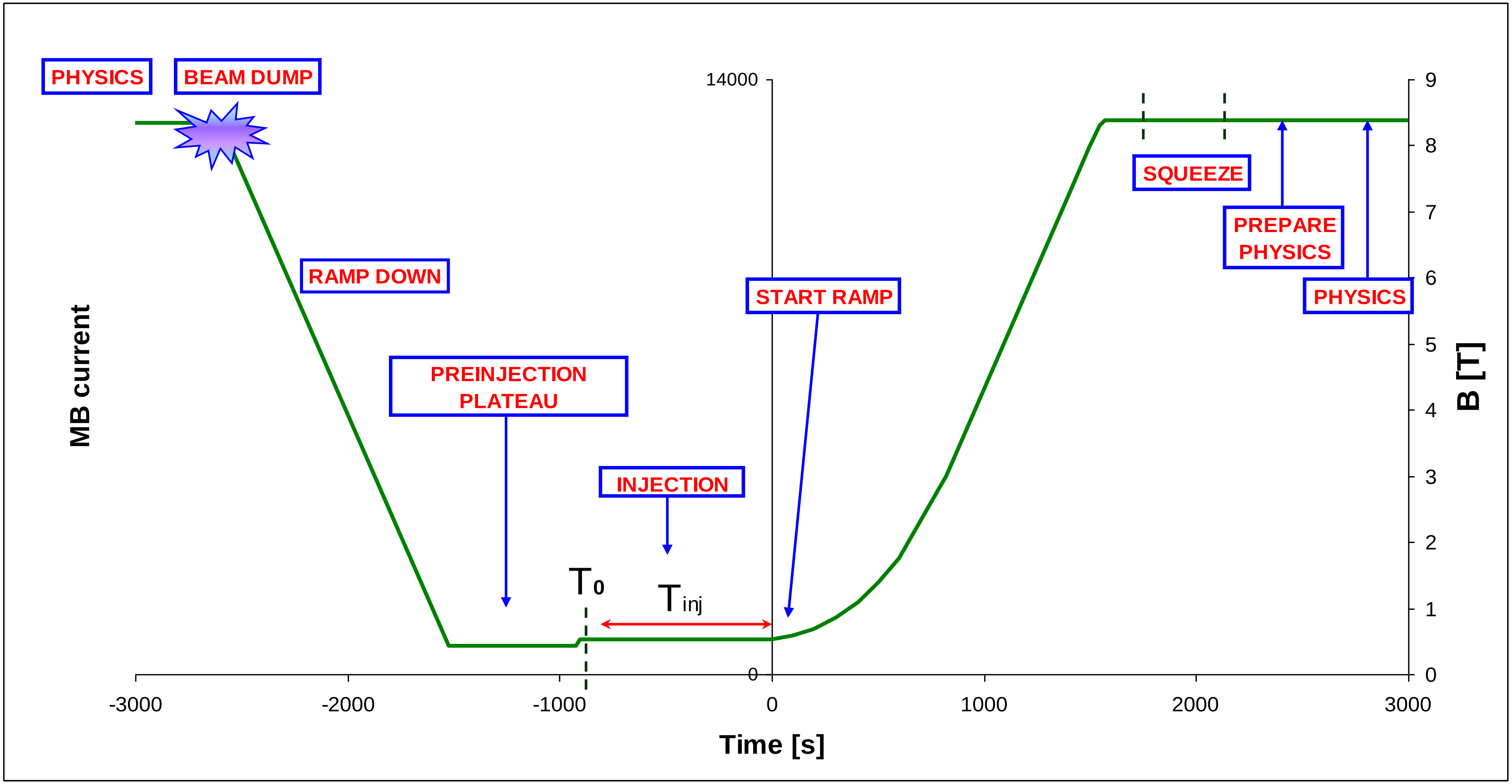
BEAM LOSS MECHANISMS: OBSERVATION FROM THE LHC

L. Ponce

Acknowledgements: V. Kain, J. Wenninger, T. Baer, W. Bartmann, C. Bracco, M. Pojer, R. Denz, M. Brugger, L. Drosdal

LHC hypercycle

- Nominal LHC hypercycle : a different world
- divided in phases (= beam processes) between 10 and 30 min

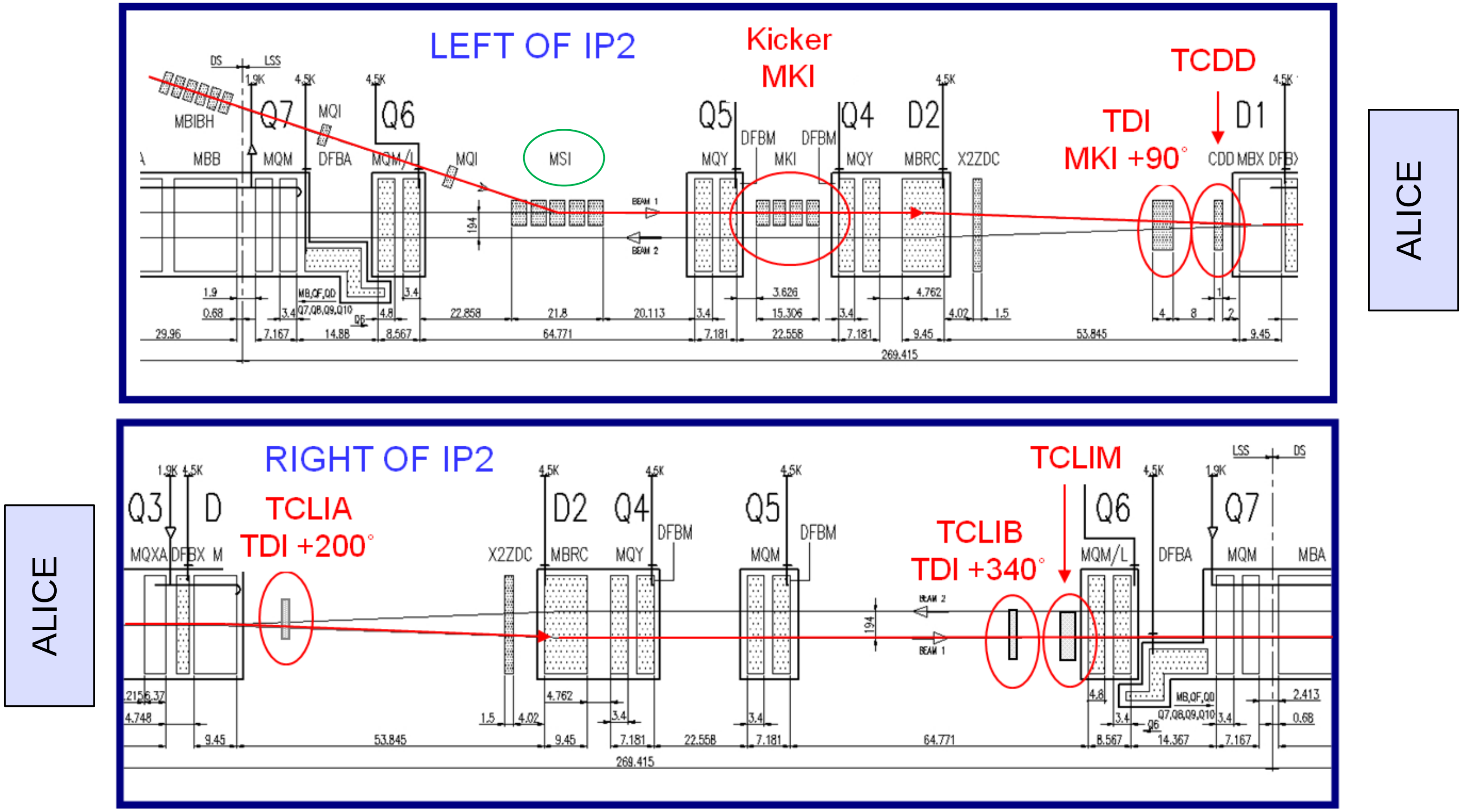


Outlines

- Losses at injection
  - Injection region layout
  - Standard injection losses
  - Injection failure examples
- Losses along the cycle
  - Typical loss pattern during ramp
  - Orbit excursion during the squeeze
- Losses when in collisions
  - Luminosity fragment
  - UFO
  - SEU
  - instabilities

