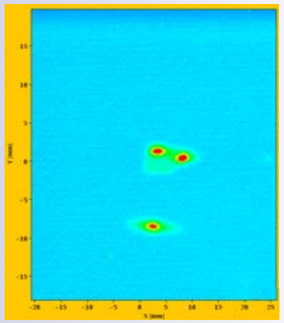
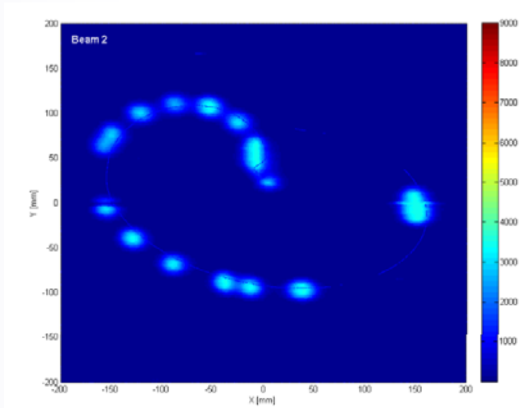
Mike Lamont
for the LHC commissioning team

Turning on the LHC: commissioning with beam and the outlook for 2010

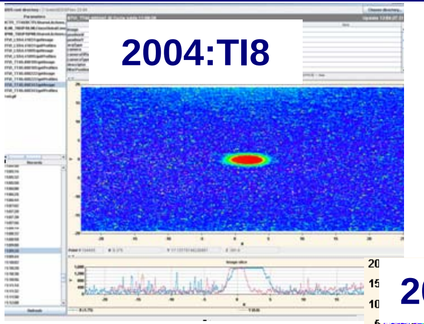




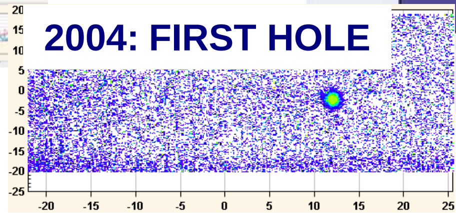
Prep: beam tests through the years

2003:TT40

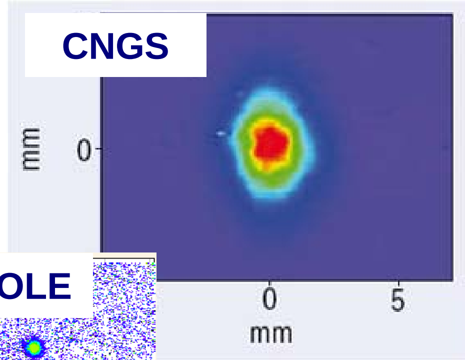
2004:TI8



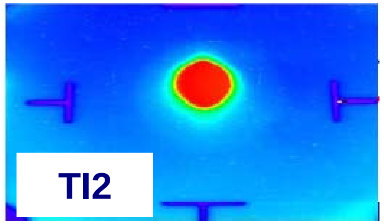
2004: FIRST HOLE



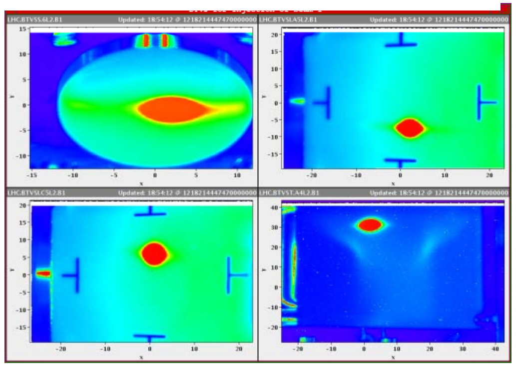
CNGS



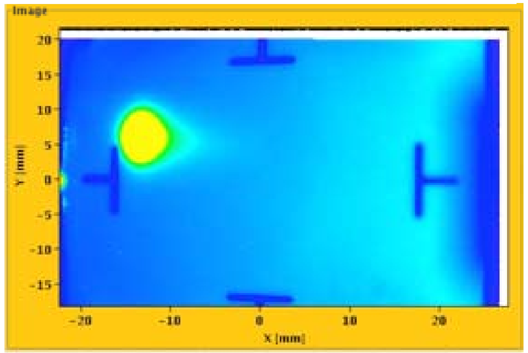
TI2



2008: FIRST BEAM TO LHC

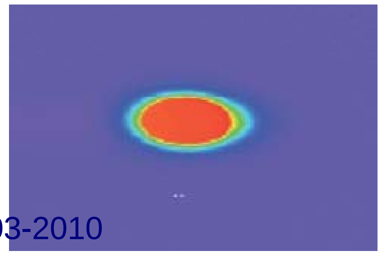


2008: FIRST BEAM TO IR3

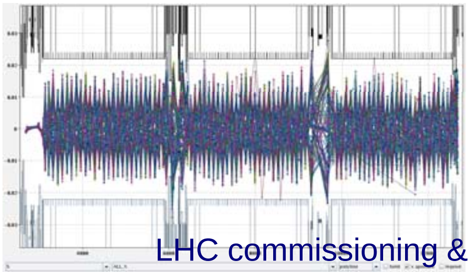


2008: SEPT 10

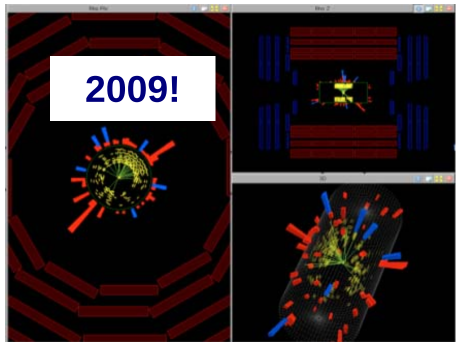
2009: FIRST IONS TO LHC



2009: Sector test

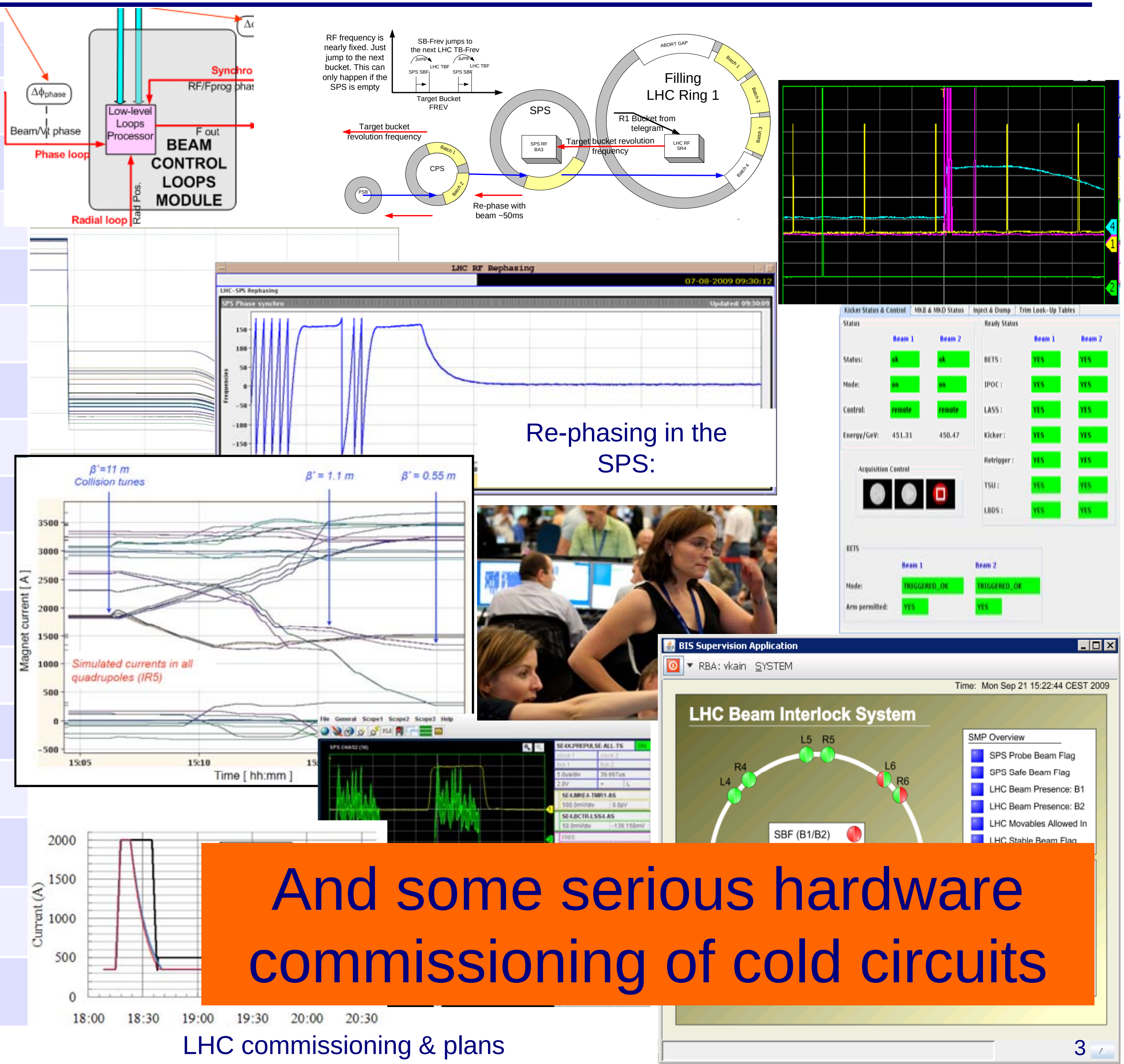


2009!



