First demonstration with beam of the Achromatic Telescopic Squeeze (ATS)

S. Fartoukh

→ **The Achromatic Telescopic Squeeze (ATS): motivations and basic principles**

→ **2011 ATS MDs: Overview, Highlights and Lessons**

→ **Plans for 2012**

→ **Do we need the ATS for the LHC-2012 (pre-squeezed optics)?**

→ **Summary**

Main References:
sLHC-PR0038 & sLHC-PR0049/0053 → Phase I LHC Optics limitations & description of the ATS scheme
ATS Notes 2011-033, 2011-060, 2011-132 → 2011 ATS MD results
ATS optics repository for the existing LHC:
/afs/cern.ch/eng/lhc/optics/ATS_V6.503 → ATS optics compatible with the layout version V6.503 of the LHC

Motivations

Phase I optics limitations (Chamonix 2010)

… Lower β^* need magnets of larger aperture, but also new hardware or sophistication (crab-cavity, flat optics …) to "profit from the low β^*"
→ **the HL-LHC Project**

… But this does not tell how to produce the β^* → **the ATS scheme** which solves **many optics limitations coming from the overall ring**:

1. **Optics matchability** to the arcs:

→ Some IR quads going to 0 T/m, others to max. field (200T/m)

→ Simply the matching section becomes too short at some point!

2. **Correctability of the chromatic aberrations induced**, not only Q', but also Q'', Q''',…, and off-momentum β-beating.

→ Arc sextupole strength (<600A)

The ATS scheme (Chamonix 2011)

The basic principles of the ATS

- **A new injection optics** (~ π/2 FODO lattice → new integer tunes)
- **A <u>squeeze in 2 steps</u>**

1) An "almost" standard squeeze, **the Pre-squeeze**:

→ acting on the matching quads of IR1 and IR5,

→ with new matching constraints on the left/right IR phase

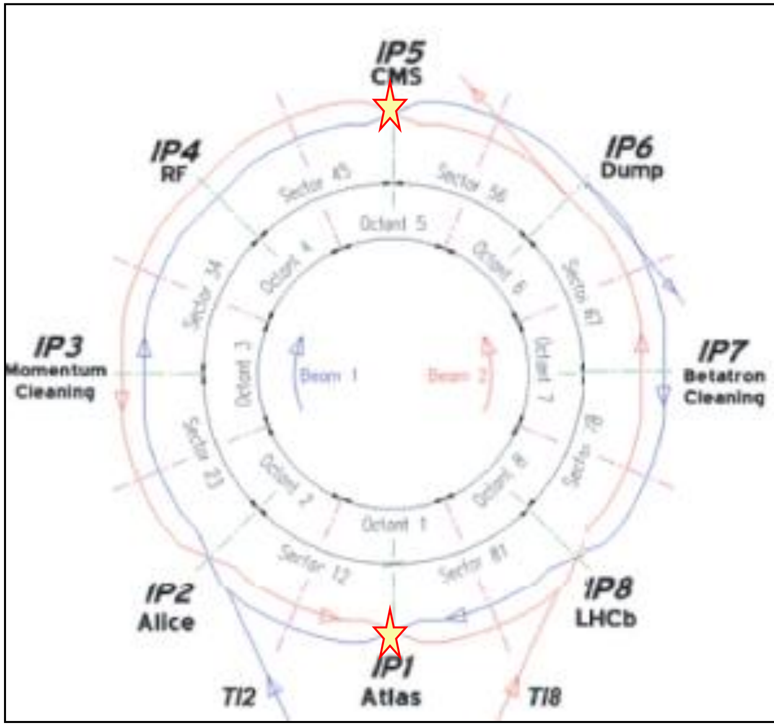
→ till reaching some limits (sextupoles, matching section).

2) A further reduction of β^*, **the Squeeze**:

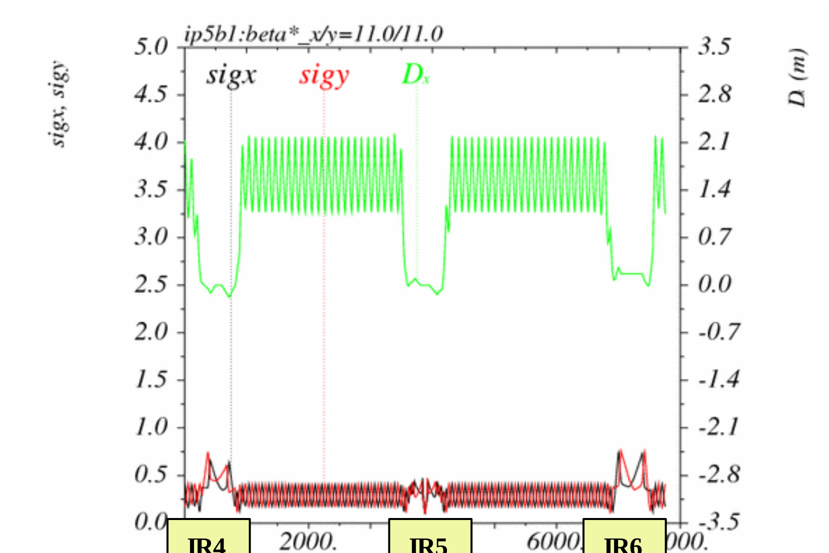
→ acting on IR2/8 for squeezing IR1 and IR4/6 for IR5,

→ inducing **β-beating bumps in sectors 81/12/45/56 to boost the sextupole efficiency at constant strength.**

$$\rightarrow \quad \beta^*_{\text{Squeeze}} = \beta^*_{\text{Pre-Squeeze}} \times \frac{\left(\hat{\beta}_{\text{Arc}}\right)_{FODO}}{\left(\hat{\beta}_{\text{Arc}}\right)_{Mismatched}}$$

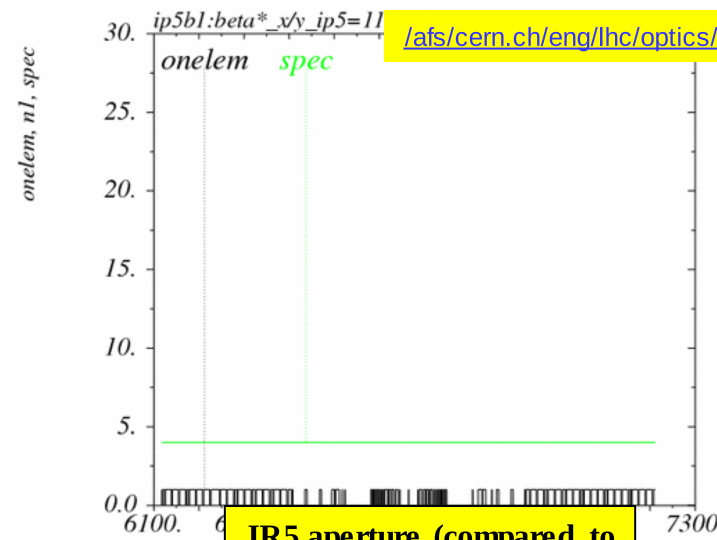


Reaching β*=10 cm in the existing LHC for ATLAS & CMS … a small animation

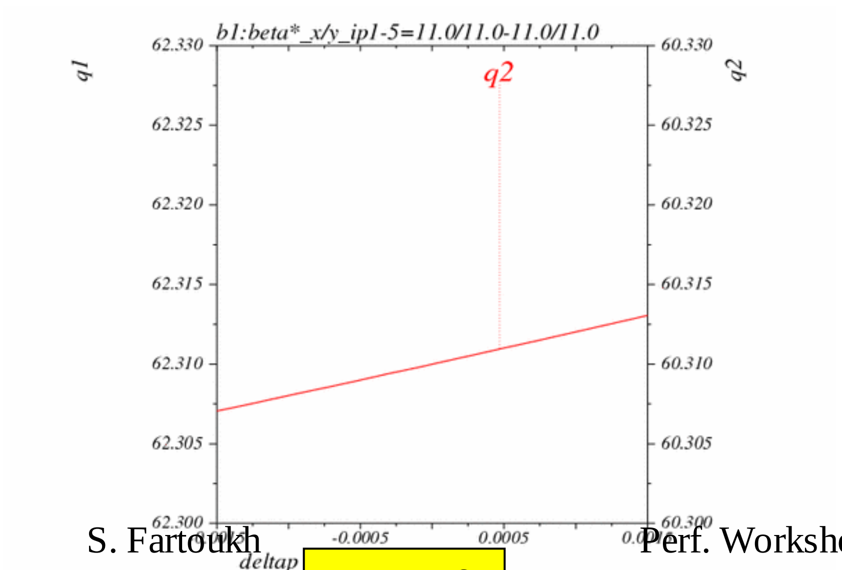


Beam size [mm] and dispersion (IR4→IR6) at 3.5 TeV (for γε=3.5 μm)

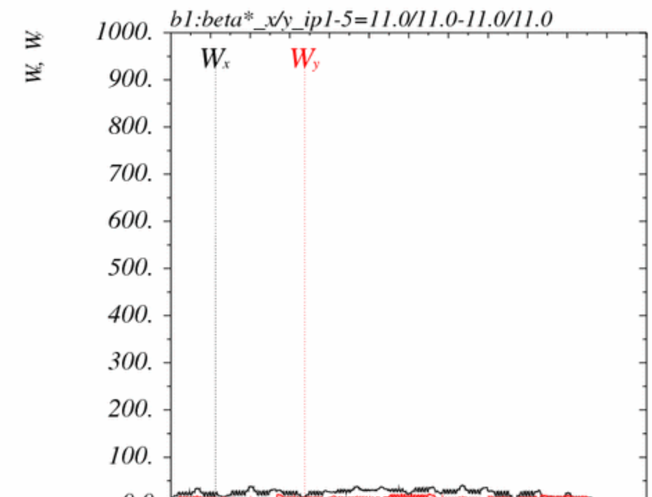
/afs/cern.ch/eng/lhc/optics/ATS_V6.503



IR5 aperture (compared to 4 sigma's (X-angle OFF)



Tunes vs. δ_p



Chromatic Montague functions over the full ring (off-momentum β-beating)

Highlights of the ATS MD over 2011

→ **A full program deployed in 2011, with a total of 8h spent for dry runs (w/o beam) + 23 h with beam:**

1. **Bloc 1** (2h+8h): **ATS injection optics and ramp** (new integer tunes, new arc and IR optics).

   → **successful**

2. **Bloc 2** (3h+9.5h): **Pre-squeeze to β^*=1.2 m** in IR1&5 (no X-angle), and **telescopic squeeze demonstrated for IR1**, reaching **β^*= 30 cm.**

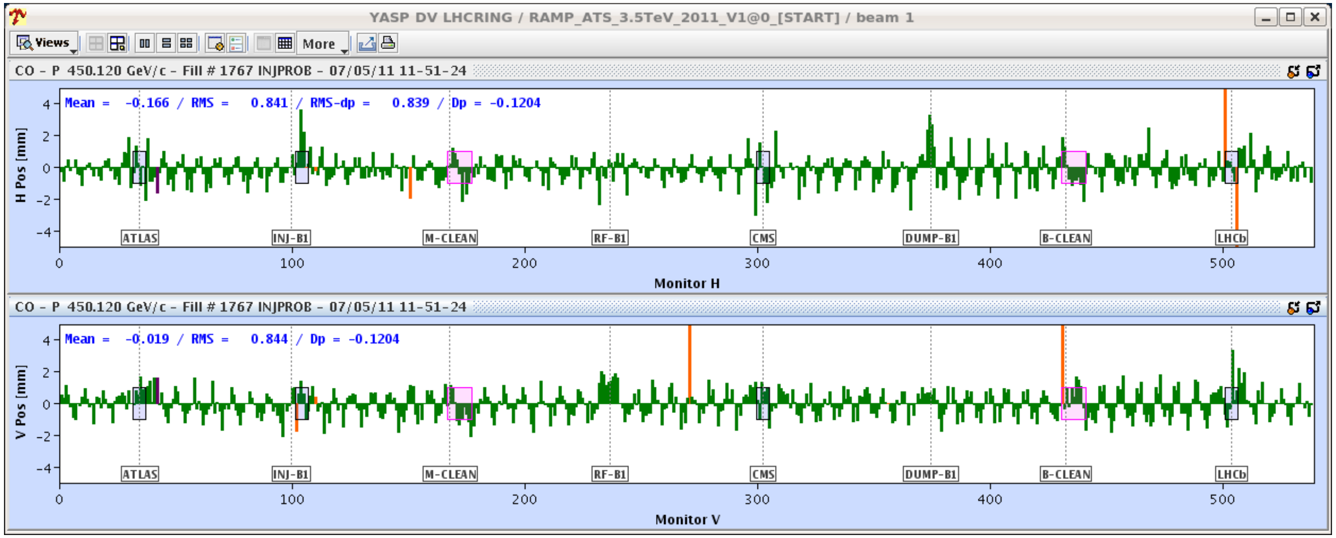
   → **successful**

3. **Bloc 4** (2h+4.5h): **Pre-squeeze to β^*=40 cm** in IR1&5 (no X-angle), and **squeeze of IR1 and IR5 down to β^*= 10 cm.**

   → **Pre-squeeze successful, beam lost when preparing the squeeze** ("misunderstanding" between QFB and new tune knobs)

Highlights of the ATS MD Part I (new inj. optics and ramp)

- **Beam1 captured and circulating at the first injection!**



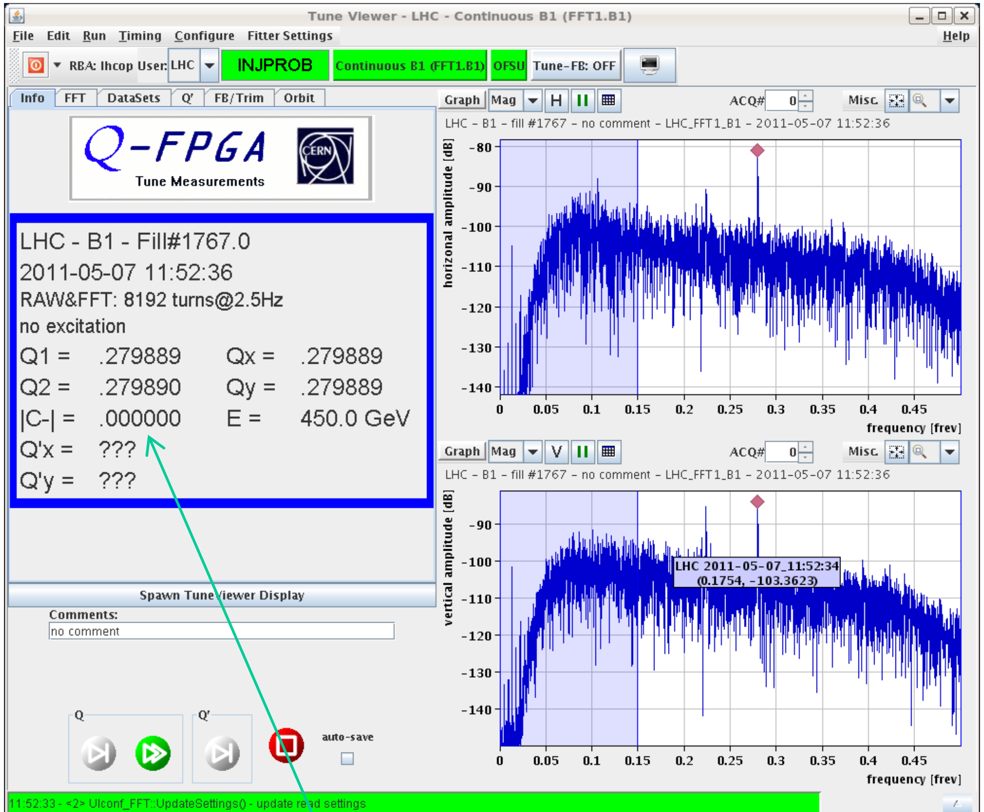
… using nominal injection MCB pre-settings, which means that the CO correction of the nominal optics is very local.

