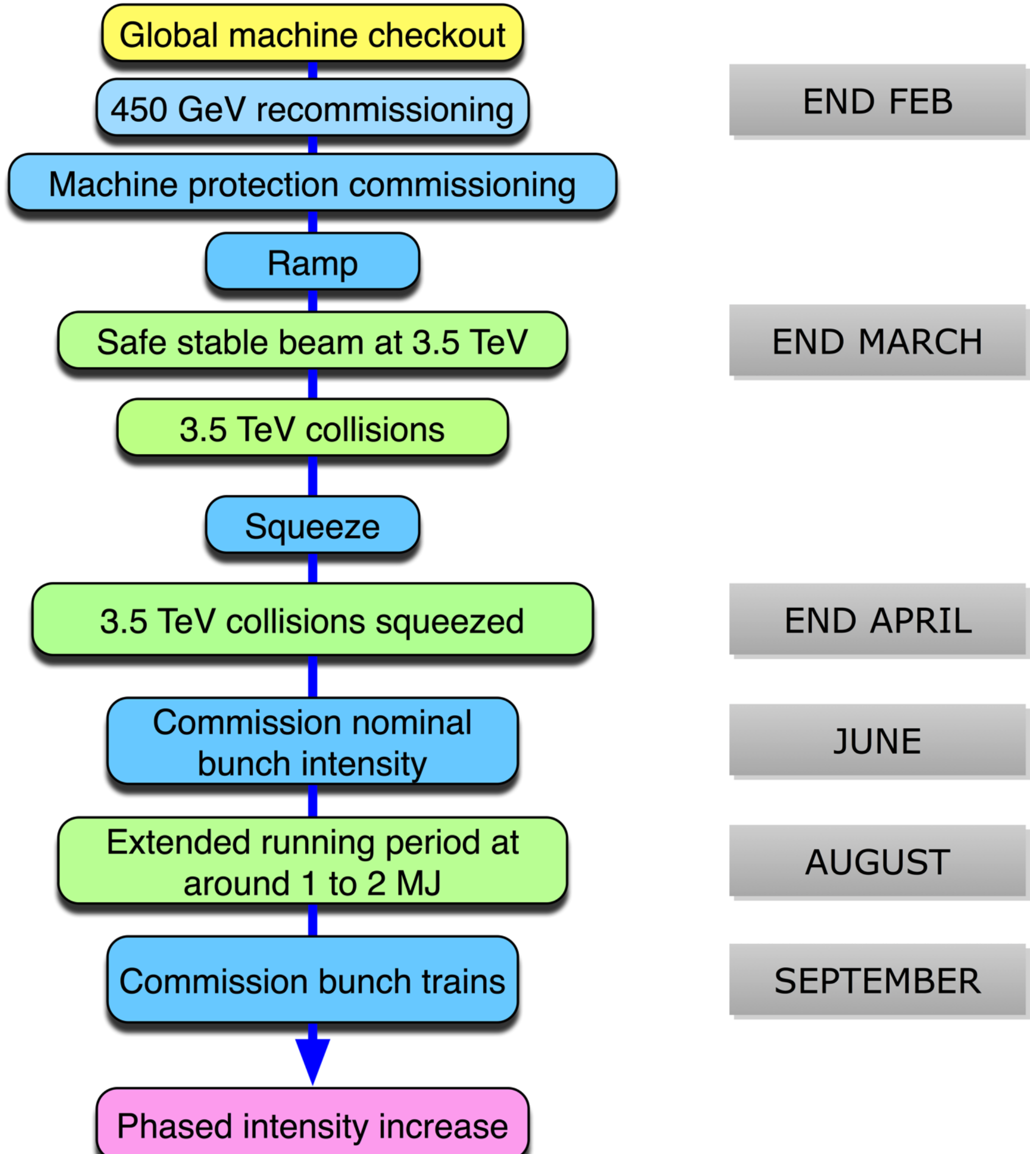
LHC machine commissioning and the near future

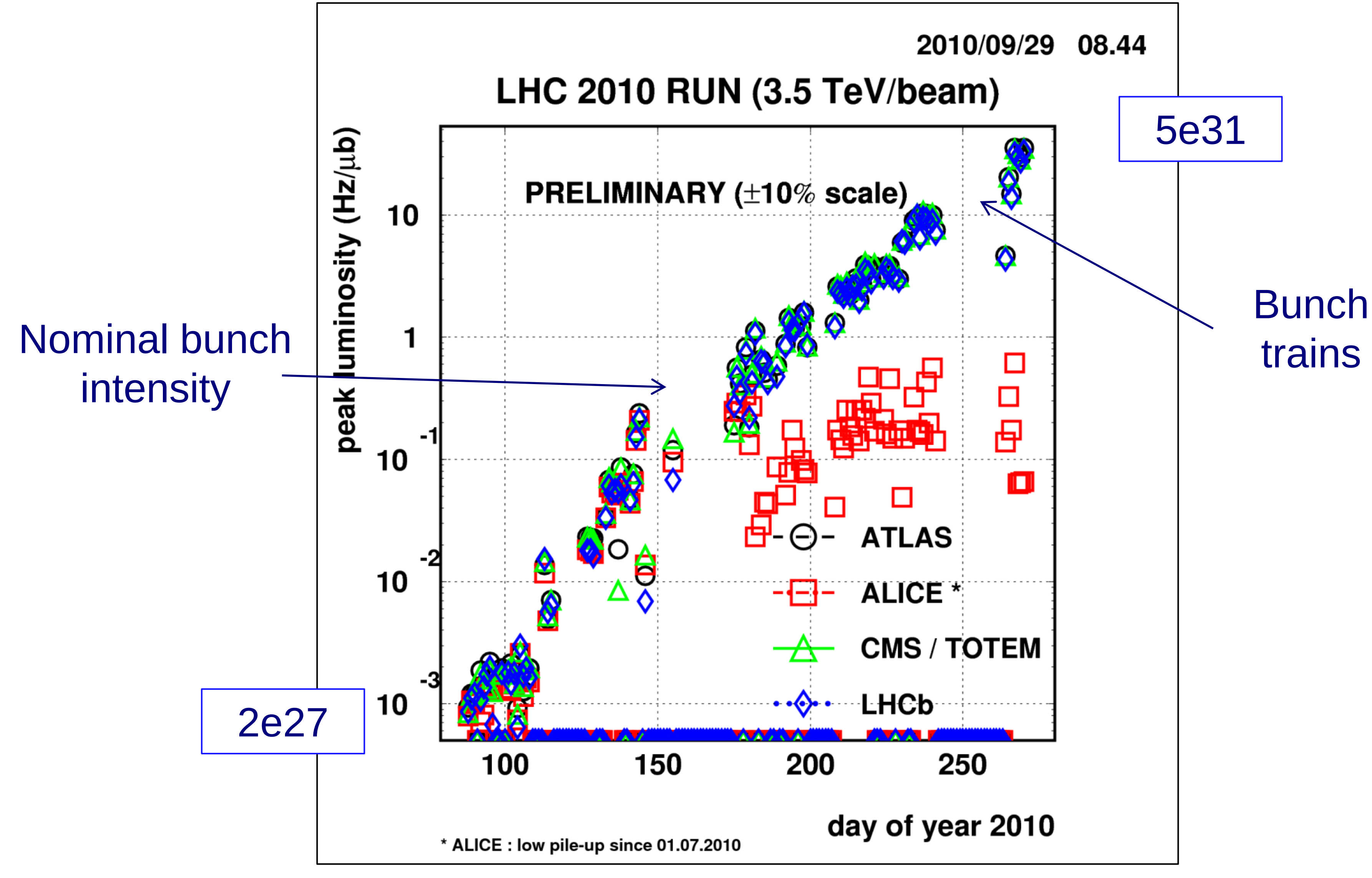
Mike Lamont
for the LHC team

It’s been a long year…



From diddly-squat…

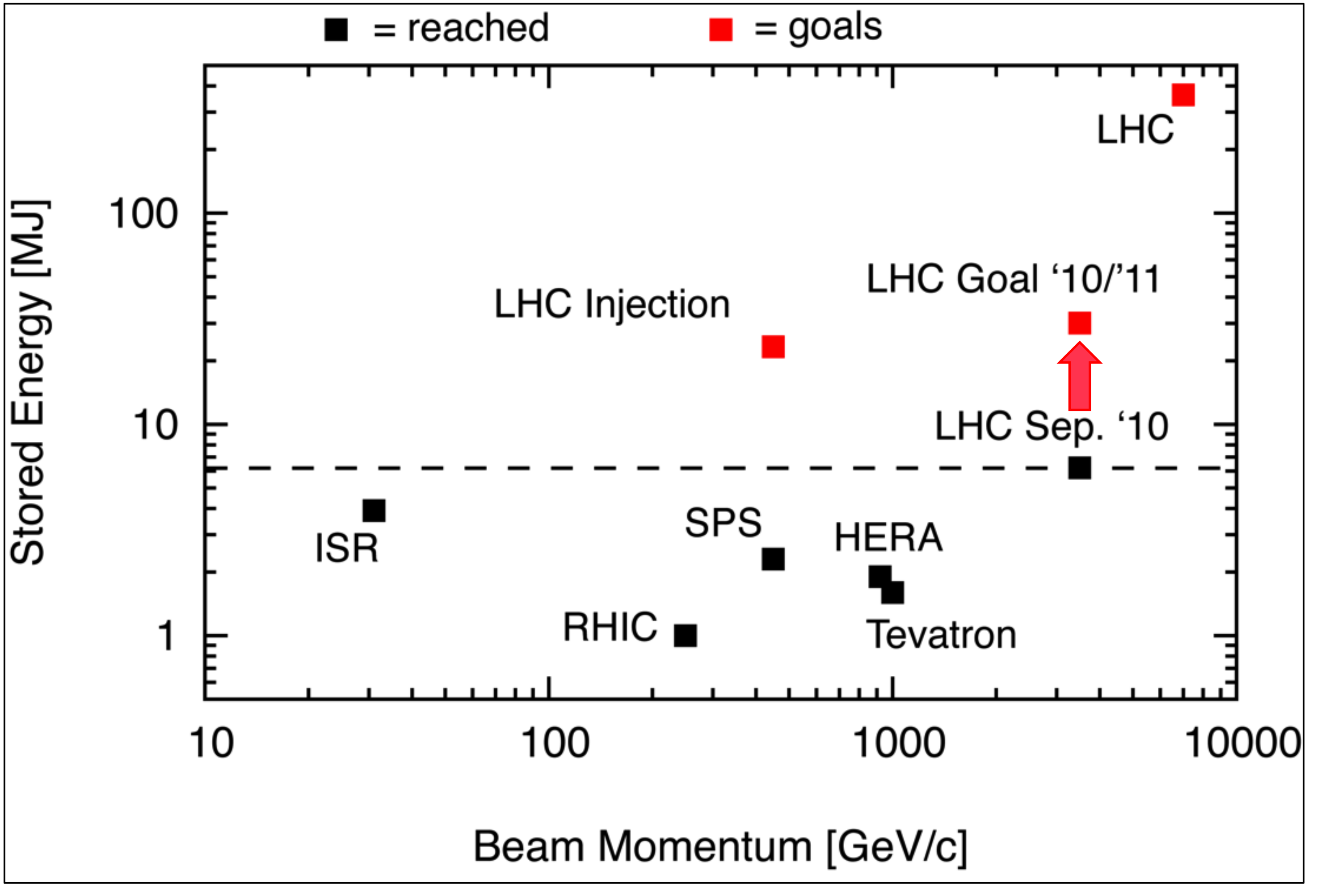


> 4 orders of magnitude in 6 months

Associated parameters

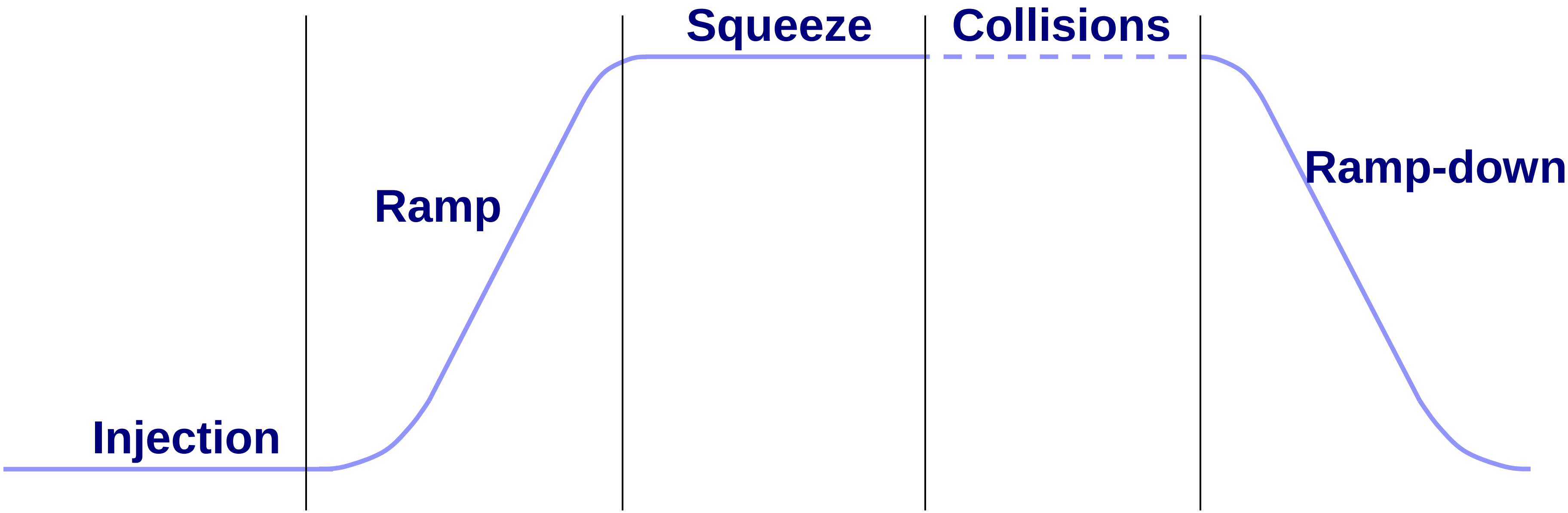
	Present	Design
Energy [TeV]	3.5	7
beta* [m]	3.5,3.5,3.5,3.5 m	0.55,10,0.55,10
Emittance [microns]	2.5 – 3.5 start of fill	3.75
Transverse beam size at IP [microns]	around 60	16.7
Bunch current	1.1e11	1.15e11
Number of bunches	152 140 collisions/IP	2808
Stored energy [MJ]	10	360
Peak luminosity [$cm^{-2}s^{-1}$]	5e31	1e34

Stored energy



COMMISSIONING – WHERE DO WE STAND?

Operational Cycle



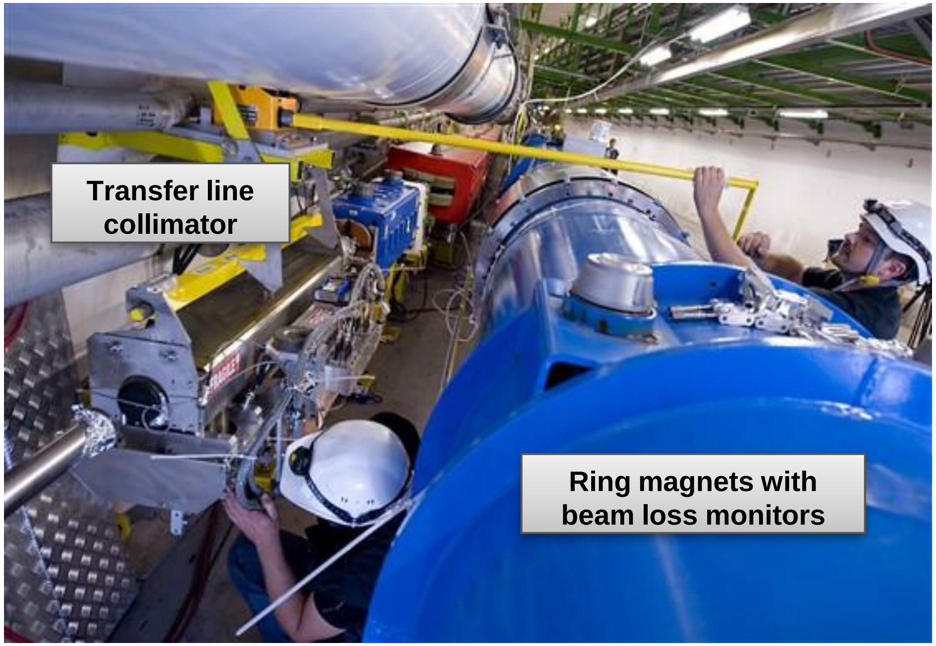
Injection	Ramp	Squeeze	Collisions	Ramp-down
Multi-bunch, unsafe beam	Dynamic effects Feedbacks	Optics Collimators	Beam steering Beam-beam	Ramp rates Reproducibility