Prep: dry runs and machine checkout

- Extraction
- Transfer lines
- Injection
- RF, injection sequence
- Timing System
- Beam Interlock System
- Collimators
- Vacuum
- Interlocks, SIS
- BLMs, BPMs
- BTV, BCT
- Beam dump
- PGCs
- Magnet model
- Sequencer, alarms
- Controls, logging, DBs
- LSA, optics model, YASP



Re-phasing in the SPS:

And some serious hardware commissioning of cold circuits

Beam milestones 2009 1/2

20th Nov	injection of both beam – rough RF capture
21st Nov	Beam 1 circulating
22nd Nov	Beam 2 circulating
23rd Nov	First pilot collisions at 450 GeV First trial ramp
26th Nov	Pre-cycle established – excellent reproducibility Energy matching
29th Nov	Ramp to 1.08 TeV and then 1.18 TeV
30th Nov	Solenoids on
1st – 6th Dec	Protection qualified at 450 GeV to allow "stable beams"
6th Dec	Stable beam @ 450 GeV
8th Dec	Ramp 2 beams to 1.18 TeV – first collisions
11th Dec	Stable beam collisions at 450 GeV with high bunch intensities: 4 x 2 10^10 per beam

Milestones 2/2

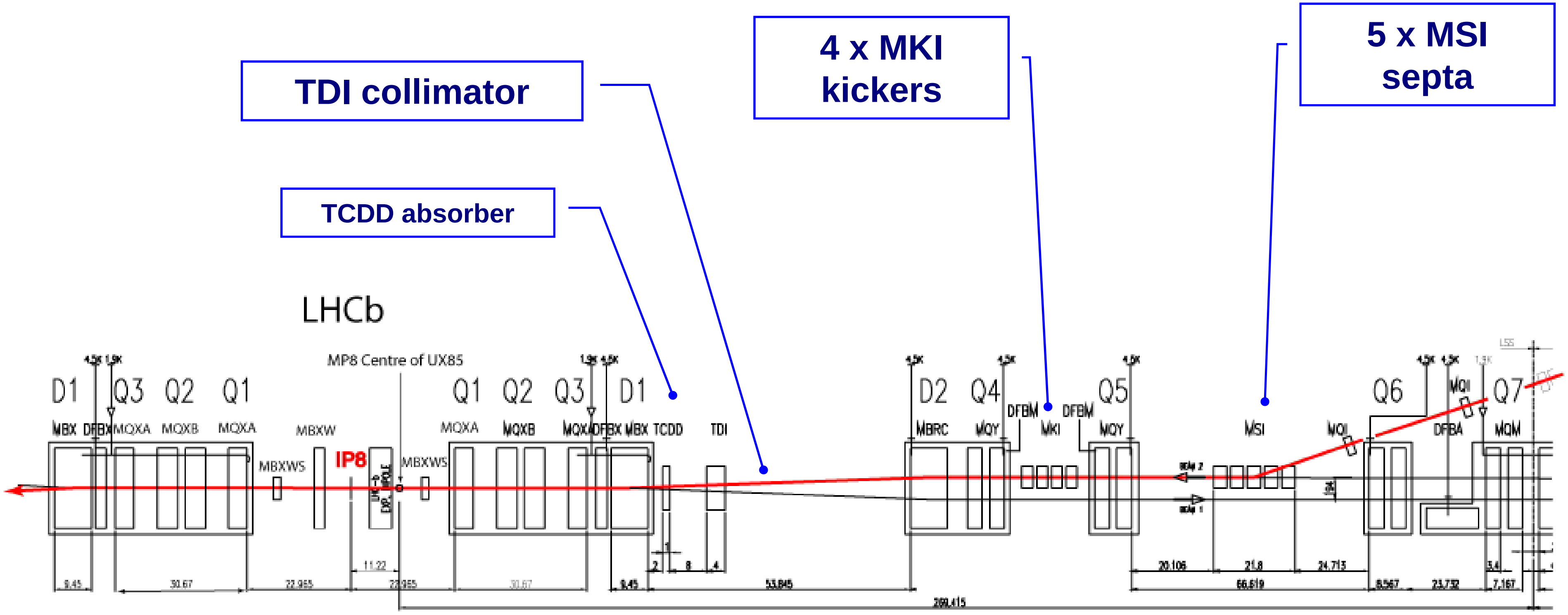
14th Dec	Ramp 2 on 2 to 1.18 TeV - quiet beams - collisions in all four experiments
14th Dec	16 on 16 at 450 GeV - stable beams
16th Dec	Ramped 4 on 4 to 1.18 TeV - squeezed to 7 m in IR5 - collisions in all four experiments
16th Dec	End of run

- 3 days - first collisions at 450 GeV
- 9 days - first ramp to 1.2 TeV
- 16 days - stable beams at 450 GeV
- 18 days - two beams to 1.2 GeV & first collisions

General agreement that this wasn't bad

Injection - reminder

Layout (point 8)



Nominal batch from the SPS: 288 bunches of 1.15 e11 protons at 450 GeV

We injected a single bunch of 2 e10

Injection

- Delicate process
  - We will sling around a lot of beam during this process
  - Complex dance of hardware, timing, RF, interlocks etc.
  - Have to carefully position collimators and other protection devices to make sure we catch any losses
  - Issues with BLMs triggering the beam interlock system due to fast losses during the injection process
- Full program of beam based checks performed
- Generally impressive, clearly benefits from experience gained during injection tests.
- However, for the moment one would worry about routinely injecting unsafe beam.

TT40 Damage during 2004 High Intensity SPS Extraction / Goddard, B ; Kain, V ; Mertens, V ; Uythoven, J ; Wenninger, J

Or what you can do with 2.9 MJ

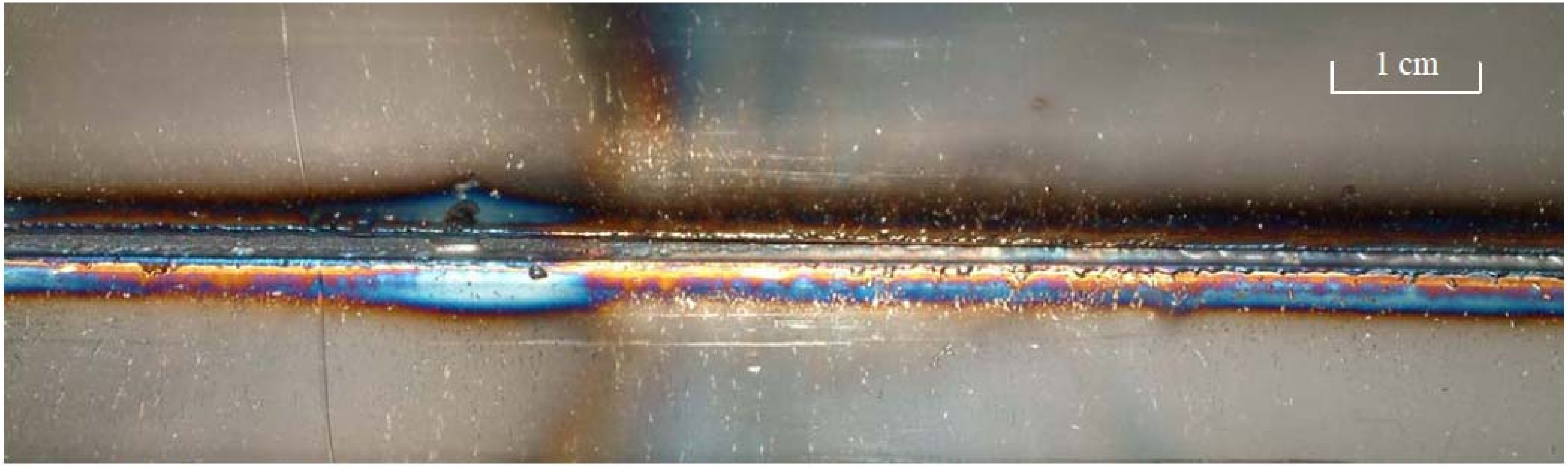


Figure 4. Damage observed on the inside of the vacuum chamber, on the beam impact side. A groove approximately 110 cm long due to removed material was clearly visible, starting at about 30 cm from the entrance.

During high intensity extraction on 25/10/04 an incident occurred in which the vacuum chamber of the TT40 magnet QTRF4002 was badly damaged.

The beam was a 450 GeV full LHC injection batch of 3.4 10^{13} p+ in 288 bunches, and was extracted from SPS LSS4 with the wrong trajectory

= 4.4 e12 at 3.5 TeV

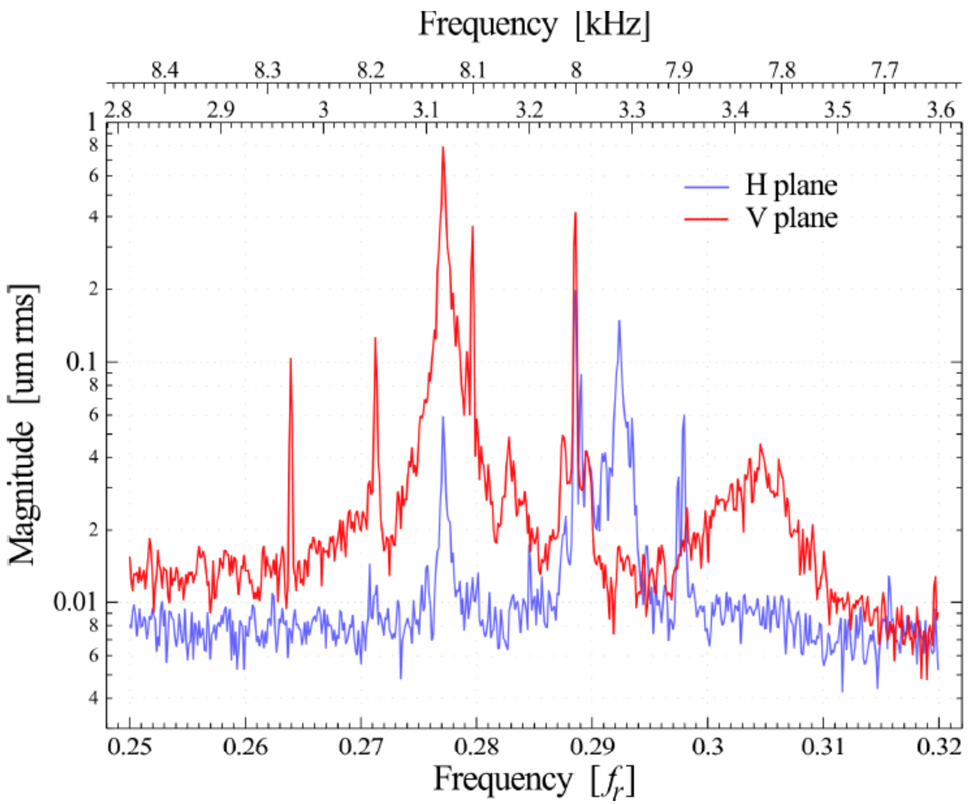
450 GeV

- Measurement and control of key beam parameters
  - Orbit, tune, chromaticity, coupling, dispersion
  - Beam loss, Beam size
  - Energy matching
  - Aperture checks
- Experiments' magnets
  - Solenoids & dipole –on and corrected
- Two beam operation both with and without bumps
- Optics checks
- Full program of polarity checks of correctors and BPMs

