Impact of non-closed crabbing bump on aperture

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WP2 Meeting 10/11/2020

Crabbing and aperture

The crab cavities create a time correlation in the transverse motion. We can then write:

$$x(s) = \sqrt{2J_x\beta_x(s)}\cos(\phi_x(s)) + D_x(s)\,\delta + C_x(s)\frac{\sin(k\,z)}{k}$$

$\sim z$

$$\sigma_x^2(s) \ = \epsilon_x\beta_x(s) + \sigma_\delta^2 D_x^2(s) + \sigma_z^2 C_x^2(s)$$

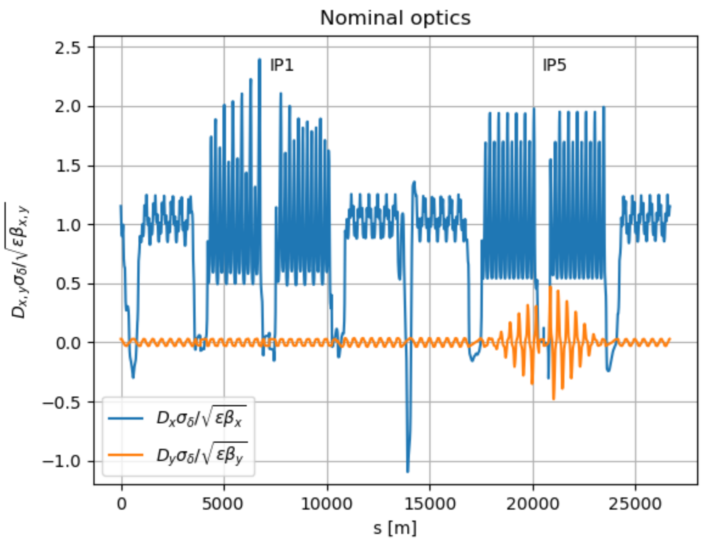
neglecting the RF curvature

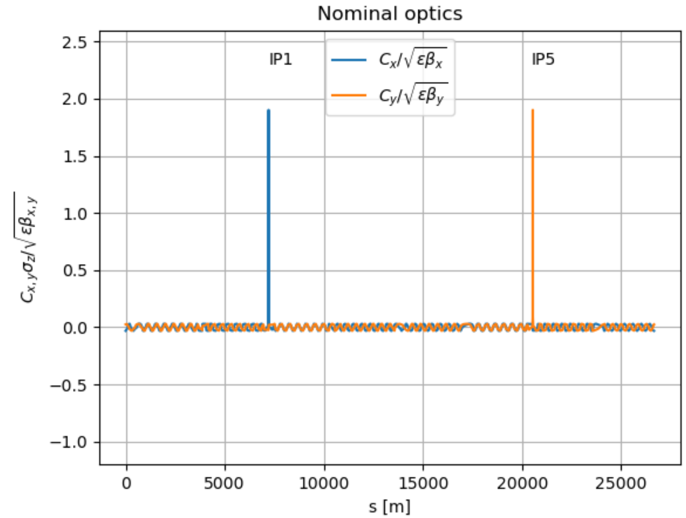
where δ, z are the longitudinal coordinates and C_x is the “crab dispersion”.

It is then interesting to compute the normalized quantities below in relevant locations:

$$\frac{C_x\sigma_z}{\sqrt{\epsilon_x\beta_x}}, \frac{D_x\sigma_\delta}{\sqrt{\epsilon_x\beta_x}}$$

Normalized dispersions (β*=15cm)