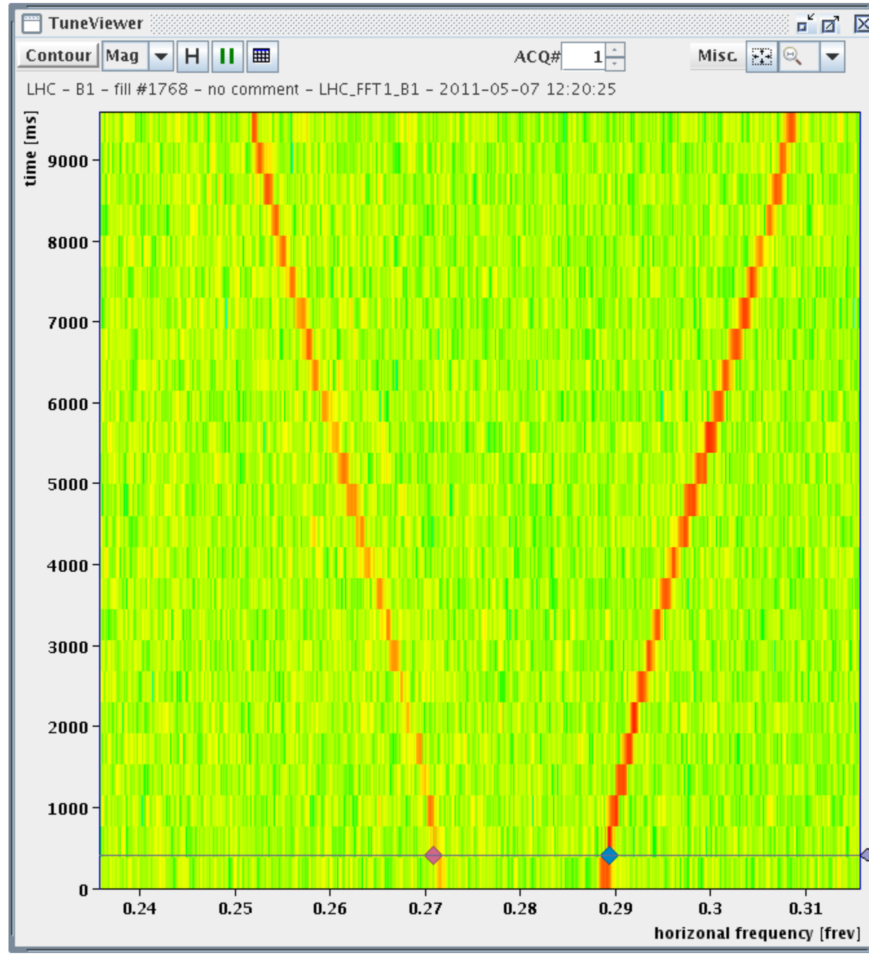
- **30 min. later: 0.15 mm r.m.s. closed orbit (crossing knobs off)**

Thanks to J. Wenninger *et al.*

- **First tune measurement:**

Machine fully coupled but **with a ΔQ_{min} of only 0.06 w/o ANY correction,** and then easily decoupled with the closest tune approach (down to 10^{-3} or less)



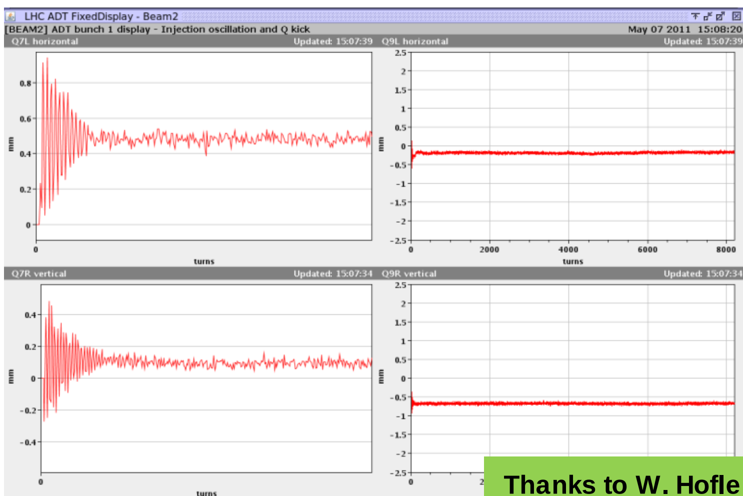


→$|C_-|$ **is given to be 0 in FPGA while the machine is fully coupled**

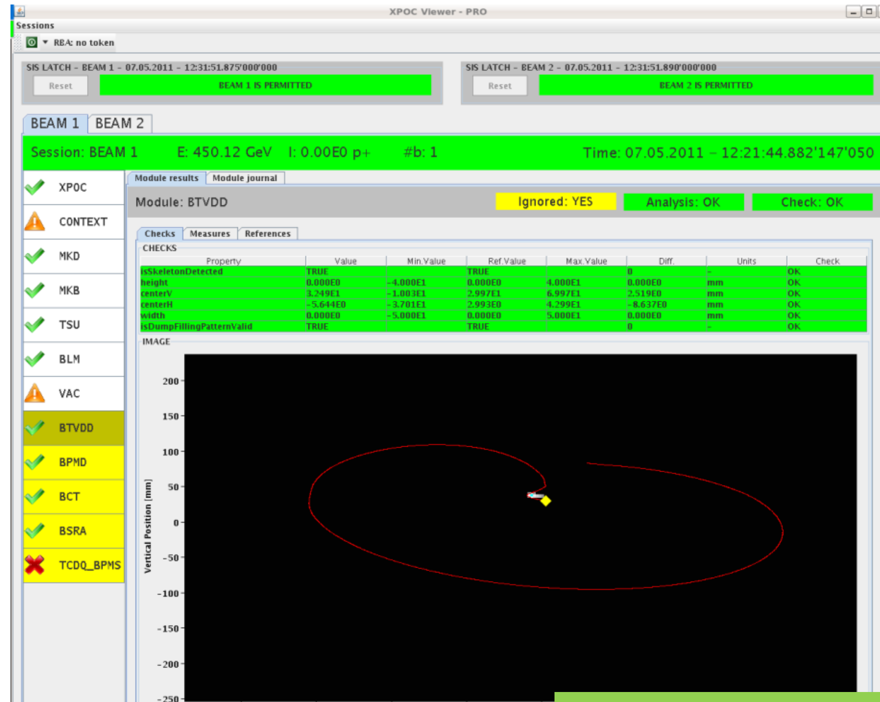
• Tests of LHC sub-systems at 450 GeV: damper, dump, RF trims

W.H.
06.05.2011

			norm	delta	ATS
H.M1.B1	phaseshift 1	Q7	-100	-8	-108
H.M1.B1	phaseshift 2	Q9	10	7	17
H.M2.B1	phaseshift 1	Q7	-105	-8	-113
H.M2.B1	phaseshift 2	Q9	10	7	17
V.M1.B1	phaseshift 1	Q7	-174	1	-173
V.M1.B1	phaseshift 2	Q9	120	-60	60
V.M2.B1	phaseshift 1	Q7	166	1	167
V.M2.B1	phaseshift 2	Q9	120	-60	60
H.M1.B2	phaseshift 1	Q7	-110	2	-108
H.M1.B2	phaseshift 2	Q9	-3	-20	-23
H.M2.B2	phaseshift 1	Q7	-90	2	-88
H.M2.B2	phaseshift 2	Q9	20	-20	0
V.M1.B2	phaseshift 1	Q7	-160	-1	-161
V.M1.B2	phaseshift 2	Q9	70	77	147
V.M2.B2	phaseshift 1	Q7	-160	-1	-161
V.M2.B2	phaseshift 2	Q9	70	77	147



Thanks to W. Hofle *et al.*

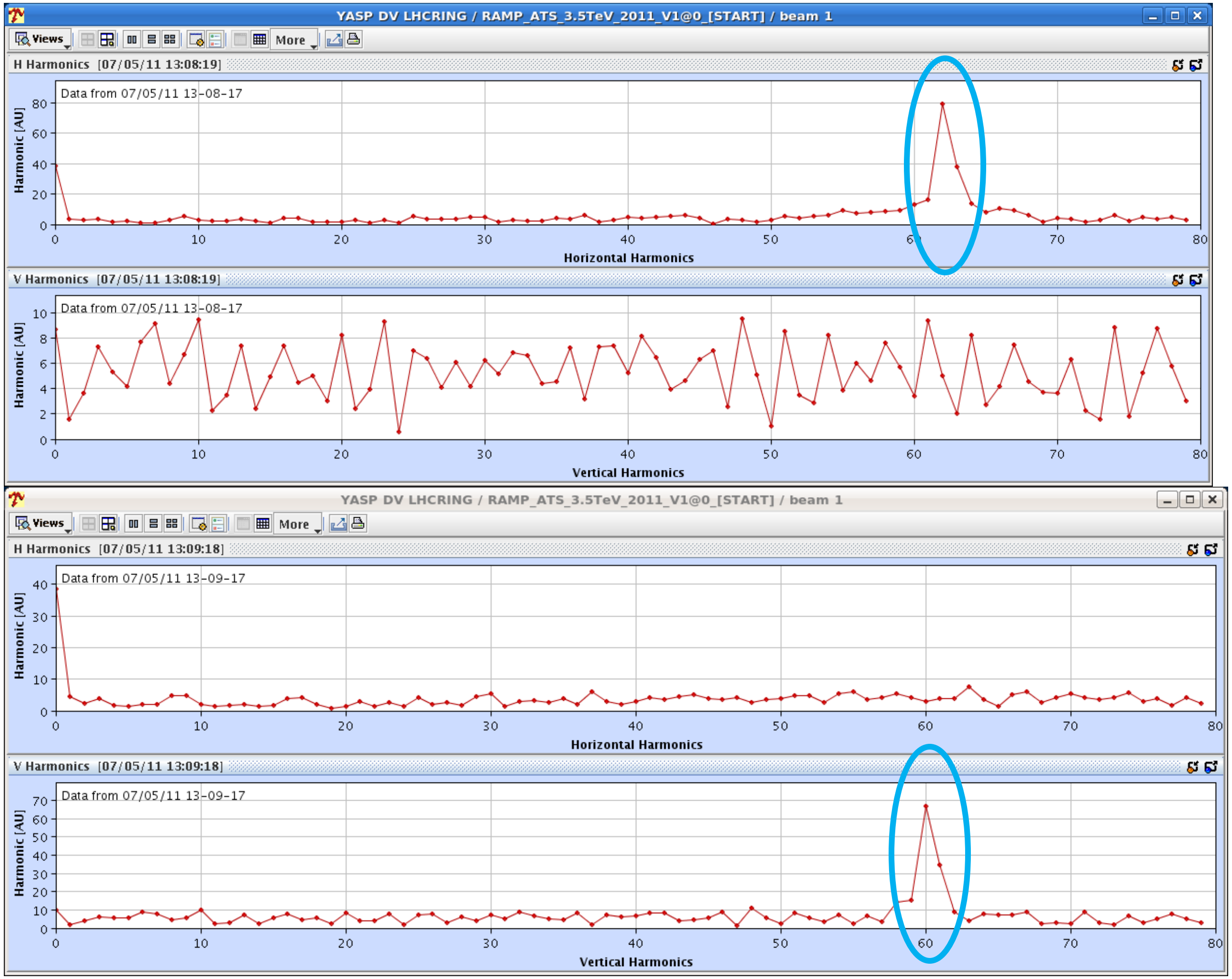


Thanks to B. Goddard *et al.*

First **dump** test … with the beam right onto the target

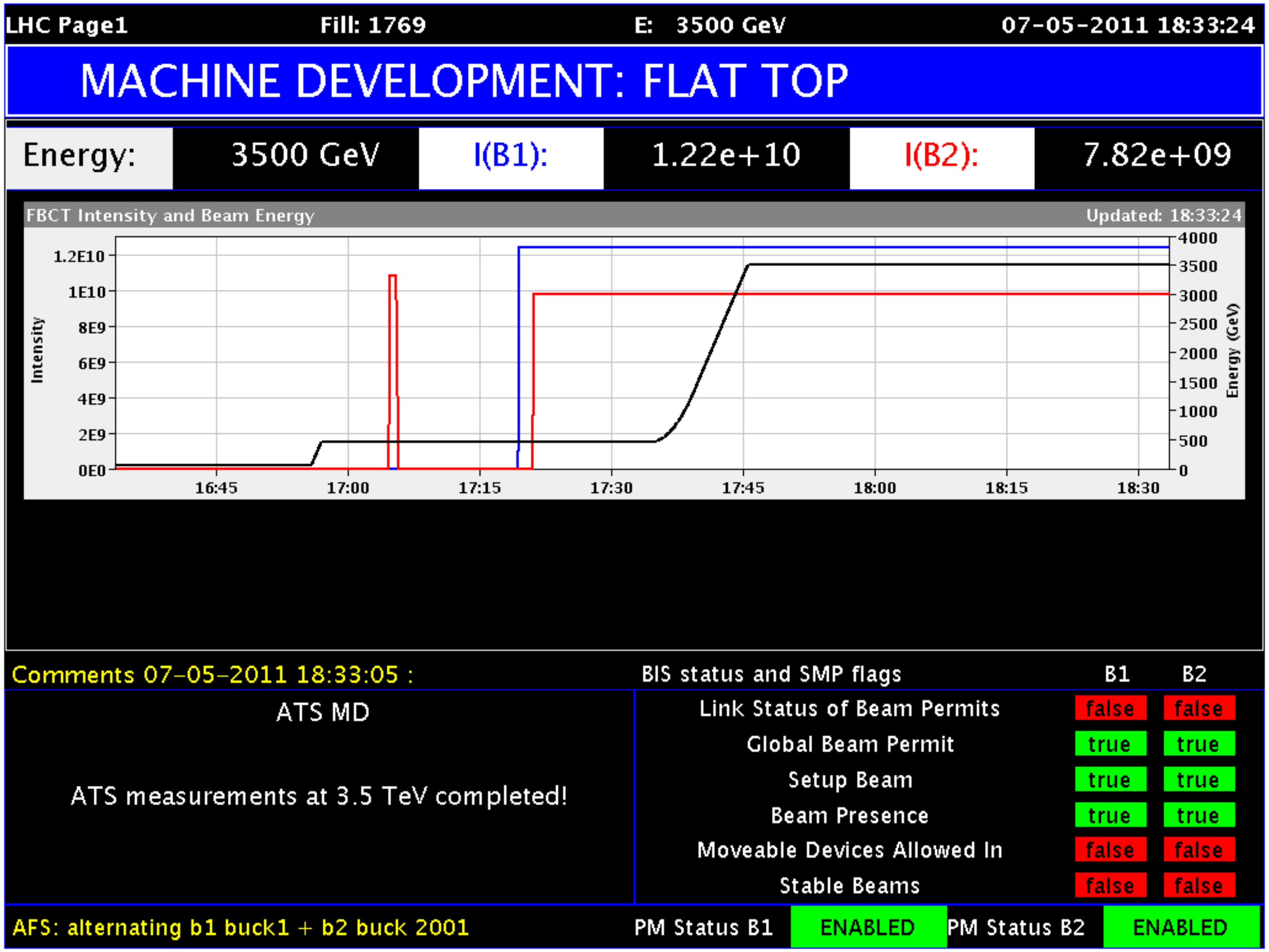
New settings for the **damper** (phases) and < 50 turns damping time at the first attempt

