The LHC from commissioning to operation

Mike Lamont for the LHC team

The LHC

- Very big
- Very cold
- Very high energy

Energy

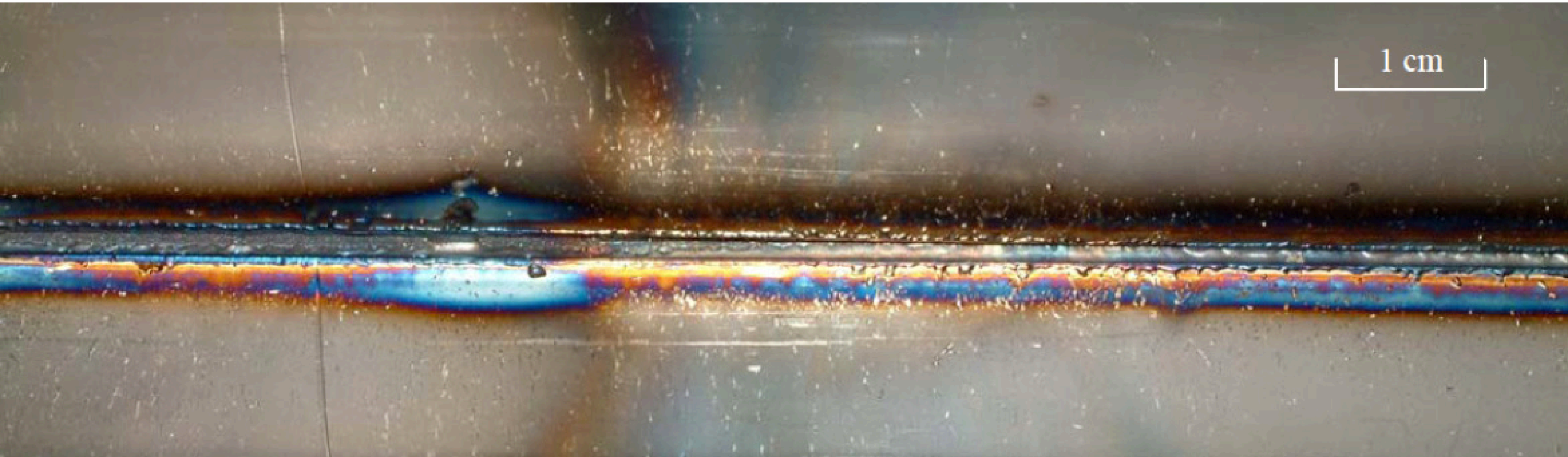
At 3.5 TeV with 1380 bunches – August 2011

- **~3 GJ** of energy stored in the magnets
- **100 MJ** stored in each beam ~21 kg of TNT.

Underpinned our thoughts during commissioning

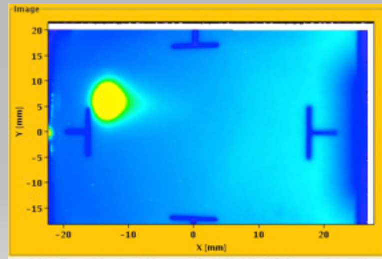
During an SPS extraction test in 2004…

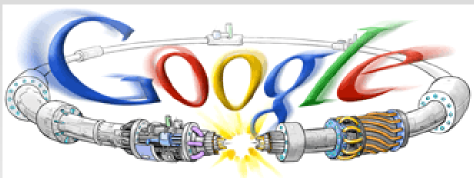
The beam was a 450 GeV full LHC injection batch of 3.4 10^{13} p+ in 288 bunches [2.5 MJ]



LHC Timeline

August 2008
First injection test



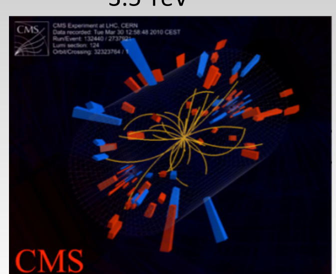


September 10, 2008
First beams around

September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

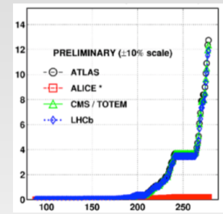
November 29, 2009
Beam back

March 30, 2010
First collisions at 3.5 TeV

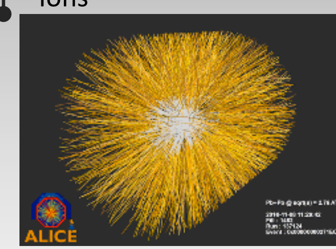


April 2010
Squeeze to 3.5 m

October 14 2010
1e32
248 bunches



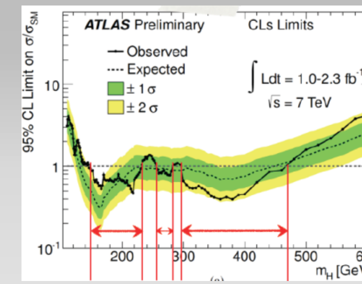
November 2010
Ions



June 28 2011
1380 bunches

1380

August, 2011
2.3e33, 2.6 fb^{-1}
1380 bunches

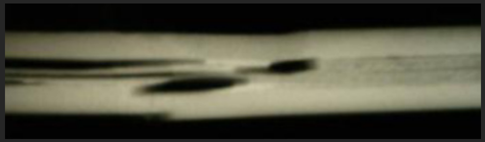


2008 | 2009 | 2010 | 2011

2009: besides massive repair and consolidation

Understanding the problem

- Copper stabilizer issue identified
- Measurement campaign warm and cold
- Simulations
- Test set-up (FRESCA)



Prevention

- Deployment of new Quench Protection System (design, prototyping, production, deployment, testing)

Caution

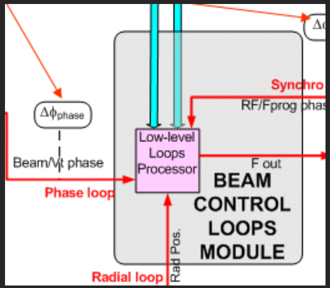
Run at 3.5 TeV

TUPS071 **Performance of the Protection System for Superconducting Circuits during LHC Operation**

2009: That which does not kill us…

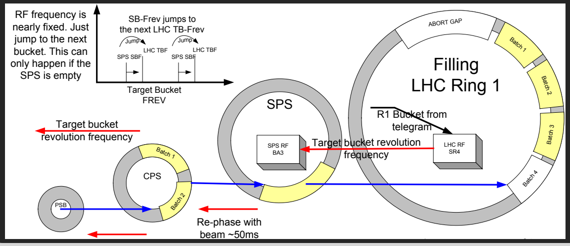
Beam based systems

- Injectors & transfer lines
- Instrumentation: BPMs, BLMs
- Beam interlock System
- RF
- Collimators

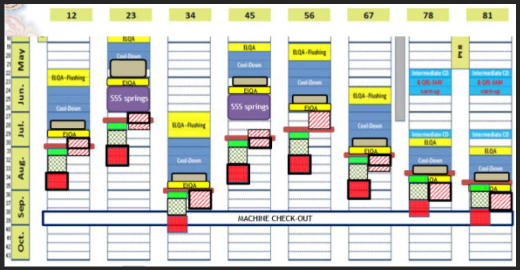


Controls & software

- Sequencer
- Injection sequencer
- Settings management
- Middleware
- Timing
- Software interlocks
- Magnet model
- On-line model
- Logging



Dry runs, system tests and hardware commissioning



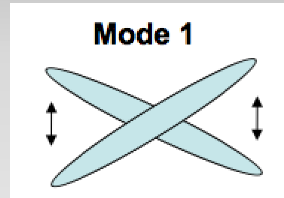
“Unprecedented state of readiness”