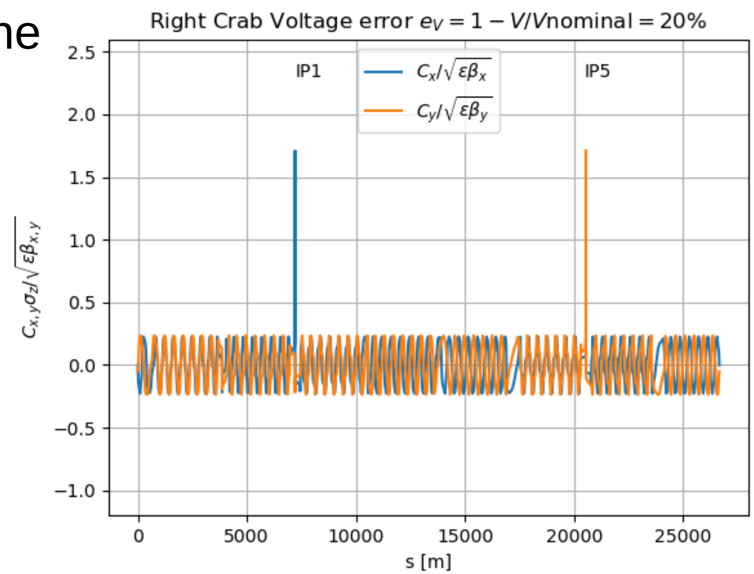


Crab dispersion is normally small besides the IP if the crab bump is closed.

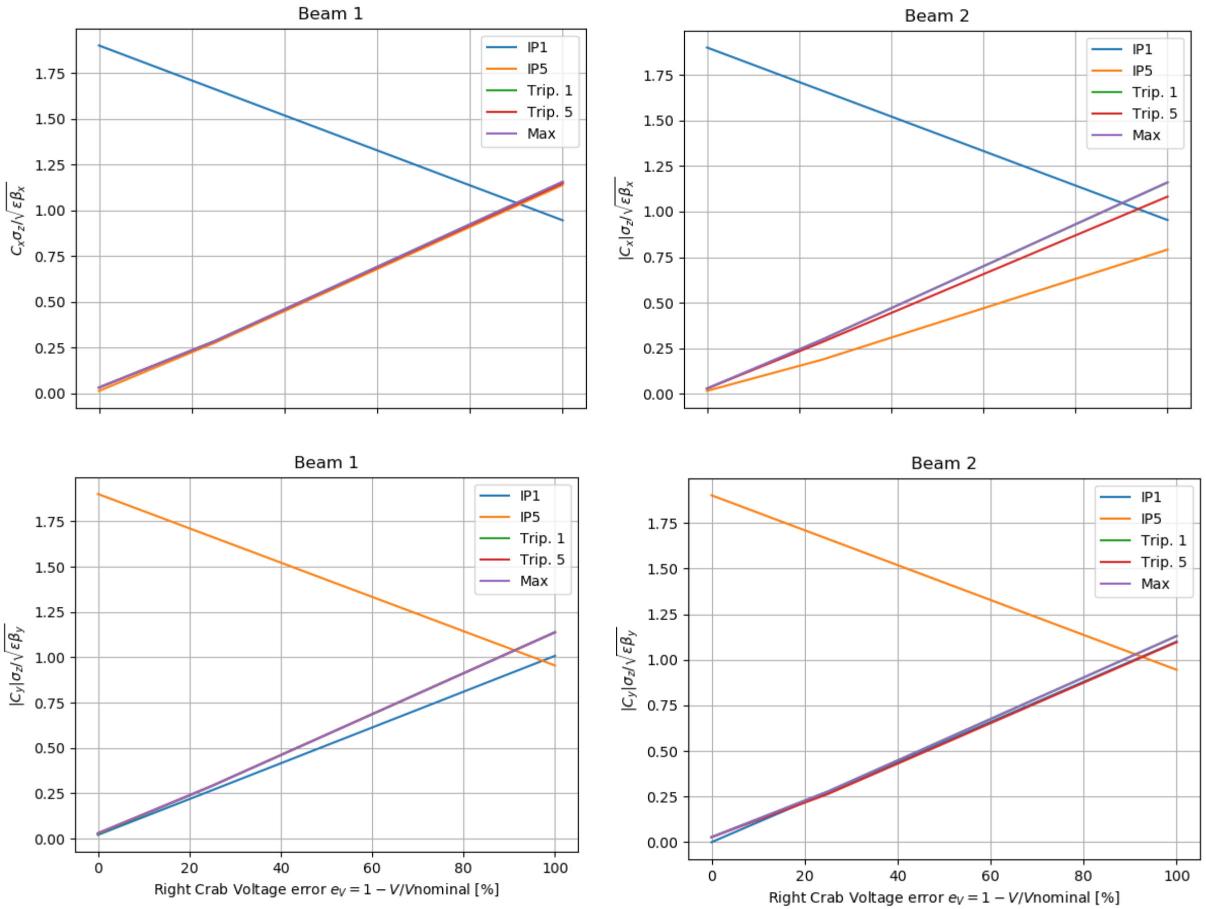
In case of non closure, the normalized crab dispersion leaks in the rest of the machine following:

$$C_{NC}\cos(|\mu(s)-\mu_{\text{crab}}|-\pi Q)$$

where C_{NC} depends on the uncompensated voltage.



Crab dispersion vs voltage error



In general

$$e_V = 1 - \frac{V}{V_{\text{nominal}}}$$

IP Crabbing Angle (N.)

$$C_{\text{IP}} = 1.9 - 0.9e_V$$

Max Crabbing non closure

$$C_{\text{NC}} = 0.03 + 1.1e_V$$

Crabbing non closure reduces crabbing angle and influences the other IPs depending on the relative phase advance.

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Impact on aperture and β* reach

Impact on collimator settings needs to be evaluated by WP5:

- Collimator settings depend on the combination of beam size, impedance, machine protection, imperfections
- Primary and secondary settings are dominated by impedance considerations, should not depend on crab dispersion as long is small.
- However given that the crab dispersion depends on the local phase advances, the analysis of collimators retractions needs to be evaluated for each optics.

In the following I assume that collimation are not perturbed, therefore the aperture in "standard sigma" is obtained by rescaling unperturbed apertures with the normalized crab dispersion

$$A_{\mathrm{crab}} = A_{\mathrm{nom.}}(1-F) \text{ where } 1-F = \sqrt{\frac{\epsilon_x\beta_x + D_x^2\sigma_\delta^2}{\epsilon_x\beta_x + D_x^2\sigma_\delta^2 + C_x^2\sigma_z^2}} = \frac{1}{\sqrt{1+\frac{C_x^2\sigma_z^2}{\epsilon_x\beta_x + D_x^2\sigma_\delta^2}}} = \frac{1}{\sqrt{1+C_{\mathrm{NC}}^2}}$$

C_{NC}[%]	10	20	30	50	80	100
F[%]	0.5	1.9	4.2	11	22	29

Detailed calculations

Round 15 cm	IP1 (H xing)	IP5 (V xing)
Aperture [σ] [H/V]	13.1/16.5	16.5/13.1
MKD-TCT [°] [B1/B2]	5/19	30/31
Ap. Protected W [σ] [H/V]	11.2/11.2	11.7/11.2
Ap. Protected CuCD [σ] [H/V]	11.2/11.2	11.2/11.2
Ap. Margin W [σ] [H/V]	1.9/5.3	4.8/1.9
Ap. Margin CuCD [σ] [H/V]	1.9/5.3	5.3/1.9
Ap. Margin W [%] [H/V]	14%/32%	29%/32%
Ap. Margin CuCD [%] [H/V]	14%/32%	14%/32%

FlatCCHV 18/7.5 cm	IP1 (H Xing)	IP5 (V Xing)
Aperture [σ] [H/V]	14.2/12.7	12.7/14.2
MKD-TCT [°] [B1/B2]	13/22	39/54
Ap. Protected W [σ] [H/V]	11.3/11.2	14.1/11.2
Ap. Protected CuCD [σ] [H/V]	11.2/11.2	13.1/11.2
Ap. Margin W [σ] [H/V]	2.9/1.5	-1.4/3.0
Ap. Margin CuCD [σ] [H/V]	3.0/1.5	-0.4/3.0
Ap. Margin W [%] [H/V]	20%/13%	-11%/21%
Ap. Margin CuCD [%] [H/V]	21%/13%	-3%/21%

Conclusion

If the crab bump is not closed the crabbing leaks in the machine as an orbit distortion proportionally to the missing voltage.

