Orbit corrector budget for HL-LHC v1.5

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CERN

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General assumptions

- **HL-LHC Optics V1.5**
  - **7 TeV**; **β* = 15cm round**; ϵ_N = 2.5 μm; δ_p = 1.1e-4
- Here shown only at **right side of IP5**
  - **V crossing** and H separation
    - *for H crossing (IP1) and left side symmetries apply*
  - **Residual orbit** and corrector strength given in **2*r.m.s.**
    - *Standard approach considered to fit LHC experience (Chamonix08)*

- **Note**: results obtained with **Python framework** by Joel:
  - Assuming **fully linear optics**
  - Most computations using **SVD inversion of response matrices** generated from Twiss functions
  - Orbit correction at **BPMs only**
  - **Framework source code** and **examples**: POCKPy on GitLab
    - Also **documented** in Joel's **master thesis**: *A Linear Framework for Orbit Correction in the High-Luminosity Large Hadron Collider* - link

Orbit Correction and Corrector Budget

Orbit correction due to errors

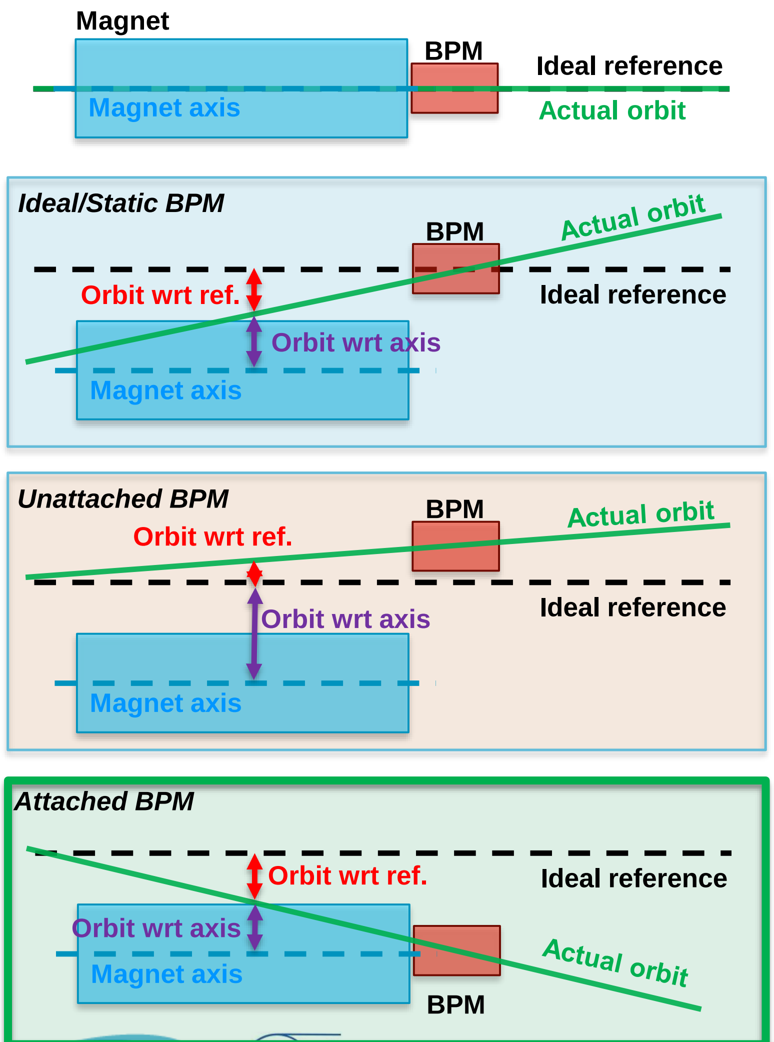
- **Considered** element **errors** (all **square distributions**):
  - **Quadrupoles**:
    - Transverse offset: $\pm\mathbf{0.5}\ \boldsymbol{mm}$
    - Rotation (DPSI): $\pm\mathbf{1}\ \boldsymbol{mrad}$
    - Relative field strength error: $\pm\mathbf{0.2}\%$
  - **Dipoles**:
    - (**NEW**) Transverse offset: $\pm\mathbf{0.5}\ \boldsymbol{mm}$
      - *Used only to give orbit w.r.t. center of magnet and nearby BPM*
    - Rotation (DPSI): $\pm\mathbf{0.5}\ \boldsymbol{mrad}$
    - Relative field strength error: $\pm\mathbf{0.2}\%$
  - **BPMs**:
    - (**NEW**) Transverse offset: $\pm\mathbf{0.5}\ \boldsymbol{mm}$
      - Several cases considered, **finally assumed to move with nearby quadrupole**

- **Missing** errors w.r.t. previous studies:
  - **Longitudinal misalignment**
    - Not easy to implement in present (analytical) framework
    - **Deemed to be negligible** in previous studies

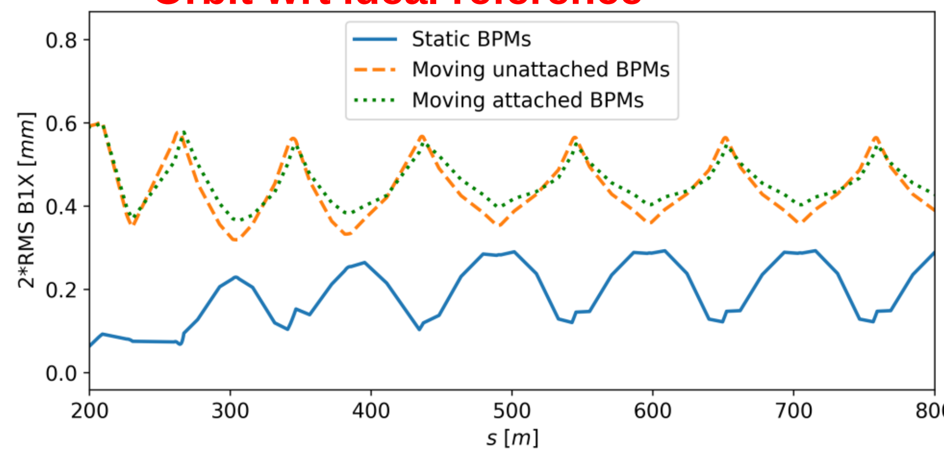
- **Important remark:**
  - Still using "**standard**" numbers for **expected errors**
  - **Update numbers** may come from **WG Alignment** (espace)
    - **Natural entanglement** between what is **desirable** and what is **achievable**!

