HL-LHC Optics Constraints for Dump Region

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Acknowledgment: ABP

Main Constraints:

- Q4 gradient fixed within maximum ±1%
- Horizontal phase advance MKDs➔TCDQ 90˚± 4˚
- TCDS: $\beta_{y,min}$ ≥ 200 m (no more than 10% smaller than present value)
- TCDQ: $\beta_{y,min}$ ≥ 145 m (no more than 10% smaller than present value), $\beta_{x,min}$ ≥ 630m and |Dx| ≤0.2m
- TDE: $(\beta_x \times \beta_y)^{1/2}$ ≥ 4500 and $\beta_{x,min}$ ≥ 4000 m and $\beta_{y,min}$ ≥ 3200 m (no more than 20% smaller than present value)
- TCDQ movement during squeeze unidirectional and towards the beam, accumulated mechanical play ➔ degraded alignment precision (required ±0.1 mm)! **Need BETS redesign**.
- Phase advance MKD➔TCTs 0˚ or 180 ˚(± 10˚)
- TCDS-MSD: $\beta_{x,max}$ ≤ 175 m (aperture limitation extraction channel at injection).

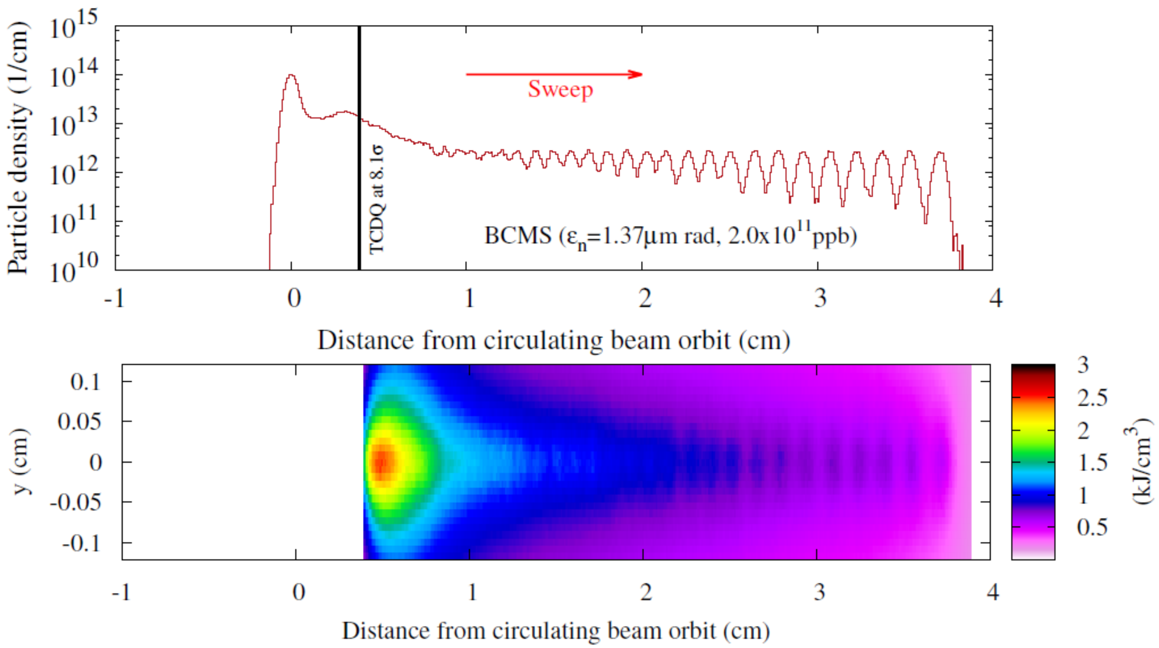
Disclaimer:

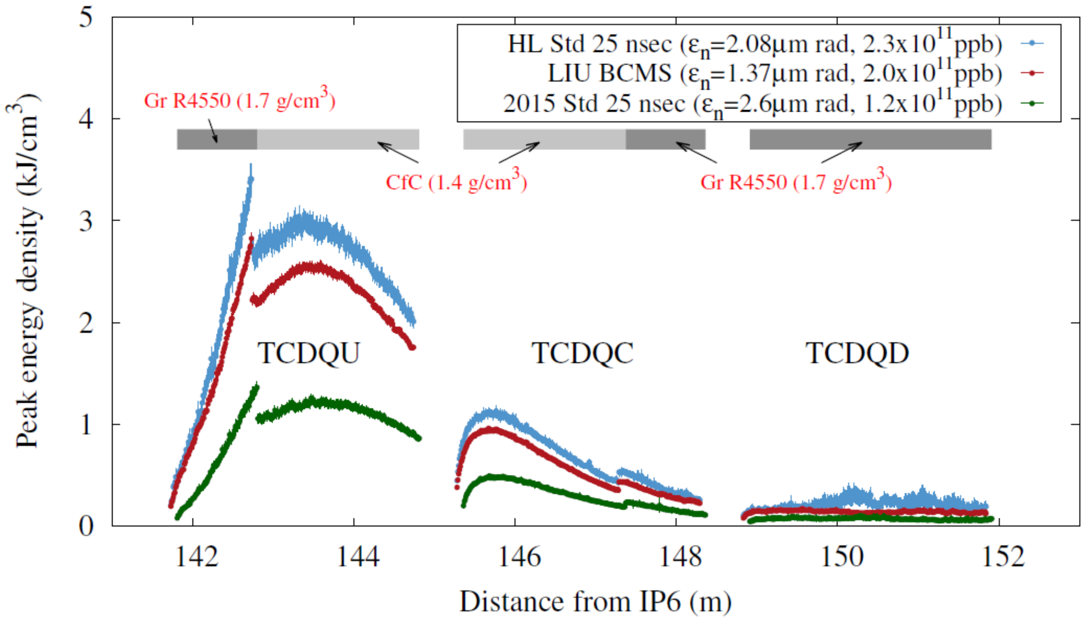
Optics constraints related to machine aperture (circulating beam) are not treated in this talk (assumed as part of standard checks performed by ABP team)

FLUKA calculations at TCDQ

7 TeV, TCDQ Half gap = 8.6 σ_β ➔ 0.5 σ (~250 μm) misalignment included ➔ 8.1 σ = 4 mm (present optics and 3.5 mm mrad normalised emittance)

