What do we need to understand and optimize the LHC

O. Brüning

Potential Performance Limitations in 2011

- electron cloud effects → vacuum instabilities
  → cryogenic load
  → bunch spacing → beam scrubbing
- UFOs → fill abort and overall efficiency
  → beam scrubbing?
- beam-beam effects: → working point
  → collision patterns
- faults and overall efficiency: → average turnaround time
  → statistics

Electron Cloud Effects and Scrubbing

- First observations with bunch train operation (> 100)
  - ➔ pressure rise in common vacuum region
    - ➔ first indications of cleaning
  - ➔ instabilities & emittance growth at end of bunch trains (24 & 36)
    - ➔ can be stabilized by Q'
  - ➔ heat load increase in cold regions with trains of 50ns (24 & 36)
    - ➔ first indications of cleaning

104 - 8 bunch injection

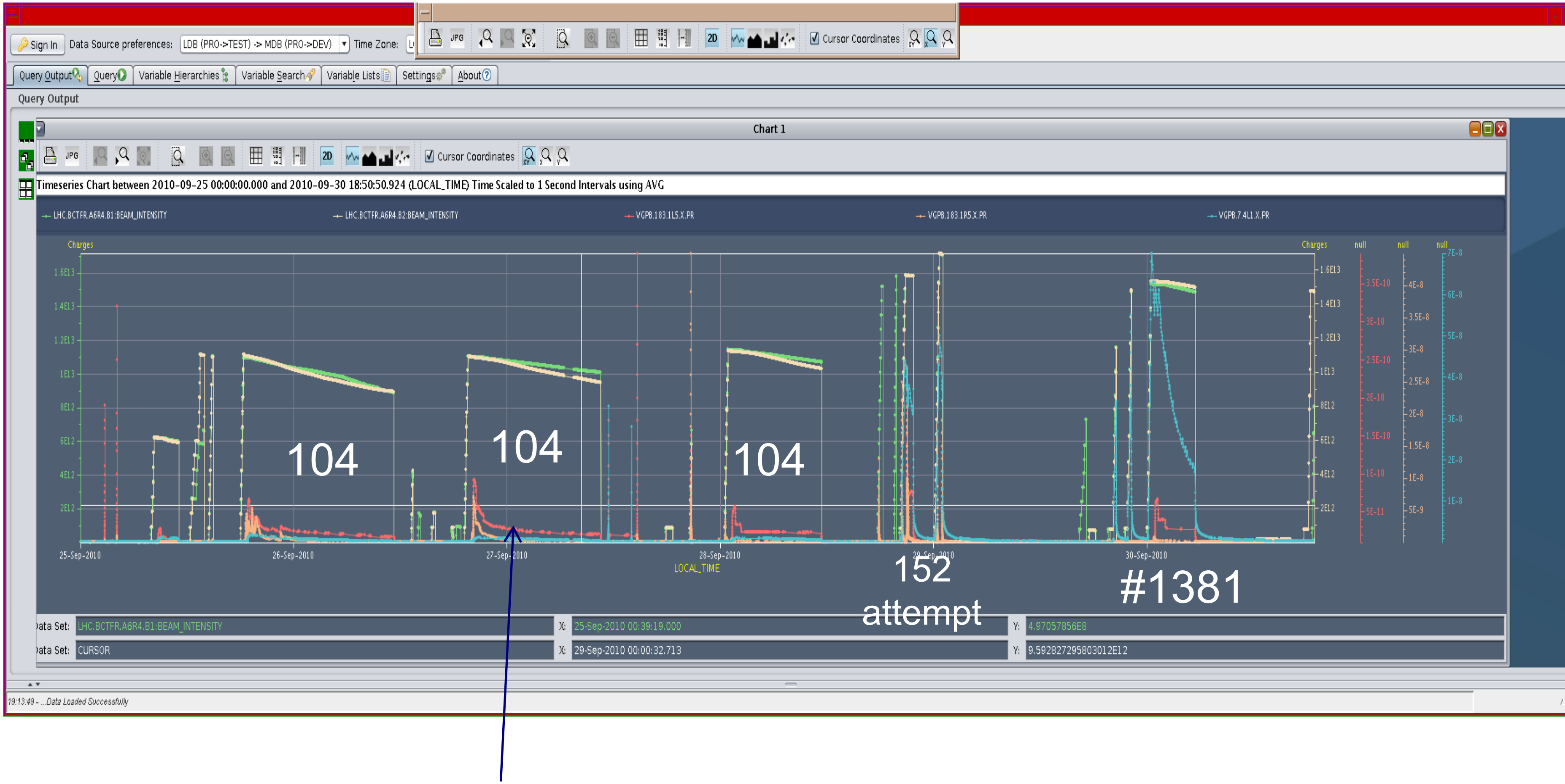
Pressure at Pt 1 from fill 1373

Relatively low increase in ramp

Gauges in question between DFBX & D1 around 58.8 m from IP

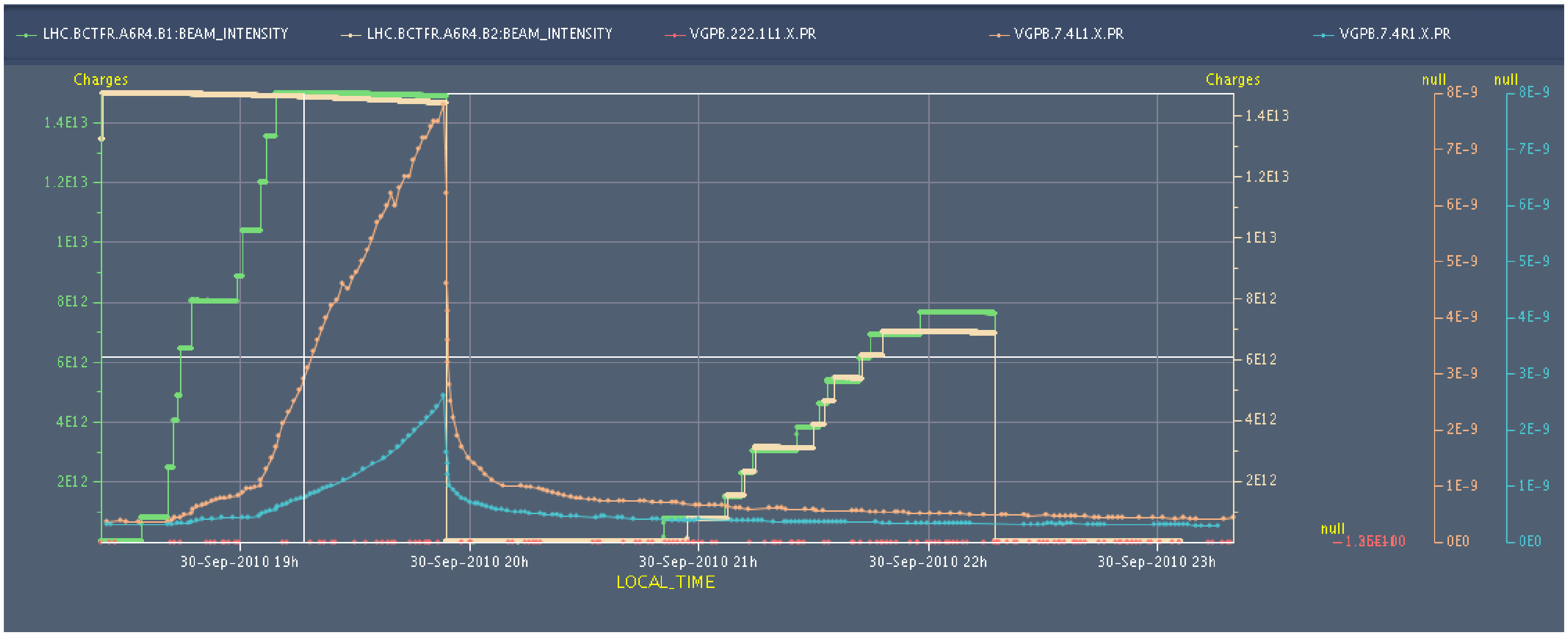
And wider context still

ML @ LHC 8:30 01.10.10



CMS

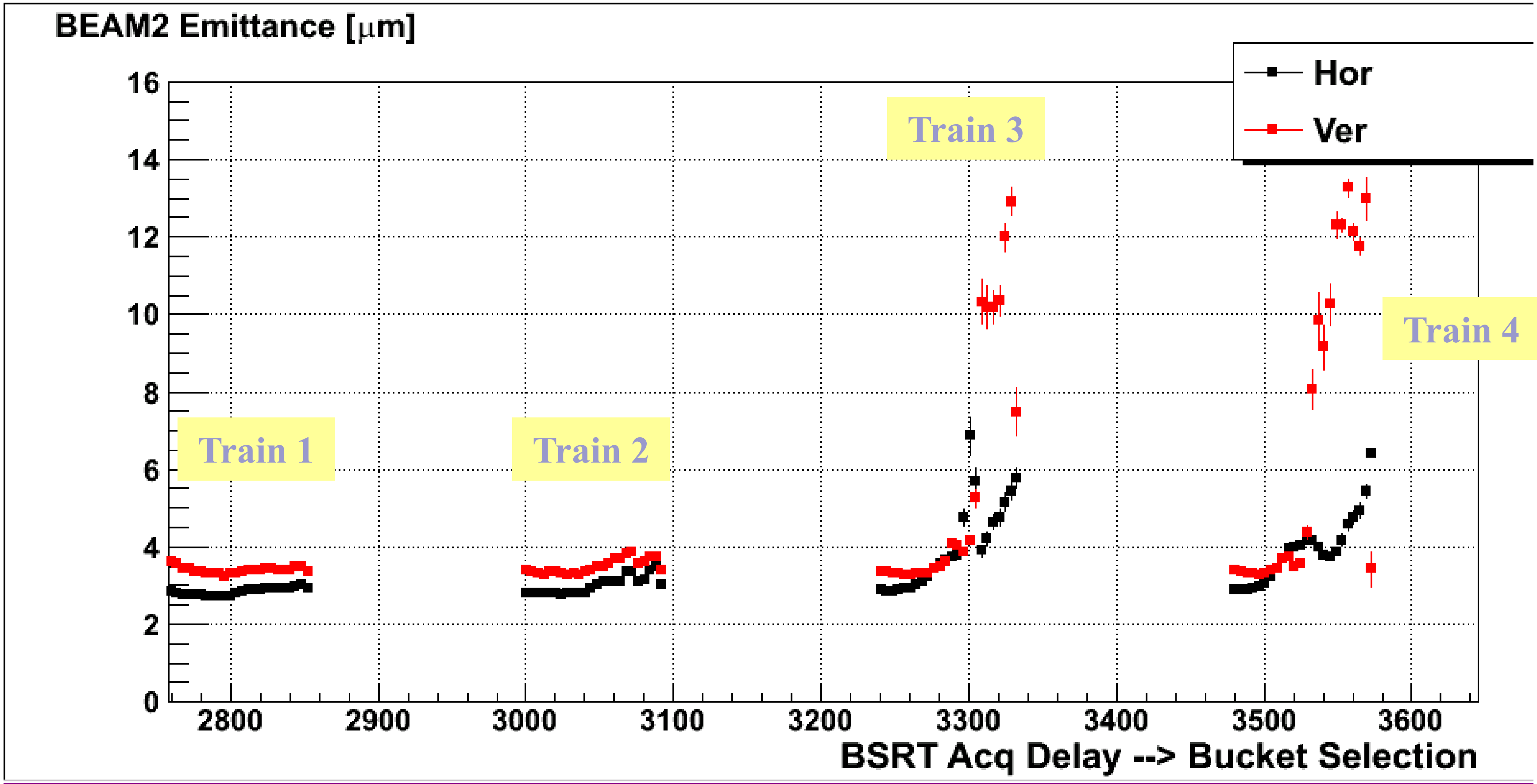
152 and then 104…



104 nothing

Emittances along bunch trains (24 b trains 8 μs)