Residual orbit post-correction (in the arc)

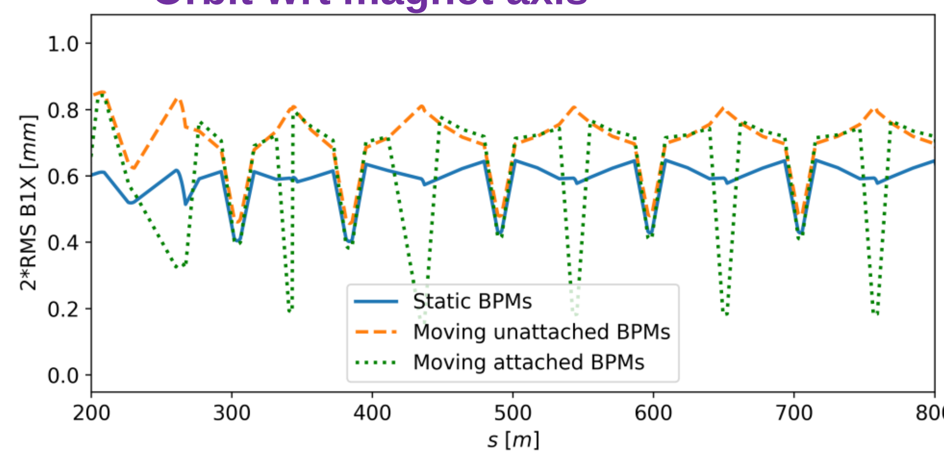
- Depending on assumption on BPM behavior, one gets different results.
  - **Note:** correcting such to **minimize orbit wrt center of all BPMs** with the **same weight**



Orbit wrt ideal reference



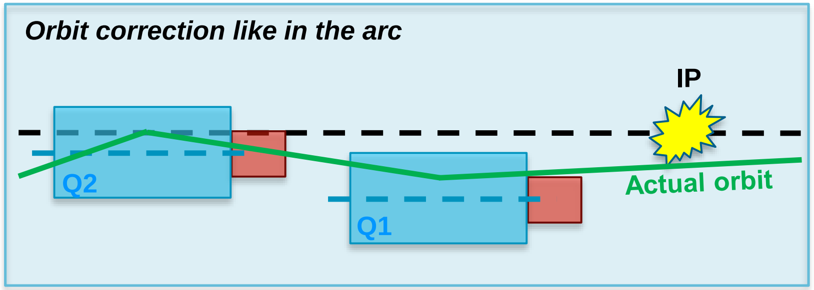
Orbit wrt magnet axis

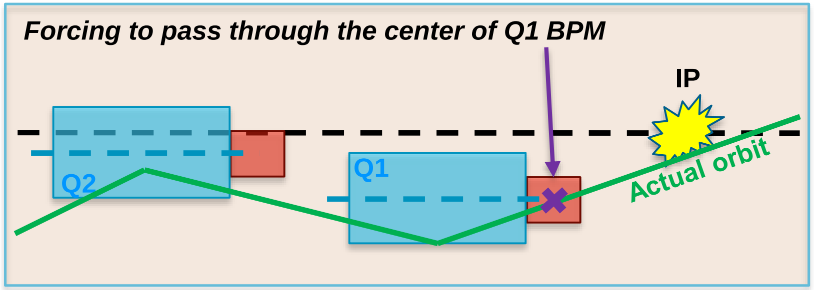


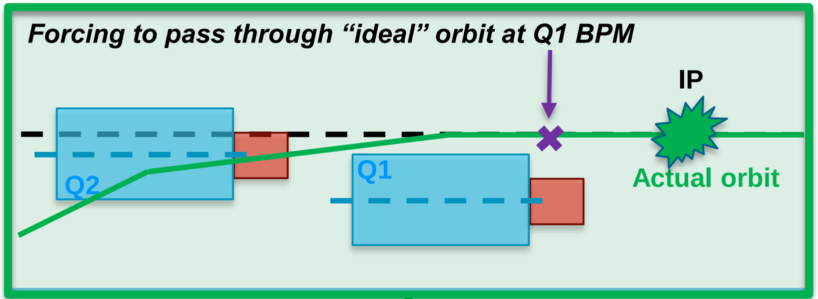
Assumption used in the following slides

Orbit correction strategy in the triplet

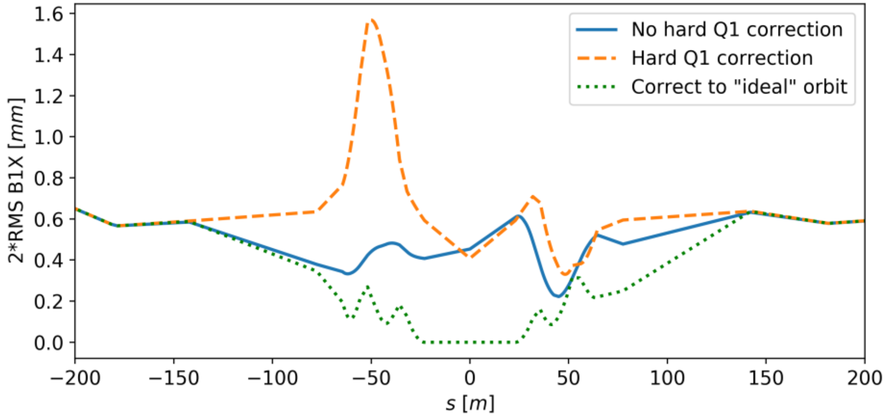
- Need to assume a **strategy** to “**define**”/ “**find**” **ideal IP position**