← All through the cycle →

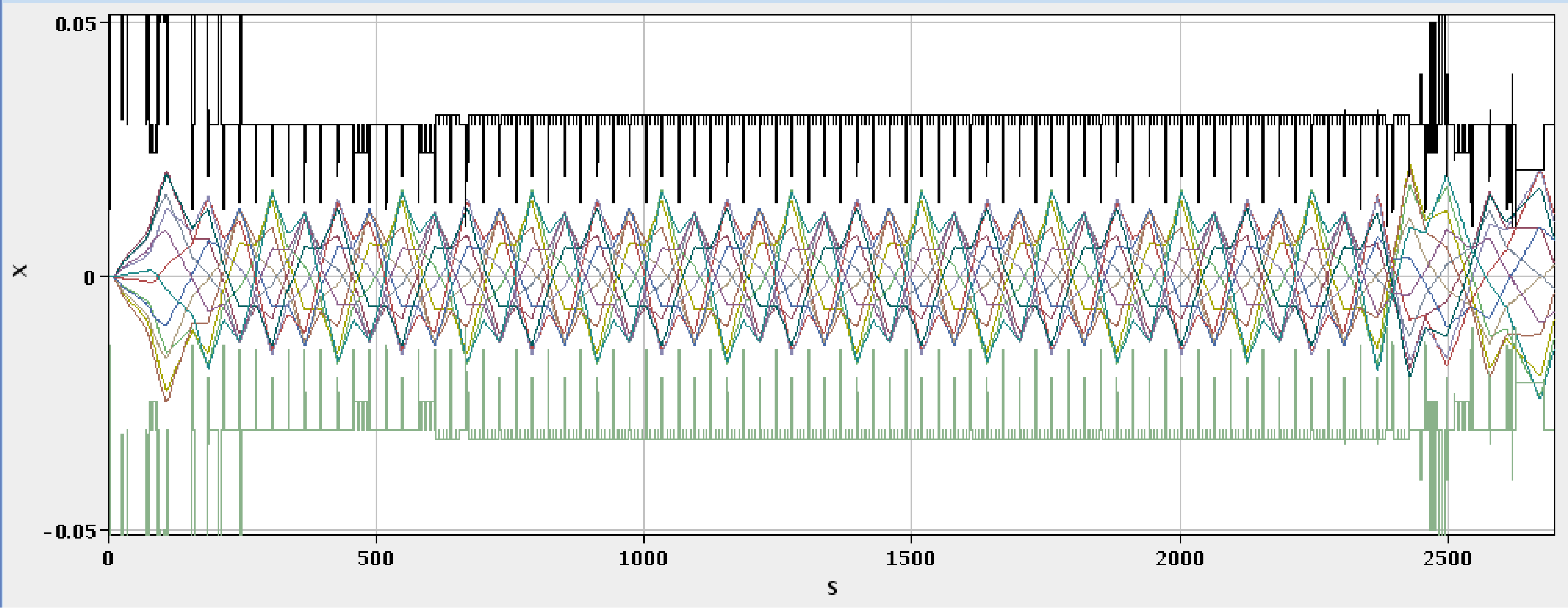
Beam dump
Collimations system
Protection devices

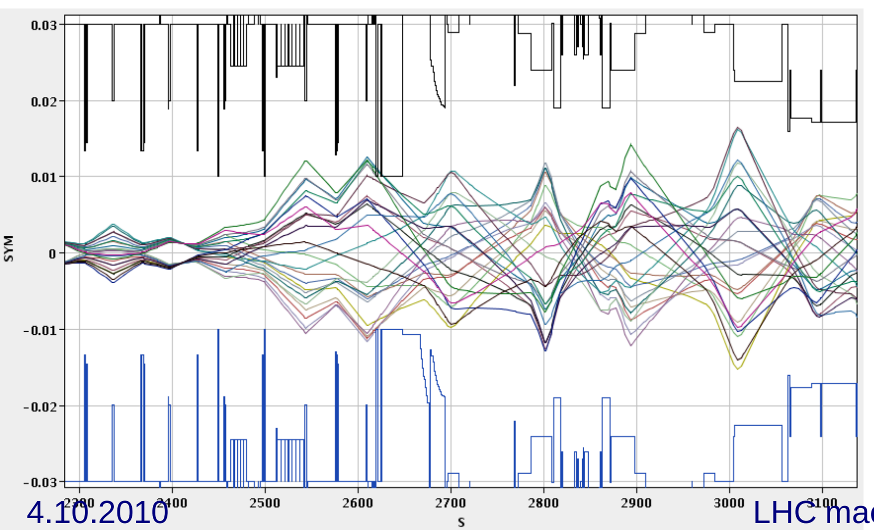
Injection

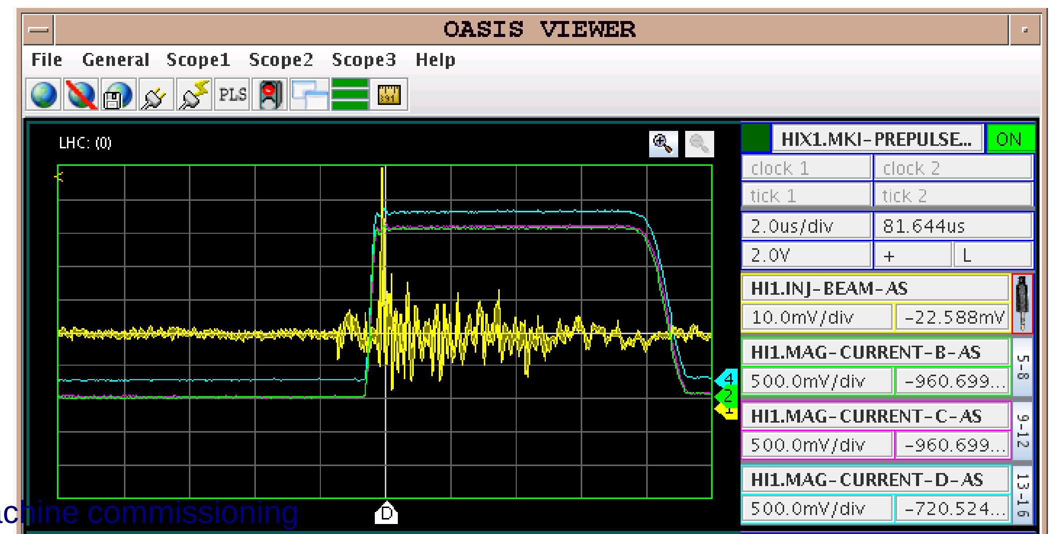
- Now inject 16 nominal bunches per extraction from the SPS
  - 1.6e12 protons is above the safe beam limit at 450 GeV
  - Careful adjustment of:
    - transfer lines and collimators
    - energy matching between SPS and LHC
    - injection protection devices (transfer line collimators etc.)
  - Transverse damper fully operational to damp injection oscillations



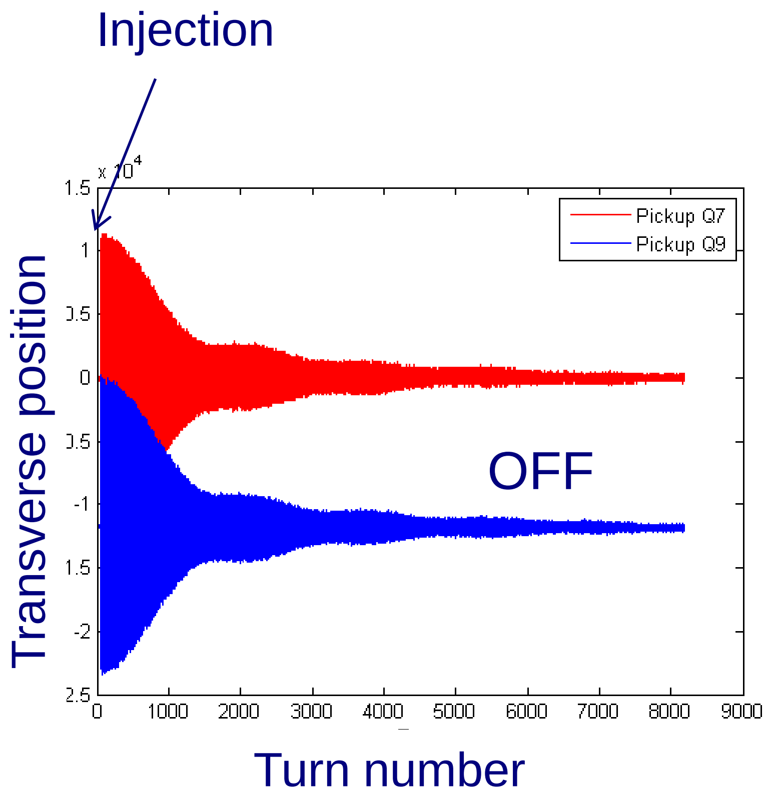
Beam transfer and Injection





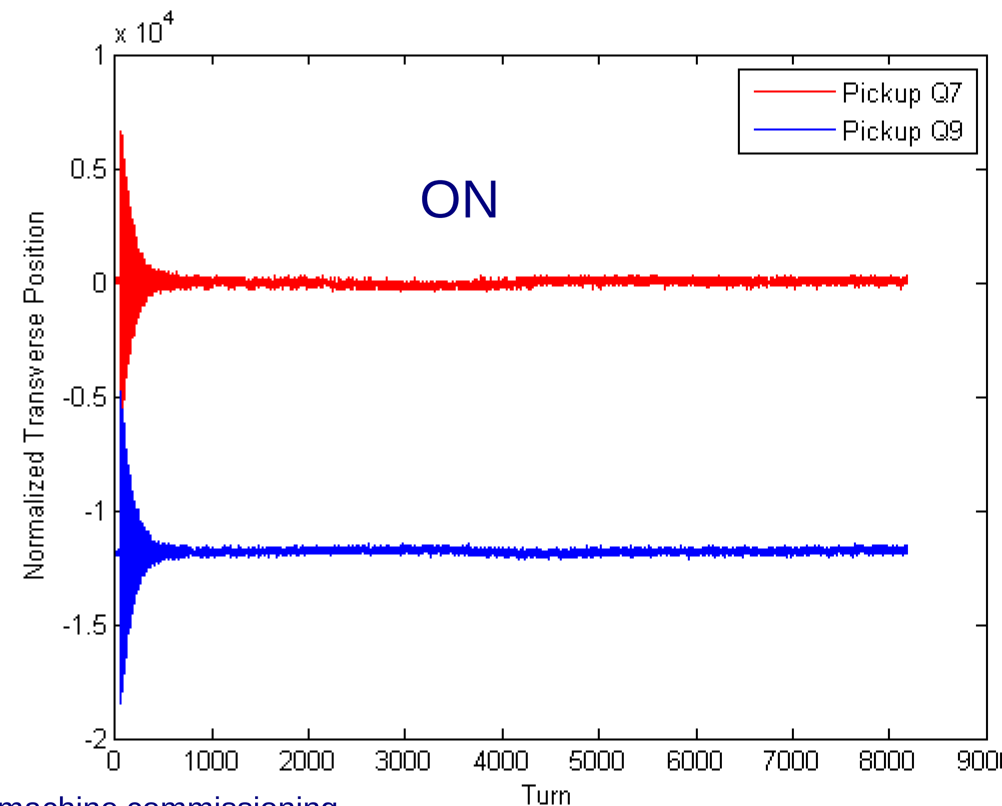


Transverse dampers



Operational through the cycle – including stable beams

Crucial to keep emittance growth under control

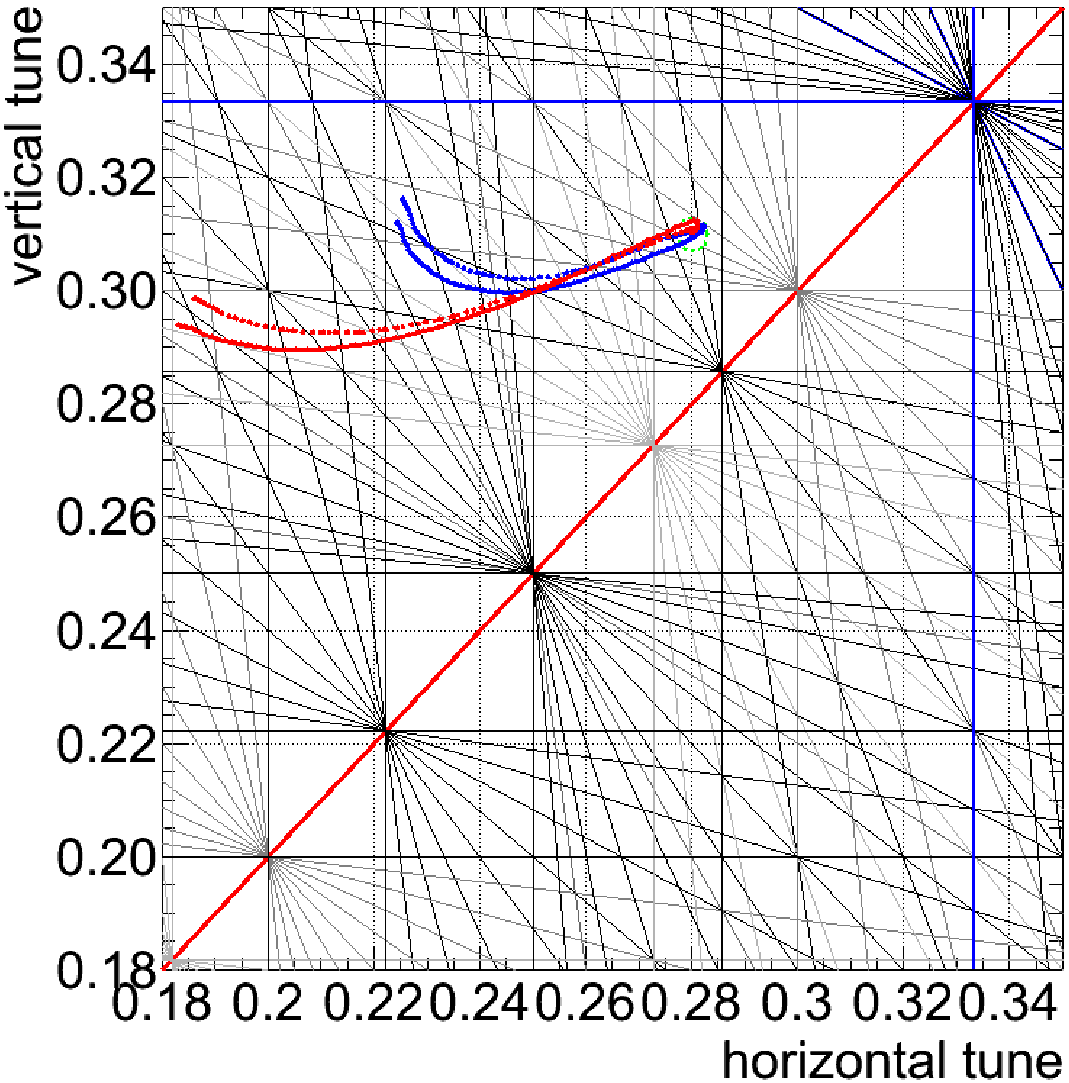


Ramp

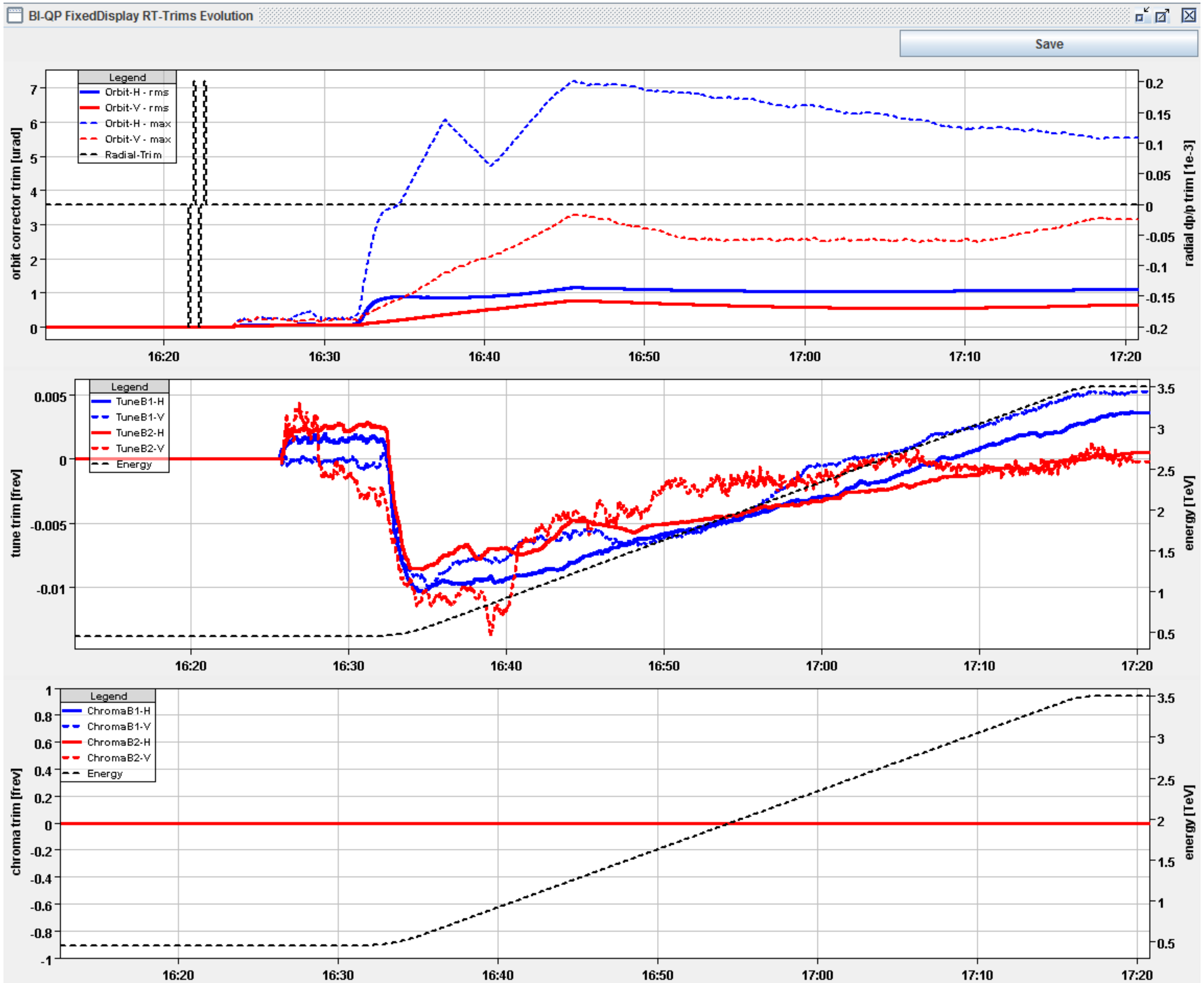
- 450 GeV – 3500 GeV
  - 17 minutes
  - Parabolic – exponential – linear – parabolic to minimize effects of snapback and duration
  - Snapback correction pre-programmed for b2,b3,b4,b5,a2,a3 based on FIDEL predictions for full decay
- Preloaded functions to power converters, collimators, RF
  - ramp initiated with timing event
- Fill-to-fill feed-forward performed intermittently
- Tune and orbit feedback considered mandatory
  - The performance of the FBs is good and the LHC only operates reliably with both orbit and tune FBs (ramp and squeeze).
- Ramp and squeeze essentially without losses….

