Optics limitations and solutions for the Phase-I LHC IR upgrade Project

S. Fartoukh BE-AP
with contributions from *B. Holzer, E. Laface, J. Miles, F. Schmidt, R. Tomas*

- → **Basic concept with wide aperture NbTi quadrupoles.**
- → **Optics & Performance limitations … a simplified overview**
  - **- Inner triplet (IT) and Matching Section aperture**
  - **- Chromatic aberrations**
  - **- Field quality**
  - **- Beam-beam**
- → **Complete solution for $\beta^* \geq 30$ cm**
  - **- Layout, Optics & Aperture of the new IR**
  - **- Chromatic correction** (off-momentum β-beat, non-linear chromaticity)
  - **- Squeeze**
- → **Tracking results at injection and collision**
- → **Summary and discussion**

The basic Principle

→ **Simple & Universal but "*à consommer avec modération*"!**

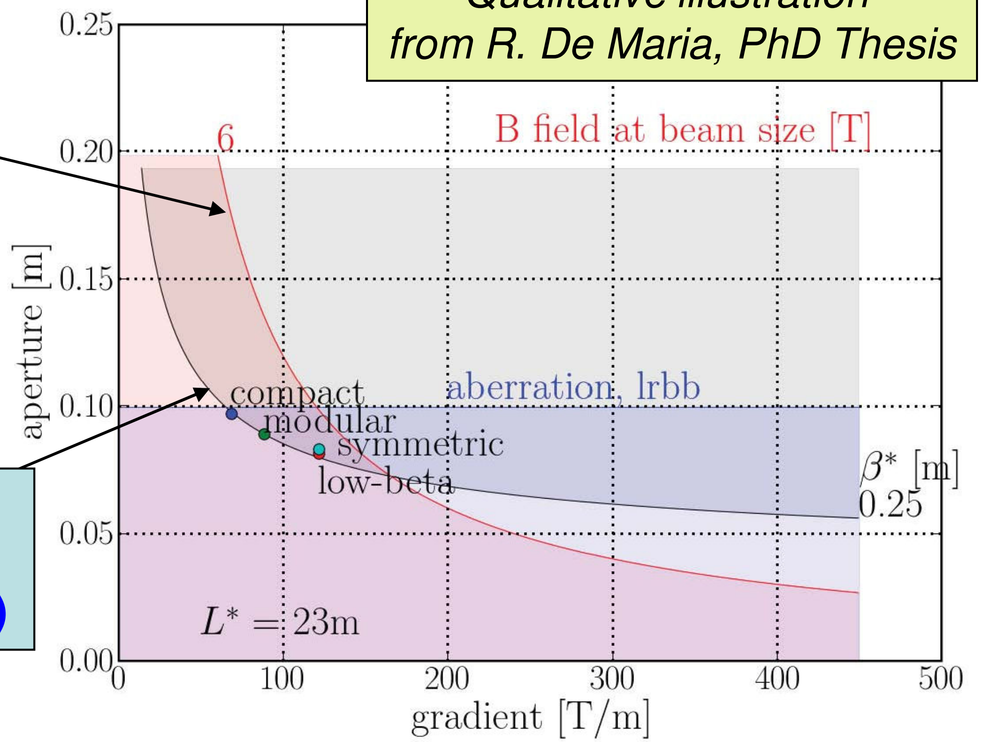
"For any given β^*, a long enough inner triplet with weaker gradient can always offer more aperture than needed by the beam" … Where is the limit?

Max coil aperture for a given gradient G_q and a given technology:
→ Roughly: **Coil-ID $\propto B_{peak}/G_q$**

Max useful aperture (beam-screen)
→ **B.S.-ID ~ 80% × Coil-ID $\propto 1/G_q$**

Min beam-clearance needed
at a given β^*, roughly:
Beam-OD $\propto (\beta_{max})^{1/2} \propto 1/(\beta^{*\,1/2}\, G_q^{\,1/4})$

Qualitative illustration from R. De Maria, PhD Thesis



Limitations (1/4)

- **Inner triplet (IT) aperture & Gradient (2008 CDR):**
  - → Phase-I Proposal : **120 mm coil_ID @ 121 T/m** (80% of the short-sample limit).
  - → **~ 100 mm beam clearance** (beam-screen ID).
  - → **Max. possible β_{max} <11 km giving β^* ≥ 30 cm @ G_{mqx} ~120 T/m,** with almost no aperture margin in the new IT(n1~7.5).
  - → Why not having proposed **~ 140 mm @ ~ 100 T/m** to reach **β^* = 25 cm with still a comfortable aperture margin in the IT** (n1~9) **?**

- **Matching section (MS) aperture (LPR1050 & LIUWG-2 & 15)**
  - → **β_{max} < 12 km in the new IT** imposed by **MS aperture restrictions** & **gradient limits for the MS and DS quadrupoles** (Q5/Q6→0T/m, Q7→200T/m)
  - → **Ultimate β^* of 27-28 cm @ 120 T/m** but with **strictly 0 optics flexibility.**
  - → **β_{max} < 11 km (β^* ≥ 30 cm)** imposed by the **IT chromatic correction** (for 550A nominal current in the sextupoles, see later).

The second principle: *"With a limit on β_{max} imposed by an non-upgraded part of the ring, the min. possible β^* (for a given secondary halo and X-angle in units of σ) is no longer a free design parameters BUT a simple OUTPUT!"*

Limitations (2/4)

- **Chromatic Aberrations** **(LIUWG-15): Cure needed!**

Off momentum β-beat $\Delta\beta(\delta)/\beta(0)$

→ $\partial\beta/\partial\delta \propto \beta_{max}$, $\partial^2\beta/\partial\delta^2 \propto (\beta_{max})^2$, …

→ **$\Delta\beta(\delta)/\beta(0)$ up to 160% @ $\delta=10^{-3}$** in one of the two collimation IR's

→ **Hierarchy of the collimation devices!**

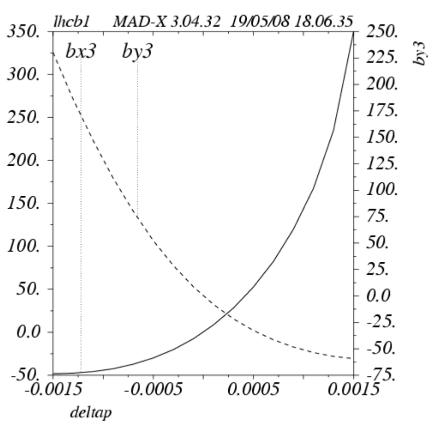
Non-linear chromaticities Q'', Q''' …

→ Q'' can be cured by IR phasing

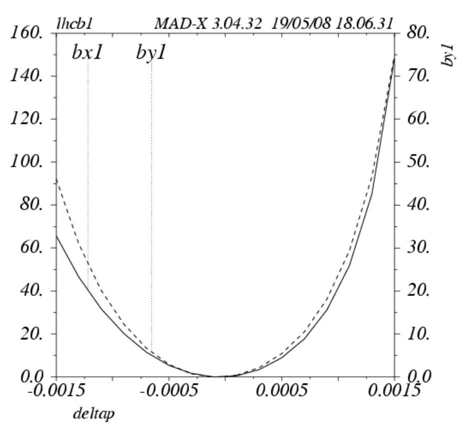
→ **$Q''' \propto (\beta_{max})^3$: WP sent to the 3[rd] order @ $\delta=10^{-3}$**

→ **Clear impact on DA (1 σ effect).**

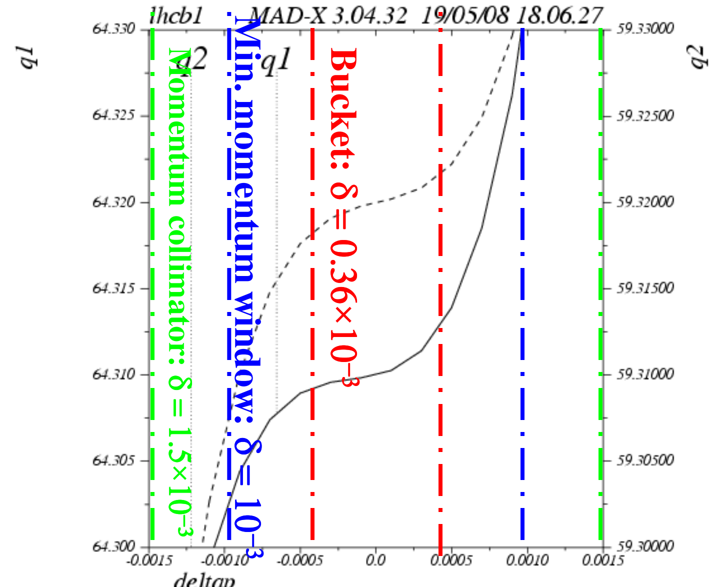
→ **Impact on beam life time vs δ** (RF trims, tidal effects)?



$\Delta\beta(\delta)/\beta(0)$ [%] in IR3
→ **Up to 160% @ $\delta=10^{-3}$**



$\Delta\beta(\delta)/\beta(0)$ @ the TCP of IR7
→ **Up to 60% @ $\delta=10^{-3}$**

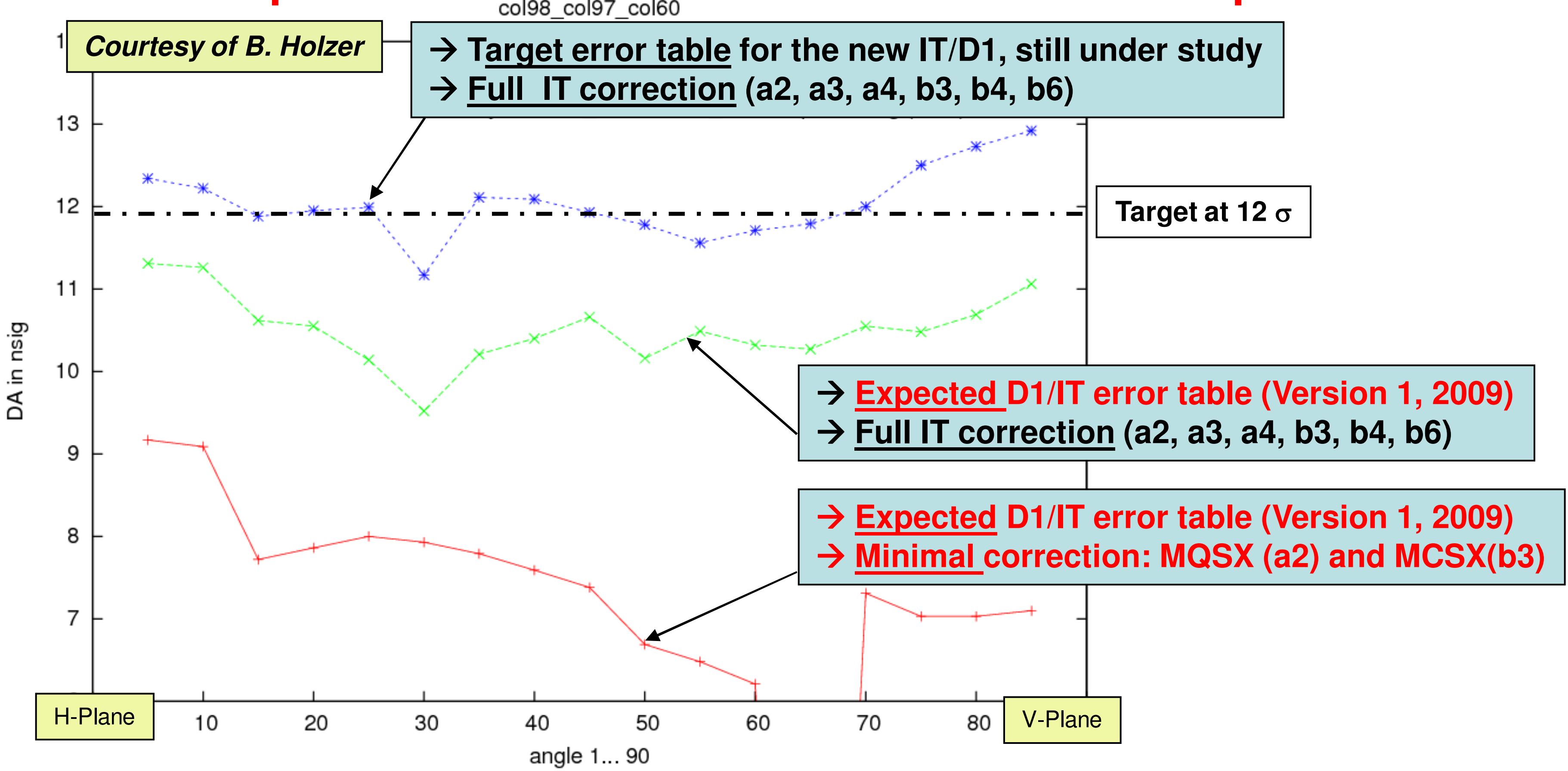


Tunes vs δ: $Q_{x,y}(\delta)$

Limitations (3/4)

- **Field quality**

→ Must be improved & full set of IT correctors must be implemented



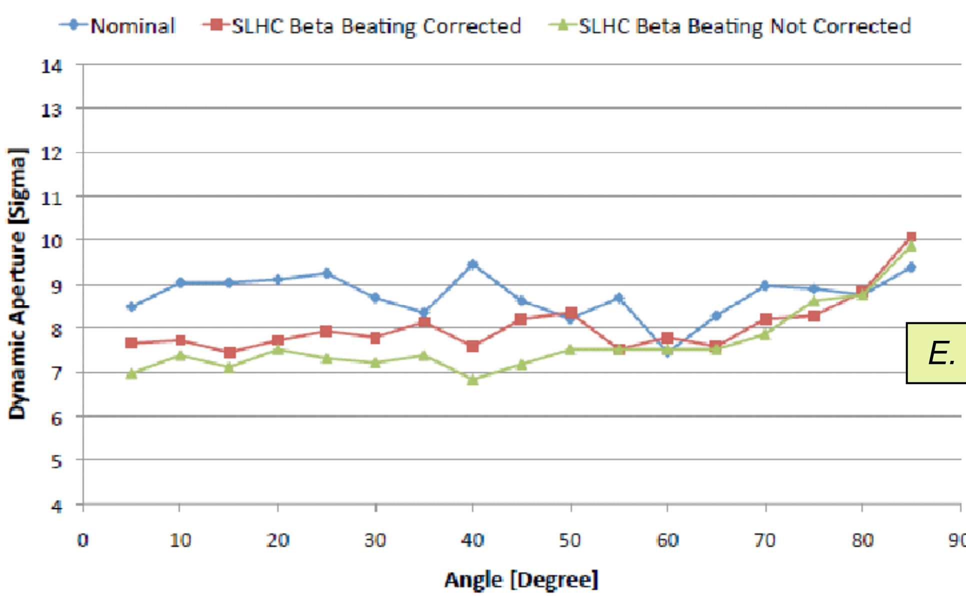
100'000 turns Dynamic aperture of the SLHC in collision (β^* = 30 cm):
→ Minimum found for 60 different field error realizations (seeds).

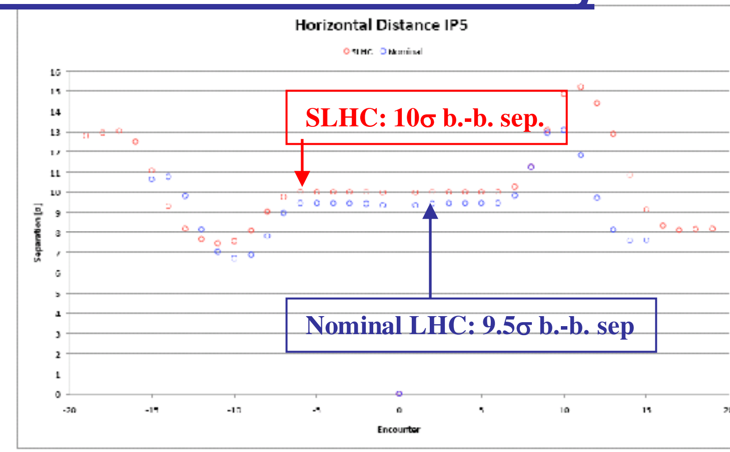
Limitations (4/4)

- **Beam-beam**

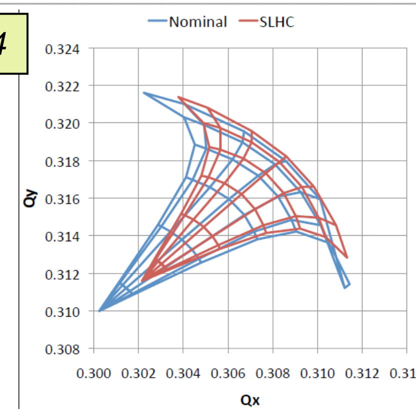
→ **From 15 (nom. LHC) up to 21 long-range beam-beam interactions** for the latest IT layout, not only justified by the lengthening of the new IT.

