Heavy Ions in 2012 (and the plan up to LS3)

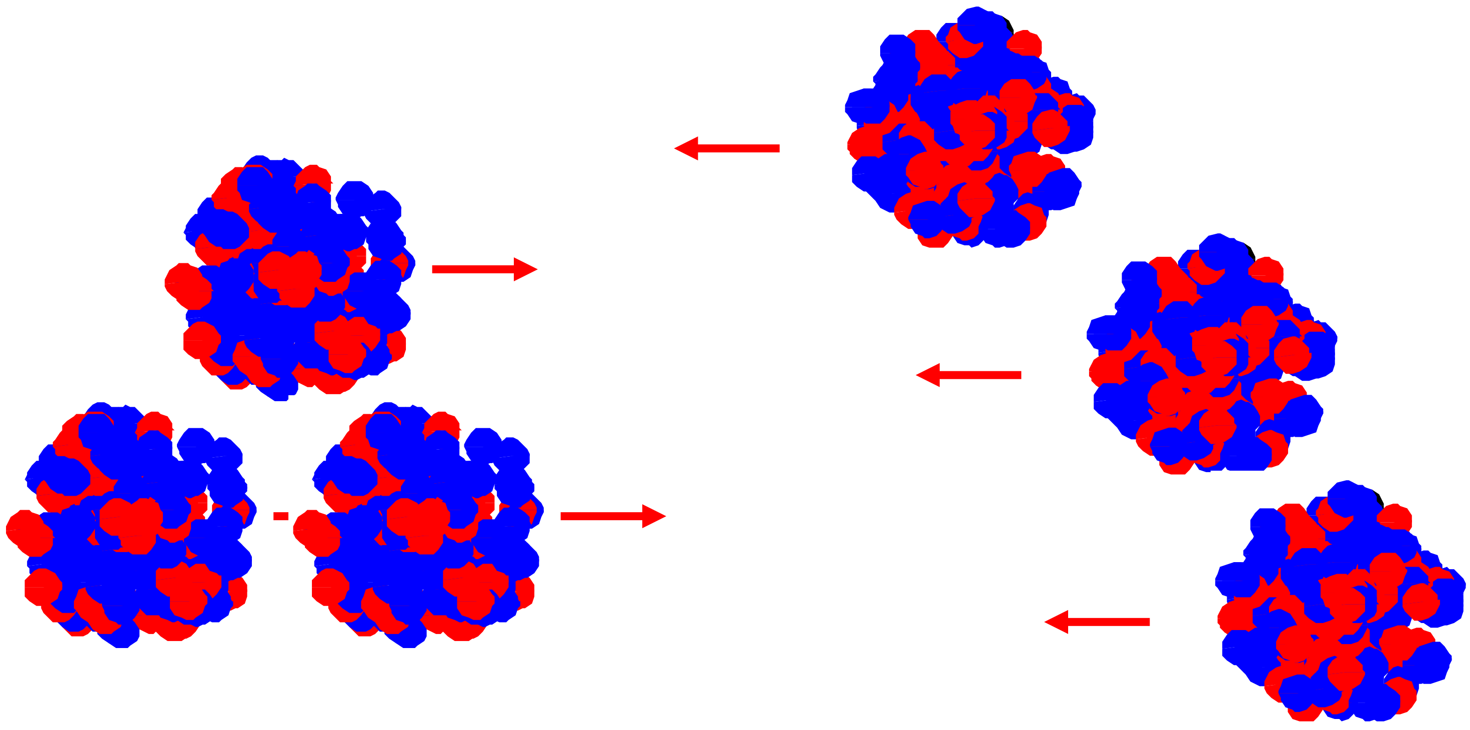
J.M. Jowett, R. Alemany-Fernandez, R. Assmann, P. Baudrenghien, G. Bellodi, S. Hancock, D. Manglunki, S. Redaelli, M. Sapinski, M. Schaumann, M. Solfaroli, R. Versteegen, J. Wenninger, D. Wollmann

Thanks to many others in Heavy-Ion Injectors, OP, Machine Coordinators, Physics Coordinator (much solicited), ABP (optics corrections, aperture, …), RF, BI, … involved in the 2011 Pb-Pb run

Plan of talk

- The 2011 Pb-Pb run
- Potential Pb-Pb run in 2012
- The p-Pb feasibility test
  - The missing second half …
- The 2012 p-Pb run
- The LHC heavy-ion programme up to 2021 (LS3)

A lot changed since I wrote the abstract



THE 2011 LEAD-LEAD RUN

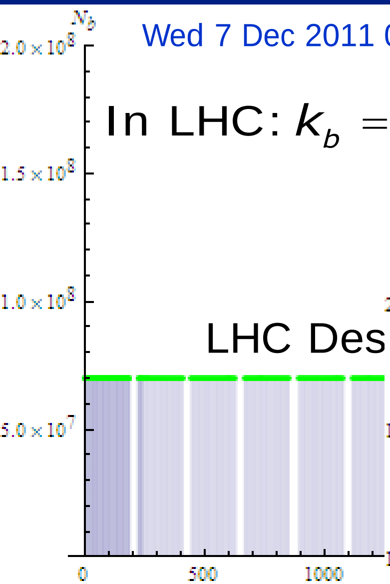
- See talks by Massi Ferro-Luzzi and Alick Macpherson yesterday for details of luminosity performance, operating efficiency, etc.
  - 4 days of physics
  - 29 days operation
  - Many things happened and it is impossible to give even a minimal account here

Ion Injector Chain Performance (!)

Wed 7 Dec 2011 07:44:32

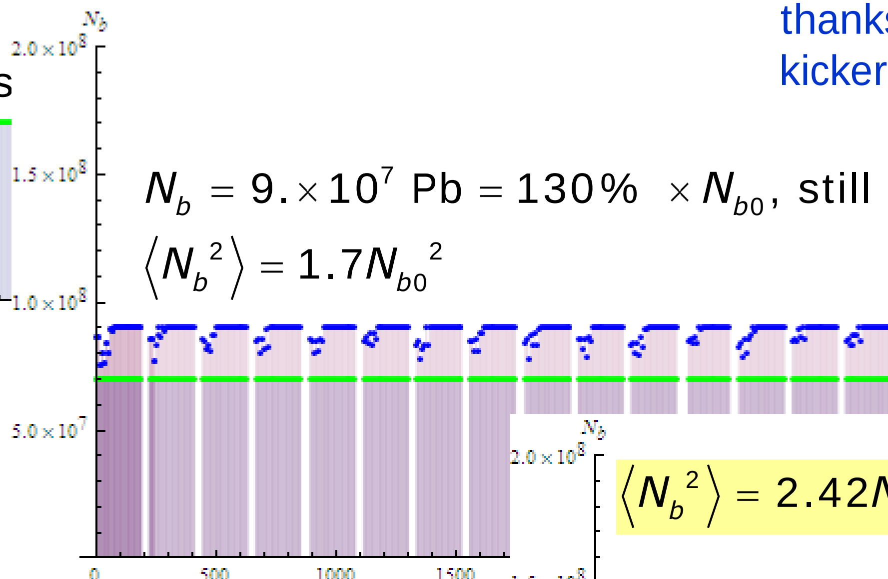
In LHC: $k_b = 385 \approx 0.6 \times 592$ (design)

"Intermediate" filling scheme
proposed Chamonix 2011,
200 ns created in 2 bunch PS batches,
sustained in 24 bunch SPS batches
thanks to shortened SPS injection
kicker rise time (E. Carlier)

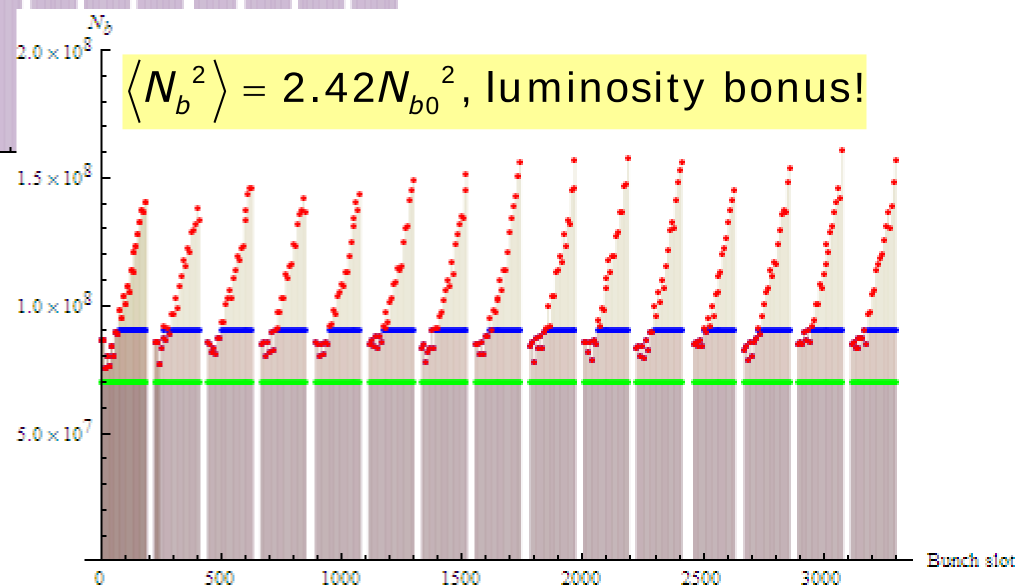


$N_b = 9. \times 10^7$ Pb $= 130\% \times N_{b0}$, still very even!

$\langle N_b^2 \rangle = 1.7 N_{b0}^2$



$\langle N_b^2 \rangle = 2.42 N_{b0}^2$, luminosity bonus!

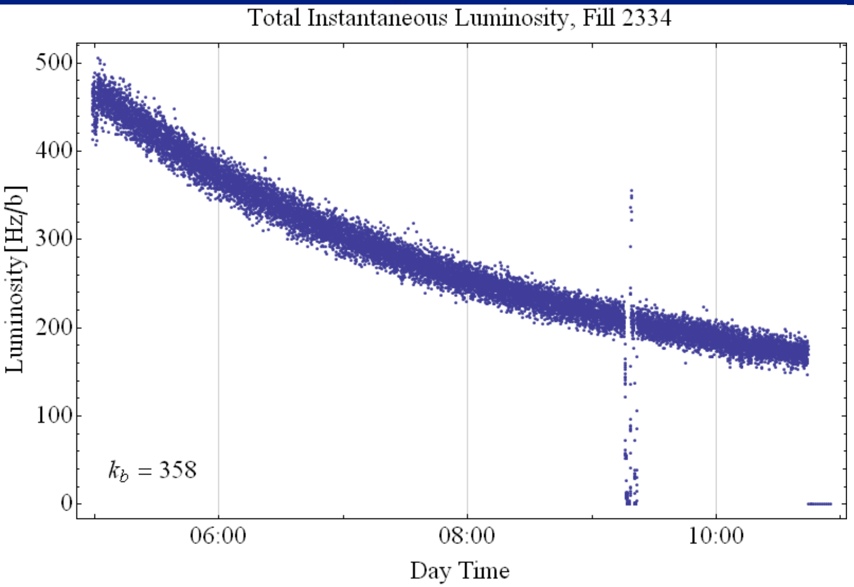


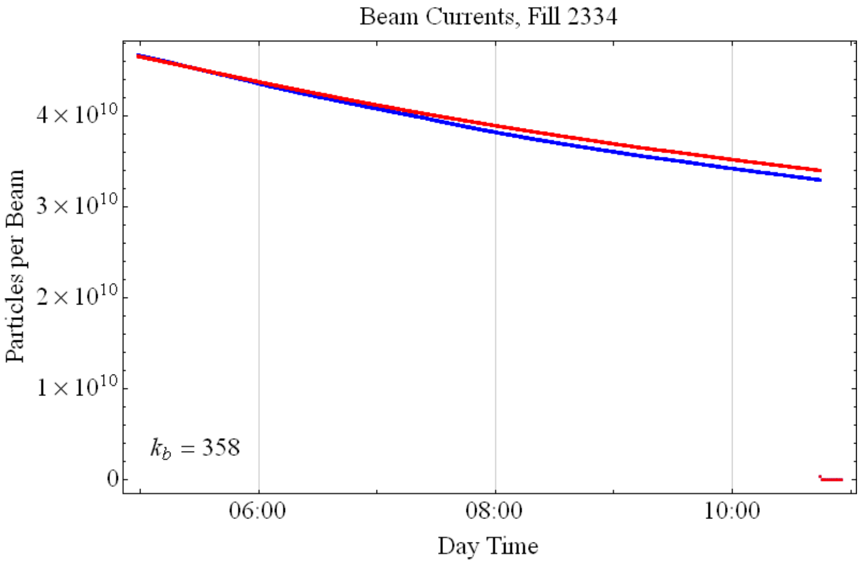
Uneven intensity (and emittance) along batches due to IBS (etc ...) on long injection porches in SPS and LHC.

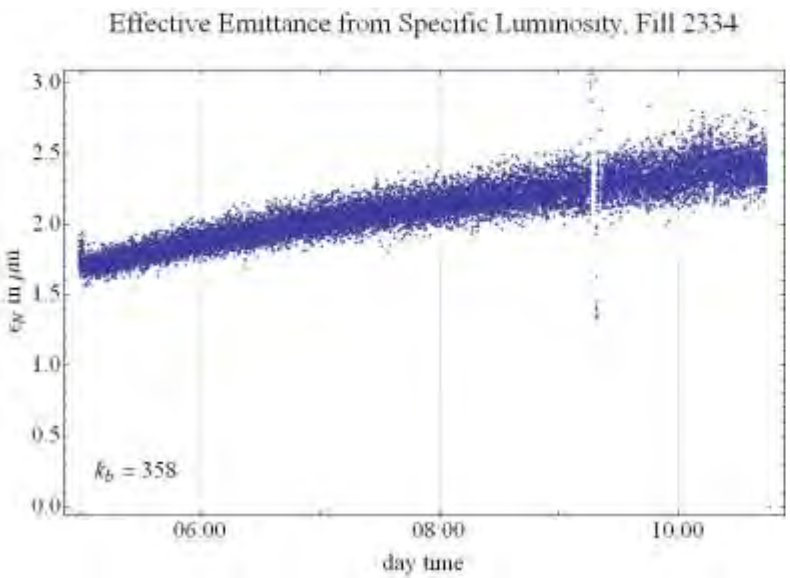
Aperture in IR2

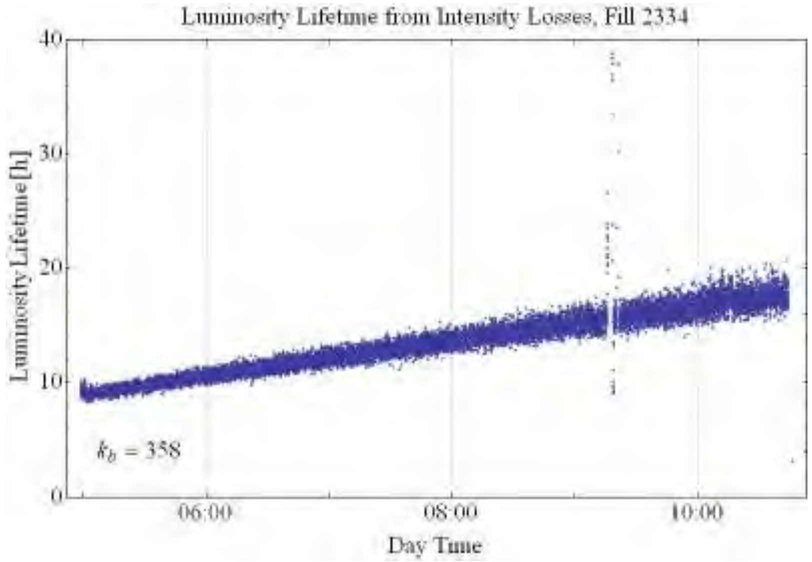
- As in 2011, the heavy-ion run will use the most squeezed (normal) optics yet in LHC
- Aperture limits in IR2 constrained choice of crossing angle in 2011
- Substantial modifications of IR2 going on now!
- Imperative to measure available aperture as early as possible in 2012

