Achromatic Telescopic Squeezing (ATS) scheme: principle, by-products and experience with beams

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With contributions from the OP, OMC, Collimation,

Lumi, Beam-beam & ADT teams

Content

- Recap: ATS motivations, principles, by-products and MD's in Run I
- ATS MD's in 2016/2017 (round & flat optics)
- 2017 ATS LHC optics: Check-up after one operational year (2017 vs. 2016)
- Expected ATS driven limitations for future LHC operation (7.0 TeV, lower β^*, flat optics, LIU beams ..)
- Summary & Conclusions

ATS <u>motivations</u>, principles & by products (1/5)

- Lower β^* need magnets of larger aperture, and new HW 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** (PRSTAB 18-111002, 2013) 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 b-beating.
   → Arc sextupole strength (<600A)

ATS motivations, principles & by products (2/5)

- How? a squeeze in two steps

1. The Pre-squeeze:

An “almost” standard squeeze,

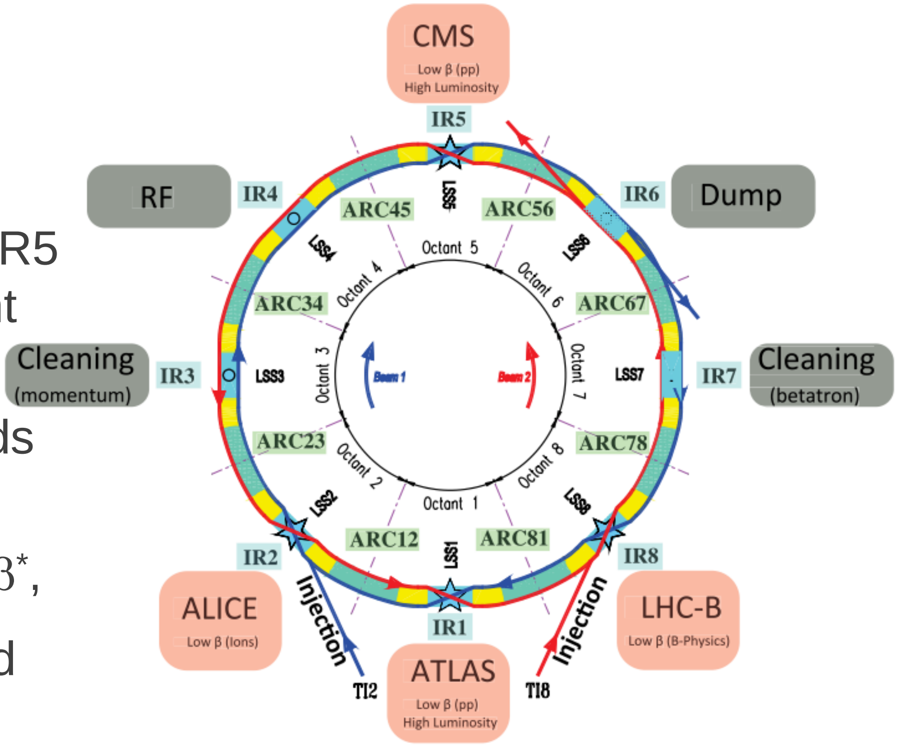
→ Acting on the matching quads of IR1 and IR5 with new matching constraints on the left/right IR phase,

→ Till reaching some limits on matching quads (or sextupoles)

2. The Tele-Squeeze: A further reduction of β^*,

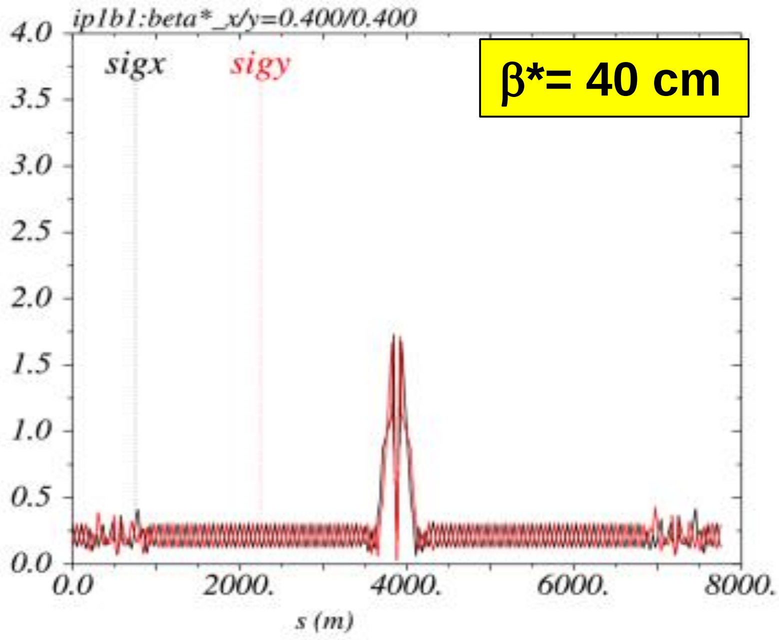
→ Acting only on IR2/8 for squeezing IR1 and IR4/6 for IR5,

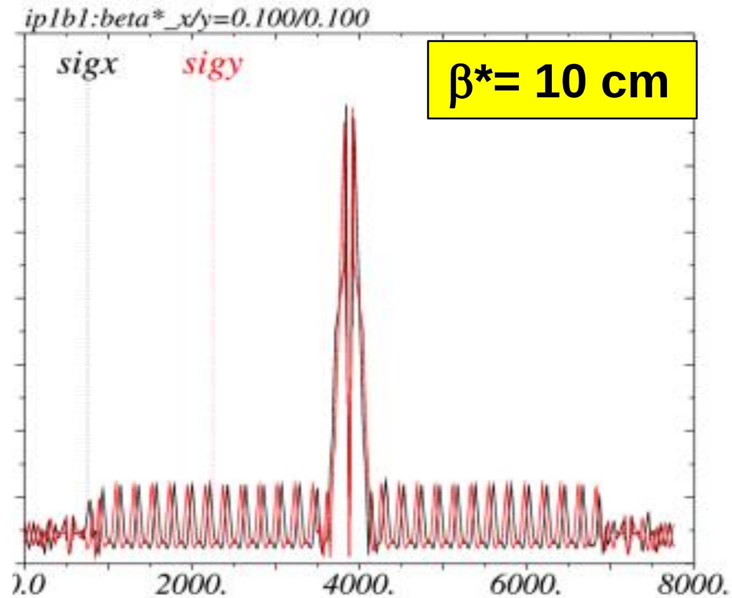
→ Inducing β-beating bumps in s81/12/45/56 to boost the sextupole efficiency, but also the octupoles (see later).



→ A kind of generalized squeeze involving 50% of the ring !

Beam sizes [mm] @ 7 TeV from IR8 to IR2 for typical ATS “pre-squeezed” optics (left) and “telescopic” collision optics (right)



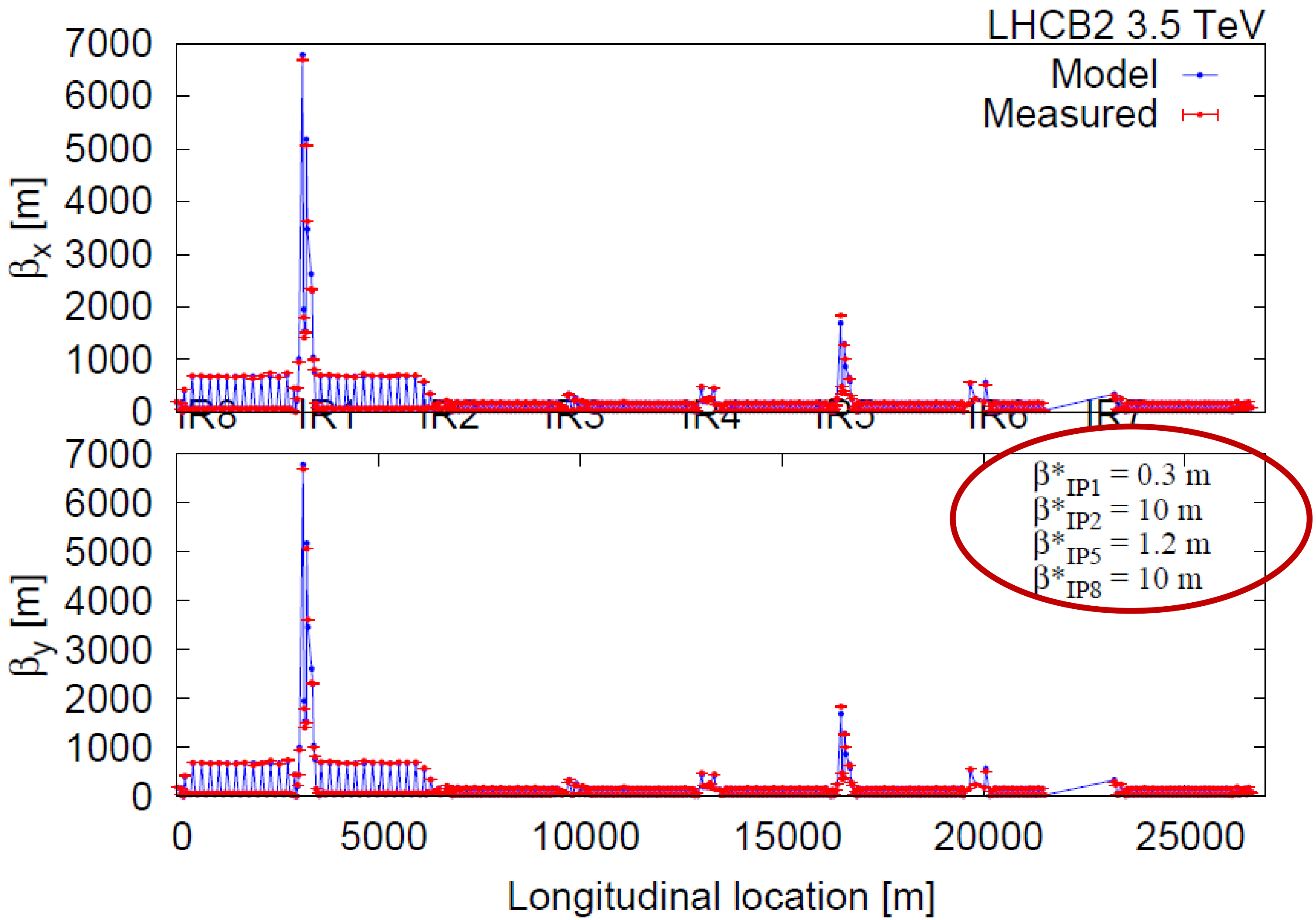


The new IR is sort of 8 km long !

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

First demonstration with beam in 2011 (.. already with 30 cm β^* !)

→ Telescopic principle (×4) demonstrated in IR1

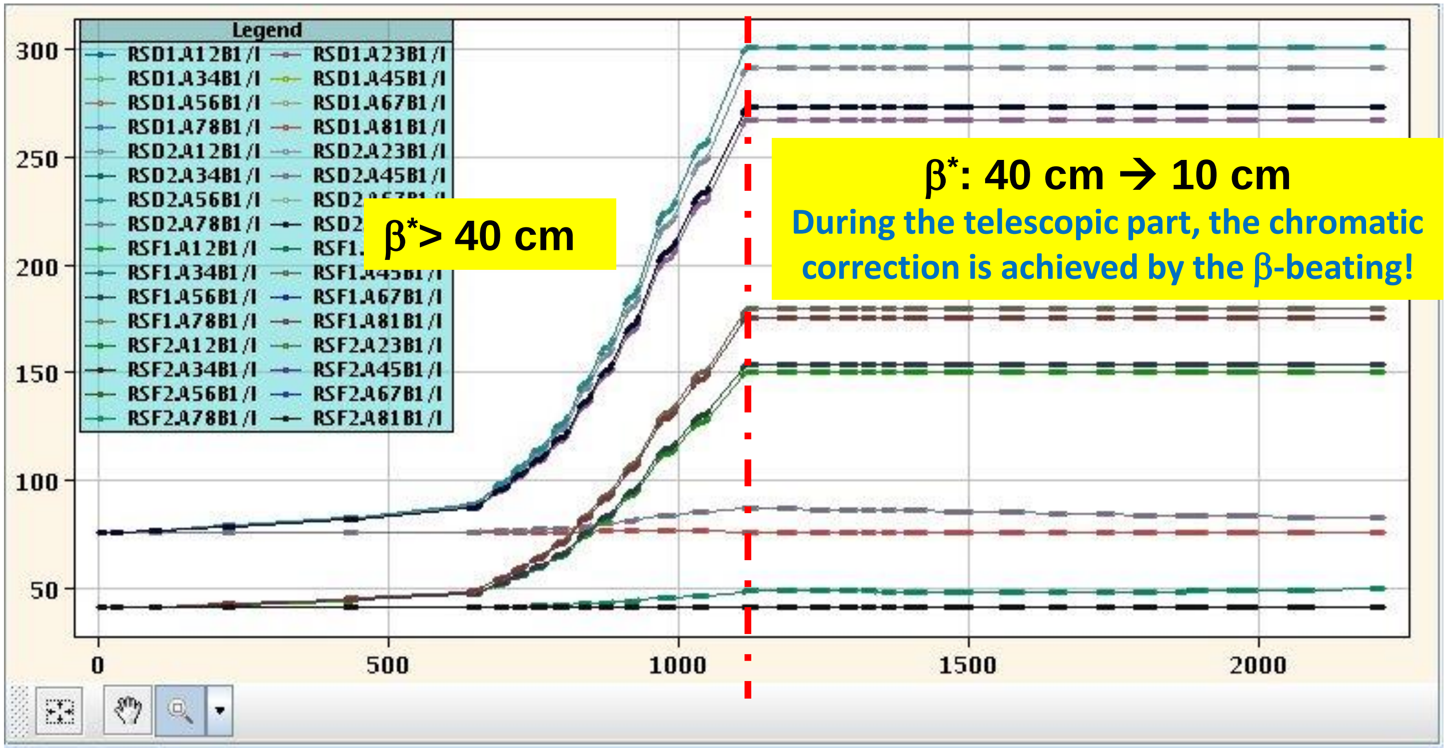


Thanks to G. Vanbavinckhove & OMC team

ATS motivations, principles & by-products (3/5)

Chromatic corrections (Q'): No β^* limits

Typical sextupole settings [A] for the 32 families available per beam (from MD in 2011 @ 3.5 TeV)

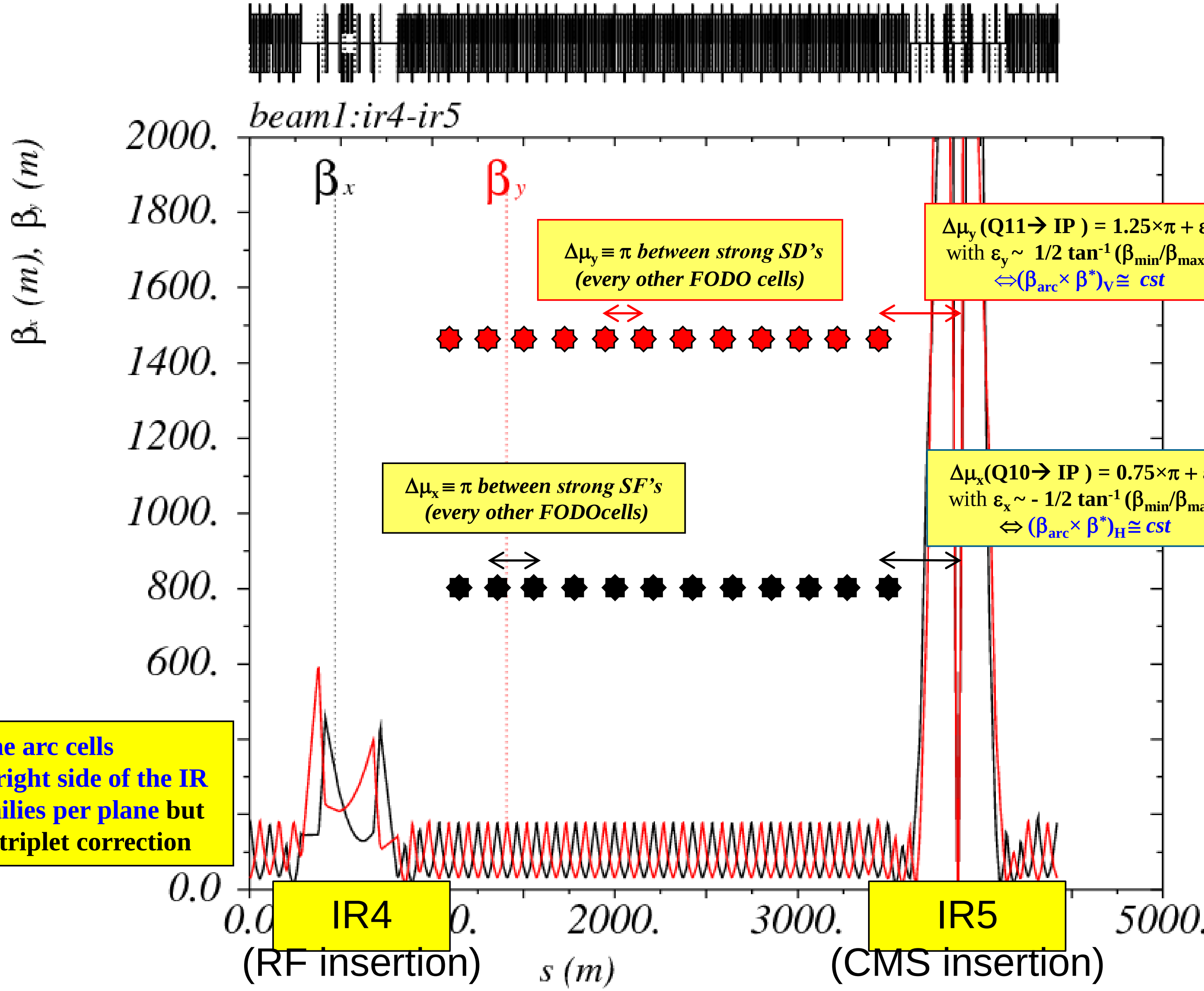


→ Only 25% of the RS circuits participates to the chromatic correction during the pre-squeeze

