Potential of wire compensation for (HL-)LHC & Optimal optics and hardware conditions

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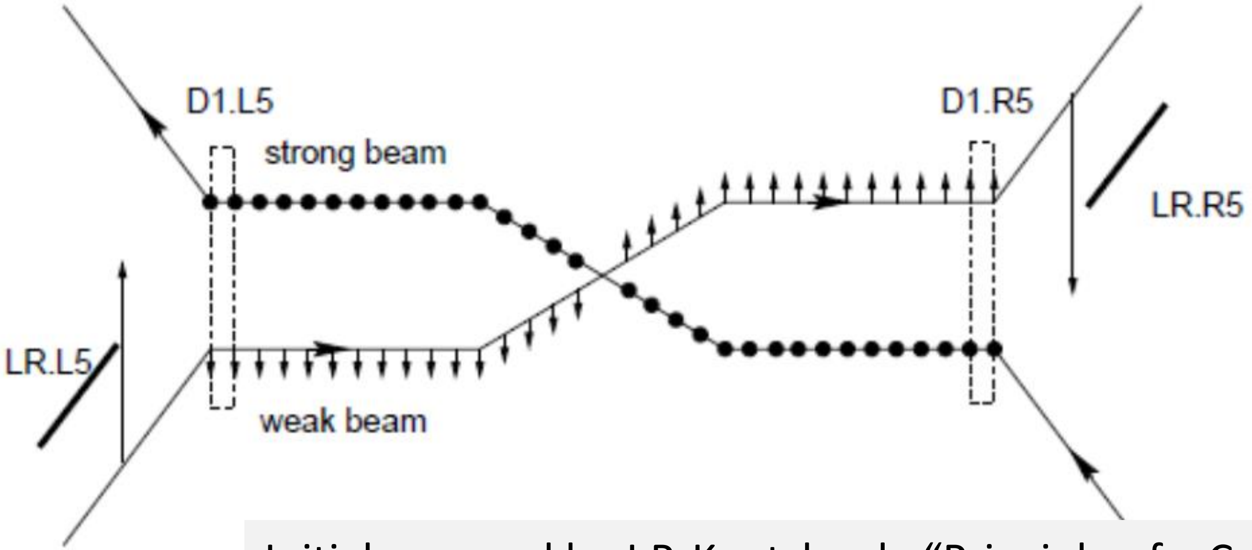


Initial proposal by J.P. Koutchouk, "Principle of a Correction of the Long-Range Beam-Beam Effect in LHC Using Electromagnetic Lenses", LPN 223, 2000

Contents

- **Introduction to flat optics and potential of wire compensation**

→ LHC & “HL-LHC Plan B”

- **Principle of the correction and wire specification**
- **Optimal optics and HW conditions**
- **“Round”, “Oval” or “Flat” optics? Which beam emittance ?**

→ Is there any natural direction where to go for the 2017 MDs ?

- **Conclusions & Outlook**

Introduction to flat Optics and potential of wire compensation

- Flat optics (not flat beams!) means

$$\varepsilon_x \sim \varepsilon_y \sim \varepsilon \text{ but } \beta_x^* \equiv \sqrt{r}\,\beta^* \text{ and } \beta_y^* \equiv \beta^* / \sqrt{r} \text{ with } r \neq 1, \text{ typically 3 to 4 in LHC}$$

- The Xing plane is always the plane of largest β^* (i.e. smallest β in the triplet)

1. **To preserve/gain aperture in the triplet** (smaller X-angle requested, and better matching between beam-screen and beam aspect ratio for LHC, see later)
2. **To gain in luminosity** (geometric loss factor closer to unity)

$$L(r,\beta^*) = \frac{L_0}{\sqrt{1+\frac{1}{r}\times\left(\frac{\alpha\sigma_z}{2\beta^*}\right)^2}}$$

- L_0: Luminosity calculated for head-on colliding round beams
- α: Full normalized X-angle (9-10 σ for LHC, up to 12.5 σ for HL-LHC with more current and longer triplet with more LR's)
- σ_z: r.m.s. bunch length (7.5 cm nominally but 9-10 cm in practice for various reasons)
- $\beta^* \equiv \sqrt{\beta_x^* \times \beta_y^*}$ (30 - 40 cm for LHC, 10 - 20 cm for HL - LHC)
- r the beta* aspect ratio (defined as $\beta_X^*/\beta_{||}^* \geq 1$)

→ Increasing the beta* aspect ratio **could in principle** rapidly mitigate the geometric luminosity loss w/o need of crab-cavities

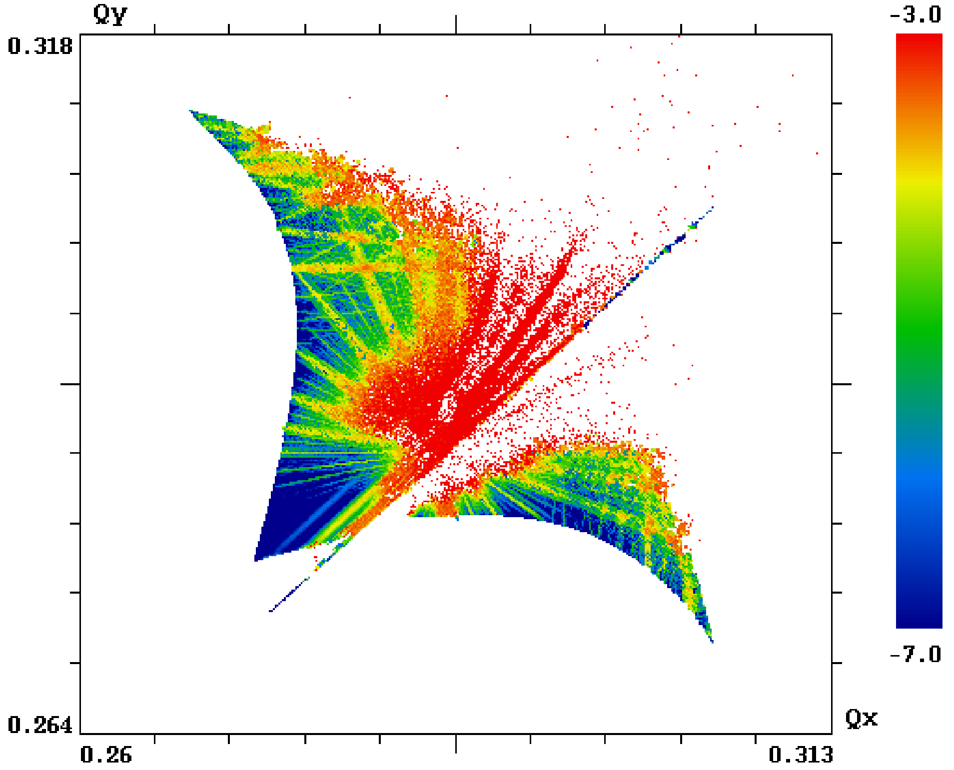
→ But w/o dedicated action, the **normalised X-angle should unfortunately as well increase with the beta* aspect ratio** …