JW @ LHC 8:30 08.11.10



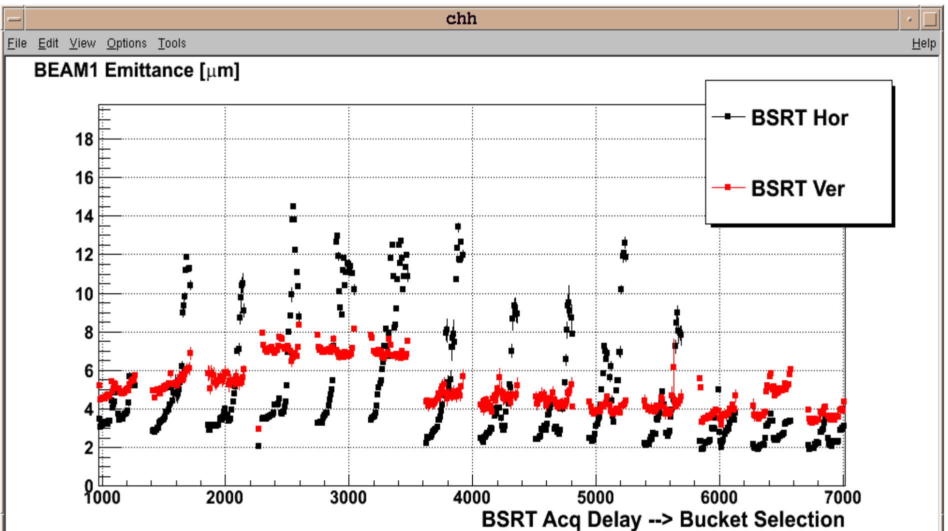
F. Roncarolo

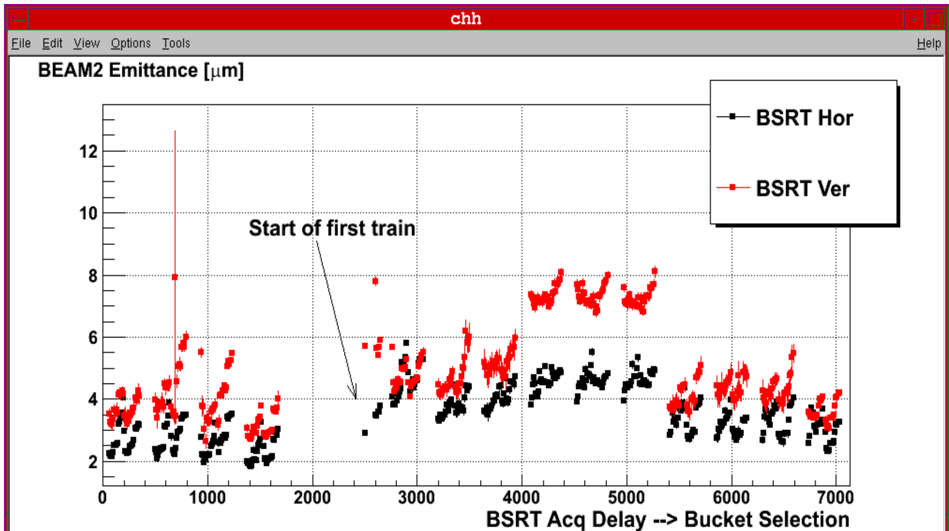
Emittances with 680 bunches

Not clear yet if really connected to e-cloud! Could also be coupled bunch

Time evolution being analyzed. B1 affected by H instability at the tail of each batch ➔ Stabilized by chromaticity ➔ data being analyzed to understand origin.

Bunch population = 0.9×10^{11} p - batch spacing 1.85 μs



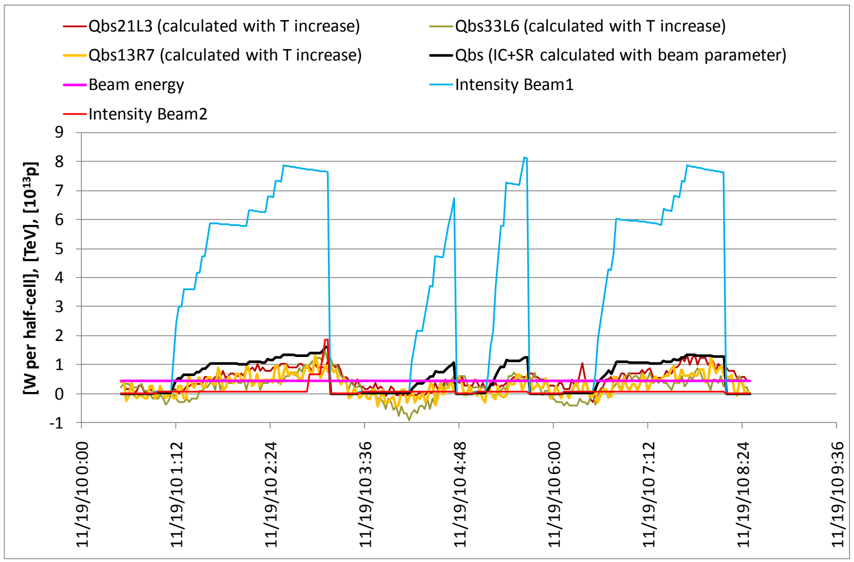


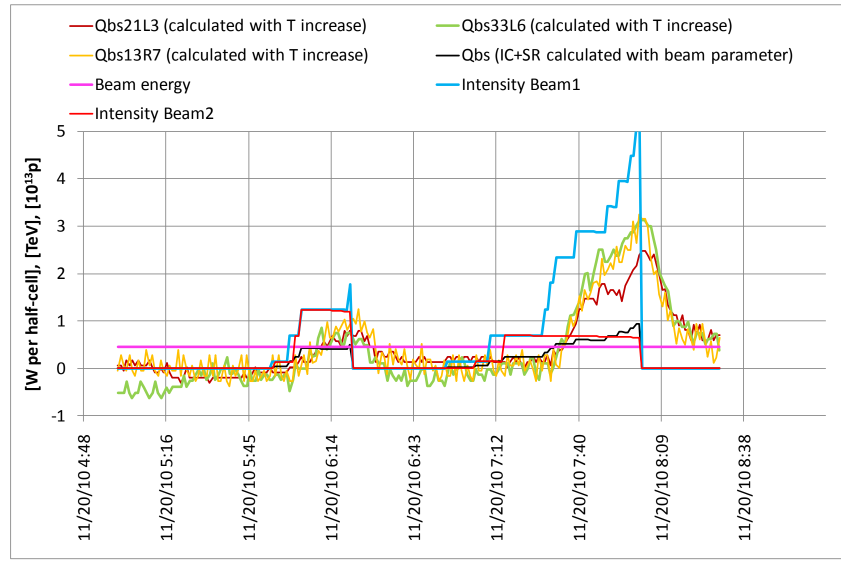
$Q'_{H,V}=14$ $Q'_{H,V}=24$ $Q'_{H,V}=24$ $Q'_{H,V}=14$

Cryogenics: 75 ns vs. 50 ns (see Laurent)

75 ns up to 824 bunches (Beam 1).

50 ns up to 444 bunches (Beam 1)



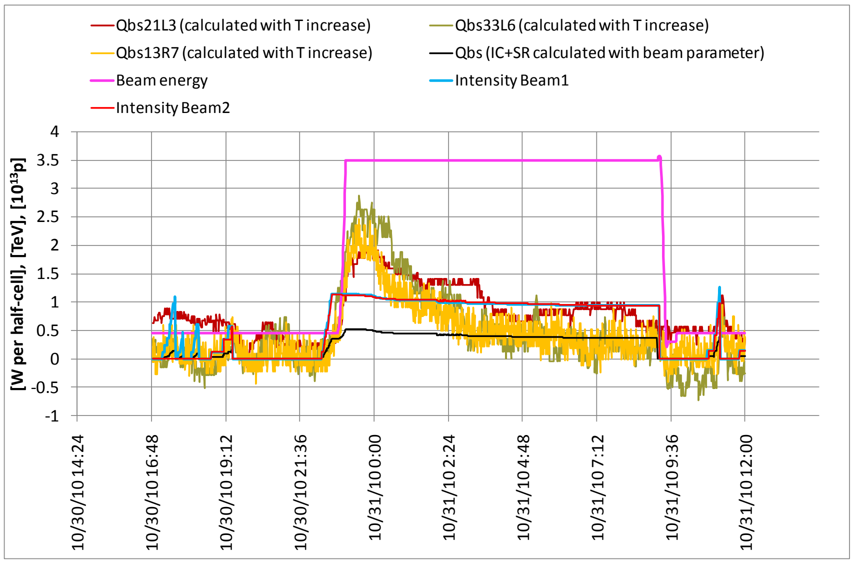


L. Tavian

For both beams significant heat load in the beams screens of the triplets-cold D1 region (particularly L8)

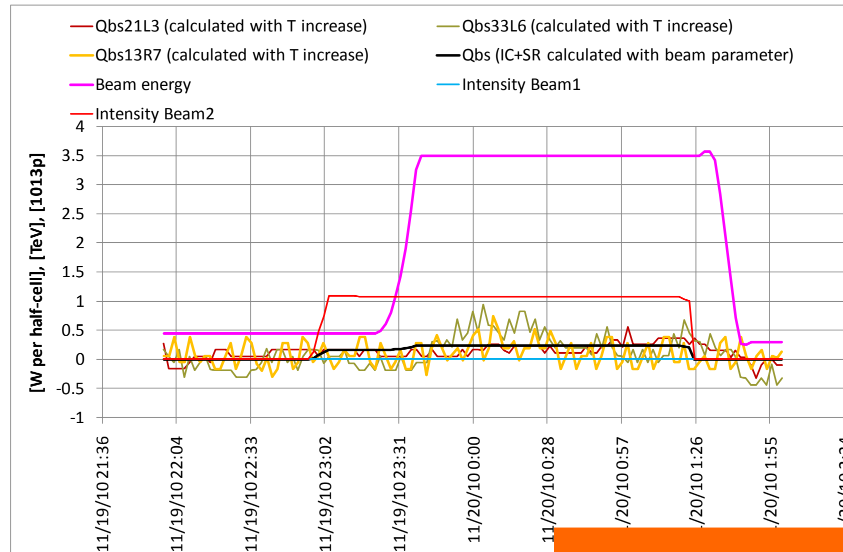
Effect of scrubbing

Before scrubbing (30/10): Heat load ~20 mW/m/beam



After scrubbing (19/11)

Heat load <10 mW/m/beam. Only B2



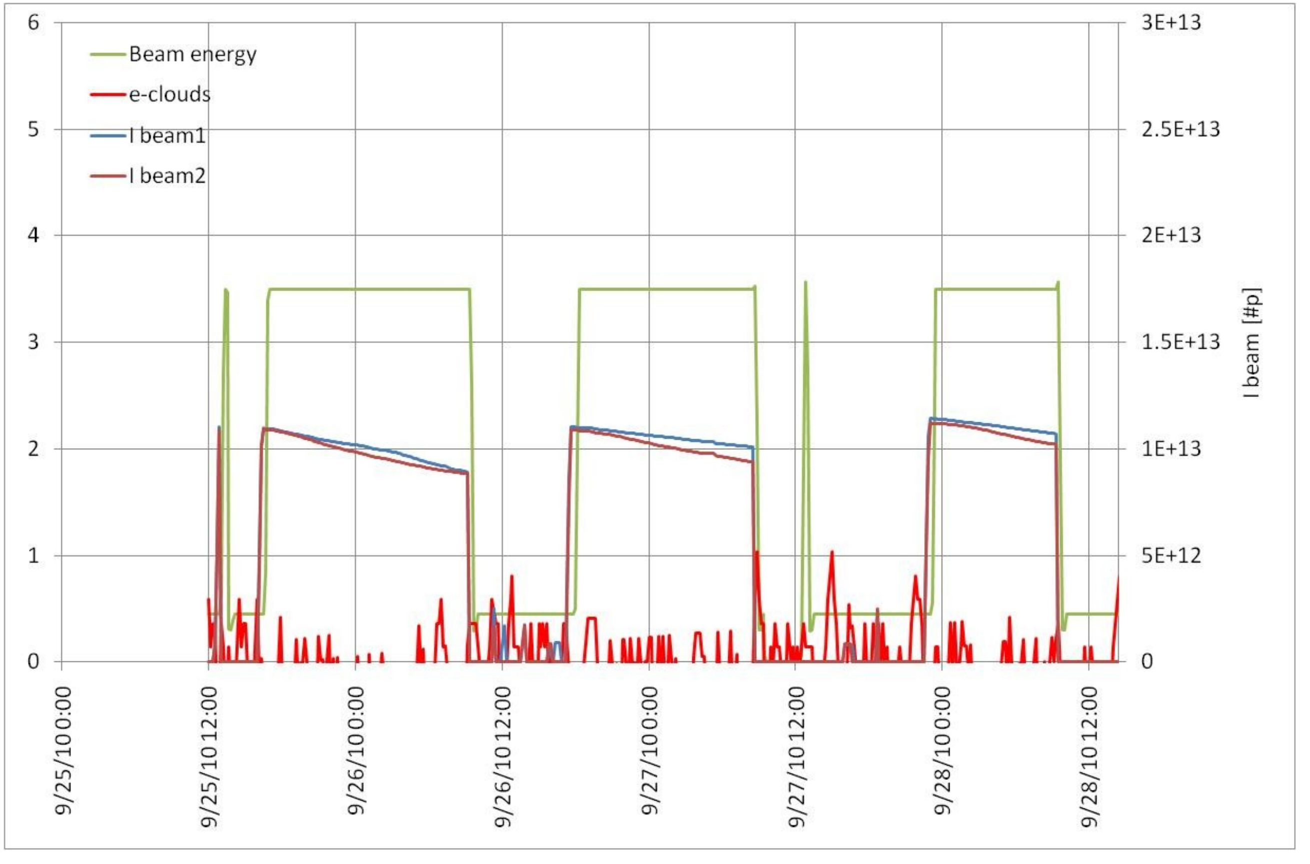
L. Tavian

Same filling pattern (9x12 b) and bunch population (~10^{11} p). Scrubbing at 450 GeV effective also for 3.5 TeV in the arcs

Comparison with RF measurements (stable phase – E. Shaposhnikova – preliminary results are encouraging)

Heat load on beam screens (33L6)

- Not seen during runs with 104 bunches per beam with 150 ns spacing for comparison.



