Flat optics for (HL-)LHC

S. Fartoukh, N. Karasthatis, M. Solfaroli

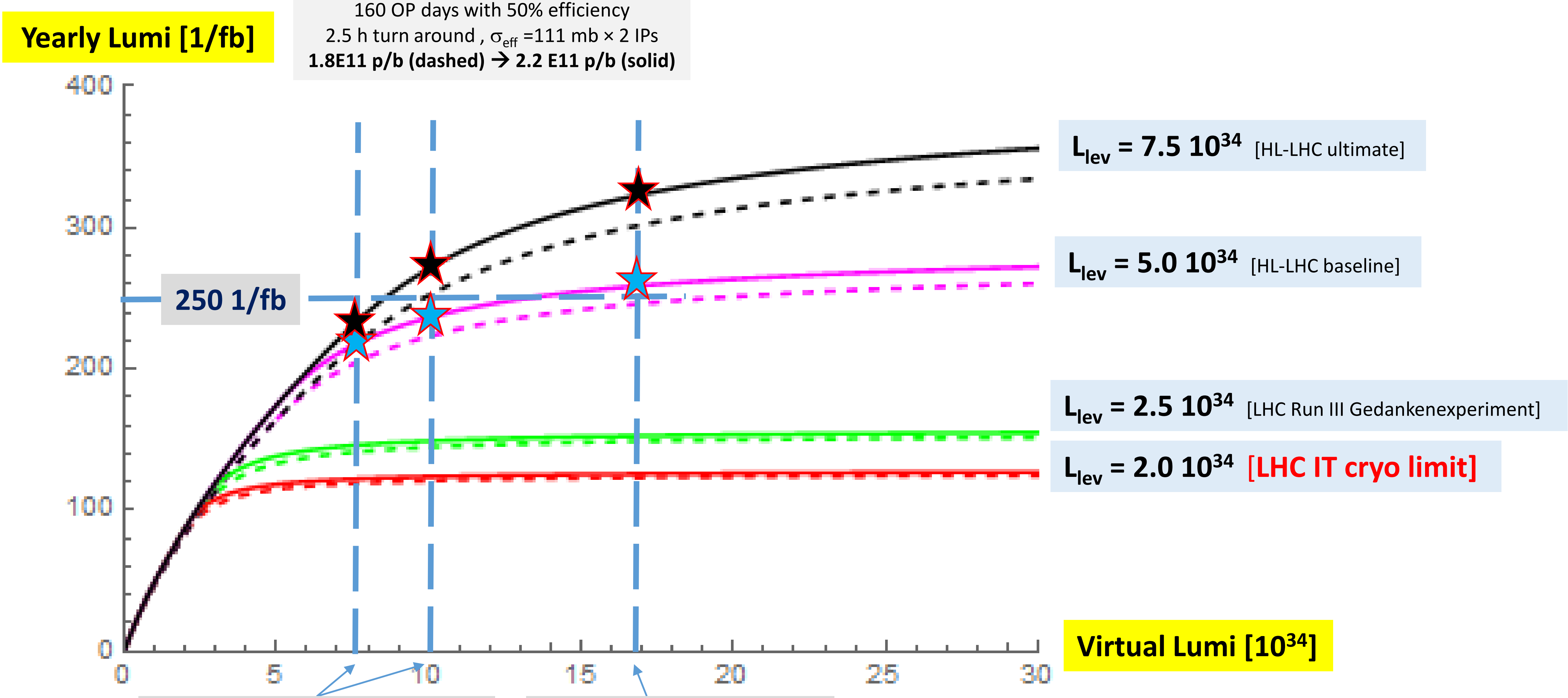
Acknowledgements: ***WP2, LHC-OP***

- **HL-LHC Performance & Data ility**
- **Flat optics in practice (op aperture, X-angle,…)**
- **Optimum flat optics s arios**
- **BBLR mitigation te iques: wires vs. octupoles**
- **Highlight from f optics MD in the LHC**
- **Summary**

Disclaimers on some parts: on-going work

HL-LHC Performance: The overall picture

WITH TYPICAL (HL-LHC) ASSUMPTIONS:
160 OP days with 50% efficiency
2.5 h turn around , σ_{eff} =111 mb × 2 IPs
1.8E11 p/b (dashed) → 2.2 E11 p/b (solid)

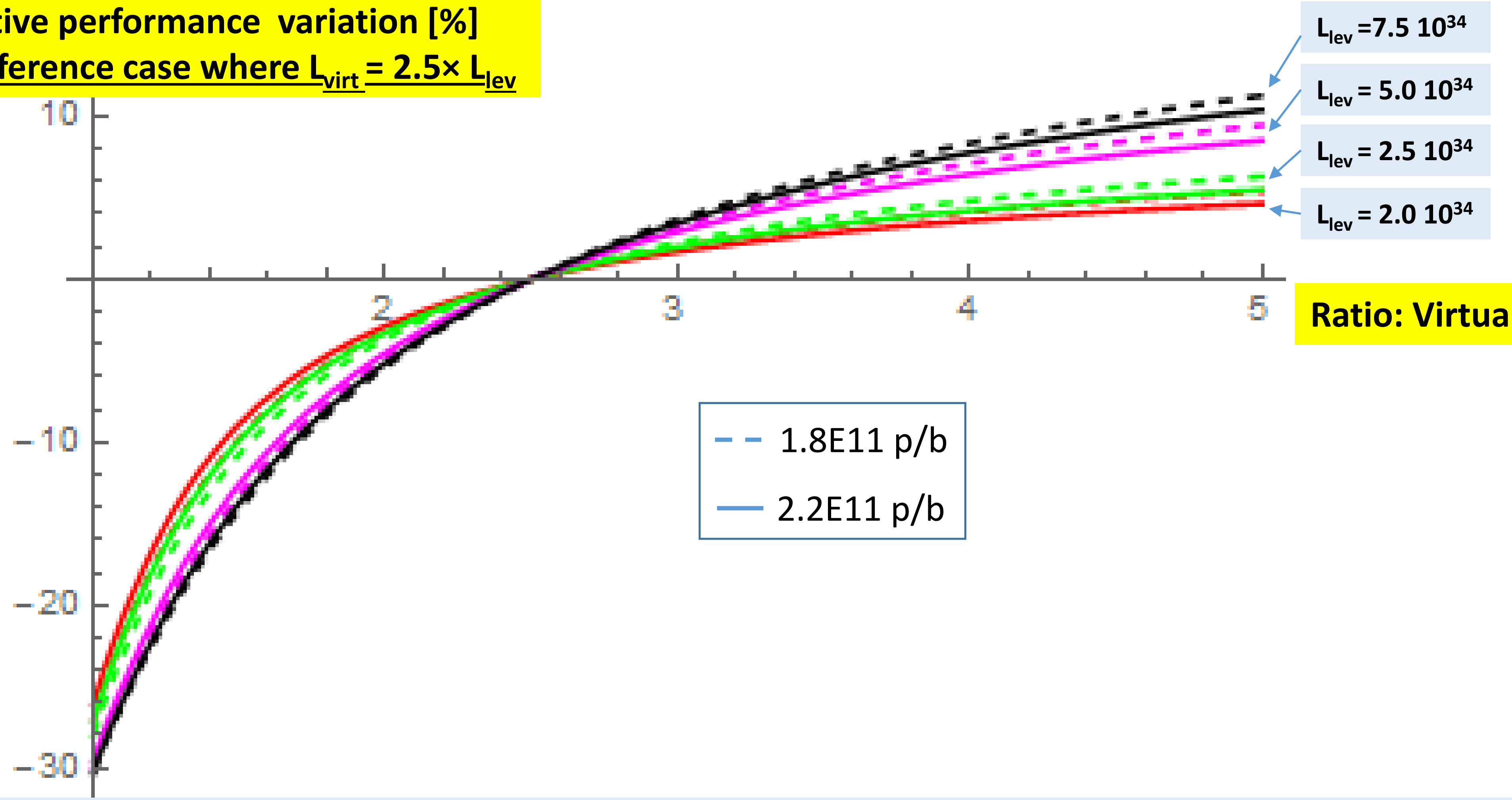


Round –> Flat LHC optics discussed for Run III
(L_{virt} =7.6→ 9.8 × 10^{34} @ 2.2E11 p/b)

HL-LHC baseline
(L_{virt} =16.9 × 10^{34} @ 2.2E11 p/b)

.. *In more quantitative details*

Relative performance variation [%]
vs. a reference case where $L_{virt} = 2.5\times L_{lev}$



Ratio: Virtual / Levelled Lumi

It is inefficient to design for a virtual lumi which is more than ~ 250% of the levelled lumi

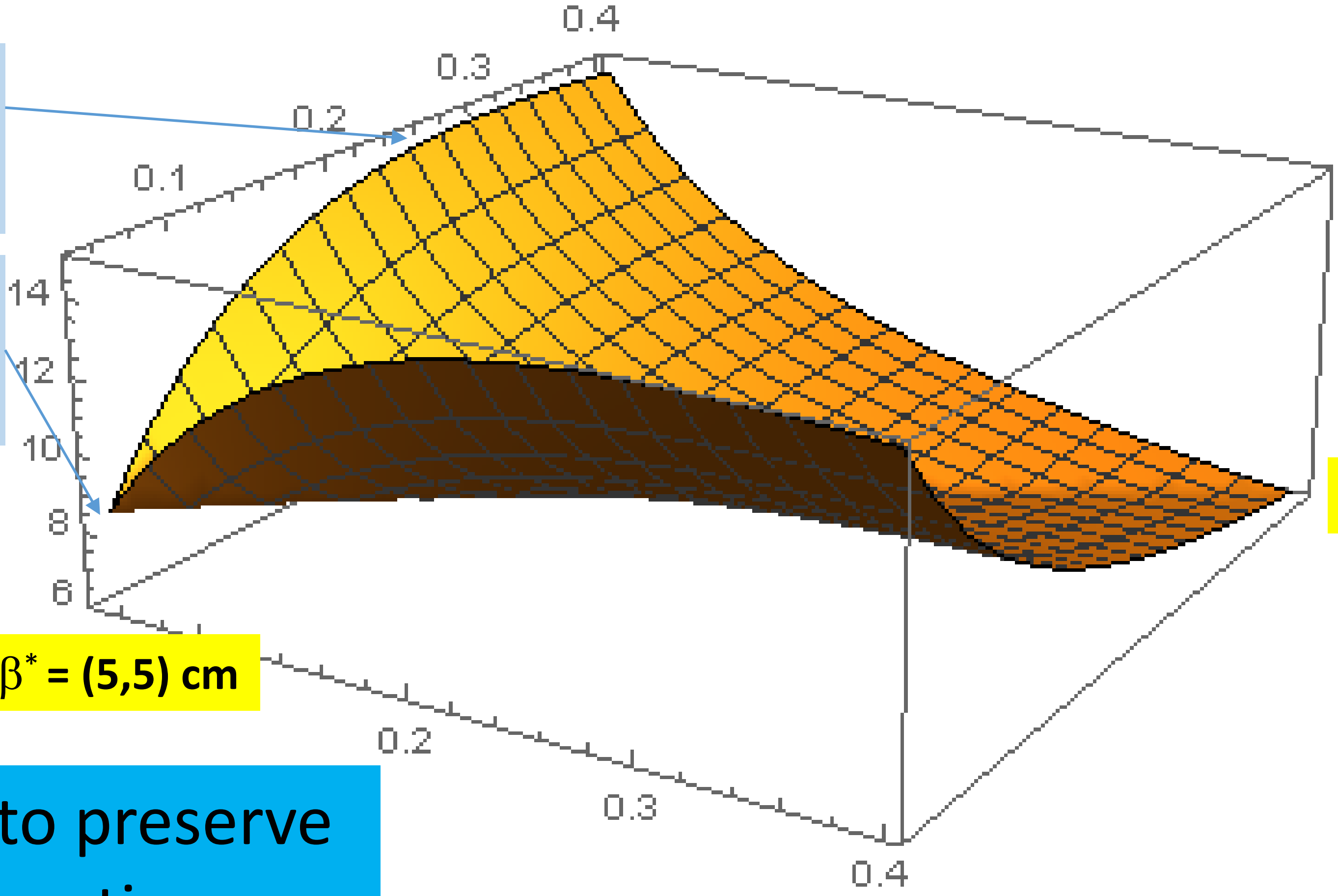
$$\Rightarrow \begin{cases} L_{virt} \approx 12.5 \times 10^{34} \ @ \ L_{lev} \equiv 5.0 \times 10^{34} \\ L_{virt} \approx 19.0 \times 10^{34} \ @ \ L_{lev} \equiv 7.5 \times 10^{34} \end{cases} \quad [L_{virt} = 16.9 \times 10^{34} \text{ for the HL baseline}]$$

Virtual Luminosity reach vs. β   in H & V planes*

W/o crab-cavity and assuming a fixed normalized X-angle of 10.5 σ in the plane of largest β* (so lower in μrad for flat optics, see later)

The virtual lumi. can rise up to
15.0 E34 for flat optics (@ 2.2E11 ppb)
[PU density not yet mentioned]

The luminosity saturate at
8.5 E34 for round optics (@2.2E11 ppb)
[PU density not yet mentioned]



β* = (40,40) cm

β* = (5,5) cm

β* = (40,5) cm

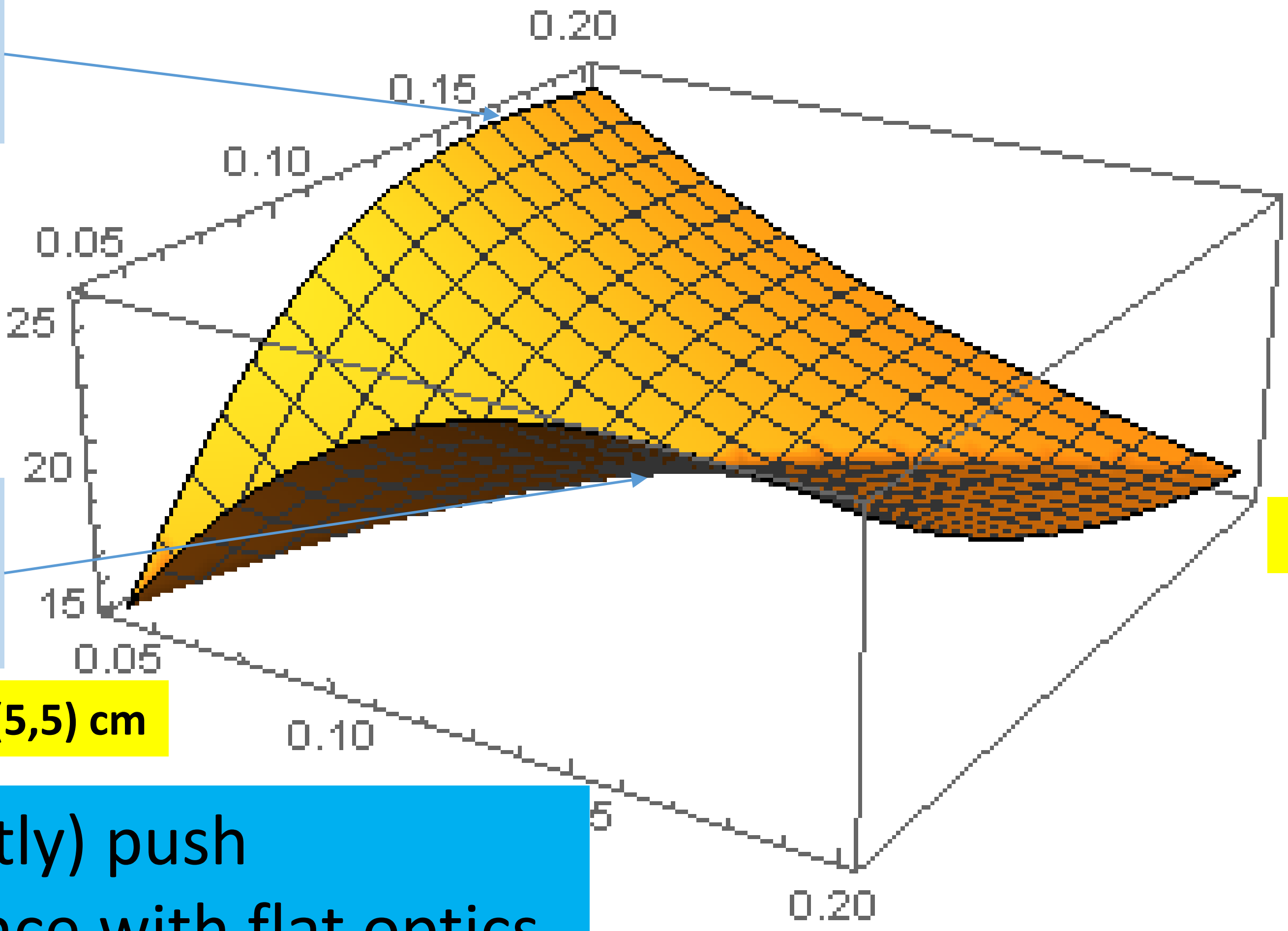
A substantial room exists to preserve the performance with flat optics

