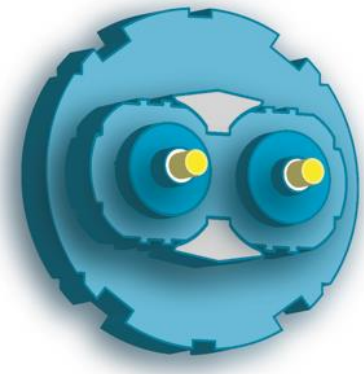


High Luminosity LHC

Review of the aperture margins for the new HL-LHC magnets

R. De Maria with input from G. Arduini, O. Brüning, R. Bruce, F. Cerutti, L. Esposito, S. Fartoukh, P. Fessia, M. Fitterer, M. Giovannozzi, R. Kersevan, S. Redaelli, E. Todesco.

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Status HL-LHC layout

- HLLHCV1.0 is the present baseline model for layout and optics.
- The layout has been frozen since April 2013.
- Several updates have been requested (4 cavities with in case a displacement, new D1 length, masks in front of D2, Q5, Q6, review of the D2 length and associated orbit correctors, new Q5 types).
- A new layout and optics is foreseen for Spring and will sum up the requests and integrate the changes.
- Today I will:
  - review the aperture margins for the frozen HL-LHCV1.0 and
  - illustrate the impact of few requested variations.

Aperture margin estimations

Aperture margins are determined by:

- A model of the inner cross section of the beam screen:
  - triplet area: best guess from vacuum but without manufacturing tolerances;
  - aperture scaling for D2 and Q4.
- A model of alignment accuracy and ground motion;
- The optics scenarios (round and flat β*) that provides the ideal position of the beam and the transverse beam size
- An operation scenario for estimating orbit and optics imperfections.
- The aperture that the collimation system can protect. It is conveniently expressed in sigma@3.5µm/γ regardless of the emittance of the beam and depends whether or not a TCT protects the aperture by asynchronous dumps.

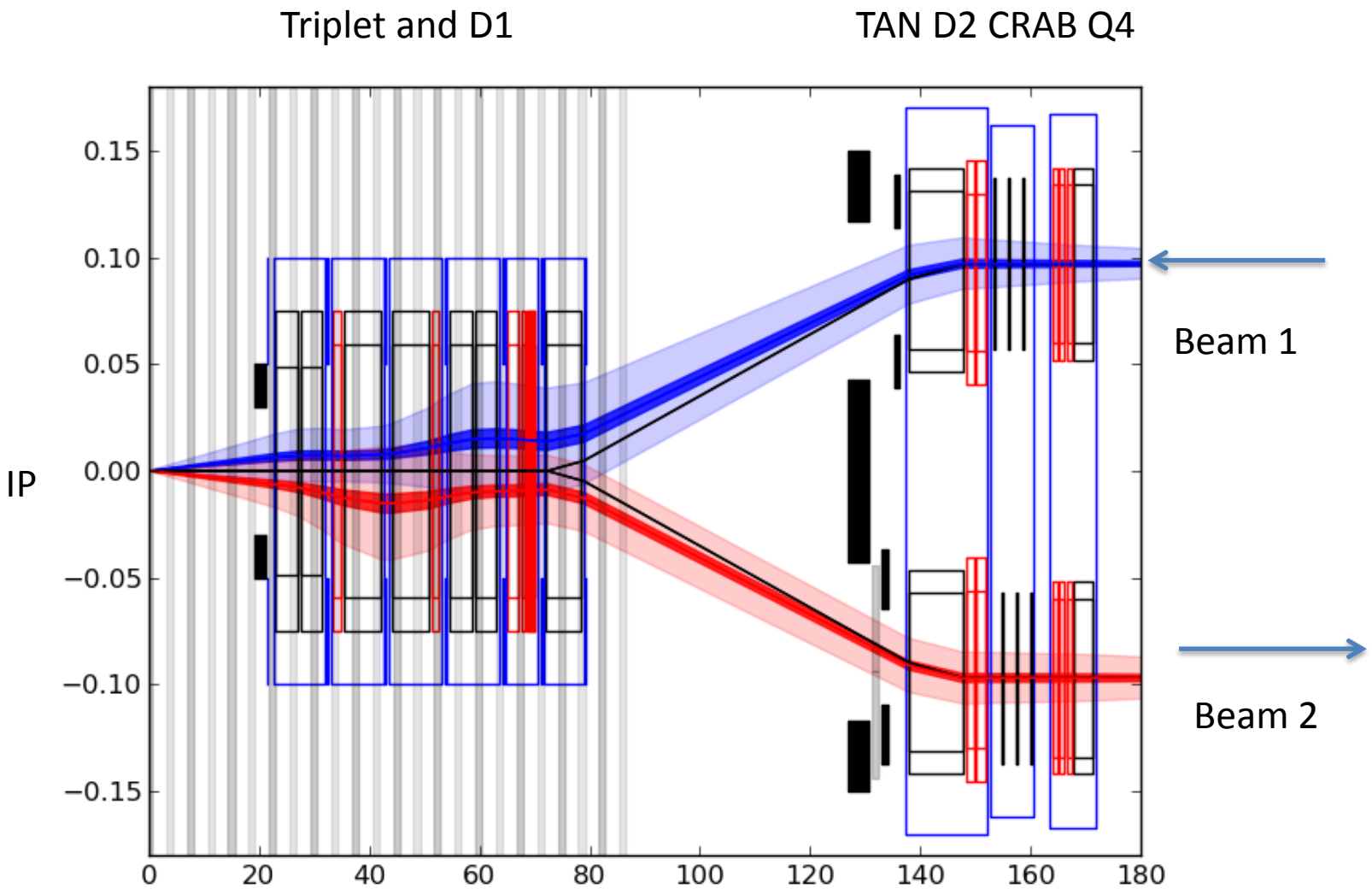
Collision low-β optics parameters

Name	IP1-5			IP2			IP8		
	β* [cm]	Angle [murad]	sep [mm]	β* [m]	Angle [murad]	sep [mm]	β* [m]	Angle [murad]	sep [mm]
Round	**15**	**590**	**0.75**	**10**	**340**	**2**	**3**	**340**	**2**
flat	**7.5, 30**	**550**	**0.75**	**10**	**340**	**2**	**3**	**340**	**2**
flathv	**30, 7.5**	**550**	**0.75**	**10**	**340**	**2**	**3**	**340**	**2**
sround	10	720	0.75	10	340	2	3	340	2
sflat	5, 20	670	0.75	10	340	2	3	340	2
sflathv	20, 5	670	0.75	10	340	2	3	340	2

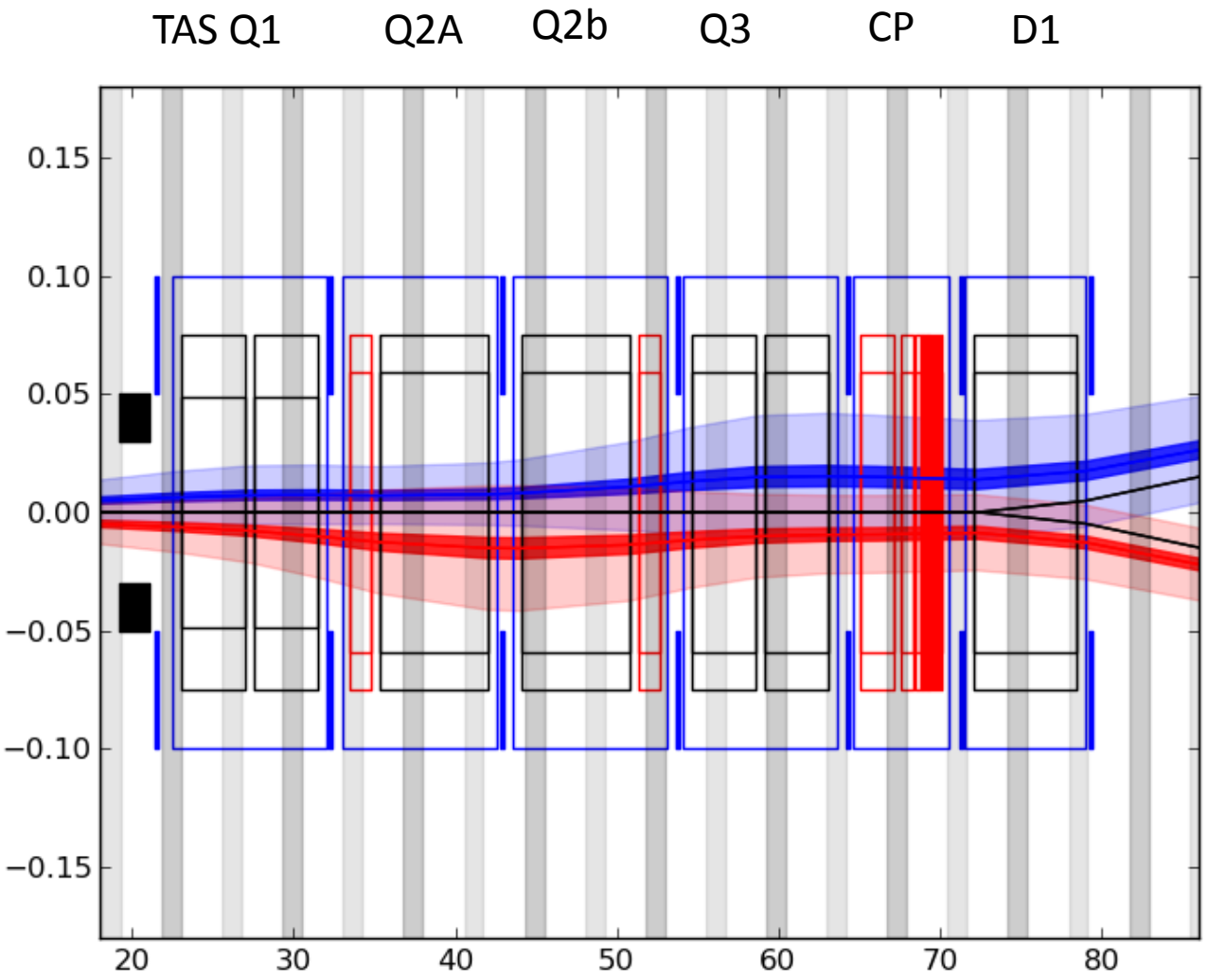
- Optics available under /afs/cern.ch/eng/lhc/optics/HLLHCV1.0
- In the following baseline round and flat optics at 15 cm and 7.5/30 cm are considered.
- Ultimate squeeze for improved performance provided tight collimation settings.