L. Tavian

Monitoring for Electron Cloud Effects in 2011:

- Vacuum display: already available with logging
  ➔ but would be nice to have window with locations and vacuum values for top 10 pressure maxima

- Heat load display in cold sections:
  ➔ heat load per sector during scrubbing
    - ➔ can be generated offline but requires:
    - ➔ time correction for cryo heat reading
    - ➔ subtraction of non e-cloud heat load ($\propto$ beam intensity)
    - ➔ but would be nice to have an online display in order to adjust bunch intensity during scrubbing
    - ➔ required for robustness tests (e.g. orbit variations)

Monitoring for Electron Cloud Effects in 2011:

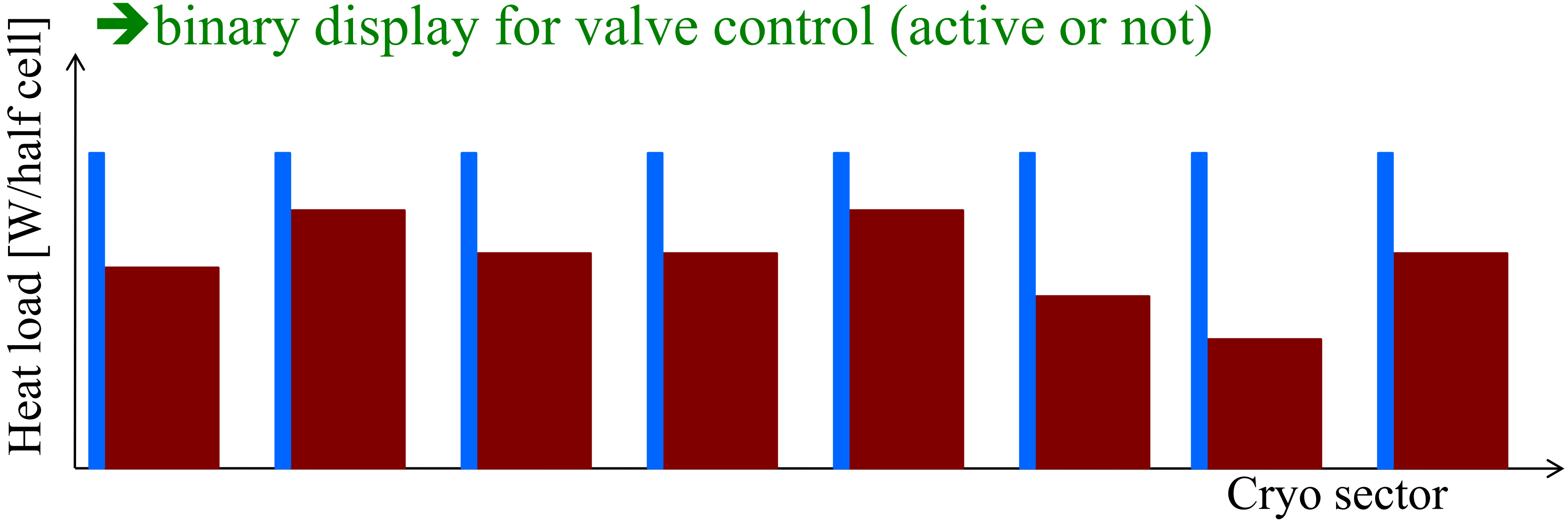
Heatload display:

monitoring of cryo load for all sectors
with possibility to reduce to e-cloud related contribution

➔subtraction of resistive wall and synchrotron light related load

➔only possible if valves are not in control mode: 15K – 20K
only possible for 'low' intensities

➔binary display for valve control (active or not)



Monitoring for Electron Cloud Effects in 2011:

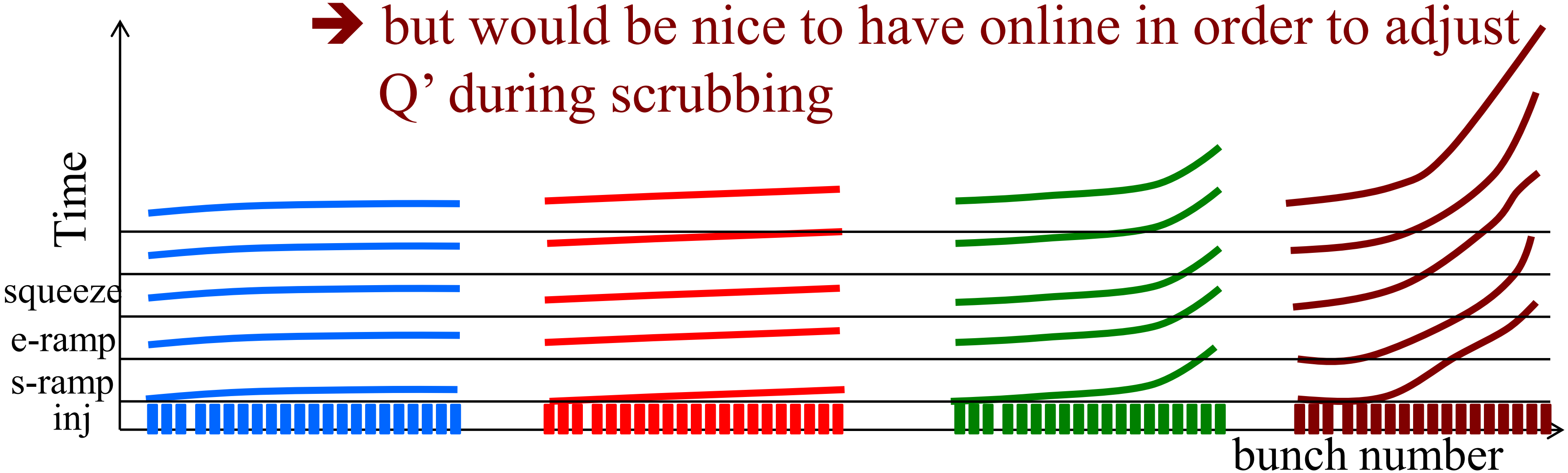
- Emittance display:

BSRT emittances and wire scanners available in TIMBER

➔But for bunch by bunch measurements and not easy to display when stored in vector format (Wire Scanners)

➔ differnce of bunch emittances ($\varepsilon(t) - \varepsilon^{inj}$) in mountain range

- ➔ vertical axis: $\Delta\varepsilon$ for time slices; horizontal axis: bunch #
- ➔ can be generated off line from TIMBER
- ➔ but would be nice to have online in order to adjust Q' during scrubbing

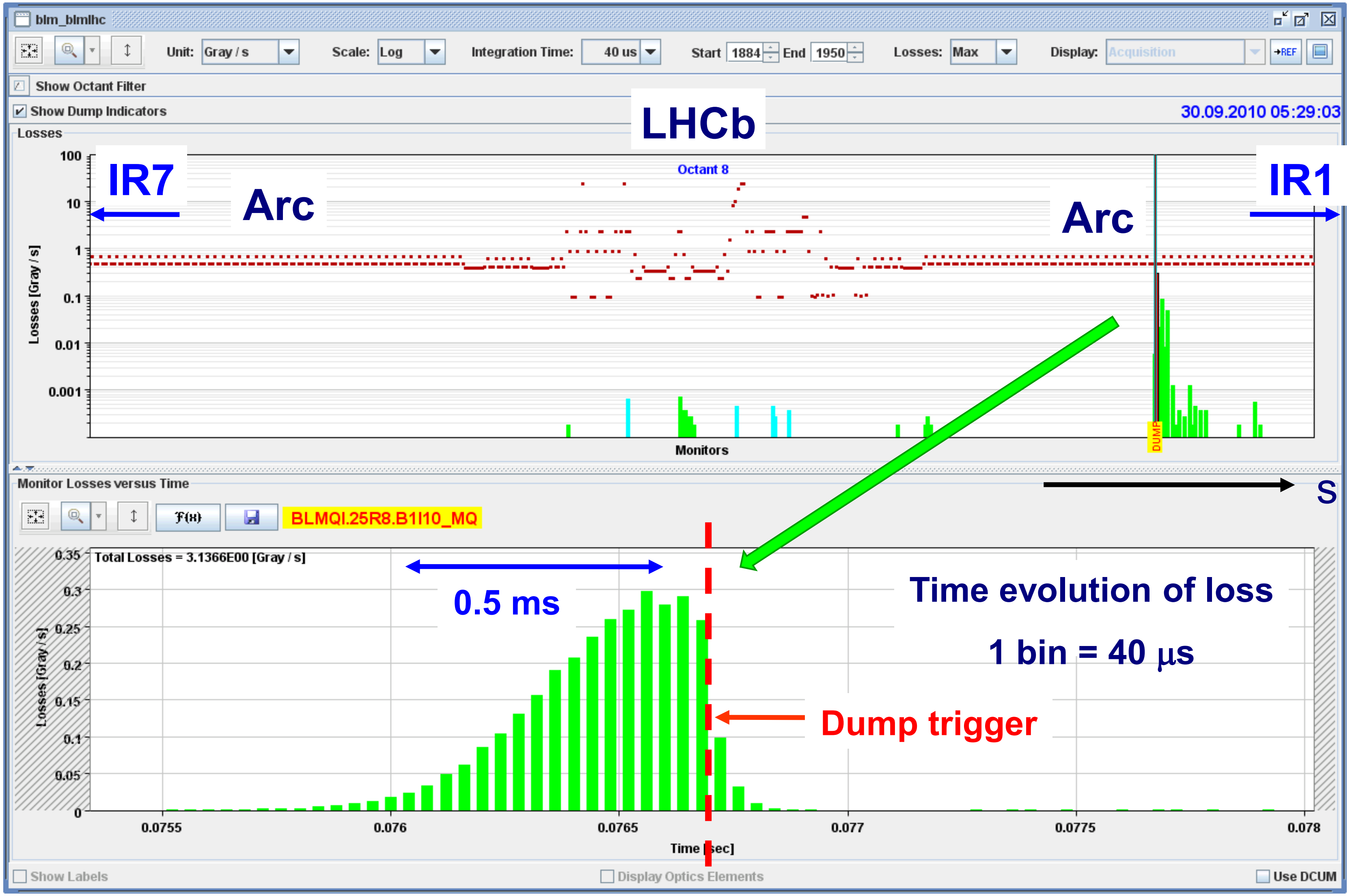


UFOs

- UFO dependencies:
  - ➔ rate proportional to total beam current (# bunches)
  - ➔ occurrence in all locations
  - ➔ most UFOS occur below BLM threshold
  - ➔ no UFOs observed at injection (even with 680 bunches)

