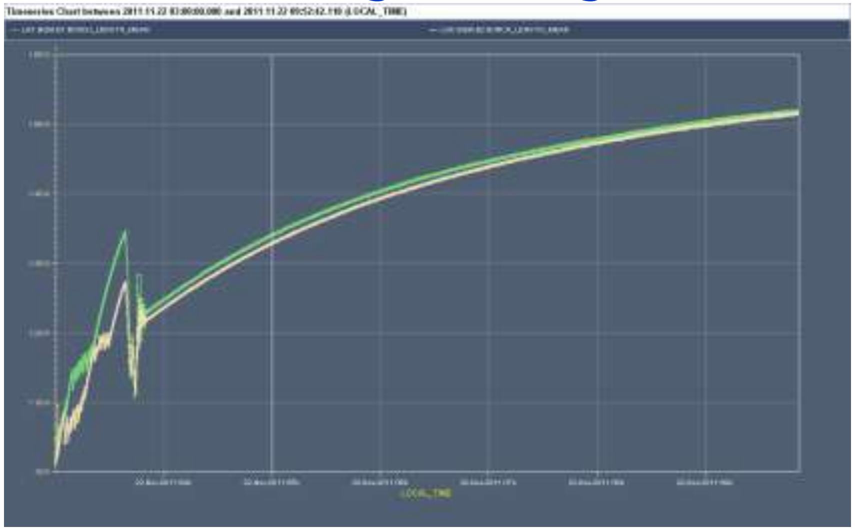


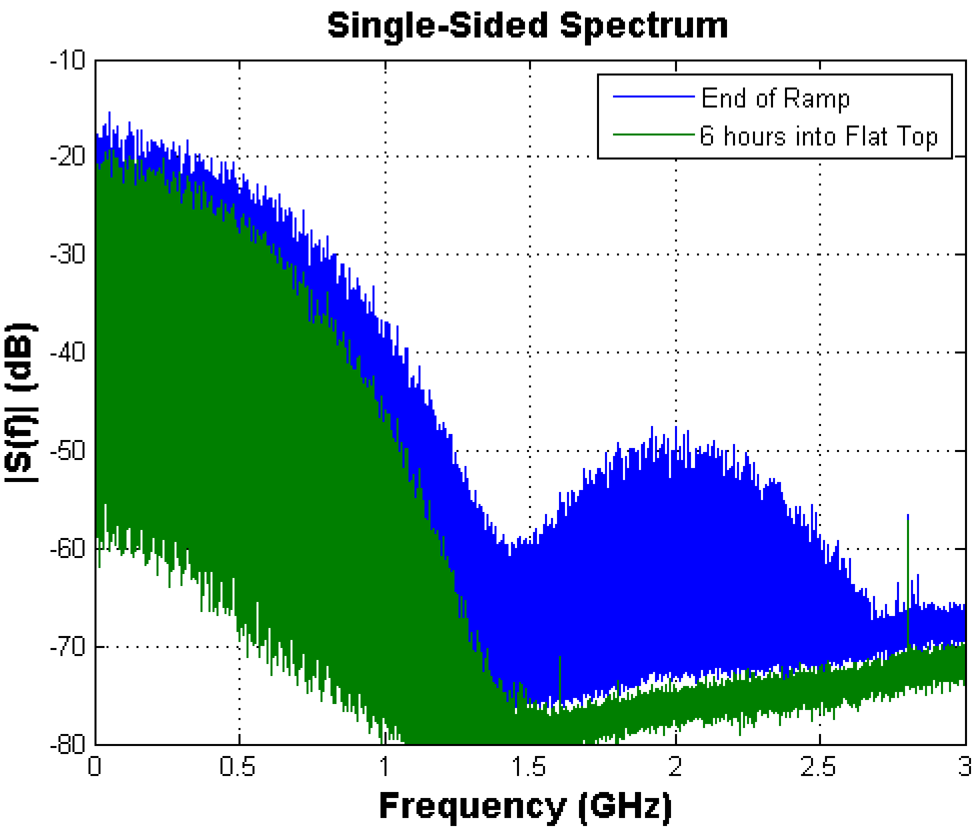
M. Schaumann

Bunch evolution in physics

P. Baudrenghien,
T. Mastoridis

Bunch-length during a fill



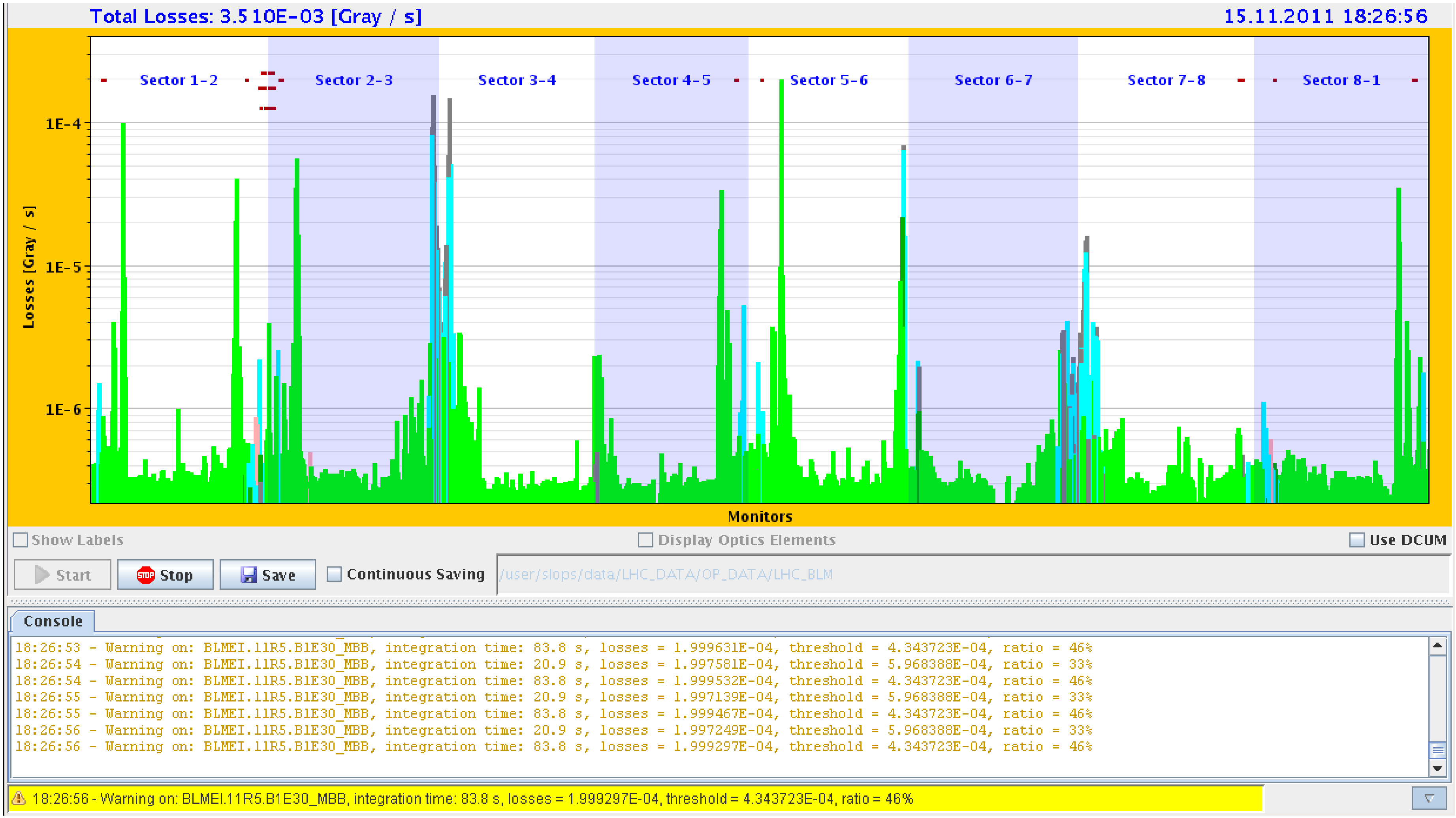


Water-bag-like distribution created by blow-up in ramp, transformed into gaussian-like distribution by IBS.

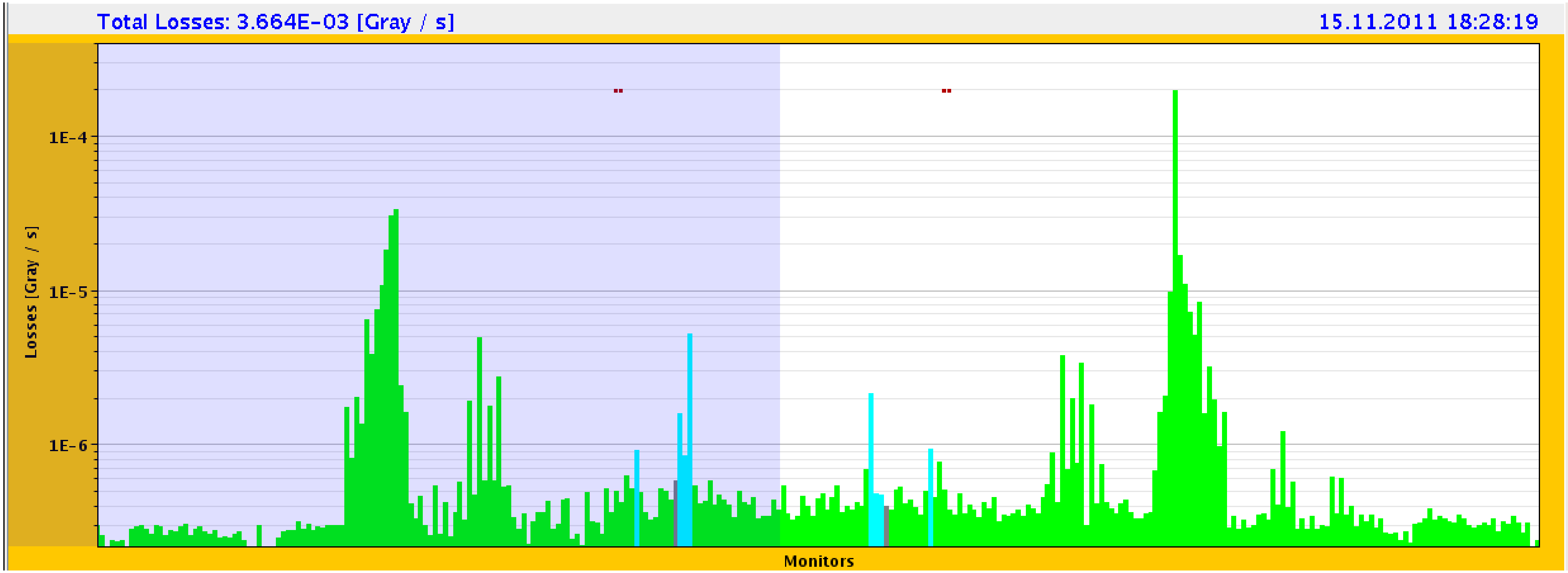
Gain is mainly at beginning.

Will be further measured and simulated.

Losses in Collision



Bound-free Pair Production in IR5

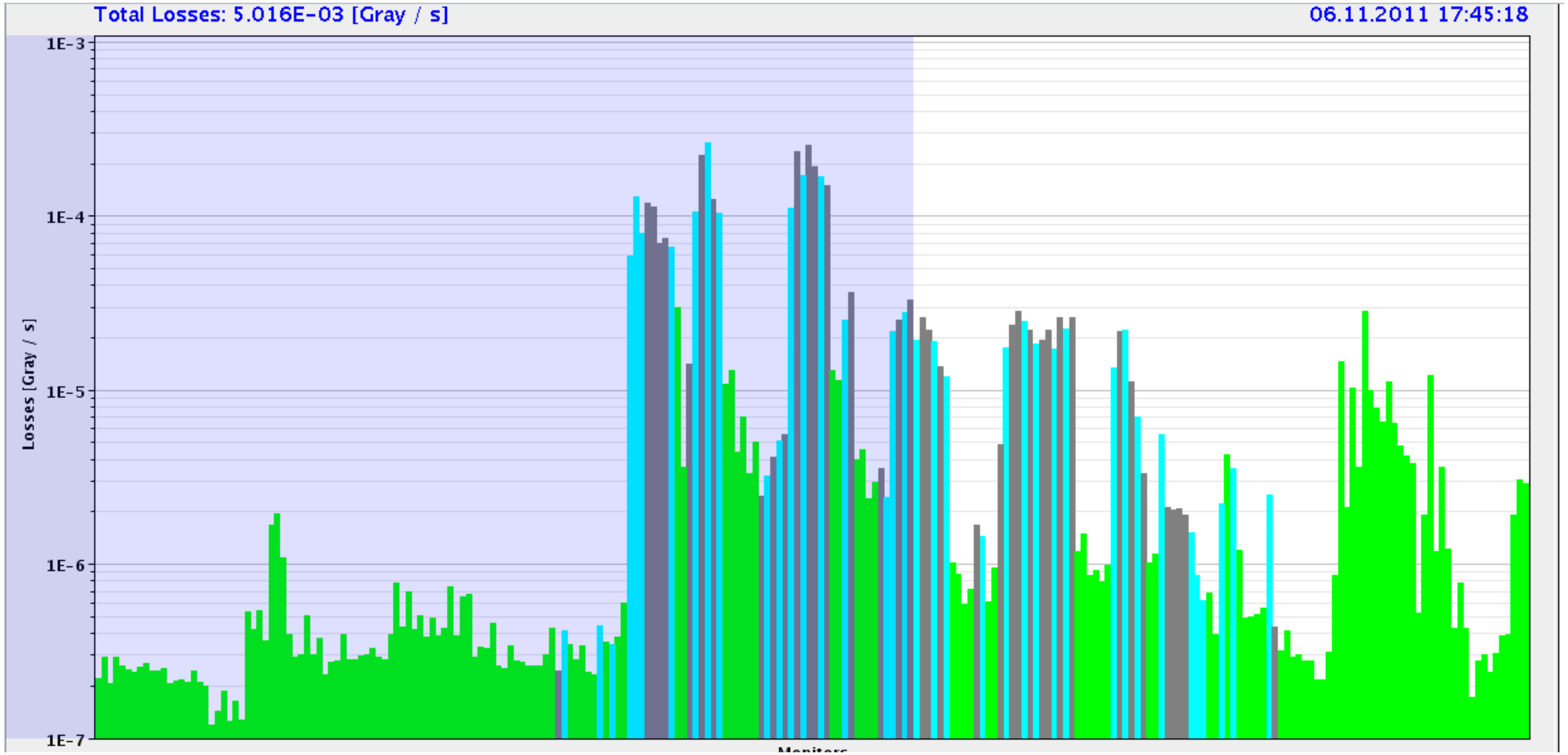


Special BLMs were installed in predicted locations, up to 36% of threshold on 170 bunch fill.

Thresholds have been doubled.

As predicted: see published papers for shower and quench limit studies.