Virtual Luminosity reach vs. β^* in H & V planes

With crab-cavity (crabbing angle limited to 380 μrad with 2 CC / IP side)

The virtual lumi. culminates at
25.2 E34 for flat optics (@ 2.2E11 ppb)
at β^* ~ 17/5 cm in X/|| planes

The virtual lumi culminates at
17.2 E34 for round optics (@2.2E11 ppb)
at β^* ~ 12 cm



β^* = (20,20) cm

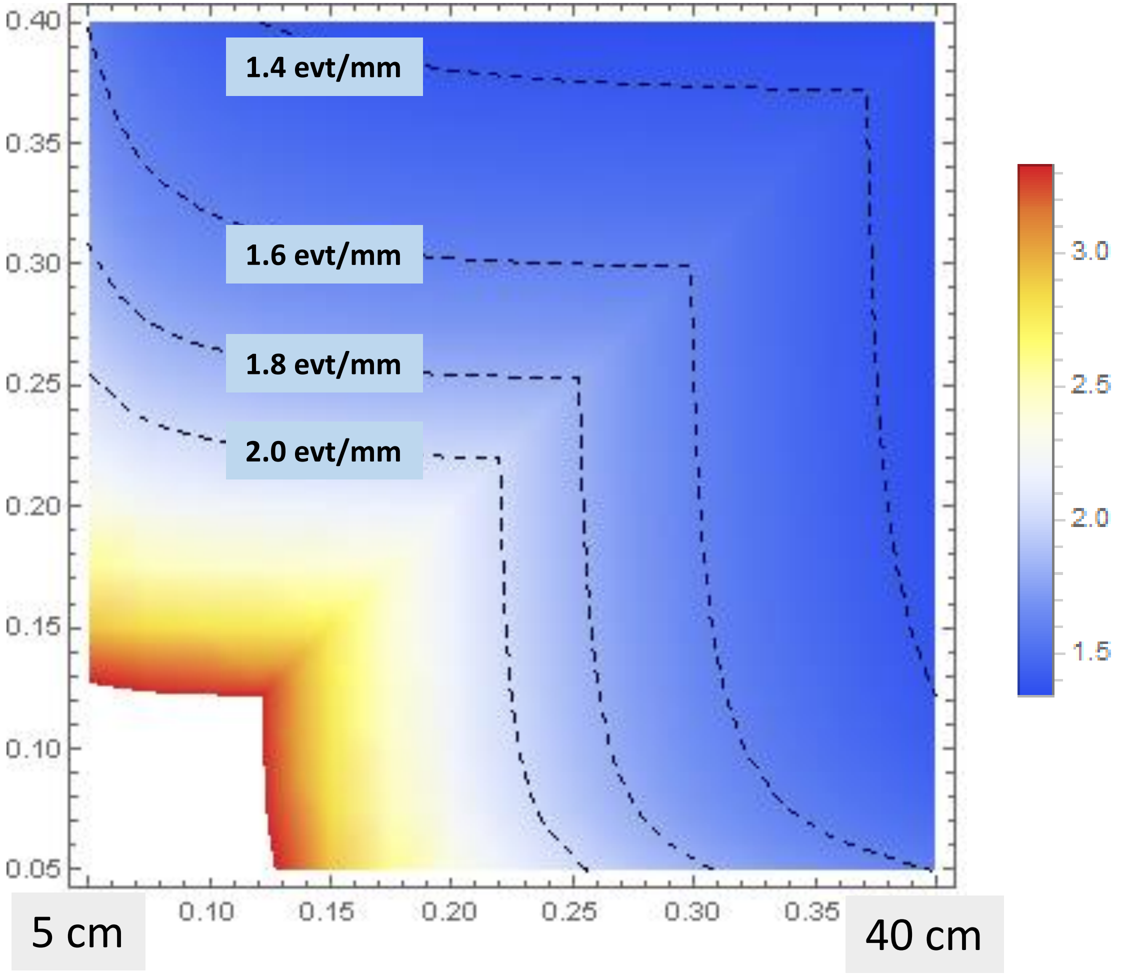
β^* = (5,5) cm

β^* = (20,5) cm

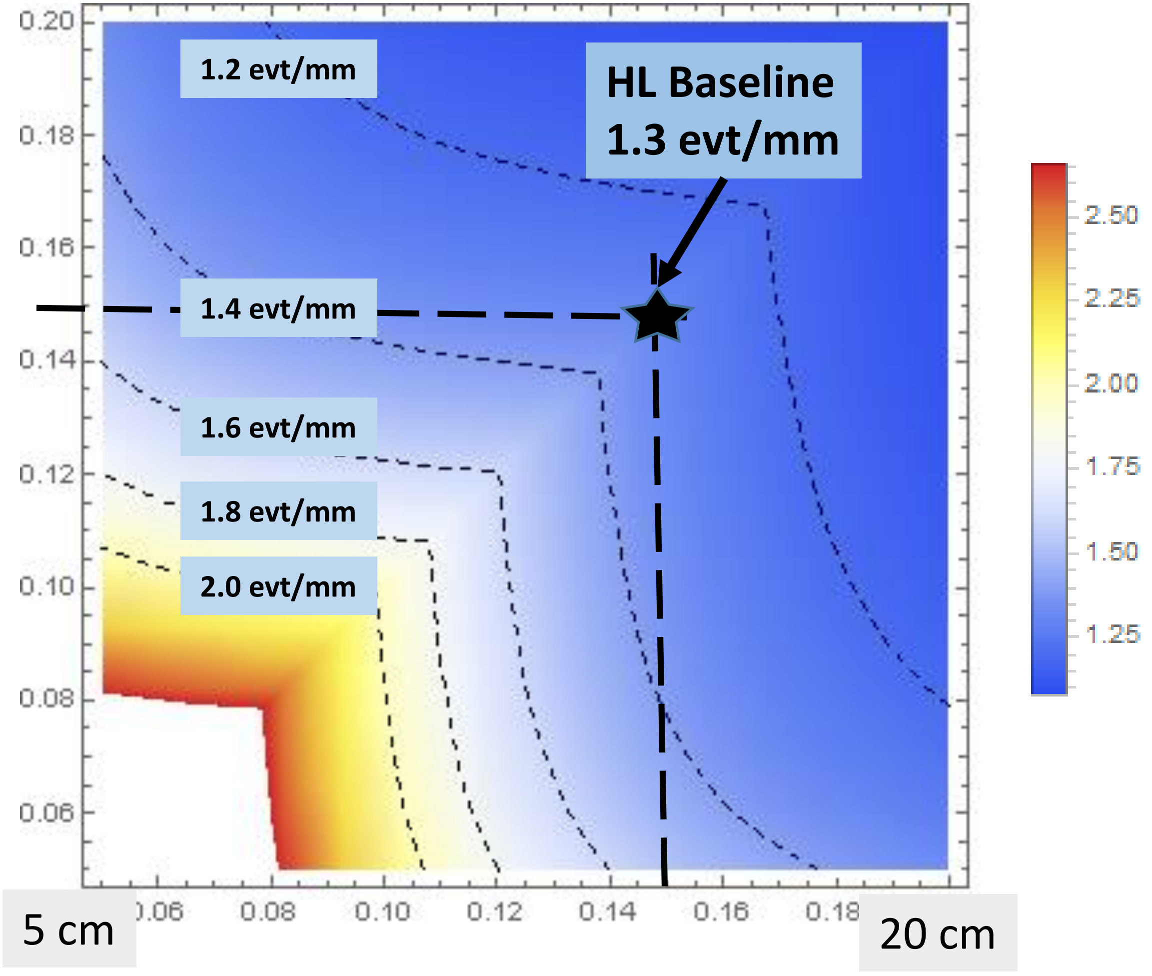
Some room exists to (slightly) push
the (integrated) performance with flat optics

Data quality (PU density) vs. β in H & V planes*

No crab:
Peak PU density [evt/mm] @ 5E34



With crab
Peak PU density [evt/mm] @5E34



A lot of room exists to preserve the PU density (within 10-20%) with flat optics

Flat optics in Practice: General considerations

CERN-ACC-2018-0018

- **Performance-I:** Preserve the product of the two β*'s w.r.t. to round optics

$$\sqrt{\boldsymbol{\beta}_x^* \times \boldsymbol{\beta}_y^*} \overset{\text{def}}{=} \boldsymbol{\beta}^*_{\mathbf{eq.}} \approx \boldsymbol{cst}$$

→ Compared to round optics of same $\beta^*_{\text{eq.}}$, β* is increased in one plane (back to typical β* of Run II), and decreased in the other plane

$$\begin{cases} \textbf{In the crossing } (\boldsymbol{X}) \textbf{ plane: } \boldsymbol{\beta}_X^* \overset{\text{def}}{=} \sqrt{\boldsymbol{r}^*} \times \boldsymbol{\beta}^*_{\mathbf{eq.}} \\ \textbf{In the parallel sep. } (||)\textbf{plane: } \boldsymbol{\beta}_{||}^* \overset{\text{def}}{=} \boldsymbol{\beta}^*_{\mathbf{eq.}}/\sqrt{\boldsymbol{r}^*} \end{cases}$$

β* aspect ratio

- **Aperture:** The X-angle is deployed in the plane of largest β* : $\boldsymbol{r}^* \geq \mathbf{1}$

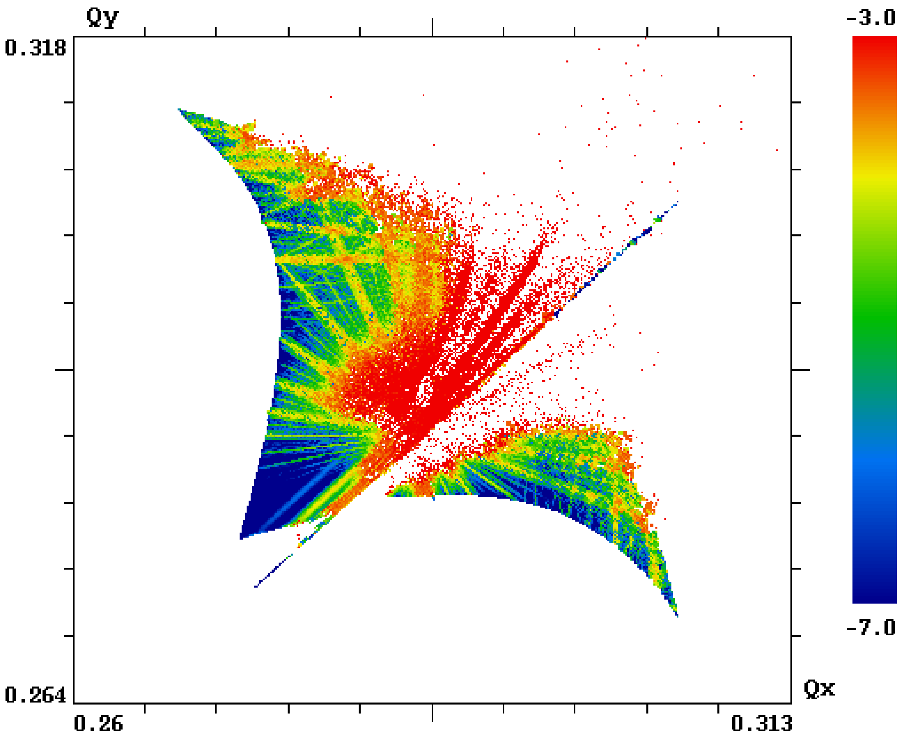
- **Performance-II (and PU density):** The **normalized X** angle is (tried to be) kept constant, i.e. smaller in μrad compared to round optics

$$\boldsymbol{\beta}_X^* = \sqrt{\boldsymbol{r}^*} \times \boldsymbol{\beta}^*_{\mathbf{eq.}} \Rightarrow \boldsymbol{\Theta}_X^{\boldsymbol{Flat}} \approx \boldsymbol{\Theta}_X^{\boldsymbol{Round}}/\sqrt[4]{\boldsymbol{r}^*} \Rightarrow \textbf{Loss factor} \propto \mathbf{1}/\sqrt{\mathbf{1}+\mathbf{cst}/\boldsymbol{r}^*} \xrightarrow{\boldsymbol{r}^* \gg 1} \mathbf{1}$$

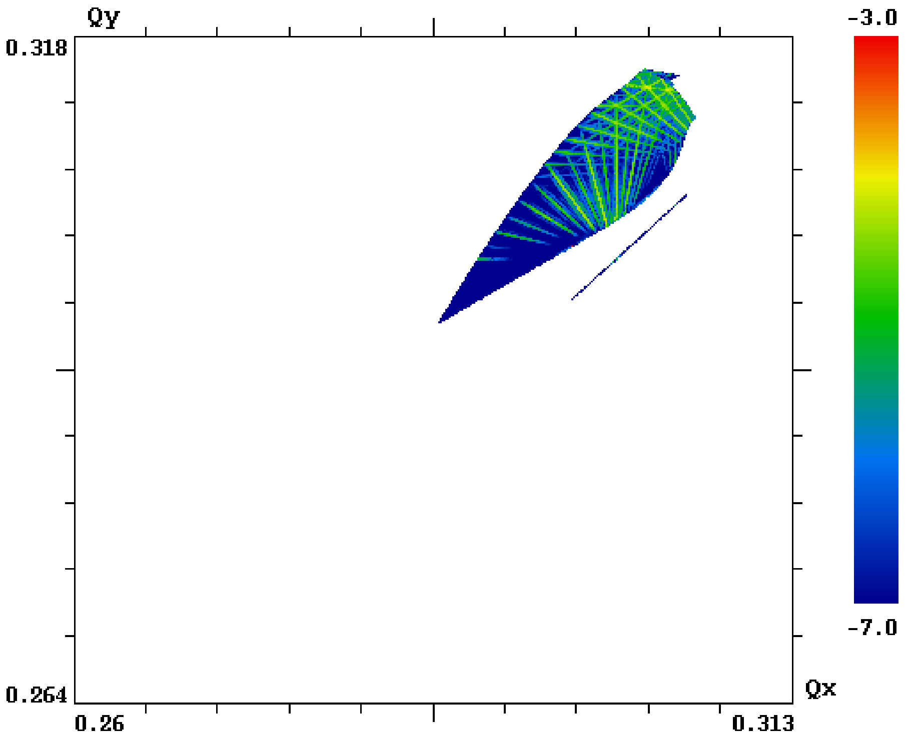
PRSTAB 18-121001, 2015

Flat optics in Practice: X-angle reach

To stick to ~ 10 sigma X-angle level with flat optics (e.g. 280 μrad for flat optics 40/10 cm), **BBLR mitigation techniques** are however **vital**, either with **wire**, or with **octupoles boosted by ATS optics** (see later MD results)