- **The new integer tunes**

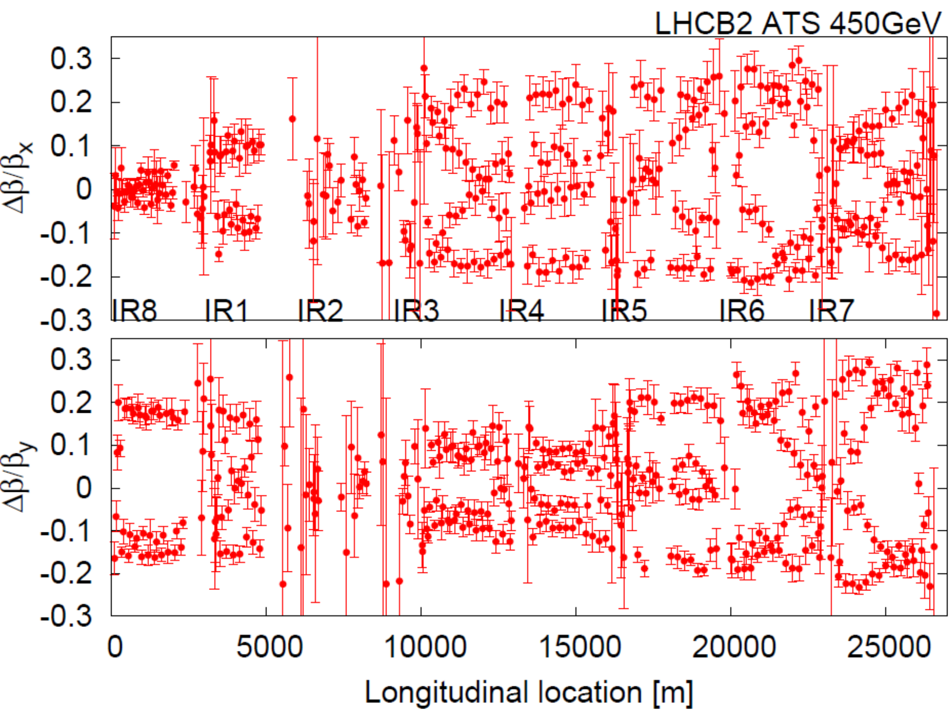


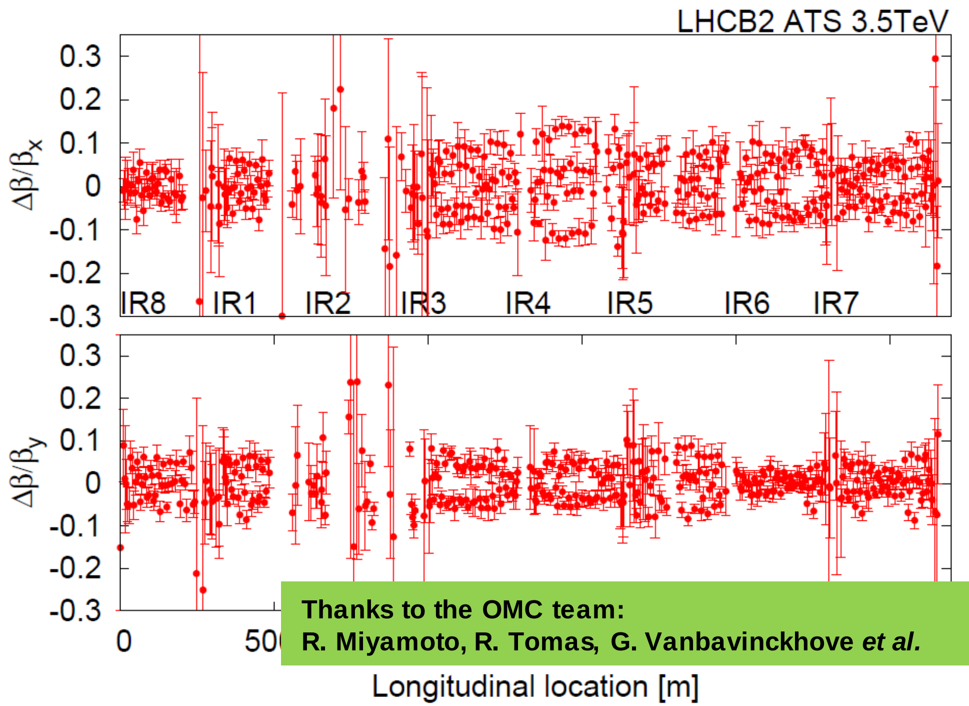
→ New integer tunes 62/60 (instead of 64/59)

…The ramp: excellent life time, transmission of intensity, and no emittance growth



- **<u>Beta-beating measurements</u> at 450 GeV and 3.5 TeV (inj. optics)**





Thanks to the OMC team:
R. Miyamoto, R. Tomas, G. Vanbavinckhove *et al.*

<u>Beta-beating at 450 GeV</u> (no correction)
→30-35% dominated by the IRs
(accuracy of the magnet model at low current)

<u>Beta-beating at 3.5 TeV</u>(no correction)
→10-15% residual from the arcs (random b2)
→ Signature of the MQ sorting

Lessons from the ATS MD Part I

The LHC performs as MAD, if not better

→ **Extremely well optimized** such that e.g. the choice of integer tunes is transparent, the fractional tunes can be widely moved for a closest tune approach

→ **Extremely well sorted at installation**

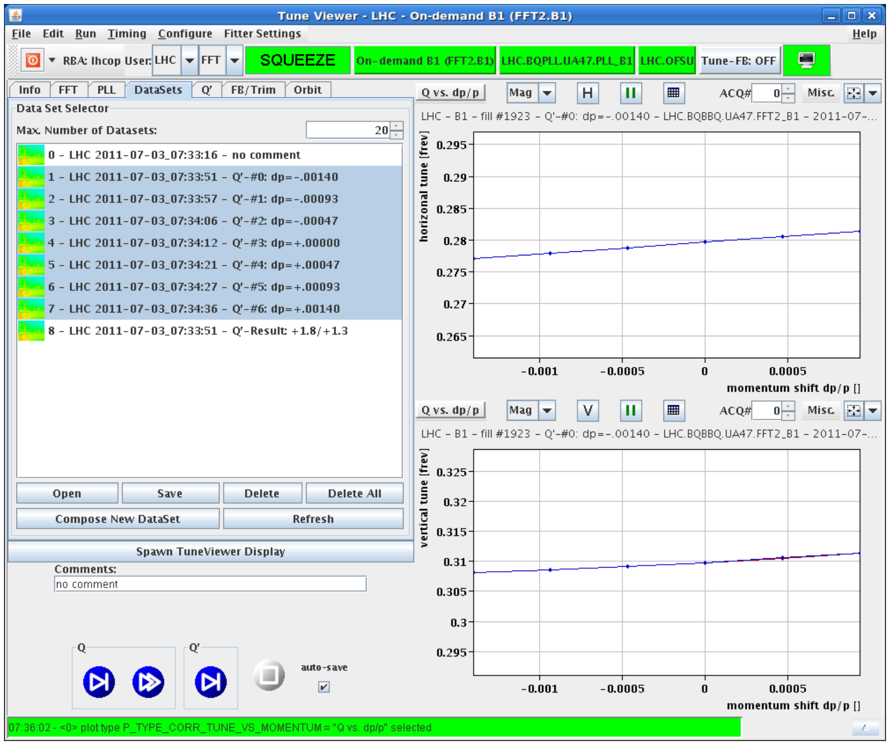
→A priori **fully debugged**

→.. And **much faster** for simulations!

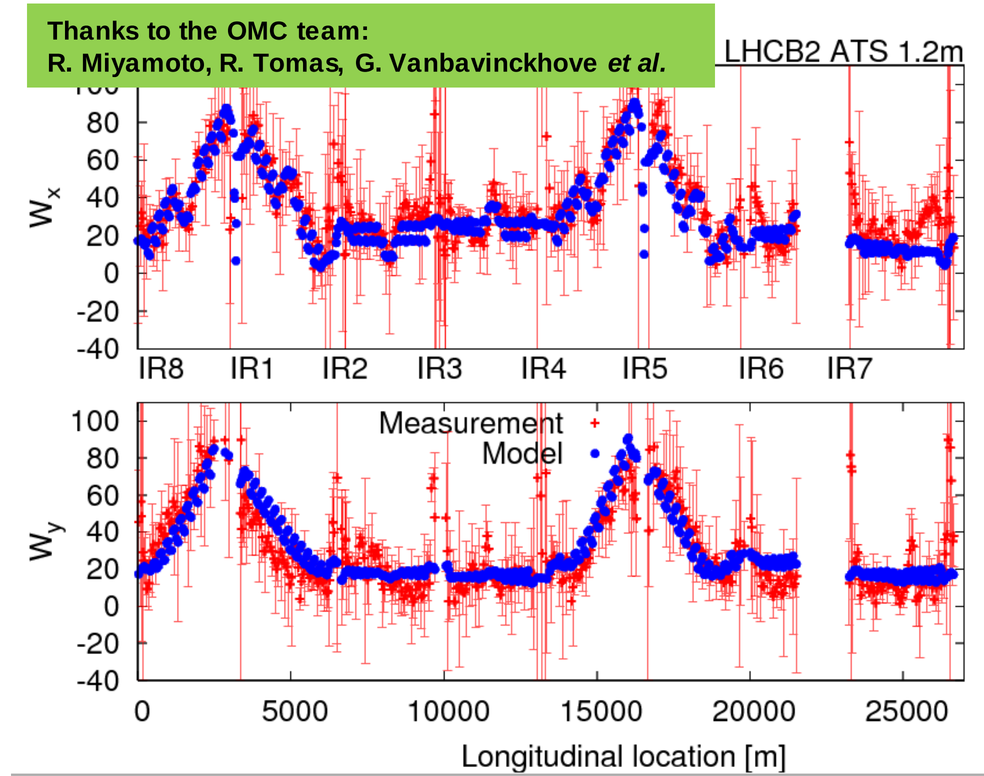
Highlights of the ATS MD Part II

(pre-squeeze to 1.2 m in IR1 and IR5, and telescopic squeeze to 30 cm at IP1)

- **Chromatic measurements** of the pre-squeezed optics (β^*=1.2 m).



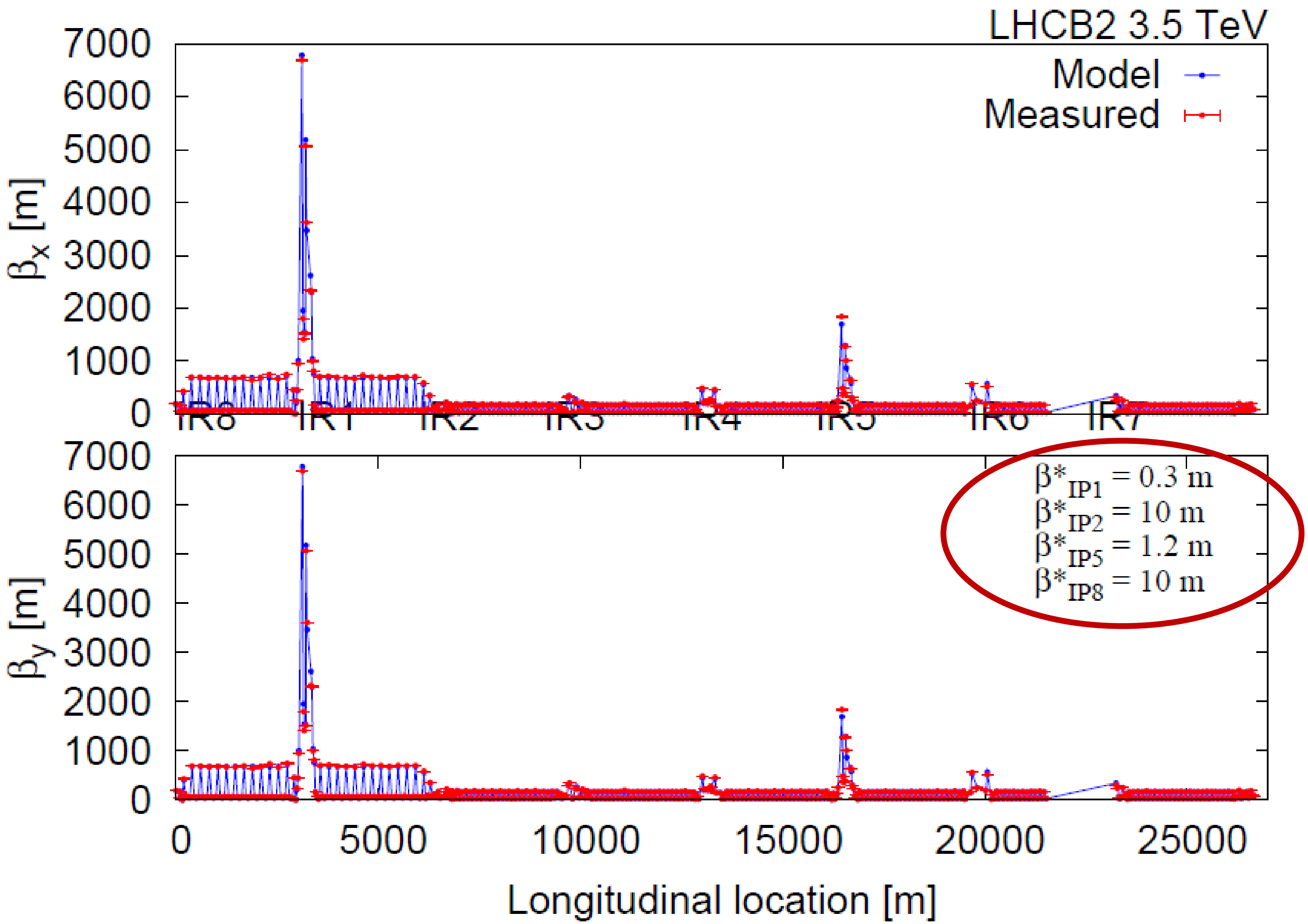
Thanks to the OMC team:
R. Miyamoto, R. Tomas, G. Vanbavinckhove *et al.*