→ With **a target of 19 b.-b. encounters**, simulations w/o field errors already show a **DA reduction of 1-1.5 σ w.r.t. the LHC at nominal intensity.**





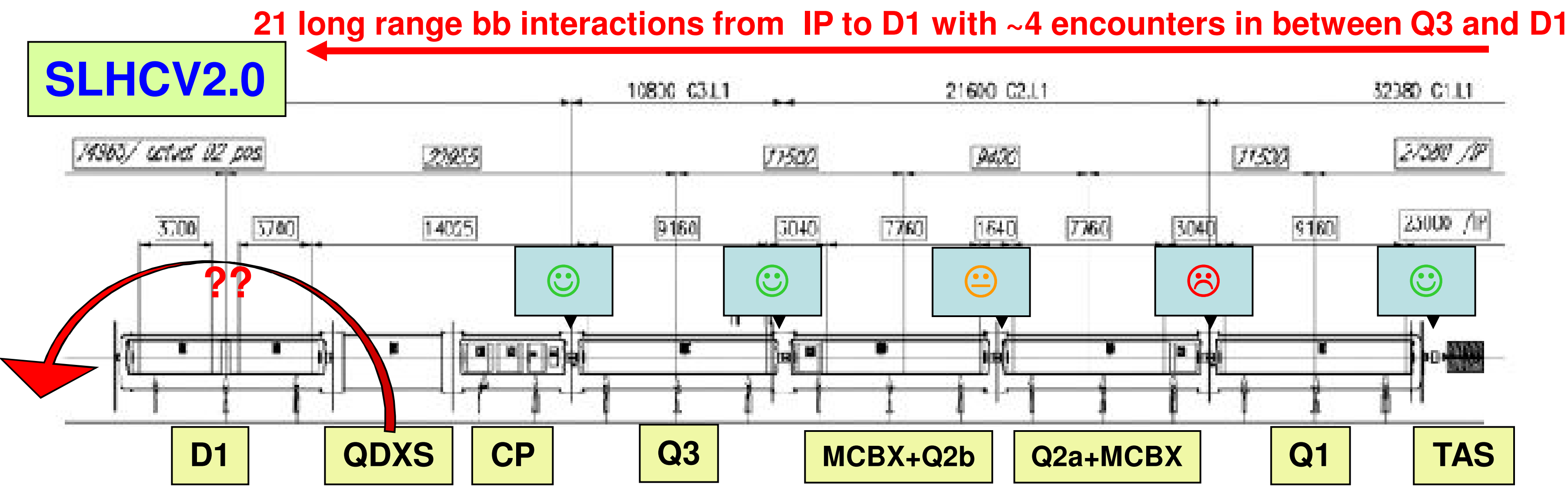
E. Laface, LIUWG-24



A complete solution for $\beta^* \geq 30$ cm (1/4)

- **Layout**

→ **Two different versions developed in 2009 with similar β_{max}**



Triplet → **2 types of different length** Q1/Q3 & Q2a/b**:** 120 mm coil ID, 123T/m(Q1,Q2) & 122T/m(Q3)

Orbit corrector → **MCBX in the Q2a & Q2b cold masses: Double plane highly desirable (sLHC-PR30)**

BPM → BPMSW in front of Q1, 4 cold BPM's in the IT: **all except 1 BPM very close to optimal positions.**

Corrector package (CP) → MCBXH/V, MQSX(a2), MCSX(b3), **(a3, a4, b4, b6) not yet implemented.**

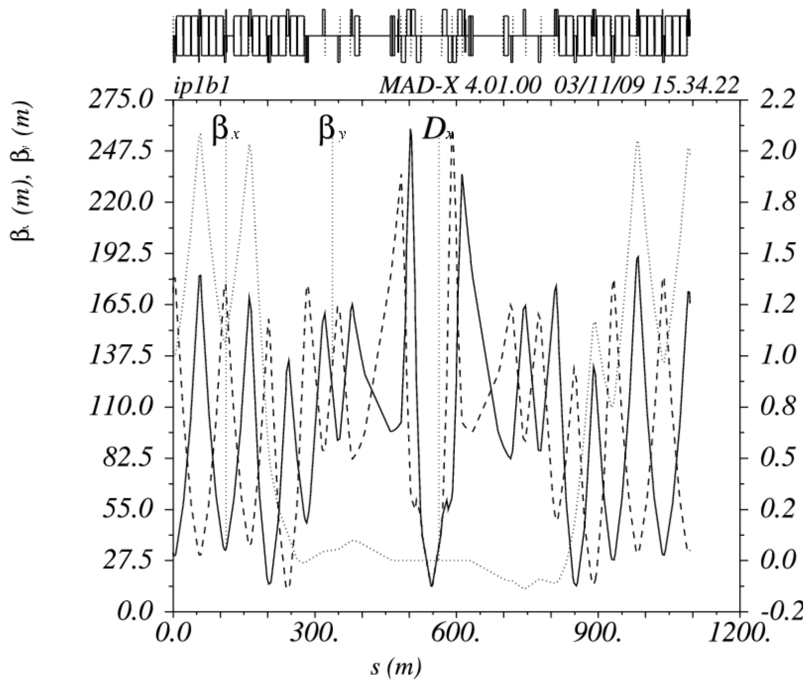
Separation dipole → **New D1** using 2 RHIC DX magnets per D1: 180 mm aperture, ~30Tm ITF.

TAS/TAN → **New TAS** (50 mm aperture), **new TAN** with wider aperture not yet defined.

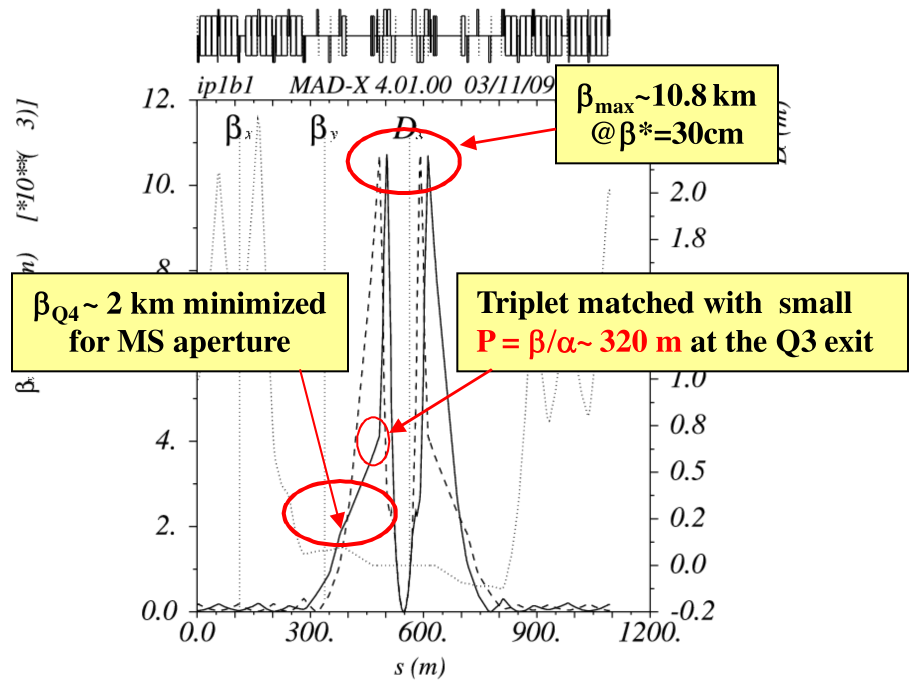
Matching section → **Nominal**

A complete solution for β* ≥ 30 cm (2/4)

- **Optics, X-scheme & Aperture**

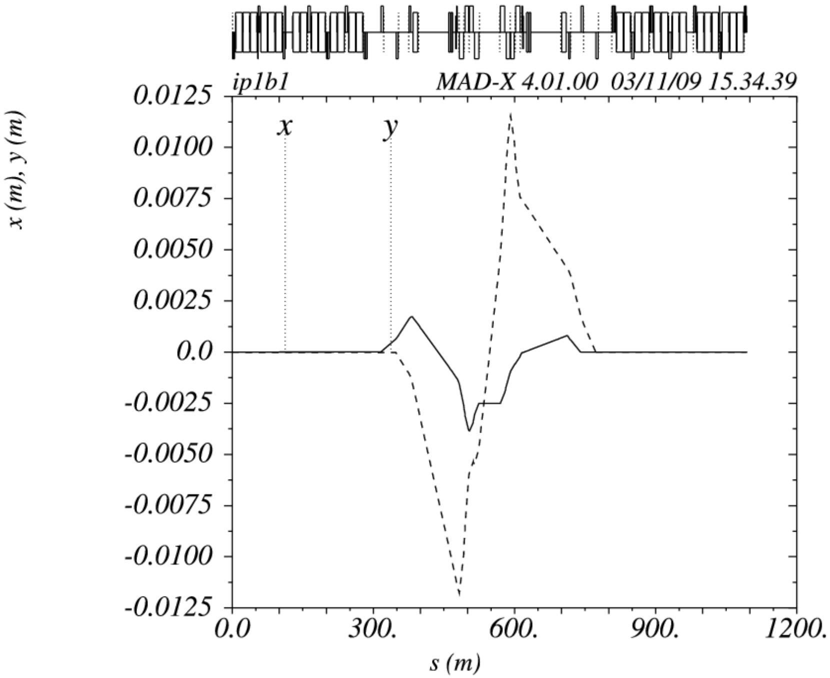


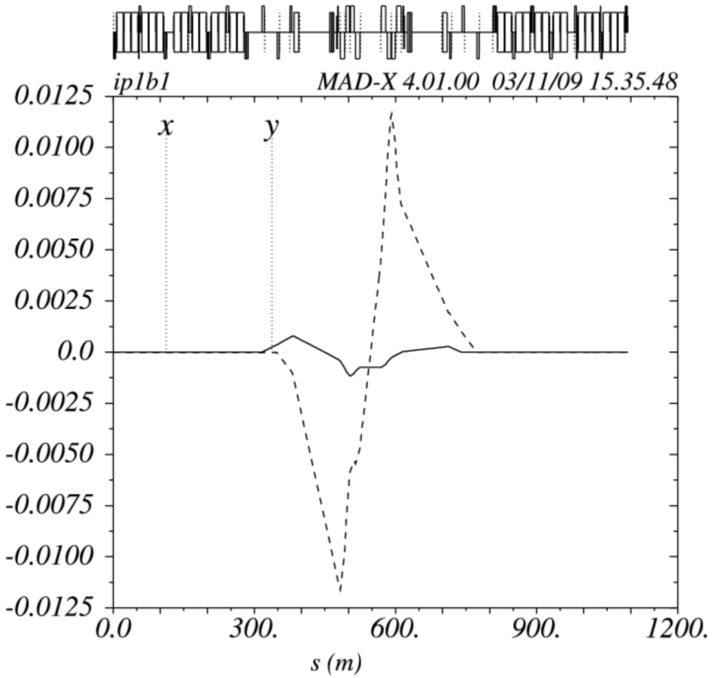
Injection: β*=14 m



Low-P Collision optics: β*=30 cm
(matched with specific L/R phase advances for IT chromatic correction, see later)

- **X-scheme**

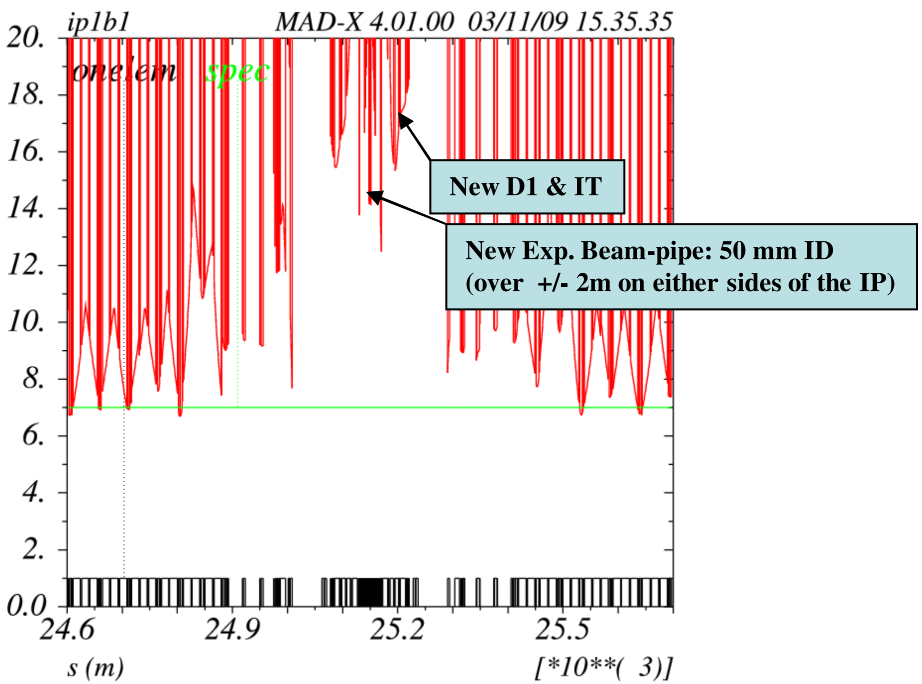


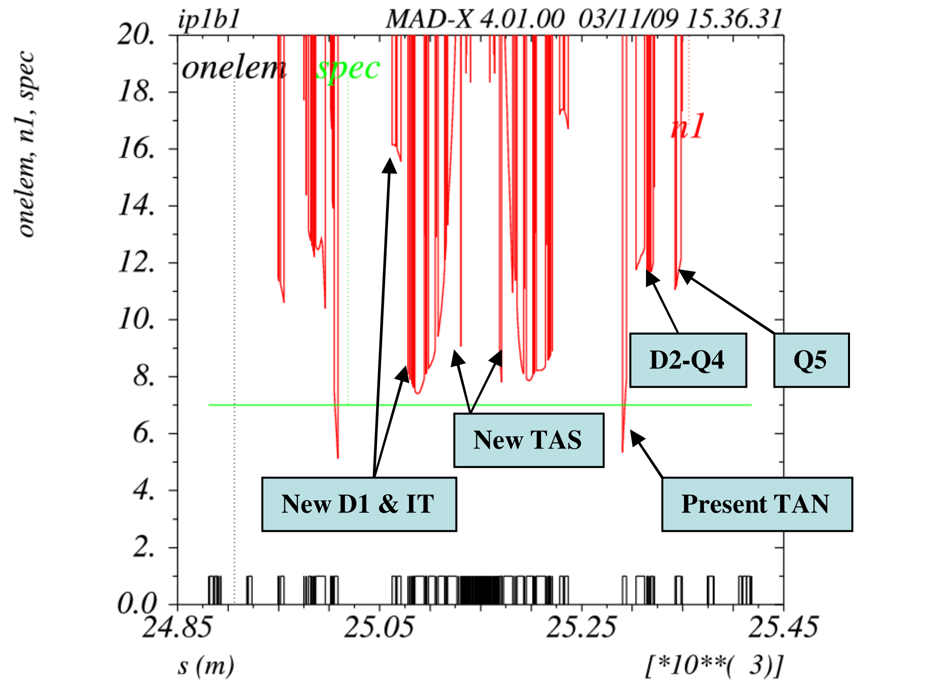


Injection (β^* =14 m):
→ 5.0 mm full separation
→ 410 μrad full X-angle
(~17σ bb separation with X-angle)