Ramp – Tune feedback

Feedback employed early. Reconstructed tune excursions



Feedbacks in action: ramp



Fill 1309

29.08.2010

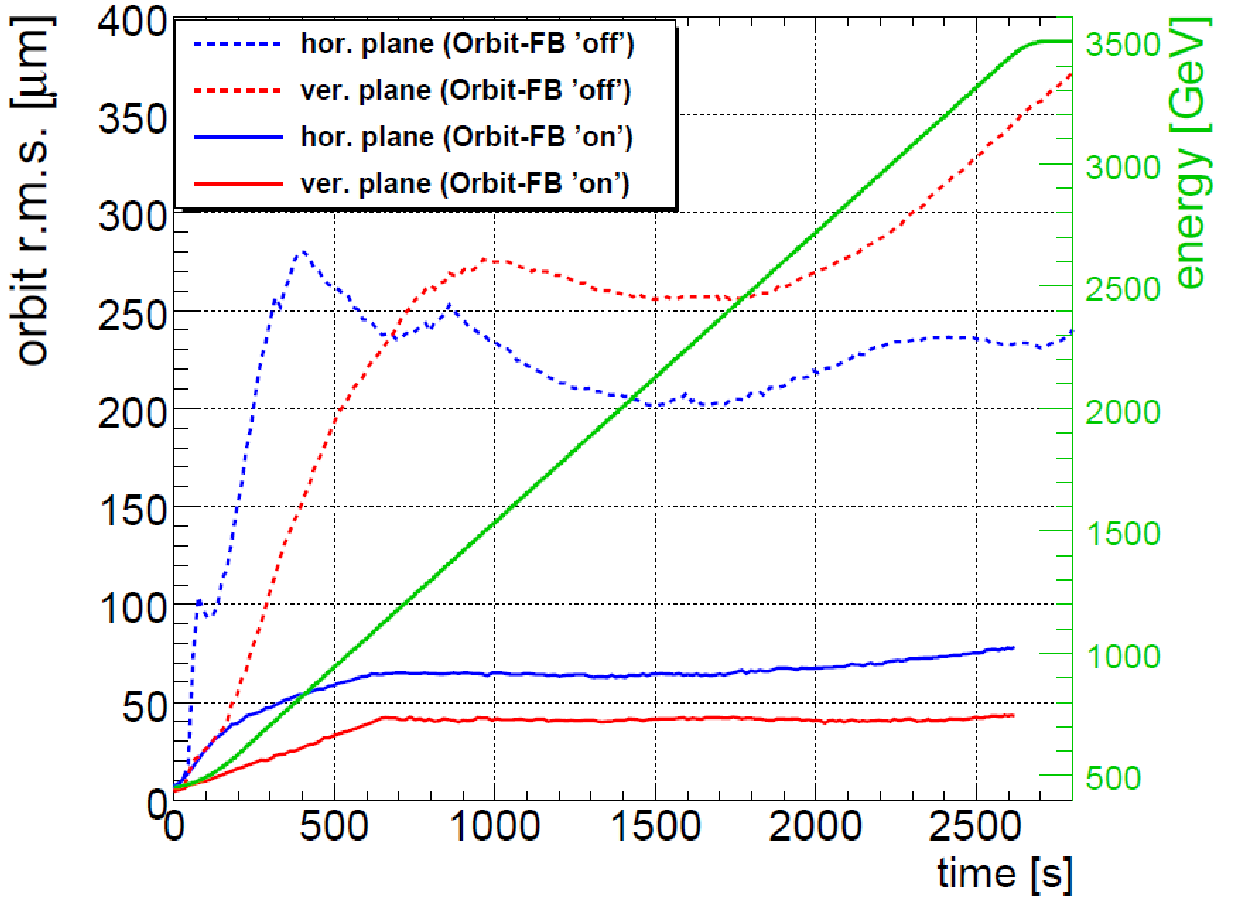
OFB trims (μrad)

QFB trims

Energy (TeV)

Orbit feedback performance: ramp

Orbit stability in the ramp: ≤ 80 μm rms



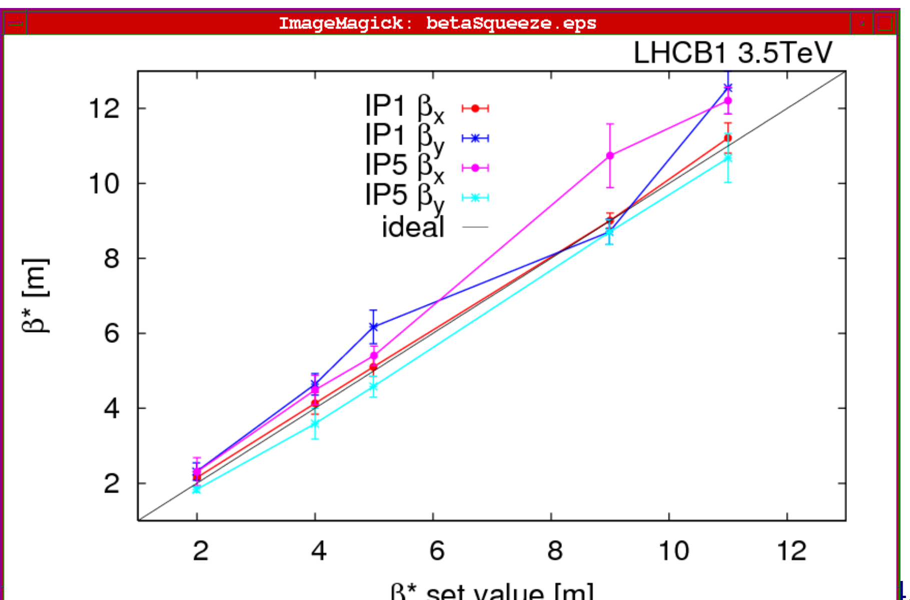
R. Steinhagen

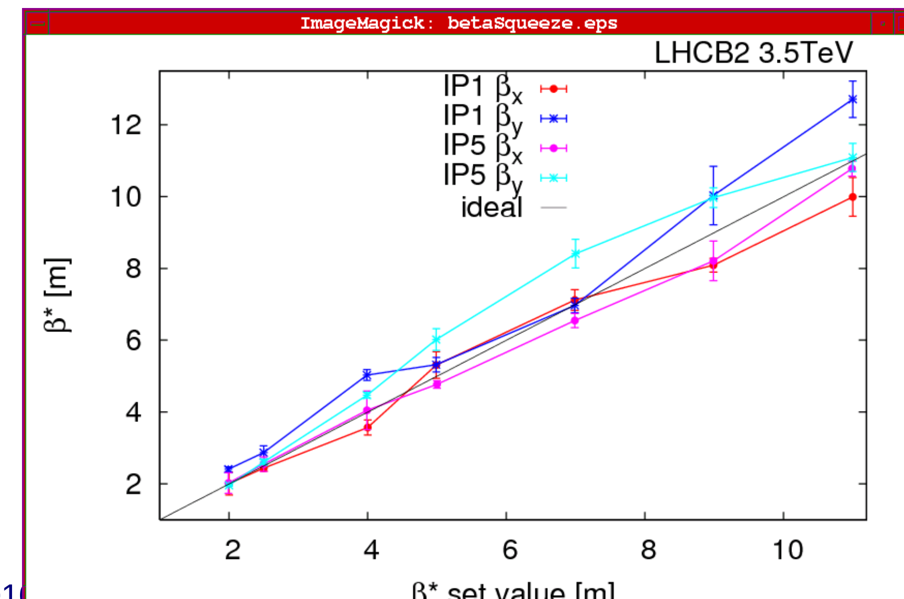
Beam current during fill 25/08/2010

Quite frankly: we're dreaming…

Squeeze: a delicate process

- From 11-10-11-10 to 3.5-3.5-3.5-3.5 m
- Move to collisions tunes at start
- Tune and orbit feedback on
- Worry about
  - Tune, Q', coupling, orbit, optics corrections
  - Positions of tertiary collimators
- Squeeze in three stages at the moment



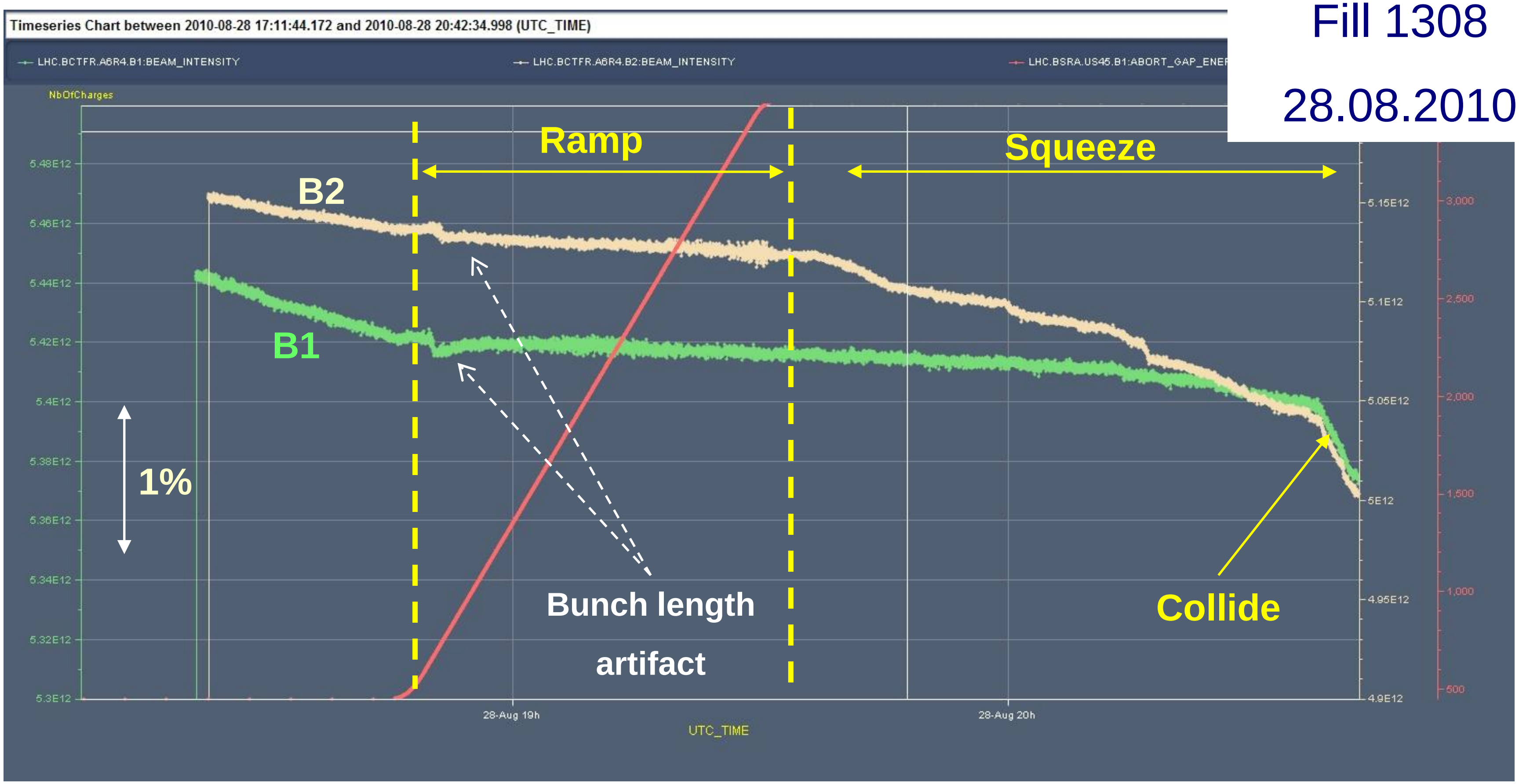


Beam intensities up the ramp…

…and through the squeeze

Fill 1308

28.08.2010



again essentially without loss

Measured betas at interaction points

β^* from K-modulation & ac dipole (4 Sep)

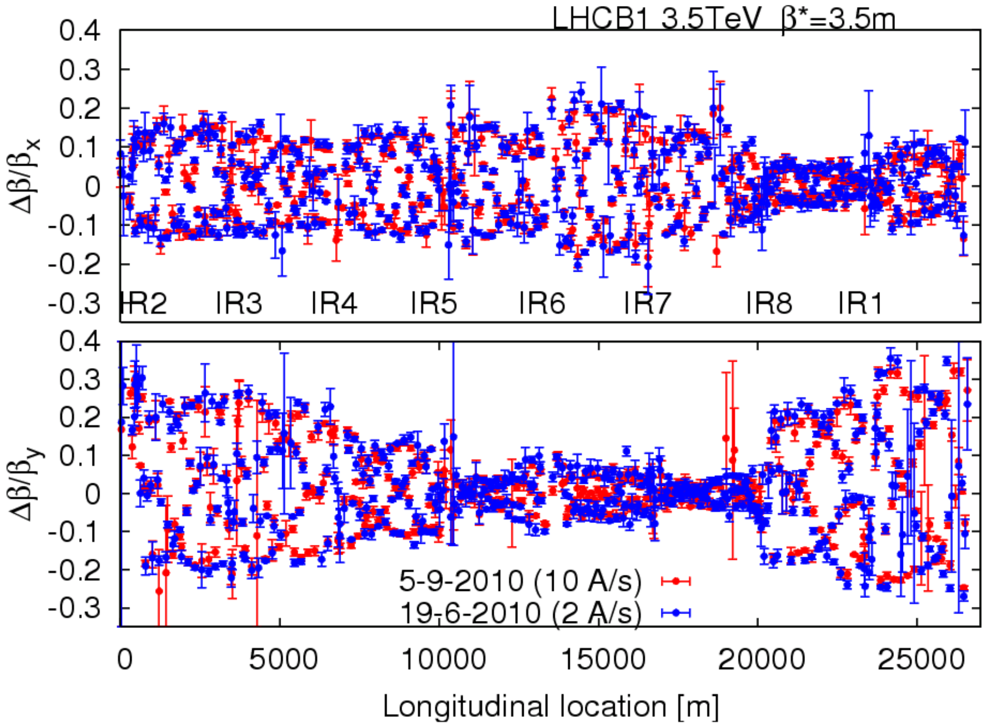
	β_x^1	err	β_y^1	err	β_x^2	err	β_y^2	err
IP1	3.6	0.1	3.7	0.1	3.8	0.1	4.2	0.1
IP2	3.4	0.1	3.3	0.1	3.7	0.1	3.5	0.1
IP5	3.8	0.1	3.7	0.1	3.8	0.1	3.7	0.1
IP8	3.6	0.1	3.4	0.1	5.5	0.1	5.5	0.1

from ac dipole

IP1	3.9	0.1	3.8	0.6	3.4	0.7	3.8	0.2
IP2	3.5	0.2	3.5	0.1	3.8	0.4	3.6	0.1
IP5	3.7	0.1	3.4	0.1	3.7	0.1	3.8	0.1
IP8	3.3	0.1	3.6	0.1	3.7	0.1	3.4	0.1

