LHC Beam Operation Workshop

Royal Hotel, Evian, France

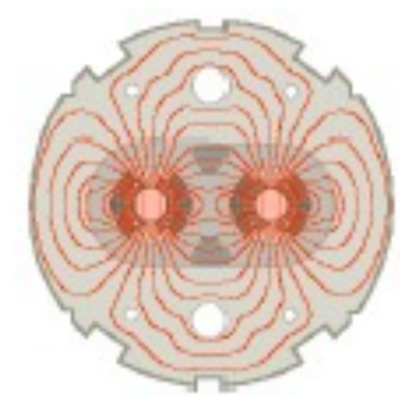
December 12th-14th, 2011

LHC aperture & optics

S. Redaelli, R. Bruce, X. Buffat, M. Giovannozzi,

M. Lamont, G. Müller, R. Tomás, J. Wenninger

CERN - BE department



Acknowledgements and references

Controls: G. Kruk, M. Strzelczyk (ABP)
LHC operations: M. Lamont, L. Ponce, J. Wenninger, N. Ryckx (EPFL), OP crews, machine coordinators
Aperture: M.C. Alabau Pons, R. Assmann, R. Bruce, M. Giovannozzi, E. Maclean, G. Müller, S. Redaelli, F. Schmidt, R. Tomas, J. Wenninger
Beta-beat: M. Aiba, R. Calaga, R. Miyamoto, R. Tomás and G. Vanbavinckhove
Collimation: R. Assmann, R. Bruce, S. Redaelli, G. Valentino, D. Wollmann
FiDeL: P. Hagen, E. Todesco
Orbit/Tune FB: R. Steinhagen, J. Wenninger
Other: W. Herr, S. Fartoukh, J. Jowett

Recent 2011 presentations on aperture and squeeze:
- G. Müller, **LBOC, Nov. 22nd, 2011**: IR2 aperture
- R. Bruce, **LBOC, Oct. 11th, 2011**: IR1+IR5 aperture; **LBOC, Mar. 8th, 2011**, 450 GeV aperture
- J. Wenninger, **LMC, Nov. 2nd, 2011**, IR2 aperture (β^*=1.0m)
- S. Redaelli, **LMC, Aug. 31st, 2011**, IR1/5 aperture at 3.5 TeV (β^*=1.5m); **LBOC, Feb. 8th, 2011**, Squeeze baseline

References to published papers/notes:

PAC2009: S. Redaelli, I. Agapov, R. Calaga, B. Dehning, M. Giovannozzi, F. Roncarolo, R. Tomas, "First beam-based aperture measurements for arcs and insertions of the LHC"
Evian2010 (Jan.): M. Lamont, G. Müller, S. Redaelli, M. Strzelczyk, "Betatron squeeze: status, strategy and issues"
IPAC2010: C. Alabau Pons, M. Giovannozzi, G. Müller, S. Redaelli, F. Schmidt, R. Tomas, J. Wenninger, "LHC aperture measurements"
HB2010: S. Redaelli, X. Buffat, M. Lamont, G. Müller, R. Steinhagen, J. Wenninger, "Commissioning of ramp and squeeze at the LHC"
IPAC2011: R. Assmann, M. C. Alabau Pons, R. Bruce, M. Giovannozzi, G. Müller, S. Redaelli, F. Schmidt, R. Tomás, J. Wenninger, D. Wollmann, "Aperture determination in the LHC based on an emittance blowup technique with collimator position scans"
ICALEPCS2011: G.J. Müller, K. Fuchsberger, S. Redaelli, "Aperture meter for the LHC"
CERN ATS notes: CERN-ATS-Note-2011-110 MD, Notes on IR2 aperture and squeeze commissioning in prep.

Introduction

$$\mathcal{L} \propto \frac{1}{\beta^*}$$

Luminosity

For given E_{stored}, **β^*** is a key parameter producing luminosity!
Pushing β^* requires enough **aperture** in the triplet magnets.
β^* changes are not “adiabatic” but require commissioning time.

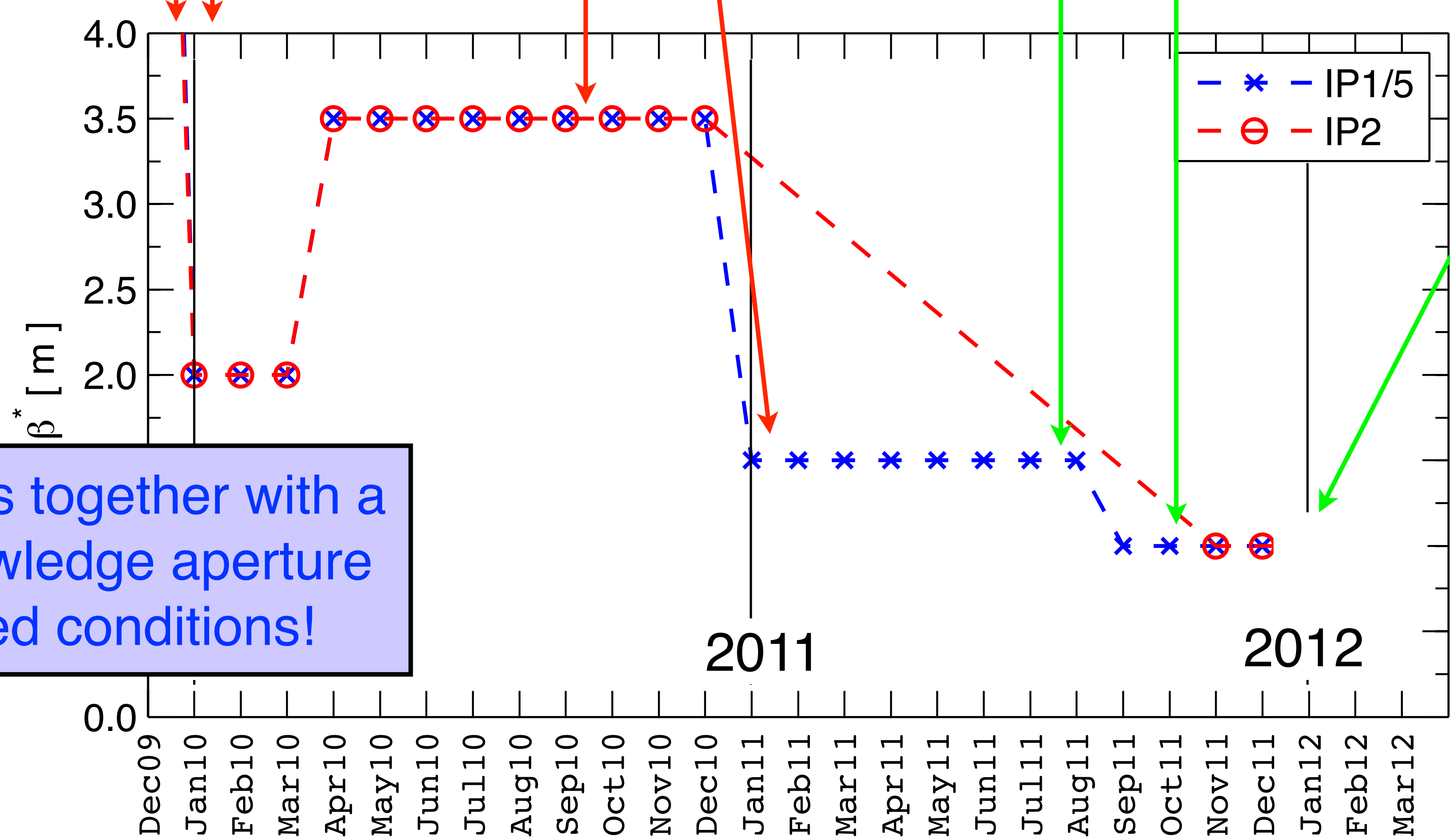
Initial 450 GeV measurements

MQX aperture at 450 GeV

IR1/5 aperture at 3.5 TeV

IR2 aperture at 3.5 TeV

2012 β^* must also rely on aperture measurements!



β^* reach goes together with a detailed knowledge aperture in squeezed conditions!

Outline

- **Introduction**
- **2011 machine config.**
- **Squeeze in 2011**
  - *Overall performance*
  - *Outstanding issues for 2012*
- **LHC Aperture**
  - *Injection aperture*
  - *IR aperture at 3.5 TeV*
  - *Beam-based β* reach*
- **Conclusions**

2011 parameter table

Parameter	Injection	Squeeze 1	Squeeze 2	Squeeze ions
	Feb.-Dec.	Feb.-Aug.	Sep.-Oct.	Nov.-Dec.
Energy [GeV]	450	3500	3500	3500
β* IP1/5 [m]	11.0	1.5	1.0	1.0
β* IP8 [m]	10.0	3.0	3.0	3.0
β* IP2 [m]	10.0	10.0	10.0	1.0
Sep. [mm]	2.0	0.7	0.7	0.7
$Xing^{IP1/5}$ [μrad]	170	120	120	120
$Xing^{IP2}$ [μrad]	170	80	80	80
$Xing^{IP8}$ [μrad]	170	250	250	250
Ramp [s]	1020	1020	1020	1020
Squeeze [s]	-	475	558	1233
Collision [s]	-	56	56	260

In addition to physics, special optics for forward physics and MDs:
β^* = 90m and **ATS** (H. Burkhardt, S. Fartouhk, *et al.*)

What does this mean in practice?

Optics models	Number of optics	Knobs per optics *(Q, Q', C, Xing, ..)*
p/Pb operation	90 (30 used)	50
β*=90m IP1/5	18	20
ATS	57	40
TOTAL	**165**	**7140**

Efficient handling of optics and knobs + systematic validation of settings is crucial a successful commissioning

Taken care of by the **LHC Online Model**

The MADX online packages take care of:

- The definition of models from ABP inputs
- Generation and upload of Twiss tables required in the LSA database
  - → *This is the input used to generate all settings within LSA*
- Generation and verification of knobs with JMAD
  - → *Virtual trims, verification of knob definitions*
- Validation of settings for power converter functions (ramp, squeeze)
  - → *Beam process scanner*

Many thanks to Gabriel M.

Outline

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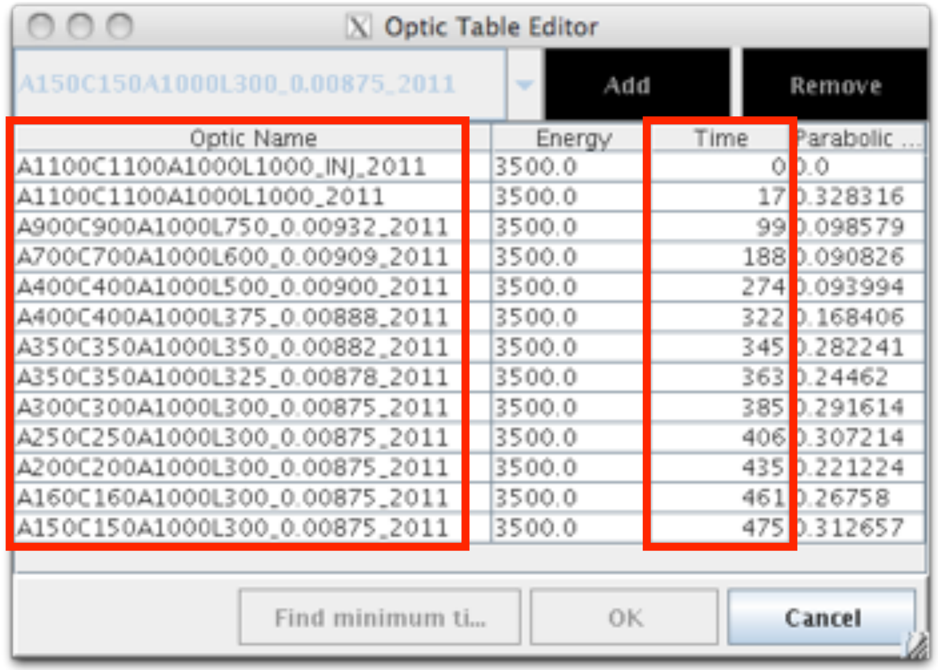
  - ***Overall performance***
  - ***Outstanding issues for 2012***
- LHC Aperture
- Conclusions

Recap. of squeeze mechanics

Matched optics for β = 1.5m in IP1/5*



Optic Table Editor

A150C150A1000L300_0.00875_2011 | Add | Remove

Optic Name	Energy	Time	Parabolic ...
A1100C1100A1000L1000_INJ_2011	3500.0	0	0.0
A1100C1100A1000L1000_2011	3500.0	17	0.328316
A900C900A1000L750_0.00932_2011	3500.0	99	0.098579
A700C700A1000L600_0.00909_2011	3500.0	188	0.090826
A400C400A1000L500_0.00900_2011	3500.0	274	0.093994
A400C400A1000L375_0.00888_2011	3500.0	322	0.168406
A350C350A1000L350_0.00882_2011	3500.0	345	0.282241
A350C350A1000L325_0.00878_2011	3500.0	363	0.24462
A300C300A1000L300_0.00875_2011	3500.0	385	0.291614
A250C250A1000L300_0.00875_2011	3500.0	406	0.307214
A200C200A1000L300_0.00875_2011	3500.0	435	0.221224
A160C160A1000L300_0.00875_2011	3500.0	461	0.26758
A150C150A1000L300_0.00875_2011	3500.0	475	0.312657

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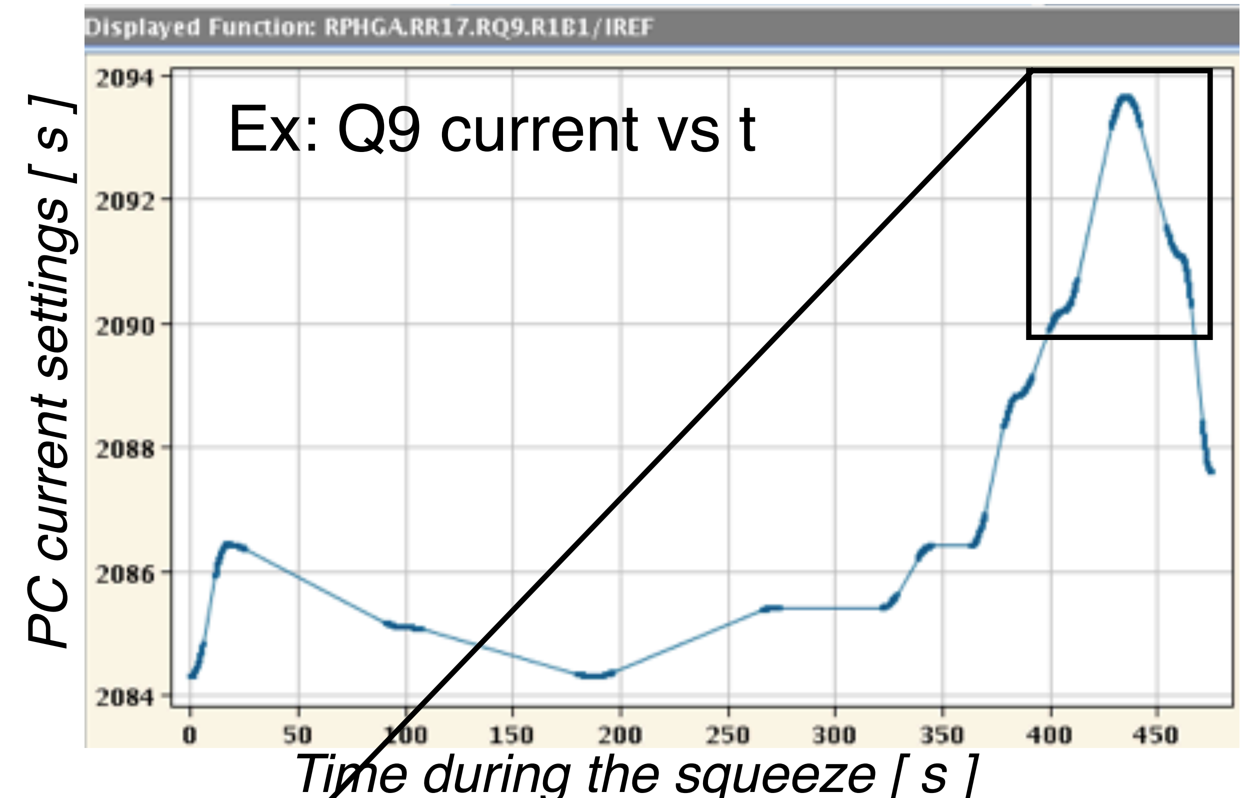
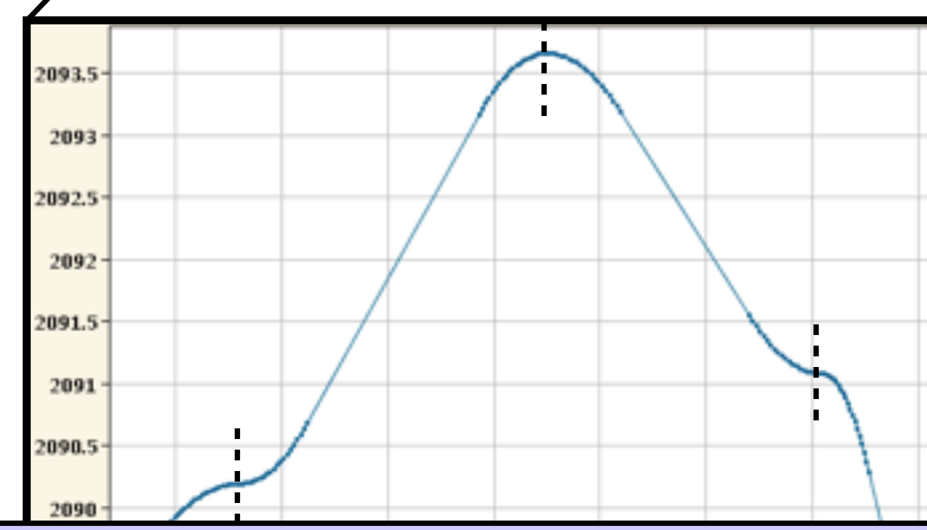




1. Define the list optics (different β*'s) from the ones available by ABP
2. LSA calculates the minimum time for the power converters to step through → β*(t)
3. Quadrupole settings generated with round-offs at matched points
4. Generate settings for other systems *(orbit bumps, sextupoles, collimators, RF, ...)*

Note: round-off not applied for all circuits types

Can "stop" the squeeze execution at the matched points.
This is done in the first commissioning to optimize the machine parameters!

Masters of generation:
Greg K. + Marek S., with Mike L.

Optimization of squeeze duration

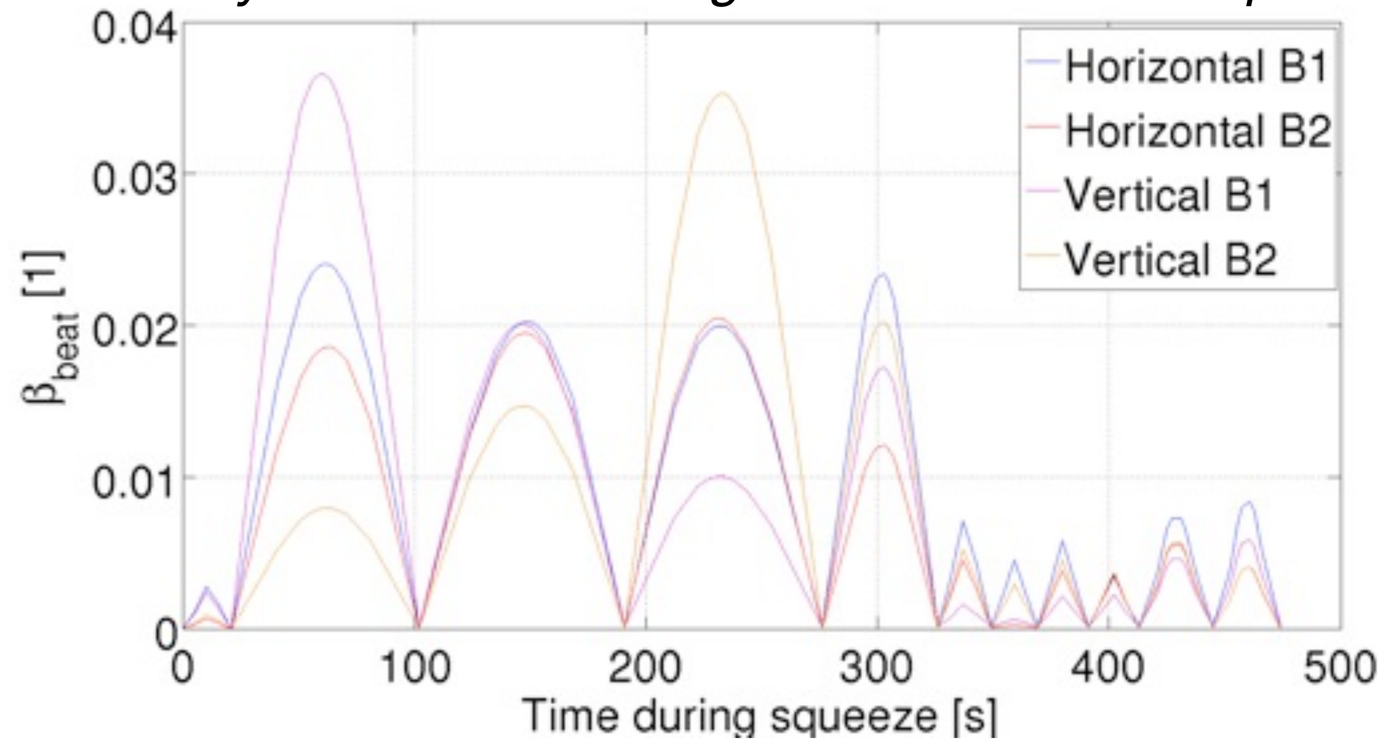
(X. Buffat: CERN-THESIS-2011-006)

Beam process scanner

Simulates the **dynamic errors**, using the LSA settings functions:

1. *Independent verification of generated settings, based on MADX calculations*
2. *Optimize function duration by reducing number of optics with small errors*
3. *Calculation of dynamics errors vs t (tune, beta-beat, orbit), which can be fed back into settings!*