A closer look at 2010

Feb 27
Beam back

March 30
First collisions
3.5 TeV

June
Commission
nominal bunch
intensity

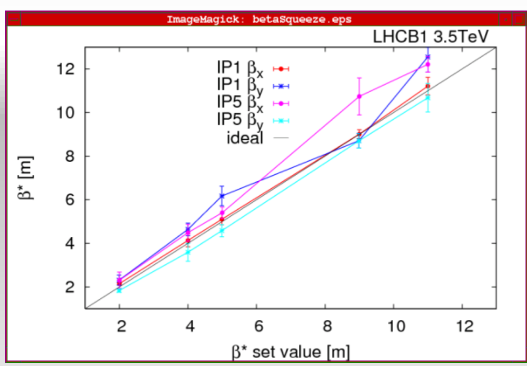


November 4
Switch to lead
ions

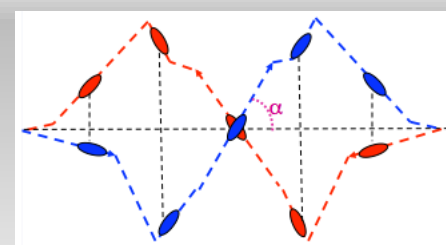
QUALIFICATION

February	March	April	May	June	July	August	September	October	November

April
Commission
squeeze

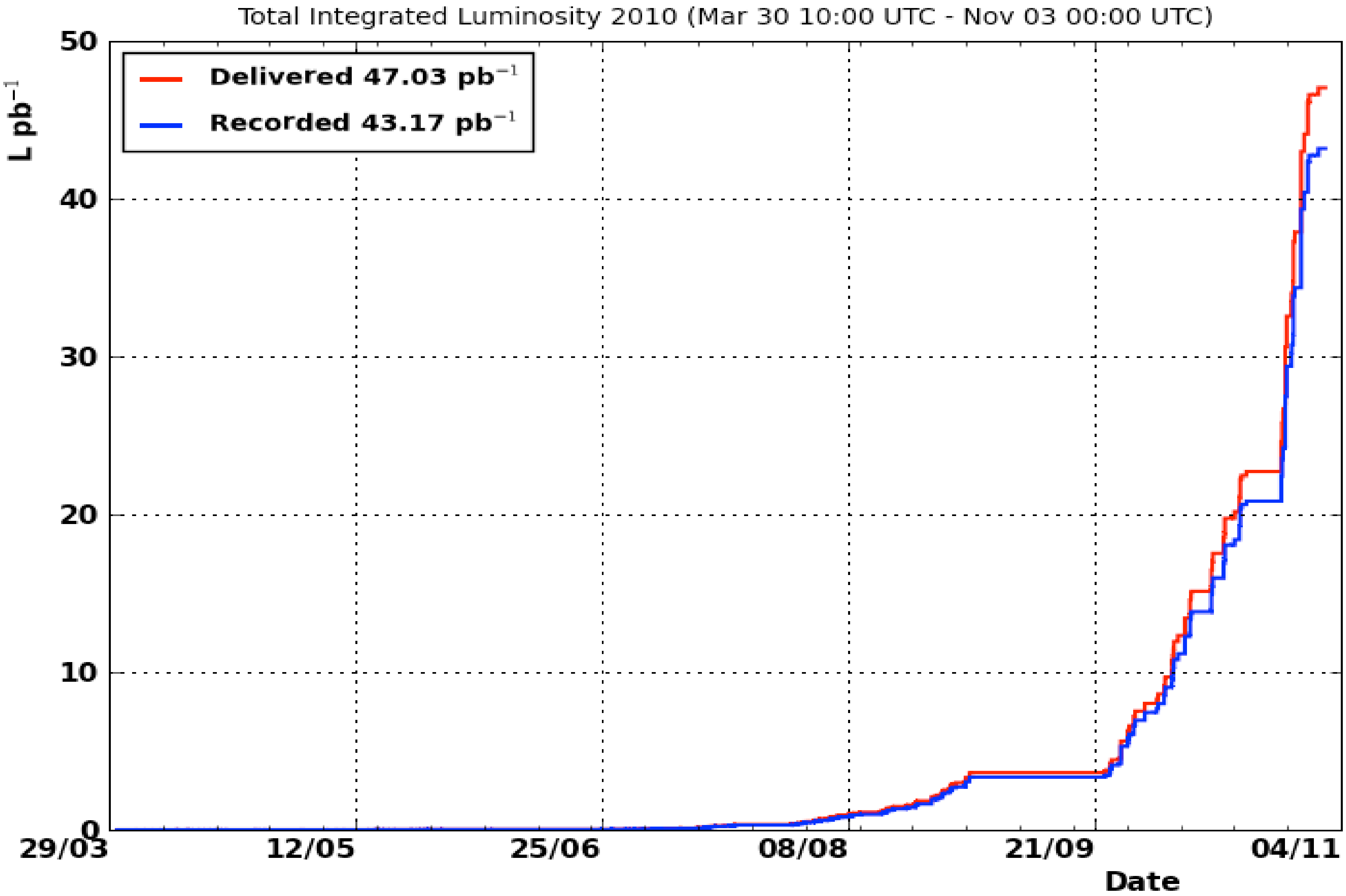


September
Crossing angles on

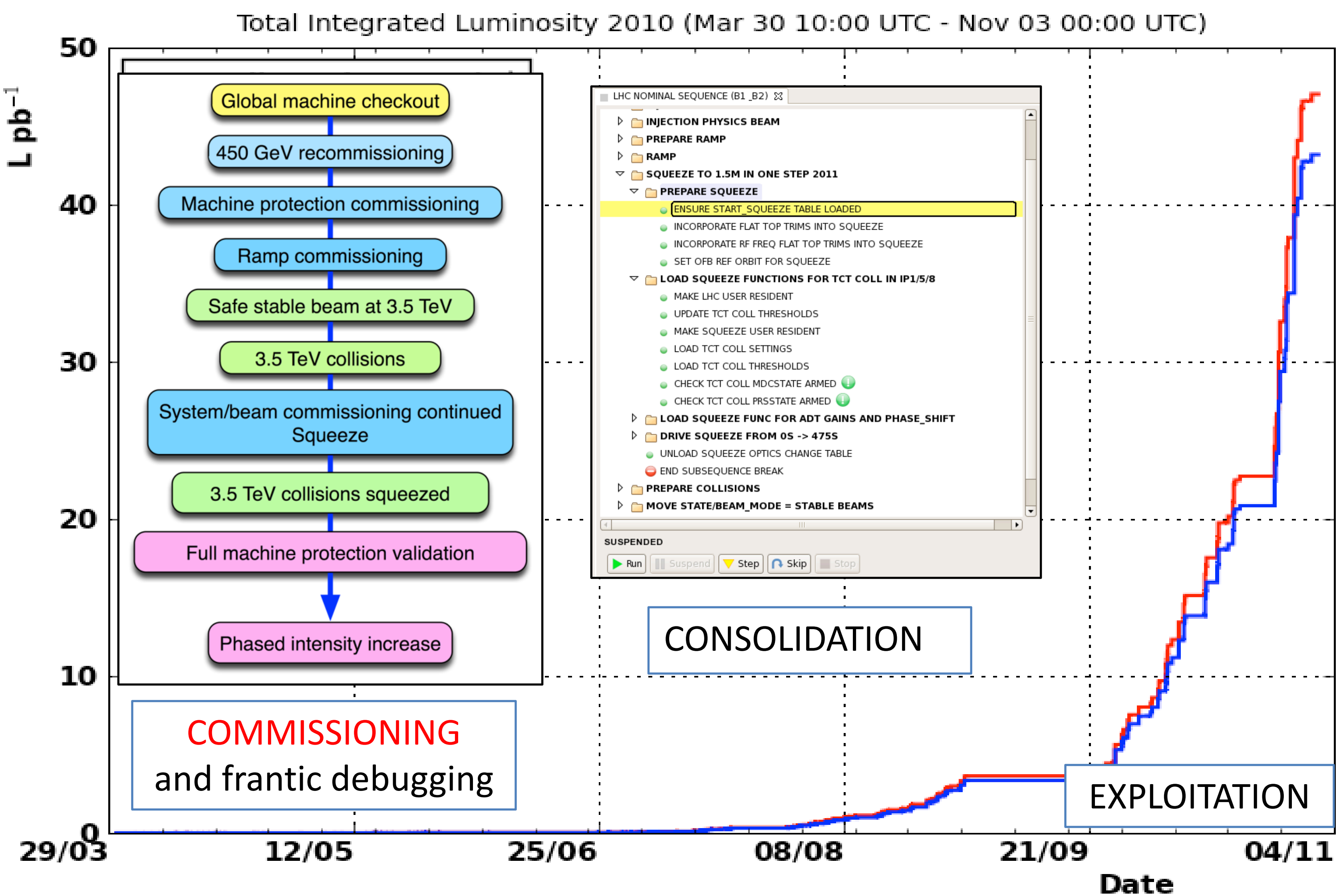


October
Luminosity
production

2010 – integrated luminosity



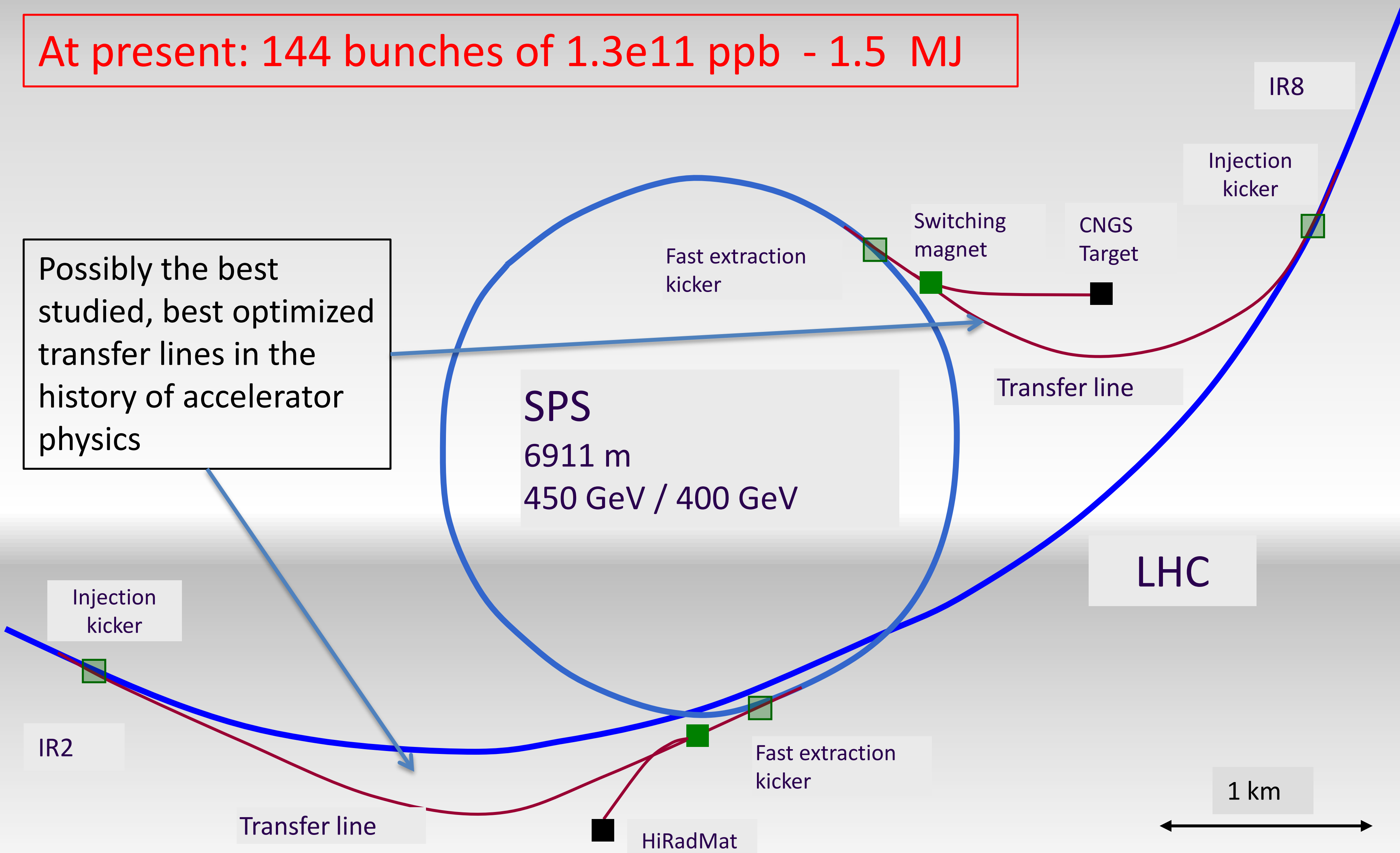
2010 – integrated luminosity



Transfer & injection

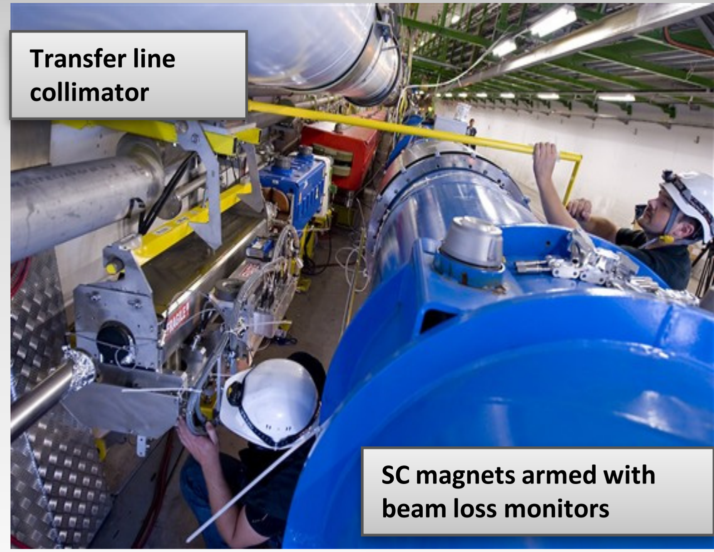
At present: 144 bunches of 1.3e11 ppb - 1.5 MJ

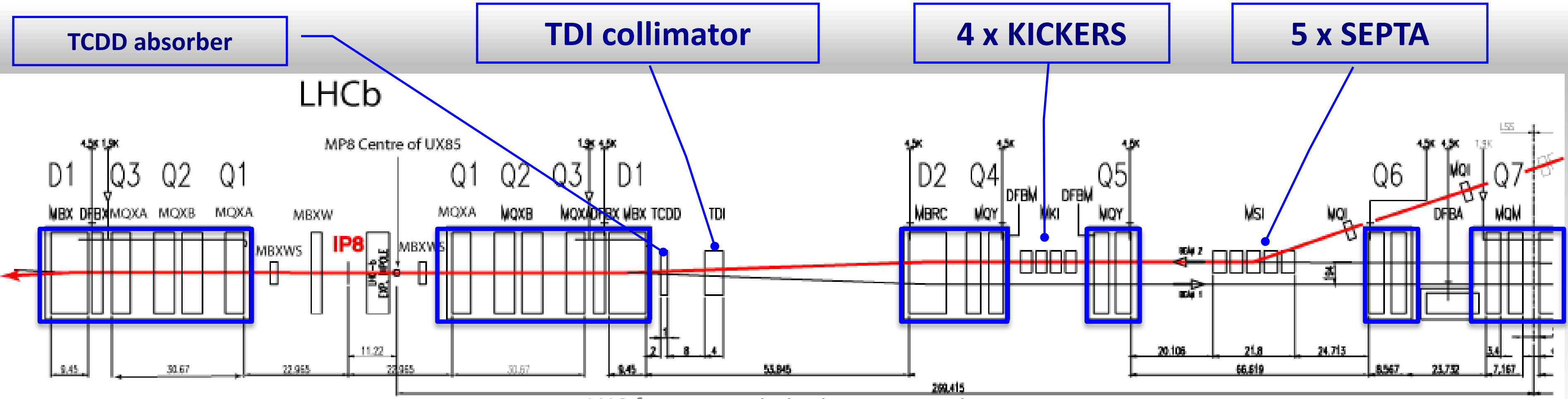
Possibly the best studied, best optimized transfer lines in the history of accelerator physics



Injection

- Complex process – wrestle with:
  - Re-phasing, synchronization, transfer, capture
  - Timing, injection sequencing, interlocks
  - Injection Quality checks – SPS and LHC
  - Abort gap keeper
  - Beam losses at injection, gap cleaning
- Full program of beam based checks performed
  - Carefully positioning of collimators and other protection devices
  - Aperture, kicker waveform

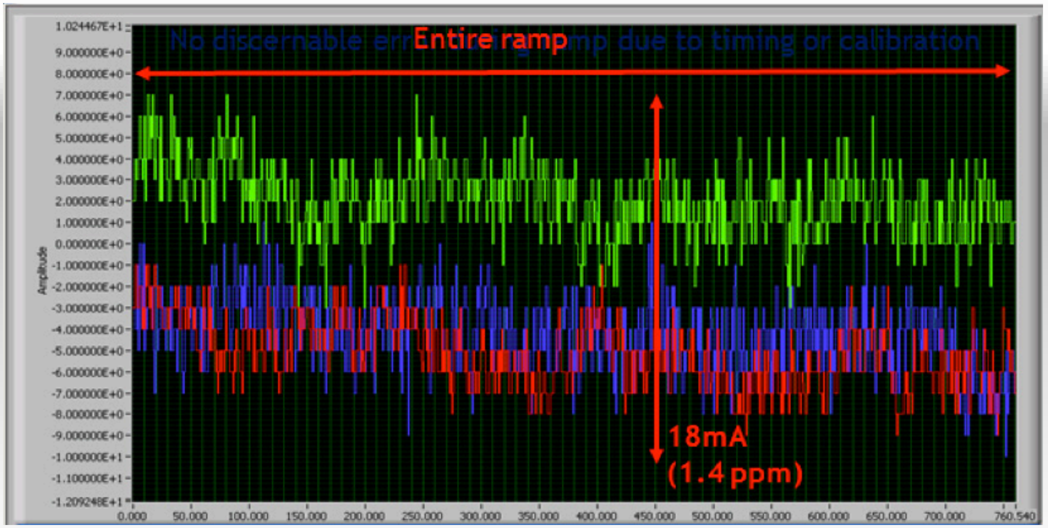




Ramp

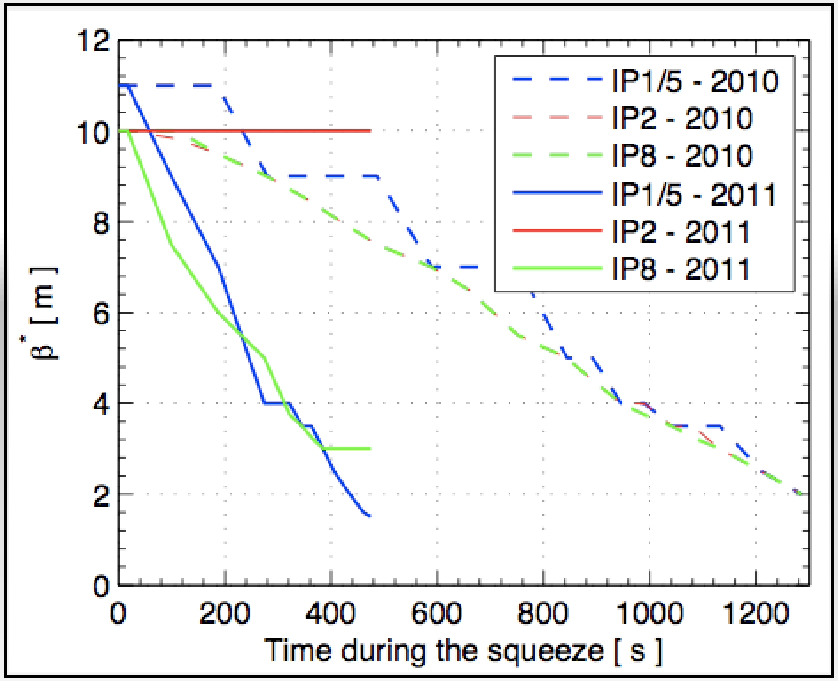
- Power converters (all magnet circuits), magnet model, RF, collimators, beam dump, transverse damper, orbit and tune feedback, BLM thresholds etc.
- Reproducible and essentially without loss (after a lot of work)

Main bend power converters: tracking error between sector 12 & 23 in ramp to 1.1 TeV

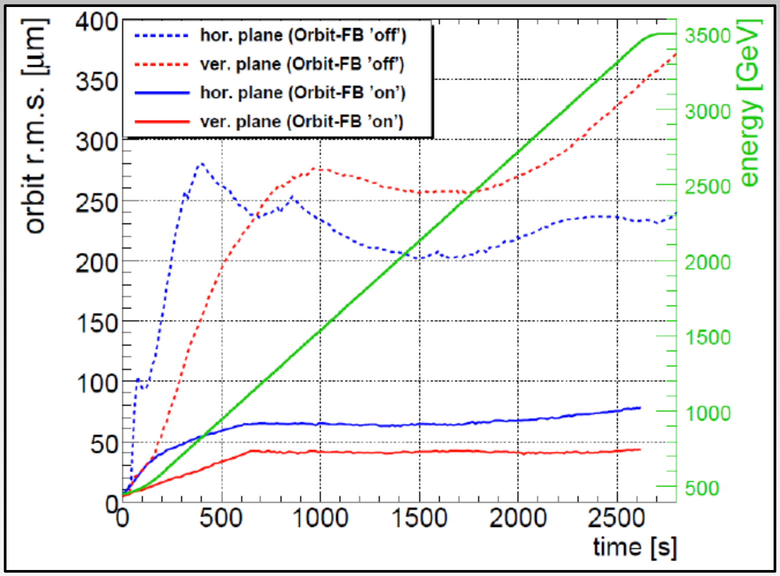


Squeeze

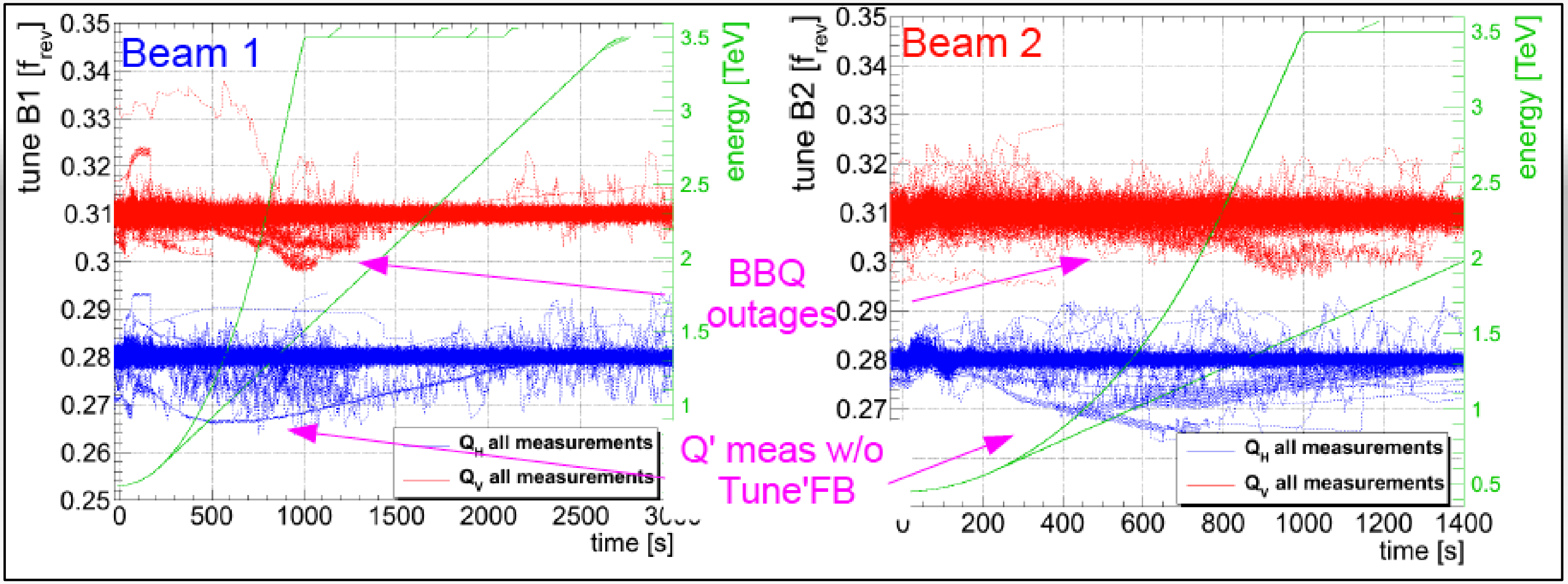
- Programmed functions making smooth transition between matched optics
- Tune and orbit feedbacks mandatory
- Reproducible and essentially without loss (a.l.w.)