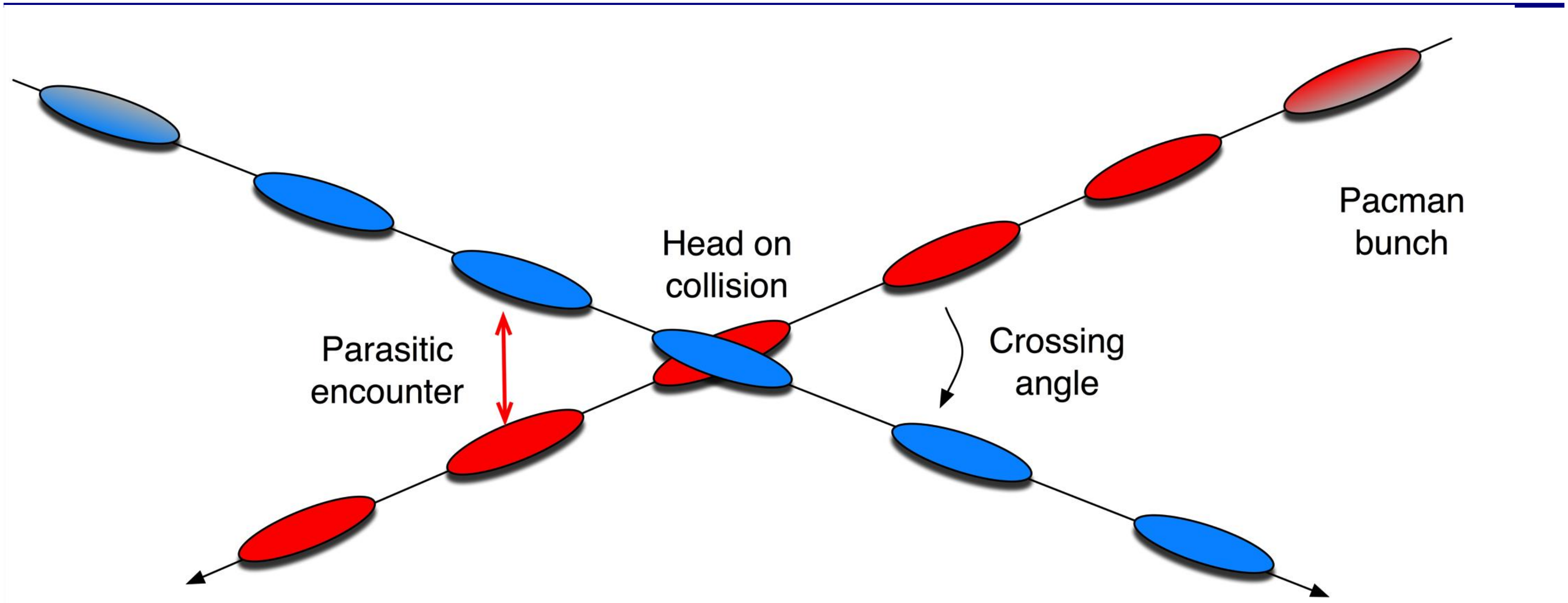
Optics & magnetic machine

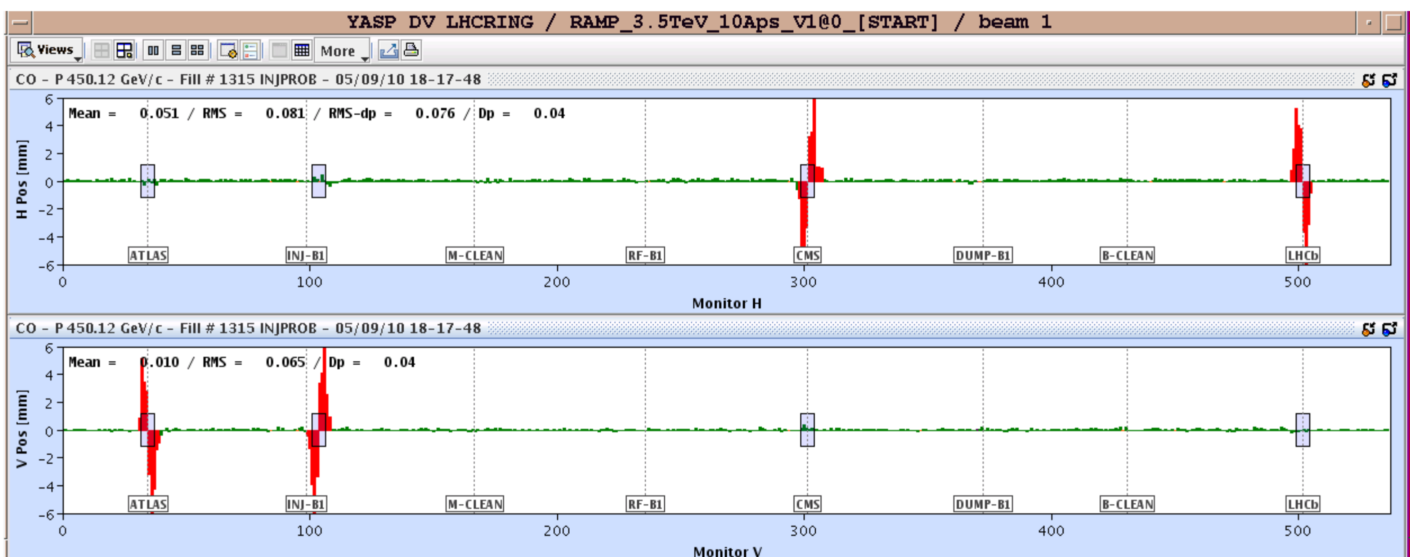
- Optics stunningly stable



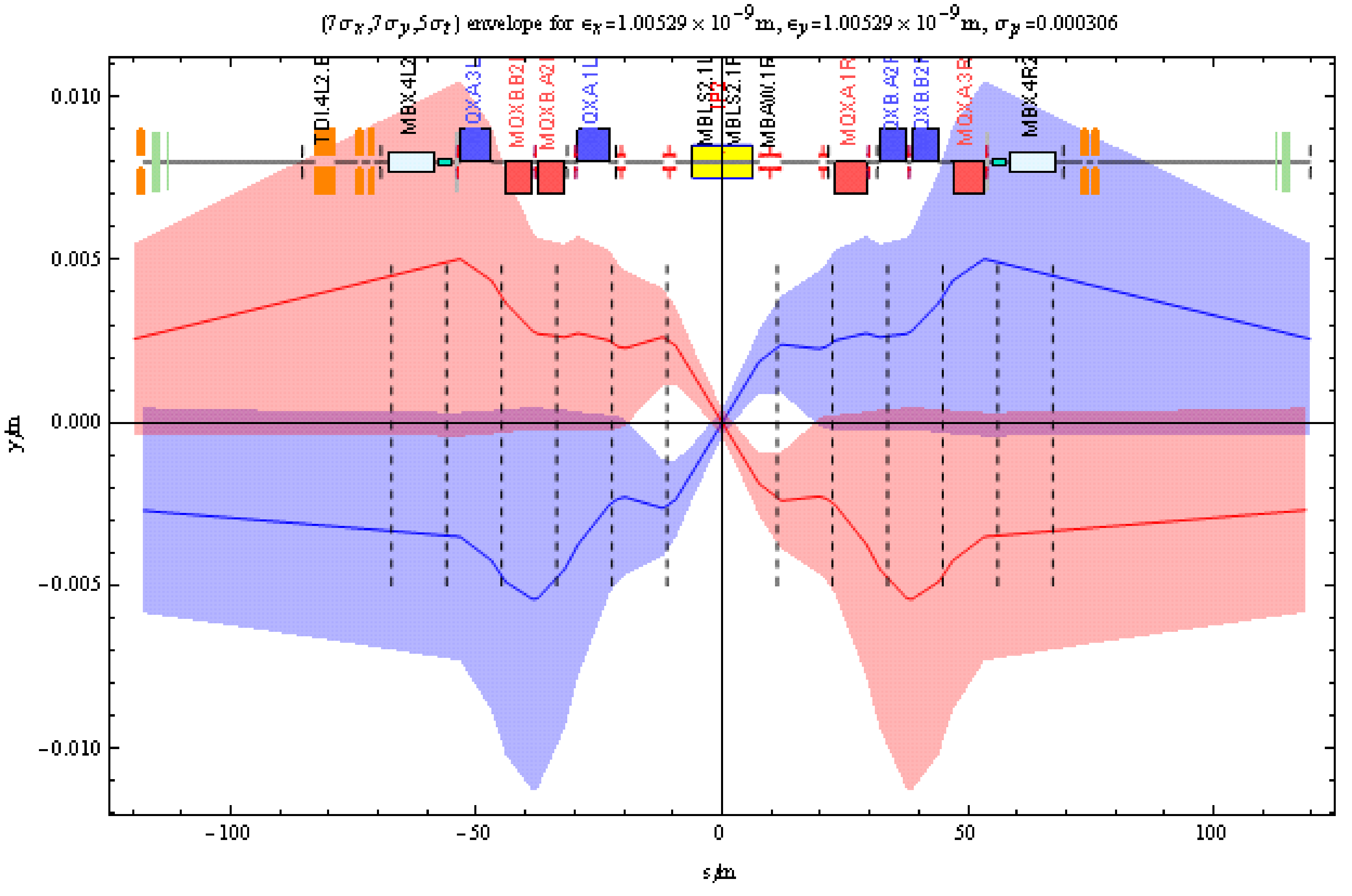
- Machine magnetically and optically well understood
  - Excellent agreement with model and machine
- Magnetically reproducible
  - Important because set-up remains valid from fill to fill

Crossing angles





Crossing angle – IP2



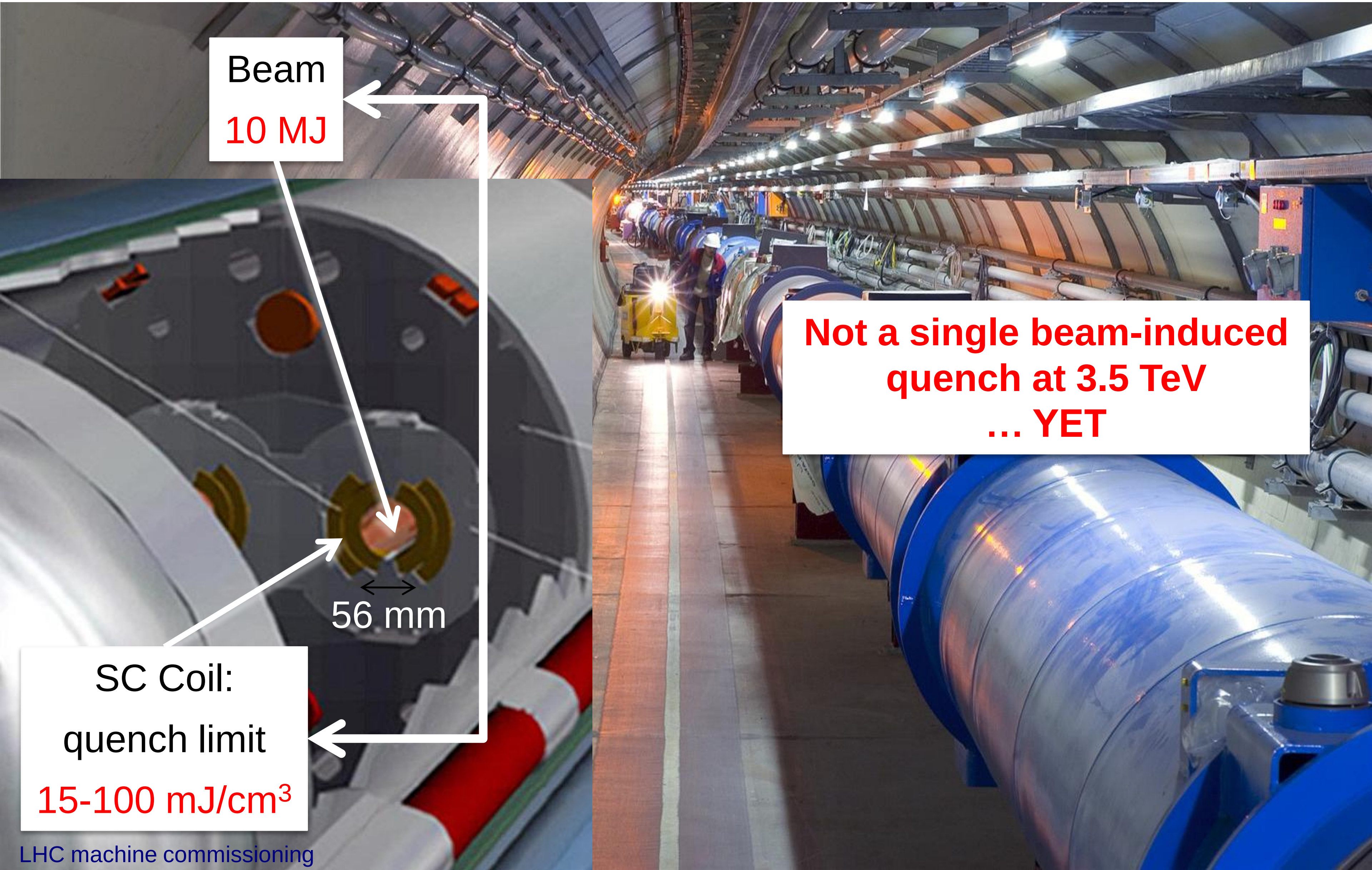
John Jowett

Briefly, why we can't deliver 1e32 $cm^{-2}s^{-1}$ immediately

MACHINE PROTECTION

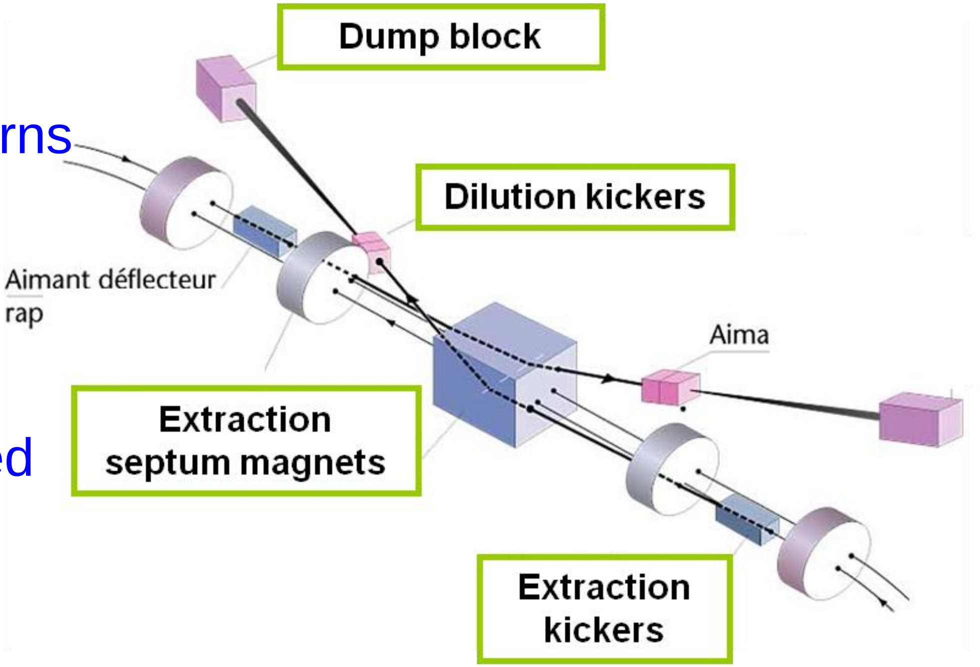
Quench Limit of LHC Super-Conducting Magnets

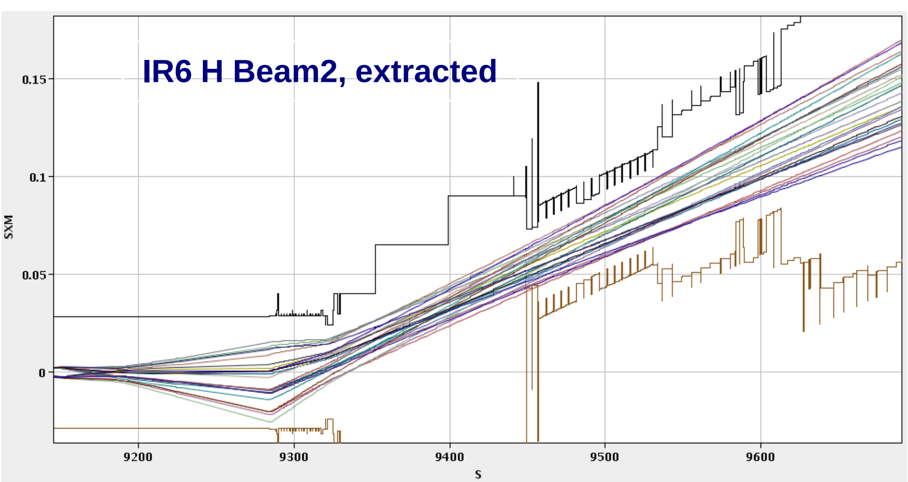
Situation at 3.5 TeV (in October 2010)

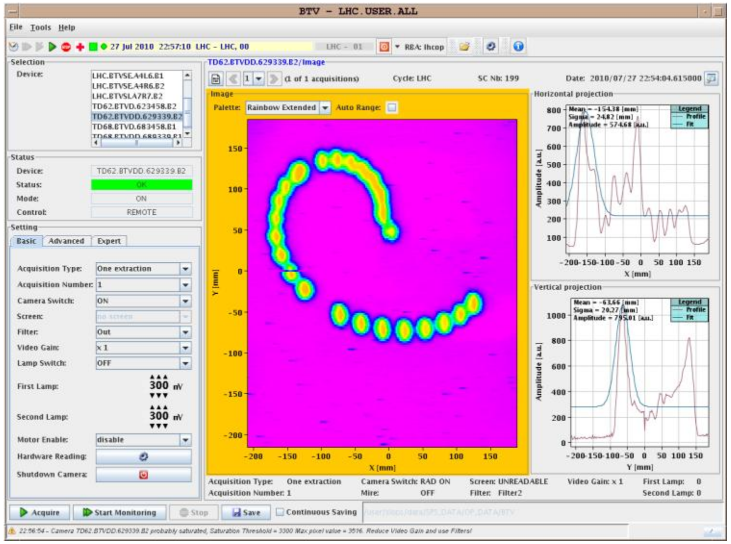


Beam Interlock System & Beam dump

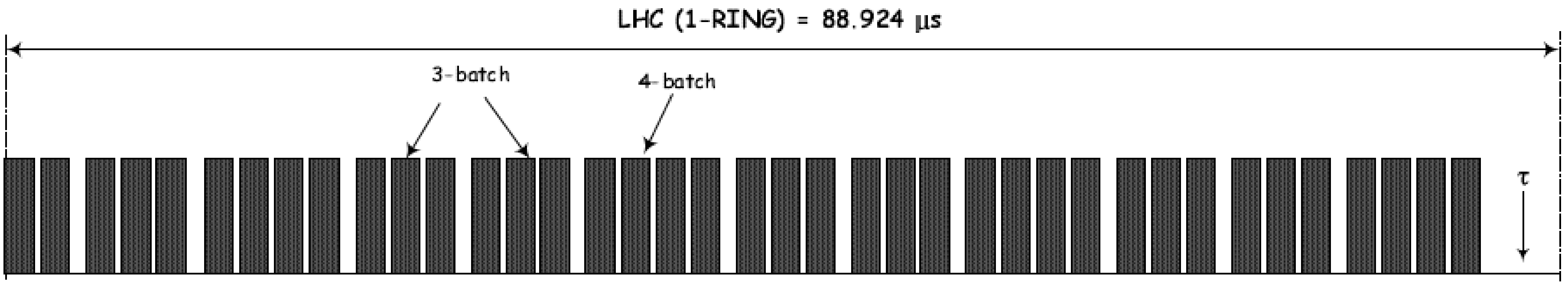
- Beam interlock system
  - Tells beam dump to fire with 3 turns
  - Around 20,000 inputs
  - Caught everything so far
- Beam dump system (LBDS)
  - Well set-up and closely monitored
  - No major issues yet