Dynamic beta-beating between matched optics

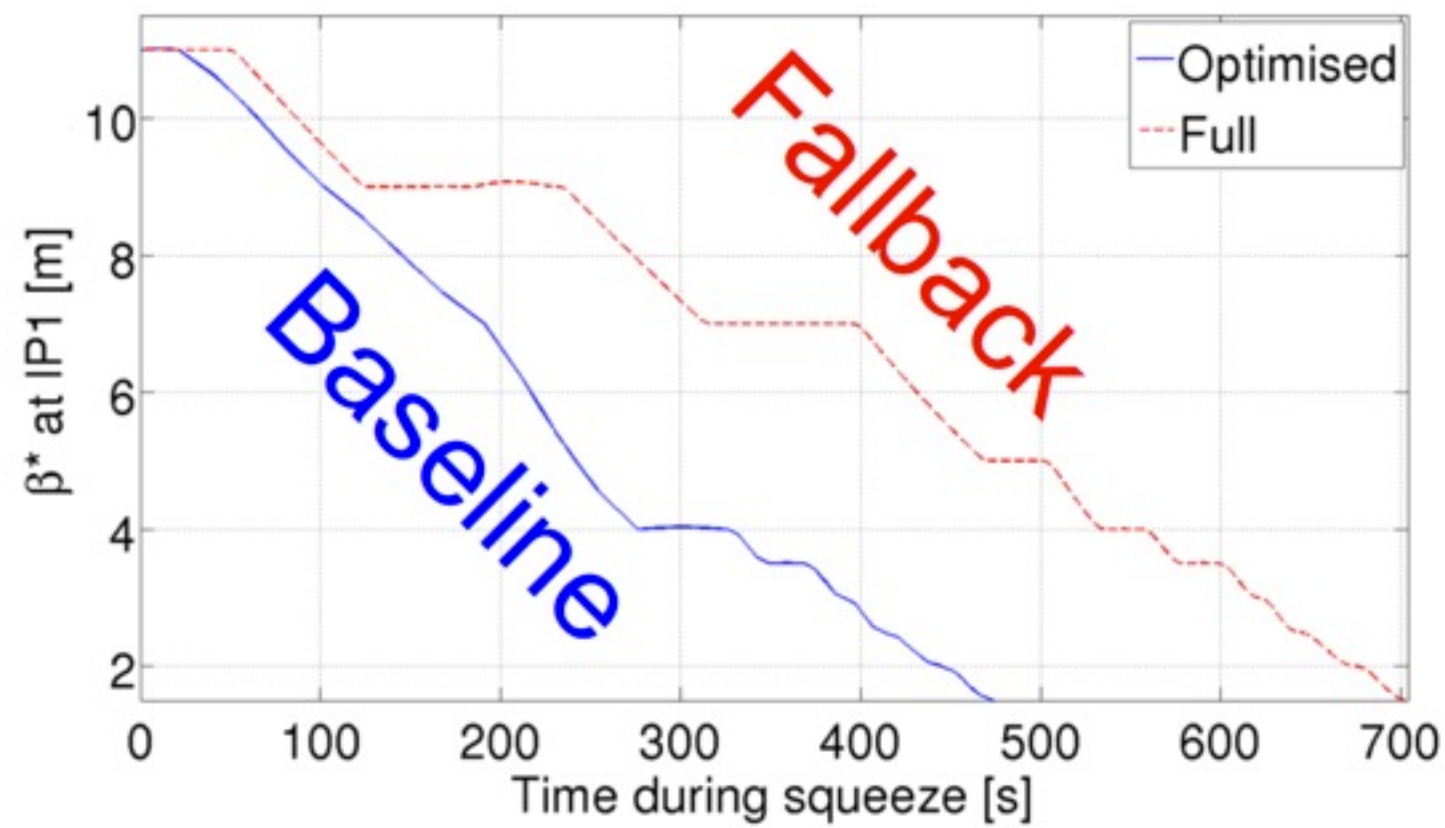


We proposed a shorter squeeze for 2011:

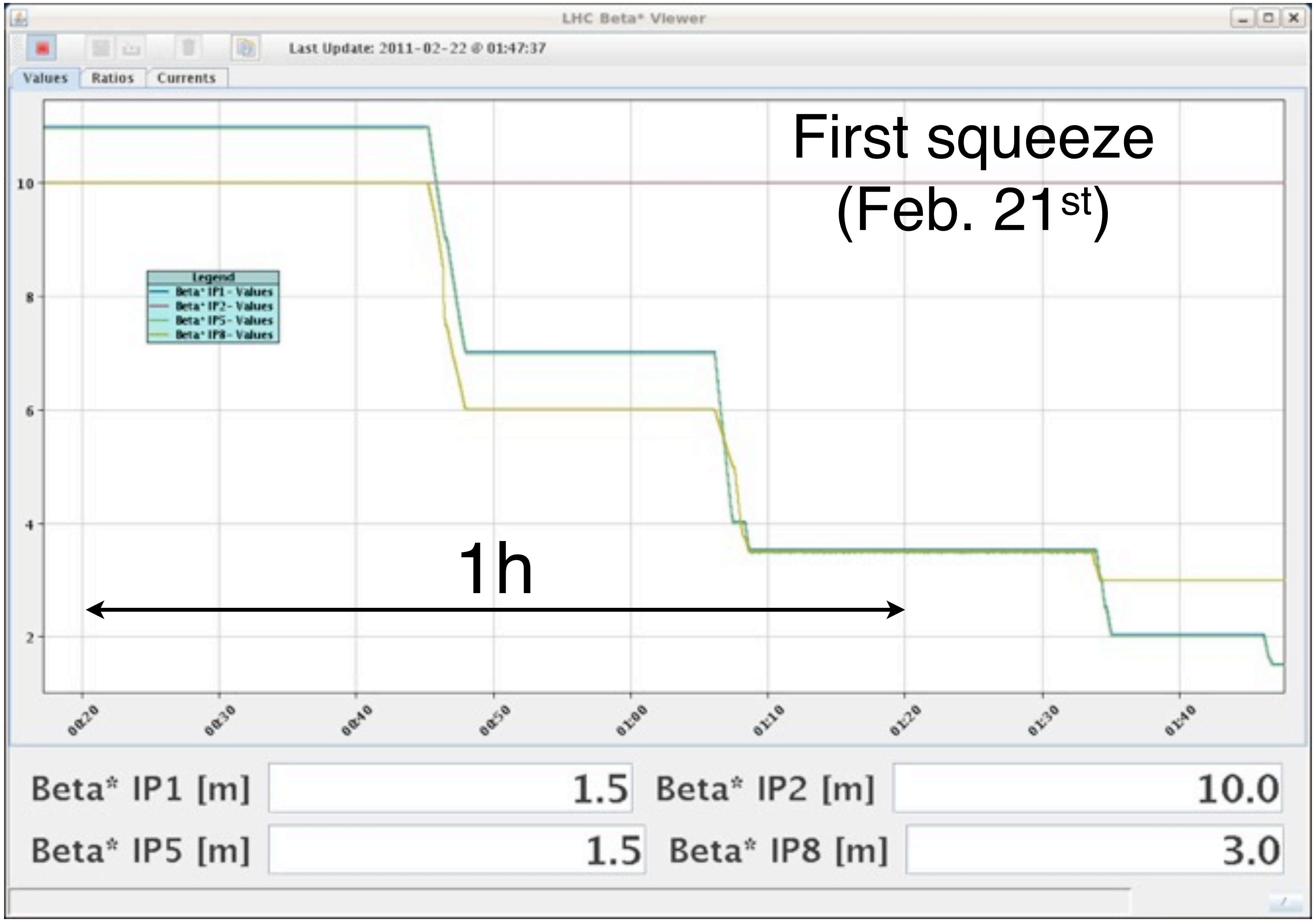
1200s (2 m) → 475 s (1.5 m)

(558 s for 1.0 m)

Idea: Reduce optics in the region > 2m relying on 2010 commissioning experience



Optics commissioning experience

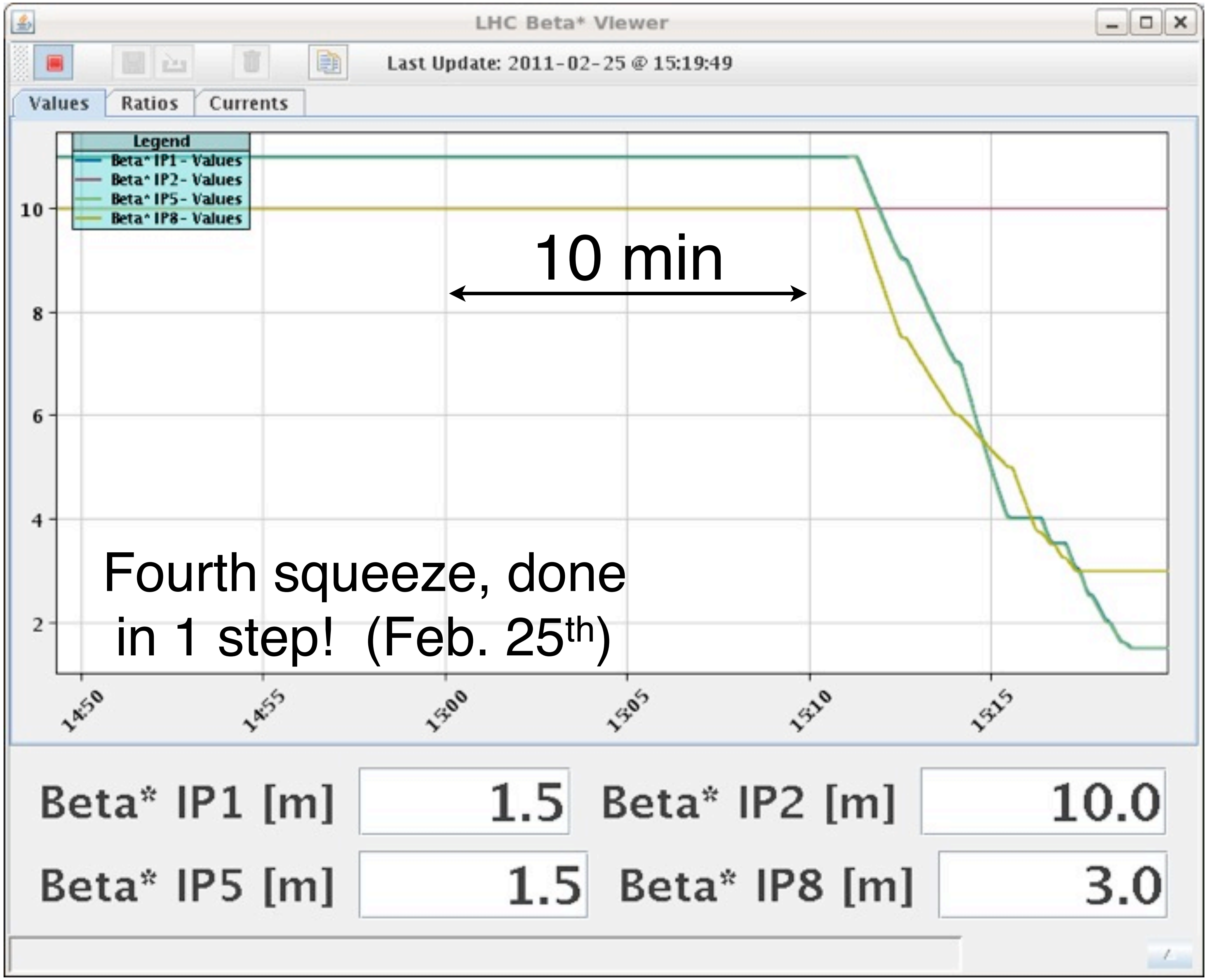


At the 4th attempt, we achieved continuous run through functions without stopping!

Similar smooth commissioning for
- further squeeze to 1 m
- IP2 squeeze to 1m
- 90m (H. Burkhardt et al.)
- ATS (S. Fartoukh et al.)

No time to review all.

Optics commissioning experience



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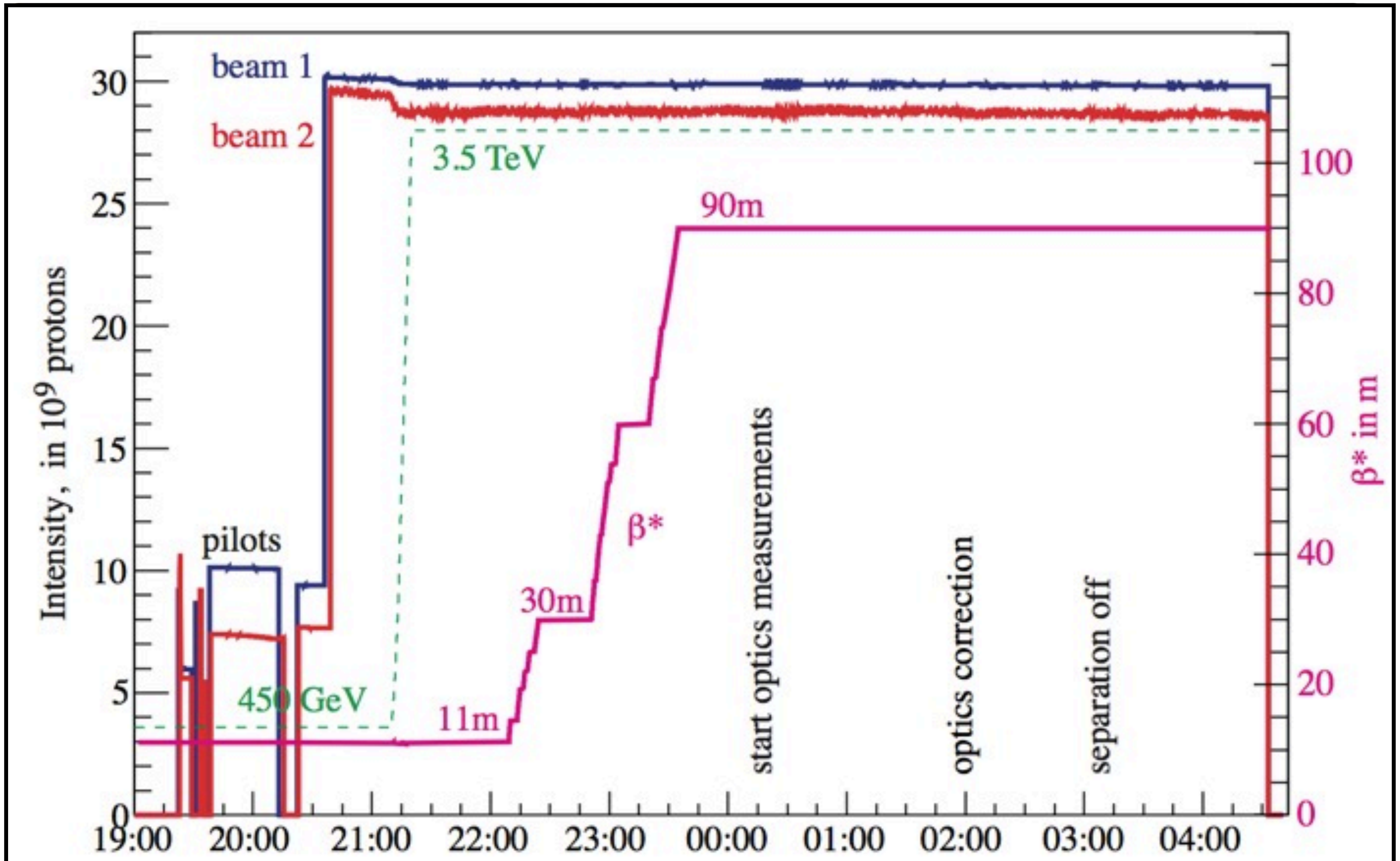

H. Burkhardt *et al.*

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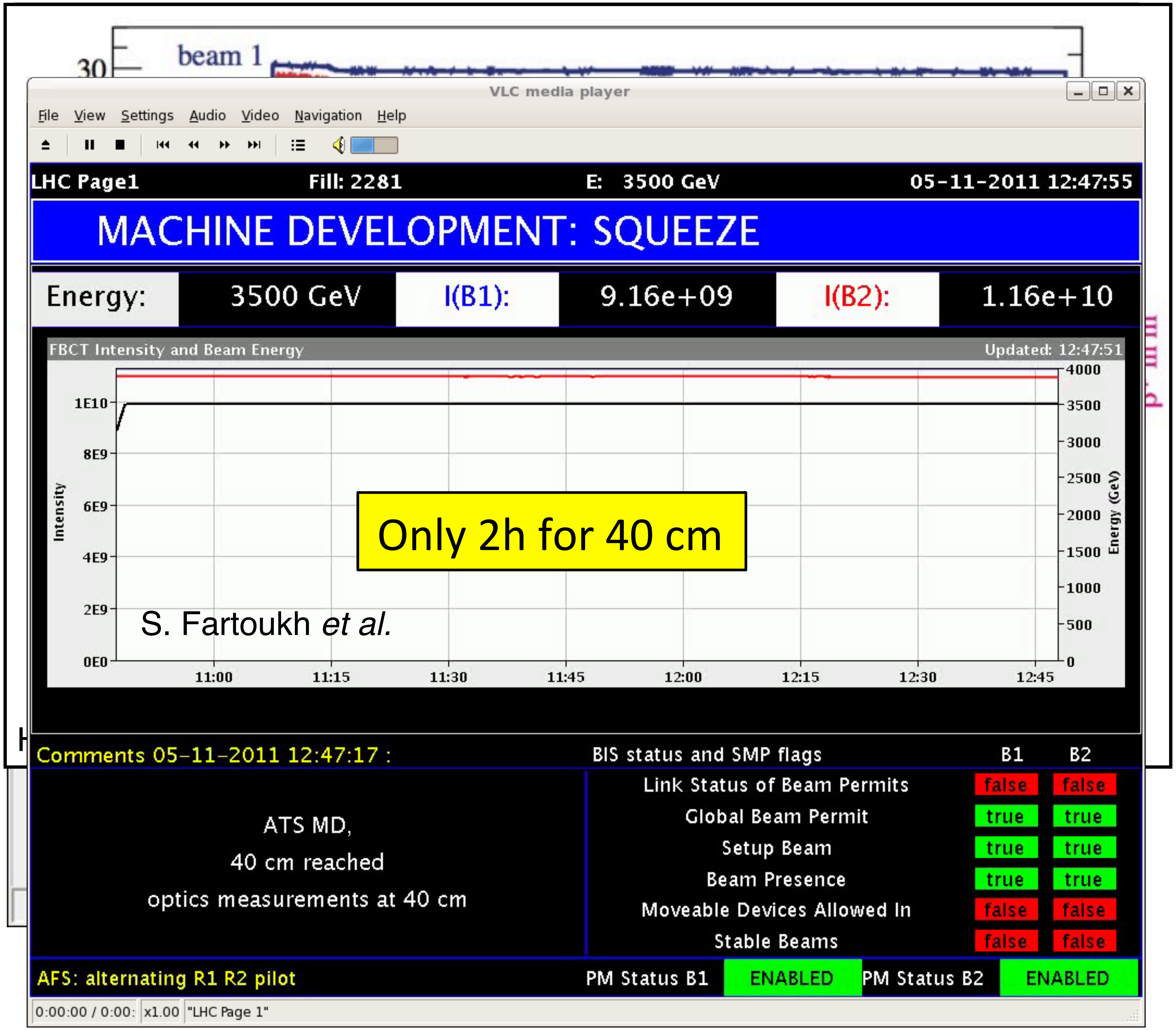

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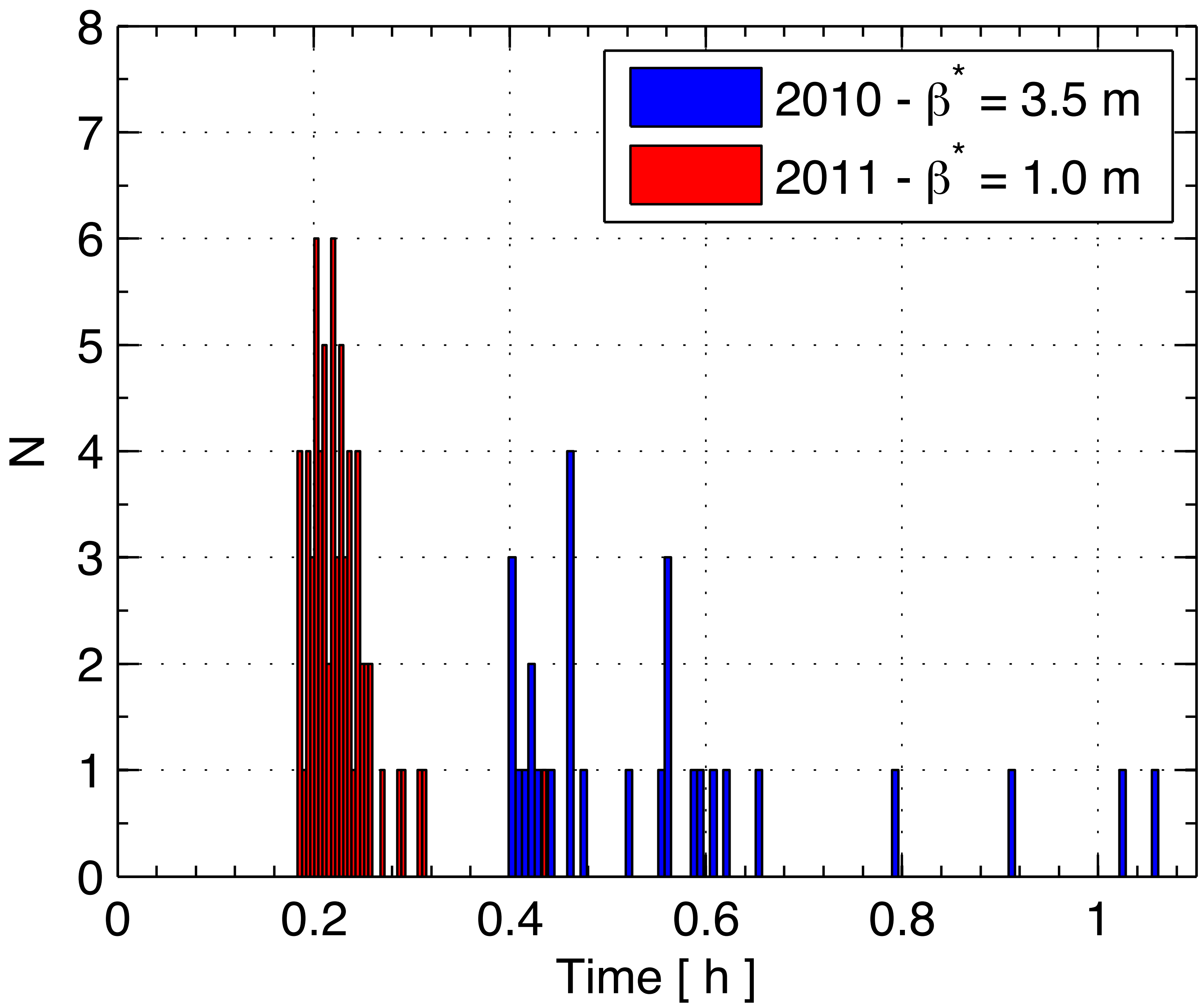
Squeeze duration