Based on the ATS scheme (S. Fartoukh, SLHC report 49, 2010.)
R. De Maria et al, IPAC'13 and reference therein for the last public version.

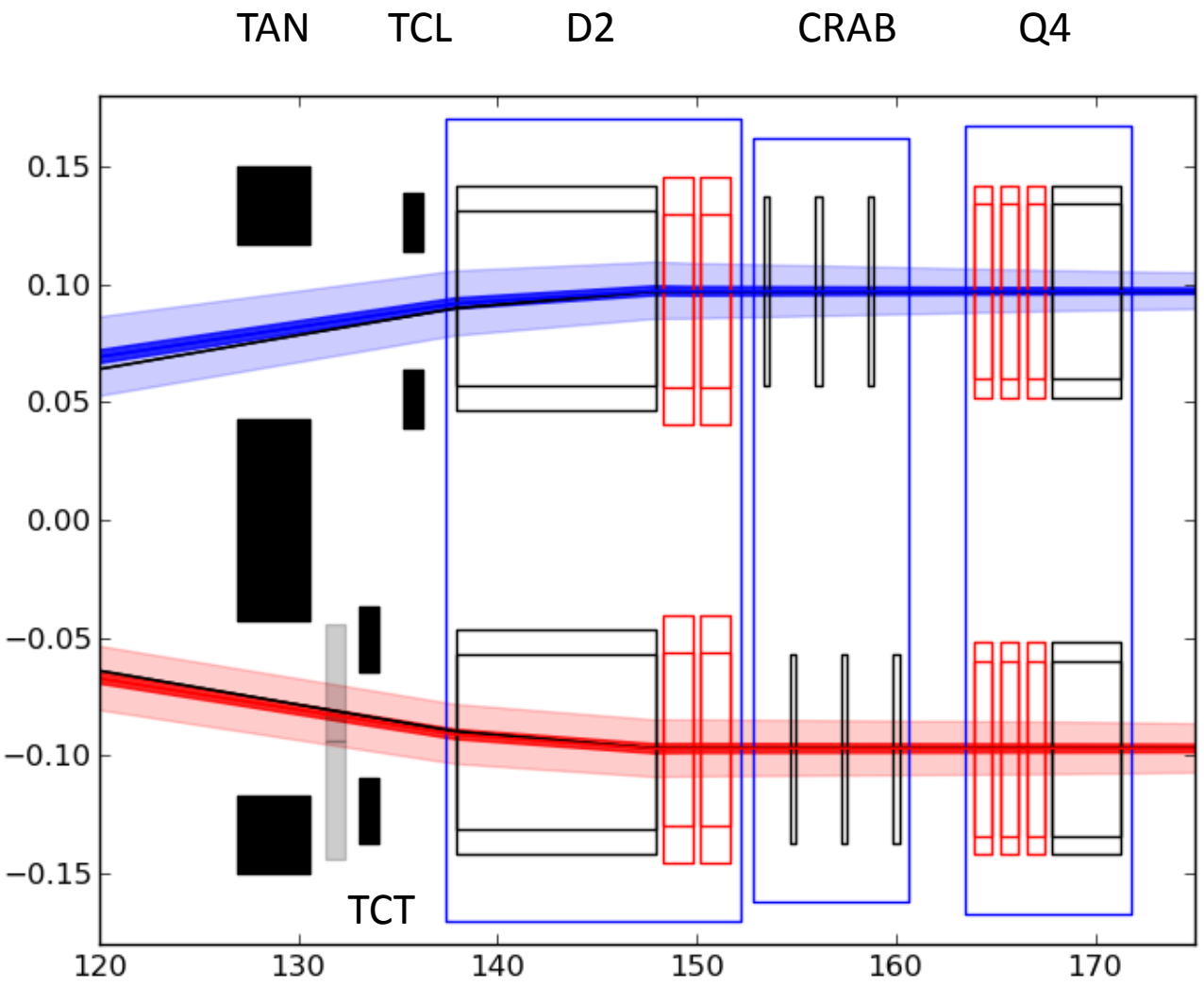
Layout overview HL-LHC V1.0



Layout Triplet HL-LHC V1.0



Layout TAN – Q4 HL-LHC V1.0



Aperture model in LHC

Element	Coil ap. [mm]	Sep. [mm]	Shape	Specs [mm]
TAS			Circle	30
Q1	70		Rectellipse (HV – pol)	23.85, 18.95
Q2-Q3	70		Rectellipse (HV – pol)	28.9, 24.
D1 warm	70		Rectellipse (HV – pol)	64.0, 26.5
D1 cold	70		Rectellipse (HH)	33.7, 28.8
TAN	n/a	160	Circle	26
D2	80	188	Rectellipse (HV- opt)	31.3,26.4
Q4	70	194	Rectellipse (HV - opt)	28.9, 24
Q5	56	194	Rectellipse (HV - pol)	22.55,17.65
Q6	56	194	Rectellipse (HV - pol)	22.55,17.65

pol./opt.: orientation follow polarity / collision optics

Aperture model in HLLHCV1.0 (4/2013)

Element	Origin
TAS[1]	Rescaled to be in the shadow of triplet aperture without shielding
Q1[2]	He (1.5 mm), CB (5 mm) , CB to BS (1.5 mm), BS (2 mm), W(16mm)
Q2-Q3 to D1[2]	He (1.5 mm), CB (5 mm) , CB to BS (1.5 mm), BS (2 mm), W(6mm)
TAN[3]	Optimized for parallel aperture and smaller or equal aperture
D2[3]	scaled like D2: 105·31.3/80 -> (41,41-5)
Crab Cavities[4]	As big as to be largely in the shadow of D2 and Q4
Q4[1]	scaled like Q4: 90·28.9/70 -> (37,37-5)
Q5[1]	As MQY
Q6[1]	Nominal MQM

1) S. Fartoukh, SLHC-PR-49, 2010. 2) E. Todesco, R. Kersevan, 1st and 2nd PLC, 2012
3) R. De Maria, S. Fartoukh, SLHC-PR55, 2011 4) R. Calaga, CC Workshop, 2010.

Aperture model in HL-LHC V1.0 (2013)

Element	Coil ap. [mm]	Sep. [mm]	Shape	Specs [mm] (radius, half-gap)
TAS[1]			Circle	30
Q1[2]	150		Octagon	49 (hv), 49 (45)
Q2-Q3 to D1[2]	150		Octagon	59 (hv), 59 (45)
TAN[3]	n/a	144	Ellipse	42(h), 36(v)
D2[3]	105	186	Rectellipse HH	41(h),36(v)
Crab Cavities[4]	84	194	Circle	42
Q4[1]	90	194	Rectellipse (HV - opt)	37(h),32(v)
Q5[1]	70	194	Rectellipse (HV - opt)	28.9, 24
Q6[1]	56	194	Rectellipse (HV - pol)	22.55,17.65

1) S. Fartoukh, SLHC-PR-49, 2010. 2) E. Todesco, R. Kersevan, 1st and 2nd PLC, 2012
3) R. De Maria, S. Fartoukh, SLHC-PR55, 2011 4) R. Calaga, CC Workshop, 2010.

