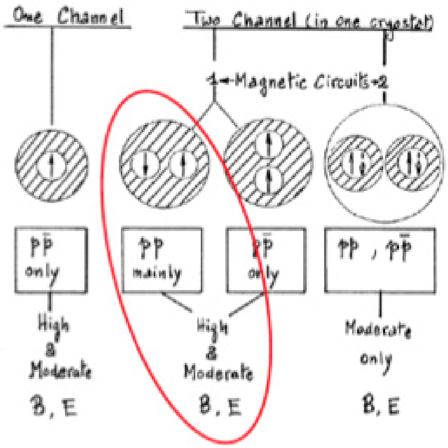
Lessons from LHC Commissioning

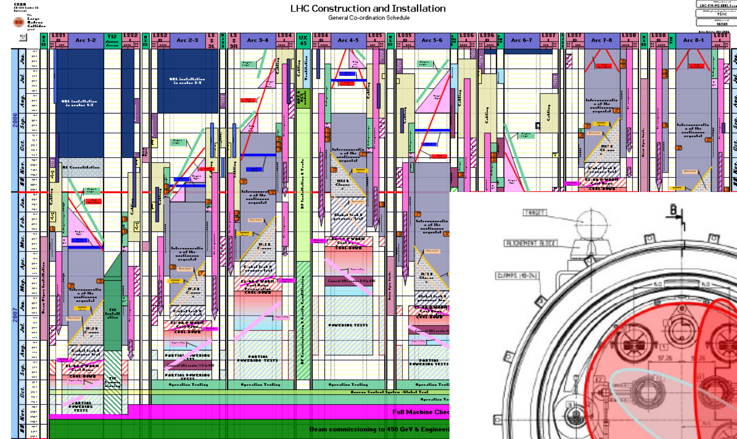
And some things that should not have been forgotten were lost. History became legend, legend became myth.

Conception

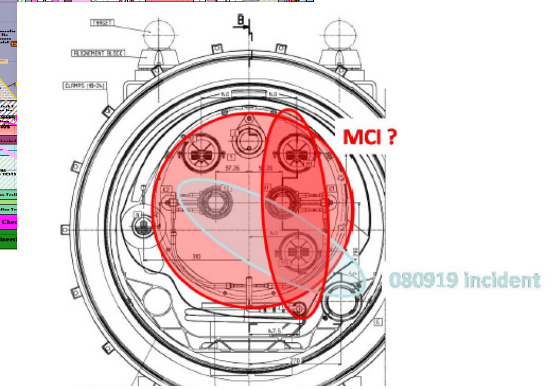


Initiation

LHC approved by the Elders



Birth – overdue



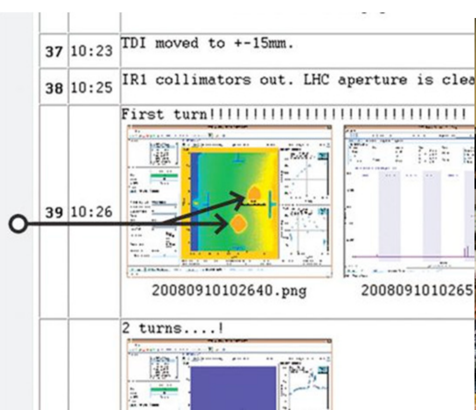
Withdrawal from community for mediation and preparation

Rival stumbles

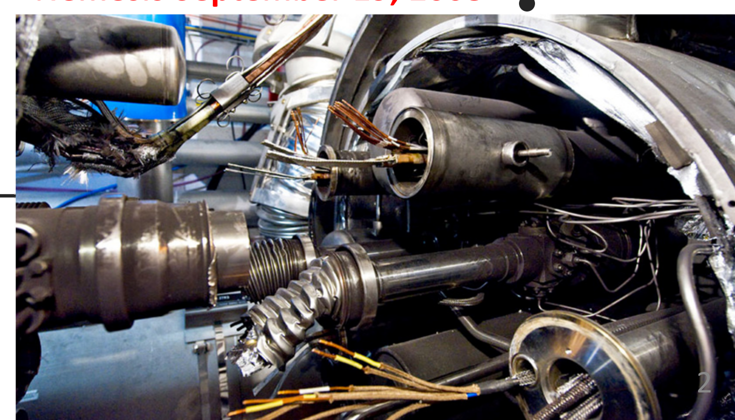
SSC cancelled

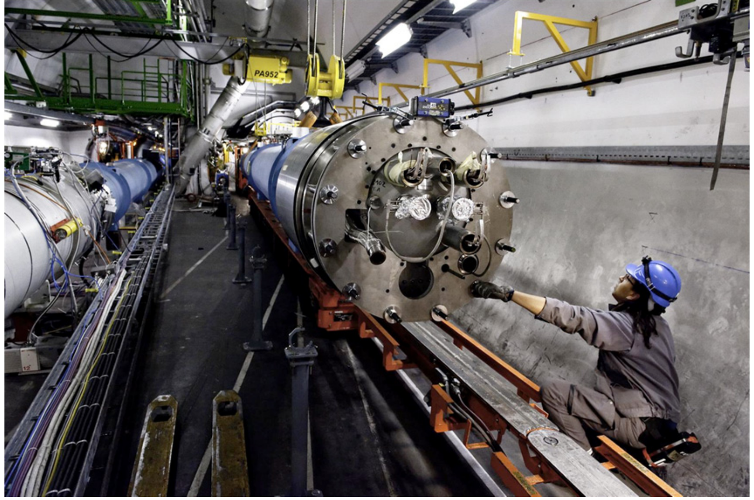
1984	//	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10

Hubris (?) September 10, 2008

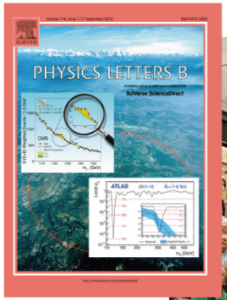


Nemesis September 19, 2008





Apotheosis and atonement



Trial/descent in the underworld

4 July, 2012

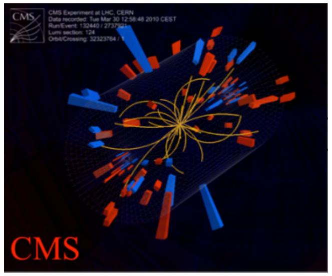
November 29, 2009

Resurrection and rebirth

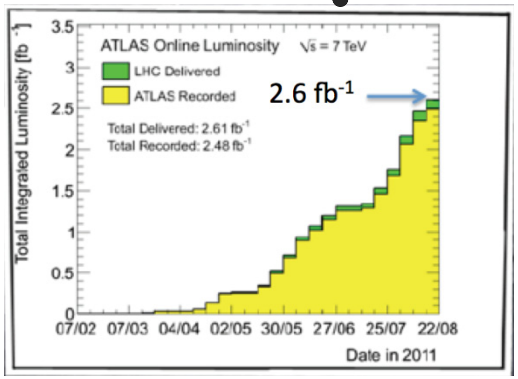
2009 | 2010 | 2011 | 2012 | 2013

March 30, 2010

First collisions at 3.5 TeV



Ascension



Heroic subplot

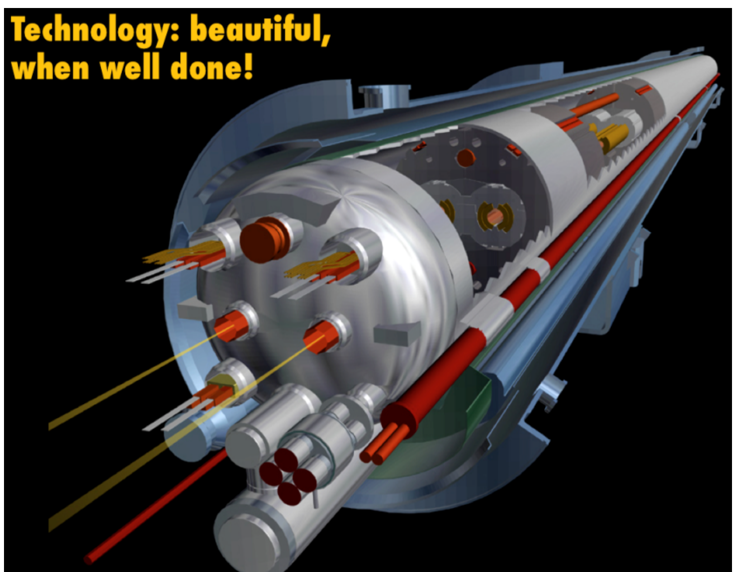
Let us not forget Fortuna

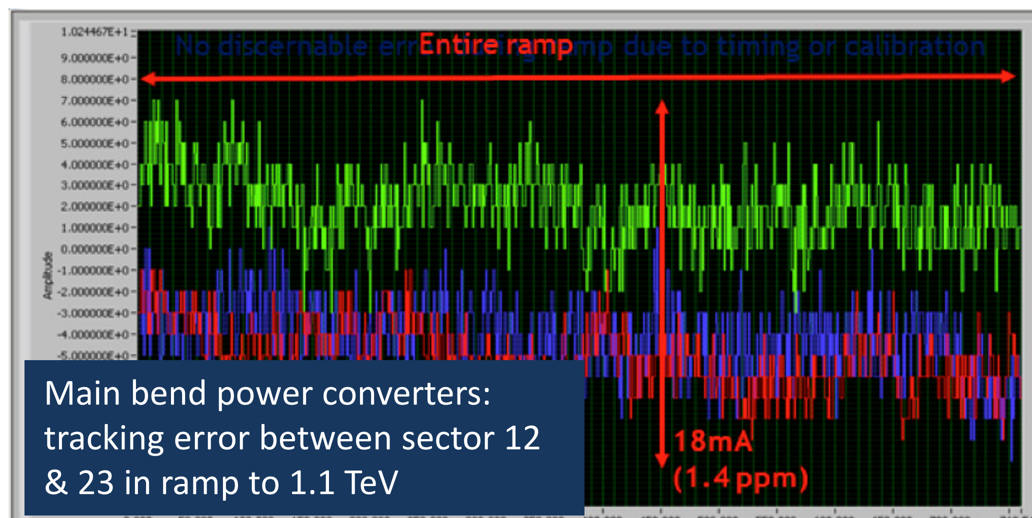
- Late
- Over budget
- Blew it up after 9 days
- Costly, lengthy repair
- Rival coming up fast on the outside
- Had to run at half energy
- And yet…