Collision (β^* =30 cm):
→ 1.5 mm full separation
→ 410 μrad full X-angle
(10σ bb separation with X-angle)

- **Aperture**





Aperture at Injection (β^* =14 m):
→ **Clear**

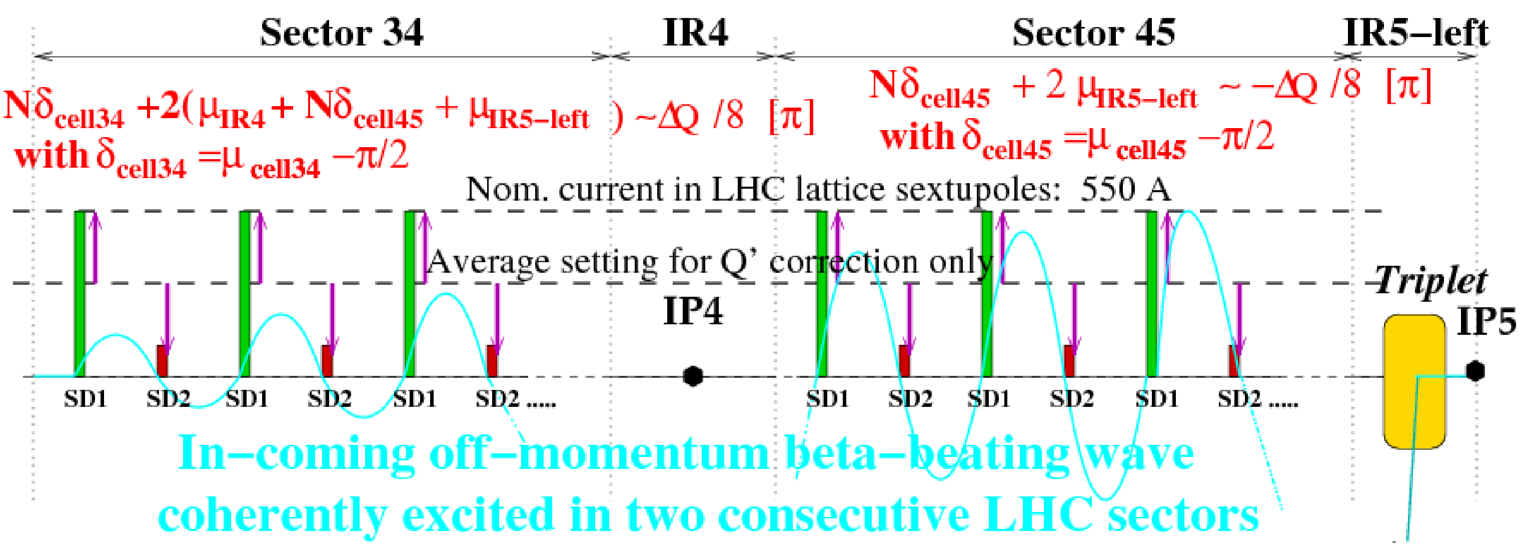
Aperture in Collision (β^* =30 cm) calculated with nominal CO (3mm) & β-beat (20%) tolerance
→ n1~7.4 in the IT
→ n1~10-11 in the MS
→ **The TAN is the bottle-neck (n1~5.5 in V-crossing)**

A complete solution for β* ≥ 30 cm (3/4)

- **Solution for the IT chromatic correction (LIUWG 15 & 22)**

→ A new LHC overall optics fulfilling specific phasing conditions

Schematic vertical off-momentum beta-beating wave induced by the SD families in sectors 34 and 45



→ **SD1/2 & SF1/2 families excited in up and down mode to generate an off-momentum beta-beat wave.**
→ **Two sectors of sextupoles are needed for the chromatic correction of one single triplet.**
→ **For the Phase I triplet (120 T/m), this limits β* to 30cm (some SD families pushed 550A).**
→ **Specific phasing conditions imposed all over the ring (arc cells, IR's, left & right phases of IR1/5), with still some room for fine tune adjustment.**

→ **A new overall LHC optics with appropriate phasing properties** has been constructed to allow the chromatic correction of the new IT in collision.

→ **Overall tune split of 3** (63.28/60.31 at injection, 63.31/60.32 in collision).

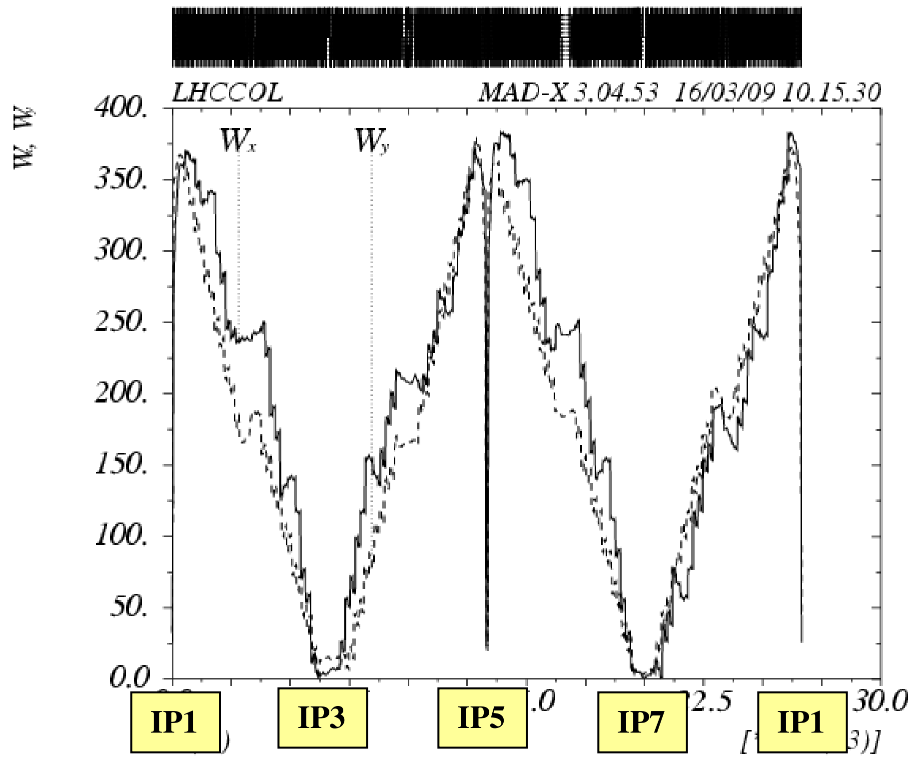
→ **Arc optics**: QF/QD strengths all different in the 8 LHC sectors (with some symmetries) and arc MQT's (from Q14 to Q22) with non-zero nominal settings.

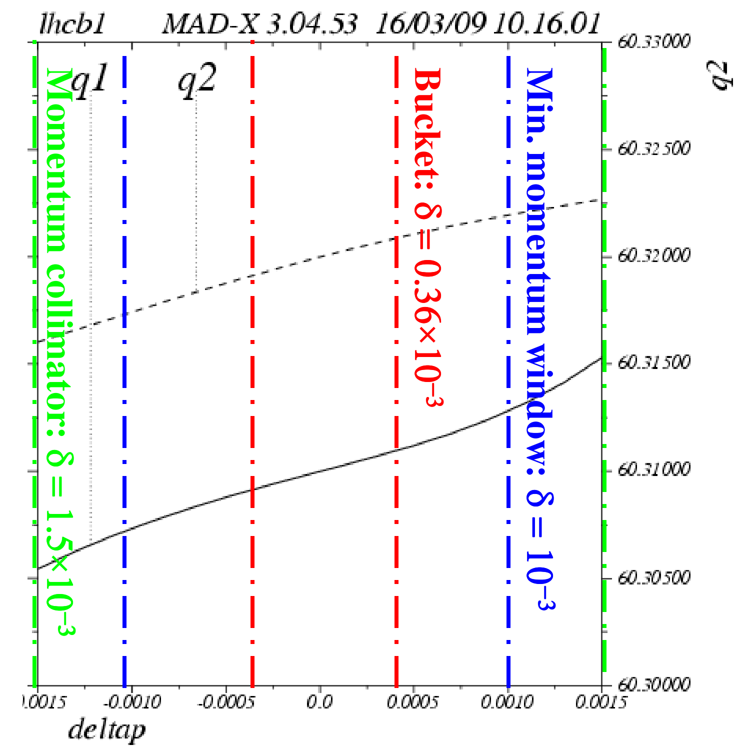
→ **IR's: New phase advances in the 8 LHC IR's (with some symmetries) and <u>left/right phase of IR1&5 constrained individually in collision.</u>**

Arc cell phase $\Delta\mu_x$ / $\Delta\mu_\psi$ [2π] and MQT settings	V6.503	SLHCV2.0
Sector 12	0.2635 / 0.2431	0.2598 / 0.2500
Sector 23	0.2635 / 0.2431	0.2531 / 0.2489
Sector 34	0.2635 / 0.2431	0.2530 / 0.2486
Sector 45	0.2635 / 0.2431	0.2600 / 0.2504
Sector 56	0.2635 / 0.2431	0.2598 / 0.2500
Sector 67	0.2635 / 0.2431	0.2541 / 0.2488
Sector 78	0.2635 / 0.2431	0.2525 / 0.2483
Sector 81	0.2635 / 0.2431	0.2600 / 0.2504
RQTF RQTD	0 0	10→12A @ 450 GeV 2→3A @ 450 GeV

IR phase $\Delta\mu_x$ / $\Delta\mu_\psi$ [2π] and overall tune	V6.503		SLHCV2.0	
	Beam1	Beam2	Beam1	Beam2
IR2	2.974 / 2.798	2.991 / 2.844	3.020 / 2.900	3.020 / 2.900
IR8	3.183 / 2.974	3.059 / 2.782	3.020 / 2.900	3.020 / 2.900
IR3	2.248 / 1.943	2.249 / 2.007	2.255 / 1.955	2.255 / 1.955
IR4	2.143 / 1.870	2.143 / 1.870	2.260 / 1.650	2.260 / 1.650
IR6	2.015 / 1.780	2.015 / 1.780	2.010 / 1.900	2.010 / 1.900
IR7	2.377 / 1.968	2.483 / 2.050	2.455 / 1.970	2.455 / 1.970
IR1&IR5	2.633 / 2.649	2.633 / 2.649	2.670 / 2.644	2.670 / 2.644
IR1 & IR5 left	Never specified		1.070 / 1.754	1.605 / 0.890
IR1 & IR5 right	Never specified		1.600 / 0.890	1.065 / 1.754
Qx/Qy	64.31/59.32		63.31/60.32	

→ Off-momentum beta-beating amplitude W(s) (linear) and **chromatic variation of the tunes after correction** (β*=30 cm in IR1&5 and β*=10 m in IR2&8)





Off-momentum β-beating envelop after correction (W=100 ⇔ $\Delta\beta(\delta)/\beta(0)$=10% @ $\delta=10^{-3}$)

→ Vanishing in the collimation IR's

→ Vanishing in the new IT of IR1 & IR5

Betatron tunes vs energy

→ Almost linear up to δ=1.5 10^{-3}

(with Q' matched to 2 units)

A complete solution for $\beta^* \geq 30$ cm (4/4)

- **Squeeze … A very complex gymnastic!**

→ The LHC IR's were designed to be squeezable at **constant overall phase.**

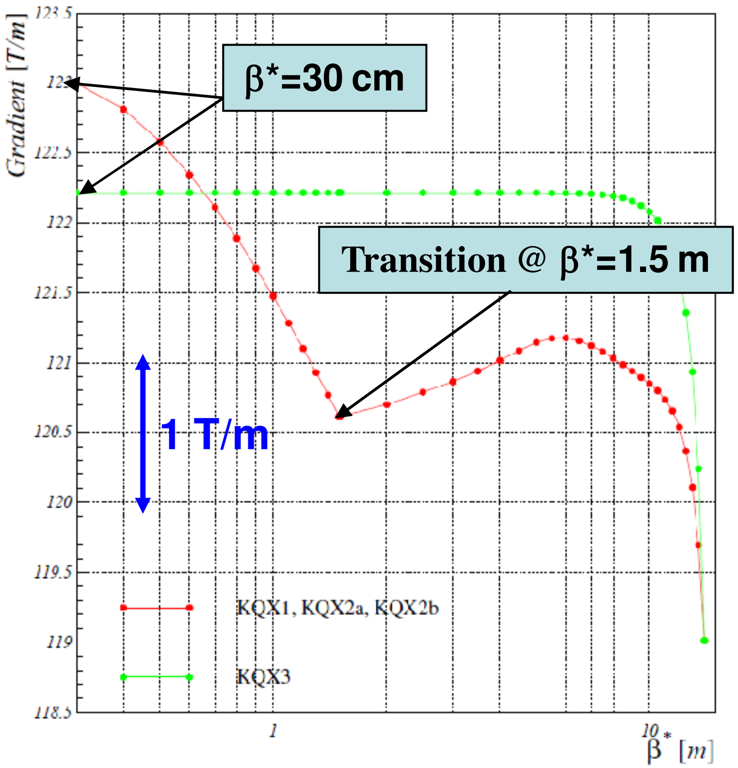
→ **Not enough tunability in the dispersion suppressors to make a full squeeze at constant Left and Right phase individually.**

→ Playing with the triplet settings during the squeeze (at the 2-3% level) is found the only way to **keep constant the Left/Right IR phase advance at least over a certain range of β^* : 30 cm < β^* <1.5m.**

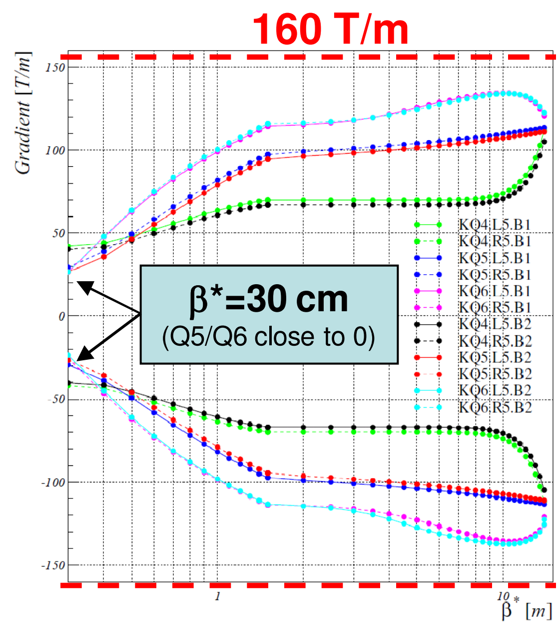
→ The squeeze is then done in **3 steps:**

1) **More or less "standard" up to β^*=1.5 m** at cst overall phase advance
2) **Stop at β^*= 1.5 m** to prepare the correction of the off-momentum β-beat (full use of the 32 sextupole families per beam).
3) **Continue up to β^*_{min} =30 cm** at cst Left/Right IR phase advance (to preserve the chromatic correction efficiency).

