Optics Considerations for PIC and US1 scenarios for HL-LHC

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Introduction

PIC and US1 are alternative scenarios to the full HL-LHC (US2) upgrade:

- PIC (Performance Improving Consolidation): replace Triplets and D1
- US1 (Upgrade Scenario 1): reach intermediate integrated luminosity without crab cavities and minimizing any matching section change.

Typical questions: Shall we upgrade TAN for PIC and D2 for US1?

The PIC and US1 scenarios presented in this talk are technically similar to the Phase-I upgrade [1], but:

- Triplets are shorter and with larger aperture: (120 mm, 128 T/m) to (140mm, 140T/m)
- ATS [2] scheme removes optics limitations
- Stronger orbit correctors (MCBX) and smaller emittance are available

For Phase-I, the TAN was to be replaced, but no new hardware was designed.

[1] LHC PR. 1050, 1163; [2] SLHC Pr. 49.

Outline

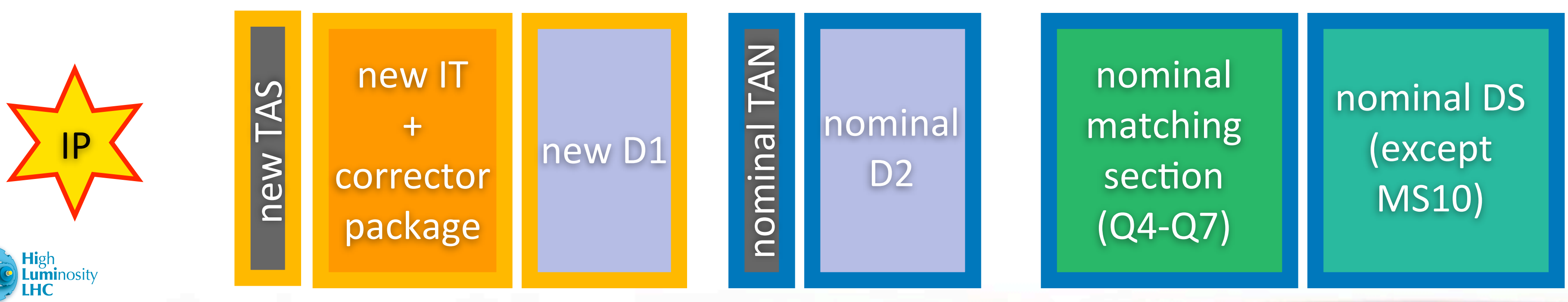
- Layout and optics
- Crossing scheme and aperture considerations
- X-scheme optimization
- Aperture for different beta * and possible rotation of the beam screen

Layout

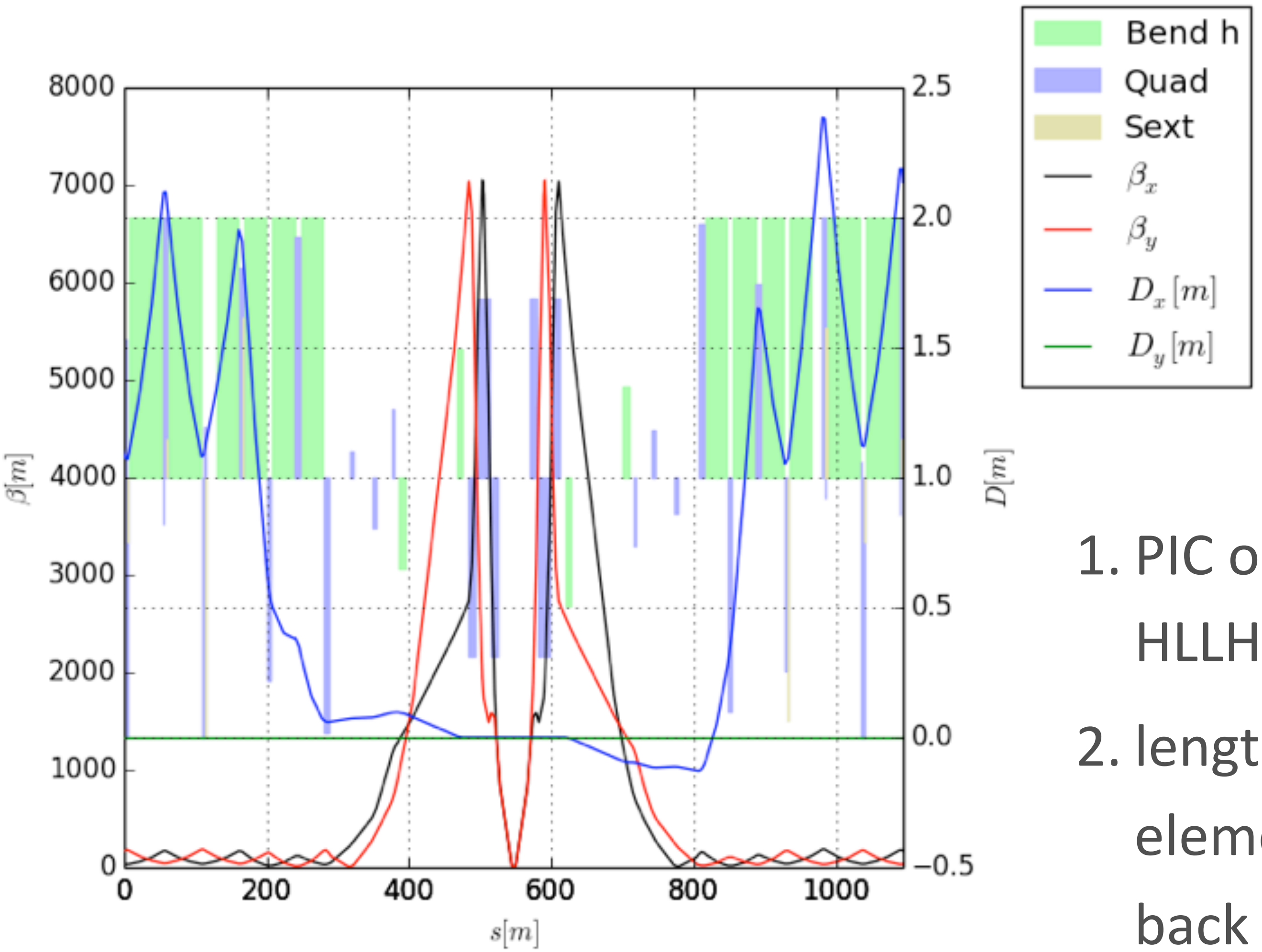
PIC changes to nominal layout:

- inner triplet: 150 mm aperture in P1 and P5
- corrector package for IR (MCBX)
- TAS: 60 mm aperture
- superconducting D1
- MS10?: needed or not depending on the ATS squeeze (S.F.)

Note: TAN, D2 and matching section as in nominal optics



Presqueeze optics



IR1 beam 1

β*=0.44/0.44 m

1. PIC optics is based on HLLHCV1.0 optics
2. length/position of MS elements are adjusted back to nominal V6.503 (except triplet region)

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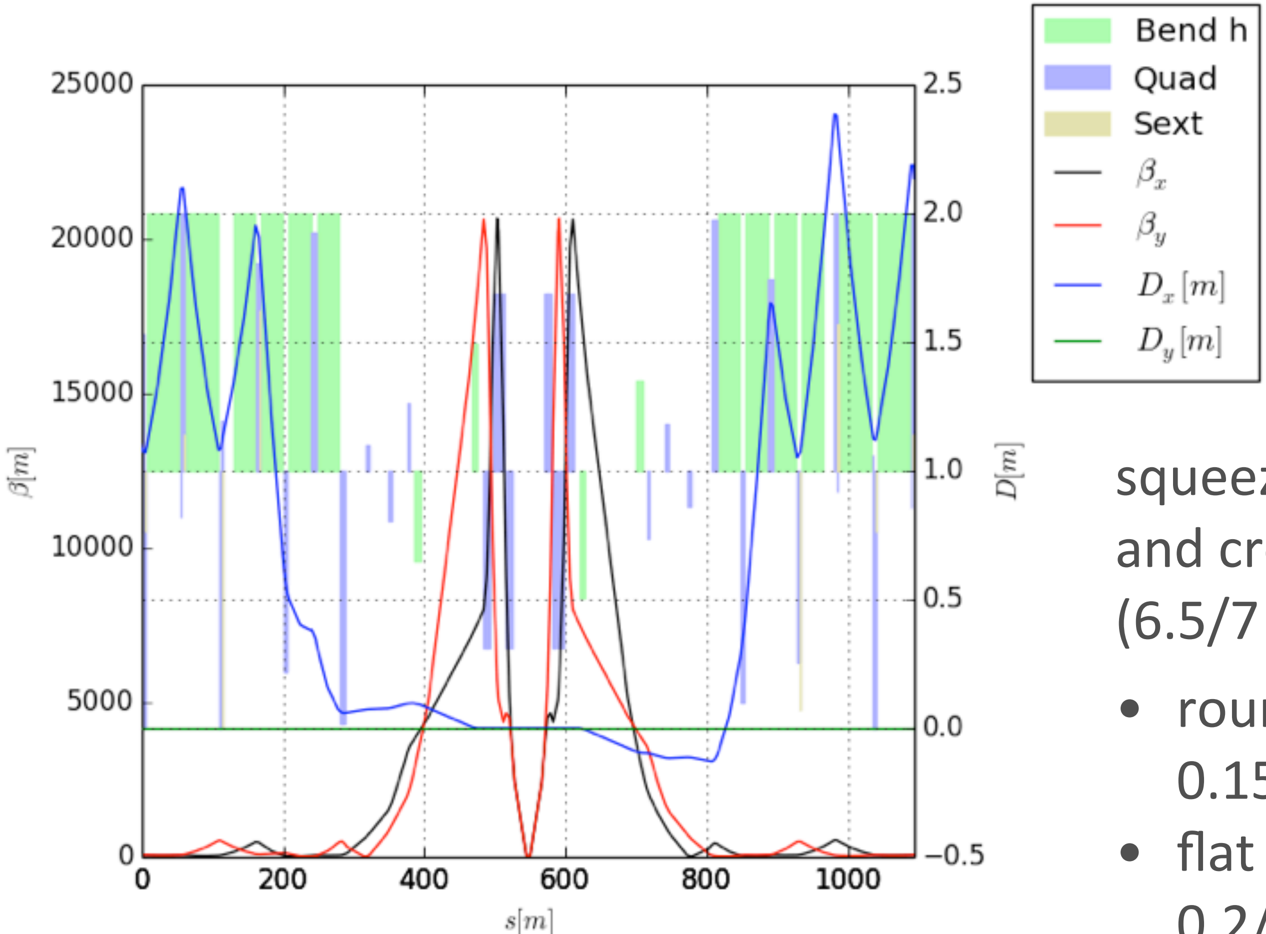
Squeeze optics



IR1 beam 1

β*=0.15/0.15 m

squeeze optics for different β* and crossing angles (6.5/7 TeV):

- round optics:
  0.15/0.15 m, 0.3/0.3 m
- flat optics:
  0.2/0.4 m, 0.1/0.4 m

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Beta* reach from optics

- ATS: presqueeze beta* / ATS arc blow up
  - Presqueeze
    - 43 cm limited by Q7 (too high), Q5, Q6 (too low)
    - 44 cm limited by chromatic correction with MS in Q10 and MS at 600A
    - 48 cm limited by chromatic correction with no MS in Q10, strong sextupolar resonance not suppressed (DA minus 3 sigma for (2x, 8x) slhc pr. 50, optics with different Ir phase advance not found yet, maybe a b3 spool in D2 can be used instead but only one resonance can be suppressed)
    - 52 cm limited by chromatic correction with a disabled MS in Q14, sextupolar resonances suppressed
  - ATS blowup
    - (1.2x,2.75x) limited by Q5 at 160T/m in IR6 (new ir phase advance 2.00, 2.00, some dispersion leakage in IP6)
    - (1.25x,4.4x) Q5.L6B2=167 T/m, Q12.L6B2 128T/m at 7 TeV (dispersion leakage)
- No ATS:
    - 25cm limited by chromatic correction: 20% beta beating in the bucket, large Q''', large beta functions in the MS
    - Strength limits not assessed yet.