The Tunes are linear vs. δ_p over a momentum window of +/- 1.5 permil

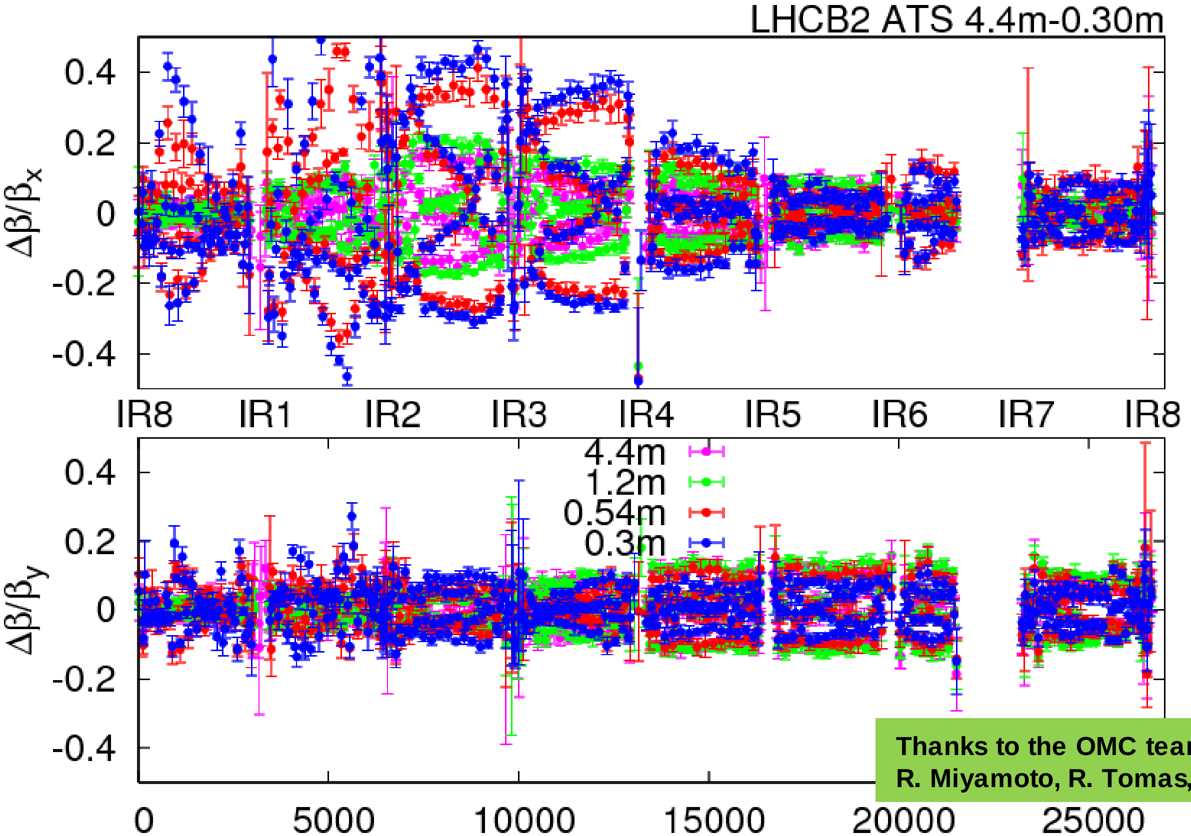
The off-momentum β-beating wave induced by the IT starts to show up but is contained in s81/12/45/56

- **Telescopic principle (×4) demonstrated in IR1**



- **Beta-beating measurements at β*= 4.4, 1.2, 0.54 m, and 30 cm**

(3 trims, extracted from the nominal optics and incorporated for Q2.R1, Q2.L5 and Q2.R5)

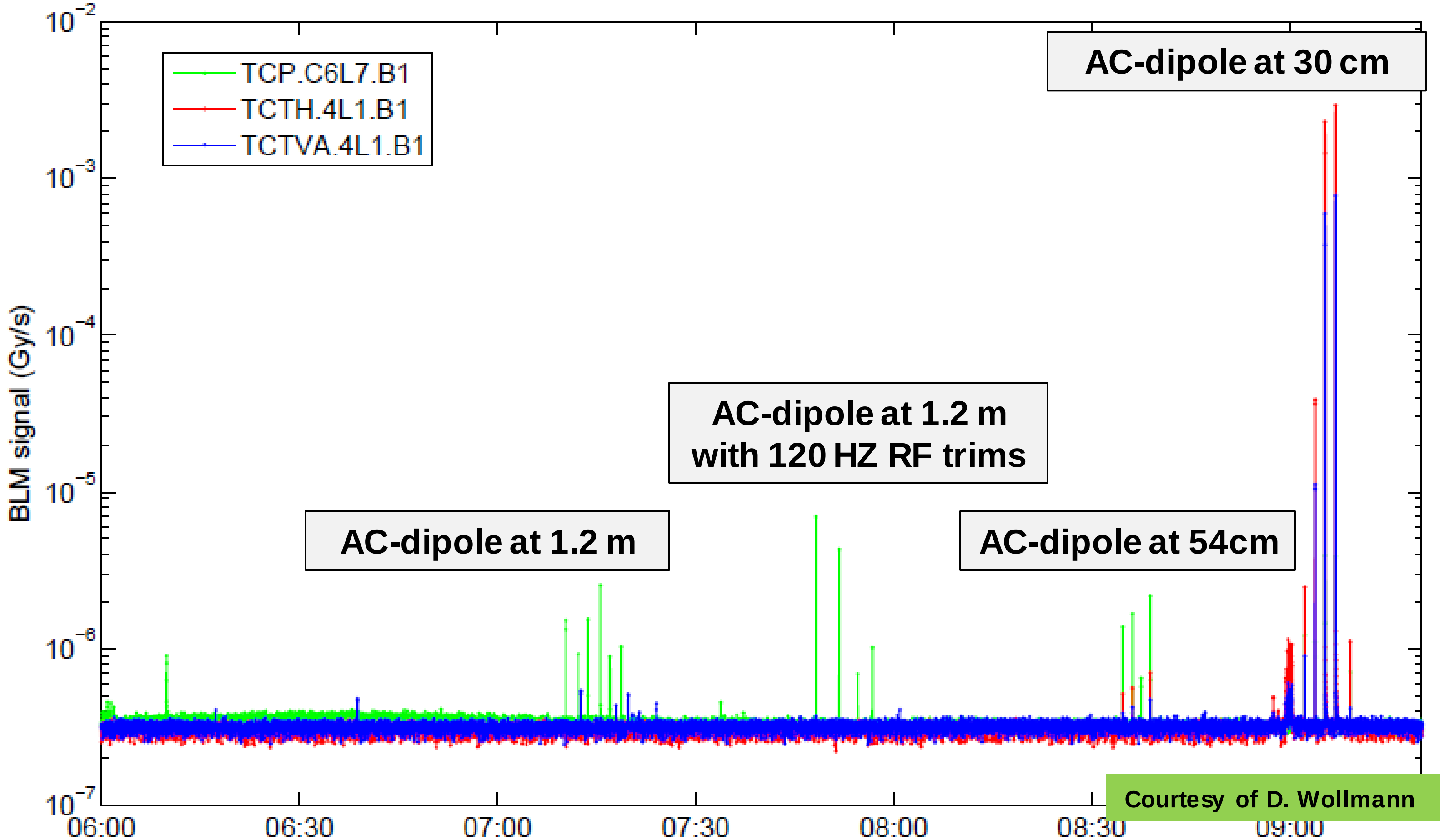


Thanks to the OMC team:
R. Miyamoto, R. Tomas, G. Vanbavinckhove *et al.*

→ Could have been much worst with a β_{max} of 7 km in IR1 and by increasing by a factor of 4 the β's in s81 and s12.

→ Optimization still needed (IR8, IR4, arc by arc fine-tuning of the b2 correction)

- **<u>Losses (hystory over the last 3 hours)</u>** with TCPH/V set at ~9 σ in IR7, TCTH/V set a ±12/10 mm in IR1 and IR5.



→ No losses except during AC-dipole measurement

Lessons from the ATS MD Part II

The **"Telescopic" part** of the ATS is demonstrated,

… at least for IR1.

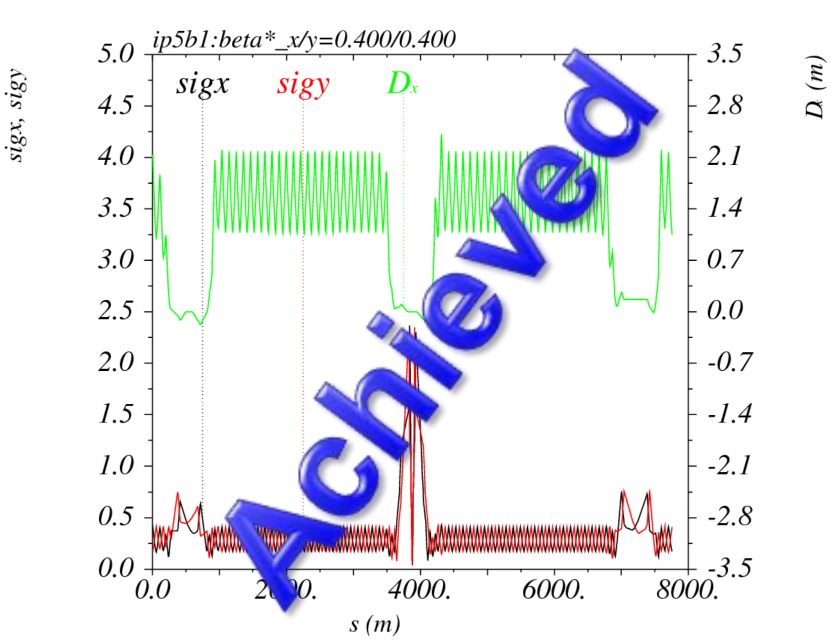
→ **Additional squeeze lever arm by a factor of 4!**

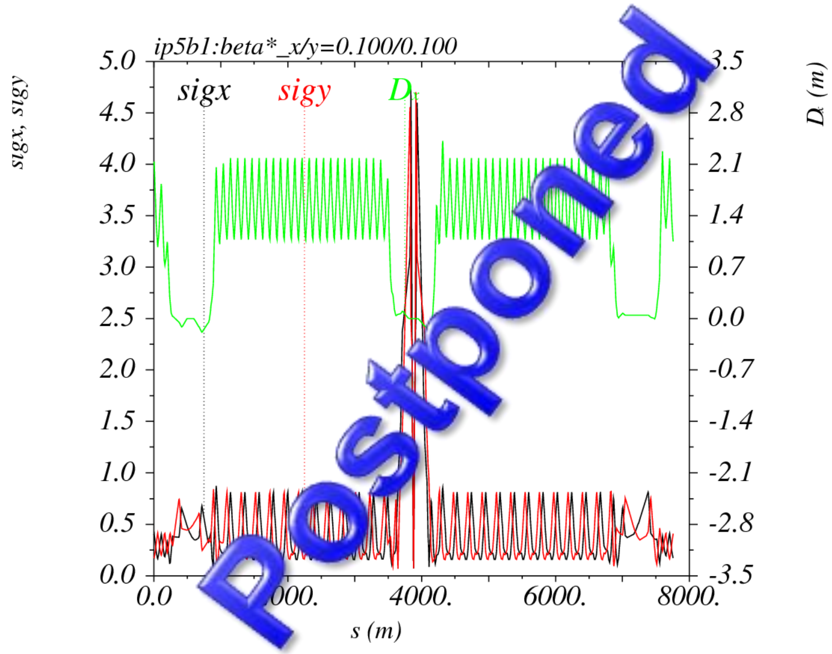
The **"Achromatic" part** of the ATS is validated … at least down to the "relaxed" pre-squeezed β^* of 1.2 m.

→ **Non-linear chroma and off-momentum β-beating under control!**

Highlights of the ATS MD Part III

(pre-squeeze to 40 cm and telescopic squeeze to 10 cm both at IP1 & IP5)



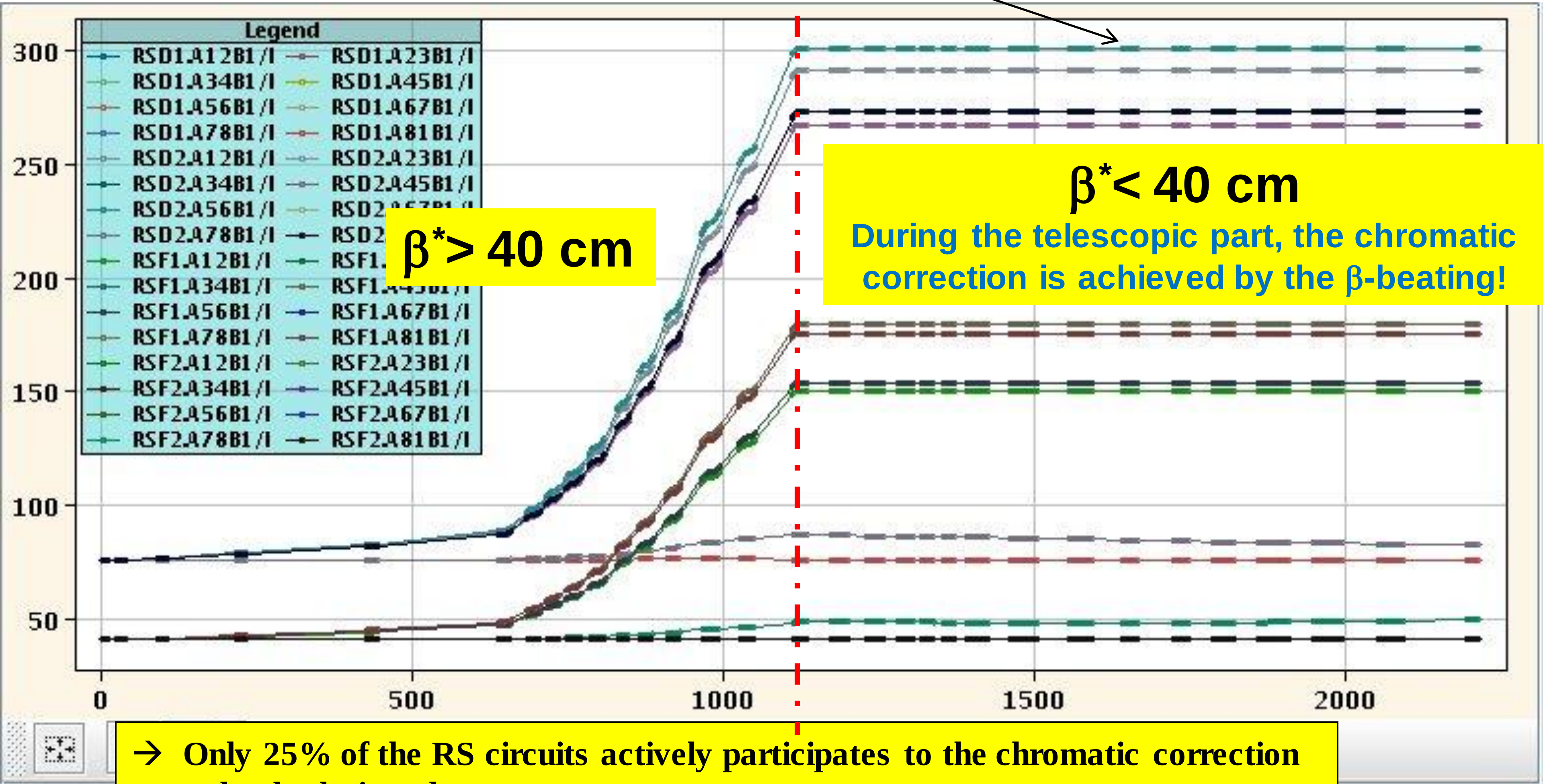


IR5 pre-squeeze at β^*= 40 cm
→β_{max}= 6 km in the triplet
(σ ~2.5 mm @3.5 TeV, $\gamma\varepsilon$ = 3.5 μm)
→FODO β's in arcs 45 & 56
→FODO dispersion

IR5 squeeze at β^*= 10 cm
→β_{max}= 24 km in the triplet
(σ ~5 mm @3.5 TeV, $\gamma\varepsilon$ = 3.5 μm)
→400% β-mismatch in arcs 45 & 56
→ FODO dispersion

- **Pre-squeezed pushed to the limit for the sextupoles**

300 A is reached in some RSD circuits at 3.5 TeV, which means 600 A at 7 TeV!



$\beta^* > 40$ cm

$\beta^* < 40$ cm

During the telescopic part, the chromatic correction is achieved by the β-beating!