Assuming crab dispersion does not change collimator settings:

- For round optics, by using present margin up 50% voltage errors could be accepted for the aperture, but at the cost of strong luminosity loss.
- For flat optics with CC, or any other optics limited in aperture, the non closure starts to become significant (4% β^* reach) when voltage error around 20%.

There are optimal phase advances that minimize the impact of crab cavity closure, but they are not taken into account for the sake of keeping flexibility.

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Back-up

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Protected Apertures

Parameters	7 TeV	0.45 TeV
Radial CO [mm]	2	
Mom offset	$2\ 10^{-4}$	$8.6\ 10^{-4}$
Dispersion	0.1	0.14
Beam size	1.1	1.05
Min Ap. no TCT [σ]	19.4	12.6
Min H. Ap. with TCT [σ]	table	12.6
Min V. Ap. with TCT [σ]	11.2	12.6

$\Delta\mu_x$ MKD-TCT [°]	H. Ap. W [σ@2.5μm]	H. Ap. CuCD [σ@2.5μm]
0-20	11.2	11.2
30	11.9	11.2
40	12.9	11.9
50	13.8	12.8
60	14.5	13.6
70	14.6	14
80-90	14.6	14.3

R. Bruce et al. CERN-ACC-2017-0051 and proposal of differentiating H/V collimators (R. Bruce).

- CuCD collimators give about ~1 σ additions H margin from 40° to 60° MKD-TCT phase advance.
- MKD-TCT phase advance constrains:
  - mostly IR6 optics for TCT5 for both beams and
  - mildly IR4 and arcs 23, 34, 67, 78 optics for TCT1

Impact of CuCD is relevant when Point 5 bottlenecks is in H plane.

Optics, aperture, crossing plane

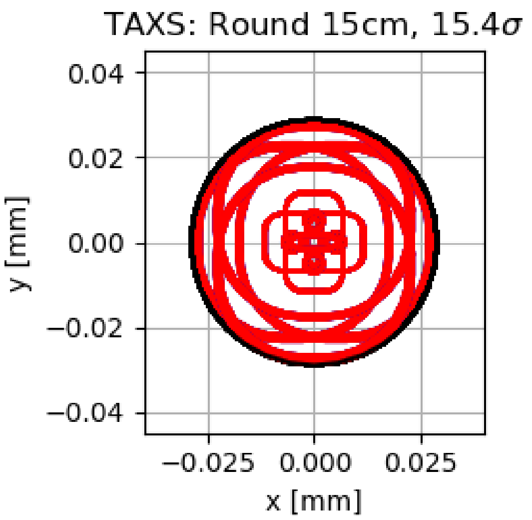
	Round	Flat	FlatCC	FlatCCHV	FlatCCHV
β* Xing/Sep [cm]	15/15	30/7.5	18/7.5	18/9	18/7.5
Xing angle [μrad]	±250	±245	±240	±240	±240
Crossing plane IP5	V (or H)	H	H	V	V
Aperture Xing plane [σ]	13.1	15.6	14.2	14.2	14.2
Aperture Sep plane [σ]	16.5	12.7	12.7	13.9	12.7
H Aperture Point 1/5	13.1/16.5	12.7/15.6	12.7/14.2	14.2/13.9	14.2/12.7
MKD-TCT [°] IP1 [B1/B2]	5/19	23/10	4/6	13/22	8/22
MKD-TCT [°] IP5 [B1/B2]	30/31	14/22	27/25	40/45	51/54
H Ap. Protected IP1 W/Cu	11.2/11.2	11.4/11.2	11.2/11.2	11.3/11.2	11.3/11.2
H Ap. Protected IP5 W/Cu	11.9/11.2	11.3/11.2	11.7/11.2	13.3/12.3	14.1/13.1
Ap. Margin W [σ]	1.9 (or 1.2)	1.3	1.5	0.6	-1.4
Ap. Margin CuCD [σ]	1.9 (or 1.9)	1.5	1.5	1.6	-0.4