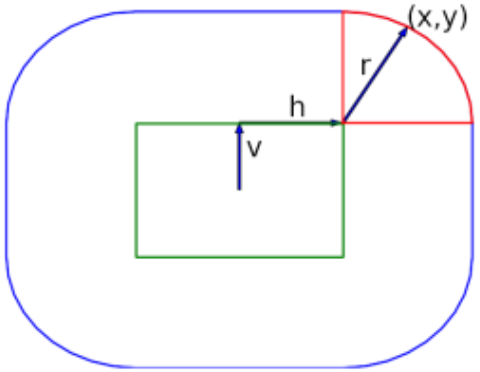
Aperture model in HL-LHC (Study)

Element	Coil ap. [mm]	Sep. [mm]	Shape	Specs [mm] (radius, half-gap)
TAS			Circle	reduction
Q1	150		Octagon	wait for tol.
Q2-Q3 to D1	150		Octagon	wait for tol.
TAN	n/a	148-158.6[1]	Circle non parallel[1]	38[1]
D2 and mask[1]	105 or 100[1]	186 or 188	Rectellipse HH or oct. [2]	wait for 1st design
Crab Cavities	84	194	Circle	42
Q4	90	194	Rectellipse (HV - opt)	wait for 1st design
Q5 and mask[1]	70 or 90[2]	194	Rectellipse (HV - opt)	
Q6 and mask[1]	56	194	Rectellipse (HV - pol)	22.55,17.65

[1] see energy deposition model (see L. Esposito, F. Cerutti, WP2 meetings)
[2] for crab cavities optimized optics (under study)

Ground motion and fiducialization

- Ground motion span a racetrack area[1]:
  - Triplet (r=0.6 mm, h= 0, v=0)
  - Matching sections (r=0.84 mm, h= 0.36, v= 0)
- Fiducialization for MQ (h=0.9 mm, v= 0.6 mm)
- Summary[2]:



Element	r_m+r_f [mm]	h_m+h_f [mm]	v_m+v_f [mm]
TAS	2+0	0+0.5	0+0.5
IT	0.6+0	0+1	0+1
D1/D2	0.84+0	0.36+1	0+1
TAN	0.6+0	0+1	0+1
Q4/Q5	0.84+0	0.36+0.9	0.6

[1]JB. Jeanneret, LHC Report 1007, 2007. [2]S. Fartoukh, SLHC aperture models.

Aperture protection in the IR1 – IR5

- Target:
  - If an aperture is protected by a dedicated TCT: -> 12σ.
  - If an aperture is not protected: -> 14σ to 20σ to be evaluated with detailed simulations.
  - Avoid adding too many TCTs if not strictly necessary due to the operational overhead.

- Values expressed as the beam sigma at 3.5µm@7TeV (regardless of the emittance of the beam for $\epsilon<4\mu m/\gamma$) after the ground motion and orbit effects are accounted for the worst the case scenario.
- First estimates, under validation by collimation team.
- No gain from the button BPM include or additional retraction due to impedance issues.

R. Bruce, S. Redaelli, WP2 meeting 13/9 and private communication.

Beam Tolerances

New beam tolerances are being reviewed based on the positive experience of the last LHC run and including the remaining uncertainties of new operation regimes (low β*, levelling, short crossing scheme bumps)

Quantity	LHC Design	HL-LHC
Closed orbit	3 mm	2 mm
Beta-beating	20% (10% in sigma)	20% (10% in sigma)
Dispersion errors	54 cm in the arcs	20 cm in the arcs
Energy Error	$8 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
Energy	7000 GeV	7000 GeV
Emittance	3.75 µm	3.5 µm

ATS Note in preparation R. Bruce, R. De Maria, S. Fartoukh, M. Giovannozzi, S. Redaelli, R. Tomas, J. Wenninger.

Aperture summary for HL-LHCV1.0

Element	Target[1] [σ]	Ideal beam [σ]	+ imp. [σ]	Sensitivity [2] [σ/mm]
TAS	≥12	15.11	12.41	0.55
Q1	≥12	15.42	13.19	0.30
Q2-Q3	≥12	12.54	10.83	0.20
D1	≥12	12.86	11.07	0.22
TAN (new)	≥12	12.60 (13.46)	10.59 (11.39)	0.34 (0.33)
D2 (mask)	≥14-20	15.06 (13.12)	12.75 (11.01)	0.38 (0.37)
Crab cavities	≥18-20	23.30	19.94	0.53
Q4	≥16-20	20.10	16.86	0.61
Q5 (mask)	20	30.26 (28.67)	24.79 (23.48)	1.26 (1.29)
Q6 (mask)	20	33.88 (32.23)	19.52 (18.52)	1.04 (1.01)
Q7	20	31.09	25.36	1.37

[1] Tentative target to be validated by collimation simulations.

[2] Gain/Loss in sigma if aperture increased/reduced by 1 mm in radius

Conclusion

Critical points for the hardware:

- Additional tolerances and cooling tube size have a cost in the β* reach.
- Beam screen designs should be as optimized as new magnet design (one can easily loose 1cm in triplet tolerances, e.g. PhaseI).
- D2 coil aperture cannot be specified without a design of the beam screen.
- An increase of the mask aperture for the MS magnets should be evaluated.
- Need of additional TCTs to be validated by collimation simulations, but it should be avoided by maximizing MS apertures.
- Aperture of the MS magnets may reduce the possibility to further enhance the crab cavity efficiency.

Backup

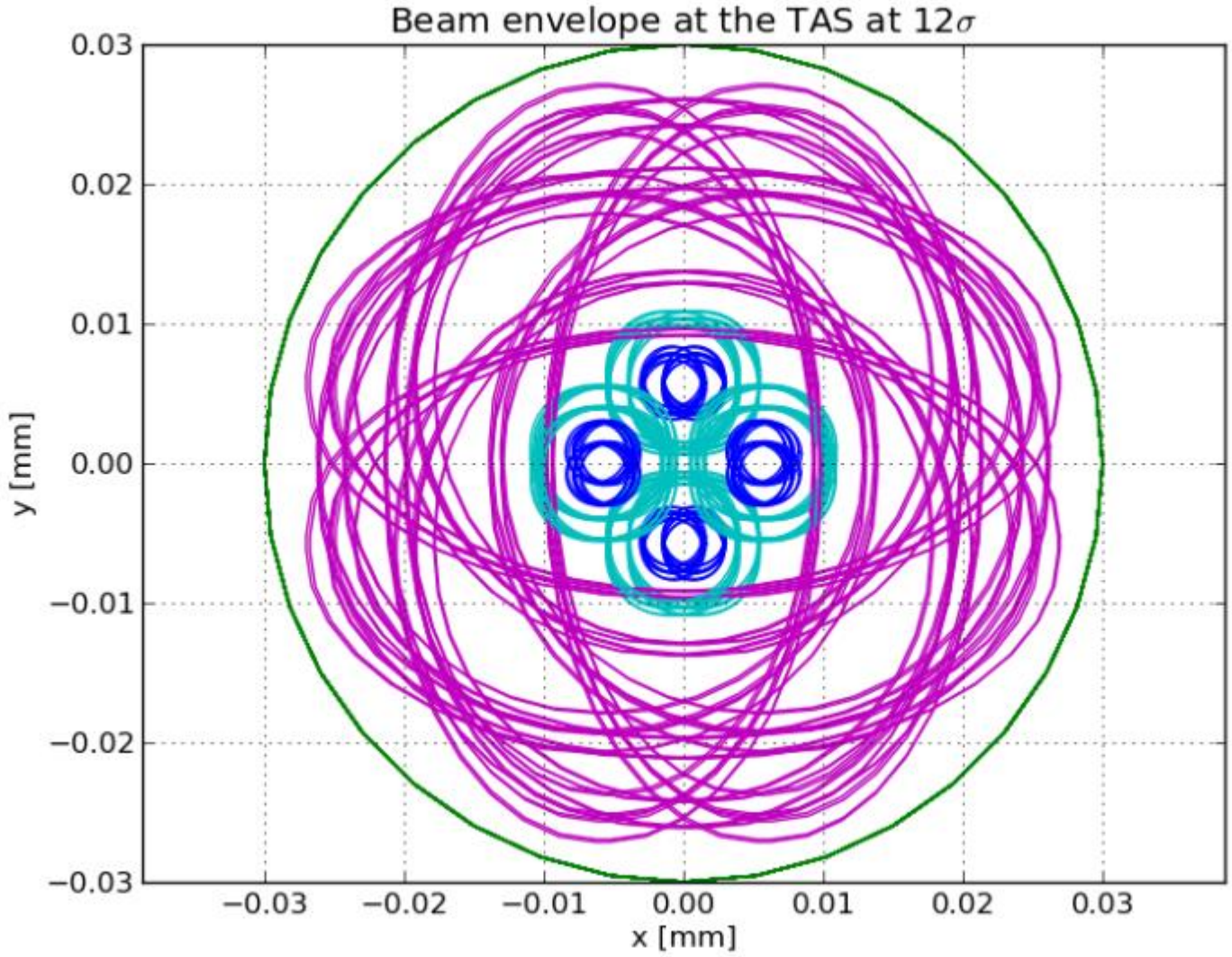
Aperture summary HL-LHCV1.0 (round)