UFOs: Unidentified Falling Objects

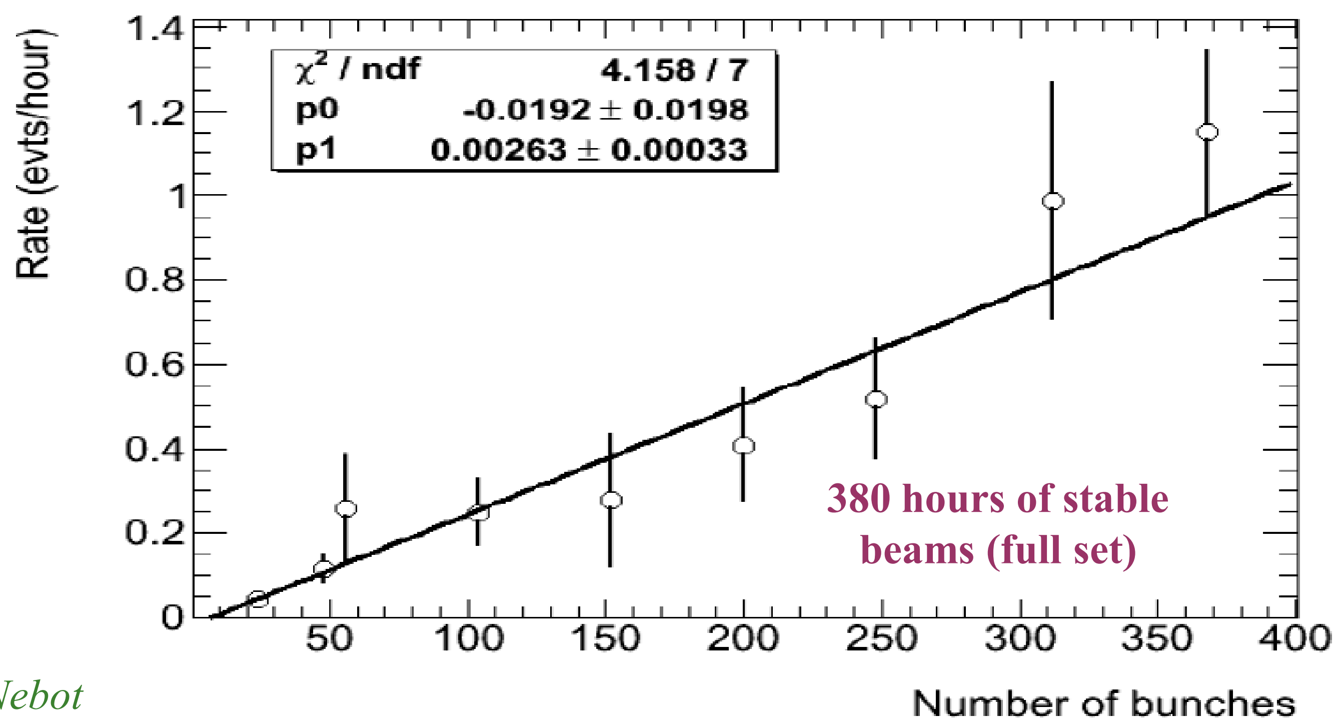
Beam loss monitor post-mortem



UFOs

JW @ LMC 1.12.10

- UFO dump count now 18.
  - ***UFOs have reappeared despite threshold increase.***
  - *2 UFO dumps triggered by exp. BCMs (LHCb, ALICE) and not by machine BLMs.*
- UFO rate at ~ 1 event/hour with 360 bunches at 3.5 TeV.



E. Nebot

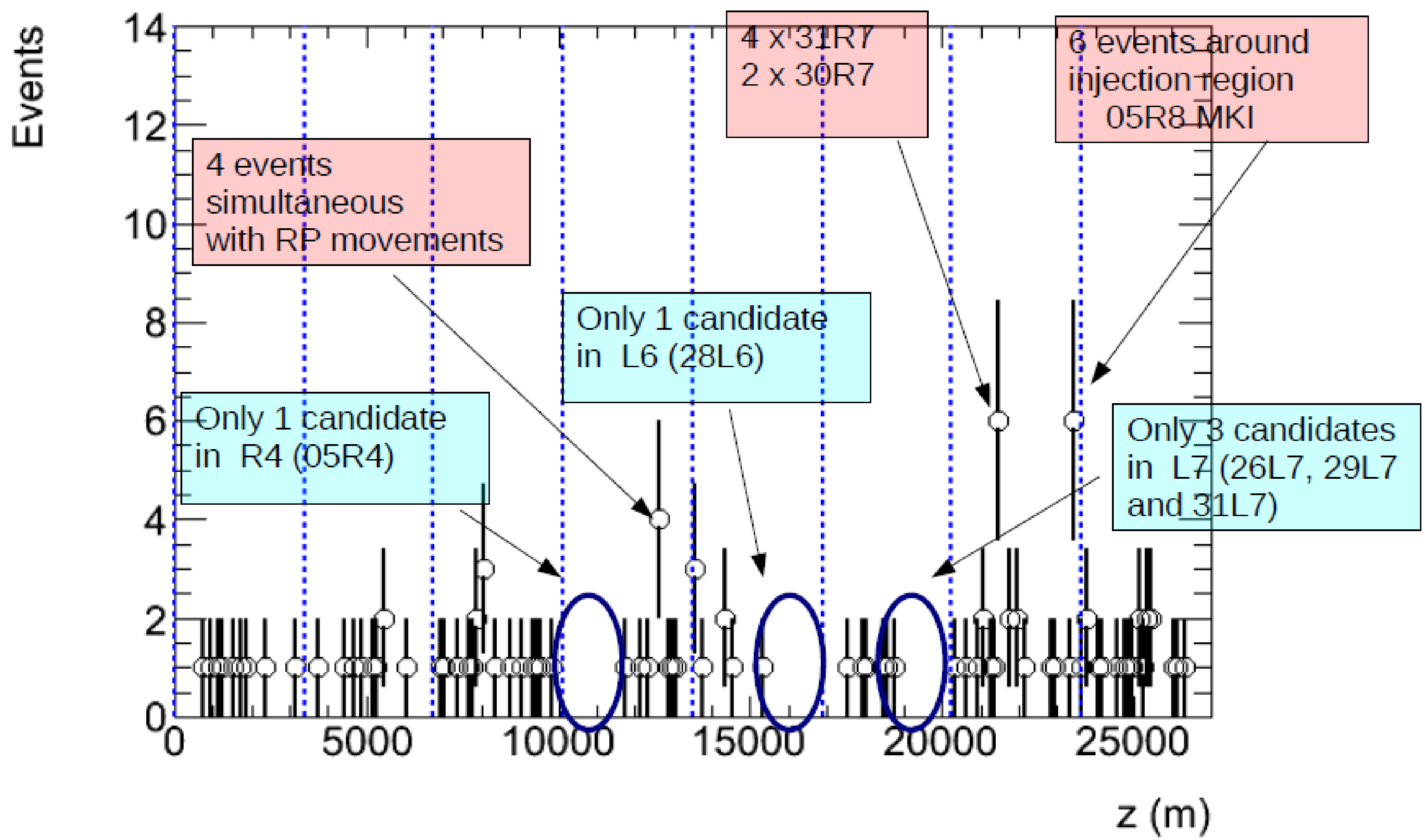
UFO distribution

JW @ LMC 1.12.10

- Structure significant ?

E. Nebot

Histogram => 100m/bin

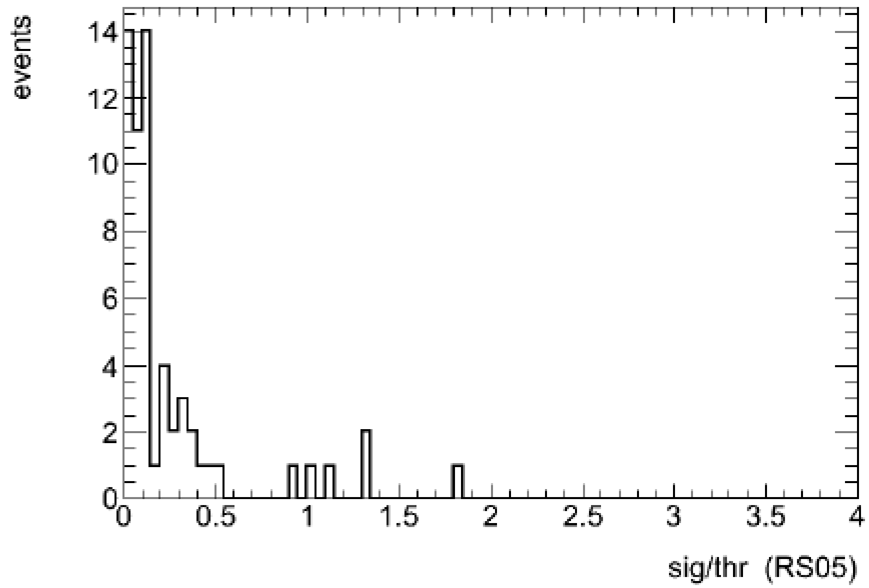


UFOs

JW @ LMC 1.12.10

- Most UFOs clustered at low loss.

E. Nebot



- No UFOs observed at injection, even with 680 bunches / beams.
- No UFOs with ions.
- 3.5 TeV quench test analysis ongoing (loss map simulations etc) – more news in a few weeks.

UFO Monitoring

- Online UFO display:
  - ➔ Simple counter of # of UFO events over a fill
    (even if losses are below BLM threshold)
    Expect ca. 1 to 2 UFOs per hour for 2011 operation!
    ➔ 10 to 20 per fill and 200 to 300 per week
  - ➔ Ratio of observed losses over BLM threshold (0.5ms?) per incident with captures display of all UFOs
  - ➔ Histogram of loss location along the machine; integrated over full run (color code per month or week?)

  ➔ could help observing if UFOS occur during scrubbing (inj!)
  ➔ could help observe patterns of occurrence (or cleaning)

Beam-Beam

- Beam-Beam:
  - ➔ Tune shift and spread proportional to N_b; $1/\varepsilon_n$; # collisions
  - ➔ drives non-linear resonances
  - ➔ tune varies over a fill as function of bunch intensity

LHC Challenges: Beam-Beam Interaction

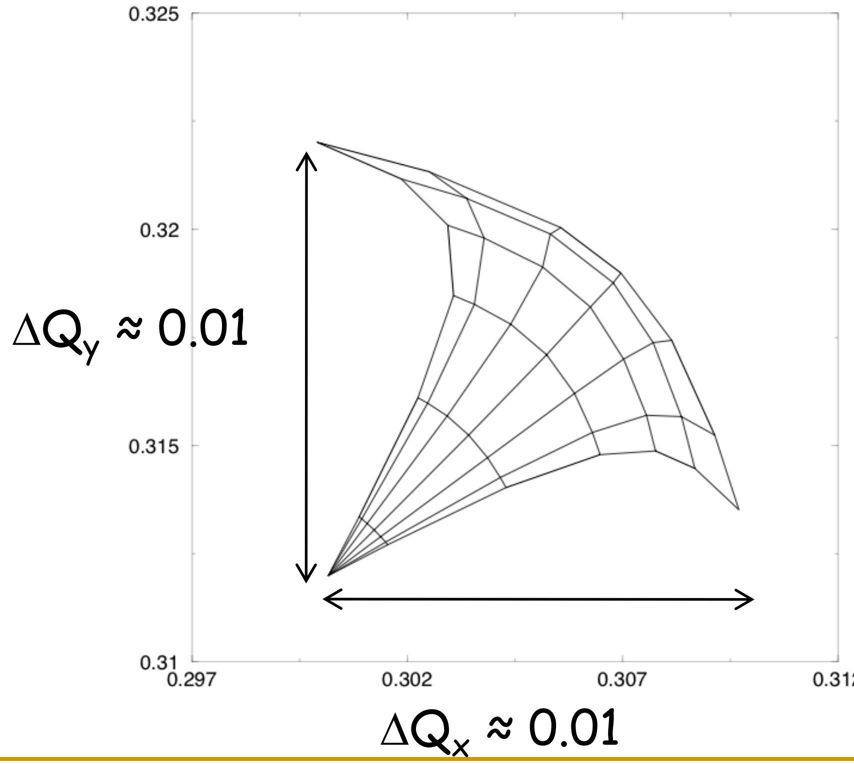
- Tune spread due to head-on beam-beam interaction:

$$\Delta Q = \frac{r_p}{4\pi} \cdot \frac{N_b}{\varepsilon_n} = \xi_{beam-beam}$$

- Tune Footprint:

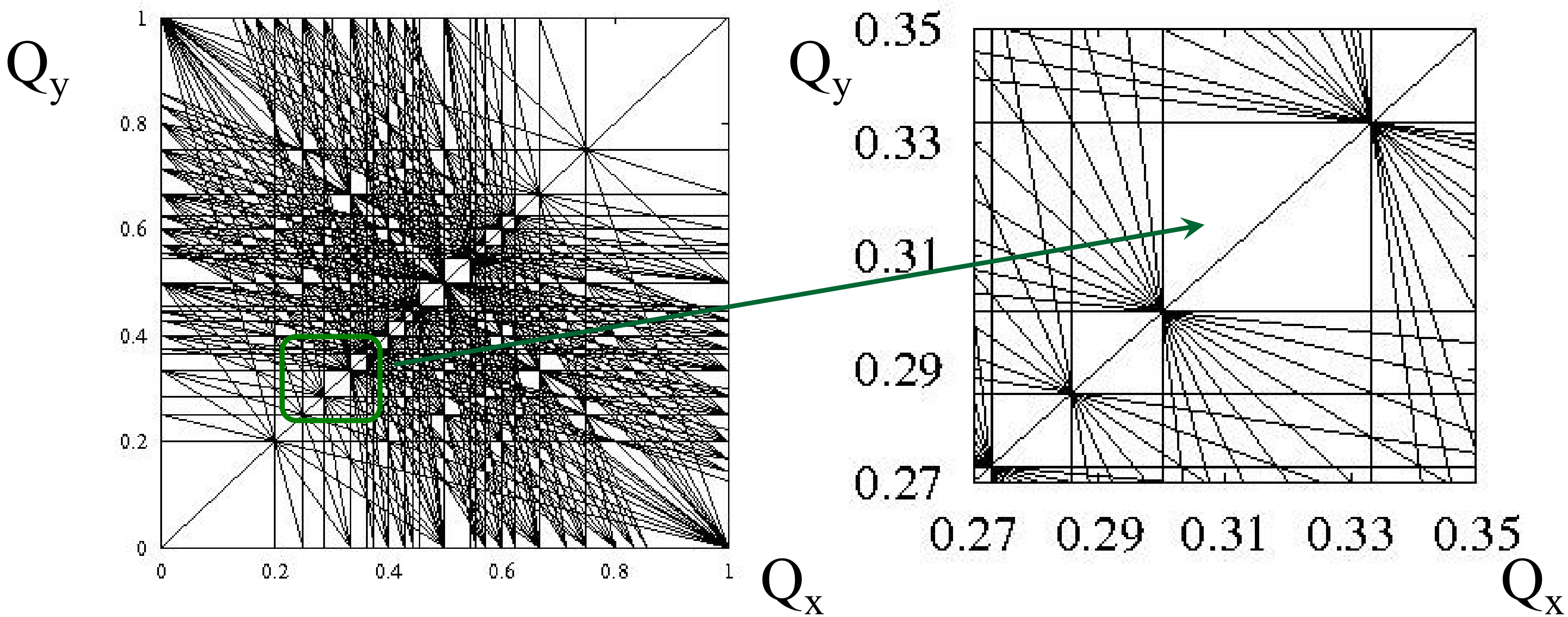
  nominal beams
  all insertions
  Head-on &
  Long range

  Werner Herr



LHC Challenges: Single Particle Stability

- **tune:** Q = number of oscillations per revolution
- **resonances:** $n\,Q_x + m\,Q_y + r\,Q_s = p$; "order" = n+m+r

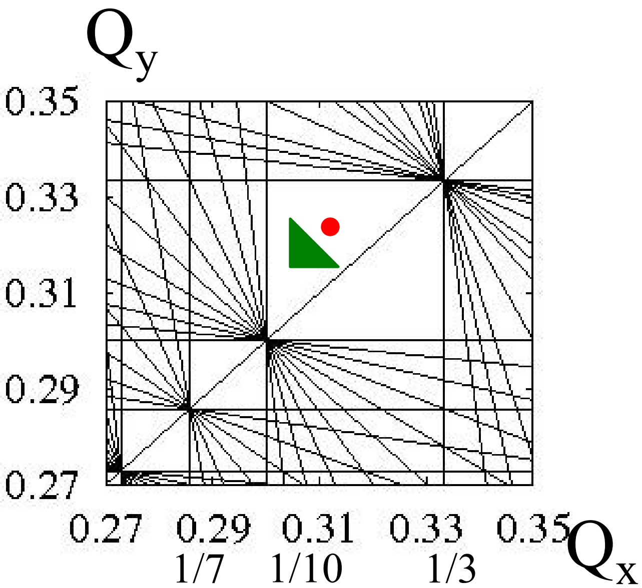


SppS experience:

➔ working point must stay clear of resonances of order 13 or lower!

LHC Challenges: Beam-Beam Interaction

- LHC working point: n+m < 12



→ $Q_x = 64.31; Q_y = 59.32$

total tune spread must be smaller than 0.02 (SppS experience)

keep $\delta Q = 5\ 10^{-3}$ for operation tolerance!

keep $\delta Q = 5\ 10^{-3}$ for other contributions

- bunch intensity limited by beam-beam force:

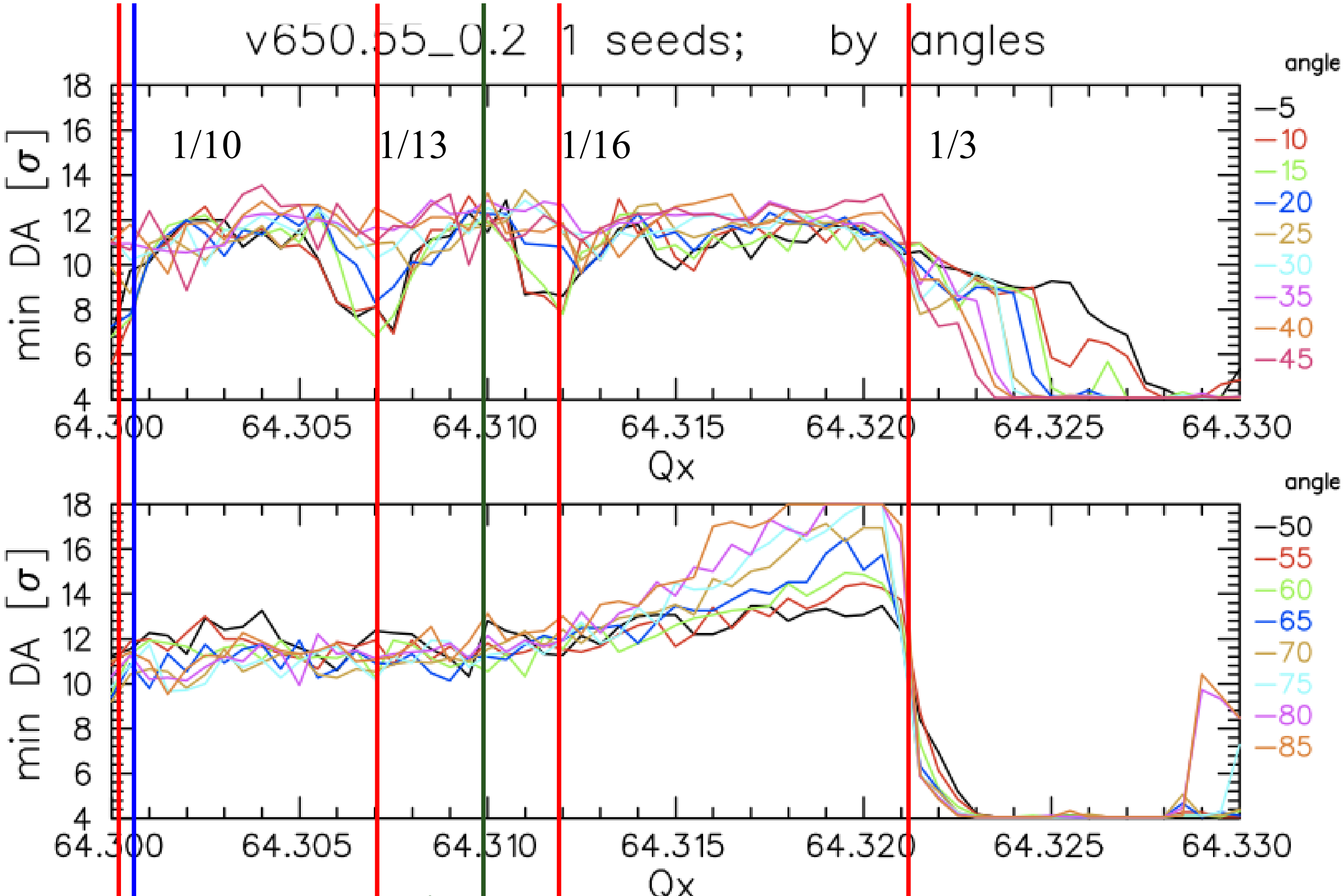
3 head-on/bunch ➔ $\xi_{beam\text{-}beam} < 3.3\ 10^{-3}$ ➔ $N < 1.2\ 10^{11}$

2 head-on/bunch ➔ $\xi_{beam\text{-}beam} < 5\ 10^{-3}$ ➔ $N < 1.7\ 10^{11}$

LHC Challenges: Beam-Beam Interaction

- DA from simulations:

Werner Herr & Dobrin Kaltchev



with b-b and ξ_{tot} = 0.01 nominal tune

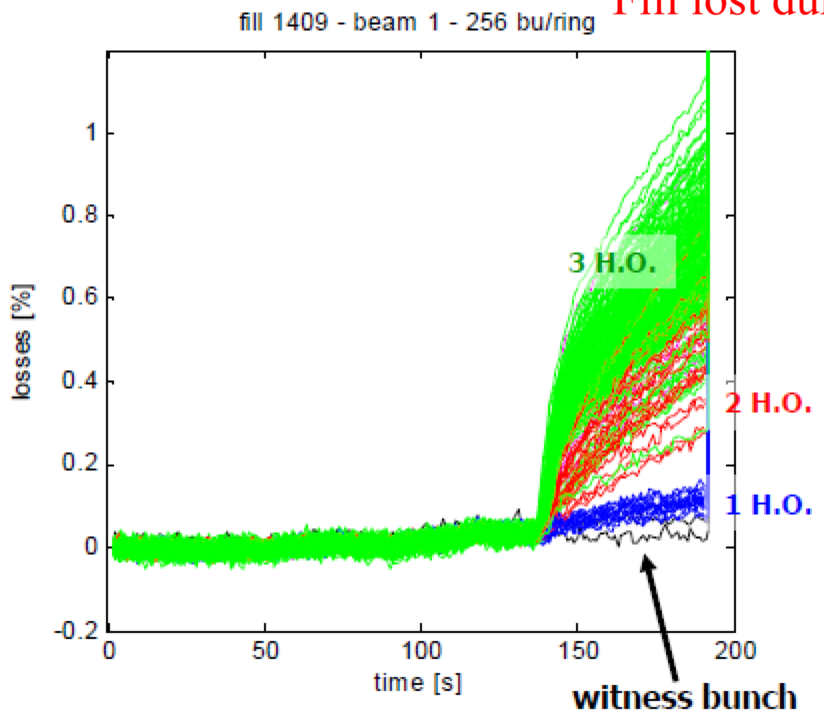
Beam-Beam: Bunch by bunch

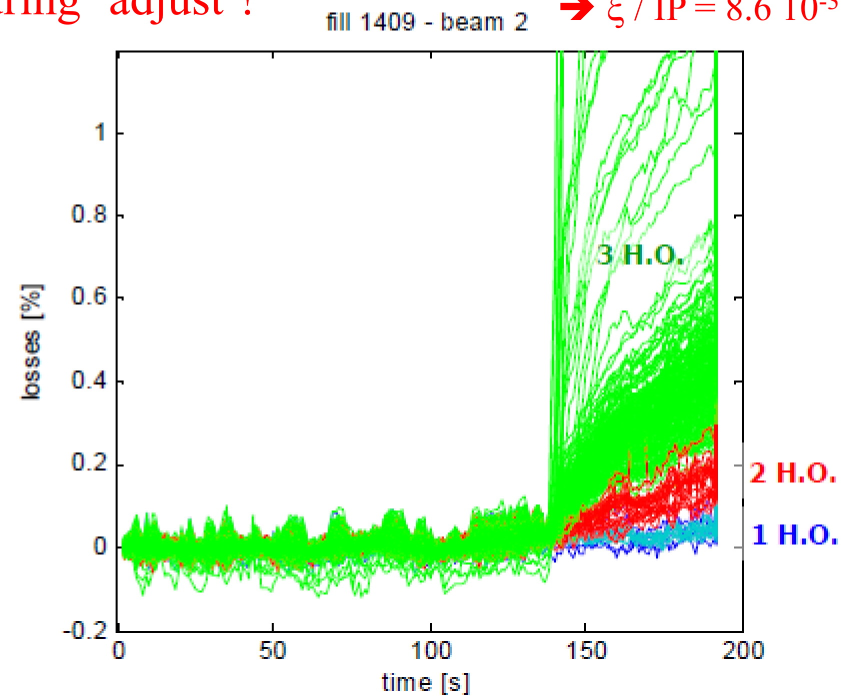
Fill 1409: 12.10.2010

$\varepsilon_n = 1.4\ \mu m$; $N_b = 10^{11}$; 256 bunches

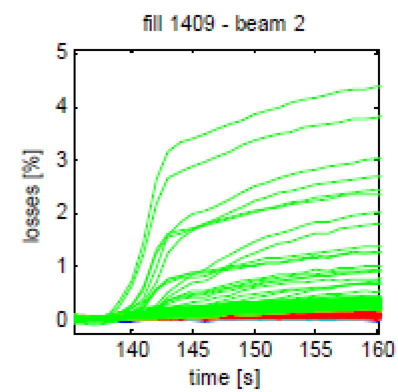
Fill lost during 'adjust'!