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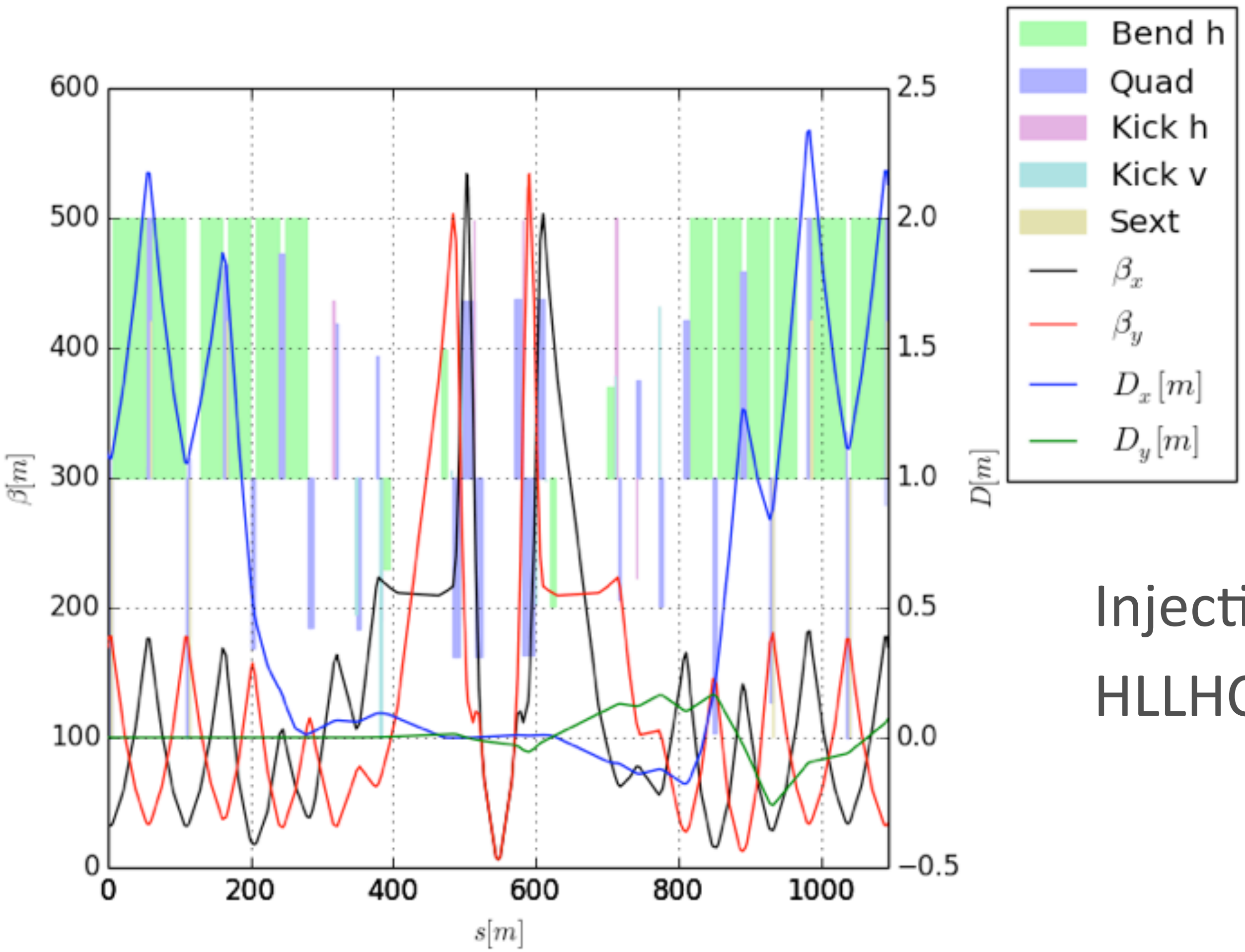
Injection optics



IR1 beam 1

β*=6.0/6.0 m

Injection optics based on HLLHCV1.0

Settings for aperture margins

squeeze optics (6.5 TeV)		minimum n1 (always at TAN)		
β* [m] (1)	x-angle [μrad] (1)	nominal (IR1/5)	"beam size + co" (IR1/5)	"beam size" (IR1/5)
0.10/0.40	±165	4.43/5.52	8.86/10.6	10.37/12.13
0.15/0.15	±270	4.17/4.56	9.40/9.78	11.27/11.72
0.20/0.40	±165	6.57/7.84	12.44/14.94	14.60/17.08
0.30/0.30	±190	7.29/7.99	14.40/15.07	17.06/17.82

(1) tentative β* and x-angle for PIC and US1 assuming 0.75 mm separation at the IP in the non x-plane and 12 sigma separation (ε_{norm} =2.1 μm) in the x-plane at the first parasitic encounter, limitations from IR6 and MS10 are not taken into account

"beam size":

emittance_norm=3.50e-6, halor=6, halox=6, haloy=6
apbbeat=1.0, COmax=0.0, dPmax=0.0

"beam size + co":

emittance_norm=3.5e-6, halor=6, halox=6, haloy=6
apbbeat=1.0, COmax=0.003, dPmax=0.0

nominal n1:

emittance_norm=3.75e-6, halor=8.4, halox=7.3, haloy=7.3
apbbeat=1.1, COmax=0.003, dPmax=0.00086

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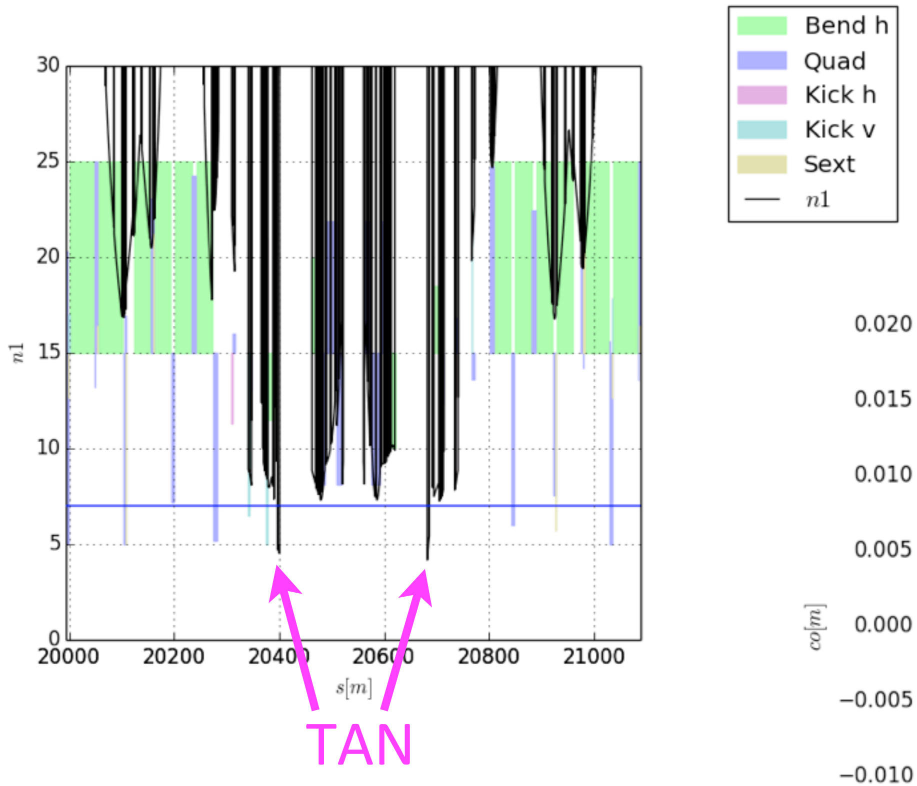
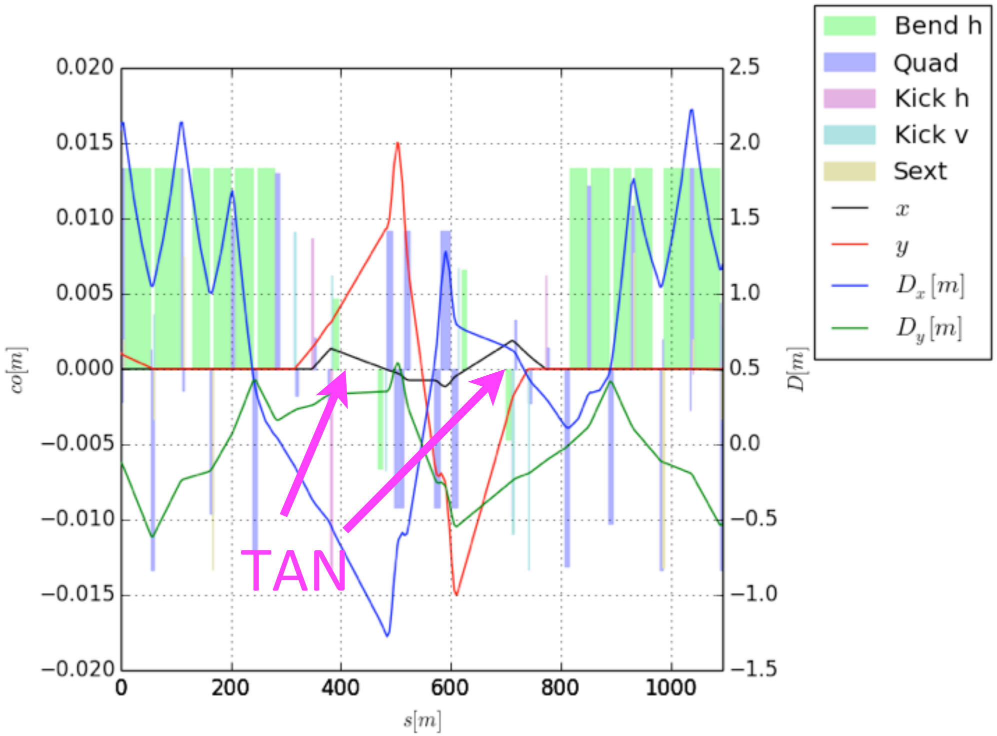
Crossing scheme and aperture considerations

main aperture bottleneck is the TAN with a relatively large contribution from the orbit