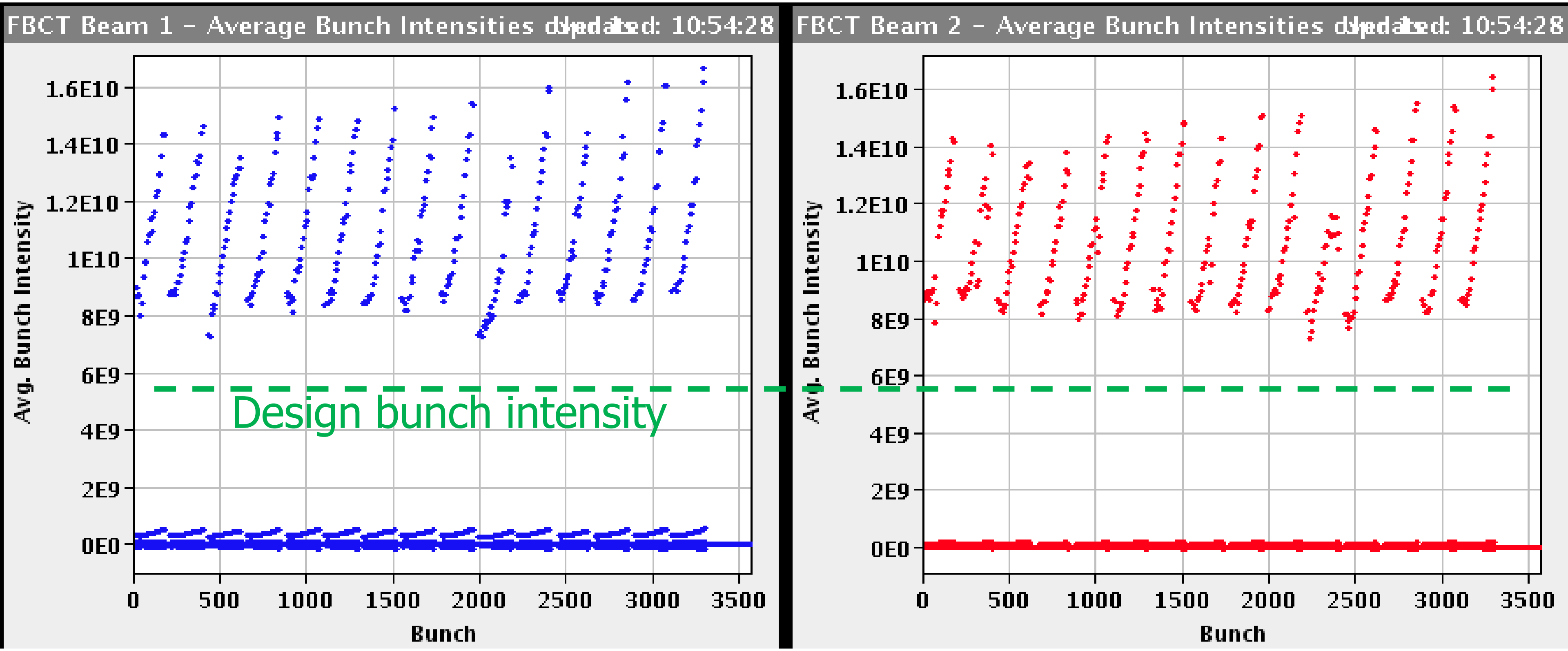
Pb ion collimation loss pattern



Expected high leakage to dispersion suppressor

All loss maps done, to be analysed.

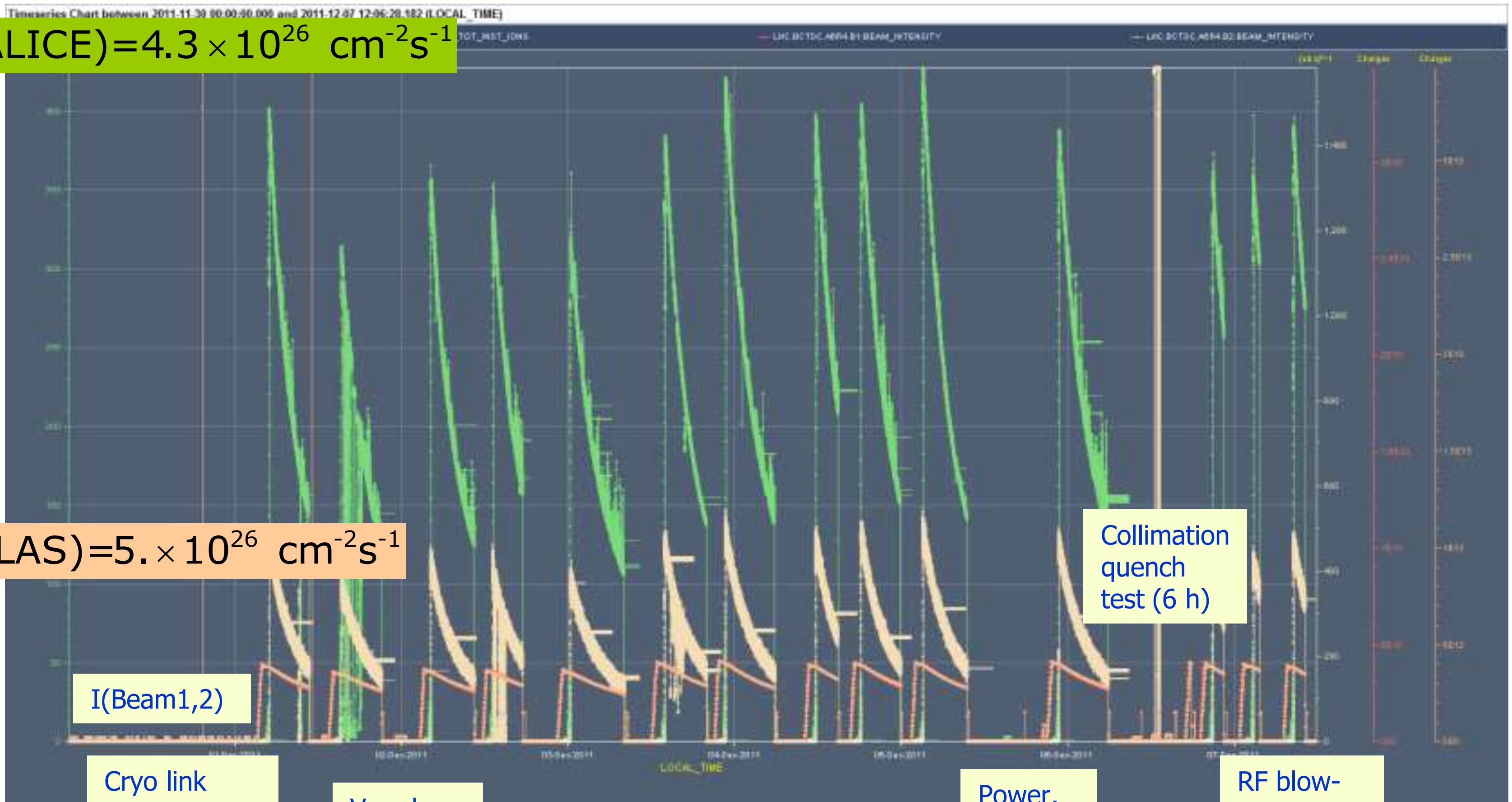
Typical bunch intensity distribution



Outstanding injector chain performance!

Intensity and luminosity ~final week

$L(\text{ALICE})=4.3\times 10^{26}\ \text{cm}^{-2}\text{s}^{-1}$



$L(\text{ATLAS})=5.\times 10^{26}\ \text{cm}^{-2}\text{s}^{-1}$

I(Beam1,2)

Collimation quench test (6 h)

Cryo link

Recovery

ELQA

Powering tests

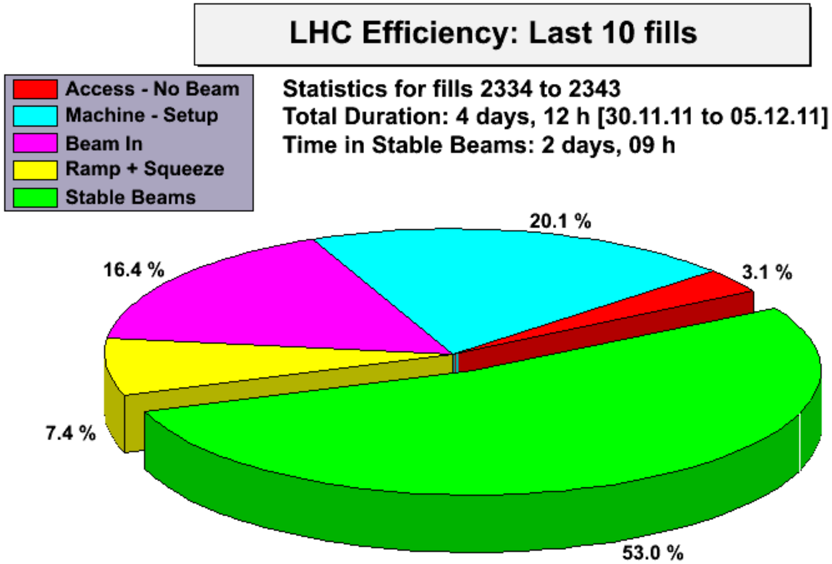
Van der Meer scans

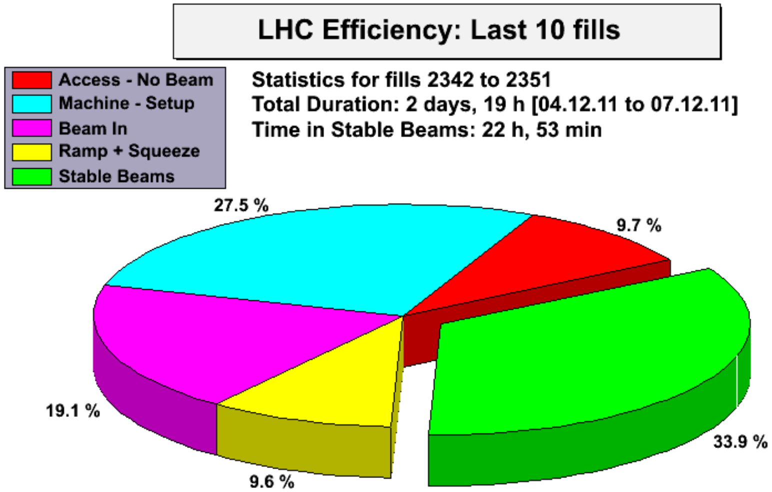
Power, cryo

RF blow-up tests

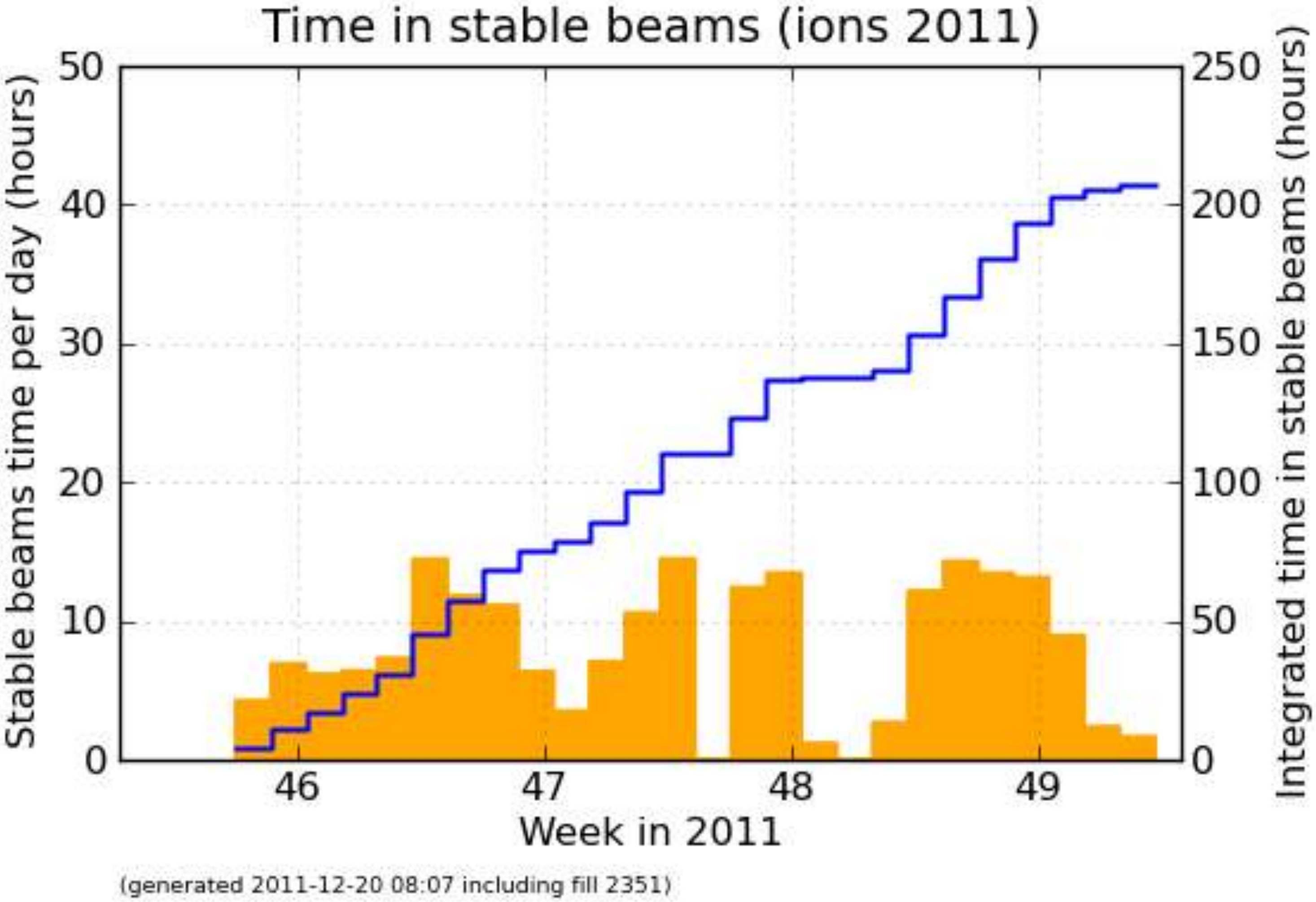
See morning meetings for more detail on down time