➔ ξ / IP = 8.6 10^{-3}





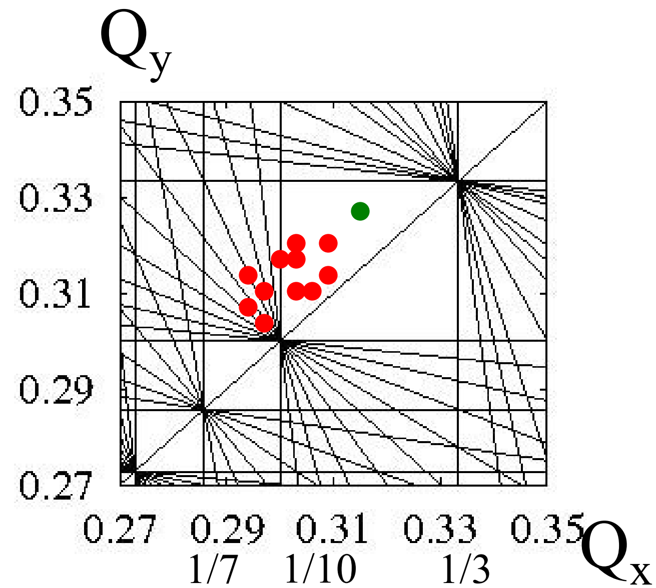
- beams dumped right after colliding (~1 minute)
- clear dependence of losses on number of H.O. collisions
- some bunches b2 lose up to 5% in the first few seconds
  - 12 out of 14 biggest losers from first 3 16-bunch injections
    - 10th 11th 12th 13th in the 16-bunch train



IPs: 1 5 2 8 - 1 5 8 - 1 5 2 - 1 5 - 2 8 - 8 - 2

giulia papotti (BE/OP/LHC)

Beam-Beam Monitoring



- Online Beam-Beam display:
  - ➔ Tune diagram with injection and bunch tunes based on ε_n and N_b numbers
    - ➔ could help to adjust tune before bringing beams in collisions
  - ➔ Tune diagram with injection and measured bunch tunes (Schottky?)
  - ➔ could help to optimize the tunes during a lumi fill

  - ➔ Offline display of losses per collision pattern (Giulia plots)
  - ➔ combined information with specific luminosity per bunch
  - ➔ can help to optimize overall machine setup and fault analysis (➔ TIMBER)

Beam-Beam: long range beam-beam

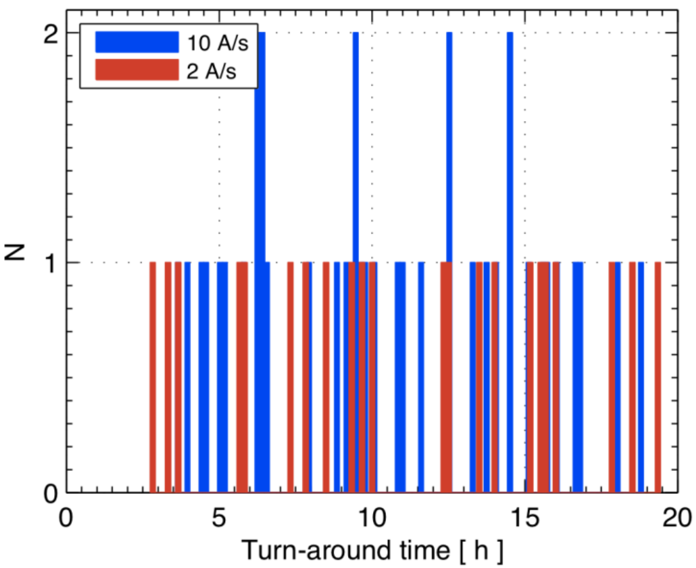
Tune and Closed orbit variations along bunch train:

Werner Herr

- ➔ large number of different collision classes
- ➔ depends on long-range collision pattern (norm. separation)
- ➔ CO variations of +/- 2 micrometer (+/- 15% rms beam size)
- ➔ Bunch-by-bunch orbit and Q measurements are essential for understanding the long-range beam-beam effects (β^* & x-in angle)

Performance Monitoring

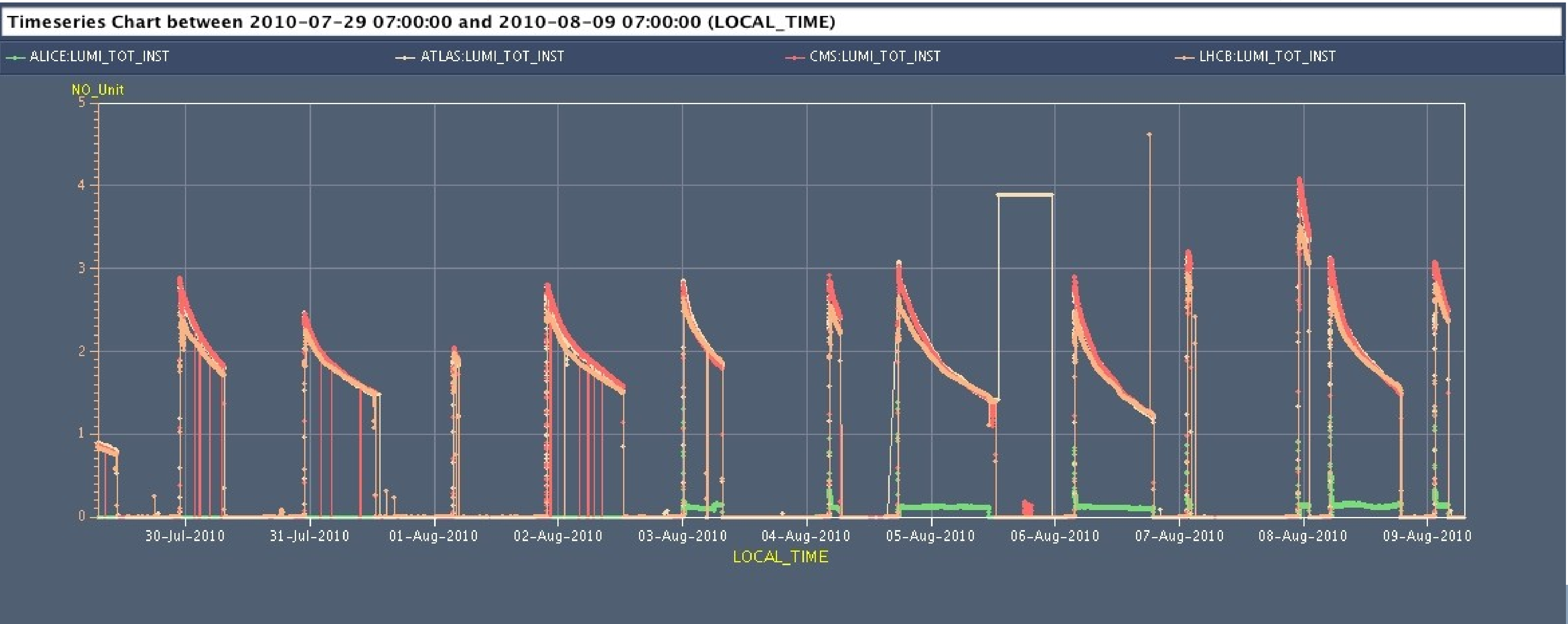
- Online Statistics (spread sheet?):
  - ➔ cumbersome to generate ‘by hand’ from Timber
  - ➔ could be filled as standard procedure for each fill
  - ➔ can help monitoring performance evolution and giving performance projections
- Minimizing the Turnaround time:
  - ➔ large spread in performance
  - ➔ logbook ‘Beam’ entries not concise (whole day marked as SU)
  - ➔ detailed analysis cumbersome!
  - ➔ markers in logbook?



Stefano

Week 31

- Operation with Multi-bunch Injection since Thursday 29.07:
  - 13 fills with up-to 120 nb^{-1} per fill ➔ 109 h of luminosity production
    ➔ ca. one fill per day; peak luminosity: L = 4 10^{30} cm^{-2} sec^{-1}
  - average fill time of ca. 9 hours (10, 9, 14, 1, 15, 7, 2, 17, 15, 0.5, 2, 14, 2.5)
  - integrated luminosity: 730 nb^{-1} (40, 60, 80, 8, 100, 60, 20, 120, 90, 8, 23, 95,25)
  - ➔ ca. 56 nb^{-1} /fill; ➔ average luminosity per fill: L = 1.7 10^{30} cm^{-2} sec^{-1}
    ➔ ca. 40% efficiency (wrt to scheduled time); ➔ total luminosity ca. 1080 nb^{-1}



Week 31

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Total
Dump events	Access system fault Pt2	S23 tripped; SIS interlock; Access system Pt1		EOF; PC trip;	EOF; BLM	BLM	Cryo; QPS	
Fauls & Interventions	3h Set Up; 3h Access System	5.5h QPS circuit braker; 2hSet Up; 1h BLM Sanity Check; 2.7h Beam Quality Injectors;	3h Set Up; 1h Access System; 0.5h BLM;	3h Set Up; 3h Access	2h Setup; 5h QPS & FGC and Access	10.5h QPS & FGC (Access); 2.5h Set Up	1.5h Cryo; 1.5h Set Up; 3h QPS	
Time without Beam [h]	**6**	**10.2**	**4.5**	**6**	**7**	**13**	**6**	**48.2**
Time ready for beam [h]	**18**	**13.8**	**19.5**	**18**	**17**	**11**	**18**	**119.8**
Physics [h]	**12**	**2.5**	**13**	**7**	**11.5**	**3.5**	**14.5**	**64.5**
Efficiency *LHC Ready*	**67%**	**18.12%**	**66.67%**	**38.89%**	**67.65%**	**31.82%**	**80.56%**	**55.51%**
Efficiency *Scheduled time*	**50%**	**10.42%**	**54.17%**	**29.17%**	**47.92%**	**14.58%**	**60.42%**	**38.10%**
Comments		Test ramp with 2 nominal bunches	Time invested for injection setup	Test ramp with 2 nominal bunches				

For periods without studies: ca. 63% efficiency relative to available beam time

ca. 45% efficiency per scheduled time

Performance Monitoring

- Statistics: simple summary sheet per fill
  - ➔ n_b; N_b; and emittances at injection and start of collision
  - ➔ initial luminosity (or maximum)
  - ➔ final luminosity before dump
  - ➔ fill length and time to previous fill
  - ➔ dump reason (operator versus fault)
  - ➔ 'Hump' active or not; frequency on β-tron frequency or not

- Statistics: online summary of run performance
  - ➔ number of fills per week
  - ➔ efficiency: time ready for beam, time wo beam; physics
  - ➔ luminosity per fill (peak & integrated)
  - ➔ turnaround times between fills

Performance Monitoring

- Minimizing the Turnaround time:
  - ➔QPS interventions: ca. 1.6 interventions / day [JPT @ LMC 1.12.]
  - ➔Routines for QPS resets by LHC operators? (could save expert call)

- Emittance monitoring:
  - ➔Bunch by bunch measurements are vital:
    - ➔ $n_b * \langle N_b \rangle / \langle \varepsilon_n \rangle \neq \Sigma_i\, n_{bi} * N_{bi} / \varepsilon_{ni}$
  - ➔Routines for continuous comparison of injector beam quality and LHC injection values (bunch by bunch for each batch)
  - ➔can help in injector-LHC setup monitoring (robustness)
  - ➔time evolution of emittances versus time (e-cloud scrubbing)
  - ➔specific luminosity versus time
  - ➔Flags / Statistics for 'Hump' activity (strong; not present; normal)
    - ➔statistics can help for establishing correlations

Timber Tools

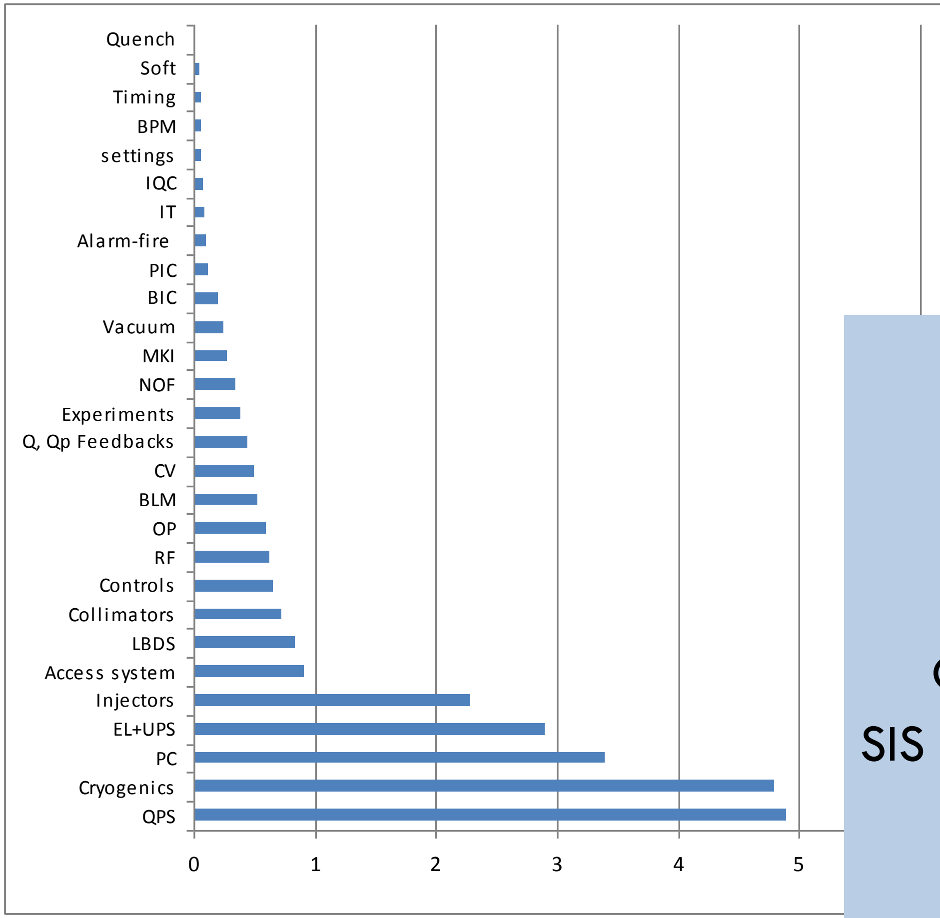
- Data analysis:
  - ➔ Possibility for cross correlation of different variables (so far all variables can only be displayed as function of time)
  - ➔ Functionality for displaying vectors?