Foundations – 27 km SC collider

Someone got some serious stuff right

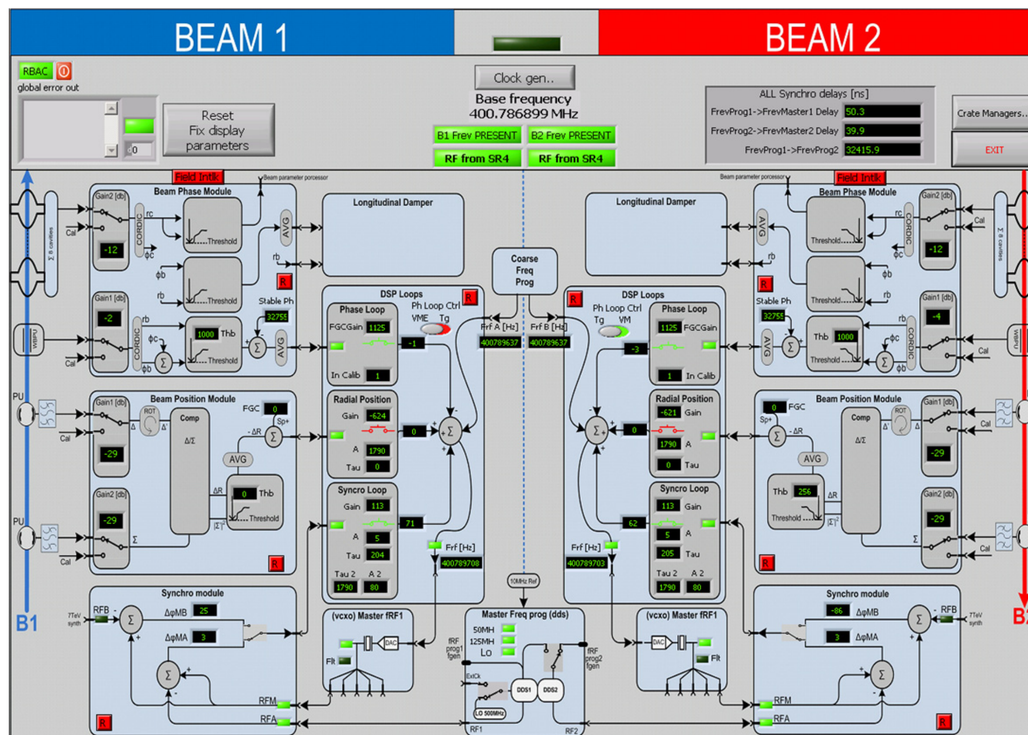
- Magnets
  - long development, industrialization, **quality control, measurements/model, sorting…**
- Vacuum, cryogenics, RF, powering, instrumentation, optics (beam-beam, DA…), collimation, beam dumps etc.
- **Machine protection**





Foundations

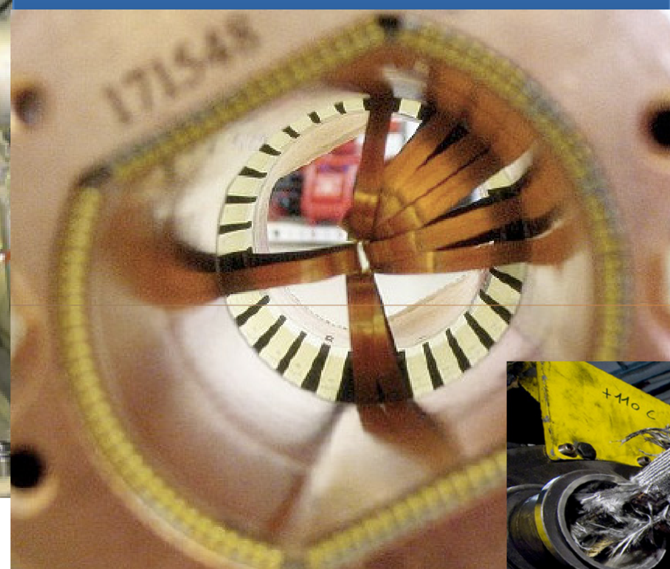
- System expertise and experience
  - Continuity, compartmentalization
  - LEP: cryogenics, RF, operating a 27 km collider etc.
  - Resources
  - Understanding
  - Technology



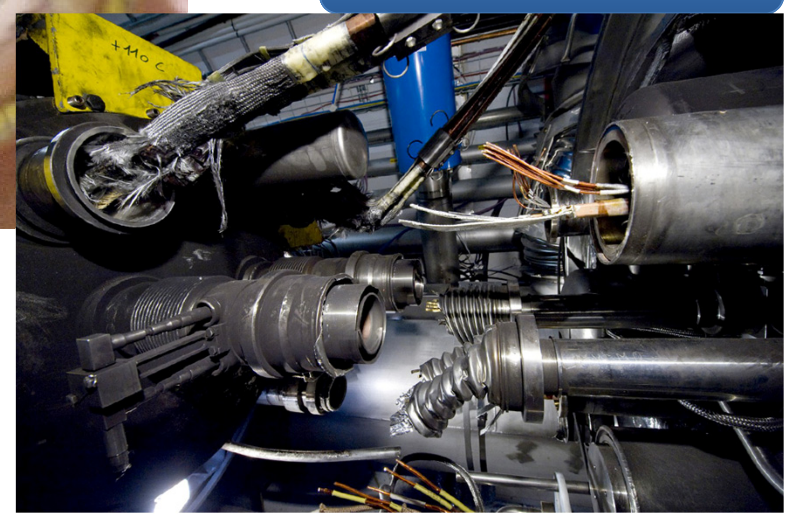
Quality control

Cryogenic supply line

Plug In Modules



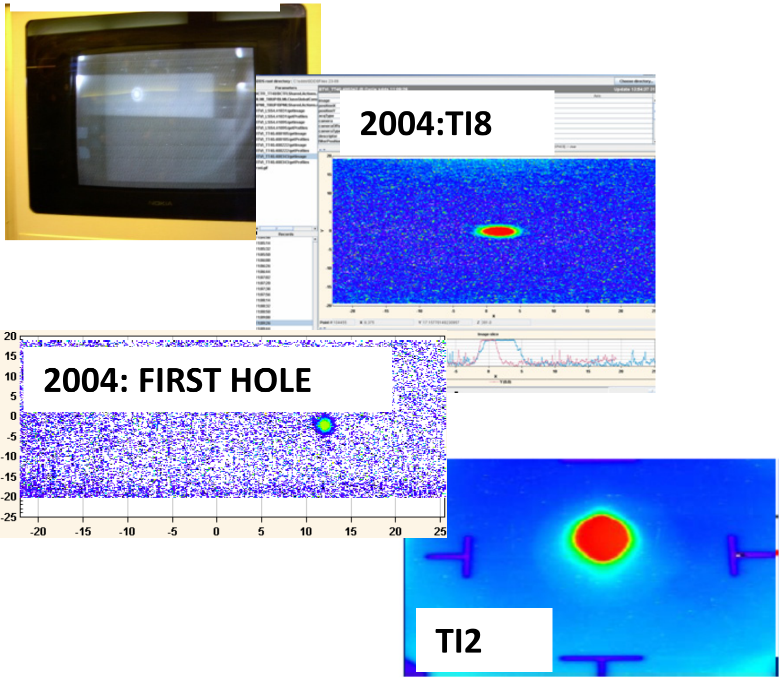
The incident



The ability to tackle problems has proved useful.