Type 2 erratic



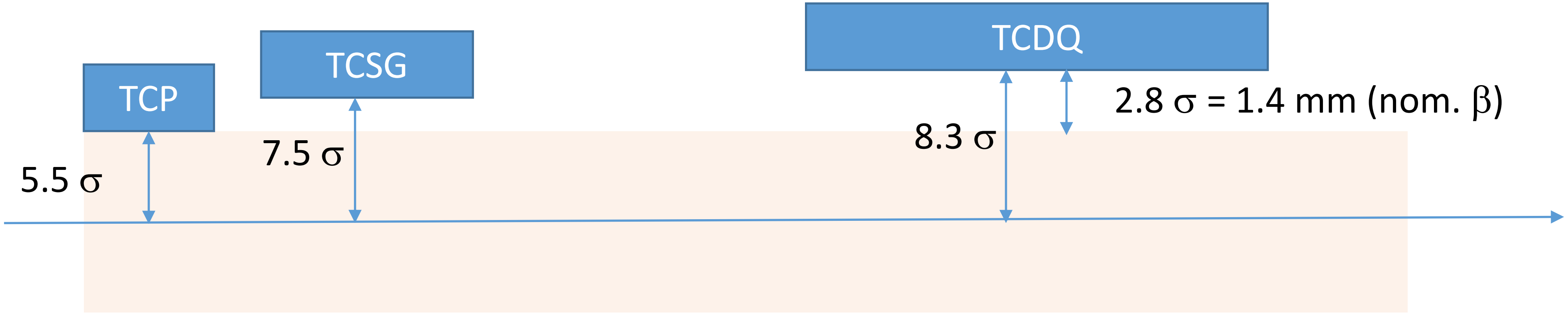


- HL-LHC std: max. energy density in low-density blocks: 3.0 kJ/cm^3 (~1300°C)
- LIU BCMS: max. energy density in low-density blocks: 2.6 kJ/cm^3 (~1200°C)

A. Lechner

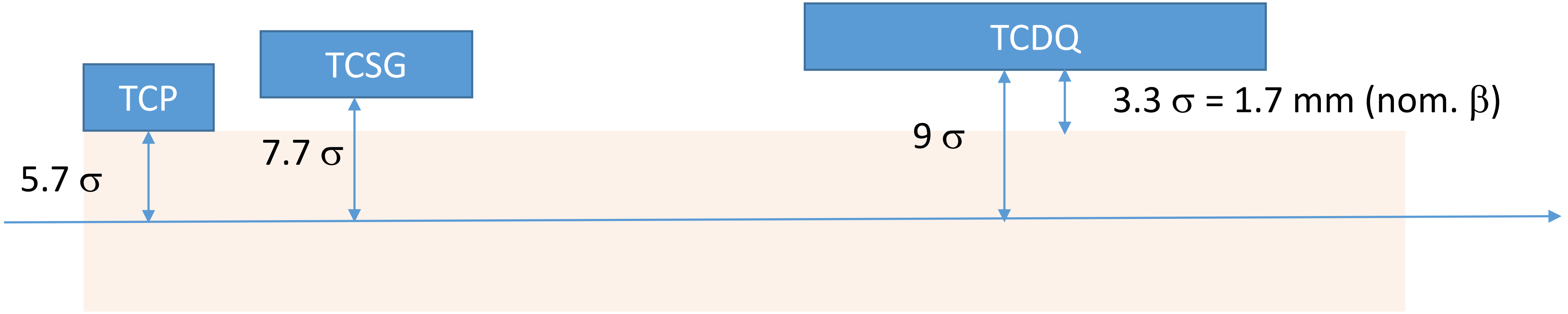
Close to limits!

Present Collimator Settings @ 6.5 TeV (40 cm β*)

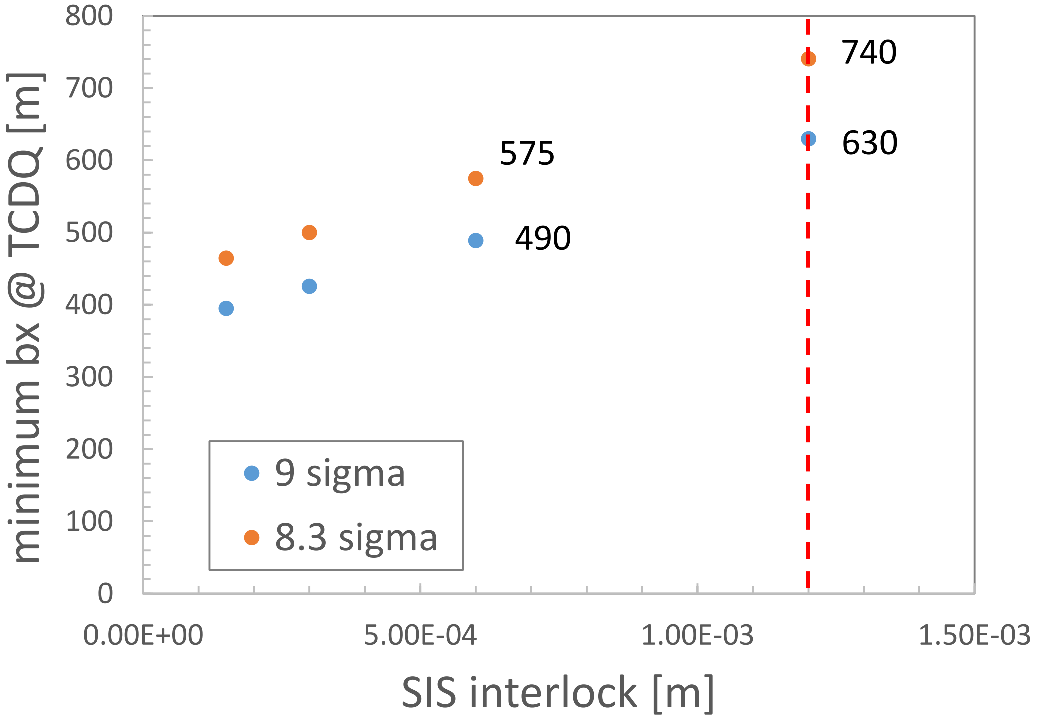


- Present SIS interlock on local orbit at TCDQ = +/- 1.2 mm ➔ possible moving orbit locally towards the TCDQ without losses (beam cut at 5.5 σ at TCPs)
- Run 2 nominal settings at collision (40 cm β* in IP1 and IP5): TCDQ at **8.3 σ = 4.2 mm**
- Consider **0.5 σ setup error** ➔ **7.8 σ = 3.95 mm**
- SIS on orbit at TCDQ = **±1.2 mm** ➔ gap could go down to **2.7mm**.
- Scaling from FLUKA calculations and assuming a bunch population of 1.15e11 p+ this gives a **maximum energy density of 2.2 kJ/cm^3** and a **maximum temperature of <1000˚C**

HL-LHC Collimator Settings @ 7TeV (20 cm β*)



- Assuming a **maximum allowed temperature of 1400 ˚C** ("grey zone" for graphite, still ANSYS simulations needed!!) ➔ **minimum gap = 3.6 mm**
- **0.25 mm** setup error ➔ minimum gap = 3.85 mm
- **SIS interlock 1.2 mm** ➔ minimum gap = 5.05 mm ➔ **Minimum allowed β_x = 630 m**



Summarising for TCDQ Minimum β_x

- Need to asses if Type 2 erratic (and any worse case) can be avoided
- Need to confirm that SIS interlock on orbit at TCDQ can be reduced and to which level without impacting machine availability
- Need to perform ANSYS calculations to assess if Graphite and CFC would withstand the beam impact in case of Type 2 erratic and limit optics conditions (e.g. 0.6 mm interlock and β_x = 490 m)
- Once defined previous points, decide if upgrading TCDQ with more robust material (3D C-C?) ➔ impact on the cost (not in baseline)!