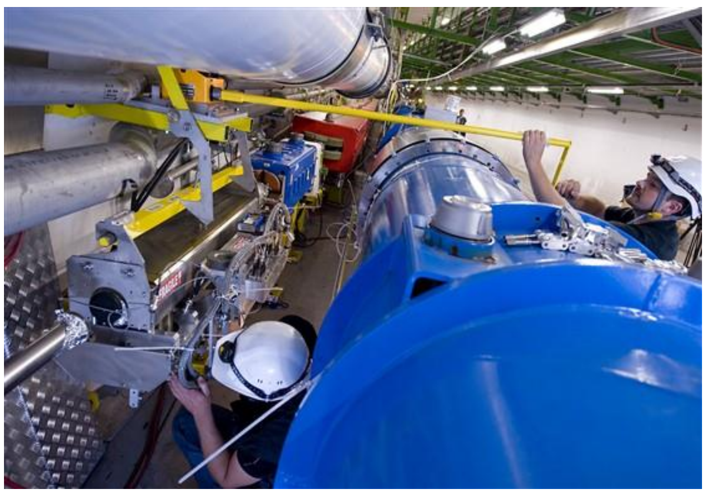
LHC injection layout

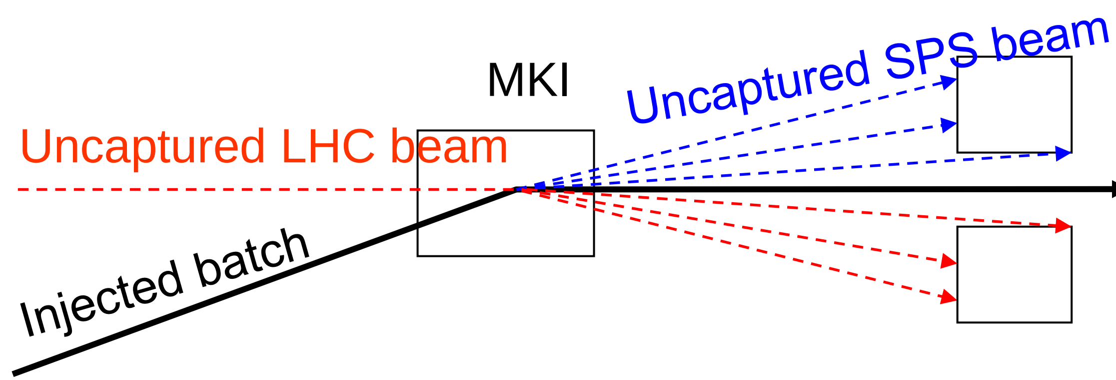
- LHC injection: horizontal injection septum MSI (12 mrad), vertical injection kicker MKI (0.85 mrad); vertically off-centre through the LHC quadrupole (Q5)
- Protection against kicker failures: TDI + TCLIs
- Experiment detector in the middle: ALICE or LHCb



Injection losses : regular losses

Loss reason	where
1) Transfer line collimators (TCDIs) cutting transverse beam tails	loss shower on cold elements: Q6,Q7,Q8, MSI
2) Uncaptured beam LHC	TDI lower jaw, showers on equipment downstream (TCTVB, MQX, MBX, TCLI)
3) Satellites, uncaptured beam from SPS	TDI upper jaw, showers on equipment downstream (TCTVB, MQX, MBX)





➢ Transfer line collimators partly close to superconducting magnets.
➢ LHC BLM trigger with TCDI shower from the outside.

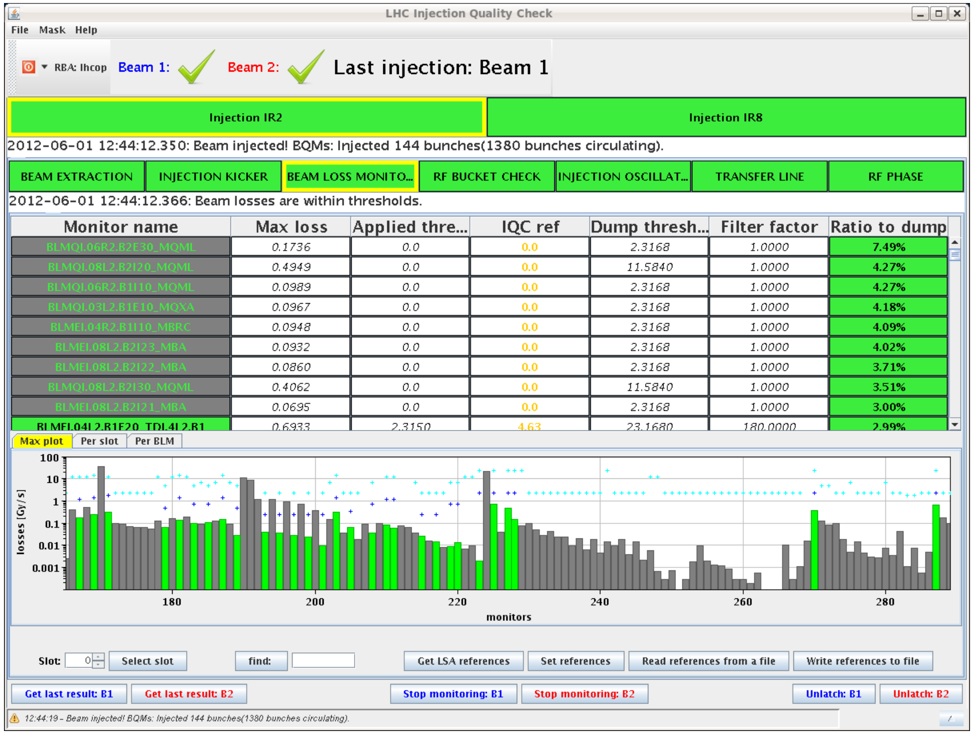
➢ Circulating uncaptured beam is kicked out onto the lower jaw of the TDI each injection.
➢ TDI showers reach LHC BLMs on TCTVB, triplets,… from the outside – and experiments' beam condition monitors

Injection Losses and Intensity Limitations

Loss type	Losses in % of dump threshold B1/B2				
	8b	16b	24b	32b	48b
TCDI shower	1/2	3/5	4/6	5/8	23/24
Uncaptured beam	4/2	12/3	12/5	16/8	20/8

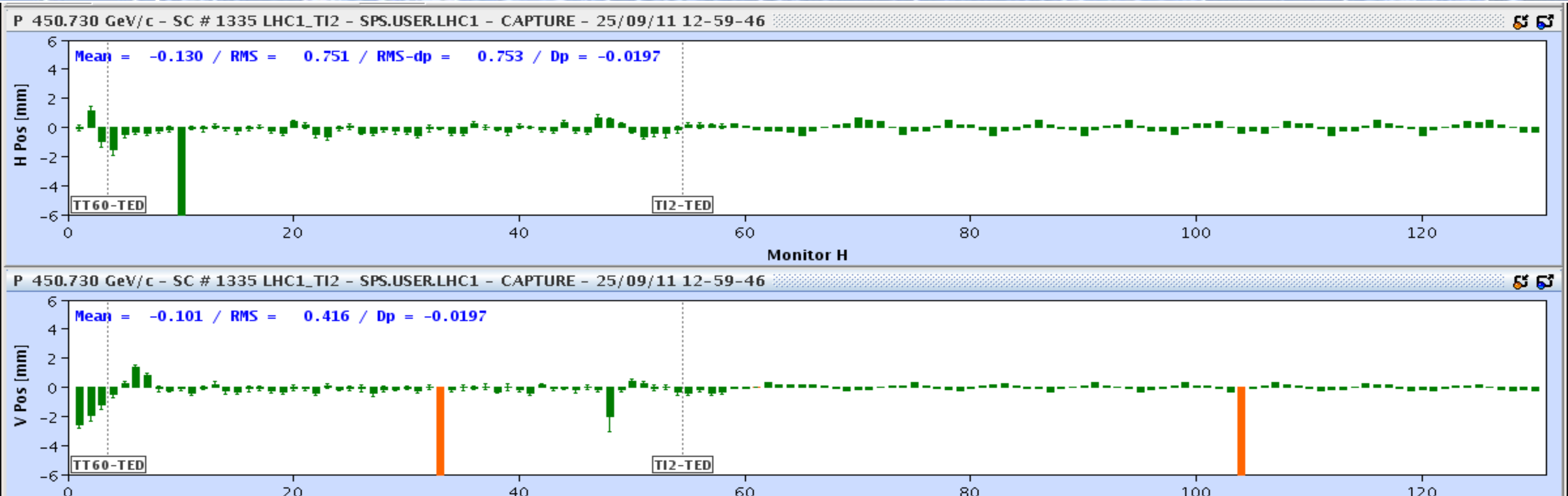
- Based on extrapolation from 2010 performances, mitigations techniques needed
- Transfer Lines showers:
  - Local shielding between TCDIs and LHC
  - Beam scraping (transverse) in SPS
- Uncaptured beam
  - Local shielding at TDI
  - Minimization of capture losses
  - Injection and abort gap cleaning