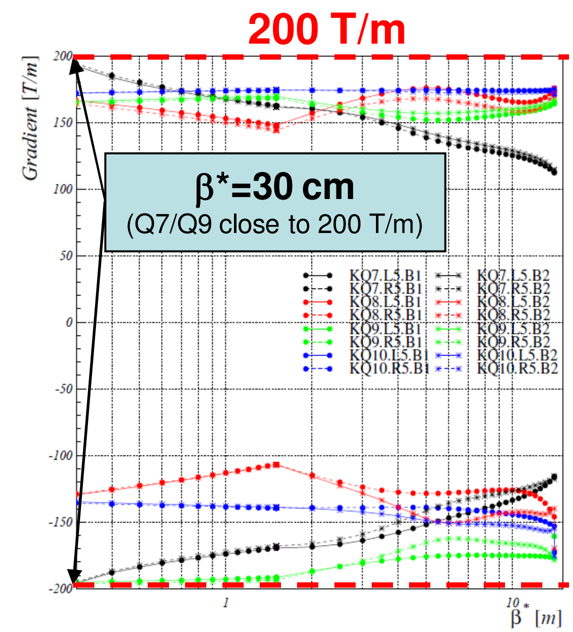
Inner triplet (IT)



Matching section (MS)



Dispersion suppressor (DS)



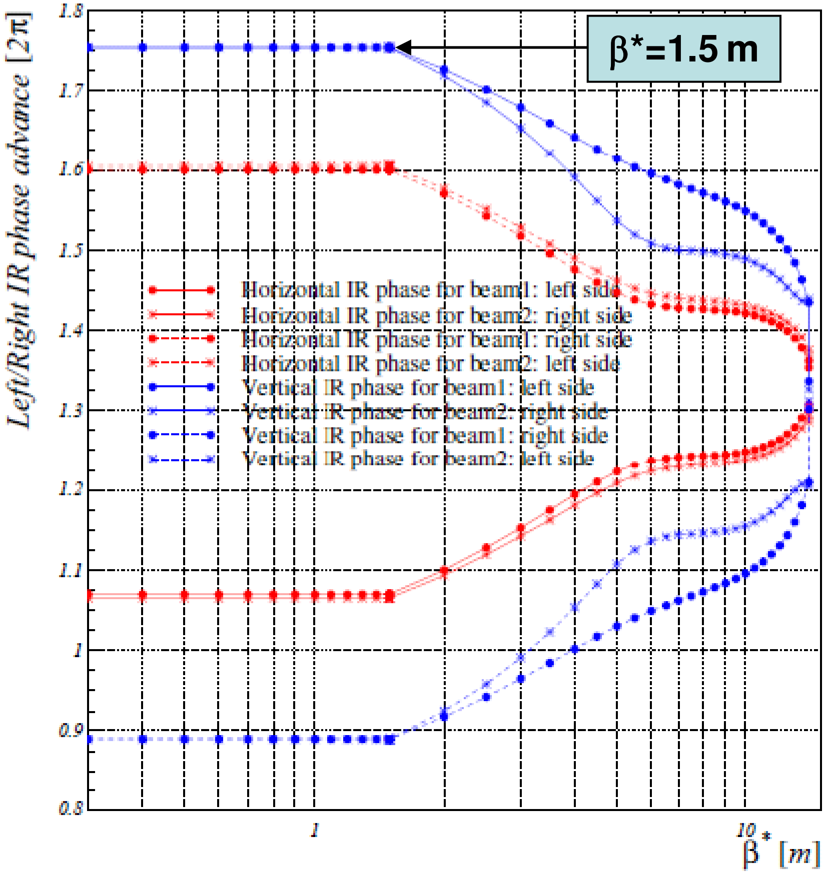
KQX gradients vs β* (log. scale)

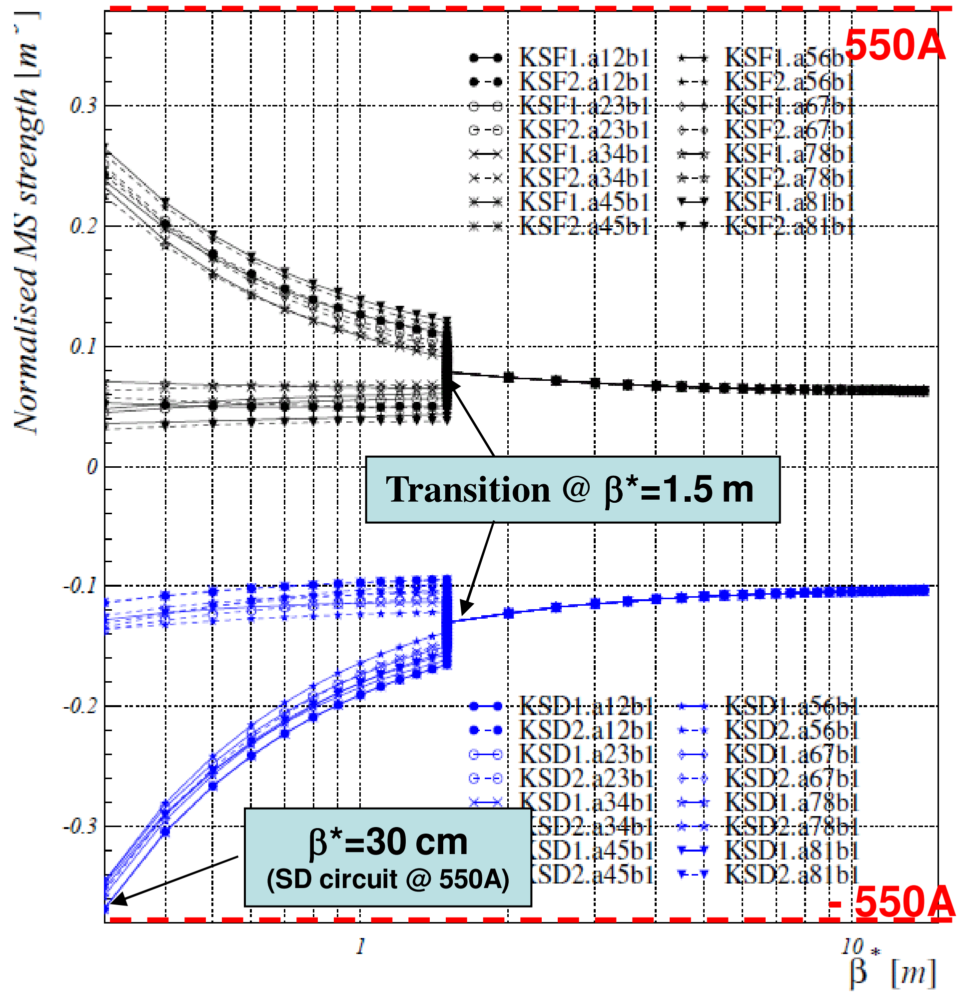
→ **Non-constant and non-monotonous**
(imposed by the IT chromatic correction and the preservation of the MS aperture at low β*)

MS (Q4/Q5/Q6) and DS (Q7→Q10) vs β*

→ **Smooth, but at the transition β*=1.5 m**
→ **KQ5 & KQ6 reaches 0 T/m at β* ~ 27 cm**
→ **KQ7 reaches 200 T/m at β* ~ 28 cm**

… Also some QT12 & QT13 close to 550 A at β*= 30cm





B1 & B2 left/right IR phase advances vs β*

→ Kept constant for 0.30 m < β* < 1.5m

Sextupole gradients (beam1) vs β*

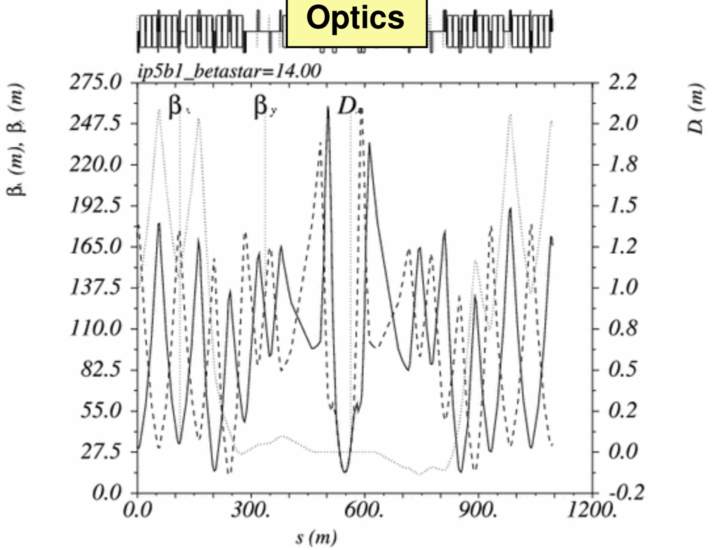
→ Squeeze at cst Q' down to β*=1.5 m (2 families)

→ Prepare the IT chromatic correction at β*=1.5 m

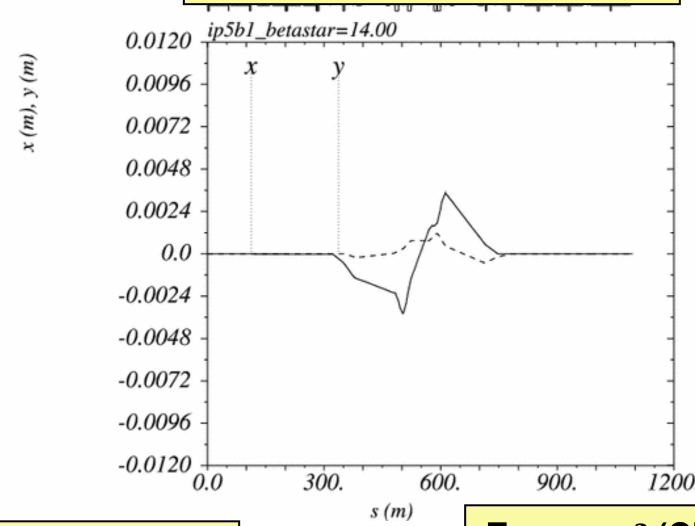
→ Squeeze down to 30 cm (some SD close to 550A)

→ How should it look like?...assuming ~**250 knobs perfectly synchronized.**

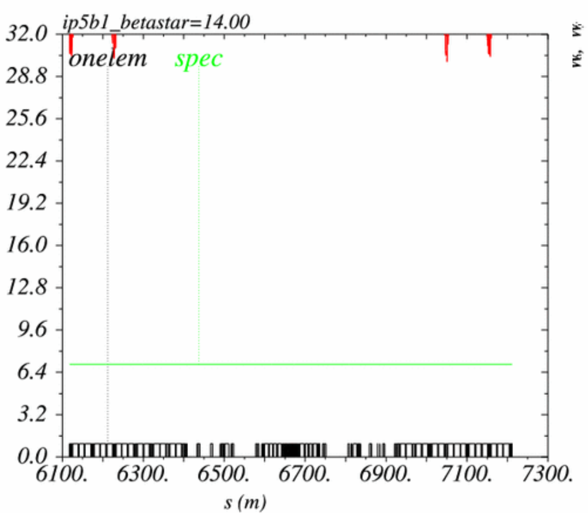
Optics



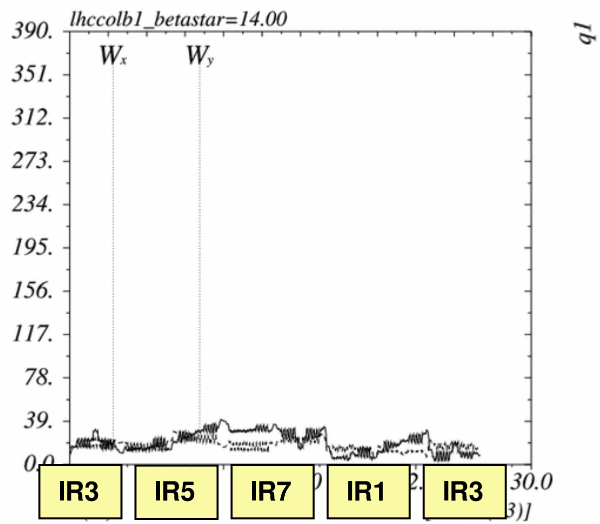
X-scheme(case of H-Xing)



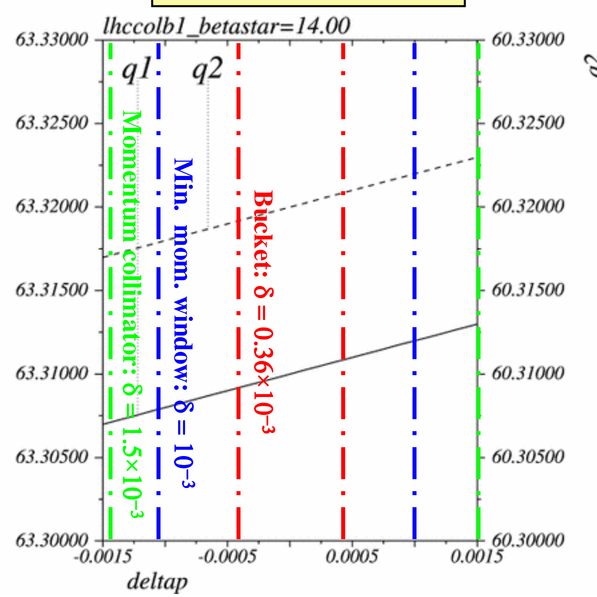
Aperture (H-Xing)



Off-momentum β-beating envelop



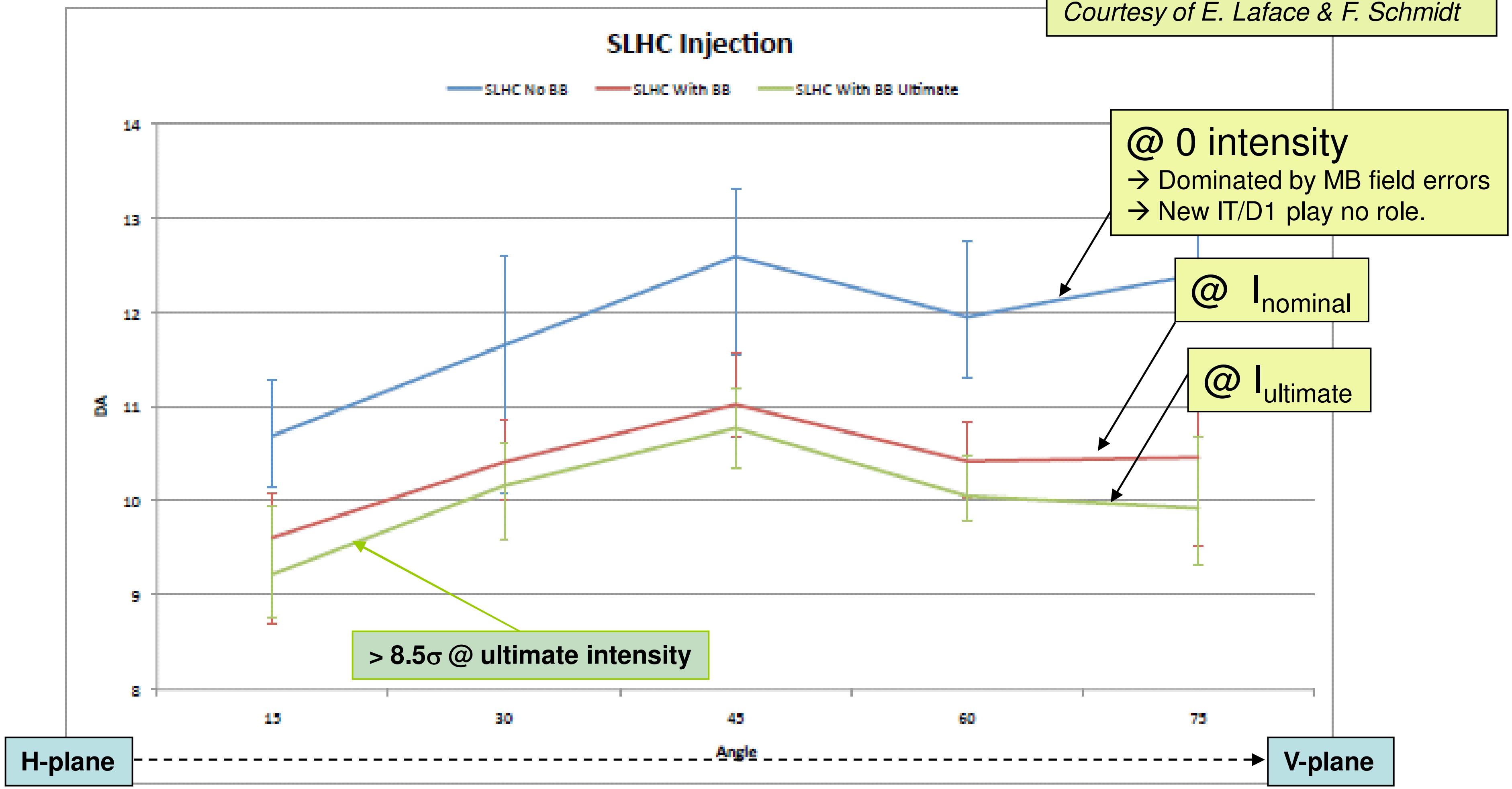
Tunes vs δ (Q'=2)