Beam parameter evolution, not the best fill



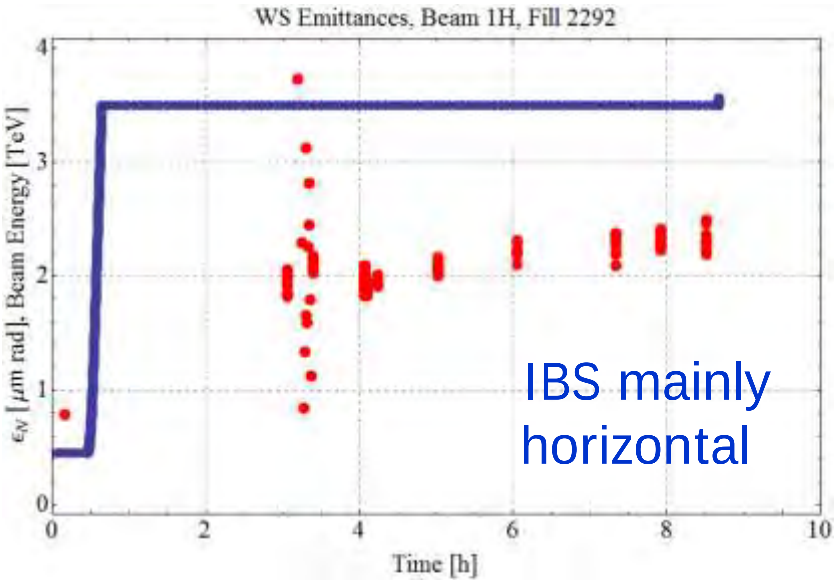


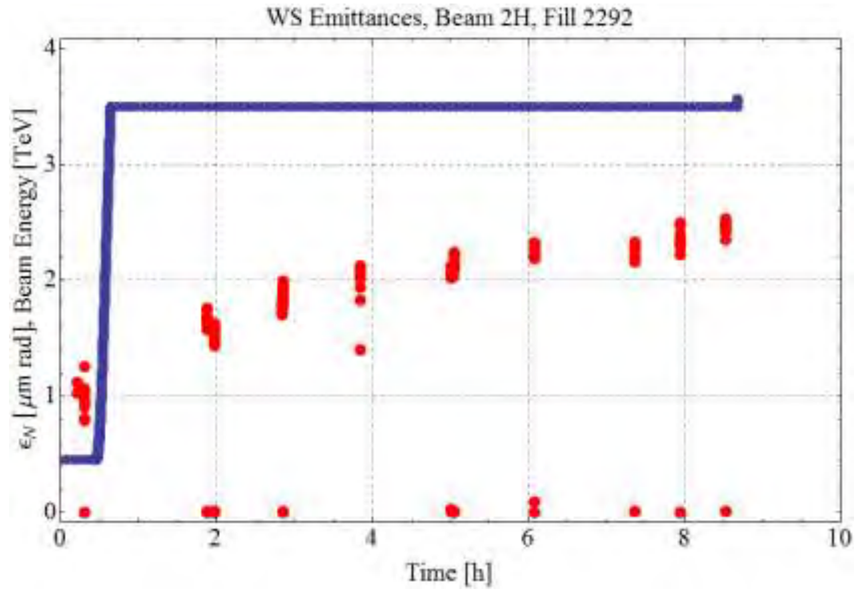


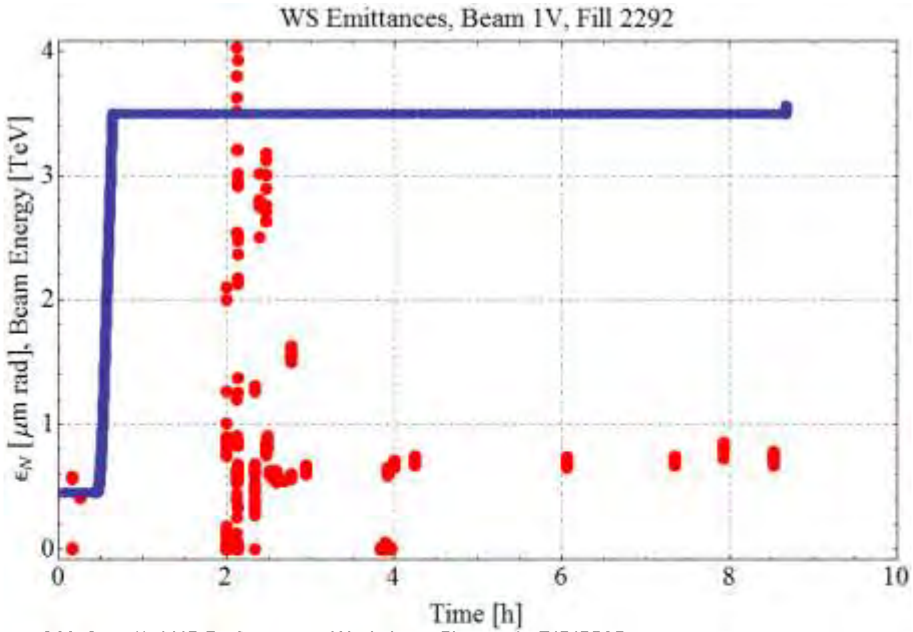


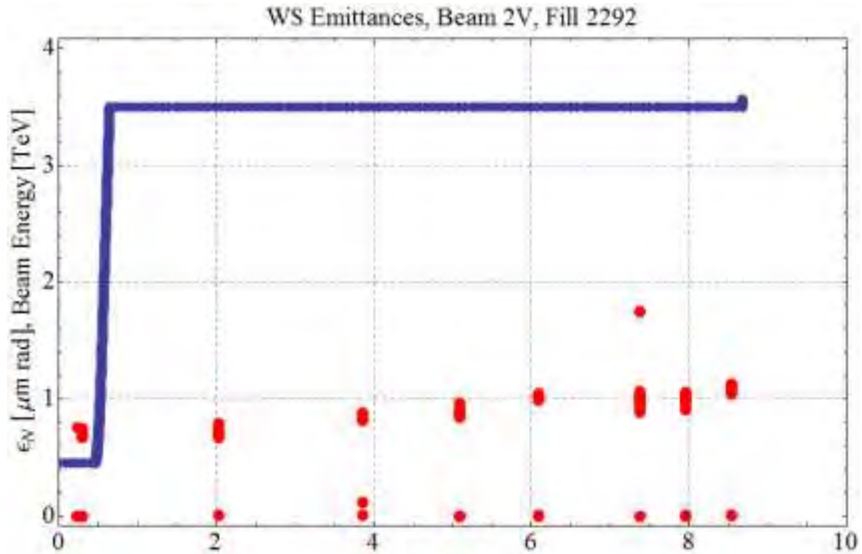
M. Schaumann

More detail on emittances from wire scans









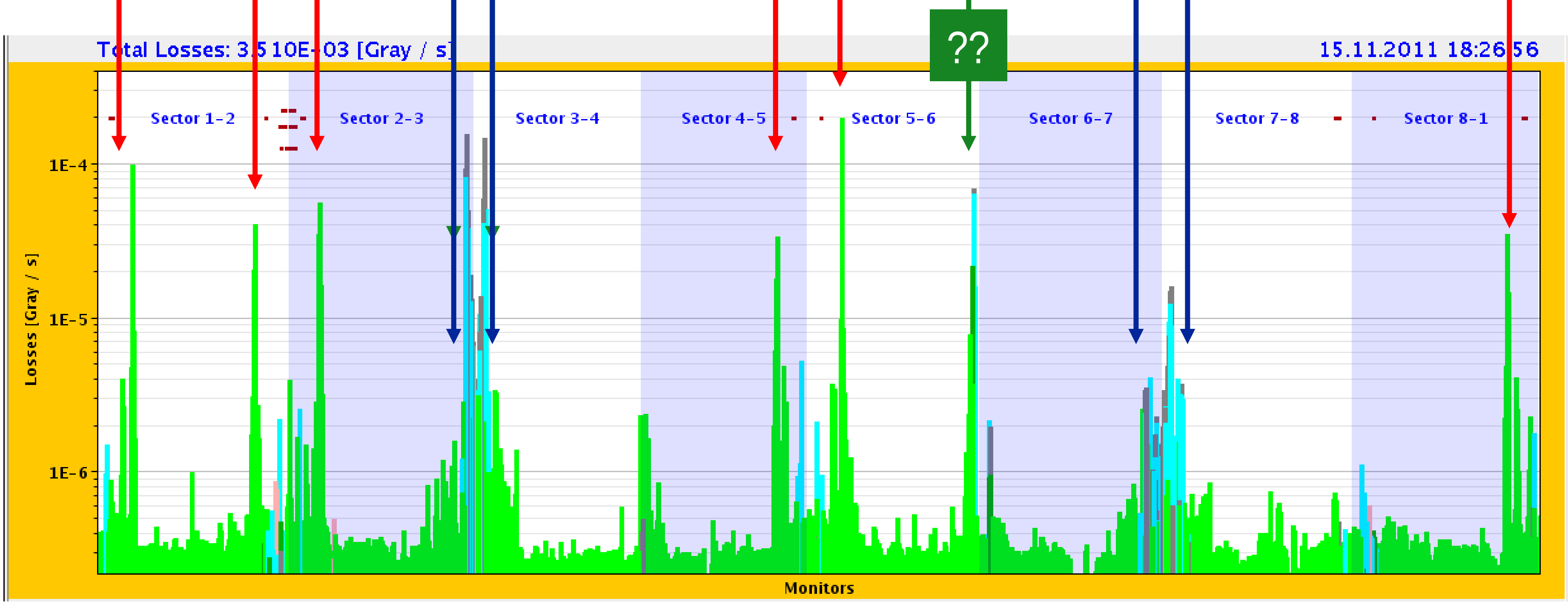
M. Schaumann

Losses during Pb-Pb Collisions in 2011

Bound-free pair production secondary beams from IPs

IBS & Electromagnetic dissociation at IPs, taken up by momentum collimators

Losses from collimation inefficiency, nuclear processes in primary collimators



But we have learned a lot from the 2011 run …
…despite no dedicated MD time for Pb-Pb.

See also M. Brugger's backup slides

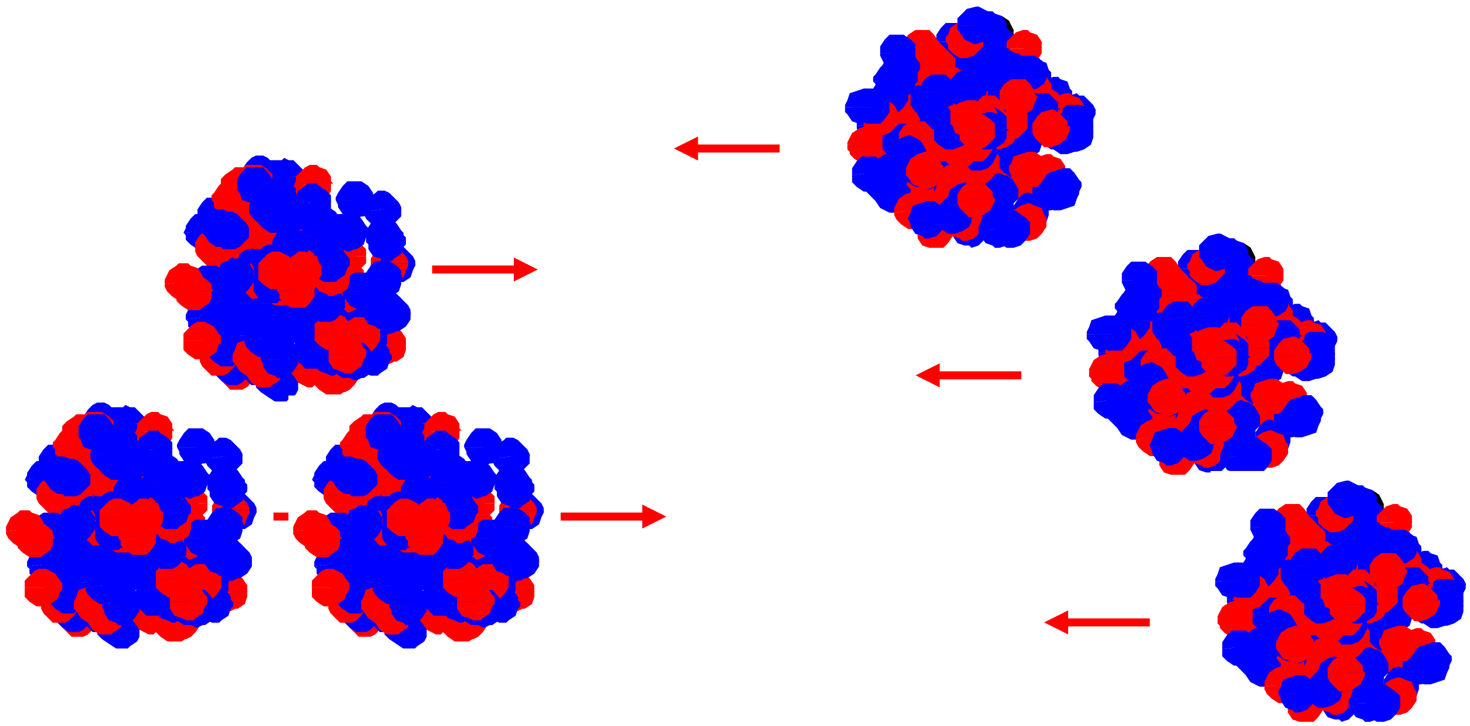
"MD" results from 2011 Pb-Pb physics time

- ALICE polarity reversal
  - 2σ is fine for long-range beam-beam …
- BFPP mitigation with orbit bumps
  - Small bumps in DS regions spread out peak loss density right of CMS by factor 5
  - Raises quench limit on Pb-Pb luminosity !!
- Heavy ion collimation quench study
  - See talk by Mariusz Sapinski yesterday
  - Raises (collimation) quench limit on Pb beam intensity !!
  - **Raises (BFPP) quench limit on Pb luminosity !!!**
    - Experiments will limit luminosity in 2015 ??
    - **We need to find ways to reduce bunch spacing**
- Miscellaneous "short" MDs for p-p

Nucleus-nucleus programme status

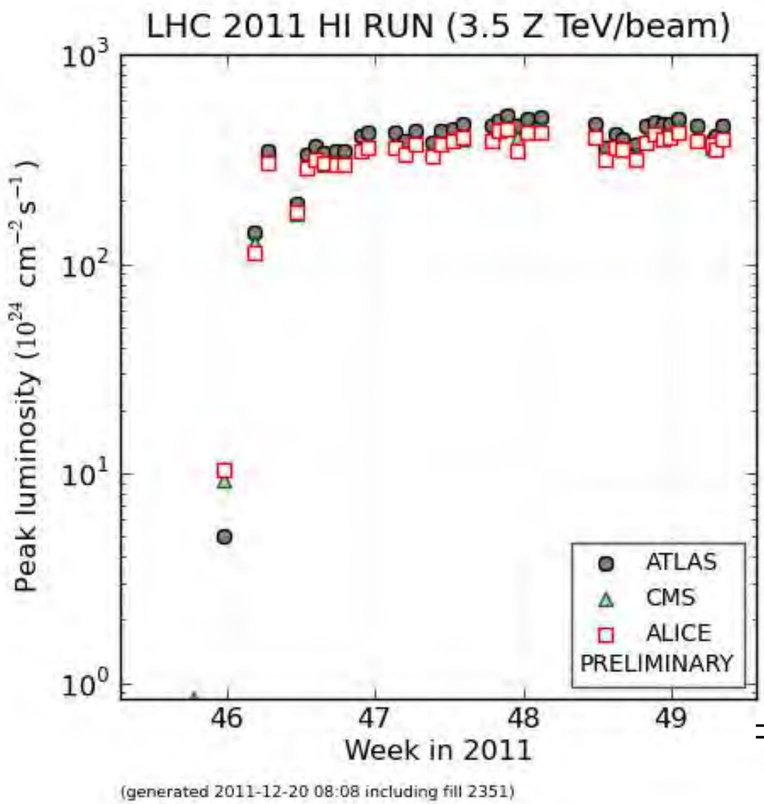
- In ~8 weeks total operation in 2010-11, we have attained twice design luminosity (scaled with E^2).

- We have produced ~15% of the overall luminosity goal (1 nb^{-1}) for the present phase of Pb-Pb.



WHAT IF WE DO A LEAD-LEAD RUN IN 2012 ?