- In 2012, clean injections :
  - 144 bunches (~1.5e11 protons per bunch, ~2 um emittance) in normal operation (< 10% of dump threshold)
  - 288 bunches (1.05e11, 2.5-2.7 um) injected with 30 % of dump threshold during MD

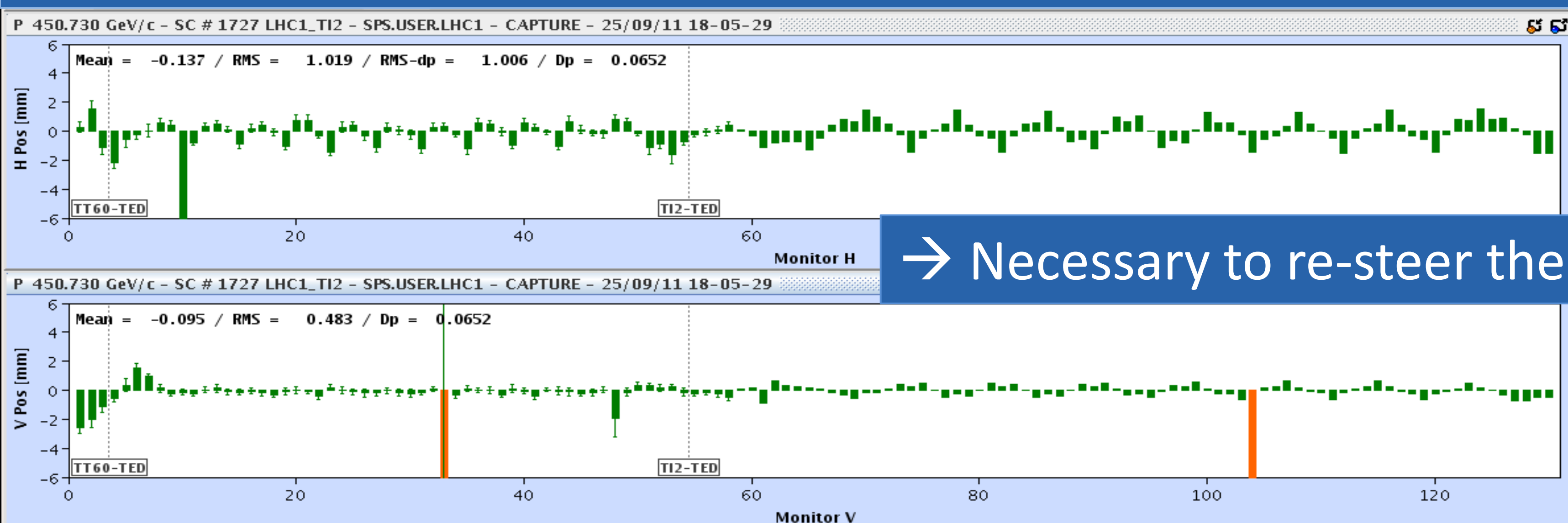


Courtesy C. Bracco

TL stability problem



5 h later – same super cycle composition → Trajectory has changed



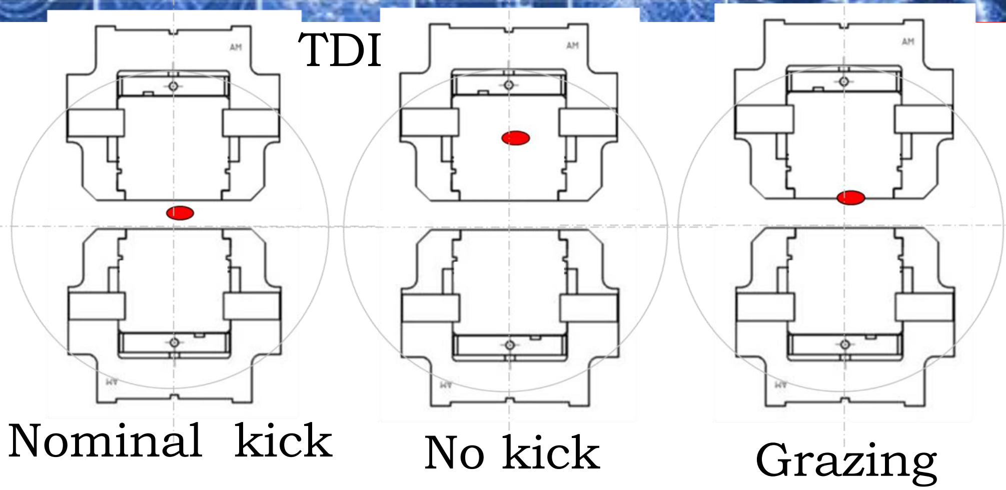
→ Necessary to re-steer the line

TL stability problem

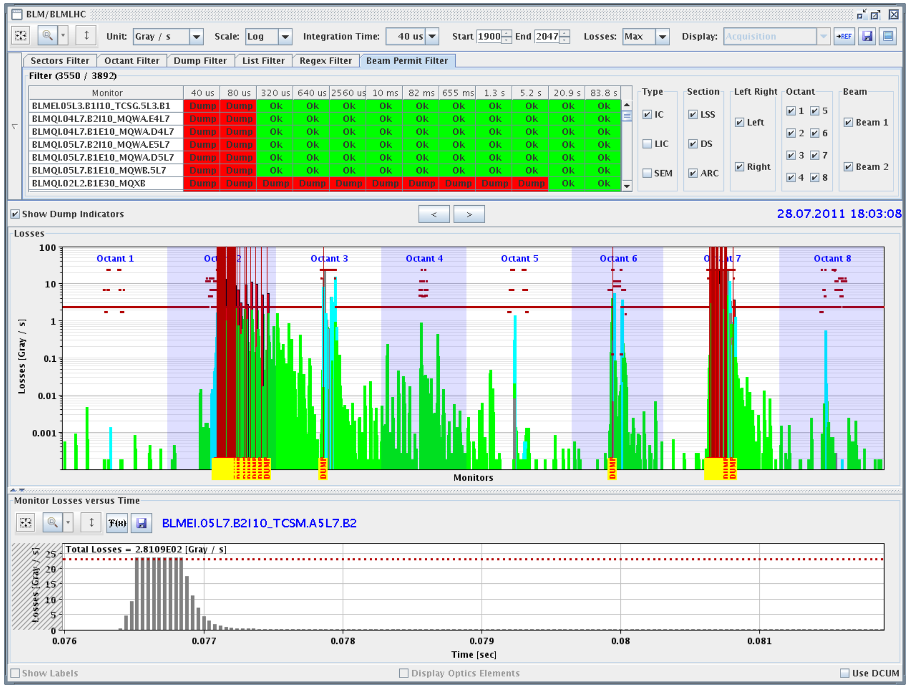
- A lot of time lost due to re-steering of Transfer Lines:
  - Tight transfer line collimators (4.5 sigma) –> high losses if trajectory not centered
  - Injection oscillations have to be below 1.5 mm to respect available aperture in the LHC
- Sometimes difficult to find a compromise between injection oscillations and trajectory at TCDIs at the same time
- During 2011 operation, studies have been done to understand the causes:
  - Large shot-by-shot variations (760 µm max) are observed for both lines in the horizontal plane – sources identified as the SPS MSE
  - Bunch-by-bunch variations (up to 1 mm difference in peak oscillation) on beam 2 in horizontal plane - caused by a ripple on MKE