– β_x change TCDQ_UP and TCDQ_DW < 5%

Horizontal Dispersion at TCDQ

Parameter set	LHC design	**HL-LHC design**	Intermediate	Run I
Primary halo extension	6 σ	**6** σ	6 σ	6 σ
Secondary halo, hor./ver.	6 σ	**6** σ	6 σ	6 σ
Secondary halo, radial	6 σ	**6** σ	6 σ	6 σ
Normalised emittance ϵ_n	3.75 μm	**3.5** μ**m**	3.5 μm	3.5 μm
Radial closed orbit excursion x_{co}	3 mm	**2 mm**	1 mm	0.5 mm
Momentum offset δ_p	8.6×10^{-4}	$\mathbf{2 \times 10^{-4}}$	2×10^{-4}	0
β-beating fractional beam size change k_β	1.1	**1.1**	1.05	1.025
Relative parasitic dispersion f_{arc}	0.27	**0.1**	0.1	0.1

CERN-ACC-2014-0044

Parameters for HL-LHC aperture calculations and comparison with aperture measurements

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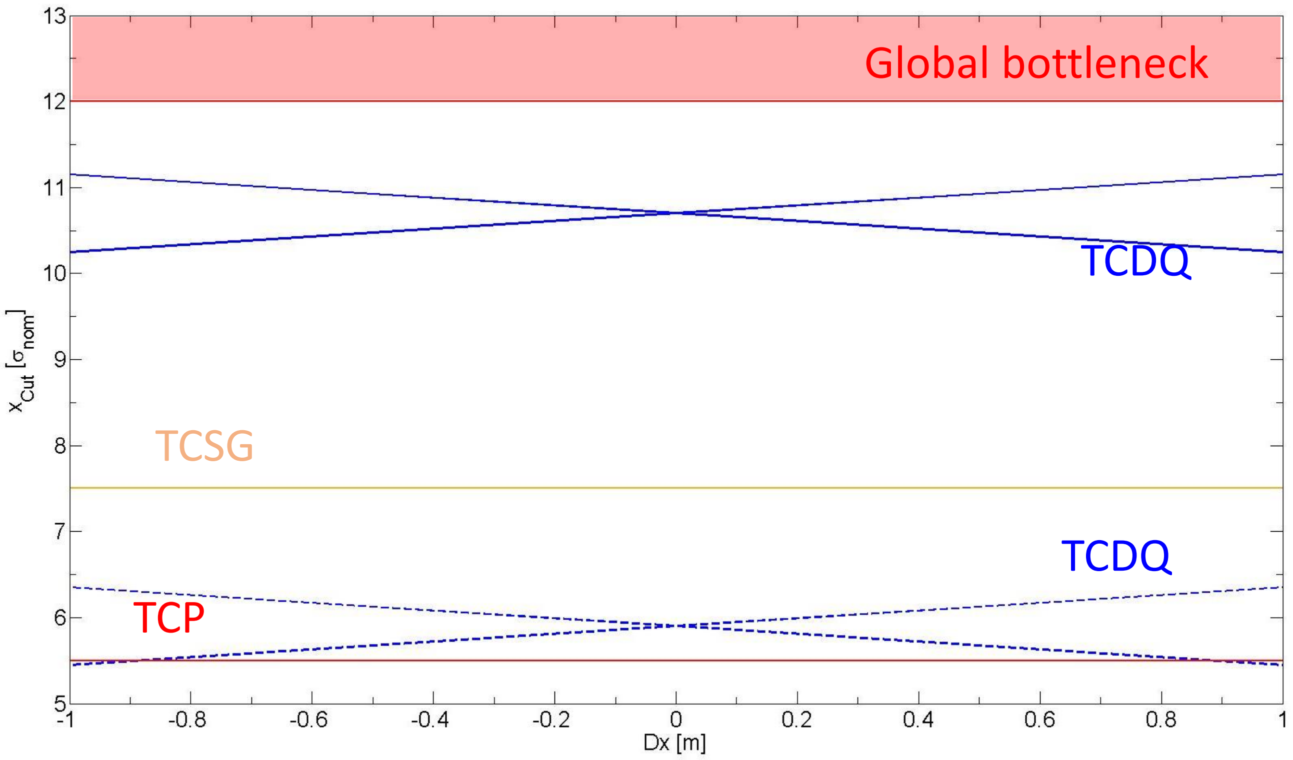
Table 4: The elements where the calculated global aperture bottlenecks were found in both beams, as well as their magnitude in units of σ_n. The calculations are performed using the parameter sets in Table 2.

(σ_n)	B1 element	B1 aperture	B2 element	B2 aperture
calc. LHC design	TCLIM.6R2	9.8	MQTLI.8L3	9.9
calc. HL-LHC	TCLIM.6L8	10.4	TCDQM.B4R6	10.5
calc. intermediate	TCDQM.B4L6	11.5	TCDQM.B4R6	11.5
calc. Run I	TCDQM.B4L6	12.0	TCDQM.B4R6	12.1

Momentum spread at top energy = 1.13e-4

Total Dp/p = momentum offset + 2*momentum spread

Present TCDQ Real Cut



TCDQ set at 8.3 σ_{nom} (betatron) ➔ x= 4.2 mm

Real cut x_{Cut} [σ_{nom}] can be calculated from:

$$x = x_{Cut} * \sigma_{nom} + Dx * Dp/p + x_{dump}$$

x_{Cut} contains optics and alignment errors during the setup

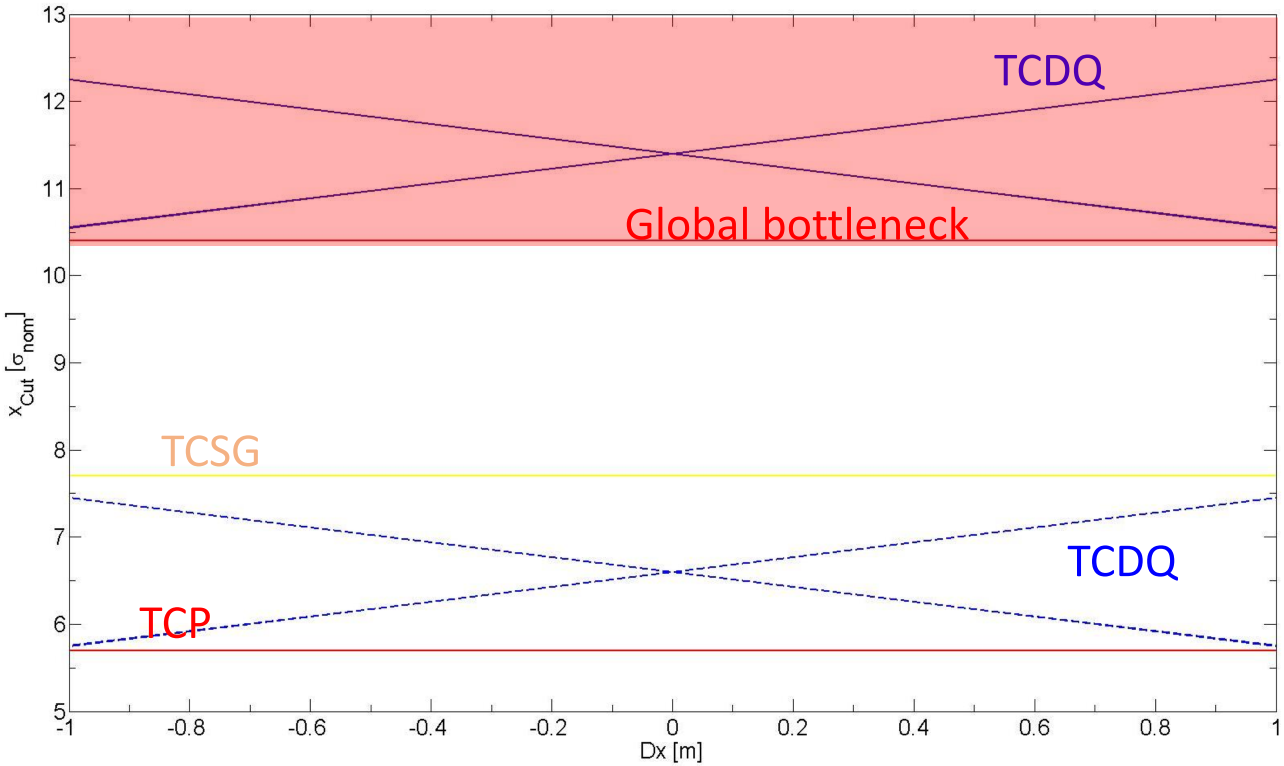
x_{dump} is the local orbit at the moment of the asynchronous dump (at present up to ±1.2 mm)

Protection of machine aperture always granted!

Hierarchy wrt TCSG broken for $x_{dump} > \pm$ 0.120 mm independently on Dx

Hierarchy wrt TCP broken for |Dx| > 0.9 m

HL-LHC TCDQ Real Cut



TCDQ set at 9 σ_{nom} (betatron) ➔ x= 4.5 mm

Real cut x_{Cut} [σ_{nom}] can be calculated from:

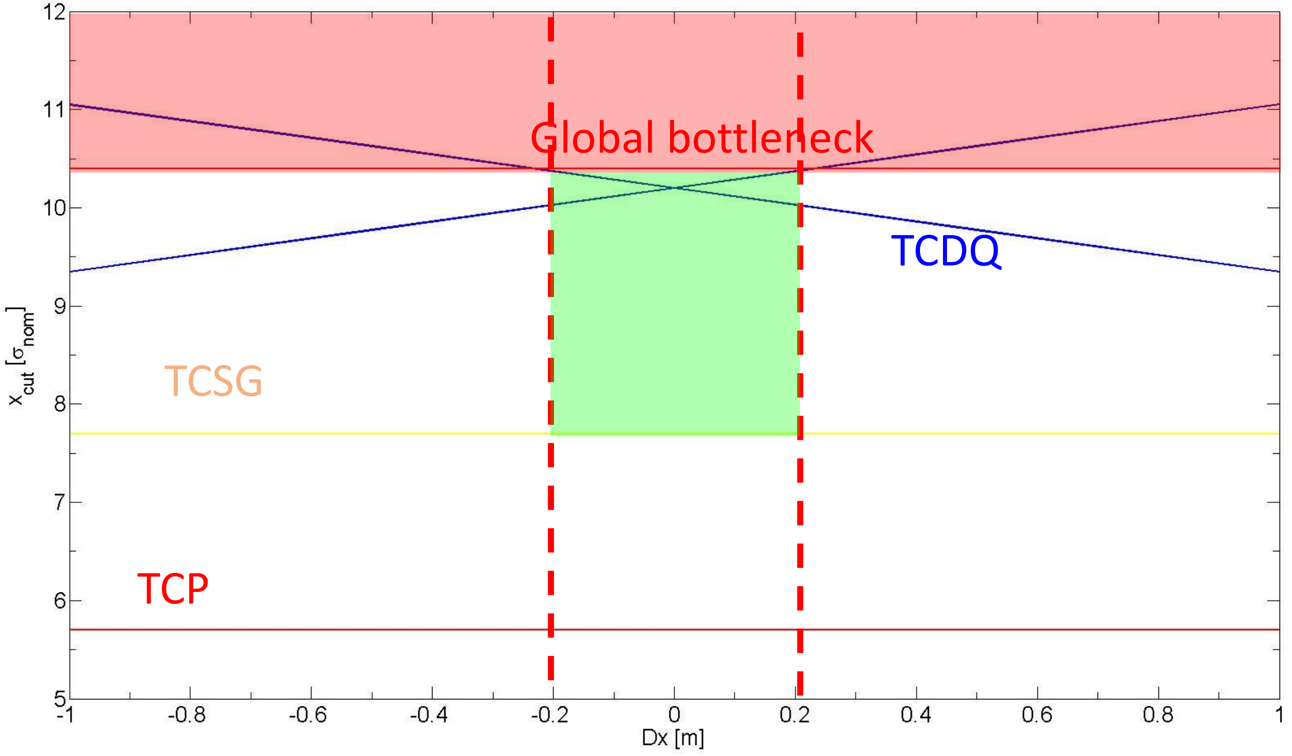
$$x = x_{Cut} * \sigma_{nom} + Dx * Dp/p + x_{dump}$$

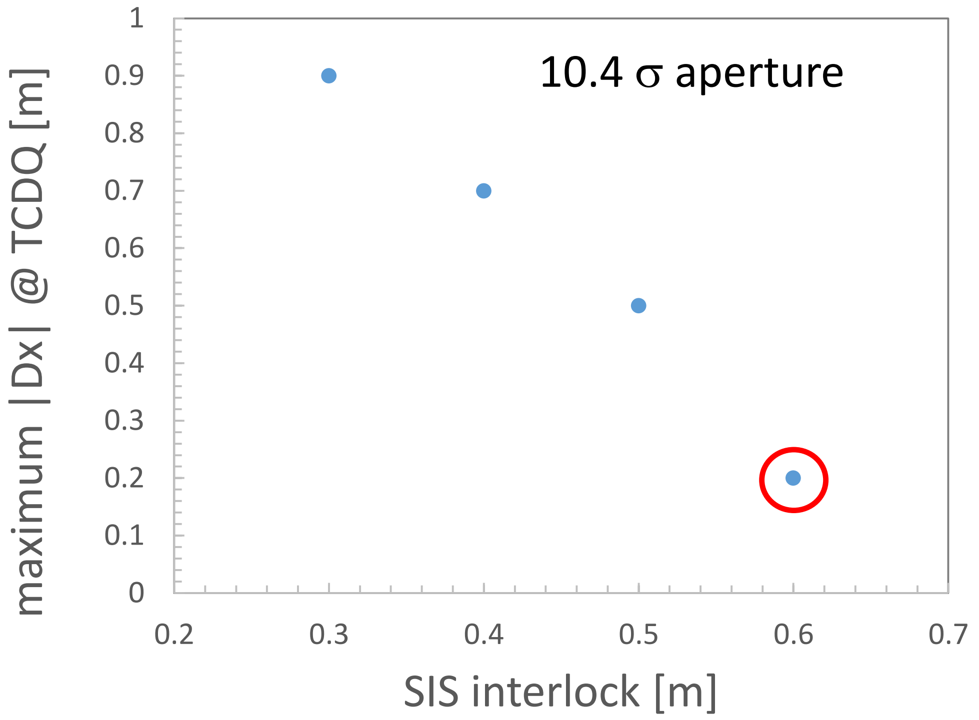
x_{Cut} contains optics and alignment errors during the setup
x_{dump} is the local orbit at the moment of the asynchronous dump (at present up to ±1.2 mm)