→ **Only 25% of the RS circuits actively participates to the chromatic correction and only during the pre-squeeze**

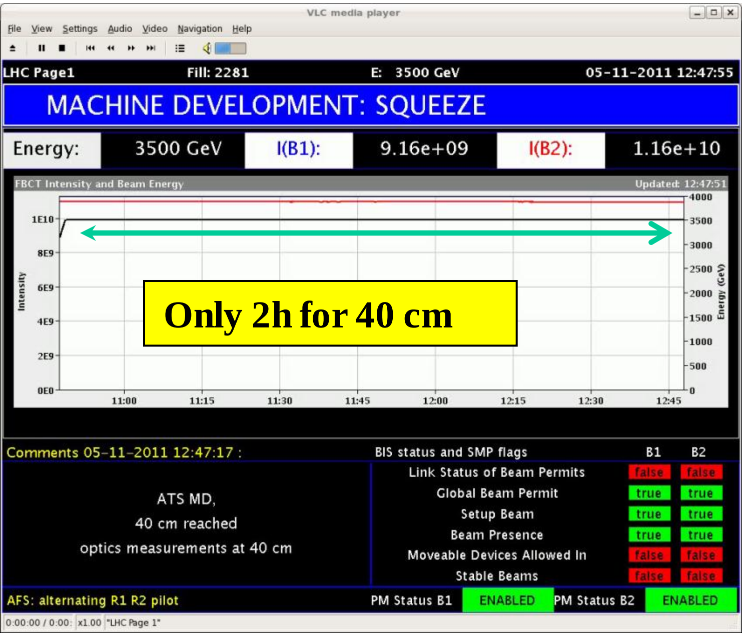
- **Pre-squeeze pushed to the limit for the RQ6 circuits of IR1 & IR5**

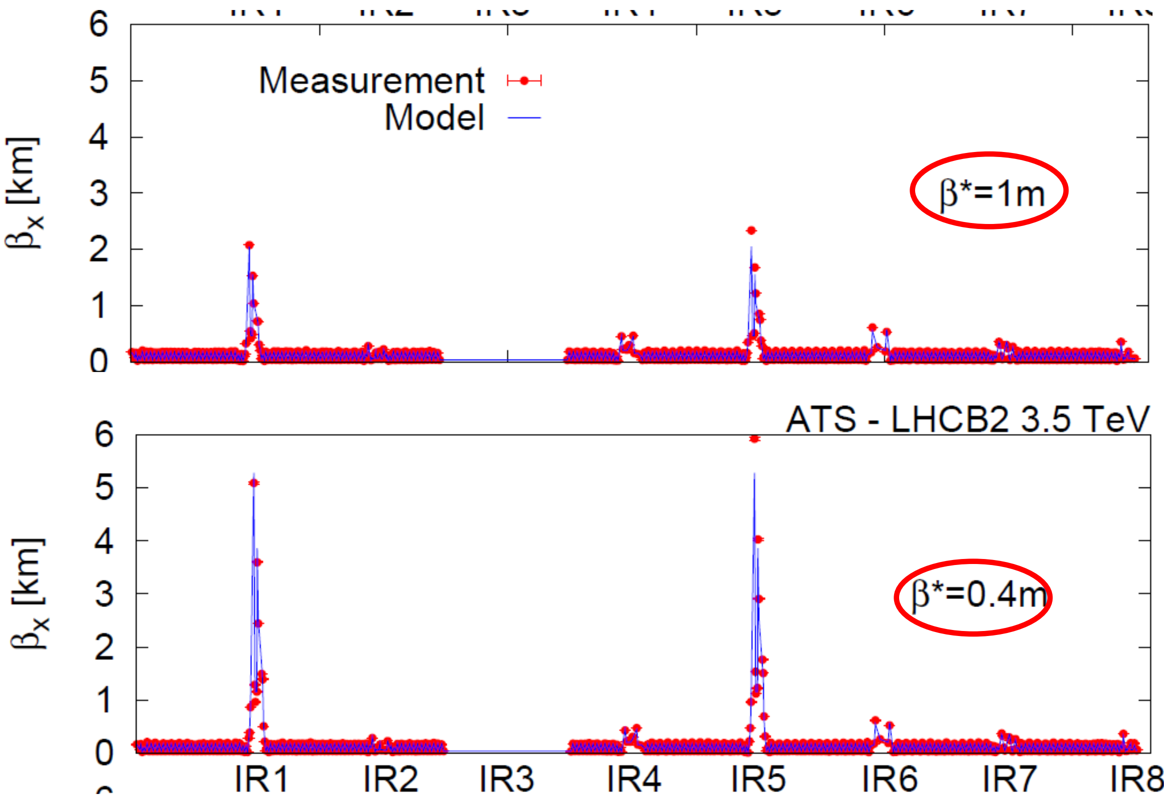
→ Already low current @ 7 TeV, therefore was even lower @ 3.5 TeV!

~ 330 A for some Q6's in IR1/5 @ β*=40 cm and 3.5 TeV
(would be 240A for the nominal collision optics @ β*=60cm and 4.0 TeV)

Only 20 mV margin left at the end of the pre-squeeze (β*=40 cm)

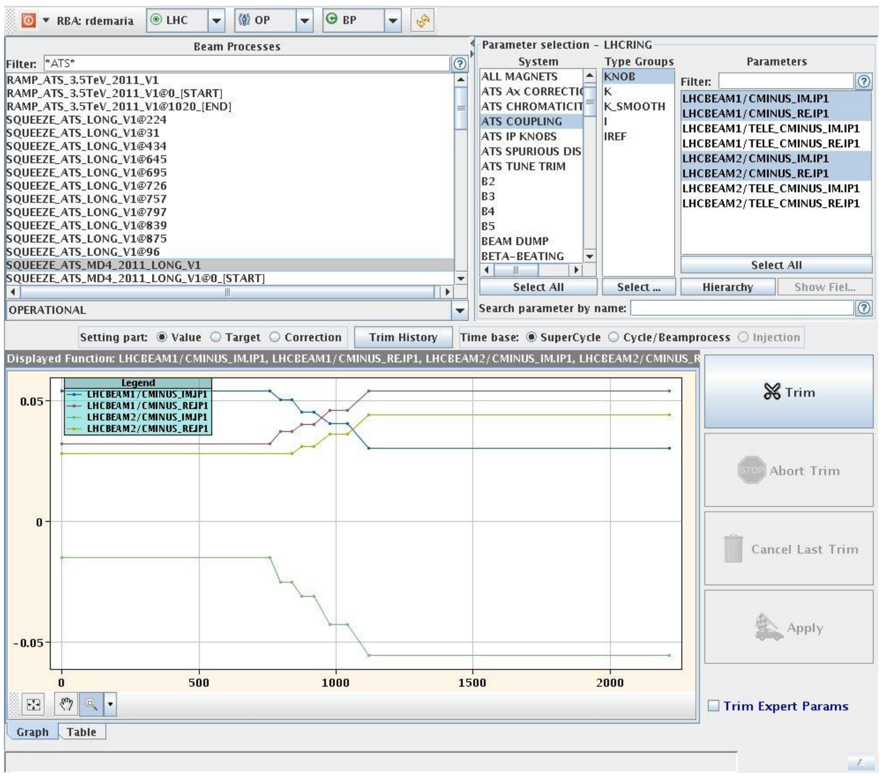
- **<u>Excellent transmission during ramp</u>** and **<u>fast pre-squeeze</u>**

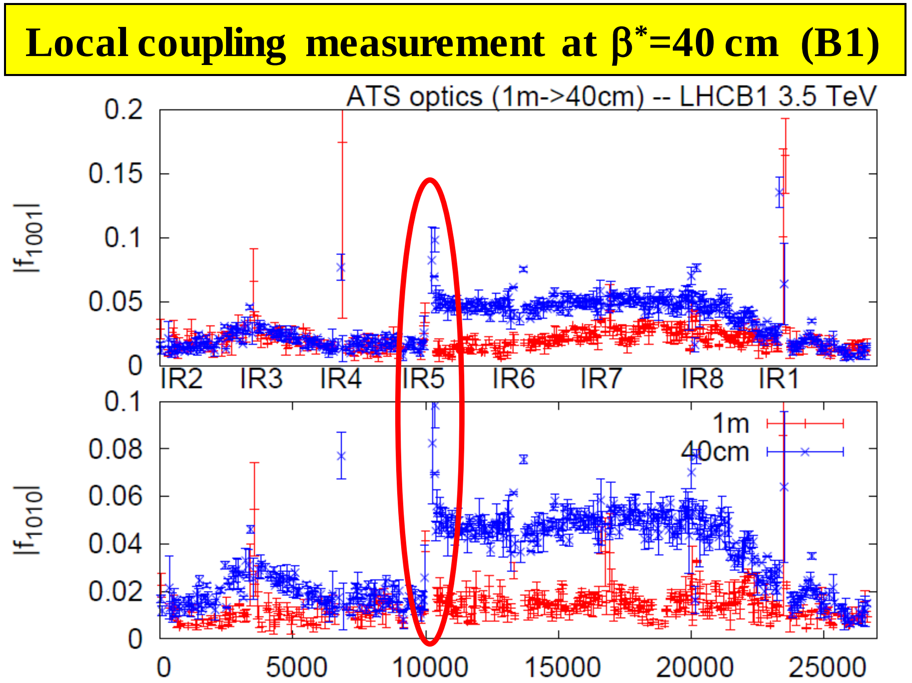




→ As fast as 3km/h in terms of β_{max}, including a stop at 1 m for optics measurement!

- **<u>Rather constant Q'</u>** during the pre-squeeze
- **<u>Coupling easily corrected</u>** with global knobs, but some trend visible

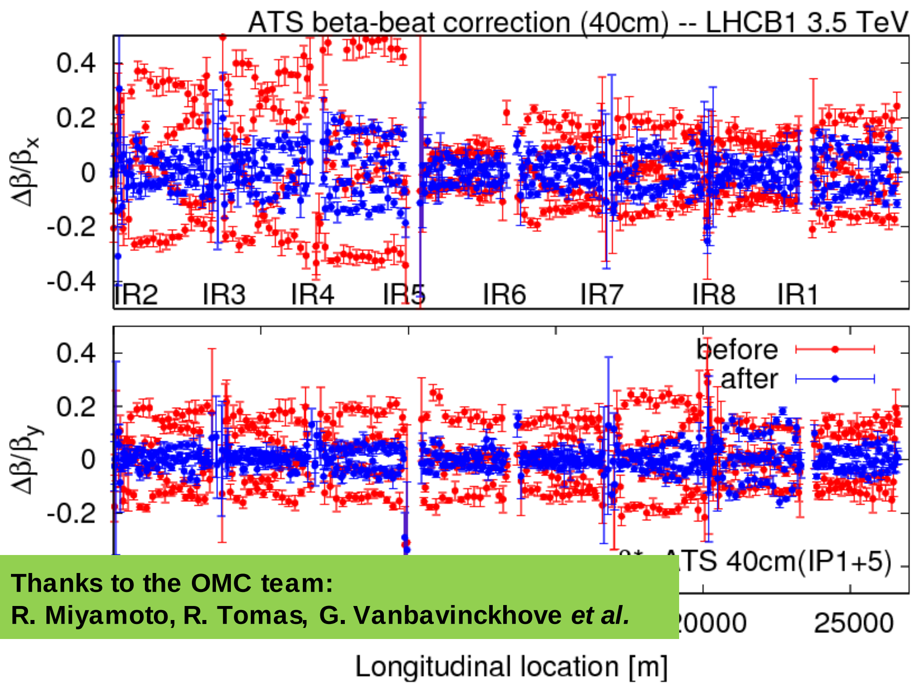




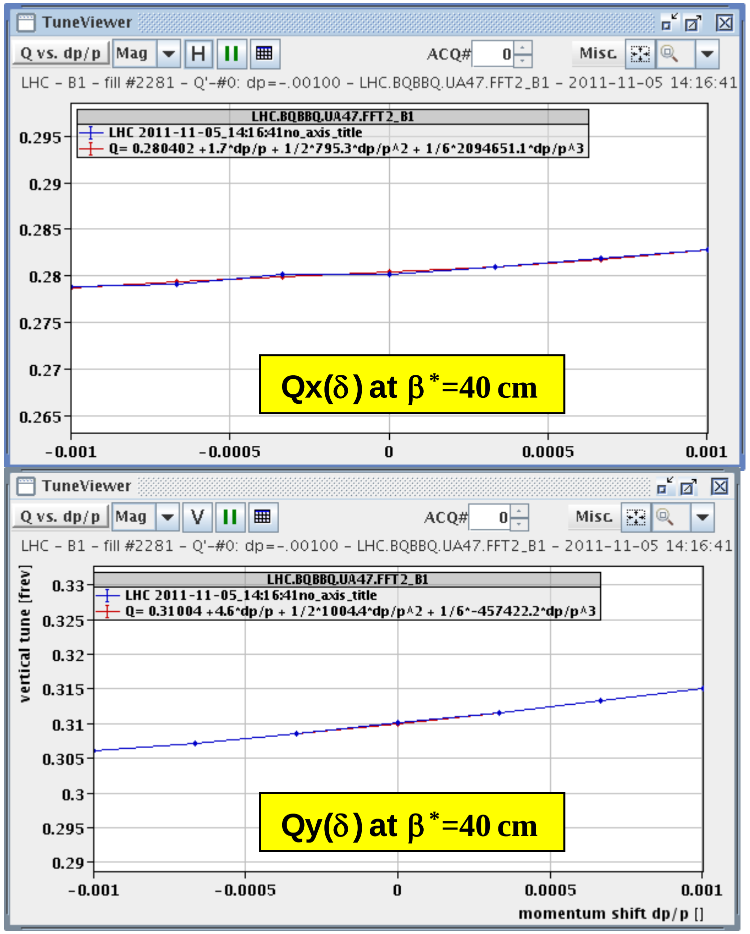
Thanks to the OMC team: R. Miyamoto, R. Tomas, G. Vanbavinckhove *et al.*