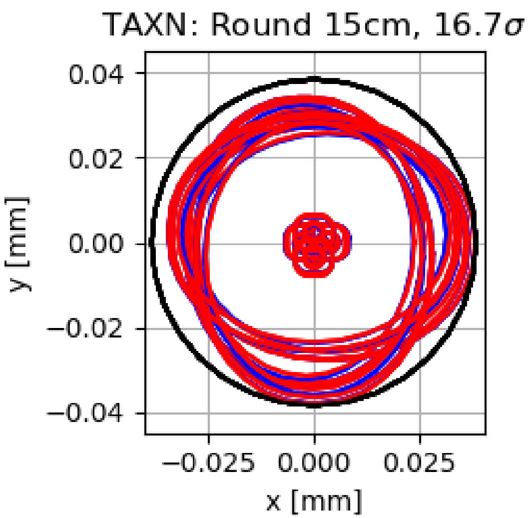
Assuming different settings for TCTH and TCTV, which is under study (R. Bruce):

- IR6 optics is constraining only for flat optics and V crossing in Point 5.
- CuCD collimators:
    - Improve β* reach for flat optics with crab cavities from about 8.7 cm to 7.8 cm (based on scaling).
    - Allow H crossing in Point 5 without performance losses (but CMS forward physics preferred V).
    - Allow ±10° additional potential flexibility in IP1 to IP5 for flat optics with crab cavities phase advance for lifetime optimization without compromising β* reach.

Apertures: Round β*=15 cm, 500 μrad

	bare	bstol	align	beam	offset
TAXS	25.1	24.1	21.6	17.6	15.4
Q1	22.2	20.8	20.8	17.7	17.7
Q23	16.4	15.6	15.4	13.1	13.1
D1	17.4	16.5	16.3	13.9	13.9
D1 (ext)	17	16.1	15.9	13.5	13.5
TAXN (85mm, 1.4)	23.4	22.5	21.2	18	18
TAXN (80mm, 1.5)	22.1	21.2	19.8	16.7	16.7
TCTPV	22.1	22.1	22.1	18.8	18.8
TCTXH	22.7	22.7	22.7	19.3	19.3
TCLX	23.3	23.3	23.3	19.8	19.8
D2	24.9	24.9	23	19.3	19.3
D2 Corr.	25.7	25.7	24	20.1	20.1
CC (b.s)	27.8	27.8	25.9	21.8	21.8
Q4 Mask	25.9	25.9	23.6	19.3	19.3
Q4 Corr.	27.6	27.6	25.2	20.6	20.6
Q4	29	29	26.9	22.2	22.2
Q5 Mask	28.7	28.7	26.4	21.5	21.1
Q5 Corr.	31.4	29.8	27.4	22.3	22
Q5	31.8	30.2	27.9	22.7	22.4
Q6 Mask	36.5	36.5	34.1	27.9	26.7
Q6 Corr.	37.6	37.6	35.1	28.8	27.6
Q6	38	38	35.5	29.1	28.2