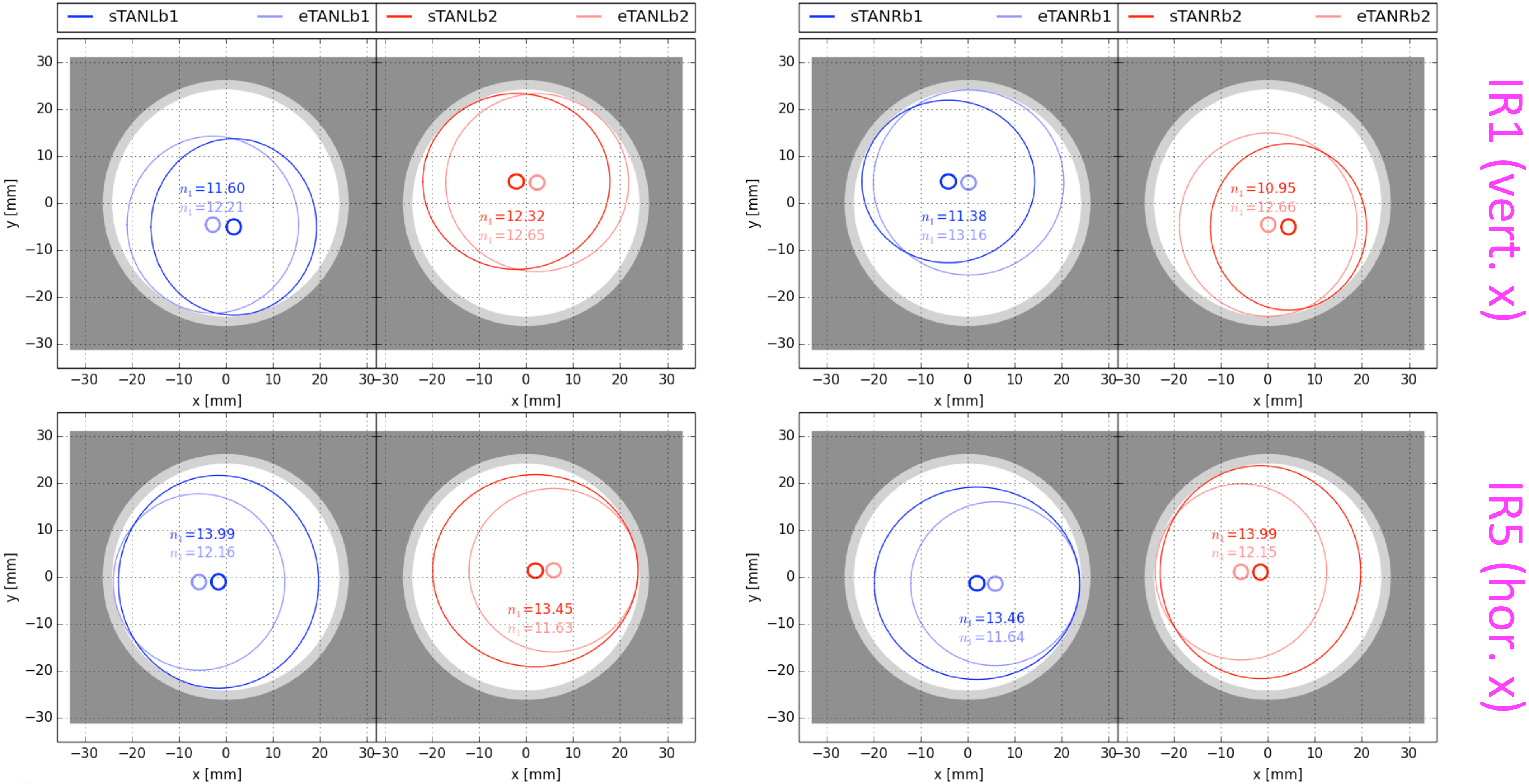
IR1 beam 1

$$\beta^* = 0.15/0.15 \text{ m}$$



Beam envelope round optics

round optics (6.5 TeV): β*=0.15/0.15 m, ϕ=±270 μrad



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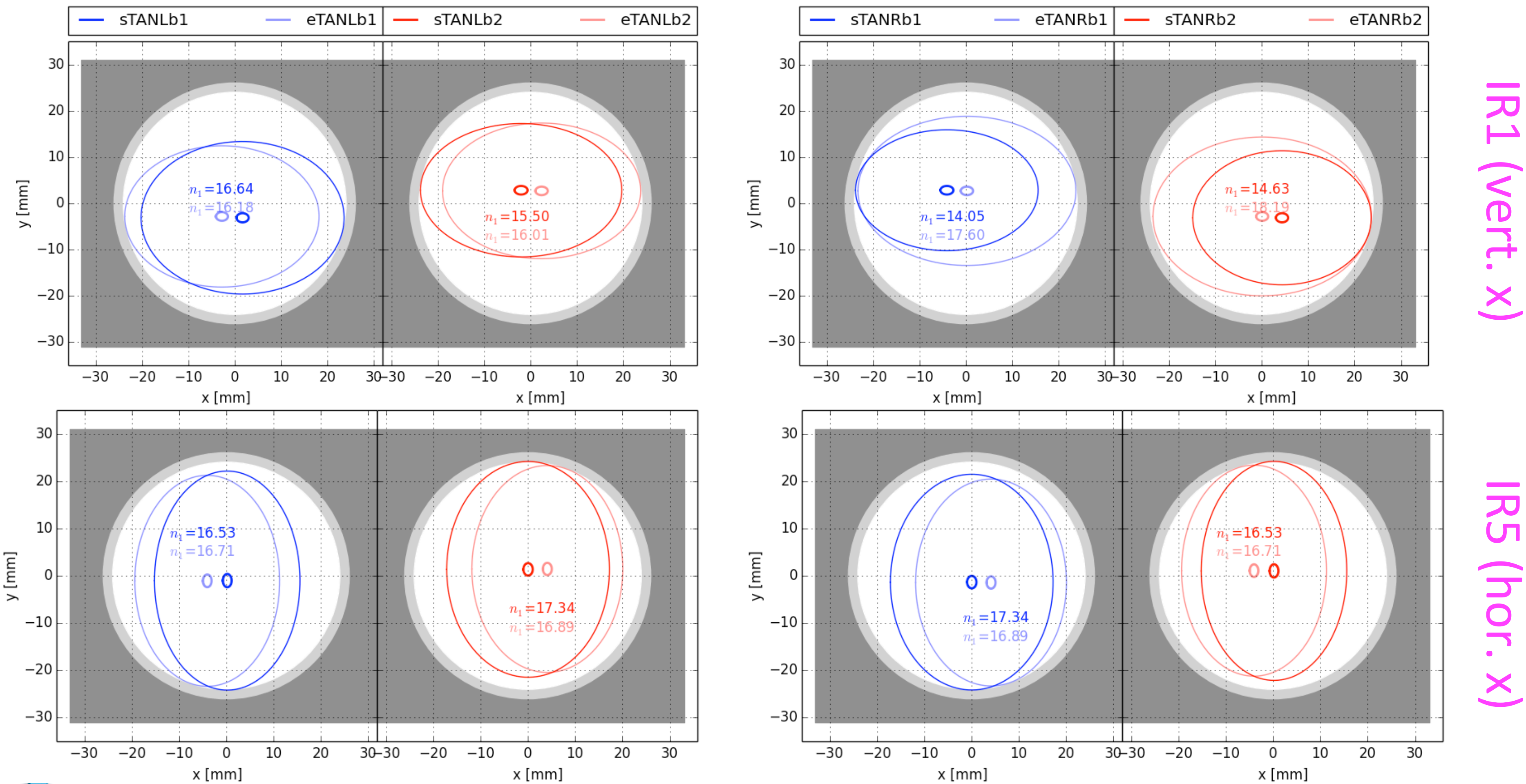
Beam envelope flat optics

flat optics (6.5 TeV): β*=0.2/0.4 m, ϕ=±165 μrad



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X-scheme optimization

Use MCBX correctors (triplet) to:

(1) reduce the overall corrector strengths in the x-plane (and keep an eye on the orbit at the TAN)

(2) minimize the orbit at the TAN in the separation-plane

➔ scan of MCBX*1.*,MCBX*2.*,MCBX*3.* in the x- and separation-plane

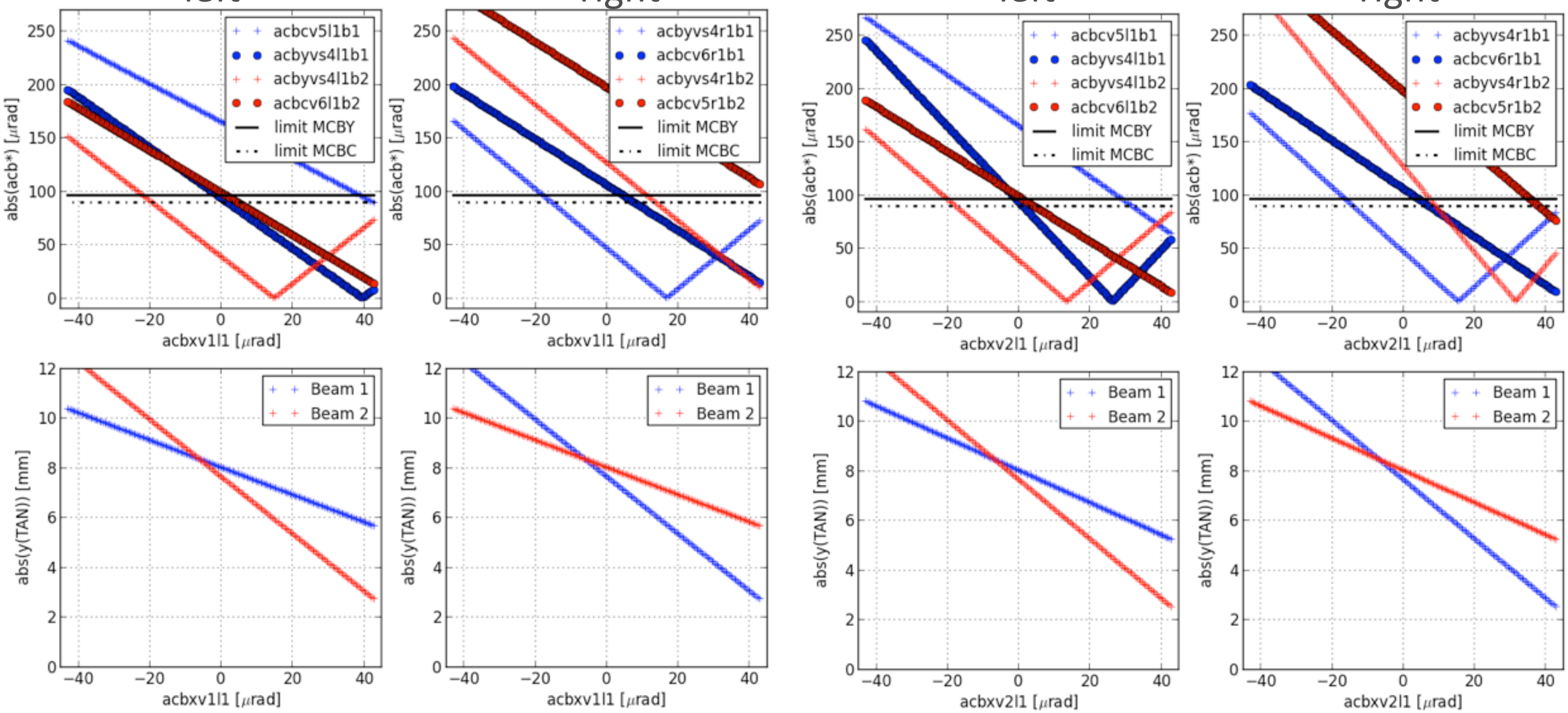
Scan conditions:

- MCBX*1.*and MCBX*2.* varied approx. between ±40 μrad
  MCBX*3.* varied between ±85 μrad
- antisymmetric cabling of MCBX for x-correctors, e.g. acbxv1.l1=-acbxv1.r1, symmetric cabling for separation-correctors e.g. acbxh1.l1=acbxh1.r1
- orbit correctors at Q4, Q5 and Q6 used for X-scheme matching (no strength limit)

MCBX Scan in x-plane

round optics (7 TeV): β*=0.15/0.15 m, ϕ=±295 μrad

left right left right

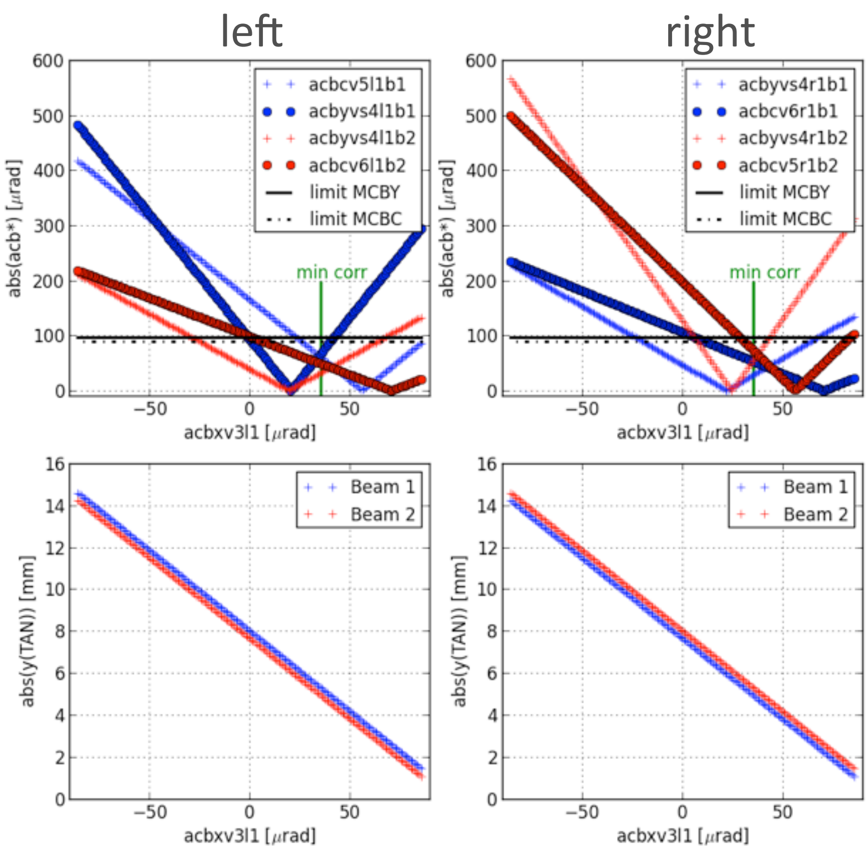


MCBXV1.L1 MCBXV2.L1

IR1

MCBX* Scan in x-plane

round optics (7 TeV): β*=0.15/0.15 m, $\phi=\pm 295$ µrad



MCBXV3.L1

IR1

Note: similar results for IR5 and for flat optics

Conclusion:

- MCBXV3.* is most efficient
- MCBX orbit correctors can be also used as knobs to optimize the orbit in the TAN for aperture

➡ Use MCBX*3.* to minimize corrector strength

MCBX* Scan in separation-plane

round optics (6.5 TeV): β*=0.15/0.15 m, sep=±0.75 mm

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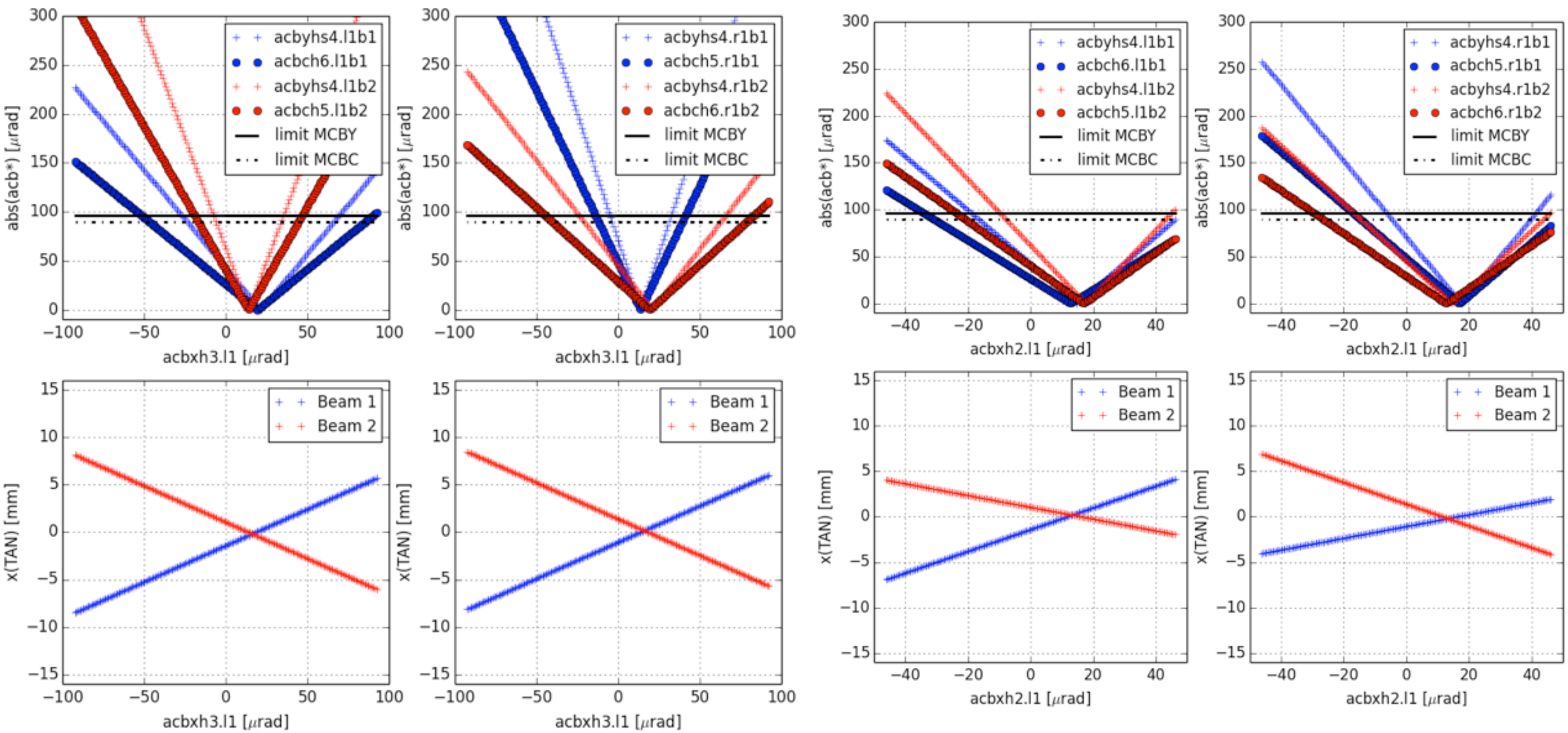
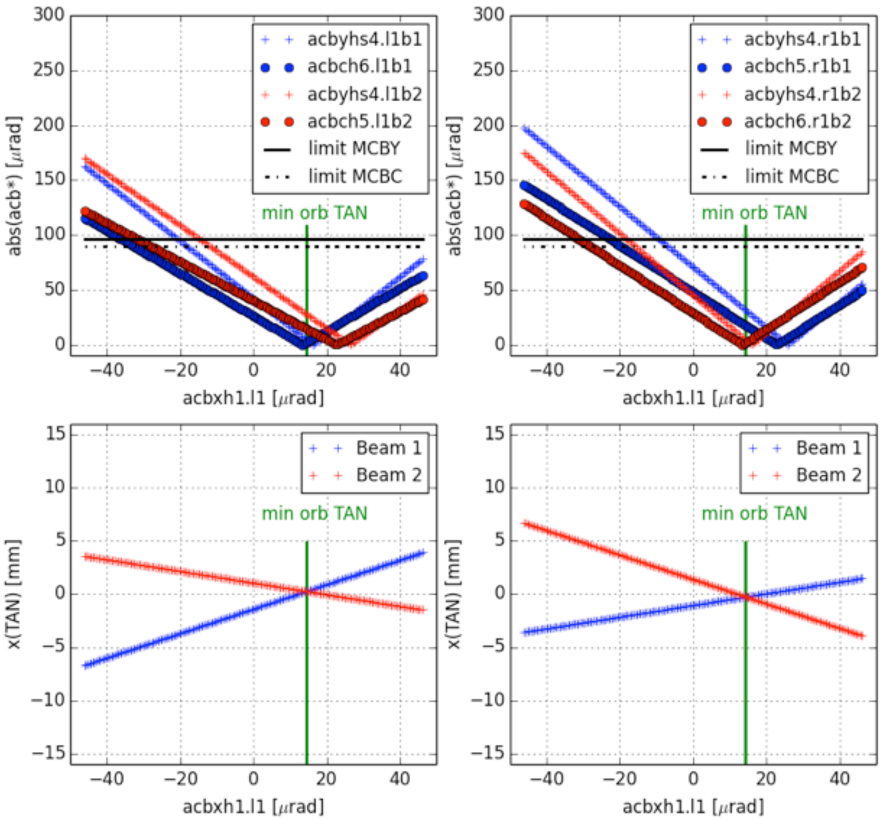


MCBXH3.L1 IR1 MCBXH2.L1

MCBX* Scan in separation-plane

round optics (6.5 TeV): β*=0.15/0.15 m, sep=±0.75 mm

left right



MCBXH1.L1

IR1

Note: same separation for all optics thus same results, similar results for IR5

Conclusion:

- MCBXH1.* is most efficient
- orbit at TAN in separation plane can be (almost) reduced to 0
- minimizing the orbit at the TAN also (approx.) minimizes the corrector strength

➡ Use MCBXH1.* to minimize the orbit at the TAN and the corrector strength

PIC optics: min. n1 per element

SQUEEZE OPTICS (6.5 TeV)		APERTURE	minimum over IR1/5					
β* [m]	x-angle [μrad]		MQX*	D1	TAN	D2	Q4	Q5
0.10/0.40	±165	nominal n1	8.08	8.76	**4.43**	7.19	**7.02**	**6.56**
		beam size + co	13.39	14.11	**8.86**	12.19	**11.92**	**11.35**
		beam size	14.15	14.95	**10.37**	13.92	13.77	13.94
0.15/0.15	±270	nominal n1	7.14	7.7	**4.17**	7.31	**6.78**	7.27
		beam size + co	12.11	12.87	**9.4**	12.38	**11.64**	12.09
		beam size	13.03	13.91	**11.27**	14.49	13.9	15.26
0.20/0.40	±165	nominal n1	12.09	13.04	**6.57**	10.63	10.54	9.92
		beam size + co	18.94	19.95	12.44	17.23	16.86	16.03
		beam size	20.01	21.14	14.6	19.67	19.4	19.7
0.30/0.30	±190	nominal n1	12.27	13.01	7.29	11.62	10.73	11.36
		beam size + co	19.1	20.12	14.4	18.56	17.33	17.8
		beam size	20.41	21.59	17.06	21.54	20.53	22.29