Tracking results

- **SLHCV2 dynamic aperture at injection** (β^*=14 m in IP1/5, β^*=10 m in IP2/8)

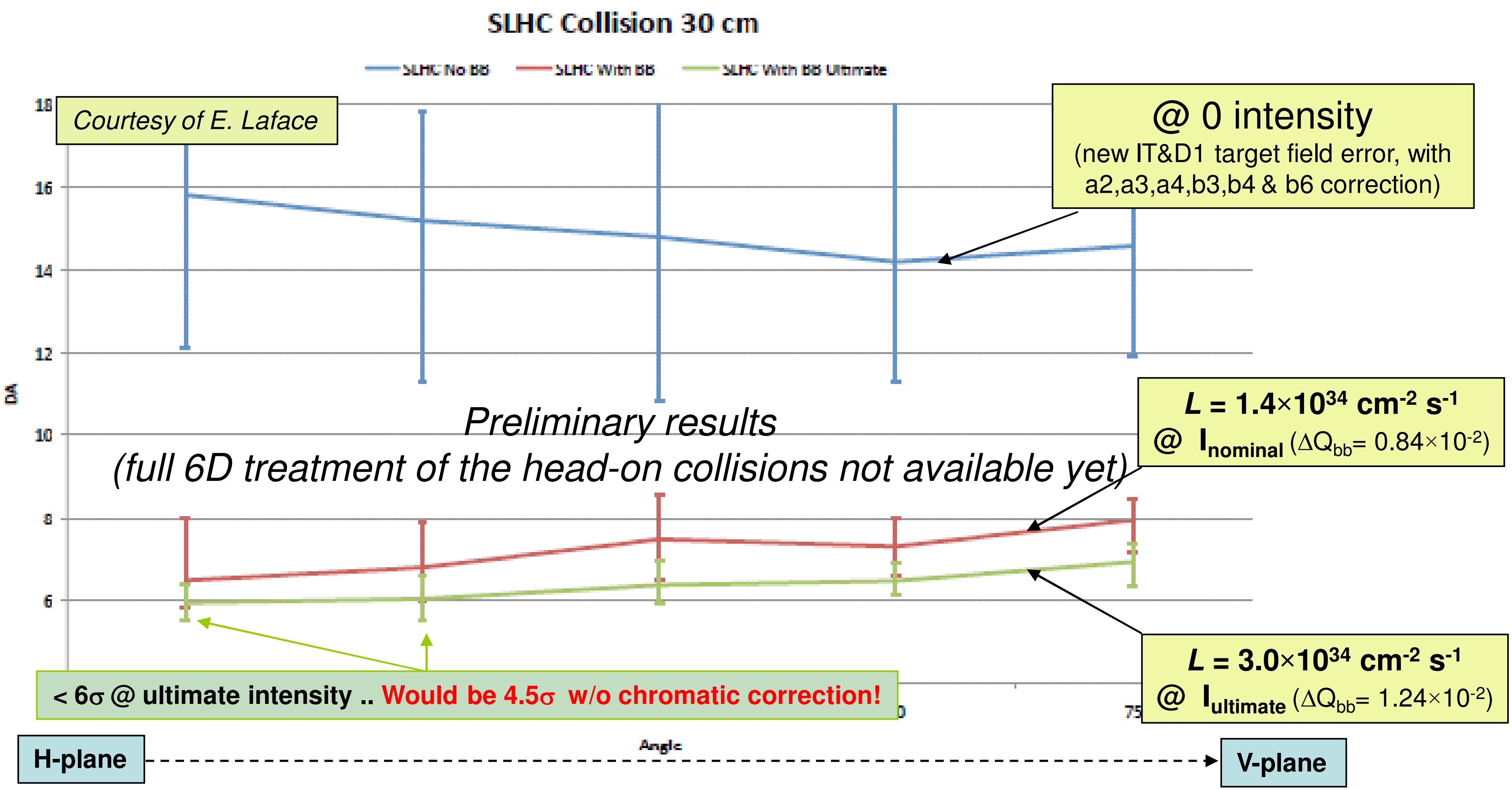
Courtesy of E. Laface & F. Schmidt



Average and min/max 1'000'000 turns SLHC dynamic aperture (DA) over 60 seeds at injection (β^*=14 m) w/o or with beam-beam effects (nominal and ultimate intensity)

- **SLHCV2 Dynamic aperture in collision**

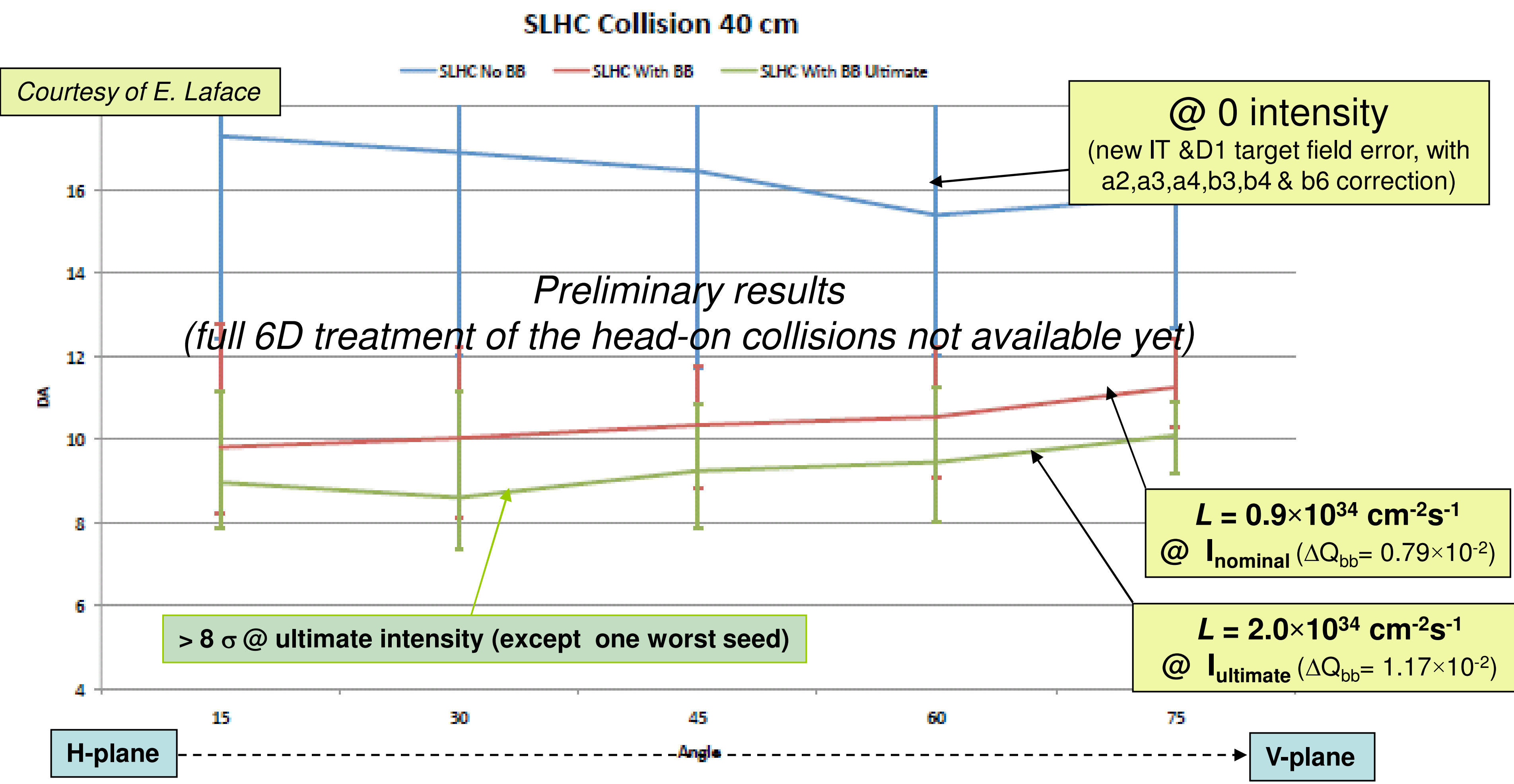
(beam colliding in IP1/IP5 @ β^*=30 cm and IP8 @ β^*=10m, halo collision in IP2 @ β^*=10m)



Average and min/max 1’000’000 turns SLHC dynamic aperture over 60 seeds in collision (β^*=30 cm, X-angle = 410 μrad = 10 σ b.-b. separation) w/o or with beam-beam effects

- **"Back-up" collision optics relaxing β^* & increasing the X-angle**

(working at cst n1~7.5, up to reach the strength limits in the MCBC/Y @ Q4/Q5/Q6)



Average and min/max 1'000'000 turns SLHC dynamic aperture over 60 seeds in collision (β^*=40 cm, X-angle = 560 μrad ~ 16 σ b.-b. separation) w/o or with beam-beam effects.

Summary and discussion

- **An new overall optics** is needed for the chromatic correction of the new IT. **This means an almost new machine to be re-commissioned.**

- **A palette of solutions is possible in collision, between two extreme configurations, each of them hitting at least one hard limit given by the LHC ring @ 7 TeV:**

→ **β* = 30 cm → 40 cm:** lower β* hardly limited by **gradient limits** (lattice sextupole, IR quads) and then **MS aperture**.
→ **Full crossing-angle = 410 → 560μrad:** higher X-angle hardly limited by **MCBY/MCBC strength**
→ Giving a peak luminosity between **2×10^{34} cm^{-2}s^{-1} and 3×10^{34} cm^{-2}s^{-1} @ ultimate intensity.**

- **While the aperture of the new IT is clearly not questioned, the IT layout shall still be optimized keeping in mind these two extreme configurations:**

→ **Double plane MCBX** highly desirable for the quality of the orbit correction in the new IT, but also to decouple it from the generation of the X-scheme, otherwise a X-angle of 560 μrad is out of reach (sLHC-PR30).
→ **Minimize the number of parasitic b-b encounters:** QDXS moved on the non-IP side of D1, solution with N-lines?
→ Further optimize the **Field Quality of the new IT** (targets still to be finalized and a good compromise to be found) with a **particular concern for D1** (e.g. a factor of 5 missing for a2/b3 comparing the requirements and the first offer).

- The next step is to decide **what is the most likely configuration to "guaranty a reliable operation of the machine with a peak lumi ≥ 2×10^{34} cm^{-2}s^{-1} @ ultimate intensity".**

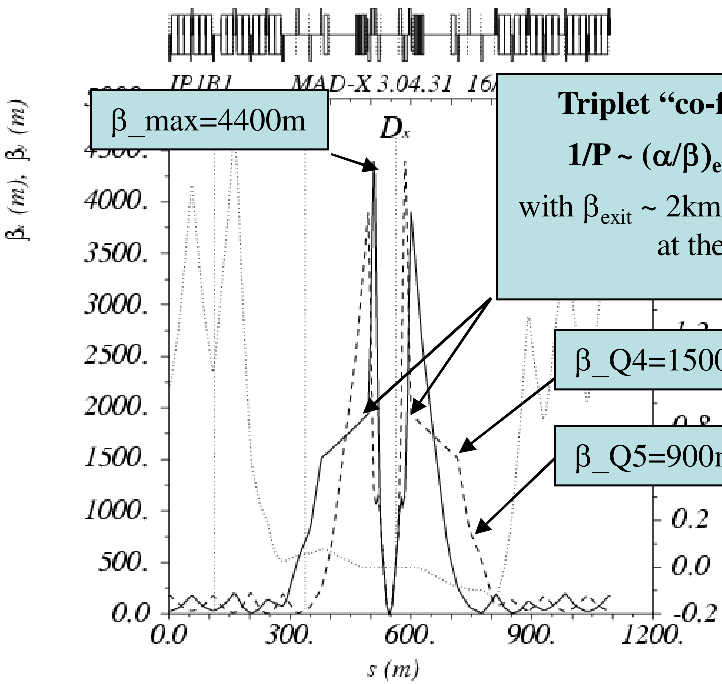
→ Why did we push for a wide aperture for the new IT?.. Certainly for beam-beam, collimation, but not necessarily **β* !**
→ **β* ~ 40 cm (→ 35 cm ?)** seems then to be the most promising option**, with a X-angle of ~13 → 16σ still to be fine tuned** for beam-beam, collimation efficiency and impedance (n1/n2), but also debris coming from the IP.

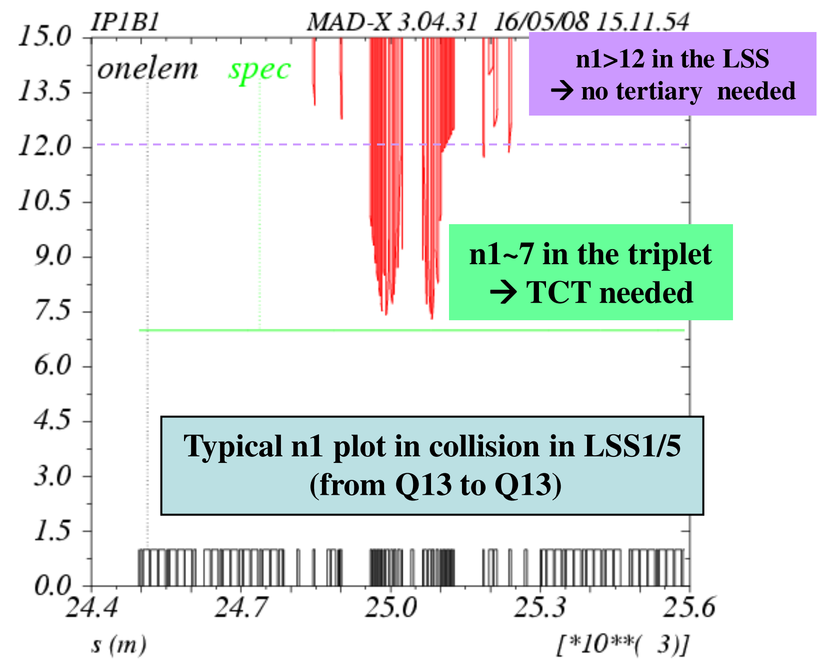
- **Further steps in this direction** shall not be forgotten **to restore operational margins on the "non-IT side"**, also because possibly easy (??) or already needed for the nominal machine:

→ Re-commission **the lattice sextupoles and Q7/Q9's (MQM @1.9K) at higher than nominal current.**
→ Install **warm orbit corrector at Q4** (~1 Tm) to reinforce the MCBY's for IP steering and Vernier scans @ 7 TeV.

… Reserve

→ A few words on the nominal low-β optics (β*=55cm)



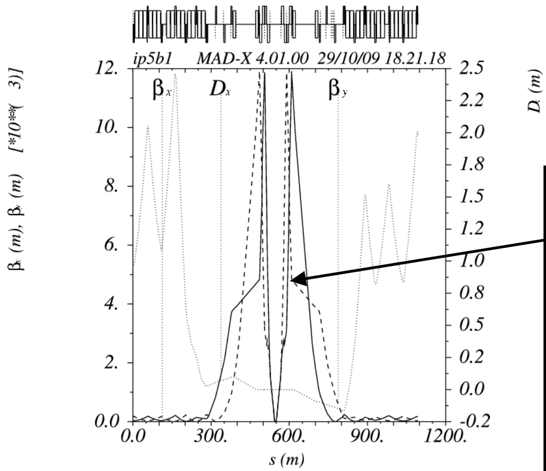


The **co-focal distance** $P_{x,y}$ is a fundamental parameter fixed by the triplet layout and powering:

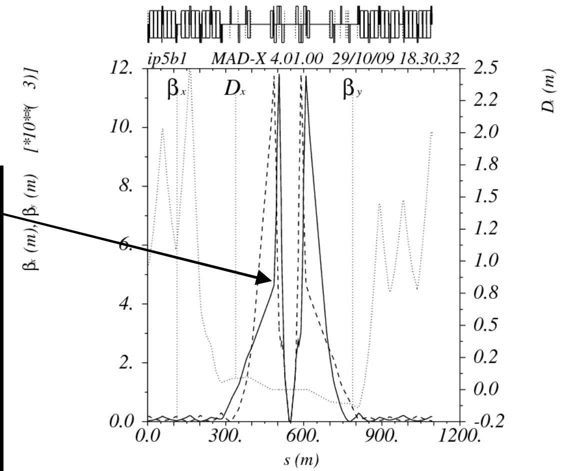
- → **Almost independent of β*** (up to β* ~1-2m) at **constant triplet layout & powering.**
- → Can be **arbitrarily chosen via the fine tuning of the triplet layout & powering.**
- → **"Low-P optics"** (i.e. larger α_{exit}) **improves the mechanical acceptance of the matching section (MS).**
- → **Too low-P optics are not "matchable" to the arcs**, i.e. MS and DS quadrupole gradients going to 0 or above nominal.

