
ations
Mike Lamont

Coming out of 2010

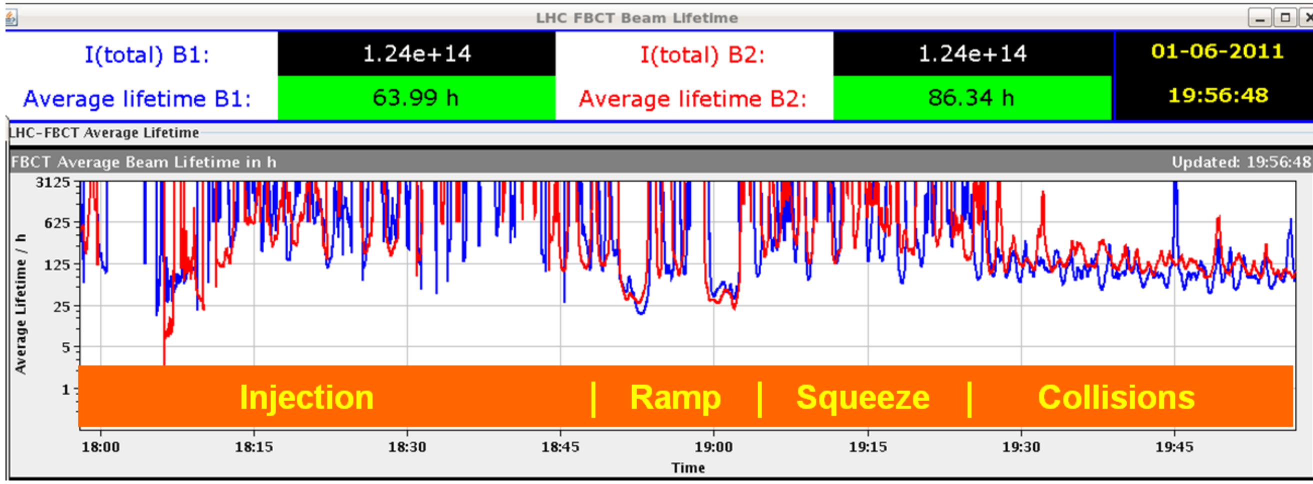
- Aperture
  - Better than expected (beating, dispersion, alignment...)
- Better than nominal from injectors
  - Emittances, bunch intensity
- Beam-beam: can collide nominal bunch currents
  - With smaller that nominal emittances
  - Now running with separation in Alice and LHCb without any problems
- Collimation
  - Relaxed settings, better than estimated lifetimes
  - No quenches above 450 GeV
- Ramp and squeeze essentially without loss

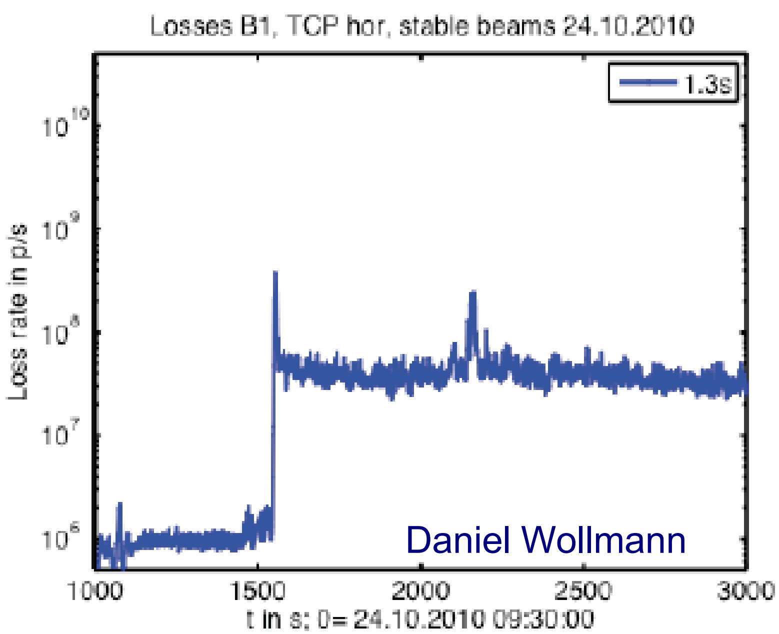
2011- at the moment

Energy [TeV]	3.5
beta* [m]	1.5, 10.0, 1.5, 3.0 m
Emittance [mm.mrad]	**~2.5 – 2.8**
Bunch intensity	1.2e11
Number of bunches	1092 1042 collisions/IP
Stored energy [MJ]	75
Peak luminosity [$cm^{-2}s^{-1}$]	1.26e33
Beam-beam tune shift	0.015 - 0.02