Injection failure

- Different types of failure:
  1. Injected beam not kicked
  2. Circulating beam hit
  3. Injected beam partly kicked

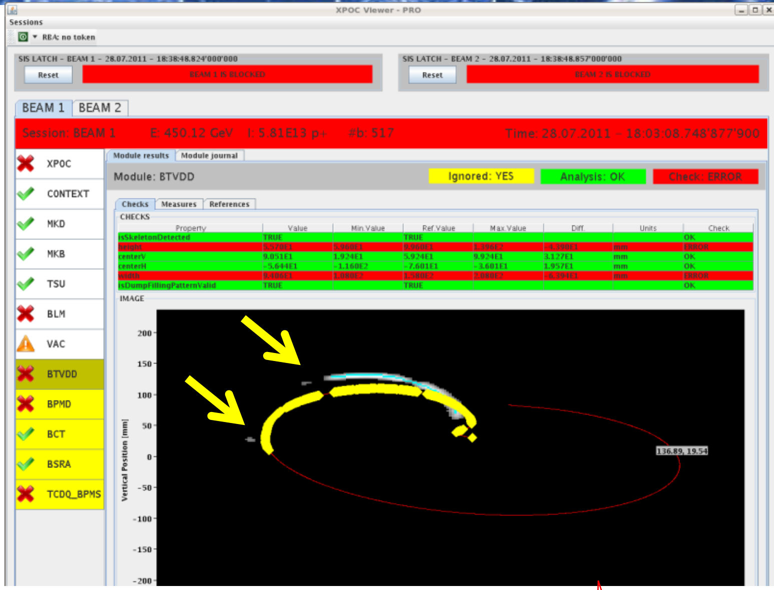


- Jul 28: erratic on the MKI
  - Erratic on the main switch detected by interlocks -> discharge
  - But too late to inhibit extraction
  - 144 bunches dumped on TDI in point 2
  - Circulating beam was not hit
  - Heavy losses in IR2, but NO quench

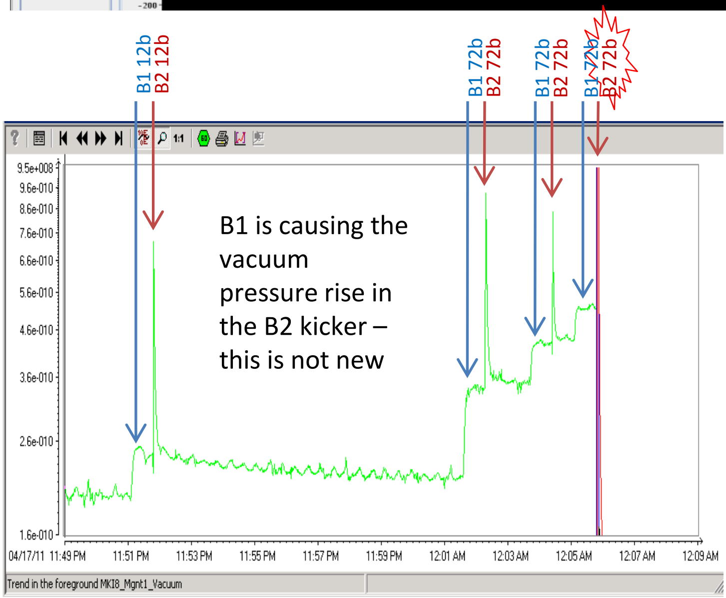


Injection failure

- July 28: second erratic on the MKI
  - During charging process, not detected by interlocks
  - Circulating beam swept over aperture (17% of normal kick)
  - 173 bunches missing in dump --> on TDI
  - Some grazing bunches quenched 3 magnets and hit ALICE (permanent damage)
  - Important leakage to S23 (but no quench)



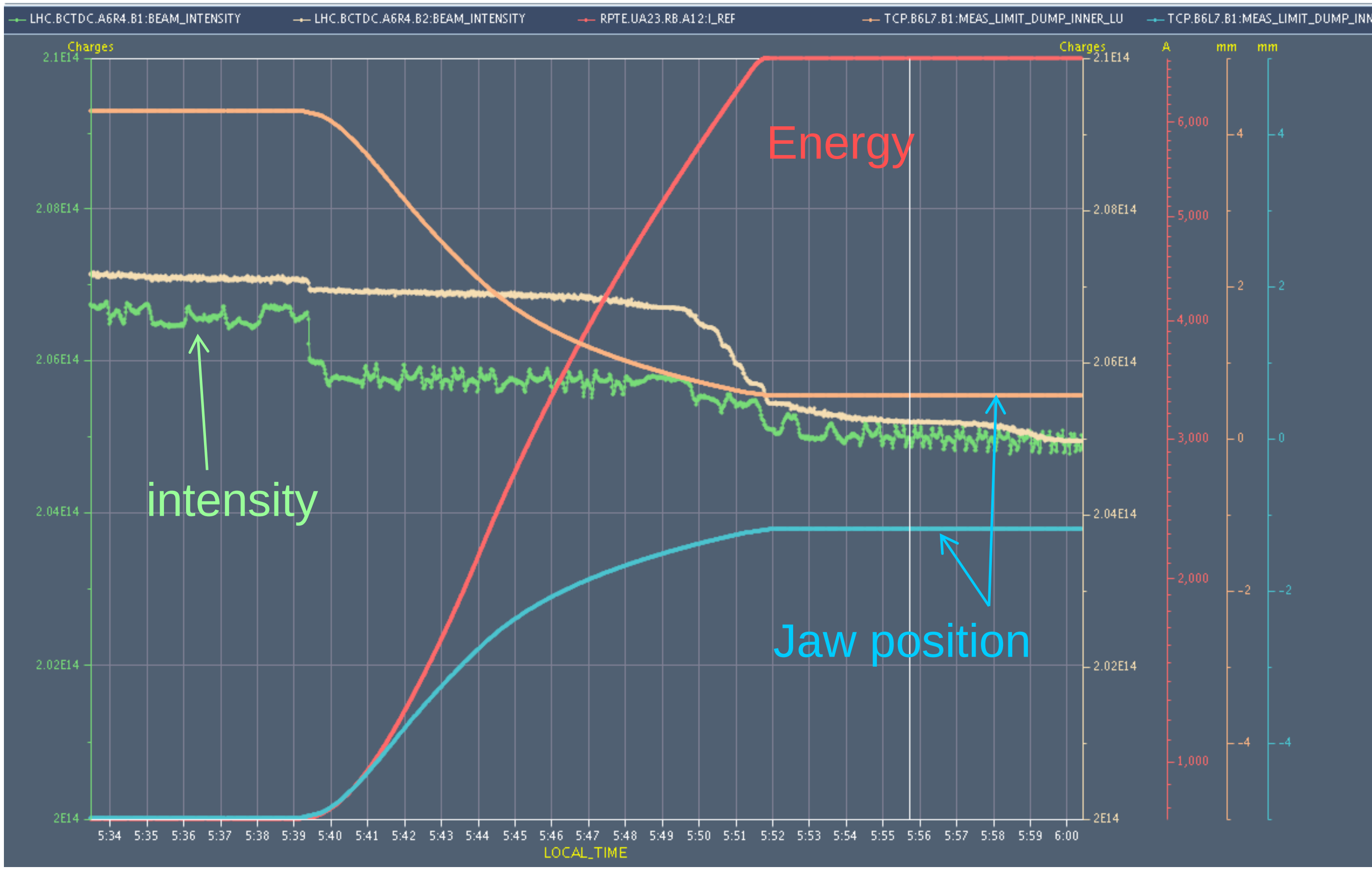
- April 28: flashover in the MKI
  - Injection of 2 × 36 bunches spaced by 2.2 μs
  - Breakdown after ~2 μs ➔ All 36b of 2nd batch were kicked with 110-125% nominal MKI deflection
  - Beam was on LOWER TDI jaw and over-kicked, i.e. breakdown in second half of magnet (LHCb signals support this)
  - Nearly all p+ of the 36b impacted on the TDI/TCLIB (grazing) -> <u>11 magnets quenched</u>