Considered only fills with squeeze to 1 m

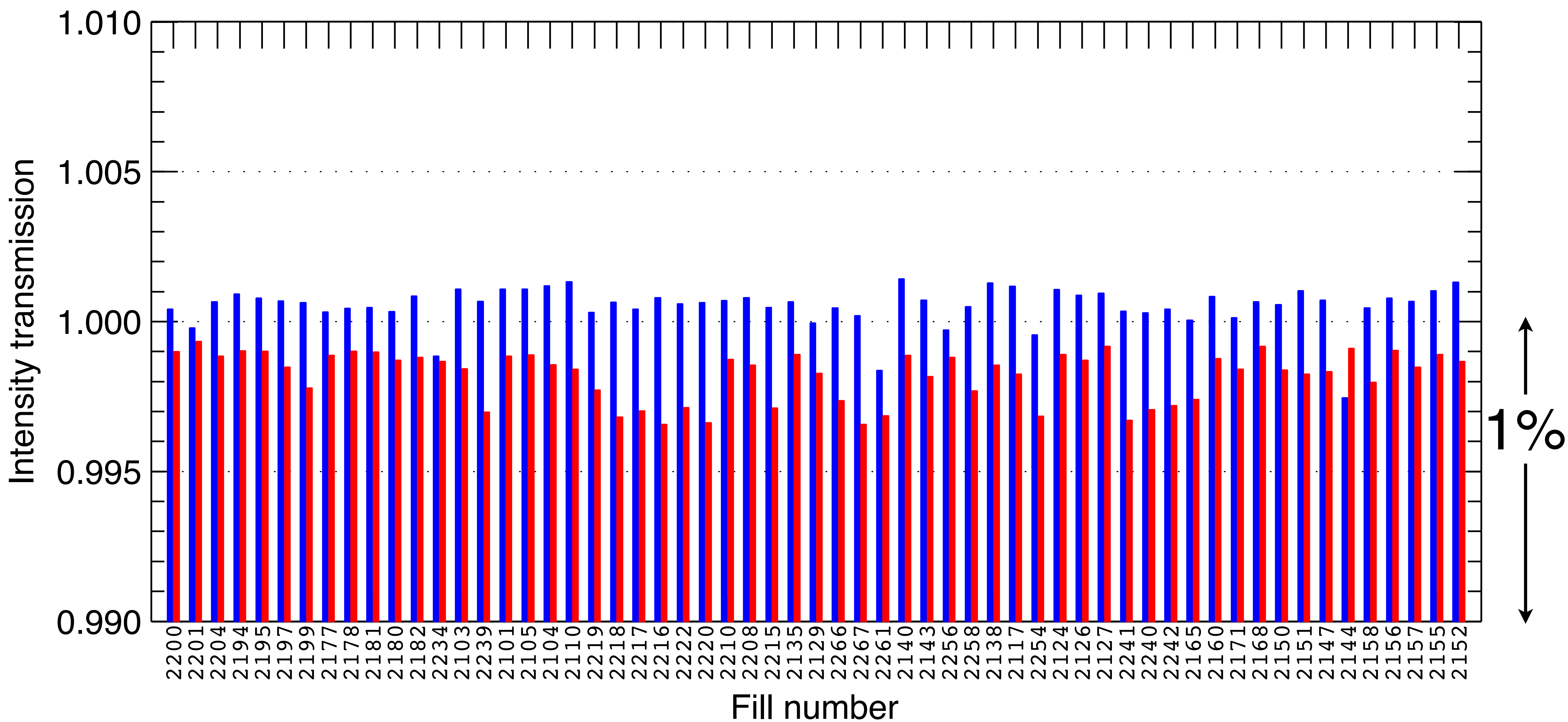


2010 operation to 3.5 m in all IPs → Average duration of 33.6 minutes

2011 operation to 1.0 m (IP1/5) and 3.0 m (IP8) → **13.7 minutes**

*More **robust operation efficiency** (no manual intervention with continuous functions, systematic feed-forward, ...); continuous collimator functions.*

Squeeze: intensity transmission

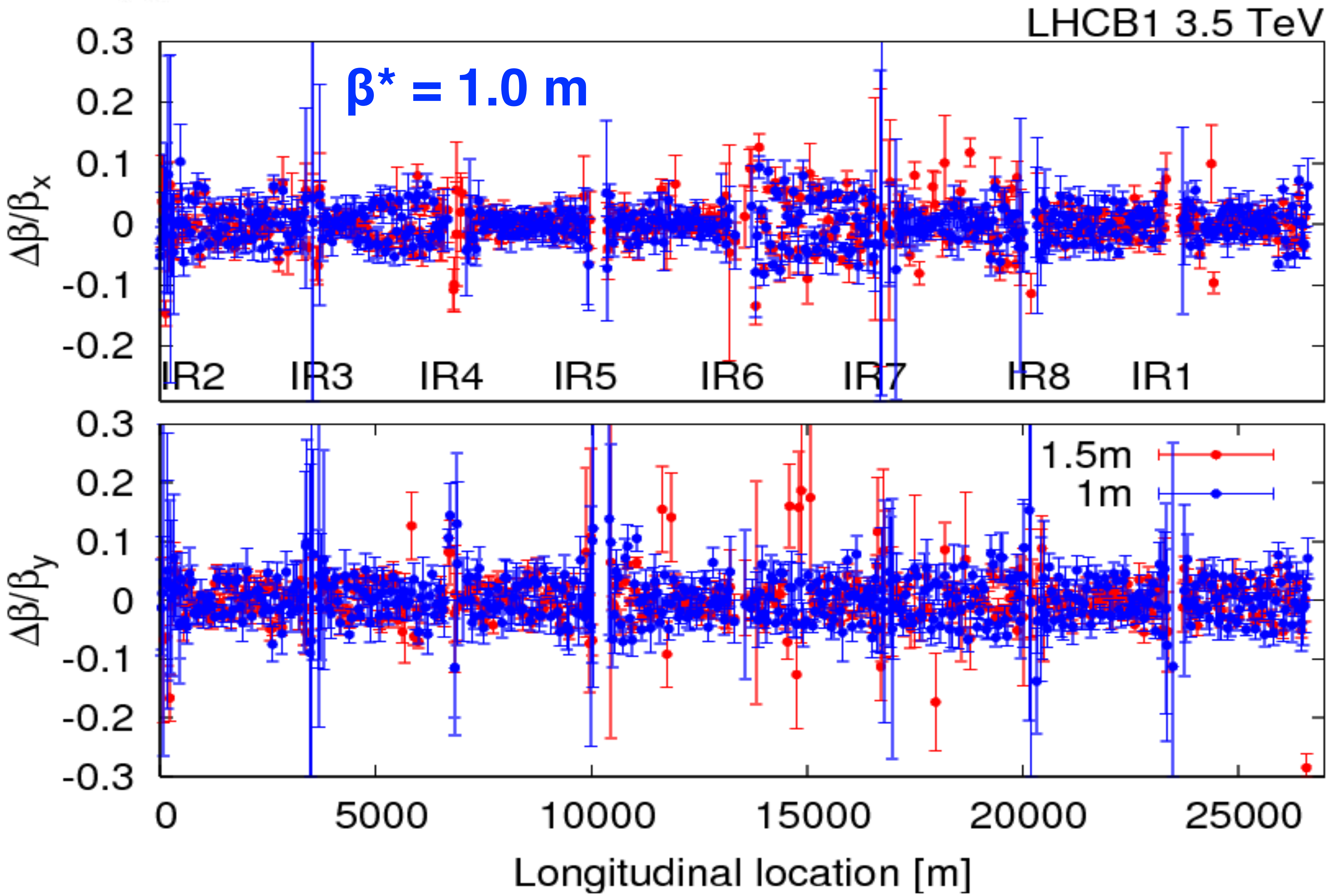


Error bars: take a few ‰ from noise on BCT signal (not shown in the plot)

~60 fills with 1380 proton bunches, β^*=1.0m, stored energy up to 110MJ:
Losses well below 1 % ! !

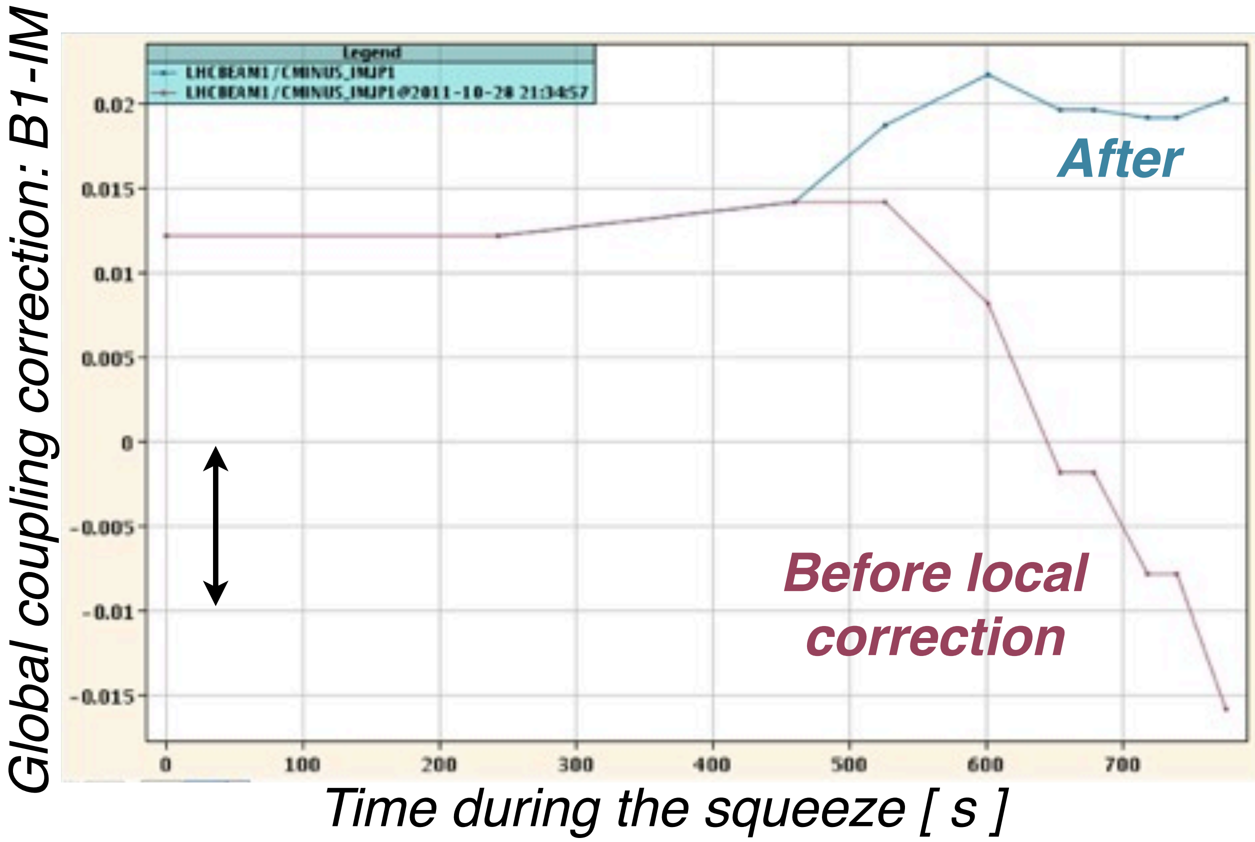
Optics performance

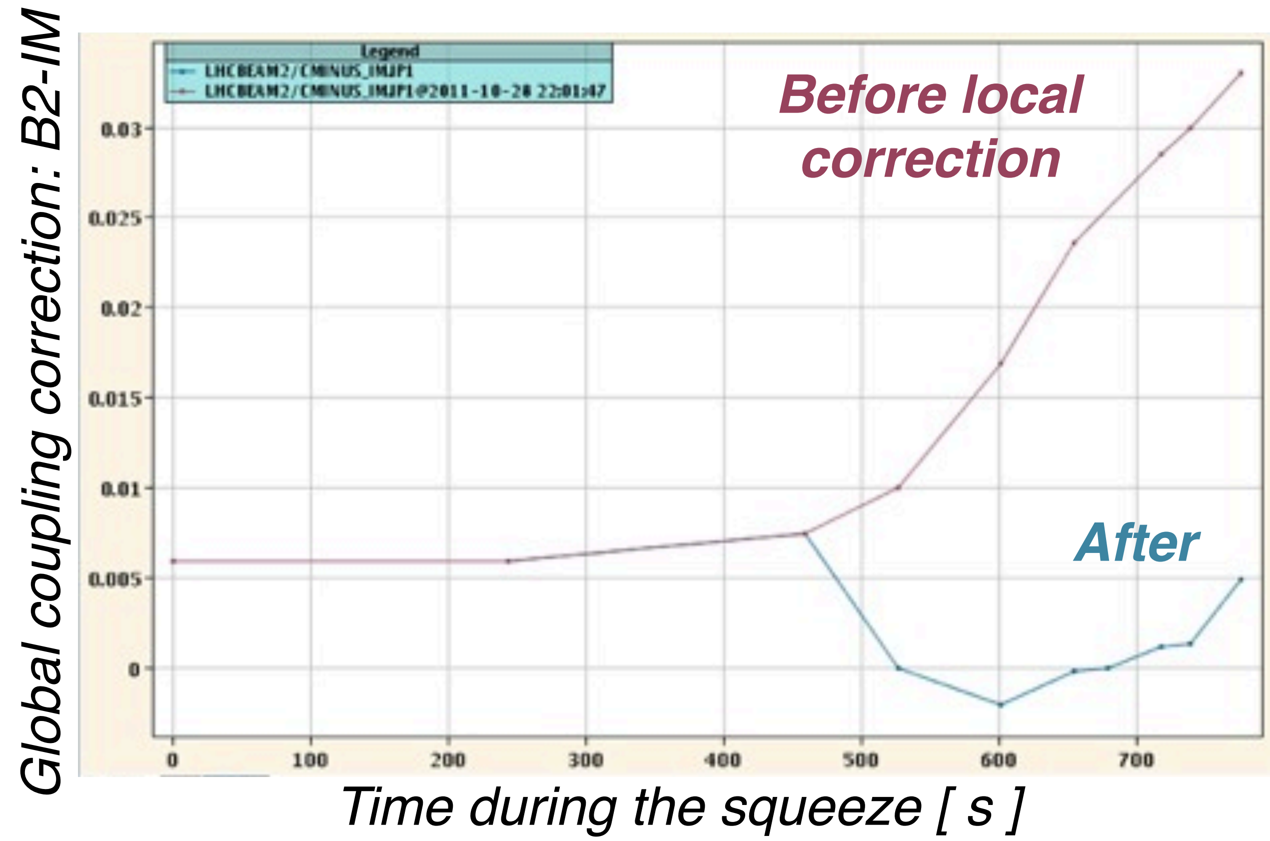
(Courtesy for R. Tomás for the beta-beat team)



Beta beating corrected to within better than 10 % at $\beta^* = 1.5$ m.
No further corrections needed at $\beta^* = 1.0$ m.

Coupling: local and global

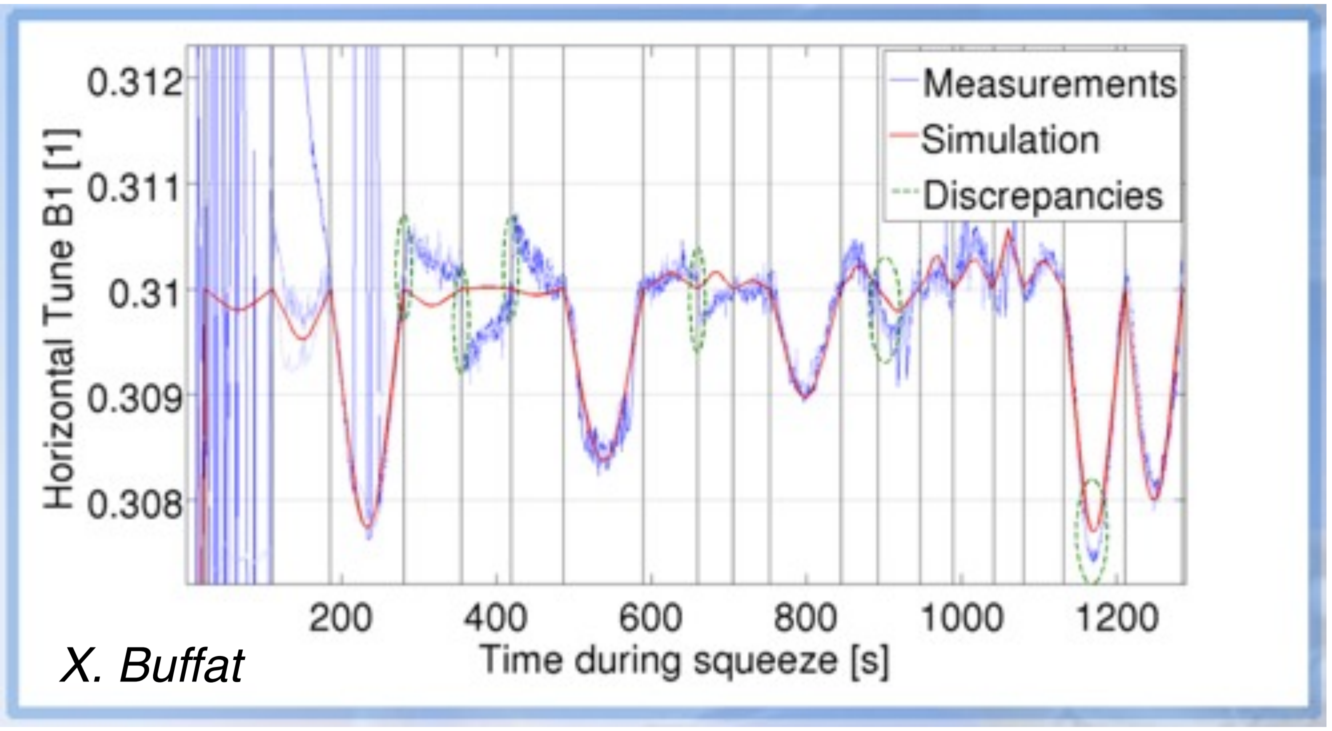




Corrections of local coupling sources in all IPs!
These are essential to minimize global corrections (otherwise, RQS's close to power converter limits).