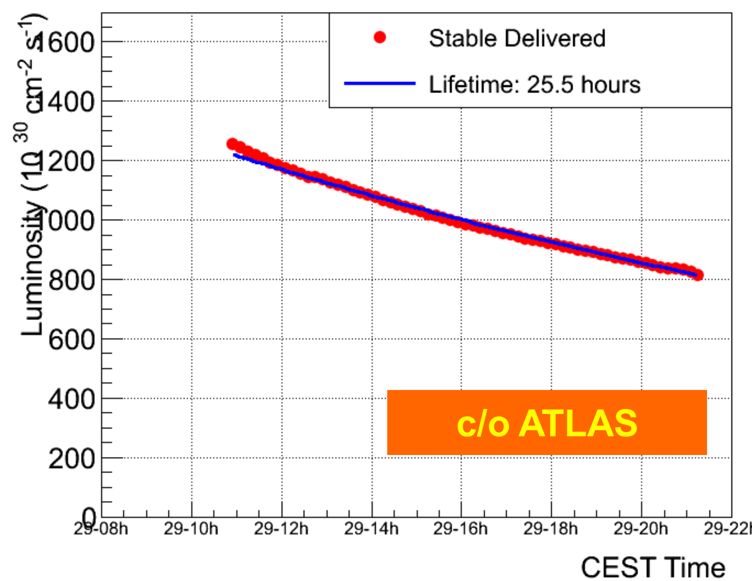
Lifetimes during a fill (1092 bunches)

- Very good lifetime during the whole process
- Lifetime dip to around 1 hour going into collisions





- Luminosity lifetime > 20 hours



Optics, Magnets, Aperture

MODELS

Models in action

- Debugging machine during commissioning
- Debugging software during commissioning
- Debugging database during commissioning
- Debugging magnet model during commissioning
- Measurement and correction
  - Beat beat
  - Coupling: global and local, triplet alignment
- Settings generation and optimization
  - Optics import, knob generation
  - Squeeze optimization
- Operational tools
  - On-line model – see Gabriel's talk
  - Aperture model

Debugging continued!

Debugging

- Started a long time ago
  - TT40, TI8, sector tests, 2008…

And has uncovered issues in….

- Polarities
- Transfer functions
- Cycling Strategy
- Corrector and BPM polarities
- Circuit cabling
- Alignment
- Software, models, settings, database, you name it…

Transfer line modelling

- Lot of effort went into modelling the lines, tracking down optics errors, sources of coupling etc.
  - Excellent results key in the transport of high intensity beams
  - Tight constraints but stable
- Matching considered carefully during commissioning
  - Not routinely revisited
- Accurate aperture model indispensible in steering and tracking down loss locations and potential misalignments
  - E.g. vacuum valve assembly in injection region

Optics

- Not to scruffy to start with, once polarity and calibration errors had been tracked down
- Beating well measured and well corrected through the operational cycle with initially local and then with global corrections

- Still using orbit response matrix from ideal model
- Instrumentation still using ideal Twiss

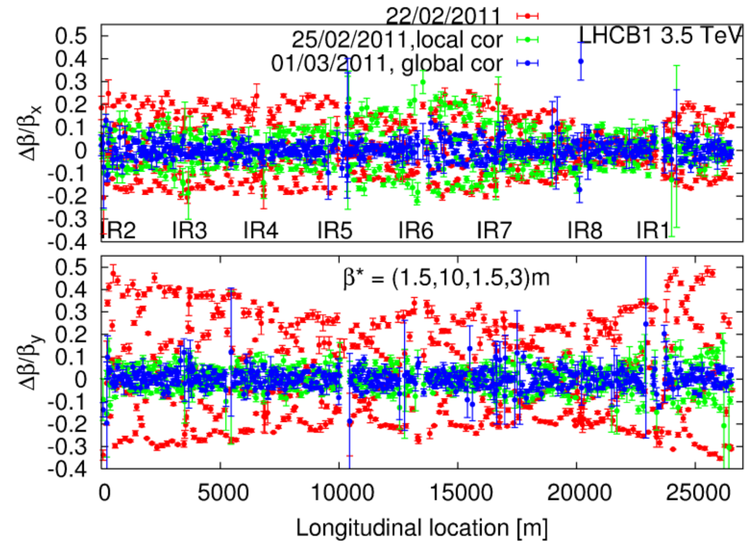
- Key point for operations: remarkably stable