Operational efficiency

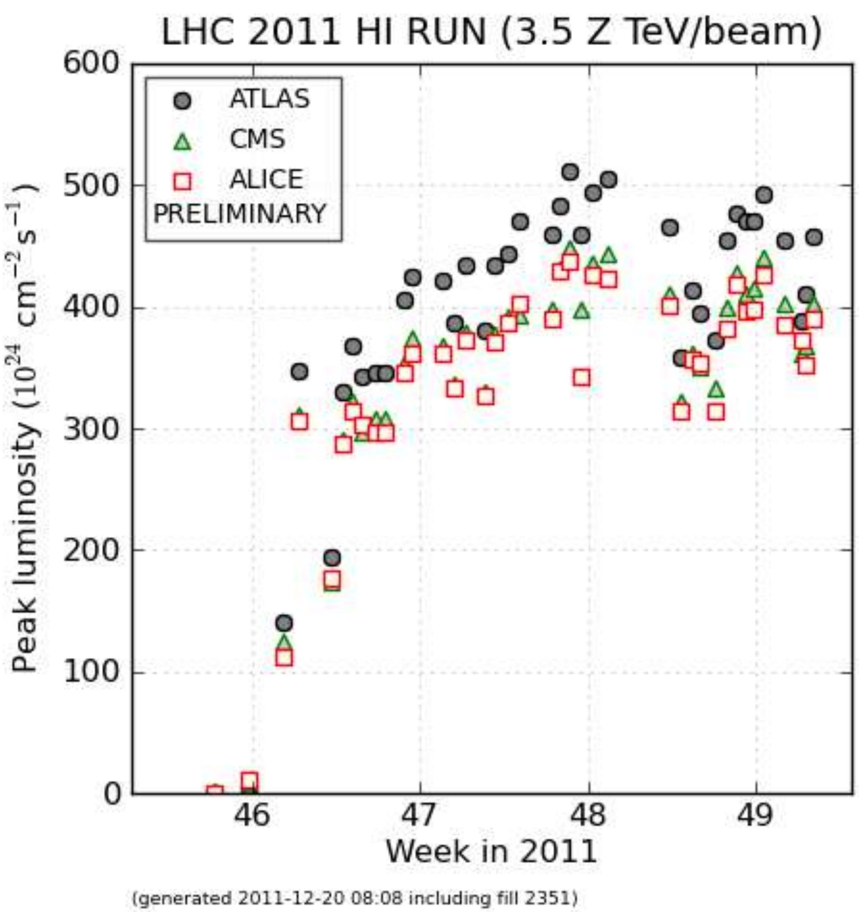


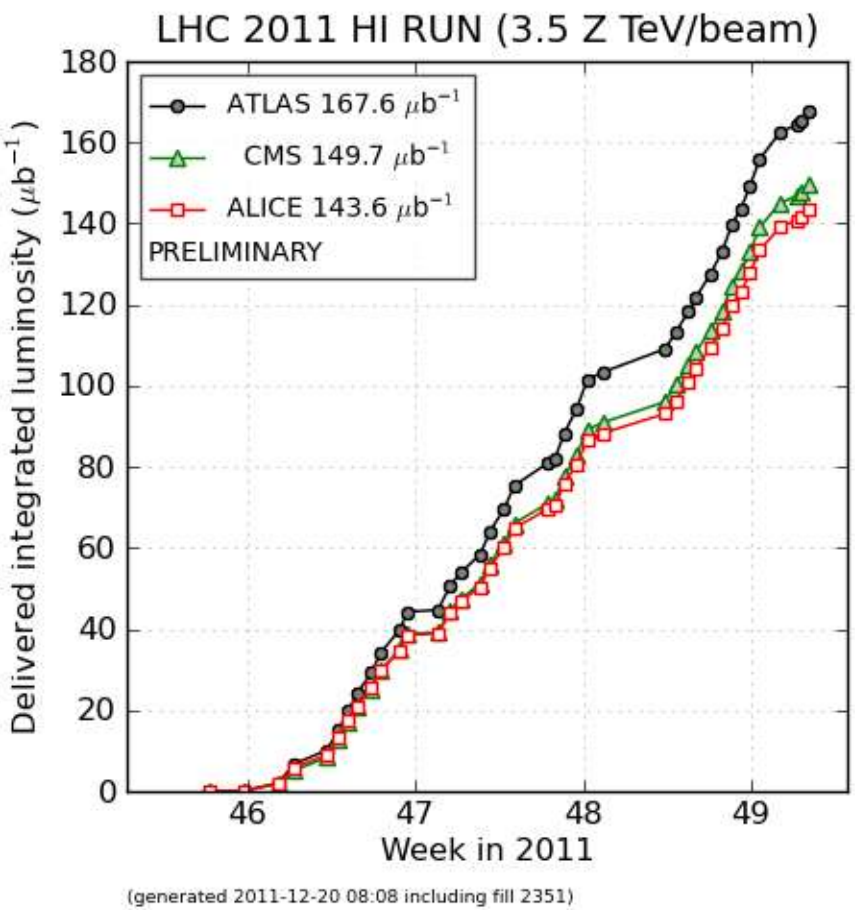


HI2011 Operational efficiency



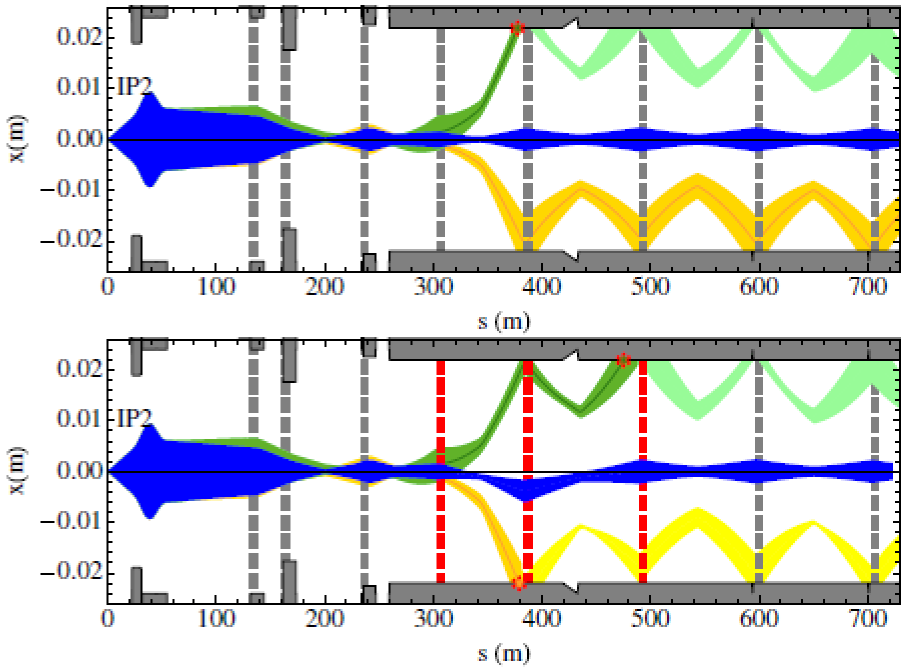
HI2011 final luminosity





BFPP alleviation

- Bump strategy studied a few years ago
  - R. Bruce et al, Phys. Rev. ST Accel. Beams 12, 071002 (2009)
  - Local bumps in DS, few mm amplitude
  - Aperture still OK at 3.5 Z TeV
  - Losses can be spread out or distributed over two loss points
  - Should be able to see changes of loss peaks in BLMs



6σ envelopes at 7 Z TeV

Could be done as end-of-fill

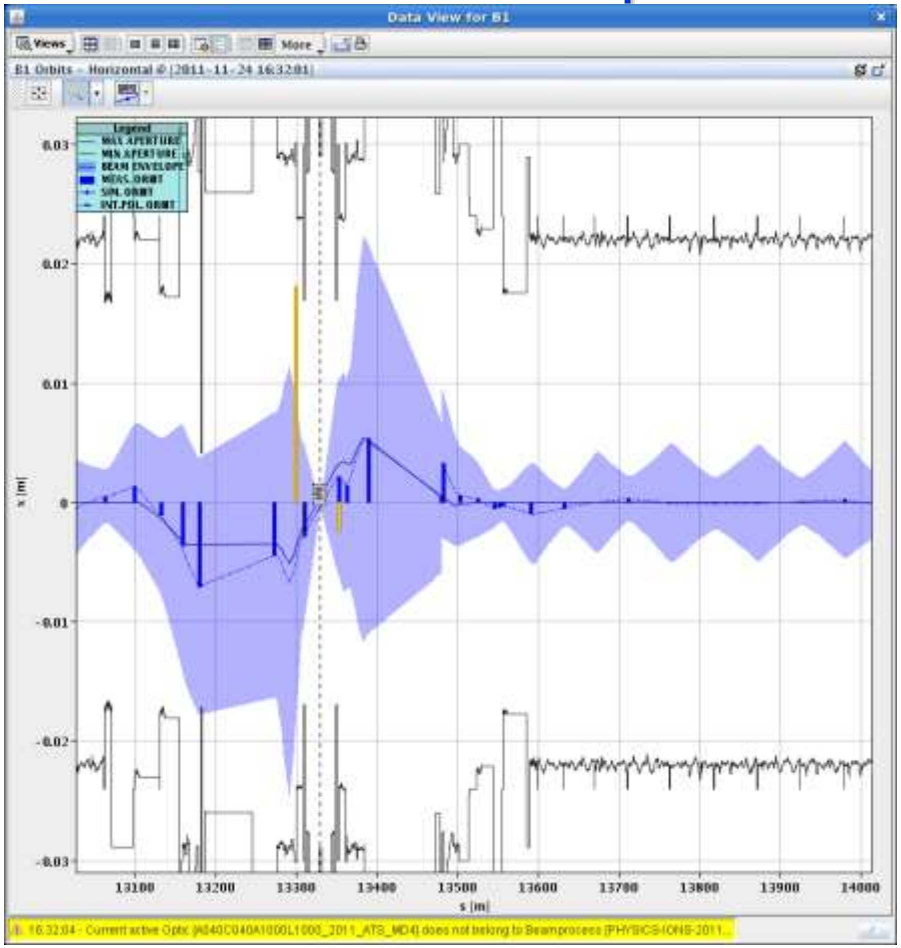
MD conditions

- Opportunity after polarity reversal test
  - No injection
- Clearance from rMPP obtained by ‘phone and email
  - Formal document in preparation
- JW implemented bump at worst loss spot (Beam 1, right of CMS)
  - Bump applied in steps of -0.2 mm up to an imposed limit of -2.6 mm (could have gone further …)

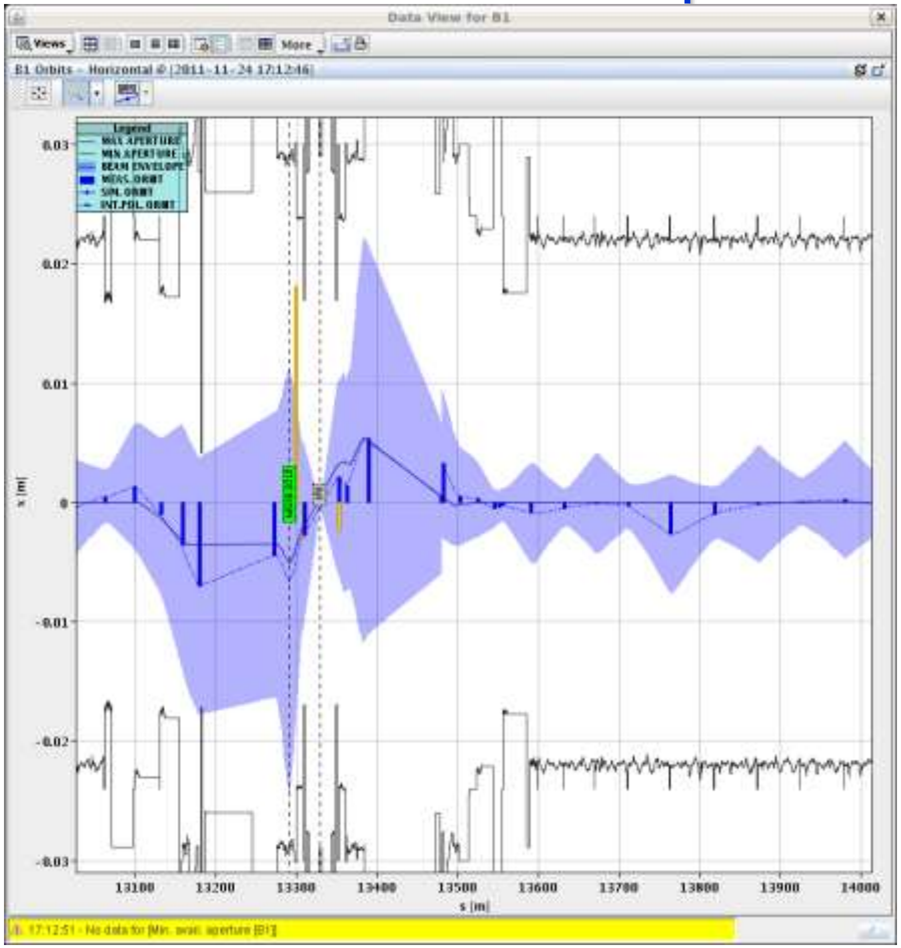
Orbit bump: -2.6 mm at Q11.R5.B1 in steps