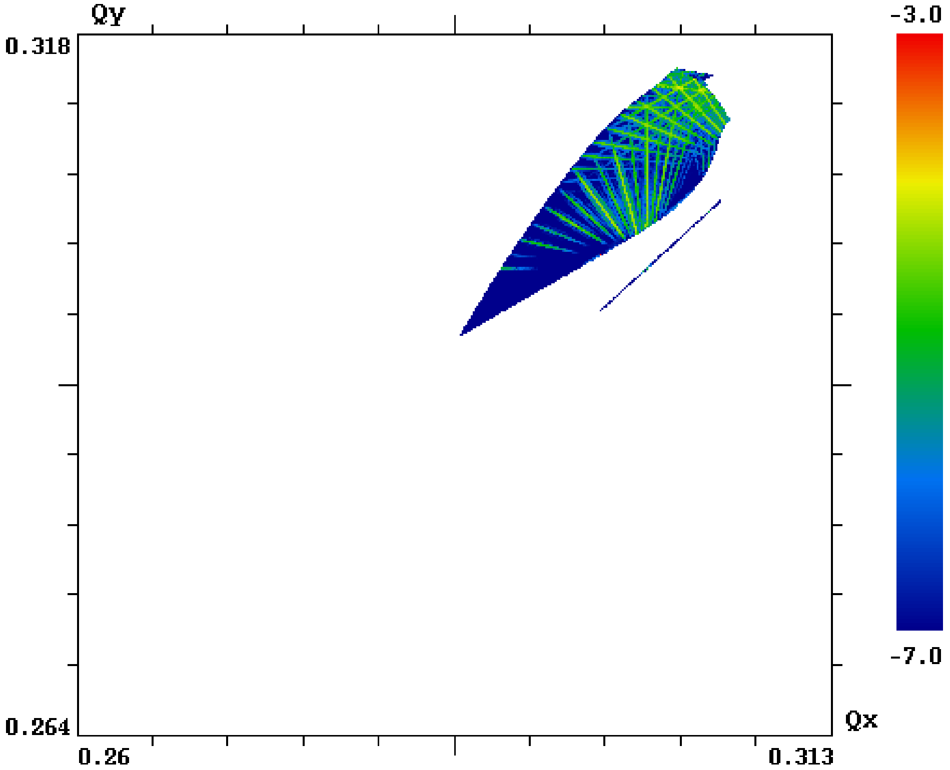
Introduction to flat optics and potential of wire compensation

- **Flat optics example:**

HL-LHC plan B for 10^{35} virtual luminosity w/o crab-cavities (HL-LHC Coordination Group, May 2013, and ***PRSTAB 18-121001, 2015***)

→ β^*=40/10 cm at IP1&5 (i.e. *r=4*), Θ_c=300 μrad, i.e. about halved vs. baseline but still 10.5 σ at β^*=40 cm in the X-plane, ho collision at full current in 3 IPs



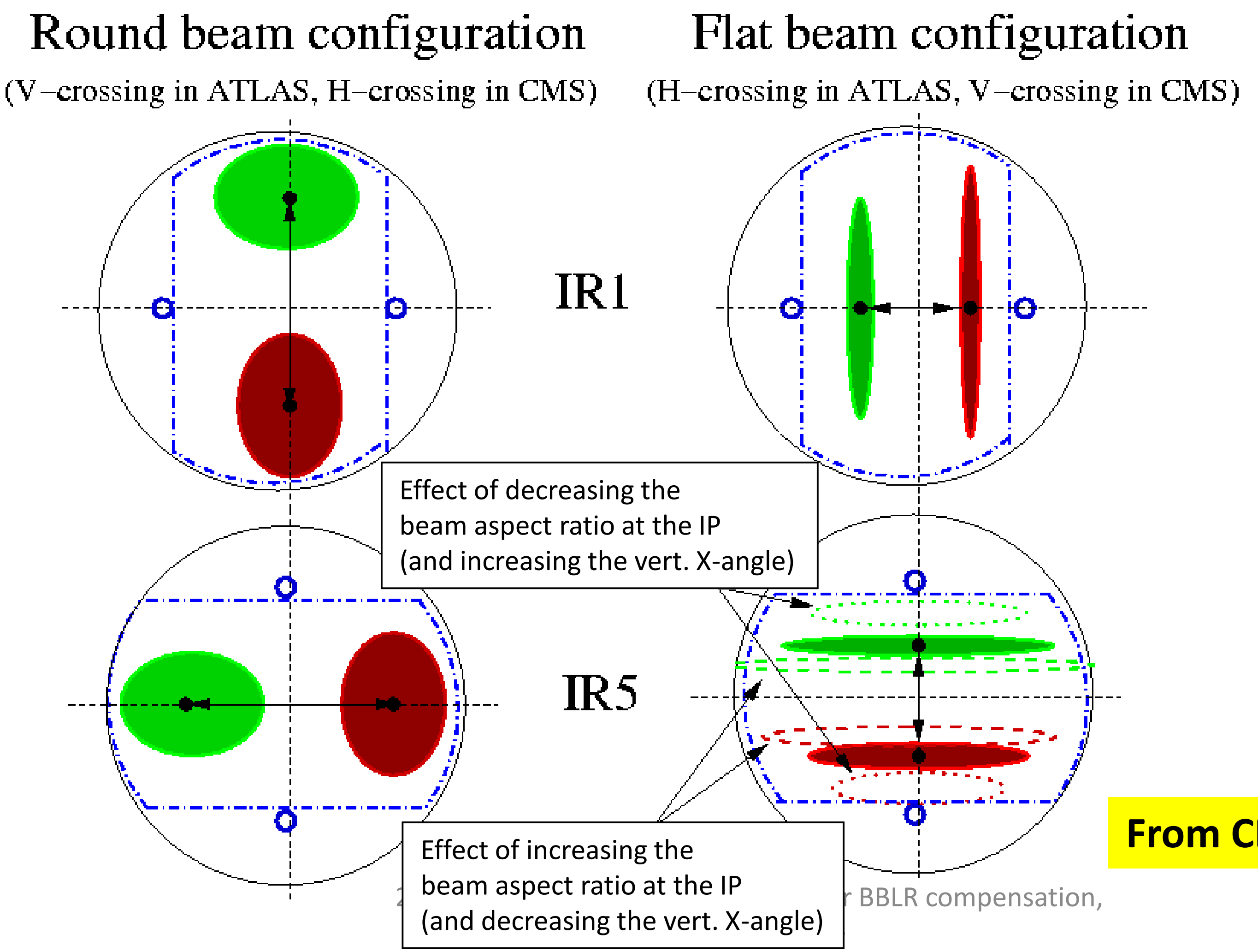


A ``monster'' before correction (ΔQ_{ho}=0.025, ΔQ_{LR}=0.015)

A regular HO footprint after correction (ΔQ_{ho}=0.025, ΔQ_{LR}=0.0) with wire installed at optimal position (see later)

Introduction to flat optics and potential of wire compensation

- **<u>Competitive flat optics in LHC</u>** (e.g. 80/20 instead of 40/40, or 60/15 instead of 30/30) requires to **change the crossing plane orientation** (IT aperture), hence installing **the wires in the right plane!..** (see later possible "oval" optics)