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US1 optics: min. n1 per element

optimum between rotated and not rotated beam screen + 28 mm TAN

SQUEEZE OPTICS (6.5 TeV)		APERTURE	minimum over IR1/5					
β* [m]	x-angle [µrad]		MQX*	D1	TAN	D2	Q4	Q5
0.10/0.40	±165	nominal n1	8.08	8.76	**5.14**	7.45	8.42	9.27
		beam size + co	13.39	14.11	**9.88**	13.32	14.47	15.01
		beam size	14.15	14.95	**11.39**	14.97	16.28	18.18
0.15/0.15	±270	nominal n1	7.14	7.7	**4.97**	7.6	8.08	9.89
		beam size + co	12.11	12.87	**10.65**	12.98	14.13	17.27
		beam size	13.03	13.91	12.52	15.07	16.36	20.44
0.20/0.40	±165	nominal n1	12.09	13.04	7.54	10.63	12.16	13.42
		beam size + co	18.94	19.95	13.89	18.76	20.38	21.21
		beam size	20.01	21.14	16.04	21.07	23.01	25.69
0.30/0.30	±190	nominal n1	12.27	13.01	8.41	11.84	12.56	15.08
		beam size + co	19.1	20.12	16.18	18.64	19.94	25.13
		beam size	20.41	21.59	18.83	21.54	23.09	29.62

Rotation of BS for possible Scenario of $\beta^* = 10/40$

Beam screen rotated by 90°
TAN aperture increased from 26 mm to 28 mm

Squeeze

β*=0.10/0.40 m ϕ=±165 μrad	minimum nominal n1							
IR	TAN	TAN 28 mm	D2	D2 rot	Q4	Q4 rot	Q5	Q5 rot
IR1B1 left	4.69	5.43	7.47	6.18	8.53	6.85	6.91	**9.65**
IR1B1 right	4.44	5.14	7.9	6.65	10.37	8.95	12.01	9.31
IR1B2 left	4.43	5.14	7.87	6.69	9.82	8.58	11.9	9.27
IR1B2 right	4.72	5.46	7.45	6.17	8.42	6.73	6.56	**9.28**
IR5B1 left	5.52	6.28	7.64	9.04	9.3	10.51	12.1	9.63
IR5B1 right	5.65	6.43	7.23	**8.43**	7.04	**8.69**	7.07	**9.77**
IR5B2 left	5.64	6.42	7.19	**8.41**	7.02	**8.7**	6.87	**9.59**
IR5B2 right	5.52	6.27	7.6	9.03	9.08	10.35	12.31	9.84

magenta = rotation beneficial for injection and squeeze with β*=0.10/0.40 m

Summary and Conclusions

(1) Injection, pre-squeeze and squeeze optics for different β*.

(2) Aperture margins estimated using 3 different tolerance budgets.

(3) MCBX correctors represent a good knob to minimize the corrector strength and increasing aperture margins both in the TAN and MS magnets.

(4) A replacement of the TAN and the rotation of the beam screen of the MS is beneficial for an upgrade scenario.

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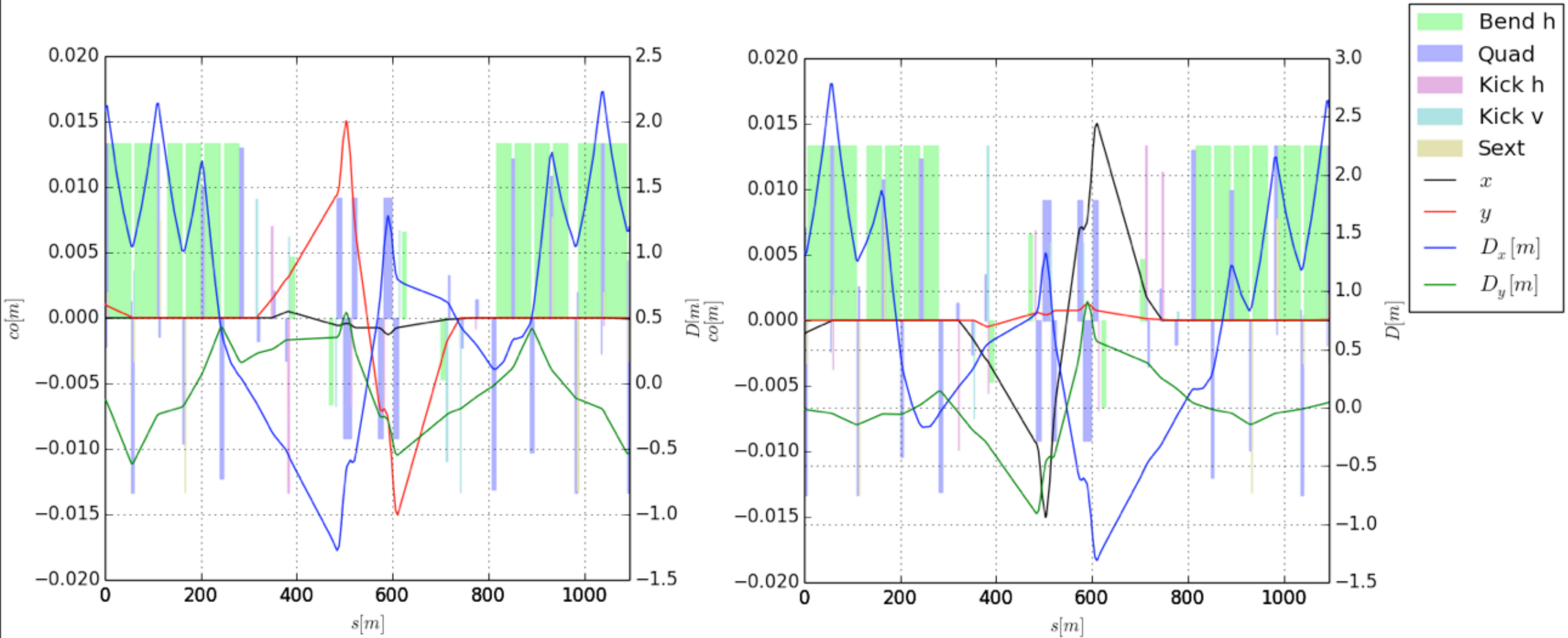
Round optics PIC β*=0.15/0.15

round optics (6.5 TeV): β*=0.15/0.15 m, ϕ=±270 μrad

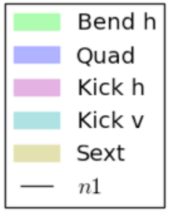


IR1 beam 2

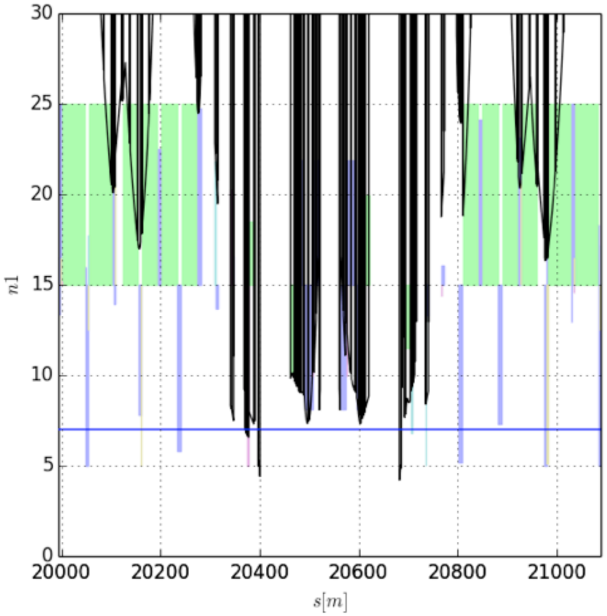
IR5 beam 1

Round optics PIC β*=0.15/0.15

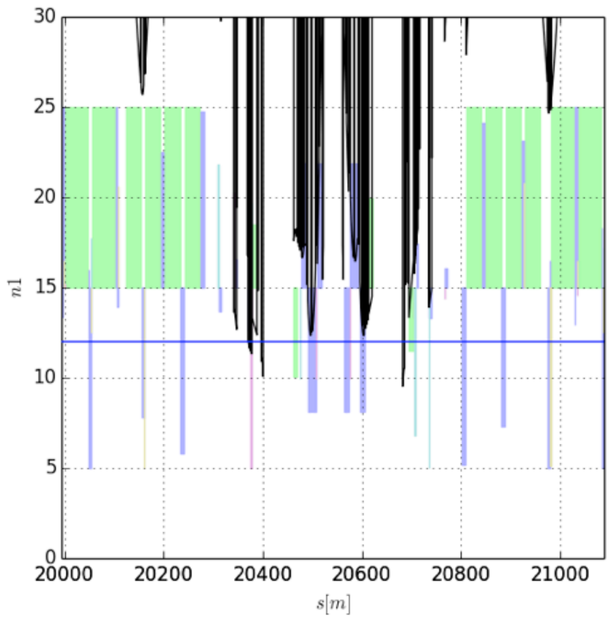
round optics (6.5 TeV): β*=0.15/0.15 m, ϕ=±270 μrad