Performance of hardware, instrumentation and software was impressive

Good preparation – fast problem resolution

450 GeV: 8 kHz & the hump



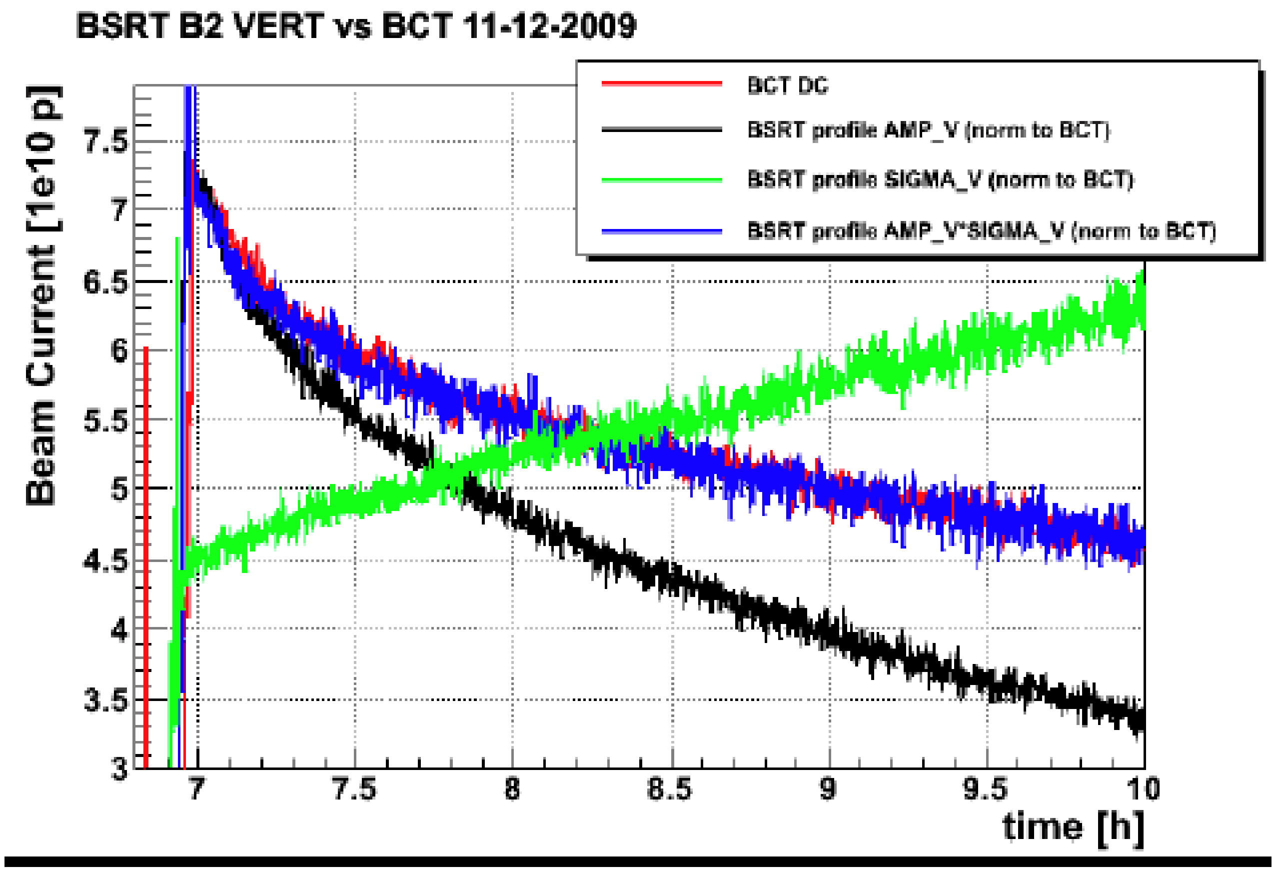
8 kHz line, broad frequency “hump”, and other spectra perturbations:

- Reduction of beam life-time, emittance blow-up, …

Maybe not of direct interest to this audience but this sort of thing can give you a real headache