Element	Ideal beam [σ]	+ imp. [σ]	Sensitivity [1] [σ/mm]
TAS	17.53	14.22	0.75
Q1	17.35	14.72	0.43
Q2-Q3	12.88	10.95	0.29
D1	14.30	12.21	0.31
TAN (new)	16.22 (16.78)	13.63 (14.14)	0.45 (0.46)
D2 (mask)	19.27 (18.13)	16.23 (15.30)	0.55 (0.50)
Crab cavities	27.86	23.87	0.63
Q4	25.92	22.03	0.67
Q5 (mask)	32.81 (31.67)	27.42 (26.47)	1.11 (1.07)
Q6 (mask)	33.88 (32.23)	27.67 (26.26	1.47 (1.42)
Q7	42.35	34.60	1.84

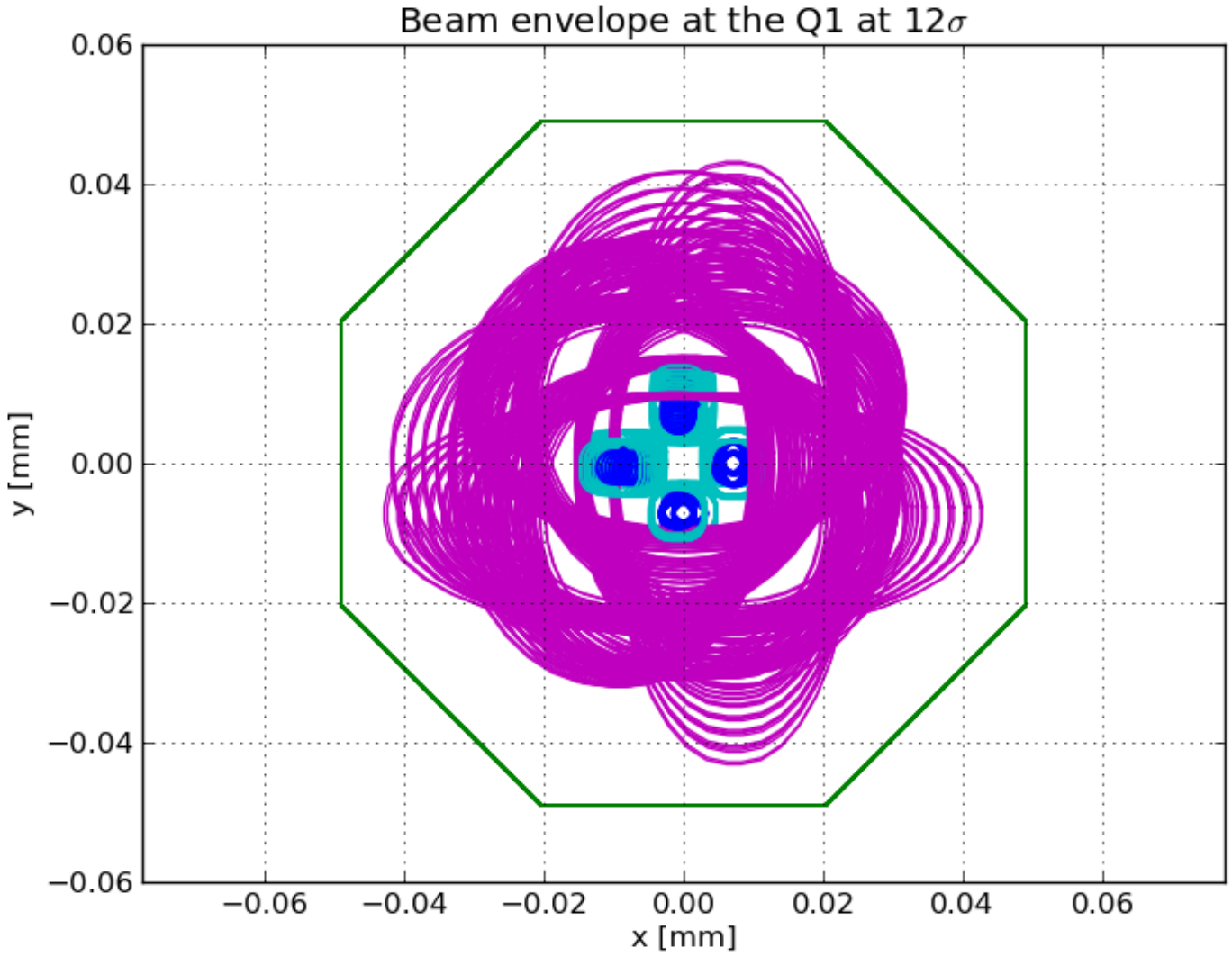
Aperture plots…

[1] gain in sigma aperture if increased by 1 mm in radius

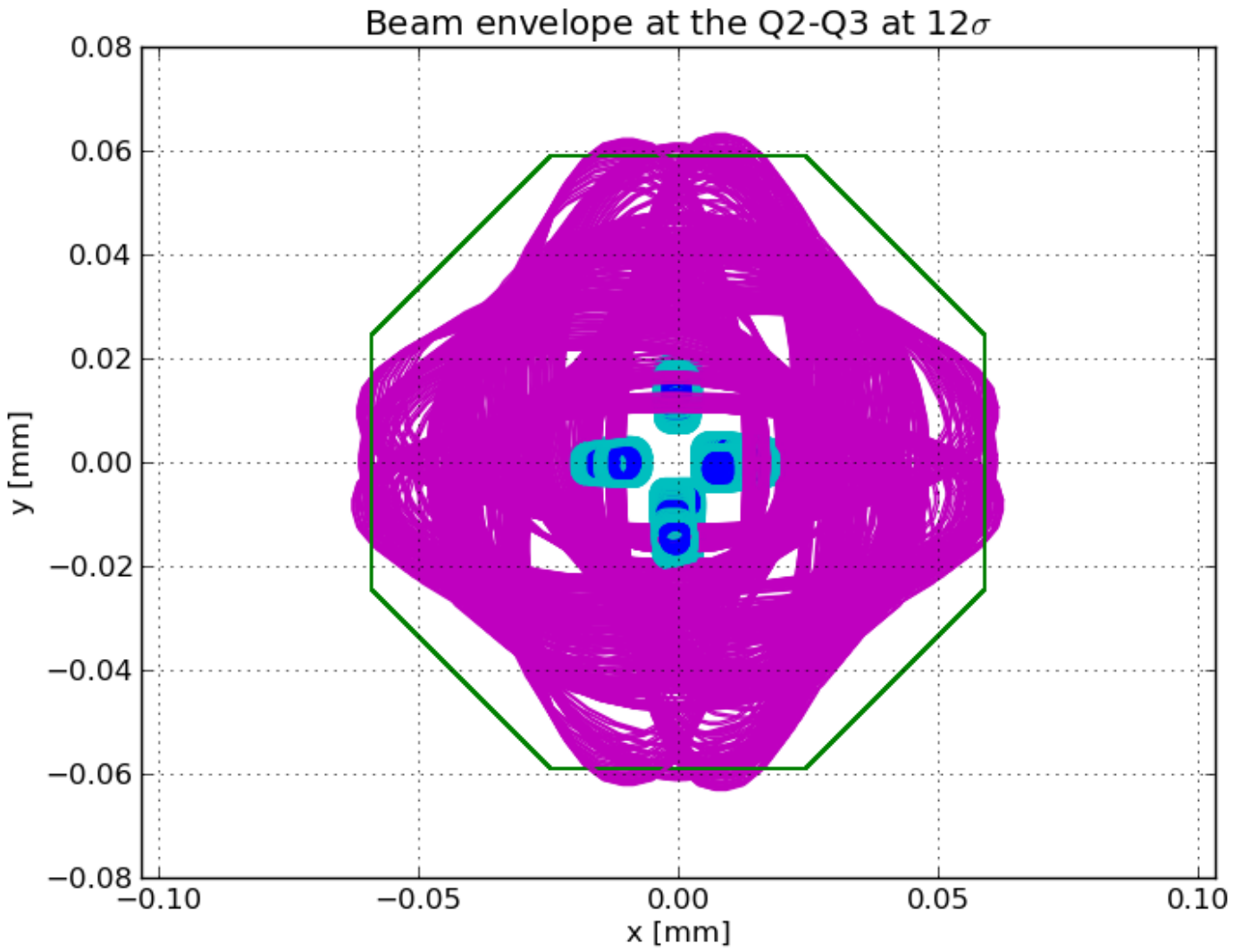
TAS


Beam envelope at the TAS at 12σ
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
y [mm]
−0.03
−0.02
−0.01
0.00
0.01
0.02
0.03
x [mm]