12 sigma envelopes from online model

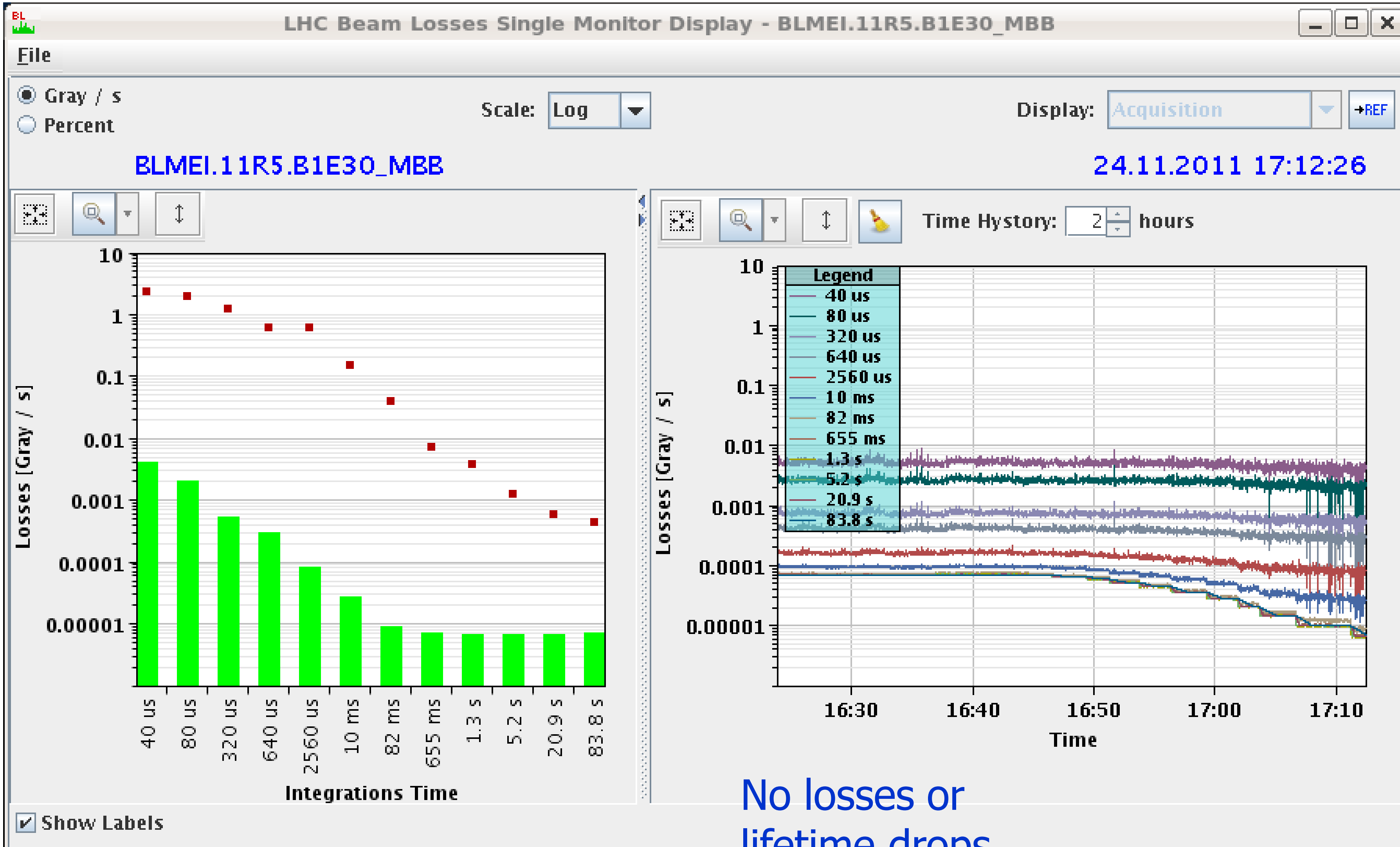
without bump



with bump

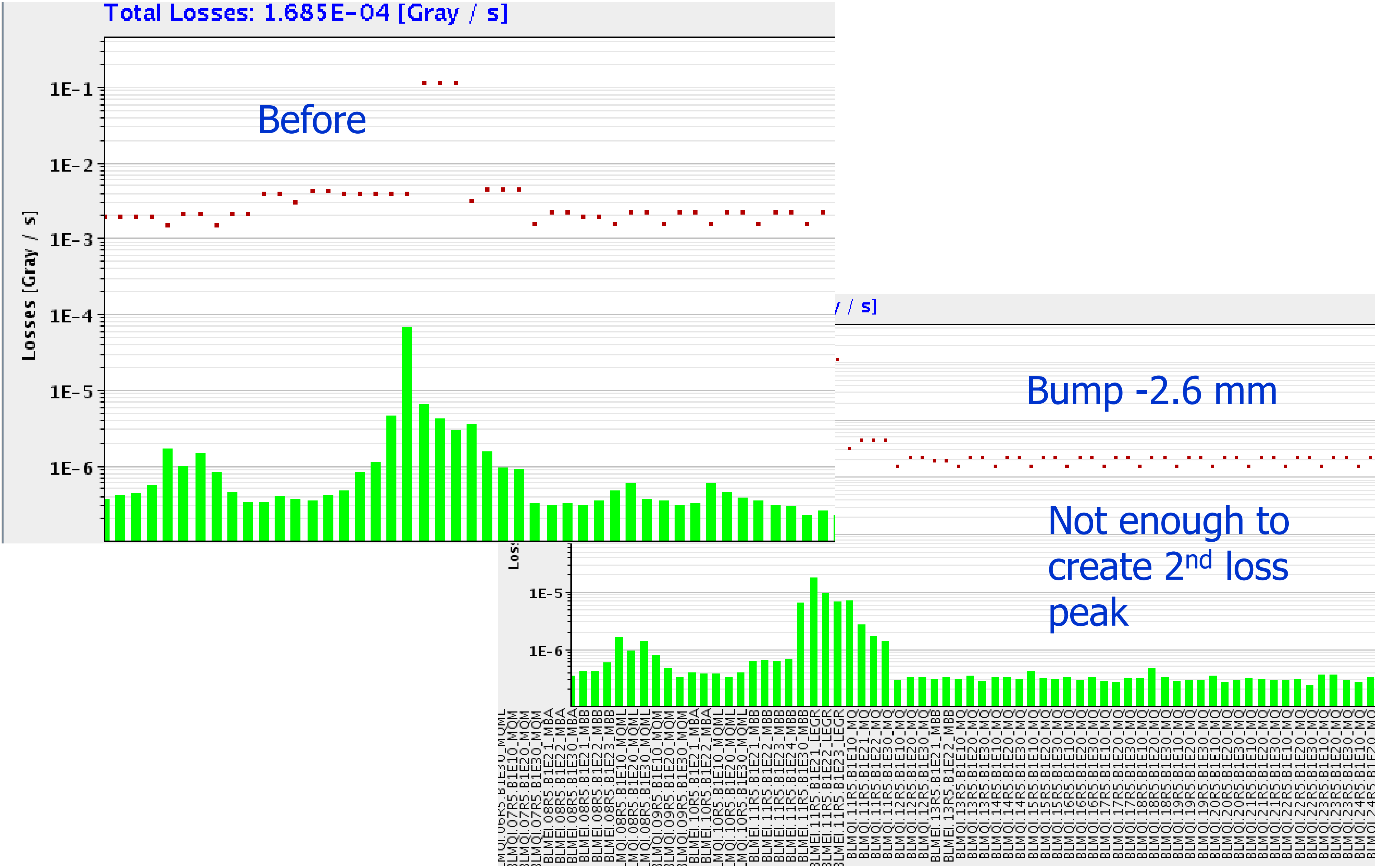


Effect on losses



No losses or lifetime drops

Effect on loss pattern



Before

Bump -2.6 mm

Not enough to create 2nd loss peak

Logbook summary

BFPP ALLEVIATION STUDY

As this unexpected opportunity arose before rMPP approval had been given, we cleared it by phone and email.

We tried to apply the procedure described in Section IX or PRSTAB 12, 071002 (2009) to the highest BFPP loss peak from Beam 1 right of CMS.

A 3 magnet bump of the horizontal orbit was set up and used to displace the closed orbit inwards at the Q11 in order to reduce the flux and the angle of incidence of the secondary Pb81+ beam from thje IP on the chamber. We observed a reduction of the highest BLM peak at the Q11 by a factor approaching 5. Signals in nearby BLMs increased somewhat, consistent with the spreading of the loss spot due to the larger angle of incidence. The amplitude of the bump was limited to -2.6 mm for machine protection reasons. This was insufficient to create a second loss spot at the Q13. Putting the bump back to zero did slightly increase the loss there but further analysis is necessary for a detailed interpretation.

6/12/2011 – quench test on physics time

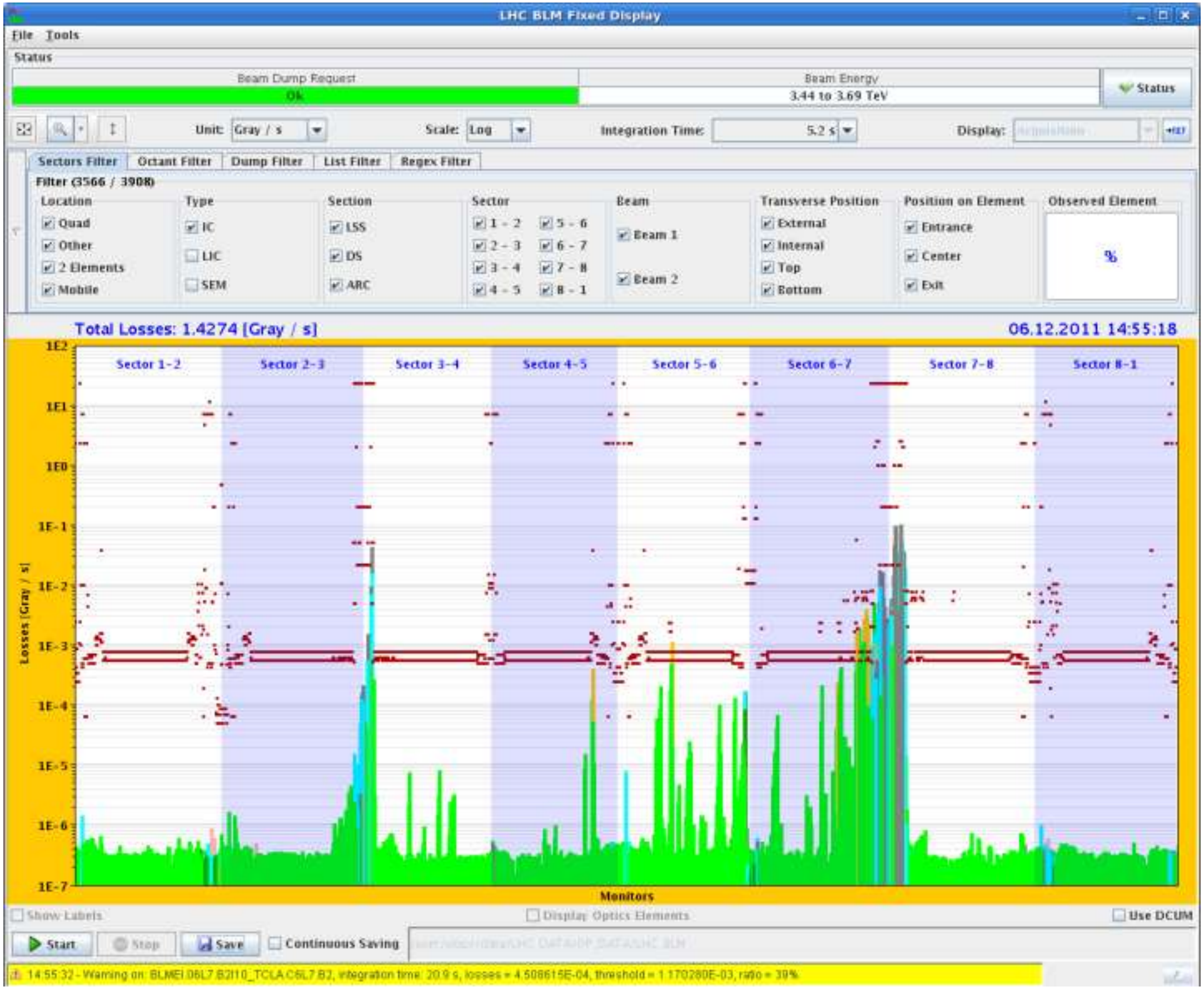
- Motivation: create enhanced losses by driving beam onto collimators to try to find level at which DS bending magnets quench
- 09:00 – 15:30 : quench test – 3 attempts – no quench.
- Attempt no.1:
  - 1.8×10^{11} charges / beam, ~20 bunches.
  - Rapid 1/3 order resonance crossing beam2 H plane. Beam dump on BLM thresholds.
  - Loss on **10 ms** int. window of monitor BLMQI.09L7.B2I10_MQ. This monitor had its master thresholds increased RS > 80 ms.
- Attempt no. 2:
  - Reverted to initial master threshold on BLMQI.09L7.B2I10_MQ (and another monitor), but set MF to 1.
  - 3.4×10^{11} charges / beam, ~37 bunches.
  - Rapid 1/3 order resonance crossing beam2 H plane. Beam dump on BLM thresholds at Q19 (not modified) on **82 ms** RS.

Quench test (continued)

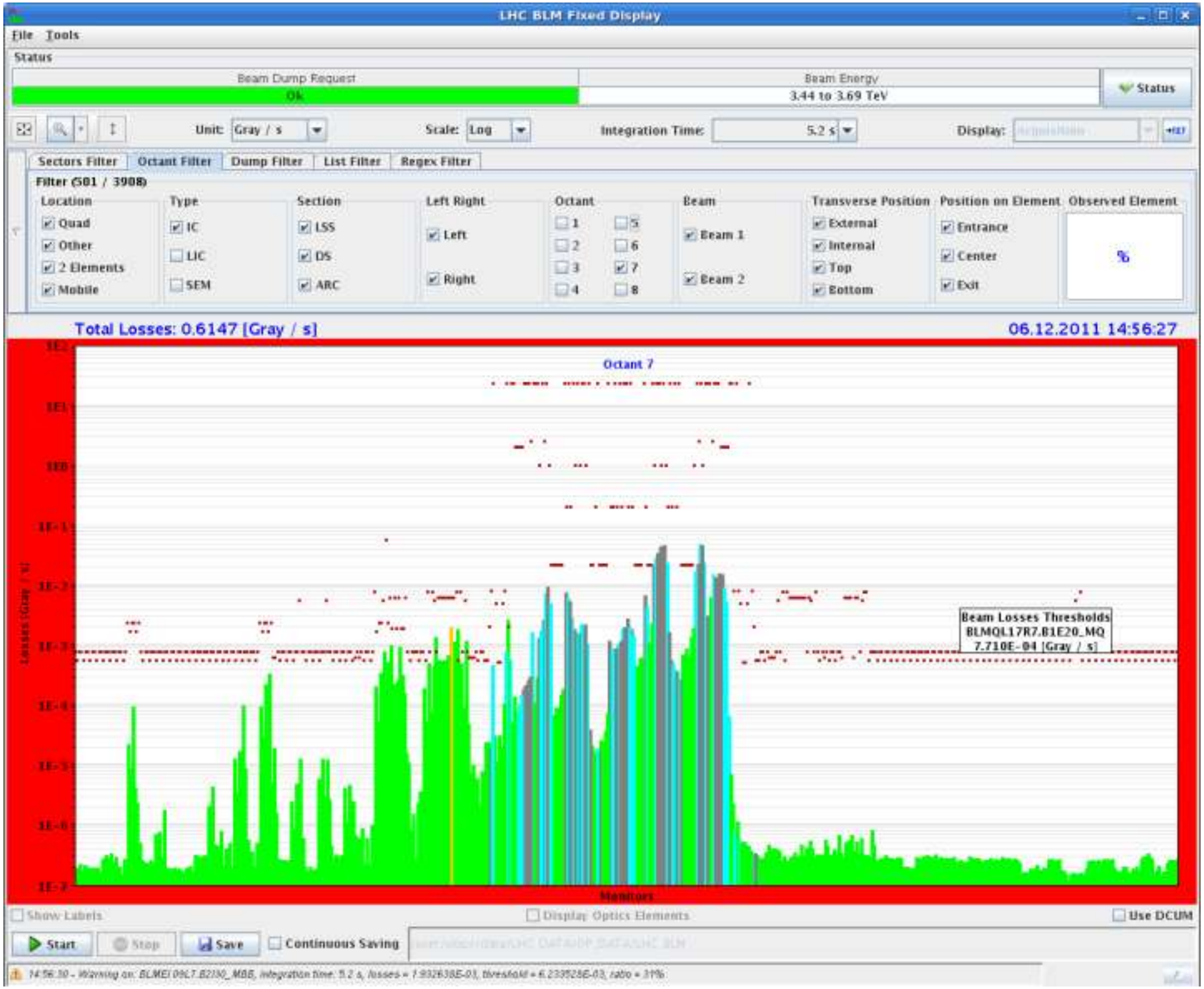
- Attempt no. 3:
  - MF set to 0.3 for 26 arc monitors (cells 11L7, 19L7, 29L7, 24R5).
  - 3.2×10^{11} charges / beam, ~37 bunches. RF M1B2 tripped.
  - Slow resonance approach on for B2 H. Lost most of the beam, but no dump.
  - B1H dumped on BLMs during fast resonance crossing.

- Comments:
  - No quench during all these exercises.
  - For fill3, beam2 shortly lost the cryo start in the matching section 67 due to increased temperature (2.7K from 1.9K) in the missing dipole. Limit is 2.15K.
  - Otherwise cryo temperature increase at the 20mK level at the Q9.

Attempt no. 3 – slow crossing B2H

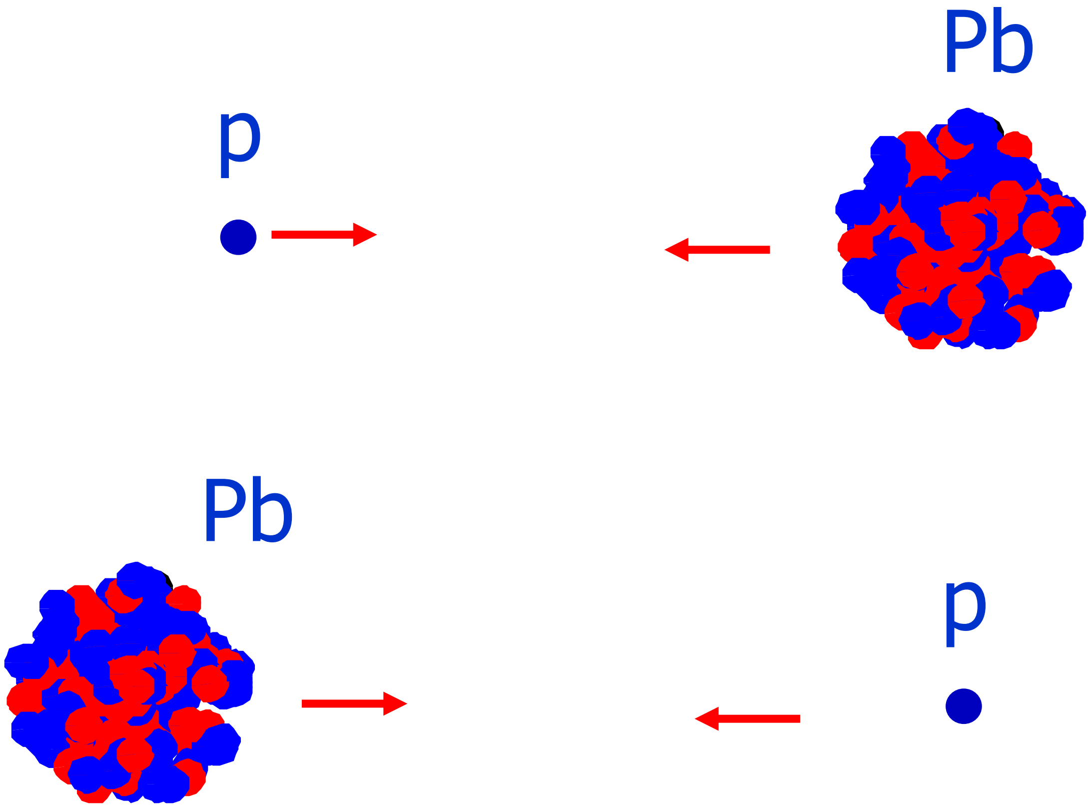


Attempt no. 3 – slow crossing B2H



Quench test summary

Test	Beam	Loss rate	Dump Location	Dump RS	Dump/ Quench limit
Fast	2	2×10^{10}/75 ms	Q9	10 ms	~1.5
Fast	2	2.5×10^{10}/100 ms	Q19	82 ms	~2
Slow	2	5.4×10^{10}/ s	Q9	-	~1
Fast	1	2.7×10^{10}/500 ms	Q11	82 ms	To be analyzed



THE LHC AS A PROTON-NUCLEUS COLLIDER

The physics potential of proton-nucleus collisions at the TeV scale

Carlos A. Salgado
Universidade de Santiago de Compostela

Quark Matter 2011 - Annecy

Partly based on: *Proton-nucleus collisions at the LHC: scientific opportunities and requirements*
arXiv:1105.3919

carlos.salgado@usc.es http://cern.ch/csalgado

Link to plenary talk

Summary

- ***Proton-nucleus essential for benchmarking***
  - Hard processes
  - Bulk particle production
- ***Nuclear PDFs badly constrained at small-x***
  - pA only possibility to reduce uncertainties
  - Very standard technology but data needed
- ***Saturation of partonic densities***
  - pA provide excellent opportunities
  - (only chance before ep/eA collider)
- ***More opportunities***
  - High-multiplicity events
  - Ultraperipheral collisions
  - Measurements of astrophysical interest

Before Jan 2011: Vox clamantis in deserto

- Not part of "LHC Baseline" … no resources.
- CERN Workshop in 2005 (link)
  - Physics case, experiments' performance, …
  - Reviewed RHIC experience with d-Au in 2002-3 (T. Satogata)
  - Schemes for LHC injector operation (C. Carli)
  - LHC operation, beam dynamics concern identified (JMJ)
  - Executive summary of accelerator part (in 2011 report)
- LHC Project Report 928 (= paper at EPAC 2006)
- Key systems groups kept aware meanwhile
  - Eyes open for any showstoppers
- Requested by ALICE for 2012
  - First Pb-Pb run successful. If not 2012 then would otherwise be much later because of shutdown schedule, energy increase.
  - Discussion at Chamonix workshop, Jan 2011.
  - ATLAS and CMS heavy-ion groups
  - Some resources now available:
    - OP, RF, BI, … collaborating on implementation and operation
    - Fellow to work on beam dynamics in ABP arrived … today

CERN-PH-TH/2011-119
LHC-Project-Report-1181

Proton-Nucleus Collisions at the LHC: Scientific Opportunities and Requirements

http://arxiv.org/abs/arXiv:1105.3919

Editor: *C. A. Salgado*[1]
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Abstract
Proton-nucleus (p+A) collisions have long been recognized as a crucial component of the physics programme with nuclear beams at high energies, in particular for their reference role to interpret and understand nucleus-nucleus data as well as for their potential to elucidate the partonic structure of matter at low parton fractional momenta (small-x). Here, we summarize the main motivations that make a proton-nucleus run a decisive ingredient for a successful heavy-ion programme at the Large Hadron Collider (LHC) and we present unique scientific opportunities arising from these collisions. We also review the status of ongoing discussions about operation plans for the p+A mode at the LHC.