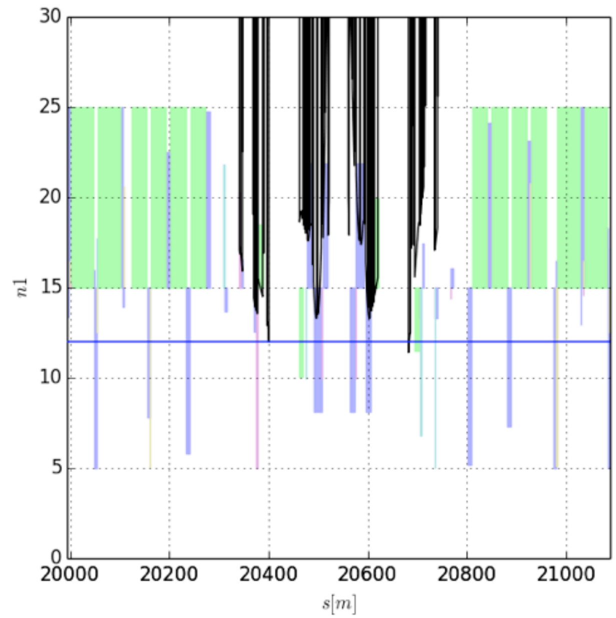
IR1 beam 2



nominal



beam size + co



beam size

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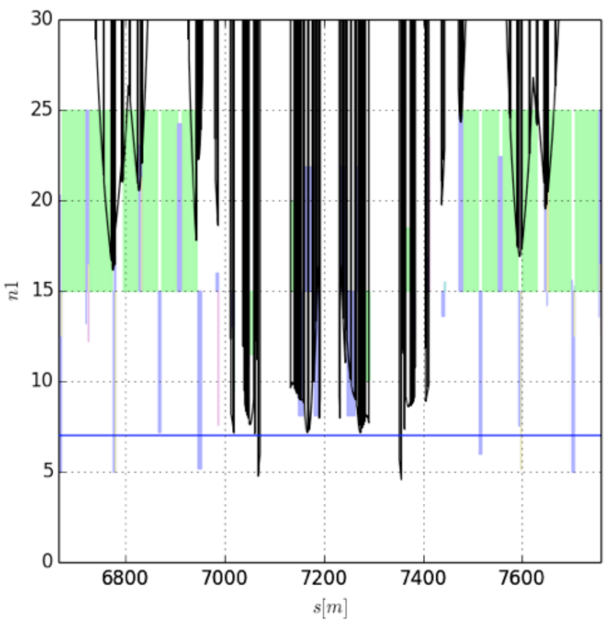
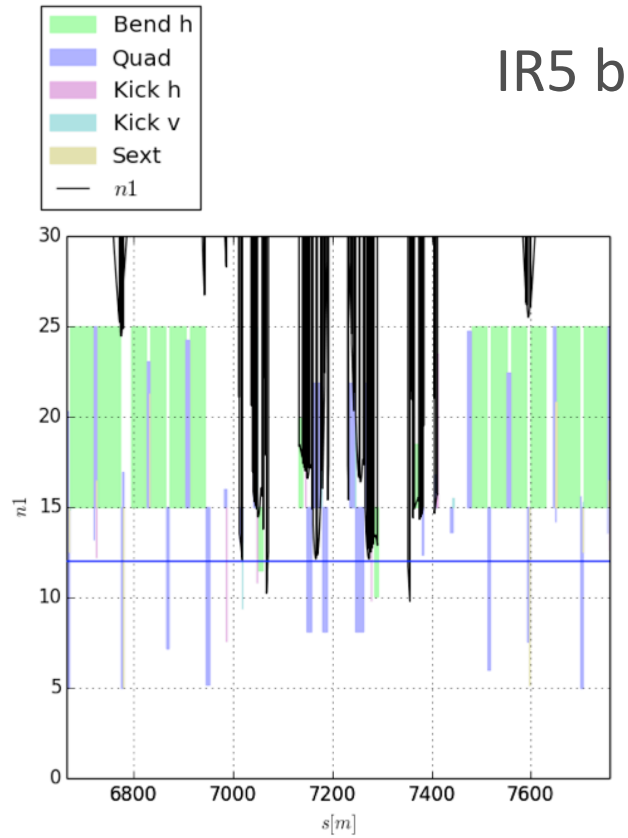
Round optics PIC β*=0.15/0.15

round optics (6.5 TeV): β*=0.15/0.15 m, ϕ=±270 μrad

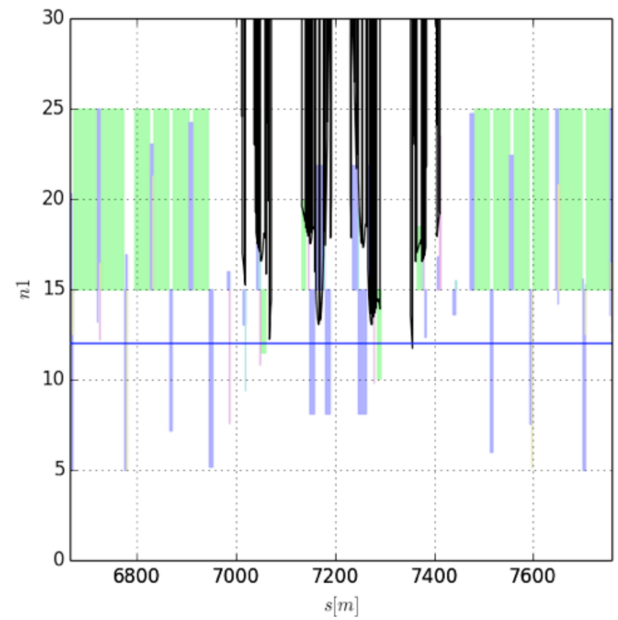
IR5 beam 1



nominal



beam size + co



beam size

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Round optics PIC β*=0.15/0.15

round optics (6.5 TeV): β^*=0.15/0.15 m, ϕ=±270 μrad

IR	MQX*	D1	TAN	D2	Q4	Q5
nominal n1						
IR1 beam 1	7.31	8.17	4.17	7.49	7.49	7.95
IR1 beam 2	7.33	8.19	4.21	7.31	6.78	7.49
IR5 beam 1	7.14	7.7	4.56	7.6	8.31	7.35
IR5 beam 2	7.25	7.8	4.66	7.69	8.56	7.27
beam size + co						
IR1 beam 1	12.33	13.54	9.4	12.53	12.51	12.92
IR1 beam 2	12.34	13.55	9.53	12.38	11.64	12.68
IR5 beam 1	12.11	12.88	9.79	14.45	14.59	12.37
IR5 beam 2	12.11	12.87	9.78	14.44	14.64	12.09
beam size						
IR1 beam 1	13.27	14.55	11.27	14.65	14.77	16.15
IR1 beam 2	13.28	14.56	11.4	14.49	13.9	15.91
IR5 beam 1	13.04	13.92	11.73	16.56	16.84	15.59
IR5 beam 2	13.03	13.91	11.72	16.55	16.9	15.26

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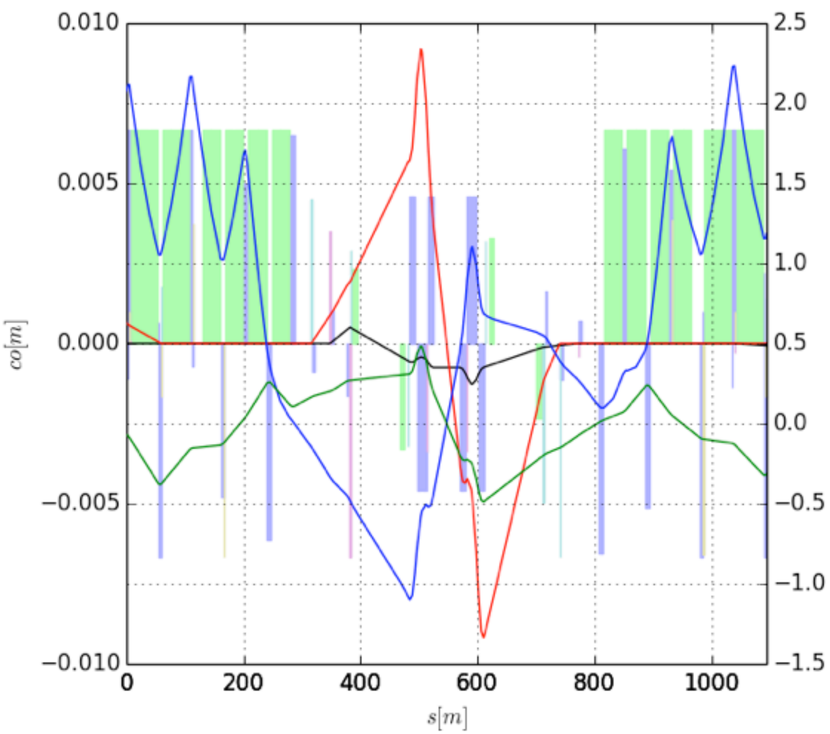
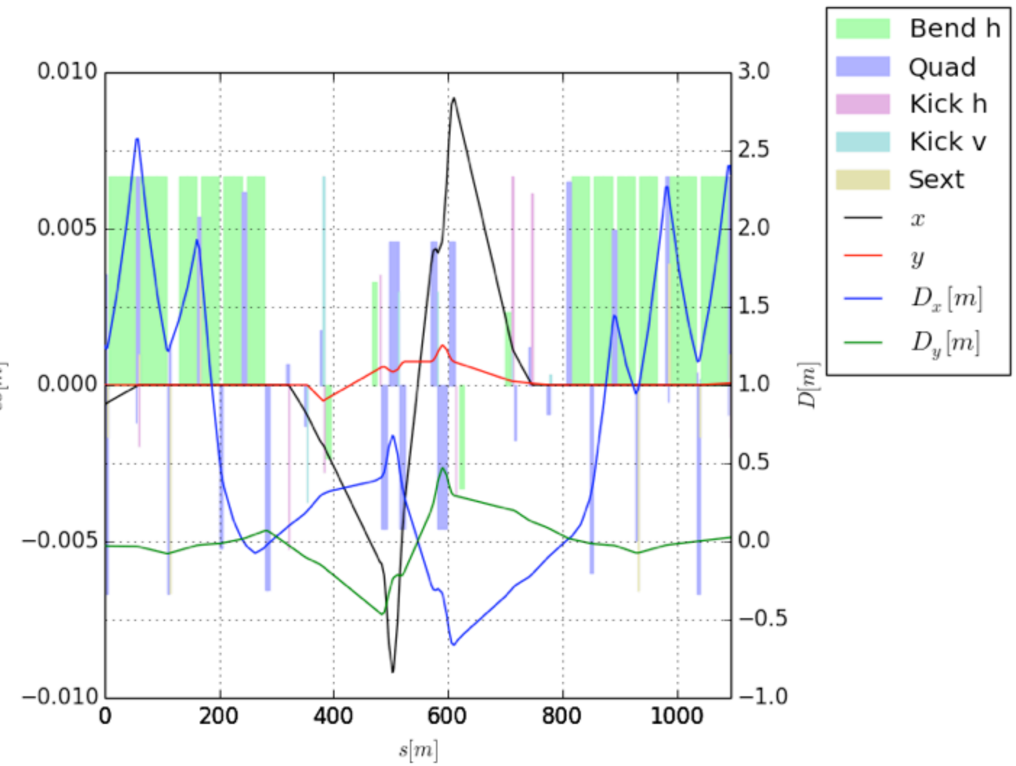
Flat optics PIC β*=0.20/0.40