Potential of Pb-Pb at 4 Z TeV in 2012



- Hard to imagine faster luminosity ramp-up
- We can gain from energy and β^* but probably not from emittance, intensity.
- Assume 2011 filling scheme

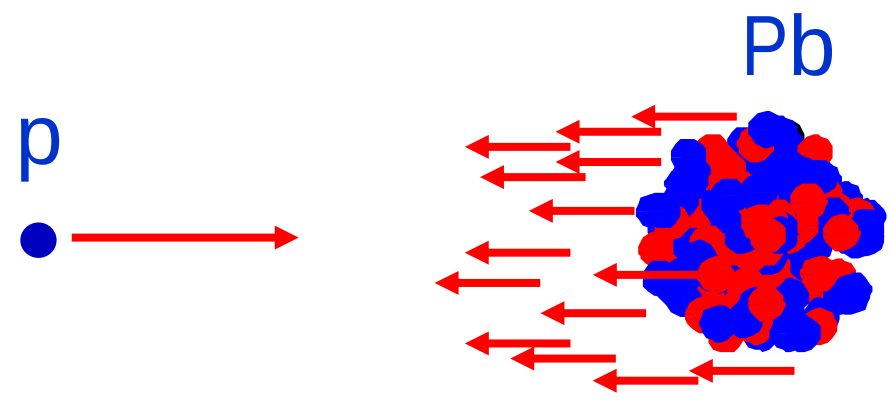
$$L = \frac{k_c N_b^{\,2} f_0}{4\pi \varepsilon_n \gamma}$$

$$\Rightarrow L_{2012} = \left(\frac{4Z \text{ TeV}}{3.5Z \text{ TeV}}\right)\left(\frac{1.\text{ m}}{0.6\text{ m}}\right)(5.\times 10^{25}\text{ cm}^{-2}\text{s}^{-1})$$

$$\approx 10^{27}\text{ cm}^{-2}\text{s}^{-1} (= \text{design for } 7\ Z \text{ TeV})$$

Allowing for faster burn-off, LS1 pressure effects, and similar up-time (can easily fluctuate!), estimate integrated luminosity ~ 250 μb^{-1}

Important β^* caveats later!!!



PROTON-LEAD FEASIBILITY TEST IN 2011

Reminder of p-Pb status, CMAC August 2011

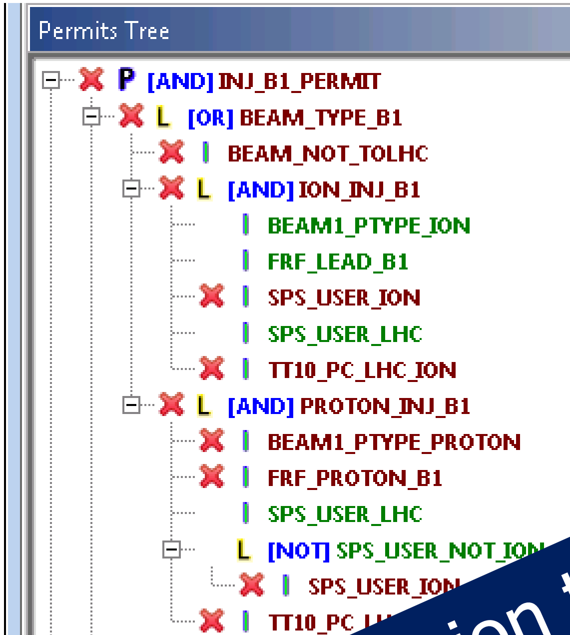
- Requested by heavy-ion physics community
  - Recognised as part of LHC accelerator programme at Chamonix 2011
- **Feasibility of this mode controversial**
  - Beams of unequal revolution frequencies, moving long-range beam-beam encounters at injection and in ramp
  - RHIC abandoned equal rigidity acceleration
    - Drastic beam losses, emittance blow-up, …
    - Option not available to LHC
  - Outline of beam dynamics calculations
    - Emittance growth etc, continuing (JMJ & R. Versteegen)
- Feasibility test proposed during 2011 heavy ion run in view of possible physics run in 2012
  - Small team started work to re-purpose LHC.

Implementation: LHC as proton-nucleus collider

- Systems/procedures developed during 2011 to enable this new mode of operation:
  - Machine Protection → new Software Interlock permit tree to avoid the injection of protons into a ring configured for ions and vice versa
  - RF → New rephasing and cogging procedure, plus FESA properties and sequencer tasks to configure each ring for the right particle type
  - BI → New BPM calibration task to calibrate independently each beam according to the bunch spacing
  - Sequences → New LHC PROTON-NUCLEUS NOMINAL Sequence
  - Timing → New Accelerator Mode = PROTON-NUCLEUS PHYSICS & new telegram line with PARTICLE TYPE "PER" RING
  - Injection schemes → New injection schemes mixing protons and ions
  - Transverse feedbacks already independent

R. Alemany-Fernandez,
P. Baudrenghien, ...

Machine Protection: new SIS permit tree



Proton/Pb conditions – applied for each ring

LHC: **RF frequency** within 1kHz of proton ... ce.

Monitoring at 0.2 Hz, accurac...

LHC : **particle type** in C... ...n/Pb

SPS: **user nam**... ... LHCIONx (x = 1,2,3,4...)

S... ...**T10 settings** consistent with ...

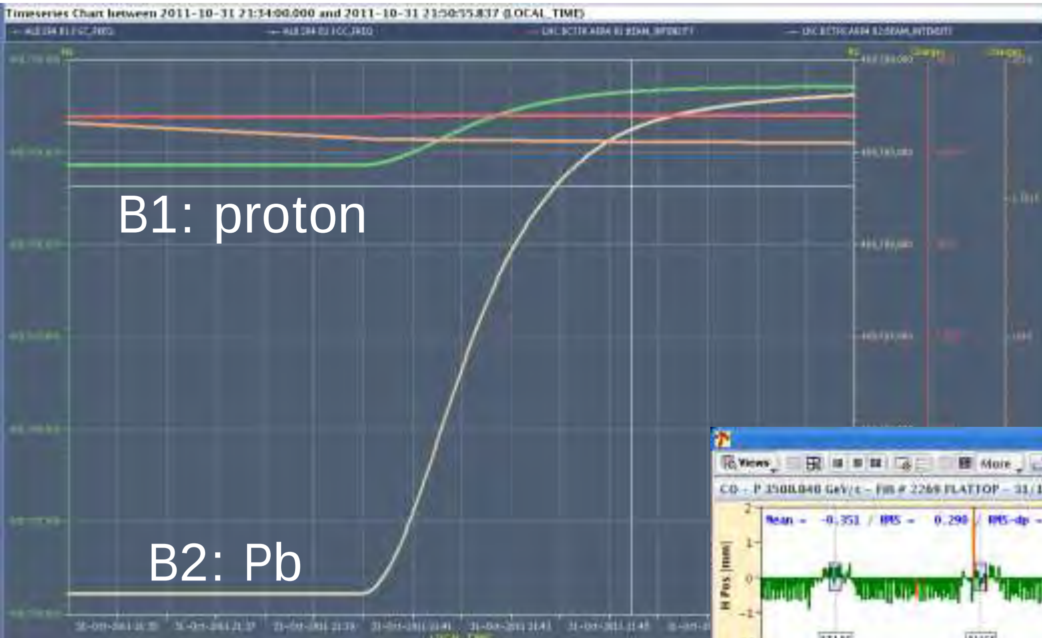
...rrent interlock on 2 dipole and 2 main quadrupole strings.

Extension to more general cases often introduces useful clarifications in system design.

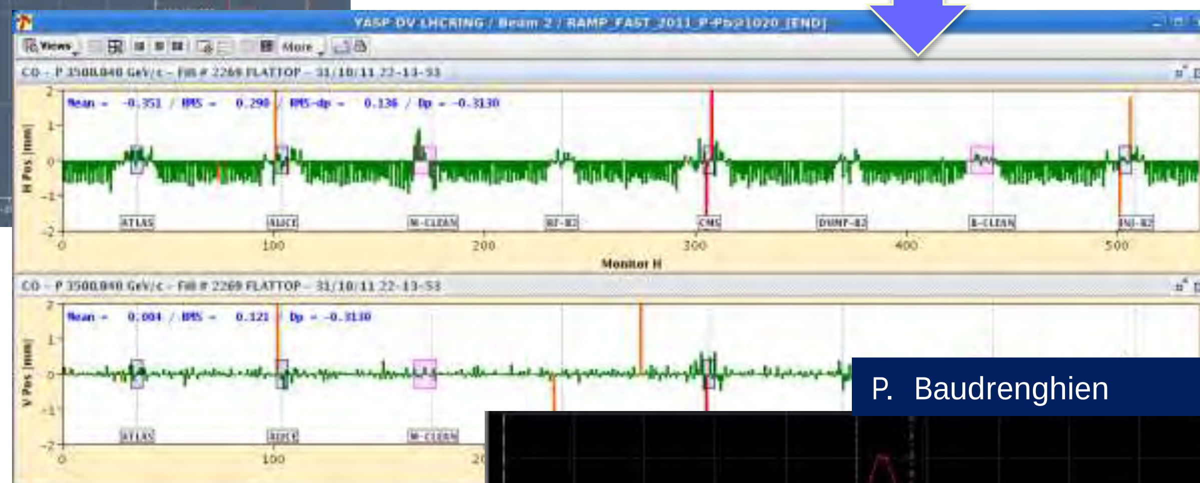
The ... allow injection into a given ring if the settings are consis... with ions or with protons. On top of being an efficient machine protection mechanism, it is flexible – no a priori knowledge on which ring is used for which species. It will also work to avoid injecting ions during p-p runs (and vice-versa).

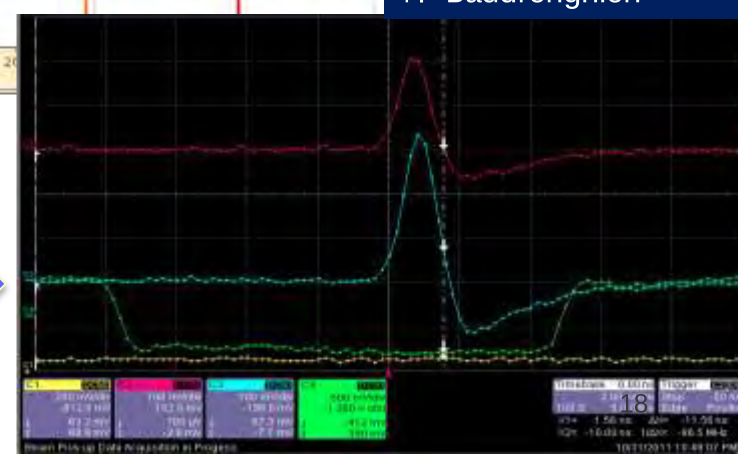
R. Alemany-Fernandez, J. Wenninger

RF: New rephasing and cogging procedure



At top energy, $f_{RF}(B1) = 400.789715$ MHz and $f_{RF}(B2) = 400.789639$ MHz. Locking RF frequencies together imposes offsets of the central trajectories. We chose to get approximately the mean RF frequency, implying that the momentum offset would be ~ $\pm 3\times 10^{-4}$

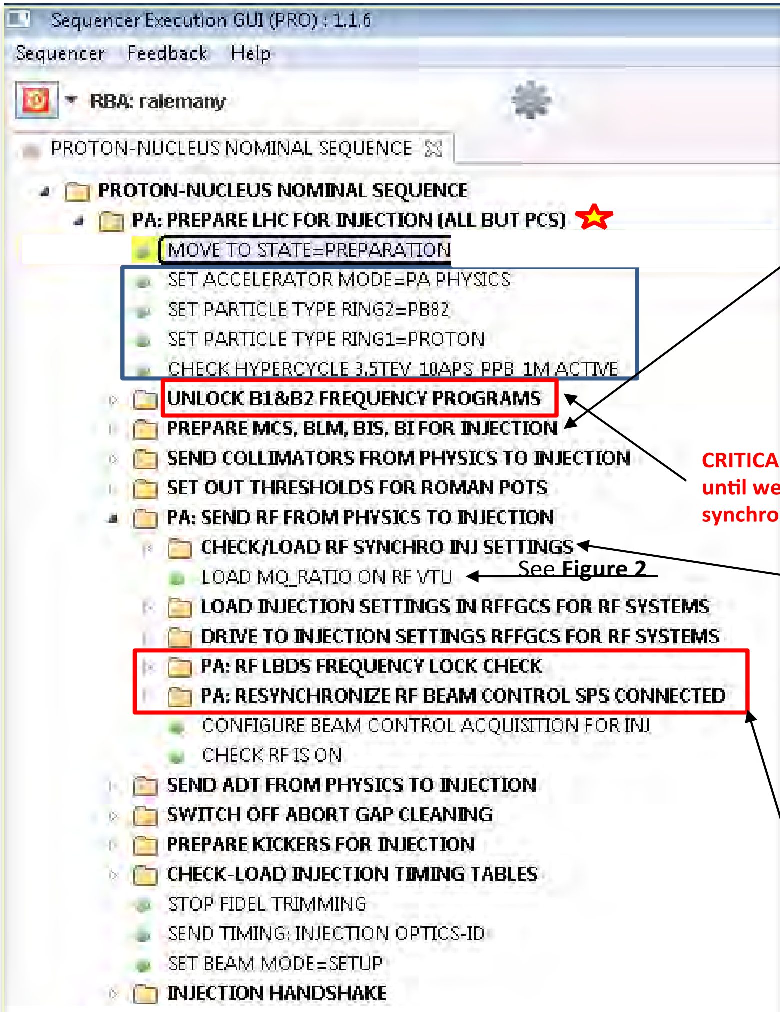


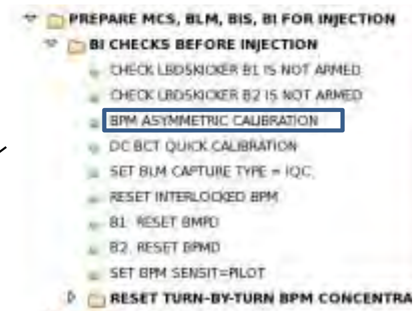


P. Baudrenghien

The final frequency was $f_{RF} = 400.789685$ MHz. After locking the two RF systems together, we used **ATLAS BPTX for the cogging**. The initial shift between buckets 1 of each beam was 19 μs (~9 km). Total time for the "cogging operation" was about 30 min.

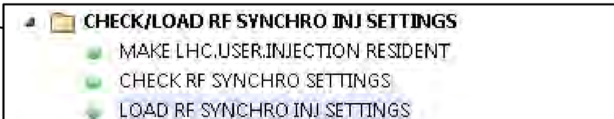
New LHC PROTON-NUCLEUS NOMINAL Sequence





BPM ASYMMETRIC CALIBRATION: Allows to use a different bunch spacing for each ring. For the **100 ns proton** beam **select 125 ns bunch spacing**, for the **single bunches** or the **200 ns Pb** trains select **single bunch calibration**.

CRITICAL: The RF FREQ are unlocked all the time until we lock them after the ramp and the RF synchronization of both beams.