→ MS aperture & Gradient versus IT co-focal length $P=(\beta/\alpha)_{@Q3exit}$

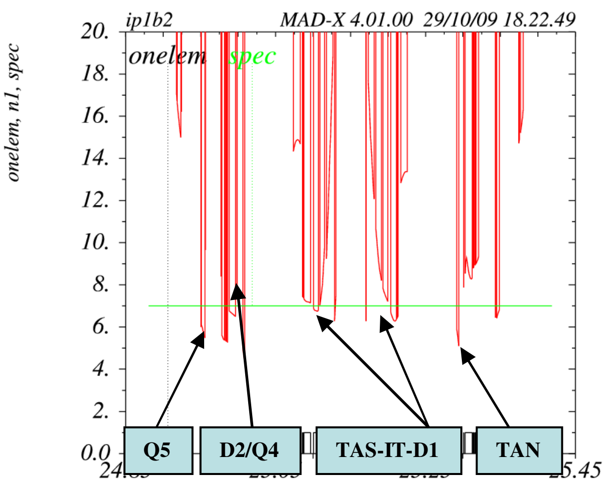
($\beta^*=0.25$ m assuming a very optimistic gradient of ~135 T/m in order to limit β_{max} below 12 km).

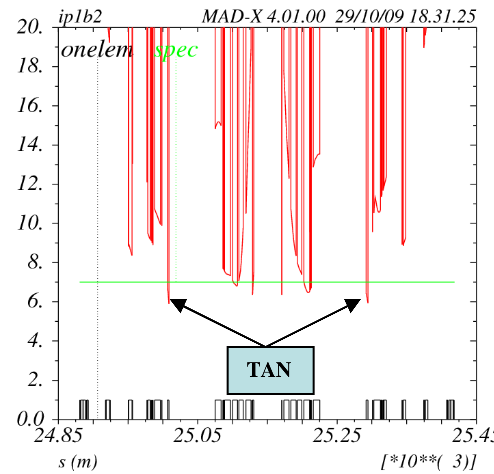


A difficult game!



Case	High P	Low P
Grad.[T/m]	**132.74**	**136.41**
Lq1=Lq3 [m]	8.70	8.50
Lq2 [m]	7.40	7.30
L* [m]	23.0	23.0
D(q1-q2a) [m]	2.50	2.70
D(q2a-q2b) [m]	1.00	1.00
D(q2b-q3) [m]	3.00	2.90
Beta_max [m]	11910	11810
P [m]	**891**	**328**
Beta_Q4 [m]	3750	2125
Beta_Q5 [m]	2220	1340





→ **DS and MS gradients well within limits but**
Aperture bottle-neck in the TAN-D2-Q4-Q5
(12km β_{max} is too much for 120 mm coil_ID)

→ **MS aperture restored (except at the TAN) but**
Quad. Gradient at the limit in the MS
(Q4/5/6→0, Q7~200T/m)

→ How to design a "good inner triplet" (IT) taking into account the **aperture constraints of the Matching Section** (MS)?

1) **Triplet Matched with 3 variables**: $L_{Q1} = L_{Q3}$, $L_{Q2a} = L_{Q2b}$ and G_{Q3}

($G_{Q1} = G_{Q2a} = G_{Q2b}$ fixed by the coil_ID, and the mag. to mag. distances between quadrupoles given by the hardware and other considerations, BPM, MCBX..)

2) **Triplet Matched with 3 constraints**:

- **Same peak beta-functions in both planes**:

$\beta_{x,max} = \beta_{y,max} = \beta_{max}$ (quite rigid quantity depending on the MQX gradient)

- **P_x & P_y matched to specified values** constrained by the **MS aperture** (→ **Pmax**) and **optics matchability to the arcs, i.e. MS and DS gradients (→ Pmin):**

$$P_{min}(\beta_{max}; \textbf{Layout}: IT \to MS \textbf{ distance}) < P < P_{max}(\beta_{max}; \textbf{MS aperture})$$

→ **$P_{max} < P_{min}$ for too high β_{max}, typically above ~ 12 or 13 km** depending on whether the Left/Right IR phase advance is constrained for the IT chromatic correction (see later).

→ **No complete optics solution can be found for β^*=25 cm with the (120 mm-120 T/m) Phase-I triplet** corresponding to β_{max} ~ 12.8 km (also IT aperture problem in this case).

→ **3 possible options**

1) **Increase P_{max}** with new **wider aperture MS magnets** → **Beyond the Phase I scope**
2) **Decrease P_{min}** **pushing the MS magnets towards the arc** (LIUWG-15) → **Rejected.**
3) **Incr. P_{max} & decr. P_{min} at cst MS**, by **reducing β_{max}** → **β^*= 30 cm** → **Approved.**

Limitations (2/4)

- **Chromatic aberrations** (LIUWG-15, LPR 308 & SLHC-PR20).

→ **Linear chromaticity:**

$$I_{x,y}^{L/R} \equiv \pm \int_{\text{Triplet L/R}} ds\; K_{MQX}(s)\,\beta_{x,y}(s)$$

with $I_x^L = I_y^R \;,\; I_x^R = I_y^L$

and $I_{MQX} \equiv I_x^L + I_x^R = I_y^L + I_y^R = 4\pi Q'_{MQX} \propto \dfrac{1}{\sqrt{G_{MQX}\,\beta^*}}$

- Nominal LHC: I_{MQX} ~ 350 @ β^*=50 cm (205 T/m)
- SLHC: I_{MQX} ~ 875 @ β^*=25 cm (120 T/m)

⇒ **For one single IR:**

Q'_{MQX} ~ -65 ~ $\Delta Q'_{nat.}$ induced by 8 LHC sectors!

→ **Q'' and linear off-momentum β-beating:**

$$\frac{\left(\frac{\partial \beta_{x,y}}{\partial \delta}\right)(s,\delta=0)}{\beta_{x,y}(s,\delta=0)} \equiv -\frac{I_{MQX}}{\sin(2\pi Q_{x,y})} \times \begin{cases} \cos(\Delta\mu_{x,y}^{1\to5} - 2\pi Q_{x,y}) \times \cos(\Delta\mu_{x,y}^{1\to5} - 2\mu_{x,y}(s)) \textbf{ between IP1 \& IP5} \\ \cos(\Delta\mu_{x,y}^{1\to5}) \times \cos(\Delta\mu_{x,y}^{1\to5} + 2\pi Q_{x,y} - 2\mu_{x,y}(s)) \textbf{ between IP5 \& IP1} \end{cases} \quad (2)$$

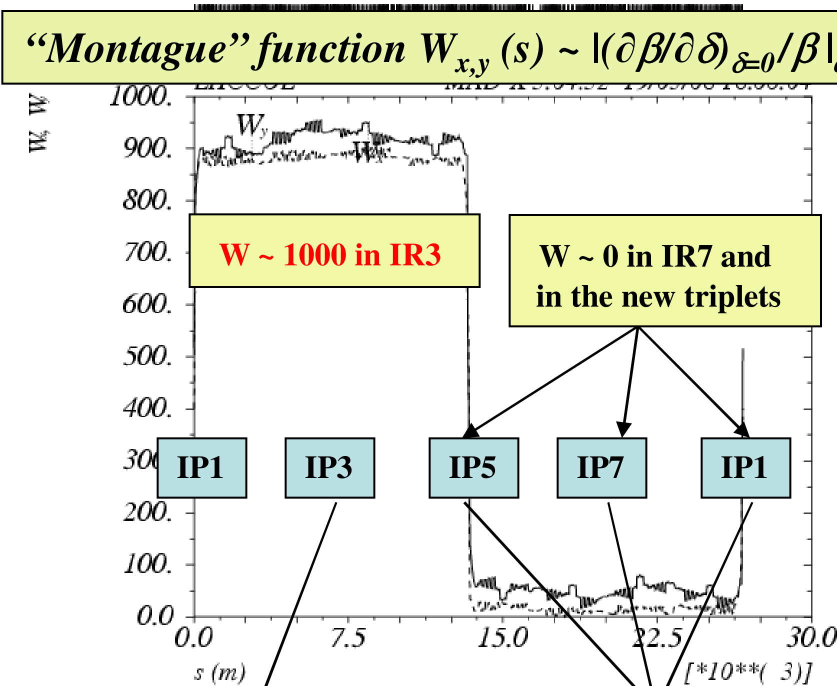
$$Q''_{x,y} = \mp \frac{1}{4\pi} \int_{\substack{\text{Triplets}\\ \text{IR1+IR5}}} ds\; K_{MQX}(s) \left(\frac{\partial \beta_{x,y}}{\partial \delta}\right)(s,\delta=0) = -\frac{(I_{MQX})^2}{2\pi \sin(2\pi Q_{x,y})} \times \cos(\Delta\mu_{x,y}^{1\to5}) \times \cos(\Delta\mu_{x,y}^{1\to5} - 2\pi Q_{x,y}) \quad (3)$$

- **The off-momentum beta-beating can reach ~100% for $\delta = 10^{-3}$.**
- **With π/2 [π] for the phase advance between IP1 and IP5**, it can be cancelled in half of the ring but then is maximized in the other half → **only one collimation can be preserved**

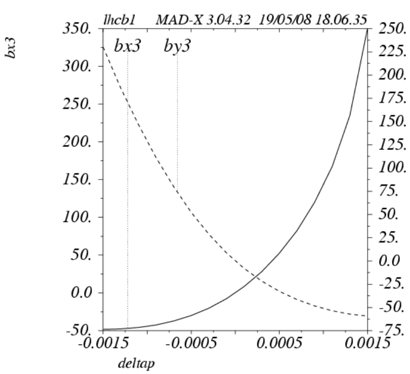
→ **Second (higher) order off-momentum β-beating** and signature by a **third (higher) order chromaticity Q'''.**

V6.503 overall optics with IR phasing and new IT in IR1 & 5 (β^*=25cm with Q4/Q5 pushed towards the arcs)

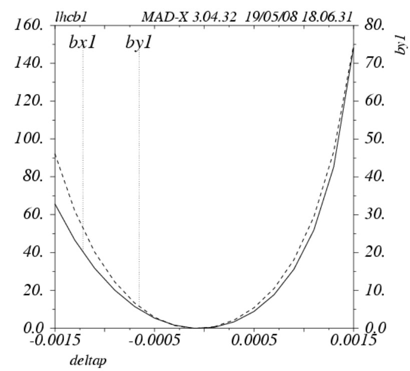
"Montague" function $W_{x,y}(s) \sim |(\partial\beta/\partial\delta)_{\delta=0}/\beta|_{amplitude}$



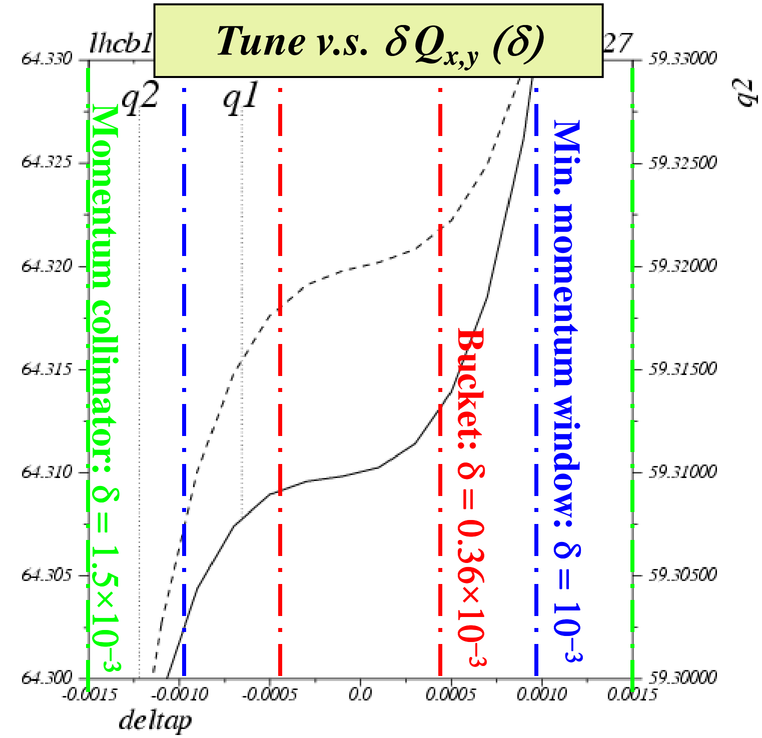
$\Delta\beta(\delta)/\beta(0)$ [%] in TCP in IP3
→ **Up to 160% @ $\delta=10^{-3}$**



$\Delta\beta(\delta)/\beta(0)$ in the IT or TCP of IR7
→ **Up to 60% @ $\delta=10^{-3}$**



Tune v.s. $\delta Q_{x,y}(\delta)$



- → **Beam life time vs tiny changes of momentum energy and background to the experiments?**
- → **Collimation efficiency!**
- → **Operational aspects (strictly same optics and simultaneous squeeze needed in IR1 & 5).**
- → **A new strategy, other than IR phasing, was needed and has been invented.**

Limitations (3/4)

- **<u>Field quality</u>**

→ Is expected to improve linearly with the IT aperture:

$$b_n\left(@R_{ref} = 1/3\,\mathbf{ID}_{\mathbf{coil}}\right) \propto 1/R_{ref}$$

(Todesco et al., sLHC-PR10)

→ Early estimate for the sLHC Dynamic Aperture (DA) in collision gave excellent results applying the above scaling law to the present field quality of the **<u>MQXA/B magnet and assuming no systematics.</u>**

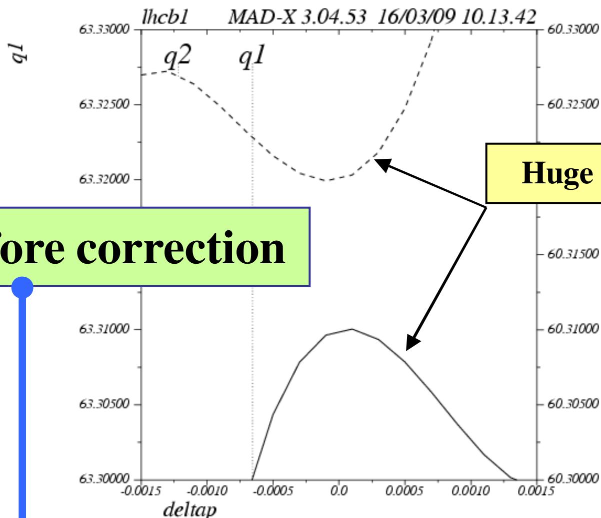
→ … Doing this exercise starting from the **<u>LHC MQ field quality</u>**, envisaging **<u>non-zero systematics</u>** and including the **<u>expected errors of a cold D1</u>** (BNL DX magnets) is a completely different story.

→ **The full set of IT corrector magnets will also be needed for Phase I**, i.e.

- Not only MCBX (a1/b1), MQSX(a2) and MCSX(b3) as initially planned
- But also MCSSX (a3), MCOX (b4), MCOSX(a4) and MCTX(b6).