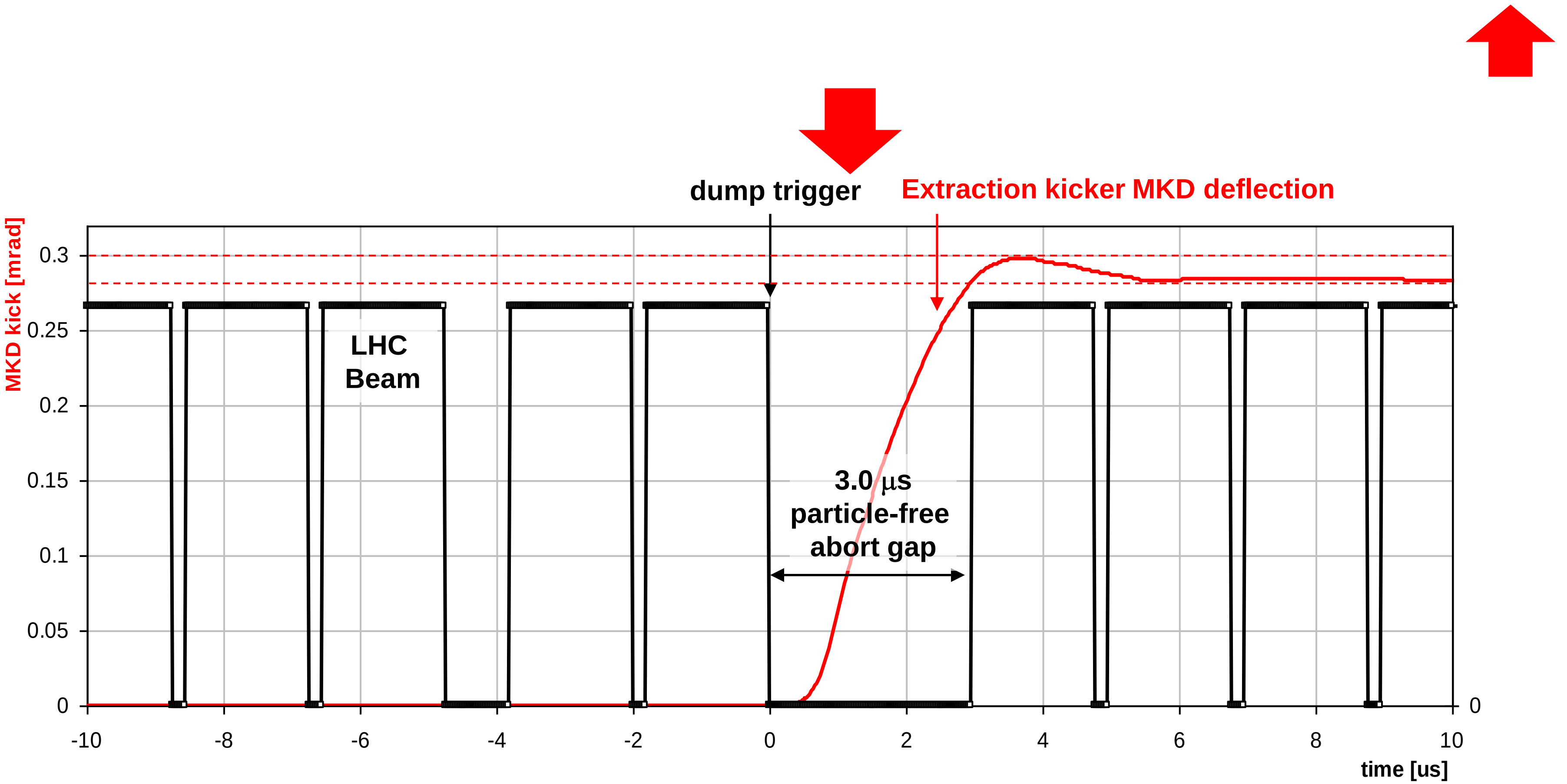




Abort Gap



LHC (1-RING) = 88.924 μs
3-batch
4-batch
τ

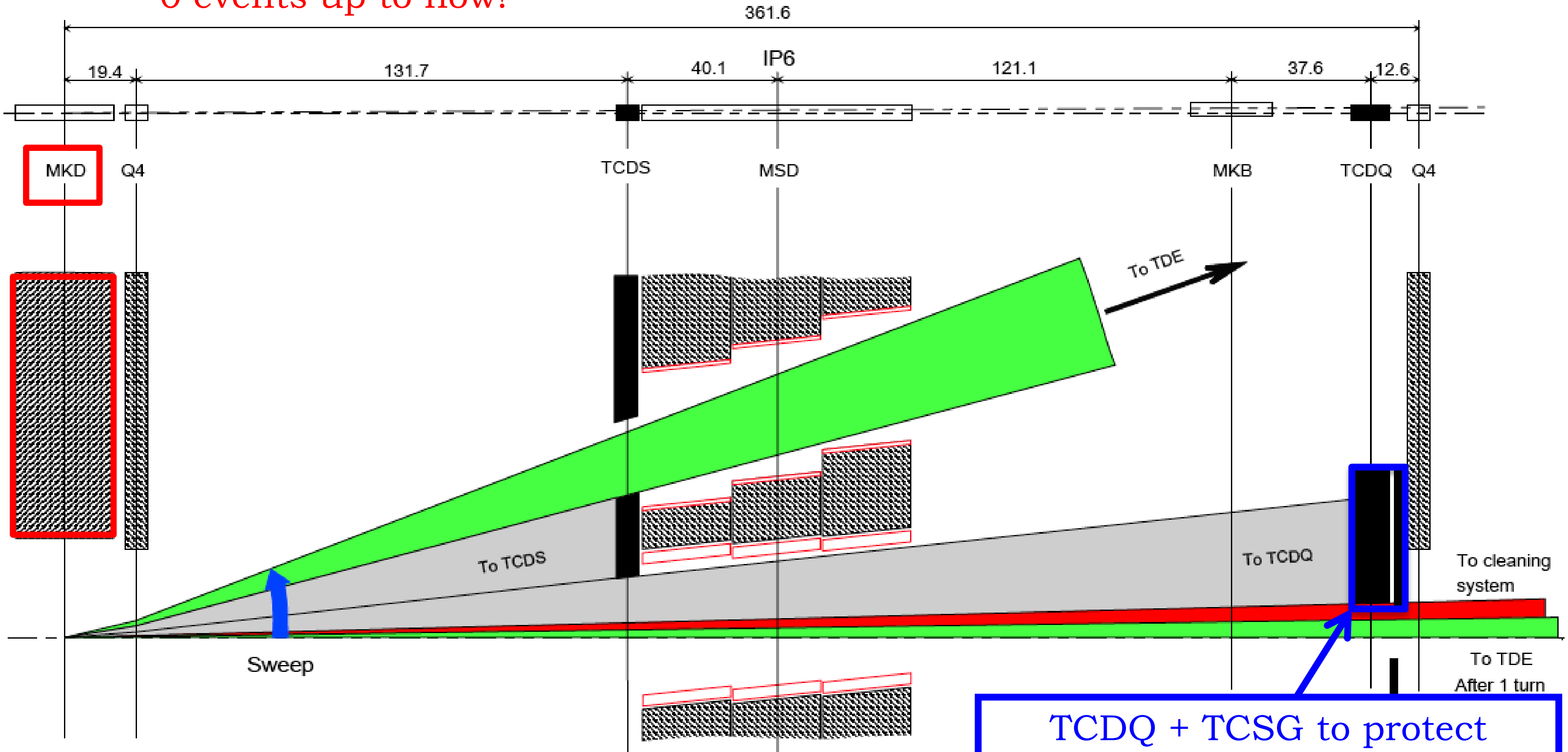


dump trigger
Extraction kicker MKD deflection
MKD kick [mrad]
0.3
0.25
0.2
0.15
0.1
0.05
0
LHC
Beam
3.0 μs
particle-free
abort gap
-10
-8
-6
-4
-2
0
2
4
6
8
10
time [us]

Asynchronous Beam Dump

Estimated occurrence : at least once per year,

0 events up to now!



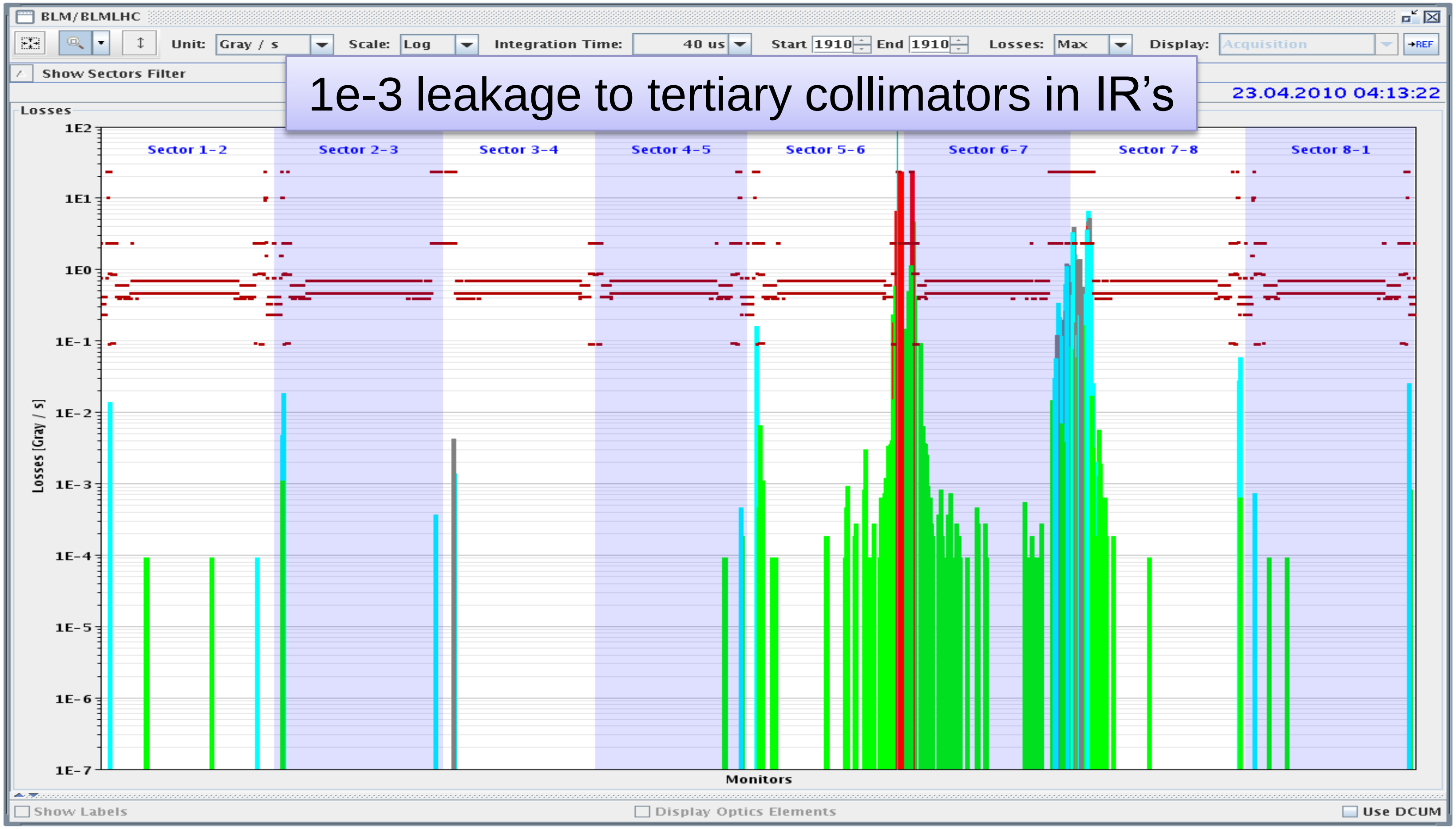
TCDQ + TCSG to protect downstream superconducting magnets (Q4)

TCDQ = 6 m long CFC* one-sided collimator
TCSG = 1 m long CFC* two-sided collimator