→ Fine tuning of the RQSX's needed in IR5 and rebalancing the arc a2 correction

• Optics measurements and correction at β*= 40 cm



Thanks to the OMC team:
R. Miyamoto, R. Tomas, G. Vanbavinckhove *et al.*



→ 15-20% level reached for the β-beating after one single correction iteration (only Beam1)

→ No (small) Q'', Q''' …

Lessons from the ATS MD Part III

- **For the LHC**

→ **The nominal β* (55 cm) or below (40 cm) is within reach (from the optics point of view)!**

- **For the ATS & HL-LHC**

→ **So far so good** …but **still a lot of work** ahead to guaranty the success of 10 cm (local coupling, β-beating and phase-beating correction at 40 cm, tune knobs & Q-feed-back,…)

Plans for 2012

- Prepare a **clean 40 cm pre-squeezed optics (no X-angle)**

→ measured and corrected for coupling, β-beating, …

- Prepare a **safe 40 cm pre-squeezed optics (no X-angle)**

→ using tight collimator settings and high brightness bunches for an **high pile up facility (up to ~120 events/crossing)**

- Approach and hopefully reach & measure **the 10 cm β* with pilot beam.**

- If time permits, **flat pre-squeezed/squeezed optics**

→ 10-15% more performance after LS1 (from the lumi loss factor)

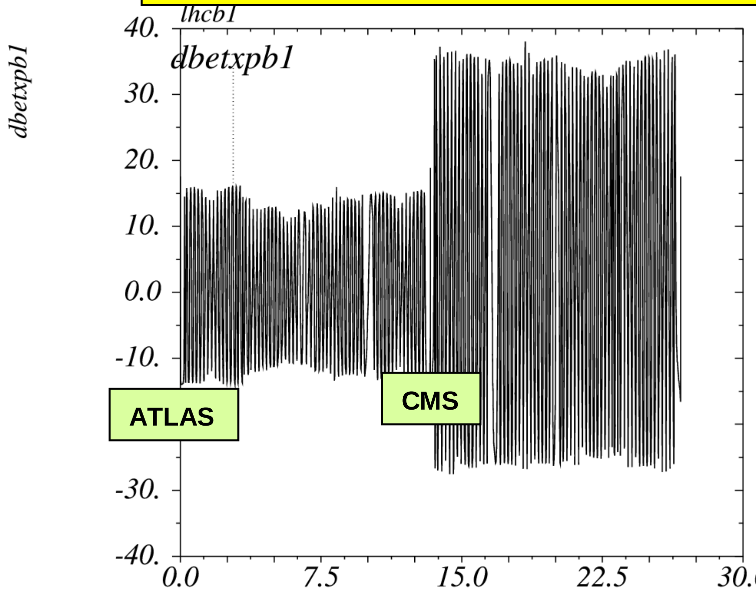
→ Plan B for an HL-LHC w/o crabs (but with 40% less performance)

Do we need the ATS (pre-squeeze) for 2012?

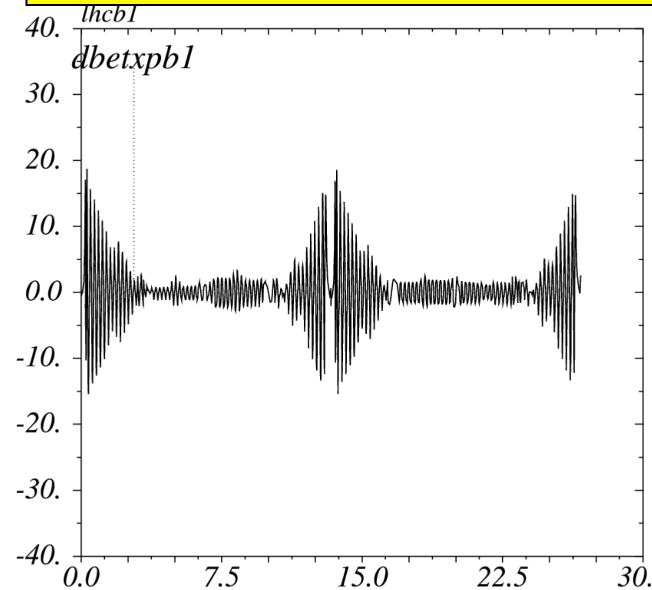
Will depend on which limit will be met first at β^*=60 cm

→ **Triplet aperture** or **chromatic aberrations** possibly impacting on **collimation, background, synchro-betatron**

Nominal optics @ β^*= 60 cm
$\Delta\beta/\beta$ [%] at δ=0.001 (Beam1, H plane)



ATS (pre-squeeze) @ β^*= 60 cm
$\Delta\beta/\beta$ [%] at δ=0.001 (Beam1, H plane)

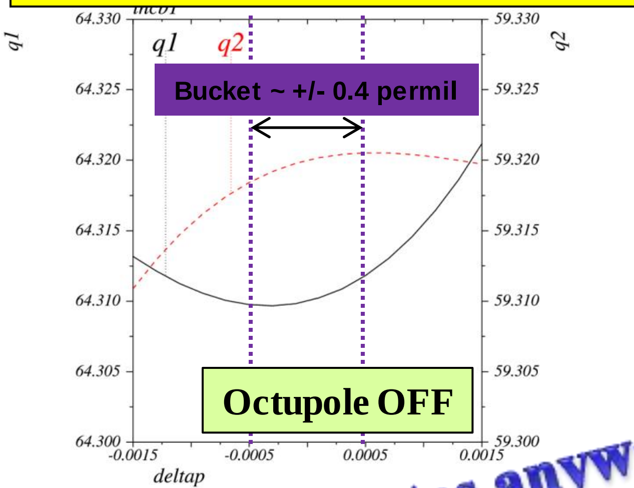


→25-35% in the IT and collimation IR3 & IR7
→ i.e. ~ 10-15% level reached at the bucket separatrix and much more for un-captured beam!

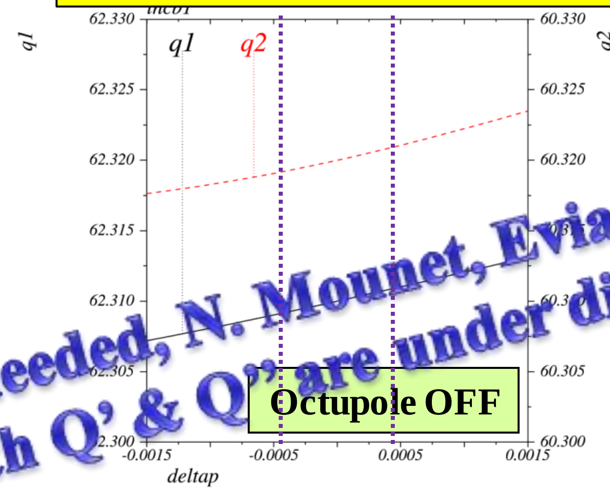
→ Only 1-2% in the IT and collimation IRs

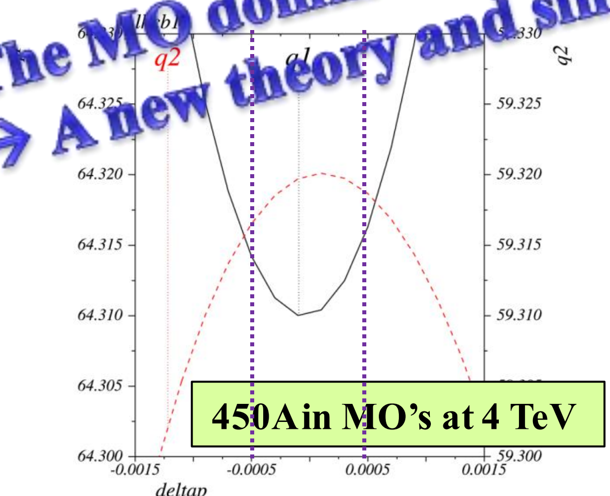
Other concerns: **Tune vs. δ_p** possibly impacting on **collective effects, sensitivity to RF trims, resonances,…**

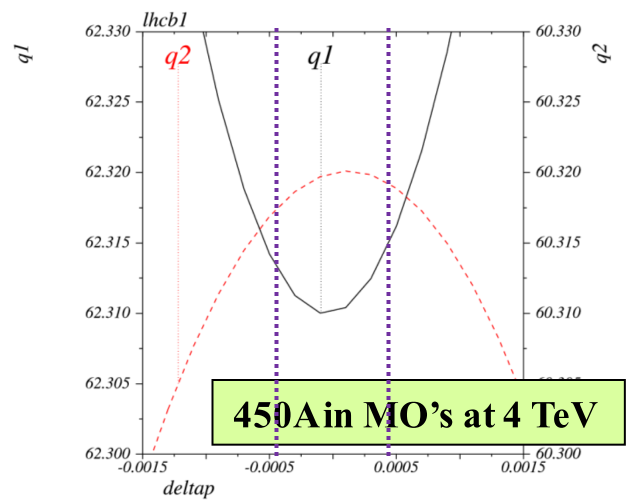
Nominal optics @ β*=60 cm



ATS (pre-squeeze) @ β*=60 cm







The MO dominates anyway (450 A needed, N. Mounet, Evian 2011)
→ A new theory and simulations with Q' & Q'' are under discussion

Summary

→ The aim of the ATS is twofold:

1. **Produce ultra-low β^* optics** (flat or round) **for HL-LHC**
2. With specific **achromatic properties, also very attractive for LHC** (pre-squeezed optics down to 40 cm)

→ Beam validation of the ATS for round optics:

1. Several key milestones already reached, but separately

   - Achromatic pre-squeeze pushed down to the limit (β^* = 40 cm at IP1&IP5)

   - Telescopic principle (×4) to reach β^* = 30 cm in IR1 (starting from 1.2 m)

2. But some pieces still missing, everything to be combined at the end

   - Telescopic squeeze of IR5 (using IR4 & IR6)

   - Produce and check the properties of the fully squeezed optics (β^*=10 cm)

Acknowledgments

… **Many thanks**

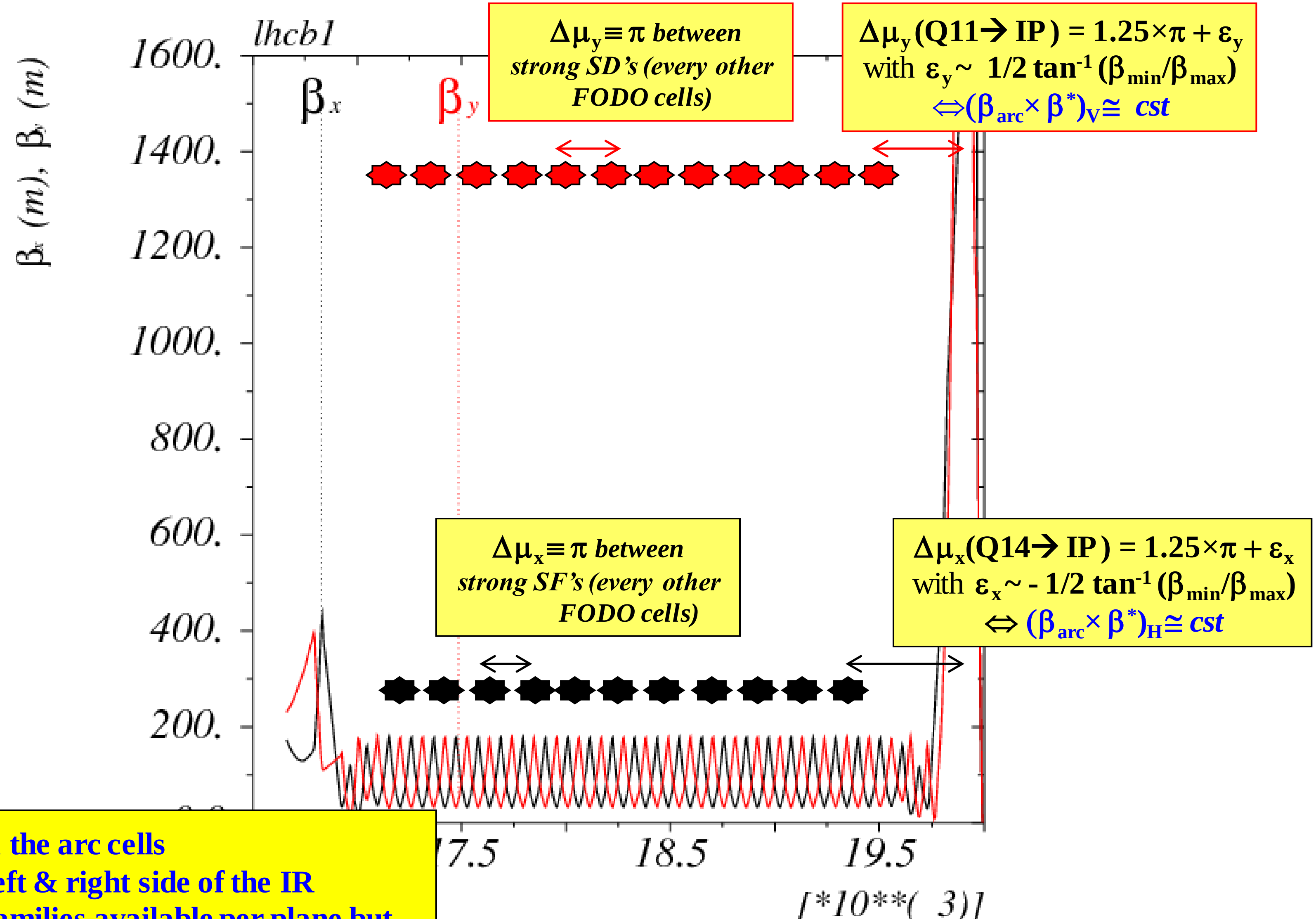
for these results which are the fruit of the work of many people: **the "pillars" of the ATS MDs**, but also many others

C. Alabau, M. Albert, R. Alemany Fernandez, R. Assmann, R. Bruce, A. Butterworth, R. Giachino, B. Goddard, P. Hagen, W. Hofle, D. Jacquet, M. Giovannozzi, V. Kain, G. Kruk, M. Lamont, E. Maclean, A. Macpherson, R. de Maria, R. Miyamoto, G. Mueller, L. Normann, G. Papotti, M. Pojer, L. Ponce, S. Redaelli, N. Ryckx, R. Steinhagen, M. Strzelczyk, R. Suykerbuyk, E. Todesco, R. Tomas, D. Valuch, V. Venturini, G. Vanbavinckhove, J. Wenninger, D. Wollmann, F. Zimmermann