Start early – stage - milestones

2003:TT40



2004:TI8

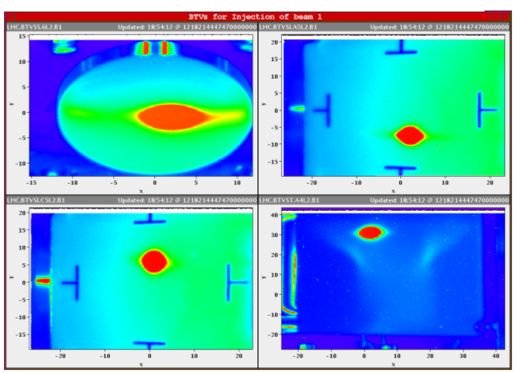
2004: FIRST HOLE

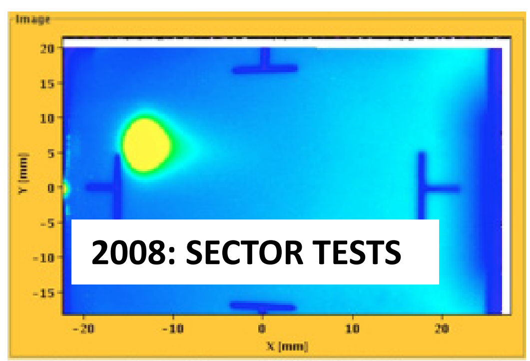
TI2

Get the teams together, test:

- instrumentation,
- powering,
- timing and synchronization
- controls and software
- measure optics, aperture, field quality, polarities

2008: FIRST BEAM INTO LHC





2008: SECTOR TESTS

2008: SEPT 10

TT40 Damage 2004 - High Intensity SPS Extraction test

What you can do with 2.9 MJ

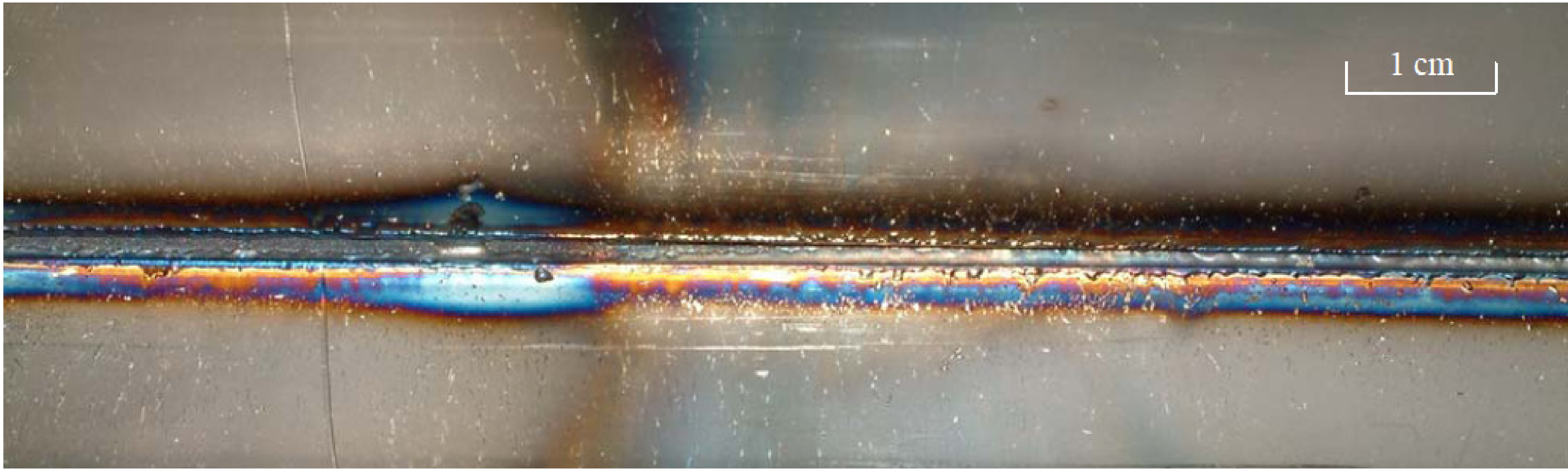
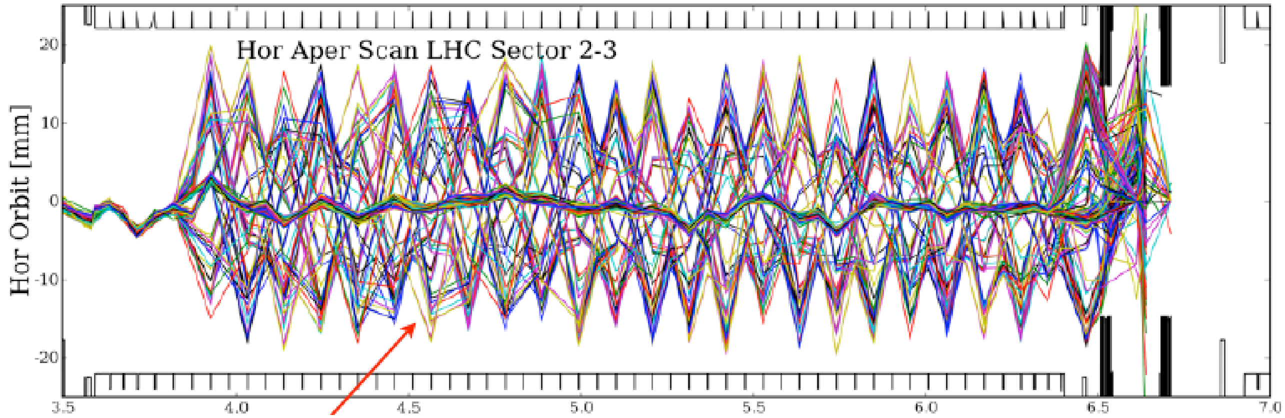


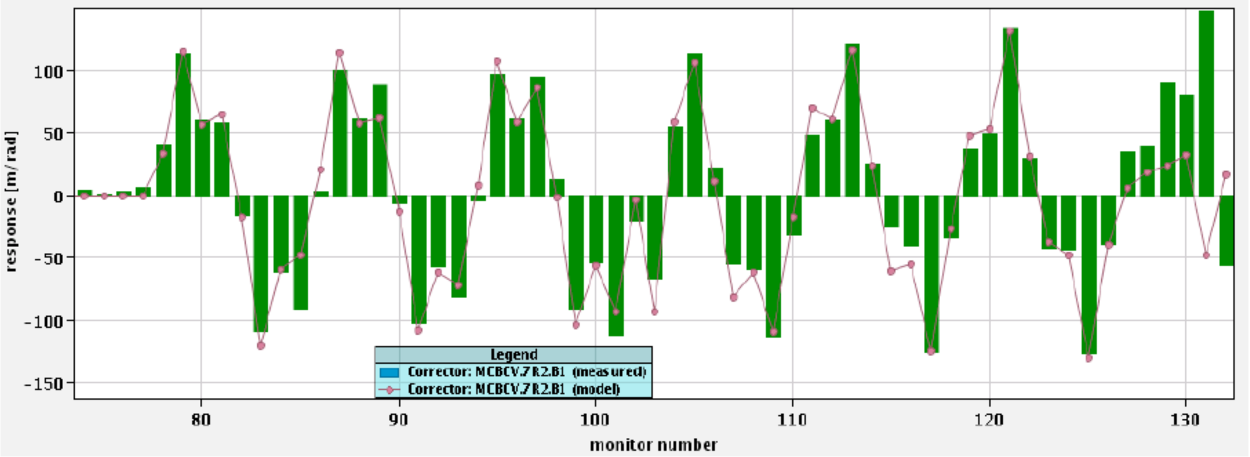
Figure 4. Damage observed on the inside of the vacuum chamber, on the beam impact side. A groove approximately 110 cm long due to removed material was clearly visible, starting at about 30 cm from the entrance.