From CERN MAC, 2006

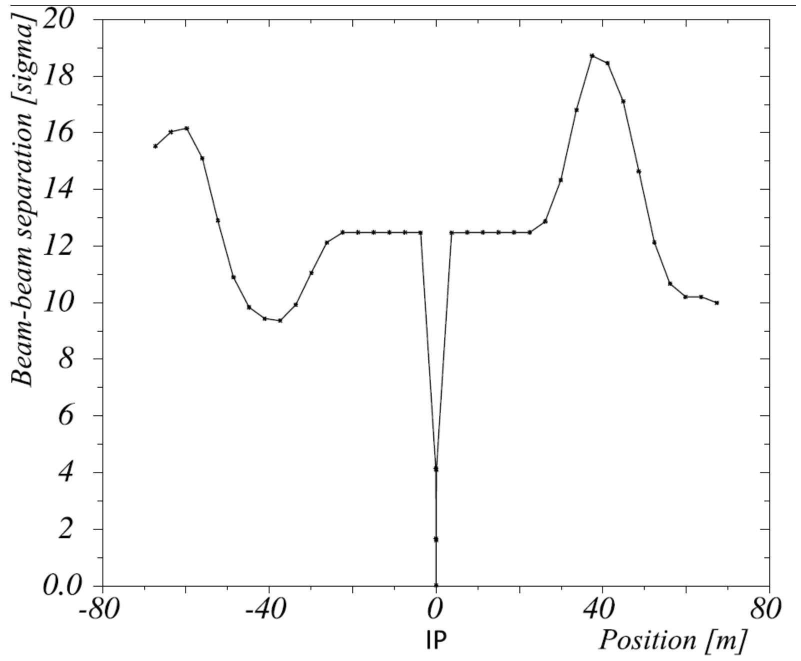
Principle of the wire correction and wire specification

- **Many questions with non-obvious answers**

1) With only 2 wires left/right the IP, can we properly compensate 15-20 LR encounters taking place at **non uniform normalized beam-beam separation**?

2) If yes, can we build an **automatic tool for setting generation** (transverse position and current) working for arbitrary optics (flat or round) and crossing angle ?

3) Are there any preferences (based on beam dynamics criteria) where to install the wire, i.e. at **which β-function aspect ratio** ? Is an aspect ratio of 1 really the optimal choice as thought in the initial proposal?



HL-LHC: Normalized beam-beam separation for 590 μrad full crossing angle (12.5 σ) at β^*=15 cm (7 TeV, γε=2.5 mrad)

Principle of the wire correction and wire specification

- **Beam-beam long-range multipole expansion**

Working in complex coordinates is the right thing to do:

$z \equiv x + i\,y$: transverse coordinate of the test particle wrt the centroid of the weak beam

$z_0 \equiv x_0 + i\,y_0$: relative centroid position of the strong beam wrt the weak beam

… And assuming $|z| \ll |z_0|$

$$\int ds\left[B_y + i\,B_x\right]_{\mathrm{eq}} = -\frac{\mu_0 \overbrace{(Qc)}^{\equiv [IL]_{\mathrm{eq}}}}{2\pi} \times \frac{1}{z - z_0}$$

$$\equiv \sum_{k=1}^{\infty} [B_k + i\,A_k] z^{k-1}$$

$$\rightarrow B_k + i\,A_k = \frac{\mu_0 [IL]_{\mathrm{eq}}}{2\pi} \times \frac{1}{z_0^k}$$

$[IL]_{eq} = 10.56$ A.m / LR for the HL-LHC beam (2.2E11)

$[IL]_{eq} = 5.76$ A.m /LR for the LHC BCMS beam (1.2E11)

90 A.m would have been fully OK for LHC (15 LRs/IP side), about 200 A.m for HL-LHC (18-19 LRs/IP side) … The TCTW has been designed for 350 A ??

Principle of the wire correction and wire specification

$$B_k + i\,A_k = \frac{\mu_0 [IL]_{\text{eq}}}{2\pi} \times \frac{1}{z_0^k}$$

1. H crossing ($z_0 = x_0$ real) induces only normal harmonics (A_k=0).
2. V crossing ($z_0 = iy_0$ purely imaginary) induces both skewed harmonics when k is odd (B_{2k+1}=0) and normal harmonic when k is even (A_{2k}=0).
3. An **alternated <u>HV Xing scheme in 2 low-β IRs with</u>** **<u>identical round optics</u>** compensates all $(4n+2)$-pole tune shift and tune spread (B_2, B_6,…) but combine additively the $(4n)$-pole tune spread (B_4, B_8,…). …That is why the LR tune spread is close to that of a **pure octupole in the LHC**, and was easy to compensate with octupole magnets, at least at 4 TeV ….
4. The compensation is only **partial for alternated HV Xing in <u>2 low-β IR's with</u>** **<u>flat optics of aspect ratio r and 1/r</u>**

Principle of the wire correction and wire specification

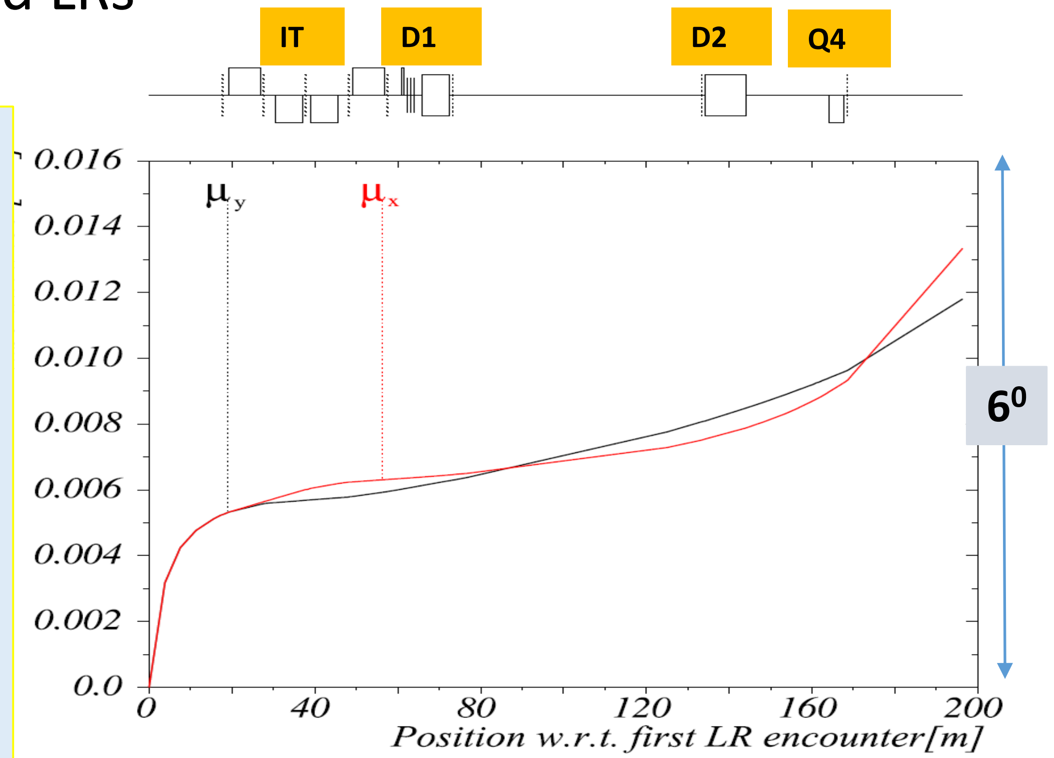
- **Resonance Driving Terms (RDT) from the LR interactions in H or V crossing**

… neglecting the small phase shift between wires and LRs

$$c_{pq}^{LR} \propto \sum_{k\in LR} \frac{\beta_{x,k}^{|p|/2}\,\beta_{y,k}^{|q|/2}}{d_{bb,k}^{|p|+|q|}}$$

with p (resp. q) even for H (resp. V) crossing, and $d_{bb,k}$ the (non-normalized) beam-beam distance (taken positive) at the k^{th} encounter.