Relation between Beam Momenta

- LHC accelerates protons through the momentum range

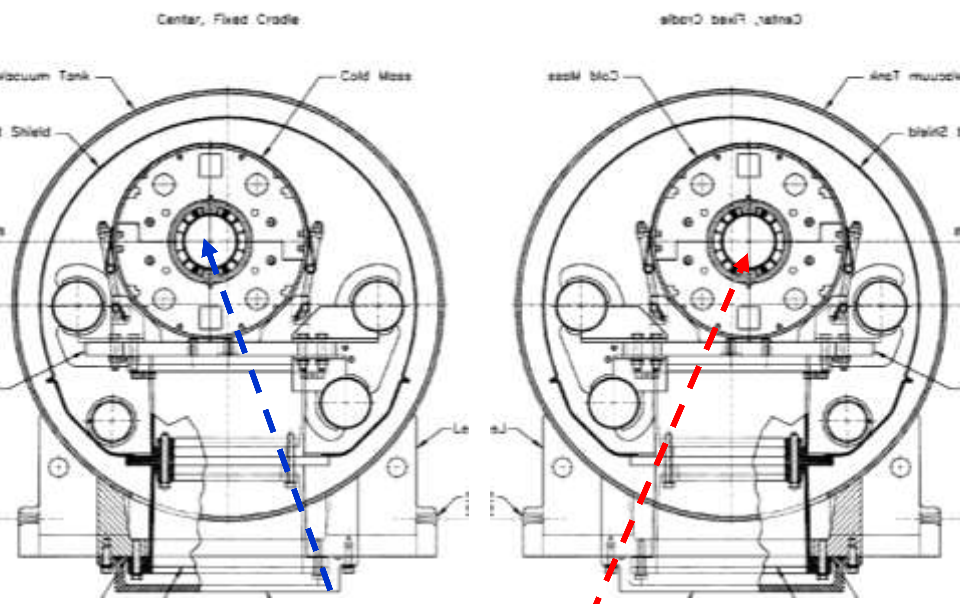
$$0.45\ \text{TeV (injection from SPS)} \leq p_p \leq 7\ \text{TeV (collision)}$$

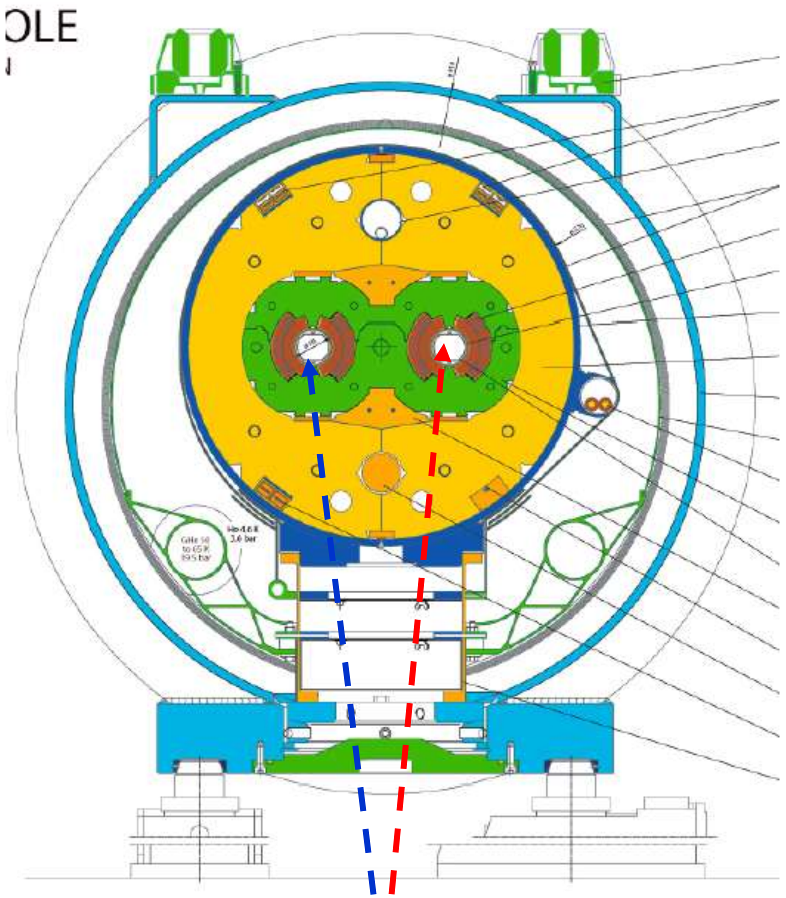
  - Use this as reference, measure of magnetic field in main bending magnets
- The two-in-one magnet design of the LHC (unlike RHIC) fixes the relation between momenta of beams in the two rings

$$\frac{p_{\text{Pb}}}{Z} = p_{\text{p}}$$

where $Q = Z = 82,\ A = 208$ for fully stripped Pb in LHC

Critical difference between RHIC and LHC





RHIC: Independent bending field for the two beams

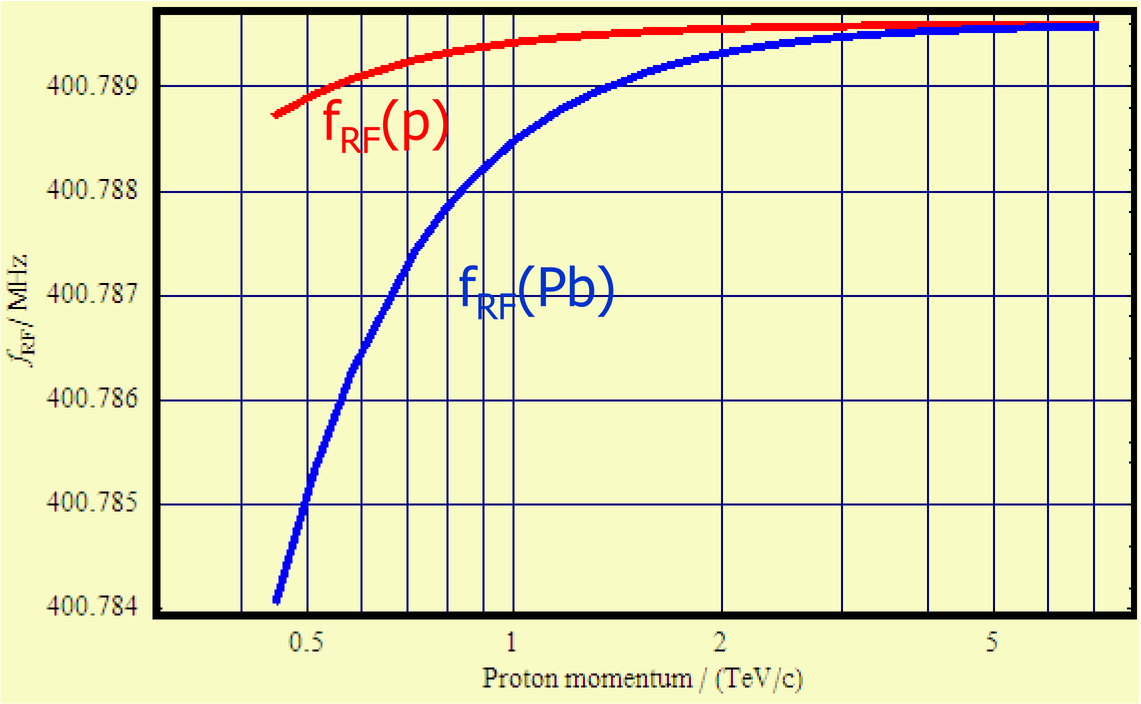
LHC: Identical bending field in both apertures of two-in-one dipole

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.

Which is Beam 1 and which is Beam 2 ?

- Initial preference for ALICE spectrometer asymmetry:

  Beam 1=p, Beam 2=Pb

- Assume this for definiteness in rest of this talk.

- But switching of the beams between the two rings **is important and requested**
  - Clearly equally feasible, just some setup time

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

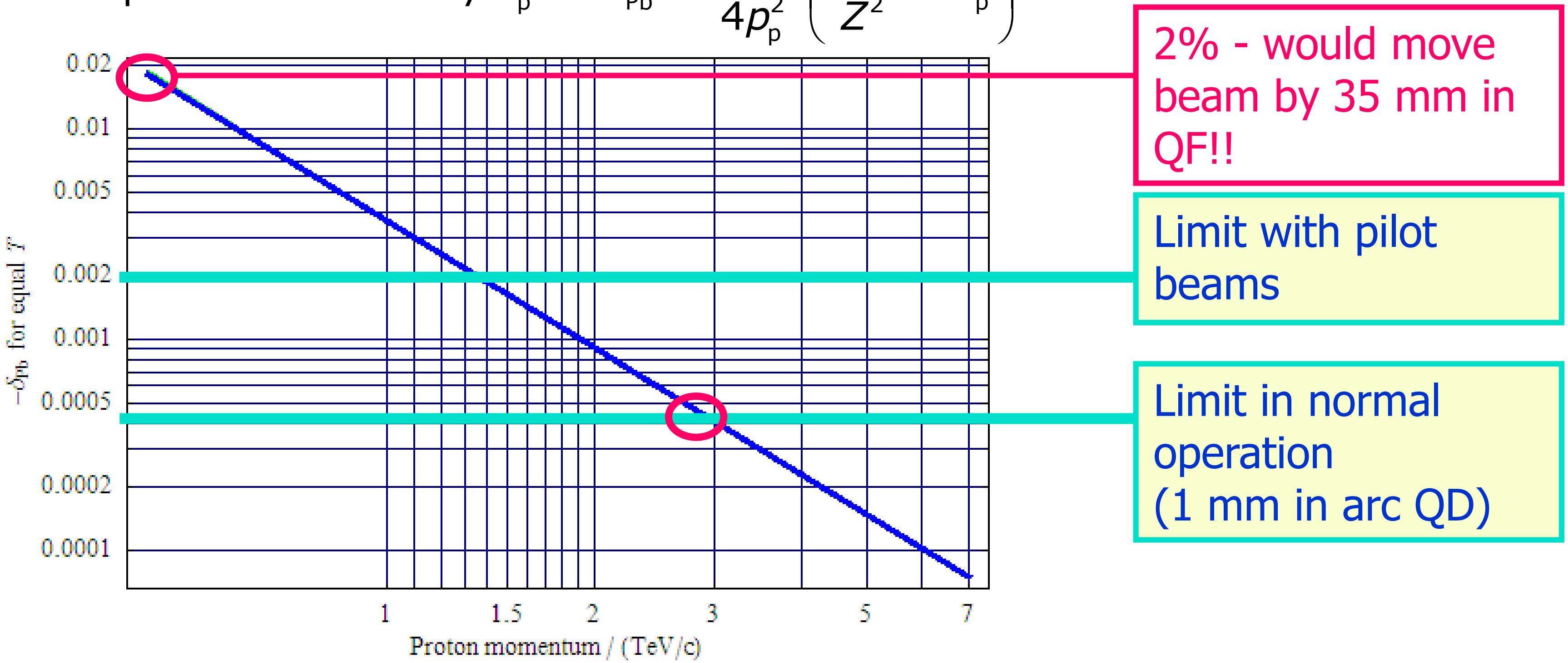
the phase-slip factor $\eta = \dfrac{1}{{\gamma_T}^2} - \dfrac{1}{\gamma^2}$, $\quad \gamma = \sqrt{1+\left(\dfrac{Qp_{\mathrm{p}}}{mc}\right)^2}$, $\quad \gamma_T = 55.8$ for LHC optics.

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 $\delta_{\mathrm{p}} = -\delta_{\mathrm{Pb}} = \frac{c^2 \gamma_T{}^2}{4 p_{\mathrm{p}}^2} \left(\frac{m_{\mathrm{Pb}}^2}{Z^2} - m_{\mathrm{p}}^2 \right).$



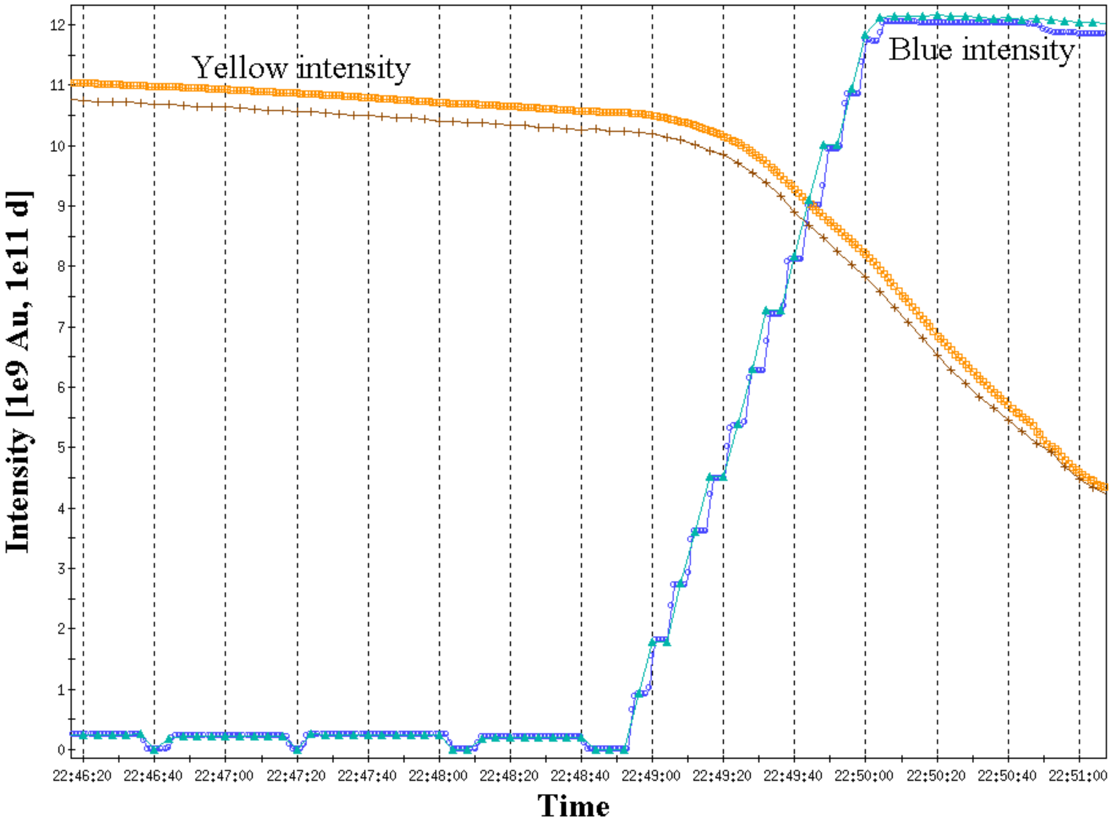
Revolution frequencies must be equal for collisions at top energy.