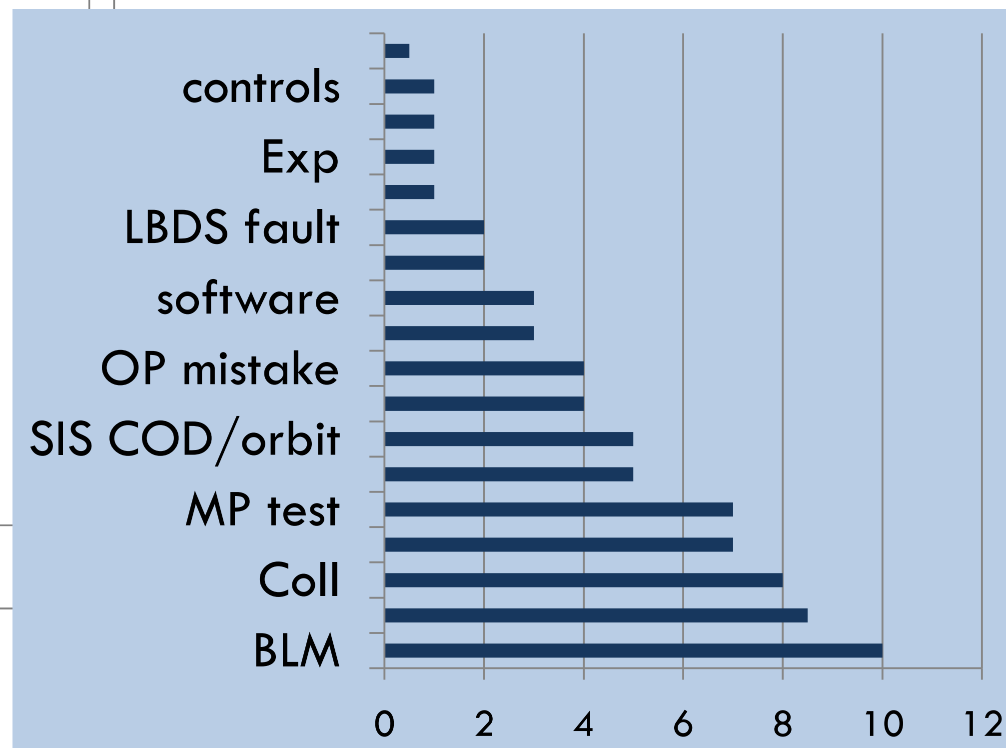
- General statistics pages:
  - ➔ Fault statistics:
    - ➔ class definition; occurrence; down time
  - ➔ Key statistics could be automatically generated from Timber (Tevatron example):

    lumi per fill; integrated lumi versus peak luminosity etc.

Fault Monitoring

Walter's presentation:

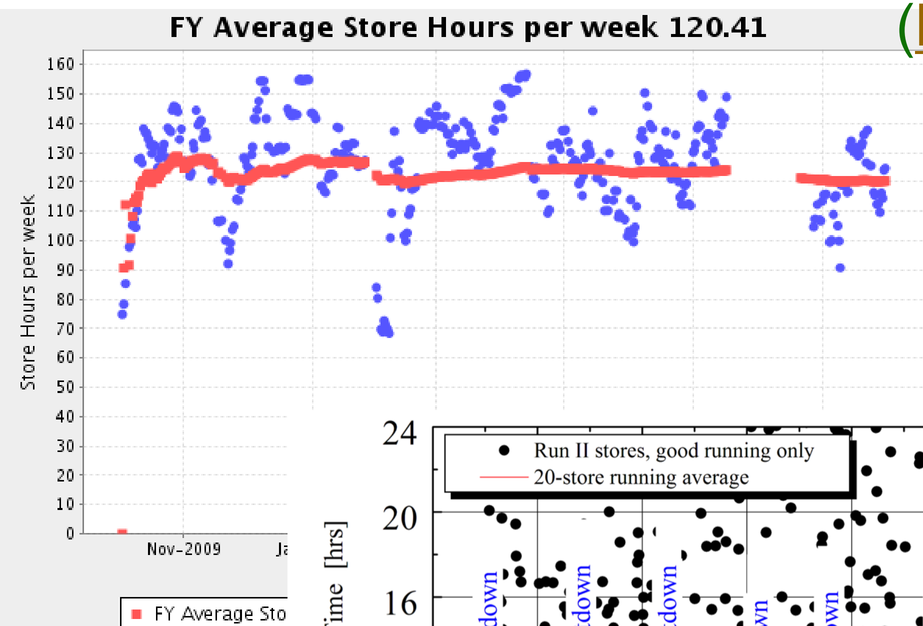


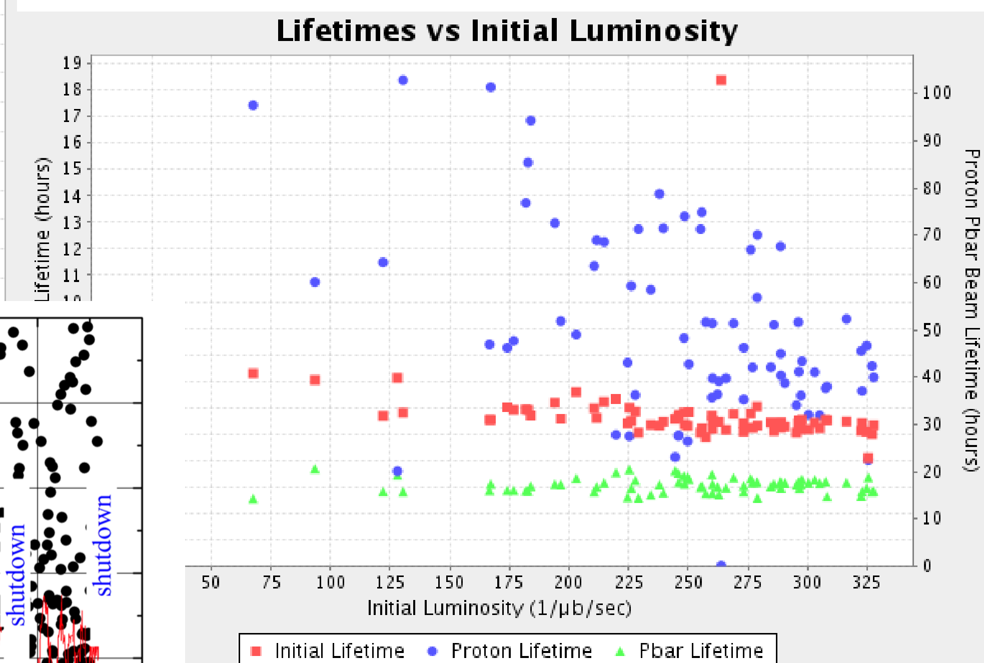


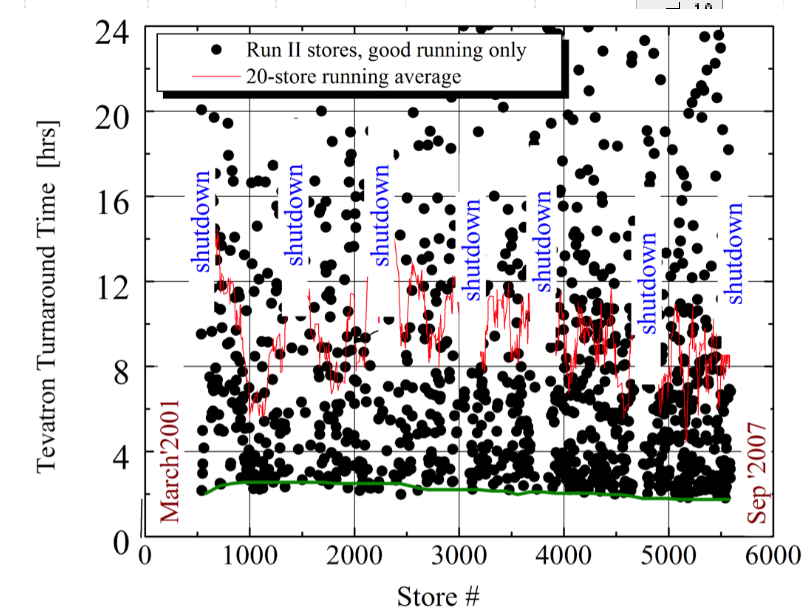
General Statistic Pages

- Tevatron operation statistics:

(http://www-bd.fnal.gov/pplot/index.html







Summary

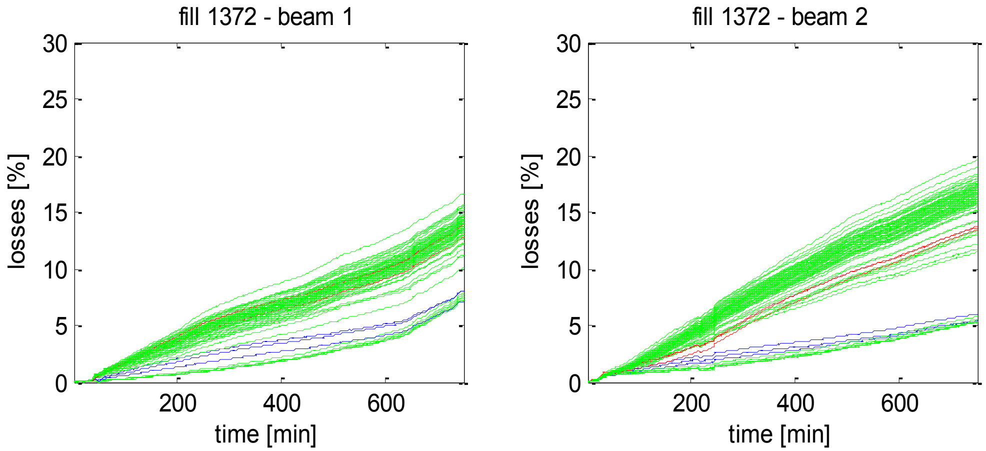
- electron cloud effects:
  - ➔ heat load display per sector
  - ➔ bunch by bunch emittance display (mountain range)
  - ➔ top 10 pressure locations
- UFOs:
  - ➔ life counter with ratio to BLM threshold
  - ➔ distribution around the machine
- beam-beam effects:
  - ➔ bunch by bunch working point in tune diagram (estim & meas)
  - ➔ offline analysis: Giulia plots and specific L per bunch
- faults and overall efficiency:
  - ➔ fill summaries (template)
  - ➔ bunch by bunch data
  - ➔ automatic run and fault statistics

Bunch train commissioning – Emittance control

Fill	# bunches	$\varepsilon_{H\ B1}$ @inj	$\varepsilon_{V\ B1}$ @inj	$\varepsilon_{H\ B2}$ @inj	$\varepsilon_{V\ B2}$ @inj	ε_{HV} @coll (from init. Lumi)	ε_{H} @end of coast (from Lumi scan or WS)	ε_{V} @end of coast (from Lumi scan or WS)
1364	25	2.5	1.9	3.2	2.7	3.2	4.0/4.5	3.8/4.9
1366	56	1.7	1.7	2.0	2.3	2.2	3.5	3.5
1369	56	2.2	2.1	2.6	2.9	2.9	-	-
1372	104	2.1	2.2	2.3	2.8	2.8	3.7	4.5