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

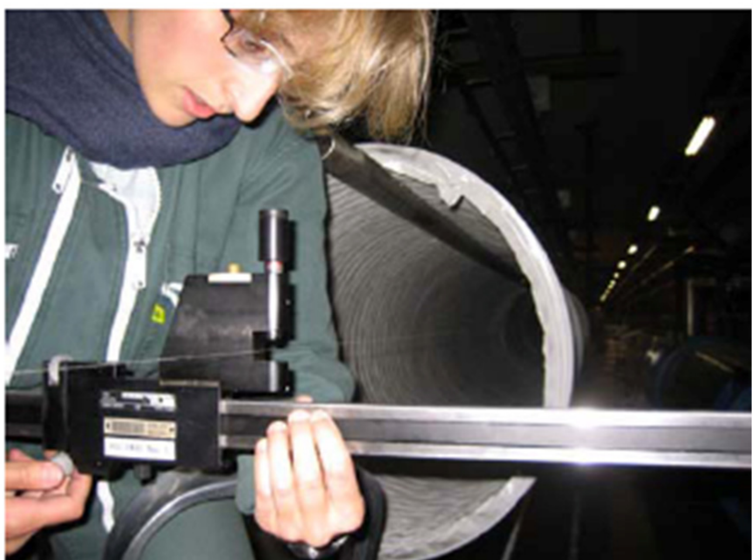
Injection tests

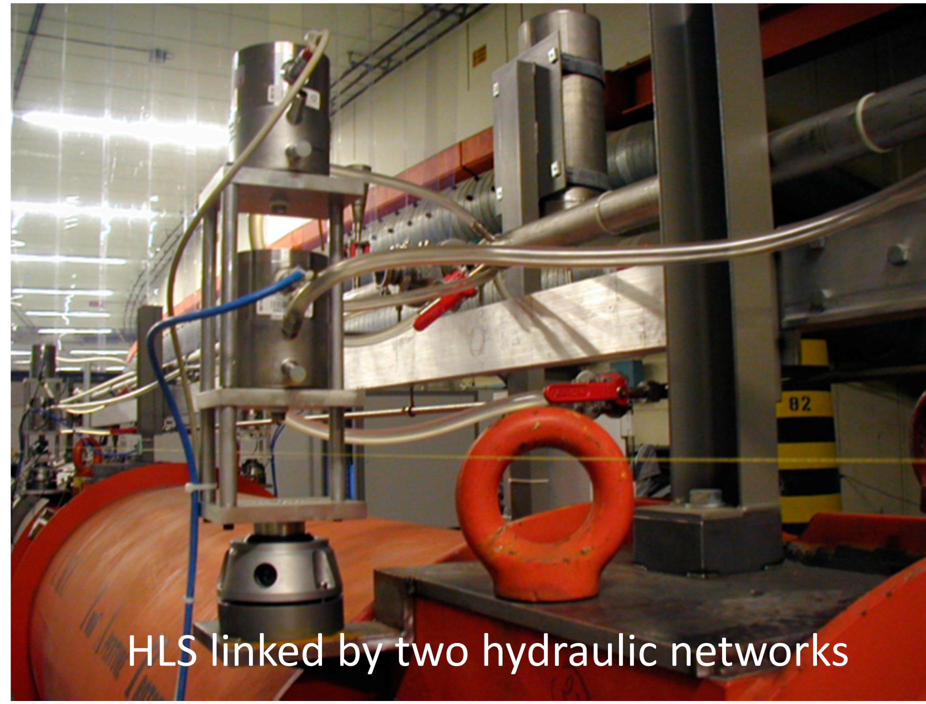
Instrumentation (BPM, BLM), controls, software, magnet model, measurement procedures, timing, synchronization



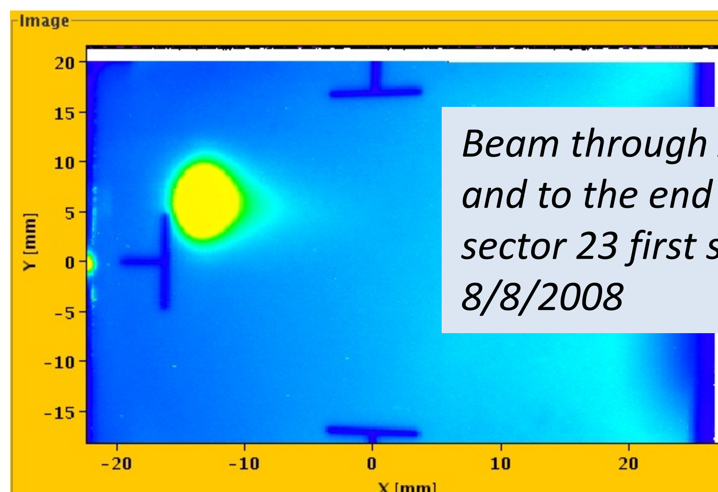


Alignment





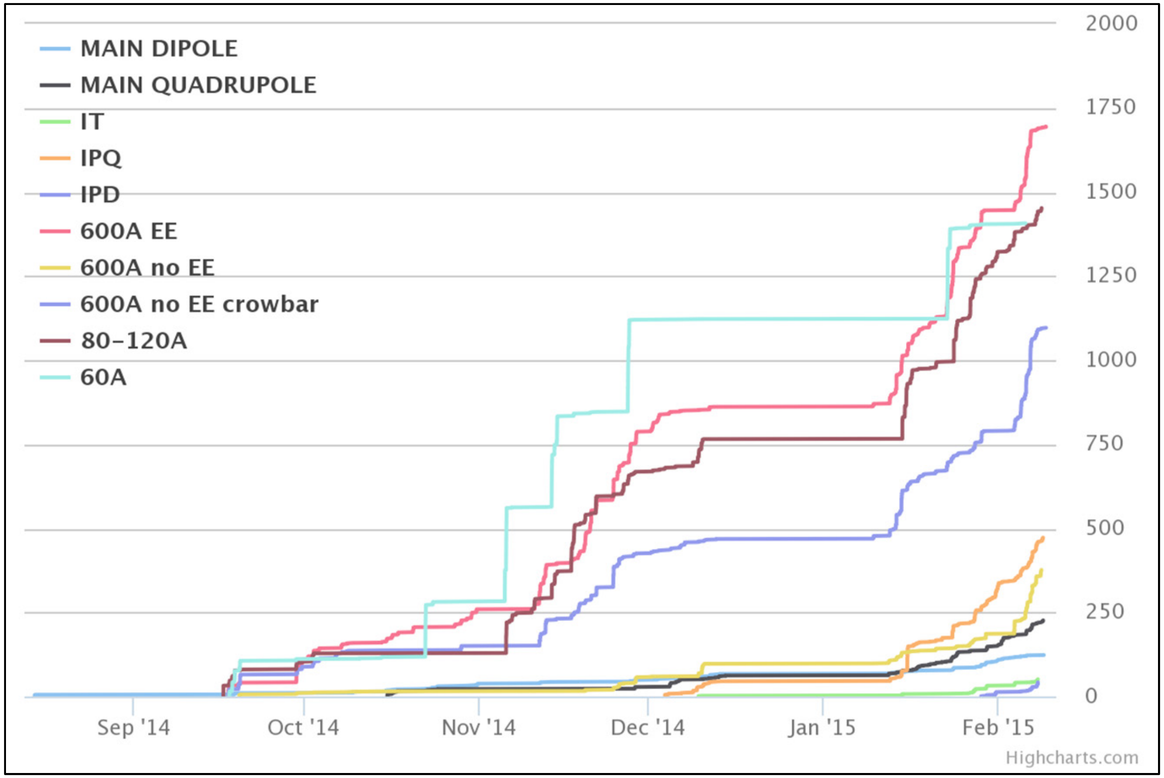
HLS linked by two hydraulic networks



Beam through Alice and to the end of sector 23 first shot 8/8/2008

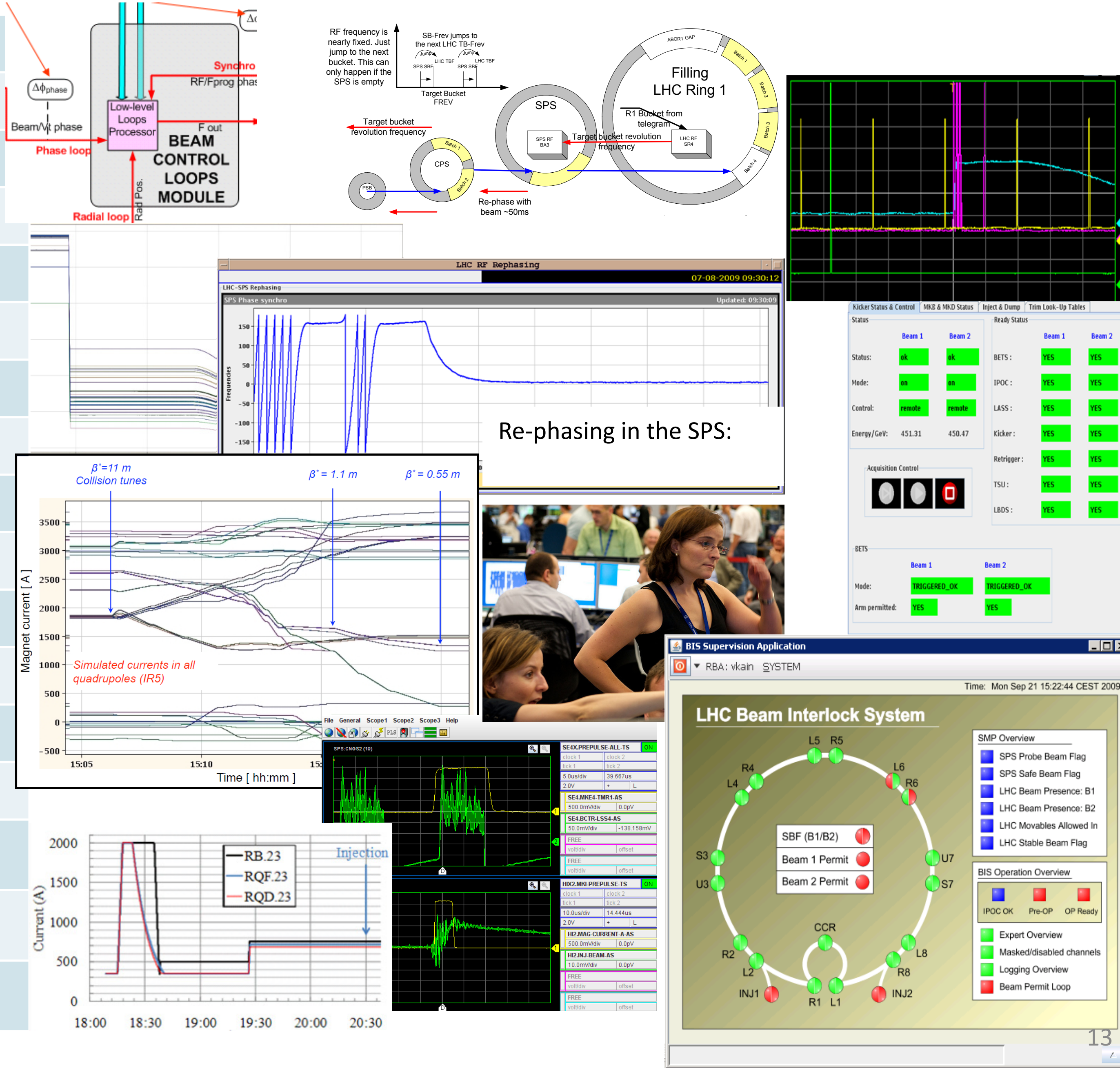
Hardware commissioning

- Full scale tests of main hardware systems
  - Cold and warm magnet circuits and protection systems
  - RF, Collimation, Injection system, Beam dump system



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
- Magnet circuits
- Magnet model
- Sequencer, alarms
- Controls, logging, DBs
- LSA, optics model, YASP



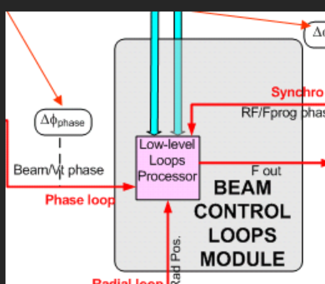
2009: That which does not kill us…

14 months of major repairs and consolidation

New **Quench Protection System** for monitoring and protection of all joints.