flat optics (6.5 TeV): β*=0.2/0.4 m, ϕ=±165 μrad



IR1 beam 2

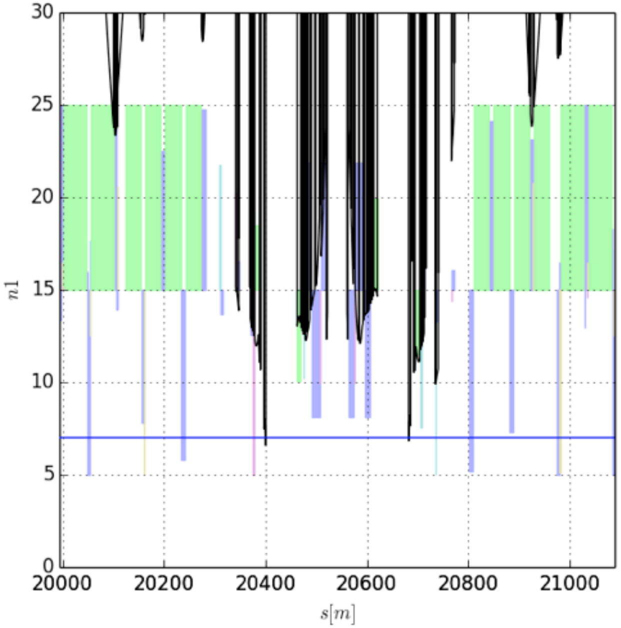


IR5 beam 1

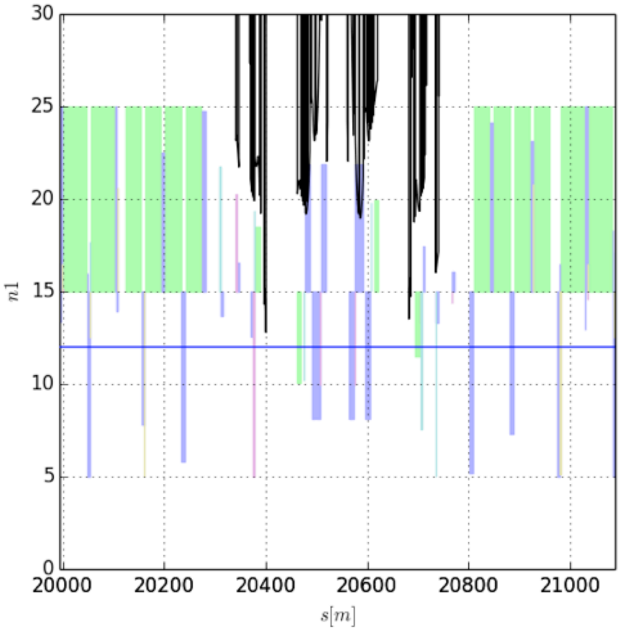
Flat optics PIC β*=0.20/0.40

flat optics (6.5 TeV): β*=0.2/0.4 m, ϕ=±165 µrad

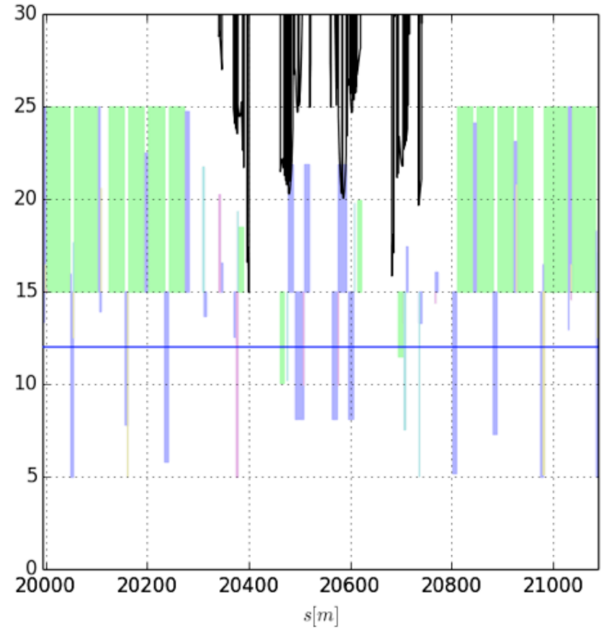
IR1 beam 2



nominal



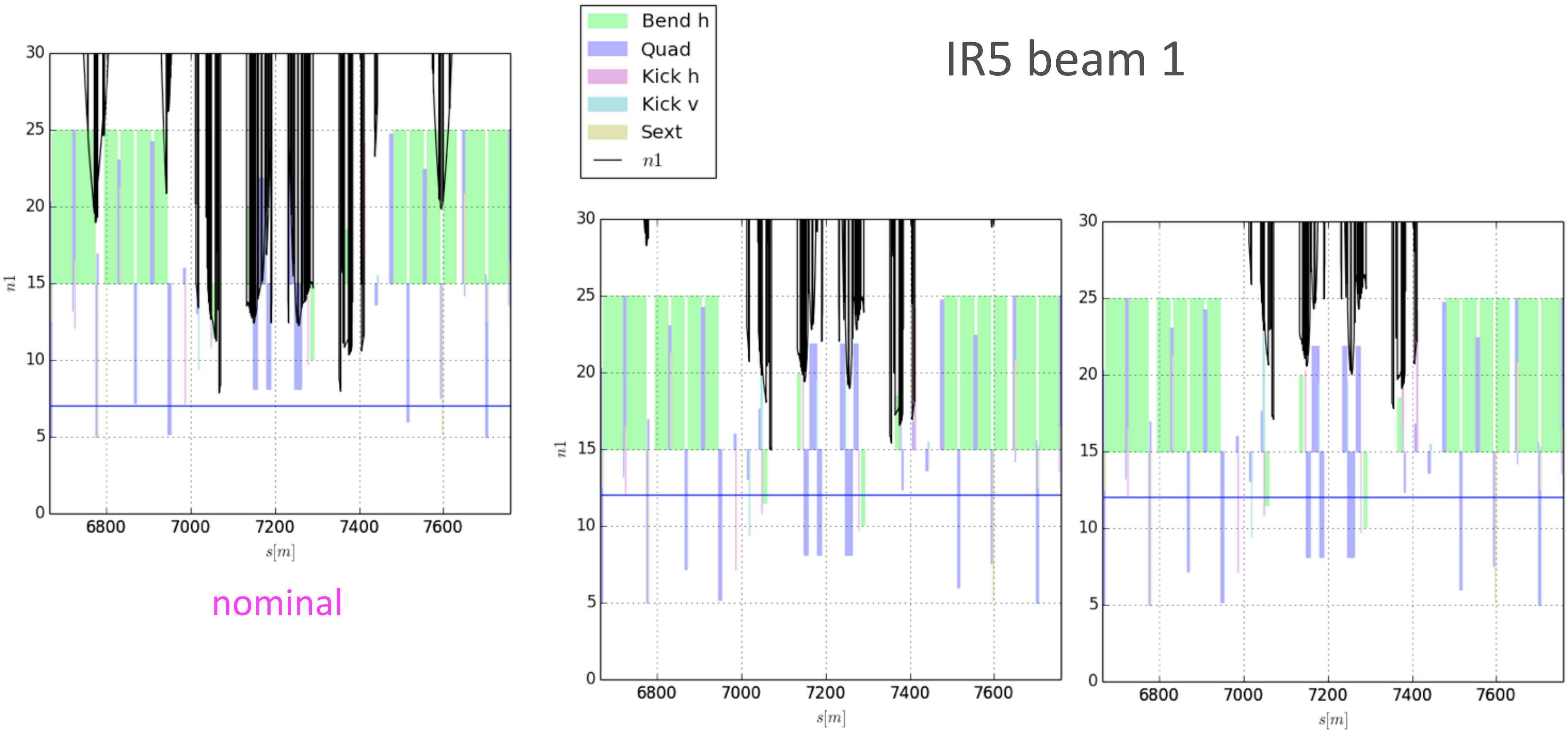
beam size + co



beam size

Flat optics PIC β*=0.20/0.40

flat optics (6.5 TeV): β*=0.2/0.4 m, ϕ=±165 μrad



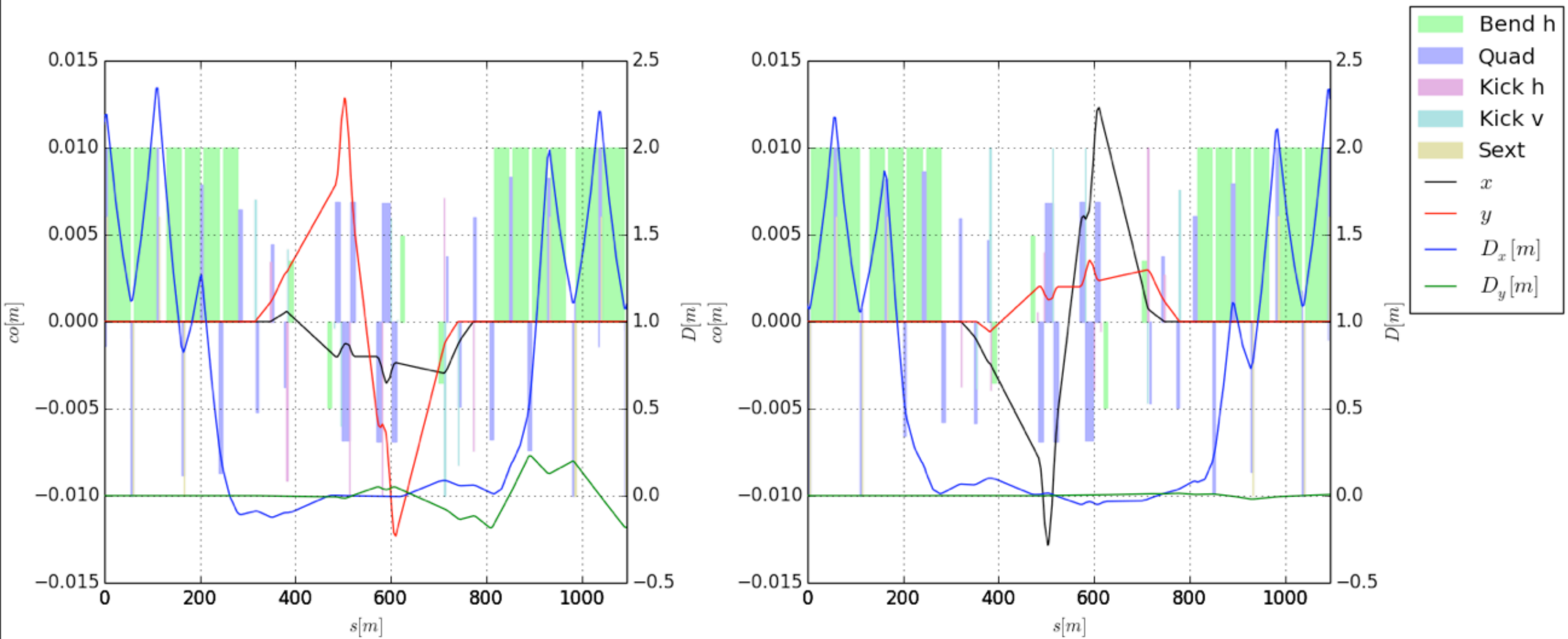
nominal

beam size + co

beam size

Injection optics

injection optics: β*=6.0/6.0 m, ϕ=±230 μrad



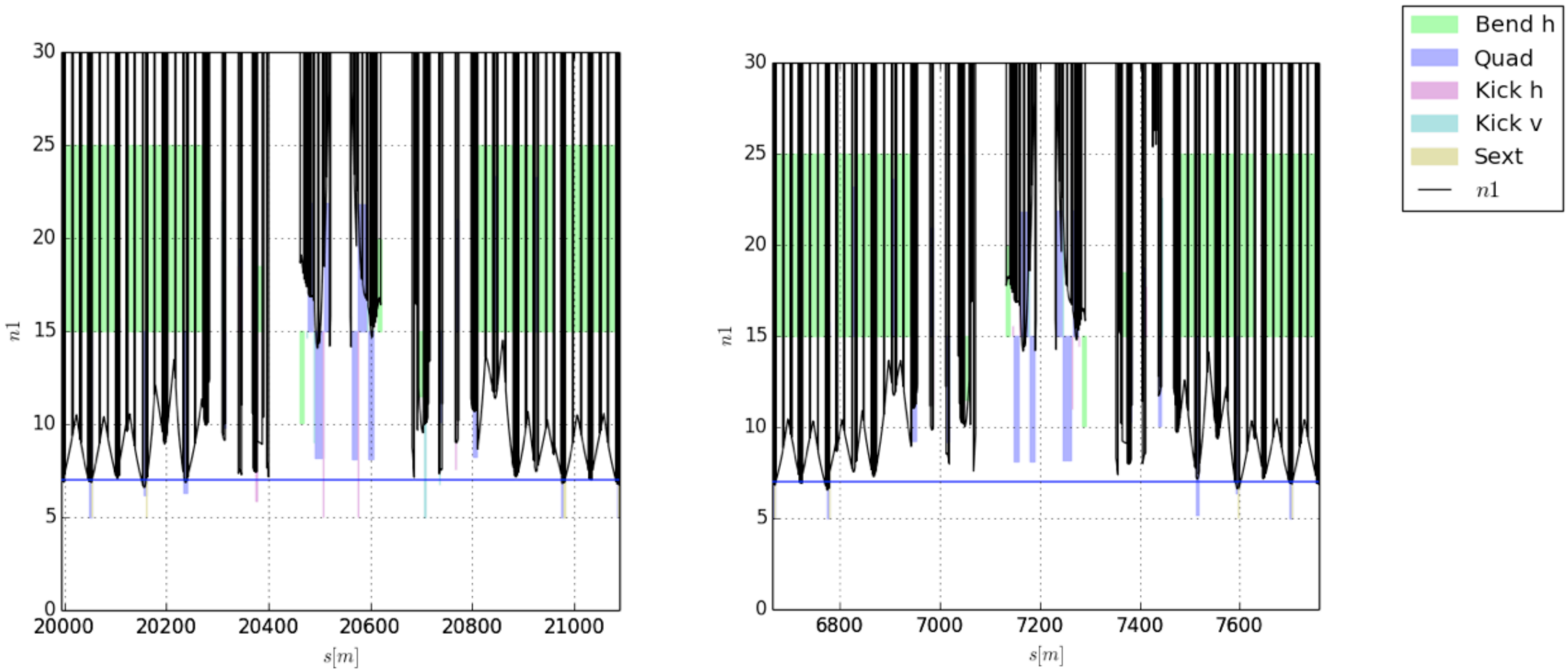
IR1 beam 2

IR5 beam 1

Injection optics

injection optics: β*=6.0/6.0 m, ϕ=±230 μrad

nominal



IR1 beam 2

IR5 beam 1

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Flat optics PIC β*=0.20/0.40

flat optics (6.5 TeV): β*=0.2/0.4 m, ϕ=±165 μrad

IR	MQX*	D1	TAN	D2	Q4	Q5
nominal n1						
IR1 beam 1	12.32	13.05	6.58	10.66	12.29	10.44
IR1 beam 2	12.09	13.04	6.57	10.63	12.16	9.92
IR5 beam 1	12.23	13.36	7.84	10.81	10.54	10.59
IR5 beam 2	12.21	13.34	7.85	10.78	10.55	10.33
beam size + co						
IR1 beam 1	18.95	19.95	12.44	18.76	20.46	16.42
IR1 beam 2	18.95	20.28	12.79	19.06	20.38	16.03
IR5 beam 1	18.94	20.73	14.94	17.23	16.86	16.93
IR5 beam 2	18.94	20.73	14.94	17.24	16.91	16.35
beam size						
IR1 beam 1	20.02	21.14	14.6	21.07	23.01	20.15
IR1 beam 2	20.02	21.47	14.95	21.38	23.11	19.7
IR5 beam 1	20.01	21.98	17.08	19.67	19.4	20.71
IR5 beam 2	20.01	21.98	17.09	19.68	19.52	20.02

High Luminosity LHC

Rotation of the beam screen + larger TAN

Beam screen rotated by 90°
TAN aperture increased from 26 mm to 28 mm

Squeeze

β*=0.15/0.15 m ϕ=±270 μrad	minimum nominal n1							
IR	TAN	TAN 28 mm	D2	D2 rot	Q4	Q4 rot	Q5	Q5 rot
IR1B1 left	4.17	4.97	7.83	7.83	9.54	8.72	8.8	**11.14**
IR1B1 right	4.41	5.21	7.49	**7.74**	7.49	**8.82**	7.95	**10.4**
IR1B2 left	4.41	5.22	7.31	**7.66**	6.78	**8.08**	7.49	**9.95**
IR1B2 right	4.21	5	7.84	7.84	9.57	8.61	8.4	**10.86**
IR5B1 left	4.75	5.59	7.6	6.29	8.31	6.82	7.35	**9.96**
IR5B1 right	4.56	5.38	8.59	7.95	8.85	**9.57**	8.89	**11.02**
IR5B2 left	4.66	5.48	8.68	8.05	8.91	**9.67**	8.72	**11.06**
IR5B2 right	4.85	5.69	7.69	6.4	8.56	7.15	7.27	**9.89**

High Luminosity LHC

blue = rotation beneficial in all scenarios, green = rotation only beneficial for this scenario

Rotation of the beam screen + larger TAN

Beam screen rotated by 90°
TAN aperture increased from 26 mm to 28 mm

Squeeze

β*=0.10/0.40 m ϕ=±165 μrad	minimum nominal n1							
IR	TAN	TAN 28 mm	D2	D2 rot	Q4	Q4 rot	Q5	Q5 rot
IR1B1 left	4.69	5.43	7.47	6.18	8.53	6.85	6.91	**9.65**
IR1B1 right	4.44	5.14	7.9	6.65	10.37	8.95	12.01	9.31
IR1B2 left	4.43	5.14	7.87	6.69	9.82	8.58	11.9	9.27
IR1B2 right	4.72	5.46	7.45	6.17	8.42	6.73	6.56	**9.28**
IR5B1 left	5.52	6.28	7.64	**9.04**	9.3	**10.51**	12.1	9.63
IR5B1 right	5.65	6.43	7.23	**8.43**	7.04	**8.69**	7.07	**9.77**
IR5B2 left	5.64	6.42	7.19	**8.41**	7.02	**8.7**	6.87	**9.59**
IR5B2 right	5.52	6.27	7.6	**9.03**	9.08	**10.35**	12.31	9.84

High Luminosity LHC

blue = rotation beneficial in all scenarios, green = rotation only beneficial for this scenario

Rotation of the beam screen + larger TAN