Feed-forward tune corrections

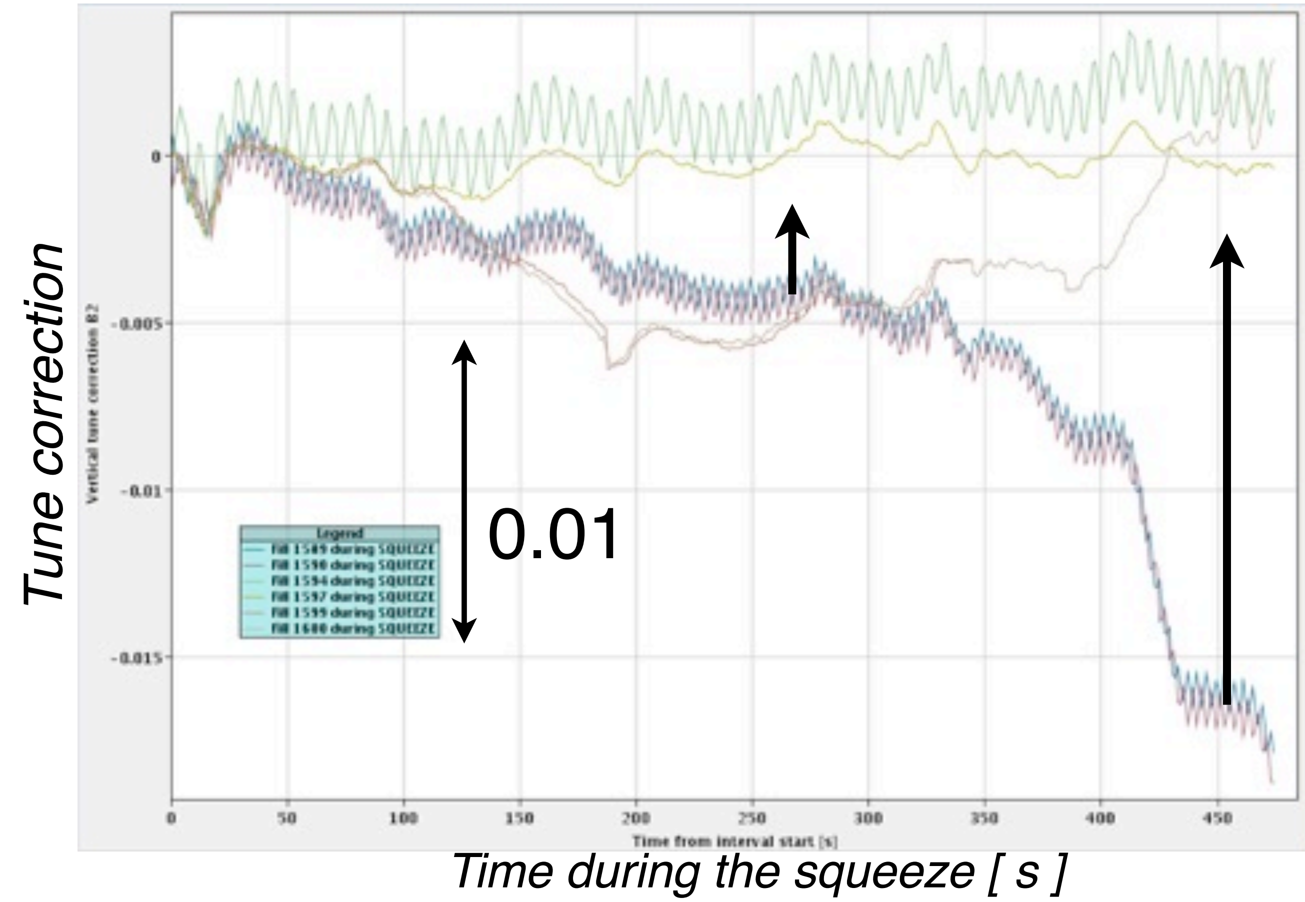
From time-dependent simulations

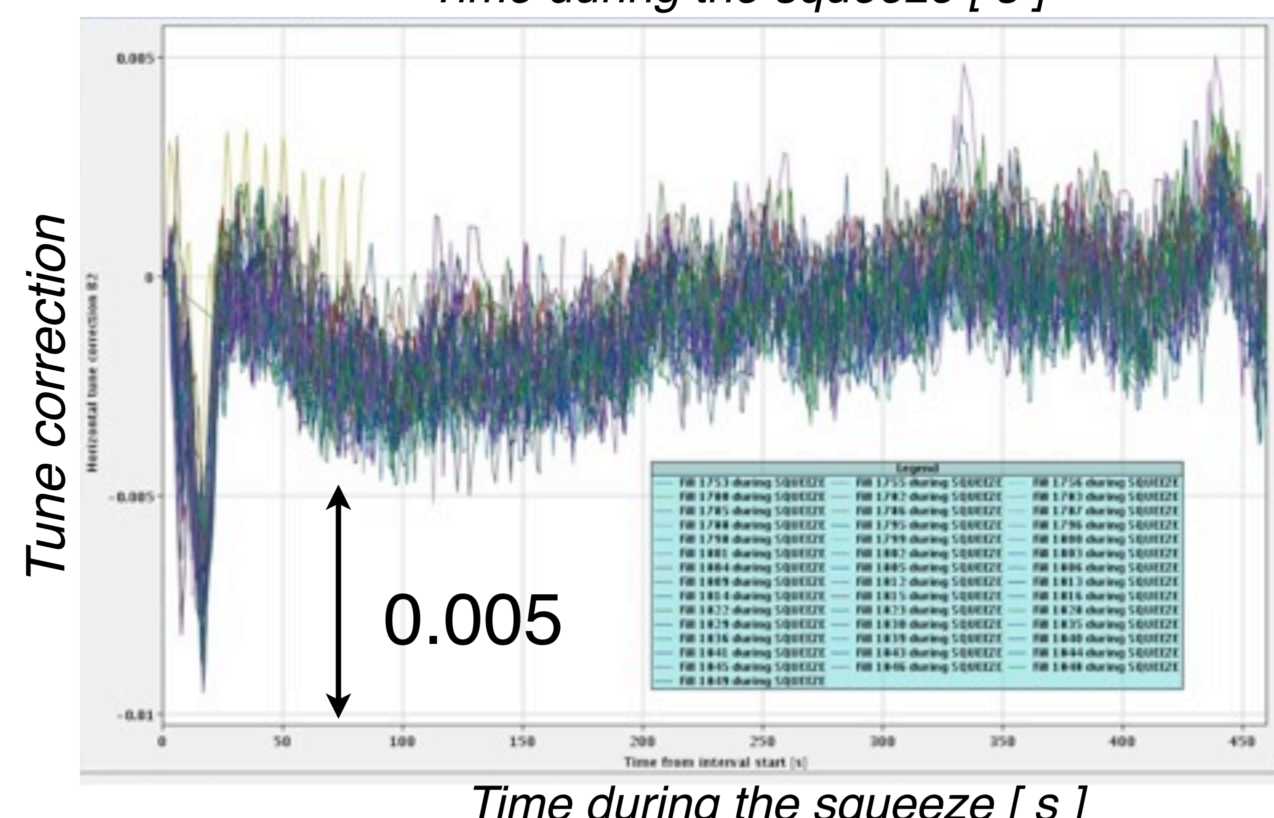


QFB can take care of these effects. But **feedforward** improves OP robustness → saved some ~ **20 physics fills** in 2011 with 2-3 iterations (machine reproducibility is remarkable)

Also: simulation-based corrections on beta errors under preparation!

From measurements





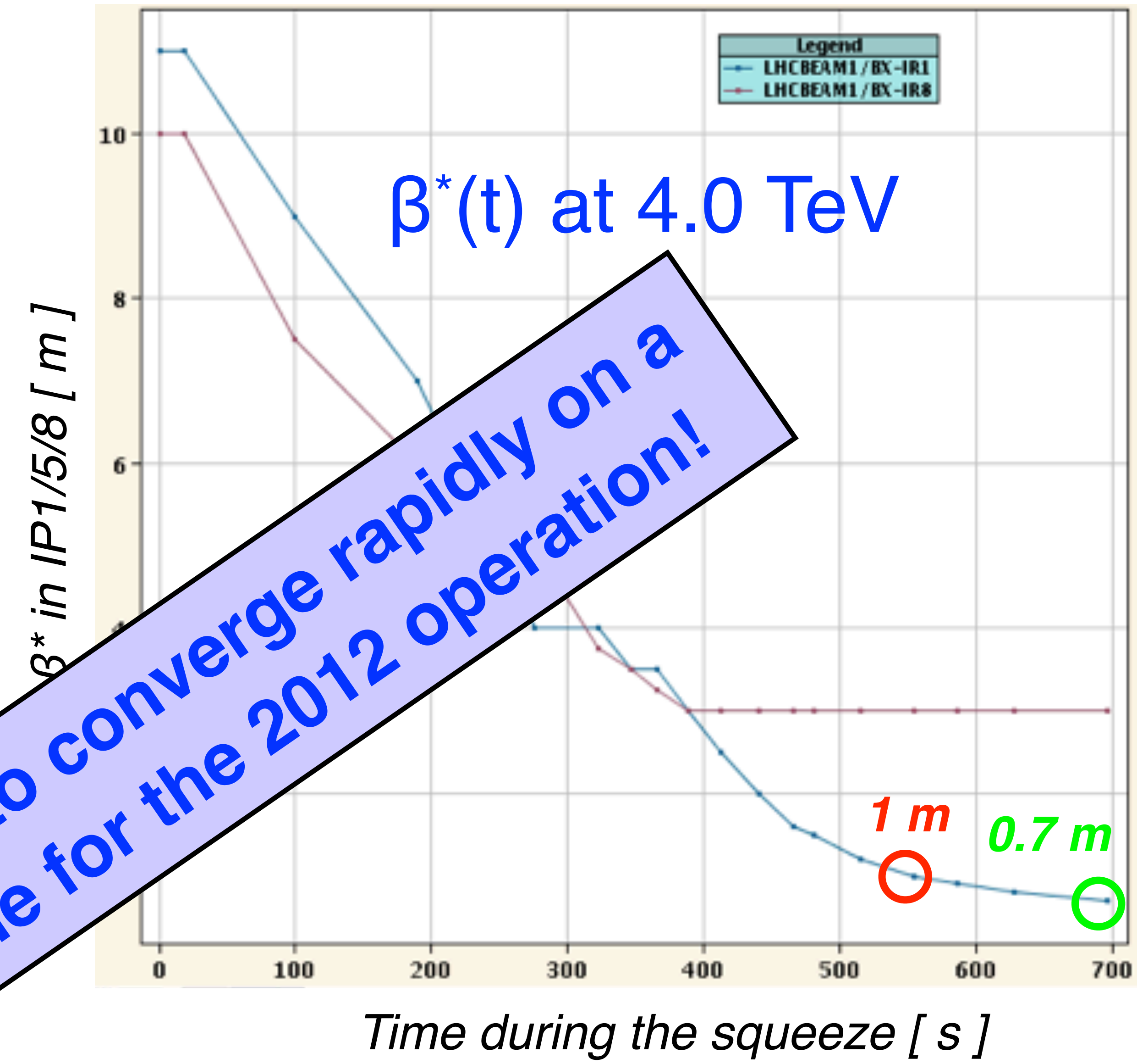
See also ICALEPCS2011, by Mario, Gabriel et al.

Squeeze in 2012

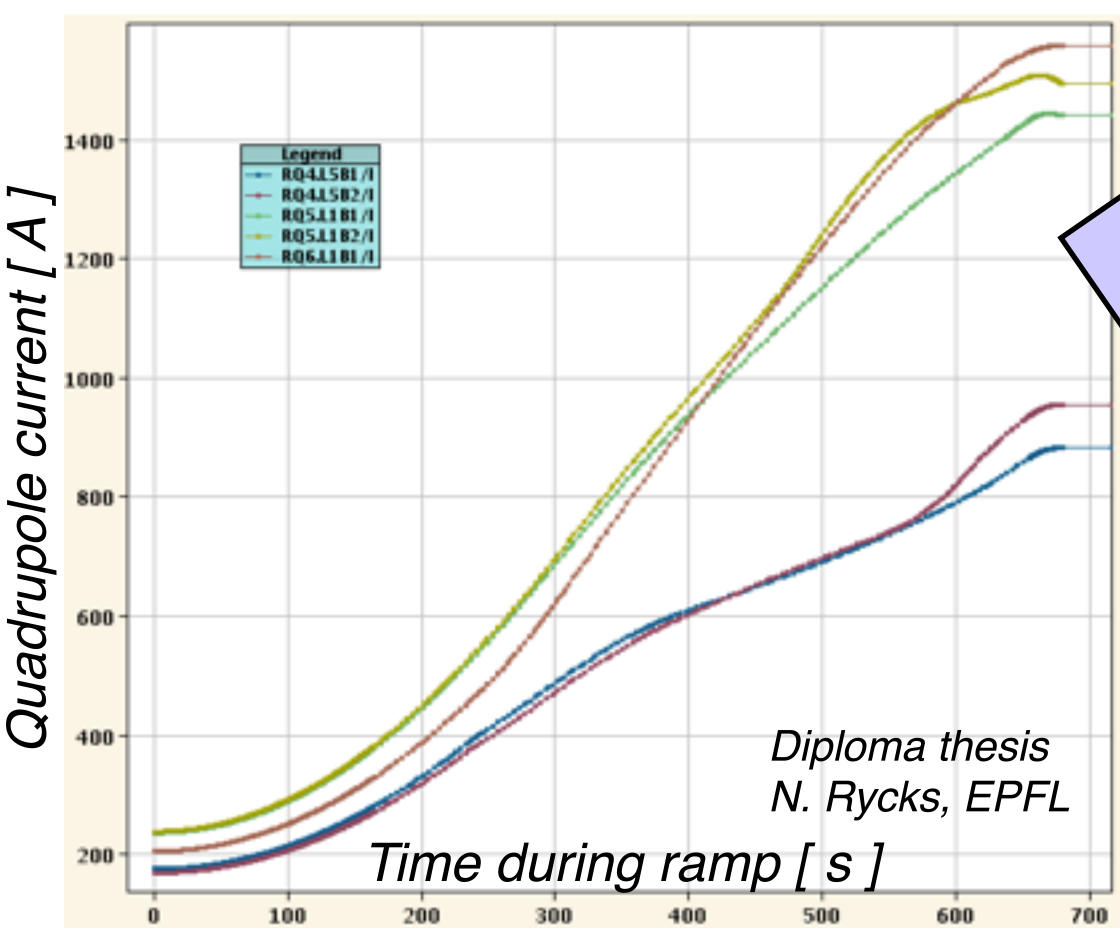
Applying the same operational strategy at 4 TeV is straightforward:

IP1/5/8 = 1.0/1.0/3.0 m → 554 s
= 0.7/0.7/3.0 m → 697 s
= 0.6/0.6/3.0 m → 784 s

Further optimization possible in the range above 2m, but difficult to gain for smaller β. Need to agree on final LHCb value.*



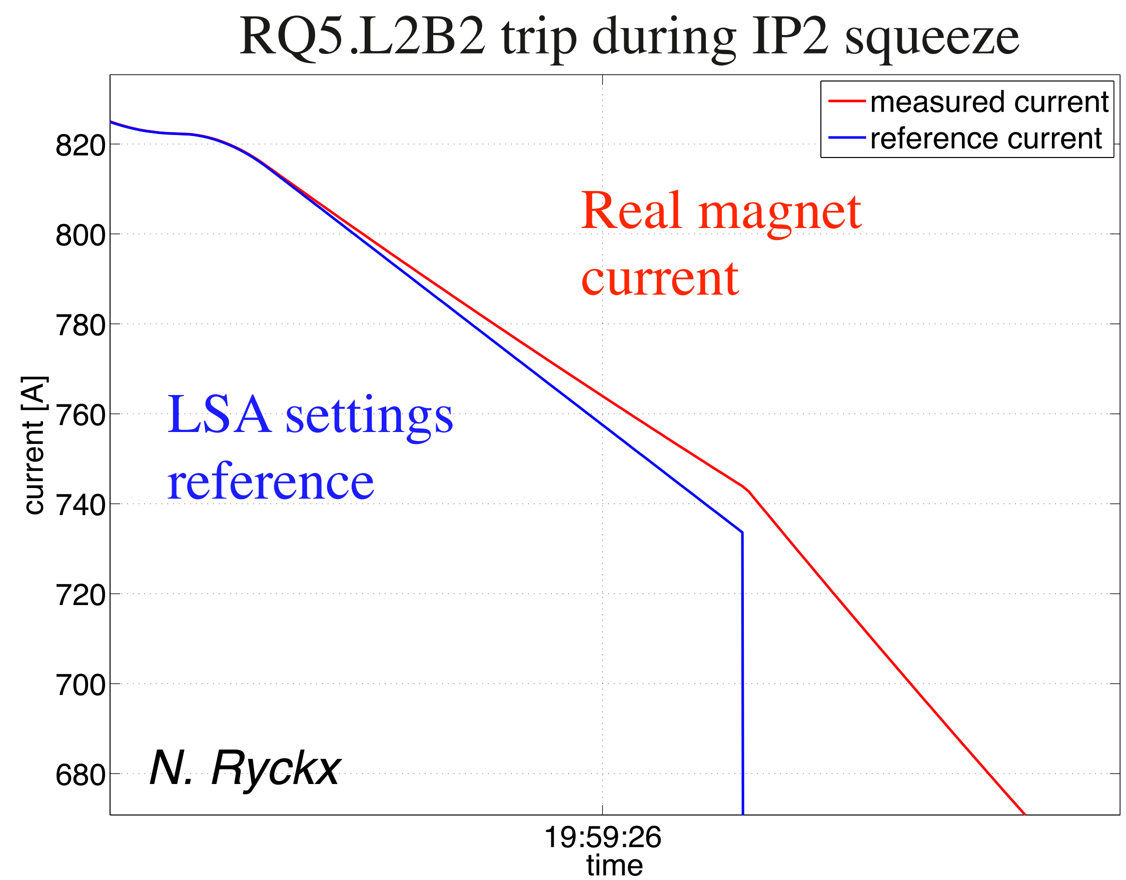
We need to converge rapidly on a baseline for the 2012 operation!



Possible improvement for next year:
Combined Ramp&Squeeze
Solution available for reaching **3.5/3.5/3.0** m at 3.5 TeV (gain ~400s), can be optimized further for 4.0 TeV
See discussion in Walter V.'s talk

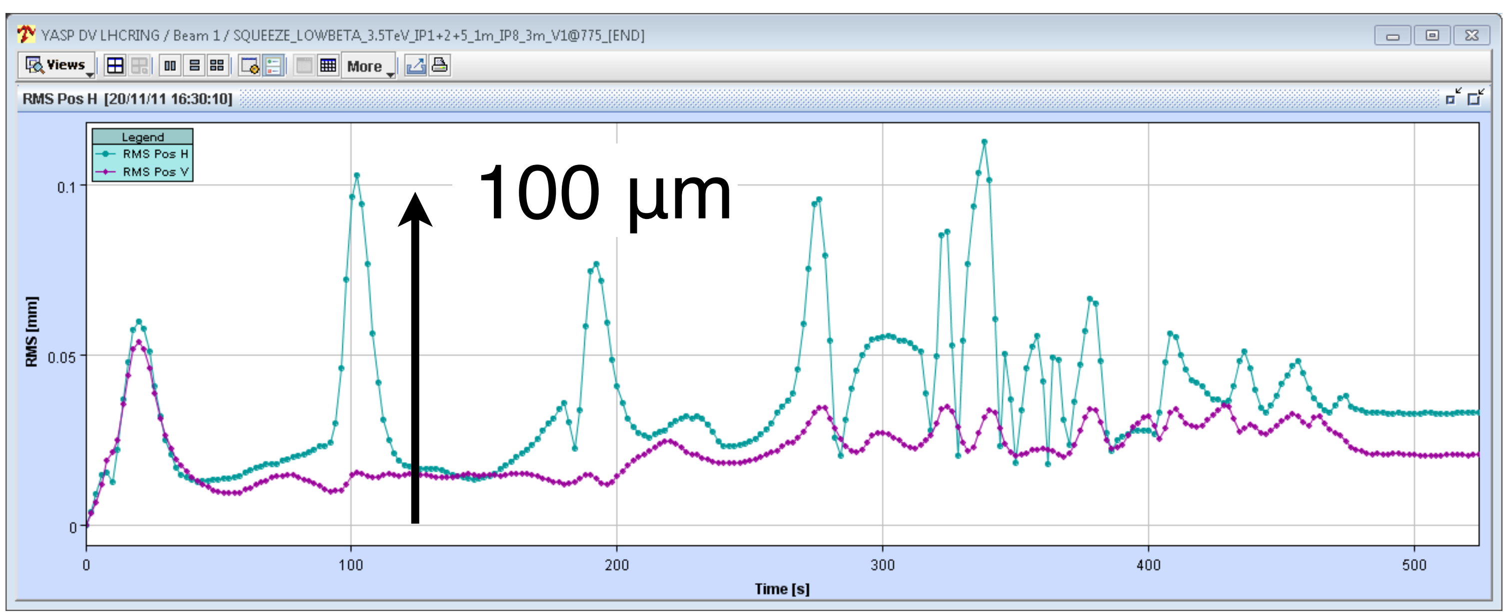
Squeeze: outstanding issues

1. LSA generation treats incorrectly the inductance of monopolar quadrupoles (Q4, Q5, Q6), causing PC trips
   Only catch problems during dry-runs



2. Round-off at matched points is not consistently applied for sextupoles and orbit correctors
   Tripped once during ATS MD
   A solution is in place (Greg K.): we need to agree on the optimized OP strategy

3. Orbit stability during squeeze is presently not compatible with tight collimator settings: spikes around matched points



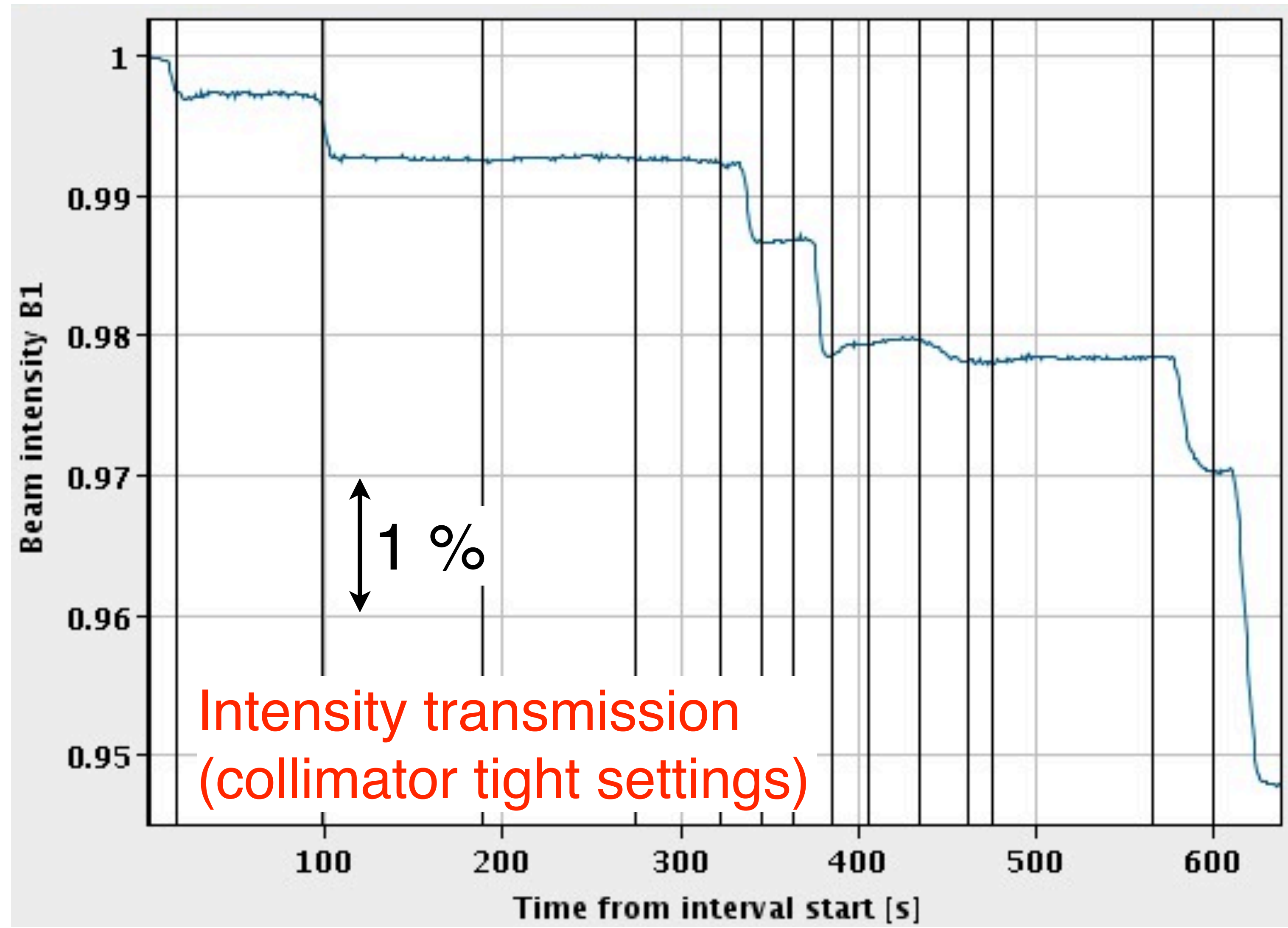
Orbit in the squeeze

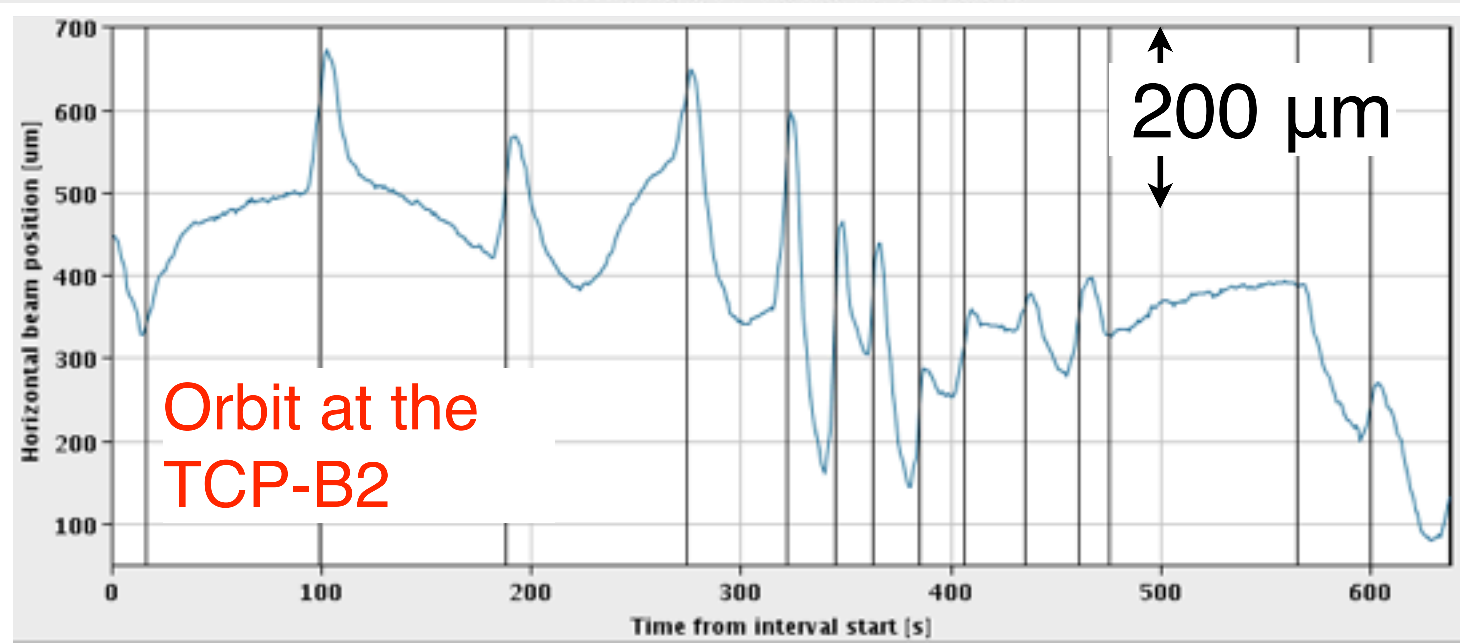
Observed **100 µm RMS** errors around matched points