→ The detuning terms (footprint) are non-zero only when both p and q are even, and are equal to the corresponding driving terms.



Betatron phases [2π] w.r.t. the first LR encounter
For Typical optics at β*=15 cm (HL-LHC)

→ **A few degrees till Q4**

→ **But rapid degradation of the situation for β* >50 cm-1 m**

Principle of the wire correction and wire specification

- **RDTs from the wire**

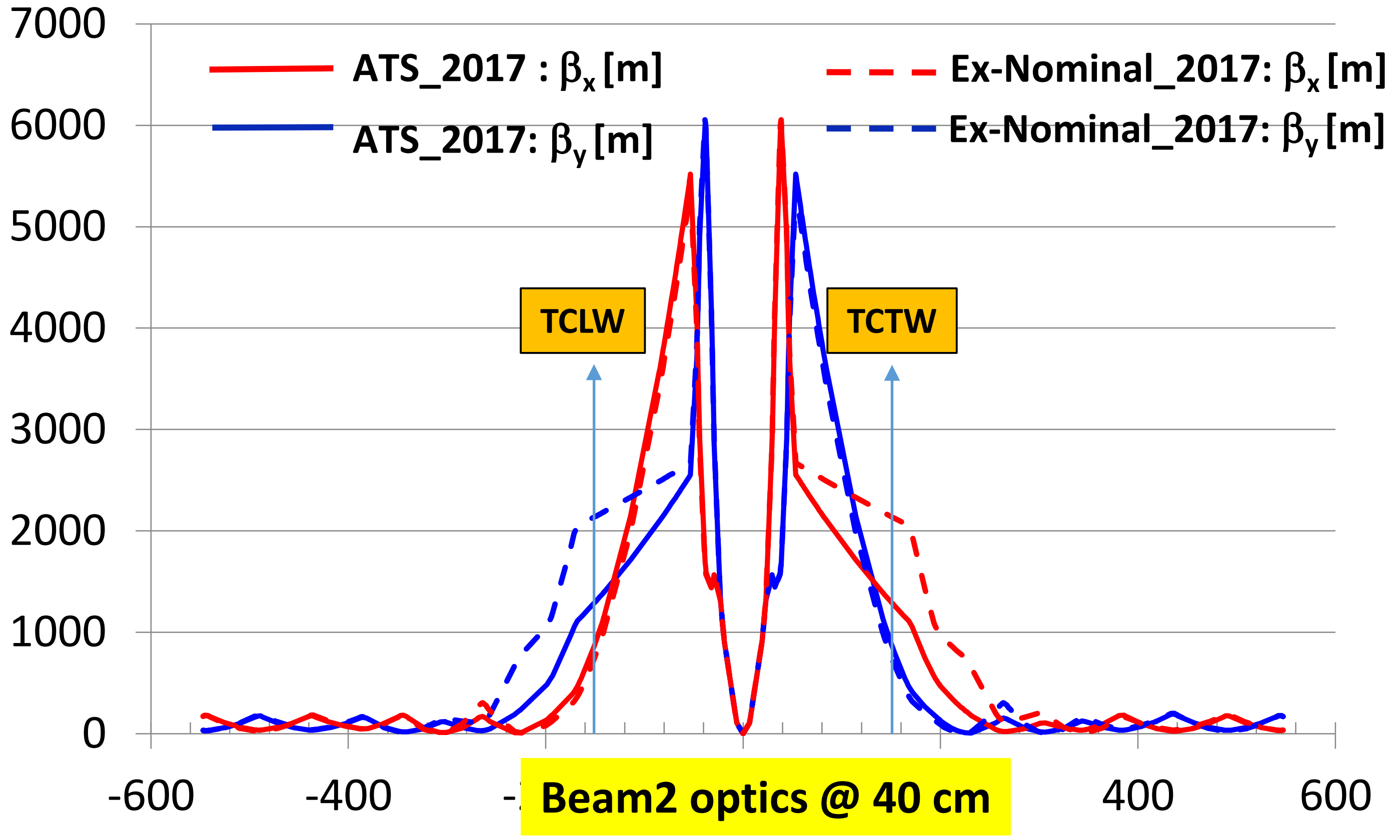
$$c_{pq}^{w} \propto N_w \times \frac{r_w^{\frac{|p|-|q|}{4}}}{\left(d_w / \sqrt[4]{\beta_{x,w}\beta_{y,w}}\right)^{|p|+|q|}}$$

d_w : (non-normalized) distance of the wire w.r.t. the weak beam

N_w : integrated current expressed in terms of equivalent number of LR encounters

r_w : β-function aspect ratio at the wire (β_x/β_y)

→ The actual product of the β's at the wire is not relevant (can be absorbed in rescaling d_w), **only the β aspect ratio is important, which can be eventually (re-)adjusted with the triplet settings**



Optics type @ 40 cm	ATS 2016	Nominal 2016	ATS 2017 (new nominal 2017)	"ex-Nominal 2017"
$\beta_{x\,(y)}$ [m] at TCT (TCL)	1654 (1645)	2149 (2144)	**1314 (1302)**	2149 (2144)
$\beta_{y\,(x)}$ [m] at TCT (TCL)	966 (935)	800 (772)	**932 (901)**	800 (772)
r_w at TCT (TCL)	1.71 (1.76)	2.68 (2.78)	**1.41 (1.44)**	2.68 (2.78)

Principle of the wire correction and wire specification

- **Correction algorithm:**

With 2 knobs (1 wire/beam/ IP-side assumed to be symmetric w.r.t. the IP), only 2 or 4 RDT's can be a priori fully corrected:

→ $(c^{LR}_{p_1q_1}, c^{LR}_{p_2q_2})$ and $(c^{LR}_{q_1p_1}, c^{LR}_{q_2p_2})$ by symmetry with **left & right wires** at the **same physical transverse distance w.r.t. the beam** and at **the same current**

For round optics

$$\begin{cases} d_{w.\mathrm{L}} = d_{w.\mathrm{R}} = d_w \equiv \sqrt{\beta^w_{\mathrm{eq}}} \times \left[\dfrac{c^{LR}_{p_1q_1}}{c^{LR}_{p_2q_2}} \dfrac{r_w^{\frac{p_2-q_2}{4}} + r_w^{\frac{q_2-p_2}{4}}}{r_w^{\frac{p_1-q_1}{4}} + r_w^{\frac{q_1-p_1}{4}}} \right]^{\frac{1}{p_2+q_2-p_1-q_1}} \\ N_{w.\mathrm{L}} = N_{w.\mathrm{R}} = N_w \equiv \left[\dfrac{(c^{LR}_{p_1q_1})^{p_2+q_2}}{(c^{LR}_{p_2q_2})^{p_1+q_1}} \dfrac{\left(r_w^{\frac{p_2-q_2}{4}} + r_w^{\frac{q_2-p_2}{4}}\right)^{p_1+q_1}}{\left(r_w^{\frac{p_1-q_1}{4}} + r_w^{\frac{q_1-p_1}{4}}\right)^{p_2+q_2}} \right]^{\frac{1}{p_2+q_2-p_1-q_1}} . \end{cases}$$

…**which is independent of β* !**

For flat optics of sufficiently small β* in both planes, these settings are still optimal for the 2 RDT's considered, but the residuals of the other RDT's remains in general optics dependent.