Losses during the ramp

- ➢ Uncaptured beam lost at the beginning of the ramp
- ➢ Losses at the end of the ramp when tight collimators settings are put in

Transmission ~ 98.5%



Losses start of ramp

Losses in momentum collimation region : up to ~50 % of dump threshold

Losses end of ramp

Losses on collimation region : scraping the beams

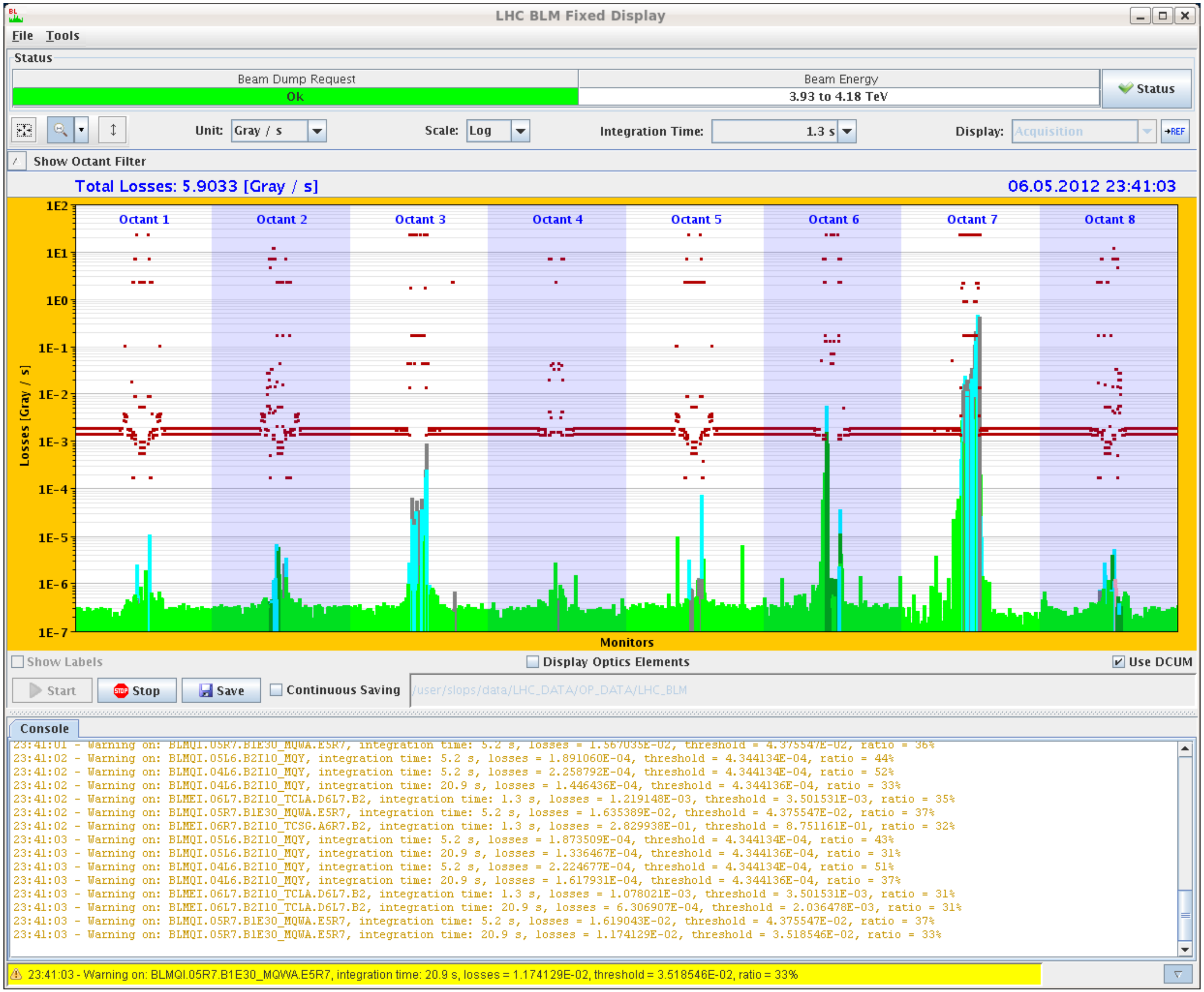
Losses during the squeeze

- Several fills dumped during the intensity ramp up in the squeeze with tight collimators settings.
- Observations from orbit correction indicate:
  - Orbit shift of 50 um at primary collimators → > 30% of BPM dump threshold.
  - Orbit shift of 100 um at primary collimators → high risk of beam dump by BLMs.
  - For losses on time scales of few seconds.
  - Corresponds to 5-10% of collimator ½ gaps.

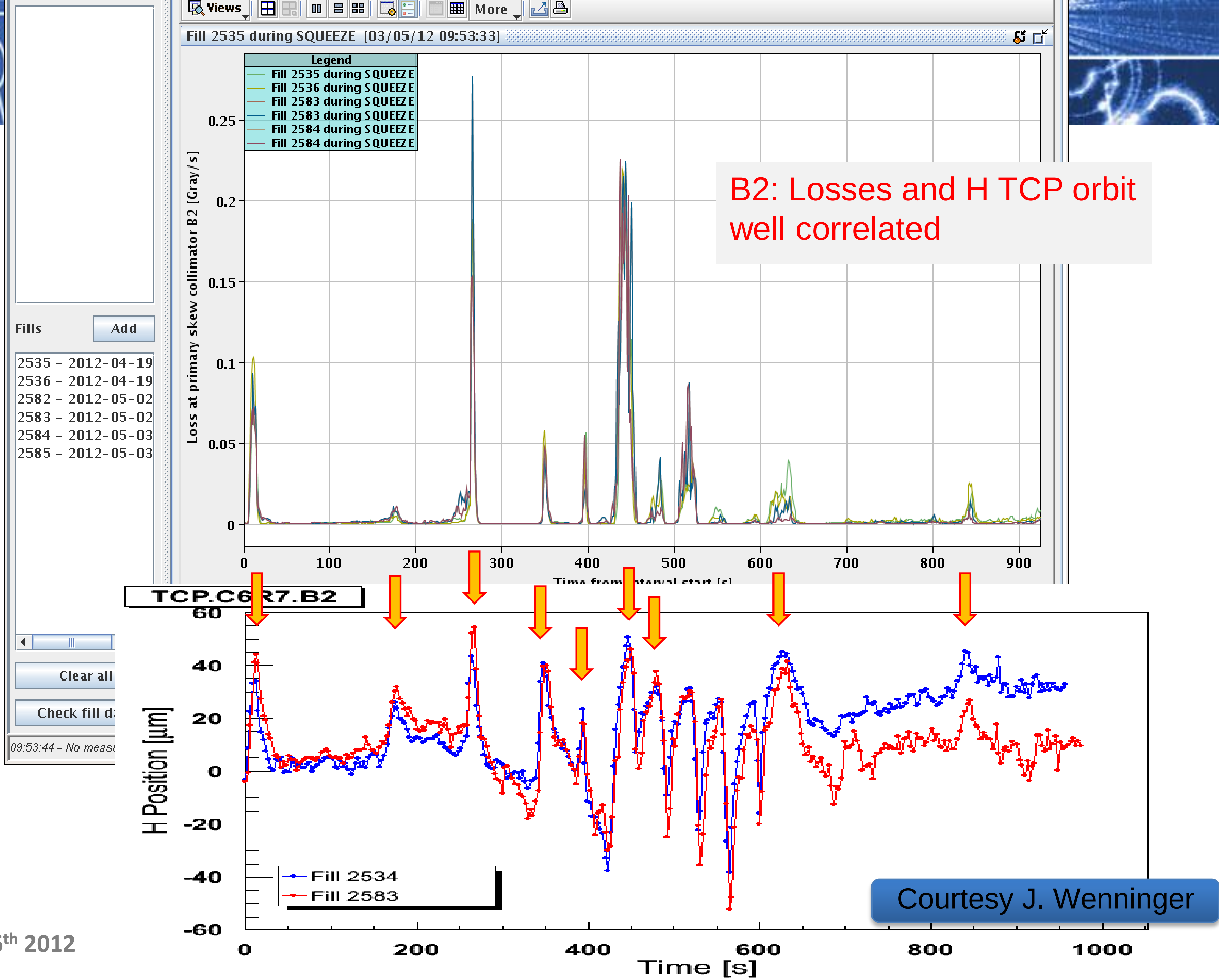
- Together with the increased tail population the orbit excursions were pushing the losses towards/above threshold.