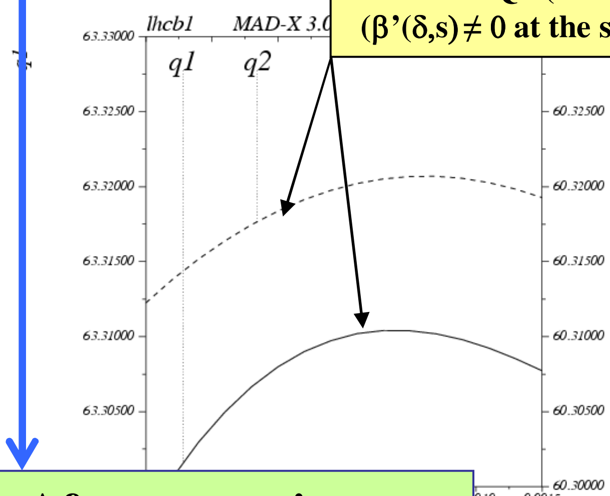
→ **The currently expected Field Quality of the new IT/D1 is not "fully satisfactory" and must be improved.**

→ **Tune vs δ** (β*=30 cm in IR1&5 and β*=10 m in IR2&8)



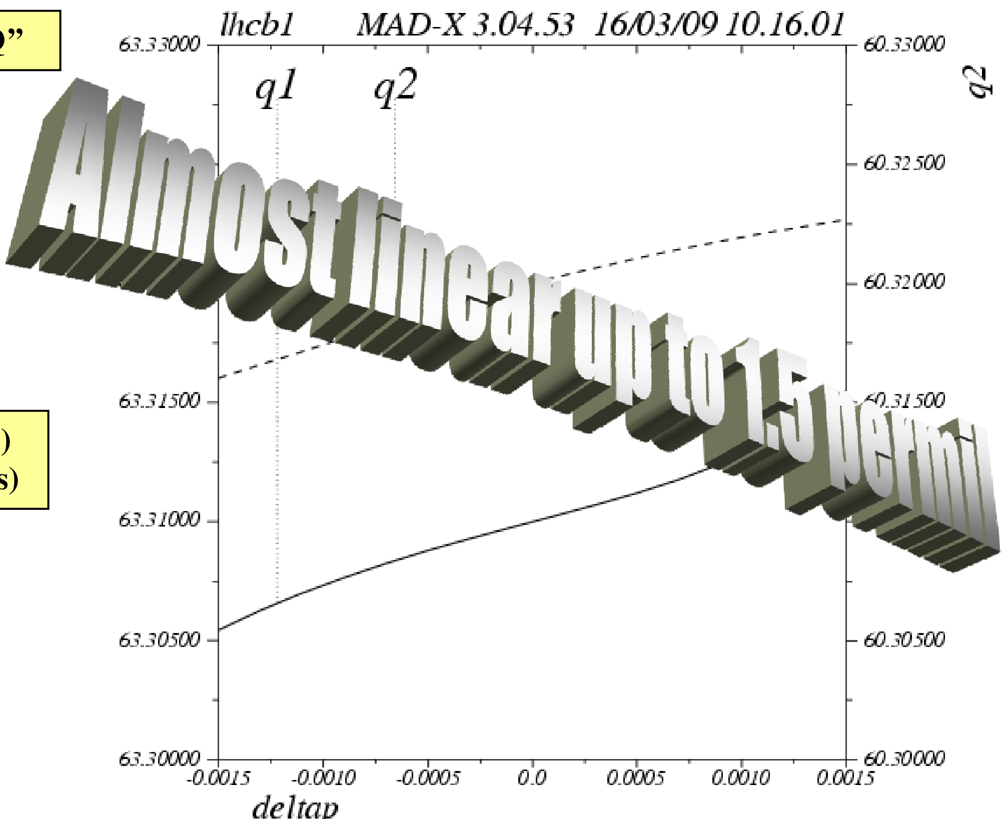
Huge Q" and Q"

Before correction



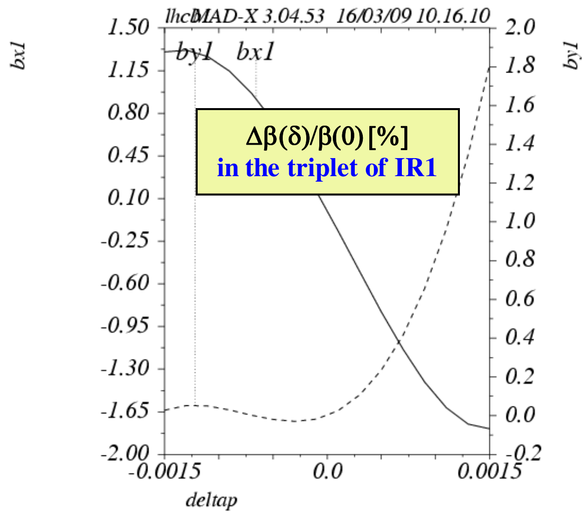
Residual Q" (~3000→6000)
(β'(δ,s)≠0 at the sextupoles)

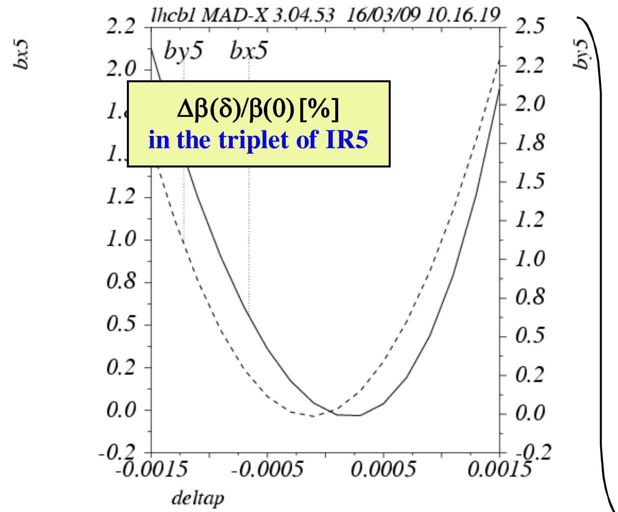
After correction
(Some SD families pushed up to 550A)

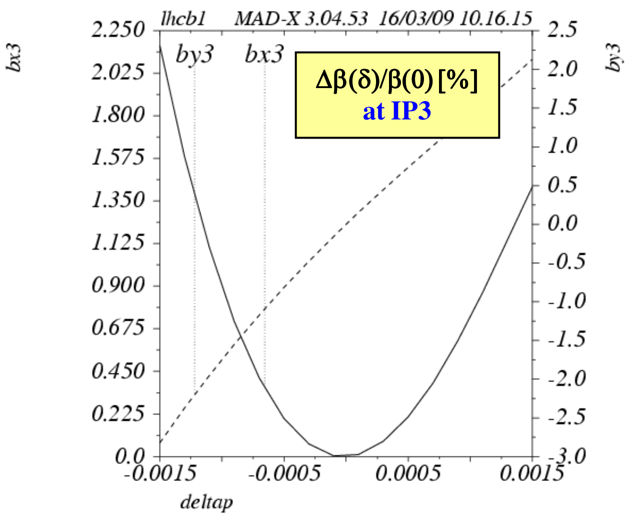


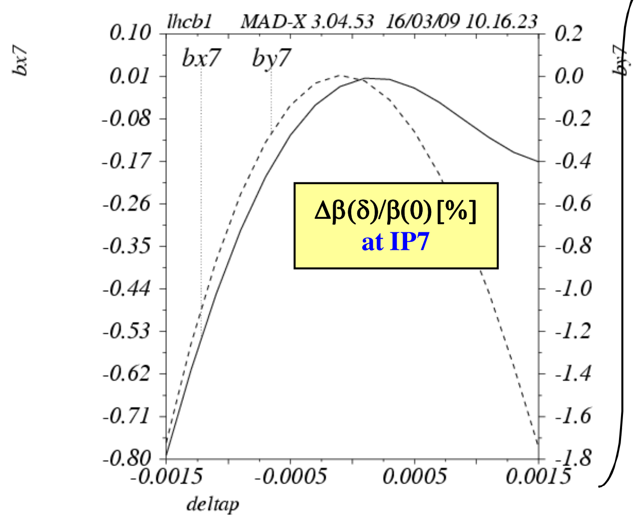
If needed,
fine tuning with octupoles MO
(~200/450A needed in OF/OD)

→ Off-momentum beta-beating versus δ at specific locations after correction (β^*=30 cm in IR1&5 and β^*=10 m in IR2&8)



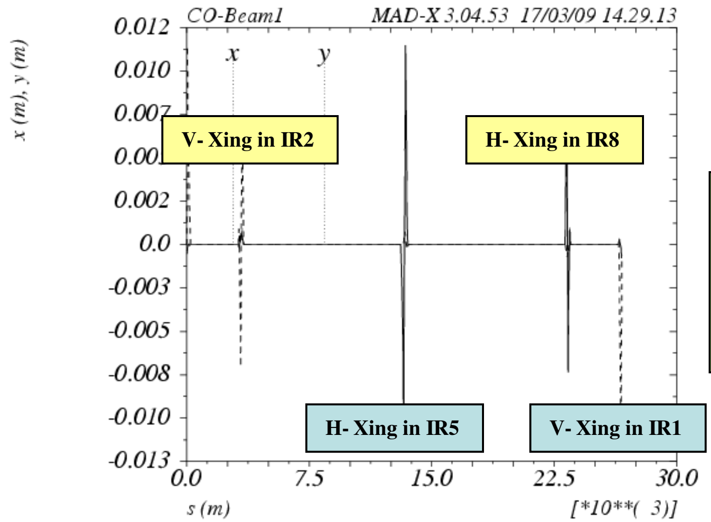




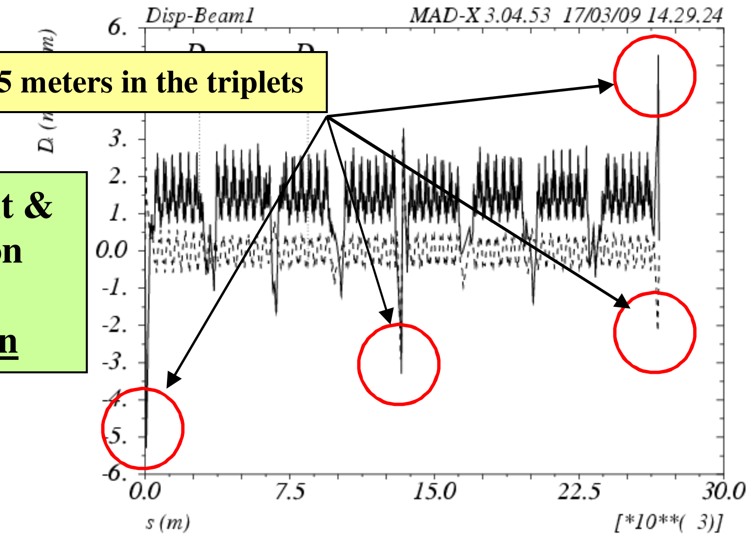


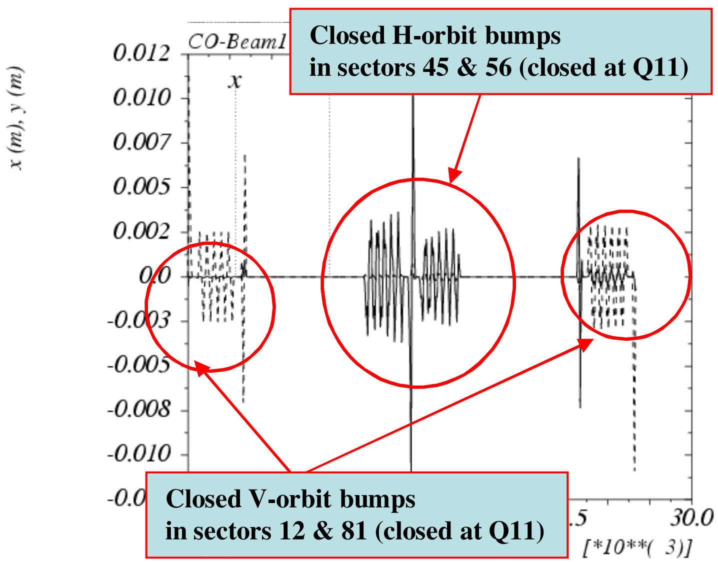
<2 % @ δ_p=1.5 ×10^{-3}

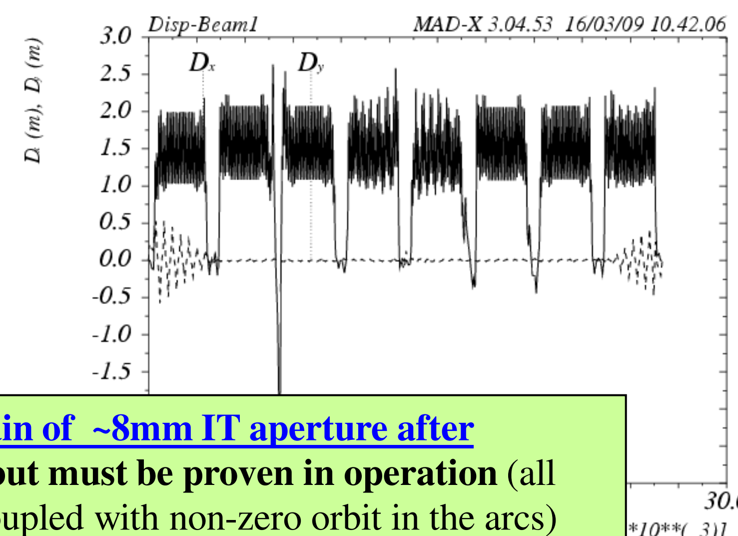
→ Correction of spurious dispersion via small orbit bumps (β*=30 cm in IR1&5 and β*=10 m in IR2&8) [redacted]



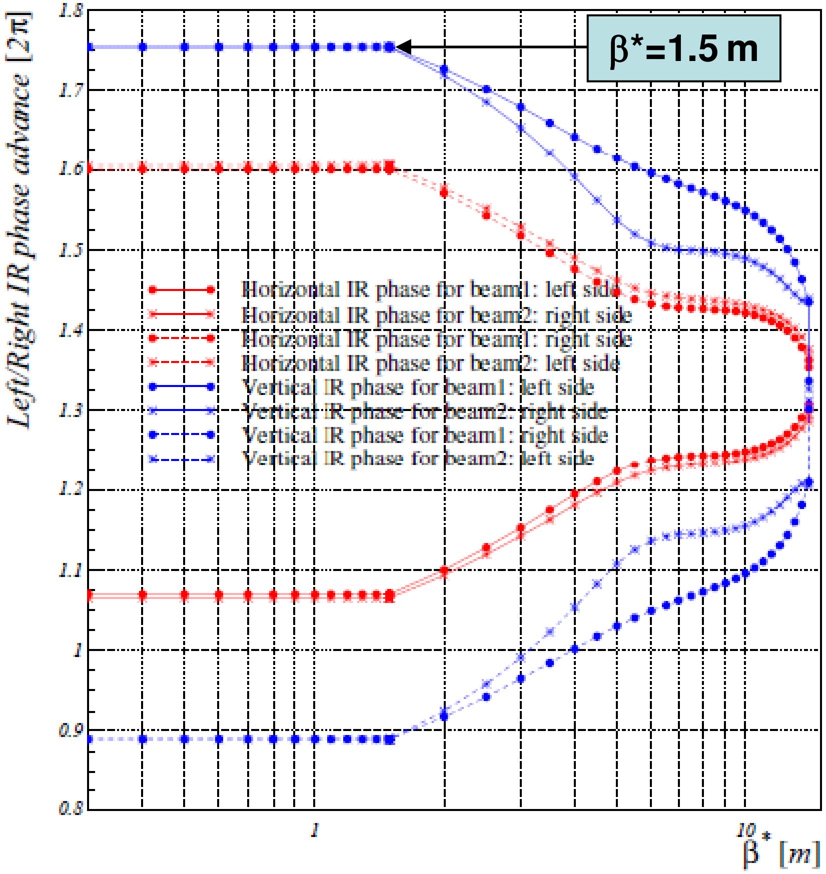
Closed orbit & dispersion <u>before correction</u>