Disclaimer

The following does not treat the **compromise case of only one driving term compensated**, as e.g. the octupolar term, where the wire can be at any distance from the beam, provided enough current is available

→ **See talk by A. Valishev** (for the very promising results alreay obtained in this case)

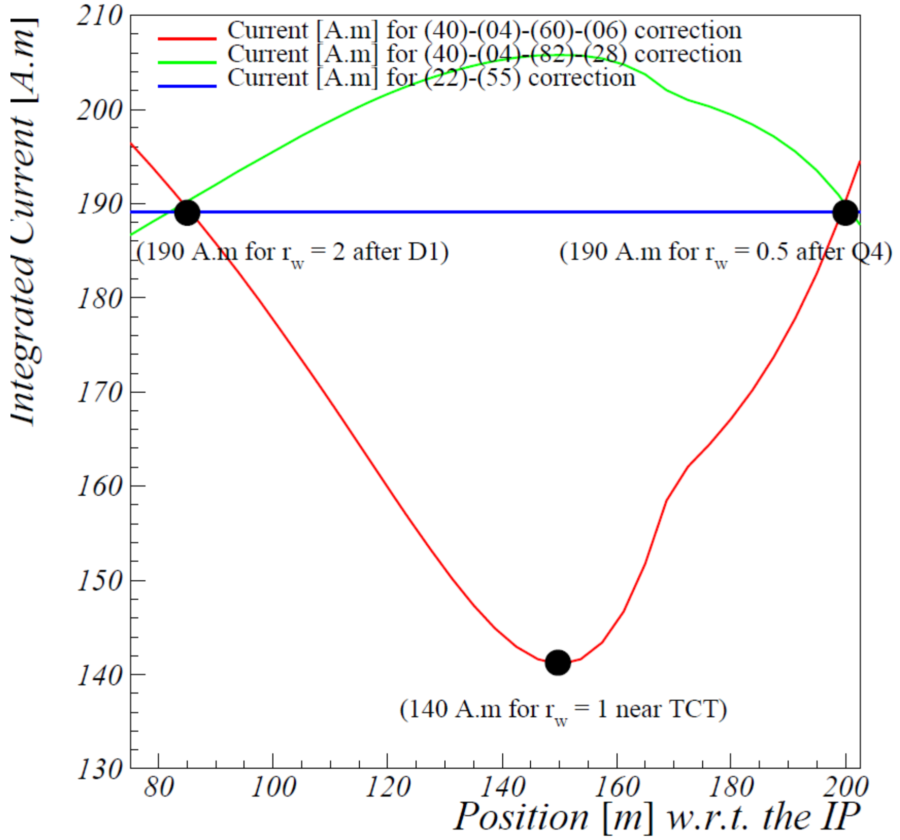
Principle of the wire correction and wire specification

- **Integrated current vs. wire positioning** (HL-LHC simulations)

→ 3 correction types tested

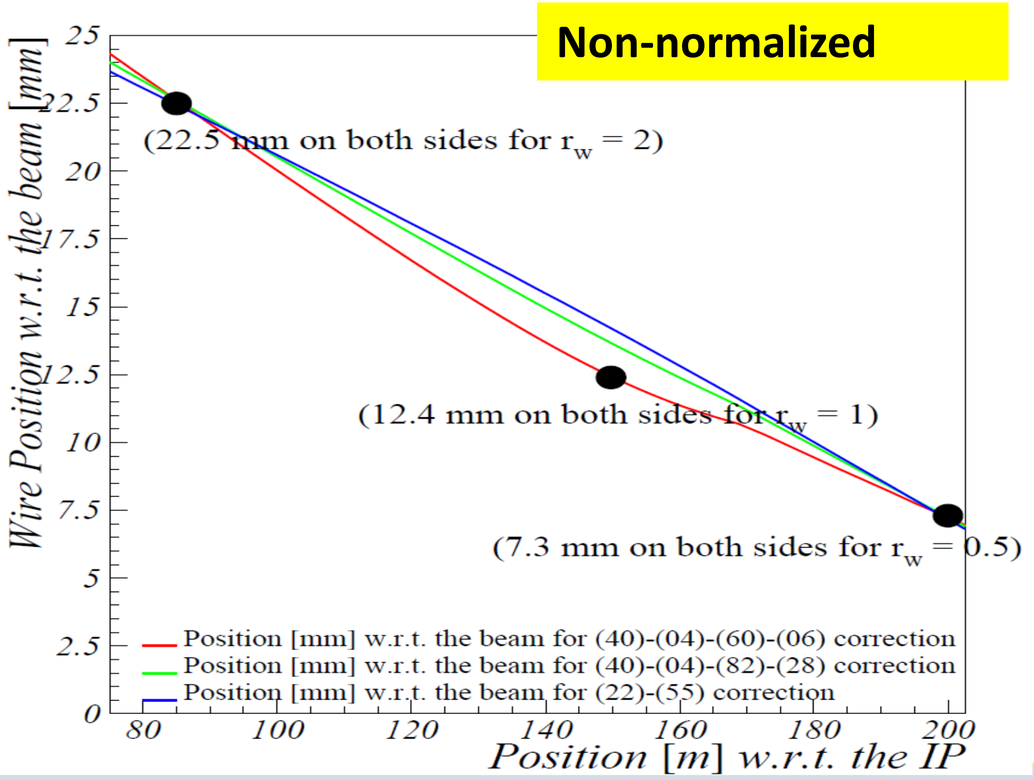
→ r_w=1 can mitigate the current needed but is always worst for the quality of the correction (see later)

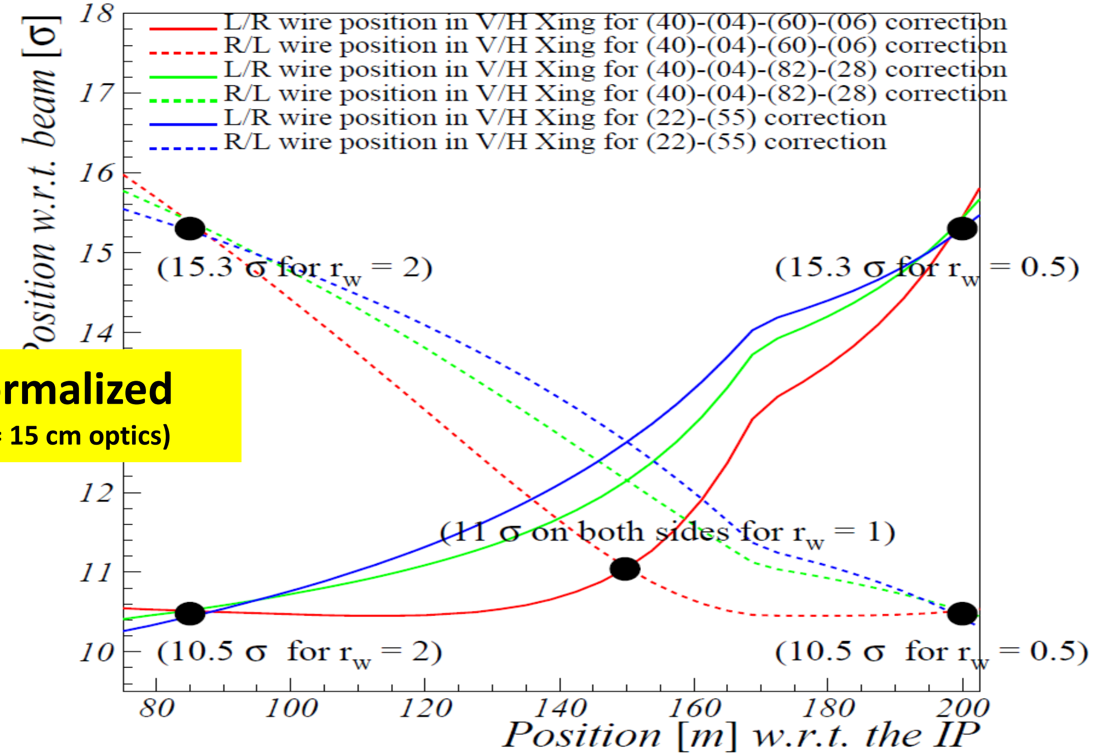
→ The current does not depend on the correction type for an aspect ratio of $r_w \approx 0.5$ or $r_w \approx 2$!
At this aspect ratio, the wire current corresponds to the strict additive contribution of each LR