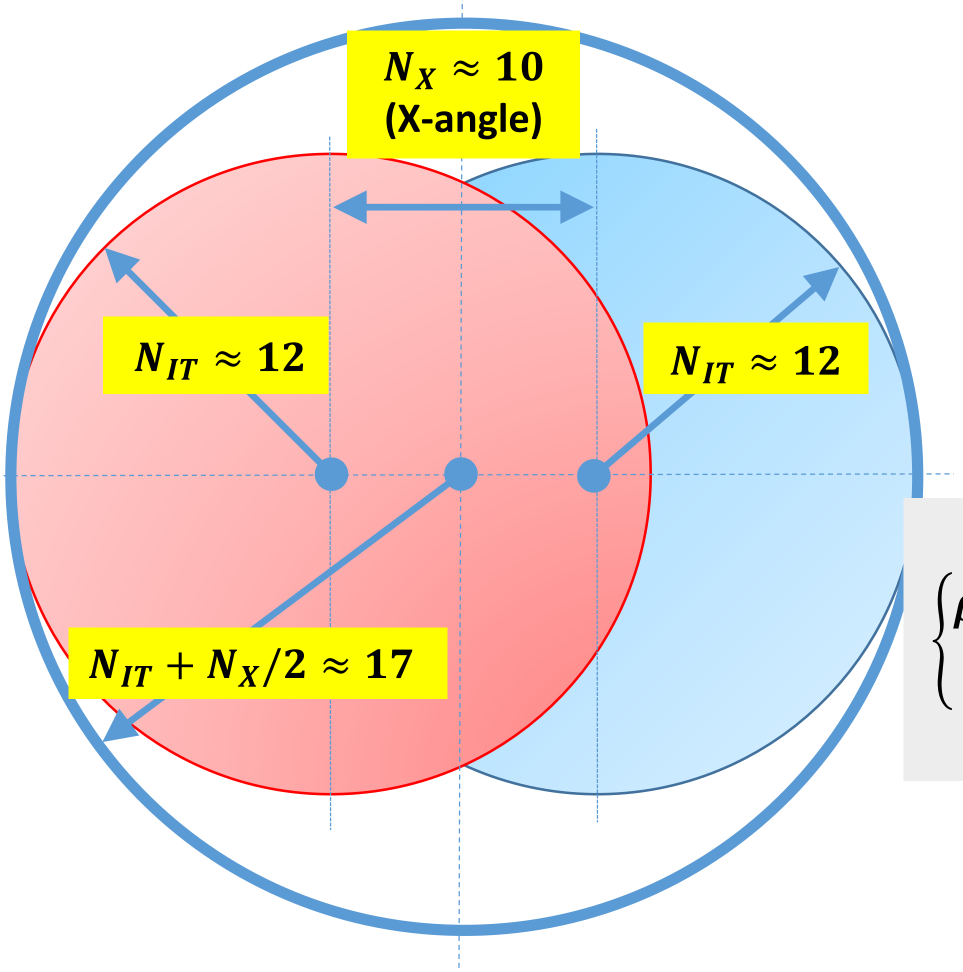
BEFORE CORRECTION



*AFTER **wire** CORRECTION*

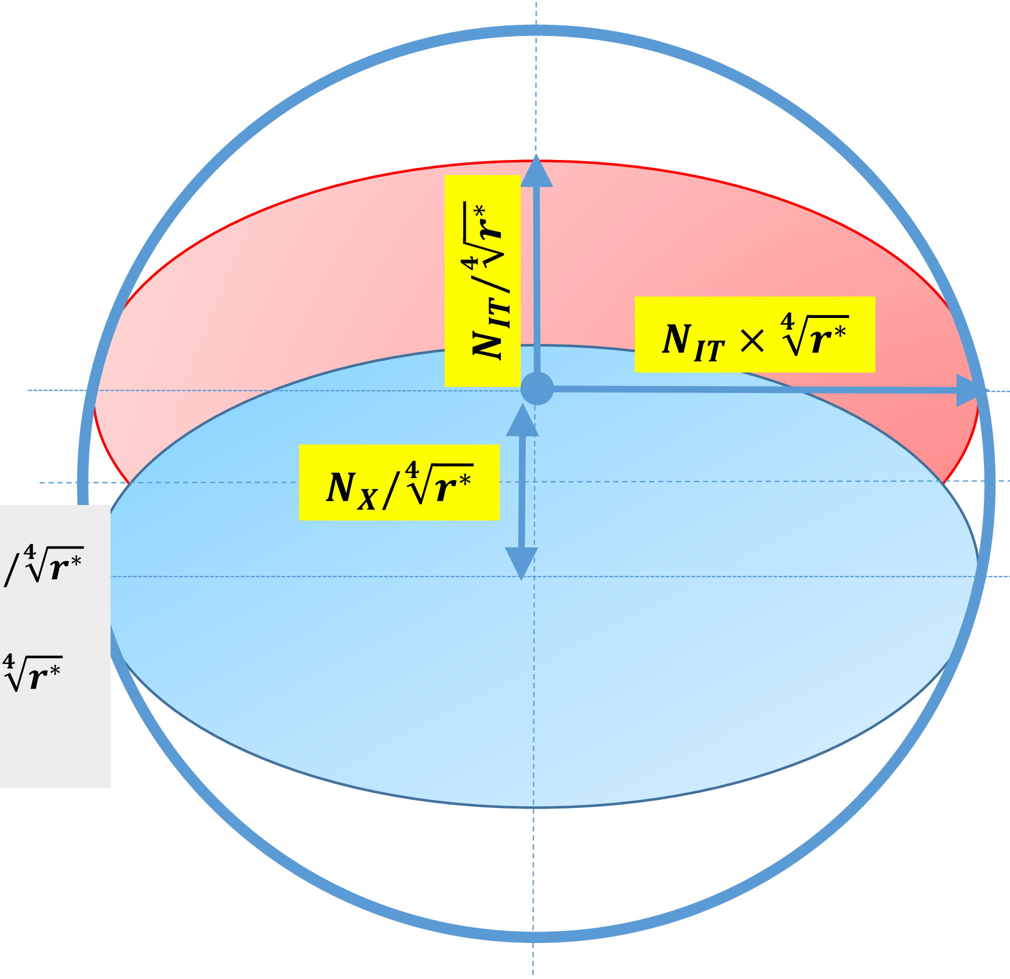
Flat optics in Practice: *Optimal aspect β^* aspect ratio to fill the aperture*

.. From elementary geometry (neglecting the 7% aperture restriction at 45° for the new b.s.)



"Optics Flattening"

$$\begin{cases}\beta^*_X \overset{\text{def}}{=} \sqrt{r^*}\times\beta^*_{eq.}\\ \beta^*_{||}\overset{\text{def}}{=}\beta^*_{eq.}/\sqrt{r^*}\end{cases}\Rightarrow\begin{cases}\sigma_X^{IT}\propto\dfrac{1}{\sqrt{\beta^*_X}}\propto 1/\sqrt[4]{r^*}\\ \sigma_{||}^{IT}\propto\dfrac{1}{\sqrt{\beta^*_{||}}}\propto\sqrt[4]{r^*}\end{cases}$$



Solving $\left(N_{IT}\times\sqrt[4]{r^*}\right)^2+\left(\frac{N_X}{2}/\sqrt[4]{r^*}\right)^2=\left(N_{IT}+\frac{N_X}{2}\right)^2$ gives $r^*\approx 4$ (e.g. 15/15 cm → 30/7.5 cm)

Flat optics in Practice: β^* reach (from match-ability and aperture)

- **Limit from Aperture** with 10 (collimation) σ minimum protectable IT aperture assuming **LHC Run II collimation hierarchy** (i.e. Run III measures put in place such as (i) TCDQ Levelling, and (ii) some telescope in the ramp if still needed with full collimator upgrade)

$$\rightarrow \begin{cases} \text{Round: } \boldsymbol{\beta}^*_{\text{HL-LHC}} = \left(\dfrac{56\ mm}{112\ mm}\right)^2 \times \sqrt{\dfrac{205\ T/m}{130\ T/m}} \times \boldsymbol{\beta}^*_{\text{LHC}} \approx 10\ \text{cm} \\ \text{Flat: } \boldsymbol{\beta}^*_{\text{HL-LHC}} \approx 20\ \text{cm}\ - 5\ \text{cm}\ (r^* \approx 4, \boldsymbol{\beta}^*_{eq.} = 10\ \text{cm}) \end{cases}$$

- **Limit from Optics feasibility**

→ **ATS optics** are even more needed.

→ The **Pre-squeeze** is limited to **48-50 cm** **(Q6/Q7 in IR1/5) @ 130 T/m in the IT**

→ The **Tele-indexes** are limited by **Q5.L(R)6** to **~4/4 (round)** and **8/3 (flat)**

- **The matchability limit is the most stringent (FQ, noise, vibration, etc. not discussed)**

$$\rightarrow \begin{cases} \text{Round: } \boldsymbol{\beta}^*_{\text{HL-LHC}} \approx 48/4 = 12\ \text{cm} \\ \text{Flat: } \boldsymbol{\beta}^*_{\text{HL-LHC}} \approx 16\ \text{cm}\ - 6\ \text{cm}\ (r^* \approx 3, \boldsymbol{\beta}^*_{eq.} \approx 10\ \text{cm}) \end{cases}$$

Optimized flat optics scenarios

Same beam (BCMS) for all scenarios
Q-Gaussian (q=2.5, σ_z =7.61 cm)

Scenarios @ 5 (7.5) E34 leveled Lumi	**HL Baseline but NO CC**	**Flat optics No CC**	**HL Baseline (strict)**	**Ultimate Flat With CC**
β^* [cm] in X-plane	15.0	37.0	15.0	19.0
β^* [cm] in $\parallel$-plane	15.0	8.5	15.0	6.0
Equivalent β^* [cm]	15.0	**17.7**	15.0	**10.7**
Aspect ratio (r^*)	1.00	**4.35**	1.00	**3.17**
Full X-angle [μrad] (10.5 σ in all cases)	496	316	496	441
Lumi loss factor	0.342	0.625	0.716	0.721
Virtual Lumi [10^{34}cm^{-2}s^{-1}]	8.07	12.46	16.88	23.87
Yearly Lumi [1/fb]	**222.3 (241.8)**	**247.6 (296.2)**	**258.8 (323.1)**	**267.8 (345.2)**
Levelling time [h]	3.2 (0.4)	5.5 (2.3)	6.9 (3.3)	8.2 (4.4)
Optimum Fill length [h]	6.1 (4.9)	7.3 (4.8)	8.1 (5.1)	9.1 (5.7)
Average number of events / crossing	131.6 @ 5.0E34 (197.4 @ 7.5E34)			
Peak PU density [evt/mm] (end of levelling)	2.75 (4.12)	**1.50 (2.25)**	1.30 (1.95)	**1.29 (1.94)**

Flat optics are definitely appealing for **performance** (with and w/o crab), but also **other aspects** (IT/D1/2/Q4 aperture, corrector strength, freedom between HV and VH crossing in ATLAS/CMS, etc., no discussed further)

BUT ..

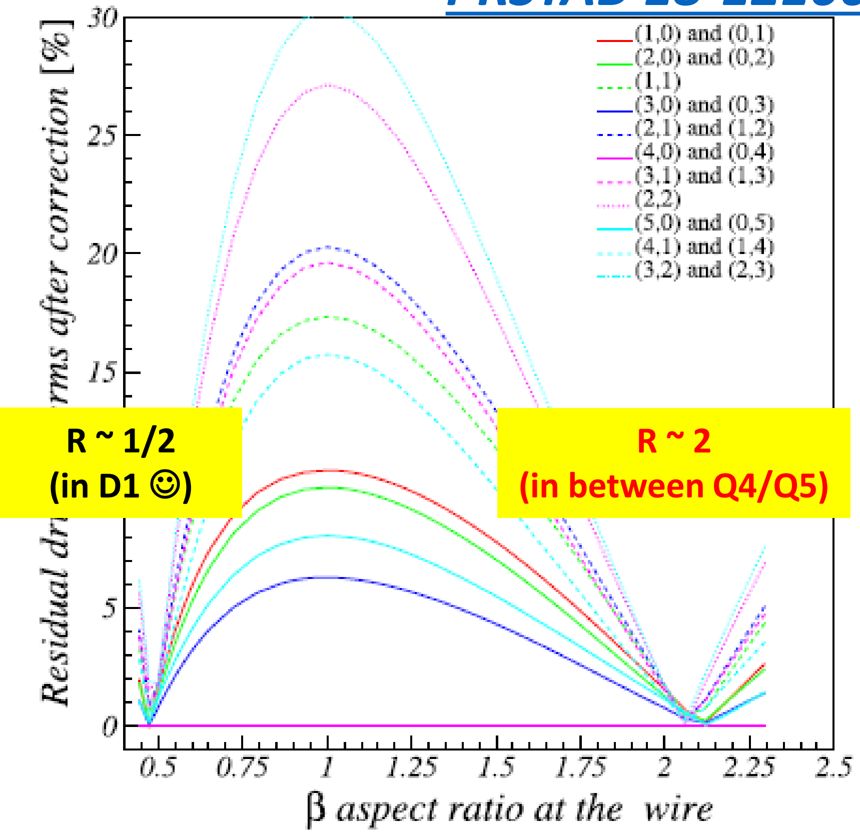
BBLR mitigation techniques (1/5)

PRSTAB 18-121001, 2015

- **With DC wires**

→ **All the BBLR driving terms compensated** by "only 2 wires/IP/ beam", but provided the L/R wires are installed at the right β aspect ratio

→ **But compatibility with collimation not yet solved**

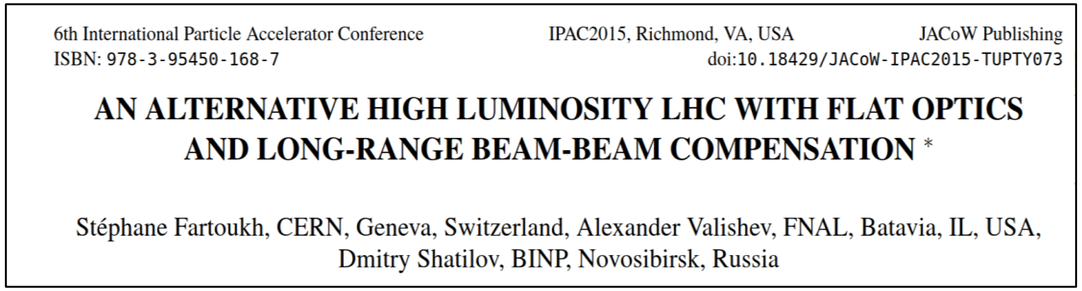


R ~ 1/2
(in D1 ☺)