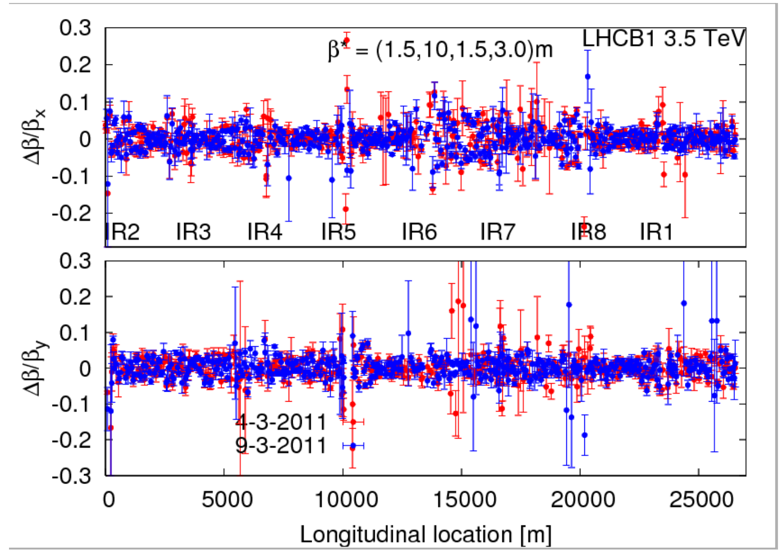
Machine still beautiful

- Beta beating corrected down to 5-10%!!
- Confirmed stability of the optics
- 'Final' β* values from K-modulation:

Beam/plane	IR5	IR1
B1H	1.50	1.53
B2H	1.48	1.57
B1V	1.52	1.50
B2V	1.52	1.57

- Errors around 4-10%
- Aperture: global > 12 σ, triplet > 14.5 σ





Fidel

- See Ezio’s talk
- Major success – “The knowledge of the magnetic model of the LHC is remarkable and has been one of the key elements of a very smooth beam commissioning”

MAD, WISE and FIDEL versus the machine

- Momentum on the button & differences between sectors
  - ~5 units peak to peak at 450 GeV
- Tune within 0.1 of nominal (a rather remarkable result) at 450 GeV
- Set tune and chromaticity more-or-less identical for both beams
- Set chromaticity off at 450 GeV

Chroma settings in LSA

Applied b3 correction

								43.6	-38.7				
		QPH.B1	delta	QPV.B1	delta	QPH.B2	delta	QPV.B2	delta	b3A12B1		b3A12B2	
Long FT	20:35	-20		-14.7		-20.4		-13.9		-4.847		-4.932	
	23:18	-14.5	5.5	-19.2	-4.5	-15.7	4.7	-18.4	-4.5	-4.908	-0.061	-4.992	-0.06
short FT	4:33	-11.7	2.8	-22.7	-3.5	-11	4.7	-22.2	-3.8	-4.87	0.038	-4.954	0.038
			8.3		-8		9.4		-8.3		-0.023		-0.022
		delta in b3	0.19		0.21		0.22		0.21	QPH	-1.0028		-0.9592
										QPV	0.8901		0.8514

Comments

- Fabulous job by the teams involved, leveraging the techniques and tools described elsewhere in this workshop.
- Staged approach (some of it unplanned) allowed some impressive evolution
- “Well integrated, interactive, intuitive and good software”
- Healthy determination to track down problems
- Of note – functionality was available when we needed it most.

OPERATIONAL EXPERIENCE

Transfer & injection

- Beam quality monitoring in SPS critical
  - Beam quality from injectors is critical
    - Worry about scraping, satellites, intensity variations..
- Stability of exit conditions from SPS critical
- Stability of transfer lines critical
- Tight transfer line collimation
  - Clear issue with the fact that these things are sitting next superconducting magnets
  - Tight constraints on steering, injection oscillations
- At present injecting 144 bunches @ 50 ns bunch spacing - nominal bunch intensity at around 2.5 micron
- Position of protection devices in LHC critical with the TDIs in close

Ramp

- The optics doesn't change, but the energy does
  - Digging deeper in the magnet calibration curves
  - Persistent current effects drop off but…
  - include 500 s for b3 decay at 3.5 TeV

- Usual stuff
  - Damper gain down to allow feedback to see tune signal
  - Octupoles increase in strength – single bunch HT
  - Longitudinal blow-up – target bunch length 1.25 ns
  - Coupling – global – empirical (OP) & deterministic (ABP)
  - Collimators track beam size reduction