Losses at 2m beta*

Up to 45% of dump threshold



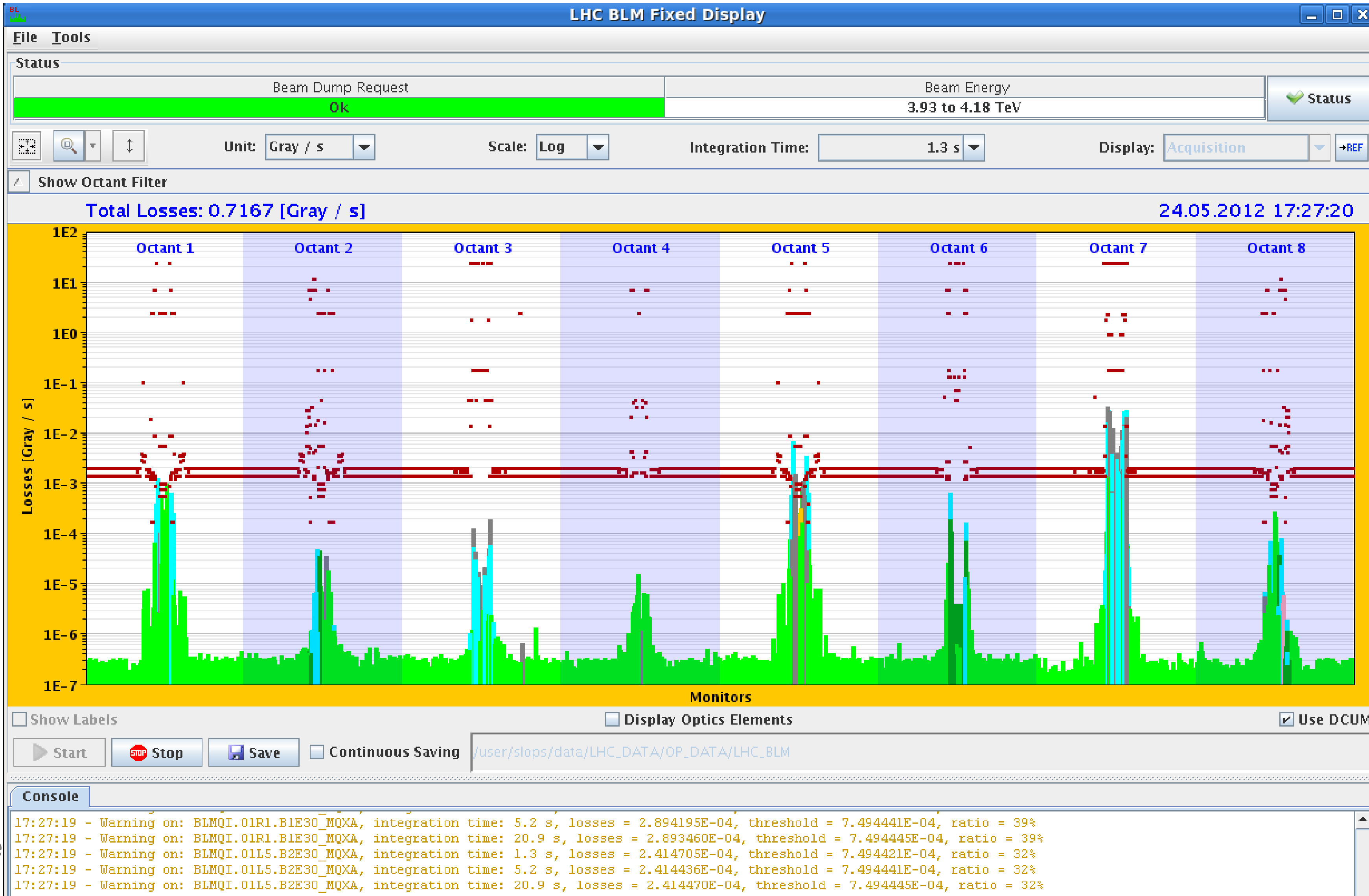
B2: Losses and H TCP orbit well correlated



Courtesy J. Wenninger

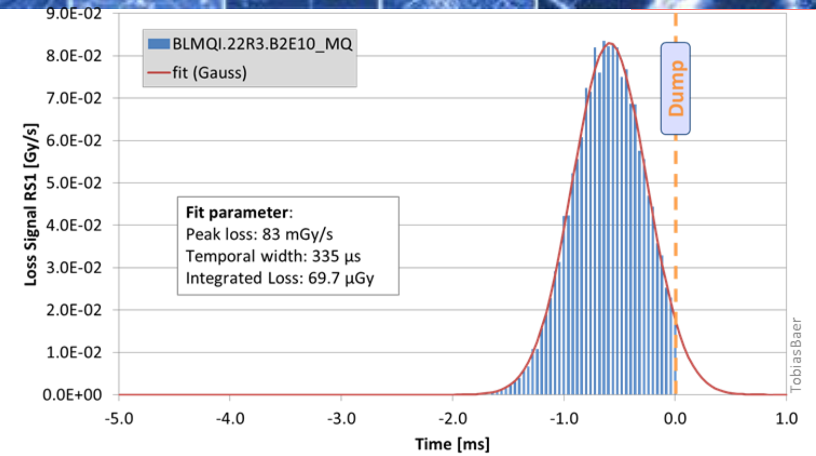
Losses in collisions

continuous losses on tertiary collimators IP 1/2/5 and 8

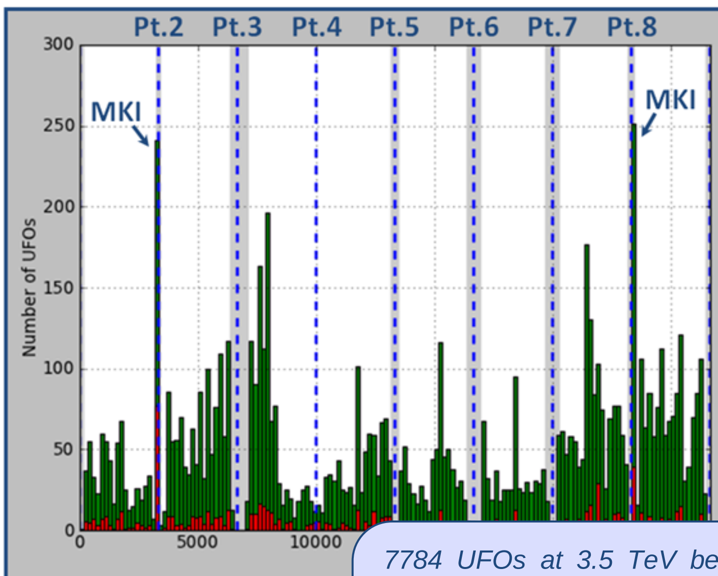


UFOs in the LHC

- 35 beam dumps due to (**U**n)identified **F**alling **O**bjects between July 2010 and August
  - Loss duration : about 10 turns
  - Often unconventional loss locations (in the arc)
  - Throughout 2011: mitigation by increase and optimization of BLM dump thresholds
- 18000 candidate UFOs below BLM dump thresholds found (2700 in 2012)
- UFOs occur all around the LHC. Particularly many around MKIs