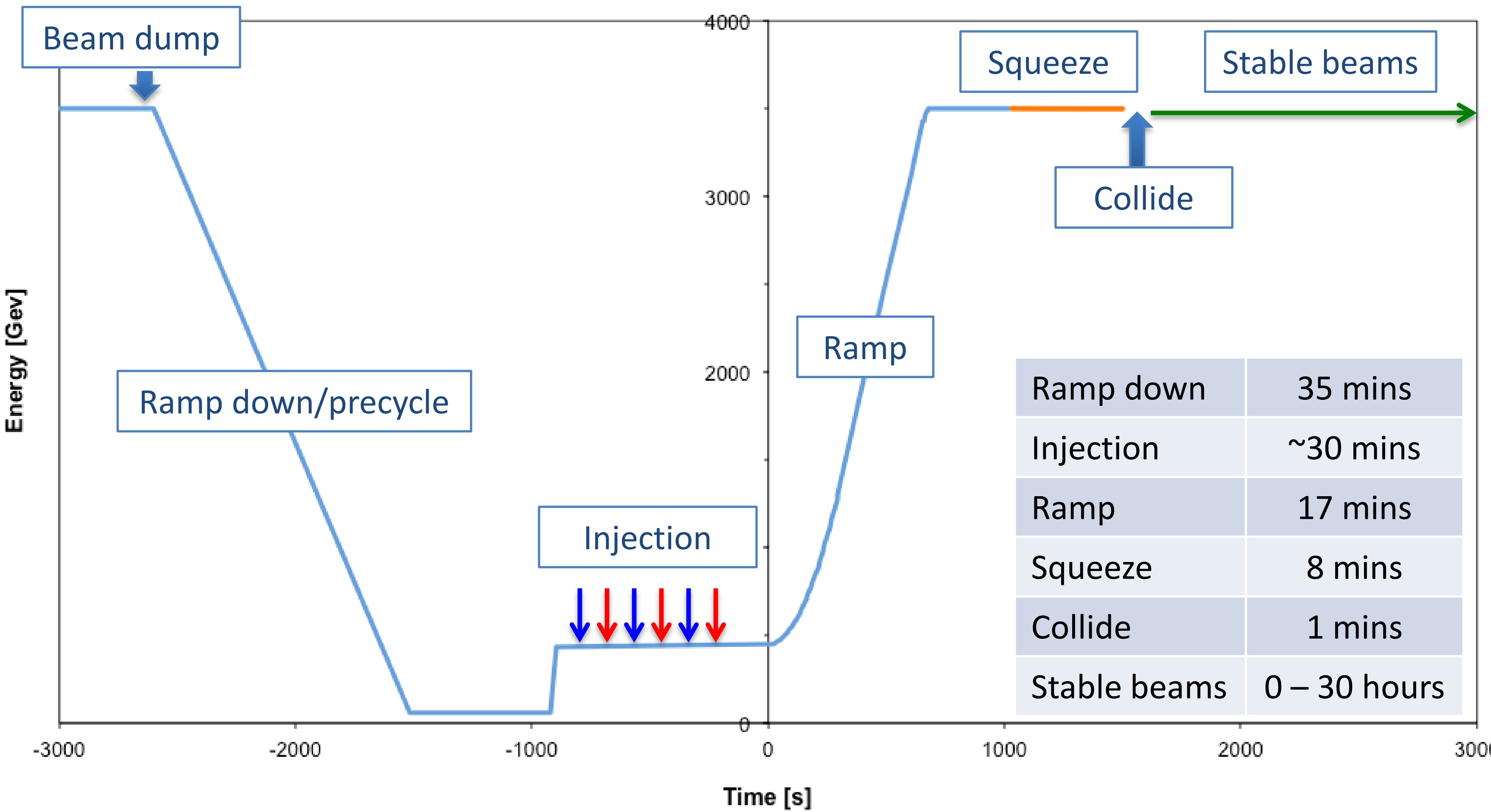
Tune and orbit feedback



- Mandatory in ramp and squeeze
- Commissioning not without some issues but now fully operational



Nominal cycle

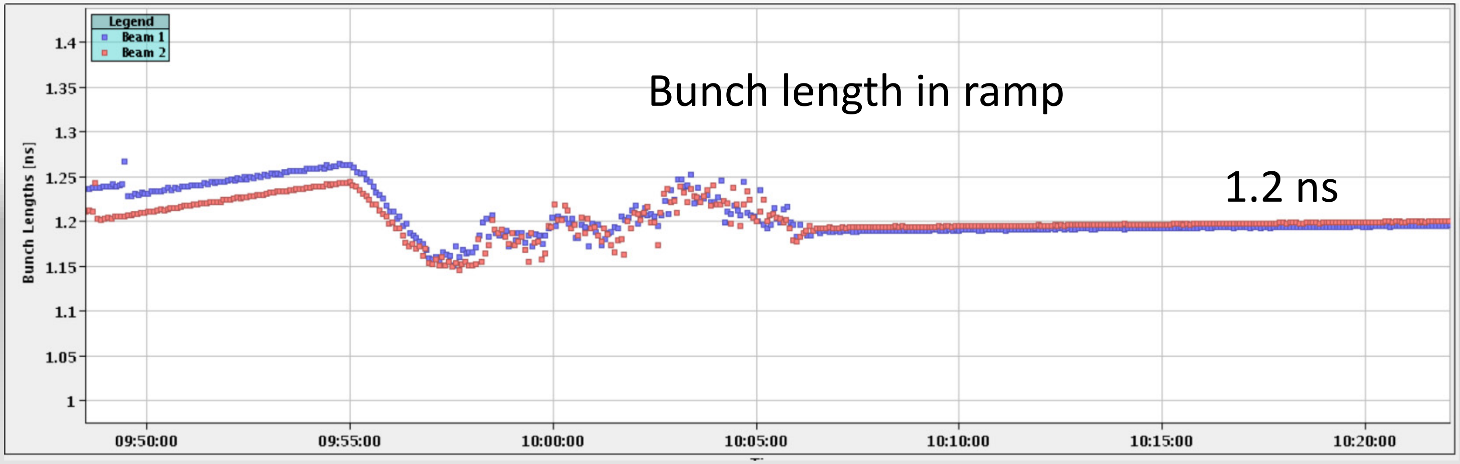


Ramp down	35 mins
Injection	~30 mins
Ramp	17 mins
Squeeze	8 mins
Collide	1 mins
Stable beams	0 – 30 hours

Fastest turn around down from 3h40m in 2010 to 2h7m in 2011 after optimization

RF

- RF noise & crossing of 50 Hz by Qs in ramp – no issue.
- Capture losses under control
- Longitudinal emittance blow-up, needed for ramping of nominal bunch intensity, rapidly commissioned.
- Beam-induced voltage and load power:
  - half nominal intensity – dump beam on 1 klystron trip - 5/43 fills to RF since July 2011

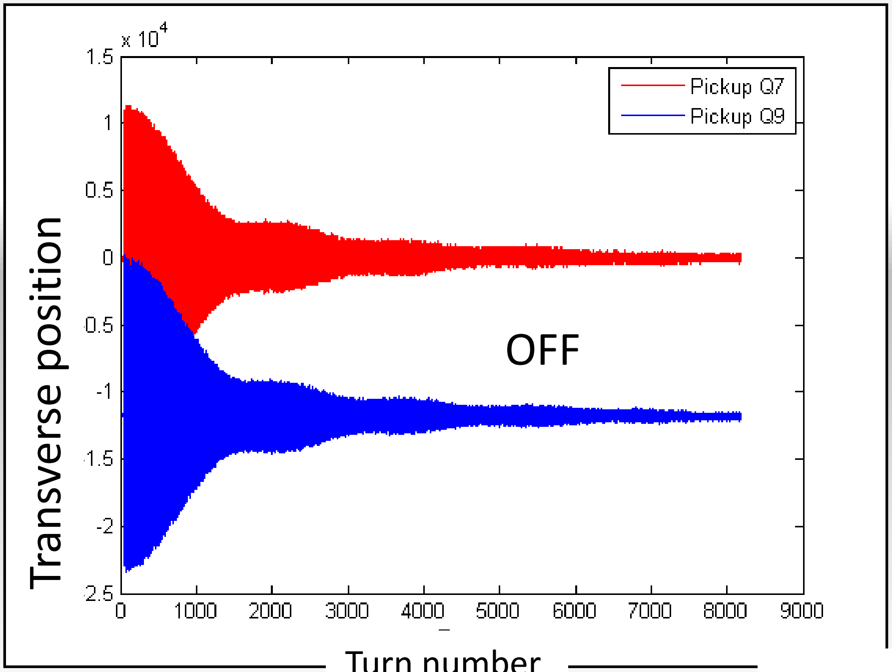


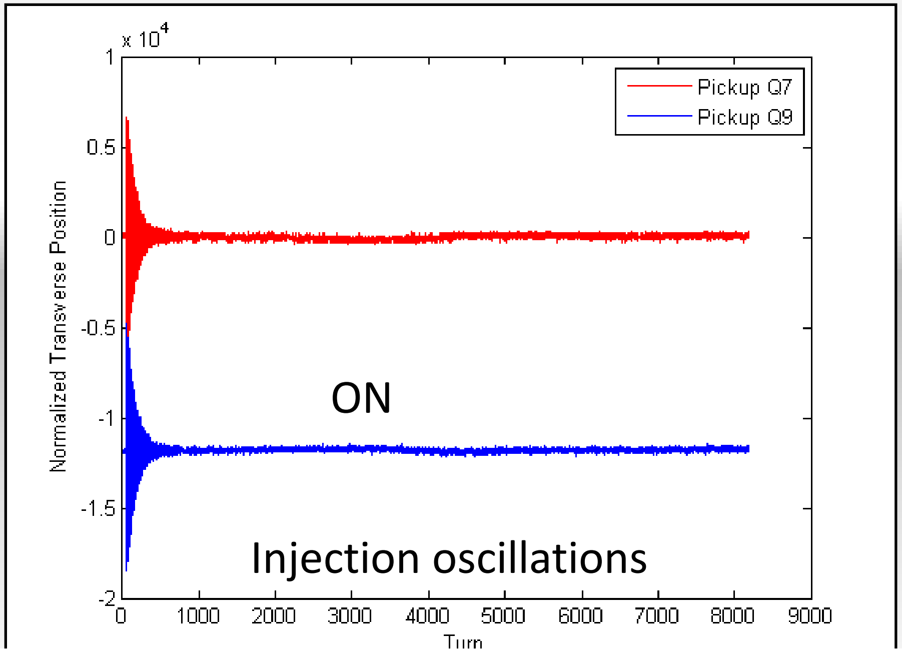
MOPC054 **The LHC RF System Experience with Beam Operation**
MOPC057 **Loss of Landau Damping in the LHC**
TUPZ010 **Longitudinal emittance blow-up in the LHC**

Transverse dampers

- Injection oscillations
- ‘Hump’ suppression
- Abort gap and injection gap cleaning
- Coherent instabilities
- (Blow-up for loss maps)

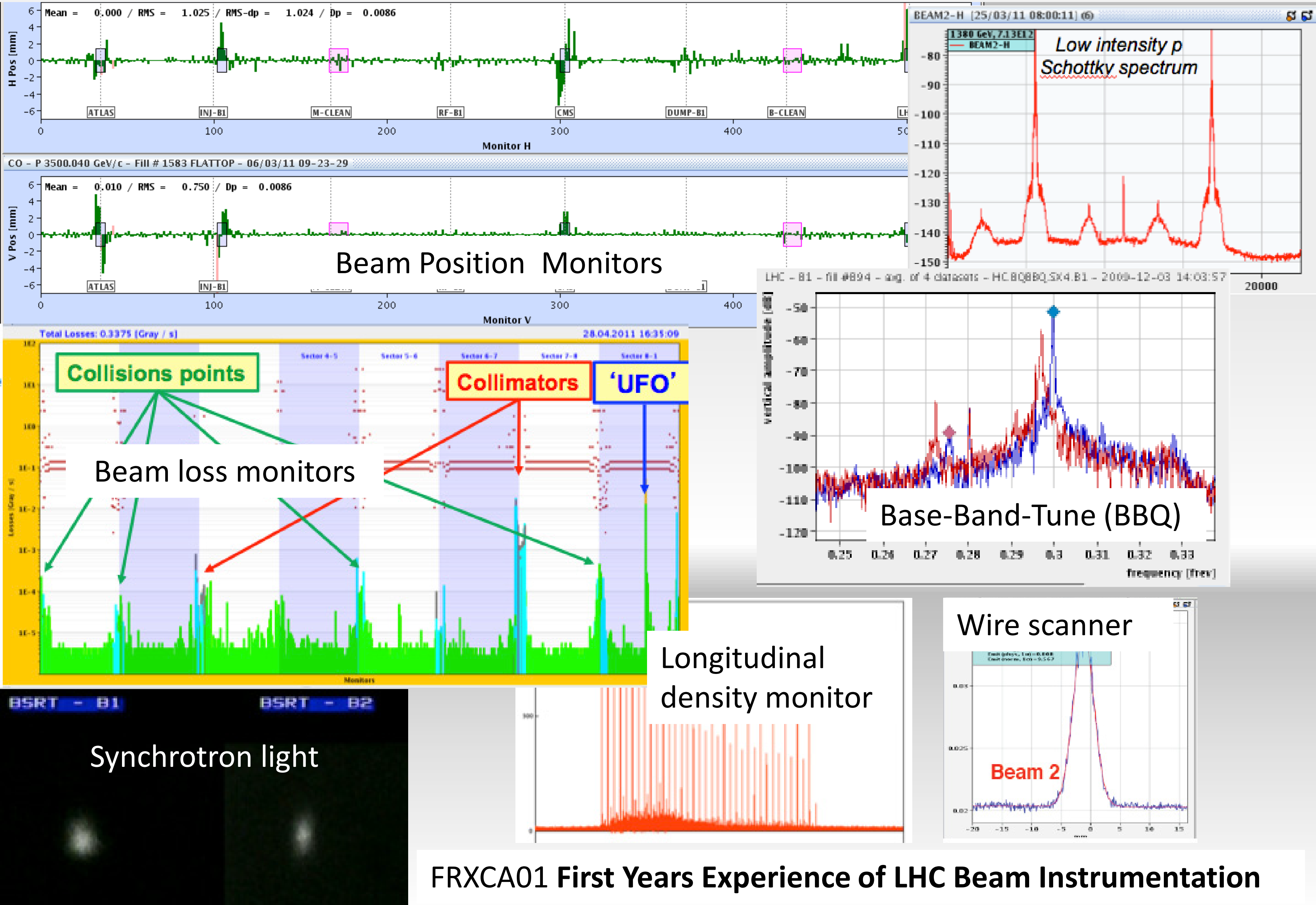
Vital and working well





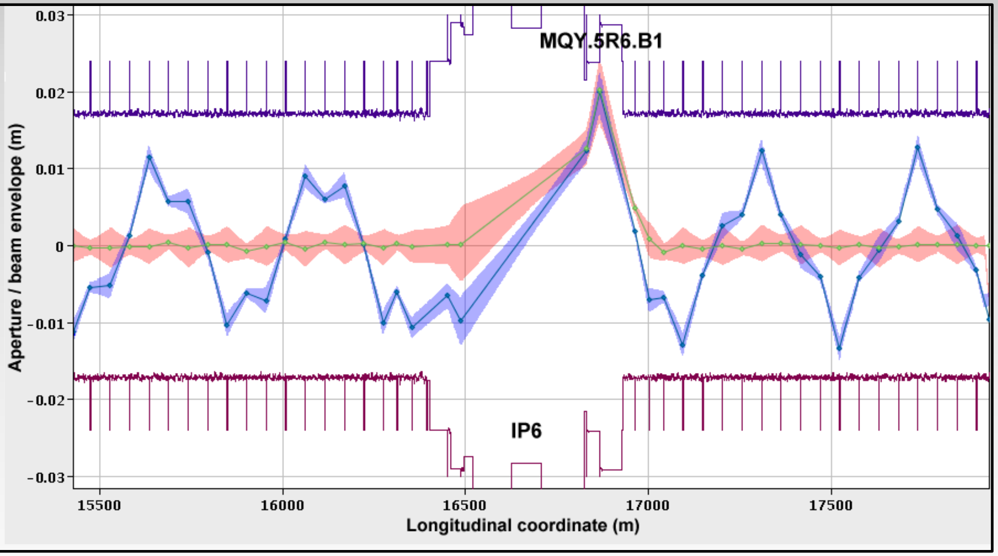
MOPO012 **LHC Damper Beam Commissioning in 2010**

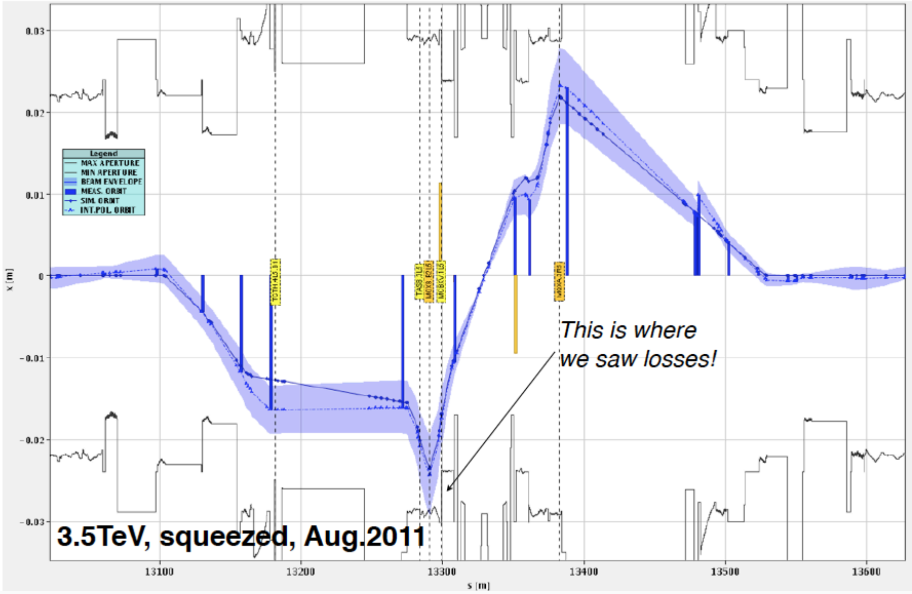
Beam Instrumentation: excellent performance