No issues in 2011
..*we have seen the transmission*

Needs to be addressed to achieve tight collimator settings
→ *see RB's talk*

Solutions in place:
1. Iterative feed-forward correction
2. Increased gain of OFB proved OK (gain x 10)
3. Chasing the settings problem





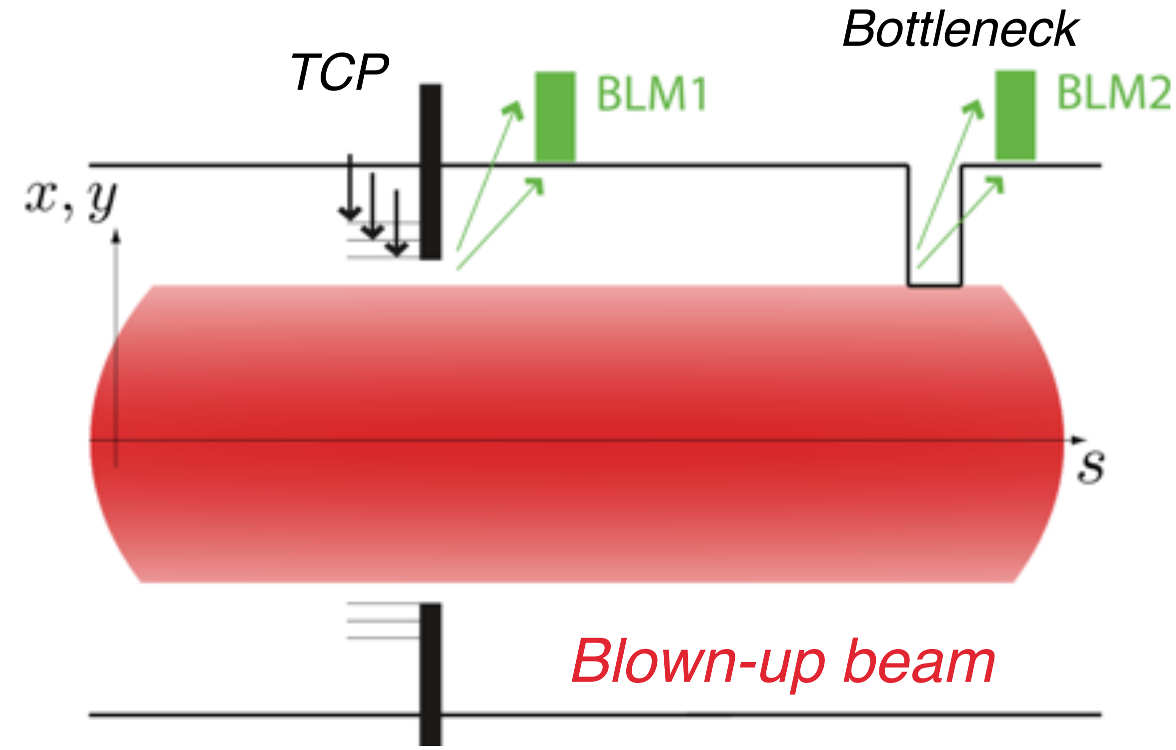
Jörg W. + Ralph S. at the LBOC of Nov. 11th, 2011
Laurette's talk on FB's

Outline

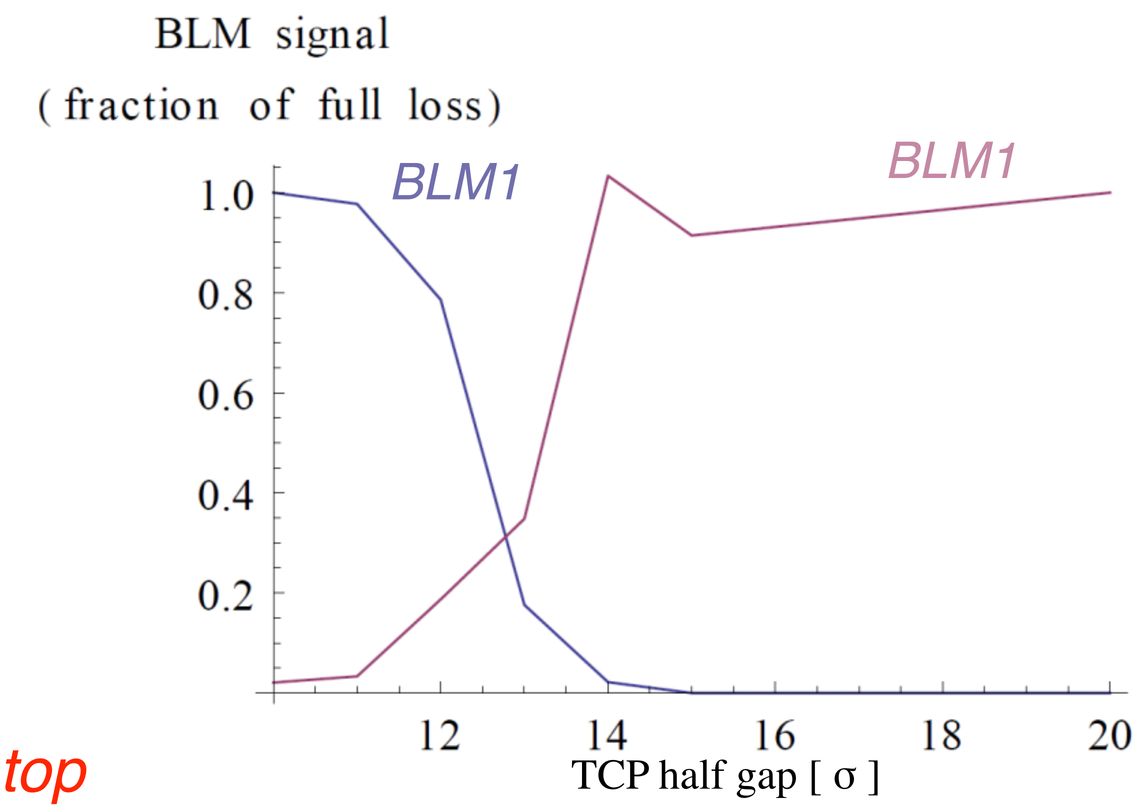
- ☑ Introduction
- ☑ 2011 machine config.
- ☑ Squeeze in 2011
- ☑ **LHC Aperture**
  - ***Injection aperture***
  - ***IR aperture at 3.5 TeV***
  - ***Beam-based β* reach***
- ☑ Conclusions

450 GeV aperture measurements

Since 2008, we have used and compared different methods:
- Trajectory oscillations (sector tests)
- Close orbit oscillations, local bumps
- Emittance blowup with aperture kicker
- Resonance blowup with collimator scans
(Ralph A. et al, IPAC2011)
Focused on the resonance method in 2011



Basic idea:
1. Emittance blow-up to find bottleneck (coll. open)
2. Perform a collimator scan and repeat blow-up
*3. When losses move to the TCP, the **precise** knowledge of **collimator gap** gives the N_σ*
4. Can be used for approximated LOCAL measurements with orbit bumps
Refined calculations use normalized BLM



R. Bruce et al.: LBOC, Mar. 8th, 2011

*Promising results from **ADT blowup**, interesting for top energy measurements → See talk by D. Valuch*

Aperture at 450 GeV (on-momentum)

Global aperture

	H [σ]	V [σ]
B1	12.0 (Q6R2)	13.0 (Q4L6)
B2	12.5 (Q5R6)	13.0 (Q4R6)

Final data analysis by R. Bruce, presented at IPAC2011

Triplet aperture, crossing plane

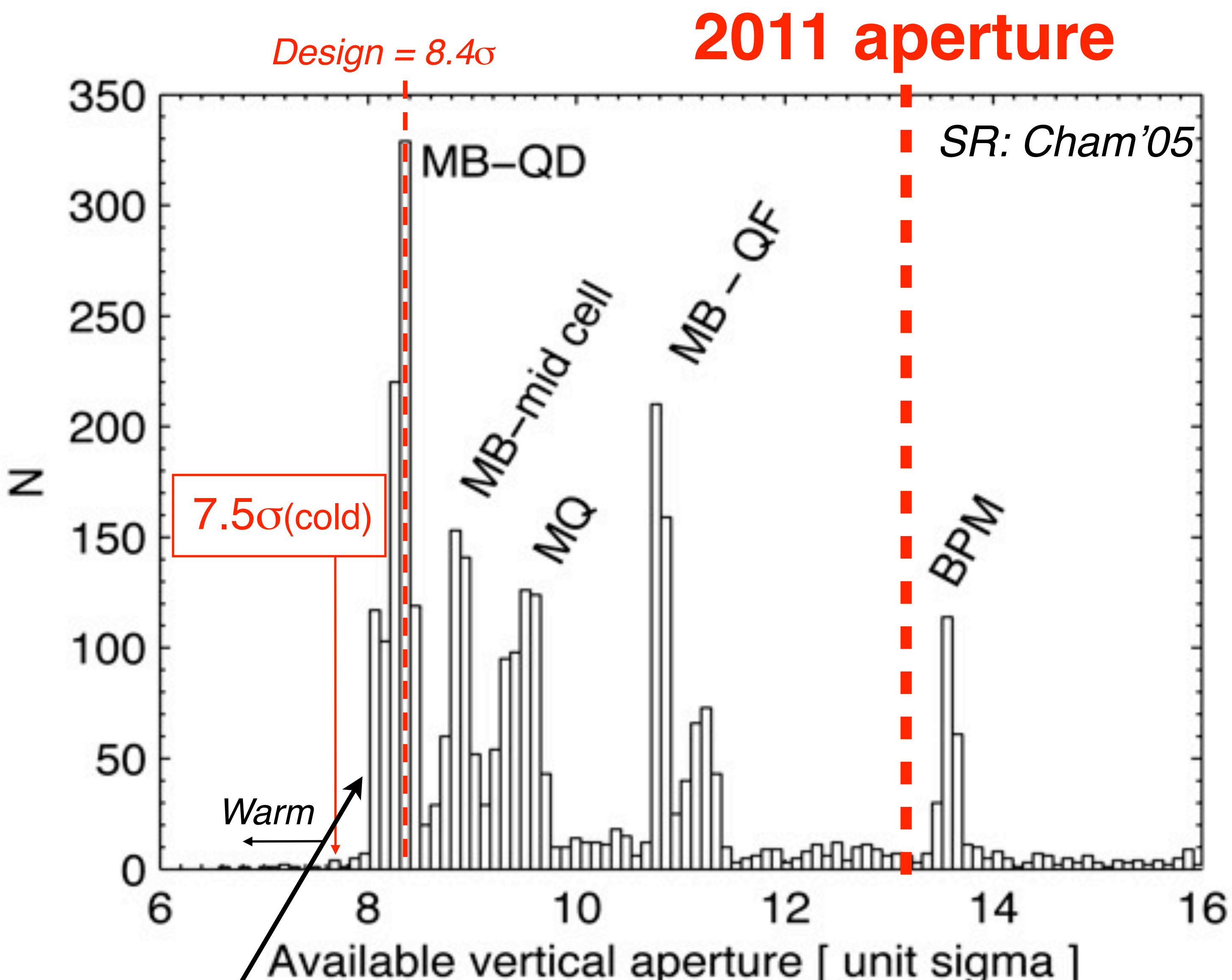
	H, B1/B2 [σ]	V, B1/B2 [σ]
IR1	-	16.0 / 16.0
IR2	-	14.5 / 16.5
IR5	15.0 / 17.5	-
IR8	15.5 / 15.5	-

2010's "Golden mine"

Remarks:

1. Measurements indicate 1 sigma reduction of aperture between 2010 and 2011
   → *it is important to measure aperture yearly and after major interventions!*
2. Off-momentum measurements only done in 2010 for B1: lost 1.0-1.5 sigmas
3. Triplet aperture affected by bump shape, as in 3.5 TeV measurements (see later)
4. Arcs present no distributed bottlenecks: limiting locations concentrated in the IRs

Comments on injection aperture



Magnet sorting within MEB improved by 1 sigma

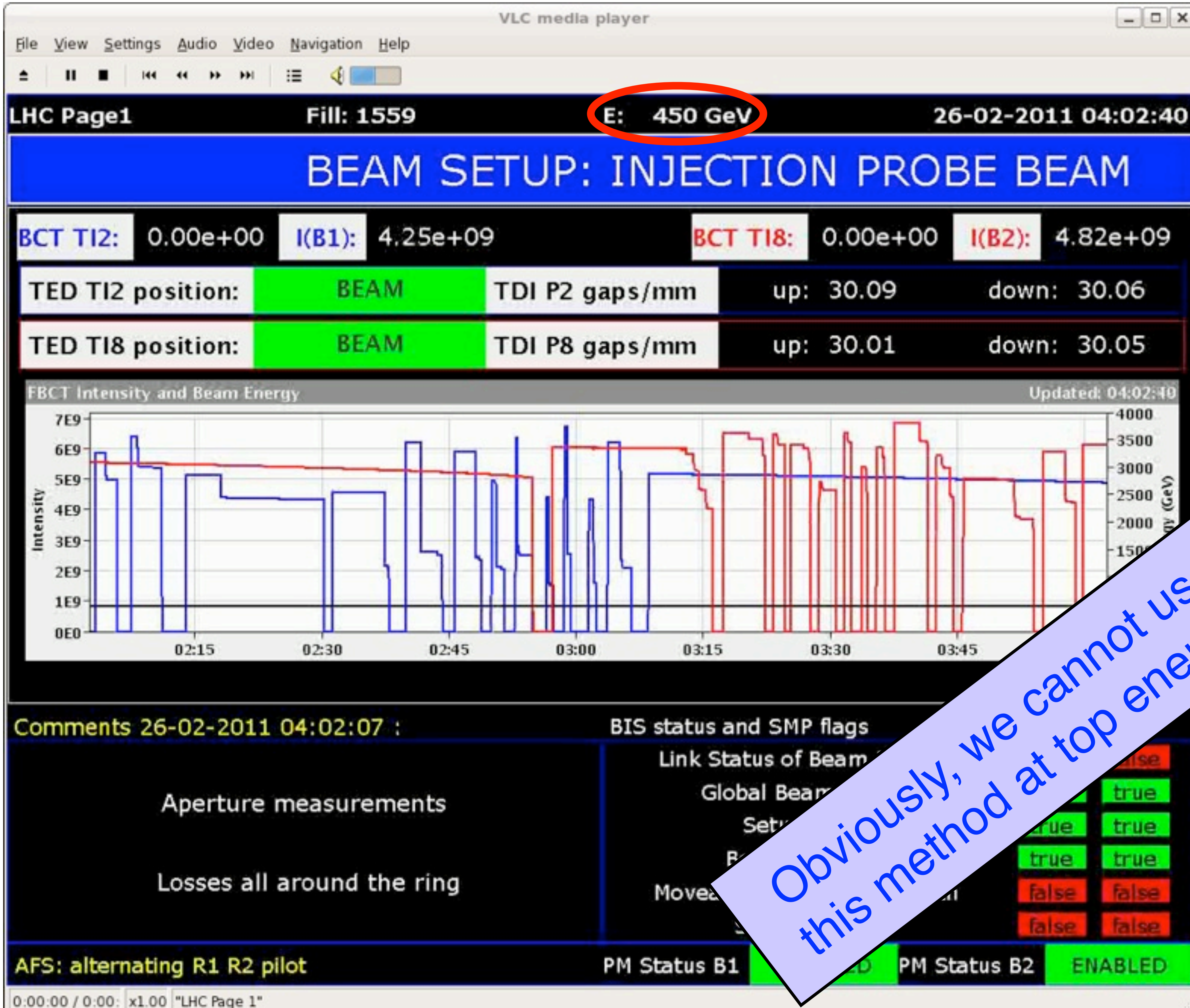
Tolerance table

Closed orbit	± 4 mm
Beta-beat	± 20 %
Spurious dispersion	27% D_{nom}^{Arc}
Mechanical tolerance	1-2.5 mm
Alignment	1.0.-1.6 mm

Achieved and surpassed the **nominal injection aperture** (170 μrad crossing angle, 3.5 μm emittance)

... and we have some margins that we could profit from (used already aperture for relaxing injection protection; injection at **smaller β***? ...)

How injection measurements look like



Obviously, we cannot use this method at top energy!

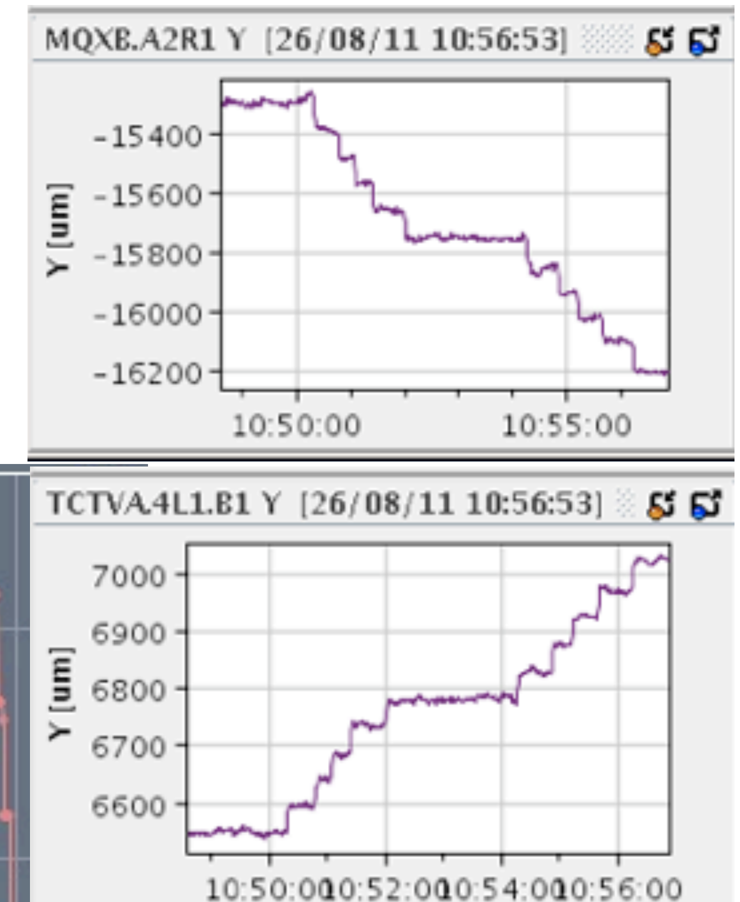
Local MQX measurements at 3.5 TeV

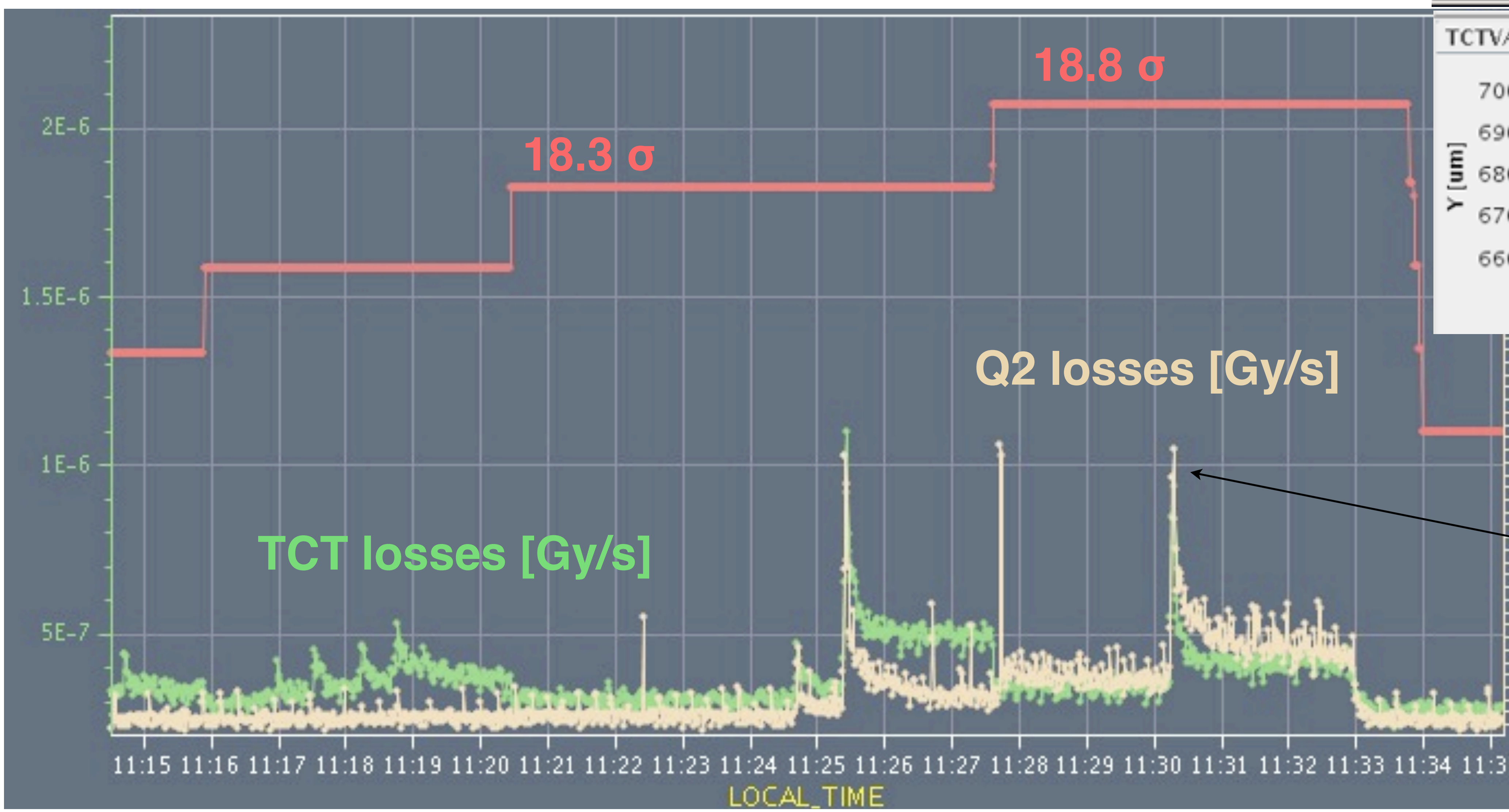
Procedure for “gentle” measurements:

Start from initial settings: TCTs at 11.8 sigmas.