Reserve

Why does it work? **The magic lies in the choice of the betatron phases**

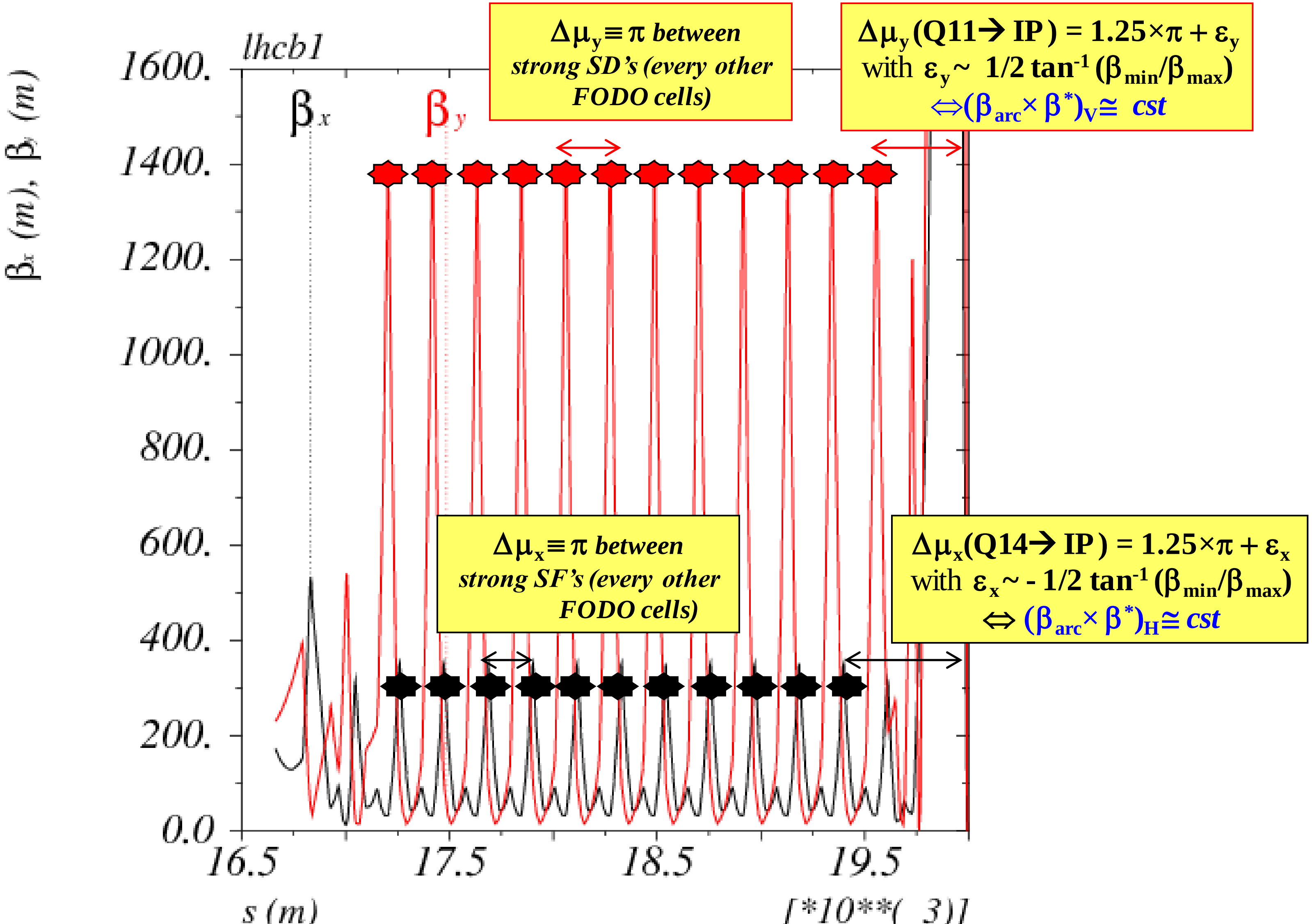
.. Zoom in arc45: **Pre-squeeze to 40 cm**



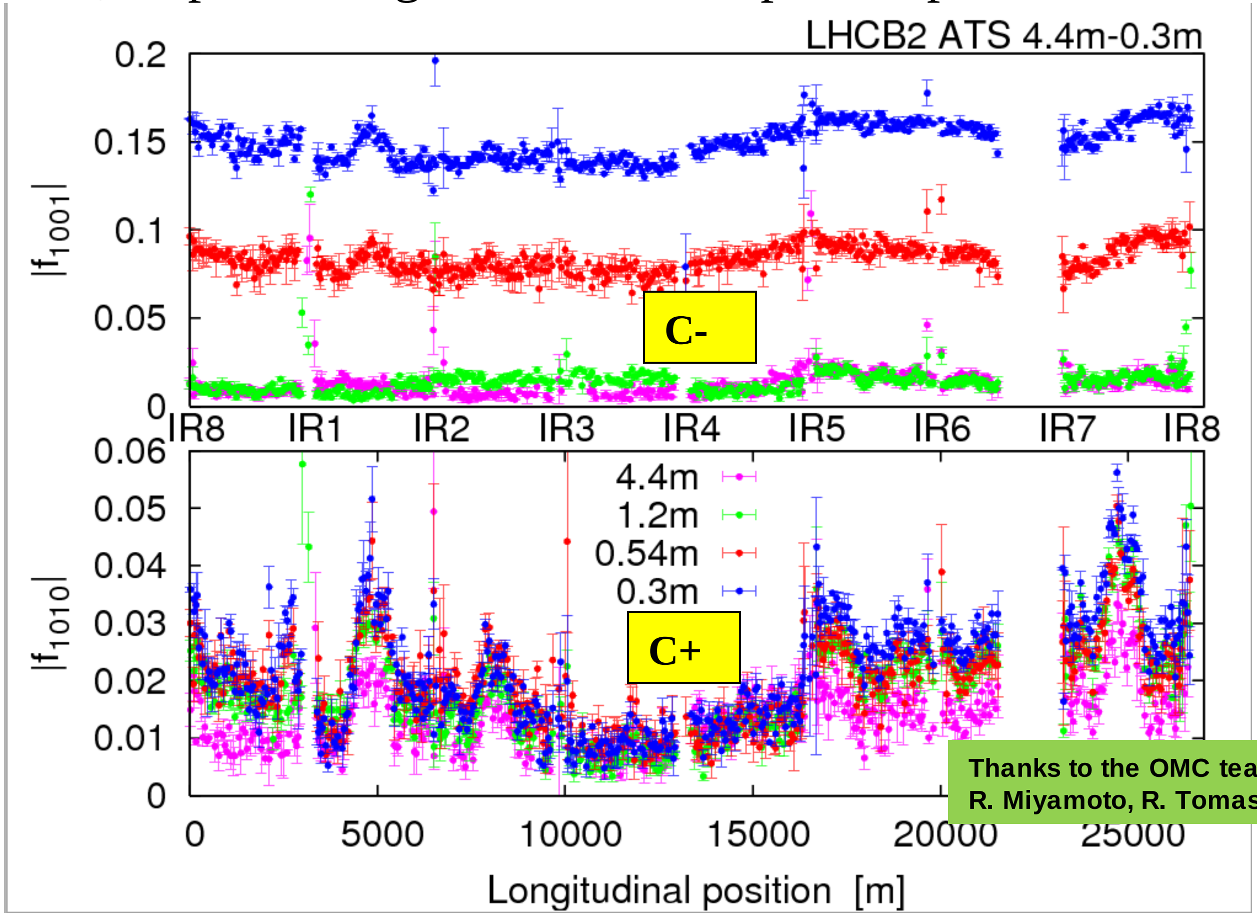
→ π/2 phase in the arc cells
→~ π/2 on the left & right side of the IR
→ 2 sextupole families available per plane but only one per plane used for triplet correction

Why does it work? **The magic lies in the choice of the betatron phases**

.. Zoom in arc45: **Squeeze to a flat optics with β^*=20cm/5cm at IP5**



→ **ATS-MD-II:** **coupling measurement at β*= 4.4, 1.2, 0.54 and 30 cm** (with RQSX pre-setting from nominal optics implemented at 450GeV)



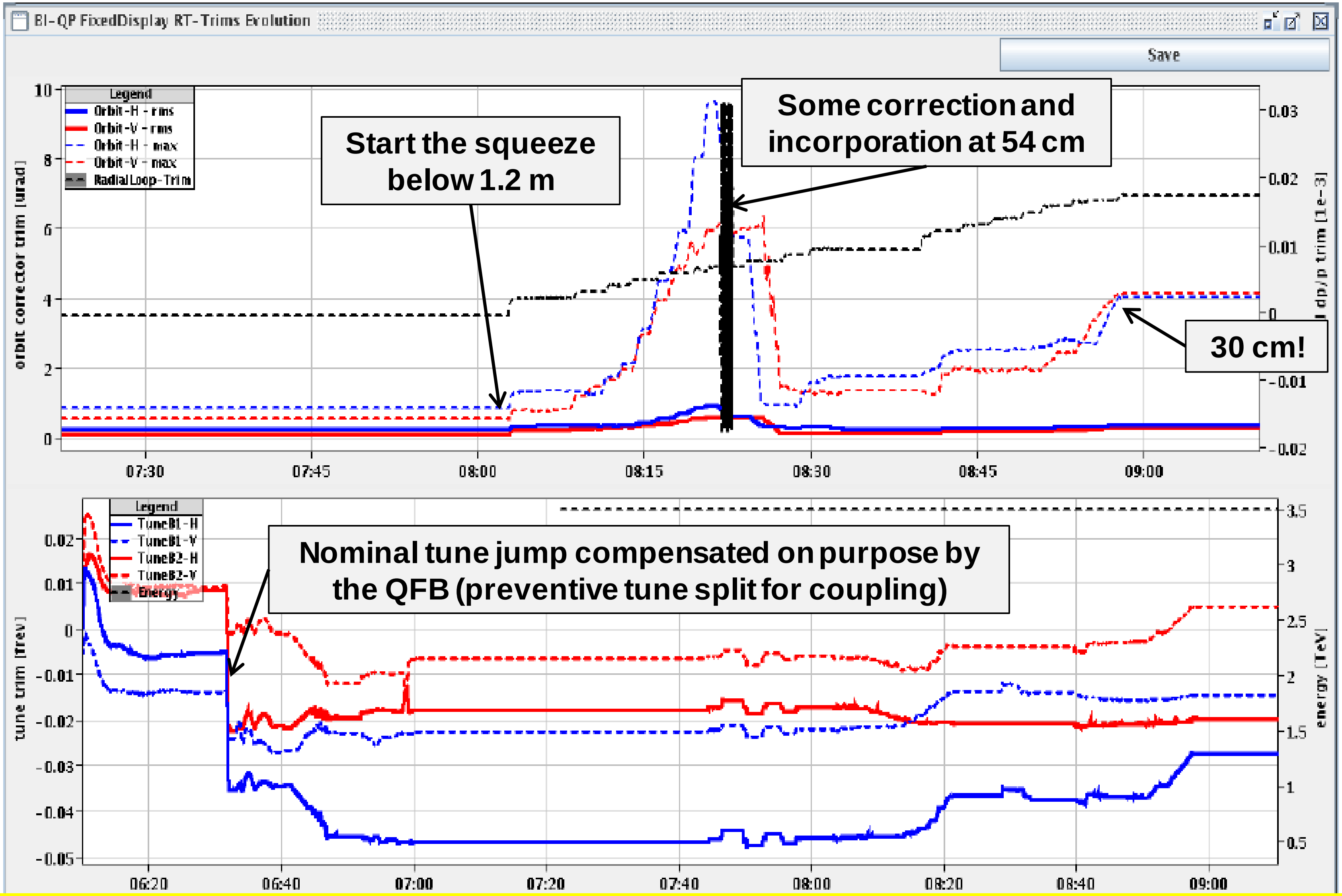
Thanks to the OMC team:
R. Miyamoto, R. Tomas, G. Vanbavinckhove *et al.*

→ No time to correct the coupling below 1.2 m but we were prudent enough **to work with the injection tune, i.e. a tune split of 0.03** (see later the QFB history).

→ ATS-MD-II: Feed-backs (trim hystory over the last hours)

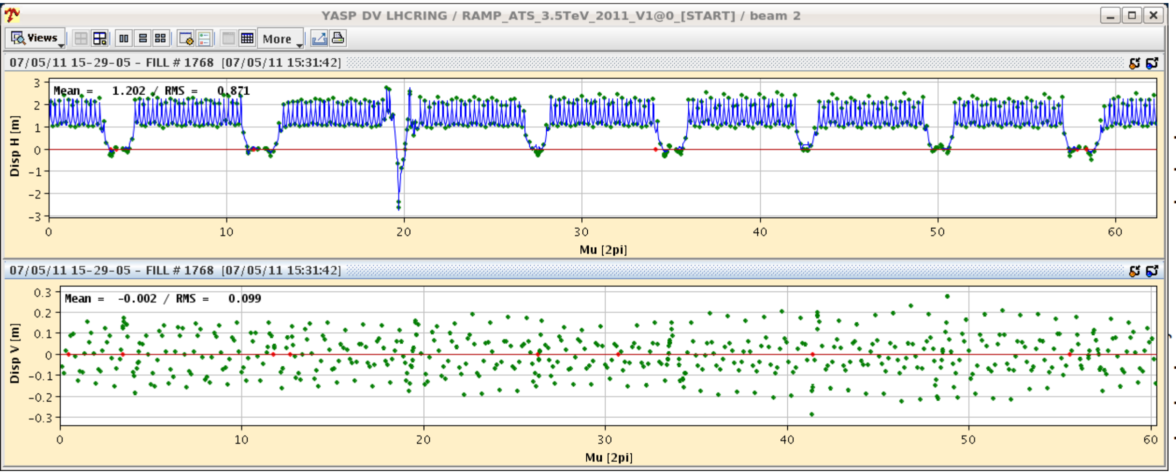
Orbit

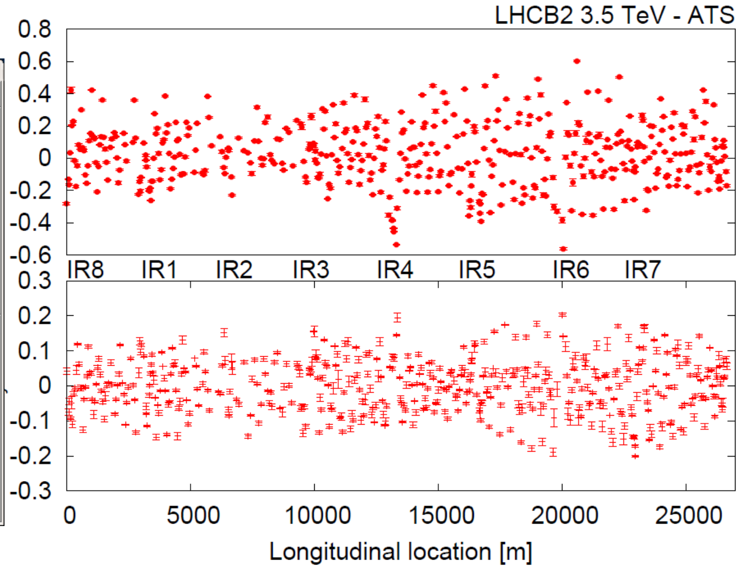
Tunes



→ Rather smooth for the FIRST squeeze of a "8km long insertion" (3 IRs+2 arcs)!