Principle of the wire correction and wire specification

- <u>**Transverse distance w.r.t. beam**</u> vs. wire positioning in **HL-LHC** for a full X-angle of 590 μrad (12.5 σ at β*=15 cm)





→**Again the results does not depend on the correction type for** $r_w \approx 0.5$ or $r_w \approx 2$!?

→ At **this optimal aspect ratio**, the normalized wire position is about:

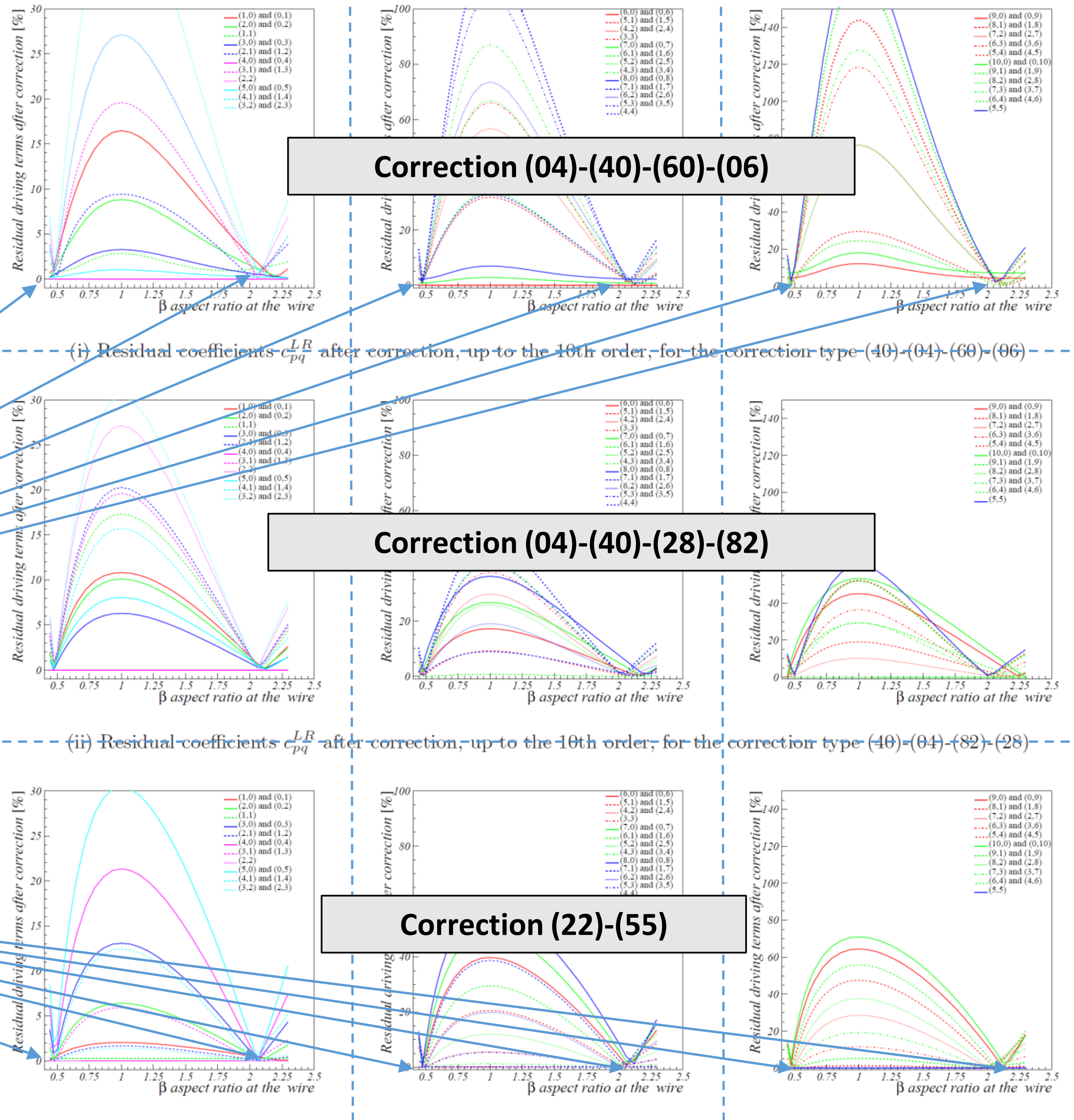
$d_w \sim 2^{1/4} \times$ **normalised X-angle on the side of the smallest β**

$d_w \sim 2^{-1/4} \times$ **normalised X-angle on the side of the largest β**

- **Other RDT's after correction vs. r_w in HL-LHC (residuals in % neglecting the small phases wire/LR)**

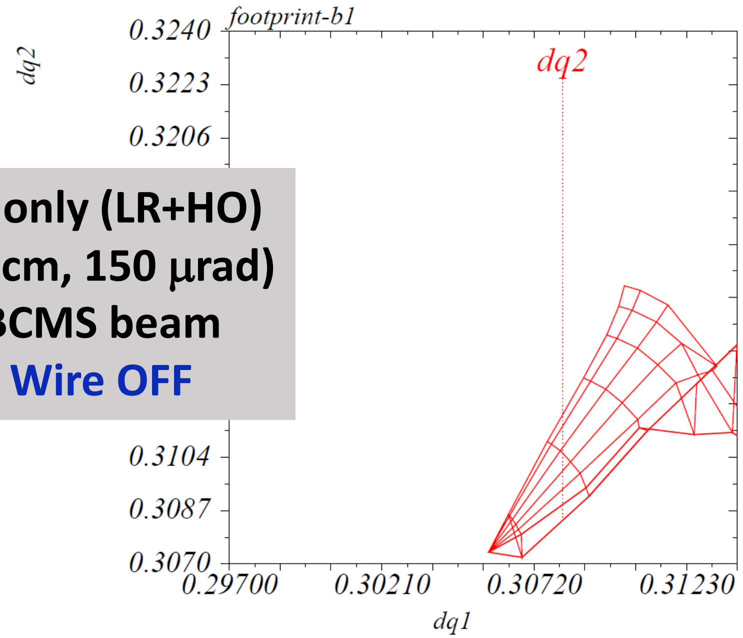
Regardless of the correction type **all the RDTs are vanishing at $r_w \approx 2$ or $r_w \approx 0.5$**

The same feature is observed for **the existing IT**, the minima is just slightly shifted at $r_w \approx 1.8$ and 0.55