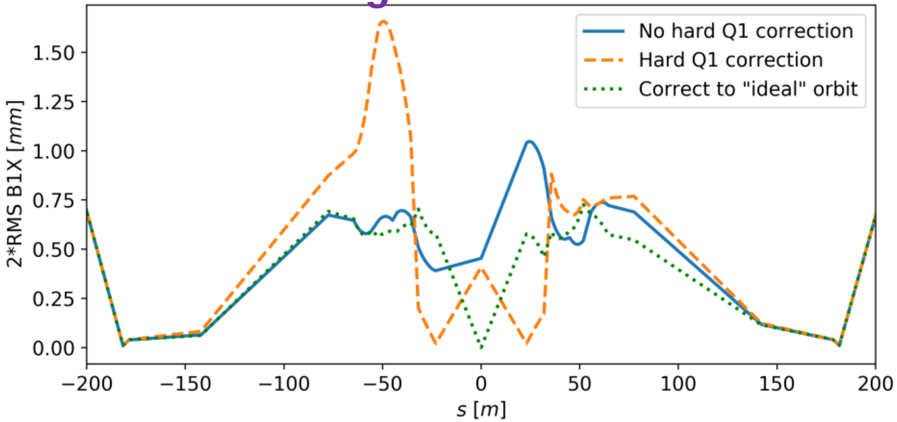




Orbit wrt ideal reference



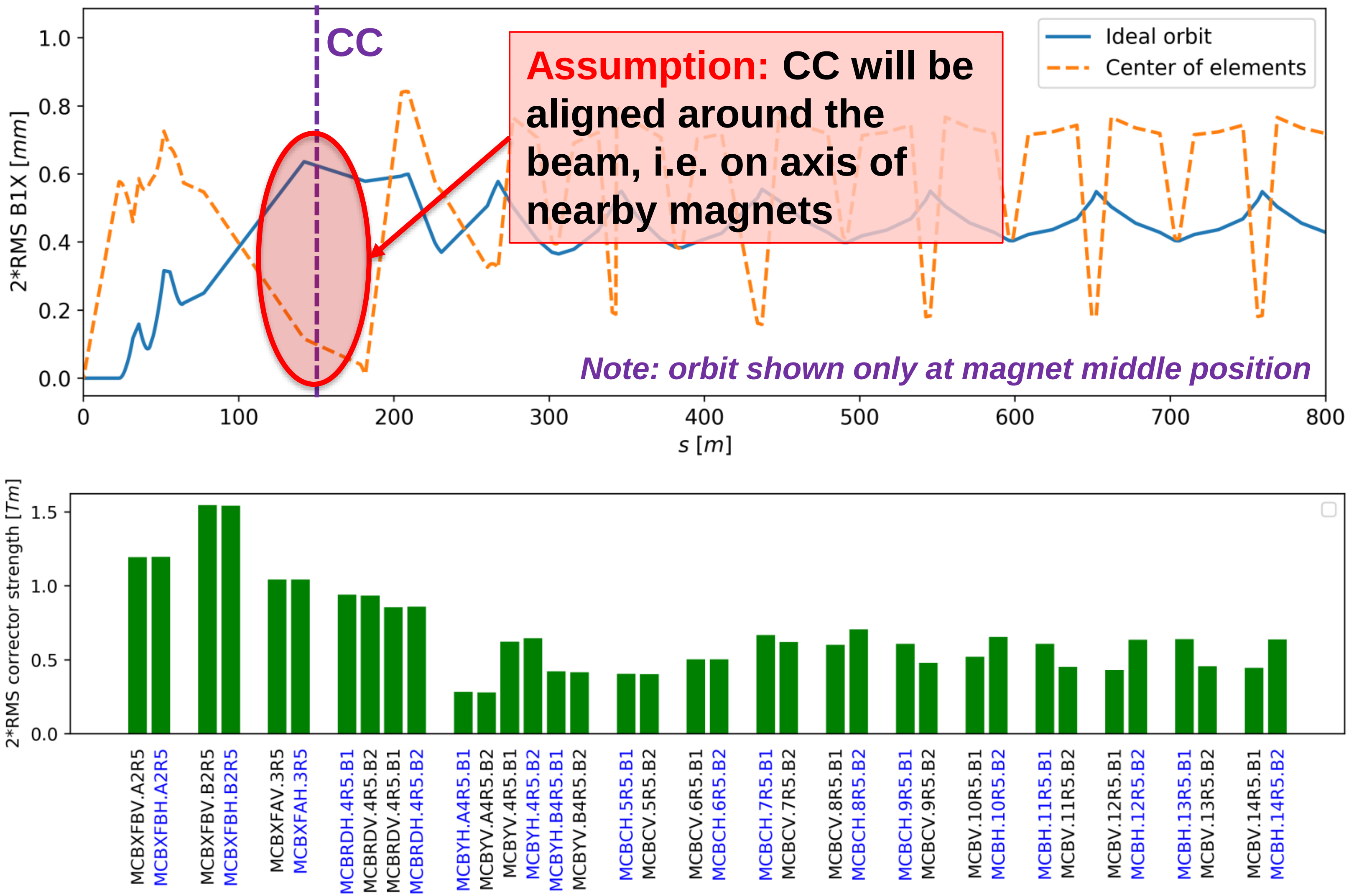
Orbit wrt magnet axis



Imagining that **ballistic optics** could **give us a good “ideal” reference** at Q1 BPM

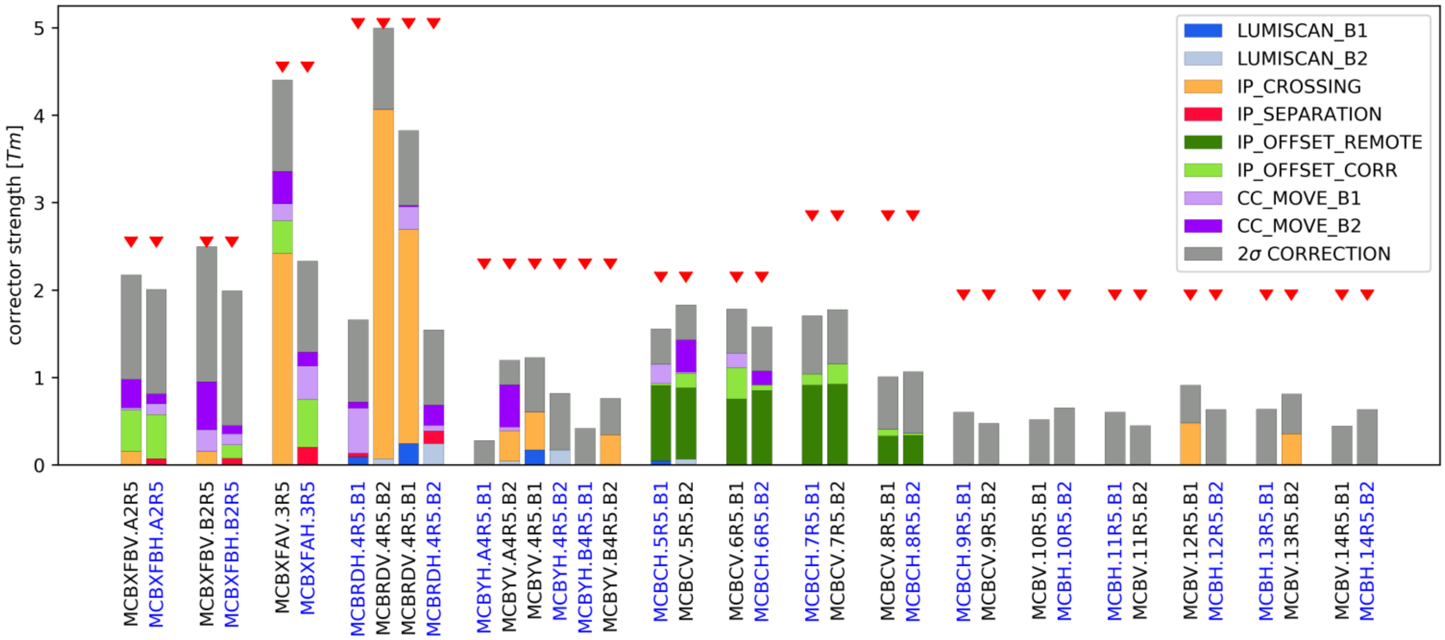
Resume: Residual Orbit and Correctors Usage