Note: we know have transverse feedback and octupoles on through the whole cycle

Fidel v. chromaticity

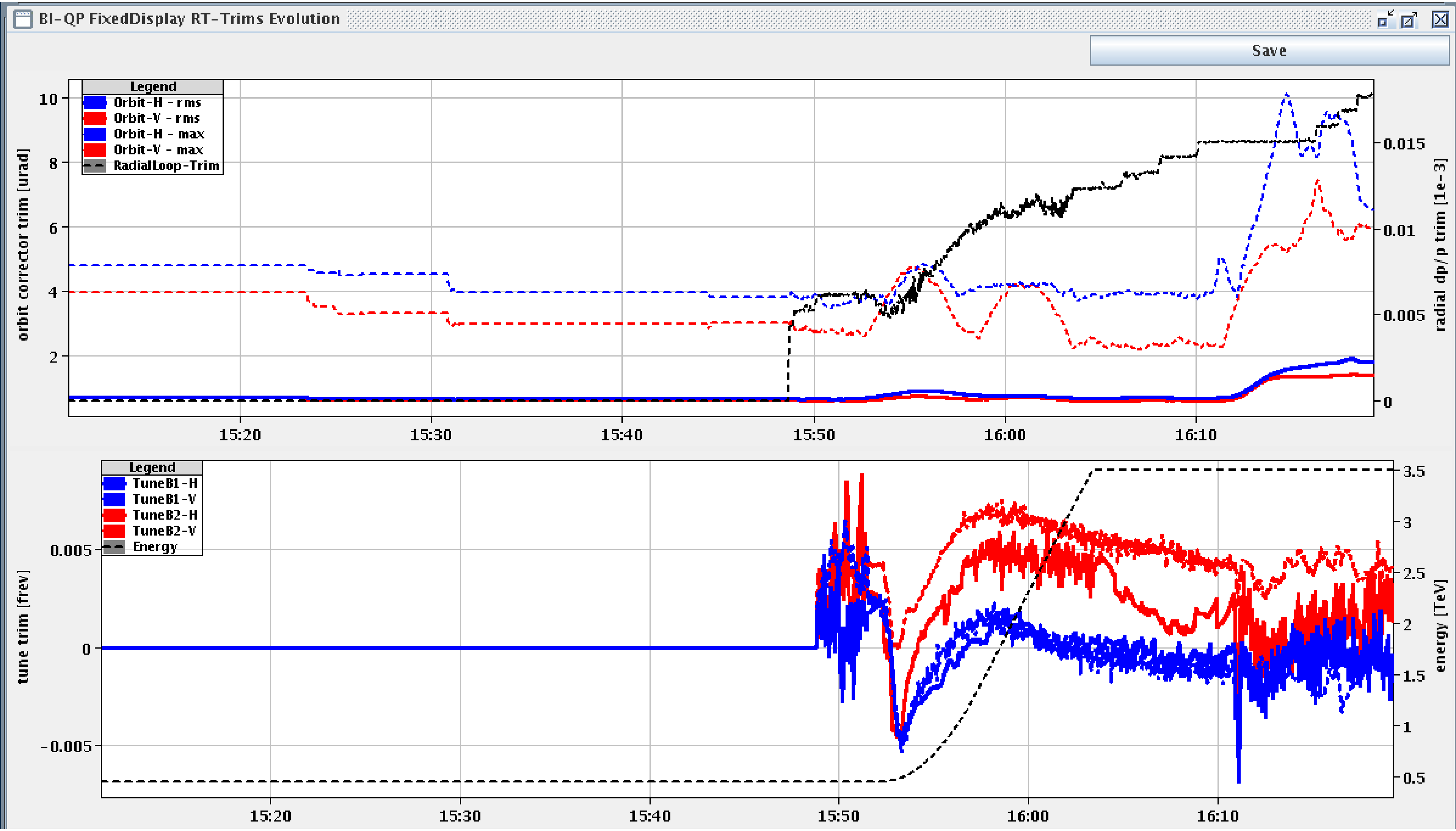
- Persistent currents
  - Corrections in for b2, b3, b4, b5, a2,
  - Dynamic tracking of b2, b3@450 GeV
  - Full decay for b4, b5

- Predicted snap-back correction applied for b3, b4, b5
- Model not perfect
- Discrepancies mopped up with lattice sextupoles
- Decay amplitudes does move around a bit, impact correction during first 30 s but not an issue
  - Q' swings between 0 and 5 in first minute of ramp – transverse feedback on – beam doesn't seem to mind