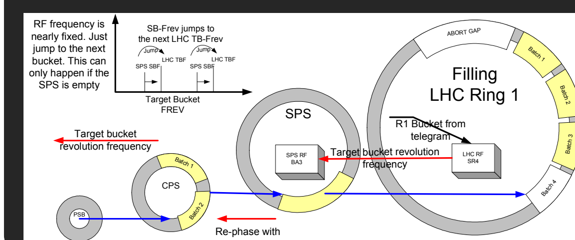
Beam based systems

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

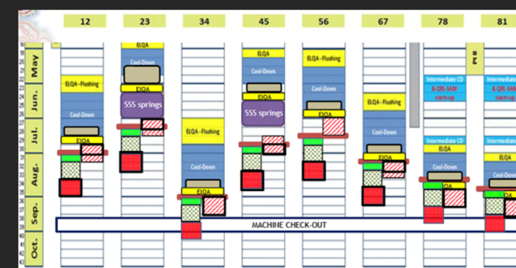


Controls & software

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



Dry runs, system tests and hardware commissioning (again)



"Unprecedented state of readiness"

“I have a plan so cunning you could stick a tail on it and call it a weasel”

	Phase
A1	Injection and first turn
A2	Circulating beam
A3	450 GeV initial commissioning
A4	450 GeV optics measurements
A6	450 GeV - two beams
A7	Collisions at 450 GeV
A8	Snapback and ramp
A9	Flat top checks
A12	Commission experimental magnets
A10	Setup for collisions - 3.5 TeV
	Physics un-squeezed
	TOTAL to first collisions
A11	Commission squeeze
A5	Increase intensity

Phase A.4

450 GeV optics

- home
- overview
- description
- entry conditions
- procedure
- exit conditions
- problems

Had established a reasonably good idea of how to run the machine

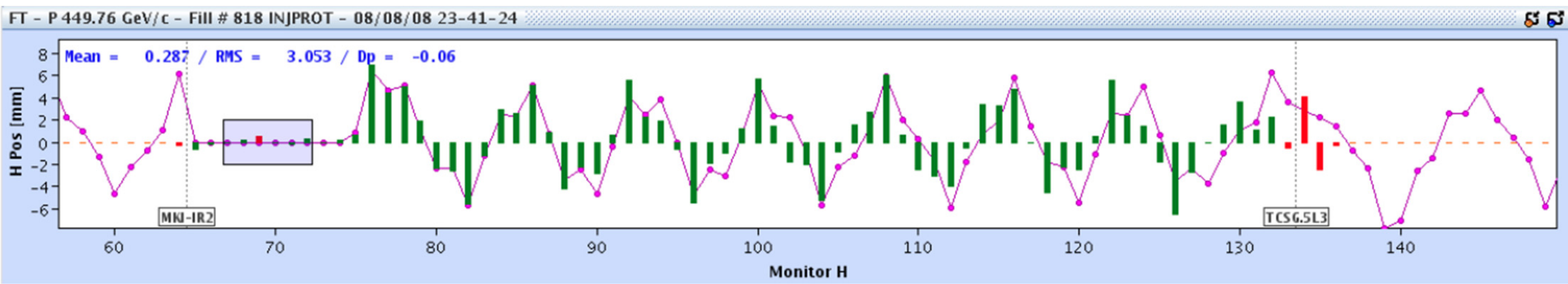
Step	Activity
A.4.1	**Measurement and correction of the closed orbit**
A.4.1.1	Measurement and correction of arcs and IPs (independentl
A.4.1.2	Measurement and correction of each IR (needs another ite
A.4.1.3	Iterate after more detailed optics knowledge, if needed
A.4.2	**Measurement and correction of the linear optics**
A.4.2.1	Commissioning of MQX linear correctors (if not in A.4.1.1), MQT, MQS circuits
A.4.2.2	Tune
A.4.2.3	Coupling (possibly needs another iteration with 2 beams)
A.4.2.4	Beta-beat (needs another iteration with 2 beams)
A.4.2.5	Dispersion (needs another iteration with 2 beams)
A.4.2.6	Refined optics model -> Response matrix, BPM calibration
A.4.2.7	Generation of new reference settings for correctors, if nece
A.4.2.8	Additional local beta measurements with K-modulation (IR'

Beam commissioning

- In depth and prolonged preparation allowed us to move rapidly through the planned commissioning program
- Nominal operation cycle
- Interleaved with commissioning of
  - main beam-based systems
  - other beam instrumentation
  - feedback systems
- Systematic measurements and optimization

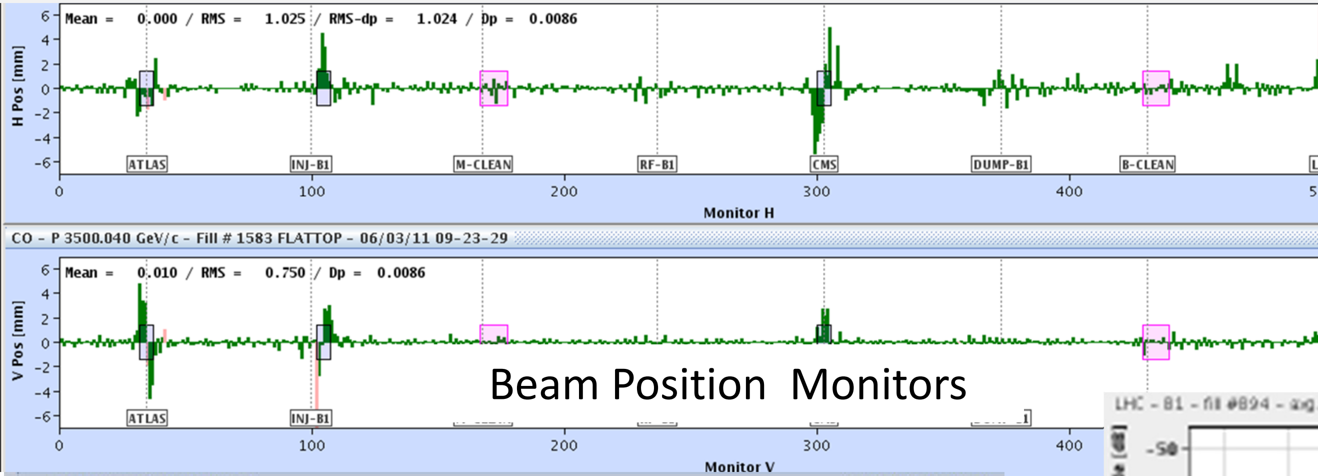
Early commissioning

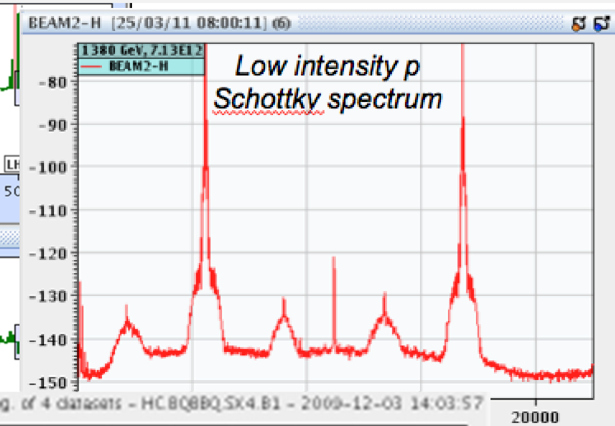
- Marked by phenomenally swift deployment of tools to measure, correct, and verify:
  - Optics, magnet model, polarities (!), aperture…
  - Fabulously fast turnaround on problem resolution
- Ramp, squeeze commissioning eased by availability of feedbacks
- Underpinned by instrumentation and software