→ All sextupole then kept ~ constant during the tele-squeeze

The magic lies in the choice of the betatron phases

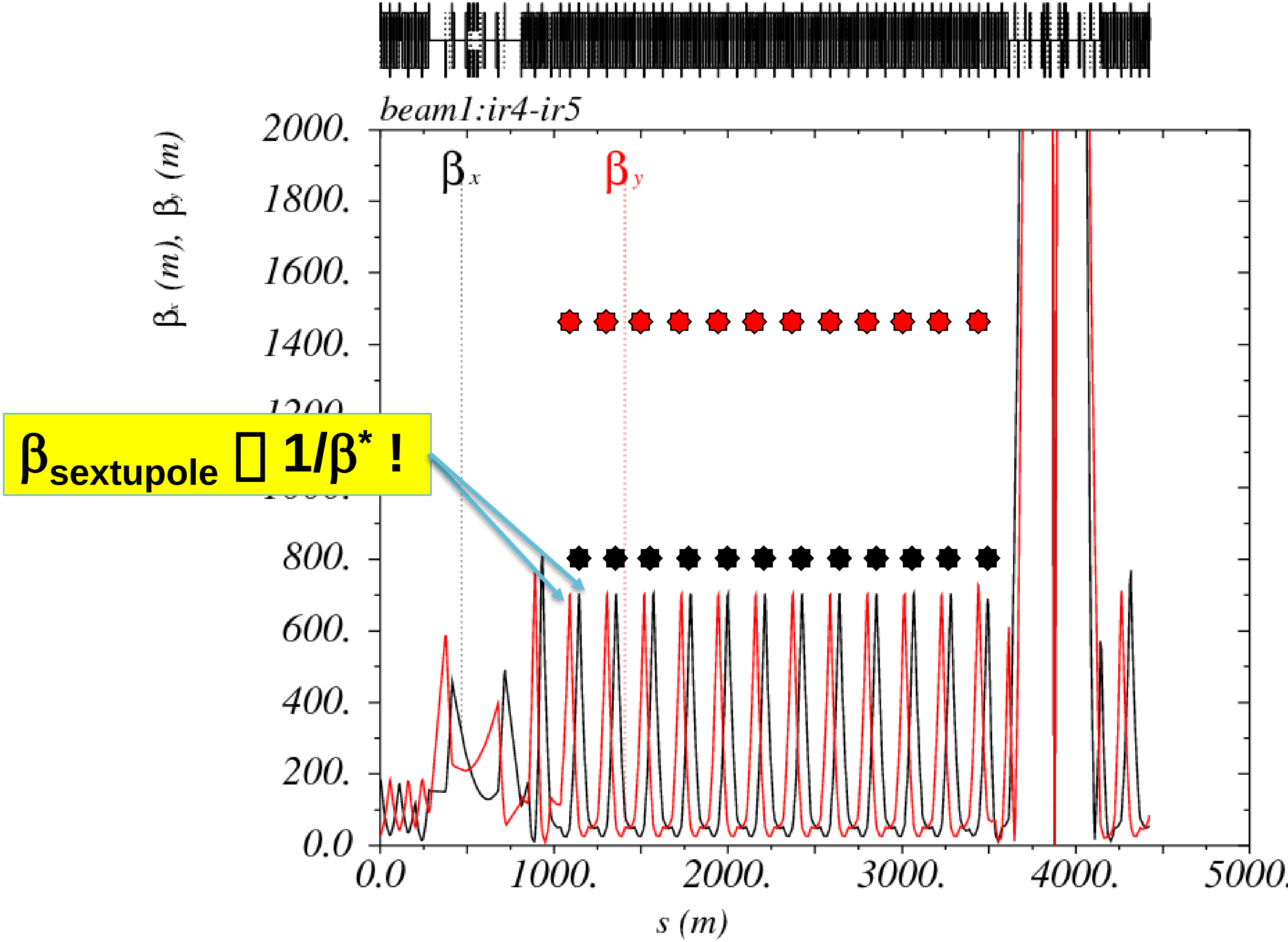
.. Zoom in arc45: **Pre-Squeeze to β^*=40/40 cm (round optics): Tele index 1H×1V**



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

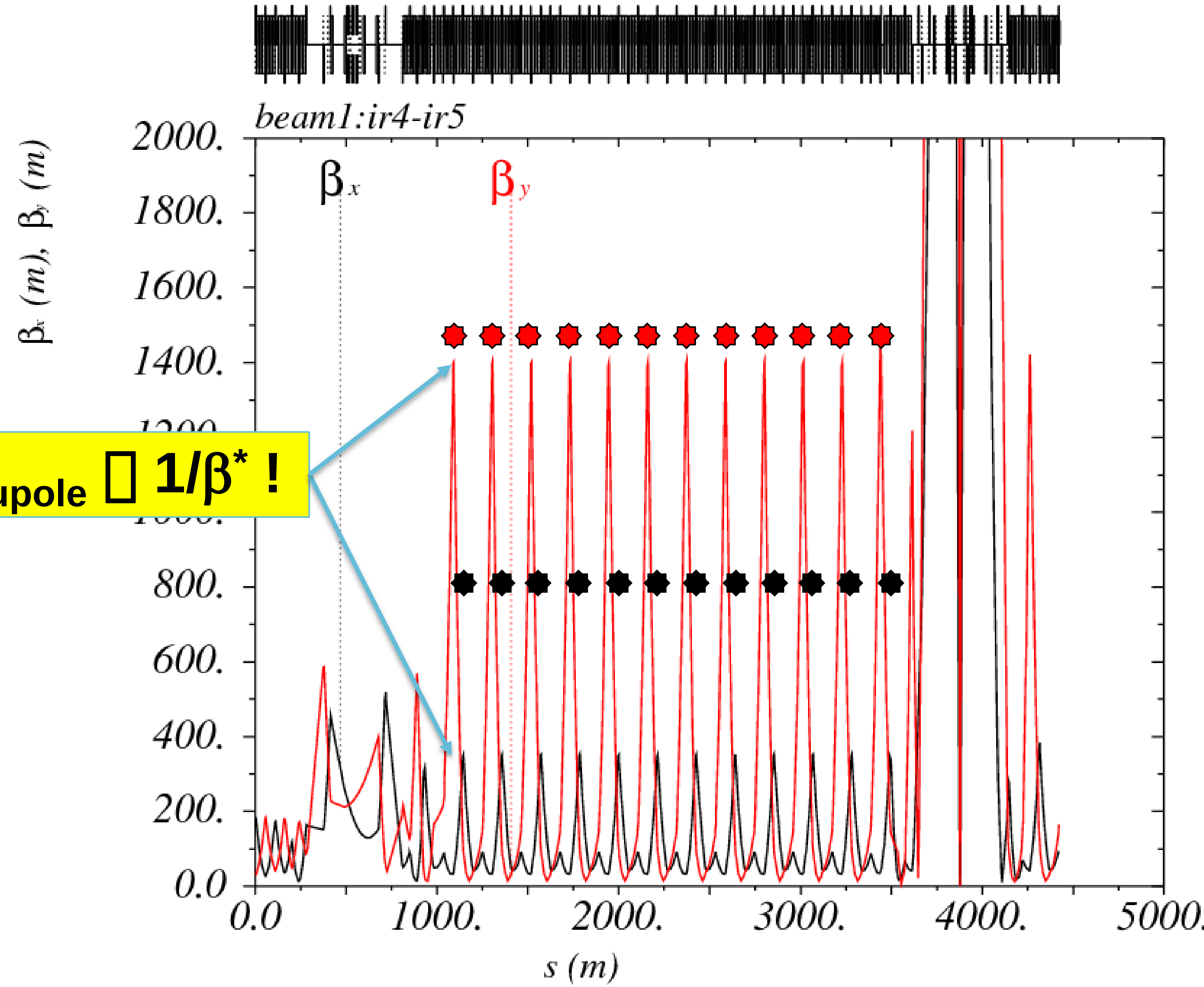
The magic lies in the choice of the betatron phases

.. Zoom in arc45: **Squeeze to β^*=10/10 cm (round optics)): Tele index 4H×4V**



The magic lies in the choice of the betatron phases

.. Zoom in arc45: **Squeeze to β^*=20/5 cm (flat optics)): Tele index 2H×8V**



$\beta_{sextupole} \propto 1/\beta^*$!

ATS motivations, principles & by products (4/5)

- **Chromatic aberrations:** **a zoo to manage carefully at low β^***

1. Off-momentum β-beating: **$\partial\beta/\partial\delta \propto 1/\beta^*$ .. Up to +/- 50-100 % in the bucket**

→ Collimation hierarchy (limits the retraction n2/n1), off-momentum aperture, etc..

2. Non-linear chromaticities: **$Q'' \propto 1/\beta^{*2}$ up to 100 K-units, $Q''' \propto 1/\beta^{*3}$..**

→ Dynamic aperture, life time, ..

3. Spurious dispersion from X-angle: **$D_{x,y} \propto \theta_x/\beta^* \propto 1/\beta^{*3/2}$, up to 10 m in the IT**

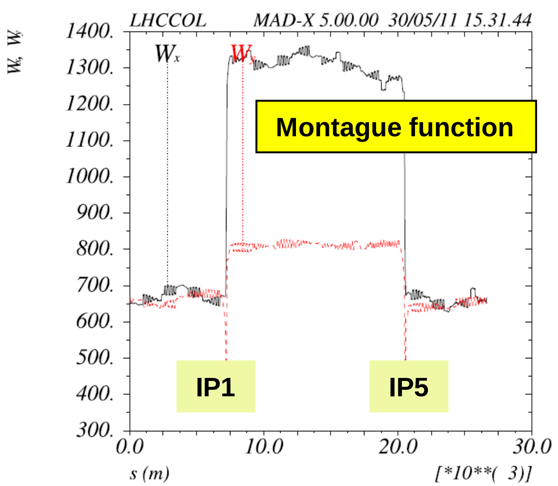
→ Aperture, background, Q' variations from bunch to bunch due to BBLR pacman effect (up to +/- 10 units from bunch to bunch in HL-LHC !)

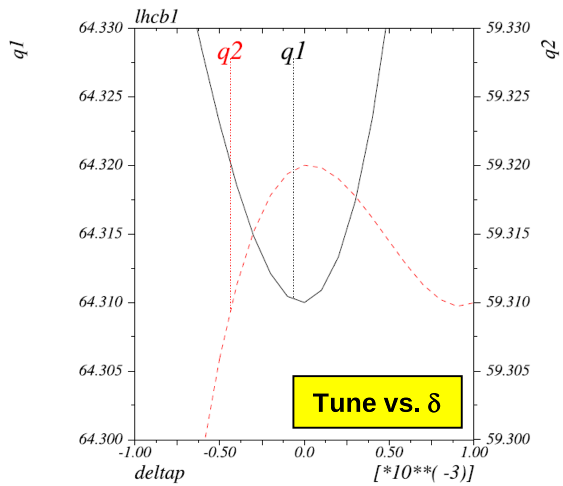
While these was NOT limiting the LHC in 2016 (40 cm β^* and "large" TCP/TCS retraction of 2 σ), a clean chromatic correction is an in-built feature of ATS optics:

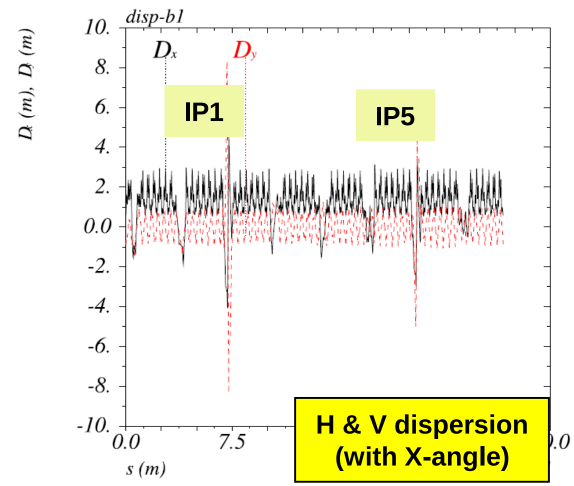
→ Optically speaking, the ATS "puts the lattice sextupole inside the triplet" thanks to its phasing configuration

Illustration with **a “non-feasible” non-ATS 15 cm β^* LHC optics** (Q7 beyond limits and Q6 @ 0 T/m)

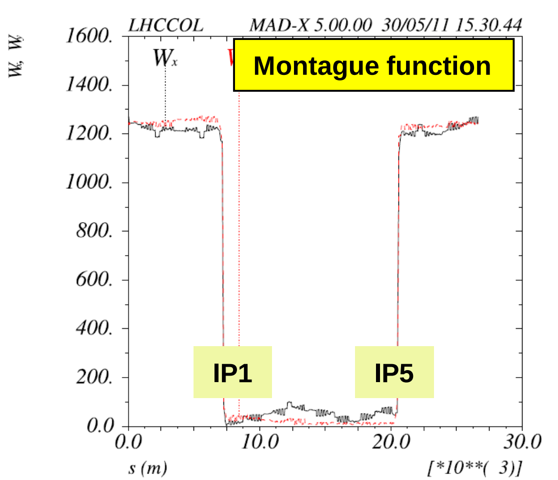
→ With **No specific IP1-IP5 phase**: chromatic β-beat, Q’’, Q’’’,.., spurious dispersion

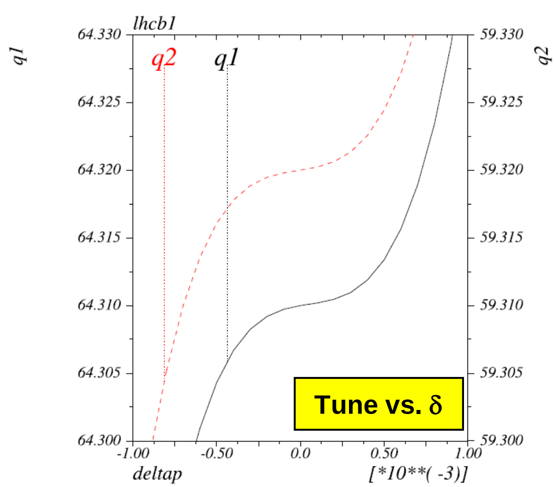


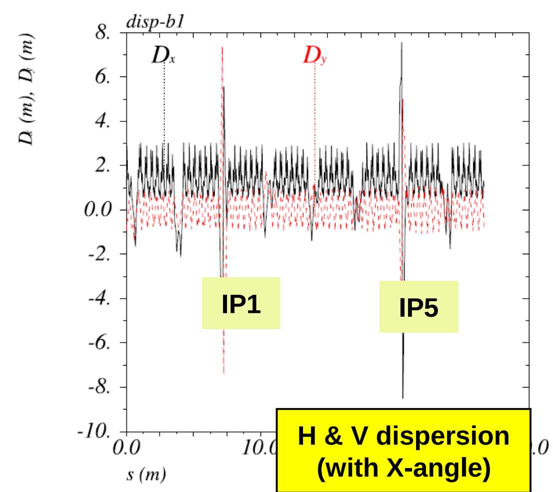




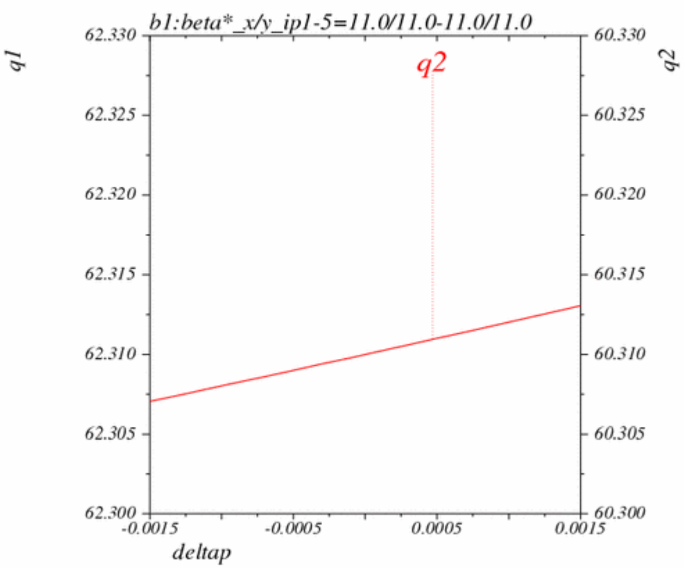
→**Phasing IP1 and IP5 by p/2 would only partly solves the problem**:
chromatic β-beat in half of the ring, huge Q’’’, still spurious dispersion.



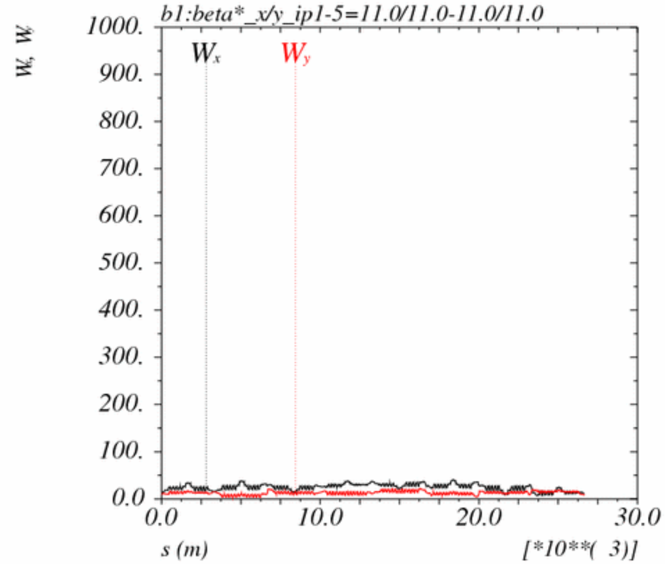




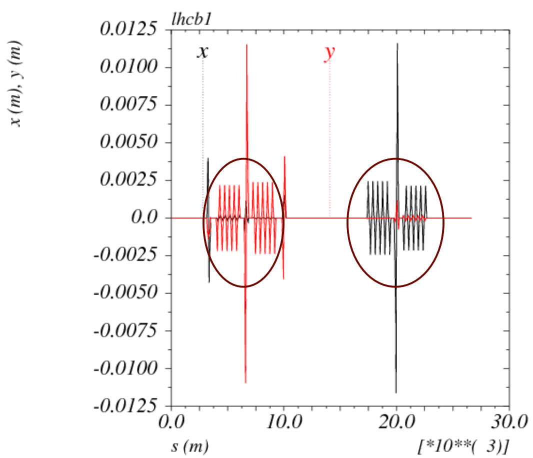
With the ATS, the non-linear chromaticity vanishes, the W's become "triangular", the spurious dispersion can be corrected



Tunes vs. δ_p

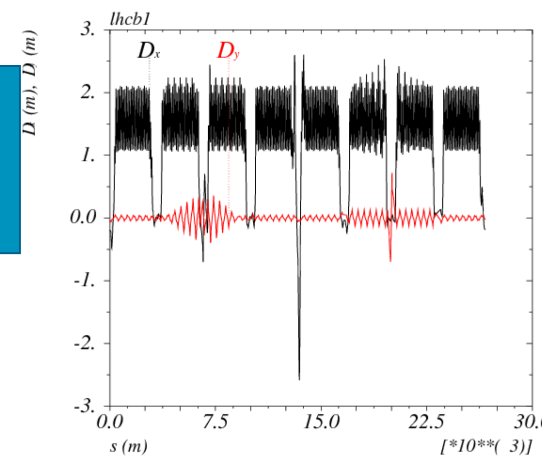


Chromatic Montague functions (amplitude of the off-momentum b-beating)



Closed orbit with X-scheme

Dispersion reduced to ~50cm in the IT (not accounting IR2/8 contribution) with ±2.5 mm bumps in s81/s12/s45/s56 (proved in MD, not implemented yet in OP)