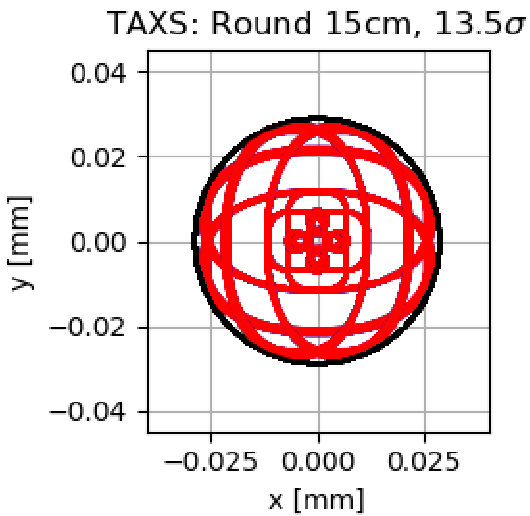


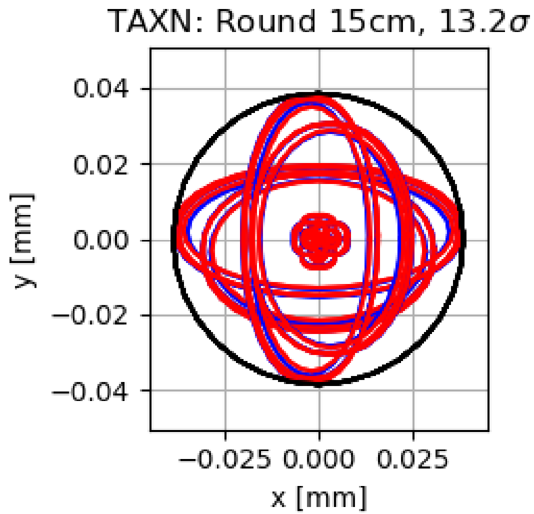


Aperture considered for TAXS-TAXN respect constraints and hierarchy

Apertures: Flat β*=7.5/30 cm, 490 μrad

	bare	bstol	align	beam	offset
TAXS	21.1	20.4	18.5	15.2	13.5
Q1	19.4	18.5	18.5	15.9	15.9
Q23	15.5	14.9	14.7	12.7	12.7
D1	15.8	15.1	14.9	12.9	12.9
D1 (ext)	15.5	14.8	14.6	12.6	12.6
TAXN (85mm, 1.4)	18.1	17.5	16.5	14.1	14.1
TAXN (80mm, 1.5)	17.2	16.6	15.6	13.2	13.2
TCTPV	17	17	17	14.4	14.4
TCTXH	17.3	17.3	17.3	14.7	14.7
TCLX	17.6	17.6	17.6	15	15
D2	18.9	18.2	17.1	14.5	14.5
D2 Corr.	21.3	20.5	19.3	16.4	16.4
CC (b.s)	20.6	19.7	18.3	15.4	15.4
Q4 Mask	19.2	18.3	16.7	13.6	13.6
Q4 Corr.	20.5	19.5	17.8	14.5	14.5
Q4	21.5	20.6	19.1	15.6	15.6
Q5 Mask	21.3	20.2	18.7	15.2	14.9
Q5 Corr.	22	20.9	19.4	15.8	15.6
Q5	22.3	21.1	19.5	15.8	15.6
Q6 Mask	25.9	25.9	24.2	19.7	18.9
Q6 Corr.	28.3	26.9	25.1	20.5	19.6
Q6	28.3	26.9	25.1	20.5	19.9