FRXCA01 **First Years Experience of LHC Beam Instrumentation**

Aperture



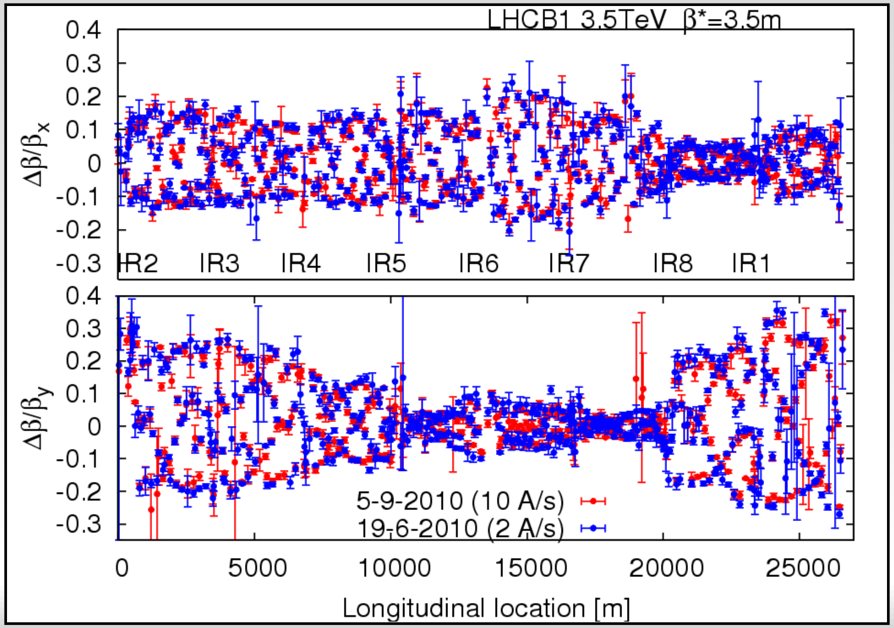


Aperture systematically measured (locally and globally)
Better than anticipated w.r.t. tolerances on orbit & alignment

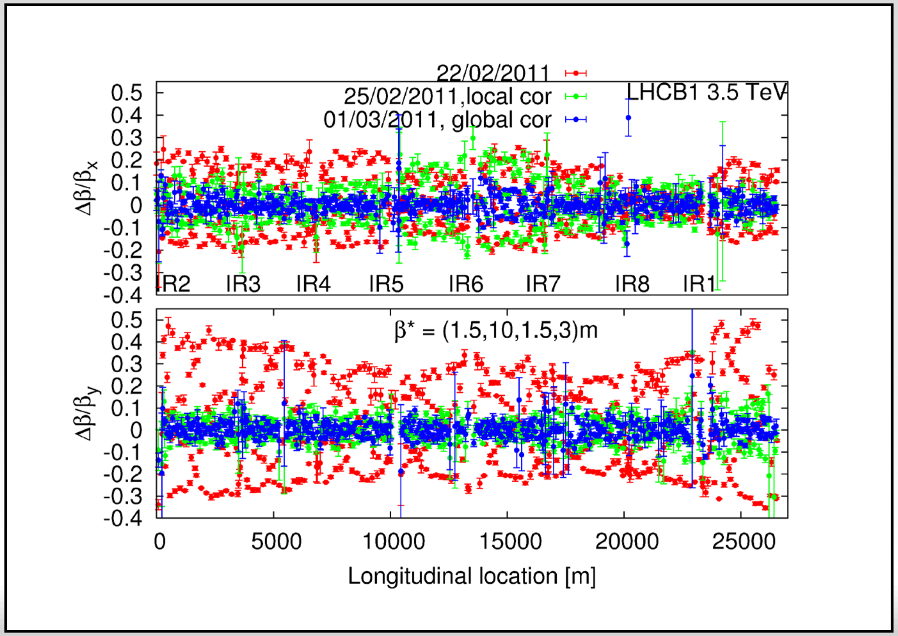
Aperture compatible with a well-aligned machine, a well centred orbit and close to design mechanical aperture

Optics

Optics stunningly stable — and well corrected



Two measurements of beating at 3.5 m
3 months apart

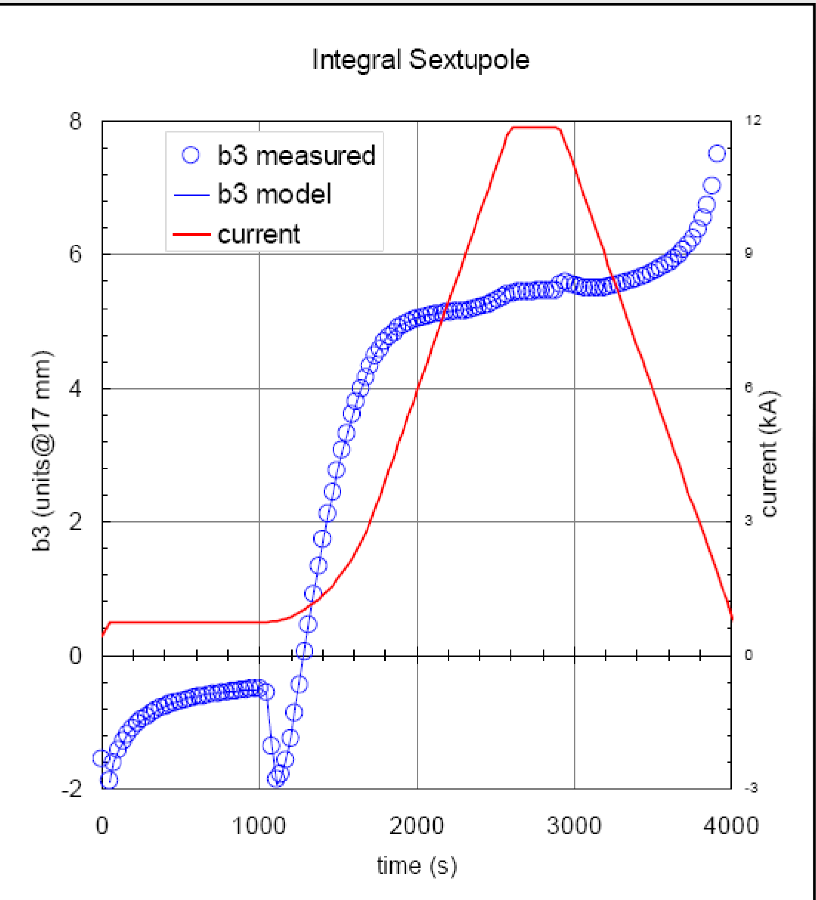


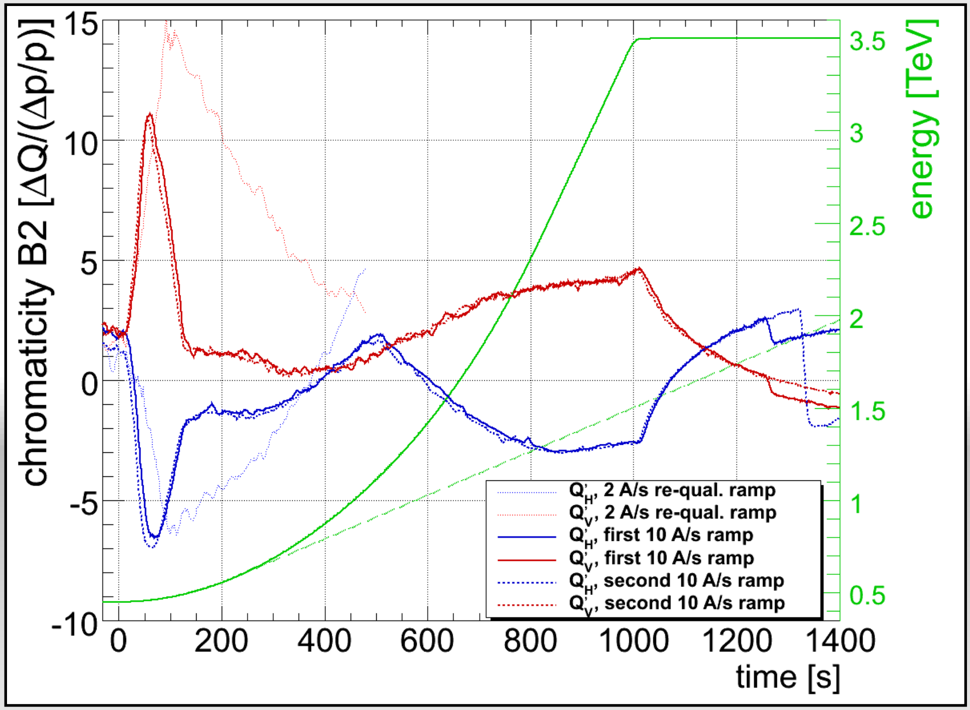
Local and global correction at 1.5 m

WEPC028 **Record Low Beta-beat of 10% in the LHC(!)**

Magnet model

- Knowledge of the magnetic machine is remarkable
- All magnet 'transfer functions', all harmonics including decay and snapback
- Tunes, momentum, optics remarkably close to the model



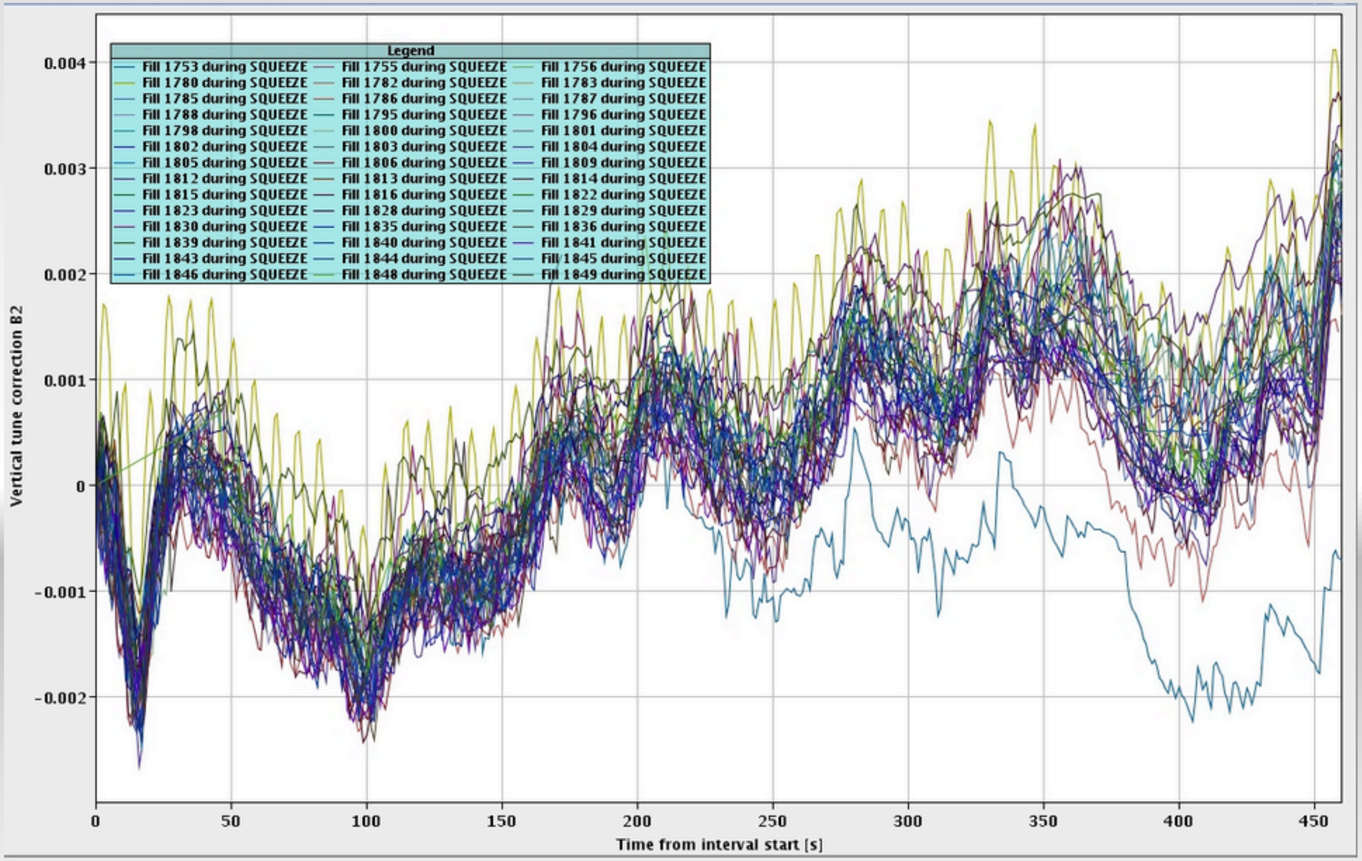


Model based feed-forward reduces chromaticity swing from 80 to less than 10 units

Reproducibility

LHC magnetically reproducible with rigorous pre-cycling - set-up remains valid from month to month