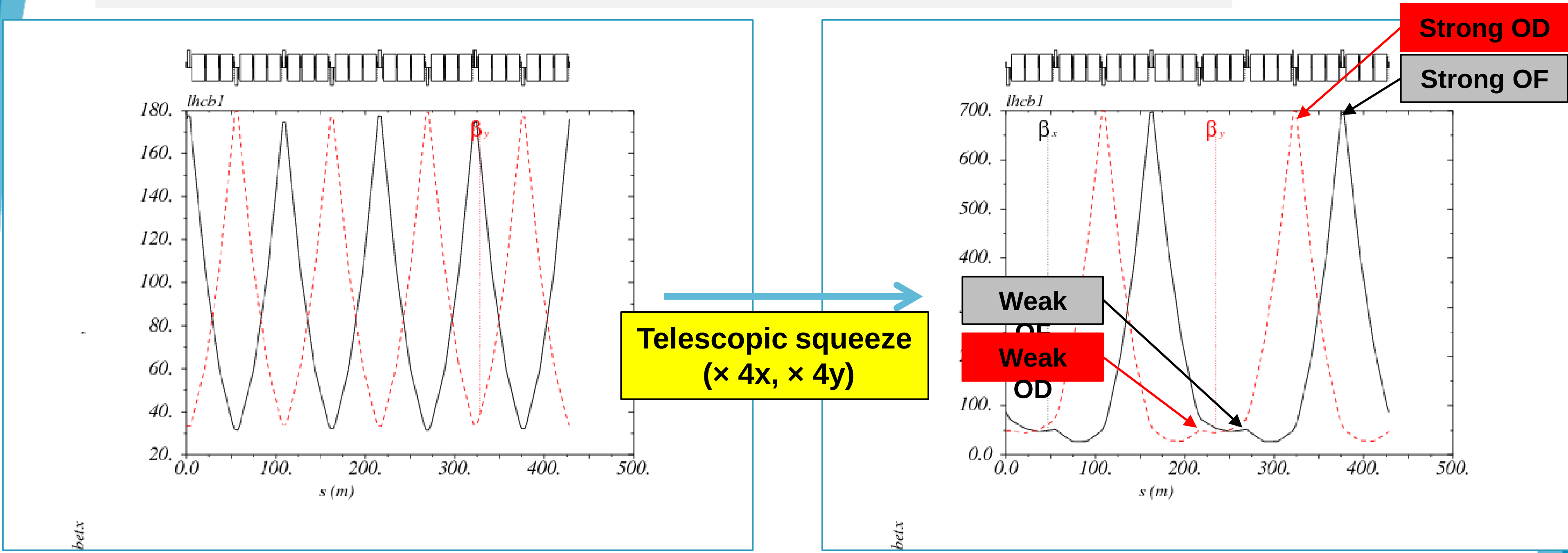


H and V dispersion

ATS motivations, principles & <u>by-products</u> (5/5)

Landau damping and beyond (BBLR mitigation)

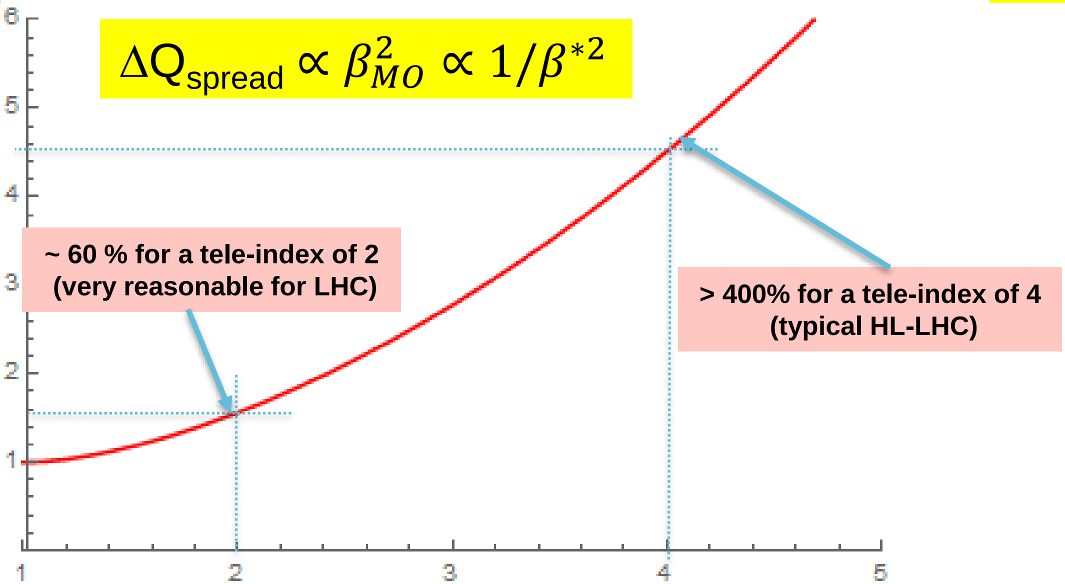
→ **<u>Two categories</u>** of octupoles in s81/12/45/56: the "**strong**" (with increased $\beta \propto 1/\beta^*$) and the "**weak**" (with decreased $\beta \propto \beta^*$)



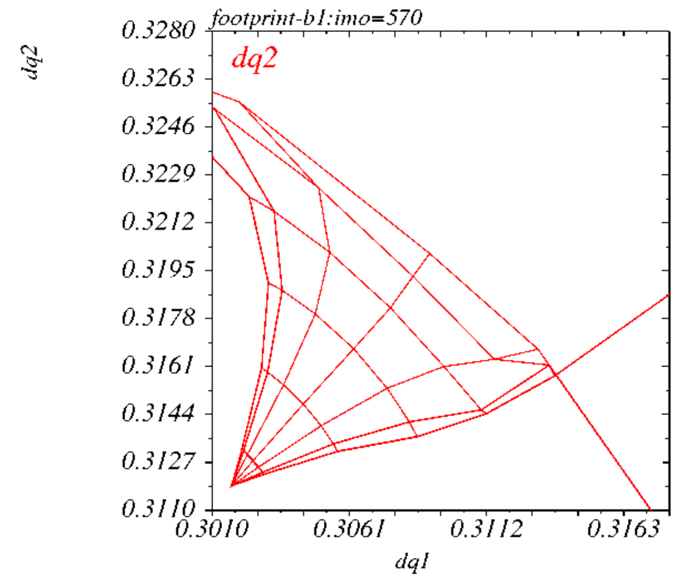
Beam 1/2	"Strong" OF.b1/OD.b2	Weak OF.b1/OD.b2	Strong OD.b1/OF.b2	Weak OD.b1/OF.b2
Sector 45 (81)	22.R4(8), 26.R4(8), 30.R4(8), 34.R4(8), 30.L5(1), 26.L5(1), 22.L5(1)	24.R4(8), 28.R4(8), 32.R4(8), 32.L5(1), 28.L5(1), 24.L5(1)	25.R4(8), 29.R4(8), 33.R4(8), 31.L5(1)	31.R4(8), 33.L5(1), 29.L5(1), 25.L5(1)
Sector 56 (12)	31.R5(1), 33.L6(2), 29.L6(2), 25.L6(2)	25.R5(1), 29.R5(1), 33.R5(1), 31.L6(2)	22.R5(1), 26.R5(1), 30.R5(1), 34.R5(1), 30.L6(2), 26.L6(2), 22.L6(2)	24.R5(1), 28.R5(1), 32.R5(1), 32.L6(2), 28.L6(2), 24.L6(2)
Total	**7+4 = 11**	**6+4 =10**	**4+7 =11**	**4+6=10**

MO tune spread amplification at constant strength during the Tele-Squeeze

At large tele-index (>3), the MO’s are so efficient that they can **mitigate the long-range Beam-Beam effect**



Tele-index r_{tele} (i.e. $\beta^*_{collision}/\beta^*_{pre-squeeze}$)



Simulated MO scan with 150 µrad X-angle
N_b=1.2E11, $\gamma\varepsilon$=2.5 µm, and r_{tele} ~ 3 (from 1 m to 35 cm)

As for the “**strong sextupoles”** (used for the IT chromatic correction), the “**strong octupoles”** are located at ~ π **w.r.t. the IT and hence the BBLR encounters.**

→ **4th order BBLR resonance driving terms are also mitigated**

ATS MD's in 2016/2017 (round & flat optics)

→ **ATS MD's in Run I** (2011-12) demonstrated **the basics**, **down to 10 cm β^*** (in non-operational machine conditions, e.g. w/o X-angle) with
(i) **low intensity beams** and
(ii) **not always with state of the art optics correction**

→ **ATS MD's in Run II** (2016-17-..18) studied **on 3 fronts** a new version of the ATS optics (optimized for machine protection aspects)

1. **Round telescopic optics** with pushed pre-squeezed β^* (40 cm), limiting the *high intensity tests to "small" tele-index*
   → **for LHC** (r_{tele} ~ 1.3 @ β^* ~ 30 cm)
2. **Round telescopic optics** with larger pre-squeezed β^* (1 m), enabling *high intensity tests @ large tele-index*
   → **for (HL-)LHC** (r_{tele}~ 3 @ β^* ~ 30 cm)
3. **Flat optics** (just started) → **for (HL-)LHC**

1. **1st Front (2016):** round optics with pushed pre-squeeze

(i) Validate the 2017 LHC optics with a few nominals

(ii) Demonstrate optics correct-ability with probes at lowest possible β^* (pushed pre-squeezed optics and pushed tele index)

→ Pre-squeeze to 40 cm (limited by sextupoles)

→ "Mini-telescope" down to 33 cm with few INDIV's

→ **"HL-LHC telescope" (× 4) down to β^*=10 cm with probes**

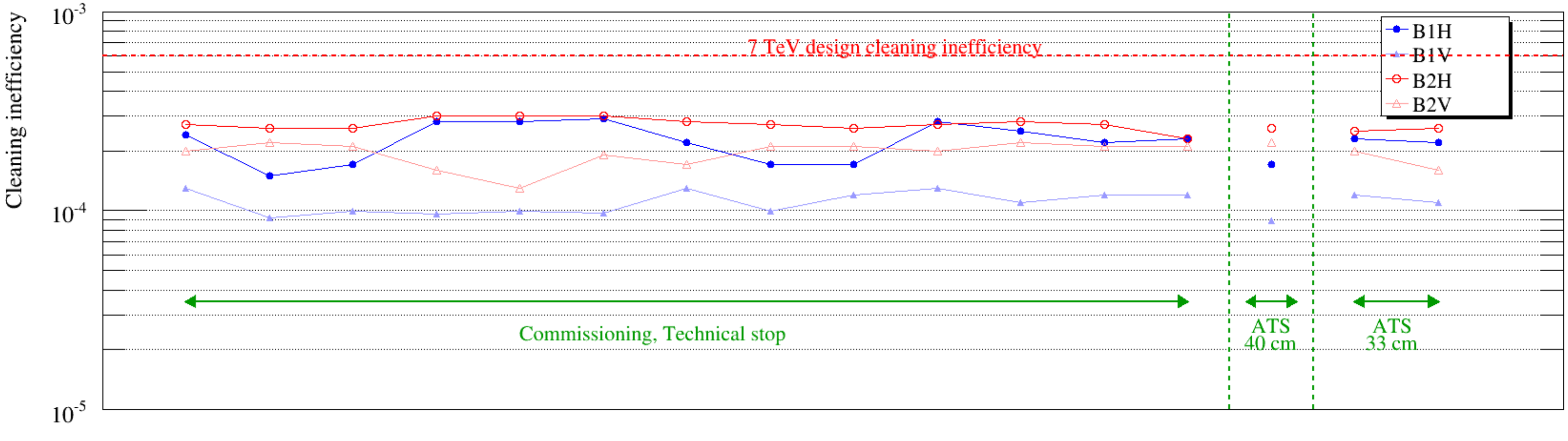
- **Tele index of ~1 @ β*=40/33 cm**

→ Changing to the ATS is transparent for collimation (at least for small telescope)

Optic Name	Time
R2016ats_A40C40A10mL300	0
R2016ats_A37C37A10mL300	90
R2016ats_A33C33A10mL300	178
R2016ats_A27C27A10mL300	258
R2016ats_A21C21A10mL300	346
R2016ats_A17C17A10mL300	452
R2016ats_A14C14A10mL300	569
R2016ats_A12C12A10mL300	676
R2016ats_A10C10A10mL300	804

2016 OP

2016 ATS MDs



Courtesy of D. Mirarchi and Collimation team

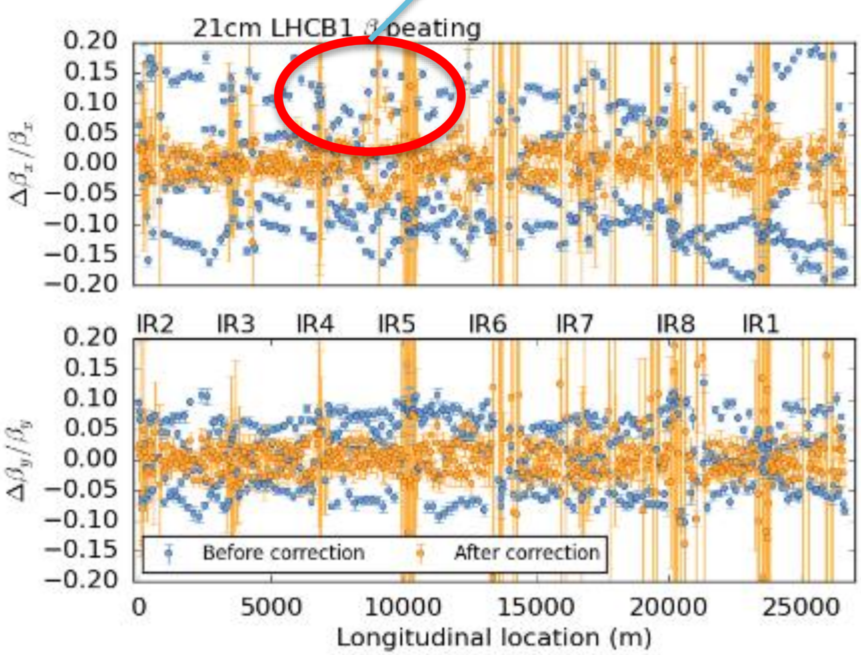
- **Tele index of 2 @ β^*=21 cm (from 40 cm)**

→~ 5-10% β-beat after correction !

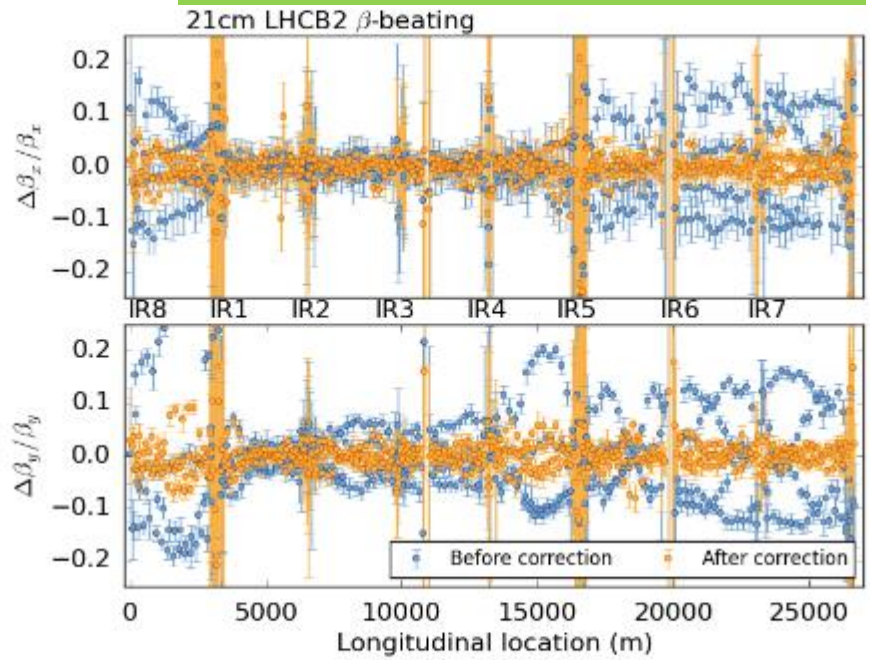
Optic Name	Time
R2016ats_A40C40A10mL300	0
R2016ats_A37C37A10mL300	90
R2016ats_A33C33A10mL300	178
R2016ats_A27C27A10mL300	258
R2016ats_A21C21A10mL300	346
R2016ats_A17C17A10mL300	452
R2016ats_A14C14A10mL300	569
R2016ats_A12C12A10mL300	676
R2016ats_A10C10A10mL300	804

Remember these locations for B1H

Courtesy of J Coello de Portugal and OMC teams.



Beam 1



Beam 2

HiLumi HL-LHC PROJECT

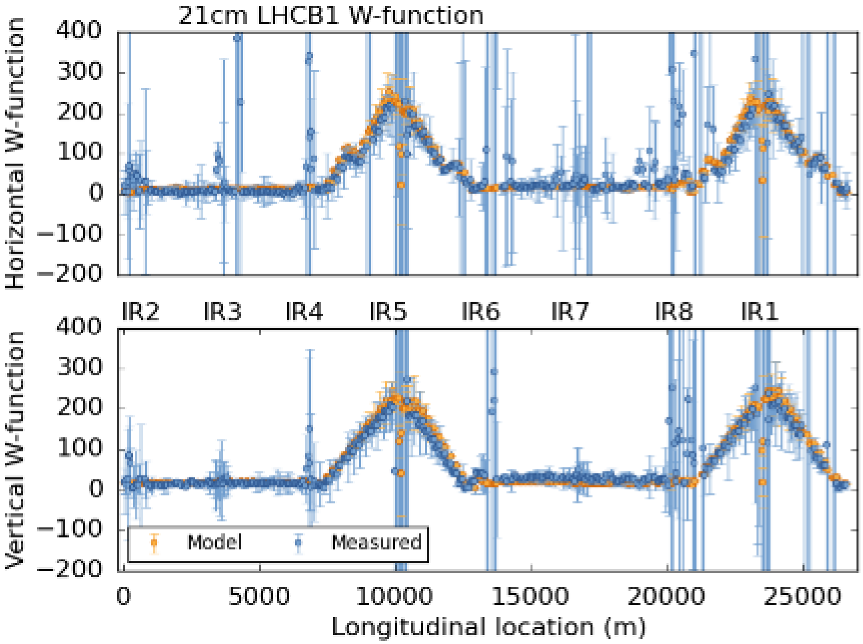
- **Tele index of 2 @ β*=21 cm (from 40 cm)**

→ As expected, the W's are "triangular" !