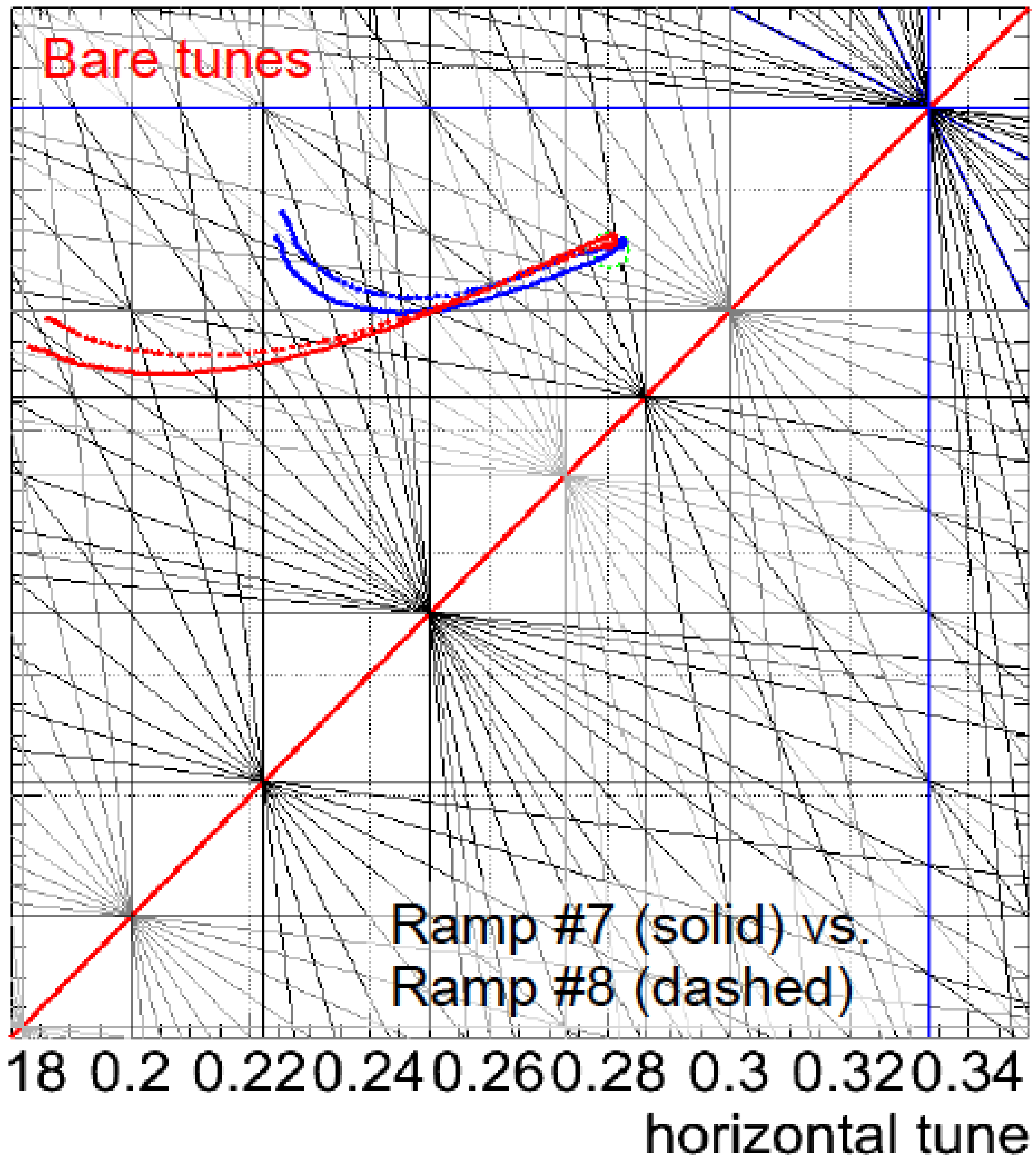
Ramp - feedbacks

- Tune feedback
  - Good reproducibility – feed-forward performed irregularly
  - Nonetheless feedback considered as mandatory
  - Battle between feedback and transverse damper (gain lowered in ramp to give feedback a chance)
  - Coupling control important
- Orbit feedback
  - Also mandatory
  - Reference plus bumps which scale down in ramp
  - SVD
  - Feed-forwarded performed but very good reproducibility

Ramp - feedbacks



Bare tune swings in the ramp



Squeeze

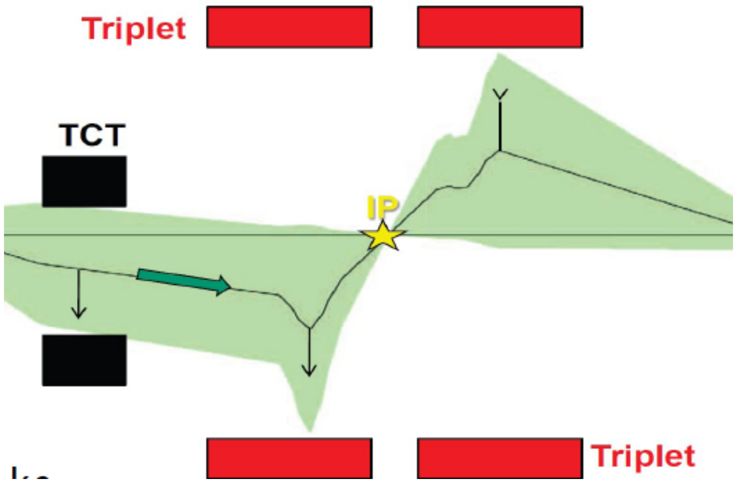
- Carefully stitched together, matched optics
  - Time evolution given by slowest circuit – usually drop in current of single quadrant power converter driven IPQ
  - Present length from 11 m to 1.5 m in 475 seconds (much improved!)
- Tune from injection to collision tunes at start of squeeze
  - Tune feedback considered mandatory, tune change followed with change of reference, always slight worrying
- Chromaticity corrected via feed-forward
  - Reproducible – not measured at all these days with high intensity
- Coupling
  - Empirical correction using global knobs
  - Deterministic global correction
  - Deterministic local correction using triplet skew quads