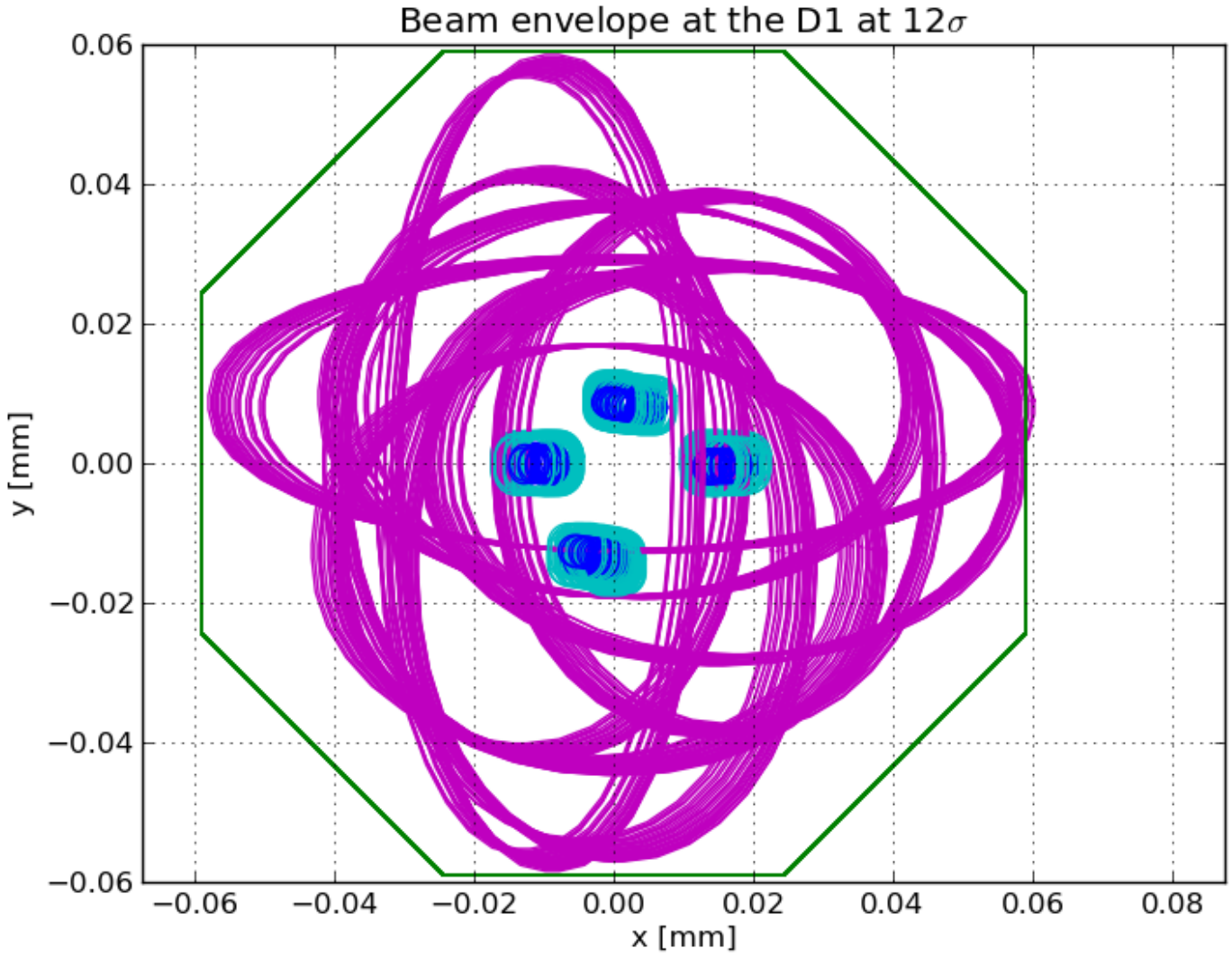
Q1


Beam envelope at the Q1 at 12σ
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
y [mm]
−0.06
−0.04
−0.02
0.00
0.02
0.04
0.06
x [mm]

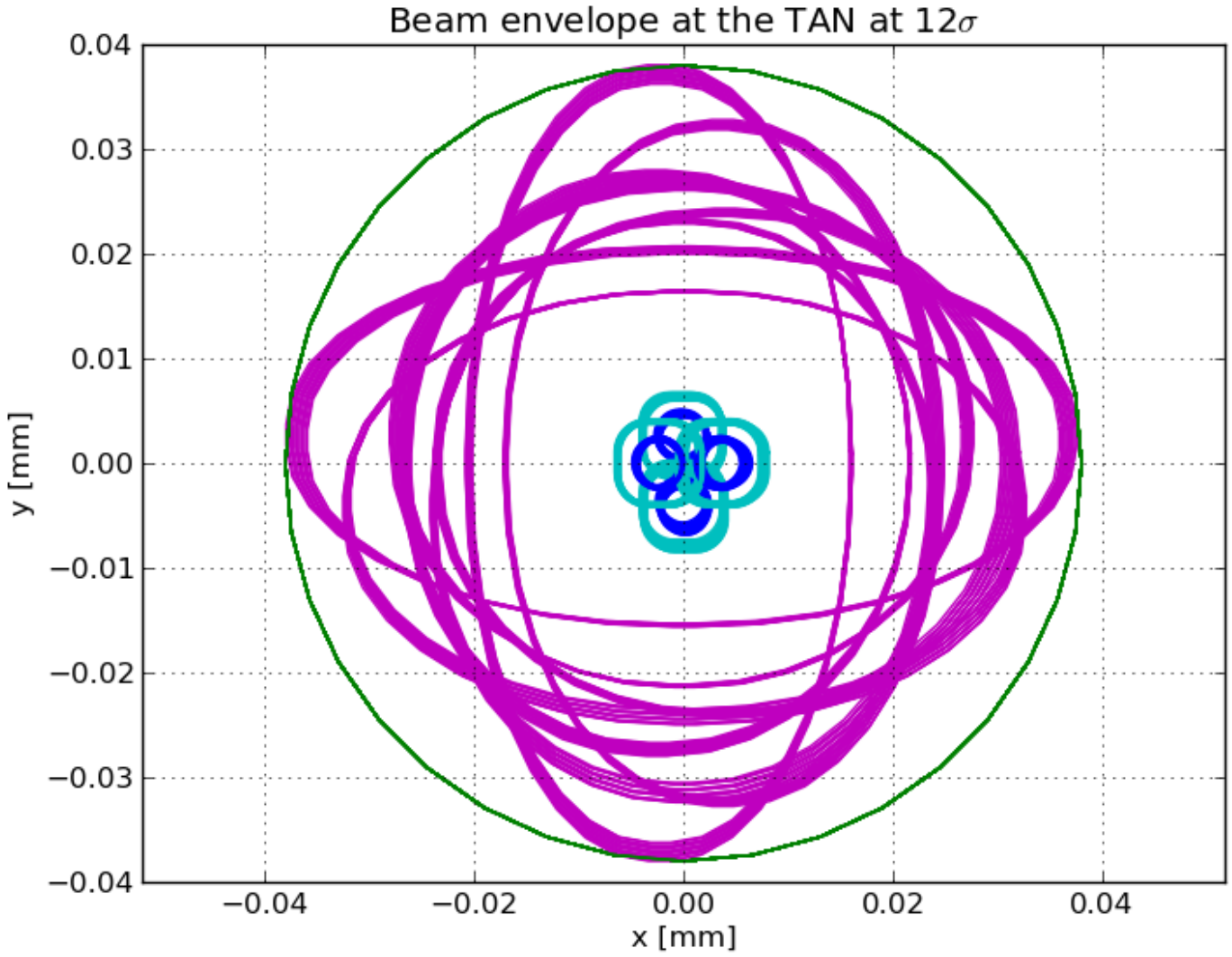
Q2-Q3


Beam envelope at the Q2-Q3 at 12σ
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.08
y [mm]
−0.10
−0.05
0.00
0.05
0.10
x [mm]