This action has to be done before the SPS-LHC synchronization sub-sequence, since each time we change the **InjPulseDelay#Ring1/2Bt one has to reset the RF synchro crate.** See **Figure 1** for details

As the pp or PbPb nominal sequences except the RF FREQ is never locked at the end of the sub-sequence

R. Alemany-Fernandez

p-Pb feasibility test, Part 1, 16h on 31/10/2011

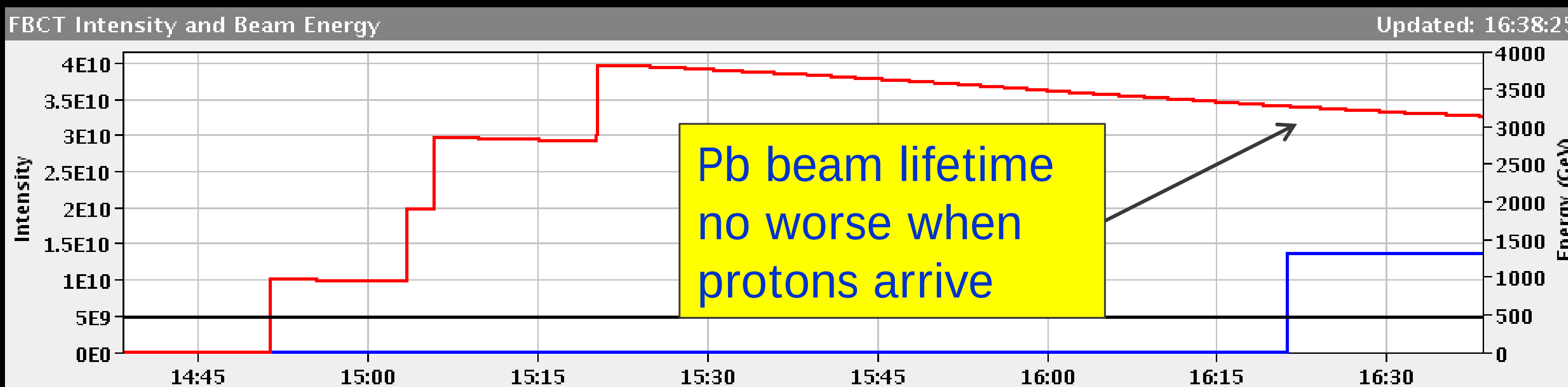
- Several hours setup (timing, many details…)
- Stored 4 Pb bunches (first of year) in presence of 304 p bunches (~10% nominal intensity) at injection
  - Lifetime no worse for presence of p bunches
  - Emittance blow-up, does not appear to be worse than for Pb alone
- Dumped and re-injected 4 fresh Pb
  - Still OK
- Ramped 2 Pb and 2 p bunches, good lifetime
- Re-phased RF (cogging) to move bunches 1 encounter point 9 km back to ATLAS, *no losses*

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

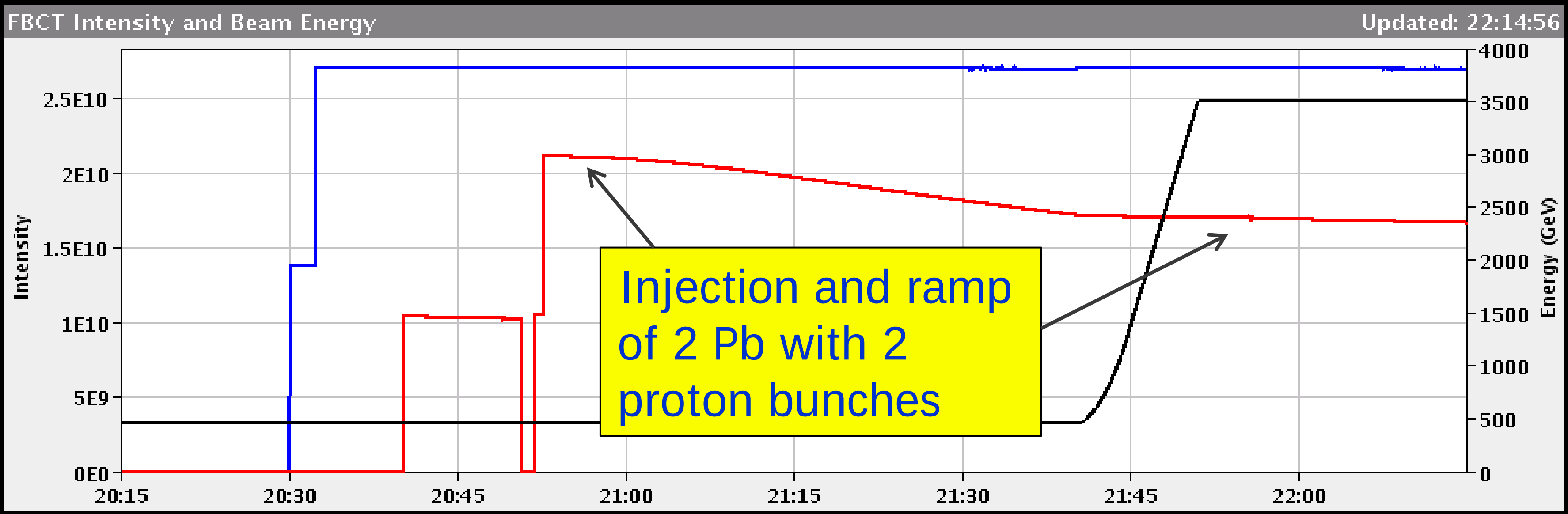
AFS: 100ns_588b_1small_0_0_0_72bpi9inj_pPb

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.

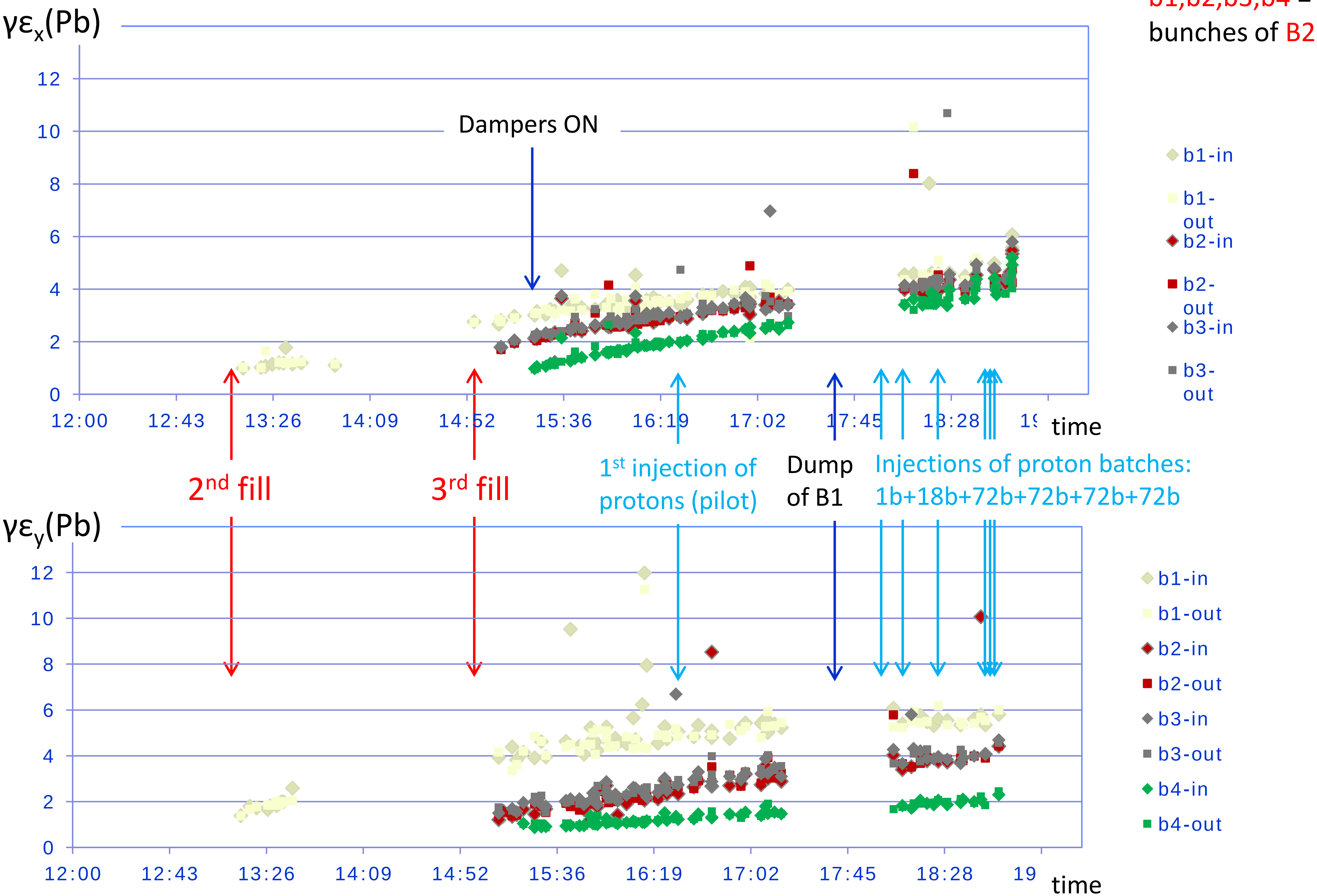
2 bunches each, will try rephasing RF.

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

b1,b2,b3,b4 = bunches of B2



R. Versteegen

P-Pb feasibility test, Part 2

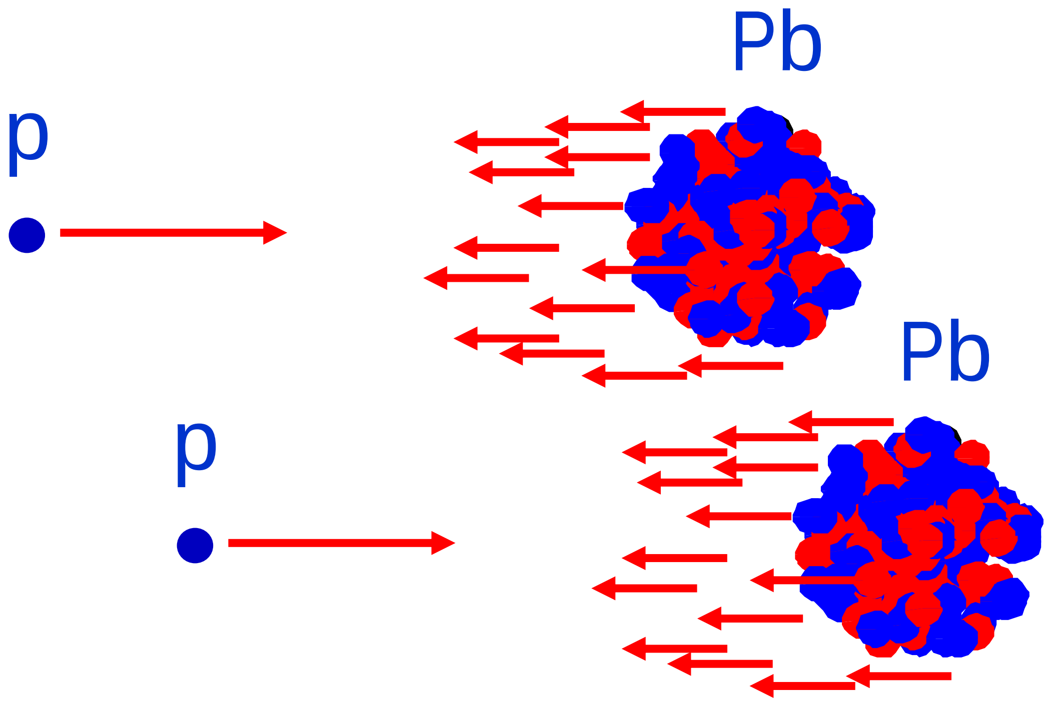
- Scheduled for 16-17 Nov 2011, plan was:
  - Ramp many p and some Pb bunches
    - We have NOT demonstrated this
  - Pilot physics fill with moderate no. of bunches
    - Would have clarified potential of detectors
- Cancelled because of leak in PS proton injection septum
  - Continuing with protons = risk of major leak and ~ 1 week of LHC down time (could have happened in p-p!).
- So … we are basing a physics programme with a complex new operating mode on a single MD
  - OK, but please tolerate a certain uncertainty in luminosity predictions!
- Strong motivation to do Part 2 in Aug-Sep 2012!

Additional Objectives

- Emittance, intensity and luminosity are no longer enough in the CERN of the 21st century.
- We must promote DIVERSITY
  - Conspicuously lacking up to now in the LHC beams
- And we should reach out and inspire ARTISTS …

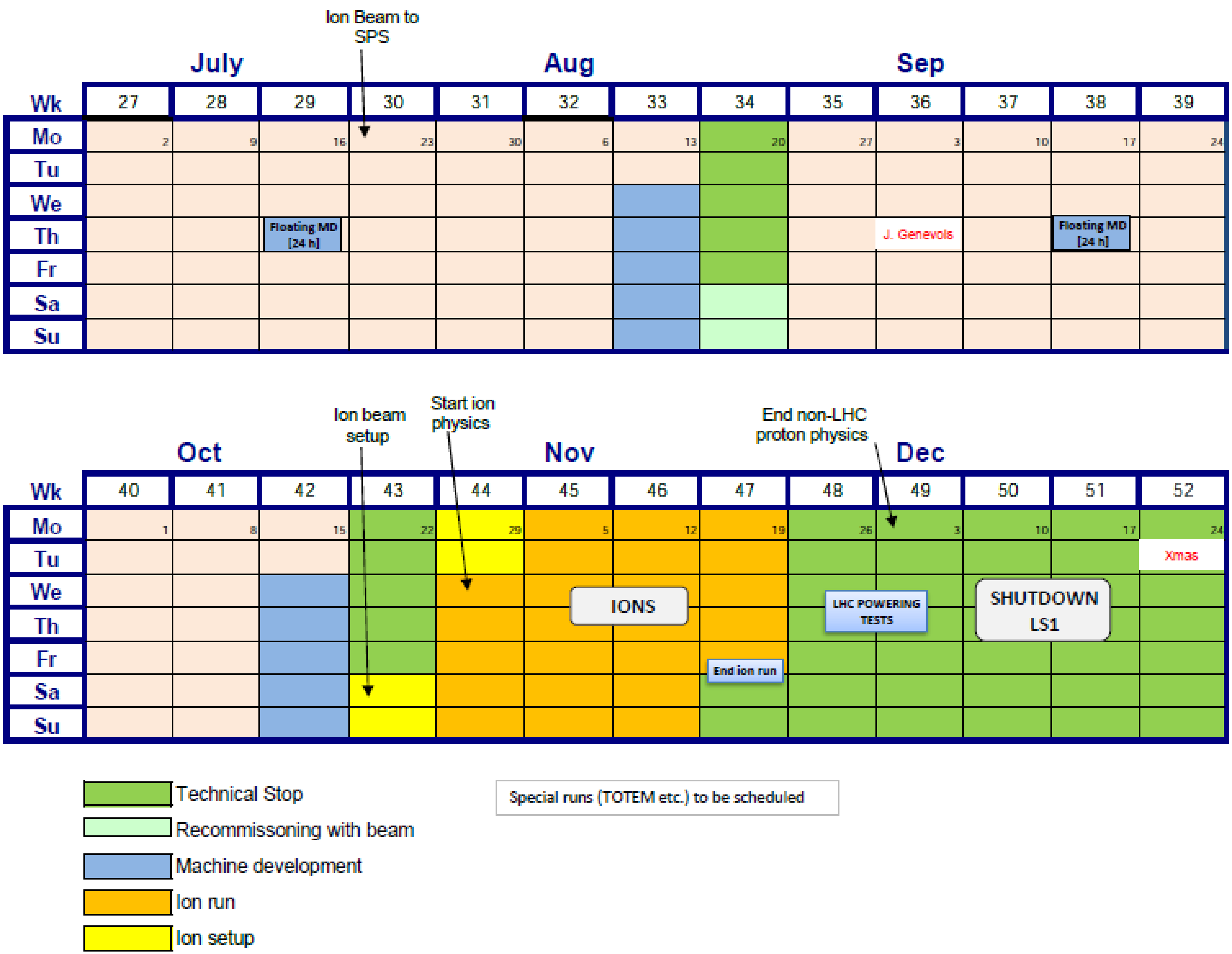
Indeed our work inspired an unknown artist working for the CERN Bulletin to create this moving depiction of an LHC proton discussing behavioural competenc(i)es with his supervisor.

Now the proton's nightmare is coming true.