Squeeze

- Orbit feedback mandatory
  - Changing bump size and configuration dealt with via overlays
- Collimators
  - Tertiaries track optics changes in IRs
- Minimum beta* used given by required collimator margins, which assume:
  - Beating corrected to below 10% and a reproducibility of better than 5%
  - Aperture at triplet is well known (i.e. measured locally)

	2010		2011	
	(σ)	(mm)	(σ)	(mm)
triplet–TCT	2.5	0.9–2.1	2.3	1.1–2.7
TCT–TCSG IR6	5.7	3.5–4.4	2.5	1.3–1.8
TCSG IR7–TCP	2.8	0.6–1.6	2.8	0.5–1.5

Roderick Bruce



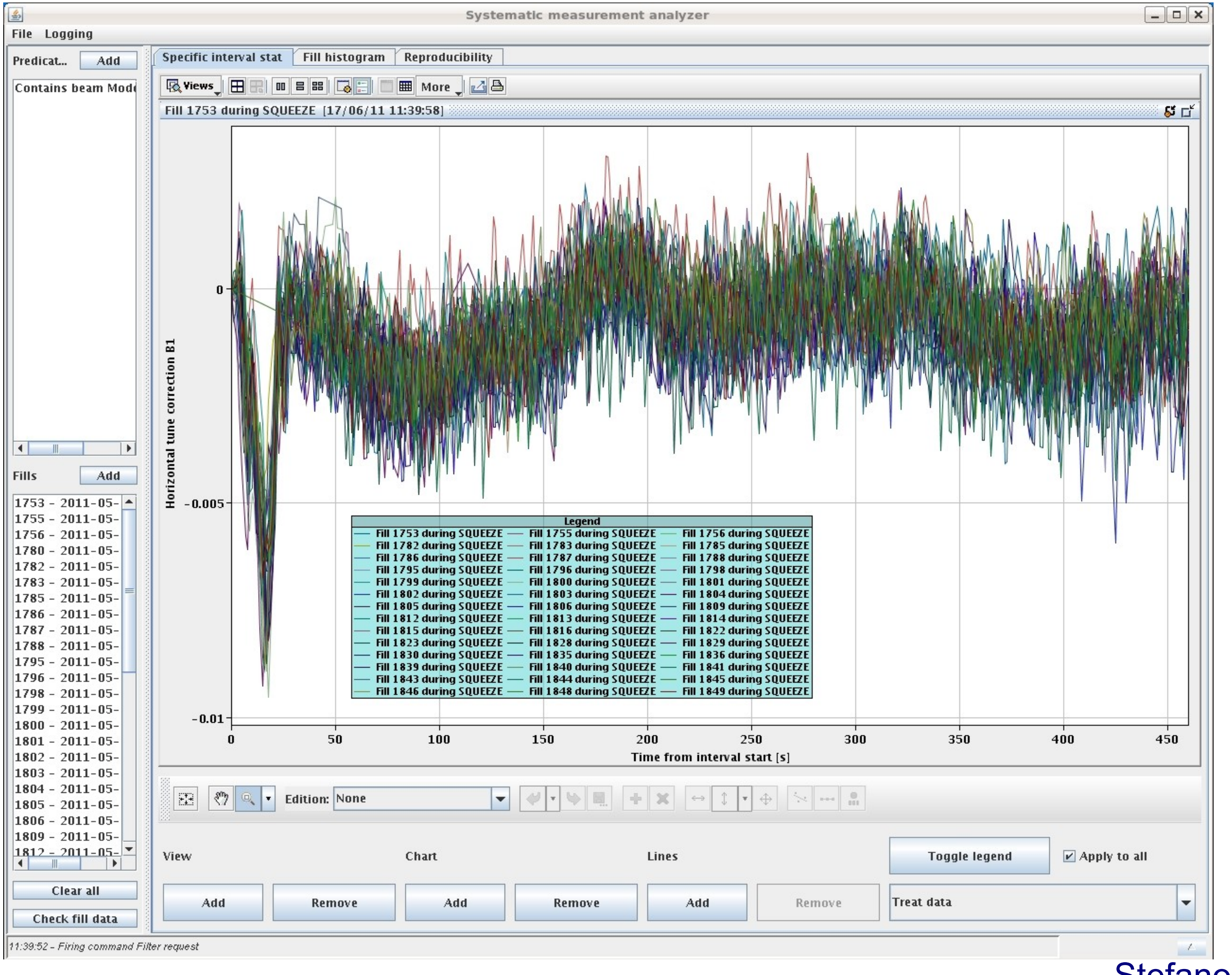
Squeeze

- In general remarkably trouble free and reproducible
- Impeccably matched optics
- Reasonably sensible implementation in LSA
- Concerted attention to optimization
  - Length, inter-optics correction
- Reproducibility very good, feed-forward performed
- Feedbacks still regards as essential