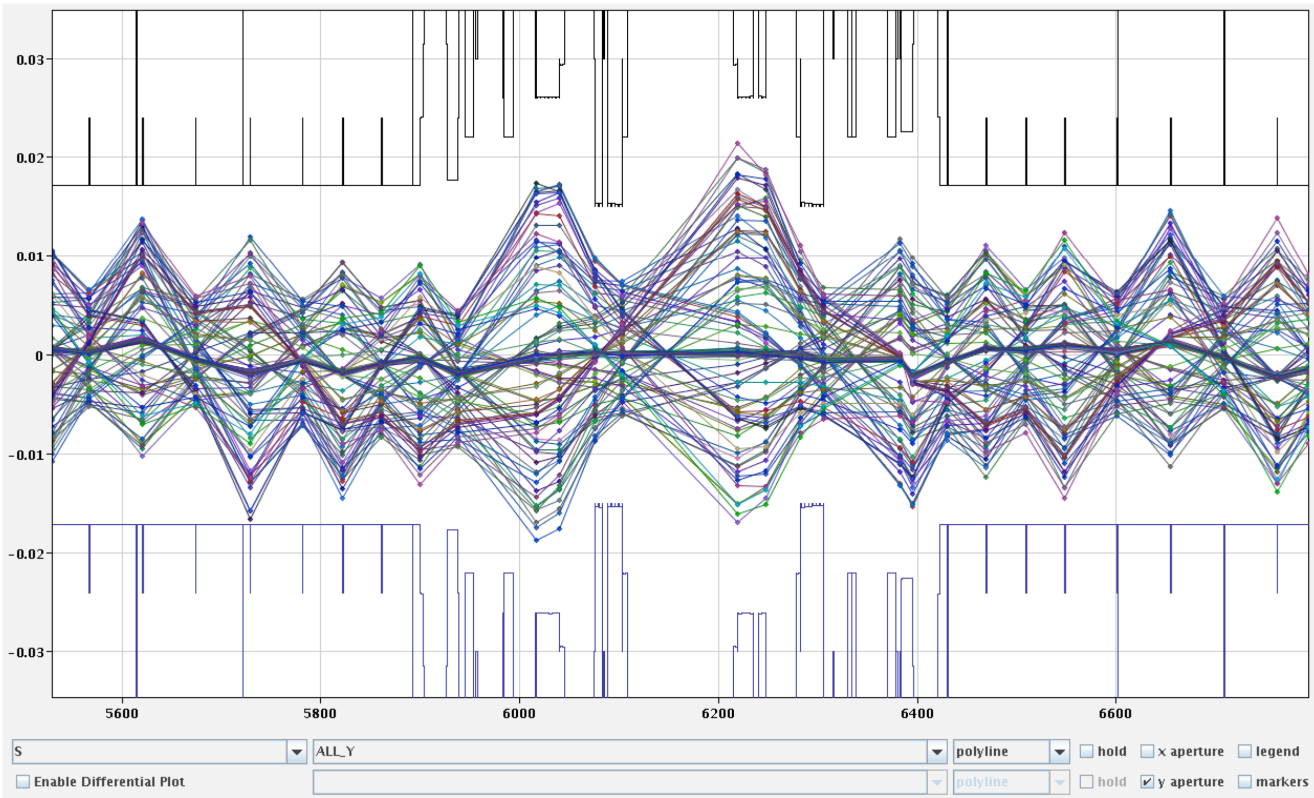
Synchrotron light monitor

Vertical emittance blow-up – beam 2

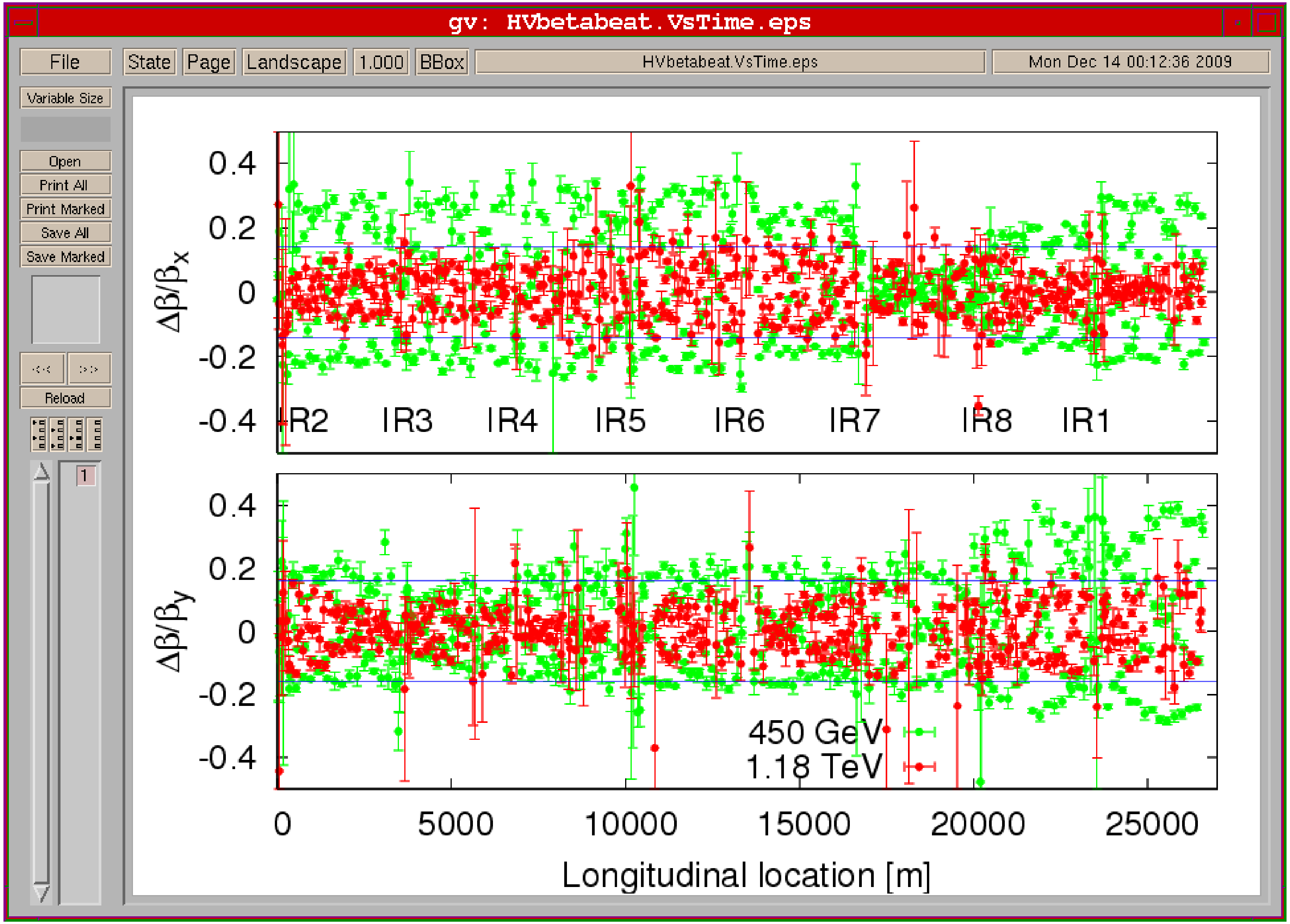


Aperture

- Beam clearance seems to be OK
- Some measured bottlenecks agree with model predictions using measured functions.
- Aperture is out of budget due to the large beta beating
- Correcting beta beating (optics) seems mandatory at 450 GeV



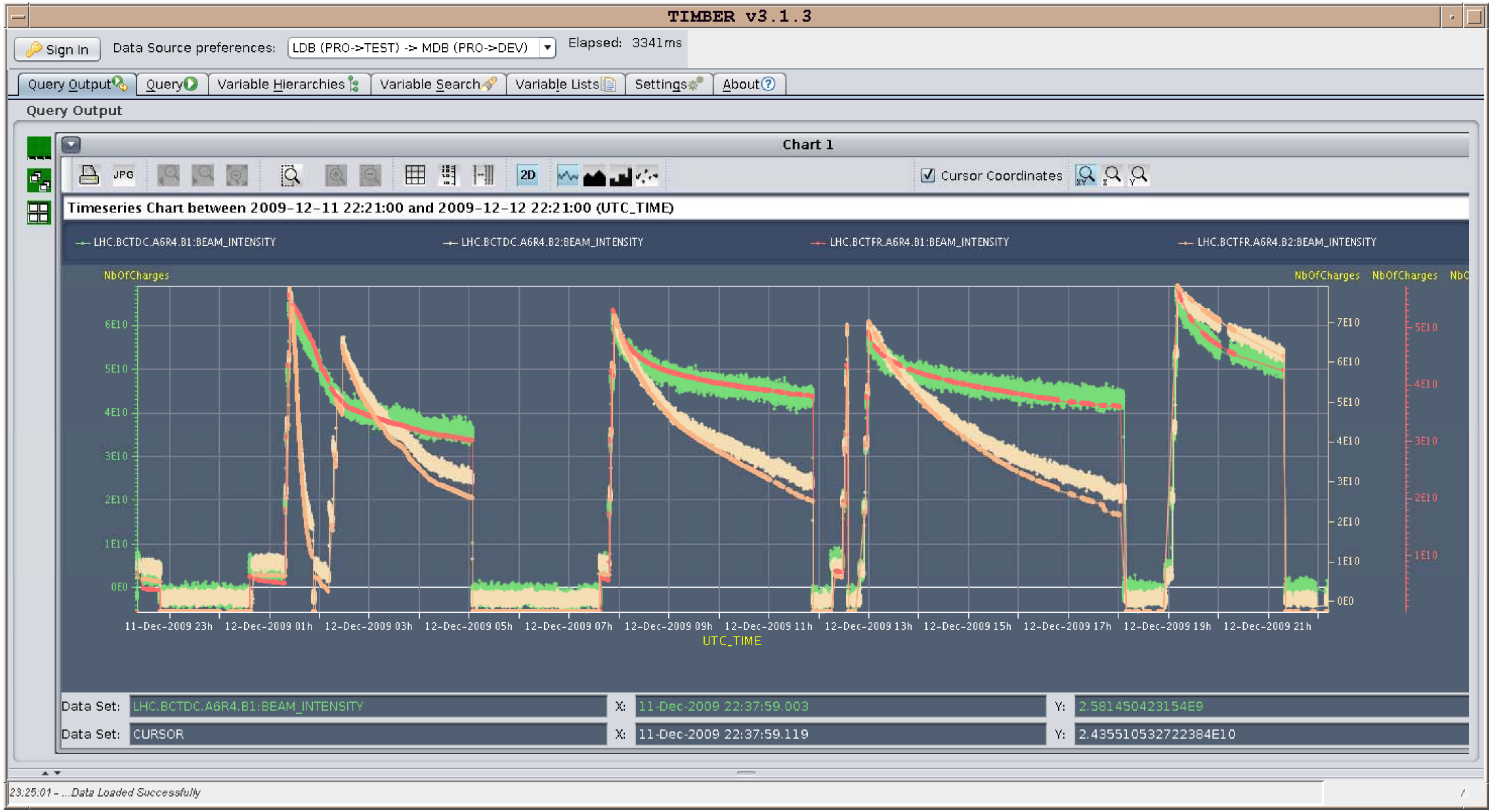
Beating: 450 & 1180 GeV



Collisions at 450 GeV

- Man was never meant to do collisions at 450 GeV (in the LHC at least)
- Full program of machine protection, collimation, aperture and LBDS checks allowed “stable beams” to be declared.
- Multi-bunch and higher intensities achieved
  - 16 bunches – total 1.85×10^{11}
- Luminosity scans tested successfully
- Lots of events collected
  - 6 reasonably happy experiments

Collisions at 450 GeV



After 20 days commissioning

Nominal cycle: ramp

8 ramp attempts

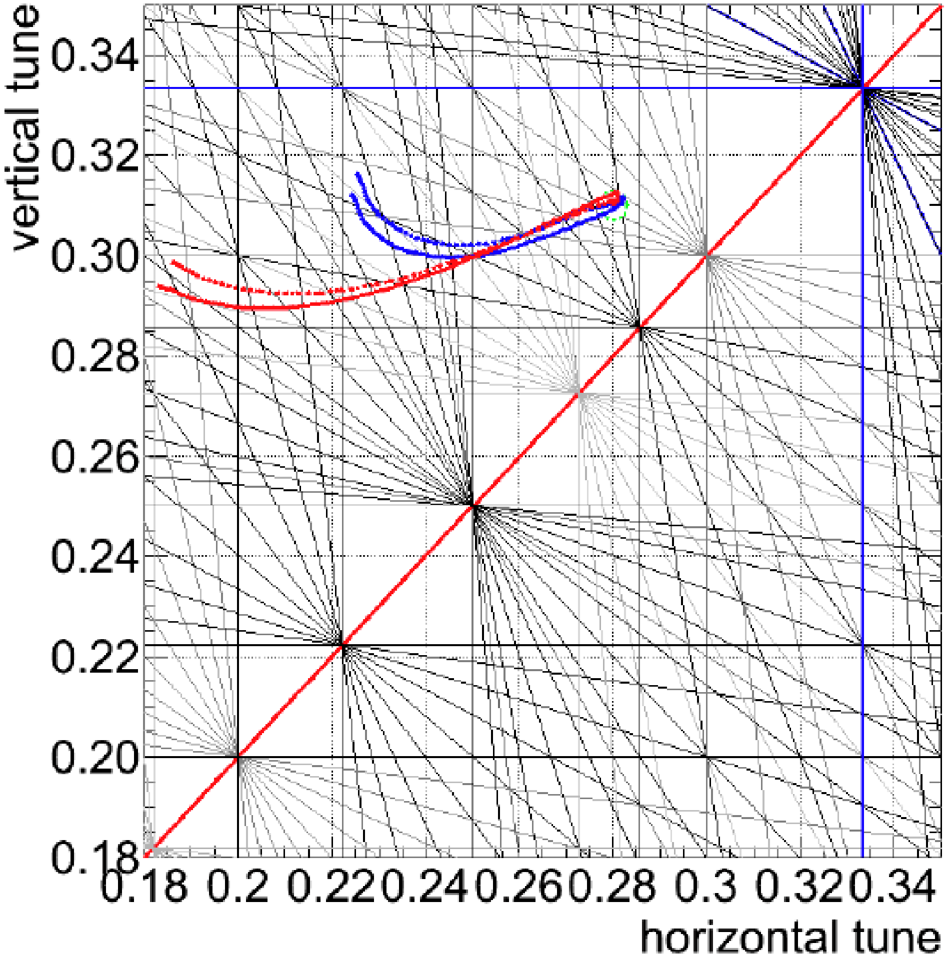
	Date	Beam	Energy [GeV]	Comment
1	24/11/09	1	560	Tunes
2	29/11/09	1	1043	1/3 integer
3	30/11/09	1/2	1180	No full precycle No feedback
4	8/12/09	1/2	1180	B1 lost after 3 minutes at top energy. Feedback on B2. Atlas saw collisions
5	13/12/09	1/2	800	Feedback on both beams from here Lost B2 – BPM interlock
6	14/12/09	1/2	1180	1 hour “quiet beams” – collisions in all 4 experiments
7	15/12/09	1/2	1180	Beam lost to rogue real-time packet
8	16/12/09	1/2	1180	Squeeze/collisions

Not bad

Ramp 7 & 8 – bare tunes

Ramp looked good (<u>and reproducible</u>)

Both tune feedback and feed-forward operational



Encouraging

Squeeze

One attempt in CMS: from 11 to 7 m.