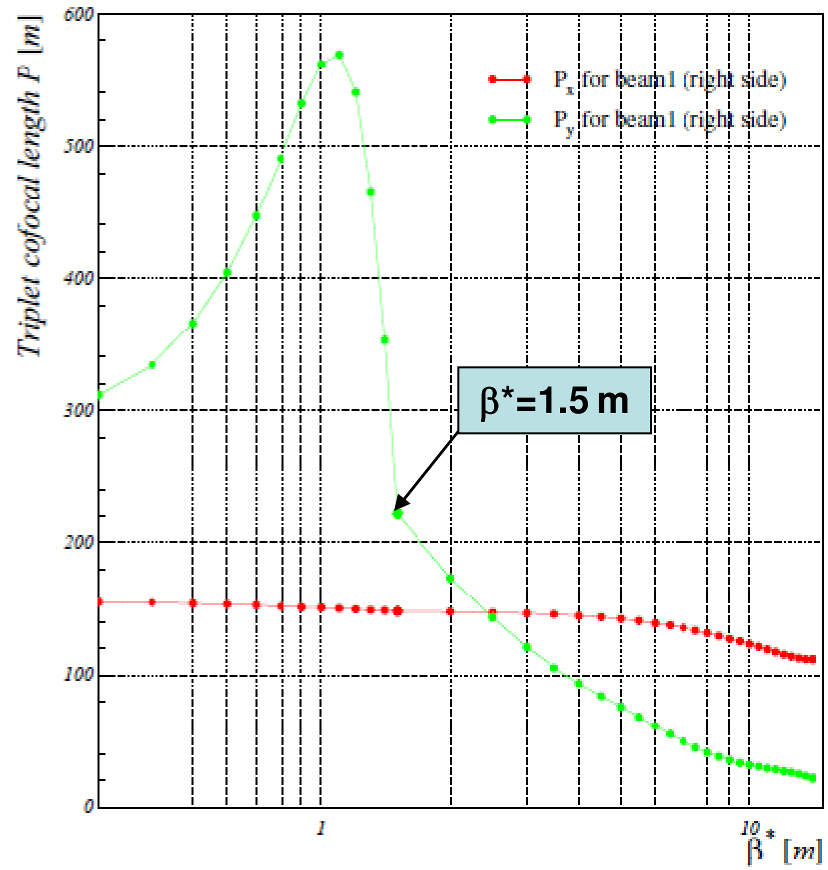






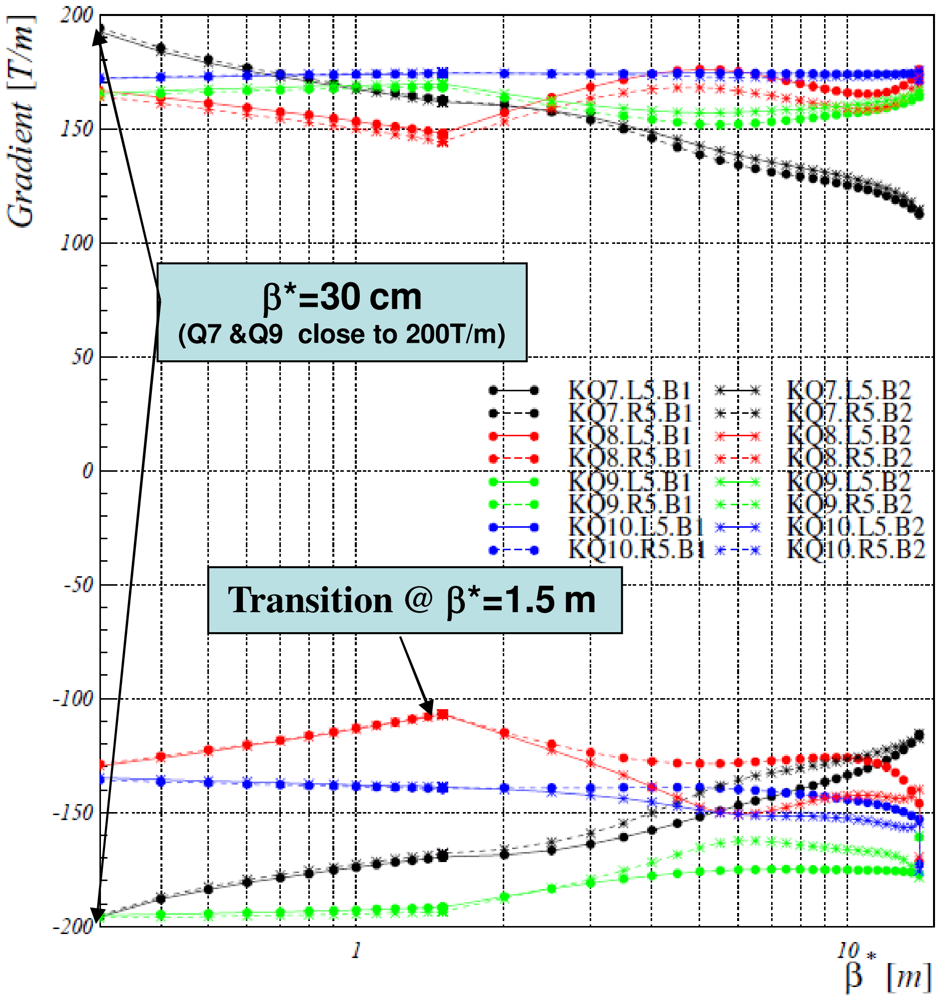
<u>Potential gain of ~8mm IT aperture after correction</u> but must be proven in operation (all knobs are coupled with non-zero orbit in the arcs)

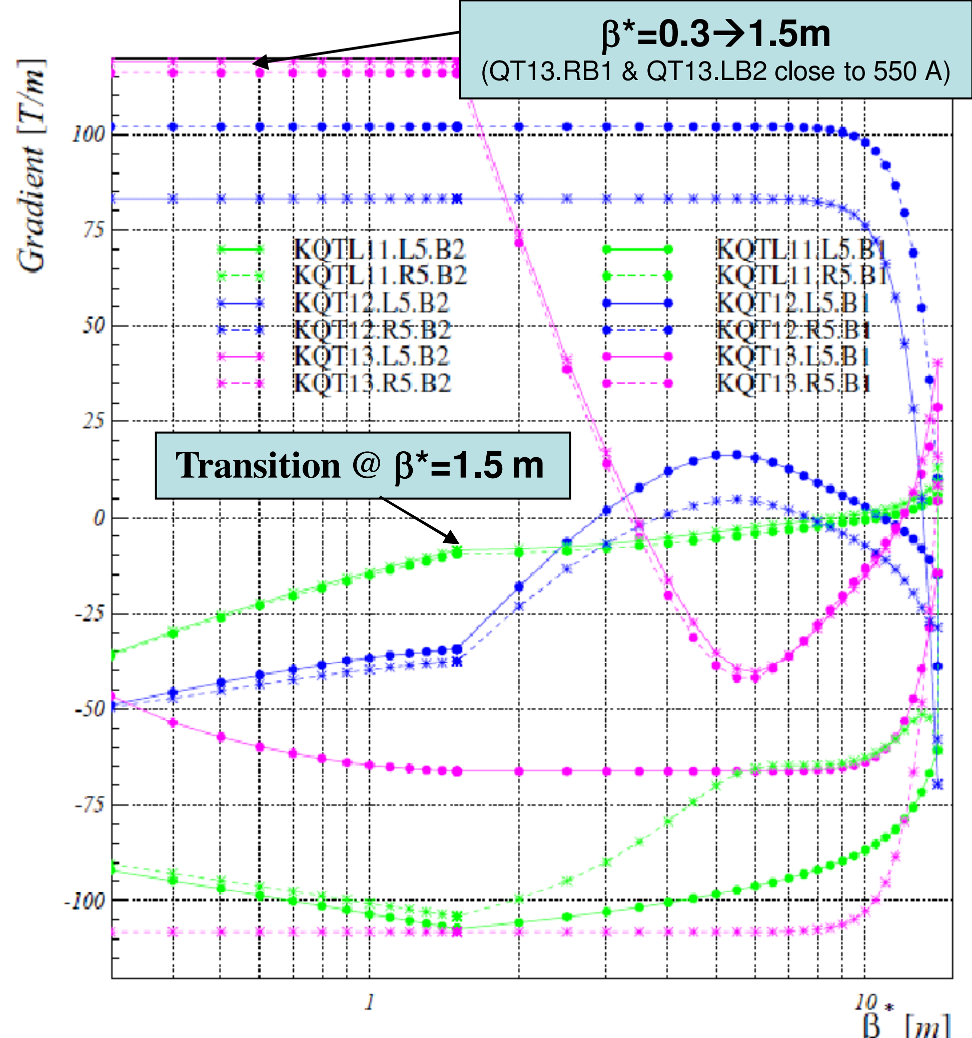




B1 & B2 Left & Right IR phase advances vs β*
→ Kept constant for 0.30 m < β* < 1.5m

IT cofocal distances $P_{x/y}$ vs β*
→ Normally kept ~cst for a standard squeeze



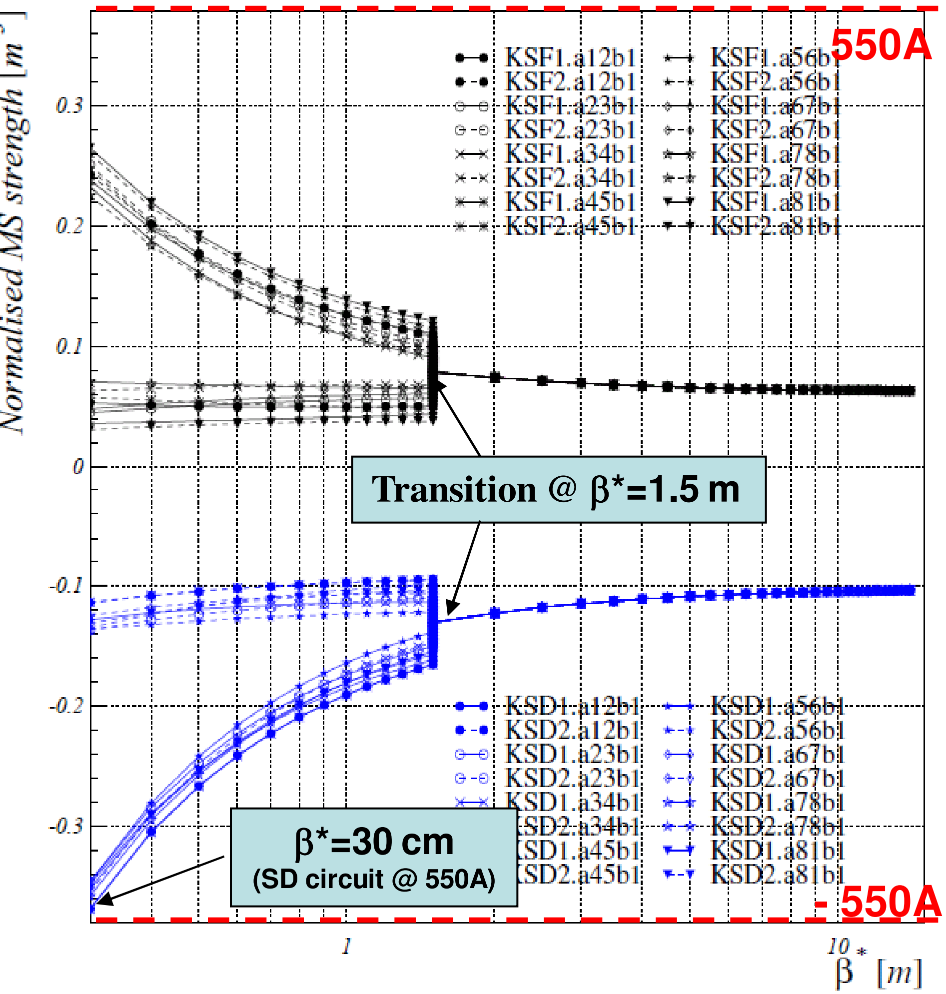


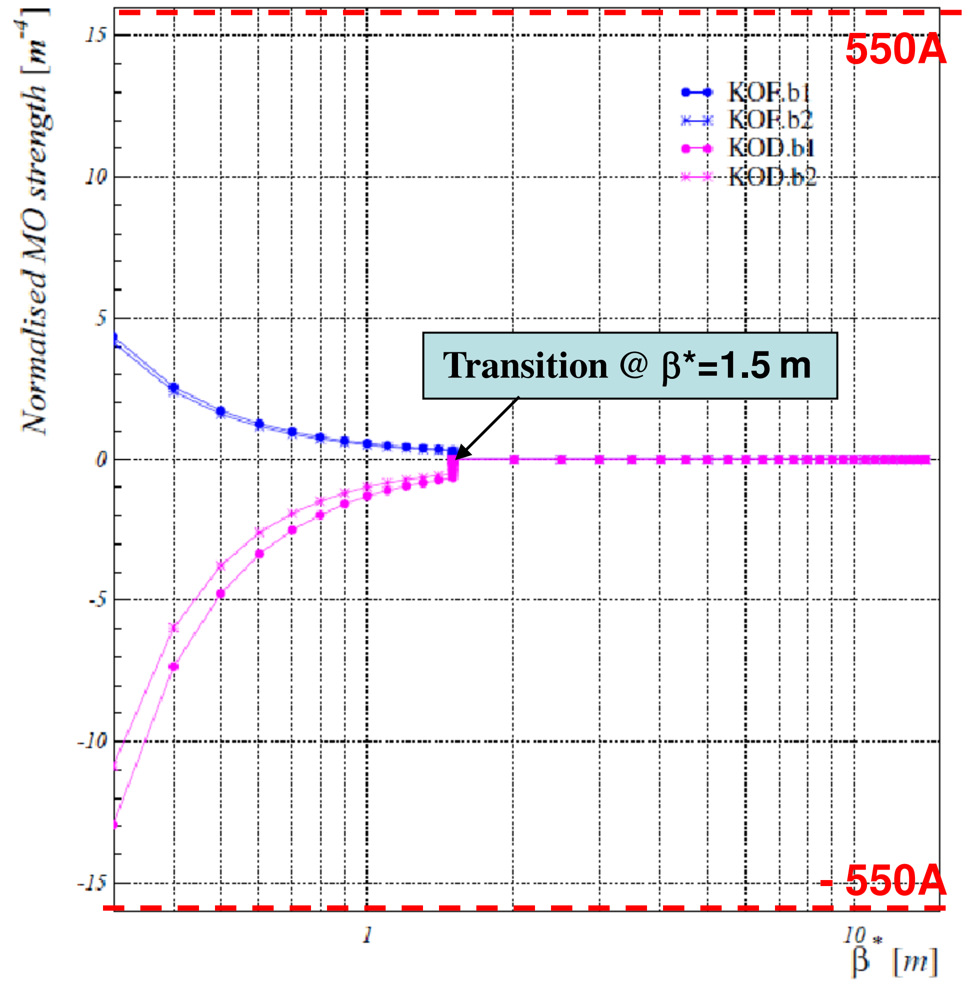
DS gradients (Q7/Q8/Q9/Q10) vs β*

→ Smooth, but at the transition β*=1.5 m
→ KQ7 reaches 200 T/m at a β* of 27-28 cm

QT gradients (QTL11/QT12/QT13) vs β*

→ Transition at β*=1.5 m
→ KQT13R.B1 & KQT13R.B2 kept constant close to 550A up to the transition β*=1.5 m.





Sextupole gradients (beam1) vs β*

→ Squeeze at cst Q' down to β*=1.5 m (2 families)
→ Prepare the IT chromatic correction at β*=1.5 m
→ Squeeze down to 30 cm (some SD close to 550A)

Octupole settings vs β*

→ No special requirement up to β*=1.5 m
→ Prepare the fine tuning of Q'' at β*=1.5 m
→ Follow the squeeze down to 30 cm