→ ATS-MD-I: Dispersion measurements at 450 GeV and 3.5 TeV





Spurious Dispersion at 450 GeV

→ **50-60 cm in the arcs in the H plane**

→ **15-20 cm in the arcs in the V plane**

Spurious Dispersion at 3.5 TeV

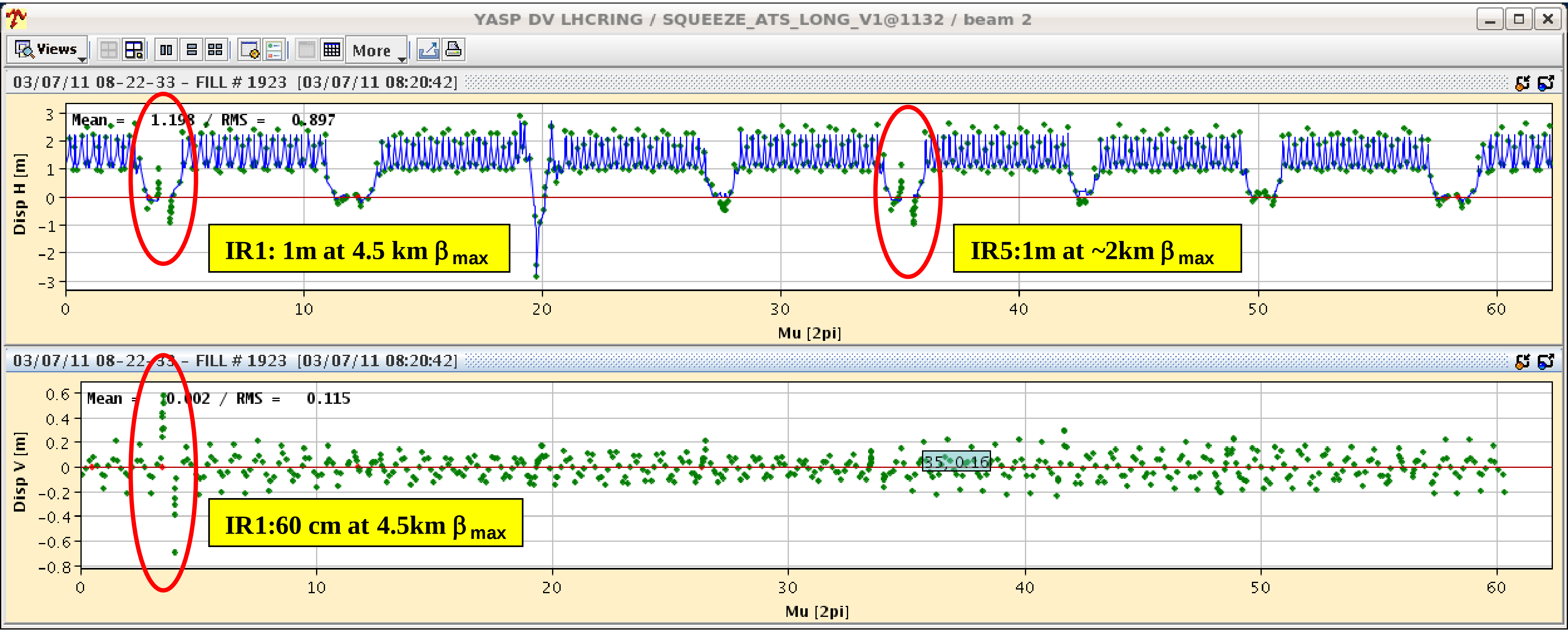
→ **No improvement!!**

- Dominated by **the contribution from the arcs** (no change from 450 GeV to 3.5 TeV, contrary to β-beating)
- **Small in the V plane**: **Signature of the MB sorting on the random a2**
- **Sizeable in the H plane: MQ sorting only optimized for beta-beating** (too many SSS types)

…

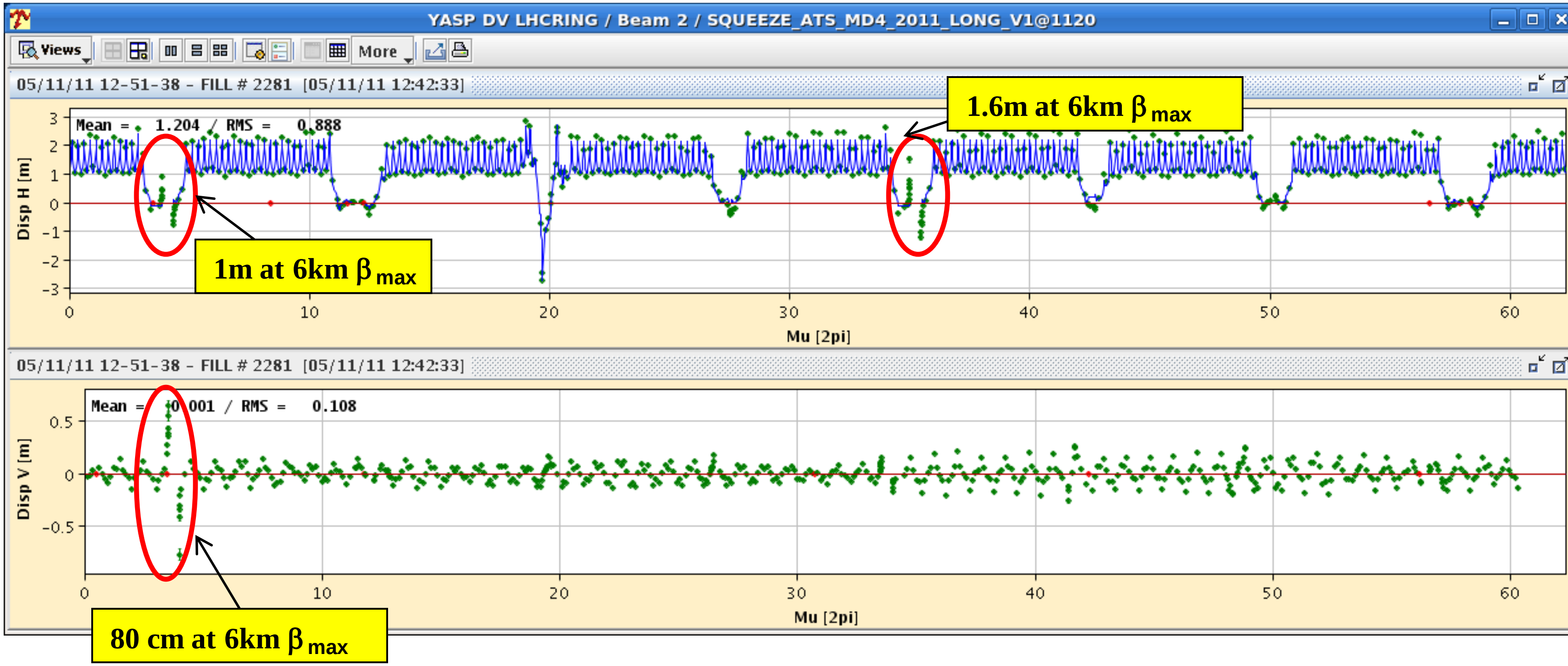
Will increase with sqrt(β_{max}) in the IT during the squeeze !

→ **ATS-MD-II:** **Dispersion measurements** at $\beta^* = 4.4$ m, 1.2 m and 54 cm. The "worst" case of **Beam2 at 54 cm** is shown.



→ **The spurious dispersion from the arcs shows up clearly in the inner triplet** (depending on whether we are lucky or not with the betatron phases)

→ **ATS-MD-III:** **Dispersion measurements** at $\beta^* = 40$ cm (the worst case of Beam2 is shown)

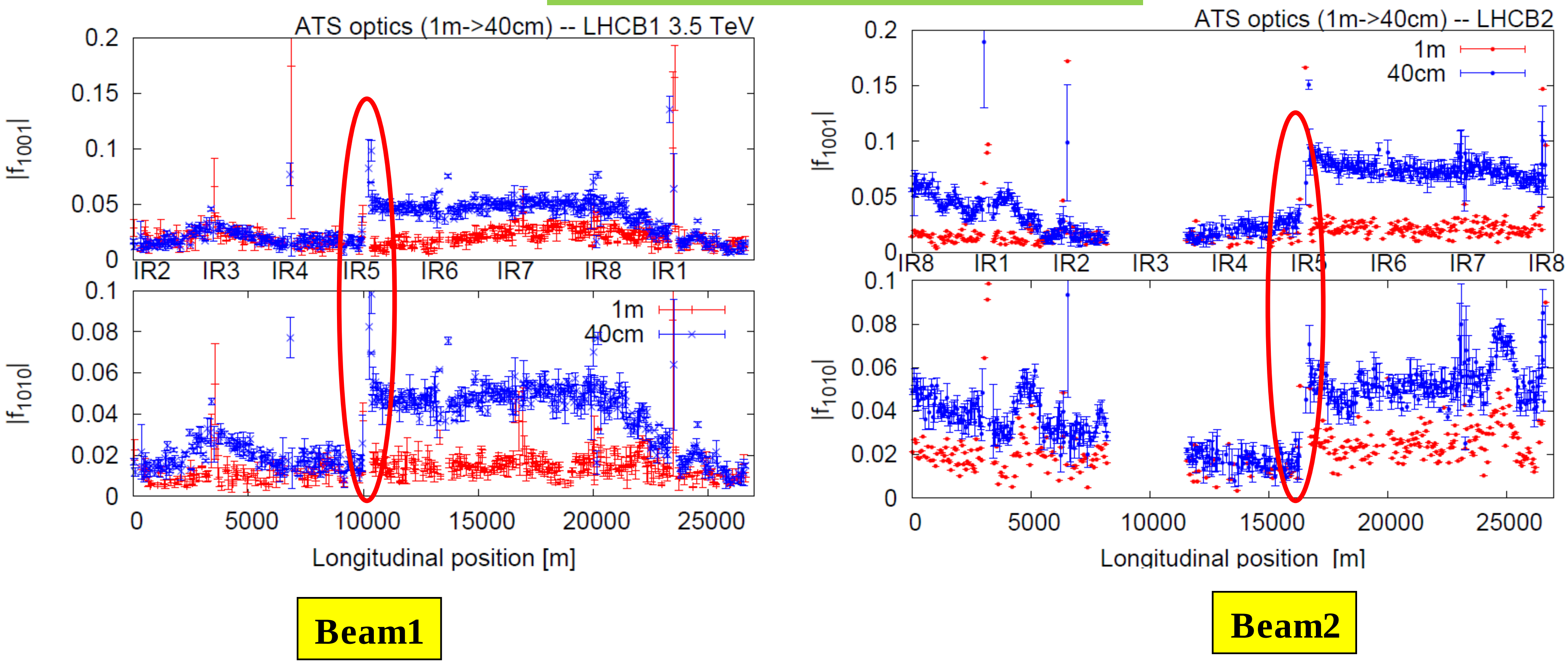


→ **Dy still acceptable**

→ **Spurious Dx starts to be worrying, but a priori correctable**

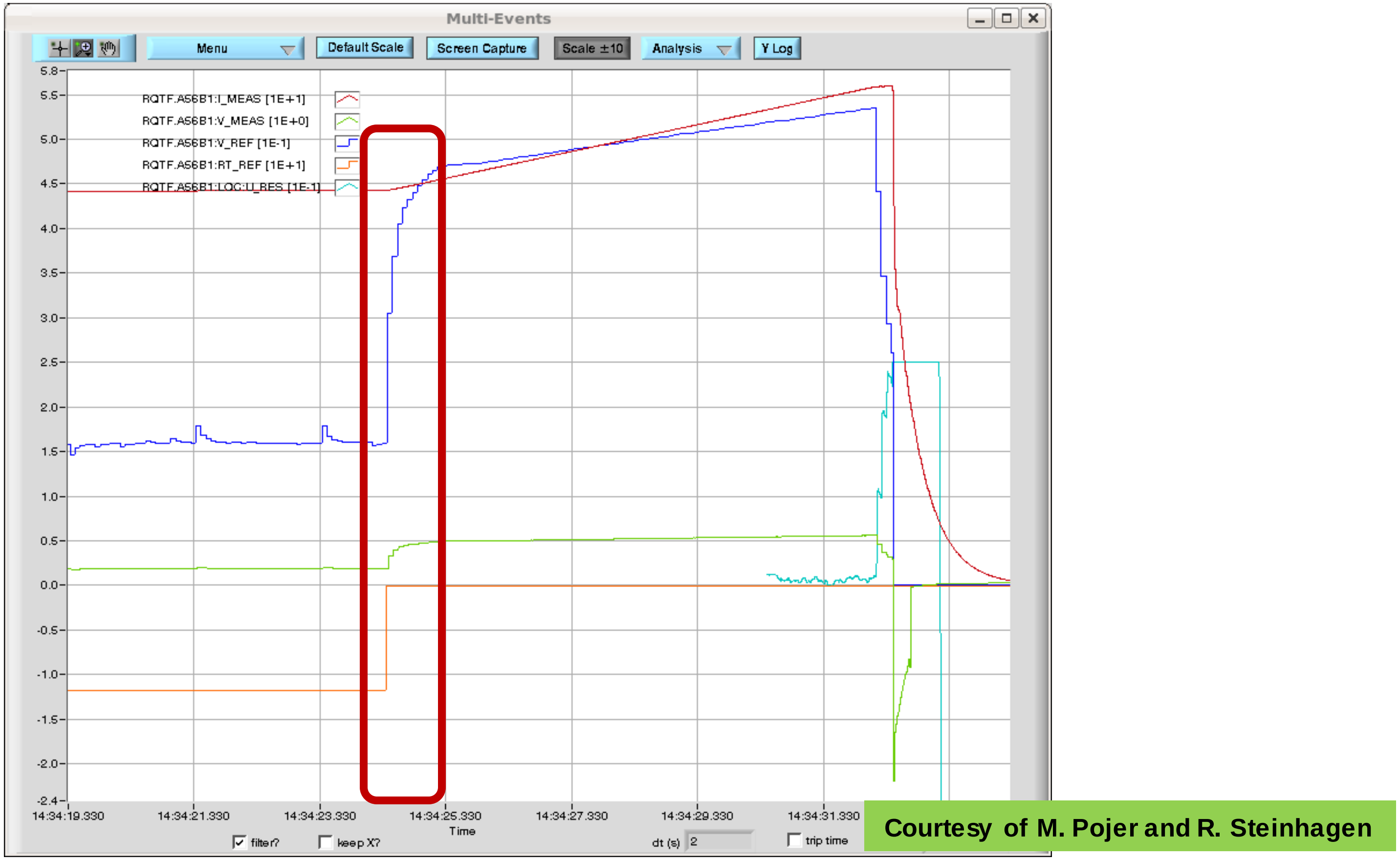
- **<u>Local coupling measurements</u> at β^*= 40 cm**

Thanks to the OMC team:
R. Miyamoto, R. Tomas, G. Vanbavinckhove *et al.*



→ **Triplet clearly tilted in IR5** while IR1 looks OK … but at 10 cm who knows?
→ **RQSX fine tuning** needed (local correction) and global correction to be re-worked during the pre-squeeze sequence.

→ **ATS-MD-III:** **Beam lost when preparing the telescopic part of the squeeze**



→ **Real time trims sent to zero** by the QFB when switching between the two tune knobs to be used above and below the pre-squeezed β*

→ **Several RQT circuits tripped by QPS**

→ **Not a conceptual limit, with some idea already proposed**

Other possible developments

- Rework a bit the ATS to transform it into a **Telescopic Un-squeezing scheme for very large β^*** (forward physics)

- Use the ATS as **IBS knob in the longitudinal plane**

→ Possible application for **Heavy Ions** but the **corresponding 1m ATS optics in IR1/5 and IR2 is not ready** (even not tried on paper)

- Any other "exotic" application: **much more Landau damping** available for impedance, or even shaping the head-on beam-beam tune spread, …