- **First beam tests of betatron squeeze were successful!**
  - Mechanics of the squeeze works well.
  - Good agreement with the expected beta values.
- **Some issues were identified and are being addressed**
  - Not the smoothest night shift ever seen in the CCC
- **Feedbacks:**
  - Orbit feedback will be needed as expected,
  - If simulations are confirmed, tune feedback seem less critical.

Magnet model

- 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
- Huge parameter space, mistakes made, lessons learnt etc but…
- Tunes, energy matching, optics close to the model already
- Some discrepancies being hunted down (450 GeV particularly)
- Bodes very well for the future.

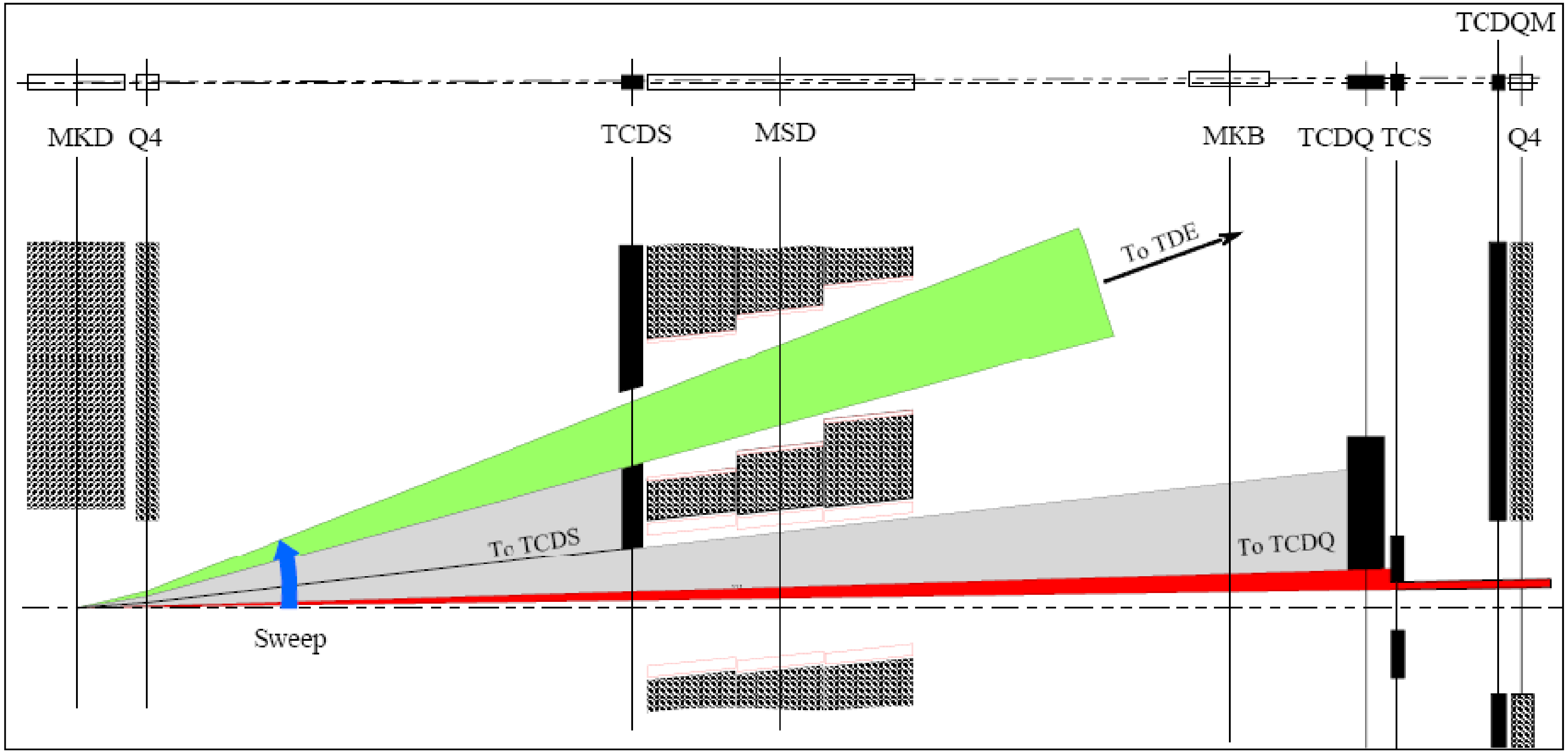
Largest momentum offsets by sector:

- -0.27 per mil in sector 56 / beam1
- +0.32 per mil in sector 78 / beam2

Beam Dump – very briefly

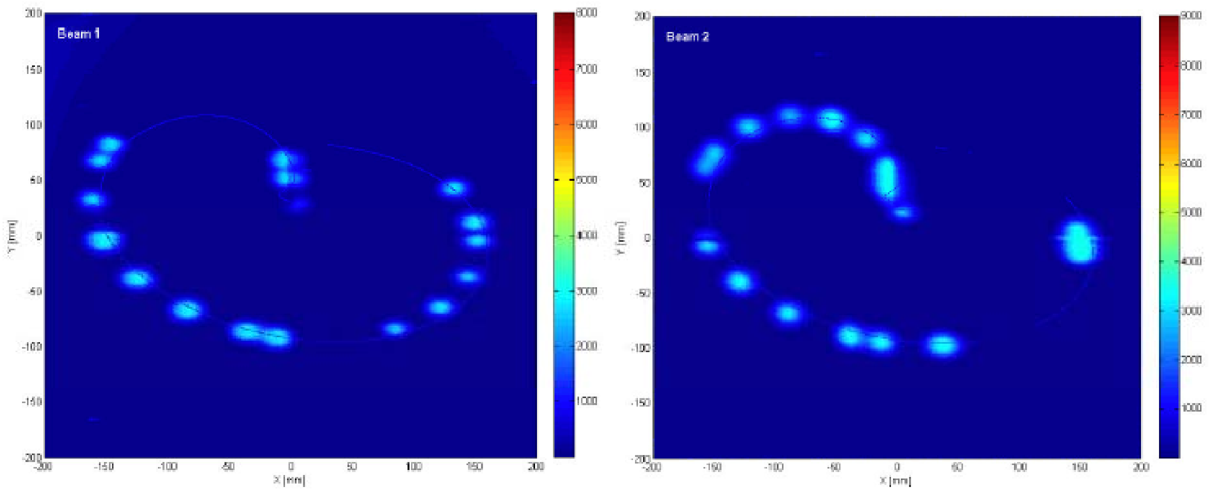
…in case of asynchronous beam dump

- TCDS (fixed) – 6 m long diluter protects extraction septum
- TCDQ (mobile) – 7 m long diluter kept at about 7-8 σ from the beam, at all times



LHC Beam Dump System

Beams for physics dumped, at the right place!   450 GeV



Beam dumps, 16 bunches + pilot, 14/12/09 around 21:00
BTVDD image = position on beam dump block TDE
Comparison with calculated positions from measured kicker magnet waveforms.

The beam dumping systems worked very well

Only real failures were the synchronous-asynchronous dumps: solved after firmware upgrade