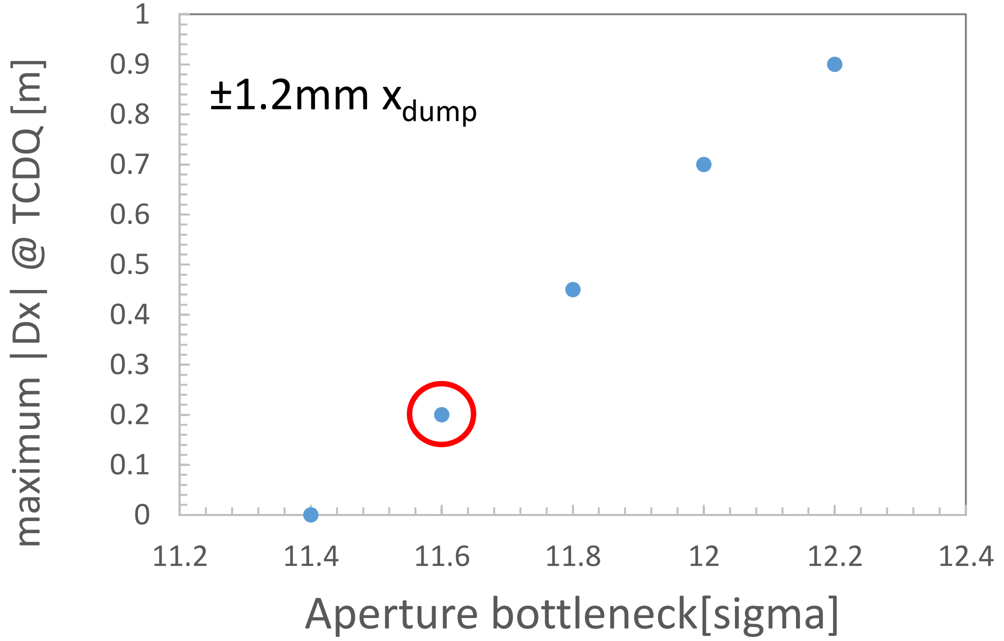
Protection of machine not provided! Either reduce SIS interlock or larger machine aperture (phase advance of global bottleneck wrt MKD not taken into account) or closer TCDQ (possible damage in case of type 2 erratic)
Hierarchy wrt TCSG broken for x_{dump} > ± 0.200 mm independently on Dx
Hierarchy wrt TCP ok