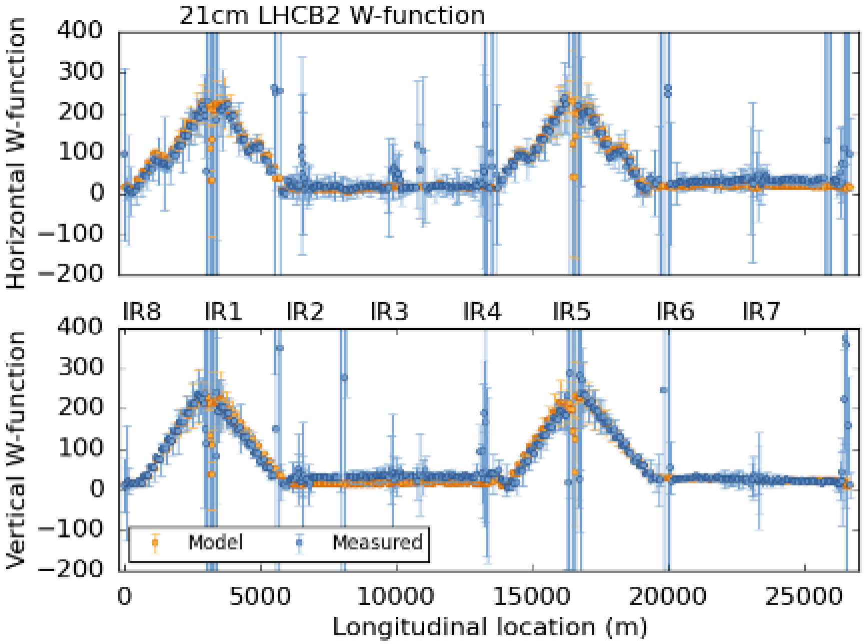
(one sector of sextupoles compensate for the chromatic effect of one triplet)

Optic Name	Time
R2016ats_A40C40A10mL300	0
R2016ats_A37C37A10mL300	90
R2016ats_A33C33A10mL300	178
R2016ats_A27C27A10mL300	258
R2016ats_A21C21A10mL300	346
R2016ats_A17C17A10mL300	452
R2016ats_A14C14A10mL300	569
R2016ats_A12C12A10mL300	676
R2016ats_A10C10A10mL300	804

Courtesy of J Coello de Portugal and OMC teams



Beam 1



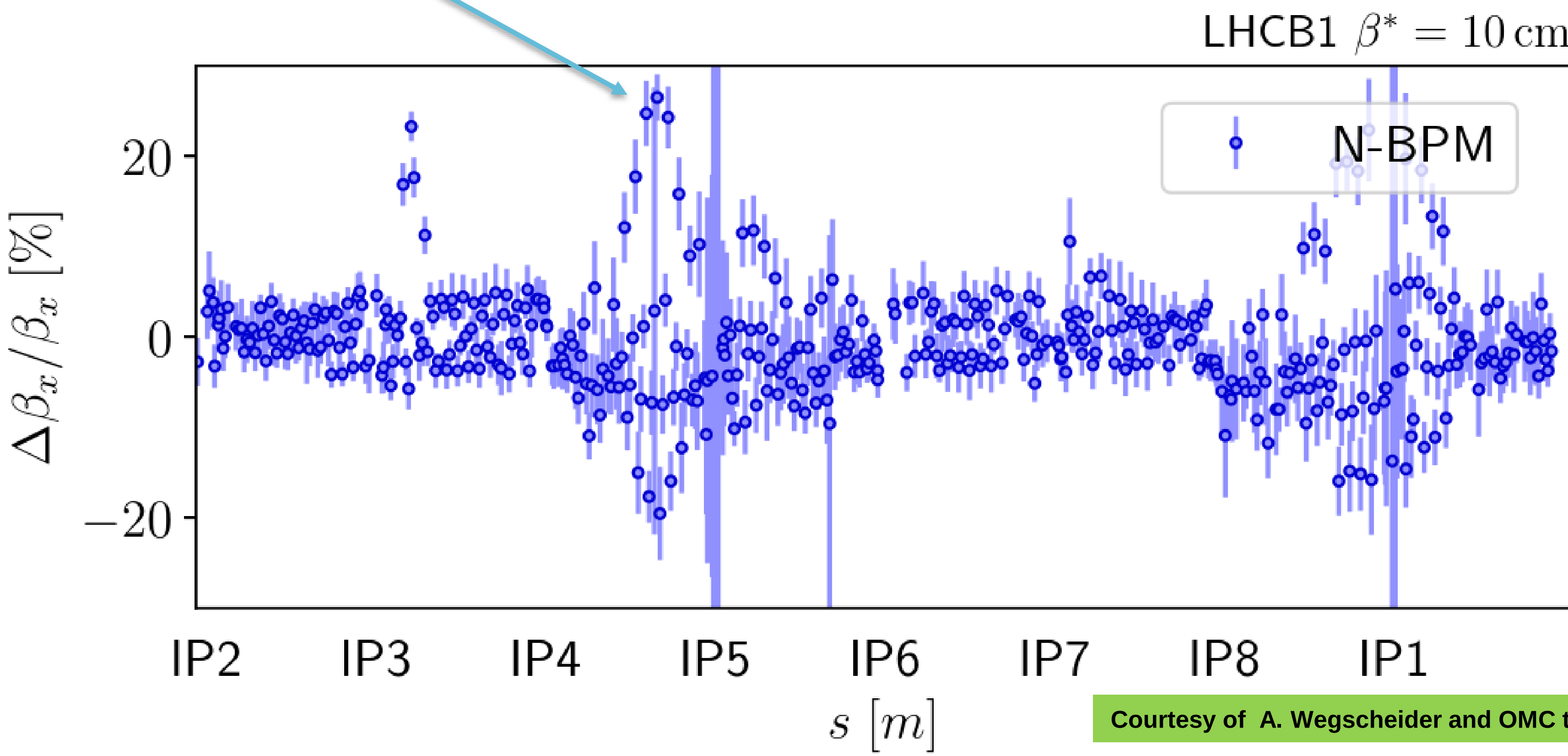
Beam 2

- **Tele index of 4 @ β*=10 cm (from 40 cm)**

→ 20% level but w/o further correction!

Optic Name	Time
R2016ats_A40C40A10mL300	0
R2016ats_A37C37A10mL300	90
R2016ats_A33C33A10mL300	178
R2016ats_A27C27A10mL300	258
R2016ats_A21C21A10mL300	346
R2016ats_A17C17A10mL300	452
R2016ats_A14C14A10mL300	569
R2016ats_A12C12A10mL300	676
R2016ats_A10C10A10mL300	804

Worst case for B1H with 26% peak β-beating (same location)



Courtesy of A. Wegscheider and OMC team

2. 2^{nd} Front (2017): round optics with "down-graded" pre-squeezed β^* to enable large telescope

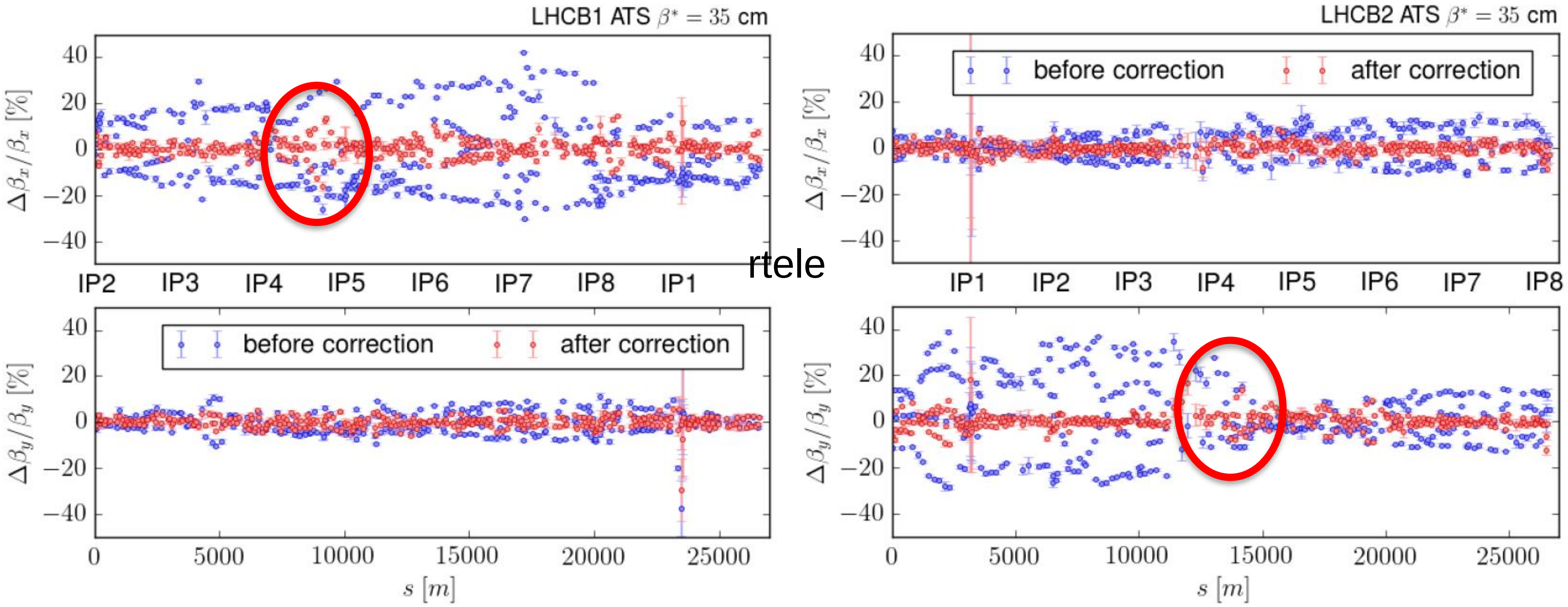
(i) Validate HL-LHC telescope with trains (OP mechanics, interlocks, collimation, life time,..)

(ii) Demonstrate long-range beam-beam mitigation with octupole

→ Pre-squeeze stopped @ 1 m (End of Ramp in 2017)

→ Reach 35cm → 25cm with telescope only (r_{tele}=3 → 4)

- **Tele index of 3 @ β*=35 cm (tele-squeeze from 1 m)**
  → ~ 10% β-beat level reached after correction, but still with peak @15-20% in B1H (and 15% in B2V)



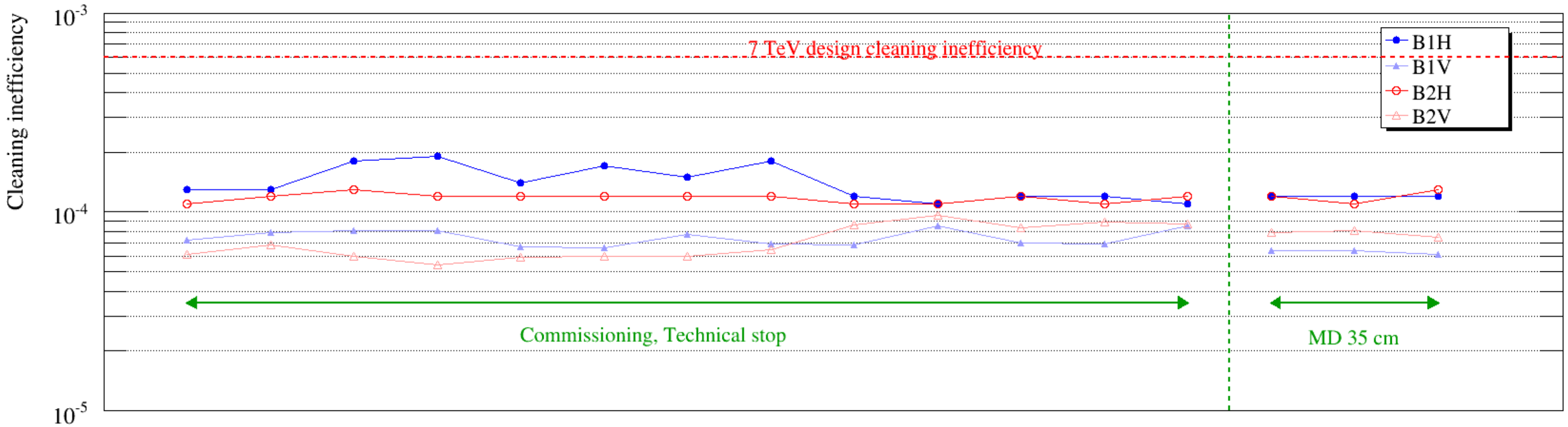
Courtesy of A. Wegscheider and OMC teams

- **Tele index of 3 @ β^*=35 cm (tele-squeeze from 1 m)**

  → Large tele index looks transparent for collimation

2017 OP

2017 ATS MDs

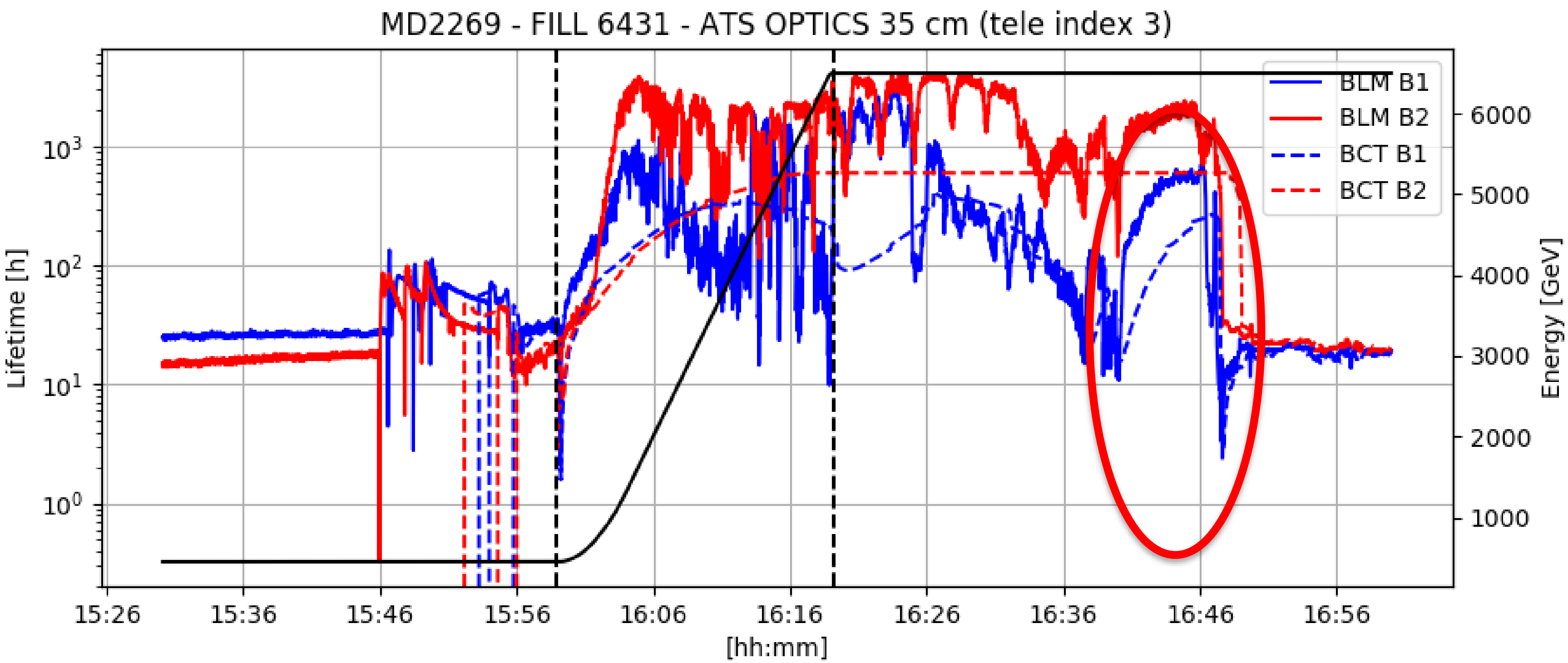


Courtesy of D. Mirarchi, N. Fuster and Collimation team

- **Tele index of 3 @ β^*=35 cm (tele-squeeze from 1 m)**

  MD with a few trains (2 BCMS + 2 BCS trains)

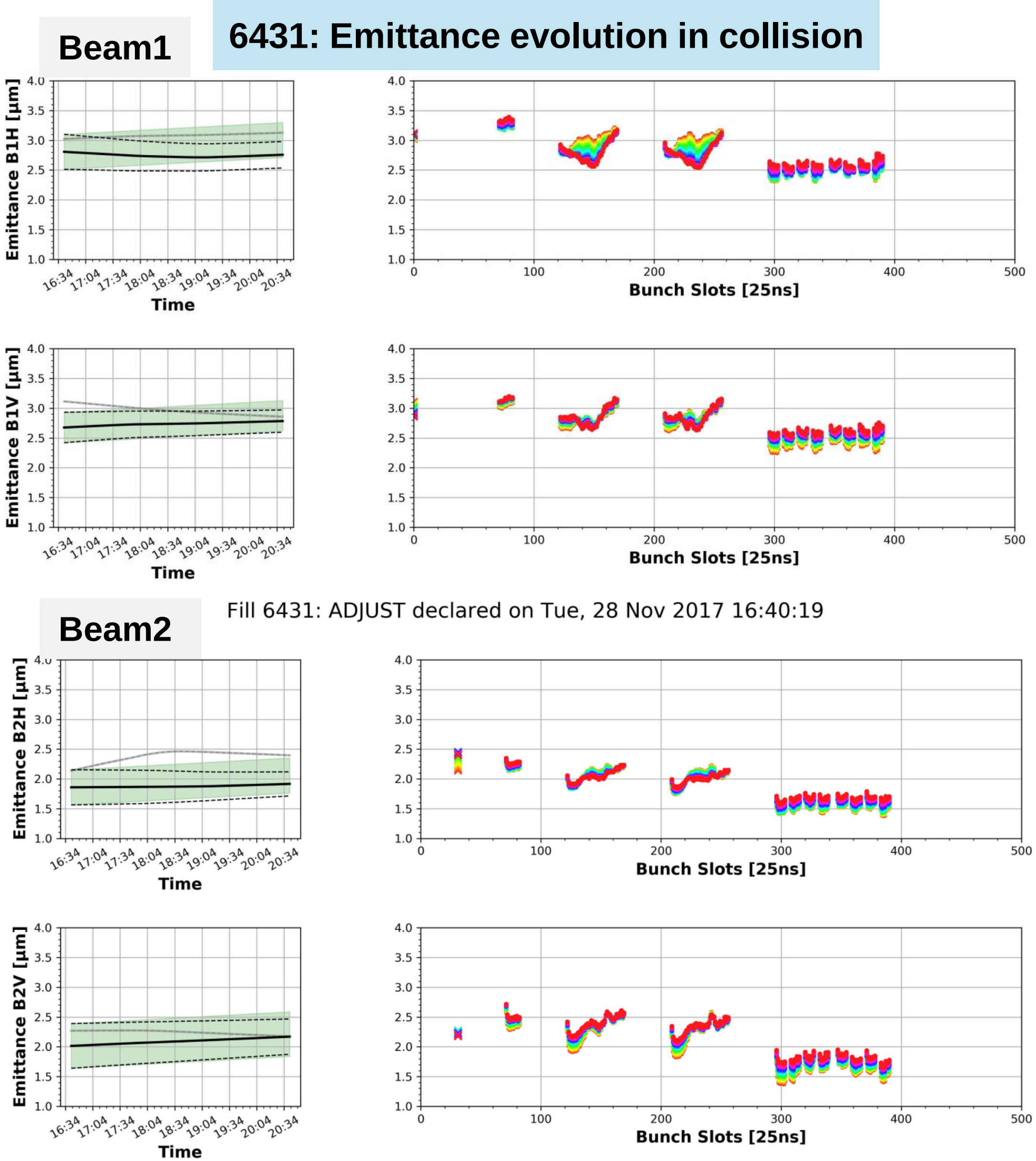
  → 500h-1000h life time in the end of the squeeze



Courtesy of B. Salvachua, A. Poyet

- **Tele index of 3 @ β^*=35 cm (tele-squeeze from 1 m)**

→ **Emittance growth in collision**: no anomaly vs. standard operation



What is the green region?