*CFC = carbon fibre compound

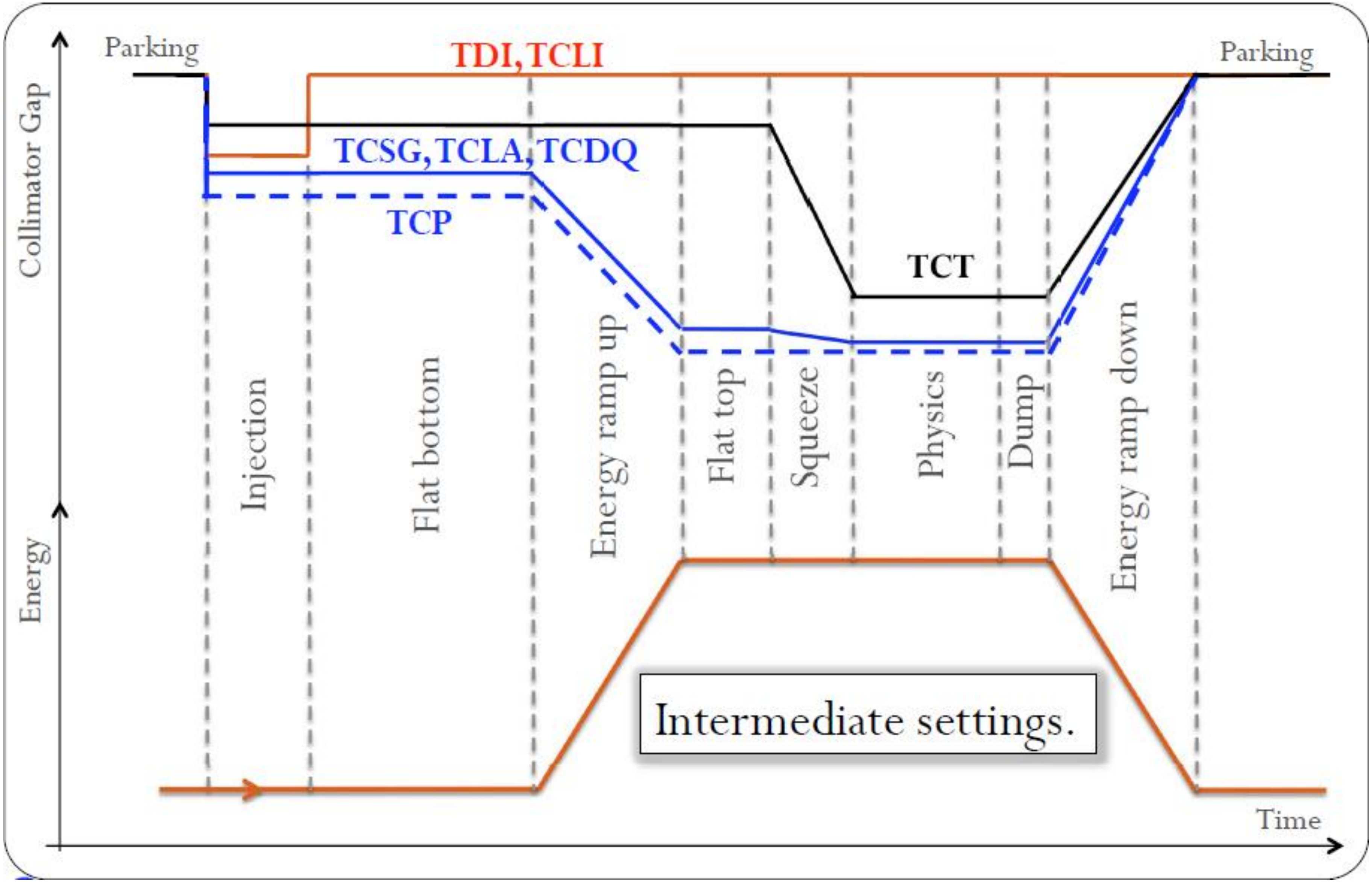
Beam dump protection systems efficiency

Provoked asynchronous beam dump

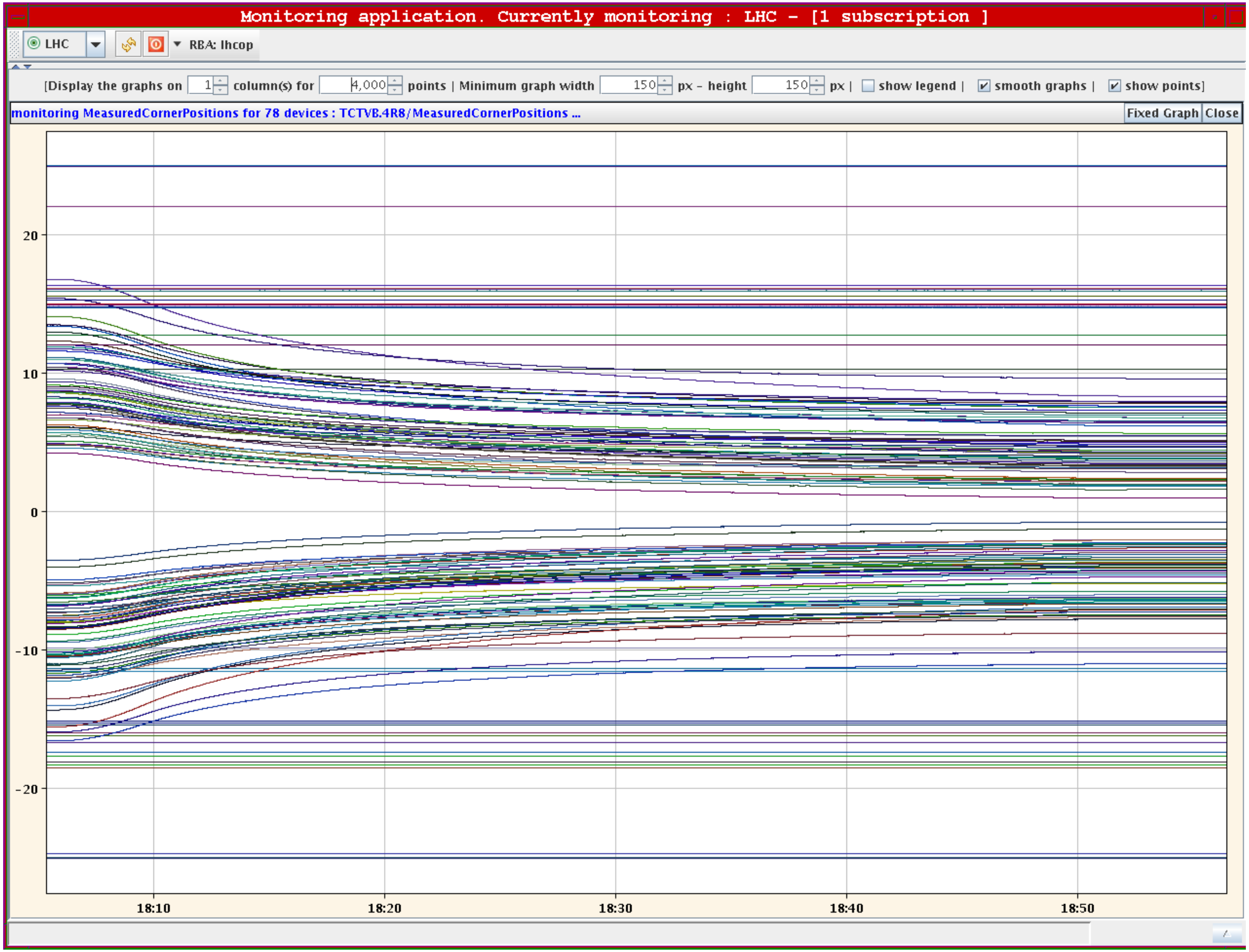


➔ OK for stable beams from beam dump

Collimation system

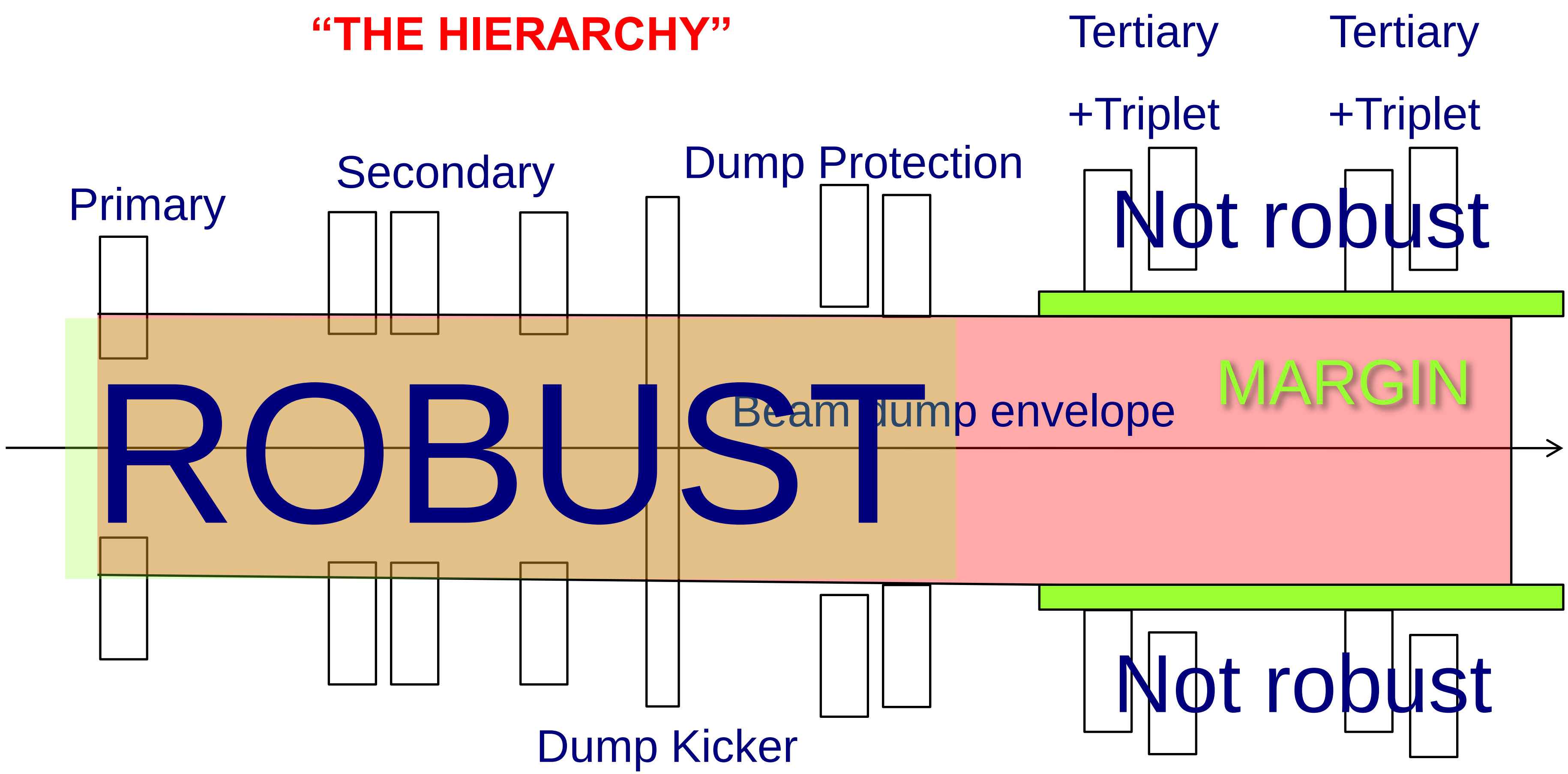


Ramp - collimators



Collimation set-up

- Collimation is set up with multi-stage logic for cleaning and protection
- In normalized phase space, talking in nominal sigmas:

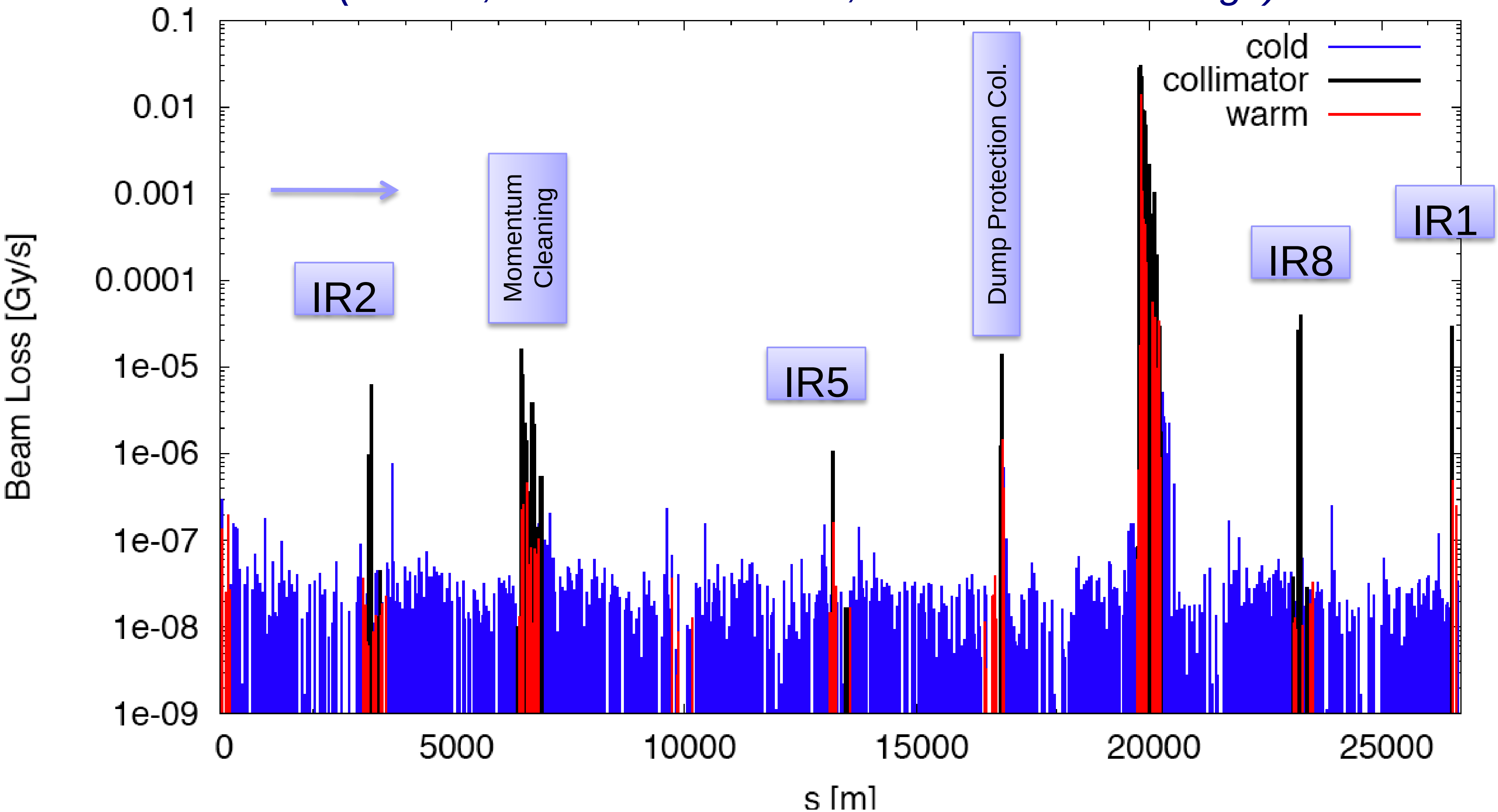


… but efficient …

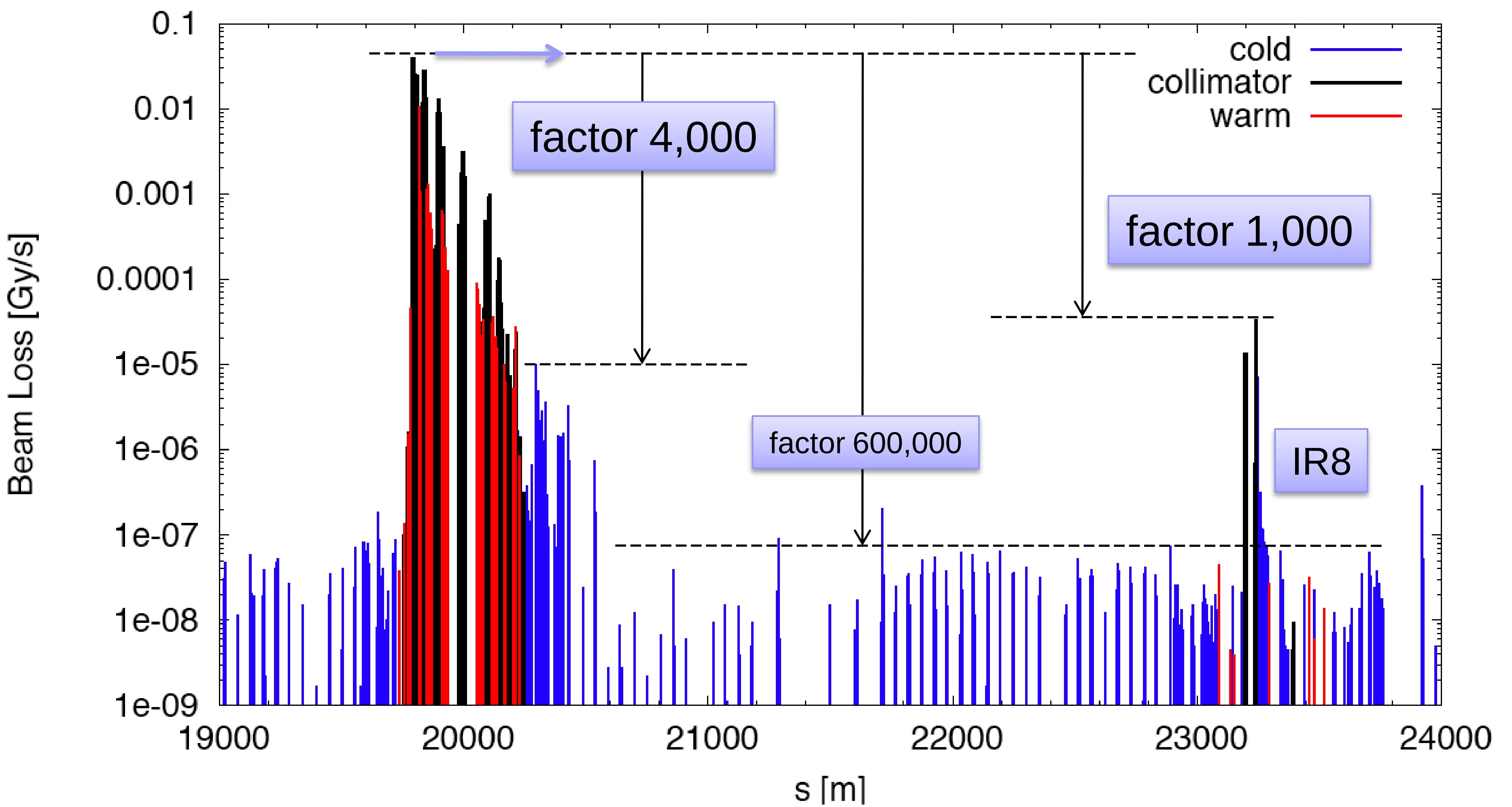
Measured Cleaning at 3.5 TeV

Making sure the hierarchy is respected

(beam1, vertical beam loss, intermediate settings)



Zoom around betatron cleaning



➔ OK for stable beams from collimation

Why we spend so long messing around…

- The collimators and protection devices must be in position at all times
- The hierarchy must be respected
- The collimators and protection devices are positioned with respect to the closed orbit
- Therefore the closed orbit must be in tolerance at all times. This includes the ramp and squeeze.
  - Orbit feedback becomes mandatory
  - Interlocks on orbit position become mandatory
- If these rules are not respected something will get broken.
- Frequent validation to make sure that the rules are respected…
- Full validation with new set-ups – takes time

Measured 450 GeV Aperture

- On-momentum, as relevant for collimation and protection.