HL-LHC TCDQ Real Cut

SIS interlock 0.6 mm ➔ |Dx|≤ 0.2 m

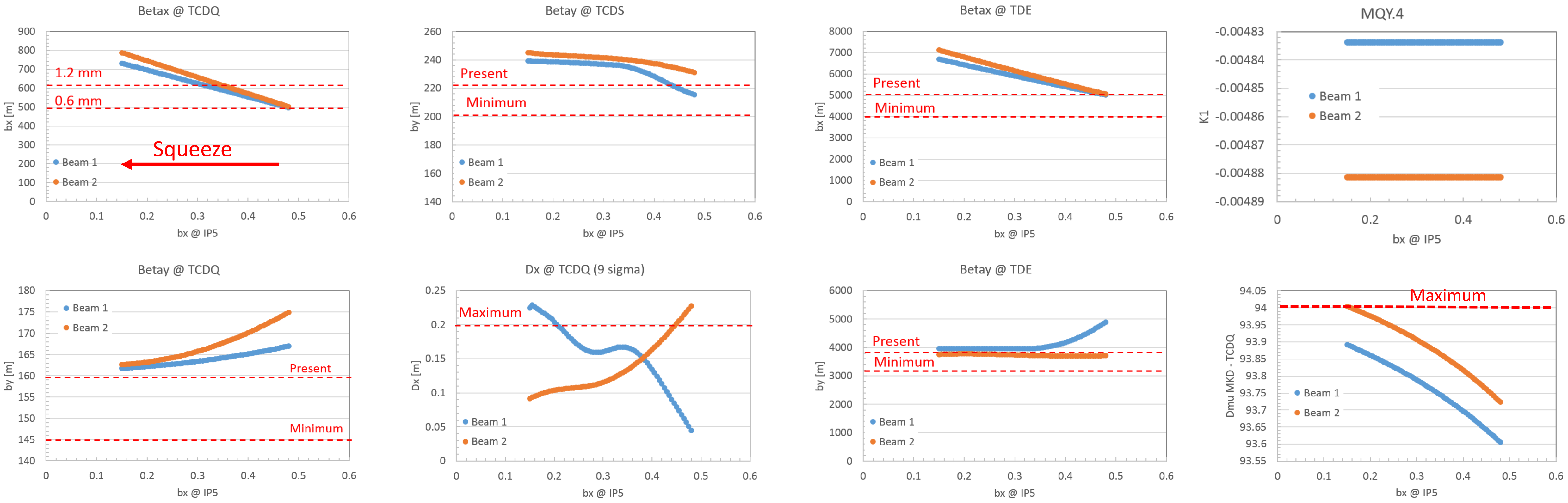






HL-LHV1.2 Squeeze Round

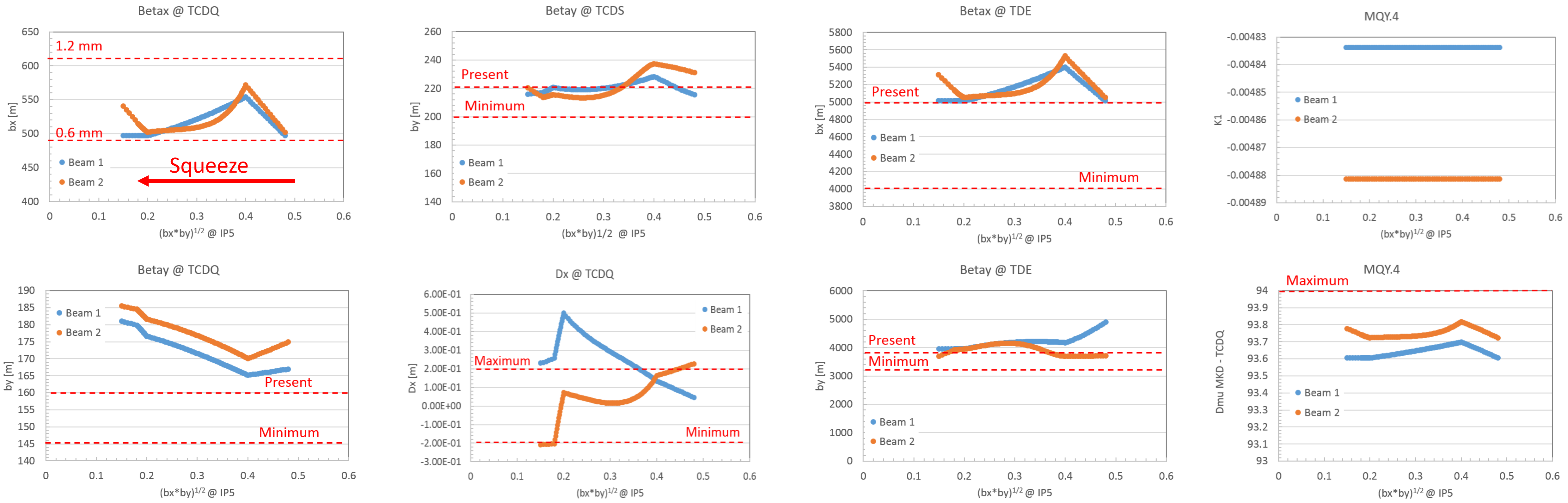
http://lhc-optics.web.cern.ch/lhc-optics/HLLHCV1.2/squeeze/



- Dx @ TCDQ calculated from Dx and DxP @ IP6
- Almost all conditions fulfilled but:
  - Dispersion @ TCDQ (to be reminded that this constraint depends on the SIS interlock for local orbit @ TCDQ and TCDQ half-gap)
  - β_x @ TCDQ only for SIS interlock of 0.6 mm and 9 σ half-gap
  - TCDQ moving away from the beam during the squeeze (4.5 mm ➔ 5.5 mm, ~2σ movement)

HL-LHV1.2 Squeeze Flat

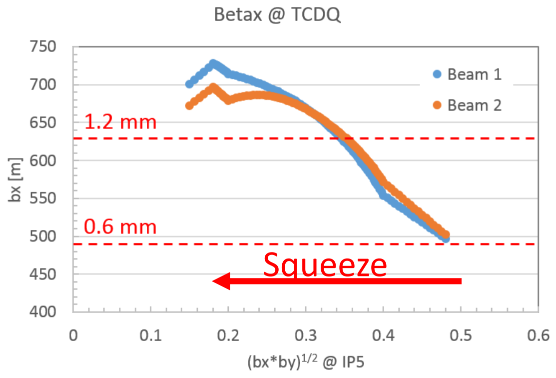
http://lhc-optics.web.cern.ch/lhc-optics/HLLHCV1.2/squeeze/

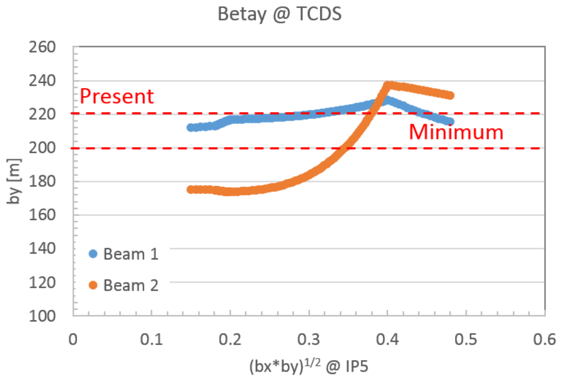


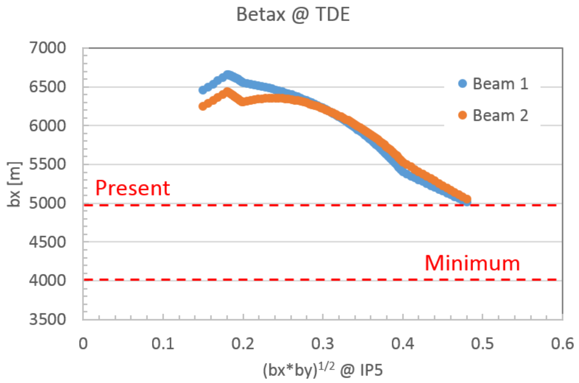
- Dx @ TCDQ calculated from Dx and DxP @ IP6
- Almost all conditions fulfilled but:
  - Dispersion @ TCDQ (to be reminded that this constraint depends on the SIS interlock for local orbit @ TCDQ and TCDQ half-gap)
  - β_x @ TCDQ only for SIS interlock of 0.6 mm and 9 σ half-gap
  - TCDQ moving away and towards the beam (maximum movement 5.00 mm ➔ 5.4 mm, ~0.8 σ). If maximum variation < 1 σ (< 0.5 mm) TCDQ could be set to the closest position already before the squeeze (possible coll. hierarchy violation)

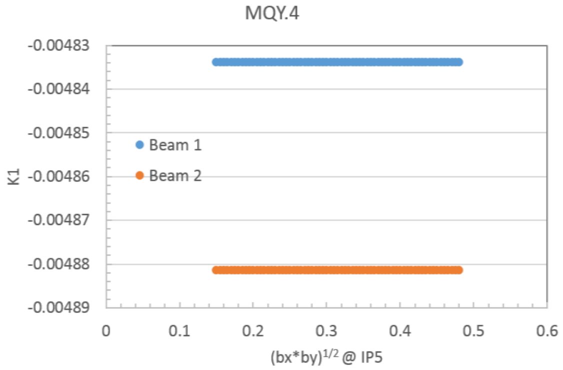
HL-LHV1.2 Squeeze FlatHV

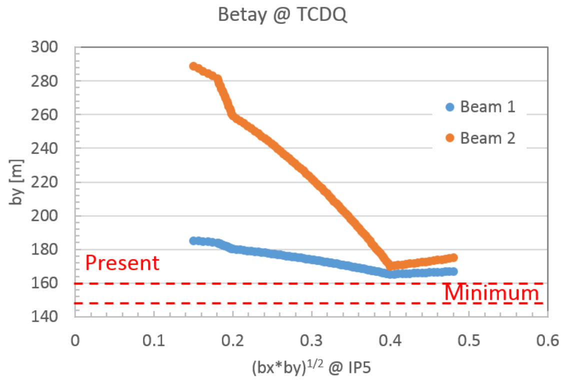
http://lhc-optics.web.cern.ch/lhc-optics/HLLHCV1.2/squeeze/