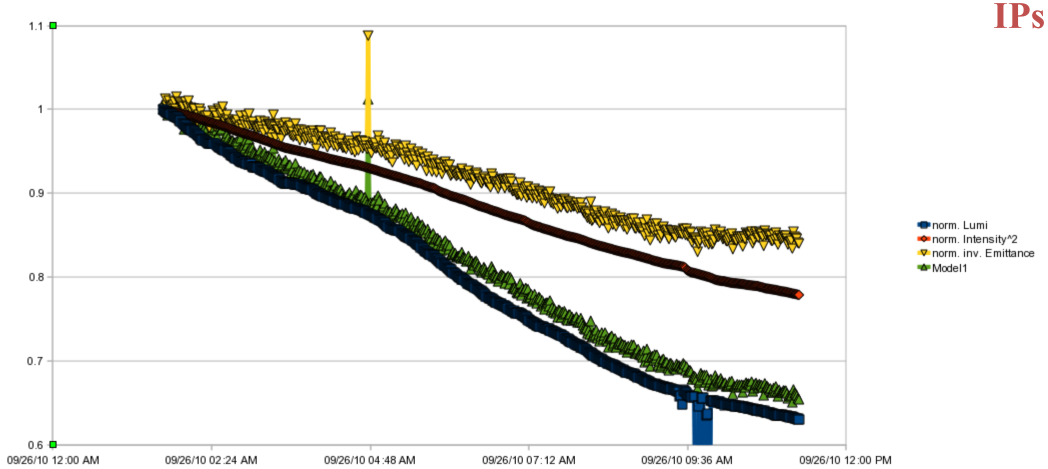
- New functions for the damper allow to mitigate blow-up due to hump in the vertical plane. Gain functions during the ramp remain to be optimized (ongoing). ~10-20% blow-up during injection plateau and ramp.
- Systematic difference B1/B2 already at injection remains an issue ➔ to be followed-up (mismatch?)
- Reproducibility of the blow-up in the PS to be followed-up
- Blow-up in collision (~40-50 %) to be further studied

Lifetimes and losses



IPs: 1 5 2 8 - 1 5 8 - 1 5 2 - 1 5 - 2 8 - 8

G. Papotti

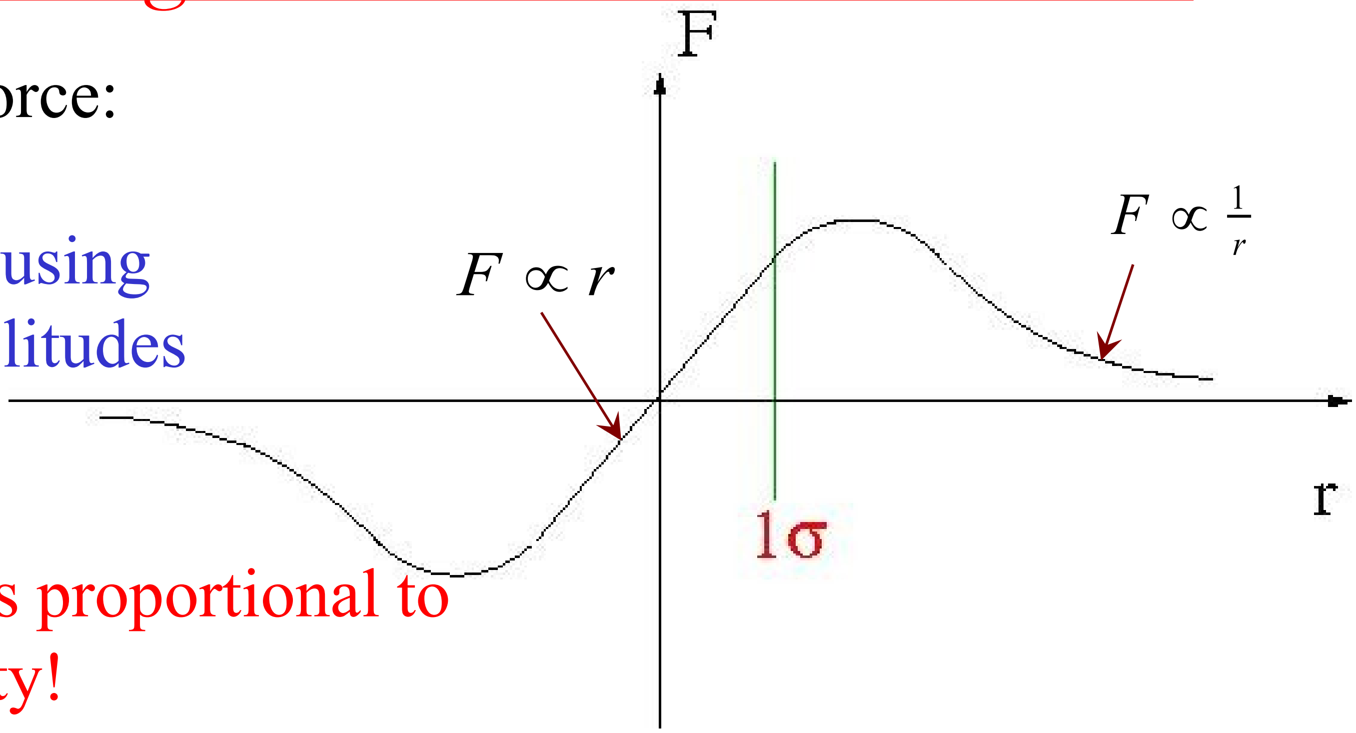


R. Steinhagen

LHC Challenges: Beam-Beam Interaction

- beam-beam force:

→ additional focusing for small amplitudes



→ perturbation is proportional to bunch intensity!

- strong non-linear field:

→ tune & perturbation depends on oscillation amplitude

→ bunch intensity limited by non-linear resonances

36 bunch trains

- Onset of e-cloud/vacuum effects at 6E10 p/bunch.
  - Strong emittance increase along the train.

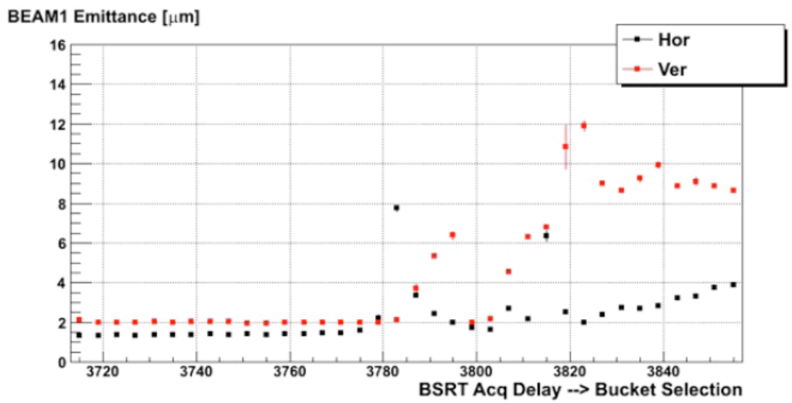
01-11-2010 - scrubbing

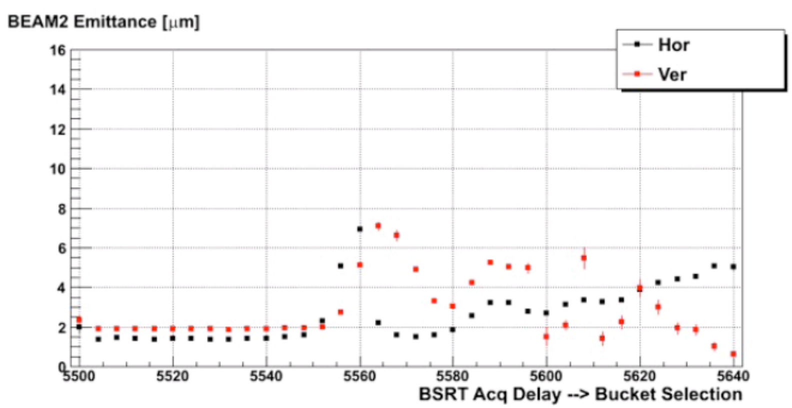
BSRT emittances bunch per bunch over the train of **36 bunches**. (first B1 and then B2 injections from 21:30 to 23:00)

Hor axis:
BSRT acquisition gate delay -->
bucket # **from 15001 to 15701**

Each point:
-average over ~10seconds two times per bunch, with a gap of ~3minutes between acquisitions on the same bunch
--> small error bars say that first bunches in the train did not change after 3 min

B1:
from bunch 18: blow up in HOR and VER (Vertical fit very bad)
B2:
same as B1, from Bunch 15



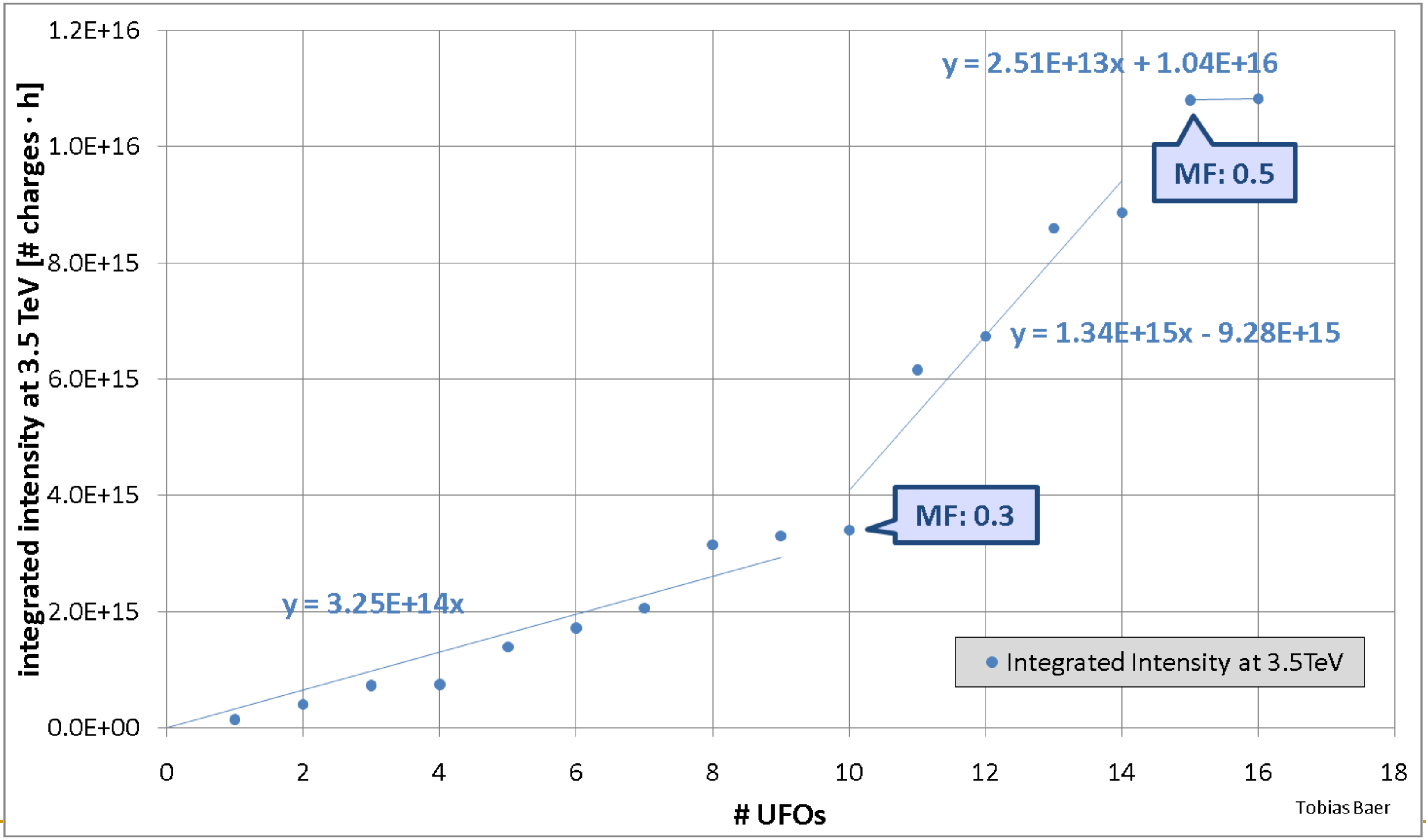


F. Roncarolo

UFO dump rate

JW @ LMC 1.12.10

- After the increase of the BLM Monitor Factor by a factor of 3 there were about **4.1 times fewer UFO related beam dumps**.



UFOs vs. Intensity JW @ LMC 1.12.10

- All UFOs in one plot. Each UFO after the increase of the Monitor Factor is equivalent to 4.11 UFOs with the initial Monitor Factor.