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

RF frequencies must be unequal for injection, ramp!

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

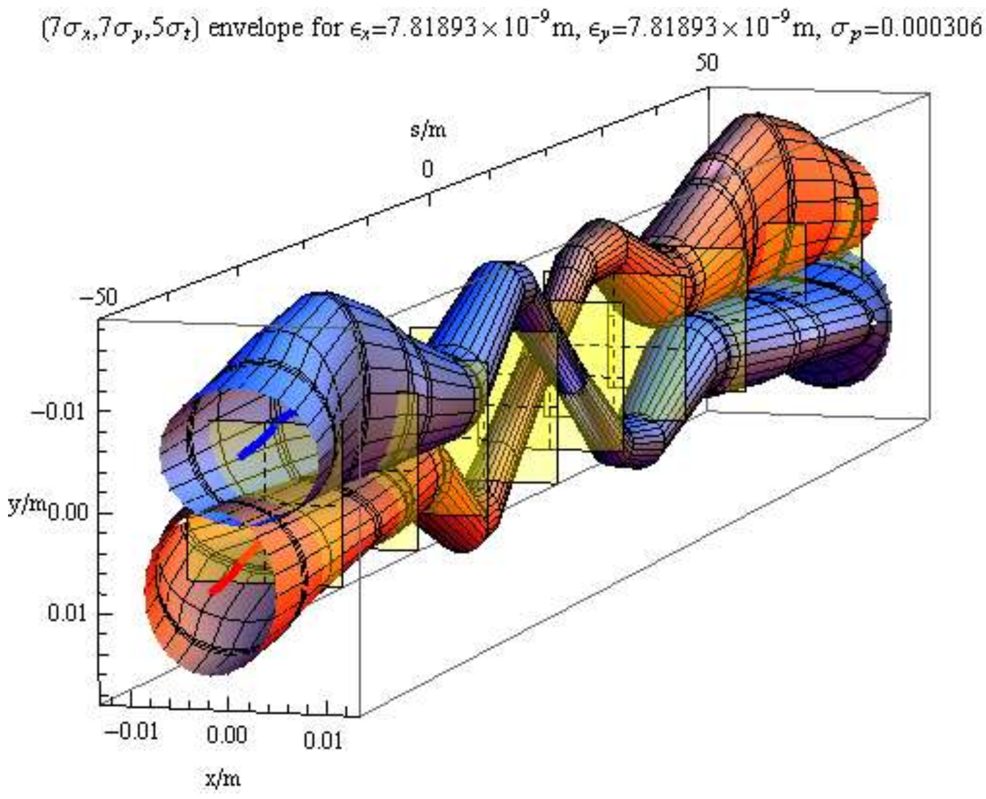
Example – beam lifetimes with $(B\rho)_d = (B\rho)_{Au}$ 2003



beam-beam effect during injection, d and Au with same rigidity,
Δf_{rf} = 44 kHz, vertical separation=10mm

[W. Fischer, et al., "Observation of Coherent Beam-Beam Modes in RHIC", BNL C-A/AP/75 (2002)]

Beam envelopes around ALICE at injection

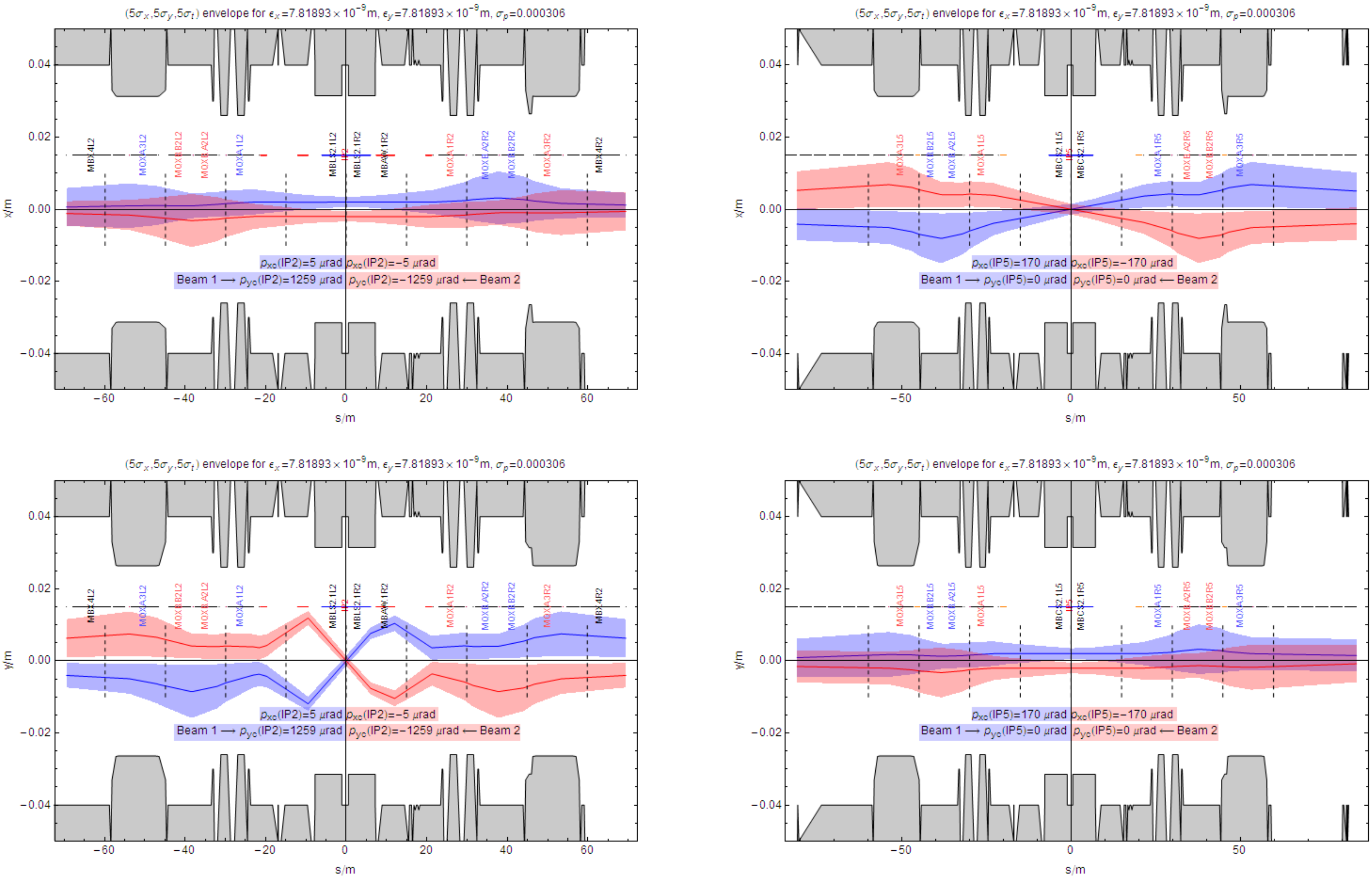


Crossing angle from spectrometer and external bump separates beams vertically everywhere except at IP (also in physics).

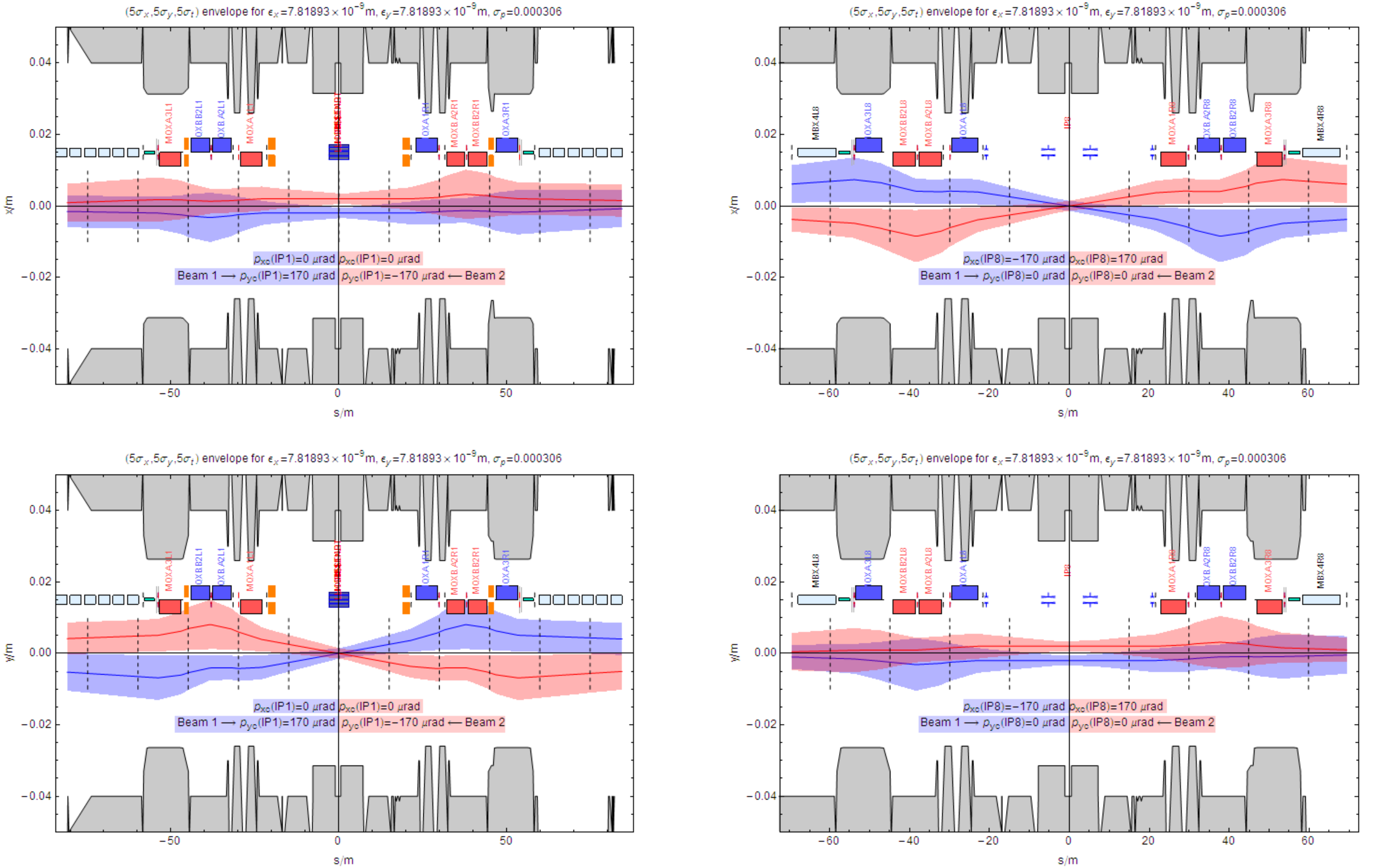
Parallel separation also separates beams horizontally at the IP during injection, ramp, squeeze.

Other experiments have different separation schemes …

ALICE – Separation at injection - CMS



ATLAS - Separation at injection - LHCb



Long-range beam-beam effects

For separations $x, y \gg \sigma_{x,y}$, the (angular) beam-beam kick on a particle of charge Ze, due to an opposing beam of total charge Ne is

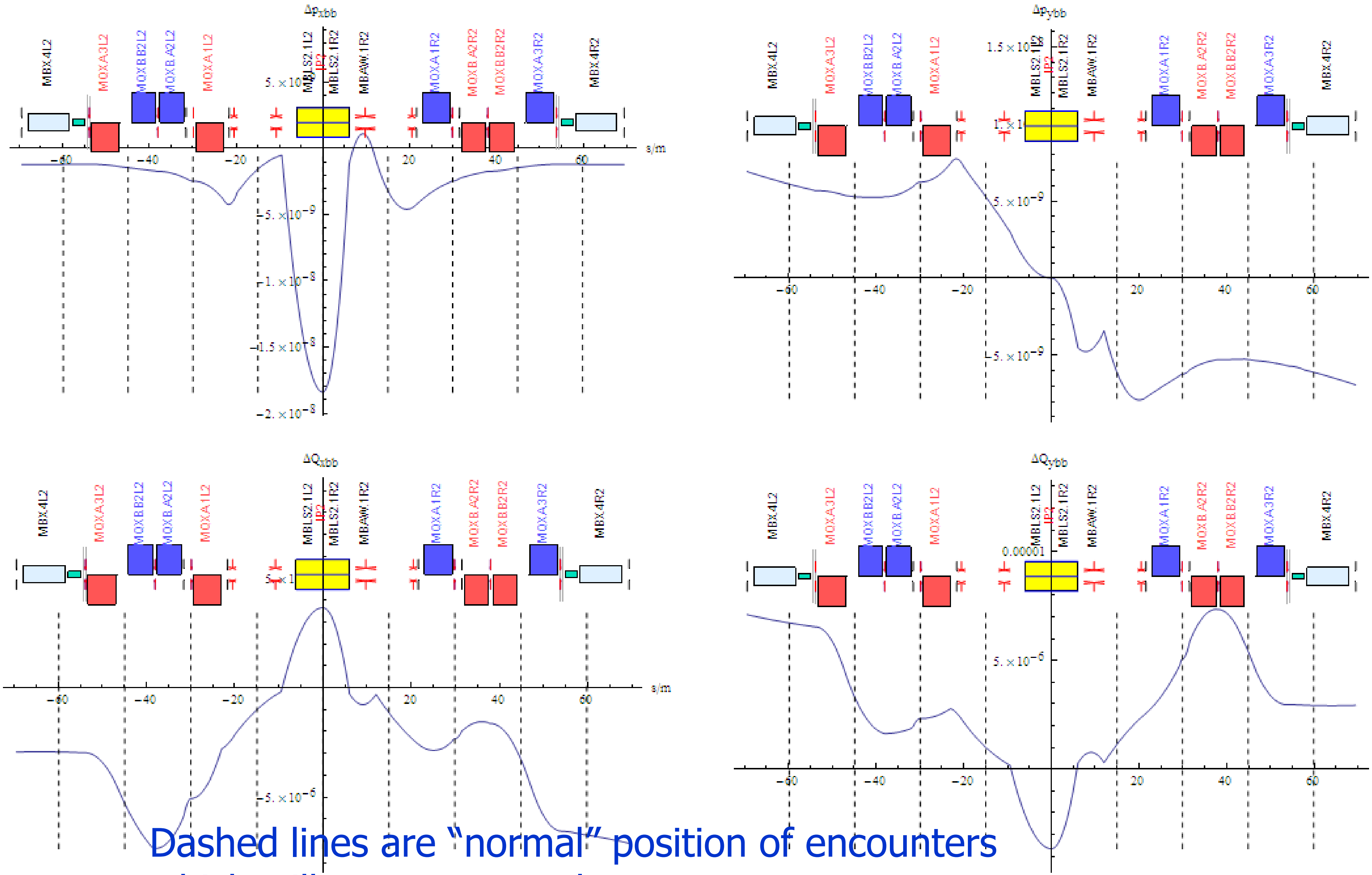
$$(\Delta p_x, \Delta p_y) = \frac{2ZNr_0}{\gamma} \frac{(x, y)}{x^2 + y^2}, \qquad \text{where} \quad r_0 = e^2 / (4\pi\epsilon_0 mc^2)$$

and gives rise to perturbative betatron tune-shifts

$$\Delta Q_{x,y} = -\frac{\beta_{x,y}}{4\pi} \partial_{x,y} \Delta p_{x,y} = \frac{ZNr_0}{2\pi\gamma} \frac{(\beta_x, -\beta_y)(x^2 - y^2)}{(x^2 + y^2)^2}$$

LHC separation configurations were chosen to minimise the tune effects in physics ("footprint").