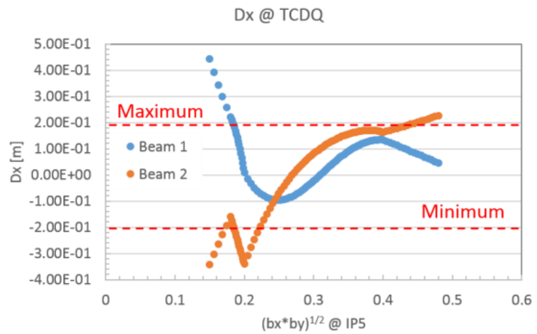


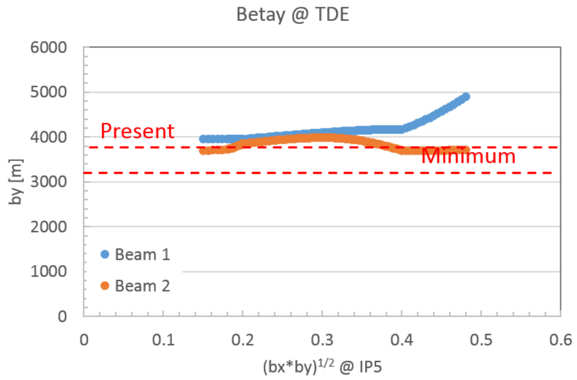


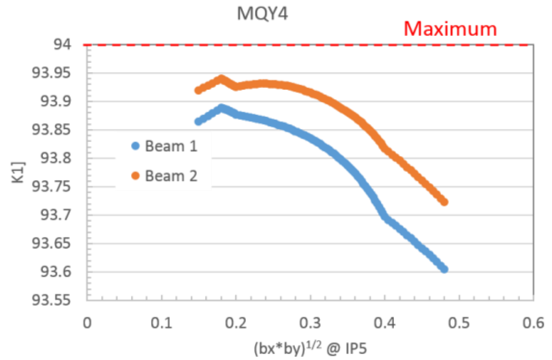






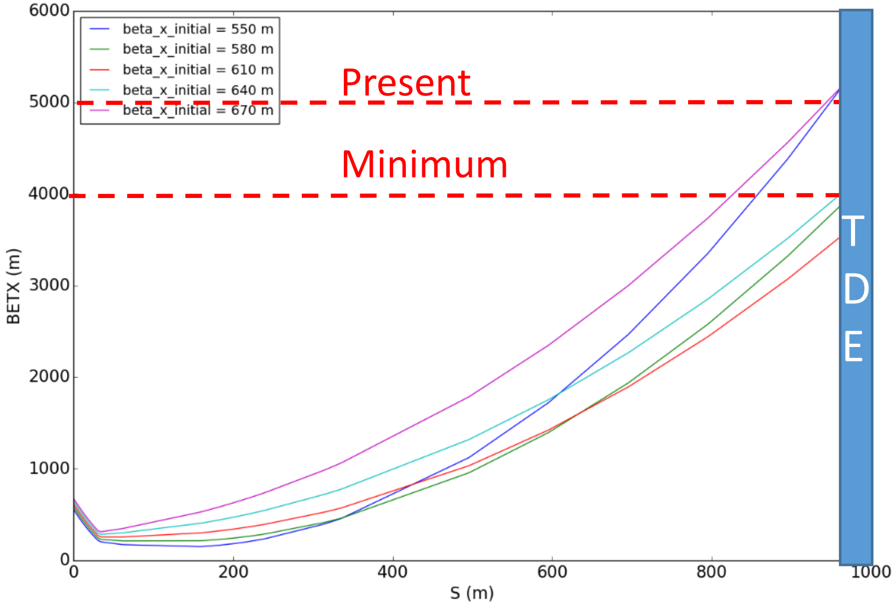


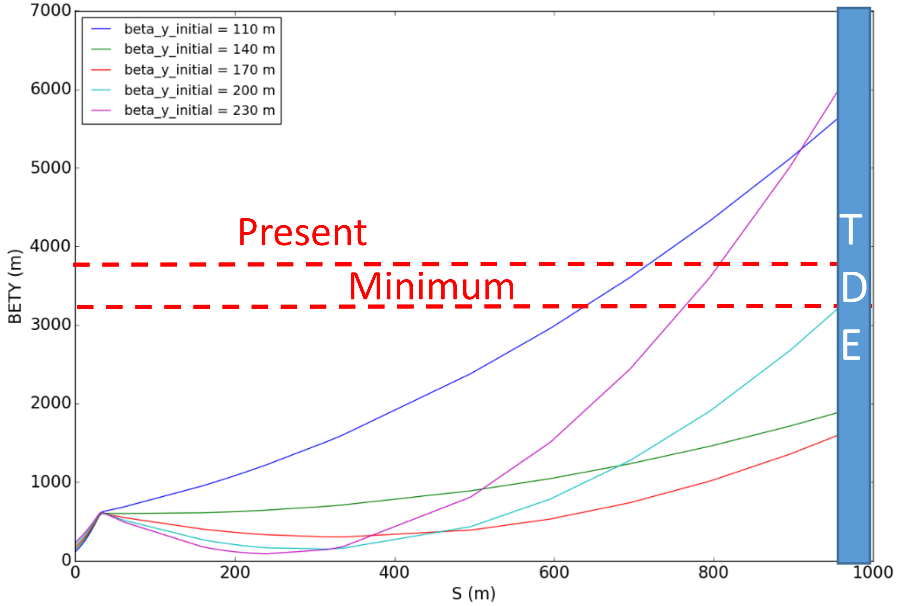


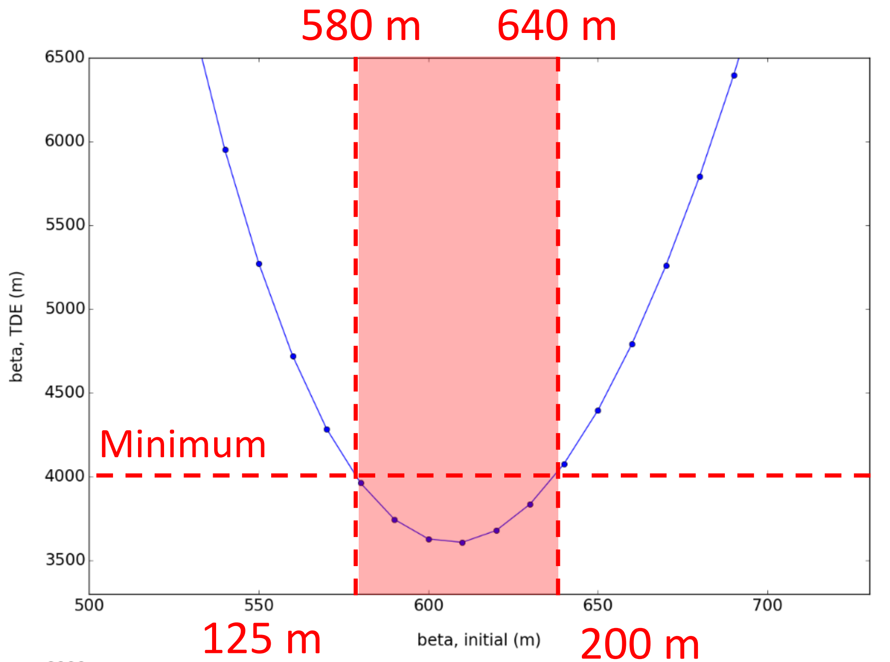


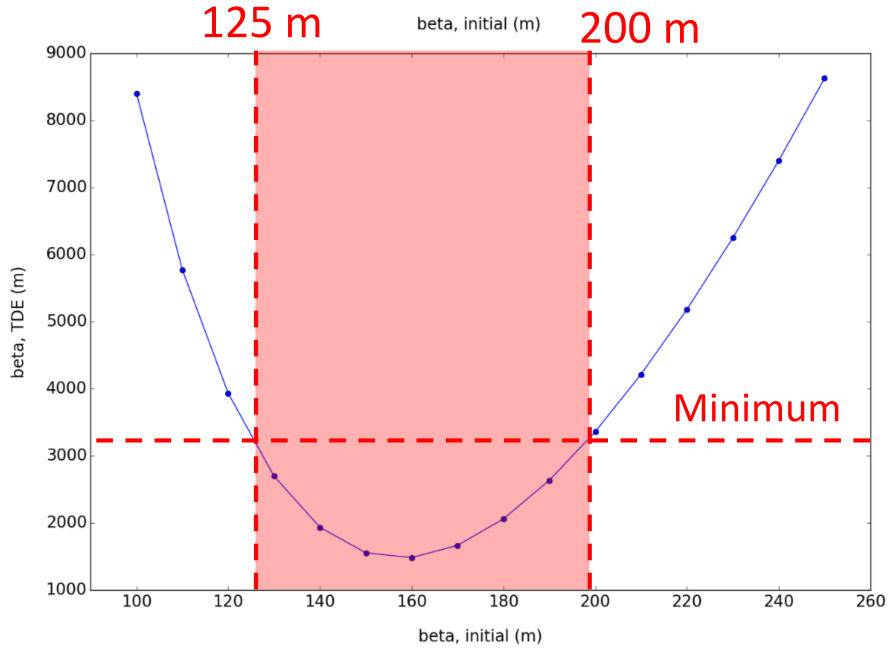
- Dx @ TCDQ calculated from Dx and DxP @ IP6
- Almost all conditions fulfilled but:
    - Dispersion @ TCDQ (to be reminded that this constraint depends on the SIS interlock for local orbit @ TCDQ and TCDQ half-gap)
    - β_y @ TCDS
    - β_x @ TCDQ only for SIS interlock of 0.6 mm and 9 σ half-gap
    - TCDQ moving away and towards the beam (4.5 mm ➔ 5.5 mm, ~2σ movement)

Beta @ MKD









Maximum βx,y (now 540 m and 216 m respectively) defined by available aperture for circulating beam at injection (ABP checks)

C. Wiesner

Conclusions 1/2

Present HL-LHCV1.2 optics:

- Q4 gradient fixed within maximum ±1%: OK
- Horizontal phase advance MKDs→TCDQ 90˚± 4˚: OK
- TCDS: $\beta_{y,min} \geq 200$ m: OK (not OK for FlatHV but probably not critical) (ANSYS calculations needed for final confirmation)
- TDE: $(\beta_x \times \beta_y)^{1/2} \geq 4500$ and $\beta_{x,min} \geq 4000$ m and $\beta_{y,min} \geq 3200$ m: OK (ANSYS calculations needed for final confirmation).
- TCDS-MSD: $\beta_{x,max} \leq 175$ m at injection (aperture limitation): OK
- Phase advance MKD→TCTs 0˚ or 180 ˚(± 10˚) (not yet checked)

Conclusions 2/2

Present HL-LHCV1.2 optics:

- TCDQ:
  - $\beta_{y,min} \geq 145$ m: OK (ANSYS calculations needed for final confirmation)
  - $\beta_{x,min} \geq 630$ m for present ±1.2 mm SIS interlock on local orbit and 9 σ half-gap (to avoid TCDQ damage in case of Type2 erratic): not OK. Need to assess if:
    - Type 2 erratic (or worse) can be avoided
    - Possible to reduce SIS limit without impacting machine availability: if ≤0.6 mm ➔ $\beta_{x,min} \geq 490$ m: OK (ANSYS calculations needed for final confirmation)
    - TCDQ material upgrade ➔ impact on cost (not in baseline)
    - TCDQ movement during squeeze unidirectional and towards the beam: not OK. Try to keep total needed displacement <1σ ➔ move TCDQ to closest position before squeeze (possible hierarchy violation) ➔ no BETS upgrade needed!
  - $|D_x| \leq 0.2$ m (TCDQ hg = 9σ) provided that either global aperture bottleneck ≥ 11.6σ or SIS interlock can be reduced to ≤0.6 mm (aperture 10.4σ): not OK

Present Optics Parameters

Beam 1	MKD	MQ4	TCDS	MSD	TCDQ	MQ4	MQ5
Bx_min [m]	250.9	203.1	153.3	157.2	483.5	549.9	147.1
Bx_max [m]	542.8	219.3	156.7	235.9	505.5	570.5	162.2
By_min [m]	215.6	588.8	224.6	134.7	161.4	197.3	602
By_max [m]	533.1	609.5	236.9	222.9	169.8	214.4	604.6
Dx_max (abs) [m]	-0.143	-0.093	-0.063	-0.061	-0.023	-0.017	+0.002
Dmux_MKD_centre [deg]	0	3	51	65	94	96	103

Beam 4	MKD	MQ4	TCDS	MSD	TCDQ	MQ4	MQ5
Bx_min [m]	248.0	217	152.2	156.1	479.2	576.0	164.2
Bx_max [m]	568.9	218.6	154.4	230.6	510.9	576.7	165.8
By_min [m]	192.4	583.4	240.0	147.2	158.9	193.4	578.7
By_max [m]	531.1	586.5	247.9	234.5	169.2	193.7	581.5
Dx_max (abs) [m]	-0.053	-0.051	-0.150	-0.205	-0.294	-0.308	-0.157
Dmux_MKD_centre [deg]	0	3	51	64	94	97	103

element name	B1H Q6R2	B1V Q4L6	B2H Q5R6	B2V Q4R6
measurement	11.5–12.5	12–13.5	12.5–14	12.5–13
calc. LHC design	10.3	10.8	10.6	10.7
calc. HL-LHC	10.9	11.3	11.0	11.2
calc. intermediate	12.0	12.3	12.0	12.1
calc. Run I	12.8	12.8	12.6	12.7

SIS interlock 0.6 mm ➔ |Dx|≤ 0.2 m