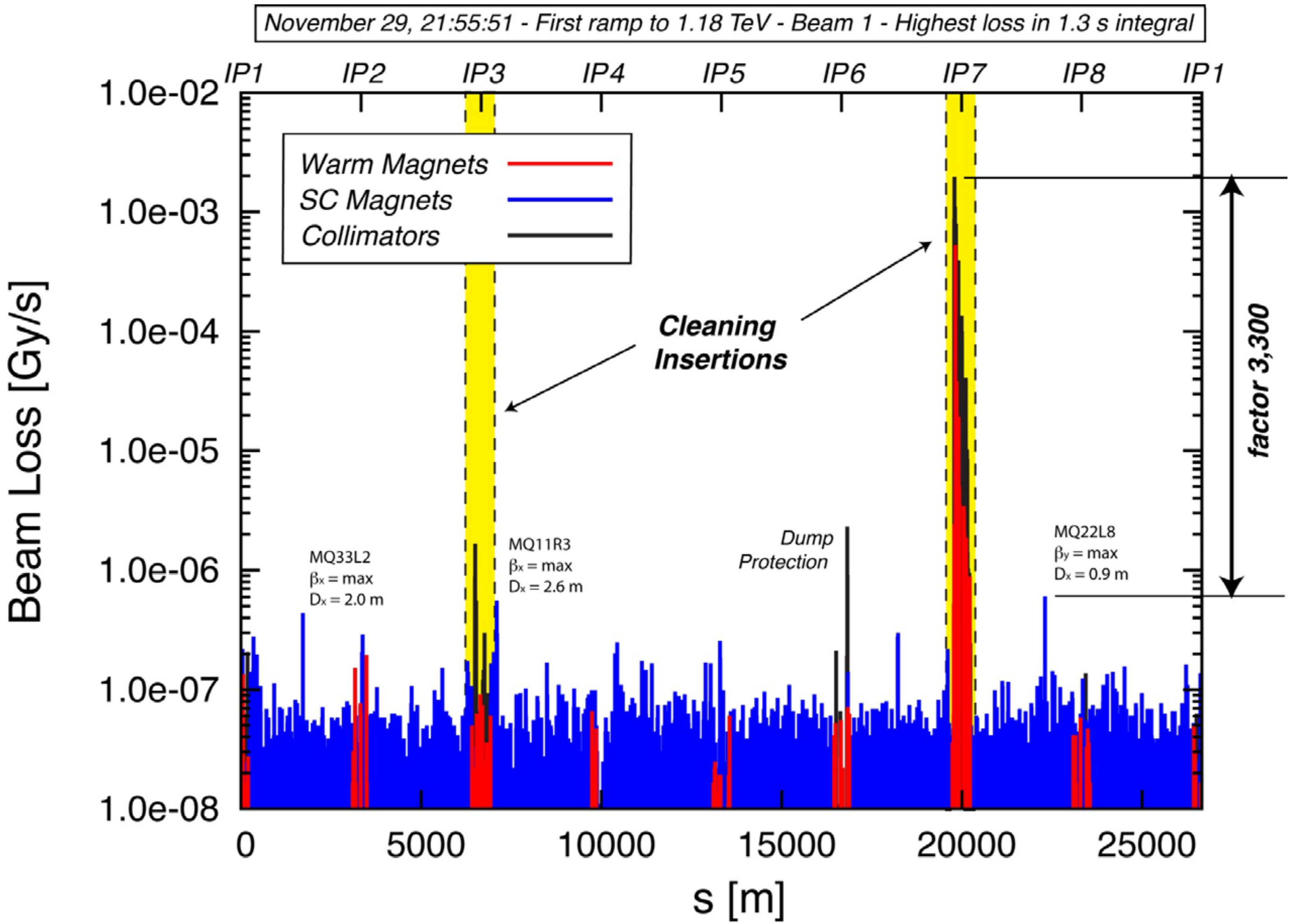
Collimation

Excellent initial beam based commissioning following careful preparation and tests

- Full program of beam based positioning
- System works as designed.
  - Expected cleaning and leakage processes seen.
- Possible to verify passive protection: losses at primary collimators.
- Hierarchy established and respected in tests
- Collimation setup remained valid over 6 days, relying on orbit reproducibility and optics stability
- Even the Roman pots got a run out

This and the beam dump are what stands between your silicon and 7 TeV protons (eventually).

Collimation



Machine Protection System

Provides the mechanism to dump the beam in around 3 turns if anything out there decides it's had enough

- Mission critical backbone
  - Beam Interlock System
  - Safe Machine Parameters
  - Plus inputs to/from other systems (e.g. timing, BCT)
- A large multitude of user inputs
- The beam driving a subtle interplay of:
  - LBDS, Collimation, protection devices, RF…
  - Instrumentation (BLMs, BCT, BPMs…)
  - Aperture
  - Optics

Careful testing before beam

Full set of beam based tests

Clearly the critical path

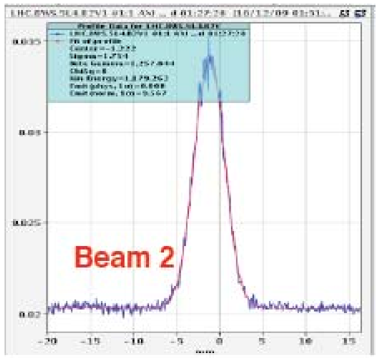
Beam Instrumentation

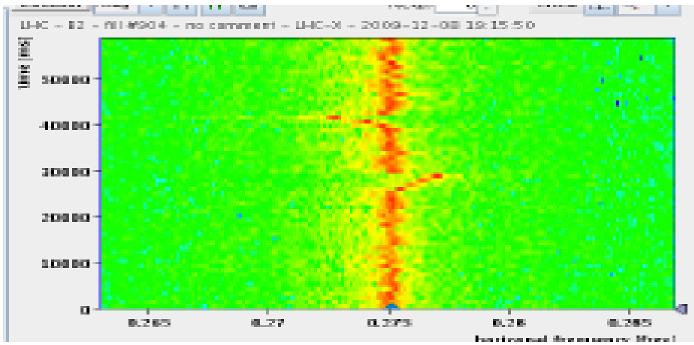
The Enabler

Excellent

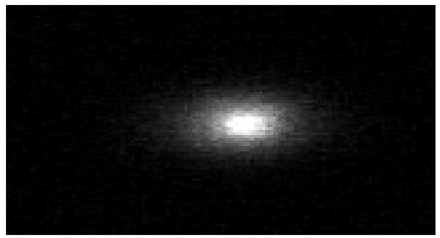
- Beam Position Monitors
  - Excellent performance
  - Very stable orbit (V drift ~ 15μm/h)
- Beam Loss Monitors
  - BLMs correctly removes the BEAM PERMIT signal if measurements are over threshold. No reliability issues observed.
- Profile monitors
  - Synchrotron light, wire-scanners operational

• Base-Band-Tune (BBQ) system was a work horse from day one giving tune, chromaticity, coupling.