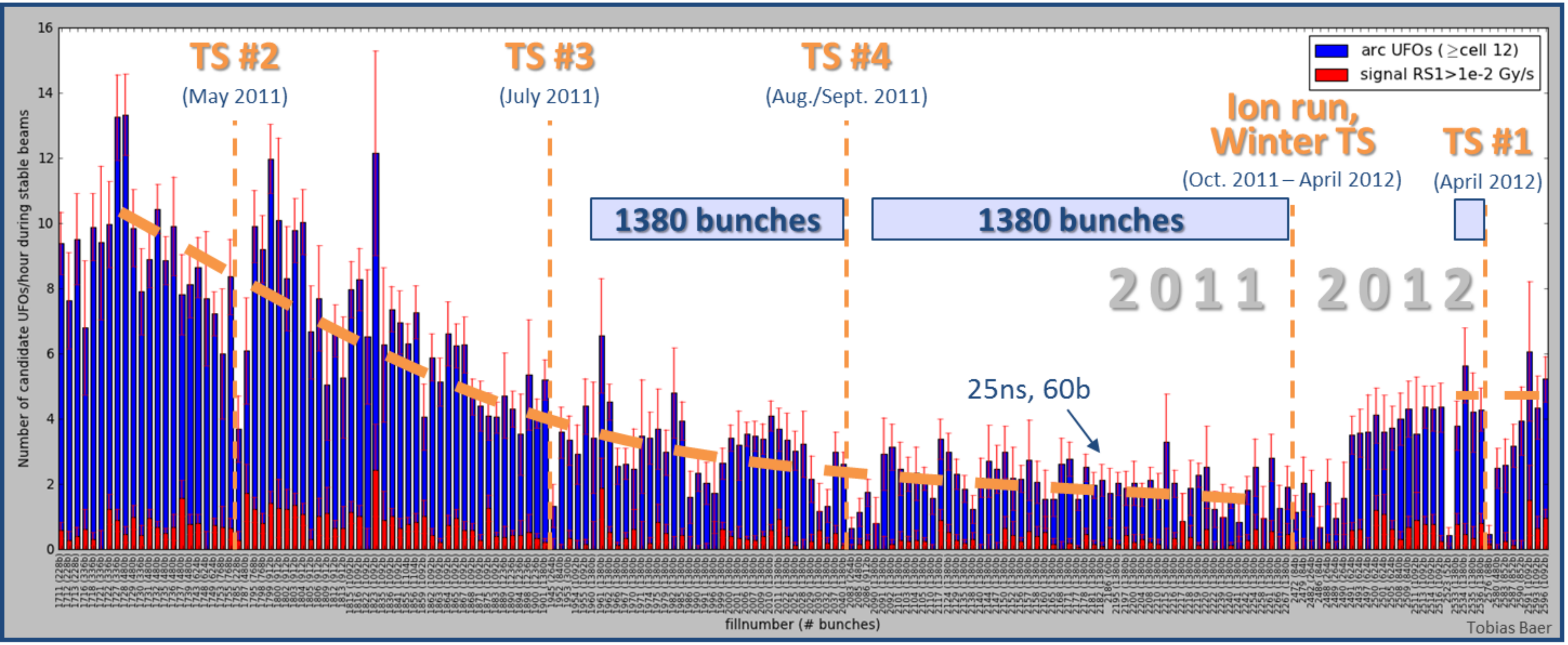
temporal loss profile of UFO on 23.08.2010



7784 UFOs at 3.5 TeV between 14.04. and 31.10.2011.
Signal RS04 > $2\cdot10^{-4}$ Gy/s.
Red: Signal RS01 > $1\cdot10^{-2}$ Gy/s.
Gray areas around IRs are excluded from UFO detection.

Courtesy T. Baer

UFO Rate

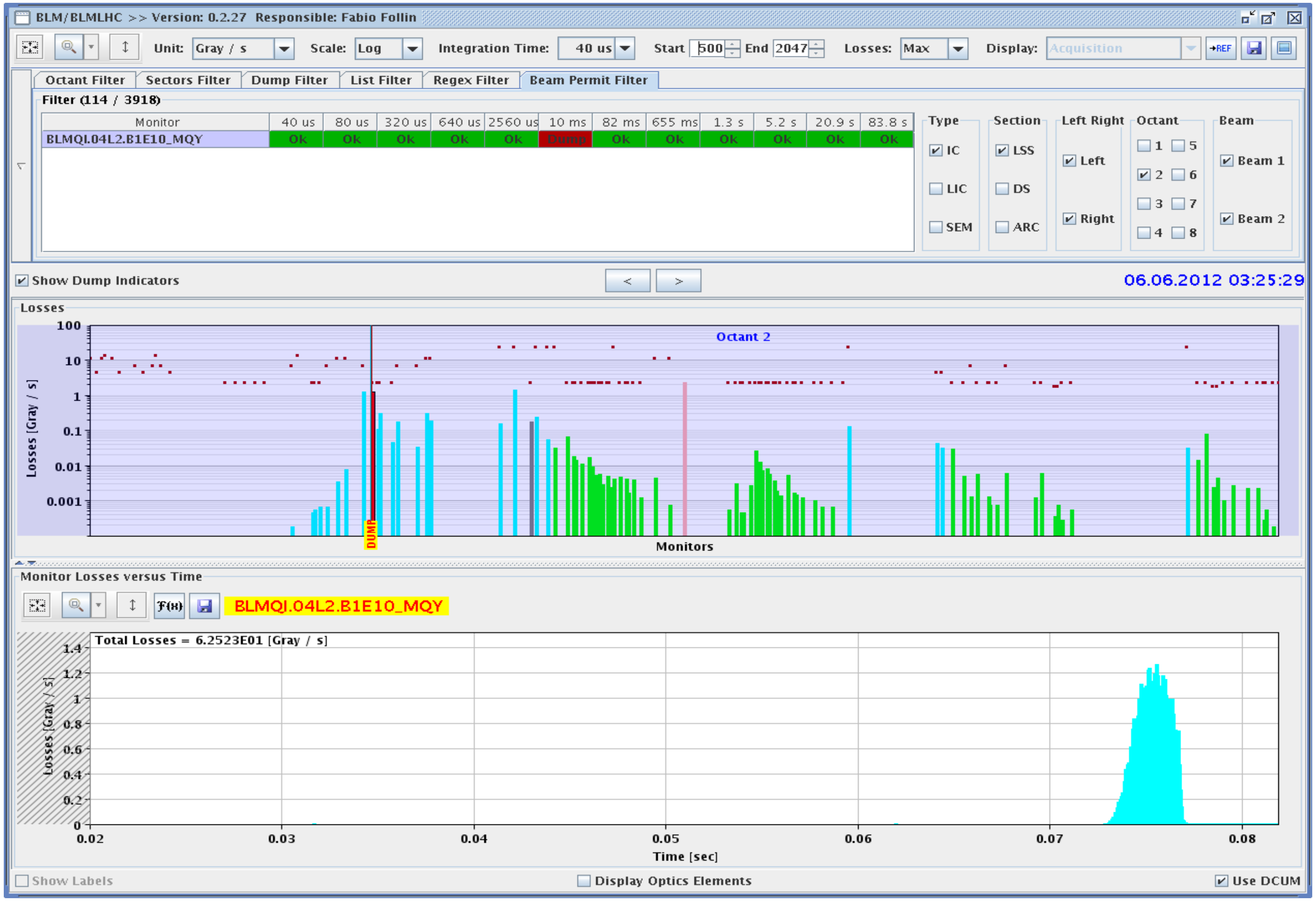


2011: Decrease of UFO rate from ≈10 UFOs/hour to ≈2 UFOs/hour.

2012: About 2-3 times higher UFO rate compared to October 2011.