The evolution of emittance if the initial value was the one measured, but the growth was **0.05μm/h**
The band shows the ±1σ bunch-by-bunch standard deviation

LEGEND

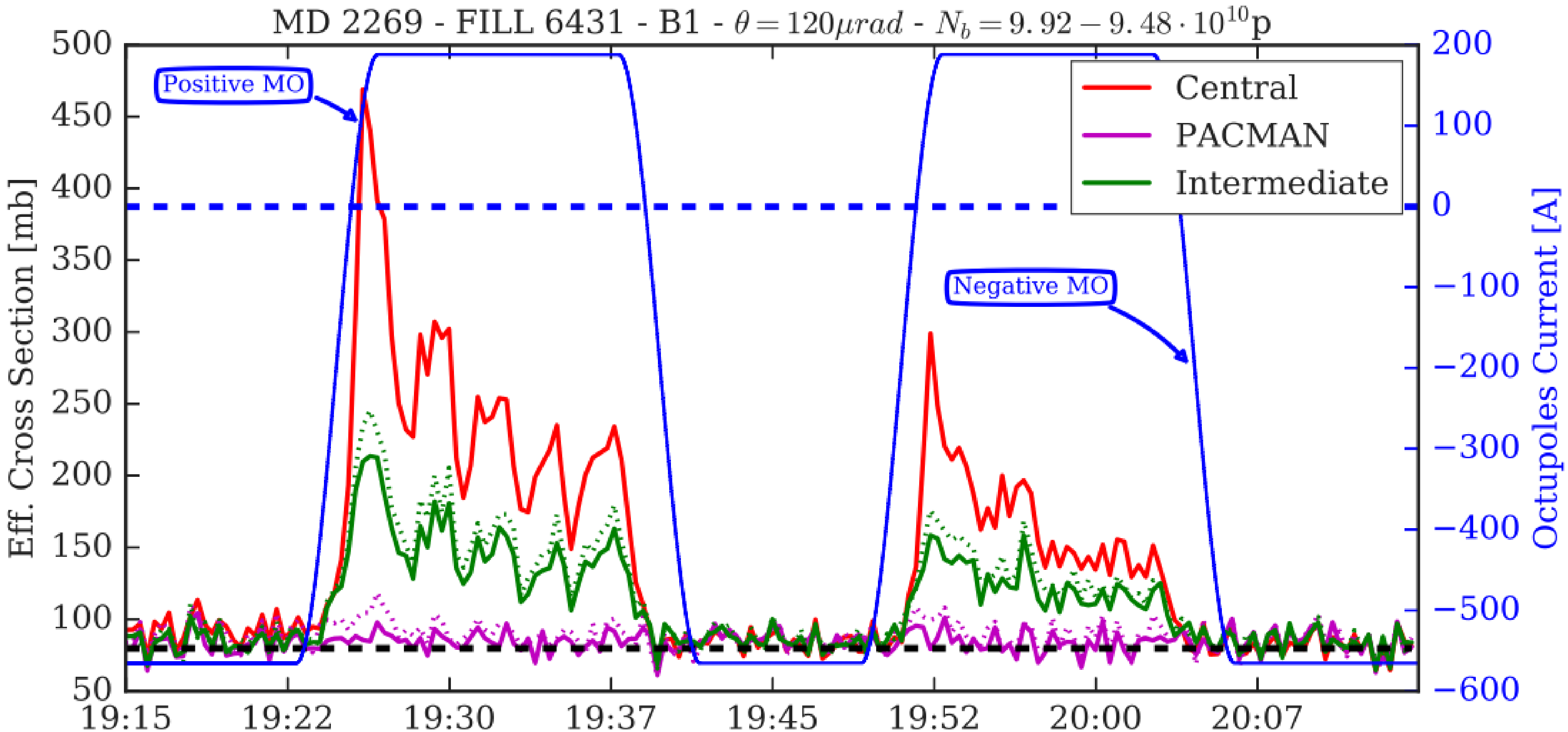
x : non-colliding bunches
● : colliding bunches
: evolution of colliding bunches (mean ± 1σ r.m.s)
— : evolution of non-colliding bunches (mean ± 1σ r.m.s)

Courtesy of N. Karastathis and Lumi team

- **Tele index of 3 @ β*=35 cm (tele-squeeze from 1 m)**

→ First demonstration of BBLR mitigation with octupole (MO)

$$\sigma_{\mathrm{eff}_i} \overset{\mathrm{def}}{=} \frac{|dN_i/dt|}{\mathcal{L}_i}$$



Courtesy of A. Poyet, G. Sterbini, and Beam-Beam team

3. 3rd Front (2017): Flat optics

(i) Assess feasibility & optics correct-ability (probe beam)

(ii) … More to come in 2018 with in mind the LHC Run III & the “HL-LHC Plan B” (with wires and flat optics)

→ Crossing angle gymnastic @ 1 m:

HV → VH crossing in ATLAS and CMS for “triplet aperture preparation”

→ Pre-squeeze down to 60 cm/60 cm at IP1 & IP5

→ Tele-squeeze (tele index 1111→ 1441 → 2552):

- ATLAS: (60/60) → (60/15) → ~~(30/12)~~
- CMS : (60/60) → (15/60) → ~~(12/30)~~

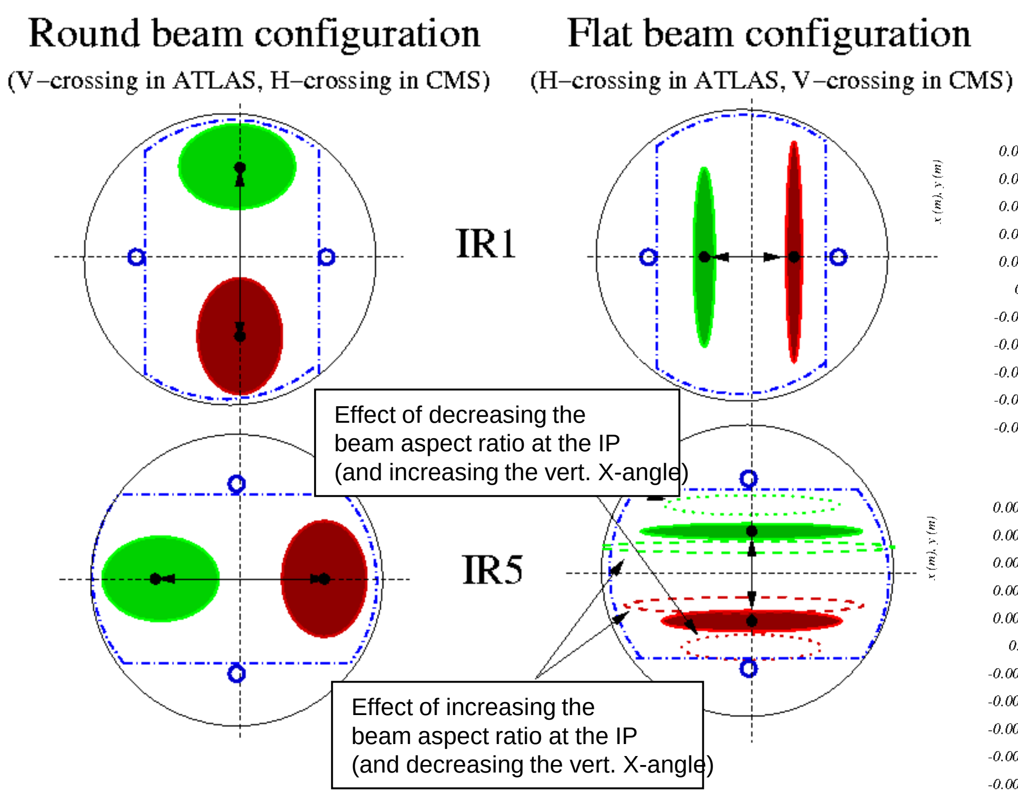
The second segment was prepared but not played (MD time)

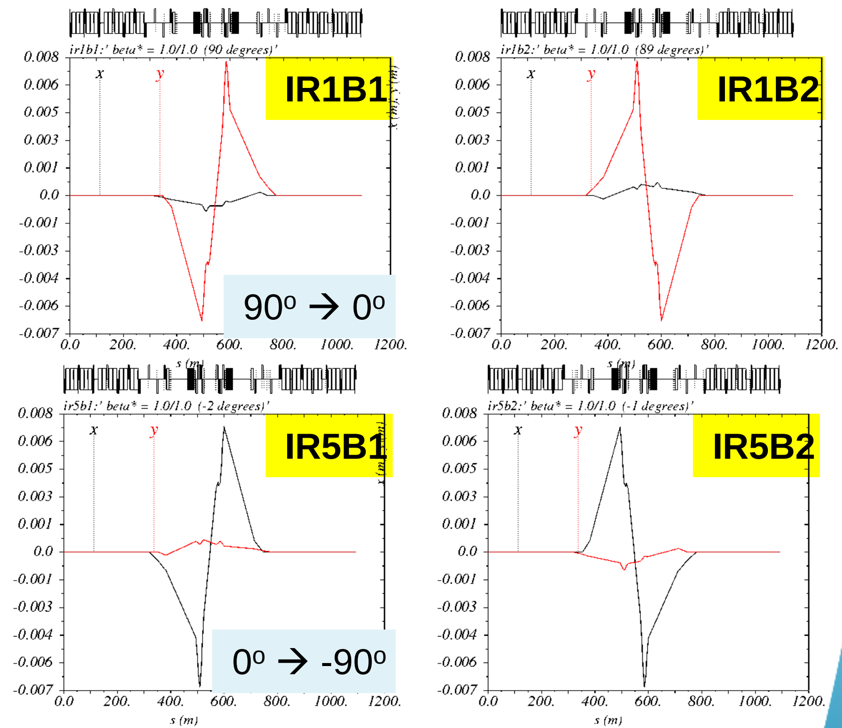
- IR1 & 5 : crossing plane rotation @ 1 m (no telescope)

→ LHC specific, not needed for HL-LHC with octagonal beam-screen

New beam Process needed

X-angle gymnastic @ flat top (β* = 1m)



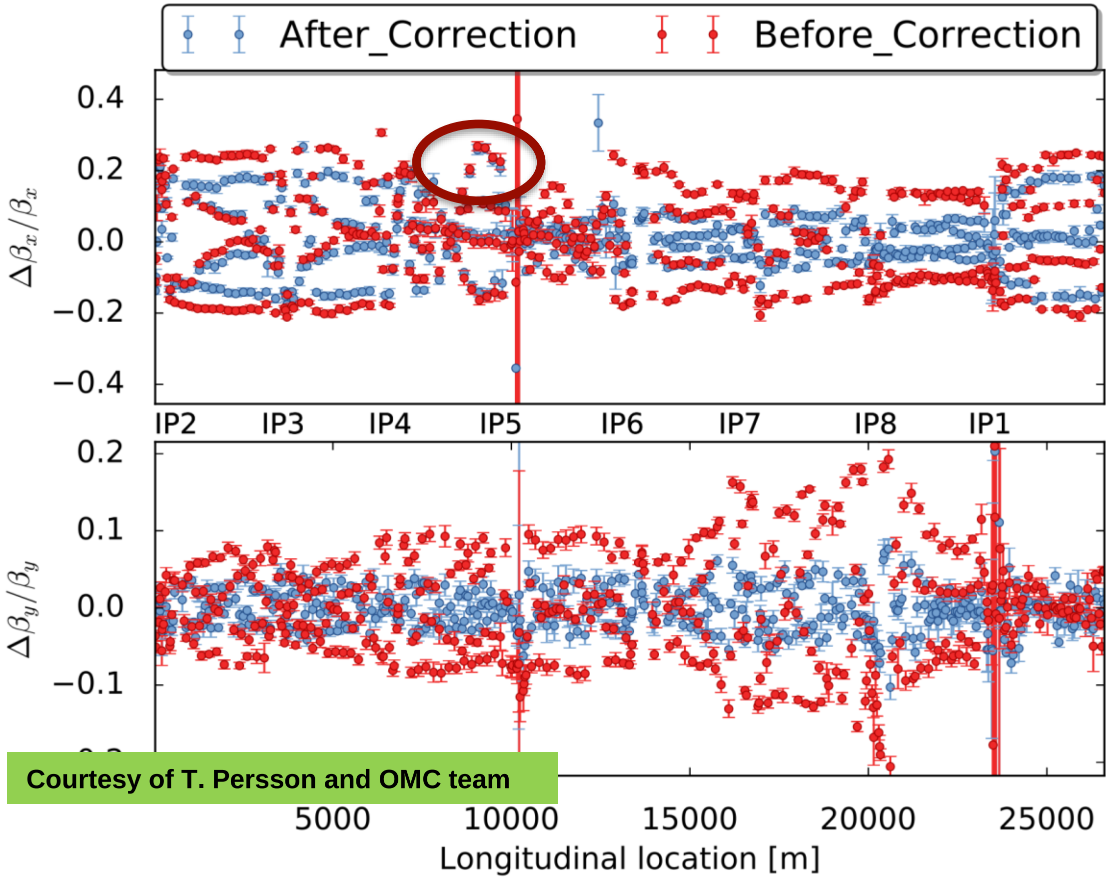


The Machine configuration page was lost ☺, but the process was successful !

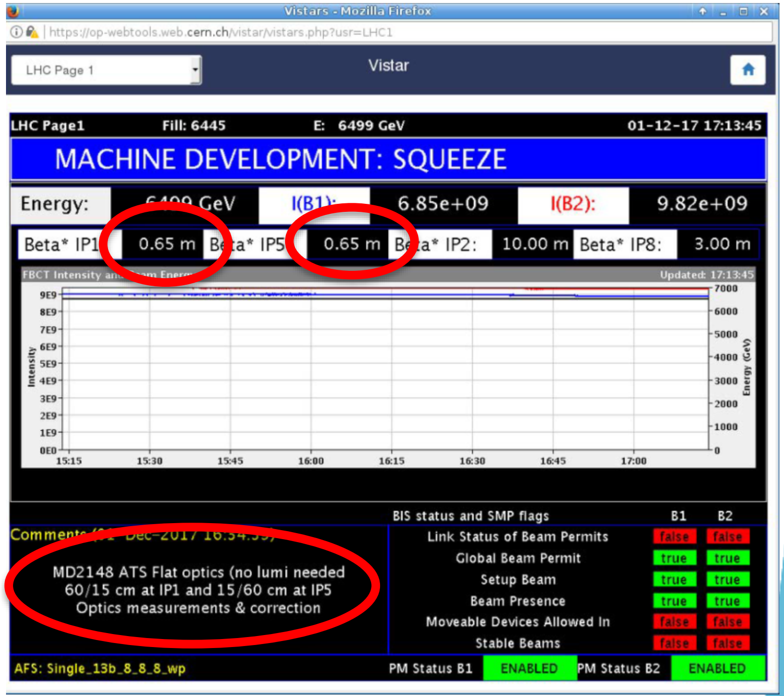
H Xing in ATLAS (and LHCb)

V Xing in CMS (and Alice)

(60-15)-(15-60) was reached and corrected, although Page 1 needs some upgrade as well ☺



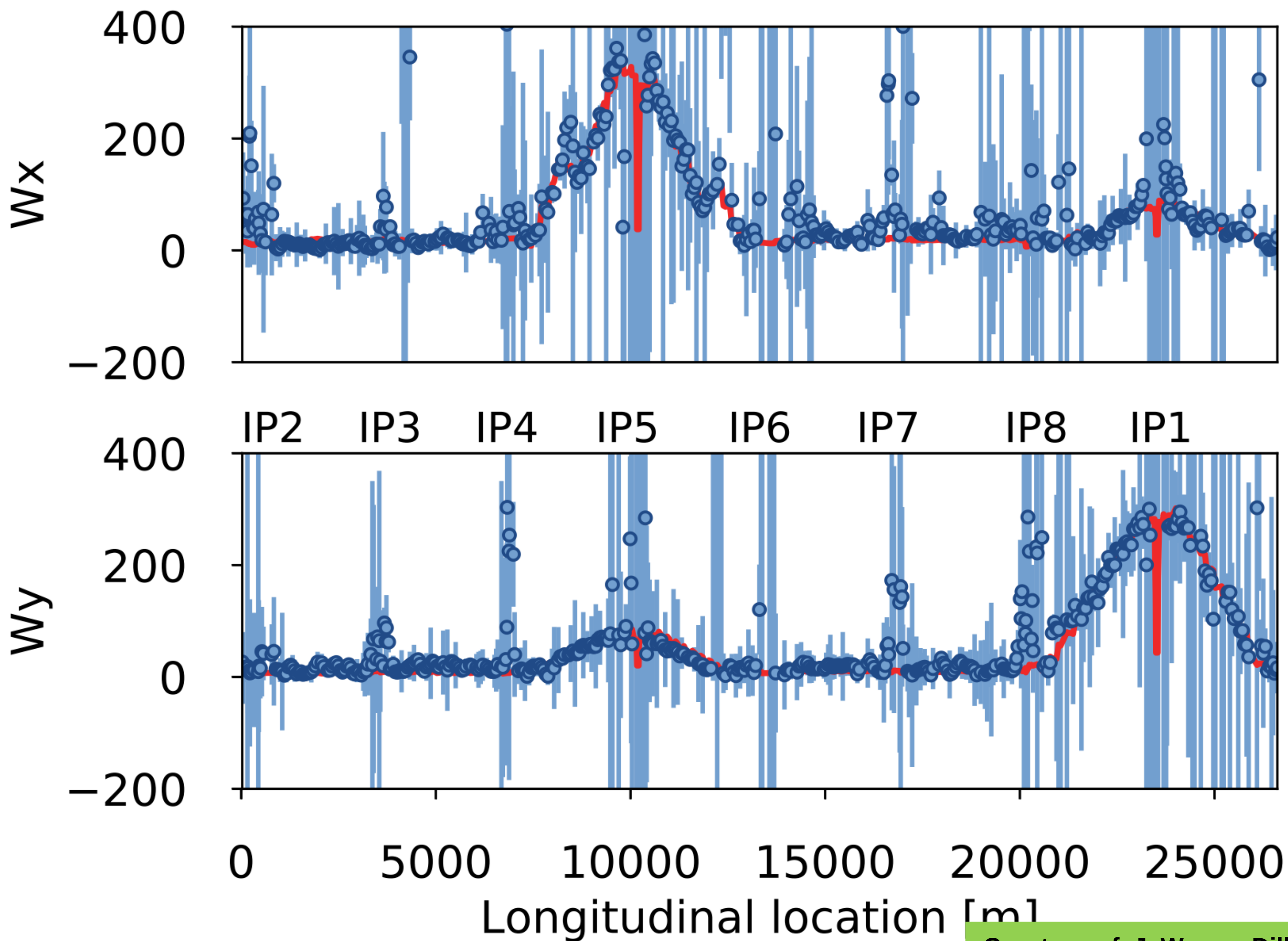
Courtesy of T. Persson and OMC team



The worst case is B1H (25% peak β-beating at same location), with <10% for B1V
→ Very encouraging after the very first try and only a few hours of OMC activities

- **Flat optics 60/15 cm @ IP1 and 15/60 cm@ IP5**

→ The W's is amazingly good after a first try !!