2012 PROTON-NUCLEUS PHYSICS RUN

Schedule for late 2012



Choice of operating energy for p-Pb in 2012

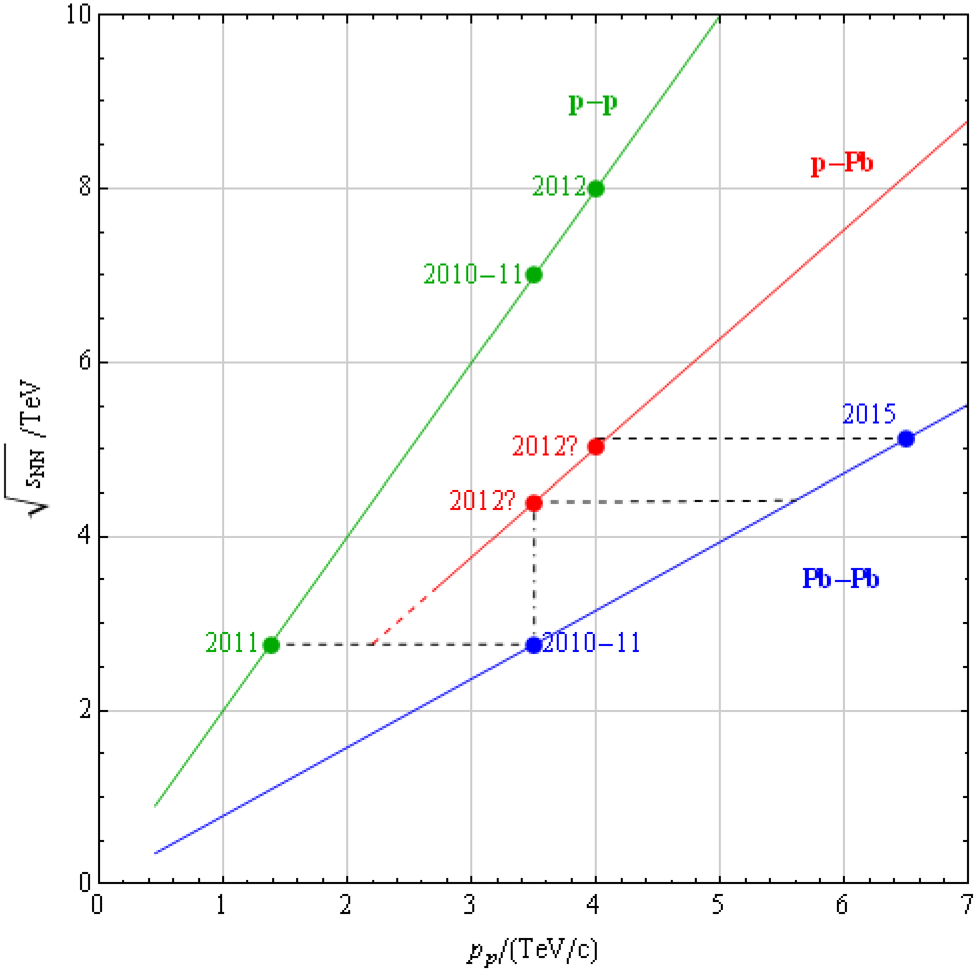
Charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p : colliding nucleon pairs have:

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

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

2.2 *Z* TeV "ideal" but would cost factor ~6-7 in integrated luminosity and exceeds 1 mm orbit limit in LHC arcs.

4 *Z* TeV would be "easiest" from accelerator point of view but experiments have expressed a preference to return to 3.5 Z TeV



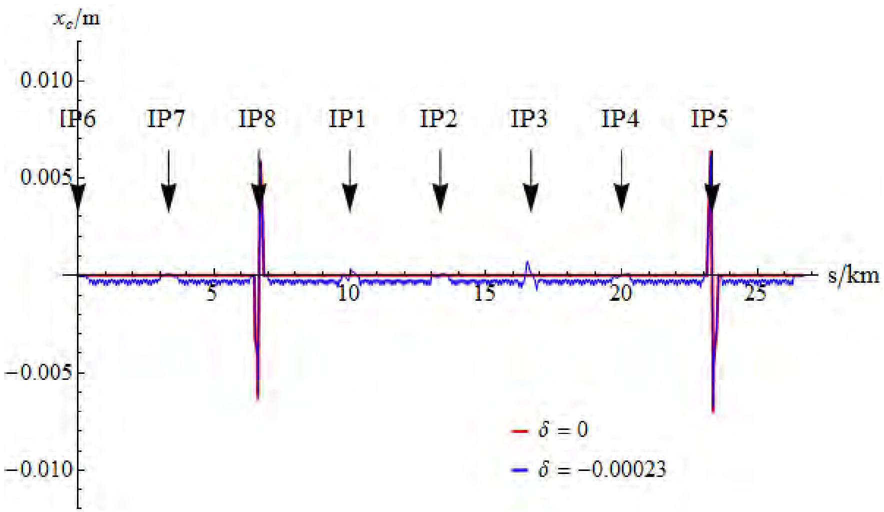
Do we need to finalise the choice of energy this week ?

Costs of experimental choices

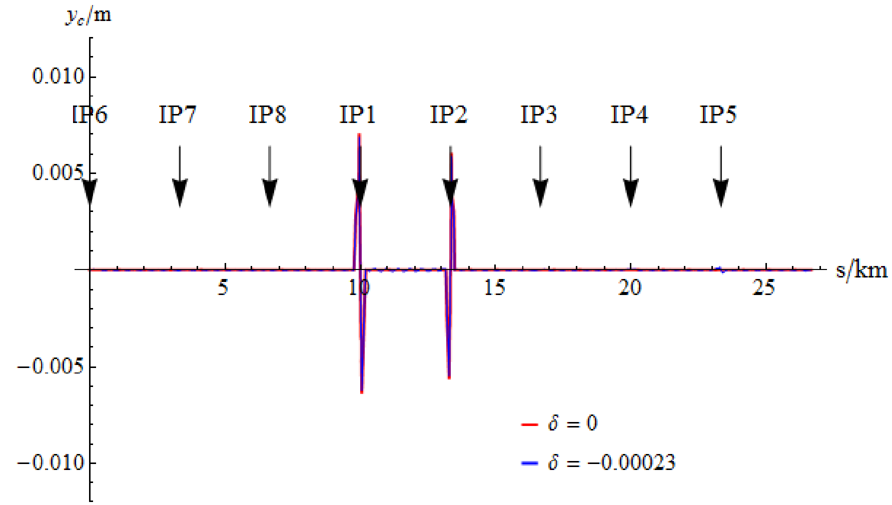
- If p-p run is done at 4 TeV, estimate *extra* ~2 days commissioning to set up p-Pb at 3.5 TeV
  - "New" ramp and squeeze in all IRs
  - Higher β*
  - Larger off-momentum orbits etc
- Reversal from p-Pb to Pb-p: about 1 day
- Two polarity reversals (if requested) total <1 day

Central orbits for β* = (0.6, 0.6, 0.6, 3.0)

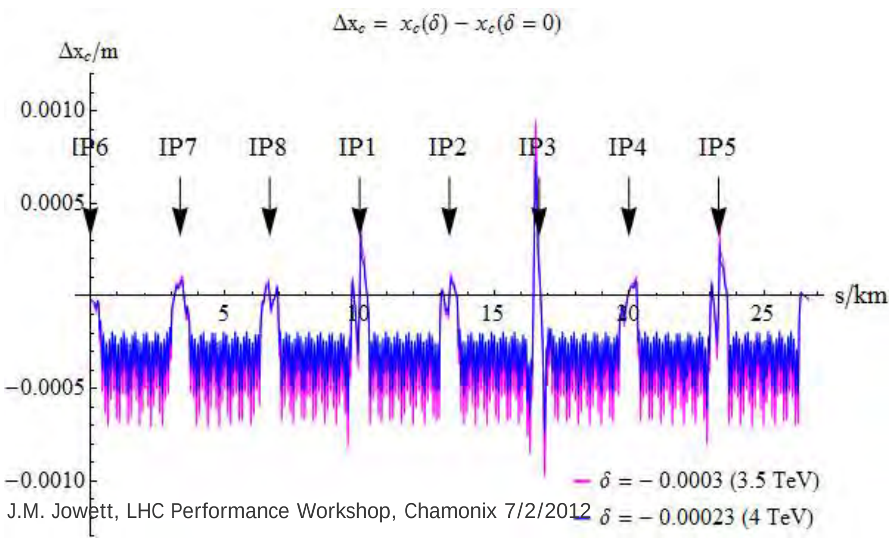
Horizontal central trajectory at 4 TeV



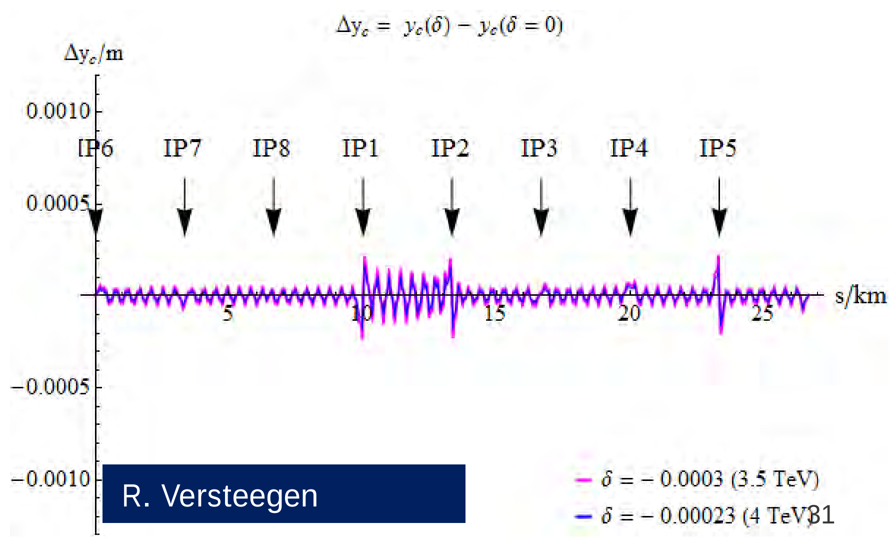
Vertical central trajectory at 4 TeV



Shift of the horizontal central trajectory, 3.5 TeV vs. 4 TeV

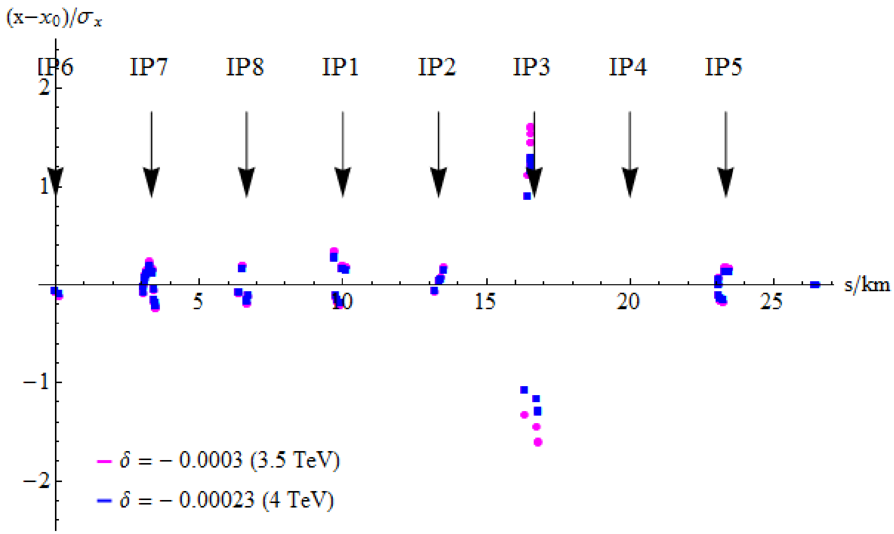


Shift of the vertical central trajectory , 3.5 TeV vs. 4 TeV



R. Versteegen

Horizontal plane

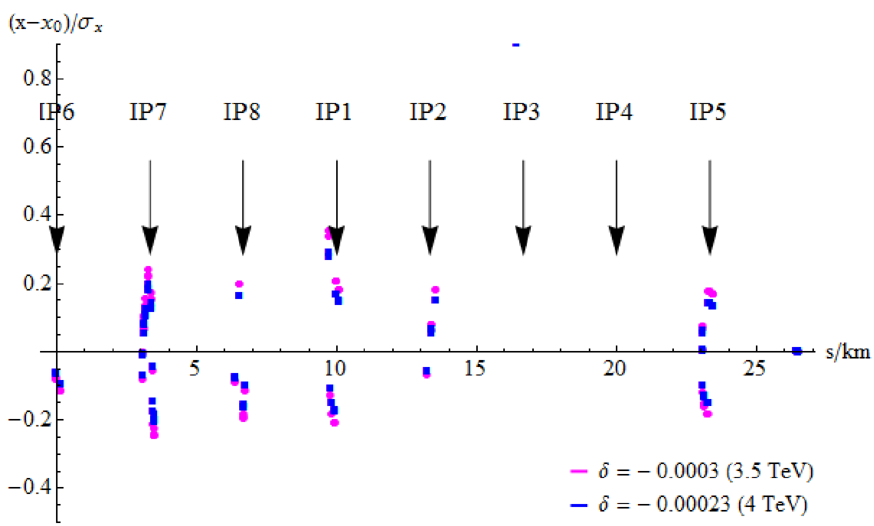


Orbit at collimators, 3.5 TeV vs. 4 TeV

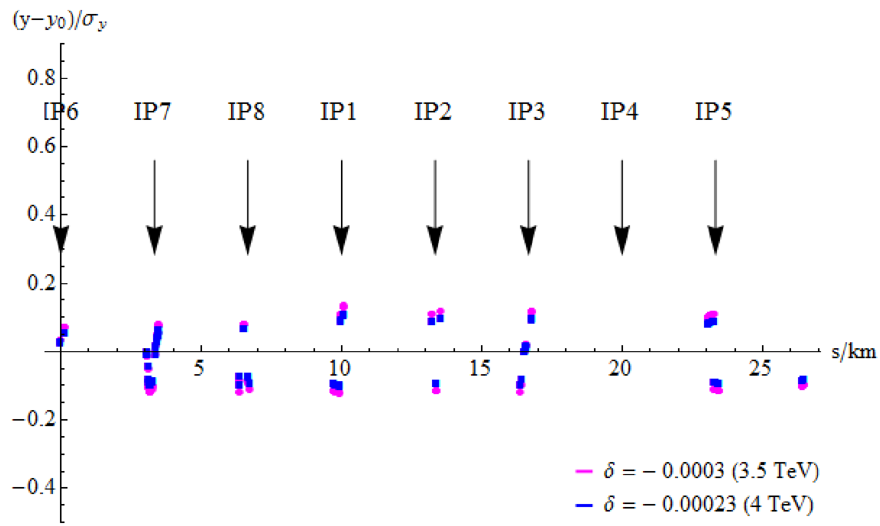
x = orbit with δ offset,

x_0= orbit with zero offset

Horizontal plane, zoomed in



Vertical plane

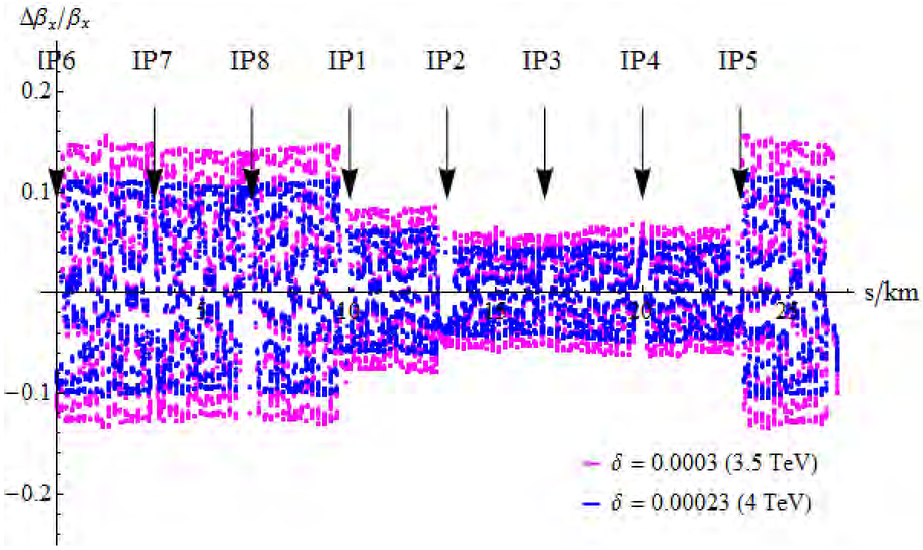


R. Versteegen

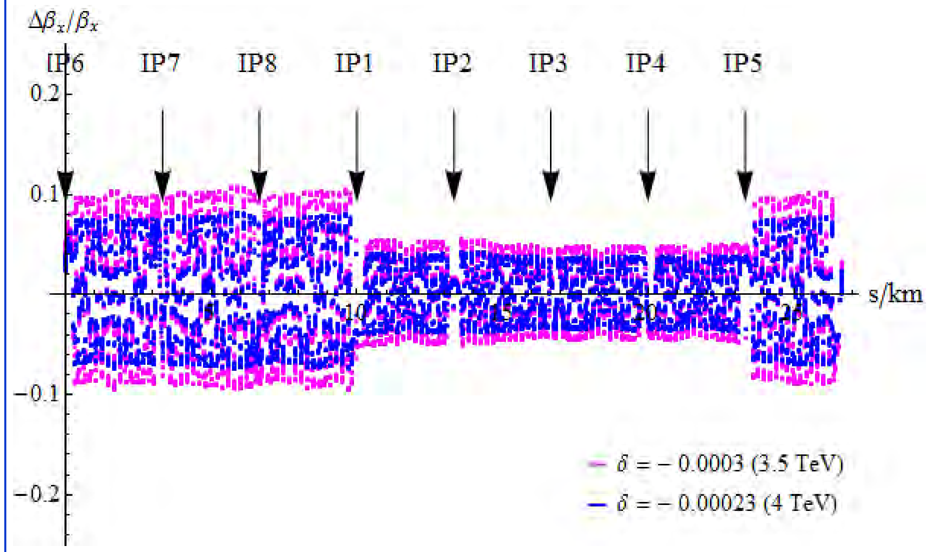
Δβ/β for β* = (0.6, 0.6, 0.6, 3.0), 3.5 TeV vs. 4 TeV

$$\frac{\Delta\beta}{\beta} = \frac{\beta(\delta) - \beta(\delta = 0)}{\beta(\delta = 0)}$$