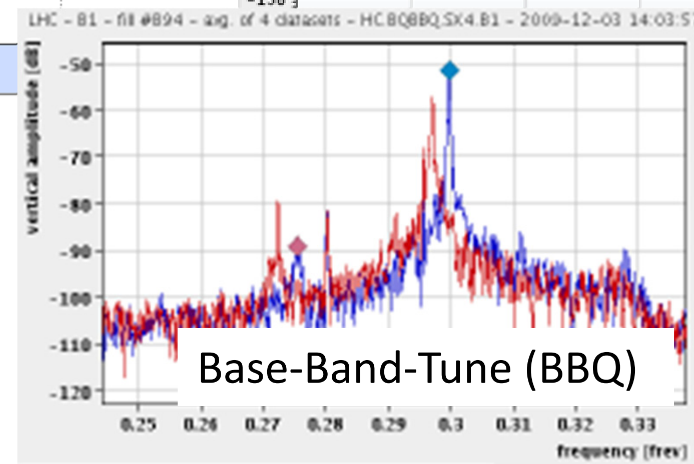


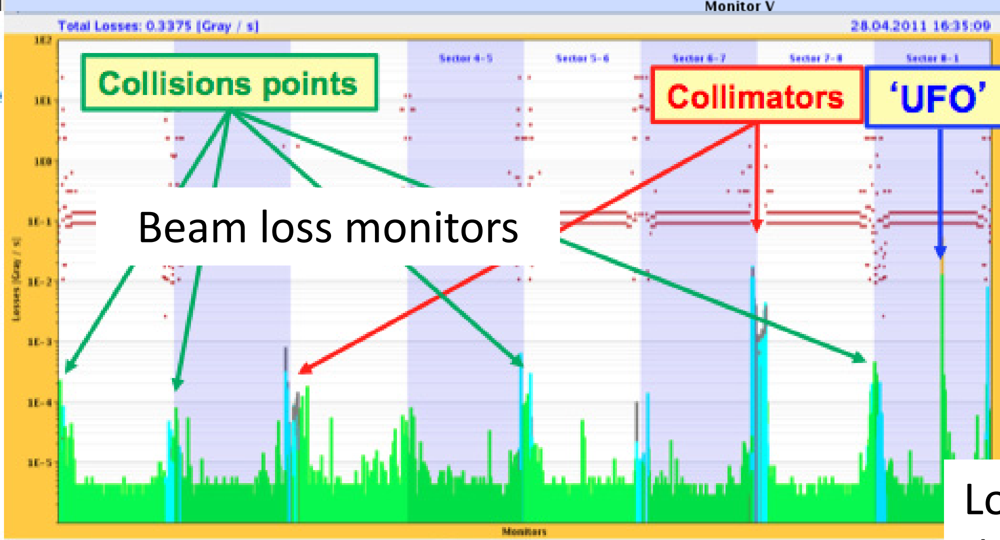
Experience meets youthful enthusiasm, talent, and stamina

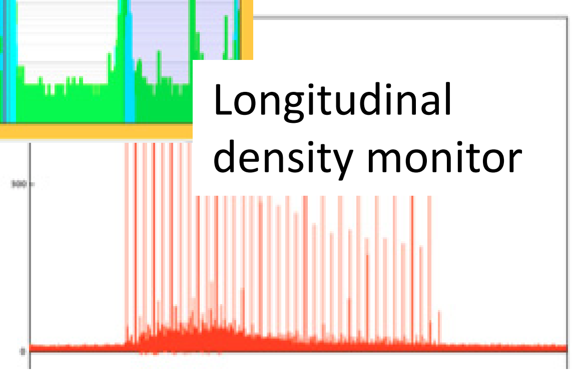
Beam Instrumentation: brilliant – the enabler