Courtesy of J. Werner Dilly and OMC team

2017 ATS LHC Optics: check-up after 1 year

- **Implementation of ATS optics in the LHC for the 2017 Run**, with additional (not necessarily ATS or HL-LHC specific) features
  - **40 cm (pre-squeeze) with option to go to 30 cm ("mini-telescope")** or beyond (full telescope prepared down to 10 cm)
  - **Combined ramp & squeeze pushed to 1 m** (more in the future)
  - **New IR6 optics with MKD/TCT phase optimization and β^* reach**
  - **New,…, new, IR4 optics** fulfilling BI & ADT requests (next one to come for HEL integration)
  - **New IR2 phase** for squeeze-ability (2018 ion run)
  - **New CMS IP shift bumps** enabling to (easily) reach -1.5 mm
  - **Concept of "CT-PPS" optics bump** to maximize the normalized dispersion at the Roman Pots
  - ...

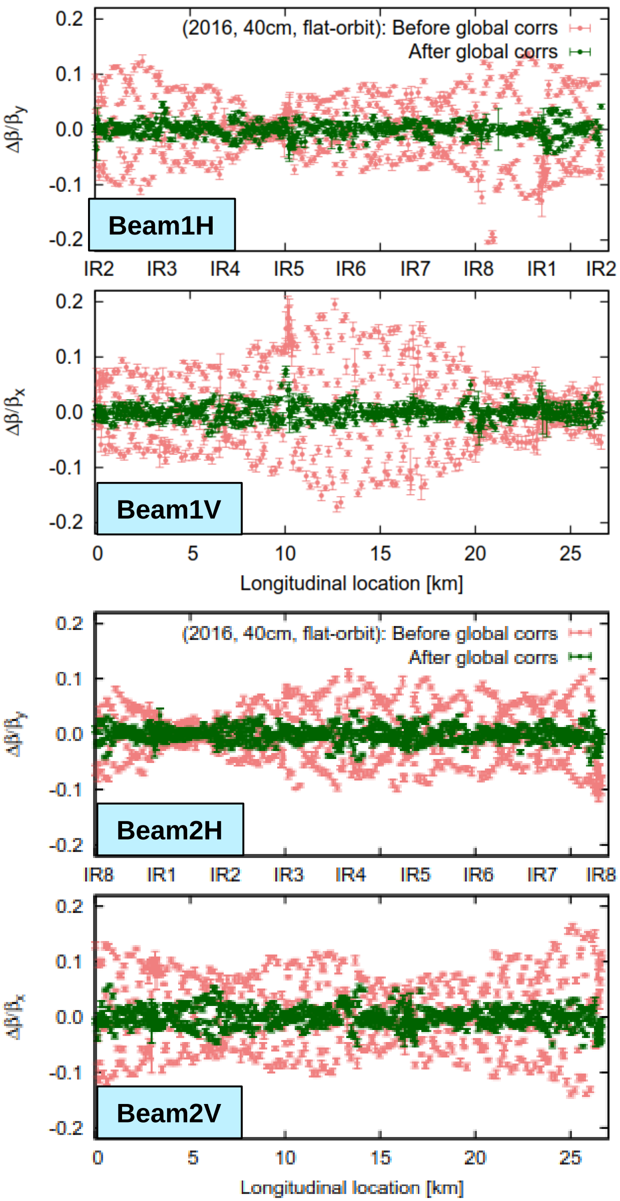
HiLumi HL-LHC PROJECT

→ Check-up summary with beam: 2017 vs. 2016

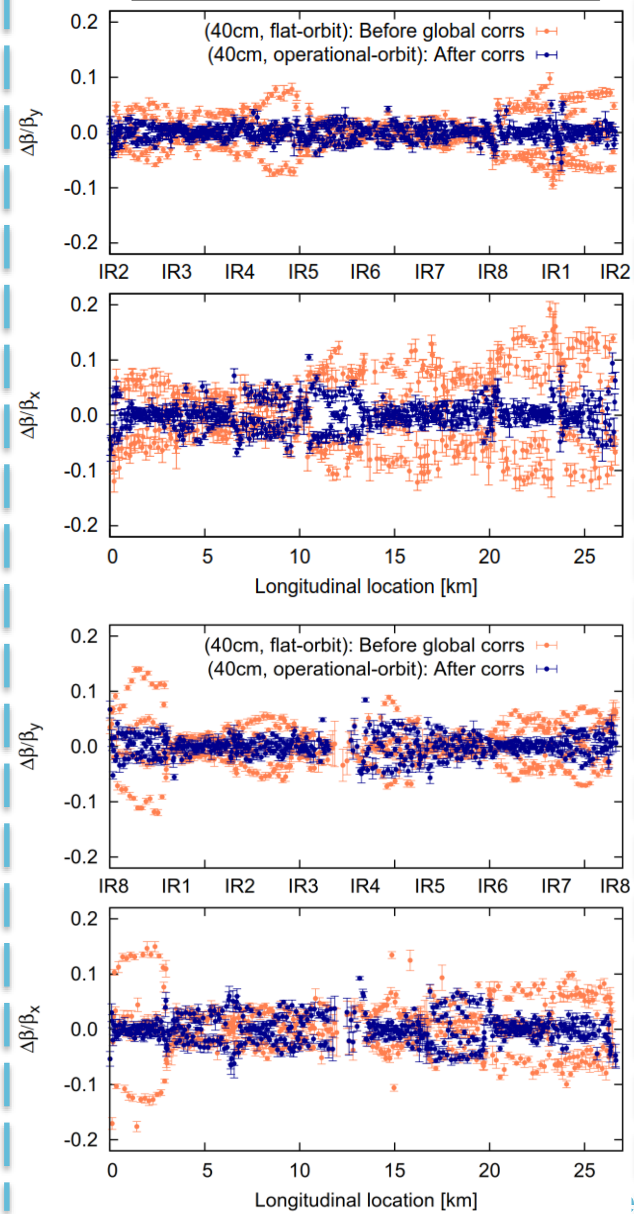
- **Optics correct-ability:** as excellent as before
- **Collimation:** even improved (not due to the ATS but to the tighter collimator settings)
- **Luminosity Life time:** qualitatively very similar (even slightly improved)
- **Integrated Performance .. we know:** of course not only the 30 cm helped, but at least the ATS did not degrade !
- Also take into a account the **many other changes:**
  - New beam types from injector in 2017 (8b4e, 8b4e BCS)
  - X-angle change (150 mrad in 2017 vs. 185/140 mrad in 2016)
  - X-angle anti-levelling in 2017 with ≥ 4 steps (150/140/130/120)
  - Lumi Levelling with parallel separation

• Optics correct-ability: excellent (5-7% peak, % level for β*)

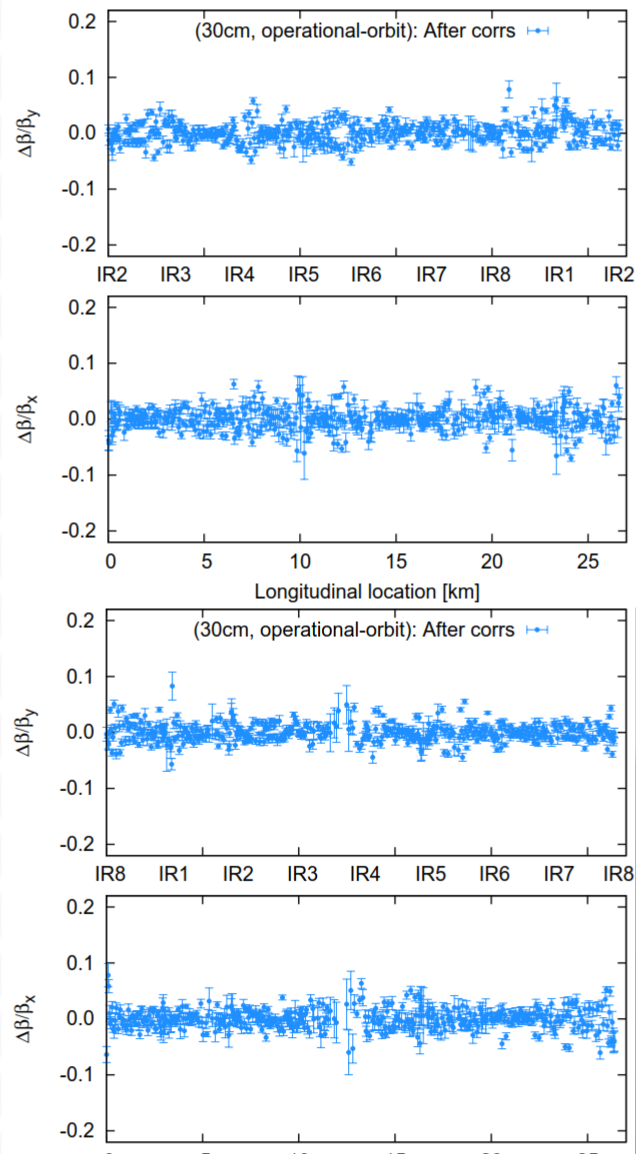
2016 @ 40 cm
(before/after global correction)



2017 @ 40 cm
(with same local correction as 2016)



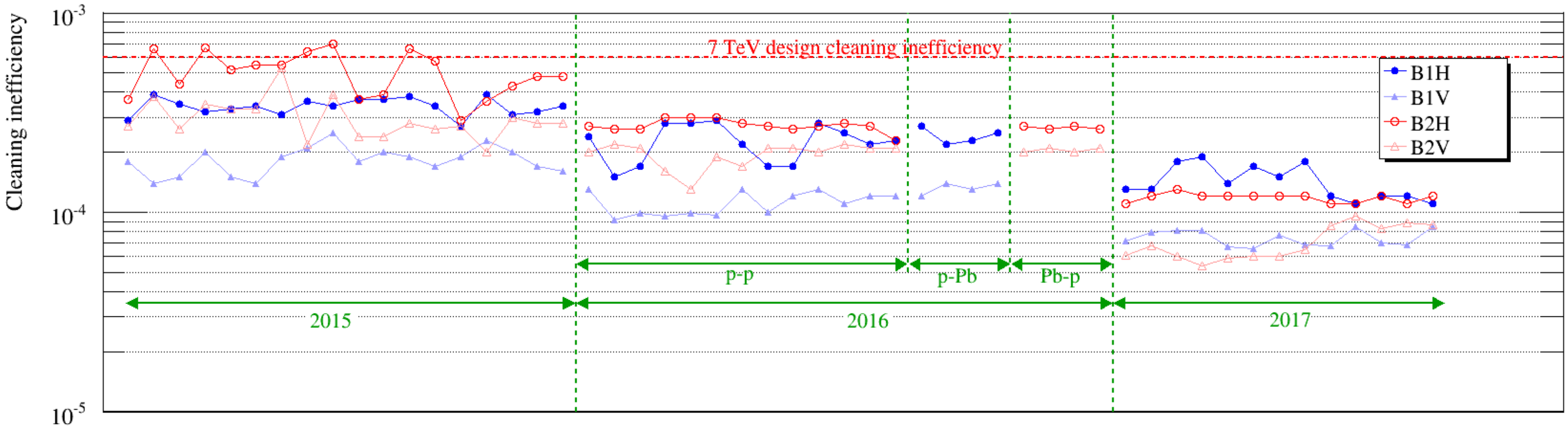
2017 @ 30 cm
(after 2nd global correction)



Courtesy of E. Maclean and OMC team

- # Collimation

Year	2015	2016	2017
TCP/TCSG/TCLA	5.5/8.0/14	5.5/7.5/11	5.0/6.5/10

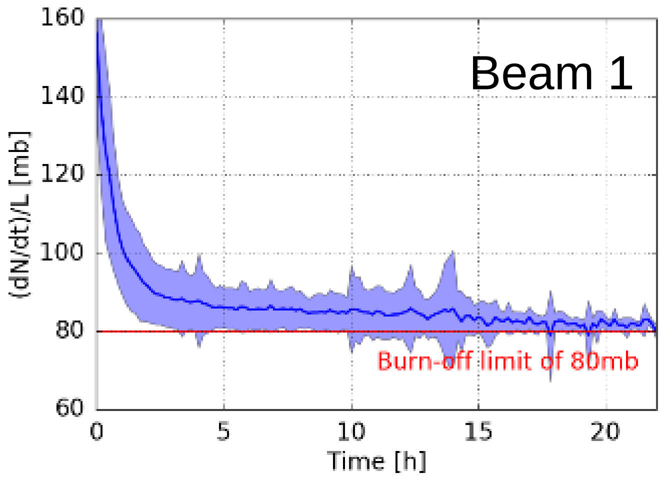


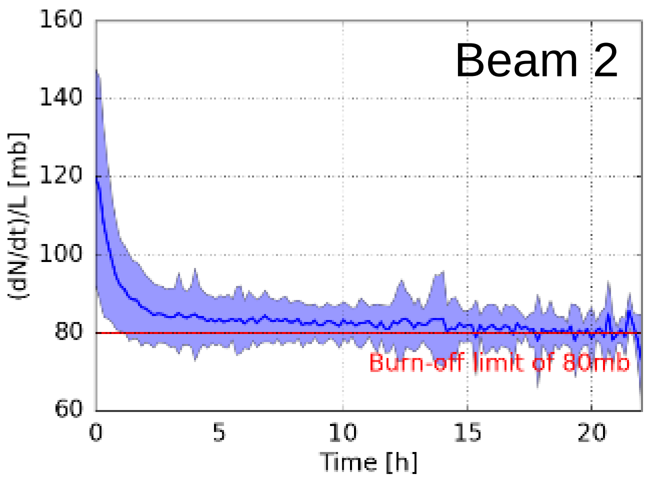
Courtesy of D. Mirarchi and Collimation team

Big improvements over the years from the collimator setting management:
→ **the ATS did not play any role, neither positive nor negative** (as expected and confirmed in MD when comparing at constant settings)

• Life time: effective cross section in SB (all fills)

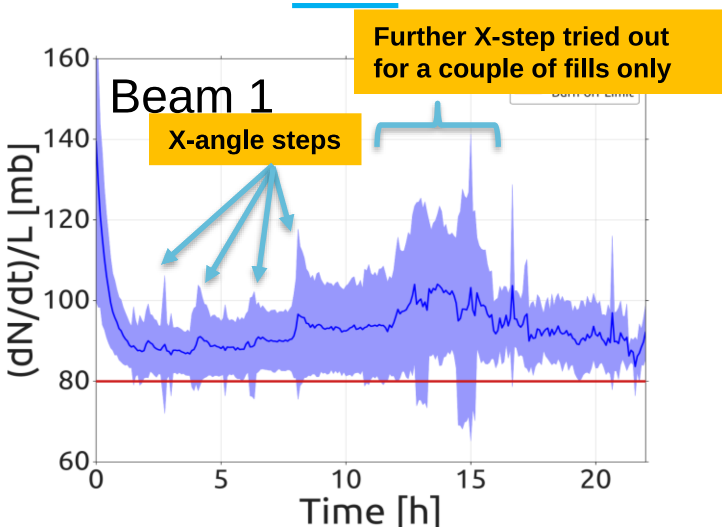
2016

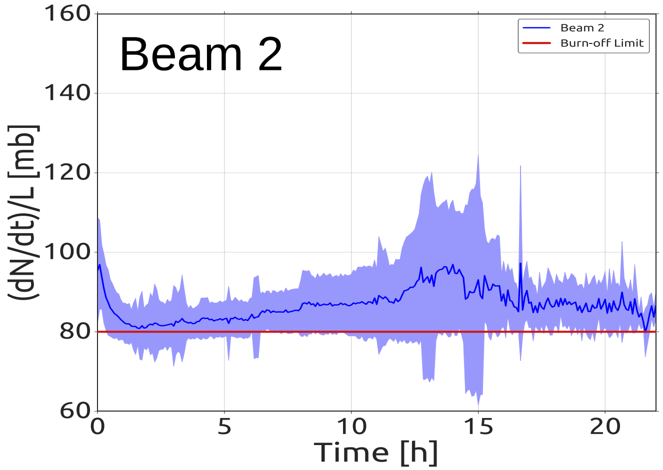




Beam2 Stabilization @ ~2.3h

2017





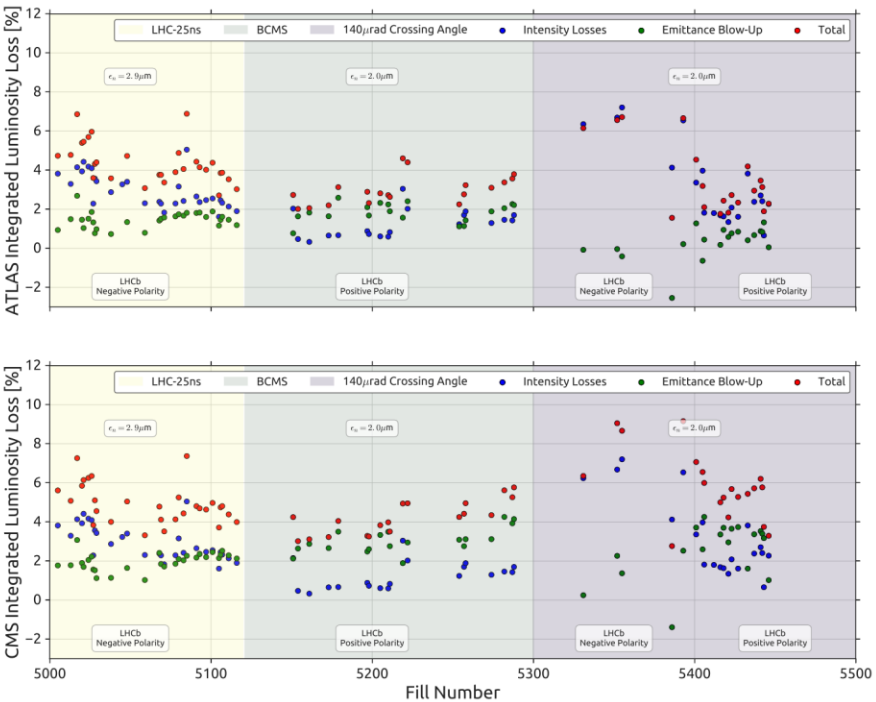
Beam 2 Stabilization @ ~1.6h

Courtesy of G. Iadarola, N. Karastathis and Lumi team

- **Luminosity:** extra lumi loss after 3 h in SB due to losses, emittance growth, or both beyond model
  → **Quantitatively very similar**