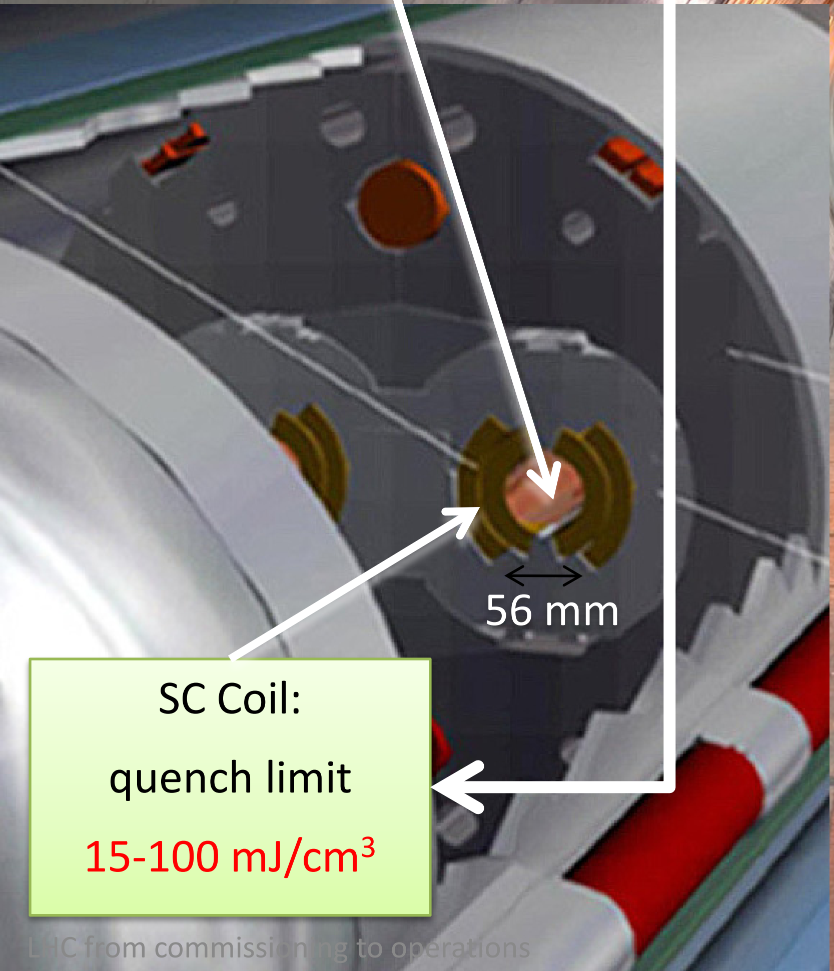
7 e-3

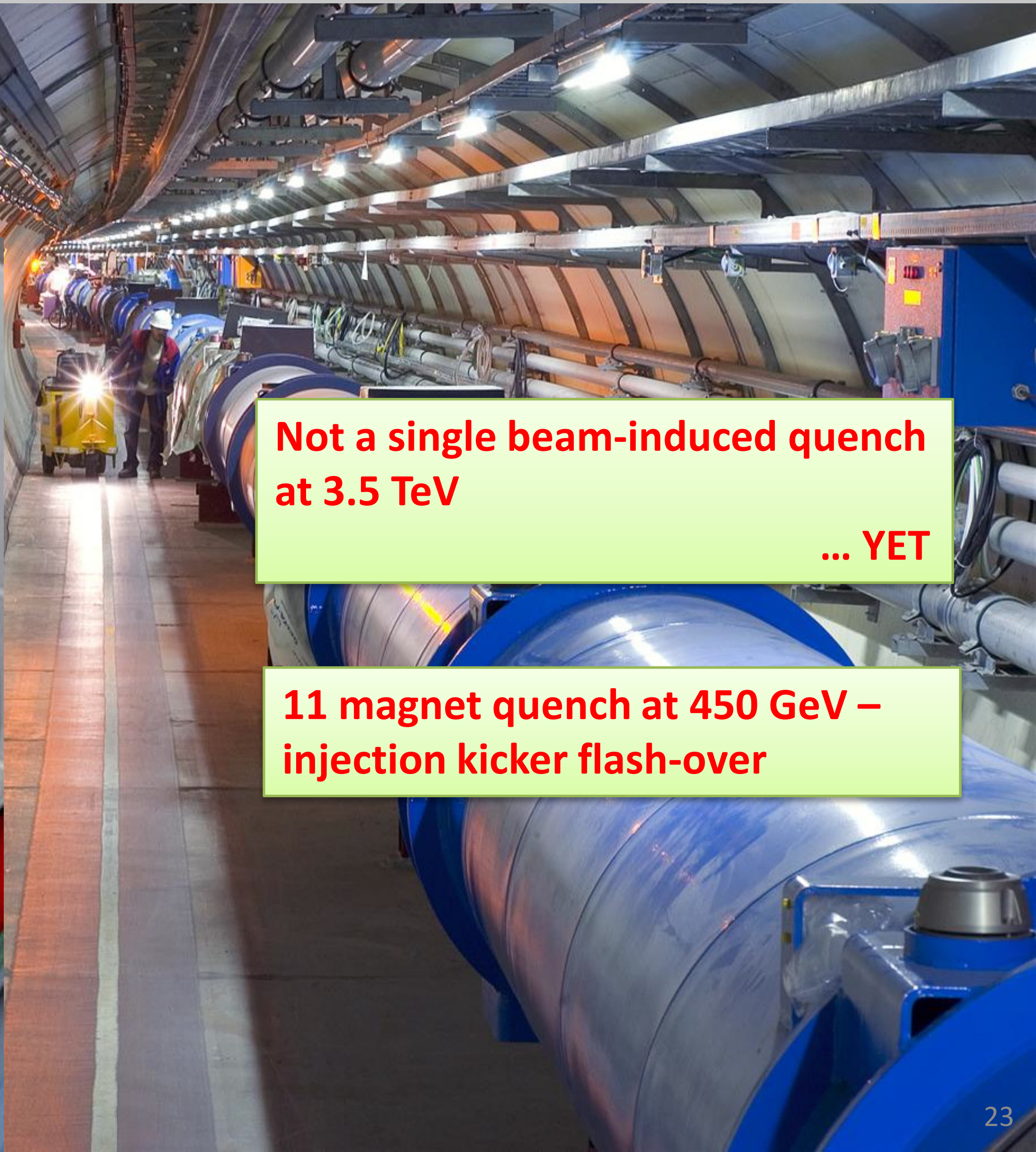


Tune corrections made by feedback during squeeze

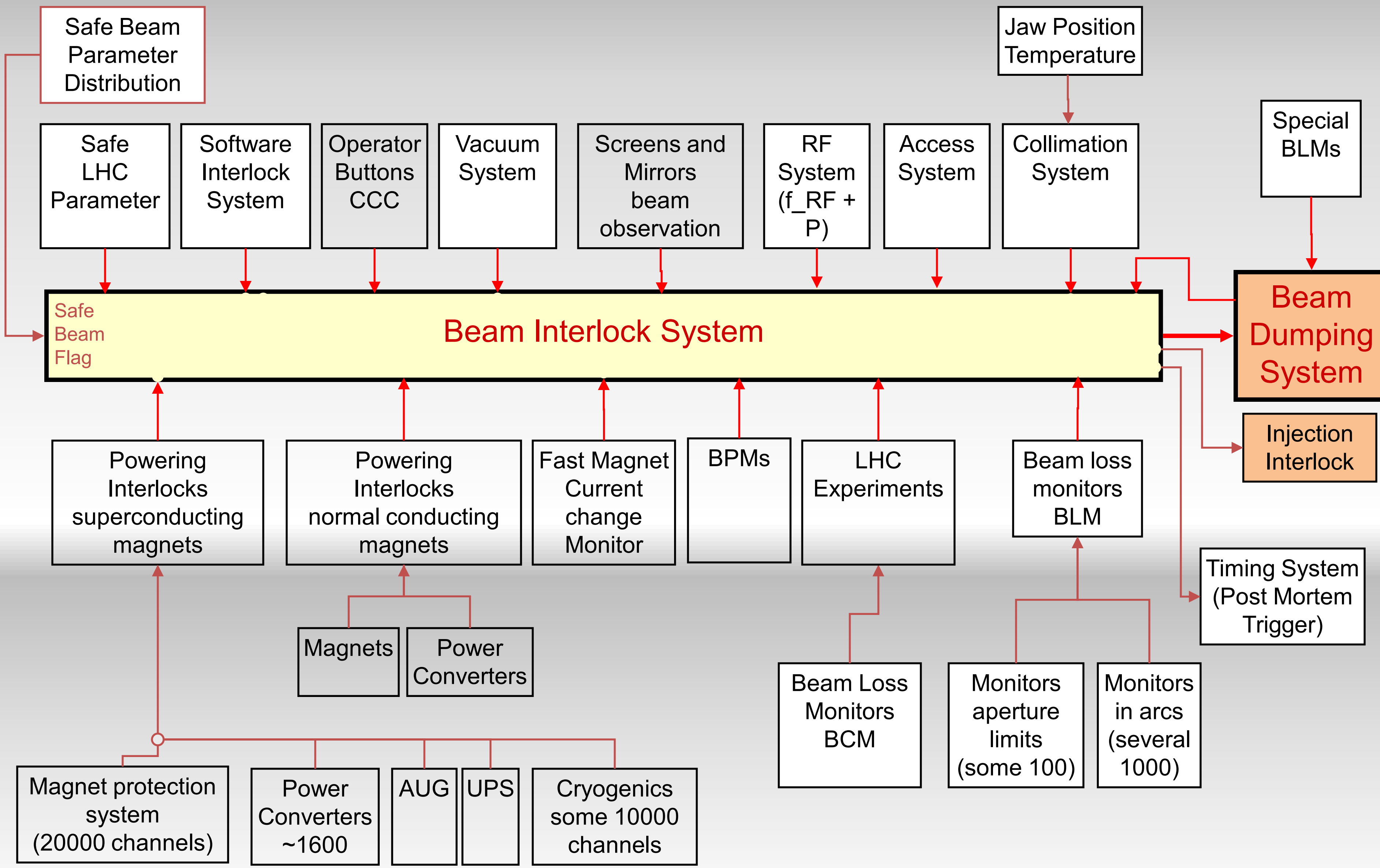
Machine protection – the challenge

Situation at 3.5 TeV (in August 2011)





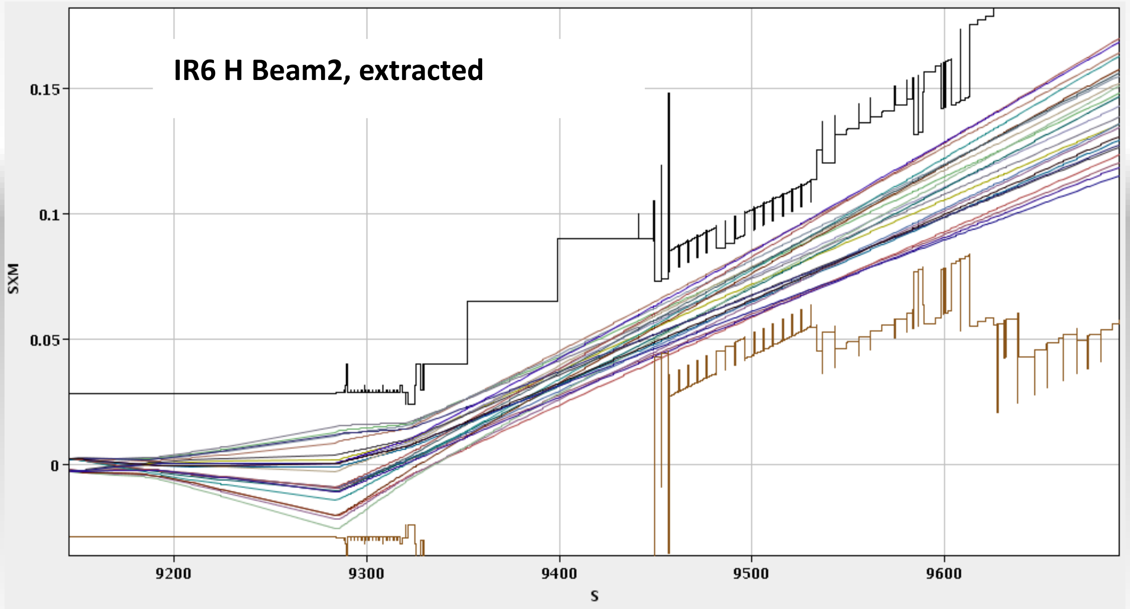
Beam Interlock System

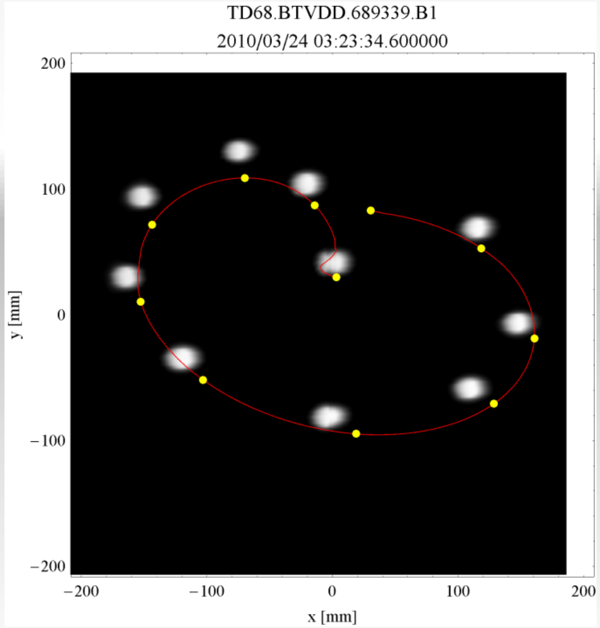


Beam Dump System (LBDS)

Absolutely critical. Rigorous and extensive program of commissioning and tests with beam.

- Expected about two asynchronous dumps per year – one to date with beam





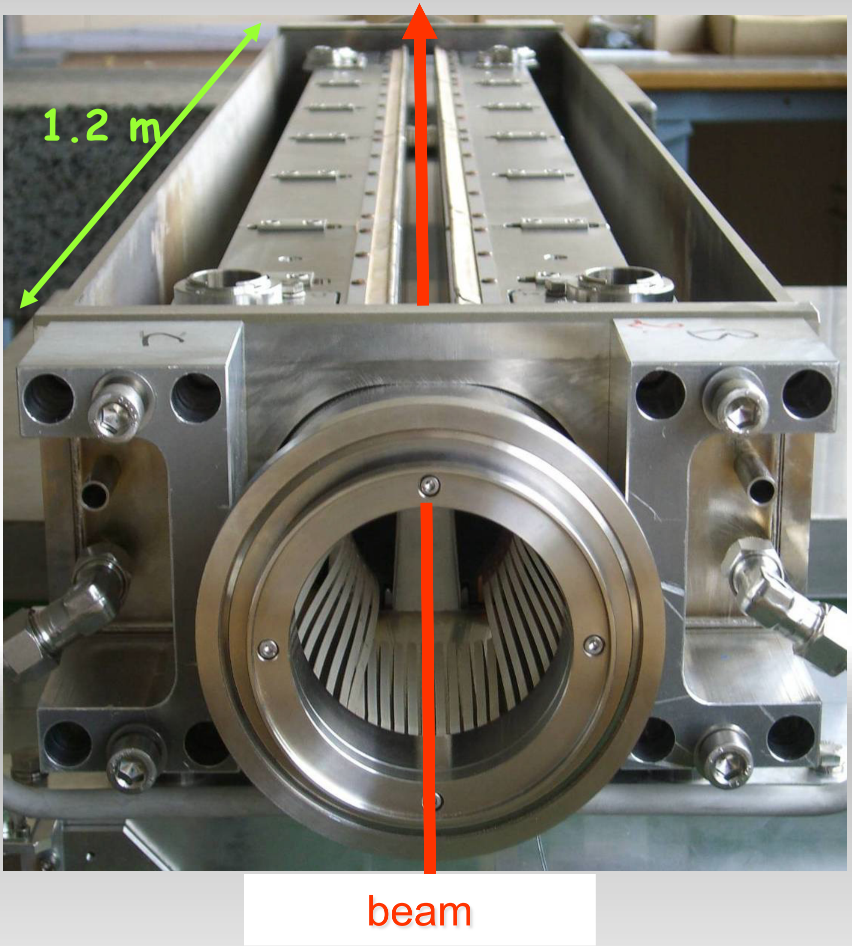
Safety critical aspects of the Dump System

- Signal from beam interlock system and triggering
- Energy tracking
- Extraction kicker retriggering after single kicker erratic
- Mobile protection device settings
- System self-tests and post-mortem
- Aperture, optics and orbit
- Extraction – dilution kicker connection and sweep form
- Abort gap ‘protection’
- Fault tolerance with 14/15 extraction kickers

Number of unacceptable dump system failures:
1 every 1000000 years

“Eternal vigilance is the price of liberty”

Collimation



Two warm cleaning insertions

IR3: Momentum cleaning
- **1 primary (H)**
- **4 secondary (H,S)**
- **4 shower abs. (H,V)**

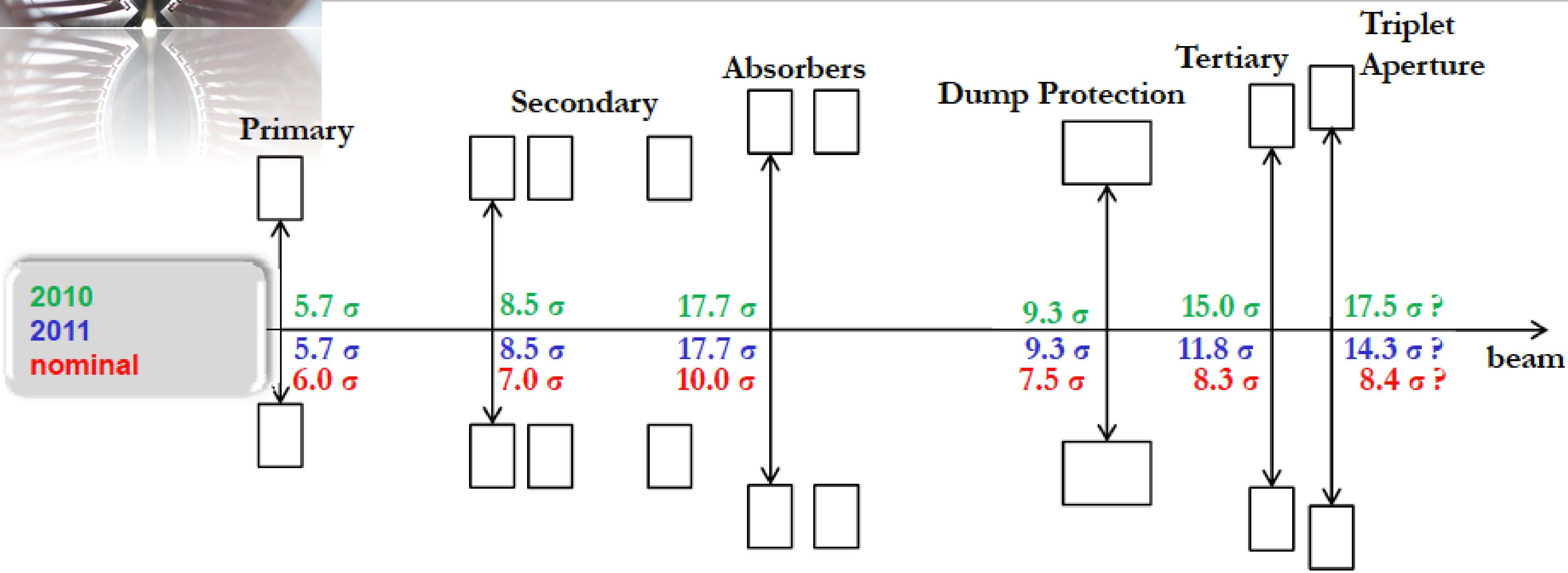
IR7: Betatron cleaning
- **3 primary (H,V,S)**
- **11 secondary (H,V,S)**
- **5 shower abs. (H,V)**

Local IP cleaning: 8 tertiary coll.

Total = 108 collimators

About 500 degrees of freedom.