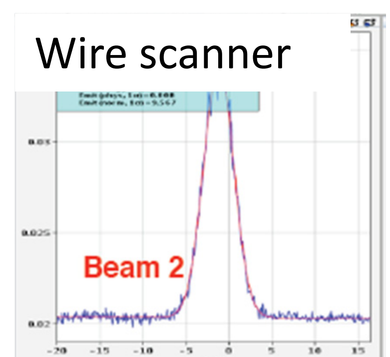








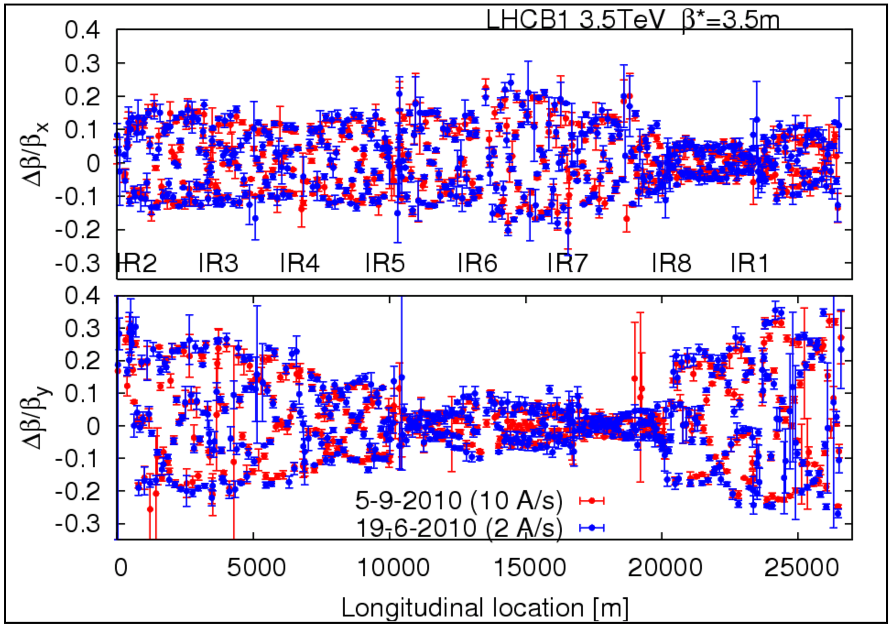




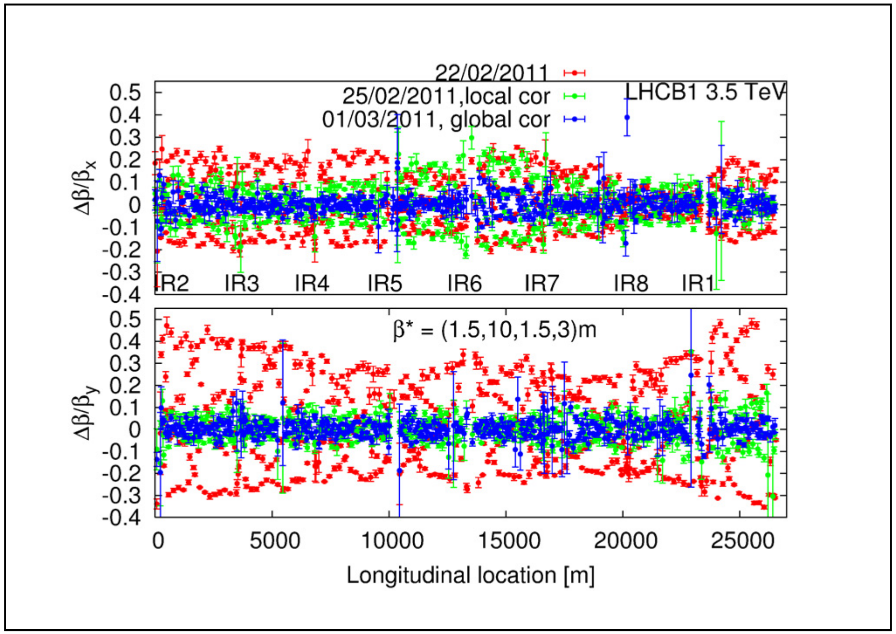
Optics

Optics stunningly stable

and well corrected



Two measurements of beating at 3.5 m
3 months apart

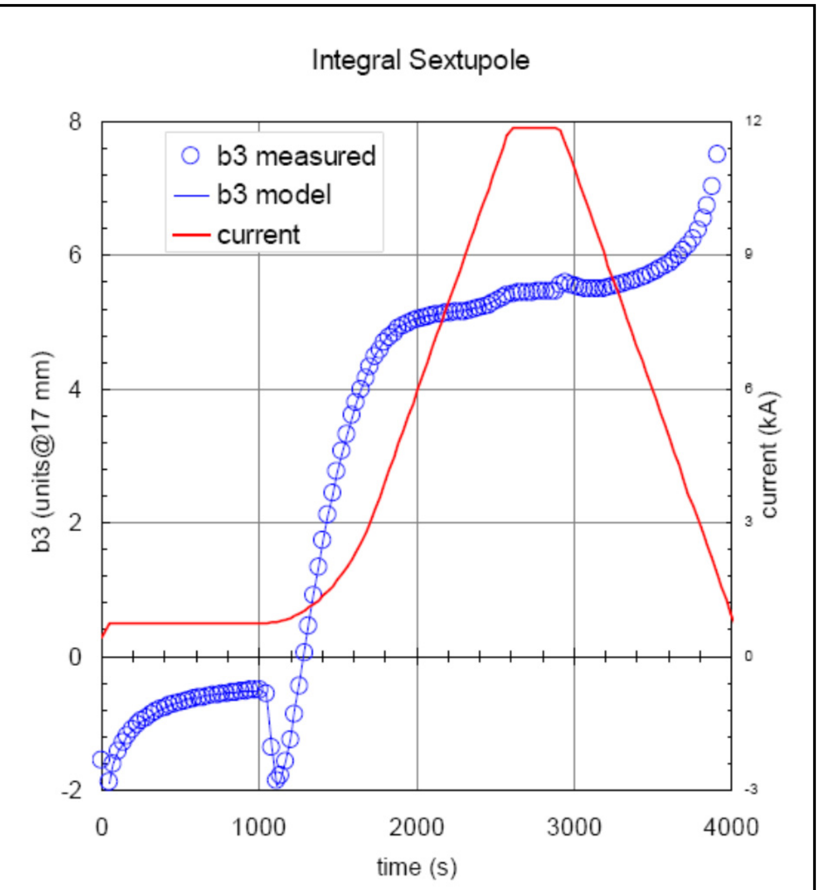


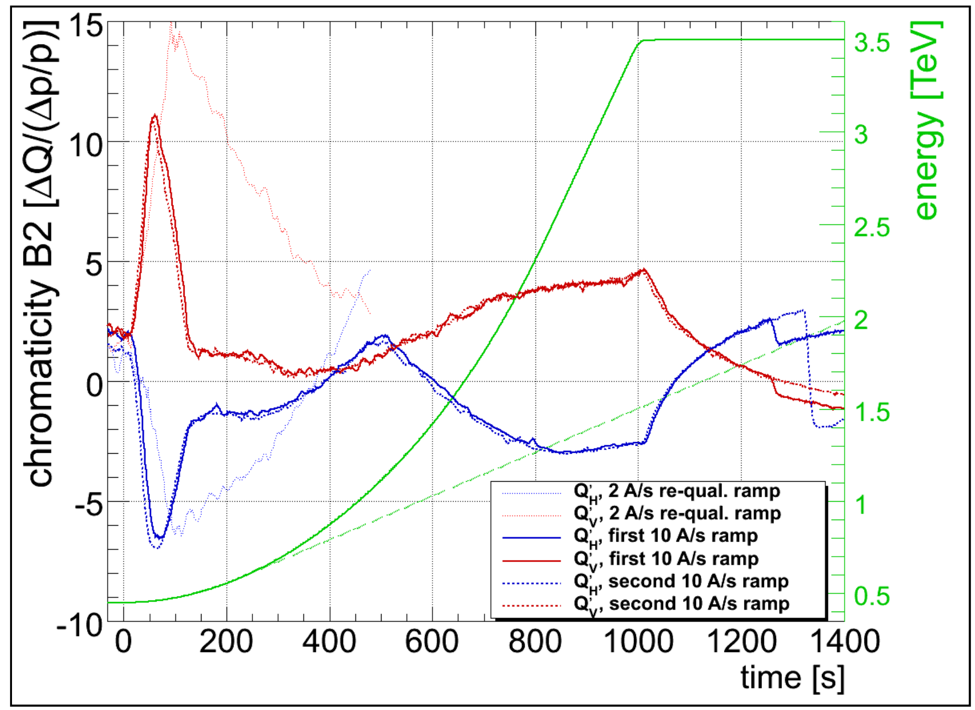
Local and global correction at 1.5 m

R. Tomas, G. Vanbavinckhove, M. Aiba, R. Calaga, R. Miyamoto

Magnet model

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

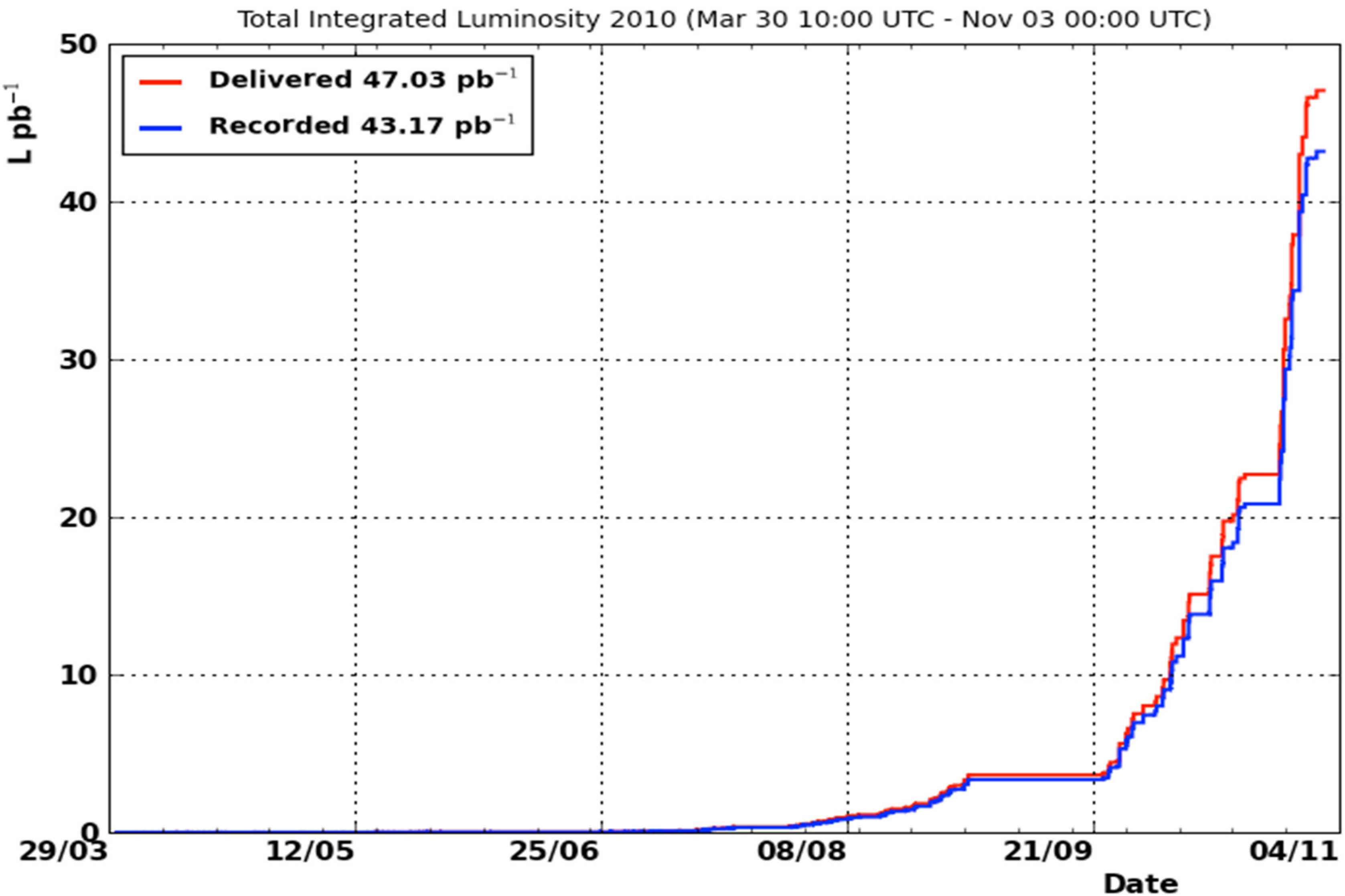




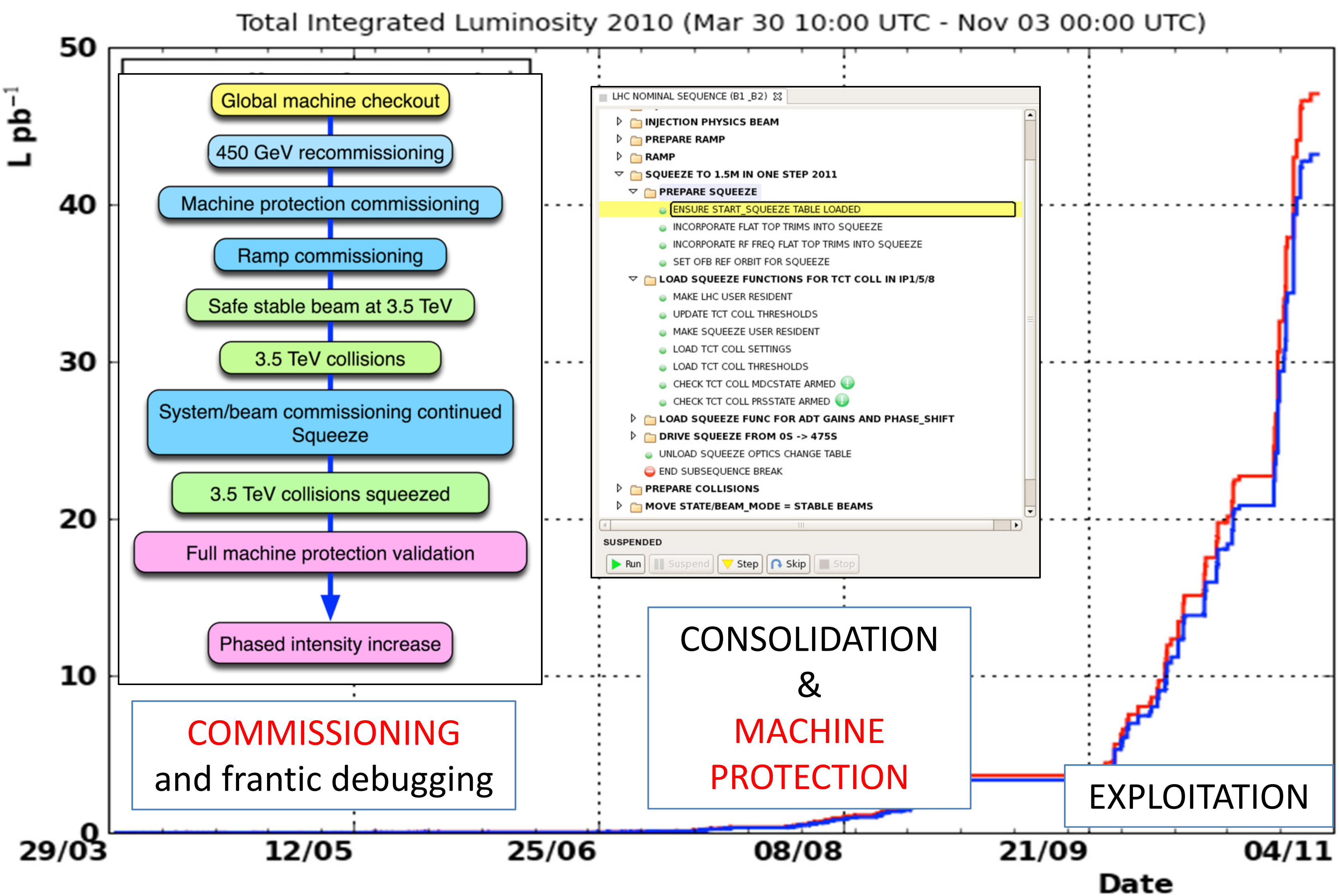
Model based feed-forward reduces chromaticity swing