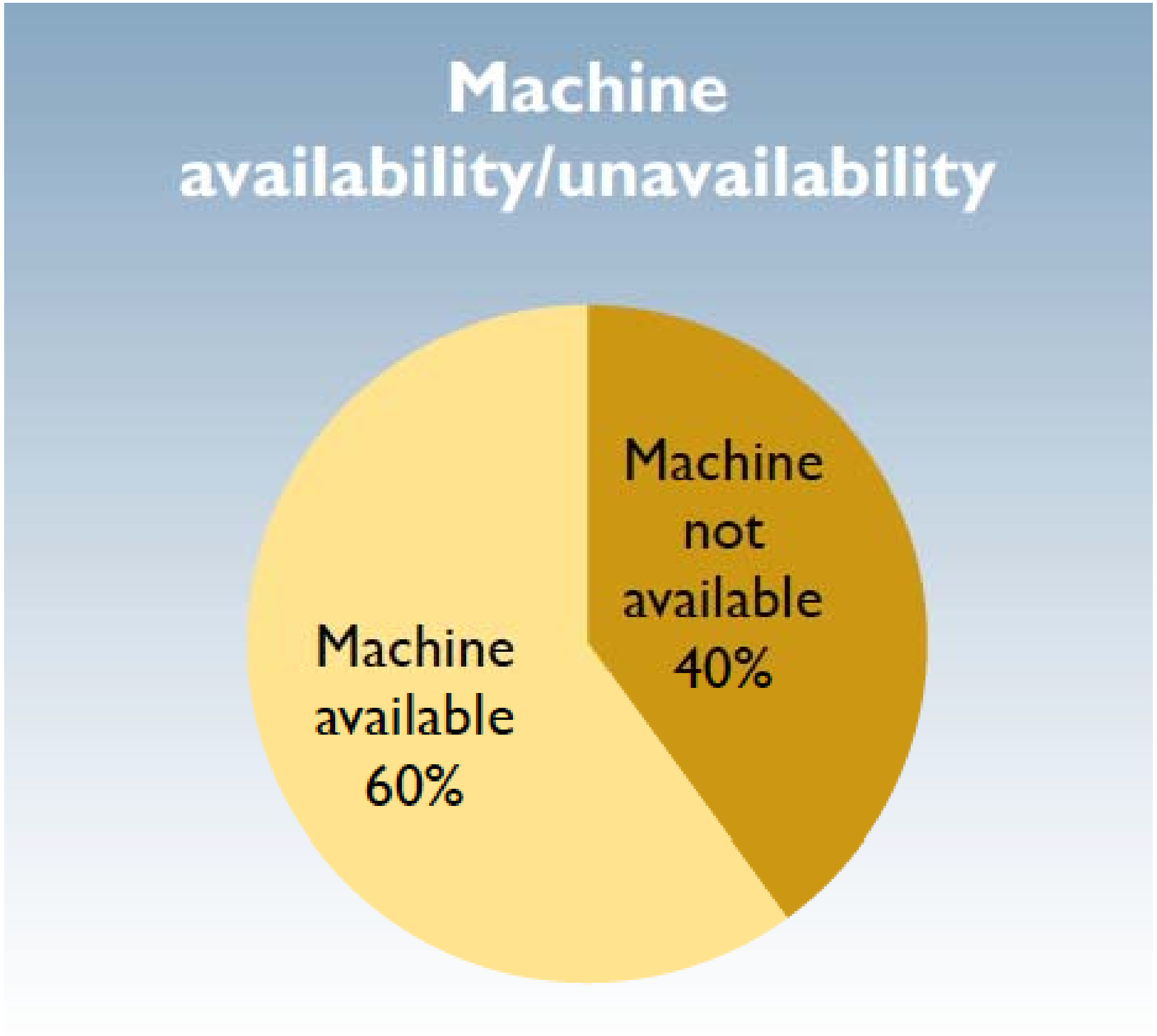




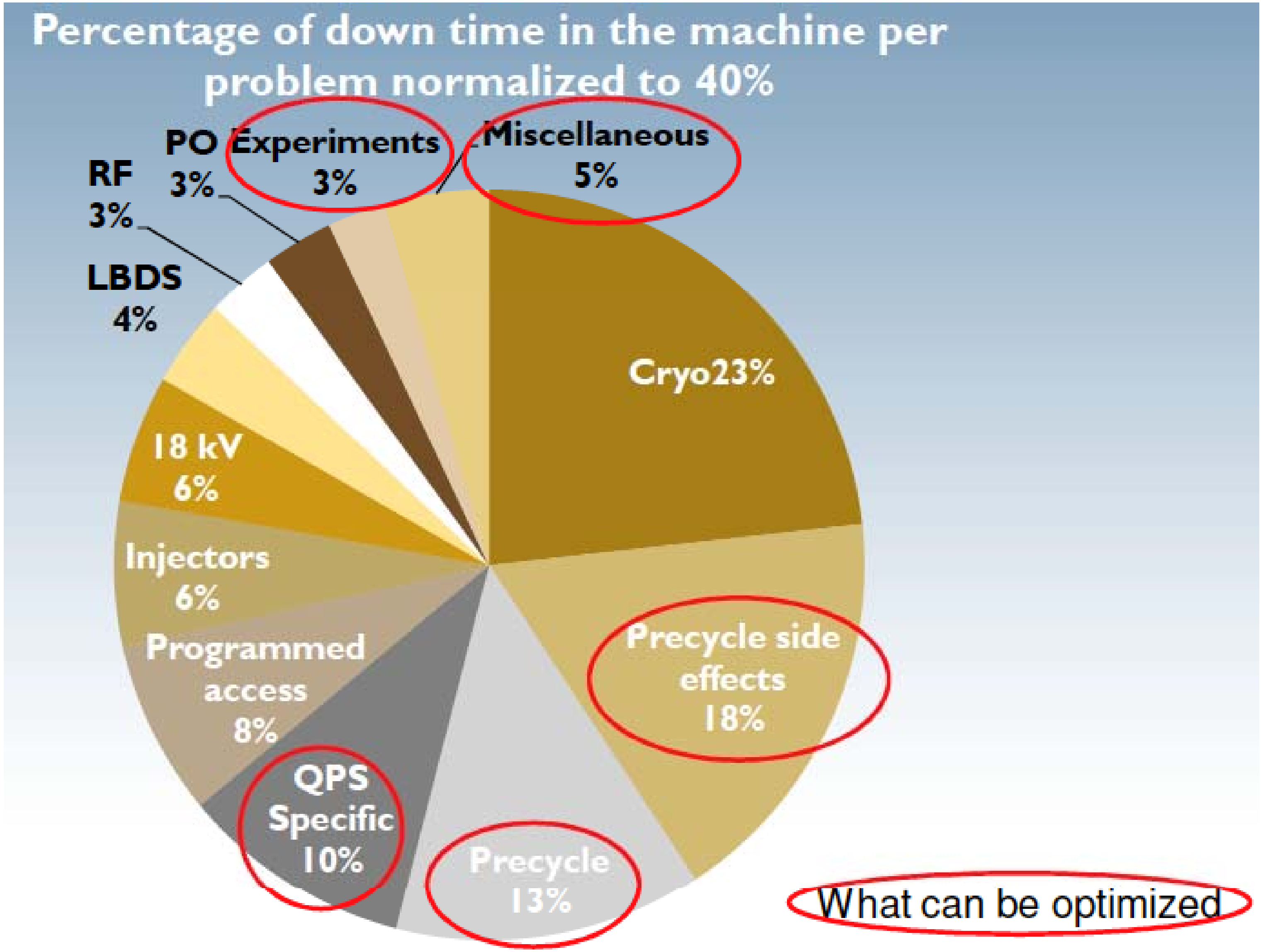
LHC commissioning & plans



Availability during initial commissioning

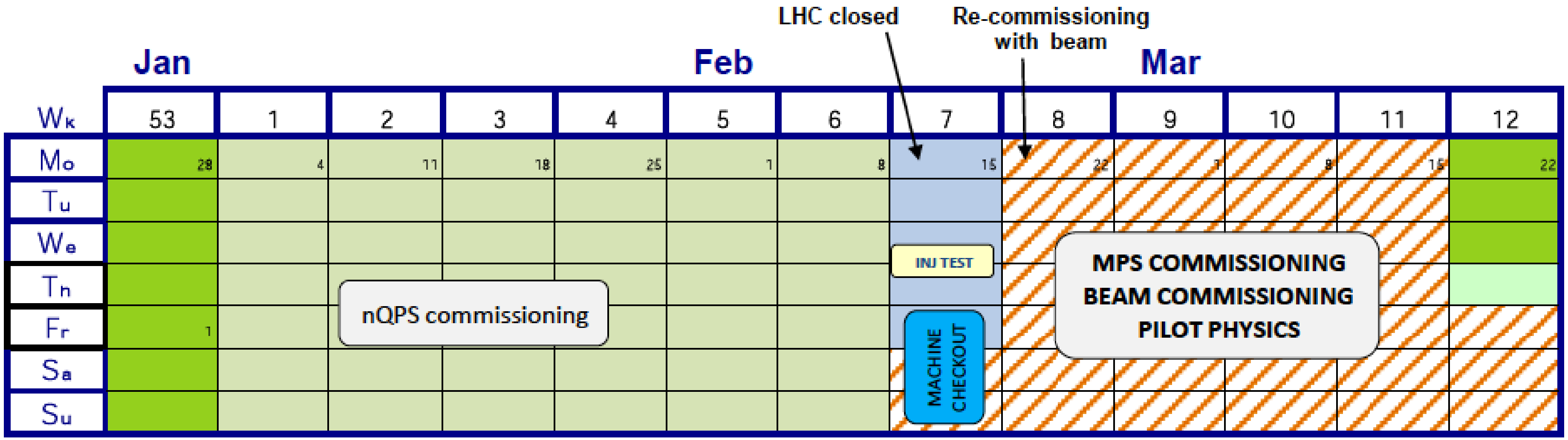


Unavailability

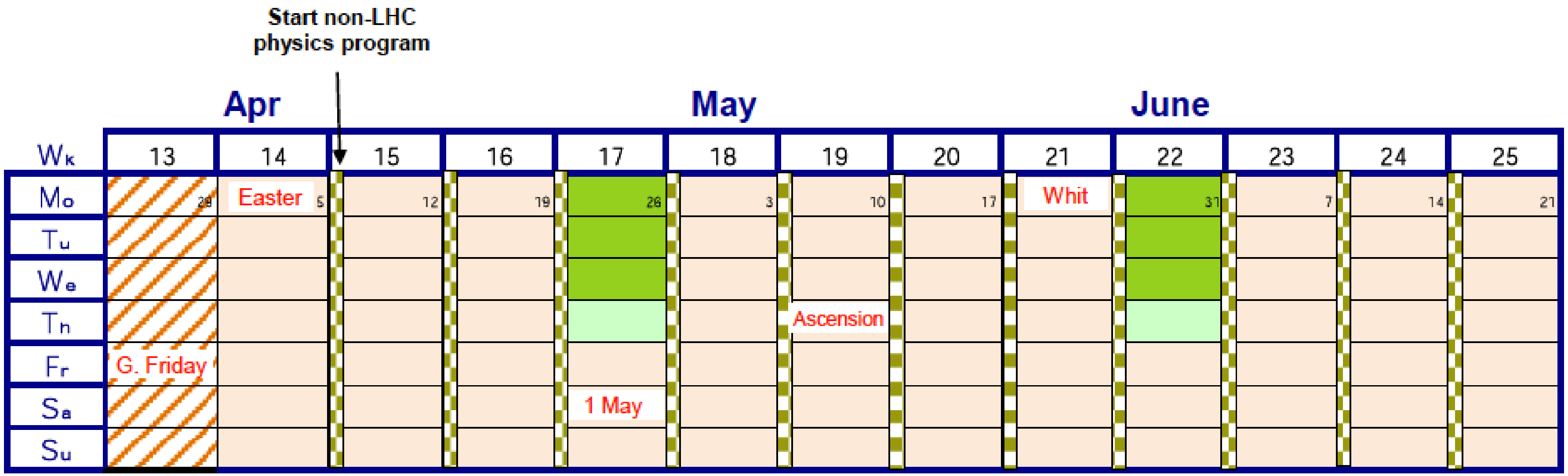


2010

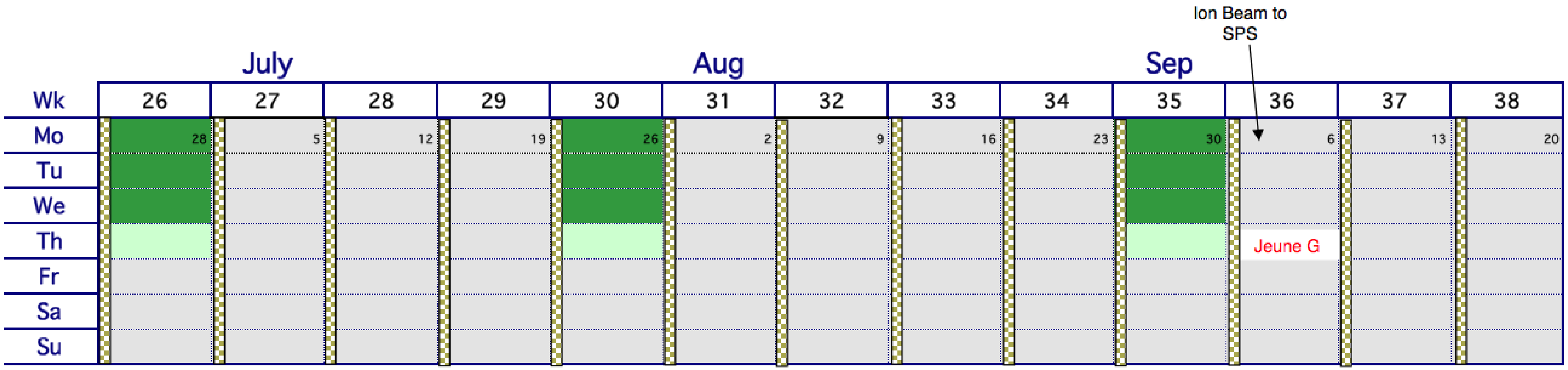
1st quarter – restart



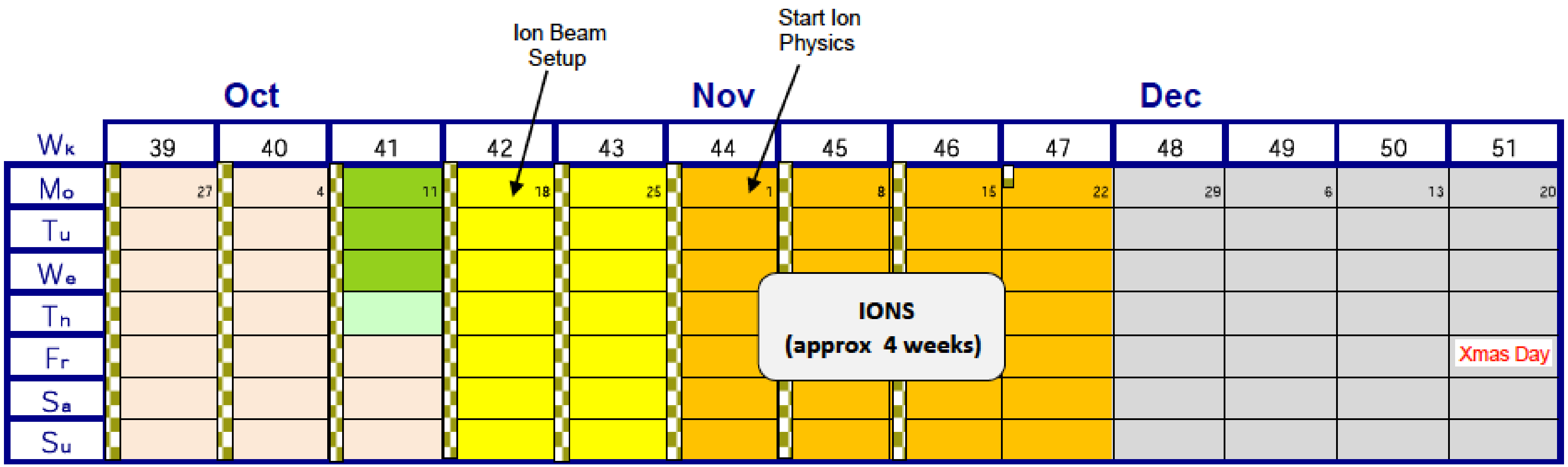
2nd quarter – physics start-up & LHC



3rd quarter – production running



4th quarter – ions



2010 overview

- Hardware commission to 3.5 TeV
  - New quench protection system (nQPS)
  - Nearly there…
- Beam commissioning continued
  - Through to colliding, safe, stable, squeezed beams
- Consolidation & pilot physics
- Phased intensity increase and associated machine protection qualification
  - Establish secure and reproducible operations and fully field test
  - Move very, very carefully
- Consolidation & physics

Beam commissioning strategy 2010

Global machine checkout

450 GeV re-commissioning

Machine protection commissioning

Ramp commissioning

Establish stable safe beams at 3.5 TeV

Collisions at 3.5 TeV

System/beam commissioning continued
Squeeze

Collisions at 3.5 TeV squeezed

Full machine protection qualification

Timeline to first collisions - estimate

Phase	Days	
Circulating beams	2	Essential checks
450 GeV re-commissioning	7	Injection, tune, Q', C-, orbit, collimators, LBDS, instrumentation
450 optics checks	3	Beating, energy matching optimization
450 two beams	1	bumps as standard set-up, adjust TDI etc
450 GeV collisions	1	experiments on at 450 GeV
Ramp to 3.5 TeV	5	commission essential machine protection, experiments' dipoles on in ramp, orbit and tune feedback
3.5 TeV	7	machine protection (beam dumps, collimation etc.) optics
Pilot collisions un-squeezed	3-5	Safe beams at 3.5 TeV, test procedures etc.
Commission squeeze	4	feedbacks, collimation, aperture, bumps, machine protection checks, beam dumps etc.
Collisions squeezed – safe, stable beams	7	Stable beams up to safe beam limit

2010 to 2 MJ

Main challenge will be learning to operate safely with destructive beams

Approved steps to 2 MJ

pb^{-1}

Stage	Ib	Nb	MJ	Lumi	Days	Int Lumi
4 pilots	5.00E+09	4	0.01	4.8E+27	14	1.44E-03
4 bunches	2.00E+10	4	0.05	7.6E+28	14	2.31E-02
4 bunches	5.00E+10	4	0.11	4.8E+29	14	0.1
8 bunches	5.00E+10	8	0.22	9.5E+29	14	0.3
4x4 bunches	5.00E+10	16	0.45	1.9E+30	14	0.6
8x4 bunches	5.00E+10	32	0.9	3.8E+30	30	2.5
43x43	5.00E+10	43	1.2	5.1E+30	14	1.6
8 trains of 6 b	8.00E+10	48	2.2	1.3E+31	14	4.0
				days	128	9.1
				months	4.3	