- **BPMs move with nearby magnet** + “strong” correction to get **beam at ideal IP**



Knobs implementation

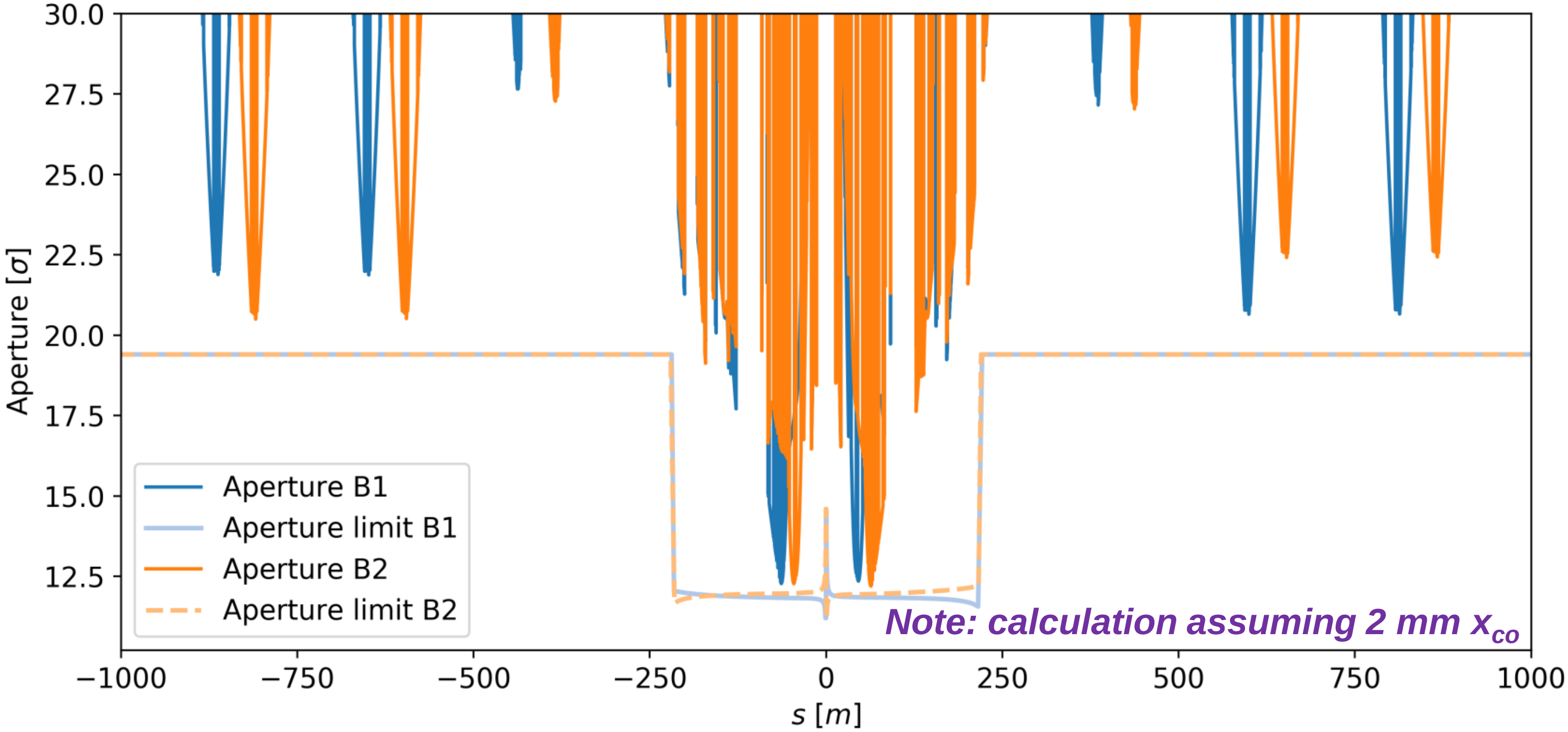
- **295 µrad crossing** angle in V plane
  - (Made of 80% “short” + 20% “long” official versions - (**~0.66 mm at CC**))
- **±0.75 mm separation** in H plane
- **100 µm** IP movement independent for B1/B2 for **lumiscan**
- **2 mm IP offset** with correctors + remote alignment
  - **Q1-Q4 displaced by 2 mm; Q5 displaced by 1 mm**
- **± 500 µm IP offset** with **orbit corrector** only (**requires ~1 mm CC re-alignment**)
- **± 500 µm** movement independent for B1/B2 for **CC alignment**