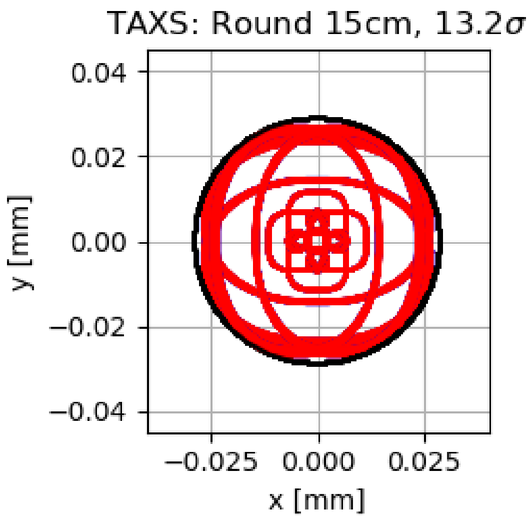


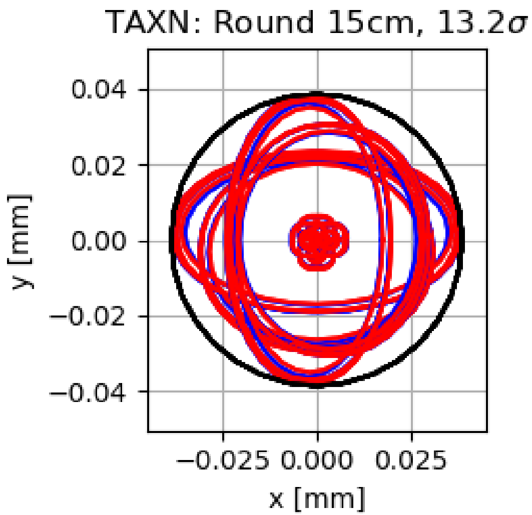


Aperture considered for TAXS-TAXN respect constraints and hierarchy

Aperture FlatCC: β*=7.5/18 cm, 480 μrad

	bare	bstol	align	beam	offset
TAXS	21	20.2	18.3	15.1	13.2
Q1	19.4	18.5	18.4	15.9	15.9
Q23	15.5	14.9	14.7	12.7	12.7
D1	15.8	15.1	14.9	12.9	12.9
D1 (ext)	15.5	14.8	14.6	12.6	12.6
TAXN (85mm, 1.4)	18.1	17.5	16.5	14.1	14.1
TAXN (80mm, 1.5)	17.2	16.5	15.6	13.2	13.2
TCTPV	17	17	17	14.4	14.4
TCTXH	17.2	17.2	17.2	14.7	14.7
TCLX	17.6	17.6	17.6	15	15
D2	18.9	18.2	17.1	14.5	14.5
D2 Corr.	21.3	20.5	19.3	16.4	16.4
CC (b.s)	20.6	19.7	18.3	15.4	15.4
Q4 Mask	19.2	18.3	16.7	13.6	13.6
Q4 Corr.	20.4	19.5	17.8	14.5	14.5
Q4	21.4	20.6	19.1	15.6	15.6
Q5 Mask	21.2	20.2	18.7	15.2	14.9
Q5 Corr.	22	20.9	19.4	15.8	15.6
Q5	22.3	21.1	19.5	15.8	15.6
Q6 Mask	25.8	25.8	24.1	19.7	18.9
Q6 Corr.	28.3	26.9	25.1	20.5	19.6
Q6	28.3	26.9	25.1	20.5	19.9



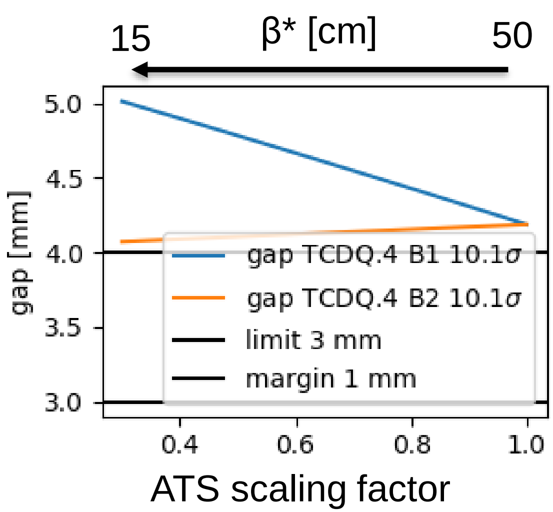


Aperture considered for TAXS-TAXN respect constraints and hierarchy

TCDQ gap for HL-LHC

TCDQ gaps margins	New [mm]	Notes
Min real gap	3	Based on present FLUKA and ANSYS studies at 2.2 10^{11}. 2.5 mm for 1.8 10^{11}.
Interlock	0.6	Based on studies with DOROS TCSP
Position accuracy, β-beat	0.3	
Dispersion δ =2e-4	~0.1	Using realistic D_x=0.5 m instead of 2 m
Total margin	1.0	

Present BETS:fixed gap at flat top in mm corresponding to the setting at the end of the squeeze.



Round squeeze

TCDQ settings nominal scenario (round optics β*=15 cm):

- Beam 1: $\beta_{x,TCDQ}$ increases during the squeeze
  - 5 mm: from 12.3σ →10.1 σ:
- Beam 2: $\beta_{x,TCDQ}$ decreases during the squeeze
  - 4.1 mm: from 9.6 σ → 10.1 σ. (not ideal but acceptable)

TCDQ setting for alternative scenarios:

- Flat optics with H crossing in Point 5 (e.g. no crab cavities): gap >4.2 mm for both beams, no issues.
- Flat optics with V crossing in Point 5 (e.g. with crab cavities): gap >3.7 mm for Beam 2. TCDQ gap levelling needed.