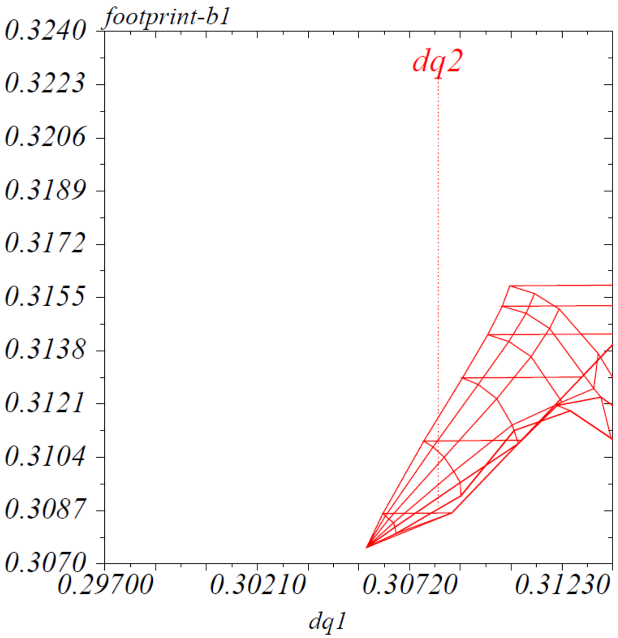


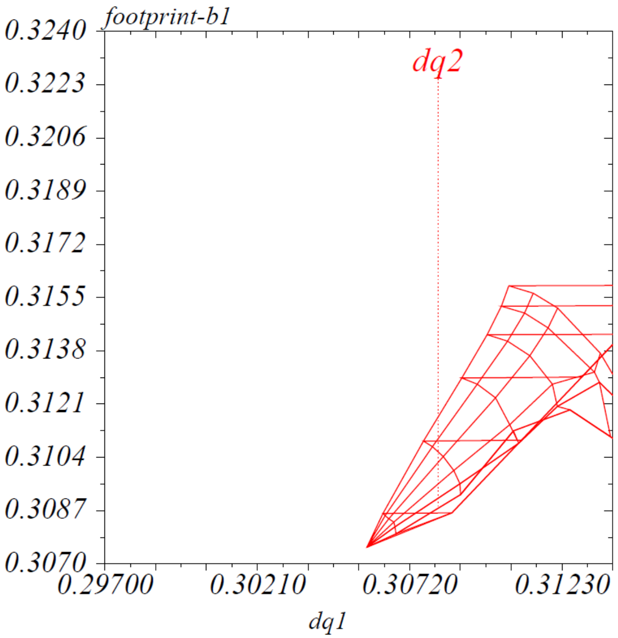
(iii) Residual coefficients c_{pq}^{LR} after correction, up to the 10th order, for the correction type type (22)-(55)

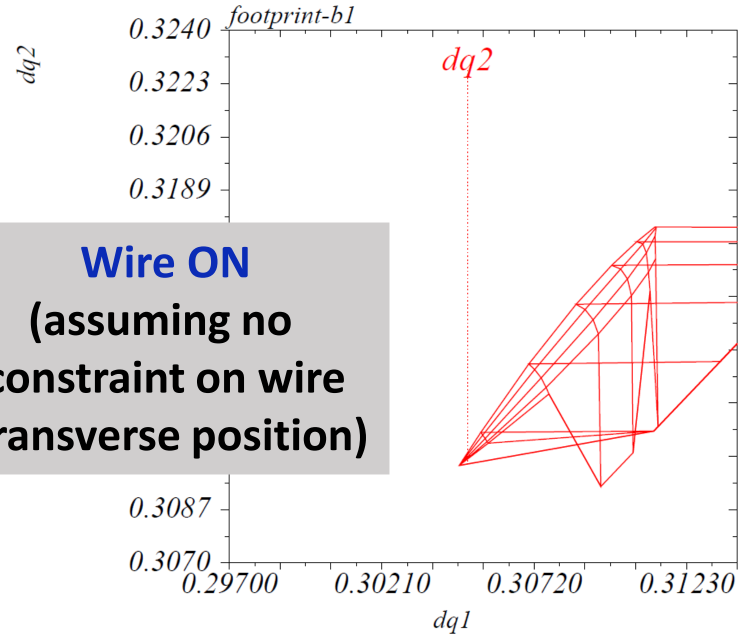
From 1rst to 3rd order | From 4th to 8th order | From 9th to 10th order



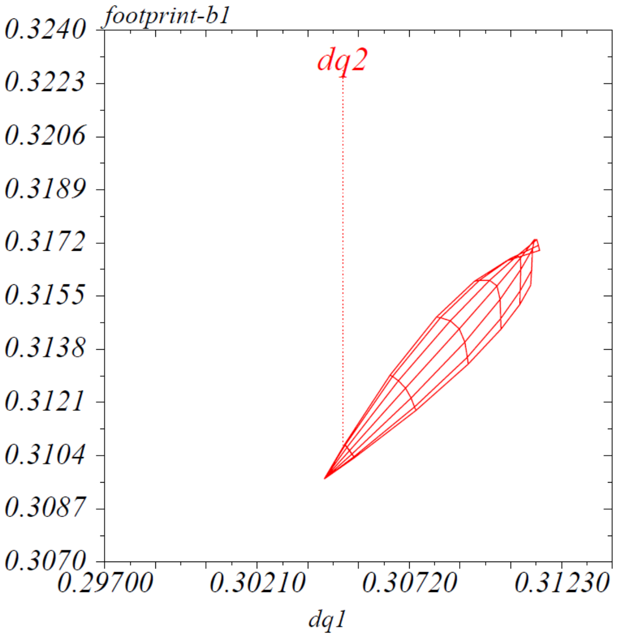
IR5 only (LR+HO)
(40 cm, 150 μrad)
BCMS beam
Wire OFF

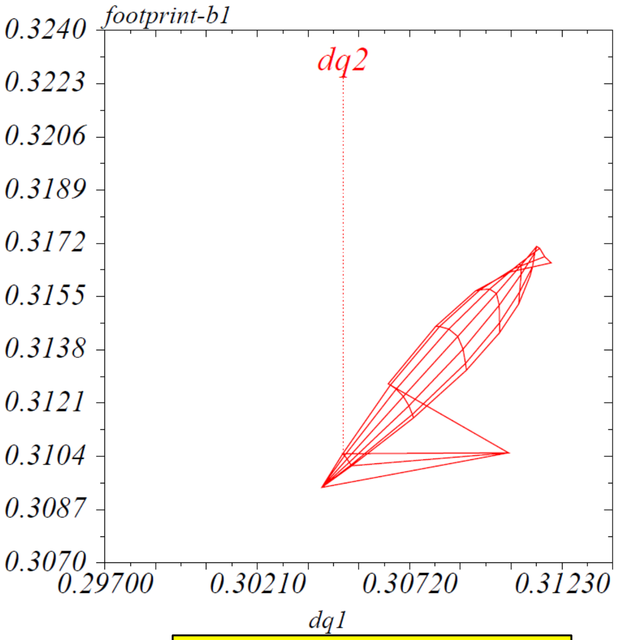






Wire ON
(assuming no constraint on wire transverse position)





Nominal optics-2016 (r_w ~ 2.7)

ATS-2016 (r_w ~ 1.7)

ATS-2017(r_w ~ 1.4)

Optimal optics and HW conditions

- **Some optimal rules for HL-LHC (and LHC)**

Rule # 1 (plane): 2 wires /beam/IR installed in the X-plane .. e.g. H in IR1 and V in IR5 for "HL-LHC-like flat optics"