R ~ 2
(in between Q4/Q5)

→ Very efficient compensation up to **1.5E11 p/b with flat optics of r*=4** (β* = 40/10 cm), and a normalized crossing angle down **to 9.7 σ** (only 280 μrad full angle)

→ First HL-LHC Plan B



6th International Particle Accelerator Conference IPAC2015, Richmond, VA, USA JACoW Publishing
ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPTY073

AN ALTERNATIVE HIGH LUMINOSITY LHC WITH FLAT OPTICS AND LONG-RANGE BEAM-BEAM COMPENSATION *

Stéphane Fartoukh, CERN, Geneva, Switzerland, Alexander Valishev, FNAL, Batavia, IL, USA, Dmitry Shatilov, BINP, Novosibirsk, Russia

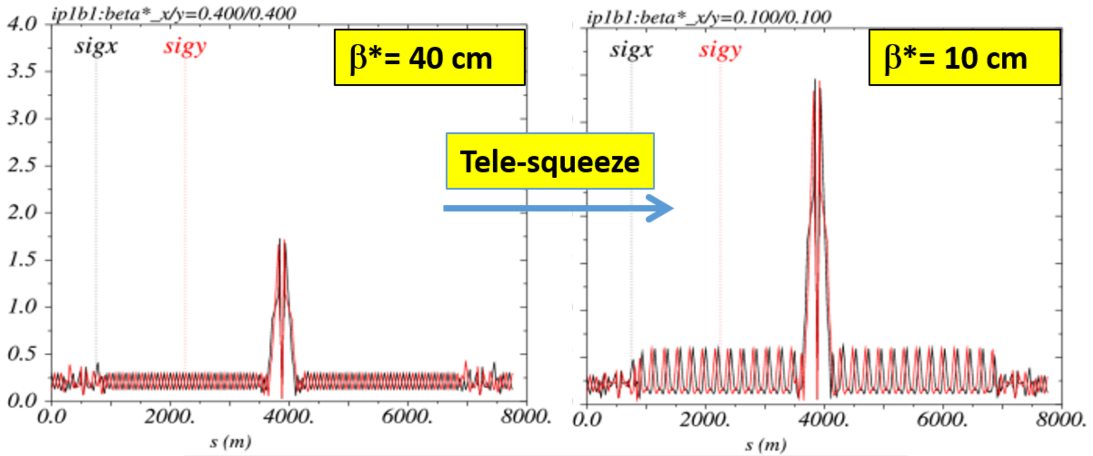
BBLR mitigation techniques (2/5)

- **With Lattice octupole boosted (and correctly phased) for ATS optics**

→ **Only 4th order RDTs are mitigated (3 RDT's for 2 knobs)**

→ **Less clean but immediately operational & for free**

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



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

→ The current needed in the octupoles critically depends on

(i) The bunch intensity at the end of β* levelling (which is the most critical period for BBLR effects)

(ii) The effective ATS optics construction: the choice of the **tele-indexes** for a given collision optics)

$$I_{\rm bb}^{\rm (MO)} \cancel{= 225\,{\rm A}} \times \frac{N_b\,[10^{11}]}{1.25} \times \left(\frac{80}{\beta_X^*\,[\rm cm]}\right)^2 \times \left(\frac{300}{\Theta_X\,[\mu{\rm rad}]}\right)^4 \times \frac{h_{\rm bb}\left(r_{||}^{\rm Tele}/r_X^{\rm Tele}\right)}{h_{\rm MO}\left(r_X^{\rm Tele}, r_{||}^{\rm Tele}\right)},$$

315 A for the HL IT

Increased current with the β* aspect ratio

Reduced current with tele-indexed

$$\text{with} \begin{cases} h_{\rm bb}(r^*) & \overset{\rm def}{=} \dfrac{{r^*}^2 + 1 + 2\,c_{\rm bb}\,r^*}{2\,(1+c_{\rm bb})} \\ h_{\rm MO}(r_x, r_y) & \overset{\rm def}{=} \dfrac{f_{\rm MO}(r_x,r_y) + c_{\rm MO}\,g_{\rm MO}(r_x,r_y)}{1+c_{\rm MO}} \end{cases},$$

$$\text{with} \begin{cases} f_{\rm MO}(r_x,r_y) \overset{\rm def}{=} \dfrac{1}{8}\left[4 + \left(r_x^2 + \dfrac{1}{r_x^2}\right) + \left(r_y^2 + \dfrac{1}{r_y^2}\right)\right] = \dfrac{1}{8}\left[\left(r_x + \dfrac{1}{r_x}\right)^2 + \left(r_y + \dfrac{1}{r_y}\right)^2\right] \\ g_{\rm MO}(r_x,r_y) \overset{\rm def}{=} \dfrac{1}{2}\left[1 + \dfrac{1}{4}\left(r_x + \dfrac{1}{r_x}\right)\left(r_y + \dfrac{1}{r_y}\right)\right] \end{cases}$$

More details in CERN-ACC-2018-0018

BBLR mitigation techniques (3/5)

Scenarios	**Flat optics** **No CC**	**Ultimate Flat Optics** **With CC**
β^* [cm] in X-plane	37.0	19.0
β^* [cm] in ||-plane	8.5	6.0
Full X-angle [μrad]	316 (10.5σ)	441 (10.5σ)
Nb [10^{11}] at the end of levelling @ **5.0 E34 - 7.5 E34**	1.39 - 1.71	1.00 - 1.23
Minimum possible tele-indexes in X/|| planes (assuming round pre-squeeze with β^* = 48 cm)	1.8/5.6	2.5/8.0
MO current [A] for min. tele-index @ **5.0 E34 - 7.5 E34**	**1210 - 1480**	**390 - 470**
Maximum possible tele-indexes (possibly **flat** pre-squeezed optics with β^* H/V ≥ 48 cm)	3.0/8.0	3.0/8.0
MO current [A] for max. tele-index @ **5.0 E34 - 7.5 E34**	**600 - 740**	**370 - 450**

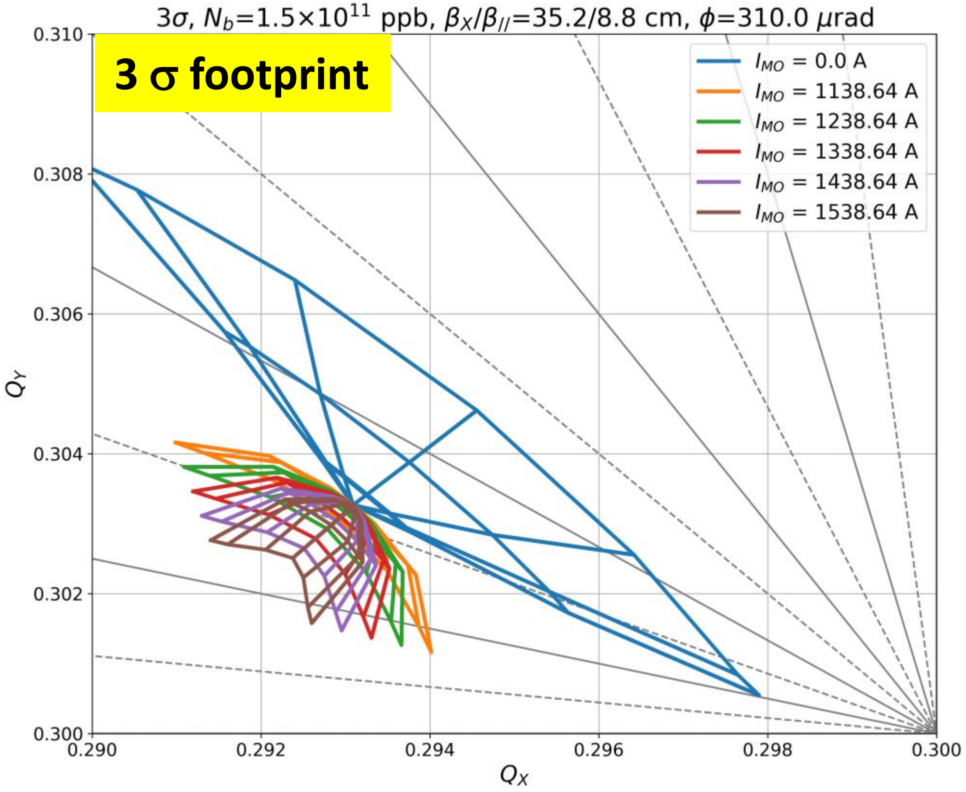
At a β^* aspect ratio > 4 (first case), the octupole current are at the limit (or slightly beyond), even pushing the telescopic index above the strict minimum required to build the optics

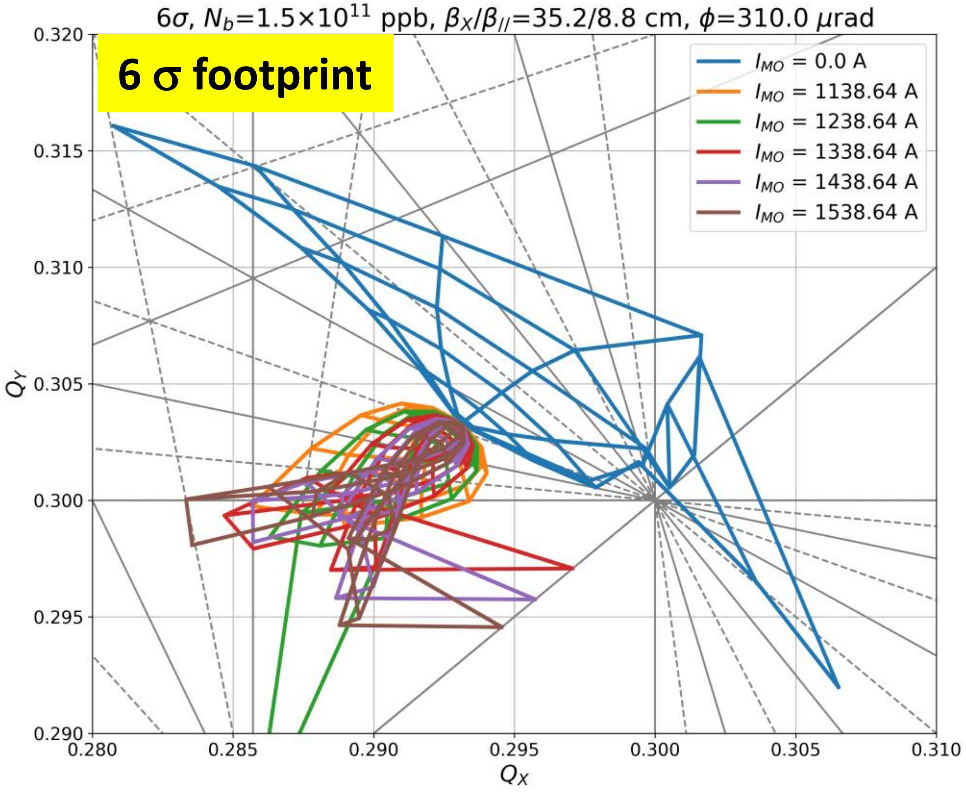
Optimized flat optics scenarios

See also N. Karastathis Talk in WP2 parallel

→ **Footprints @ 1.5E11 ppb and <u>10 σ X-angle</u> with BBLR only**:

35.2/8.8 cm flat optics, presently in the "catalogue" **with minimal telescope, i.e. MO current out of reach (to be cured later with stronger telescope)**





The effect of b6 is already visible on the 3 σ footprint, which is a sign that such flat optics parameters are at the limit for a "simple" BBLR mitigation with octupoles, but maybe still manageable …

Optimized flat optics scenarios

See also N. Karastathis Talk in WP2 parallel

→**DA scans at end of Leveling: MO vs. tunes** (35.2/8.8 cm flat optics with minimal tele-index)

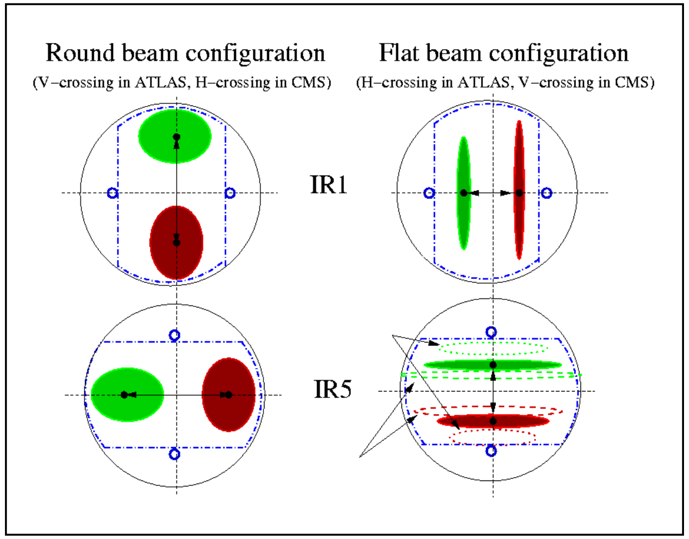
On-going work

Highlight from 2018 flat optics MDs

Brand new hypercycle to reach 60/15 cm at IP1 and 15/60 cm at IP5

.. Starting from the nominal ramp

Crossing bump rotation EoR at 1 m for IT aperture “reconfiguration”



Not needed for HL-LHC with new octagonal beam-screens [but of course still possible if usefull for something else]

Pre-squeeze 1 m → 65 cm at IP1-5 (110 s)