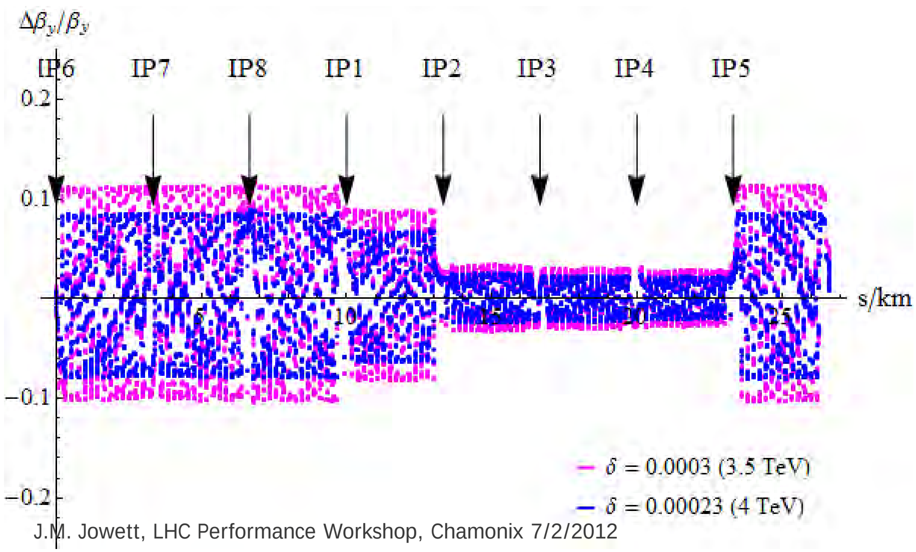
B1, Horizontal plane



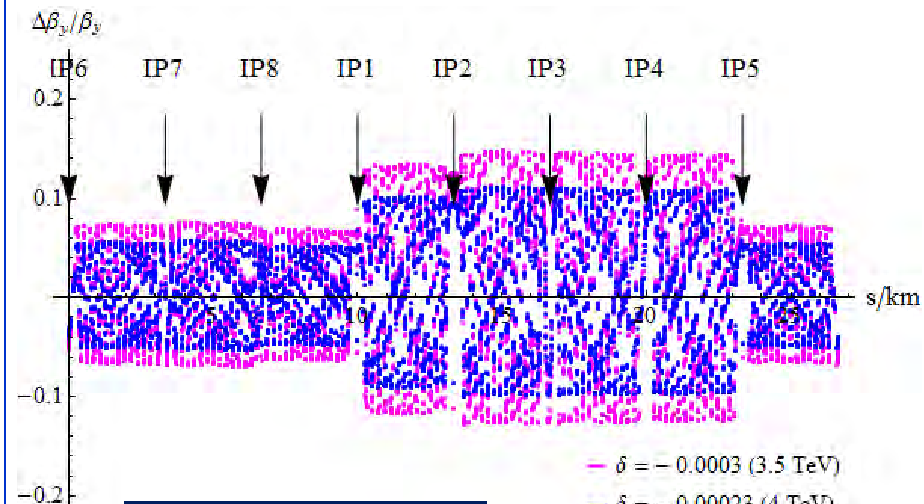
B2, Horizontal plane



B1, Vertical plane

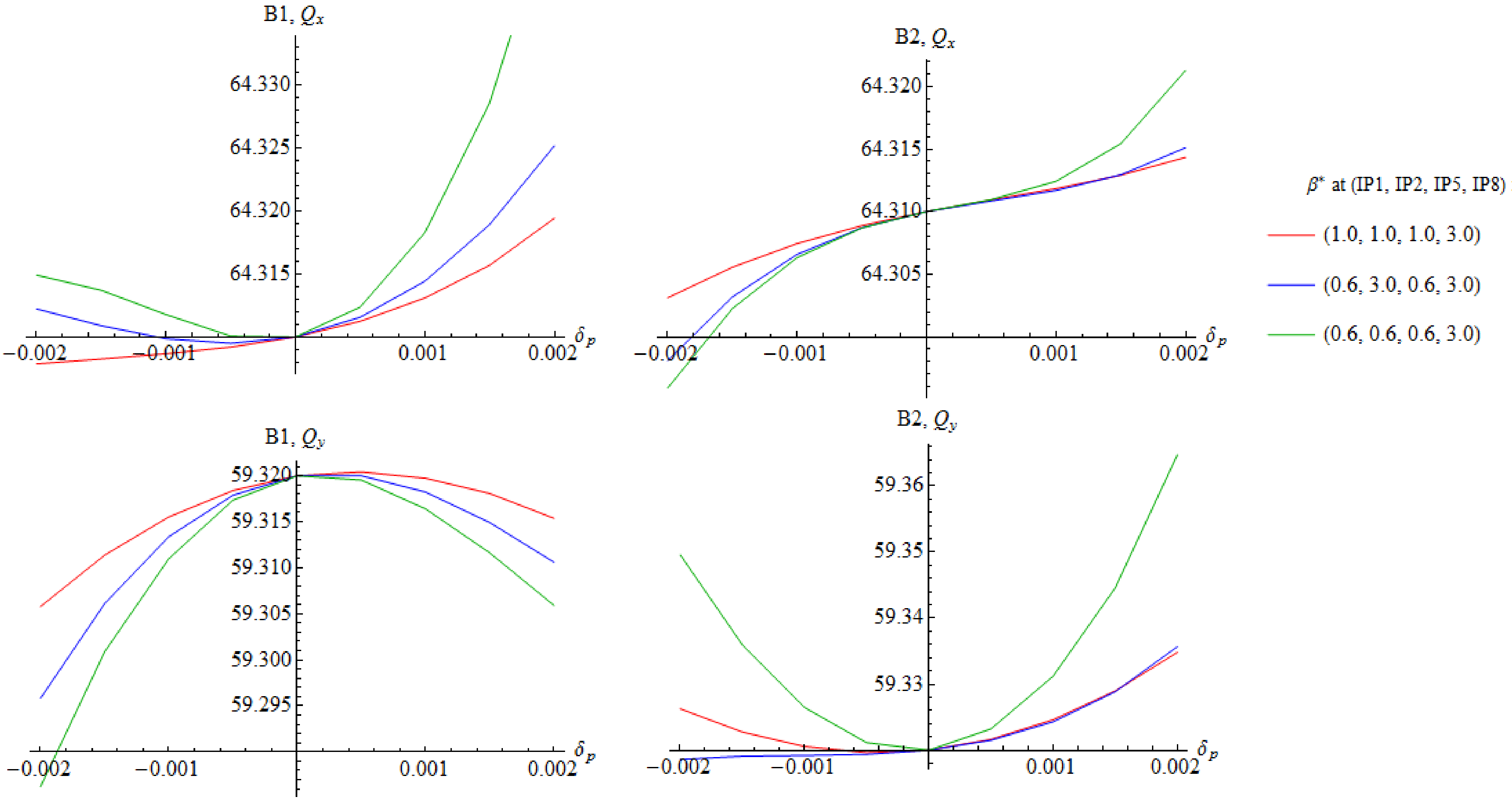


B2, Vertical plane



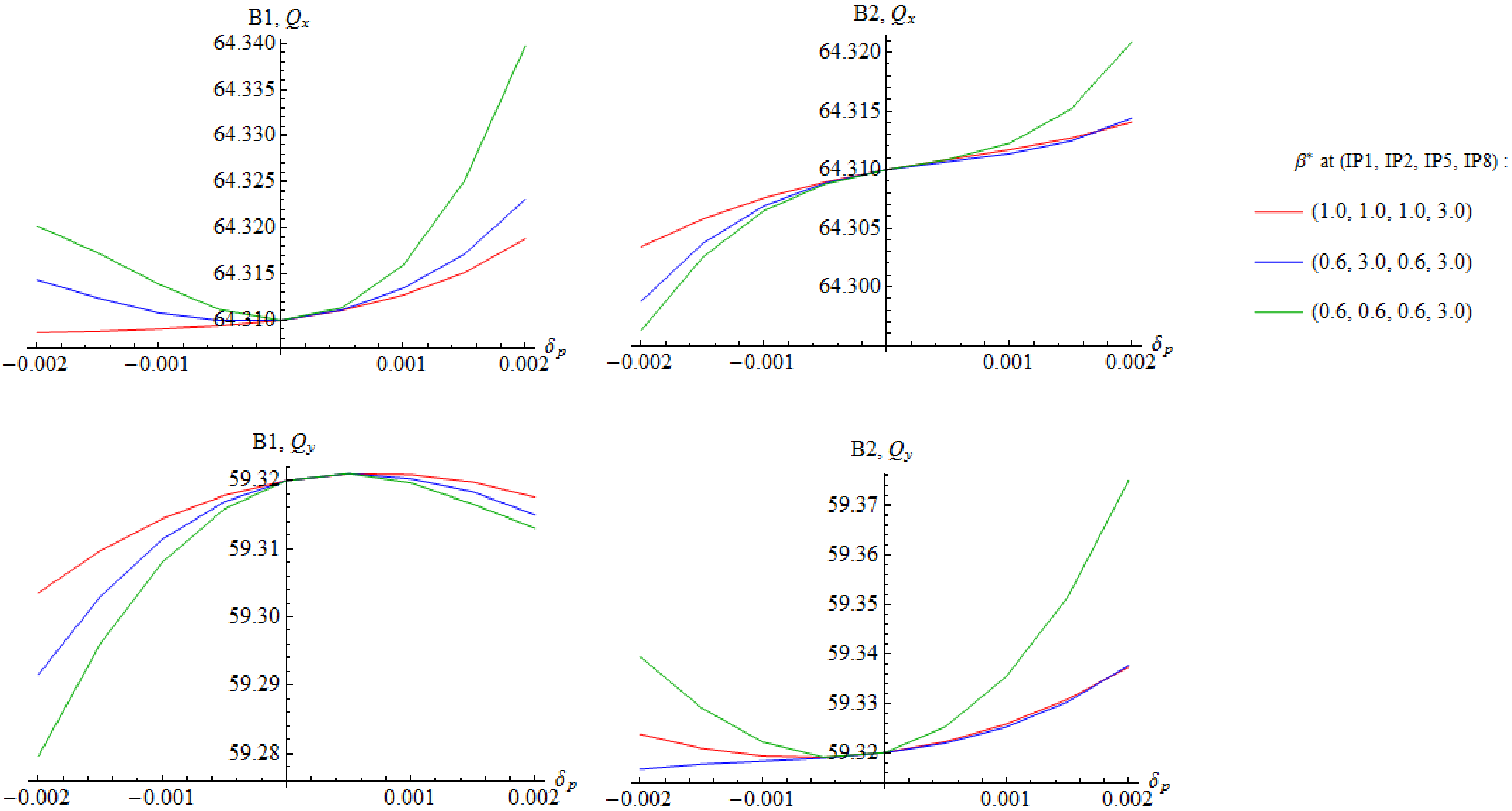
R. Versteegen

Tune vs energy offset at 4 TeV, chromaticity matching on momentum



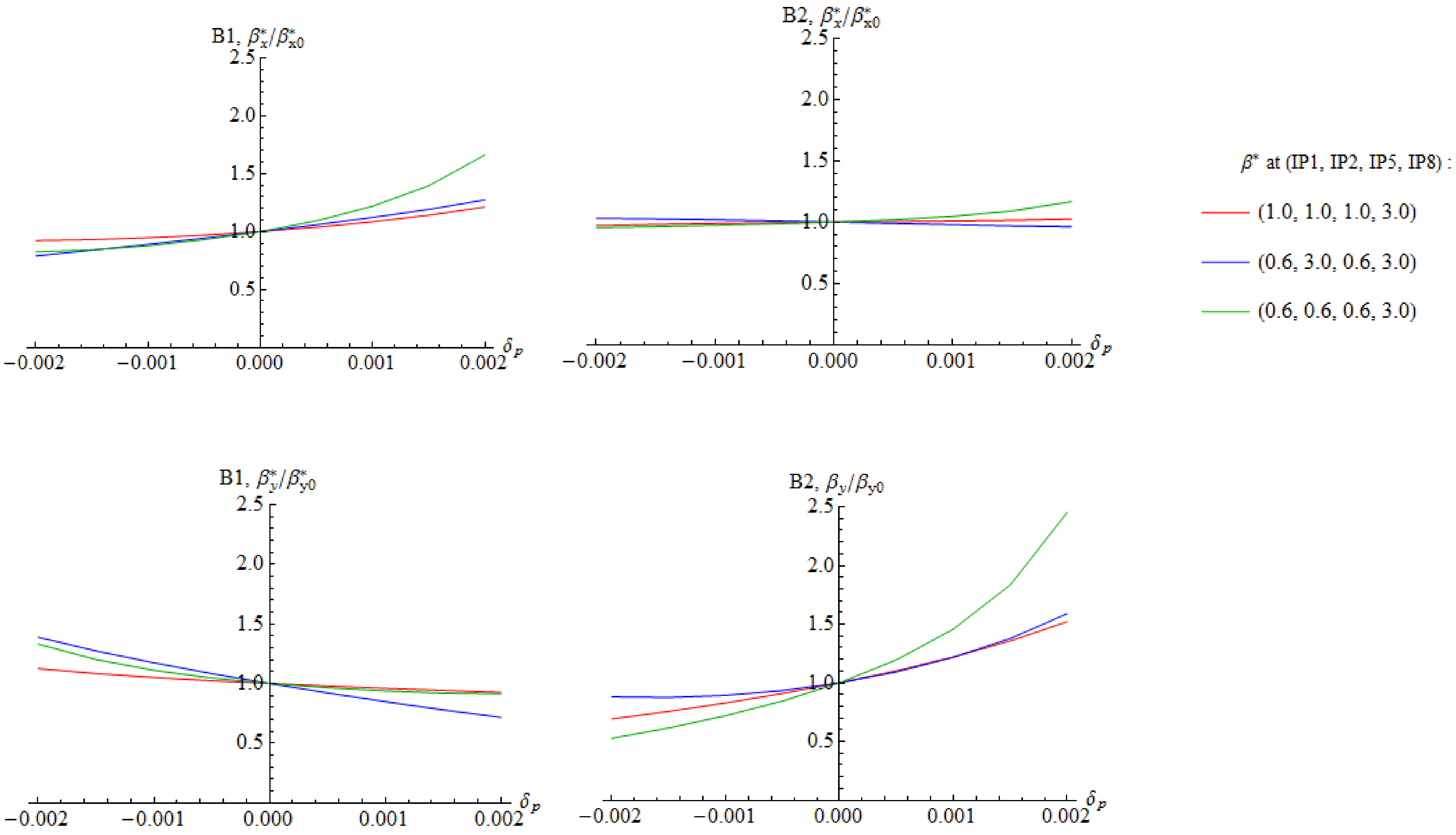
R. Versteegen

Tune vs energy offset at 4 TeV for a matching off momentum for each beam separately