Failure Scenarios

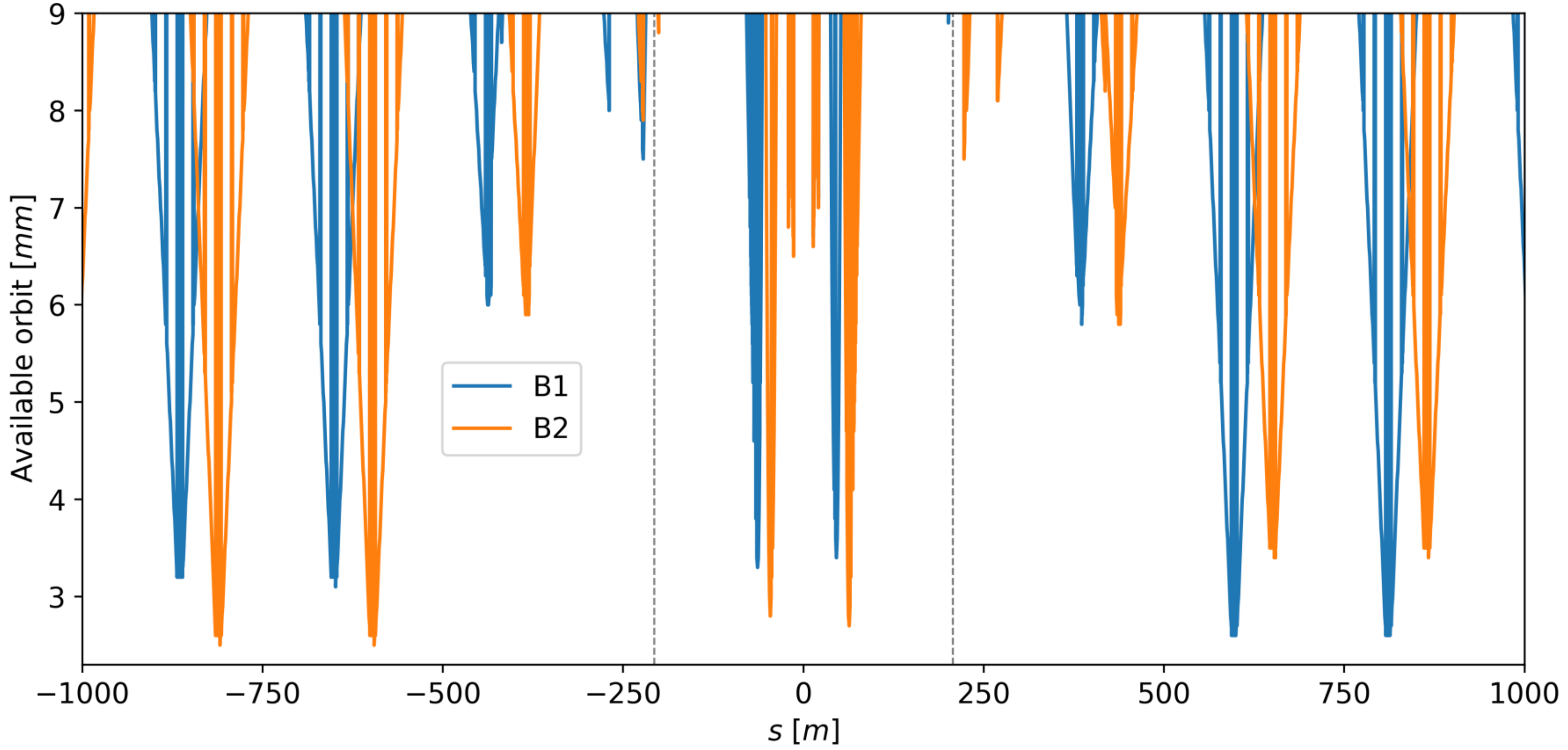
Aperture considerations

- **Previously**, e.g. 162th WP2, required aperture limits were **20/13.2σ** in the **arc/triplet**.
- **Here**, using **19.4σ** in the **arc** and **modulated (~12σ)** limit in **triplet** according to CERN-ACC-2017-0051
  - Could probably apply also to the **arc**, but **to be crosschecked**.