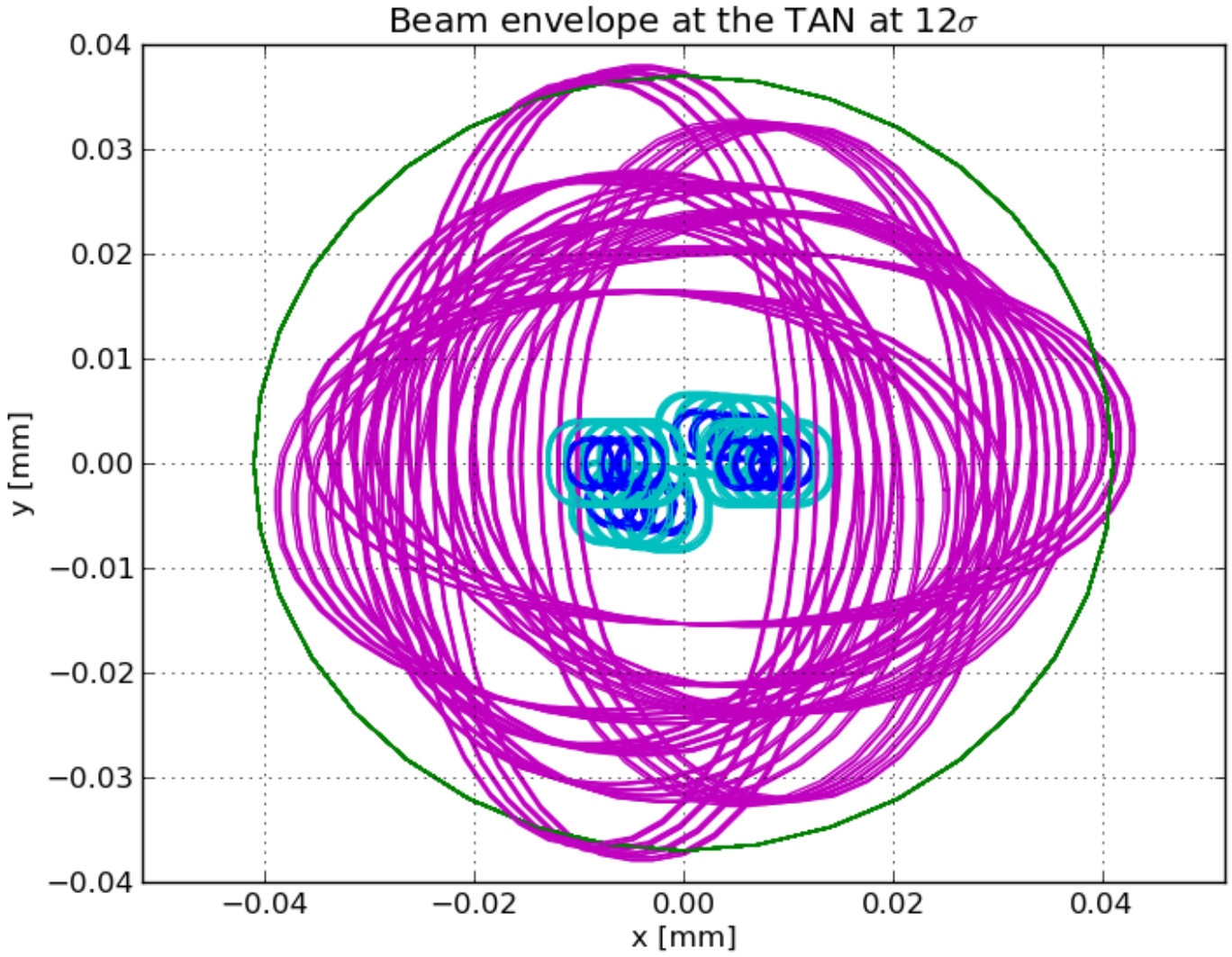
D1


Beam envelope at the D1 at 12σ
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
y [mm]
−0.06
−0.04
−0.02
0.00
0.02
0.04
0.06
0.08
x [mm]

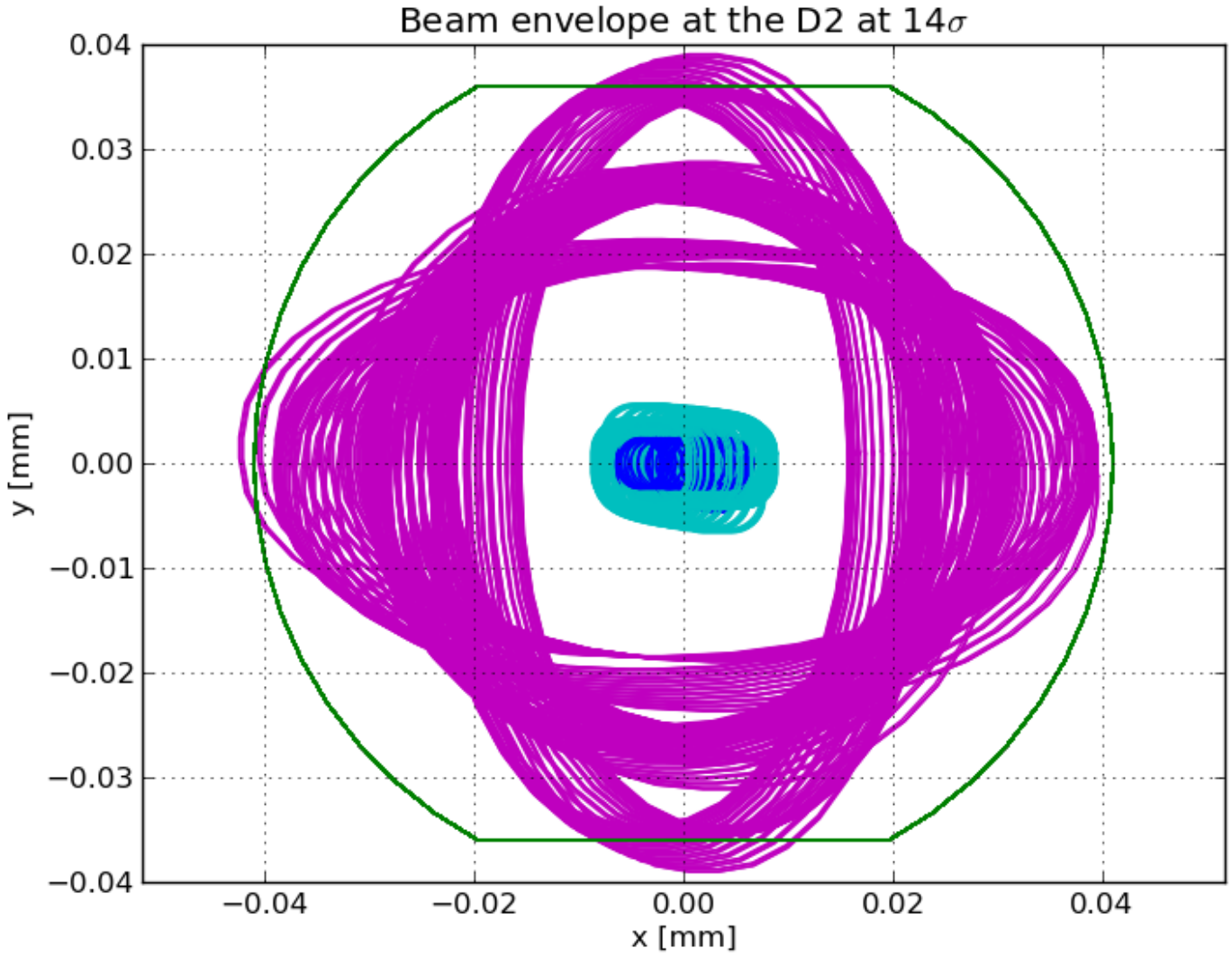
TAN (new)


Beam envelope at the TAN at 12σ
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
y [mm]
−0.04
−0.02
0.00
0.02
0.04
x [mm]