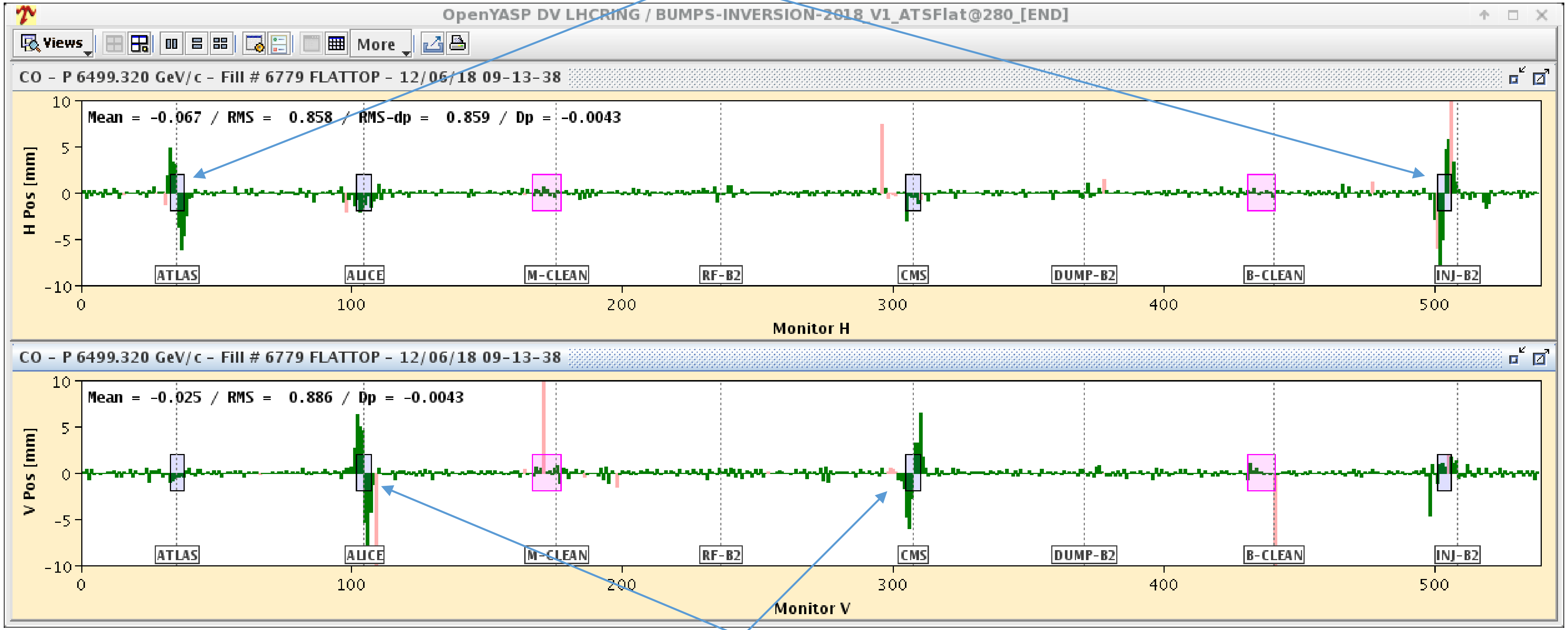
Matched Pt	Time (s)	Parab. fr.	Optics Name	Beta* [cm] at IP1 &5	Energy (GeV)
1	0	0.00	R2017a_A100C100A10mL300	100.0	6500
2	53	0.19	R2017a_A80C80A10mL300	80.0	6500
3	110	0.18	R2017a_A65C65A10mL300	65.0	6500

Tele-squeeze 65 cm → 60/15-15/60 cm at IP1-5 (526 s)

Matched Pt	Time (s)	Parab. fr.	Optics Name	Beta* [cm] H/V at IP1--5
1	0	0.00	R2017a_A65C65A10mL300	65.0/65.0--65.0/65.0
2	109	0.38	R2017aT65_A60_51C51_60A10mL300	60.0/51.0--51.0/60.0
3	210	0.39	R2017aT65_A60_41C41_60A10mL300	60.0/41.0--41.0/60.0
4	306	0.40	R2017aT65_A60_31C31_60A10mL300	60.0/31.0--31.0/60.0
5	427	0.36	R2017aT65_A60_21C21_60A10mL300	60.0/21.0--21.0/60.0
6	526	0.35	R2017aT65_A60_15C15_60A10mL300	60.0/15.0--15.0/60.0

- **Crossing bump** rotation demonstrated successfully

H in ATLAS (& LHCB)


OpenYASP DV LHCRING / BUMPS-INVERSION-2018_V1_ATSFlat@280_[END]

CO - P 6499.320 GeV/c - Fill # 6779 FLATTOP - 12/06/18 09-13-38

```
Mean = -0.067 / RMS =  0.858 / RMS-dp =  0.859 / Dp = -0.0043
```

CO - P 6499.320 GeV/c - Fill # 6779 FLATTOP - 12/06/18 09-13-38

```
Mean = -0.025 / RMS =  0.886 / Dp = -0.0043
```

V in CMS (& Alice)

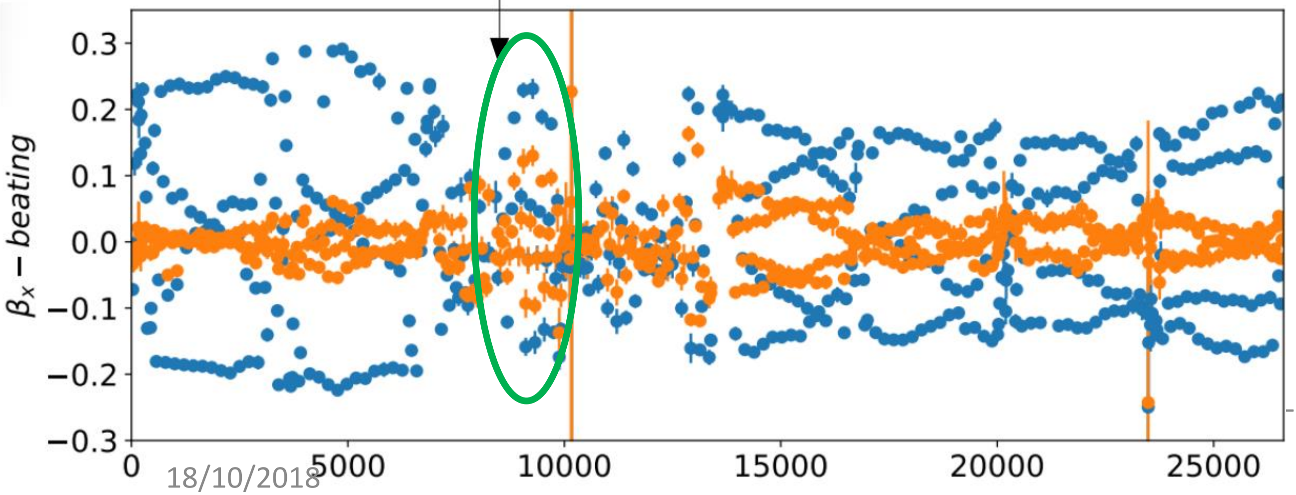
S. Fartoukh, 8th HiLumi meeting

- **Optics commissioning in MD1**: difficult but successful in the end !

→ 2 knobs reused from 2017: (i) 2017_Local_flat_ATS ,(ii) 2017_Coupling_Flat_ArcByArc_B1

→ 3 new knobs in 2018: (i) 2018_global_ats_flat_b1, (ii) 2018_global_ats_flat_b2, (iii) 2018_flat_q10r4_linked_to_orbitbump

→ .. **And one new type of knobs needed** (orbit bump for beam1, needed for beam2 in the future)



β* [cm] measurement (via K-modulation)

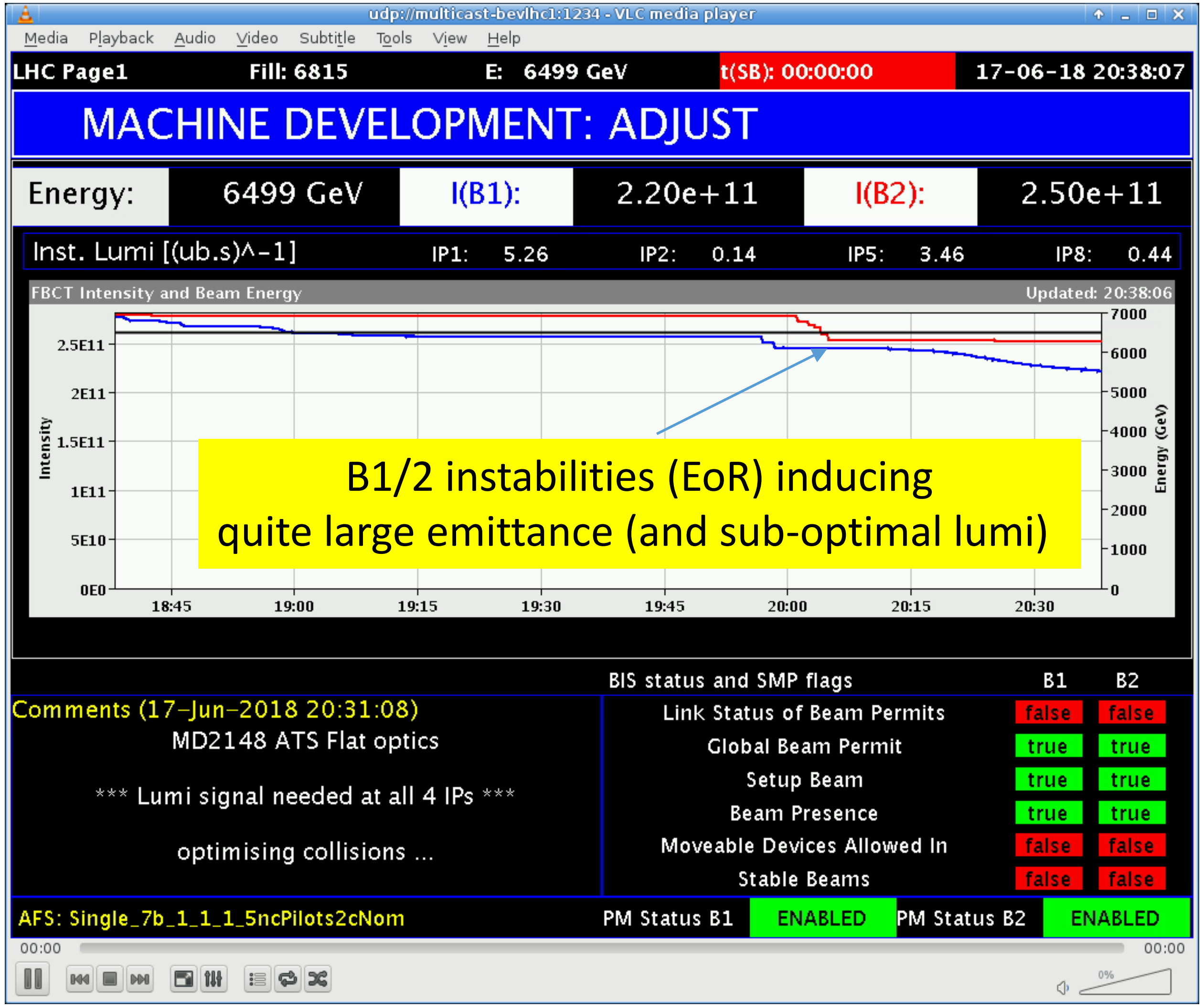
(same difficulty as in 2017 to preserve B1H in IR5 after global correction)

2017 **(before/after global corr.)**	**Beam 1**	**Beam 2**
IP1H	66.9/-	62.0/-
IP1V	16.8/-	15.7
IP5H	16.2/17.4	14.7/15.7
IP5V	-	64.4/60.2

2018 **(after global corr.)**	**Beam 1**	**Beam 2**
IP1H	-	63.8
IP1V	16.6	15.8
IP5H	18.0	15.3
IP5V	59.6	61.2

Credit to the OMC team

- **First collisions with flat optics with 2 nominal in MD1 !**



LHC Page1 Fill: 6815 E: 6499 GeV t(SB): 00:00:00 17-06-18 20:38:07

MACHINE DEVELOPMENT: ADJUST

Energy:	6499 GeV	I(B1):	2.20e+11	I(B2):	2.50e+11

Inst. Lumi [(ub.s)^-1] IP1: 5.26 IP2: 0.14 IP5: 3.46 IP8: 0.44

B1/2 instabilities (EoR) inducing
quite large emittance (and sub-optimal lumi)

Comments (17-Jun-2018 20:31:08)
MD2148 ATS Flat optics

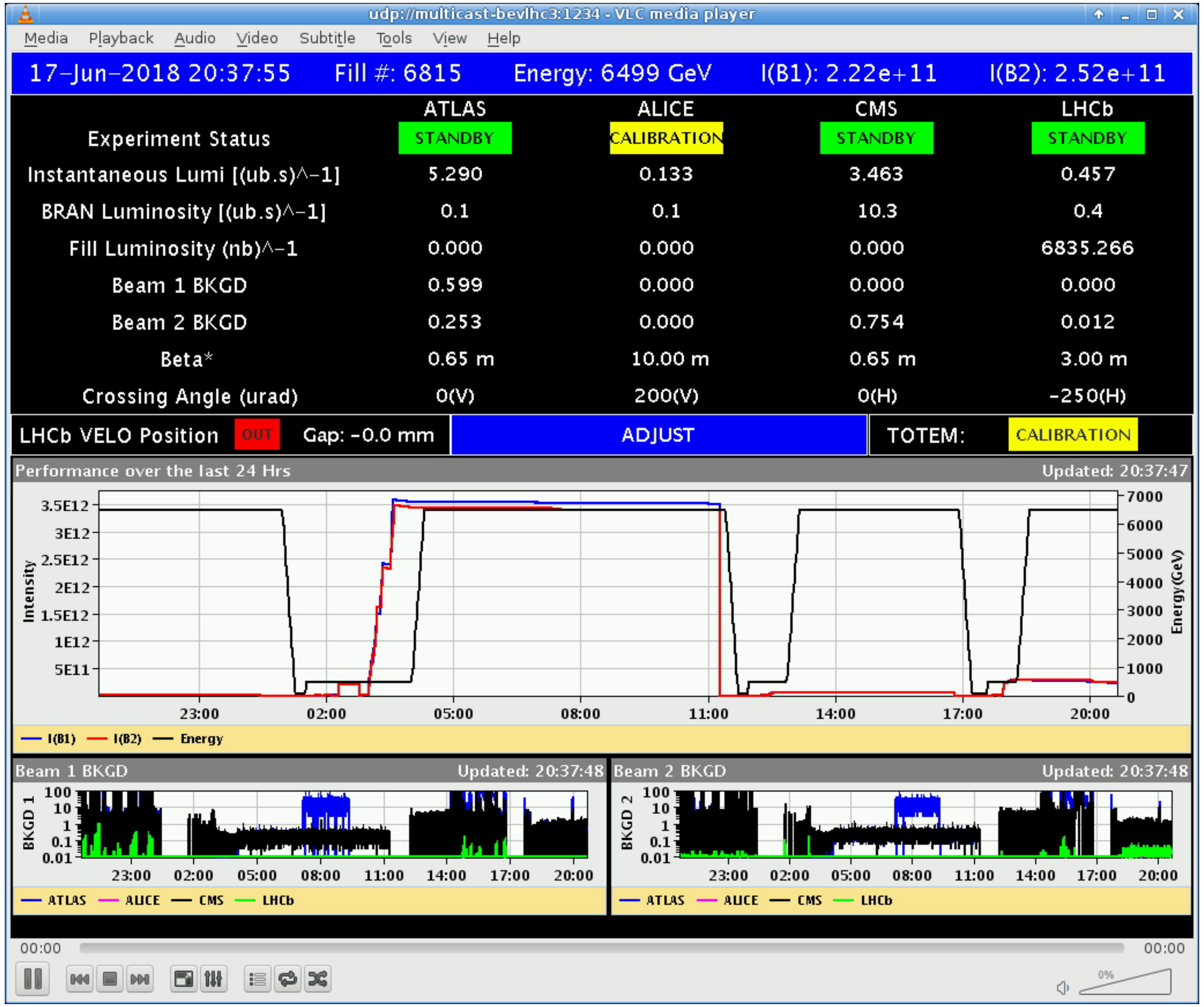
*** Lumi signal needed at all 4 IPs ***

optimising collisions ...