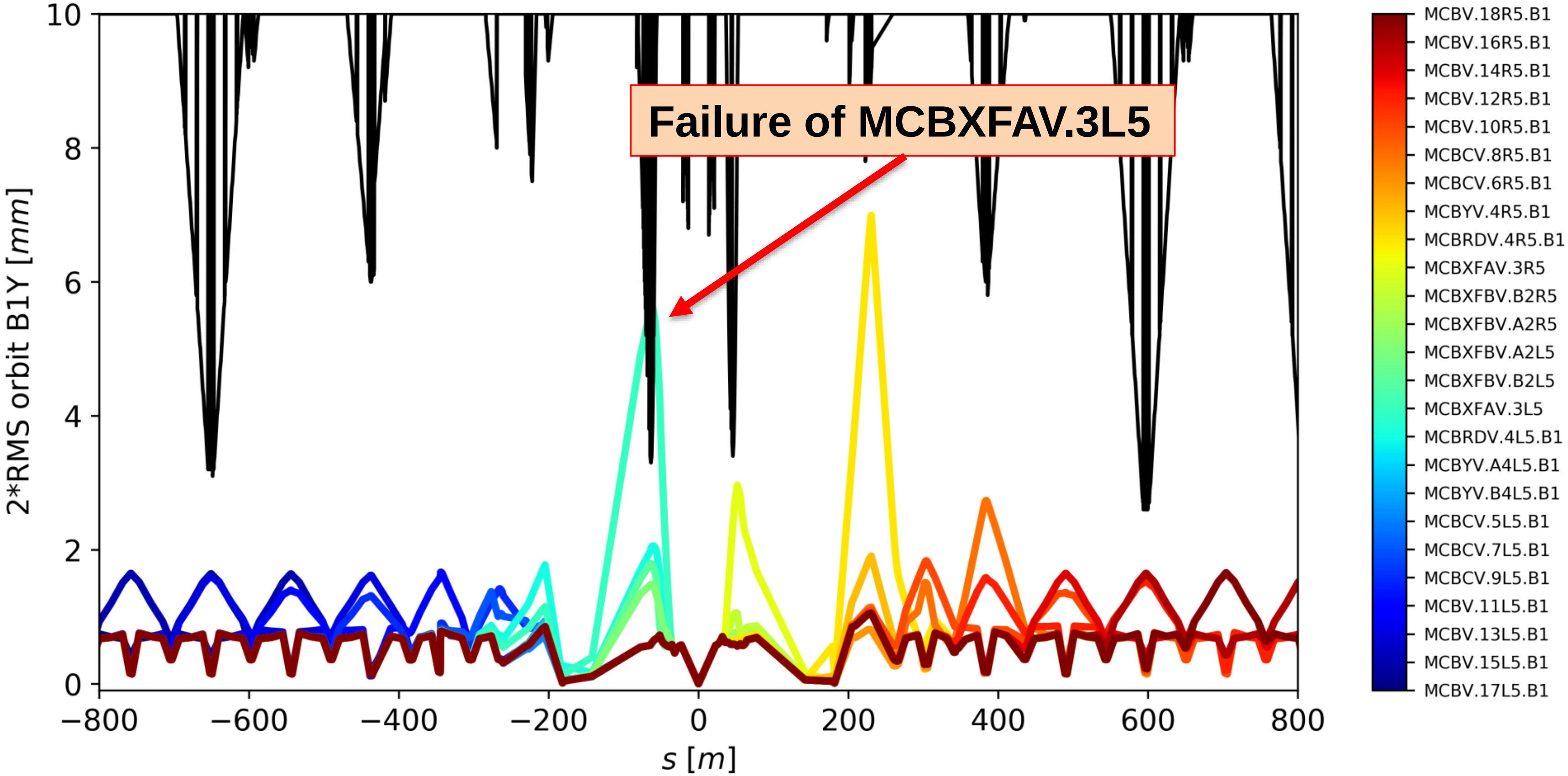
Available "aperture" for orbit

- **Scanning over x_{co}** (default 2 mm) one can get the **radial orbit clearance**, wrt to target aperture.
  - **Conservative approach**, but not too far from reality.



Failure Scenarios and Orbit Correction

- Each color represent **one orbit corrector failing**
  - but **still correcting for misalignments** with all other correctors
- In this respect, **only MCBXFA.3 seems to be fundamental!**



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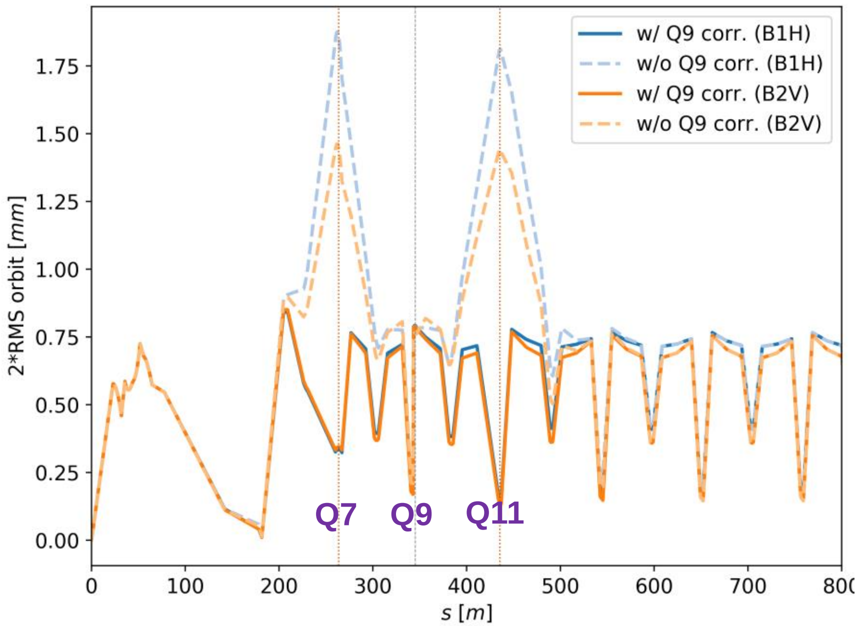
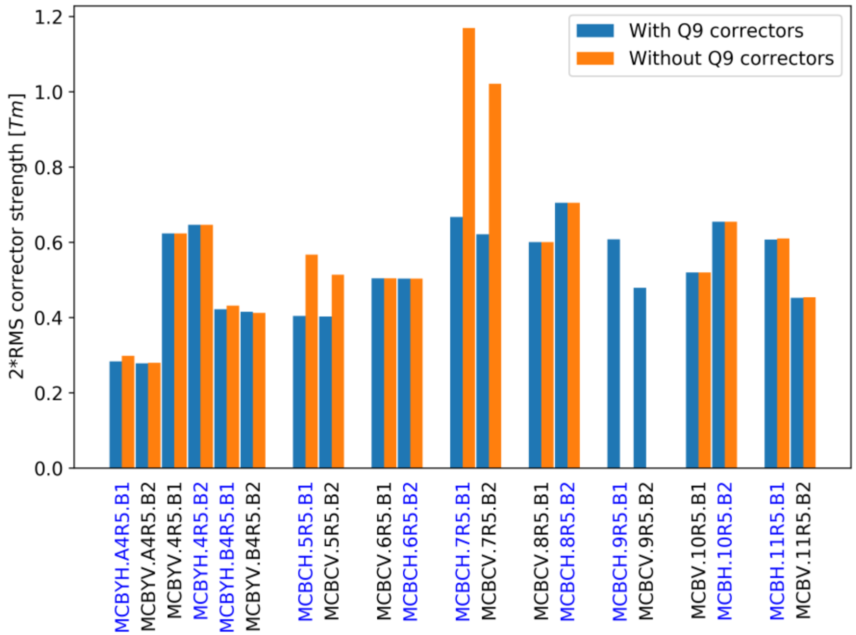
Failure Scenarios and Knobs Implementation

- Technically, **for a generic knob implementation**, **we cannot fail**: **MCBXFA.3**; **any MCBRDs**; the non-redundant **MCBYs**
  - ***Strongly used for crossing knob implementation.***
- **However**, also in other cases one should carefully verify all **knob implementations** on a case-by-case basis.
- **In practice**: main interest is to verify **failure of MCBC Q9** (e.g. [162th WP2](162th WP2))
  - Corrector **not used for any knob** implementation