1. Add a local bump until the beam touches the TCT
2. Open TCT by 0.5 sigma (250-320μm in H-V)
3. Increase bump by 0.25 sigma
4. Check relative height of BLM spikes: TCT vs MQX (Q2)

Orbit at TCT and Q2





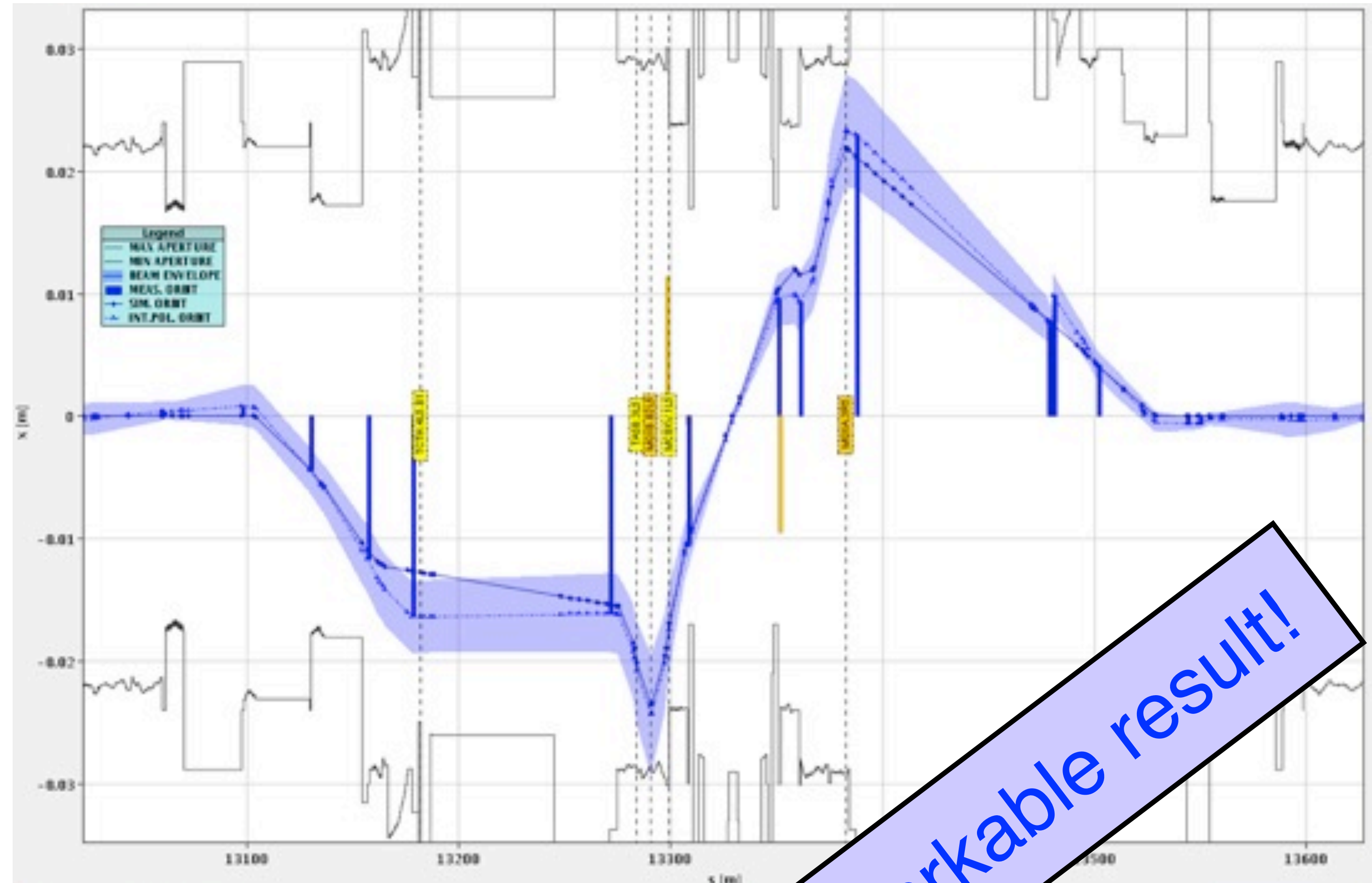
Loss spikes while the orbit is increased, touching TCT or MQX

SR: “Local aperture measurements of the triplet magnets in IP1/5 at 3.5 TeV”, MP document

IR1 and IR5 aperture at 3.5 TeV

IR	Plane	Type of bump in standard optics	Aperture [σ]
1	H	Separation	19.8 – 20.3
1	V	Crossing	18.3 – 18.8
5	H	Crossing	19.8 – 20.3
5	V	Separation	> 20.3

2011's "Platinum mine"



*We got **4-6 sigmas** more than the expected 14 sigma!*

Triplet aperture compatible with a well-aligned machine, a well centred orbit and a ~ design mechanical aperture (small tolerance)

BUT: only one side measured!

Remarkable result!

Detailed calculation of orbit bump to infer aperture in mm

IR	Plane	Total orbit [mm]	Envelope width [mm]	Envelope width [σ]	Total apert. [mm]	Design apert. [mm]
1	H	−17.4	7.1	5.6	24.5	25.2
1	V	+19.4	6.7	5.0	26.1	30.0
5	H	−24.3	7.0	5.6	31.3	30.0
5	V	+18.5	6.4	4.5	> 24.9	25.2

C. Alabau, G. Müller

What can we do with this aperture?

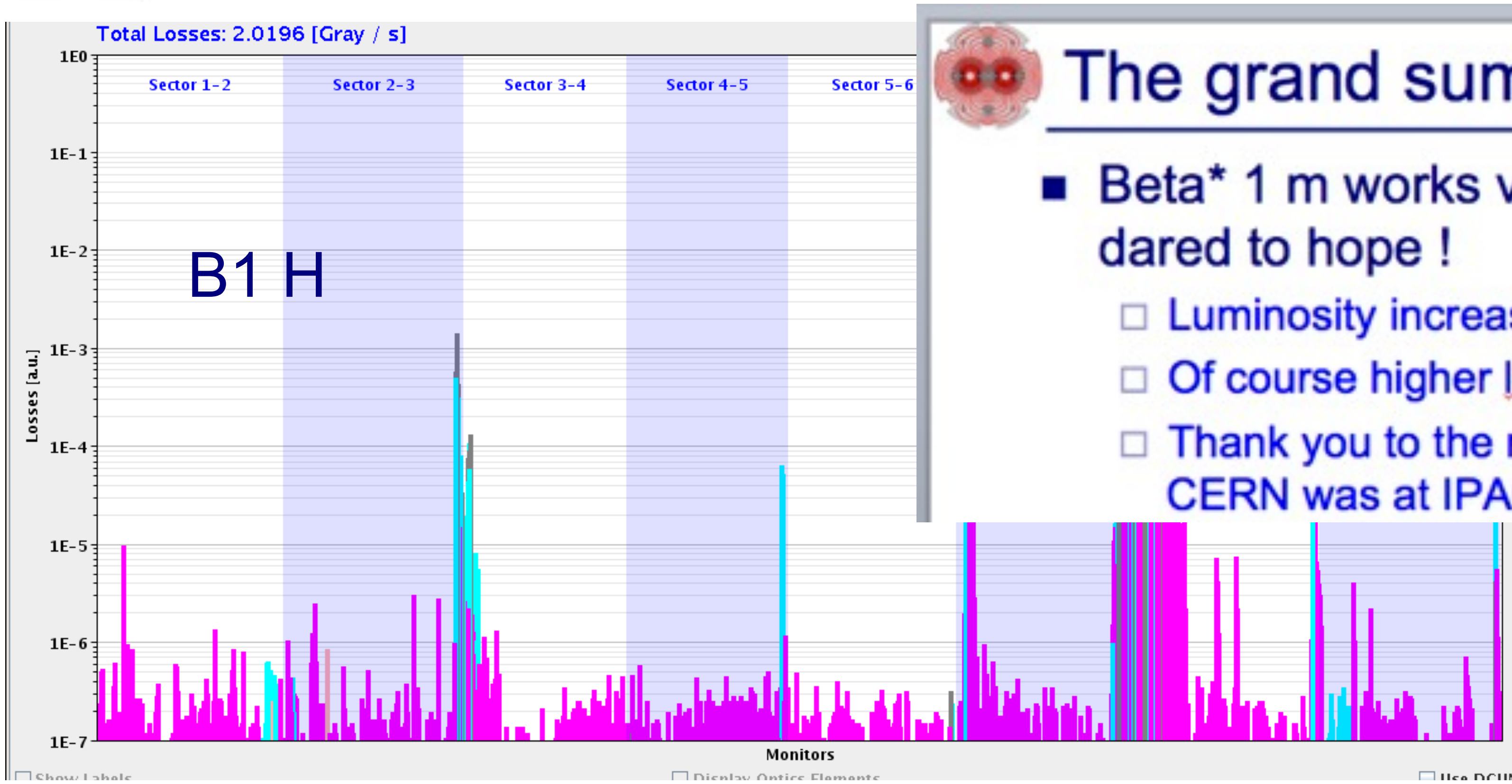
The additional margin (4 to 6 σ) allows **$\beta^* = 1$ m** at **120 μrad**
if the orbit is corrected like at 1.5 m and if the beta-beat is the same

Crash program to demonstrated that (Sep.2011, in IPAC week):

- Same beta-beat at 1.5 m and 1.0 m ✓
- Same orbit stability in [mm] at 1.5 m and 1.0 m ✓
- Beam-beam separation OK for 120 μrad for 50 ns ✓
- Re-measure aperture at 1.0m ✓
- Triplet are not exposed if TCTs at 14 σ *(suggested by Steve M.)* ✓
- Loss maps OK for TCT at 11.8 σ (complete set) ✓
- New configuration OK for intensity ramp up ✓
- New TCT collimator functions for 1m are OK ✓

Effort coordinated by Joerg W.

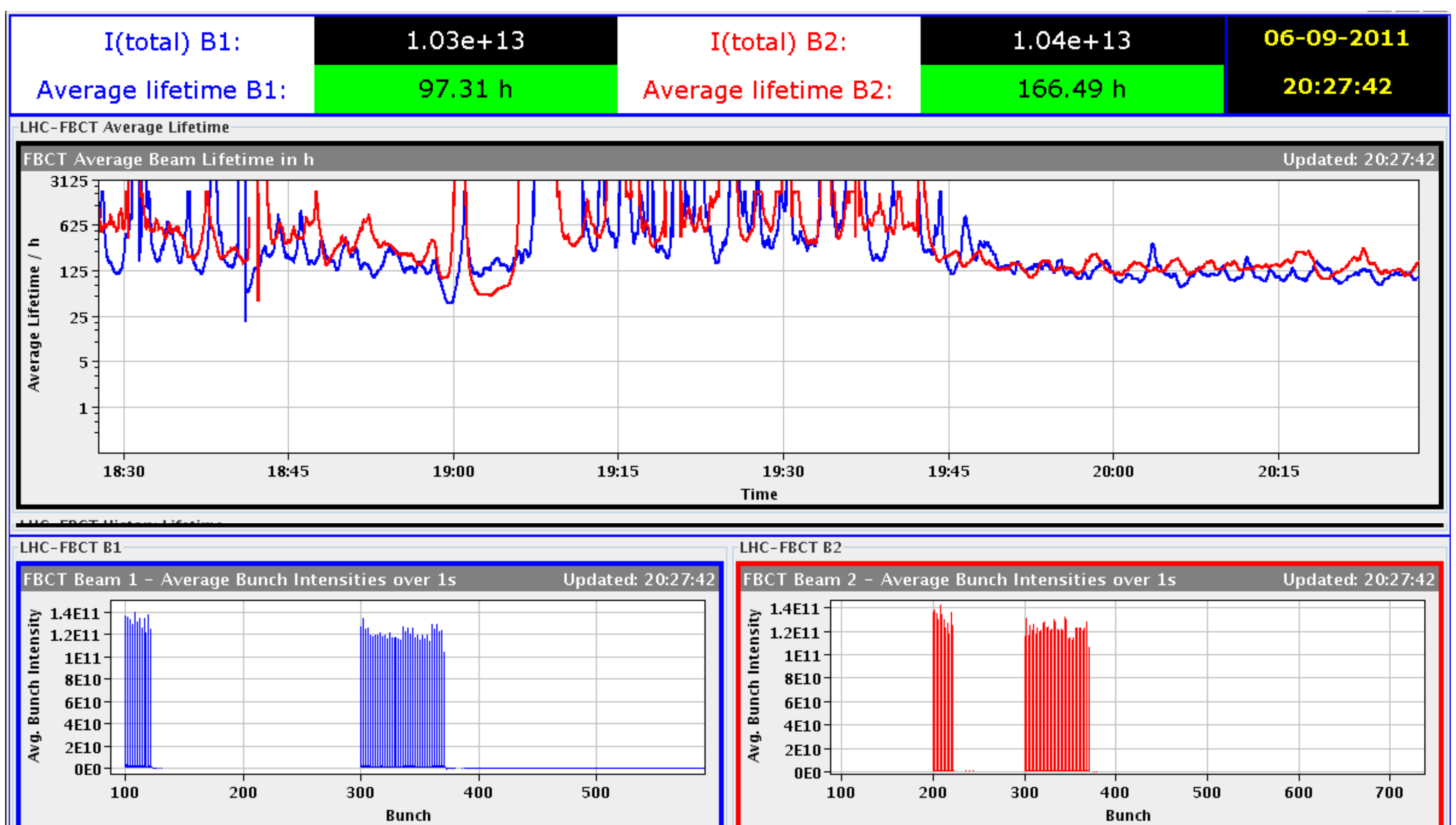
Two examples from 8h30 meeting



The grand summary

- Beta* 1 m works very well and was ready faster than we dared to hope !
  - Luminosity increase already in the pocket !
  - Of course higher lumi means more frequent SEUs…
  - Thank you to the reduced teams that made it work while most of CERN was at IPAC !

Loss maps with TCTs at 14 σ: see TCT's and not triplet!

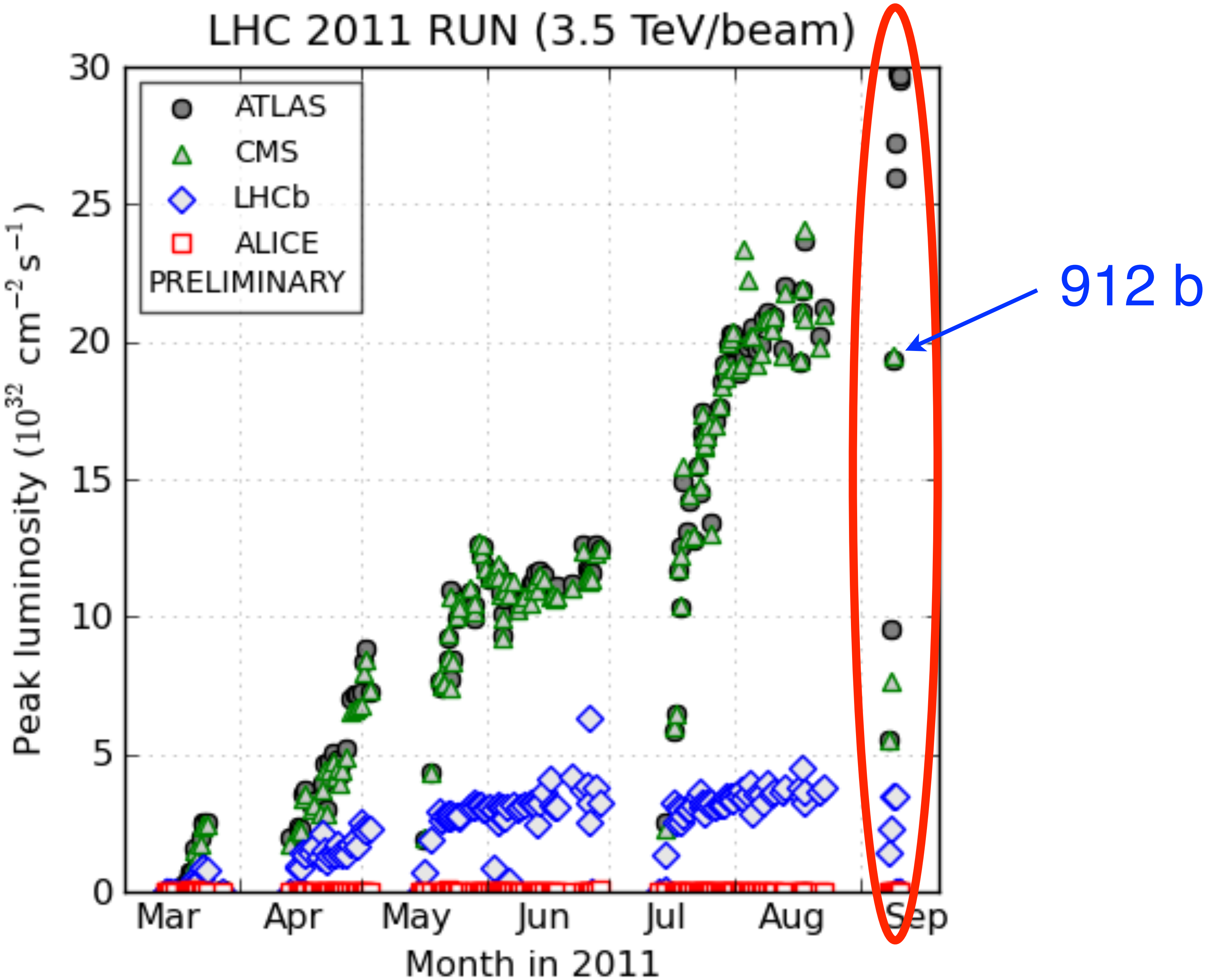


Lifetime ~ 120h while putting 50 ns beams in collision.

Intensity ramp up with $\beta^* = 1$m

Rocket ramp up

- Perfect ramp up over 4 fills to 1380b.
  - 264b, 480b, 912b, 1380b.



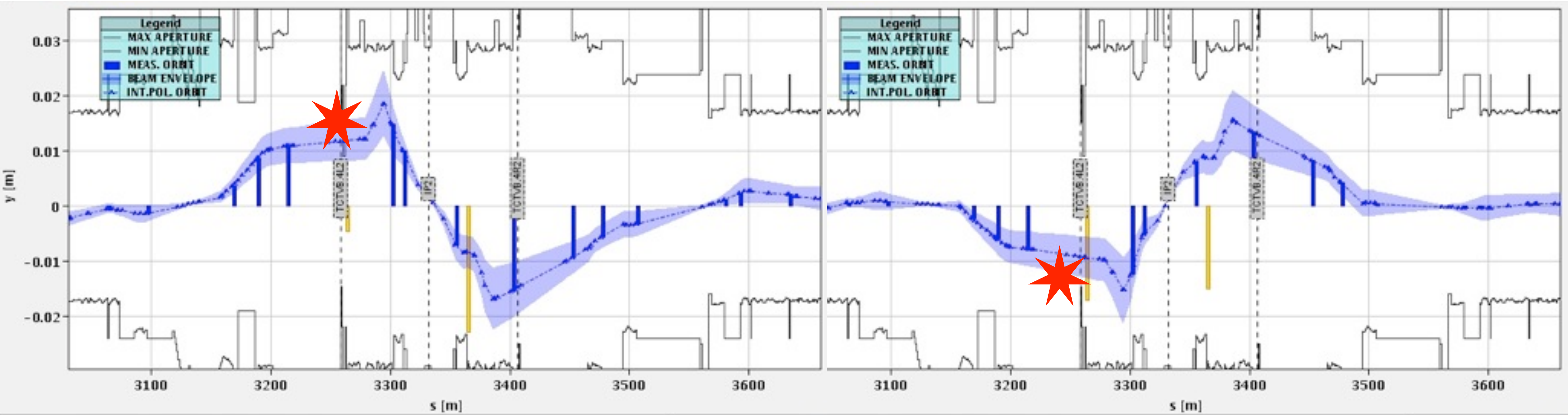
Strategy and requirements for 2012

1. Repeat global and local measurements at injection, including off-momentum cases
2. Commission the optics to a likely final β* value (70 cm?)
3. Measure the aperture at top energy in the tightest conditions to establish scaling laws / operational ranges for crossing angle and larger β* value
4. Measure on both sides of the orbit!

Note that we have followed a similar approach in 2011 for the squeeze commissioning in IP2 (ion operation)

Remark:
ADT blow-up technique at 3.5 TeV should be used from day-1!