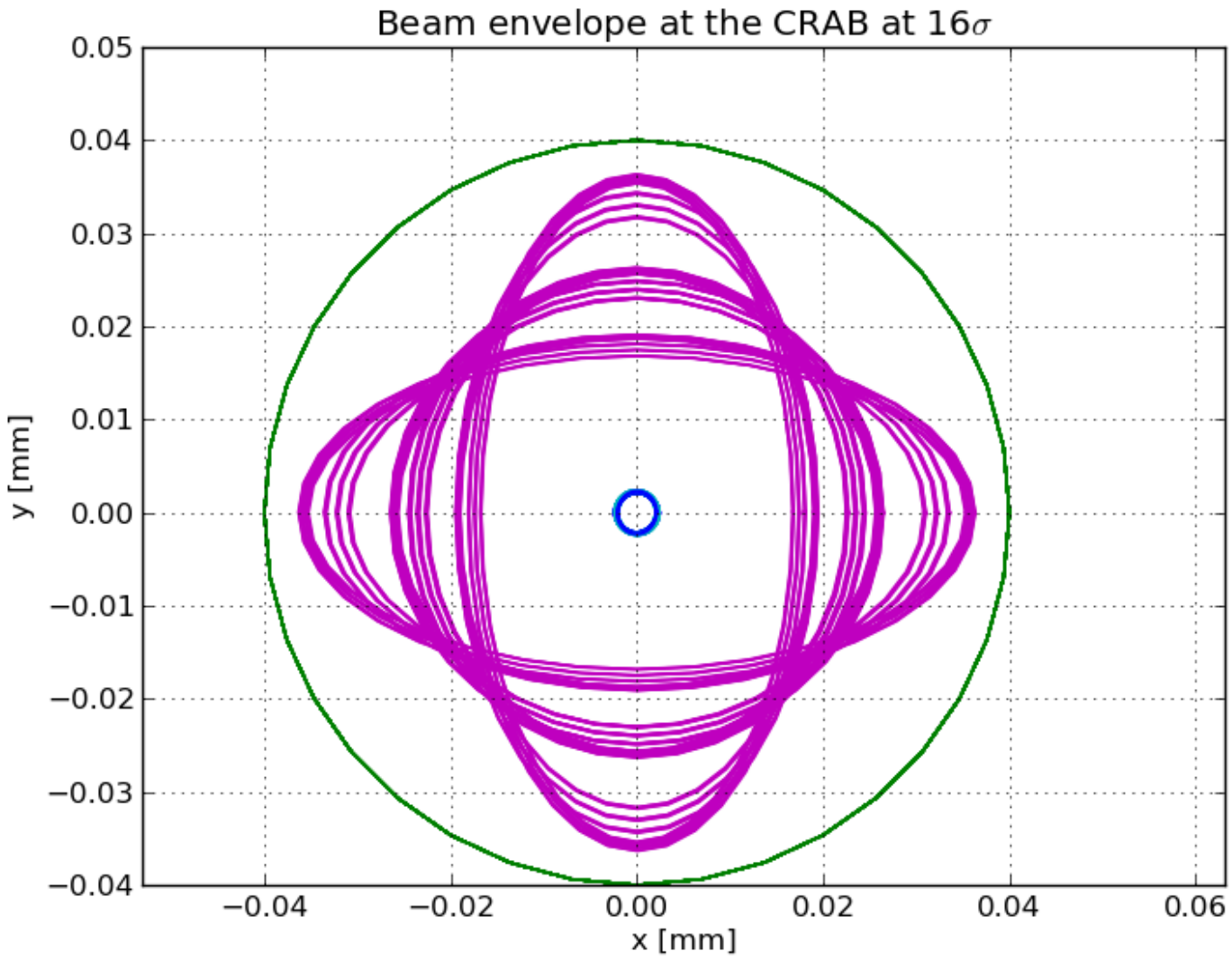
TAN


Beam envelope at the TAN at 12σ
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
y [mm]
−0.04
−0.02
0.00
0.02
0.04
x [mm]

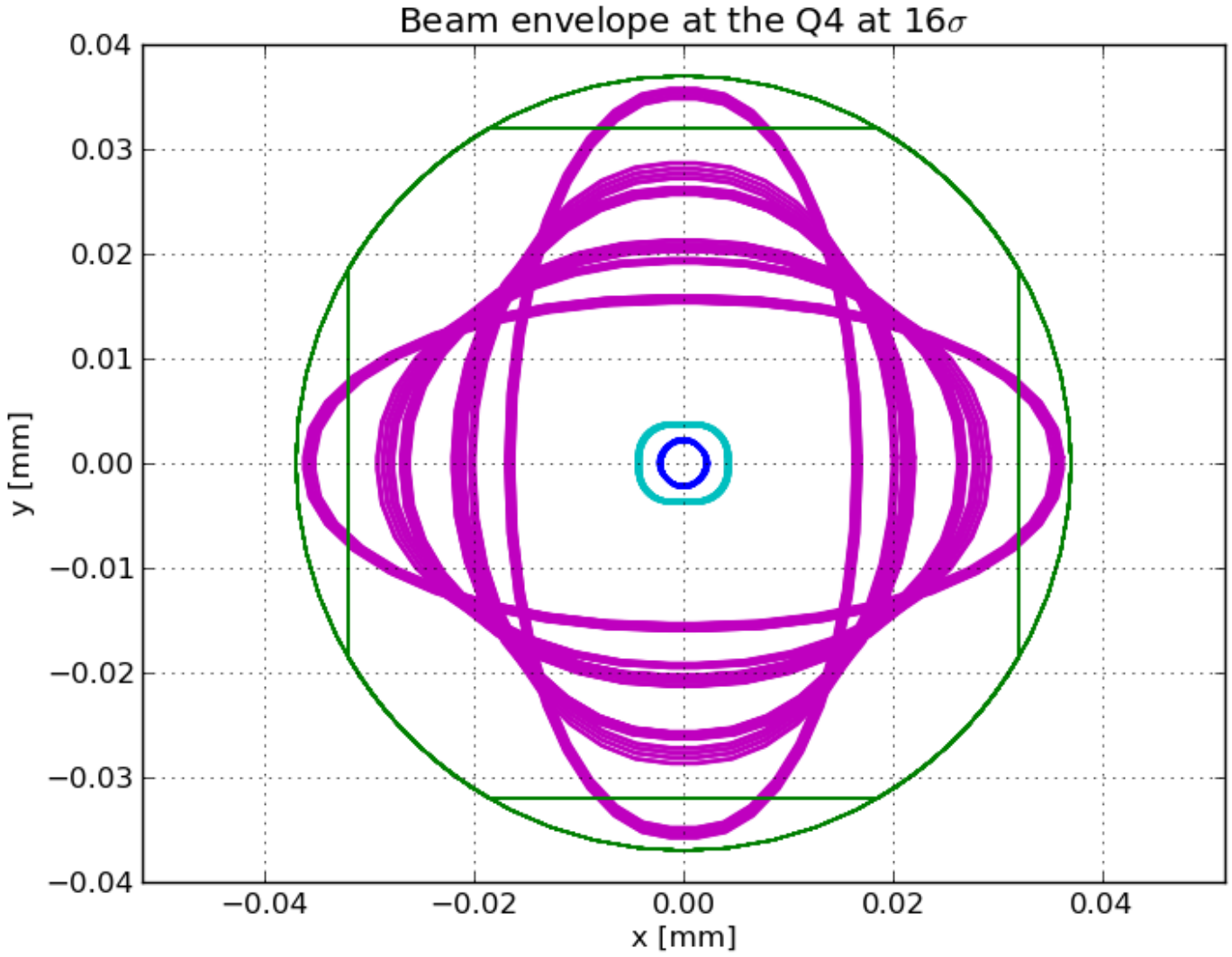
D2


Beam envelope at the D2 at 14σ
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
y [mm]
−0.04
−0.02
0.00
0.02
0.04
x [mm]

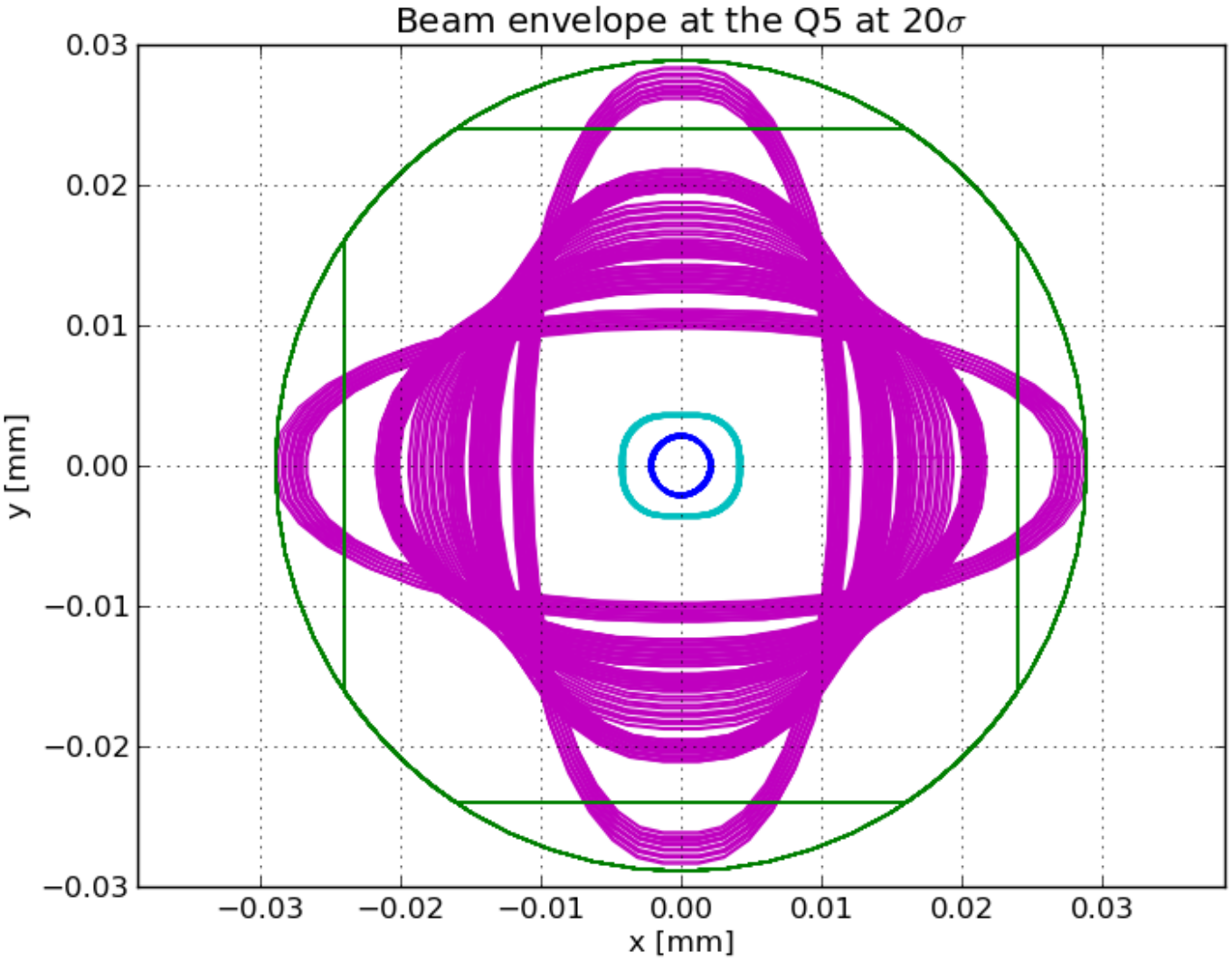
CRAB


Beam envelope at the CRAB at 16σ
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
y [mm]
−0.04
−0.02
0.00
0.02
0.04
0.06
x [mm]