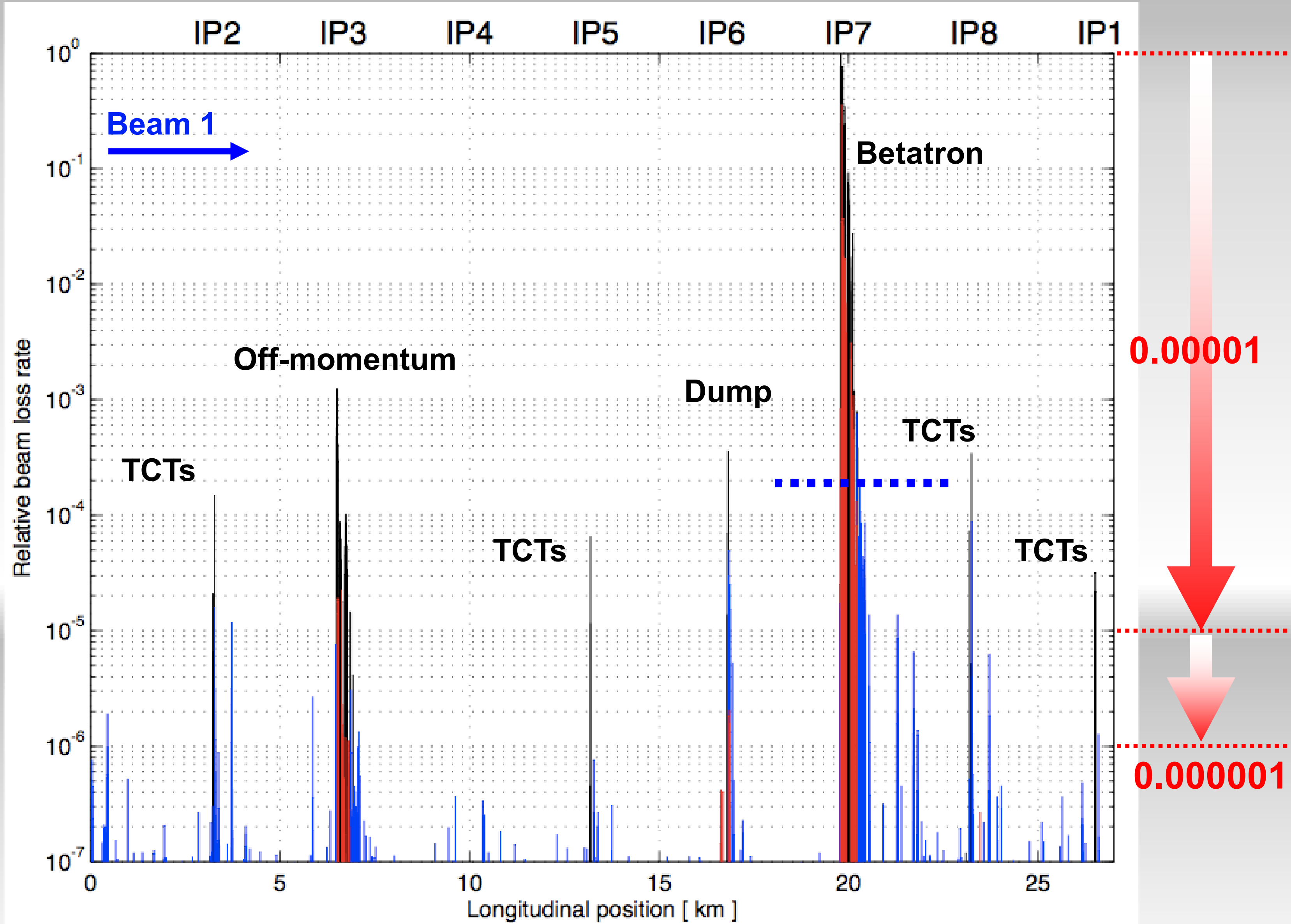
Collimation



- Triplet aperture must be protected by tertiary collimators (TCTs)
- TCTs must be shadowed by dump protection (not robust)
- Dump protection must be outside primary and secondary collimators
- Hierarchy must be satisfied even if orbit and optics drift after setup
  - margins needed between collimators

Collimation cleaning at 3.5 TeV

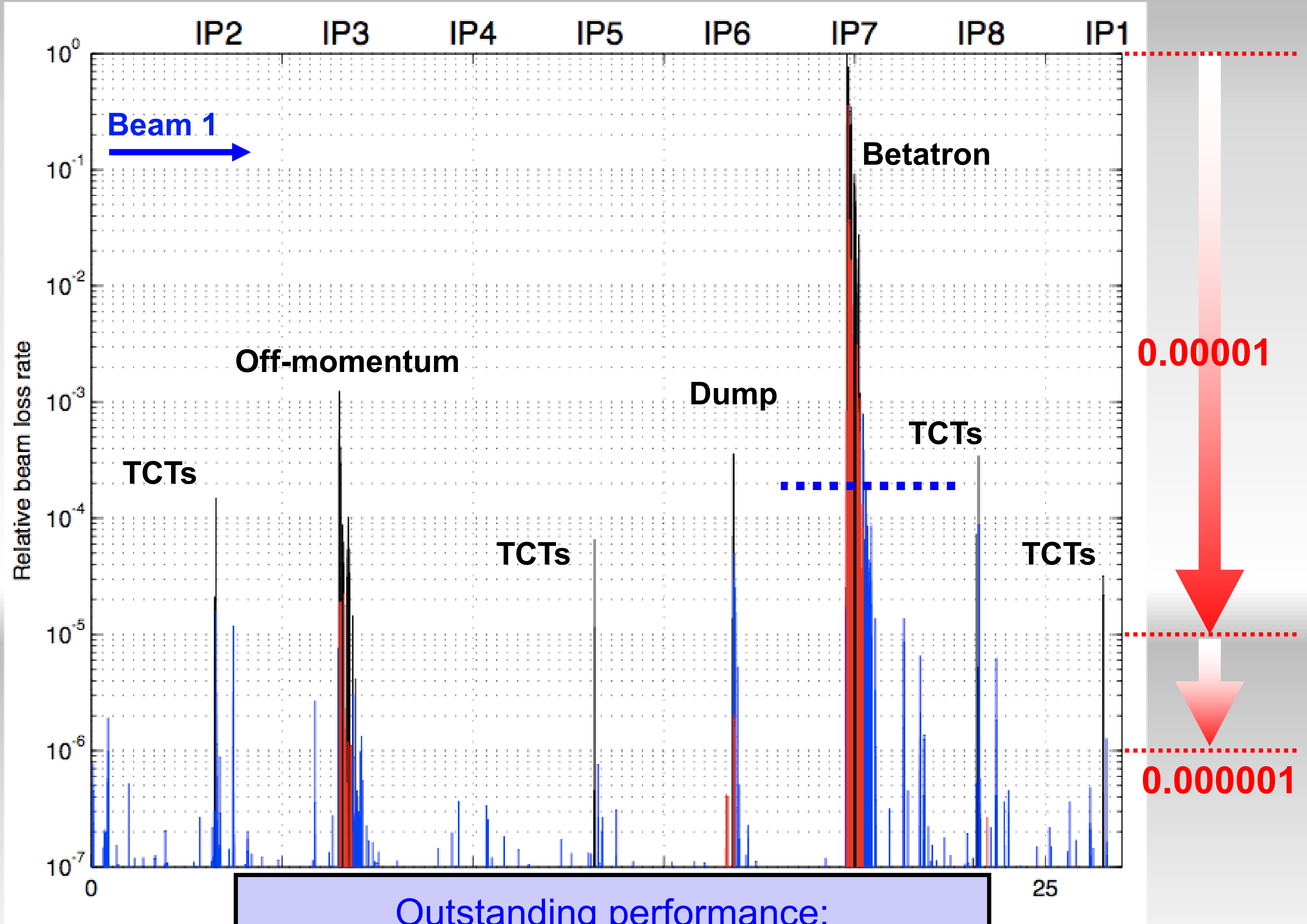
Generate higher loss rates: beam across the 3rd order resonance.



Legend:
Collimators
Cold losses
Warm losses

Collimation cleaning at 3.5 TeV

Generate higher loss rates: beam across the 3rd order resonance.



Legend:
Collimators
Cold losses
Warm losses

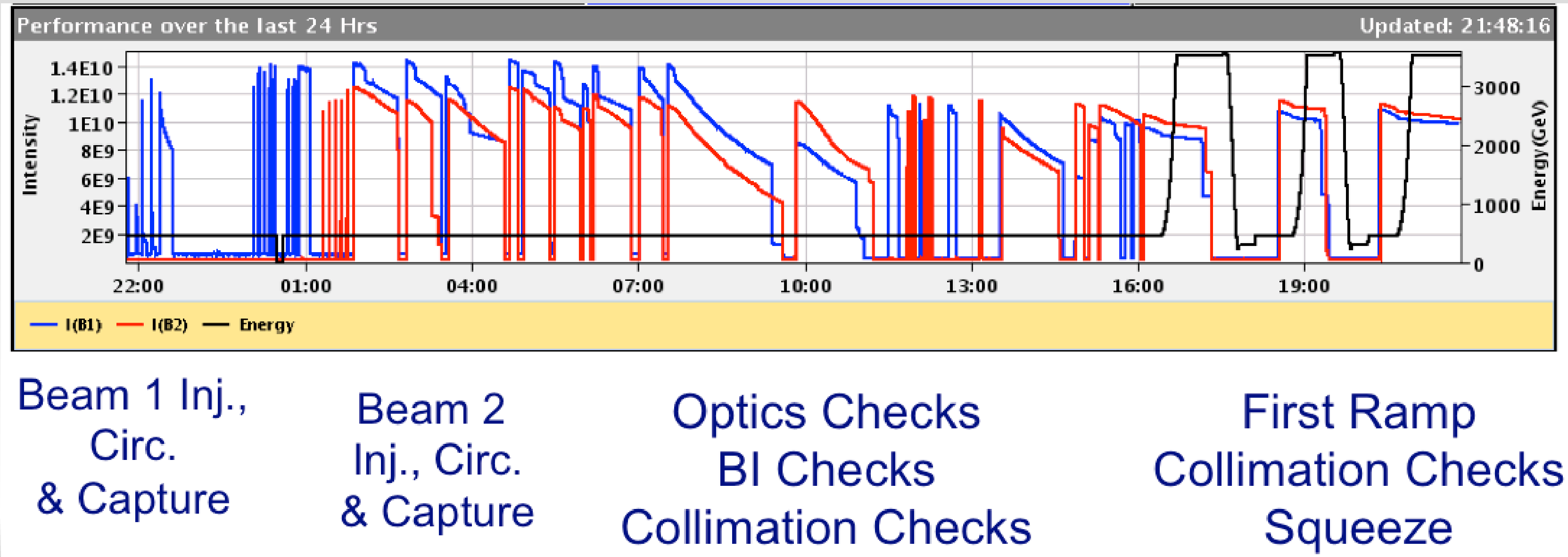
Outstanding performance:
No beam-induced quenches in 2010/2011

Exit 2010: beam parameters

	2010	Nominal
Energy [TeV]	3.5	7
beta* [m]	3.5, 3.5, 3.5, 3.5 m	0.55, 10, 0.55, 10
Emittance [microns]	2.0 – 3.5 start of fill	3.75
Bunch intensity	1.2e11	1.15e11
Number of bunches	368 348 collisions/IP	2808
Stored energy [MJ]	28	360
Peak luminosity [$cm^{-2}s^{-1}$]	2e32	1e34

Lead ion run 2010

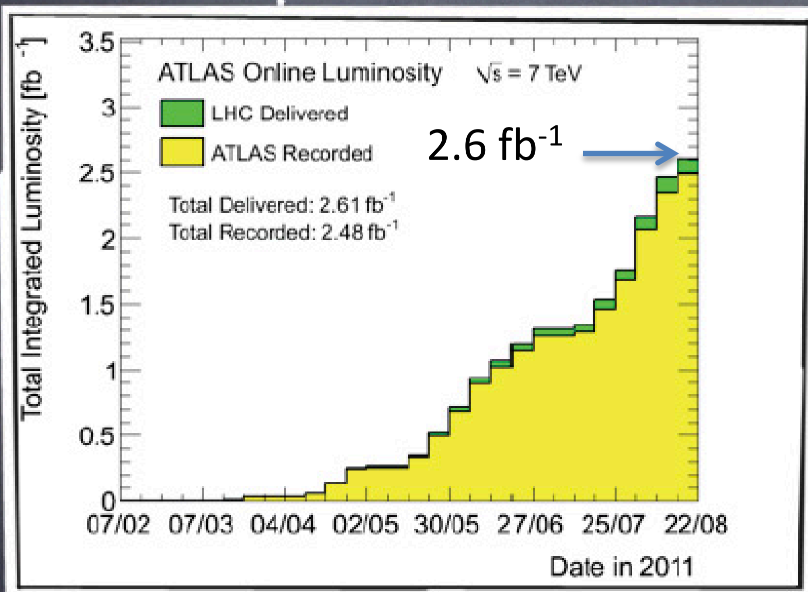
- Collisions within 54 hours of first injection

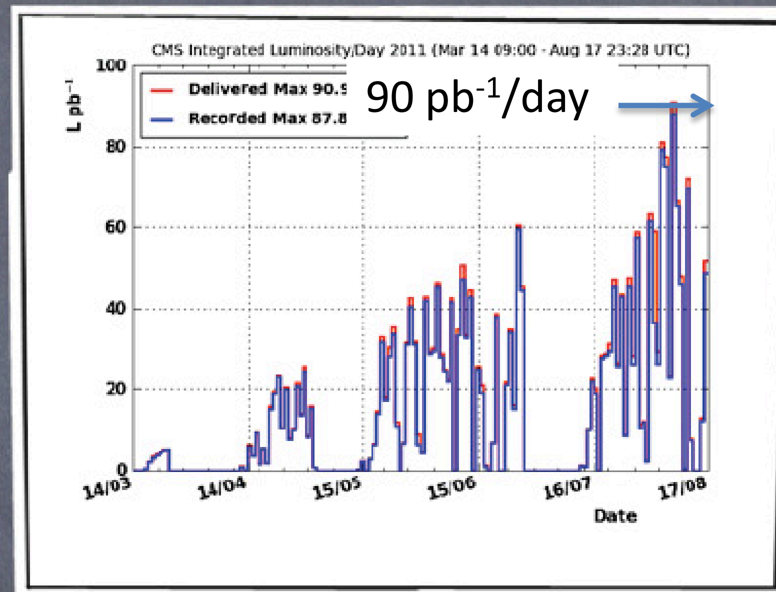


Experience and Lorentz's law.

2011 - Oh What a Year

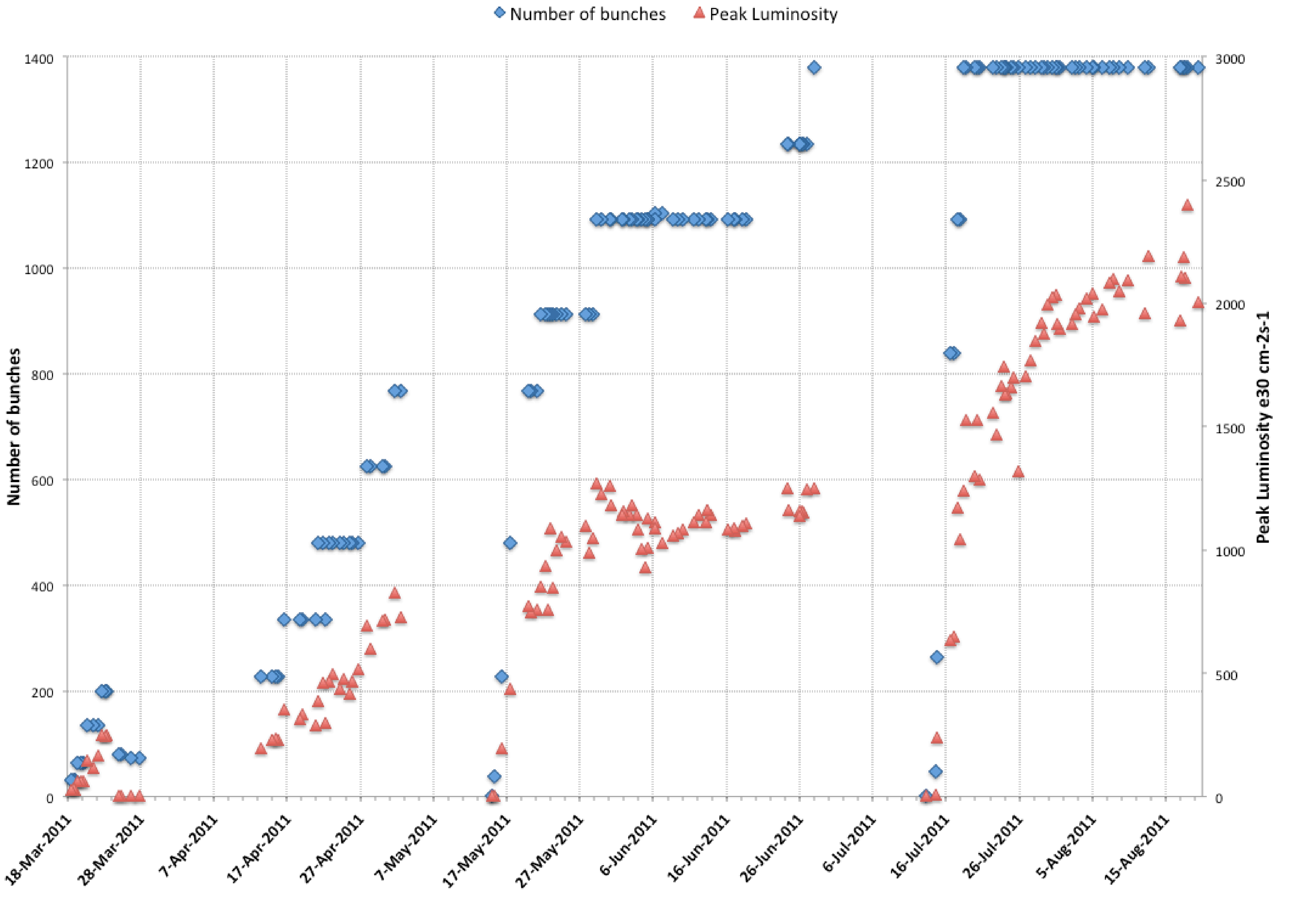
- The new thumb rule: ~500 pb^{-1}/week and more to come