R. Versteegen

β* vs energy offset at IP2, at 4 TeV, chromaticity matched off-momentum



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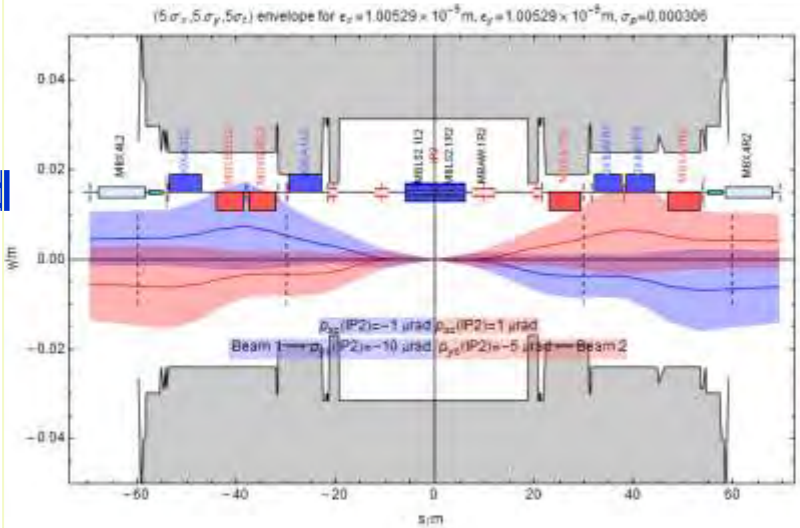
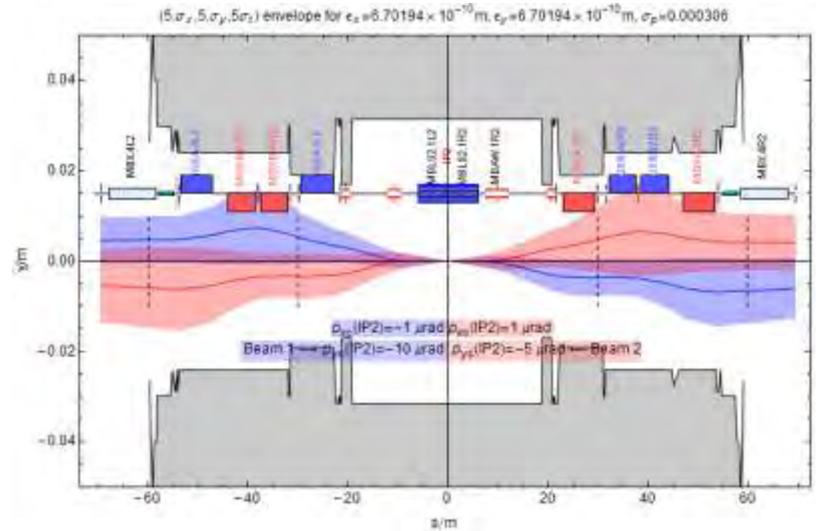
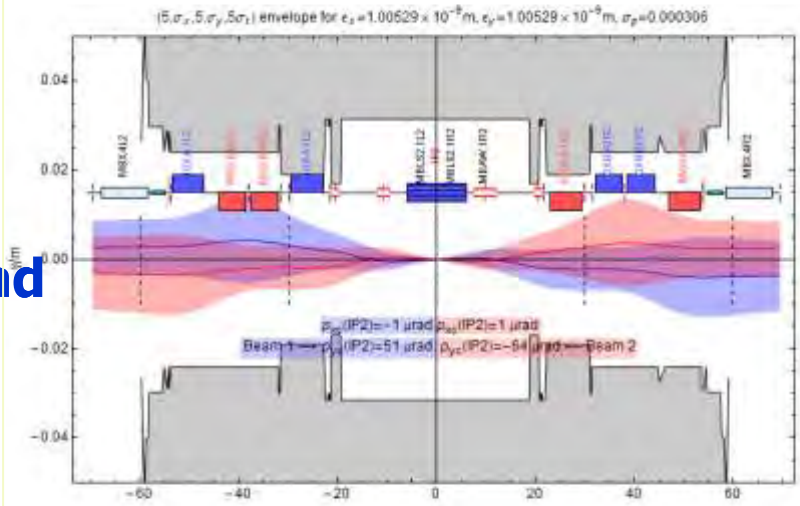
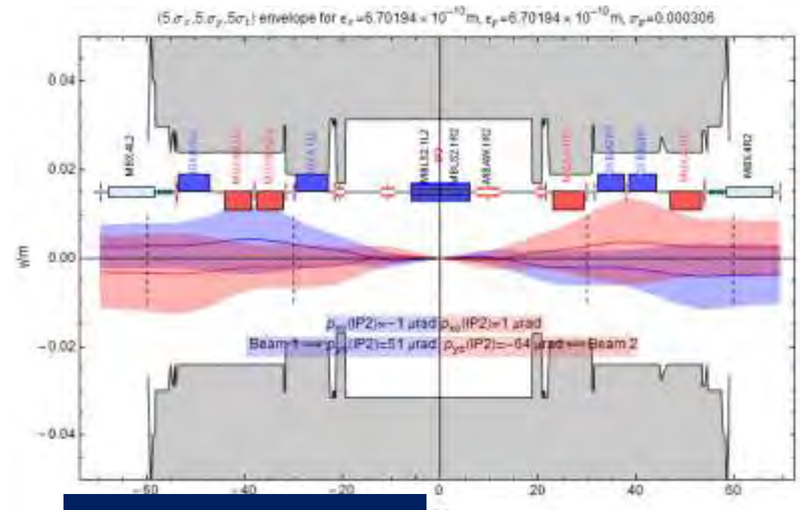
Vertical envelopes in IR2,

β*=0.7m, 3.5 TeV, $(\gamma\varepsilon)_{Pb}$=1.5μm, bunch spacing=200ns

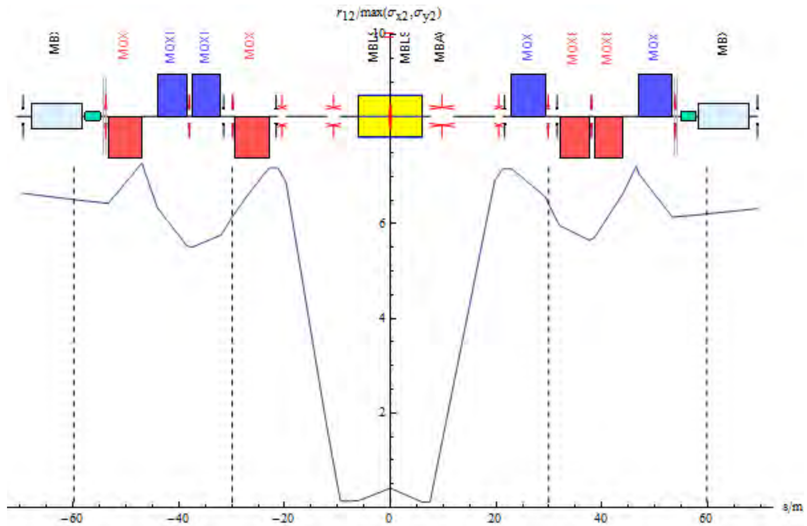
x-ing angle	**$(\gamma\varepsilon)_p$=3.75μm**	**$(\gamma\varepsilon)_p$=2.5μm**
0 μrad		
60 μrad		

R. Versteegen

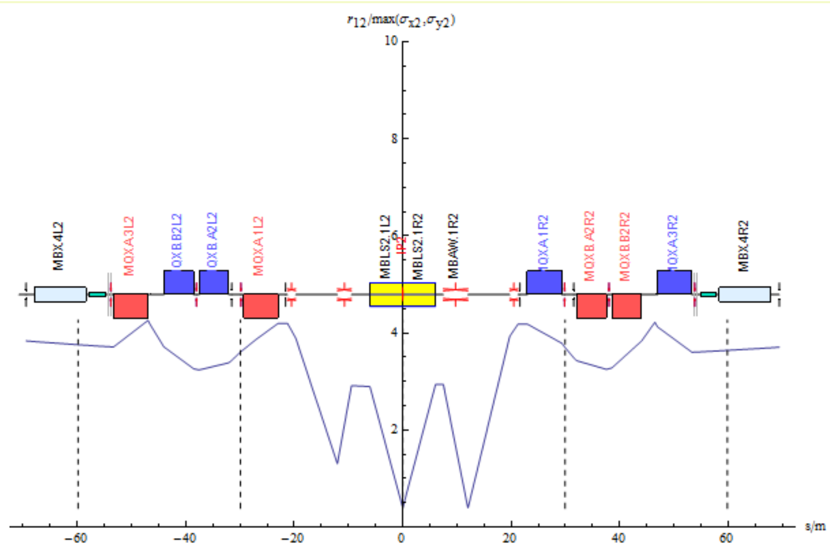
Separation in IR2 in terms of σ(B2),

β*=0.7m, 3.5 TeV, $(\gamma\varepsilon)_p$ = 2.5μm, $(\gamma\varepsilon)_{Pb}$=1.5μm, bunch spacing=200ns

0 μrad



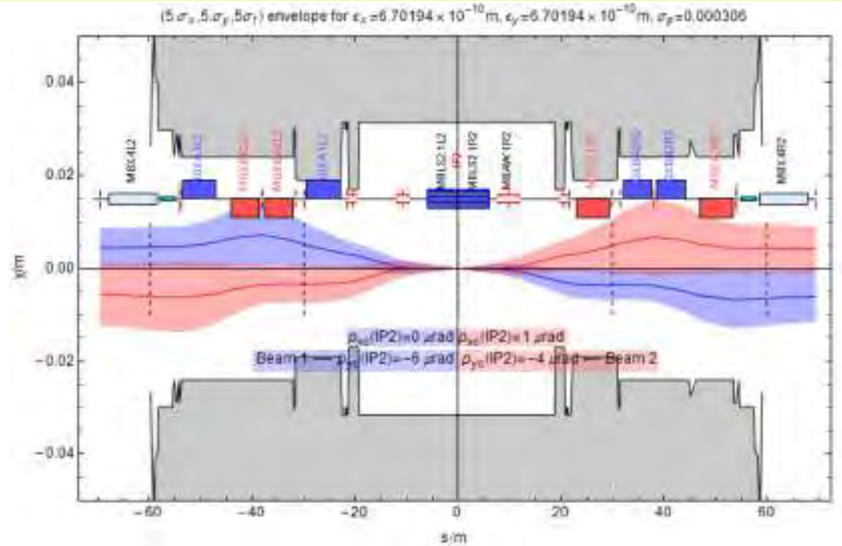
60 μrad



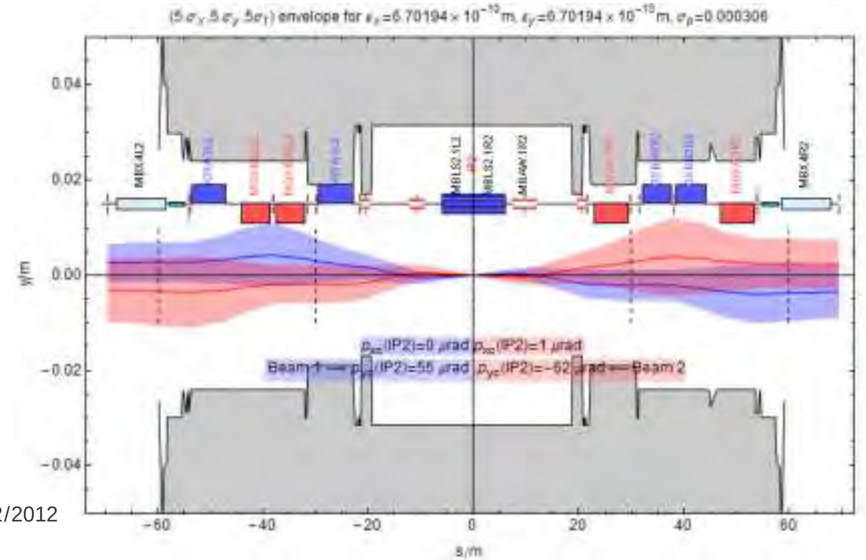
Vertical envelopes in IR2,

β*=1.0m, 3.5 TeV , $(\gamma\varepsilon)_p$=2.5μm, $(\gamma\varepsilon)_{Pb}$=1.5μm, bunch spacing=200ns

0 μrad



60 μrad

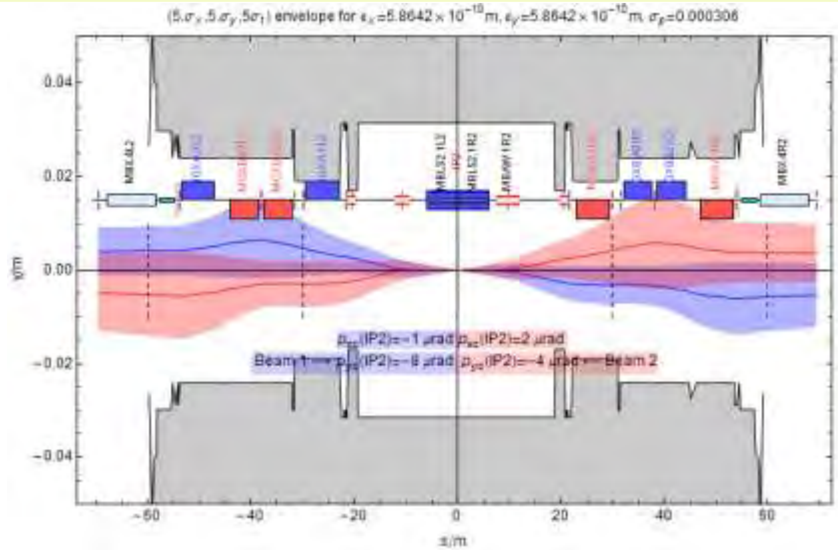


R. Versteegen

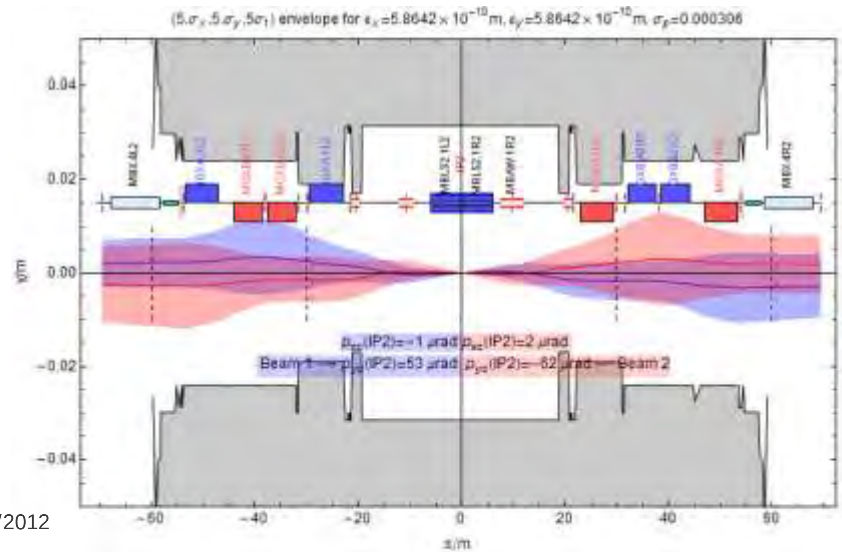
Vertical envelopes in IR2,

β*=0.6m, 4. TeV , $(\gamma\varepsilon)_p$=2.5μm, $(\gamma\varepsilon)_{Pb}$=1.5μm, bunch spacing=200ns

0 μrad



60 μrad



Injection schemes

- Need filling schemes for p and Pb to produce matching bunch trains in LHC
  - Prepared for 100 ns in 2011
  - Must operate both PS Booster, LEIR, PS to provide identical batches in SPS
- New flexible solution (S. Hancock, D. Manglunki) provides both 100 ns and 200 ns in SPS/LHC
  - Expect higher Nb with 200 ns (why we used it in 2011, but now the gain is less ...)
  - See talk by D. Manglunki Thursday

LHCb joins in ...