Feed-forward in squeeze

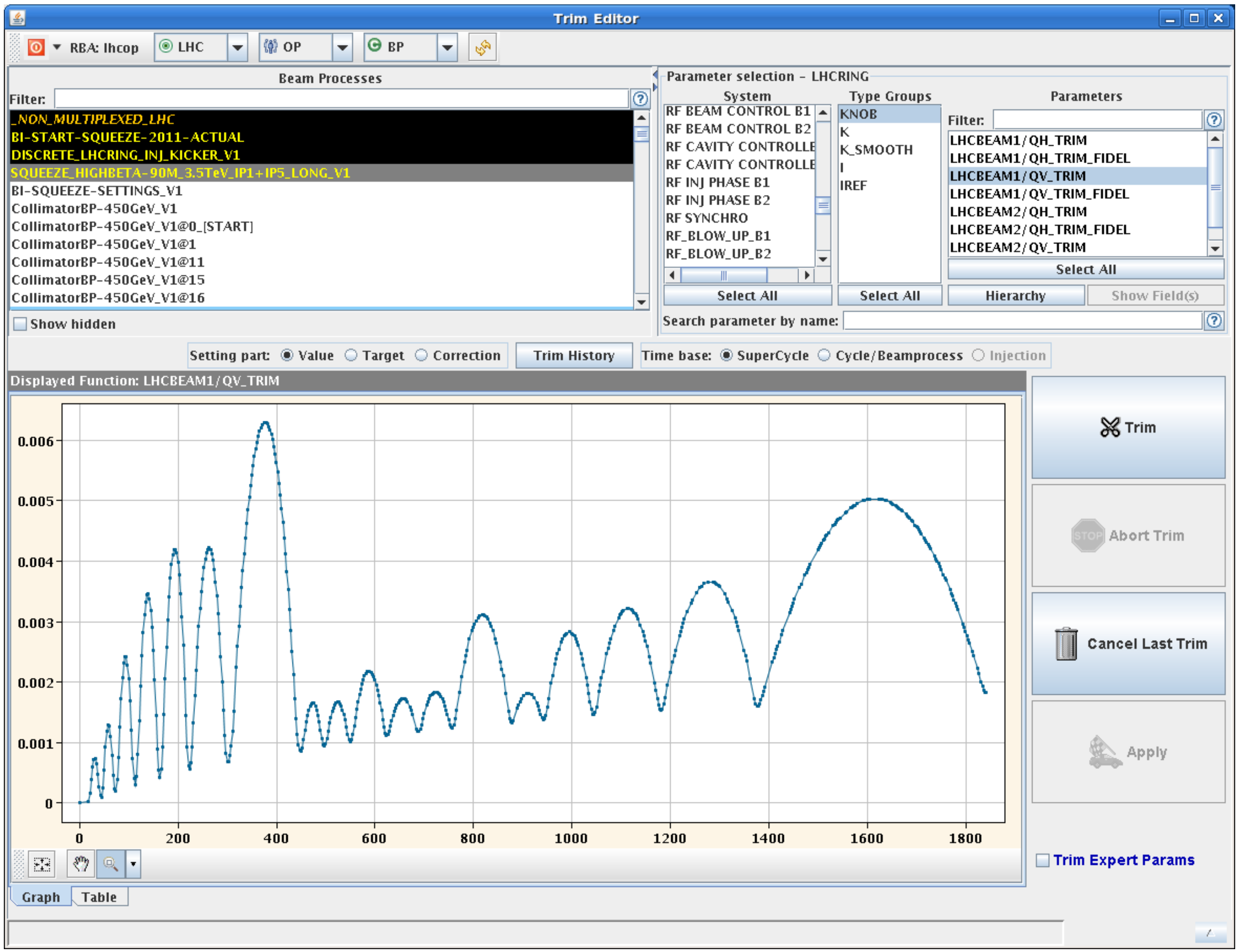
Residual corrections made by feedback

Tune reproducibility in squeeze



Squeeze – getting clever

Predicted swings in tune & chromaticity between match optics now predicted and corrected in anticipation