Beam / plane	**Limiting element**	**Aperture [σ]**
Beam 1 H	Q6.R2	12.5
Beam 1 V	Q4.L6	13.5
Beam 2 H	Q5.R6	14.0
Beam 2 V	Q4.R6	13.0

- Predicted aperture bottlenecks in triplets (n1=7) are less than expected (orbit, alignment, mechanical tolerances)
- “Measured” n1 = 10 – 12 (on-momentum) instead of the design value of n1 = 7. Excellent news…

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n\beta^*} F$$

LUMINOSITY PRODUCTION

Luminosity

- Very good single beam lifetime
  - Inject nominal bunch intensities, ramp, squeeze…
  - Vacuum, non-linearities, IBS, noise
- Beam-beam (head-on)
  - Nominal bunch intensity
  - Less than nominal emittances
  - A lot easier than expected – nominal figures exceeded
  - Resolved expected problems with predicted cures.
    - Octupoles, transverse dampers cope with instabilities

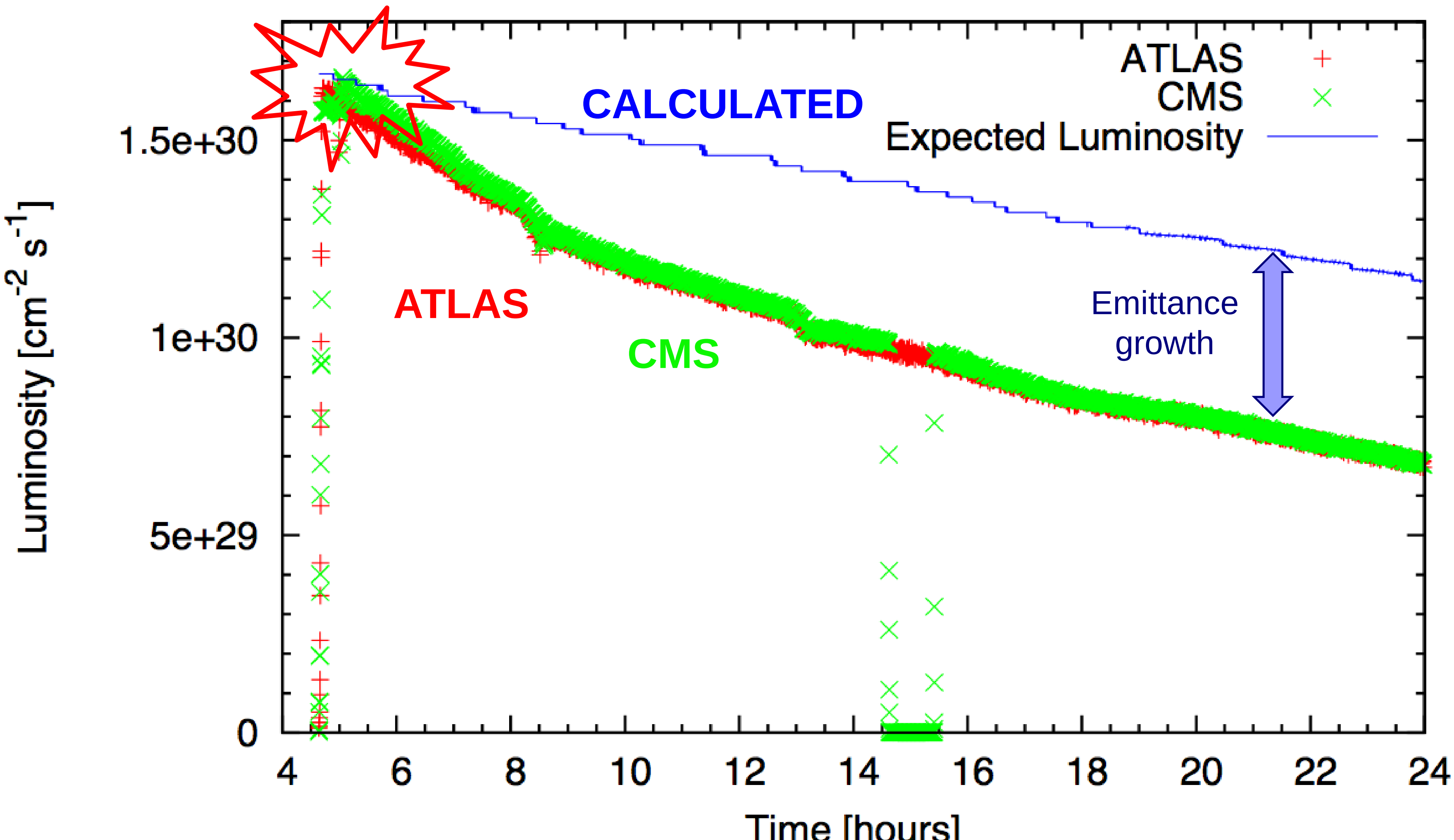
STILL SURPRISING

- Transverse emittance (read beam size)
  - Too small emittance from injectors! Blow-up required.
  - Ditto longitudinal plane
- Luminosity lifetime
  - Of the order 20-25 hours
  - Single beam, luminosity, emittance growth

Collisions – emittance blow up

Machine parameters very well controlled!

calculated with measured bunch intensity, nominal $\gamma\varepsilon$ = 3.75 μm and β^*=3.5m

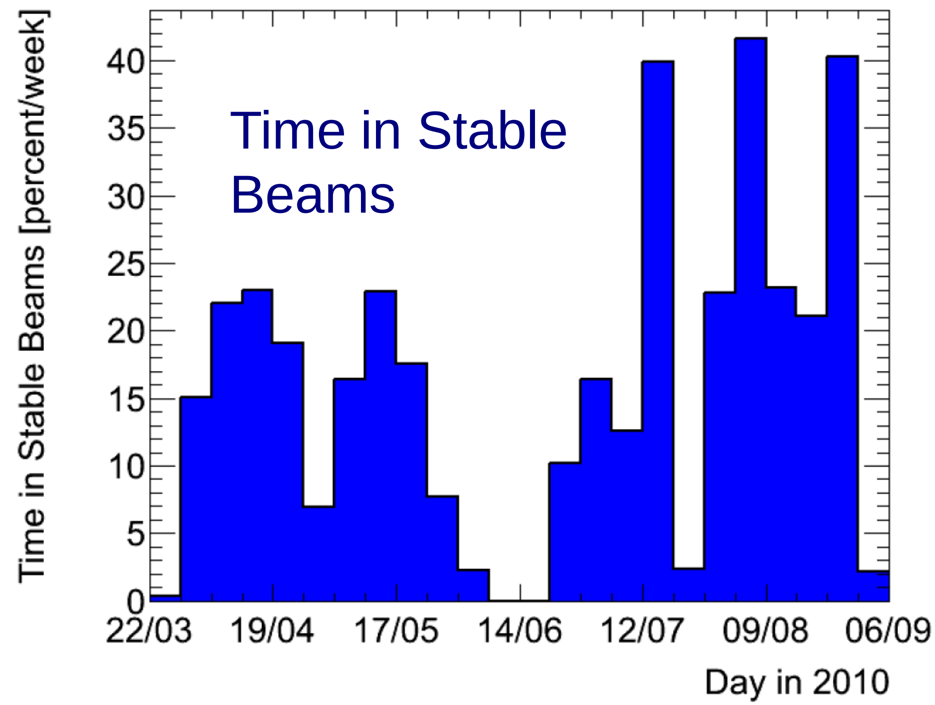


Coupled with remarkable machine availability

= integrated luminosity

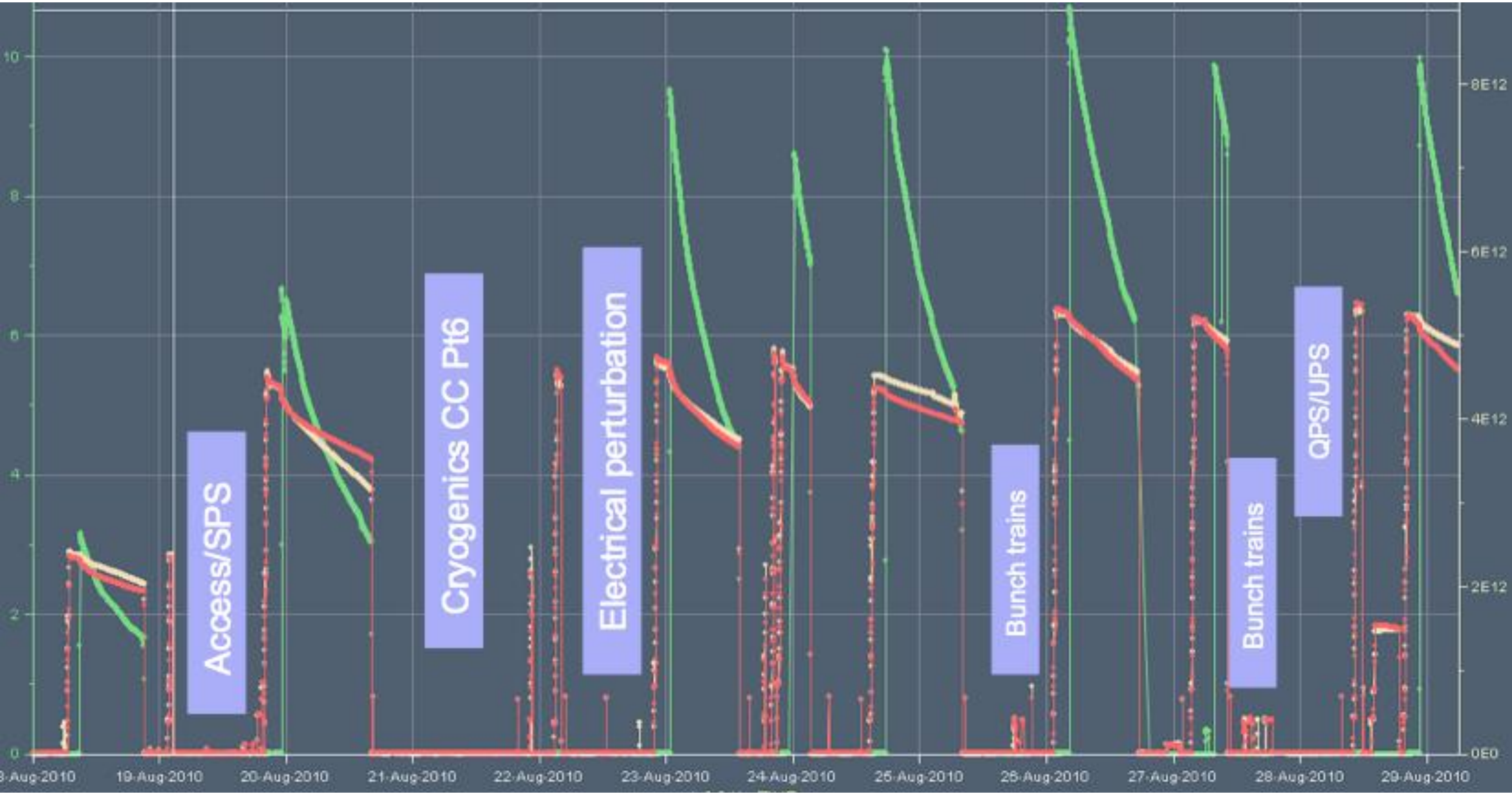
- Impressive performance of:
  - cryogenics,
  - QPS
  - power converters
  - RF
  - instrumentation,
  - collimators,
  - vacuum,
  - beam dump and kickers,
  - services,
  - Injectors, …

Courtesy ATLAS



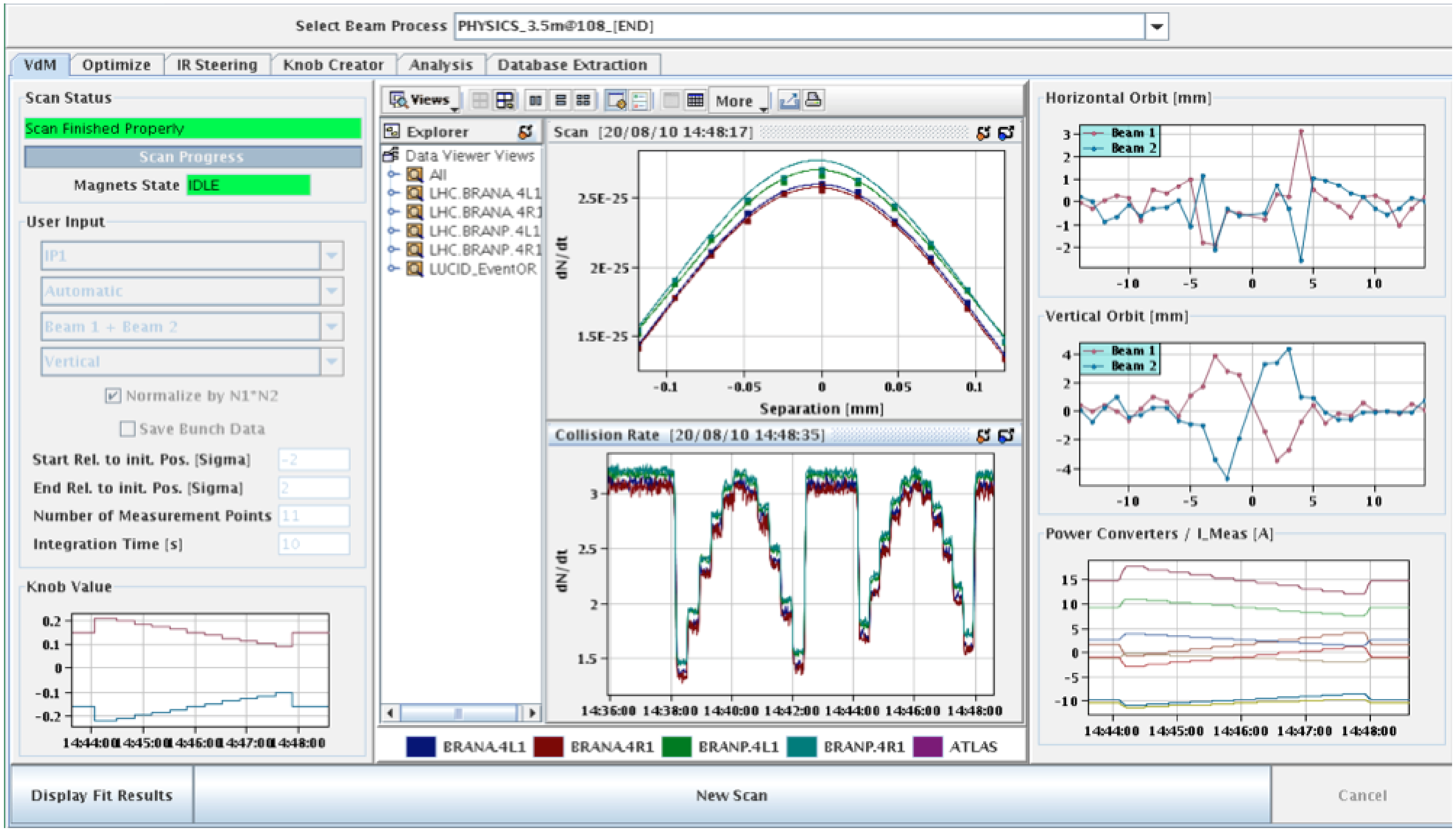
- Hard work of the many teams to constantly improve weaknesses and to keep it all working.

Two weeks in August



25b | ← 48b → | ← 50b →

Luminosity scans



Simon White

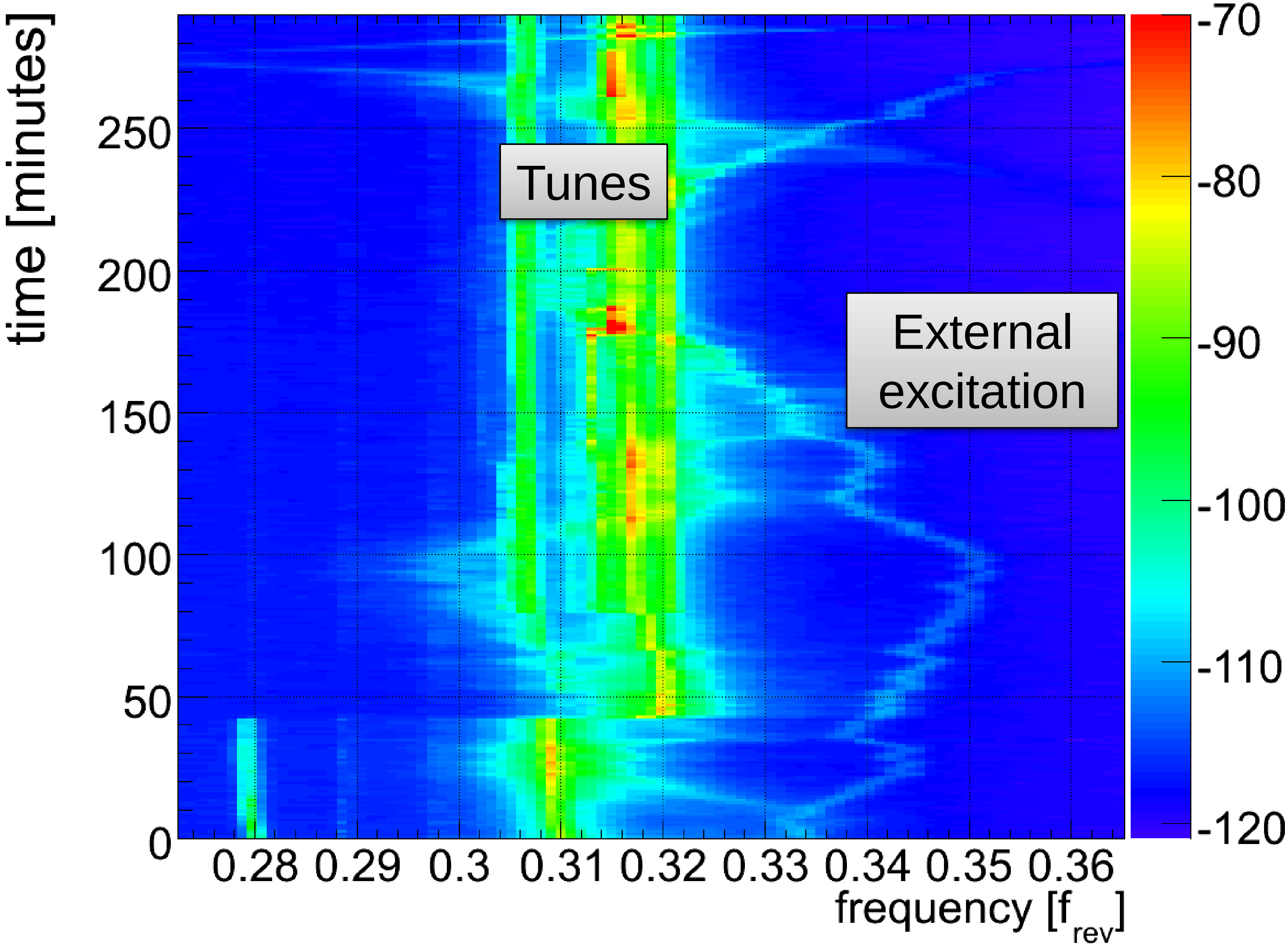
Luminosity calibrated with van der Meer scans