Courtesy Luca Bottura & Ralph Steinhagen

Commission for exploitation



Commission for exploitation



Good news from all this

- Machine aperture at limits (IR's) is 40% larger than foreseen.
- No problem with dynamic aperture (lifetime) at injection energy
- LHC magnetic model, optics and orbit controlled at unforeseen levels.
- Beam cleaning and collimation works reliably with predicted efficiency.
- Machine protection reliably catches failures, "dangerous" beam losses.
- Beam instrumentation in fine shape.
- Feedbacks on orbit and tune provide beam stability.
- A very complex controls system works very well.

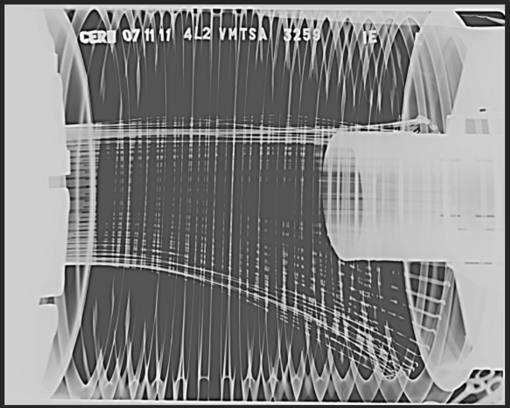
More good news

- LHC beam size growth smaller than foreseen in design.
- Transverse feedback can be used at top energy without blowing up the beam → stabilization of instabilities.
- RF system can be used to blow up the bunch length during the ramp → stabilization of instabilities.
- Octupoles can be used at top energy → stabilization of instabilities.
- Nominal beam-beam parameters achieved and weaker than expected.

Run 1 - some issues…

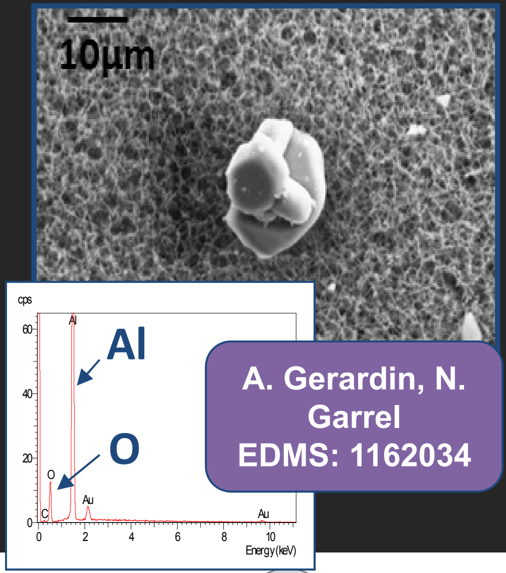
Beam induced heating

- Local non-conformities (design, installation)
  - Injection protection devices
  - Sync. Light mirrors
  - Vacuum assemblies



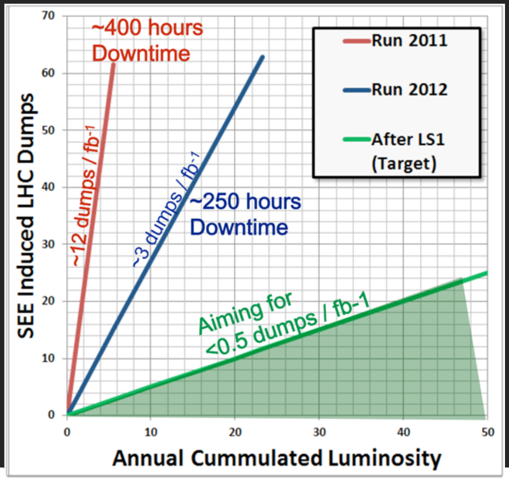
UFOs

- 20 dumps in 2012
- Timescale 50-200 μs
- Conditioning observed
- Worry about 6.5 TeV



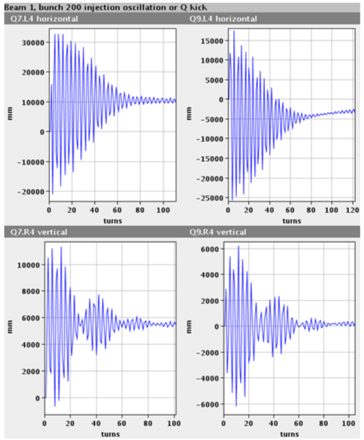
Radiation to electronics

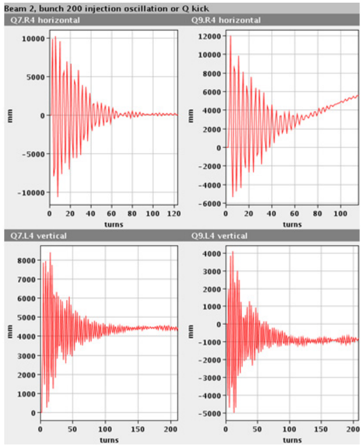
- Concerted program of mitigation measures (shielding, relocation…)
- Premature dump rate down from 12/fb^{-1} in 2011 to 3/fb^{-1} in 2012



Re-commissioning 2015

- **A lot of lessons learnt from Run 1**
- Excellent and improved system performance:
  - Beam Instrumentation
  - Transverse feedback
  - RF
  - Collimation
  - Injection and beam dump systems
  - Vacuum
  - Machine protection
- Improved software & analysis tools
- Experience!
- Availability targeted across the board





Re-commissioning 2015

- Excellent lifetime through the cycle
- Magnetically reproducible as ever
- Optically good, corrected to excellent
- Aperture is fine and compatible with the collimation hierarchy.
- Magnets behaving well at 6.5 TeV
  - ~5 additional training quenches during operation
- Operationally things well under control
  - Injection, ramp, squeeze etc.

2015 - Main issues

- Quench Protection System (QPS)
  - Non radiation hard components
- UFOs
- UFOs at the ULO
- Earth faults
  - Metallic debris near dipole diode box
  - RCS.A78B2 - 154 sextupole correctors - circuit condemned
  - Main dipoles A78 – intermittent fault (x3)

Overall

- Missed
  - Radiation to electronics
  - Anti electron-cloud coating in cold sectors
- Don’t miss
  - 200 MHz RF cavities
  - On-line reference magnets
- Didn’t expect
  - UFOs

Thankful for everything else

Don’t worry (much) about

- Single beam lifetime
- Luminosity lifetime (with nominal bunches)
- Head-on beam-beam
- Reproducibility
- Controls/databases/software (much)
- Operational flexibility
- Decay and snapback
- Klystron driven SC RF and noise

Worry (a bit) about

- Electron cloud
- Emittance growth
- Instabilities
- Losses with high bunch population
- Long range beam-beam
- Machine protection (always)
- Robustness of protection devices
- Earth faults
- Availability, availability, availability

Conclusions 1/2

- LHC enjoying benefits of the decades long international design, construction, installation effort.
- Preparation
  - Start early – break it down - set milestones
  - Dry runs – machine checkout – hardware tests – beam tests
- Controls/databases/software
  - don’t underestimate the importance of… analyze seriously what is required
- Instrumentation
  - "If you can not measure it, you can not improve it.”
- Commission for exploitation
  - And then don’t stop

Conclusions 2/2

- On the accelerator physics side - huge amount of experience & understanding gained
  - Impressive work by various teams (collective effects, beam-beam, optics, RF, beam transfer, beam loss, collimation, transverse damper…)
  - Models are important: optics, aperture, magnets, impedance
- Understanding is possible!
  - Make time for beam studies, machine development
- Progress with beam represents phenomenal effort by all the teams involved, injectors included.

PERSONAL COMPETANCIES

Leadership

Ability to relax

Teamwork