Stefano, Xavier, Gabriel

Operations' 7 pillars of wisdom

Given an impeccably debugged, optically good machine with an excellent magnet model operations then rely on:

- Availability
- Reproducibility
- Control
- Instrumentation
- Optimization and stability
- Understanding
- Safety

- Or more generally "if it ain't broke don't fix it"

INCOMING

Latest unofficial 10 year plan

	J	F	M	A	M	J	J	A	S	O	N	D
2011		1	2	3	4	5	6	7	8	9	Ions	
2012			1	2	3	4	5	6	7	8	Ions	
2013	**LS1 - SPLICE CONSOLIDATION**											
2014									1	2	3	4
2015		1	2	3	4	5	6	7	8	9	Ions	
2016		1	2	3	4	5	6	7	8	9	Ions	
2017		1	2	3	4	5	6	7	8	9	Ions	
2018	**LS2**											
2019		1	2	3	4	5	6	7	8	9	Ions	
2020		1	2	3	4	5	6	7	8	9		
2020		1	2	3	4	5	6	7	8	9		
2022	**HL-LHC upgrade**											

- Technical stop or shutdown
- Proton physics
- Ion Physics

Here be dragons

Beam from the injectors

Bunch spacing	From Booster	Np/bunch	Emittance H&V [mm.mrad]	No. of bunches from SPS
150	**Single batch**	**1.1×10^{11}**	**< 2.5 (1.6)**	**1 – 4 x 12**
75	Single batch	1.2×10^{11}	2	1 – 4 x 24
75	Double batch	1.2×10^{11} (?)	1.2 (?)	1 – 4 x 24
50	Single batch	1.45×10^{11}	3.5	1 – 4 x 36
50	Double batch	1.2×10^{11} (?)	1.5 (?)	1 – 4 x 36
25	Double batch	1.15×10^{11}	3.6	1 – 4 x 72

Rest of this year

- 50 ns – push to 1380 bunches per beam
- Double batch injection PSB/PS and then push
  - Bunch intensity and or emittance
- Worry about:
  - SEUs
  - UFOs
  - RF
  - Bunch length
- 25 ns probed in MD
  - Experiments would like to see a run with 25 ns with a limited number of bunches
- If anyone fancies some fun – proton-lead to be tried
- New optics also incoming (ATS, high beta*…)

2012

- Potentially higher energy
  - 4 or 4.5 TeV based on measurements to be made during the Christmas technical stop
- Ramp at collision tunes?
  - See Rogelio et al
- 50 ns
  - If only because the emittance offered by the injectors is that better than for 25 ns – more for less
  - Push emittance and bunch current
- Lower beta* perhaps
  - Long range beam, crossing angle, aperture
  - Limits from demands of collimator hierarchy on orbit stability

Pushing the limits: crossing angles, aperture and beta*

IP 1 & 5

ϵ_n Energy	β^* (3.5 TeV)	β^* (4.0 TeV)	α (3.5 TeV)	α (4.0 TeV)
1.5 μm	1.4 m	1.4 m	$\pm$ 120 μrad	$\pm$ 120 μrad
2.0 μm	1.5 m	1.4 m	$\pm$ 120 μrad	$\pm$ 120 μrad
2.5 μm	1.6 m	1.5 m	$\pm$ 120 μrad	$\pm$ 120 μrad
3.75 μm	1.8 m	1.6 m	$\pm$ 140 μrad	$\pm$ 140 μrad

Werner Herr

2013 - 2014

HOLIDAY!

2015 - 2017

- 6.5 TeV or thereabouts
- Injection doesn't change
  - Give or take longer pre-cycles, different powering history
  - Although 25 ns promises larger emittances - challenging
- Ramp
  - Digging deeper into transfer functions
  - Some spool piece circuits pushed into current limits
  - Persistent current effects go down
  - Tolerances lower, better control of Q, Q', orbit
- Collimation
  - No DS collimators, should be good for nominal intensity given various assumptions (including minimum lifetime)
  - Tight collimator settings will be a challenge

2015 - 2017

- Impedance
  - "Nominal 25ns beam is probably OK."
    - See N. Mounet and E. Métral - Impedance without IR3 upgrade

- Squeeze to 55 cm
  - Beating and coupling correction of course
  - Higher order triplet correction, feed-down
  - Orbit stability in IRs, orbit correction during squeeze
  - Alignment
  - Aperture
  - BPM offsets

I draw the line at LS2…

Conclusions

- LHC at present in great shape
  - Much of this down to the developments and hard work presented at this workshop
- The challenges will keep coming, tolerances will become even more demanding as the intensity and energy is pushed up
- Look after intellectual value of what's been achieved
  - Keep expertize in house and provide necessary resources
  - Fidel is going to take some looking after
    - Massive database, devil in details, software – critical for operations