Example: beam-beam for Pb around ALICE



Dashed lines are "normal" position of encounters which will move 15 cm along IR on next turn …

Overlap knock-out resonances ?

Encounter points move at speed $V = \frac{v_{\mathrm{p}} - v_{\mathrm{Pb}}}{2} = 1734\ \mathrm{m/s} = 0.15\ \mathrm{m/turn}$

Hamiltonian is no longer periodic in s.

Excites modulational resonances

$$\underbrace{m_x Q_x + m_y Q_y}_{m_{x,y}=1,2,\ldots\ \text{transverse modes}} = p + \underbrace{k}_{\text{Bunch harmonic, 891 or at most 3564}} \underbrace{\left(\frac{v_{\mathrm{p}} - v_{\mathrm{Pb}}}{2c}\right)}_{3.\times 10^{-6}\ \text{at injection, decreases in ramp}} \;;\quad m_x, m_y, p, k \in \mathbb{Z}$$

Known as "overlap knock-out resonances" at the ISR.

However with LHC tunes, $Q_x \approx 64.3, Q_x \approx 59.3$, only extremely high-order resonance conditions can be satisfied.

Very unlikely to be a problem (similar in RHIC, W. Fischer).

We are nevertheless looking at calculations of driving terms, compensation between IRs, etc.

Diffusion models

- Naively regarding the kicks as purely random
  - Works fairly well for RHIC data (W. Fischer)

$$\frac{d\varepsilon_{x,yn}}{dt} = \frac{1}{2} f_0 \sqrt{\gamma^2 - 1} \left[\beta_{x,y}(s) \left(\Delta p_{x,y}(s) \right)^2 \right]$$

where [..] denotes mean-square deviation

gives an emittance doubling time around 40 min

- Better calculate combination of beam-beam kicks on a particle on a given turn as the encounters move
  - Add them up with proper betatron phases
    - Partial compensations
  - Take out static component (closed-orbit) from long-term averaging and look at fluctuations around it
  - RMS fluctuation gives emittance growth rate ?
  - Other resonant effects, Landau damping, …
    - Work ongoing (JMJ, R. Versteegen)

Transverse Feedback

- 4 independent systems, 1 per plane and per ring
- High bandwidth to act on individual bunches
- Located in IP4, so no concerns about timing of p-Pb bunch passages.
- Potentially very important for p-Pb:
  - Damping any coherent oscillations driven by the coherent dipole kicks from moving beam-beam encounters at injection and during ramp

Outline of p-Pb physics cycle (Pb-p similar)

- Nominal Pb beam (100 ns basic spacing)
- Matching proton beam
  - See injection scheme details (C. Carli)
- Inject p beam in Ring 1, f_{RF} for p
  - Orbit, ramp established in advance
- Inject Pb beam in Ring 2, f_{RF} for Pb
  - Orbit, ramp established in advance
- Ramp both beams on central orbits
  - Orbit feedback decouples RFs
- Rephase RF and bring fRF together to lock
- Squeeze, collide, (almost) as usual Pb-Pb
  - Preliminary off-momentum set-up for 3.5 Z TeV?
- Implemented for 2011 test (R. Alemany-Fernandez)

Review of LHC systems

- RF (P. Baudrenghien, A. Butterworth)
  - Independent for two rings, OK
  - Decouple radial control
- Transverse Damper (ADT) (D. Valuch, W. Hofle)
  - Independent for two rings, OK
  - Possible variable Q reference should be OK
- Beam instrumentation (R. Jones, E. Giraldo, …)
  - Common BPMs identified as main concern at LMC50 – later slide
  - All other BI independent for two beams
- Orbit and tune feedback – very important
  - Looks OK (J. Wenninger, R. Steinhagen)
    - Q/Q' systems are independent for both beams
    - Orbit feedback does not use common BPMs
    - Need to decouple radial control
    - Check possibility of variable Q reference ?

Potential luminosity

- In possible 2012 physics run at 3.5 Z TeV

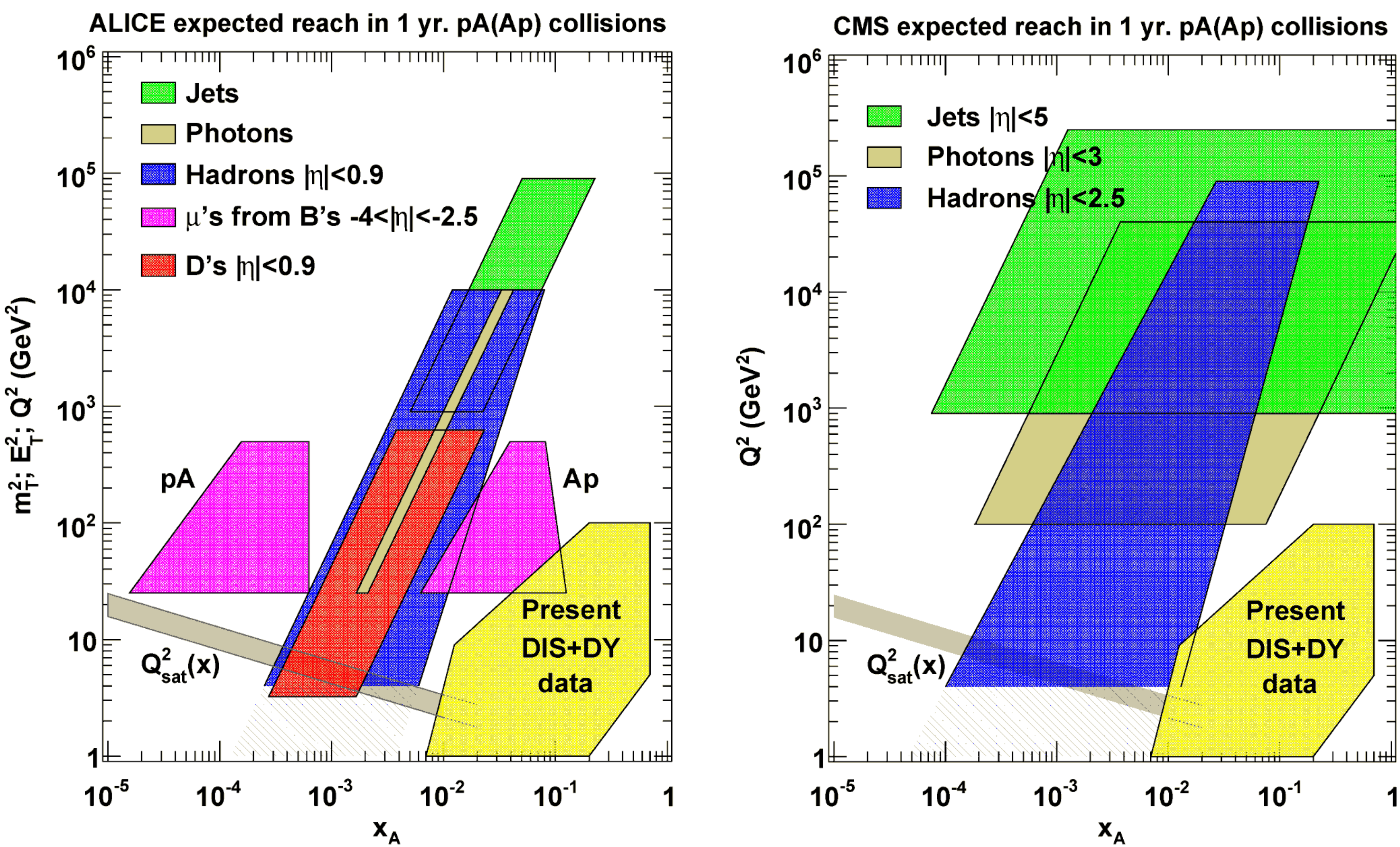
$$L = \frac{k_c N_{Pb} N_p f_0}{4\pi\,\sigma^{*2}} = \frac{k_b N_b{}^2 f_0 \gamma_{\mathrm{Pb}}}{4\pi\,\varepsilon_{n\mathrm{Pb}}}$$

$\approx 3\times10^{28}\ \mathrm{cm^{-2}s^{-1}}$ (~300 colliding bunch, ~10^8 Pb/bunch, ~10^{10} p/bunch nominal emittance 1.5 μm)

but reduction factors almost certainly apply

- But we should really wait until after the feasibility test to say anything meaningful.
  - (With extreme optimism, using full proton intensity we can dream of factors ~15 more …).

LHC detector potential in p-Pb



p-Pb feasibility test, Part 1, 31/10/2011

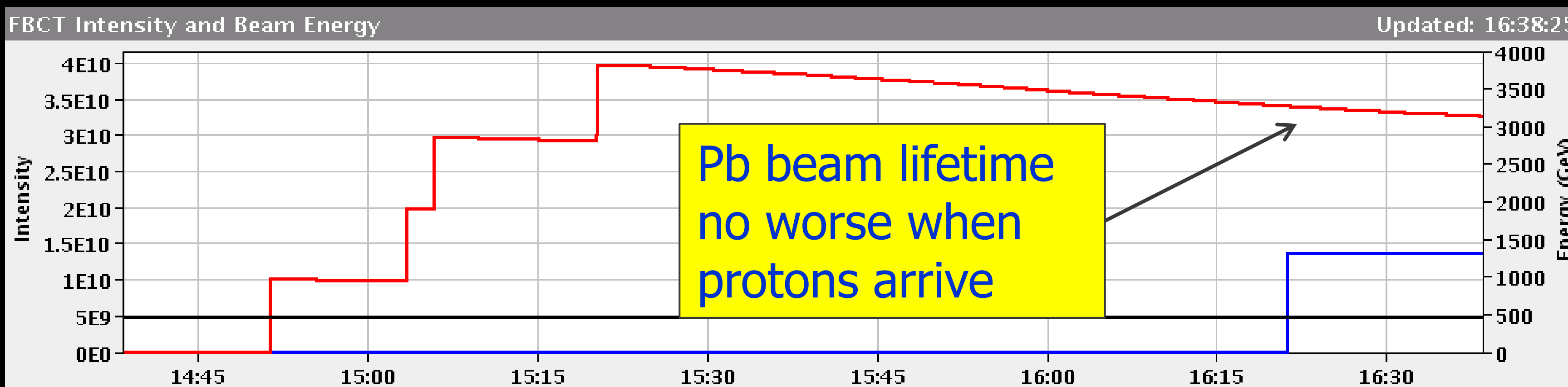
- Several hours setup (timing, many details…)
- Stored 4 Pb bunches (first of year) in presence of 304 p bunches at injection
  - Lifetime no worse for presence of p bunches
  - Emittance blow-up, does not appear to be worse than for Pb alone –
- Dumped and re-injected 4 fresh Pb
  - Still OK
- Ramped 2 Pb and 2 p bunches, good lifetime
- Re-phased RF (cogging) to move bunch 1 encounter point 9 km back to ATLAS, no losses
  - Confirmation with video from ATLAS
    - See talk of P. Baudrenghien, LSWG 8/11/2011

LHC Page1 | Fill: 2269 | E: 450 GeV | 31-10-2011 16:38:25

MACHINE DEVELOPMENT: INJECTION PROBE BEAM

BCT TI2:	0.00e+00	I(B1):	1.30e+10	BCT TI8:	0.00e+00	I(B2):	3.78e+10

TED TI2 position:	BEAM	TDI P2 gaps/mm	up: 10.84	down: 8.57
TED TI8 position:	BEAM	TDI P8 gaps/mm	up: 9.62	down: 8.92



Comments 31-10-2011 15:39:35 :

2011 Proton physics program finished!

Ions circulating in B2

Injection protons in B1

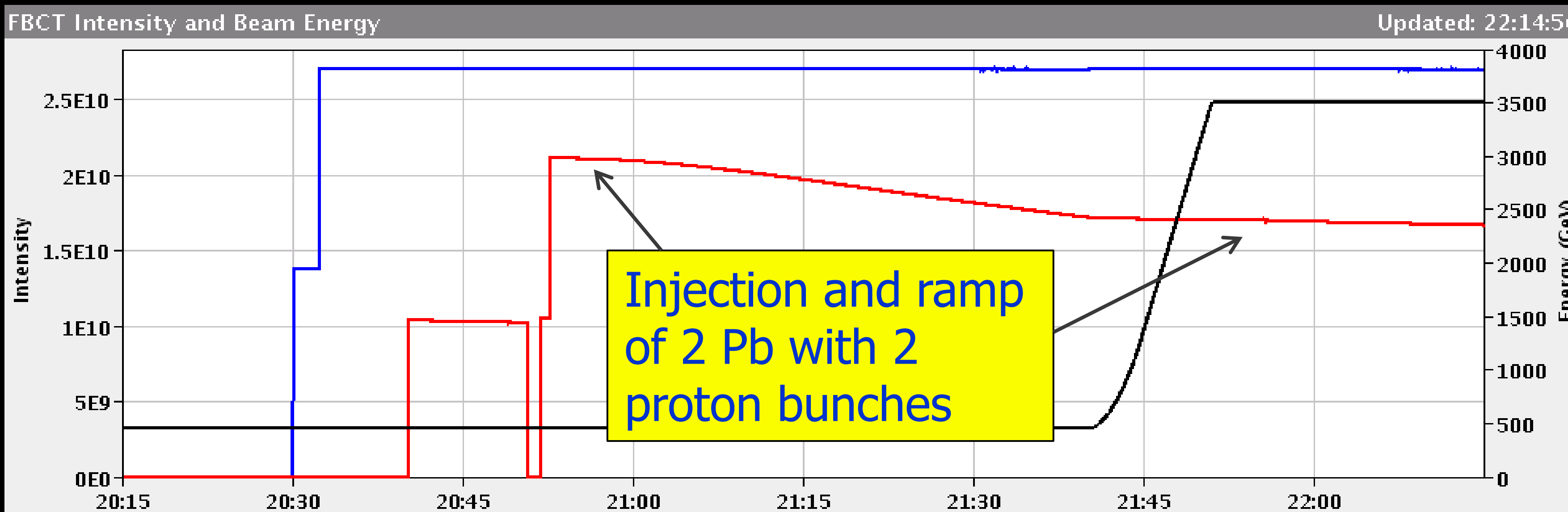
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: 100ns_588b_1small_0_0_0_72bpi9inj_pPb | PM Status B1 ENABLED | PM Status B2 ENABLED

LHC Page1 Fill: 2269 E: 3500 GeV 31-10-2011 22:14:56

MACHINE DEVELOPMENT: FLAT TOP

Energy:	3500 GeV	I(B1):	2.54e+10	I(B2):	1.87e+10



Comments 31-10-2011 21:55:27 :

2011 Proton physics program finished!

Proton and lead ion beams together for the first time at 3.5 Z TeV.