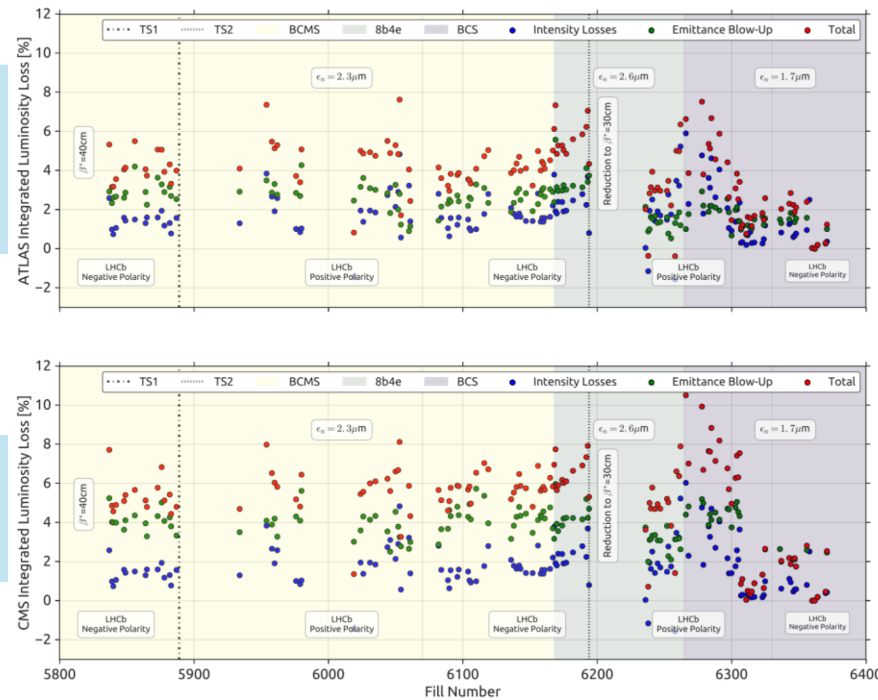
2016: ~3 – 6 % extra losses

2017: ~ 4 – 7 % extra losses



ATLAS

CMS



Courtesy of S. Papadopoulou and Lumi team

Limitations for future operation and mitigation (1/2)

- **Operation at 7.0 TeV: magnet strengths**

→ **All settings 7.0 TeV compatible**, even NC magnets (e.g. MQTL) but

a) **Some RSD circuits** in s81/12/45/56 requesting 600A ++,
→ Preferably to be cured by pushing a bit these circuits
→ Otherwise can be mitigated by more telescope (higher pre-squeezed β^*)

b) **Q5.L6:** MQY @3610 A nominal current (160 T/m @ 4.5 K)

Target currents **(w/o margin)** for various cases	LHC: round optics (20 cm) Telescope (x2Hx2V)	HL-LHC: round optics with Telescope (x4Hx4V)	LHC: Flat optics (15/60 cm) Telescope (x3-4Hx1V)	HL-LHC Flat optics with Telescope (x5Hx2V)
Q5.L6b1	< 3610 A	~ 3800 A	~3700-3800 A	**~ 3900 A**
Q5.L6b2	< 3610 A	~ 3700 A	<3610 A	~ 3700 A

→ OK for the circuits but HW commissioning needed to probe the magnet limit
→ Then decision: 1.9 K (HL-LHC baseline) or "patch" with warm quadrupole

Limitations for future operation and mitigation (2/2)

Large telescope with LIU beam: BETS & TCDQ

– The beam sizes are changing at the TCDQ during the tele-squeeze, increasing/decreasing for beam1/2, while the TCDQ gap in mm is presently fixed when the ramp is finished

→ Including β^* in the BETS would enable to move the TCDQ at FT

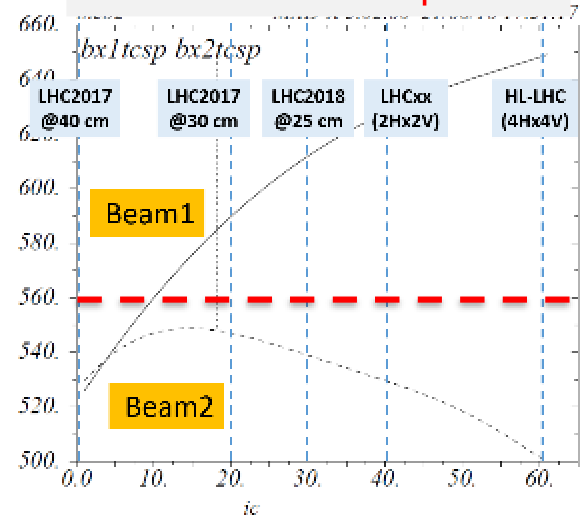
→ Or embedding the full tele-squeeze in the ramp would allow to work at cst TCDQ settings at FT (constraining but possible).

– **For the LIU beam @ full intensity, the TCDQ gap should be larger than 3.6 mm** (including 0.6 mm for the BPM interlock at P6), in order to preserve the TCDQ for the worst cases of failure scenarios (C. Bracco, A. Lechner *et al.*)

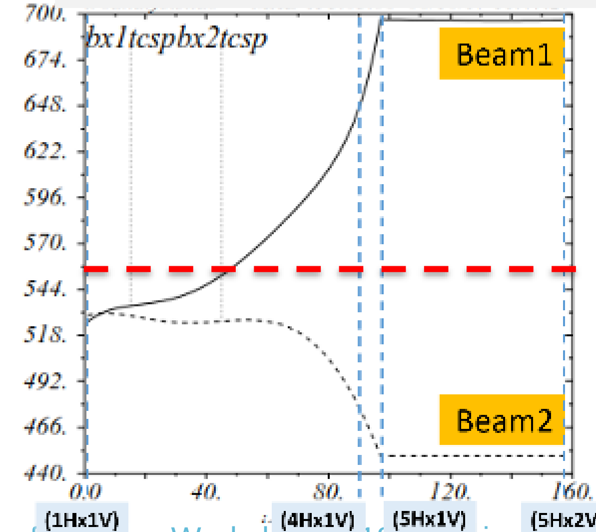
$$\rightarrow \beta_{TCDQ}\,[\mathrm{m}] \geq 560 \times \left(\frac{7.0}{n_{\mathrm{TCDQ}}[\sigma]}\right)^2 \times \left(\frac{7}{E[TeV]}\right)^2$$

→ To preserve the β^* reach (i.e. working at n_{TCDQ} ~7), a scenario with a combined "β^*-TCDQ (&TCT) levelling" seems the only possibility, requesting de facto the upgrade of the BETS.

Round IR6 tele-squeeze



Flat (HV) IR6 tele-squeeze

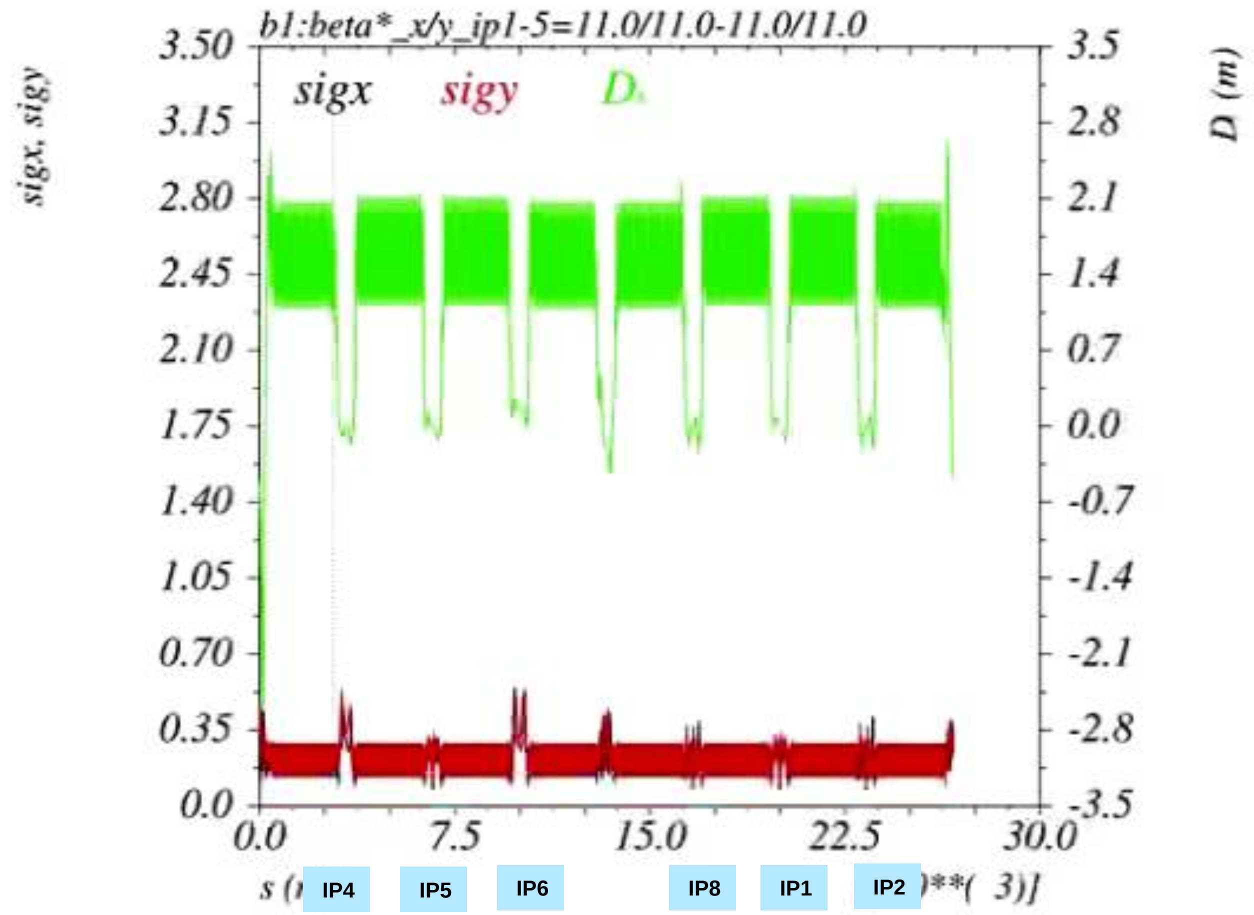


Summary & Conclusions

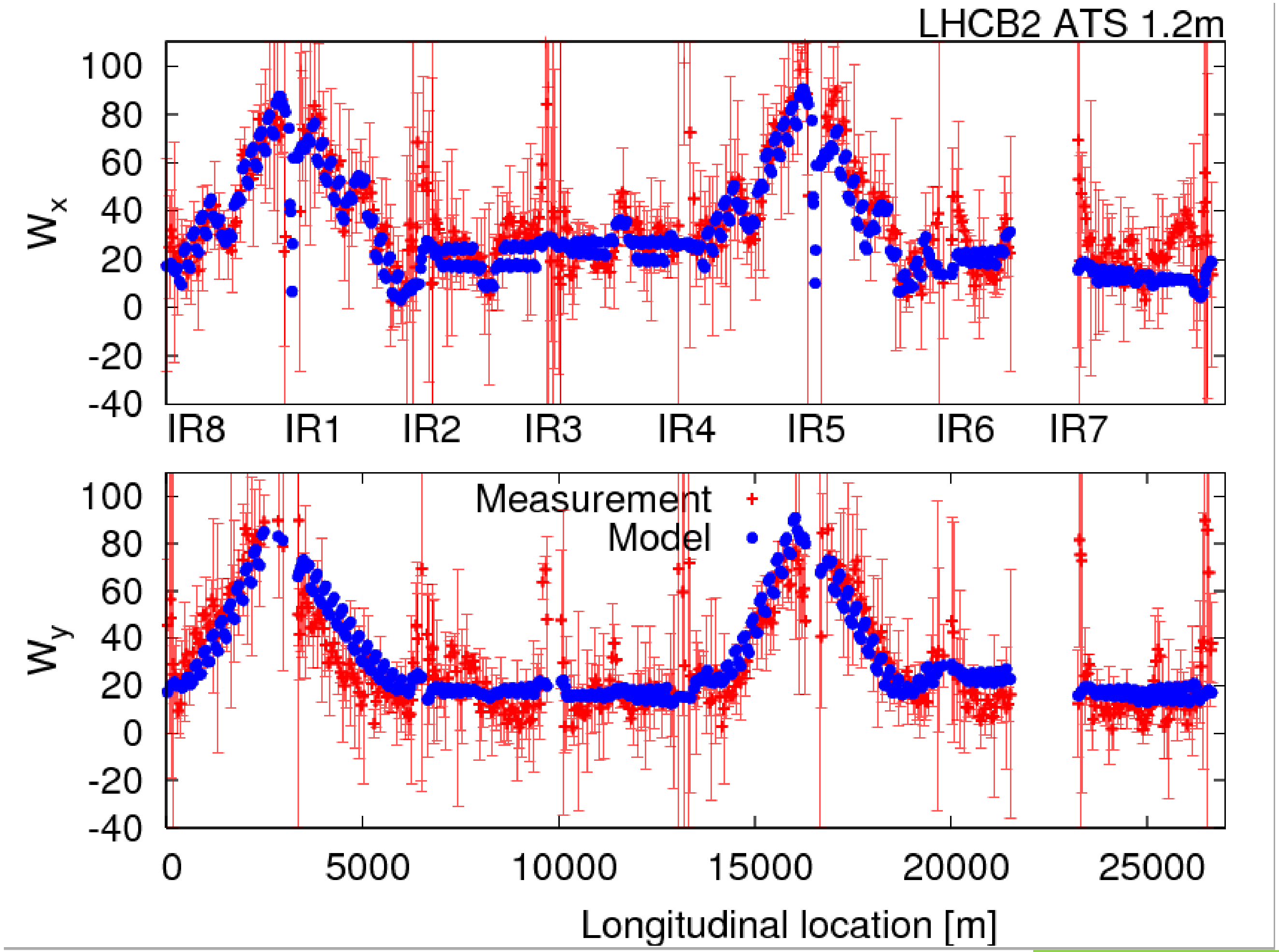
- The **ATS is NOT an option but a vital ingredient for HL-LHC**
- So far, regardless of the ATS, the beam follows precisely the MADX expectations (.. and the other way around!).
- Of course challenges are ahead, such as **preserving state of the art optics correction at large telescopic index** (very relevant for flat optics), but not a show-stopper (.. just more beam time).
- **Next steps for the 2018 ATS MD's are**
  a) The continuation of **flat optics** development, including beam-beam studies with a few trains.
  b) The completion of **round optics** validation with **large telescopic index** at **full intensity** (or nearly full) for **e-cloud studies with telescopic optics.**
  c) In this exercise, to prepare with high priority the decision making process for the **Run III optics: flat vs. round optics.**

Spares

Beam size [mm] @ 7 teV ($\gamma\varepsilon$=3 μm) during Pre-squeeze and Tele-squeeze



First demonstration with beam in 2011 @ 1.2 m (pre-squeezed optics)



Thanks to R. Miyamoto and OMC team

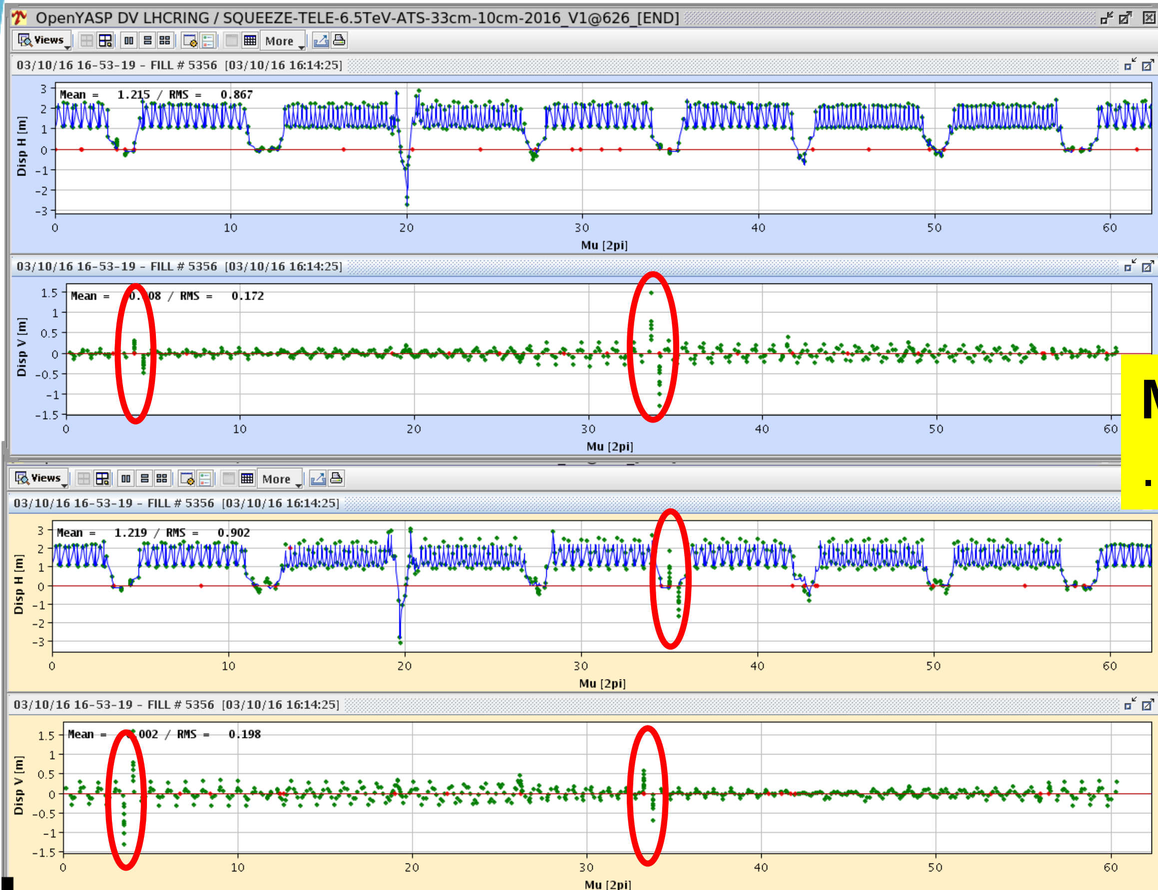
The off-momentum β-beating induced by the IT is confined in s81/12/45/56

- **Tele index of 4 @ β^*=10 cm (from 40 cm)**

The spurious dispersion (w/o X-angle) is under control

(could be further corrected in H, hardly in V)

Optic Name	Time
R2016ats_A40C40A10mL300	0
R2016ats_A37C37A10mL300	90
R2016ats_A33C33A10mL300	178
R2016ats_A27C27A10mL300	258
R2016ats_A21C21A10mL300	346
R2016ats_A17C17A10mL300	452
R2016ats_A14C14A10mL300	569
R2016ats_A12C12A10mL300	676
R2016ats_A10C10A10mL300	804