- Up till now the heavy-ion filling schemes provided no collisions at IP8

$$s_{IP8} = \frac{1039}{1188} C = \frac{7}{8} C - 6\lambda_{RF}$$

- Discussions in LPC 3/2/2012
- LHCb optics kept at $\beta^{*}=3$ m
  - Factor 4-5 down in luminosity
- Filling schemes must be adapted to provide collisions at IP8
  - Shift 1 or more batches ?
  - Reduce luminosity for others – how much ?
  - Another factor ~5-12 down for LHCb
  - Detailed schemes to be worked out
- Further motivation for early MD/pilot physics fill

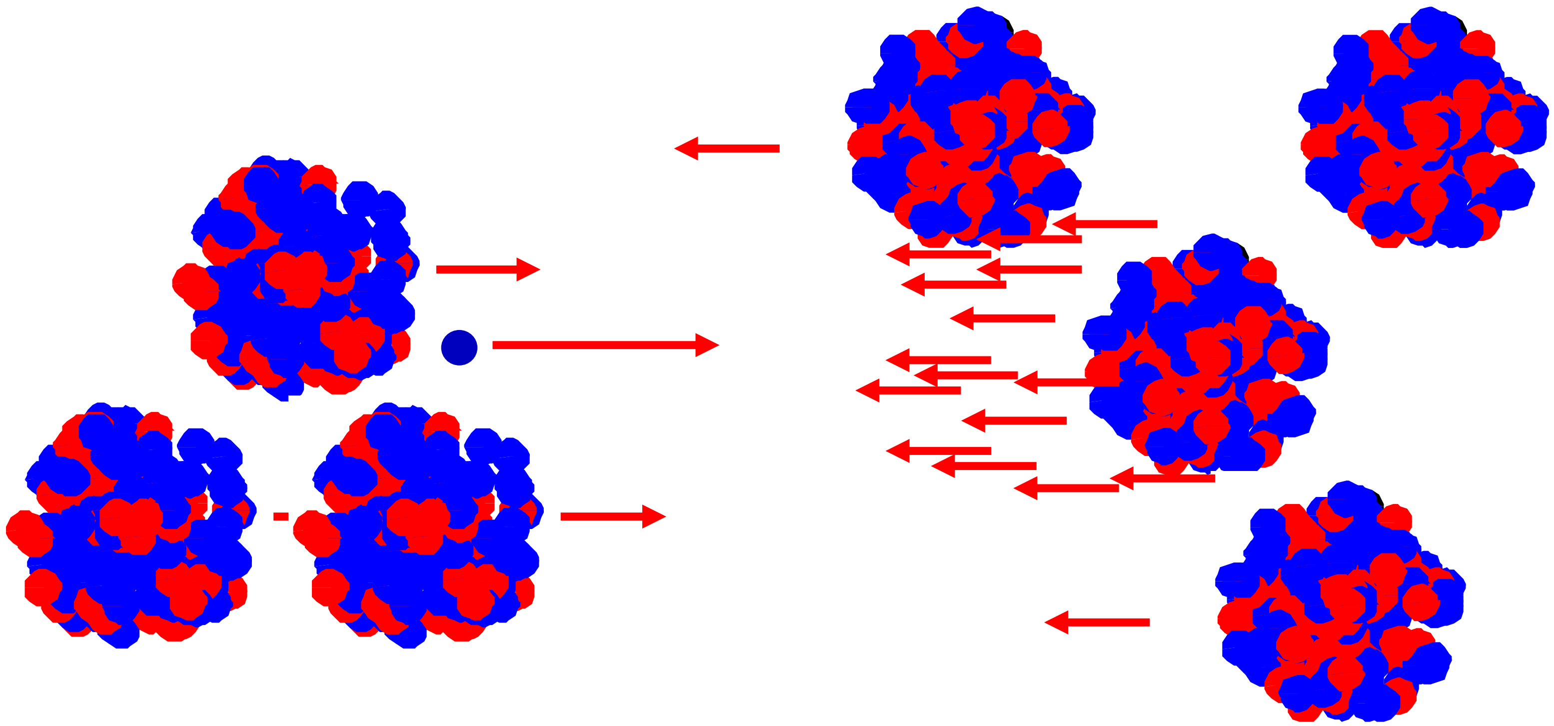
Target p-Pb performance in 2012 (ATLAS/CMS)

Main choice:	**Units**	**200 ns**	**200ns**	**100 ns**	**100**
Beam energy/(Z TeV)	*Z* TeV	3.5	4	3.5	4
Colliding bunches		356	356	550	550
β^*	m	0.7	0.6	0.7	0.6
Emittance protons	μm	3.75	3.75	3.75	3.75
Emittance Pb	μm	1.5	1.5	1.5	1.5
Pb/bunch	10^8	1.2	1.2	0.8	0.8
p/bunch	10^{10}	1.15	1.15	1.15	1.15
Initial Luminosity L_0	10^{28} cm^{-2} s^{-1}	**6.2**	**8.3**	**6.4**	**8.5**
Operating days		**22**	**24**	**22**	**24**
Difficulty (subjective)		**0.9**	**1**	**0.9**	**1**
Integrated luminosity	μb^{-1}	**15.4**	**22.4**	**15.9**	**23.1**

Integrate luminosity by scaling from 2011.
Average Pb bunch intensities from best 2011 experience.
Proton bunch intensities conservative, another factor 10 ????
Proton emittance conservative, another factor 1.37 ??
Untested moving encounter effects, possible reduction factor 0.1 ??

More predictions for p-Pb (no detail)

- Bound-free pair production rate will be reduced to a few % of the Pb-Pb rate
- Similar scaling for electromagnetic dissociation
  - Same equivalent photon spectrum of proton
- Luminosity lifetime better than Pb-Pb
  - Dominated by IBS of Pb beam or, maybe, beam-beam
- Luminosity losses in dispersion suppressors around experiments and in IR3 much reduced
  - Less irradiation, R2E, etc.



LHC HEAVY-ION PROGRAMME UP TO 2022 (LS3)

Status of this plan

- An implementation of the (long ago) approved physics programme consistent with plans for the CERN accelerator complex in coming decade
  - Takes account of p-p operation, shutdowns, SPS HI programme, etc.
  - March 2011: Agreed among ATS Director, ALICE management, S. Maury, JMJ
  - Presented to 2011 IEFC workshop
  - Presented to LHC Machine Committee 20/4/2011
  - Presented at EPS-HEP 2011 Conference, Grenoble, July 2011
- Some flexibility still available
- Next slide presents an update incorporating new knowledge from the 2011 Pb-Pb run

LHC Heavy-Ion Programme to 2021

2013-14		Long shutdown LS1, increase *E*
2015-16	**Pb-Pb**	Design luminosity, ~ 250 μb^{-1}/year, Luminosity levelling?
2017	**p-Pb *or* Pb-Pb**	P-Pb to enhance 2015-16 data. Energy? Pb-Pb if μb^{-1} still needed
2018		LS2: ? install DS collimators to protect magnets ? ALICE upgrade for 6 × design luminosity
2019	**Pb-Pb**	Beyond design luminosity … as far as we can. Reduce bunch spacing?
2020	**p-Pb**	
2021	**Ar-Ar**	Intensity to be seen from injector commissioning for SPS fixed target. Demanding collimation requirements?
2022		LS3, upgrades ?? Stochastic cooling ??
>2022		Talks on Thursday

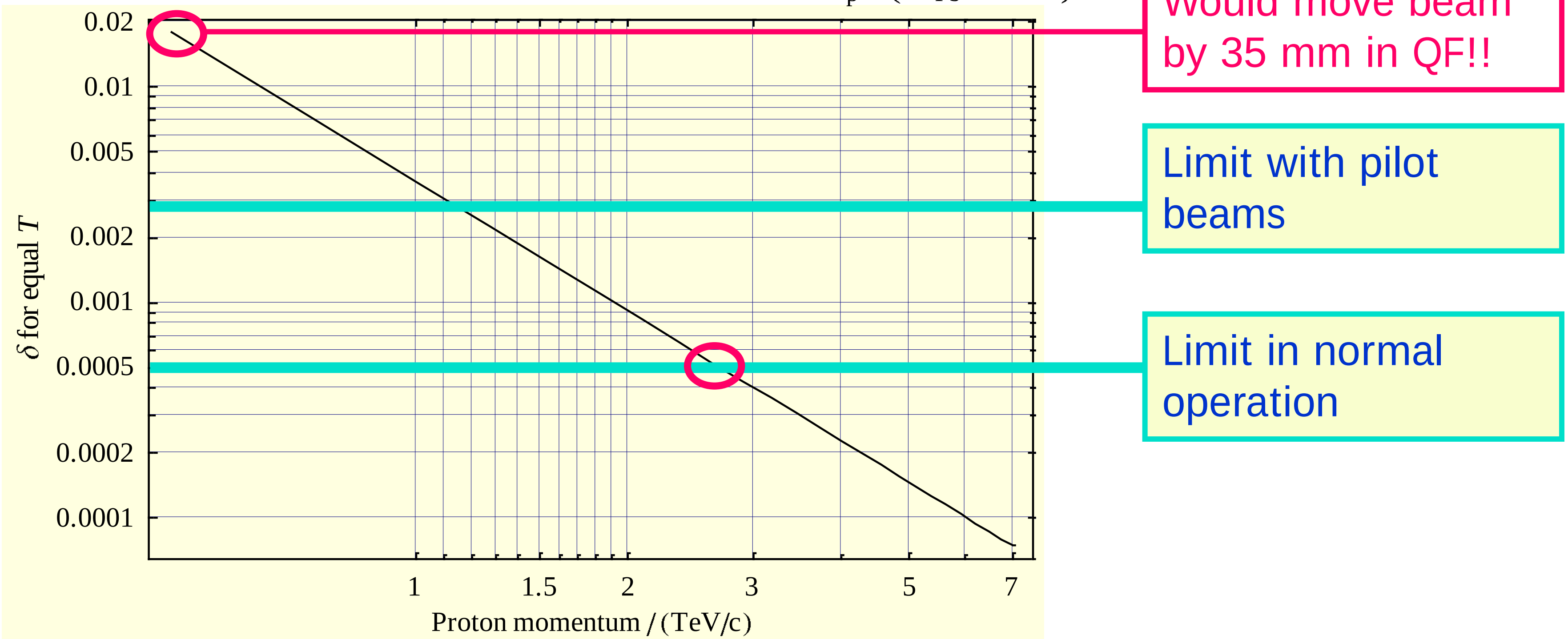
Summary

- We learned a lot from 2011 Pb-Pb run
- We are ready for a p-Pb physics run in 2012
  - Some more discussion with experiments to determine run conditions
- Important preparatory steps:
  - Part 2 of feasibility test (multi-bunch ramp + pilot physics) in Aug-Sep
  - Aperture measurements in IR2
  - RF re-phasing MD
- Heavy-ion programme up to LS3
  - Performance prospects look ever better
  - Need focus on key upgrades

BACKUP SLIDES

Momentum offset required to equalise frequencies

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

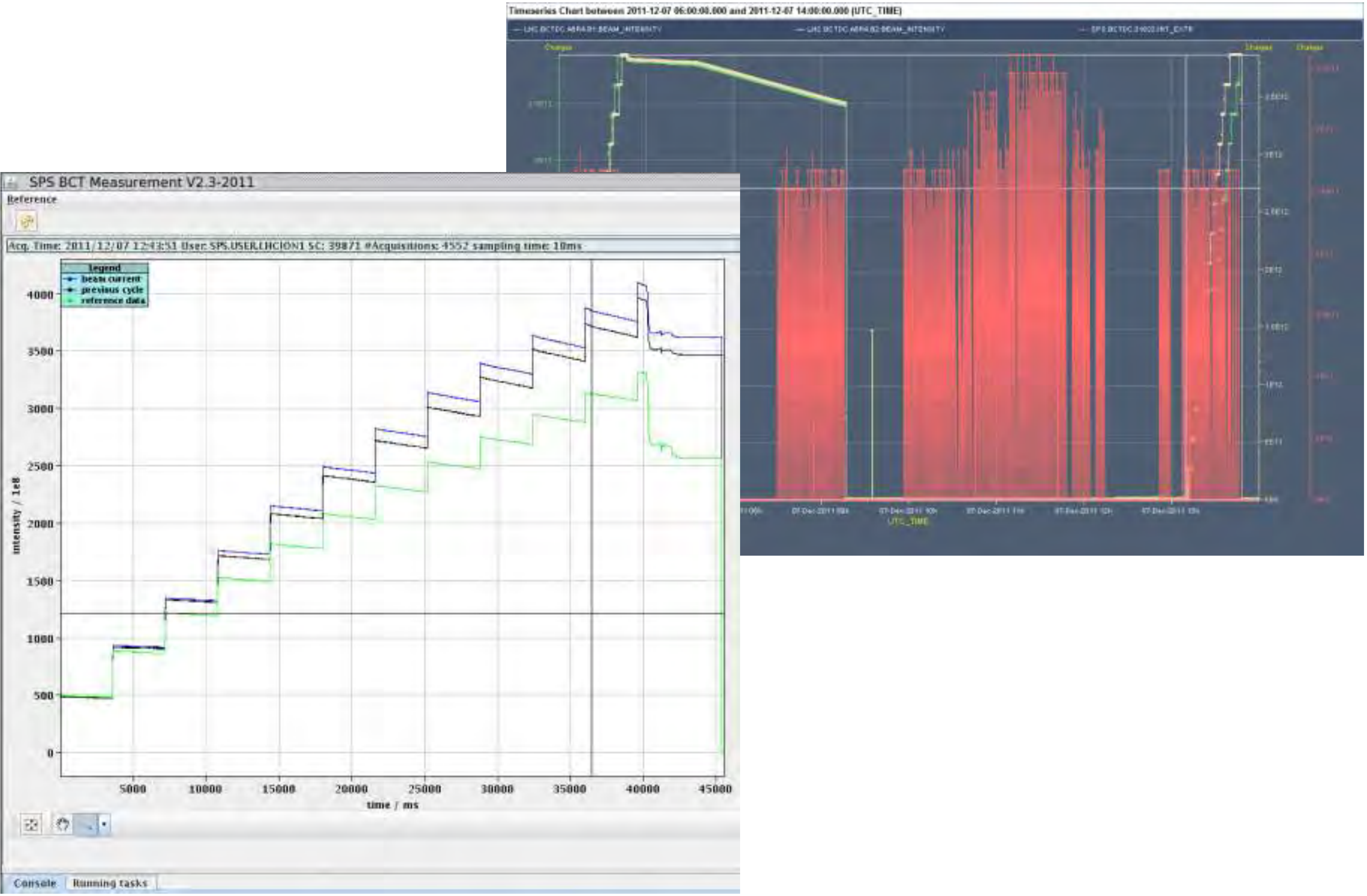


Revolution frequencies must be equal for collisions.

⇒Lower limit on energy of p-Pb collisions, $E_p \sim 2.7$ TeV

Energy where RF frequencies can become equal in ramp.

SPS 100 ns Pb intensity 7 Dec 2011



BPMs in p-Pb (1)

- Cross-talk between the pick-ups of the two channels (one per beam) of the strip-line monitors used in the straight sections.
- Although by design both channels should not suffer from it because in the ideal case the beam and signal travel at the same speed, therefore the signal at the DOWNSTREAM port cancels out completely, while the signal at the UPSTREAM port consists in the superposition of the positive beam current distribution and its negative reflection. However, in reality, due to mechanical and electrical imperfections, the complete cancellation is not possible, limiting the directivity of the monitor (to 20 dB in LHC).
- Since LHC has counter rotating beams, each port suffers from the superposition of the UPSTREAM signal of one beam and the DOWNSTREAM signal of the other beam. If both beams cross the monitor at the same time, both signal will perfectly overlap during the acquisition producing an error.

R. Alemany-Fernandez

BPMs in p-Pb (2)

- Another type of problem is the false triggers from the non-desired signal, producing an acquisition of the non-desired beam. This wrong acquisition will average with all the other "desired" acquisition in the orbit calculation, producing an error in the orbit calculation.
- The straight forward solution to this would be to mask those monitors during the operation, but experience has shown that the orbit correction is not very good and the feedback system can induce "unphysical" corrections of the orbit.
- The appropriate **solution** is to use one functionality of the BMPM called the "synchronous" orbit acquisition complemented by an algorithm that tells the monitors which beam and bunch is crossing at a particular moment.
- Knowing the beam and the bunch the acquisition chain will remove the "undesired signals from the opposite beam".

R. Alemany-Fernandez