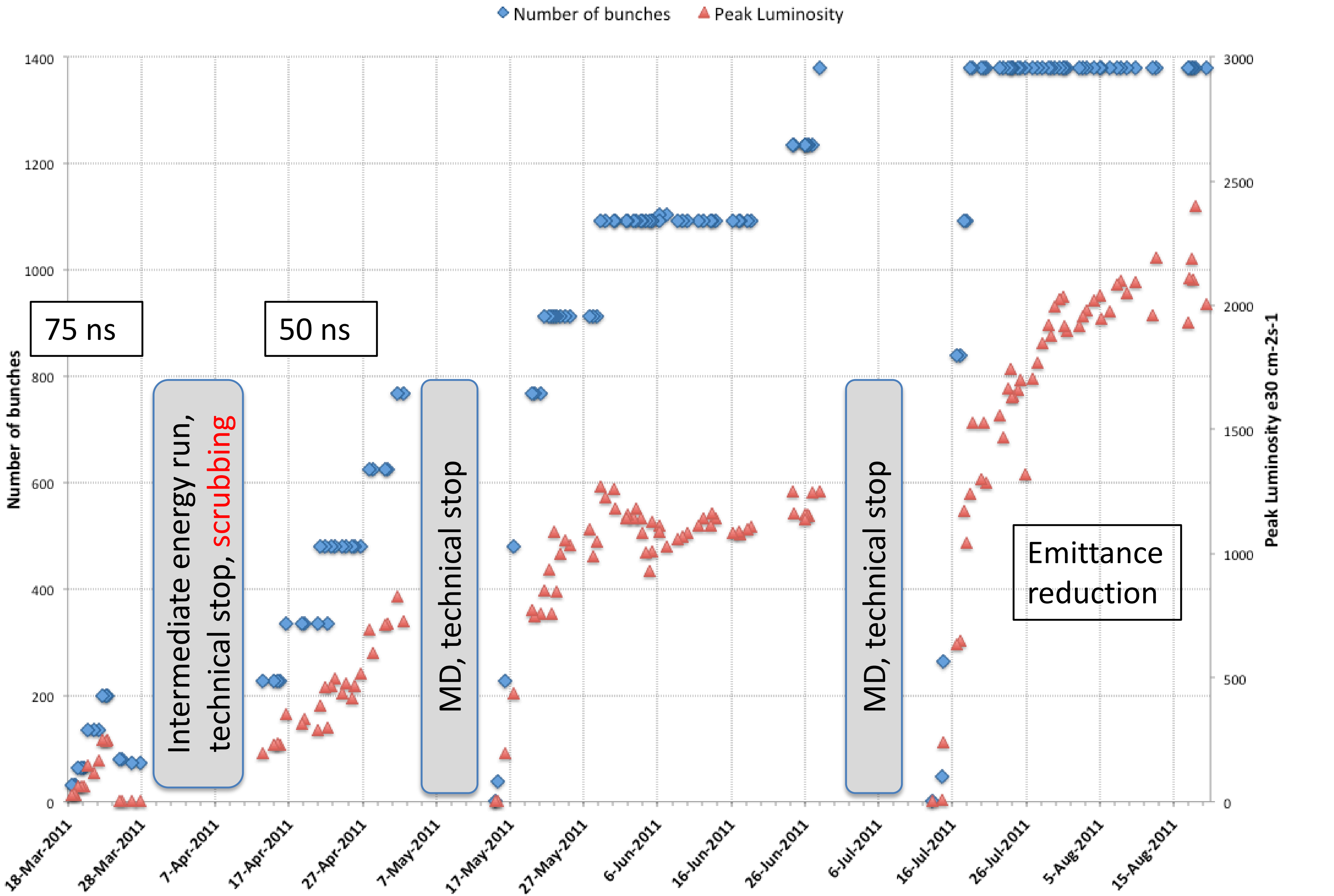
- 50 ns bunch trains with 6-8 interactions/crossing
- The analyses presented here are based on 1-2.3 fb^{-1}/experiment

2011



Number of bunches
Peak Luminosity
Number of bunches
Peak Luminosity e30 cm-2s-1
0
200
400
600
800
1000
1200
1400
0
500
1000
1500
2000
2500
3000
18-Mar-2011
28-Mar-2011
7-Apr-2011
17-Apr-2011
27-Apr-2011
7-May-2011
17-May-2011
27-May-2011
6-Jun-2011
16-Jun-2011
26-Jun-2011
6-Jul-2011
16-Jul-2011
26-Jul-2011
5-Aug-2011
15-Aug-2011

2011



Number of bunches
Peak Luminosity
Number of bunches
Peak Luminosity e30 cm-2s-1
75 ns
50 ns
Intermediate energy run, technical stop, scrubbing
MD, technical stop
MD, technical stop
Emittance reduction
18-Mar-2011
28-Mar-2011
7-Apr-2011
17-Apr-2011
27-Apr-2011
7-May-2011
17-May-2011
27-May-2011
6-Jun-2011
16-Jun-2011
26-Jun-2011
6-Jul-2011
16-Jul-2011
26-Jul-2011
5-Aug-2011
15-Aug-2011

Beam from injectors

Higher than nominal bunch intensity
Smaller than nominal emittance

Bunch spacing	From Booster	Np/bunch	Emittance H&V [mm.mrad]
150	Single batch	1.1×10^{11}	1.6
75	Single batch	1.2×10^{11}	2.0
50	Single batch	1.45×10^{11}	3.5
50	Double batch	1.6×10^{11}	2.0
25	Double batch	1.2×10^{11}	2.7

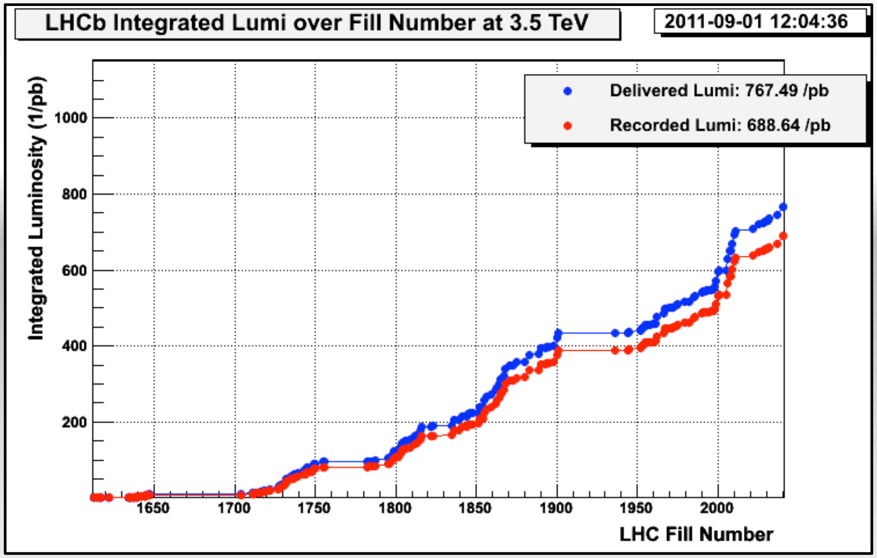
At present: ~1.3×10^{11}ppb, 2.0 microns into collision

TUPZ019 **Transverse Emittance Preservation through the LHC Cycle**
MOPS009 **Probing Intensity Limits of LHC-type Bunches in SPS with Nominal Optics**

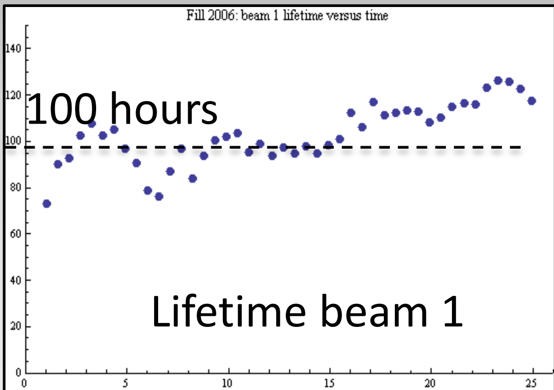
2011: (c/o Atlas & LHCb)

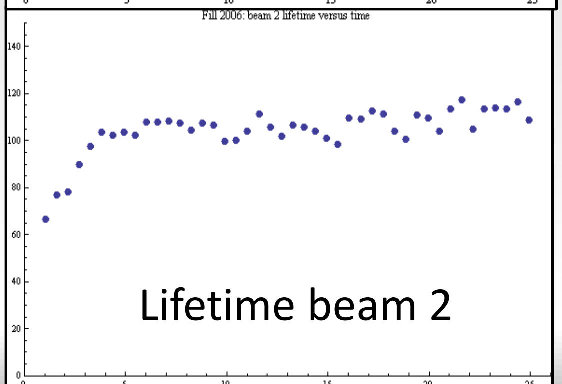
Peak stable luminosity	$2.37 \times 10^{33}\ cm^{-2}s^{-1}$
Max. luminosity in one fill	$100.71\ pb^{-1}$
Max. luminosity delivered in 7 days	$499.45\ pb^{-1}$
Longest time in stable beams	26.0 hours
Longest time in stable beams for 7 days	107.1 hours (63.7%)
Fastest turnaround	2 hours 7 minutes

24% of design luminosity:
- half design energy
- nominal bunch intensity+
- ~half nominal emittance
- beta* = 1.5 m (design 0.55 m)
- half nominal number of bunches

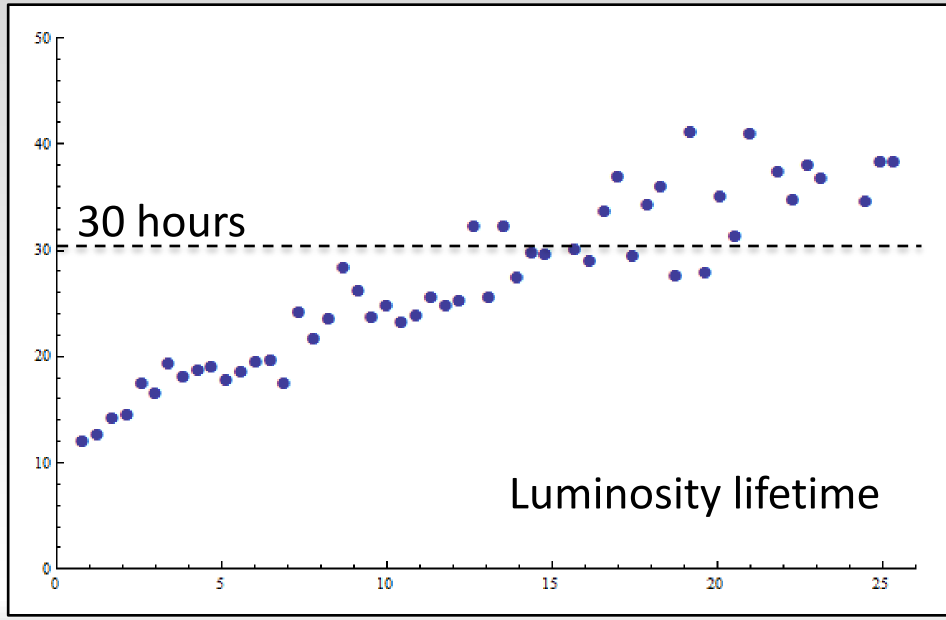


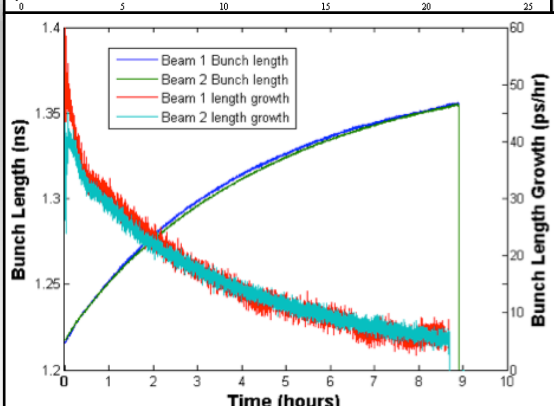
Fill 2006: Luminosity lifetime

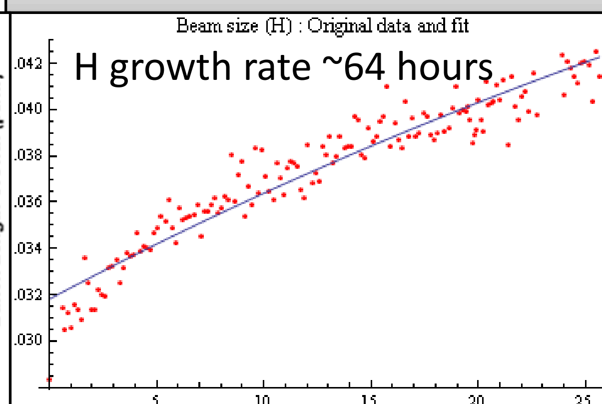


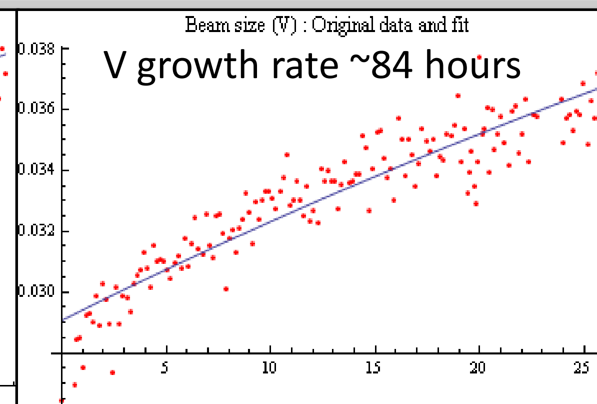


A "typical" fill that lasted 26 hours and delivered 100 pb^{-1}







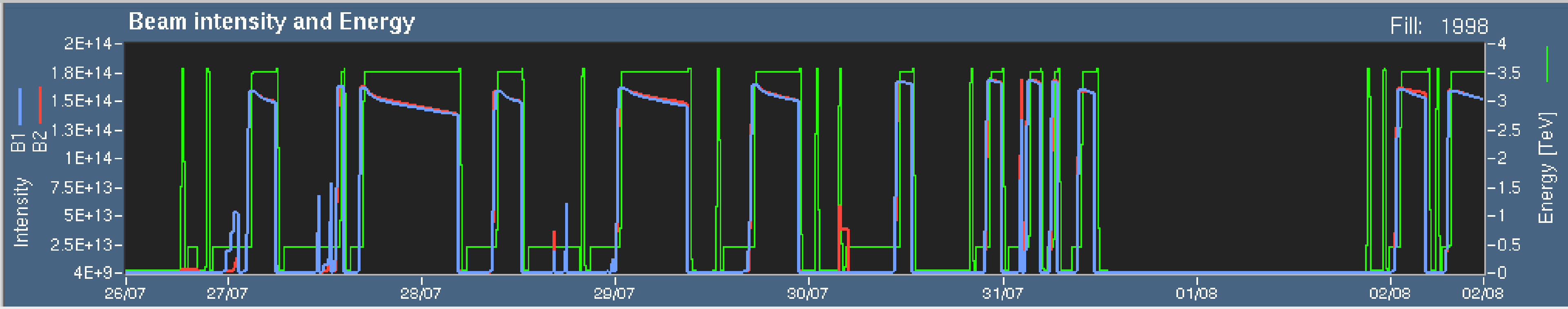


2011 parameters – end August

Energy [TeV]	3.5
Beta* [m]	1.5, 10, 1.5, 3.0 m
Normalized emittance [microns]	**~2.0 start of fill**
Bunch intensity	**1.2 – 1.3e11**
Number of bunches	**1380** 1318 collisions/IP1&5
Bunch spacing [ns]	50
Stored energy [MJ]	90 to 100
Peak luminosity [$cm^{-2}s^{-1}$]	2.37e33
Beam-beam tune shift (start fill)	~0.023