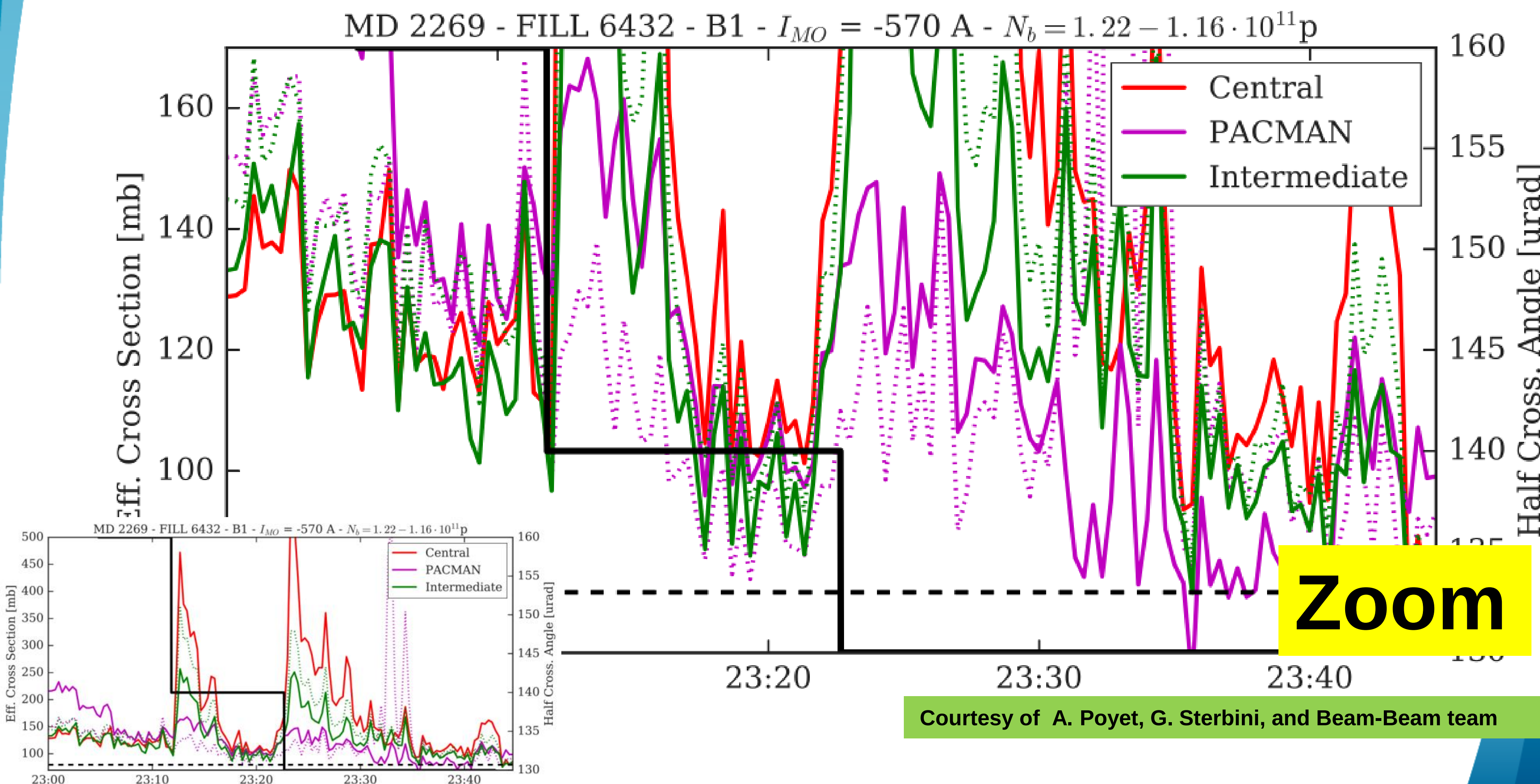
Max 1.5-2 m in the triplets

.. but for a β_{max} of 24 km !

- **Tele index of 3 @ β*=35 cm (tele-squeeze from 1 m)**

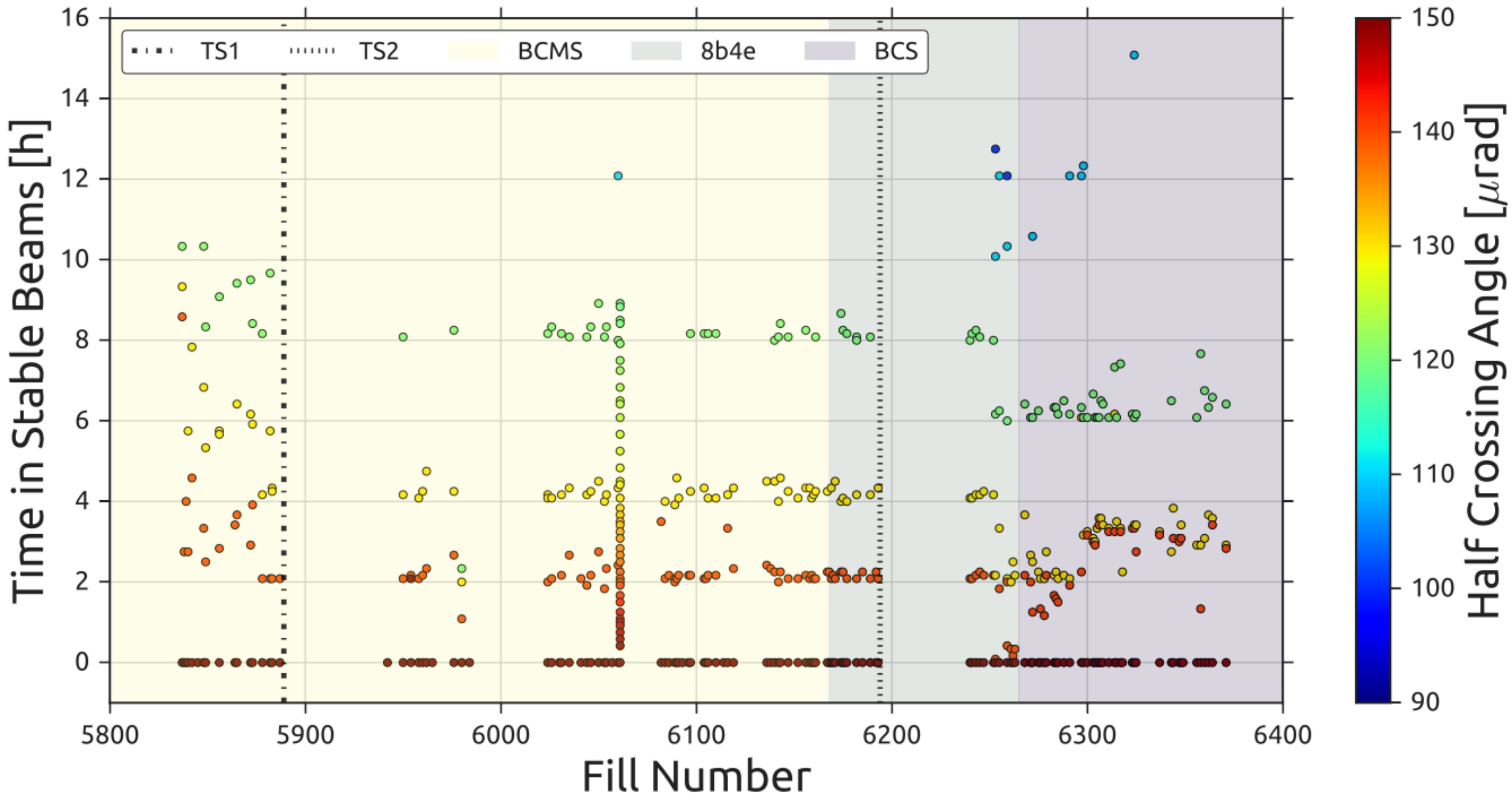
→ Starting with MO<0 in another fill (BCMS with γε ~ 3 μm), the life time improved by reducing the X-angle !

→ Up to 20 μrad (10%) could be gained in X-angle



Courtesy of A. Poyet, G. Sterbini, and Beam-Beam team

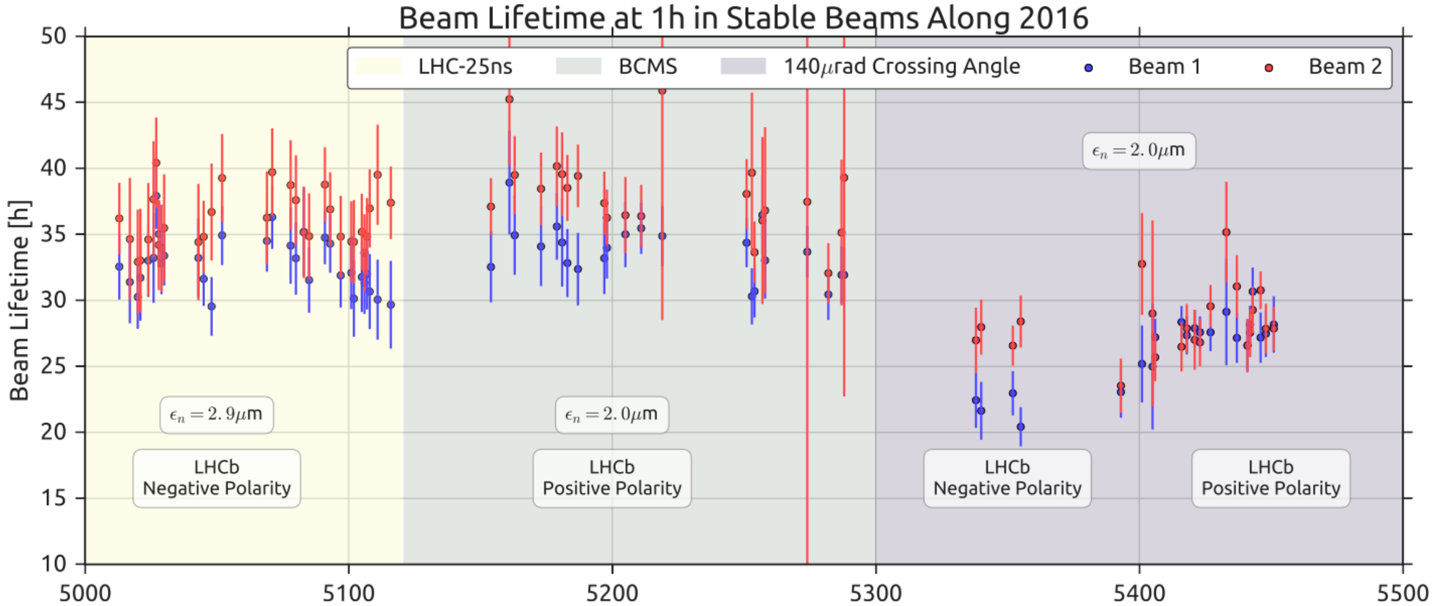
X-angle steps in 2017



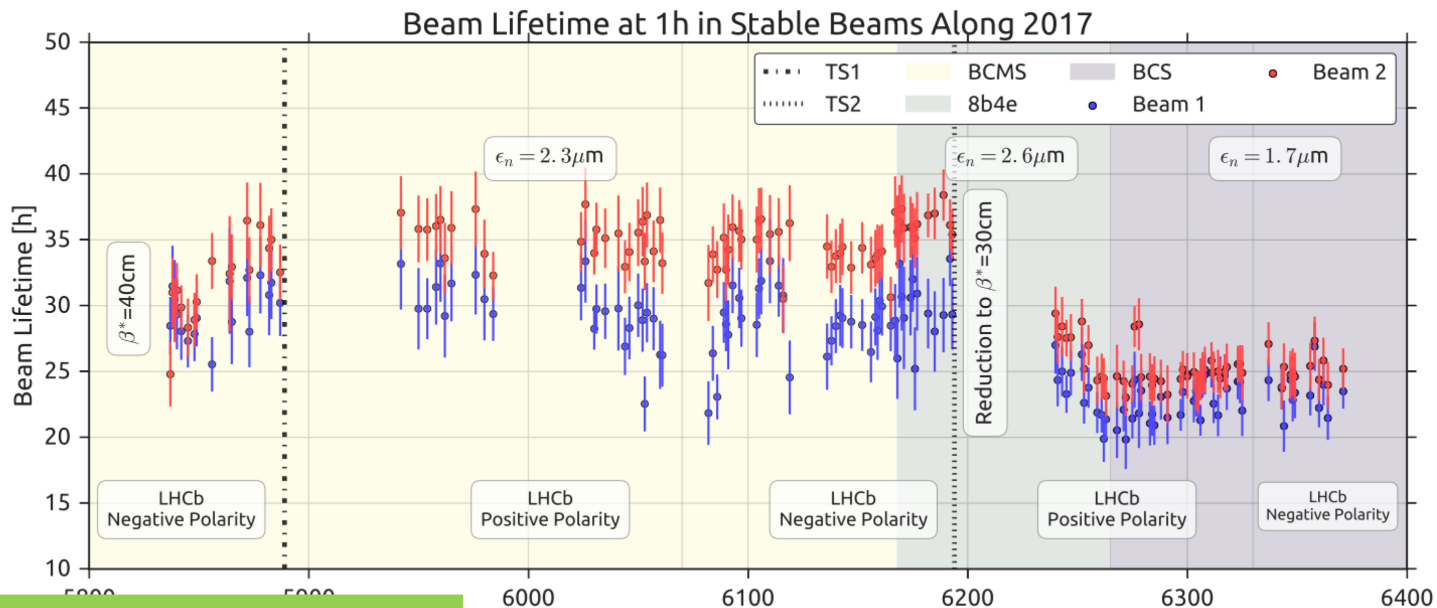
Courtesy of N. Karastathis and Lumi team

Summary of beam life time 1h in stable beam

2016



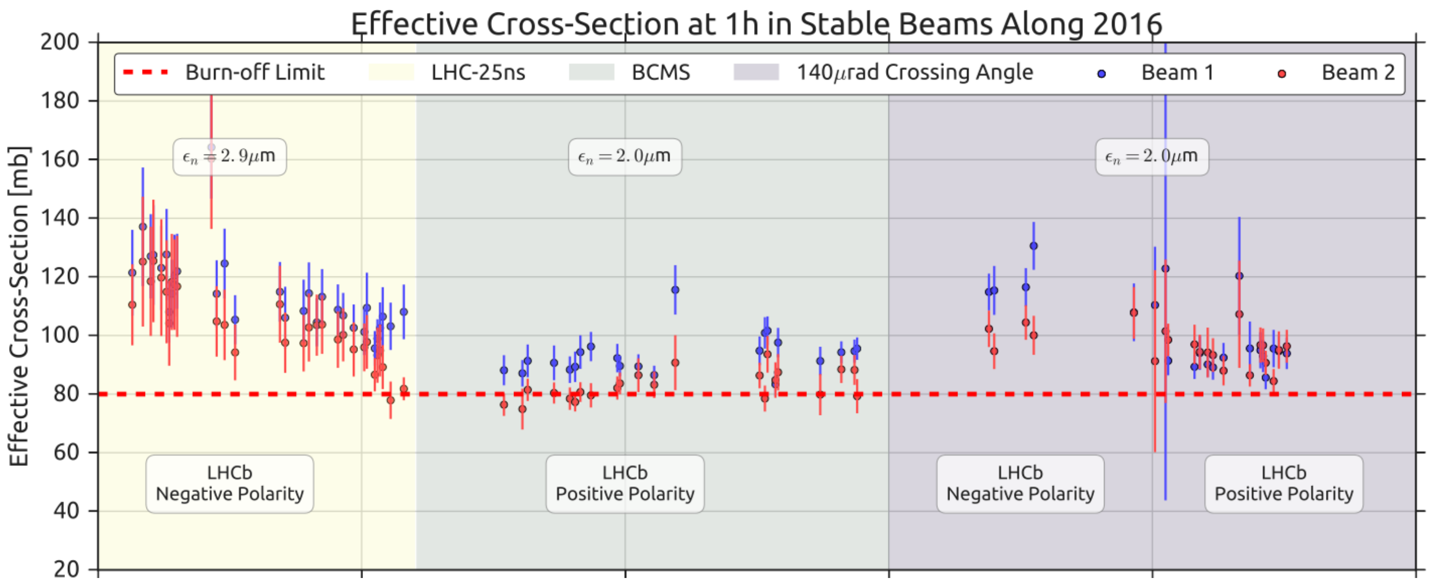
2017



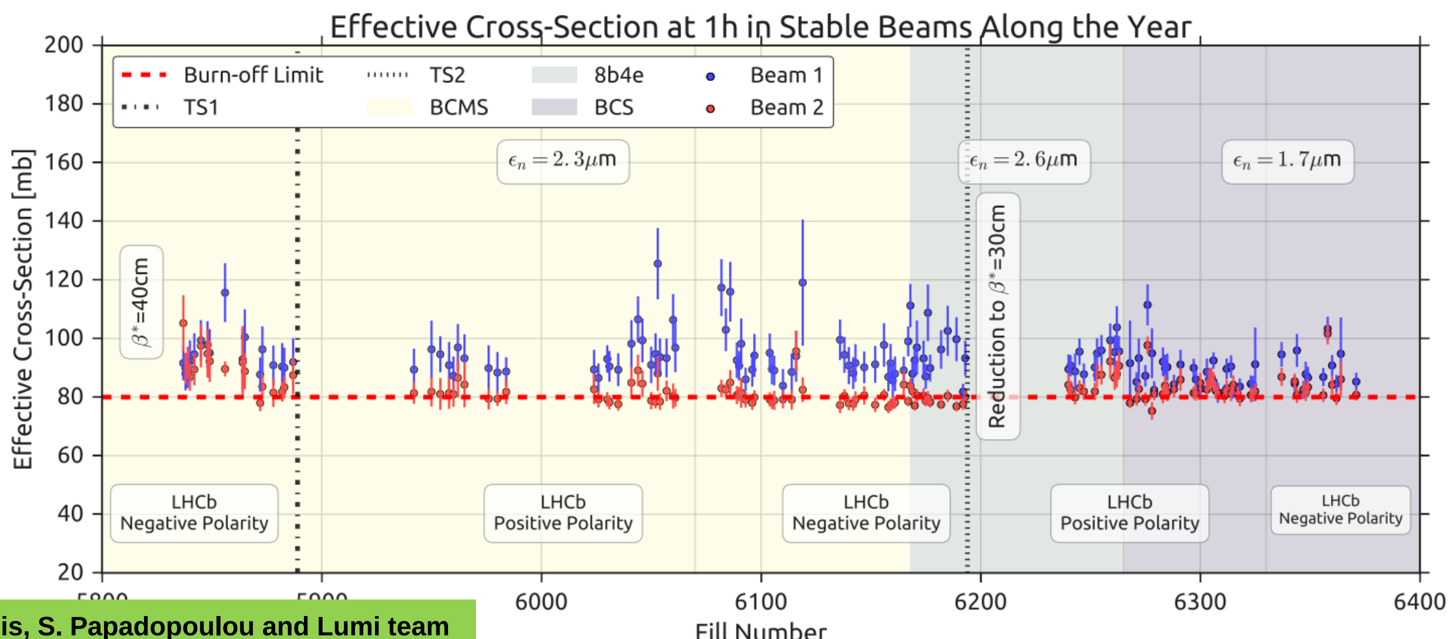
Courtesy of N. Karastathis, S. Papadopoulou and Lumi team

Summary of effective cross-section after 1h in stable beam

2016



2017



HiLumi

Courtesy of N. Karastathis, S. Papadopoulou and Lumi team