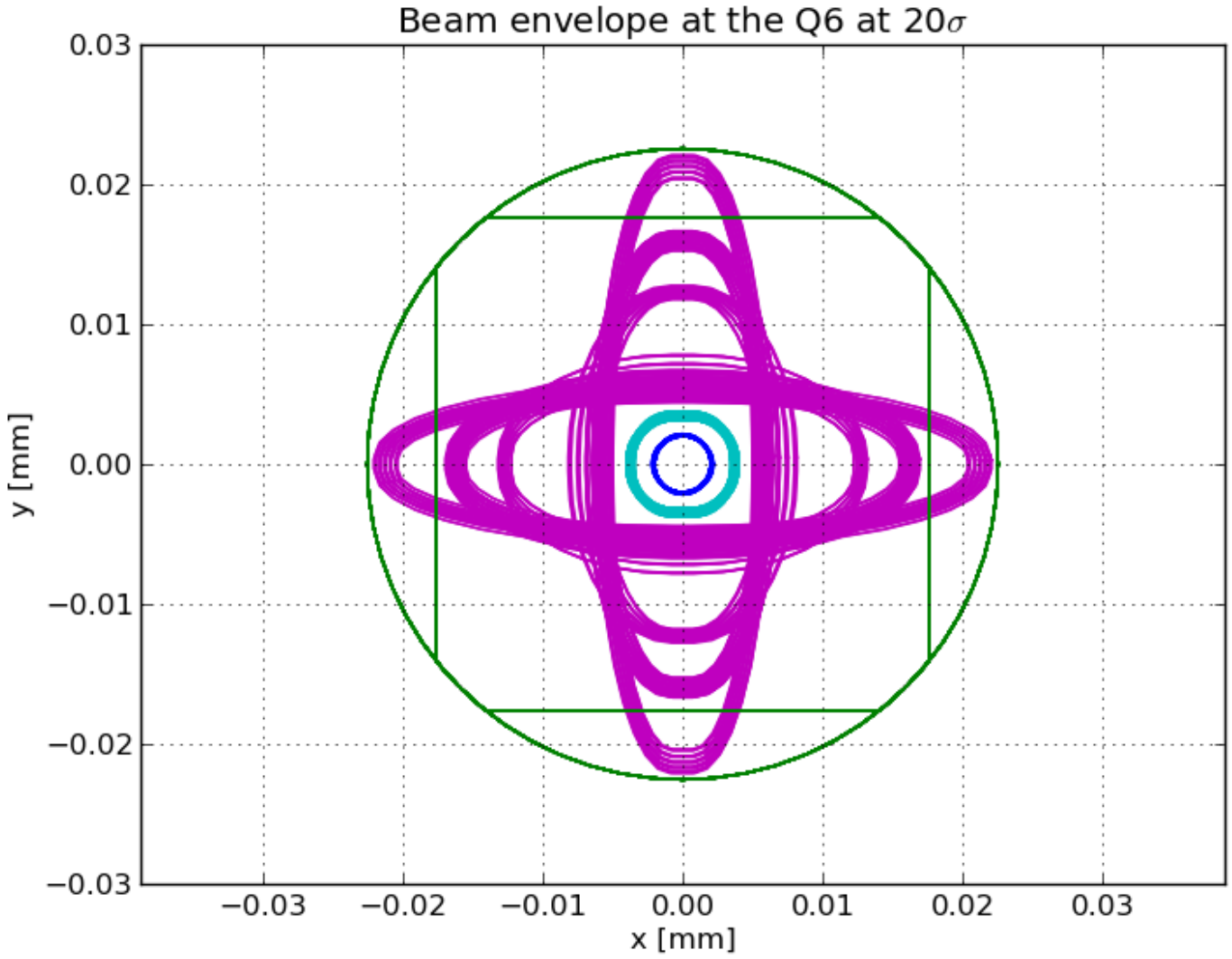
Q4


Beam envelope at the Q4 at 16σ
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
y [mm]
−0.04
−0.02
0.00
0.02
0.04
x [mm]

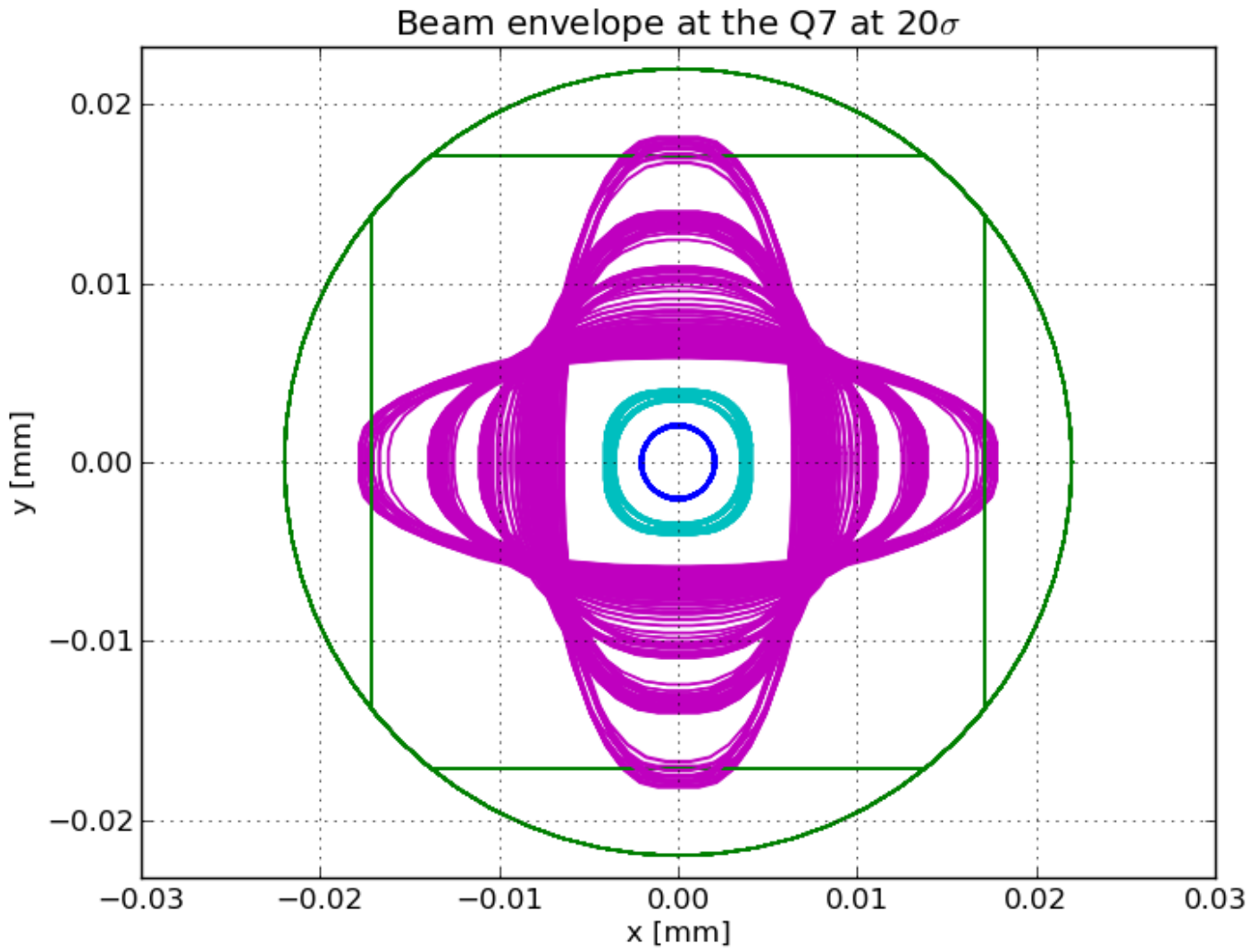
Q5


Beam envelope at the Q5 at 20σ
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
y [mm]
−0.03
−0.02
−0.01
0.00
0.01
0.02
0.03
x [mm]

Q6


Beam envelope at the Q6 at 20σ
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
y [mm]
−0.03
−0.02
−0.01
0.00
0.01
0.02
0.03
x [mm]

Q7


Beam envelope at the Q7 at 20σ
0.02
0.01
0.00
−0.01
−0.02
y [mm]
−0.03
−0.02
−0.01
0.00
0.01
0.02
0.03
x [mm]