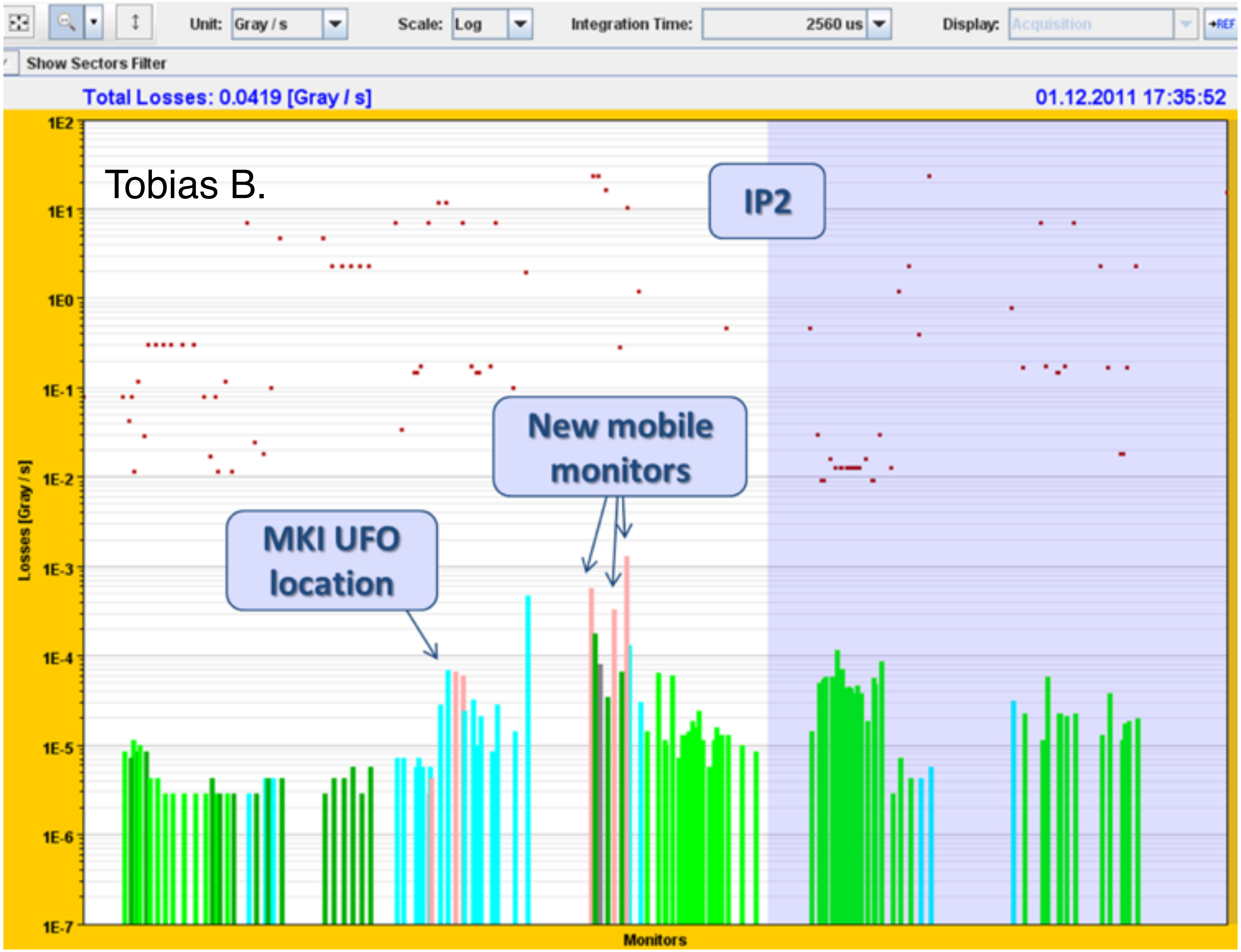
IR2 aperture



Crossing angle [μrad]	Beam	Plane	Type of bump in standard optics	Aperture [σ]
−80	B1	H	Separation	16.0 – 16.5
−80	B2	H	Separation	15.5 – 16.0
−80	B1	V	Crossing	15.5 – 16.0
−80	B2	V	Crossing	16.0 – 16.5
+120	B1	V	Crossing	12.5 – 13.0
+120	B2	V	Crossing	15.0 – 15.5

Found an unexpected bottleneck upstream of the TCTV - β^*=1m ok but could not reduce net crossing below 10 µrad.

First UFO-based aperture meas.



Many thanks to the BLM team for the new monitors

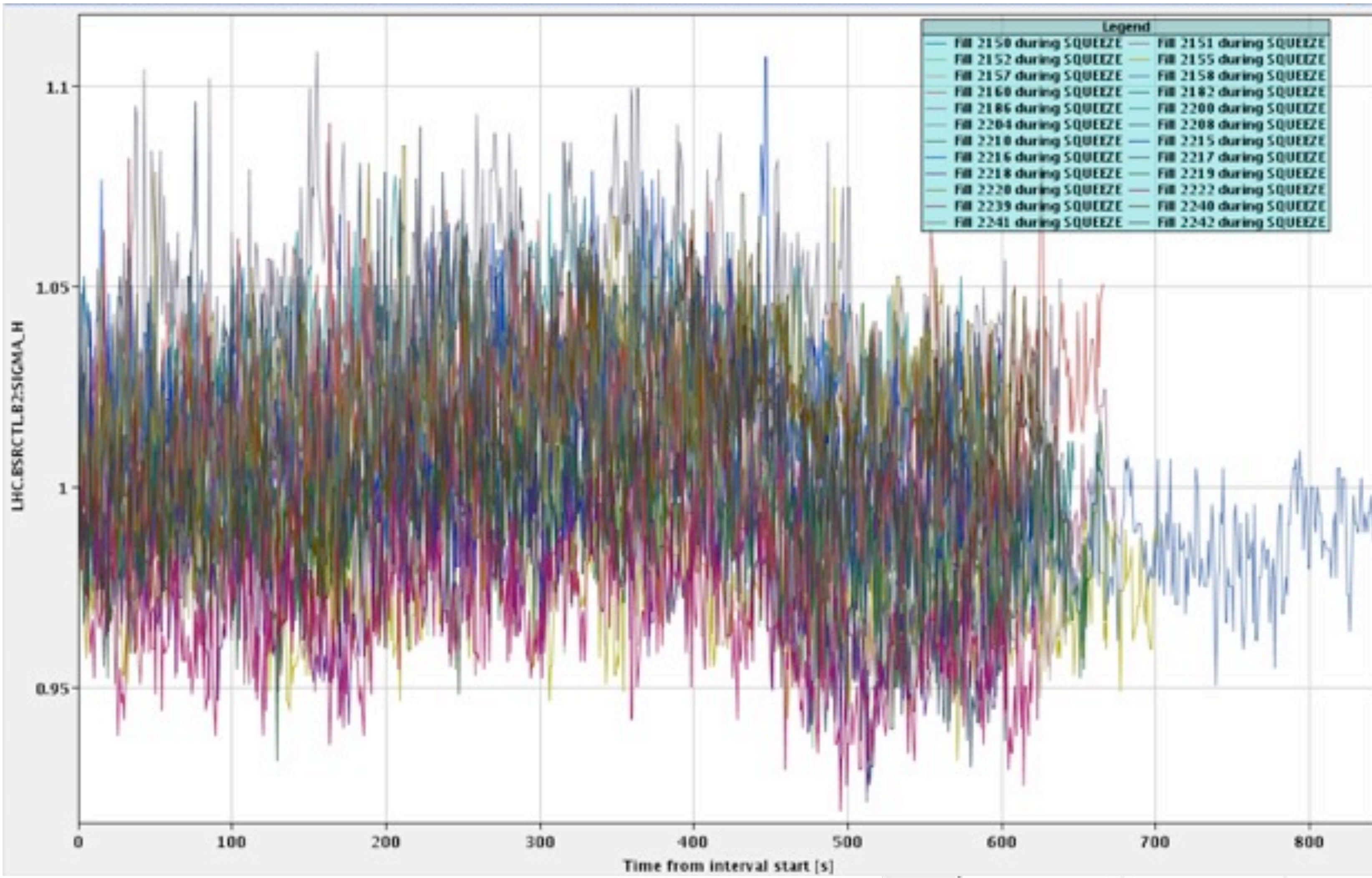
Additional movable BLMs added in the region for more detailed measurements - could not be done at the end of ion run.

Conclusions

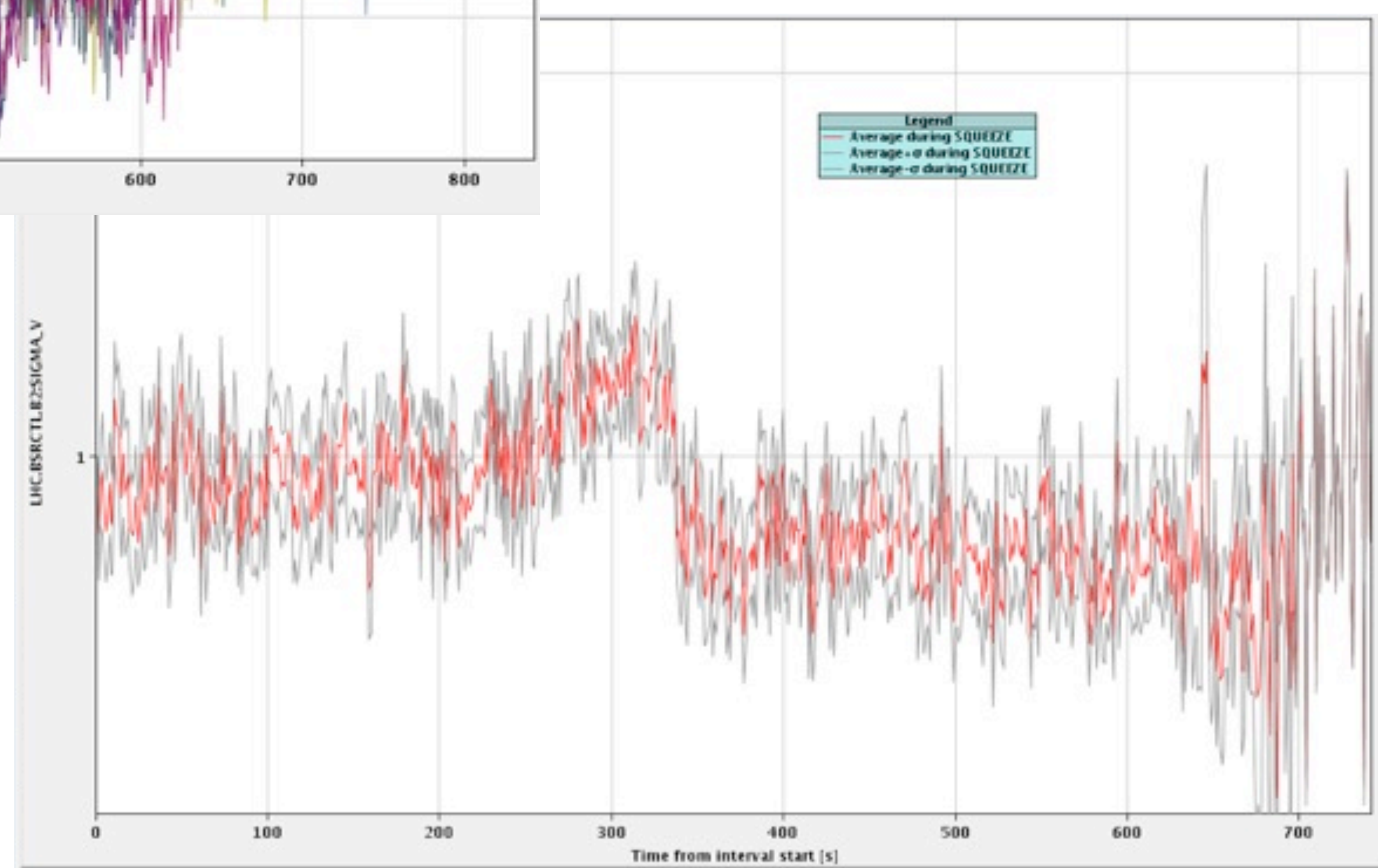
- **The LHC optics and aperture are good!**
  - *Major achievement for all the teams involved in the past and present years!*
  - *Reached performance beyond expectations and beyond design*
- **The squeeze commissioning in 2011 was a success**
  - *Many improvements from 2010: shorter and more robust operation*
  - *Commissioning of new optics as become a routine*
  - *Optics behaves well and is correctable to within ~ 10%!*
- **The LHC aperture is good**
  - *Injection aperture > 12σ → nominal aperture achieved (with margins!)*
  - *In 2011, we also performed the first "gentle" IR aperture 3.5 TeV.*
  - *This allowed a 50% step in peak luminosity, commissioned "transparently"*
  - *We established a solid base for beam-based beta* reach estimates*
- **Outlook for 2012**
  - *A couple of implementation issues for the squeeze settings addressed*
  - *Orbit stability in the squeeze must be improved to allow tight coll settings*
  - *Aperture must be re-measured at injection and at top energy.*
  - *Needs to freeze soon the 2012 configurations (combined R&S?)*

Reserve slides

Beam size during the squeeze

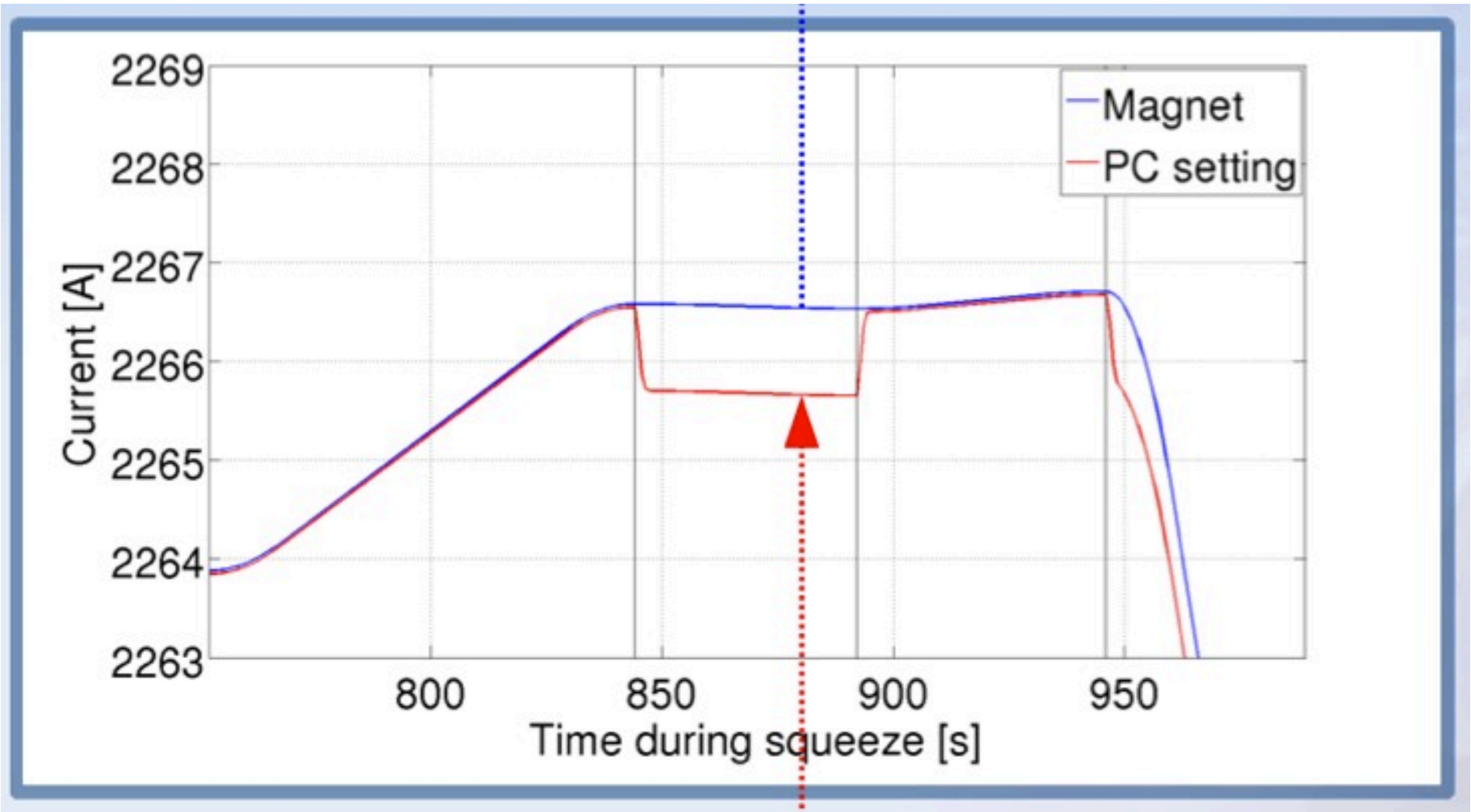


Average V size from BSRT: no indication of emittance blowup during squeeze

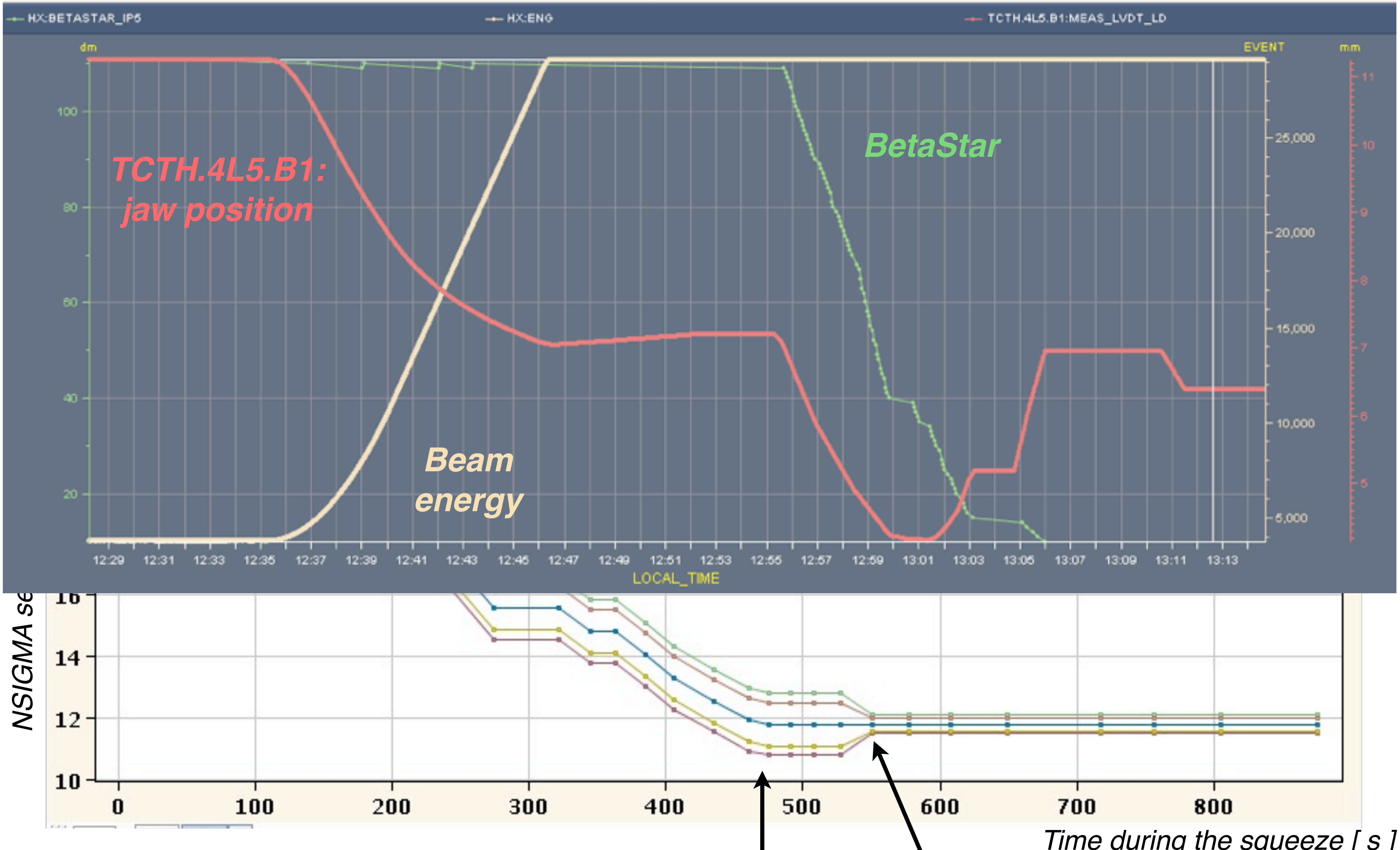


Other improvements for 2011

Do not stop during the squeeze.
Squeeze functions also for collimators for optimum protection settings.
Keep the same orbit references for Xing and separation bumps.
Removed FiDeL implementation of hysteresis that caused jumps in setting functions.