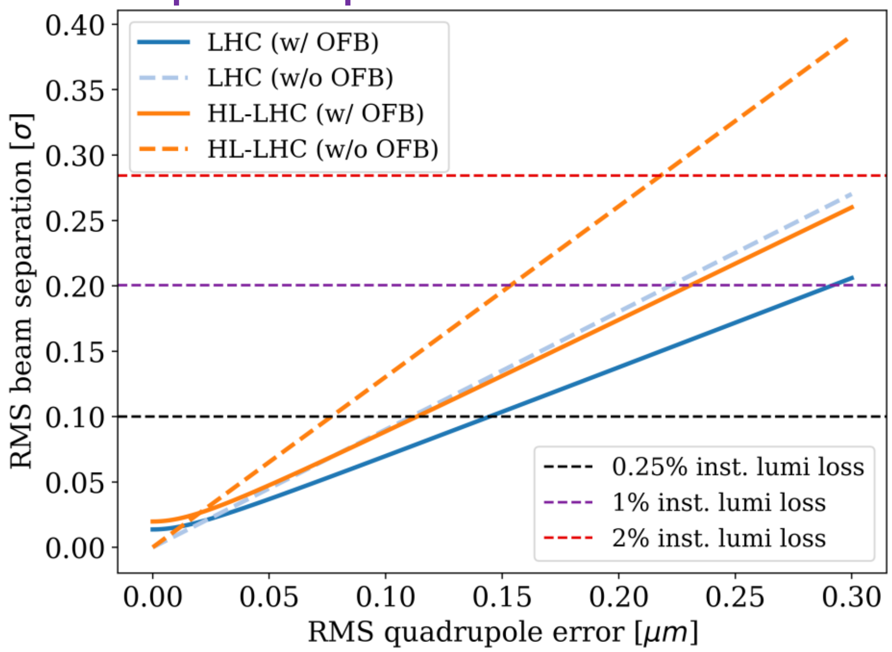


Orbit Feedback considerations

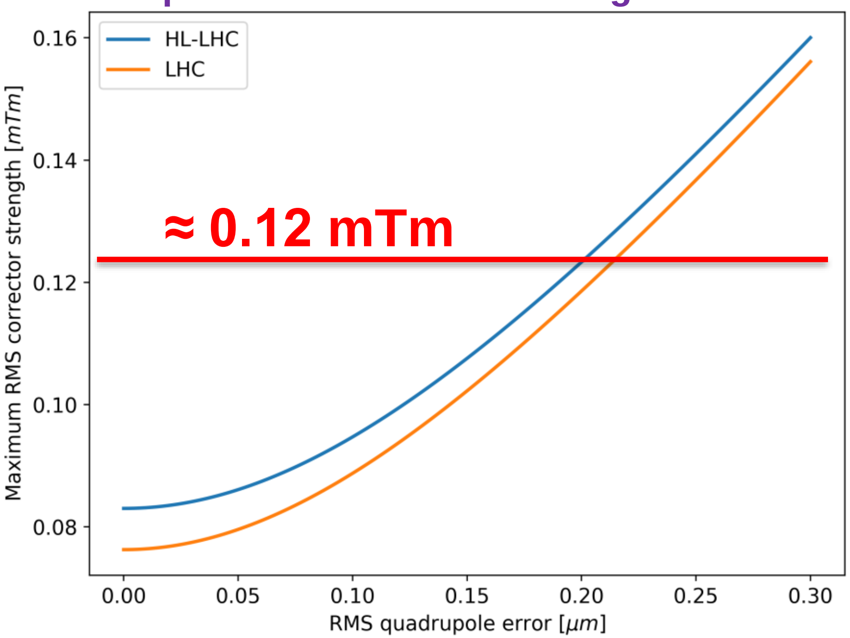
Orbit Correction during Stable Beam

- Assuming **typical** use of **orbit feedback** as today (LHC - 40/~500 singular values per plane), also **including triplet orbit correctors** (HL-LHC only).
  - *From study of Joel presented at 164th (and 156th) WP2 Meetings*

Expected separation at IP



Expected rms corrector usage



IP5; assumed RMS BPM error = 5 μm

Required speed for MCBX orbit correctors

- 0.12 mTm = **5e-5 corrector usage wrt nominal strength**
  - Corresponds to about **80 mA rms orbit corrector usage**
  - Assuming **1 Hz** oscillation**, max derivative about 0.7 A/s**
- **Required performance of PC:**

Table 15: Comparison of the relevant orbit correctors and separation dipoles [1].

	MCBXFA	MCBXFB	MCBRD	MCBY	MBXF	MBRD
Nom. Int. field [Tm]	4.50	2.50	5.00	2.79	35.00	35.00
Nom. Current [A]	1600	1600	430	88	12000	12000
Ramp rate [A/s]	15.00	15.00	2.00	0.67	12.00[a]	12.00[a]
Field Rate [mTm/s]	42.19	23.44	23.26	21.15	35.00	35.00
Angle Rate [μrad/s @ 7TeV]	1.81	1.00	1.00	0.91	1.50	1.50
Ramp Acc. [A/s^2]	5.00	5.00	1.00	0.25	2.00	2.00
Field Acc. [mTm/s^2]	14.06	7.81	11.63	7.93	5.83	5.83
Angle Acc. [μrad/s^2 @7TeV]	0.60	0.33	0.50	0.34	0.25	0.25
Time to nom. rate [s]	3.00	3.00	2.00	2.67	6.00	6.00

[a] In [1] it was specified 20 A/s as a first estimation.

Table from CERN-ACC-2017-0101

- **Concerns** that Quench Protection System (**QPS**) of **LHC MCBX** does **not allow for high dI/dt** (false-positive quench detection)
  - **Not an issue for HL-LHC** MCBXF as they will have **middle voltage tap (EDMS** 2002347, **R. Denz** – HL-LHC Coll. Meeting 2018 indico**)**

Conclusions

- A **generic tool** to quickly check correctors budget and residual orbit has been implemented (*by Joel - Thanks!*)

- **HL-LHCv1.5 β*=15 cm** round optics verified:
  - Can **safely implement** all standard **knobs**
  - **Residual orbit** (wrt magnet axis) **<1 mm (2*rms)**
  - It can **sustain loss of Q9 MCBX** in case of radiation damage
  - **IP orbit stabilisation** during stable beam is expected to require **<0.1 mTm** (assuming 0.1 um quadrupole-displacement-equivalent errors, 5 um BPMs error) keeping the **luminosity loss below 0.25%**
    - **Compatible** with required **orbit corrector speed**.

- Not covered here: **flat optics** has been also analyzed
  - **No major differences, but tighter aperture**

- All results are **being summarized** in a **detailed note.**

Thank you for your attention!