Luminosity known today to around 11% - error dominated by current measurement

Dedicated campaign underway

PROBLEMS, PROBLEMS

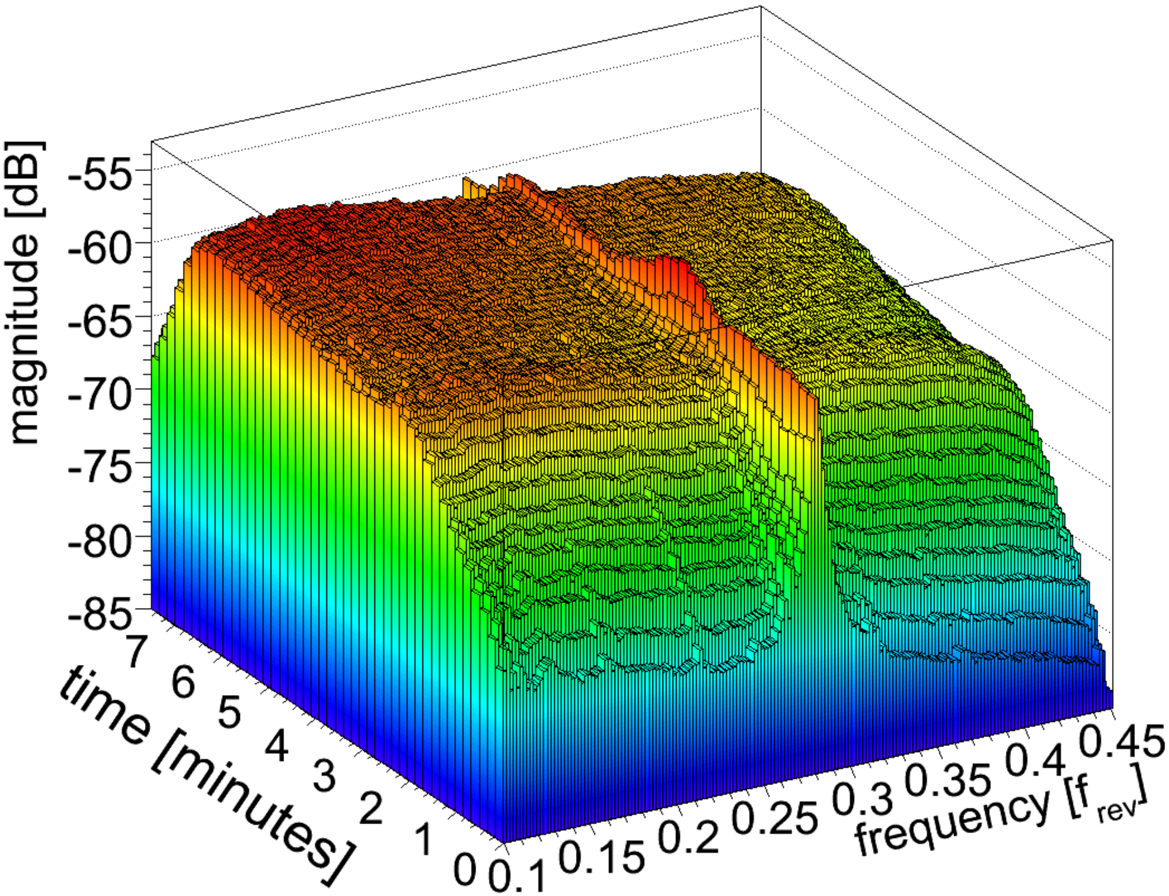
The hump - source still unknown



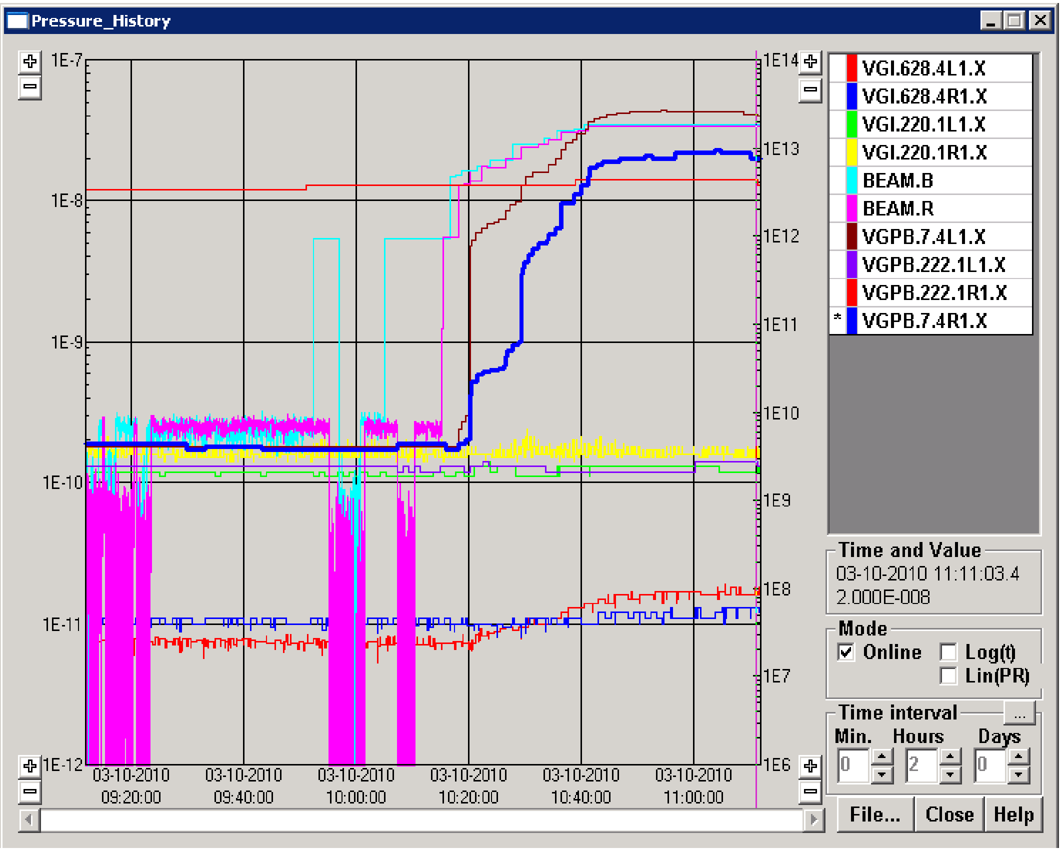
Tune signal swamped in the ramp

With increasing intensity/number of bunches

NOT good for tune feedback



Vacuum – from yesterday



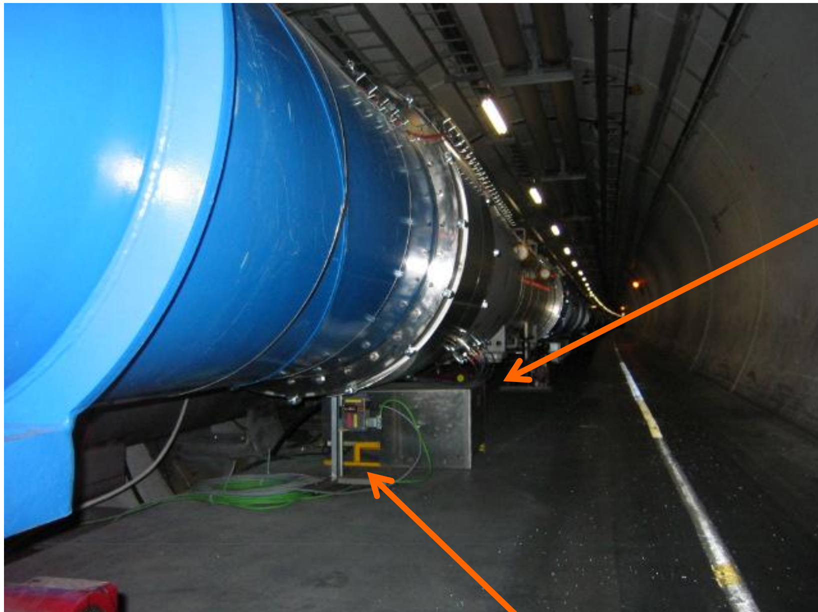
Possibly HOM induced cleaning…

Inner Triplet left 1 (VGPB.7.4L1.X):

Start pressure before filling: 1.8×10^{-10}mbar

End pressure after filling: **4.3×10^{-8}mbar**

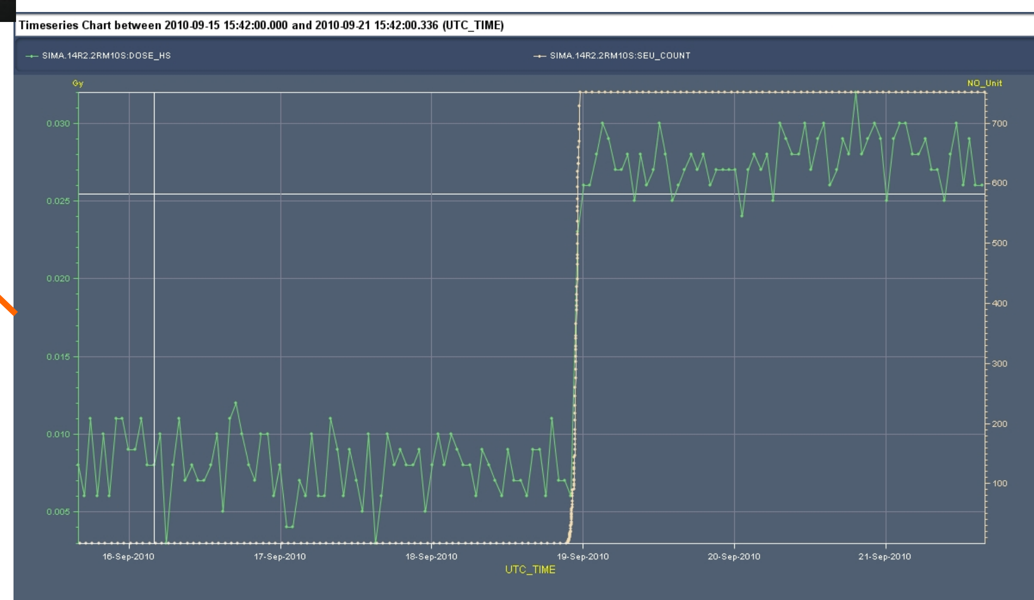
SEUs



QPS crate

SEU count (RADMON) during off momentum loss map

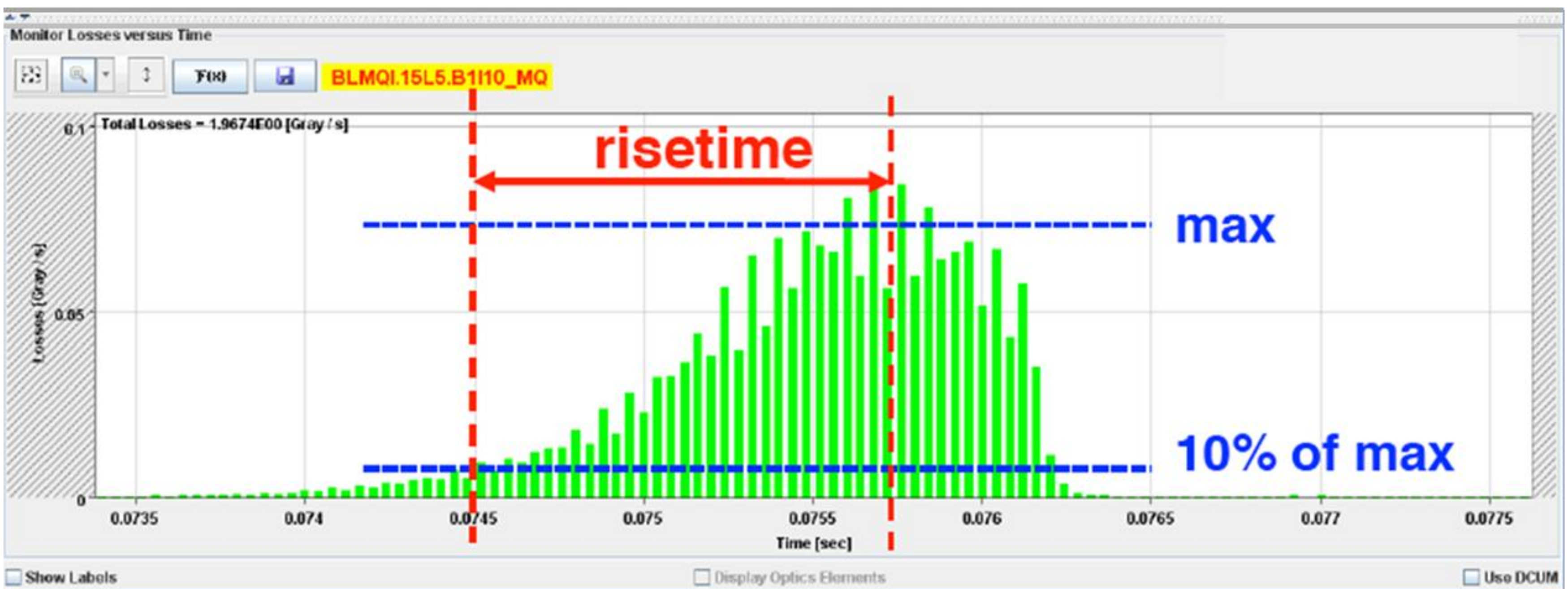
Thijs Wijnands



Not a problem at the moment but being monitored carefully

UFOs – sudden local losses

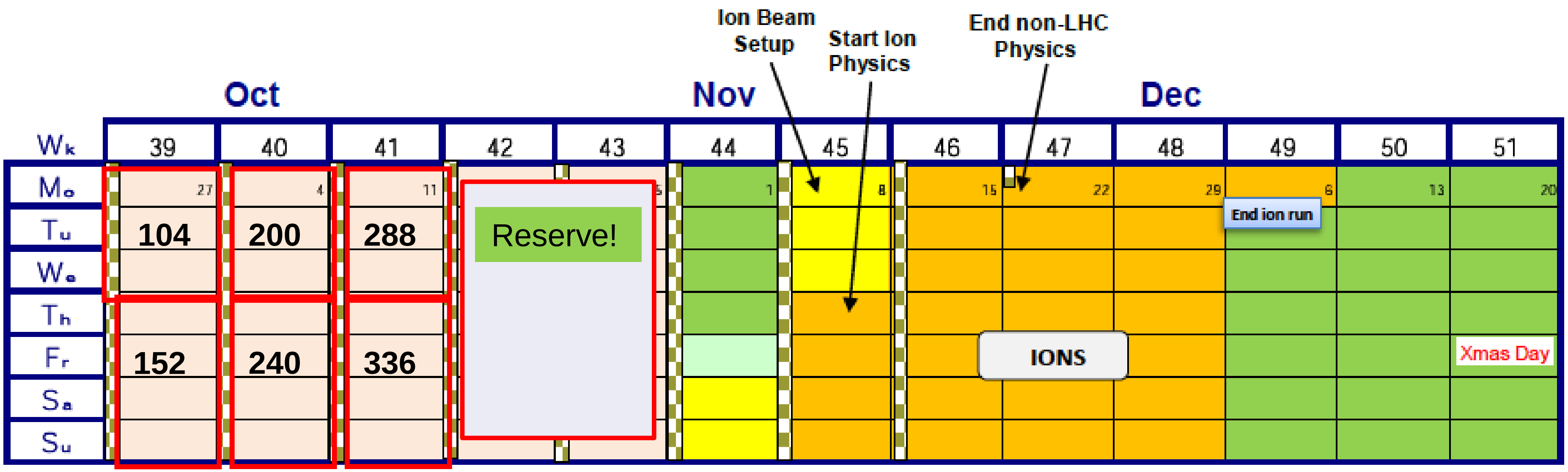
- 12 events of sudden local losses (some in the middle of the arc) have been recorded. No quench, but preventive dumps
- Rise time partly < 1 ms.
- Potential explanation: dust particles falling into beam creating scatter losses and showers propagating downstream



2010 INCOMING

Schedule – rest of 2010

Next up: 150ns_200b_186_8_186_8+8bpi17inj



Number of bunches	Peak Luminosity [cm^{-2}s^{-1}]	5day@0.2HF [pb^{-1}]	MJ
336	1.0×10^{32}	8.9	20.7

Early Heavy Ion Run

		Early (2010/11)	Nominal
√s per nucleon	TeV	2.76	5.5
Initial Luminosity (L_0)	$cm^{-2}s^{-1}$	**1.25×10^{25}**	**10^{27}**
Number of bunches		**62**	592
Bunch spacing	ns	1350	99.8
β*	m	2	0.5
Pb ions/bunch		**7×10^7**	7×10^7
Transverse norm. emittance	μm	1.5	1.5
Luminosity half life (1,2,3 expts.)	h	τ_{IBS}=7-30	8, 4.5, 3

Initial interaction rate: 100 Hz (10 Hz central collisions *b* = 0 – 5 fm)

~10^8 interaction/10^6s (~1 month)

In two years: **2 x10^7 central collisions, integrated luminosity 25 μb^{-1}**

2011 – 3.5 TeV

- Restart 4th February (?)
- 9 months protons, 4 weeks ions
- Integrated luminosity target driven: 1 fb^{-1}
- Need to run flat out above 1e32 $cm^{-2}s^{-1}$
- Beta* etc. under close examination – tests incoming

Table 4: Possible 2011 ball-park scenarios with 1.1×10^{11} protons per bunch.

N_b	β^* [m]	Energy per beam [MJ]	Peak Luminosity [$cm^{-2}s^{-1}$]	Int. Lumi per month [pb^{-1}]
432	3.5	27	1.3×10^{32}	61
432	2.5	27	1.8×10^{32}	85
796	3.5	49	2.4×10^{32}	113
796	2.5	49	3.4×10^{32}	157

Conclusions 1/2

- Injection, ramp and squeeze operational
- LHC magnetic model, optics astoundingly good.
- Beam instrumentation in good shape.
- Feedbacks on orbit and tune(?) operational
- Beam cleaning and collimation works reliably with predicted efficiency.
- Machine protection reliably catches failures etc.
- Machine aperture looks very good
- Remarkably few problems colliding nominal bunch intensities

Conclusions 2/2

- All key systems performing remarkably well & there are some hugely complex systems out there.
  - Some commissioning still required, issues still to address
  - And NB there are still problems
- Handling dangerous beams already - have to remain vigilant at all times (and not get carried away)
- Performance with beam (losses, lifetimes, luminosity, emittance growth etc.) is very encouraging
- Machine availability is excellent – the hard work of numerous teams
- On route towards 10^{32} cm^{-2} s^{-1} for end of the year - a factor 2 to go