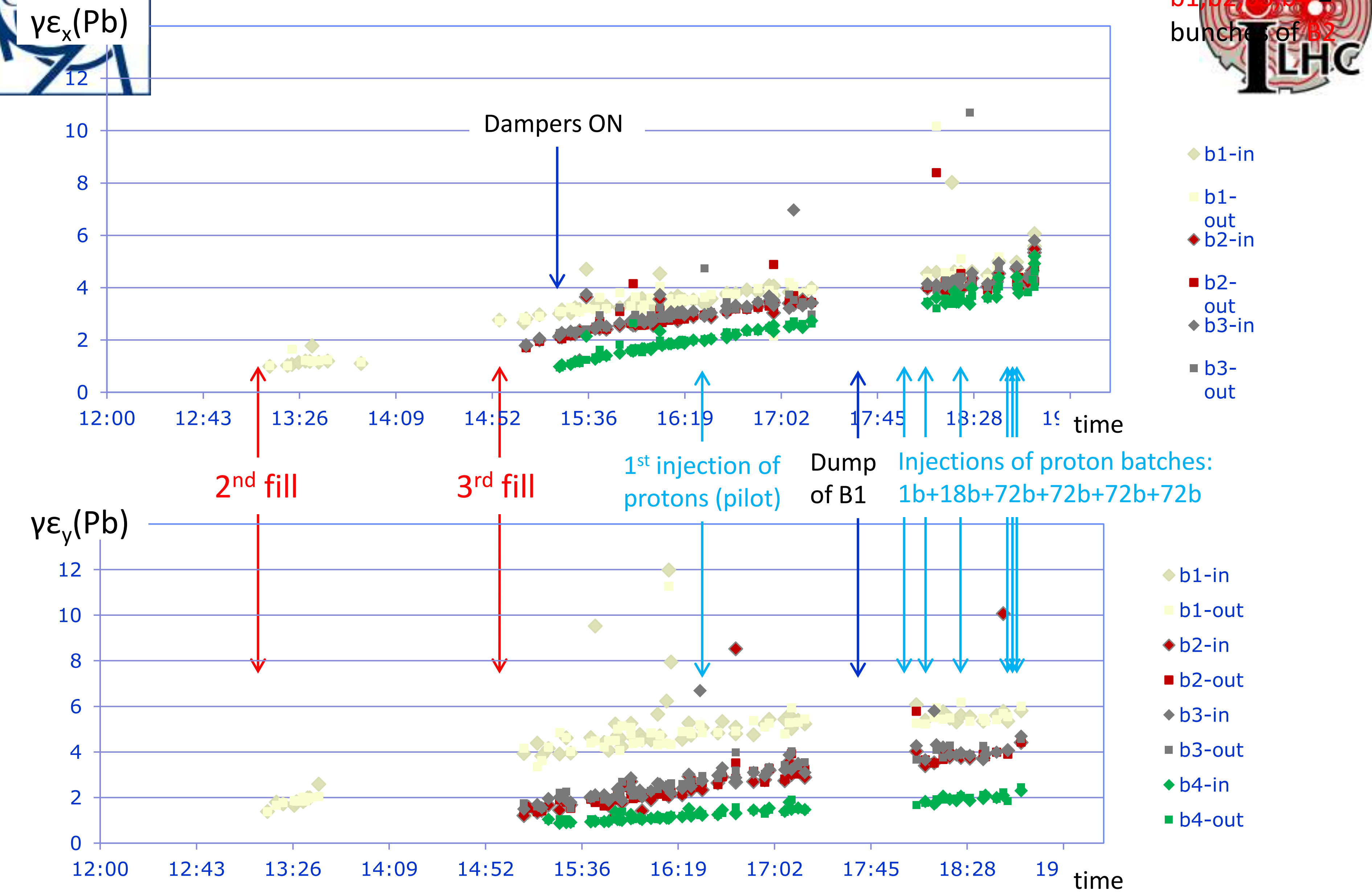
2 bunches each, will try rephasing RF.

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: pPb_2b_1_1_1_1bpi2inj

PM Status B1 ENABLED PM Status B2 ENABLED

Wire scans of Pb beam B2, 2nd and 3rd fills



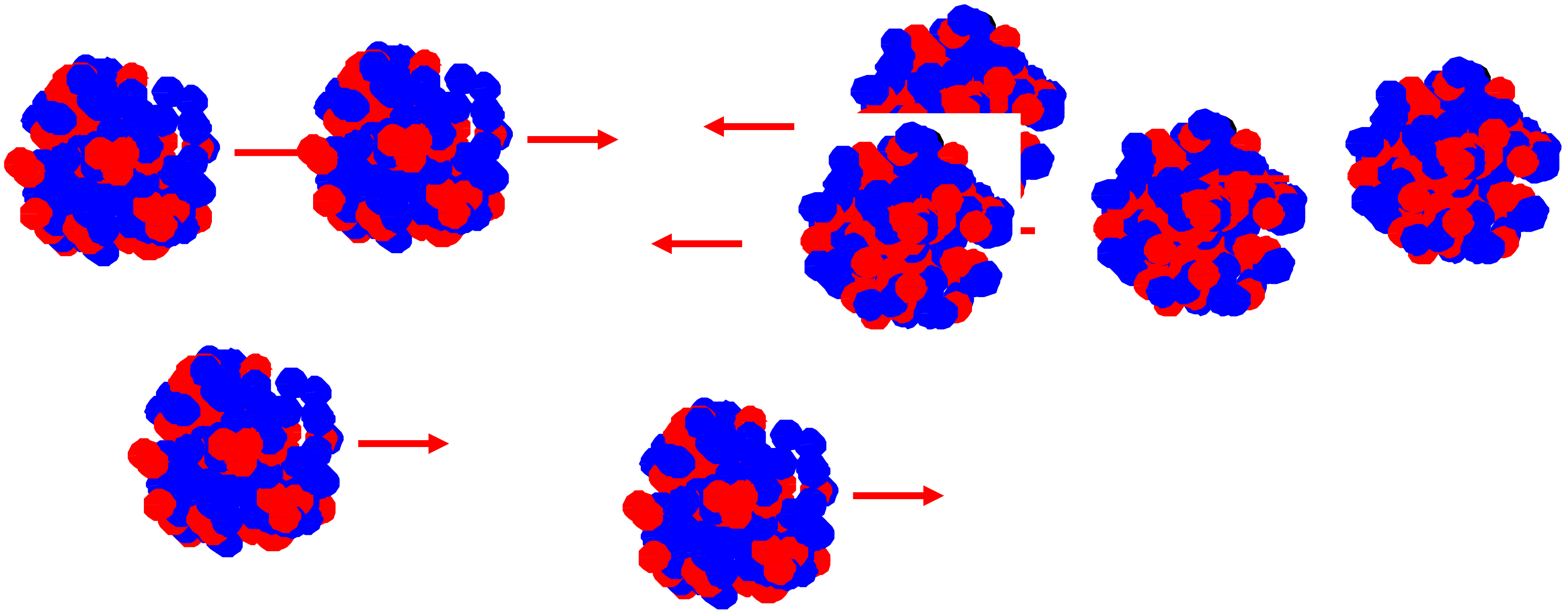
First p and Pb at 3.5 Z TeV

Vital contributors not in photo: J. Wenninger, S. Redaelli, several others …

p-Pb feasibility test, Part 2

- MD part: ramp some Pb bunches in presence of many proton bunches
  - New date proposed: daytime 16 Nov
- Physics part: collide a few (under discussion) Pb with a few p bunches as “Stable Beams”
  - Finalise details on Wednesday
  - Could follow MD part, or be in daytime 17 Nov
    - (after Pb-Pb physics overnight)

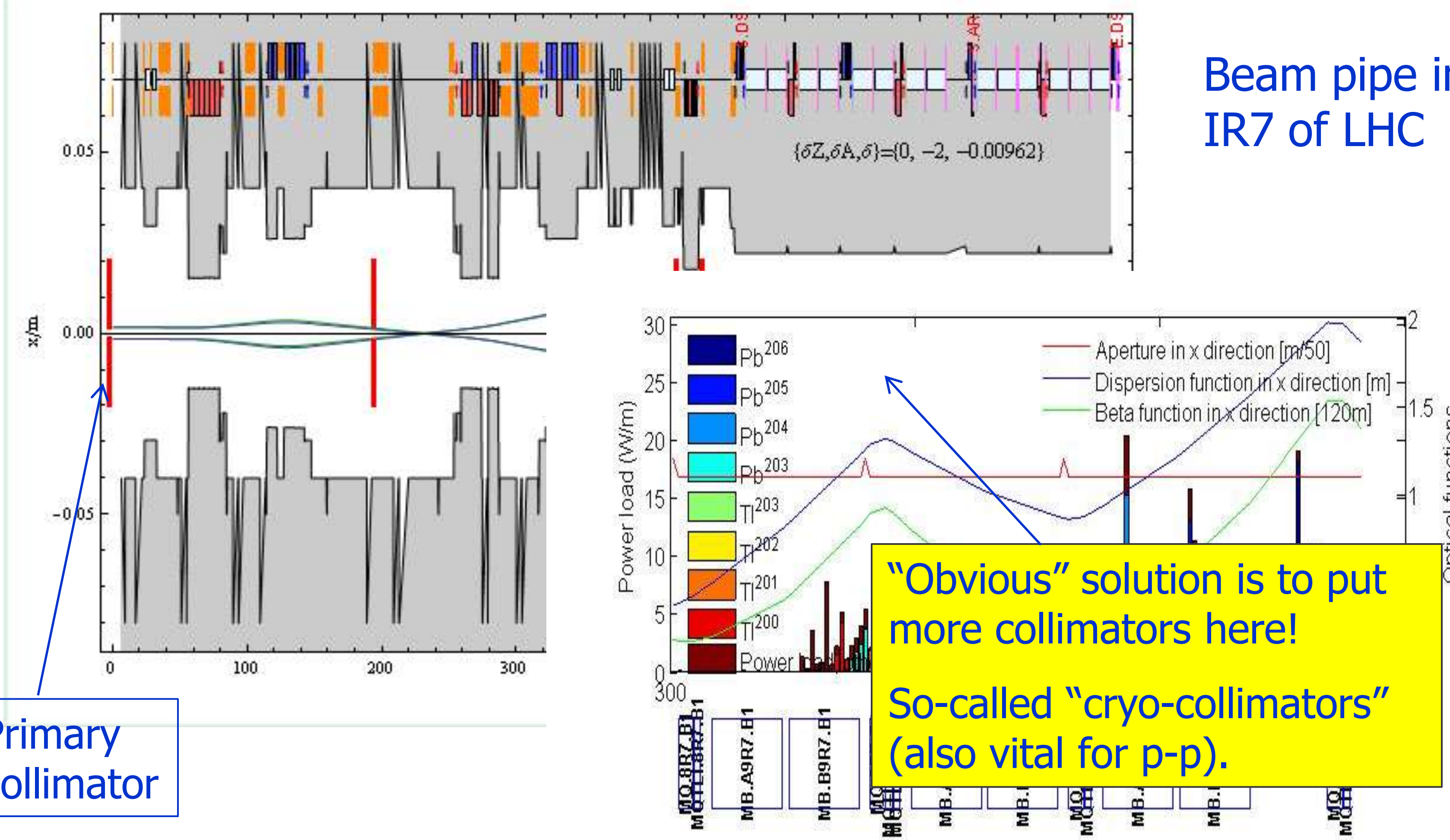
- *Had to be cancelled because of failure in PS proton injection septum … still some uncertainty about feasibility of ramping MANY bunches.*



HEAVY IONS IN THE LHC BEYOND 2012

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



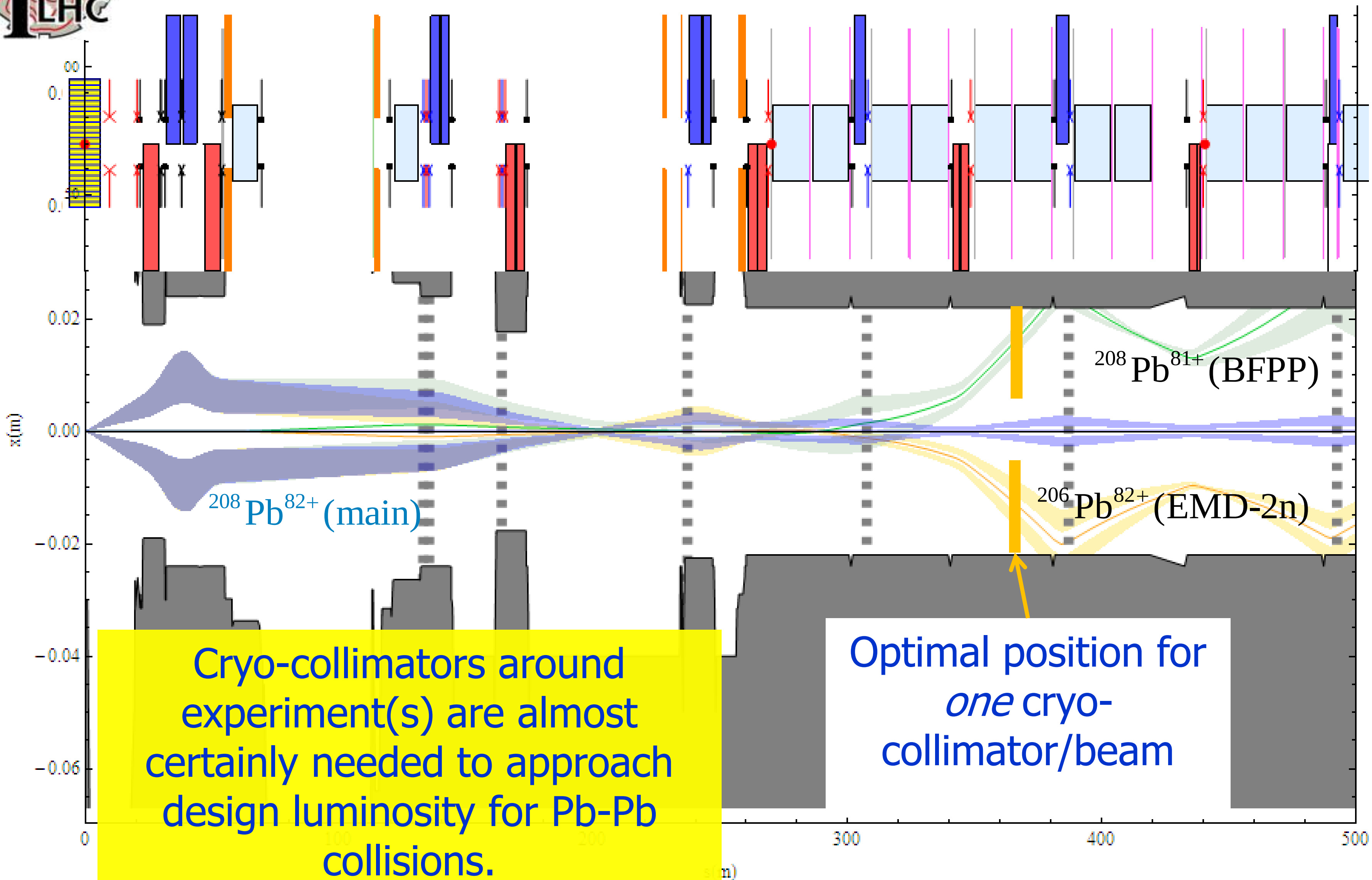
Beam pipe in IR7 of LHC

Primary collimator

"Obvious" solution is to put more collimators here!

So-called "cryo-collimators" (also vital for p-p).

Main and secondary Pb beams from ALICE IP



Cryo-collimators around experiment(s) are almost certainly needed to approach design luminosity for Pb-Pb collisions.

Optimal position for *one* cryo-collimator/beam

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
  - Upgrade of quench protection system, splices, etc, towards full beam energy ~2.6 A TeV
  - 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 higher) *intensity* at top energy (6.5-7 Z TeV/beam) but peak *luminosity* may be limited
    - Luminosity levelling in all experiments, new regime with strong luminosity burn-off, significant radiation damping (see previous talks)

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

- 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, IR1, IR5, to increase Pb-Pb *luminosity* limit.
    - N.B. collimator locations are different from IR3, IR7 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)
- All under discussion

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
  - Stochastic cooling systems ?

Summary

- Within a total ~8 weeks of operation at half design energy, LHC Pb-Pb luminosity is at twice the design value (scaled with E^2).
- Proton-nucleus collisions (not part of the official "baseline" programme until 1 year ago) have been shown to be feasible and will form the basis of the HI physics programme in 2012.
- The LHC nuclear programme will evolve towards higher energy and luminosity over the coming decase and perhaps beyond
  - Timely upgrades, interleaved with those for p-p operation are crucial, will require close attention from HI community.