Beam screen rotated by 90°
TAN aperture increased from 26 mm to 28 mm

Squeeze

β*=0.20/0.40 m ϕ=±165 µrad	minimum nominal n1							
IR	TAN	TAN 28 mm	D2	D2 rot	Q4	Q4 rot	Q5	Q5 rot
IR1B1 left	6.8	7.82	10.66	9.4	12.29	10.35	10.44	**13.9**
IR1B1 right	6.58	7.55	11.14	10.07	14.08	13.32	14.53	13.82
IR1B2 left	6.57	7.54	11.08	10.11	12.94	12.79	13.88	13.75
IR1B2 right	6.83	7.84	10.63	9.38	12.16	10.17	9.92	**13.42**
IR5B1 left	7.84	8.88	11.39	**12.38**	13.73	13.16	13.73	**14.2**
IR5B1 right	7.96	9.01	10.81	**11.85**	10.54	**12.41**	10.59	**13.95**
IR5B2 left	7.96	9.02	10.78	**11.85**	10.55	**12.45**	10.33	**13.81**
IR5B2 right	7.85	8.89	11.37	**12.45**	13.46	**13.6**	13.54	**14.53**

blue = rotation beneficial in all scenarios, green = rotation only beneficial for this scenario

Rotation of the beam screen + larger TAN

Beam screen rotated by 90°
TAN aperture increased from 26 mm to 28 mm

Squeeze

β*=0.30/0.30 m ϕ=±190 μrad	minimum nominal n1							
IR	TAN	TAN 28 mm	D2	D2 rot	Q4	Q4 rot	Q5	Q5 rot
IR1B1 left	7.32	8.44	12.22	11.86	14.4	13.01	13.12	16.51
IR1B1 right	7.51	8.62	11.94	12.24	11.78	13.67	12.25	15.74
IR1B2 left	7.45	8.57	11.62	12.05	10.73	12.56	11.6	15.08
IR1B2 right	7.29	8.41	12.16	11.84	14.35	12.8	12.49	16.01
IR5B1 left	8.24	9.42	12.14	10.33	13.11	11.02	11.59	15.28
IR5B1 right	7.99	9.15	13.44	12.61	13.21	14.52	13.26	16.41
IR5B2 left	8.02	9.18	13.47	12.62	13.3	14.61	13.02	16.37
IR5B2 right	8.27	9.45	12.17	10.34	13.35	11.36	11.36	15.1

blue = rotation beneficial in all scenarios, green = rotation only beneficial for this scenario

Rotation of the beam screen + larger TAN

Beam screen rotated by 90°
TAN aperture increased from 26 mm to 28 mm

Injection

β*=6.0/6.0 m φ=±230 μrad	minimum nominal n1							
IR	TAN	TAN 28 mm	D2	D2 rot	Q4	Q4 rot	Q5	Q5 rot
IR1B1 left	6.18	7.25	9.51	7.95	10.01	7.96	8.11	**10.64**
IR1B1 right	7.19	8.26	9.07	**10.47**	8.12	**10.28**	8.2	**10.61**
IR1B2 left	7.16	8.23	8.92	**10.41**	7.46	**9.61**	7.28	**9.87**
IR1B2 right	7.13	8.21	9.54	7.58	10.07	8.02	7.32	**9.97**
IR5B1 left	7.59	8.66	10.02	7.85	10.24	8.07	8.19	**10.79**
IR5B1 right	7.38	8.46	9.09	**10.28**	8	**10.14**	7.99	**10.53**
IR5B2 left	7.5	8.58	9.23	**10.4**	8.19	**10.32**	7.45	**10.07**
IR5B2 right	7.57	8.64	9.99	7.85	10.42	8.31	7.38	**9.99**

High Luminosity LHC

blue = rotation beneficial in all scenarios, green = rotation only beneficial for this scenario

Beneficial rotation of BS for possible Scenario of β* =10/40

Beam screen rotated by 90°

TAN aperture increased from 26 mm to 28 mm

Squeeze

β*=0.10/0.40 m ϕ=±165 µrad	minimum nominal n1							
IR	**TAN**	**TAN 28 mm**	**D2**	**D2 rot**	**Q4**	**Q4 rot**	**Q5**	**Q5 rot**
IR1B1 left	4.69	5.43	7.47	6.18	8.53	6.85	6.91	**9.65**
IR1B1 right	4.44	5.14	7.9	6.65	10.37	8.95	12.01	9.31
IR1B2 left	4.43	5.14	7.87	6.69	9.82	8.58	11.9	9.27
IR1B2 right	4.72	5.46	7.45	6.17	8.42	6.73	6.56	**9.28**
IR5B1 left	5.52	6.28	7.64	9.04	9.3	10.51	12.1	9.63
IR5B1 right	5.65	6.43	7.23	**8.43**	7.04	**8.69**	7.07	**9.77**
IR5B2 left	5.64	6.42	7.19	**8.41**	7.02	**8.7**	6.87	**9.59**
IR5B2 right	5.52	6.27	7.6	9.03	9.08	10.35	12.31	9.84

magenta = rotation beneficial for injection and squeeze with β*=0.10/0.40 m