beta* = 1 m commissioning ongoing
~50 days proton physics left in 2011

Premature end to fills



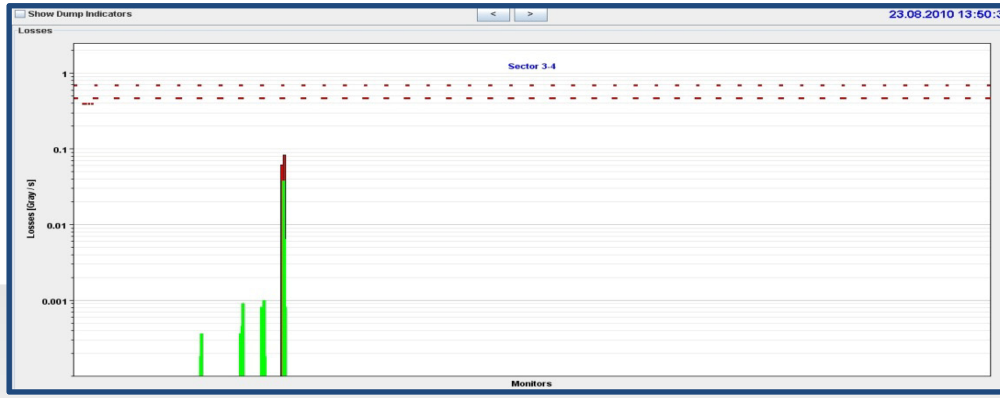
AVAILABILITY - EFFICIENCY

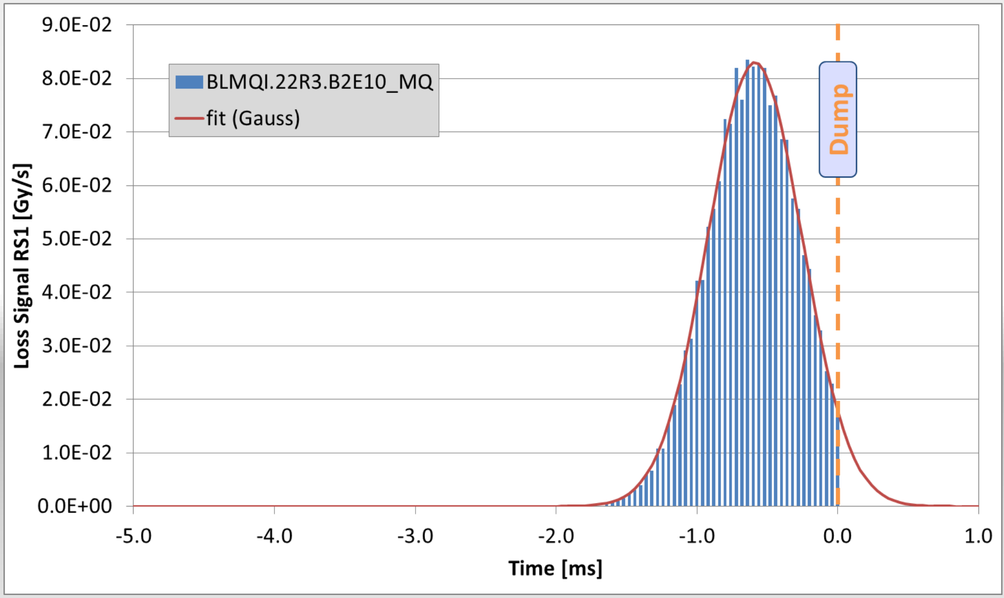
UFOs in the LHC

- Since July 2010, **35 fast loss events led to a beam dump.**
- *18 in 2010, 17 in 2011.*
  13 around MKIs.
  6 dumps by experiments.
  1 at 450 GeV.

- Typical characteristics:
  - Loss duration: about 10 turns
  - Often unconventional loss locations (e.g. in the arc)

- The events are believed to be due to (***U***nidentified) ***F***alling ***O***bjects (UFOs).





Spatial and temporal loss profile of UFO on 23.08.2010

Single Event Effects

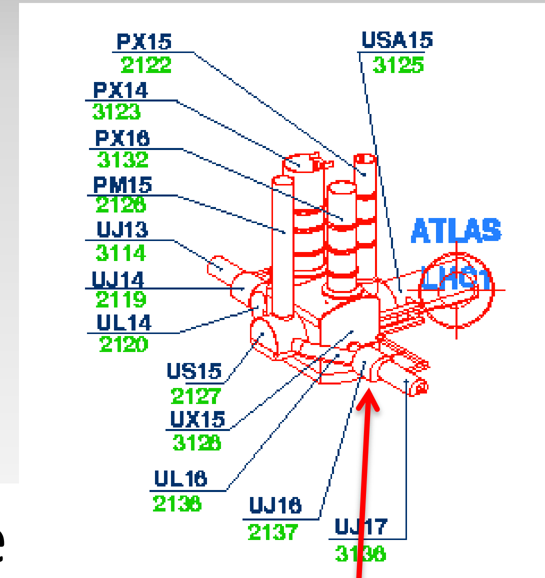
UJs	*shielded areas* HEH (cm-2/w26)	HEH (cm-2/2011)	*tun* HEH (cm-2/w26)
14 (13, tun)	3.3E+06	5.7E+07	9.8E+09
16 (17, tun)	2.3E+06	4.0E+07	7.7E+08
22	N/A	N/A	5.2E+07
23	<1.0E+6	<1.0E+6	8.6E+06
32	N/A	N/A	<1.0E+6
33	<1.0E+6	<1.0E+6	<1.0E+6
56	<1.0E+6	9.3E+06	[illegible]
76	<1.0E+6	<1.0E+6	8.8E+08
87	<1.0E+6	1.1E+06	[illegible]
88	N/A	N/A	1.5E+08

Luminosity Dominant (14, 16)

Intensity Dominant (22, 23, 32, 33)

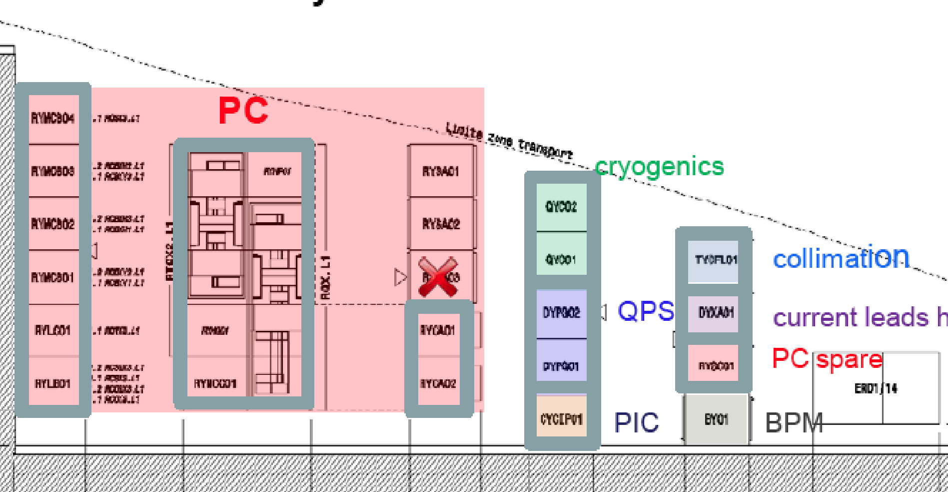
Luminosity Dominant (56)

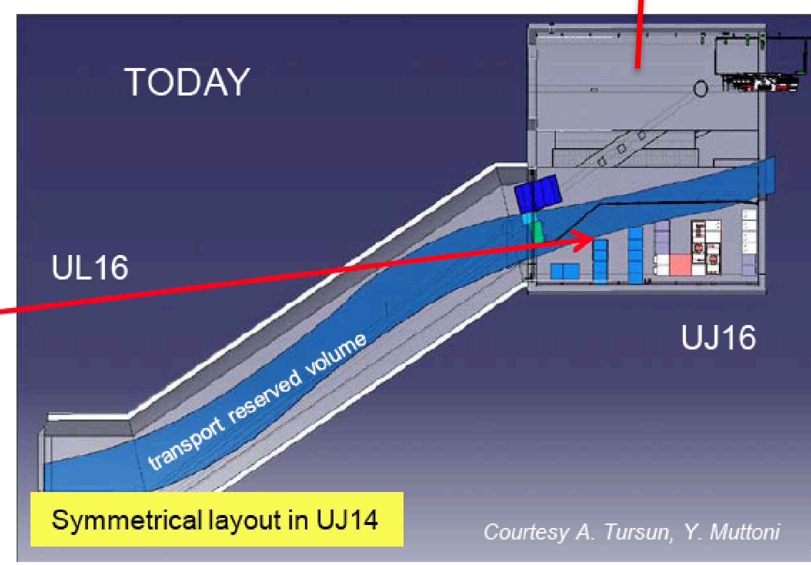
Intensity Dominant (76, 87, 88)



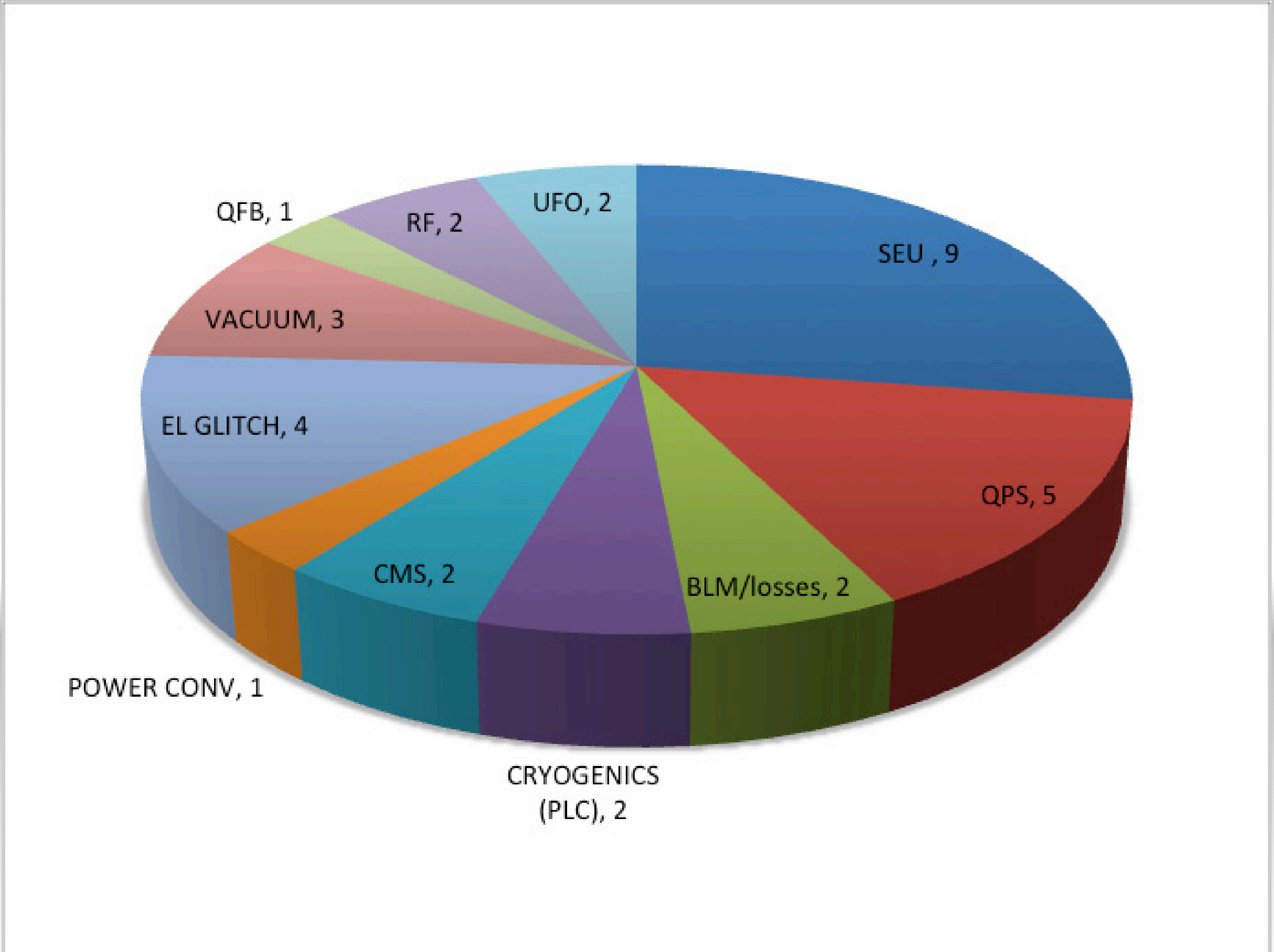
Major campaign ongoing: shield and relocate

UJ14/16 racks layout

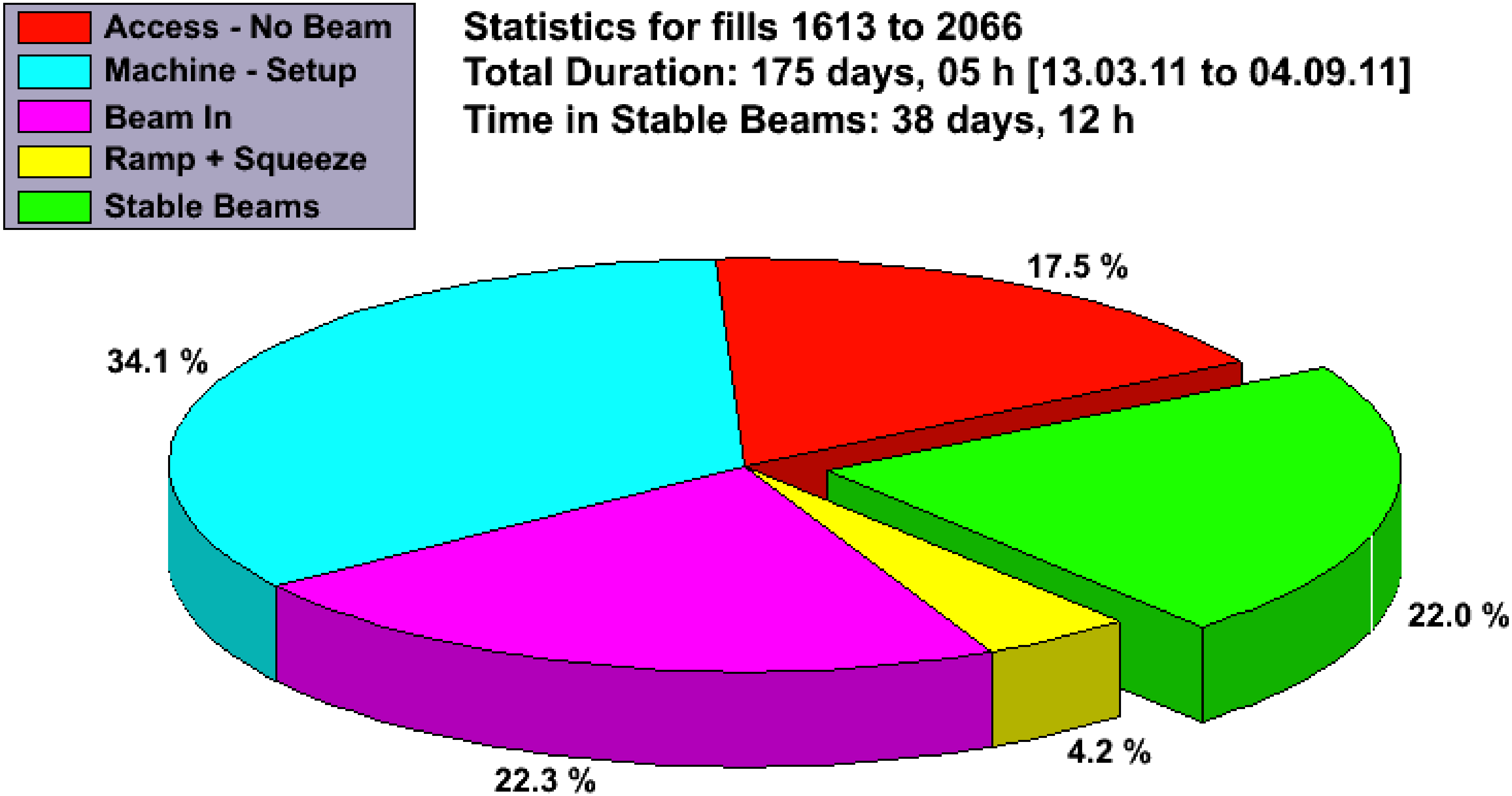




Dumps > 450 GeV July-August



Availability 2011



Beam in ~48% of the time

Conclusion

- Very successful commissioning:
  - Hard work plus experience, preparation, time, the injectors, collaboration, 21st century technology, engineering, hardware, teamwork, care, expertise, motivation, dedication, leadership, controls, diagnostics, tools, resources…
- Good transition from commissioning to operations
  - Cycle is solid
  - Machine protection working very well
  - Availability with high intensity acceptable with issues being addressed

Acknowledgements

- The LHC is a beautiful machine. The superb progress so far is a real testament to the dedication of the CERN staff and the help we have received from our international collaborators.