0.25						
1.00E-24						
1.00E-12						
50 ns trains	8.00E+10	96	4.3	2.7E+31	150	86.5

Simple Hubner Factor

2010 - 2011

Step	Phase	E [TeV]	N	Fill scheme	I/I^{nom} [%]	E_{beam} [MJ]	β* [m] IP1/2/5/8	L (IP1/5) [$cm^{-2}s^{-1}$]	Run time (indicative)
1	Beam commissioning, safe beam limit	0.45	5×10^{10}	2×2	0.03	0.0072	11/10/11/10	2.6×10^{27}	Days
2		3.5	2×10^{10}	2×2	0.01	0.02	11/10/11/10	7×10^{27}	
3	Beam commissioning, safe beam limit, squeeze		2×10^{10}	2×2*	0.01	0.02	2/10/2/2	3.6×10^{28}	
4	Bunch trains from SPS		3×10^{10}	43×43	0.4	0.7	2/10/2/2	1.7×10^{30}	Months!
5	Increase intensity		5×10^{10}	43×43	0.7	1.2	2/10/2/2	4.8×10^{30}	
6			5×10^{10}	156×156	2.4	4.4	2/10/2/2	1.7×10^{31}	
7			7×10^{10}	156×156	3.3	6.1	2/10/2/2	3.4×10^{31}	Months
8	Bring on crossing angle, truncated 50 ns.		7×10^{10}	50ns - 144**	3.1	5.7	2.5/3/2.5/3	2.5×10^{31}	
9	Increase intensity		5×10^{10}	50ns - 288	4.4	8.1	2.5/3/2.5/3	2.6×10^{31}	
10			7×10^{10}	50ns - 432	9.3	17	2.5/3/2.5/3	7.5×10^{31}	
11			7×10^{10}	50ns - 796	17.1	31.2	2.5/3/2.5/3	1.4×10^{32}	

2011

3.5 TeV: run flat out at ~100 pb^{-1} per month

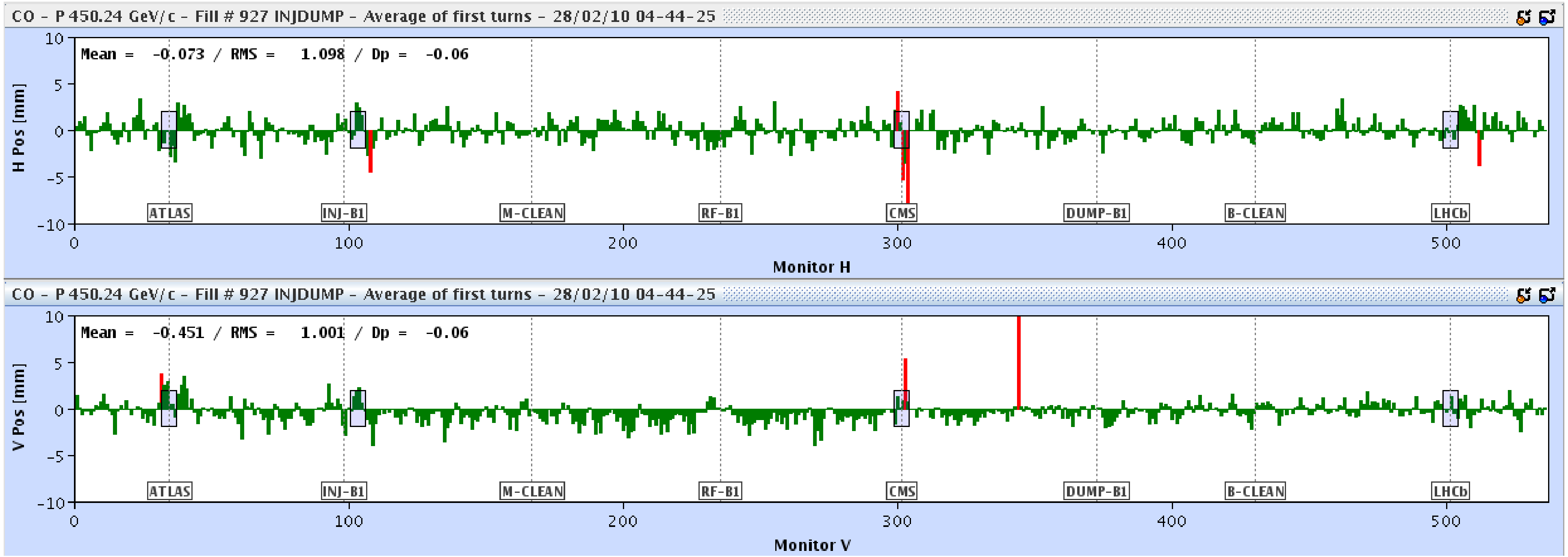
	Nb	ppb	Total Intensity	MJ	beta*	Peak Lumi	Int Lumi per month [pb^{-1}]
50 ns	432	7 e10	3 e13	17	2.5	7.4 e31	~63 (34)
Pushing intensity limit	796	7 e10	5.1 e13	31	2.5	1.4 e32	~116 (63)

16% nominal

Hope to be able to deliver around 1 fb^{-1}

LHC – startup 2010

It still works!



Circulating beams re-established last weekend

Conclusions 1/2

- A lot of hard work over the years has enable a truly impressive period of initial commissioning with beam.
- Initial indications are that the LHC:
  - **is reproducible;**
  - **magnetically well understood;**
  - **optically in good shape;**
  - **is armed with a mighty set of instrumentation, software, and hardware systems.**
- Lots still to sort out, in particular…
- Operations, controls, instrumentation etc. have the capability to unnecessarily stress the machine protection system – issues must be resolved.

Long way to go before we are ready to go much beyond the safe beam limit

Conclusions 2/2

- Starting now ~4 weeks to establish stable, safe beams at 3.5 TeV and provide first collisions

- Extended running period around the safe beam limit:
  - With blocked MD periods as required

- A very careful stepwise increase in intensity through the year with each step up in intensity to be followed by an extended running period

- Aiming for 10^{31} - 10^{32} $cm^{-2}s^{-1}$ in 2010 and hopefully between 100 – 200 pb^{-1}