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: Single_7b_1_1_1_5ncPilots2cNom

PM Status B1 ENABLED PM Status B2 ENABLED



17-Jun-2018 20:37:55 Fill #: 6815 Energy: 6499 GeV I(B1): 2.22e+11 I(B2): 2.52e+11

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	CALIBRATION	STANDBY	STANDBY
Instantaneous Lumi [(ub.s)^-1]	5.290	0.133	3.463	0.457
BRAN Luminosity [(ub.s)^-1]	0.1	0.1	10.3	0.4
Fill Luminosity (nb)^-1	0.000	0.000	0.000	6835.266
Beam 1 BKGD	0.599	0.000	0.000	0.000
Beam 2 BKGD	0.253	0.000	0.754	0.012
Beta*	0.65 m	10.00 m	0.65 m	3.00 m
Crossing Angle (urad)	0(V)	200(V)	0(H)	-250(H)

LHCb VELO Position OUT Gap: -0.0 mm ADJUST TOTEM: CALIBRATION

Credit to LHC-OP

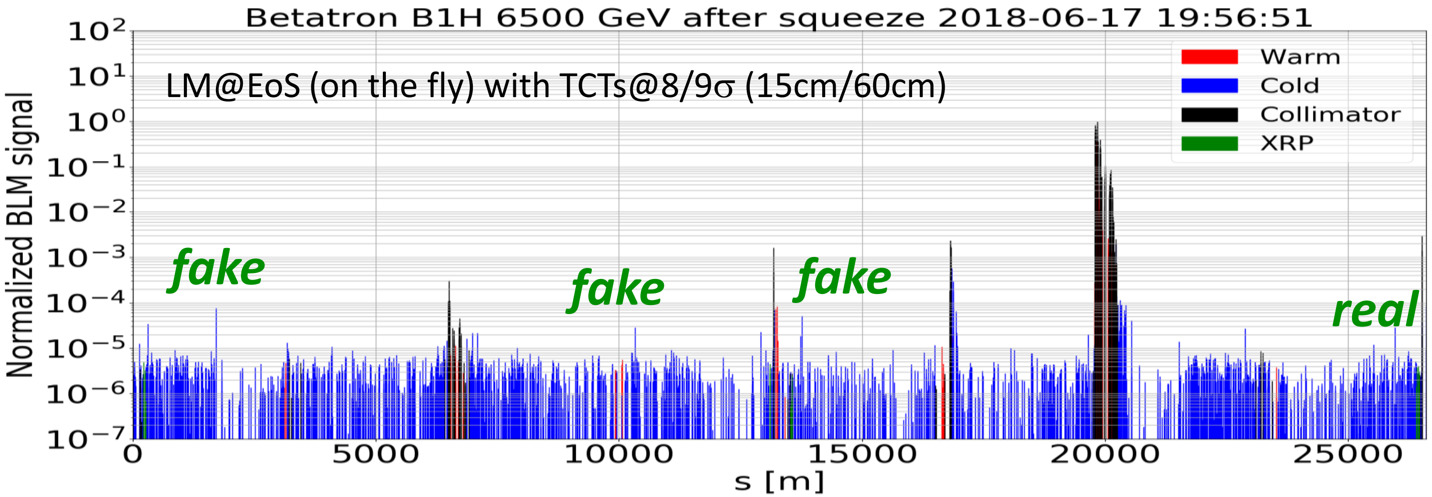
Triplet aperture and Collimation activities in MD1 & MD2

G. Azzopardi, R. Bruce, N. Fuster-Martinze, A. Mereghetti, D.Mirarchi, S. Redaelli

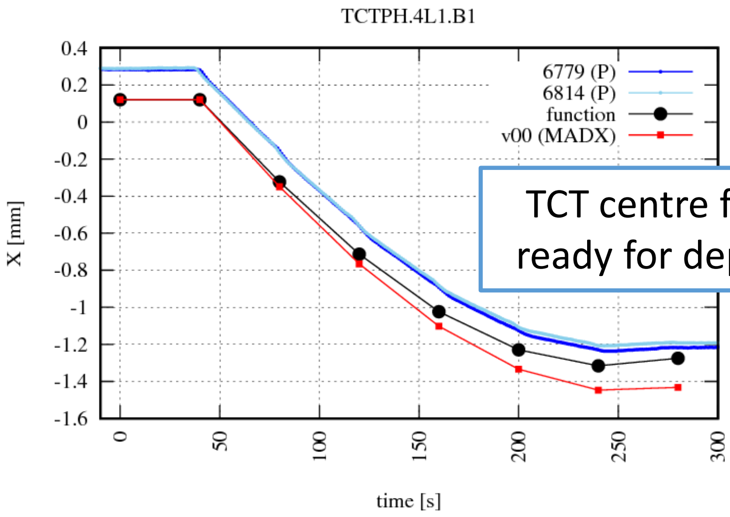
- Second MD shift during MD1 and validation shift in MD2
  - Fill with pilots: aperture measurements @EoS;
  - Fill with nominals: TCT BPM-based alignment + LMs@EoS (on the fly) aperture measurements @Collisions;

Date	B1H [σ]	B1V [σ]	B2H [σ]	B2V [σ]
65 cm	> 13	> 13	>13	> 13
EoS 15/60 cm	> 9.5	9.5-9.8 Q3R1	> 9.5	> 9.5

Aperture measurements: fundamental input for TCT Nσ functions (in preparation for MD2);



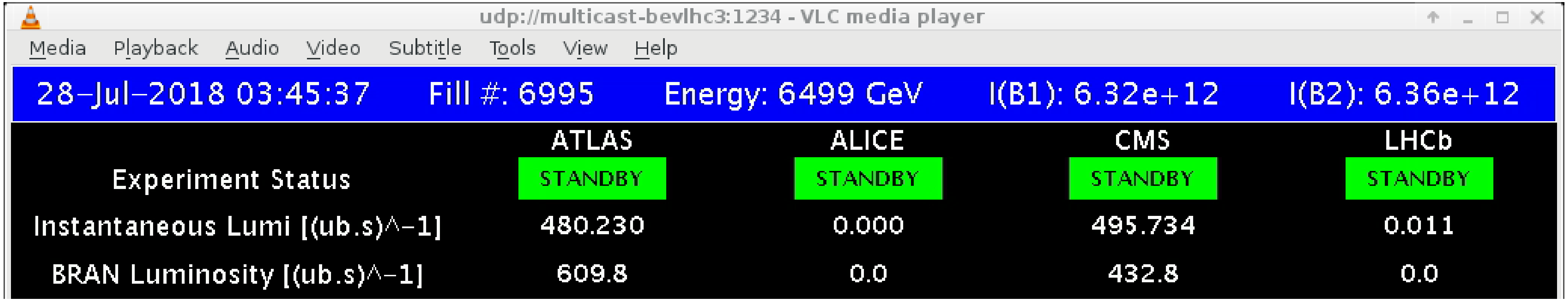
LM@EoS (on the fly) with TCTs@8/9σ (15cm/60cm)



TCT centre functions ready for deployment

Credit to LHC-coll

First collisions of train (12 + 48 = 60 colliding bunches + 1 n.c. INDIV)



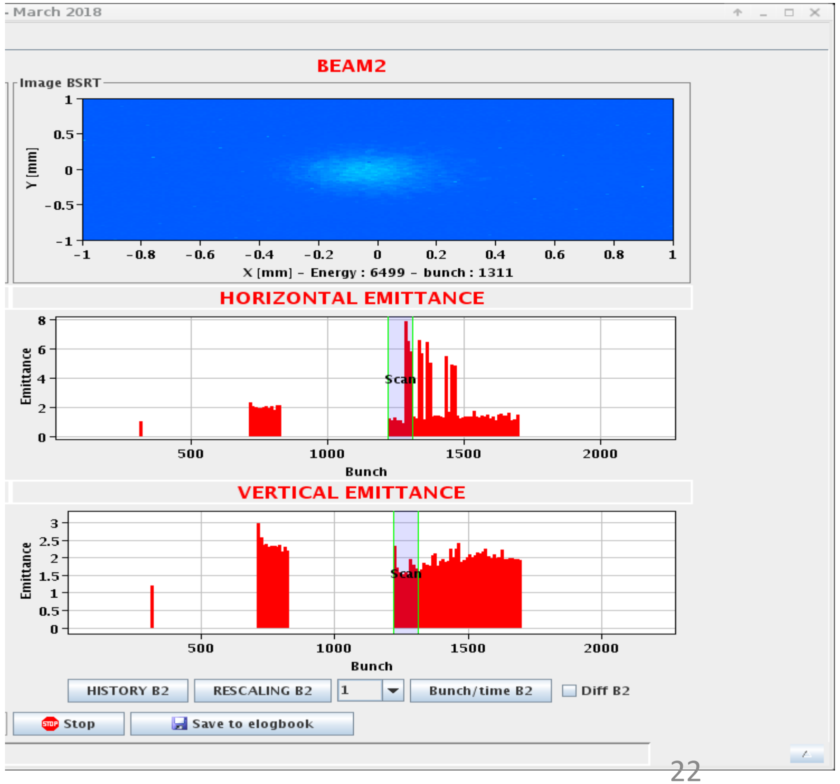
28–Jul–2018 03:45:37 Fill #: 6995 Energy: 6499 GeV I(B1): 6.32e+12 I(B2): 6.36e+12

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Lumi [(ub.s)^–1]	480.230	0.000	495.734	0.011
BRAN Luminosity [(ub.s)^–1]	609.8	0.0	432.8	0.0

.. Nearly 5E32 for 60 b @ 1.03E11
(60/15 cm @ 130 μrad)

.. **2.5E34 for 2548 colliding bunches @ 1.15E11 !**
(with a naïve scaling)

.. Despite instabilities driven emittance growth
at flat top, and start of squeeze (curable)



S. Fartoukh, 8th HiLumi meeting

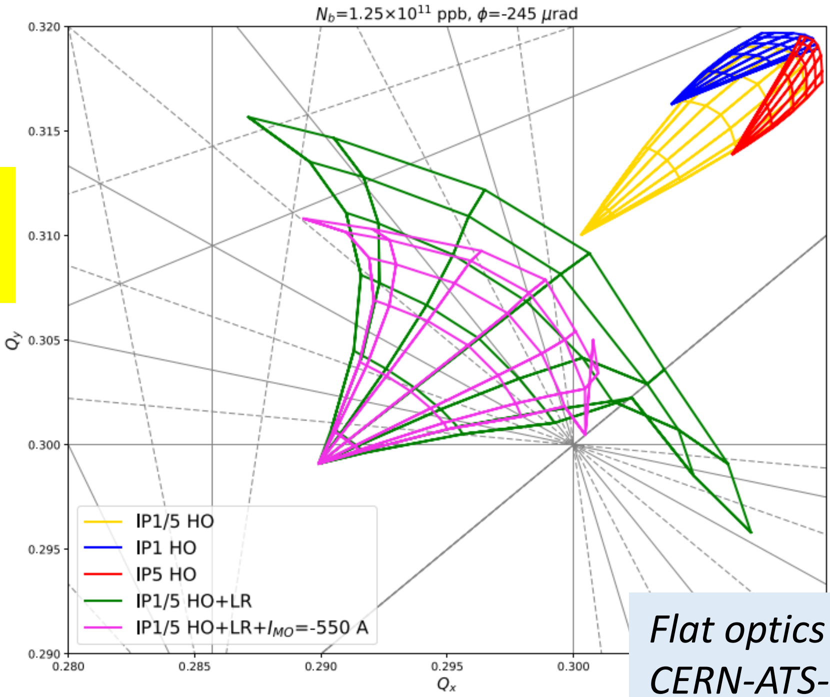
- **The Tunes need to be increased along the diagonal in collision (or earlier) to compensate for the BBLR induced tune shift which is not 0 for flat optics!**

04:11:17 - Error: The double arrays must have the same length!

ΔQ=+0.004 for B1 (by step)

20 h lifetime in collision (typical)

ΔQ=+0.004 for B2 (one step)



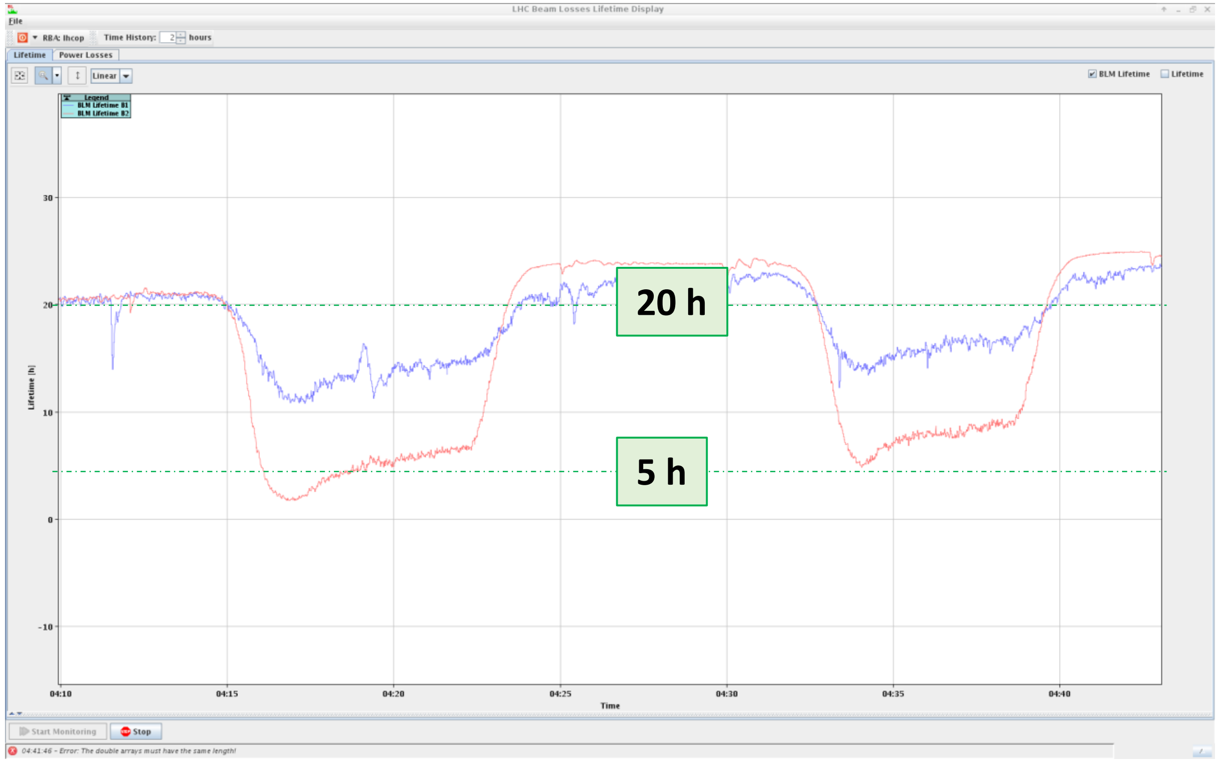
Flat optics report CERN-ATS-2018-0018

Figure 10: Various contributions to the beam-beam tune footprint (shown for particles up to $6\,\sigma$ betatron amplitudes) for the (15/60) flat optics configuration: starting from the asymmetric impact of the head-on collisions taken separately at IP1 and IP5, adding them up, then considering the long-range beam-beam effects in IR1 and IR5, which further increase the tune spread on the anti-diagonal but also shift the working point along the diagonal, and finally including the contribution from the Landau octupoles, powered with negative polarity and which mitigate the overall spread.