UFO at injection

- Last night filling interrupted by UFO candidate in the MKI region during injection (300 ms after injection)



Radiation to electronics

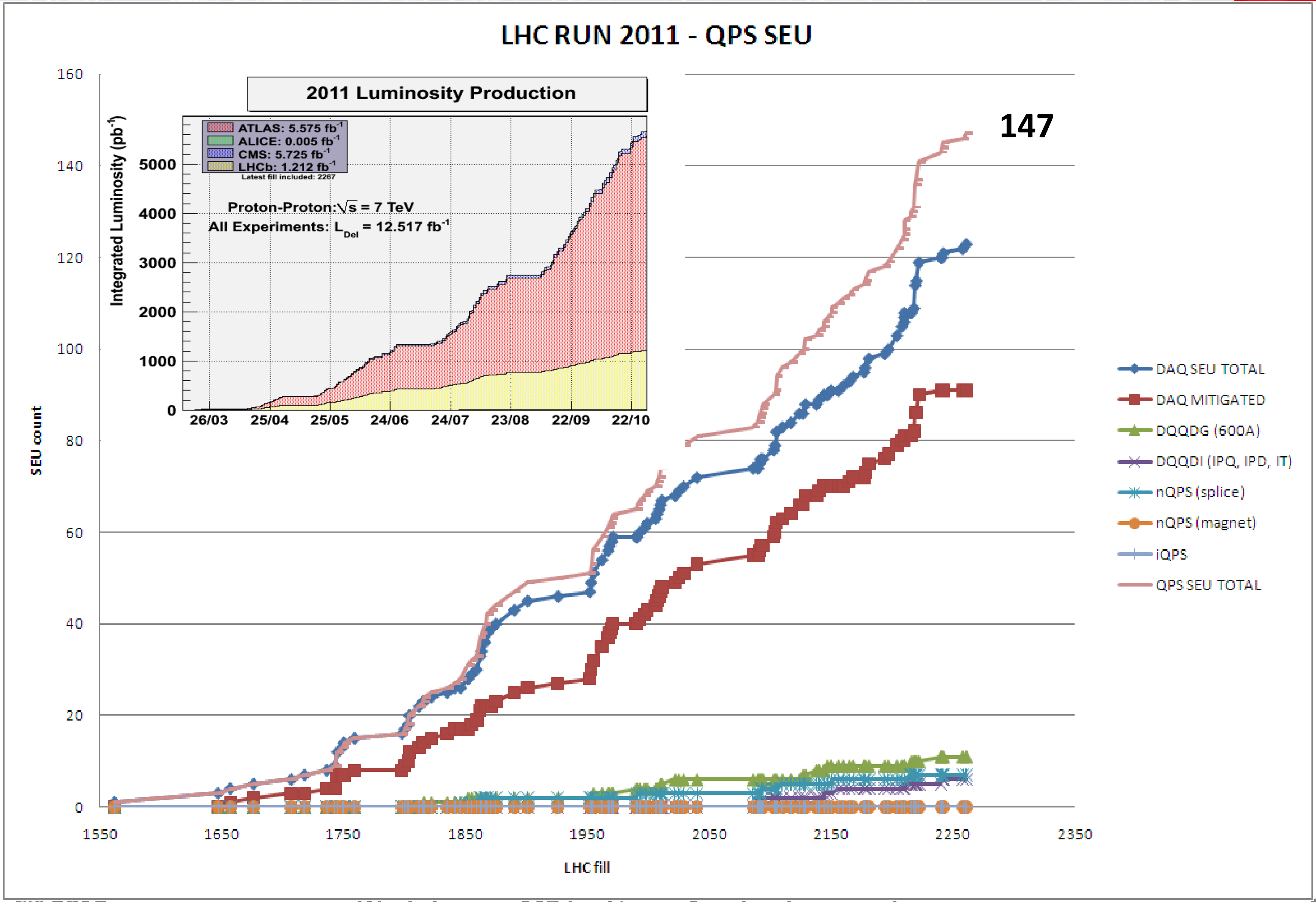
Courtesy M. Brugger

- In 2011: ~70 dump events due to SEU
  - Prediction in Chamonix 2011: 100
  - Good agreement if we consider on the fly mitigation
- Prevision for 2012: ~ 30-50 dump events expected
  - Increase in energy and bunch intensity
  - But mitigations actions: patch solutions for electronics, shielding and relocation for sensitive equipment

What do we expect for 2012

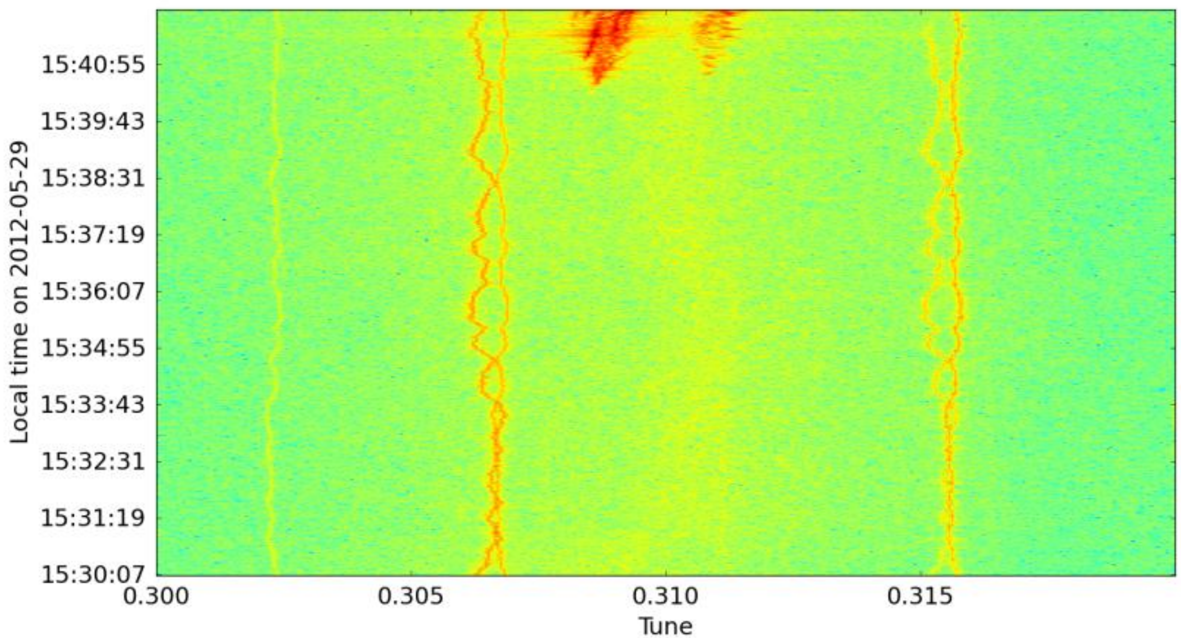
Affected Equipment Group	LHC Critical Areas	2011 #ofDumps	2011 #ofFailures	Estimated Downtime (partl. in shadow)	2011 Avoided SEE Dumps	2012 Expected Dumps (No Additional Mitigation)	2012 Estimated Dumps (With Mitigation)
QPS	Tunnel, UJs/RRs	23	140	~60 hours	150	69	~20
Cryogenics	UJs	25	48	~250 hours	~25	75	1-2
Power-Converters	Tunnel, UJs/RRs, UAs	13	15	~30 hours	few (FGC)	39	10-20
Collimation Control	UJs (P1/5)	6	8	~20 hours	-	18	7
B/P/WIC	UJs, US85	3	4	~15 hours	1-2	9	0
Access	UJs	-	~4-8	~10 hours	-	-	
EN/EL	UJ56, US85	2	3	~15 hours	-	6	~1
	Totals	**72**	**~220**	**~400h**	**~180**	**216**	**~30-50**

Radiation induced fault statistics 2011



An example of instabilities

- Just before going into collisions, 2 octupoles (out of 16) tripped at the end of the squeeze (one already missing)
- Octupole individually not linked in the beam interlock : beam not dumped
- Instability produced slow losses on beam 1 eventually dumping beam
  - 83.8 second running sum on TCLA.A7R7.B1
  - Sharp peak seen on beam 1 (and beam 2)



Conclusions

- Quick list of the different loss types observed in the LHC.
- Losses along the cycle under control: no beam induced quench above injection energy
- losses due to equipment failure caught by the BLM system
- Some surprises: UFO and SEU
- Worst case for injection failure = grazing incidence on the protection devices