Rule # 2 (layout): Left/right symmetric w.r.t the IP

Rule # 3 (optics): At an optimal beta aspect ratio of about 2 (1.8 for LHC). In case, the LHC optics is flexible enough to be changed accordingly (mitigating possible constraints from the forward physics experiments)

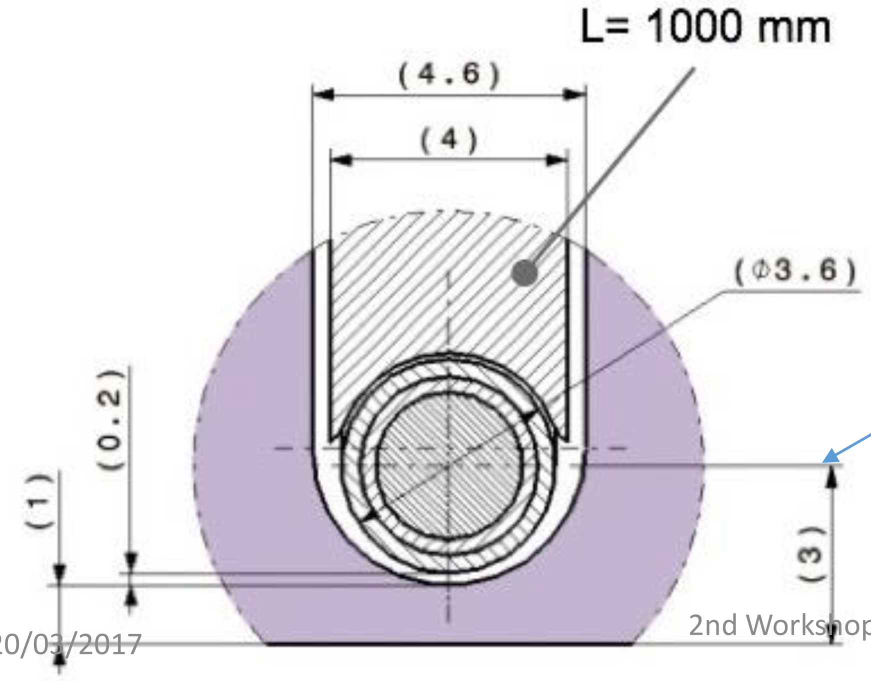
Rule # 4 (current): With a current of about 200 A (100 A for LHC), same current left and right

Rule # 5 (transverse setting): At the same physical distance w.r.t. the beam for the left and right wires, corresponding to a normalized distance which is 15-20% larger (resp. smaller) than the crossing angle for the wire on the side of the smallest (resp. largest) beta.

Optimal optics and HW conditions

- **Where are we with the present HW and which consequence?**

- ☺: Two wires at the TCT & TCL almost symmetric w.r.t. the IP
- ☺: β–aspect ratio at the wires not ideal but much better for ATS2017 than for the 2016 optics
- ☹: Wire in the H plane which rules out flat optics with very small (15-20 cm) horizontal beta*, not too large vertical beta* (~60 cm) and V crossing, as imposed by the IT aperture
- ☹: By far enough current (× 4 compared to LHC needs), **but which drove a specific HW solution with (too) many beam sigma's lost between wire and TCT edge** (see also next slide)



Round optics: 3 mm means already ~5 σ @ γε=2.5 μm and β^*=40 cm (β~900 m at the TCLW)

"Oval" optics: H crossing kept in CMS, β^* limited to ~ 35-40 cm in the V plane (parallel separation plane), and β^* ~ 1 m in the X-plane to keep a "decent" sizeable aspect ratio
3 mm becomes ~8 σ at β^*=1 m … (β shrinks to ~360 m at the TCLW)

→ Definitely the emittance of the weak beam has to be blown up.

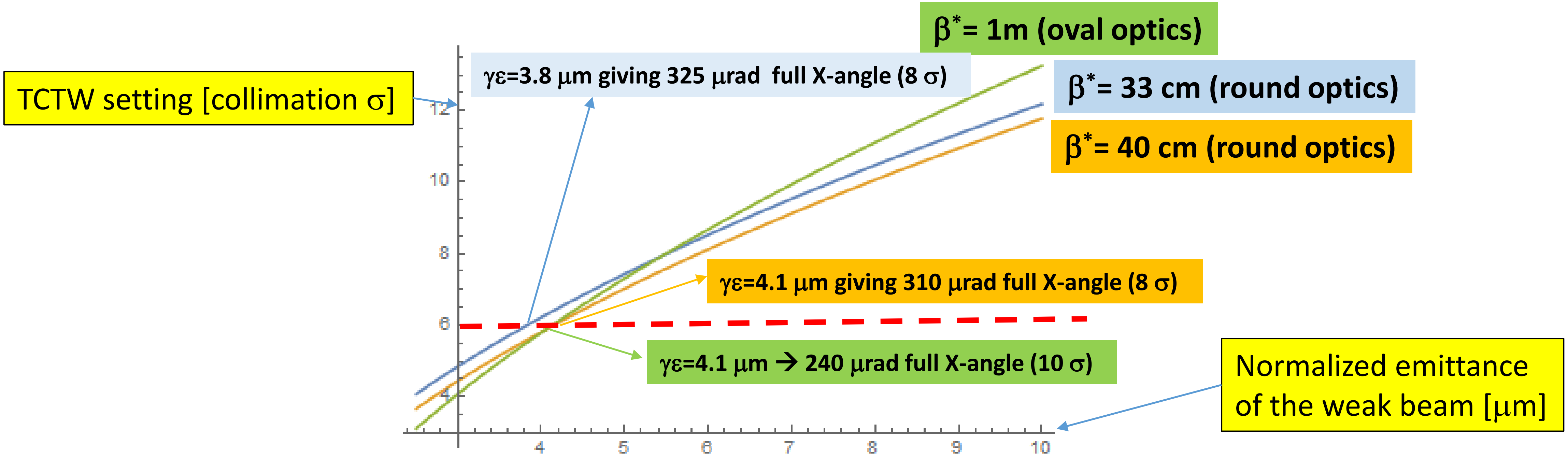
Can we find any configuration for 2017 to test the full correction?

.. Assuming

(i) <u>Minimum allowed TCTW gap</u> of 6 collimation σ (i.e. calculated for γε=3.5 μm)

(ii) <u>Targeting a X-angle of 8 (10) beam σ</u> in round (oval) optics to see convincing life time drops (.. and recovery), i.e. ~ 10 (12) beam σ for the wire at the smallest β.

(iii) Trying <u>β*=33 - 40 cm for round optics, β*= 1 m in the X-plane for "oval" optics</u>



It looks really tricky in all cases, and round optics still seems to be the most promising (easy) way to go

Conclusions & Outlook

- The present HW configuration (H-plane, 5-8 σ lost for wire integration in TCT jaw) makes the full test of the HL-LHC Plan B rather challenging

- **Testing the octupole compensation is however still perfectly within reach and potentially very beneficial, at least with round optics**

→ See Sasha's talk

- Something however still deserves work and a particular attention, which is an attempt for **global correction (all RDTs)**, re-phasing appropriately the optics, with the aim

(i) to use the **TCTW/TCLW in IR5 to compensate IR1 with "true" flat optics & H crossing** for the demonstration with beam

(ii) then, to **envisage installing wires in TCP7 or TCSG7** (existing or additional ones?), with the right current rating (..), and make the technique fully operational (i.e. w/o gymnastic needed with emittance growth and/or non-nominal collimator settings ..)