S. Fartoukh, 8th HiLumi meeting

- **The BBLR mitigation with MOs (negative polarity) is <u>mandatory</u> for <u>lifetime</u> to stick to the 10 σ X-angle level (120 µrad @ 60 cm) and actually sensibly lower**

MO scan +200 A <-> -570 A @ 130 µrad



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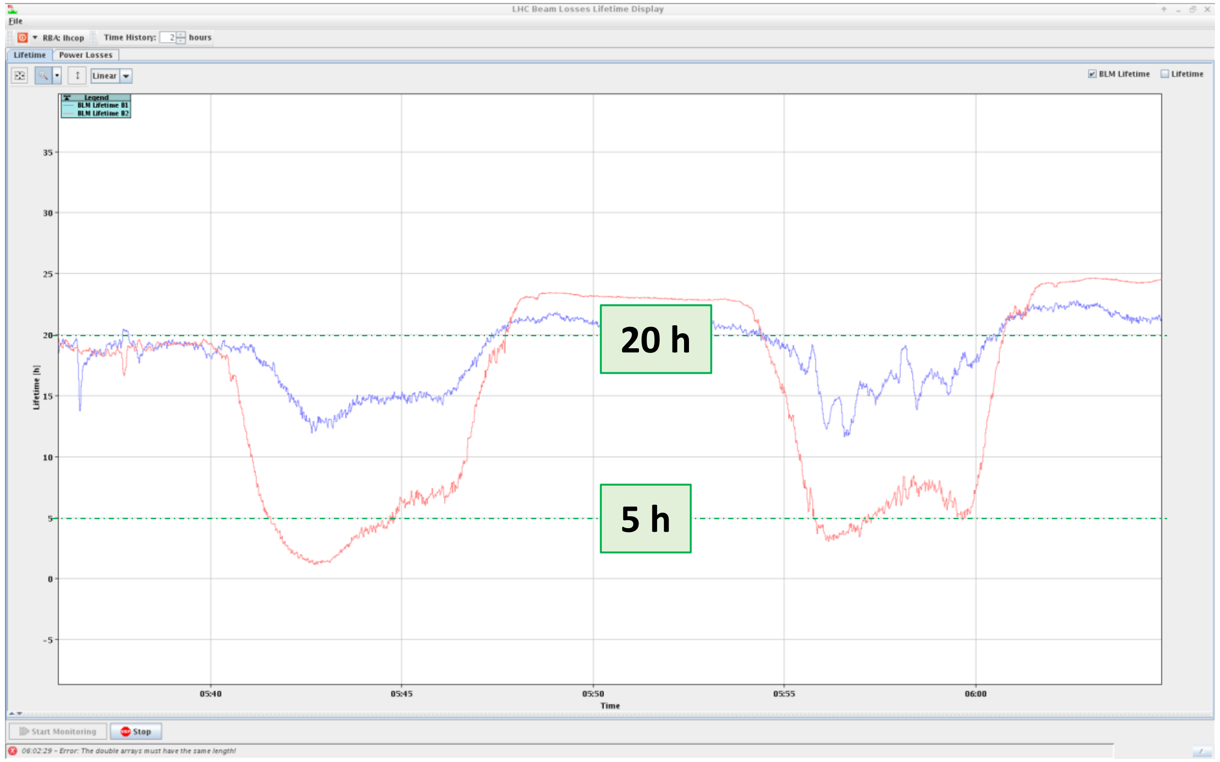
MO scan +200 A <-> -570 A @ 100 µrad



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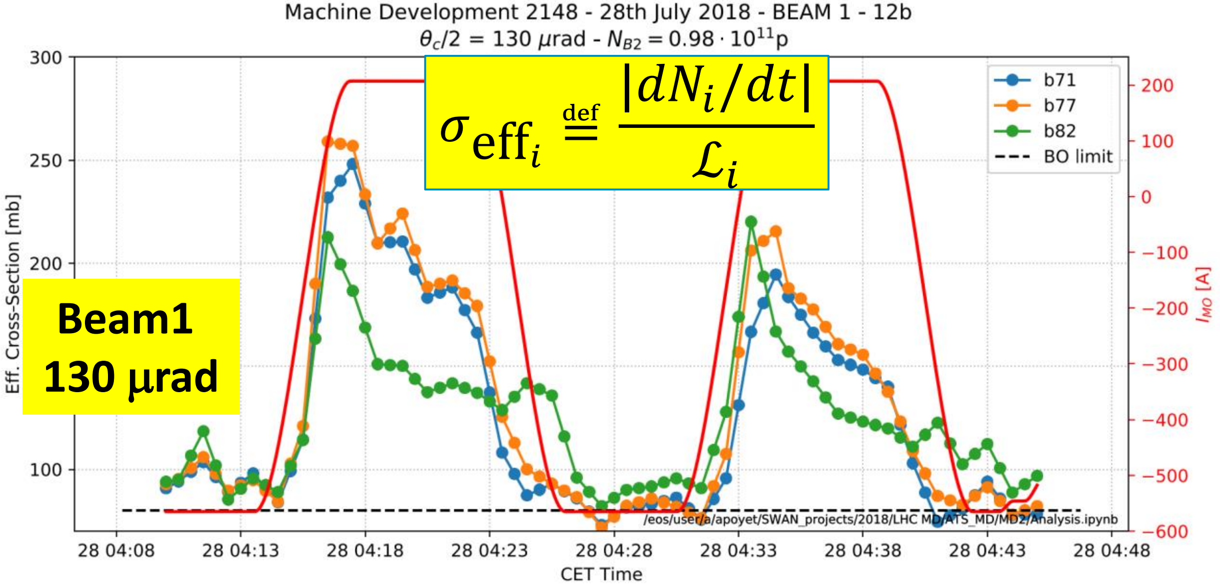
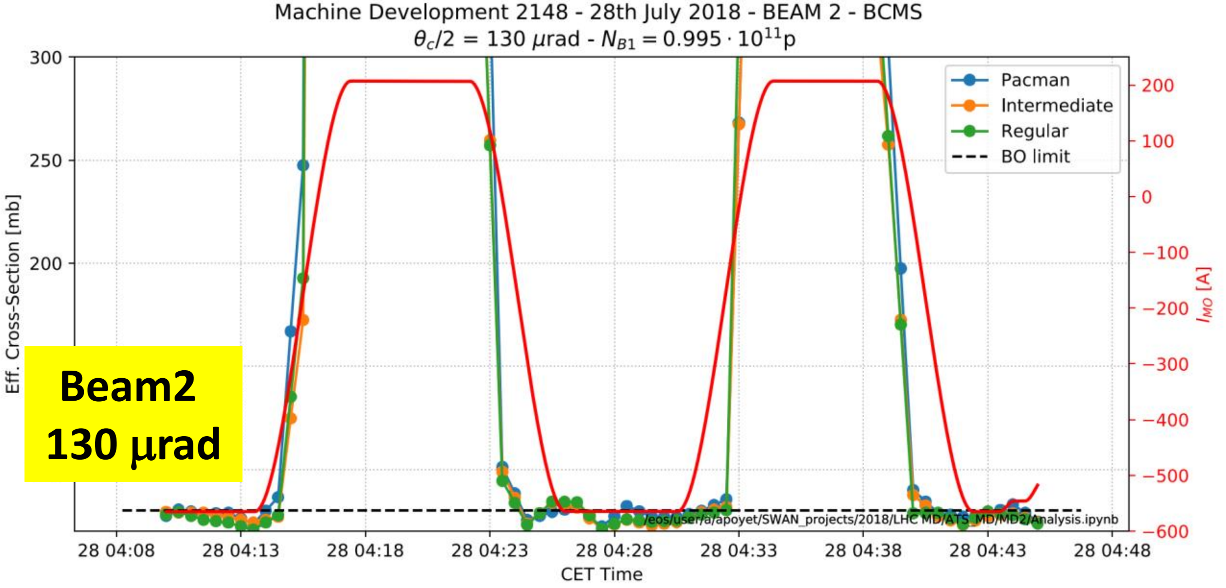
- **.. Looking at the burn-off subtracted lifetime of the various bunches (effective cross-section), the result is confirmed !**

Credit to A. Poyet and BB team

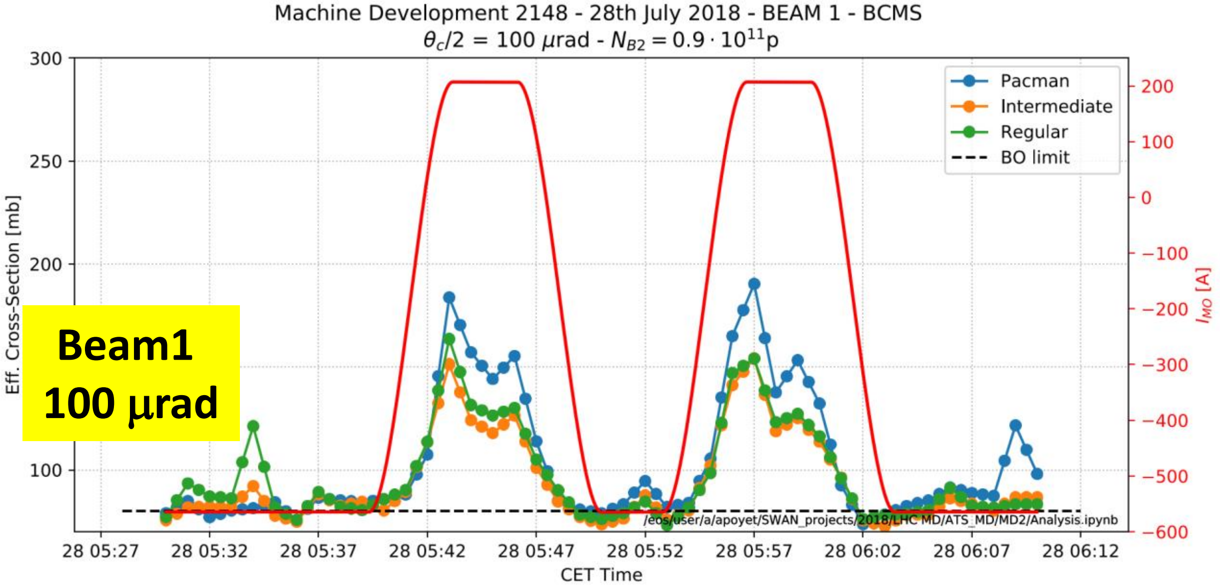

Machine Development 2148 - 28th July 2018 - BEAM 1 - 12b
$\theta_c/2 = 130\ \mu\mathrm{rad}$ - $N_{B2} = 0.98 \cdot 10^{11}$p

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

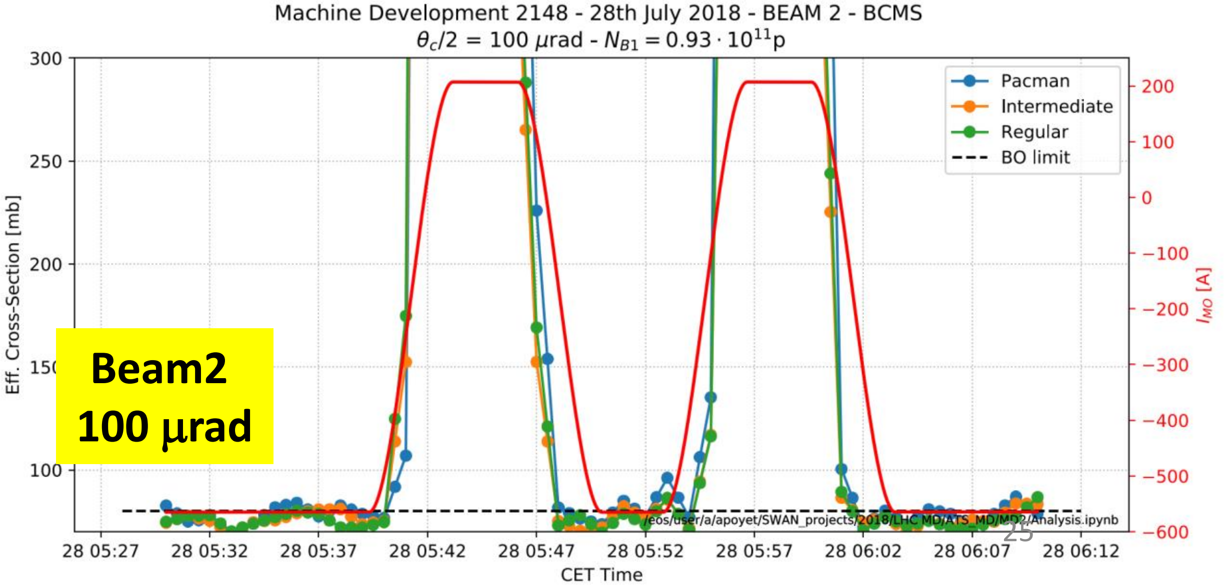
Beam1
130 µrad


Machine Development 2148 - 28th July 2018 - BEAM 2 - BCMS
$\theta_c/2 = 130\ \mu\mathrm{rad}$ - $N_{B1} = 0.995 \cdot 10^{11}$p

Beam2
130 µrad


Machine Development 2148 - 28th July 2018 - BEAM 1 - BCMS
$\theta_c/2 = 100\ \mu\mathrm{rad}$ - $N_{B2} = 0.9 \cdot 10^{11}$p

Beam1
100 µrad


Machine Development 2148 - 28th July 2018 - BEAM 2 - BCMS
$\theta_c/2 = 100\ \mu\mathrm{rad}$ - $N_{B1} = 0.93 \cdot 10^{11}$p

Beam2
100 µrad

Summary & Outlook

- **The integrated performance per fill (w/o time limit) is driven by the beam current (one cannot burn more protons than injected)**

- **The production speed is driven by order of priority by**

(i) The maximum allowed levelled luminosity (2E34 vs. 5E34 vs. 7.5E34)

(ii) The optics (β^*) & the best usage of it (Lumi loss factor mitigation via crab-cavities and/or flat optics)