Collimator functions in the squeeze

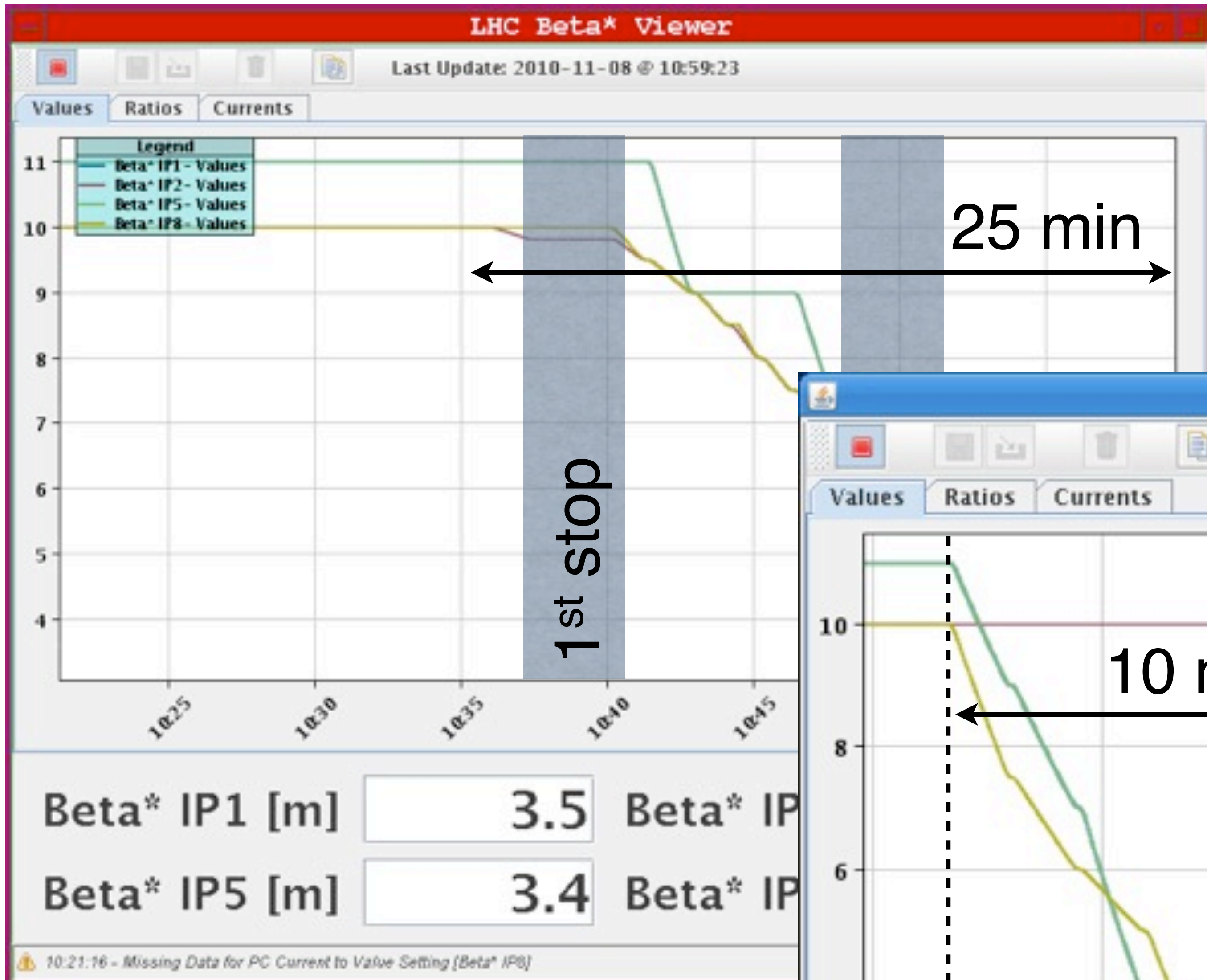


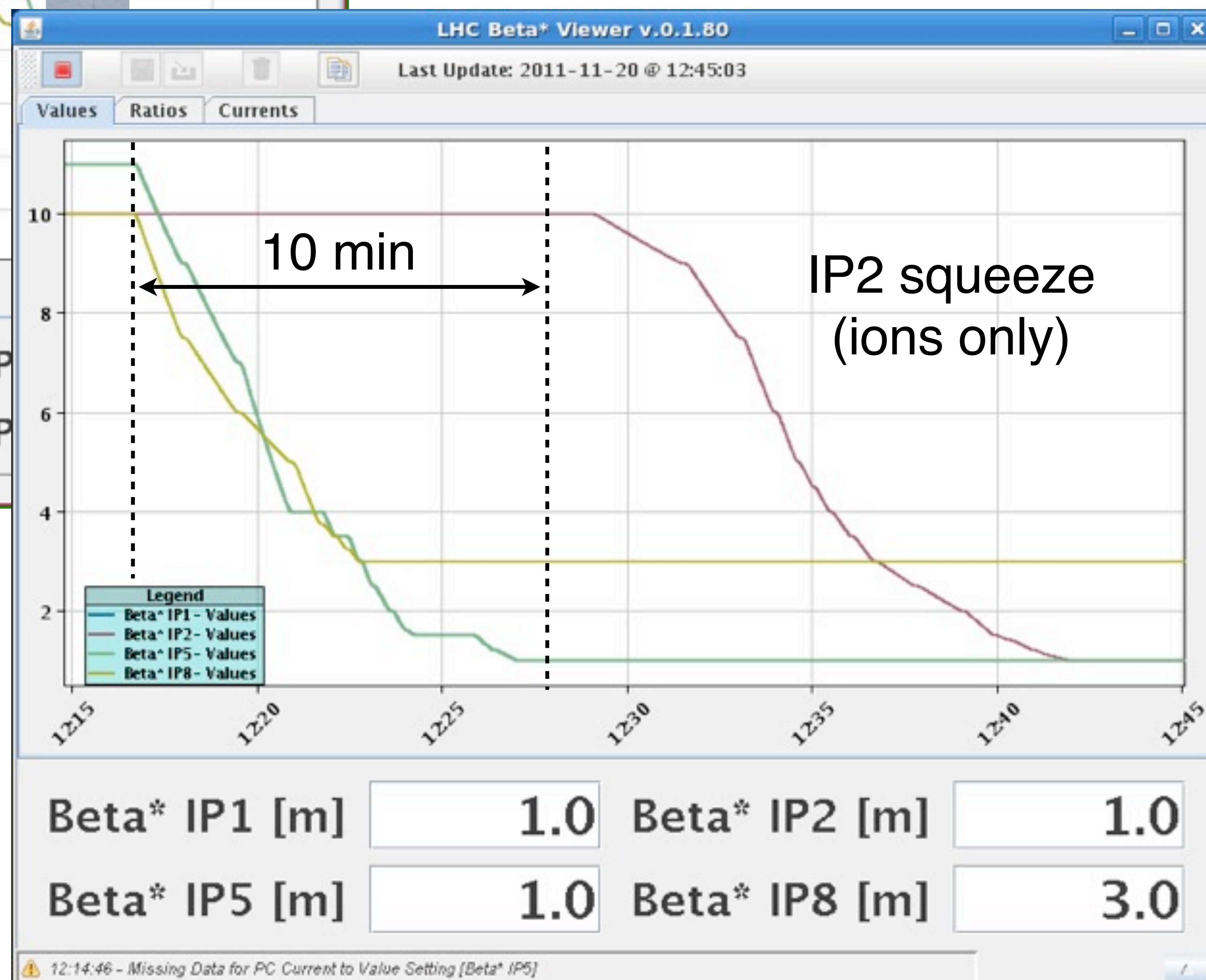
β* = 1.5m

β* = 1.0m

On behalf of the Collimation Team

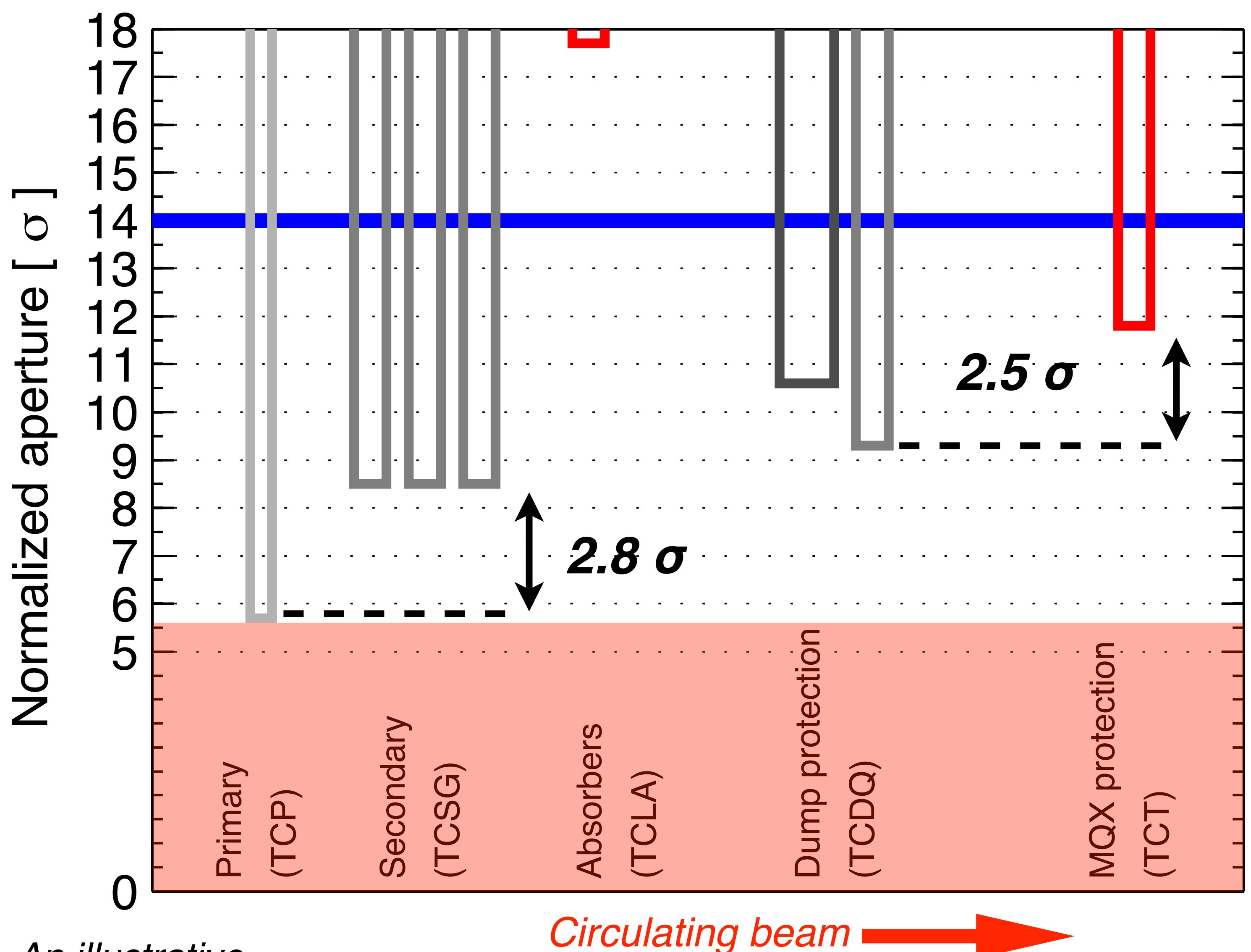
Squeeze in 2010 and in 2011





Various other improvements since 2010 that cannot be covered here (some backup slides available)

Why aperture determines the β^*?



An illustrative scheme

Machine aperture is a primary importance for the accelerator performance!

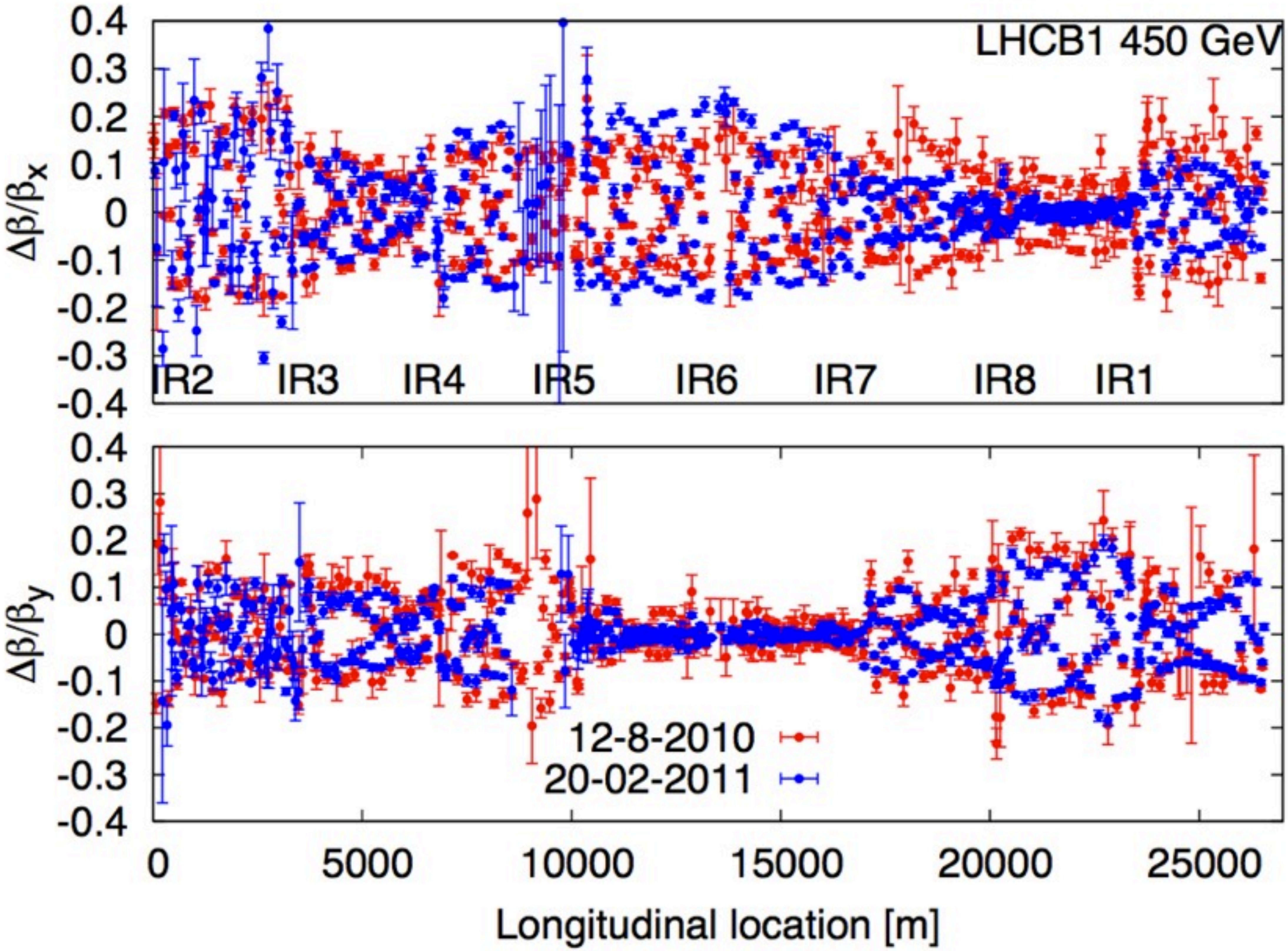
Minimum machine aperture sets the scale for collimator/protection settings.

Injection:
global bottleneck must be protected.
Top energy:
local triplet aperture determined β^*
(so far, inferred from injection measurements)

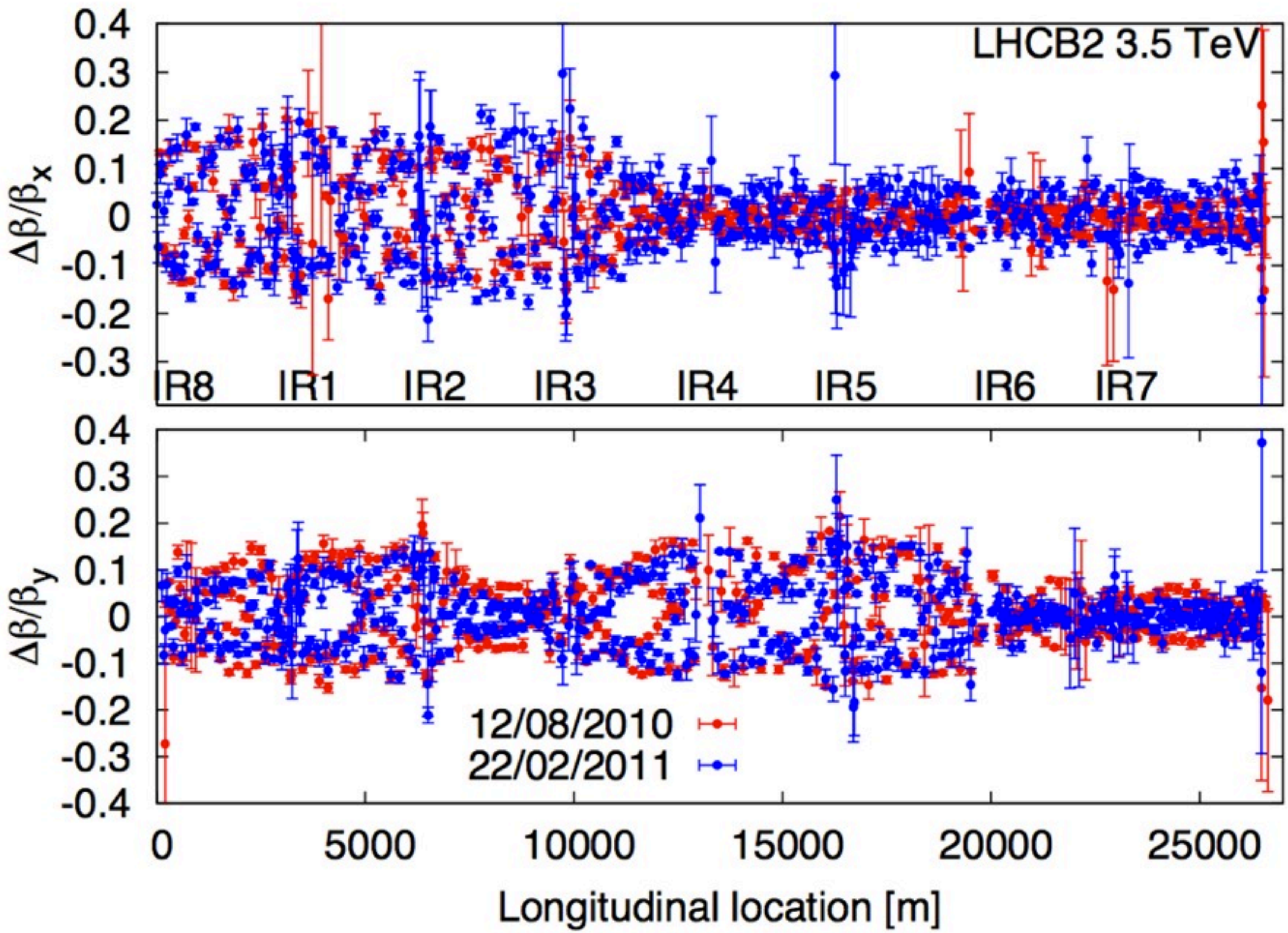
LHC aperture measurements so far:

		E_{beam}
2007	Sector tests: first look at the arc aperture, first good surprises	450 GeV
2008	Extended sector tests	450 GeV
2009	Global ring aperture: oscillating closed-orbit bumps	450 GeV
2010	Global ring aperture + local IR margins (bumps + ε blow-up)	450 GeV
2011	February, March: Global and local IR (emittance blow-up)	450 GeV
2011	*August: Local IR1/5 aperture*	*3.5 TeV*
2011	*October: Local IR2 aperture*	*3.5 TeV*

Beta-beating at injection

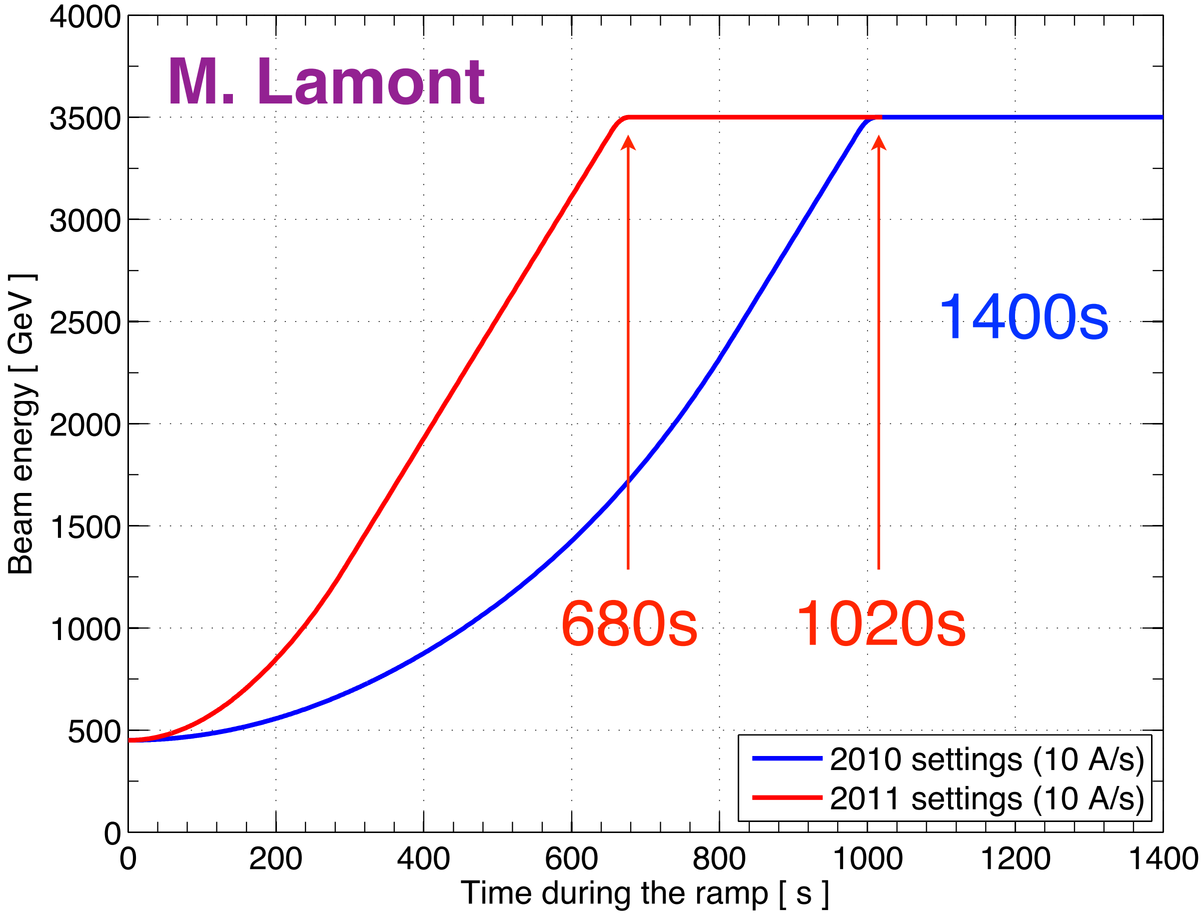


Beta-beating at flat top (inj optics)



Ramp: improvements for 2011

- ☑ **Same optics as 2010 in all IPs**
- ☑ **Faster ramp functions**
  - Gain 6.3 minutes (di/dt_{max} =10 A/s).
  - Needs beam validation.
  - Roll-back if problems.
- ☑ **Reduce parallel separation as √E**
  - Optimize aperture.
  - Reduce time for collisions.
  - Linear variation as a function of time.
  - Requires time-reference in the feedback.



- ☑ **Change crossing angles during ramp** (170 μrad → 120 μrad)
- ☑ **Maintain 380 s at flat-top for decay compensation**
- ☑ **FiDeL team working on tracking decay of Q and Q'**
  - Work ongoing on "preventive" trims at injection *plateau.*
- ☑ **Re-use beta corrections of 2010 from day 1.**