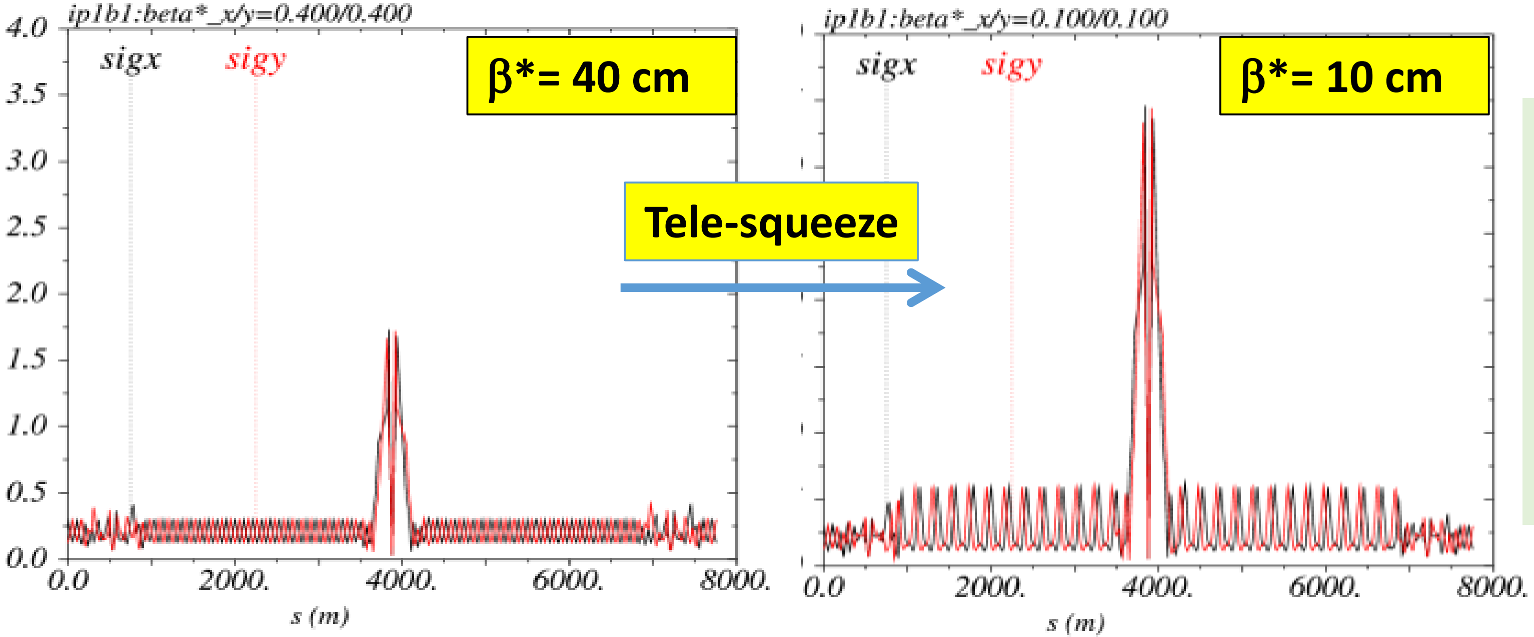
- **Flat <u>telescopic optics</u> have their role to play in the long adventure ahead of us to reach an HL-LHC operating @ 7.5E34 with crab-cavities**

Back-up

ATS scheme and By-products (1/3)

A generalized squeeze involving 50% of the ring to reach unpredecently small β* at the LHC w/o effective optics limits (matching, chromatic, …)

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



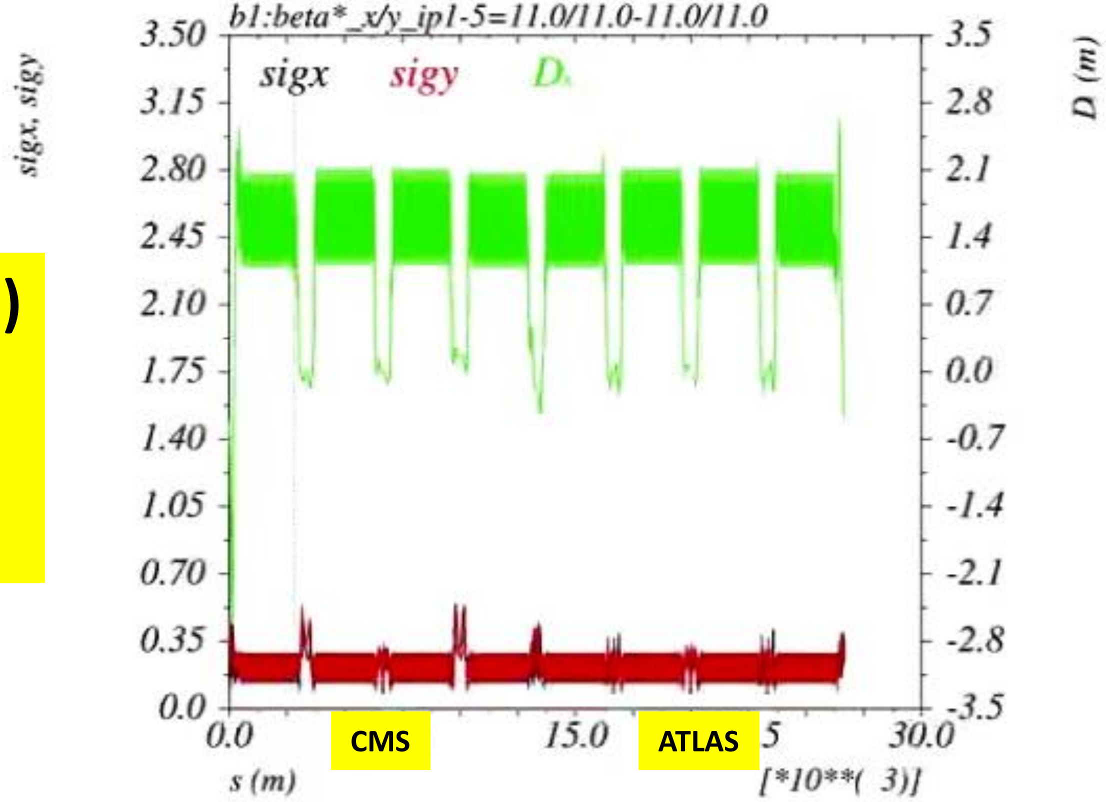
→ **Round optics for HL-LHC** (baseline) with β^* =15 (10) cm in both planes
Demonstrated in Run I (2011-2012)

→ But also **Flat optics for LHC Run III** (& HL) with β^*= 60 (45) cm in X & 15 (13) cm in || plane
Demonstrated in Run II (2017-2018)

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

ATS scheme and By-products (2/3)

Pre-squeeze (IR1/5 IPQ functions) and Tele-squeeze (IR4/6/2/8 settings) can be interleaved or combined (below a certain β^* of ~2m)



Example of an interleaved ATS sequence (animation)

1. **10 m → 2 m in Pre-squeeze mode**
2. **2 m → 50 cm in Telescopic mode**
3. **50 cm→ 10 cm in Pre-squeeze mode**

Possibility of **a Combined ramp and Double squeeze (CRDS):**

→ Pre-squeeze **& Tele-squeeze** embedded in the ramp (partially or fully)

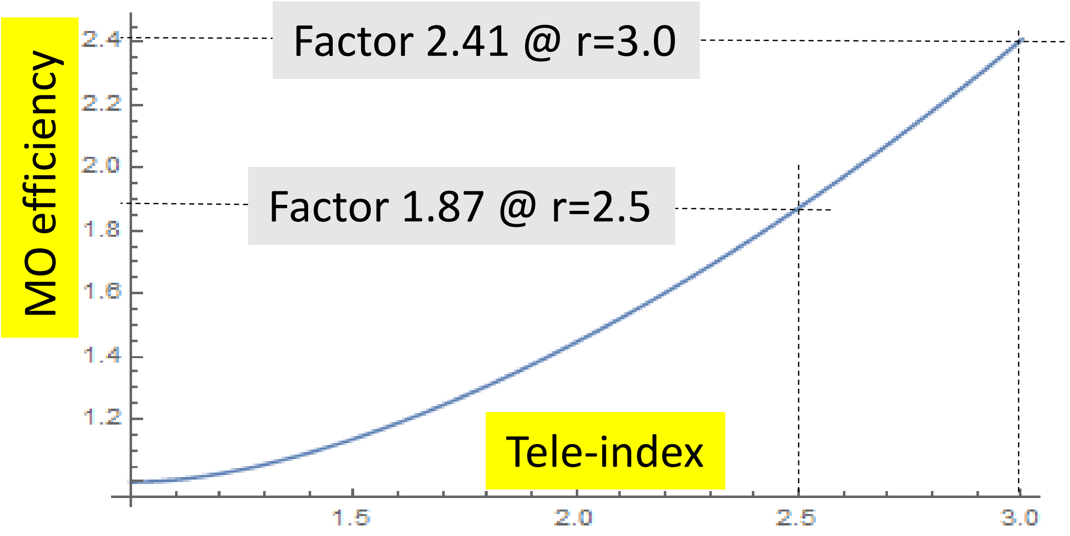
→ Vital ingredient for Run III, highly recommended for HL, see next slide

ATS scheme and By-products (3/3)

The Tele-squeeze boosts the efficiency of the lattice octupoles (increase of the peak β-functions in the arcs), making them much more efficient.

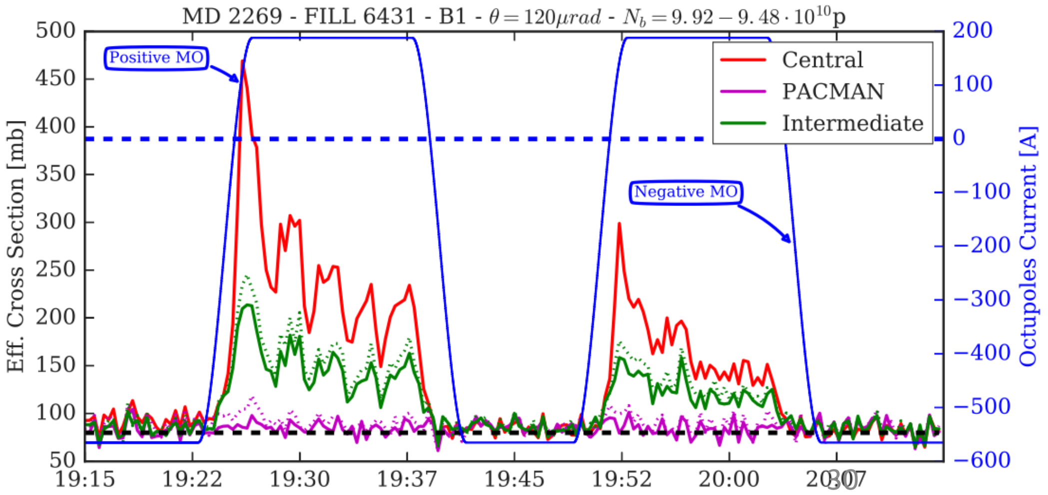
→ For **Landau damping** to swallow the LIU beam in Run III up to 7 TeV ++

- Main justification for the CRDS
- Relax the constraints on impedance budget (and IR7 collimator settings)

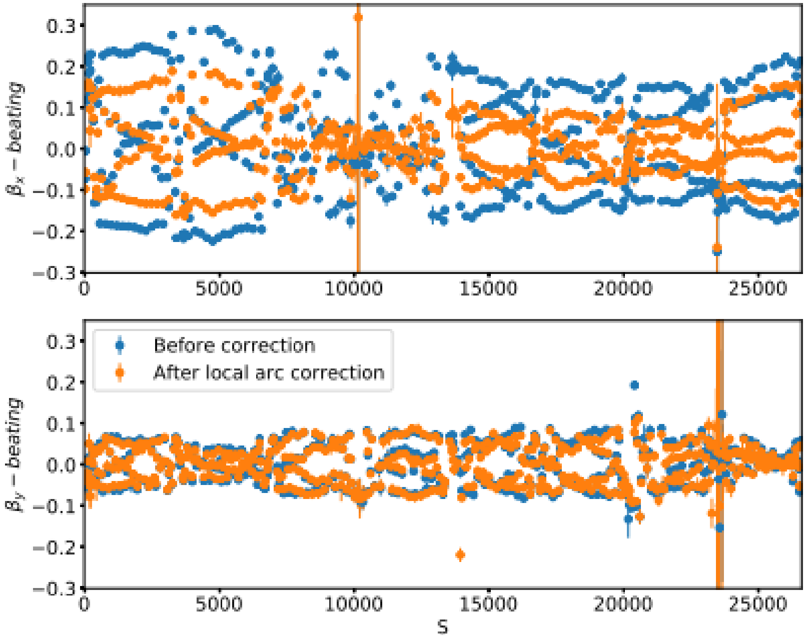


→ For **BBLR compensation** (mitigation)

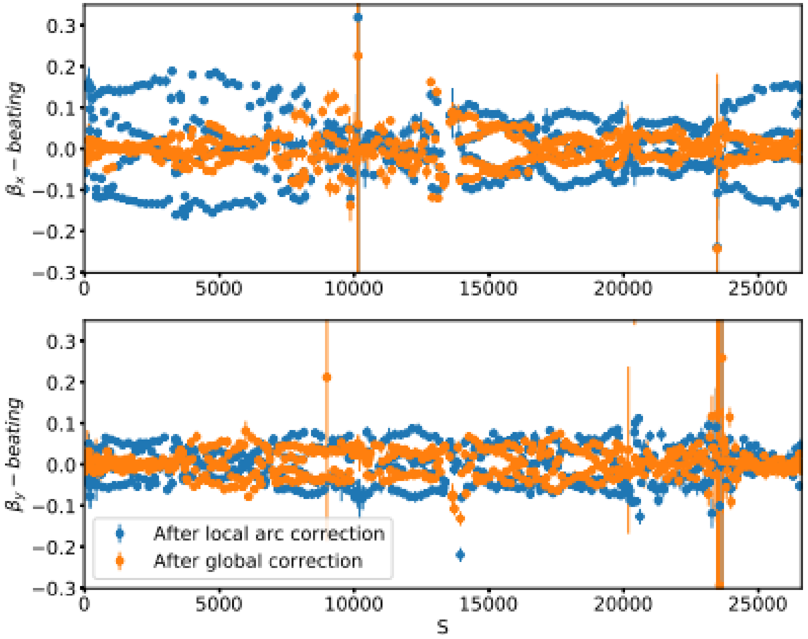
- ~ 10-15 % X-angle reduction for round optics (round optics ATS MD in 2017)
- 10 σ X-angle preservation (or less) for flat optics (down to 100 μrad in the flat optics MD, see later)



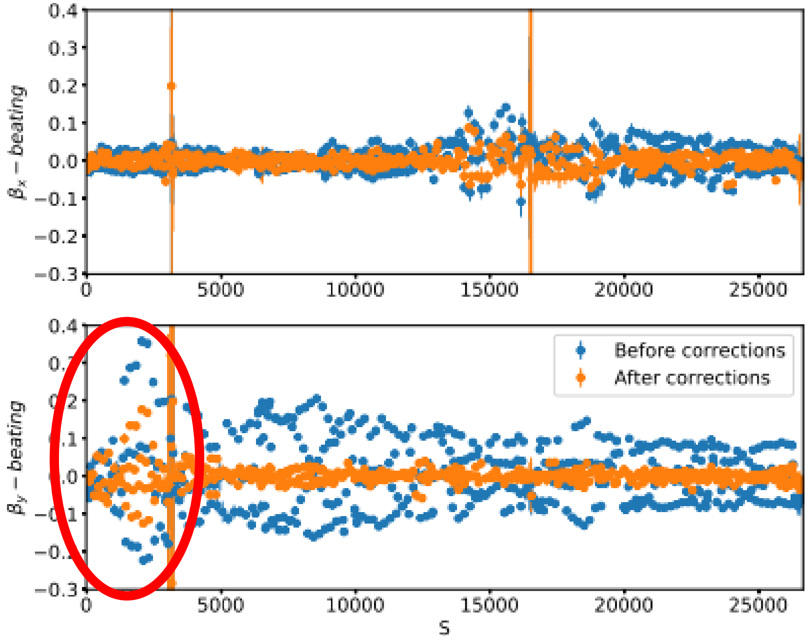
Flat Optics correction in more details (both planes, both beams)



Beam1 after local correction (Q10.R4 and bump discussed and prepared in advance from 2017 MD)



Beam1 after global correction (Q10.R4 and bump)



Beam2 after global correction
Obit bump would be needed as well to improve B2V in S81 !

Courtesy of OMC team