Backup

Flat Optics

Flat Optics: Residual Orbit and Correctors Usage

- **No difference! – strengths of elements in this region is basically unchanged!**

Flat Optics: Knobs implementation

- **295 µrad crossing** angle in **H plane**
- **±0.75 mm separation** in V plane
- **100 µm** IP movement independent for B1/B2 for **lumiscan**
- **2 mm IP offset** with correctors + remote alignment
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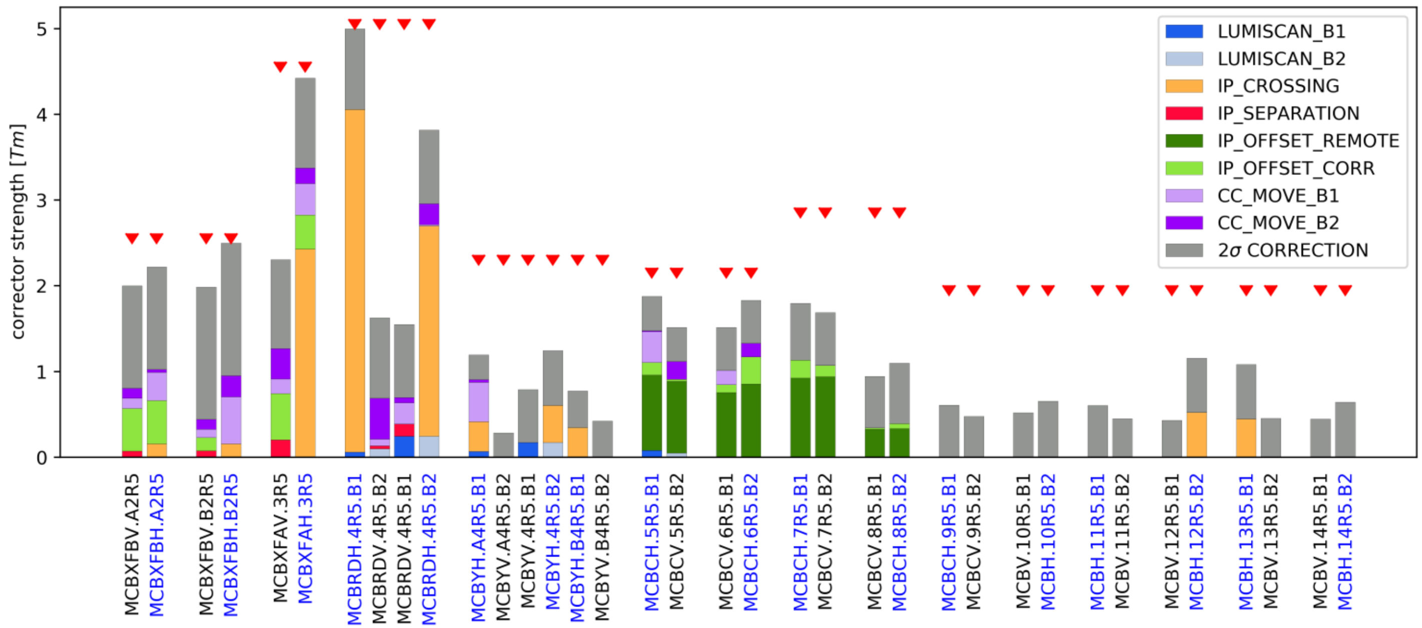
- **± 500 µm** movement independent for B1/B2 for **CC alignment**



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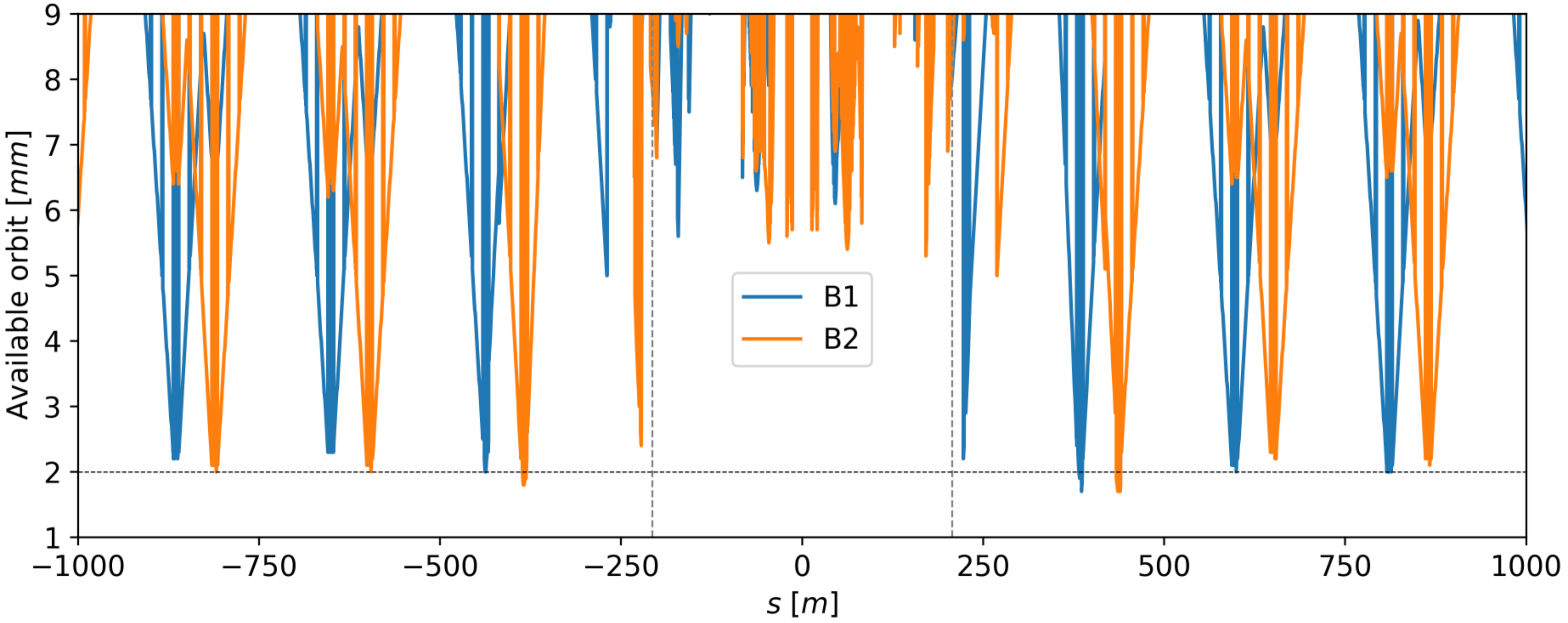
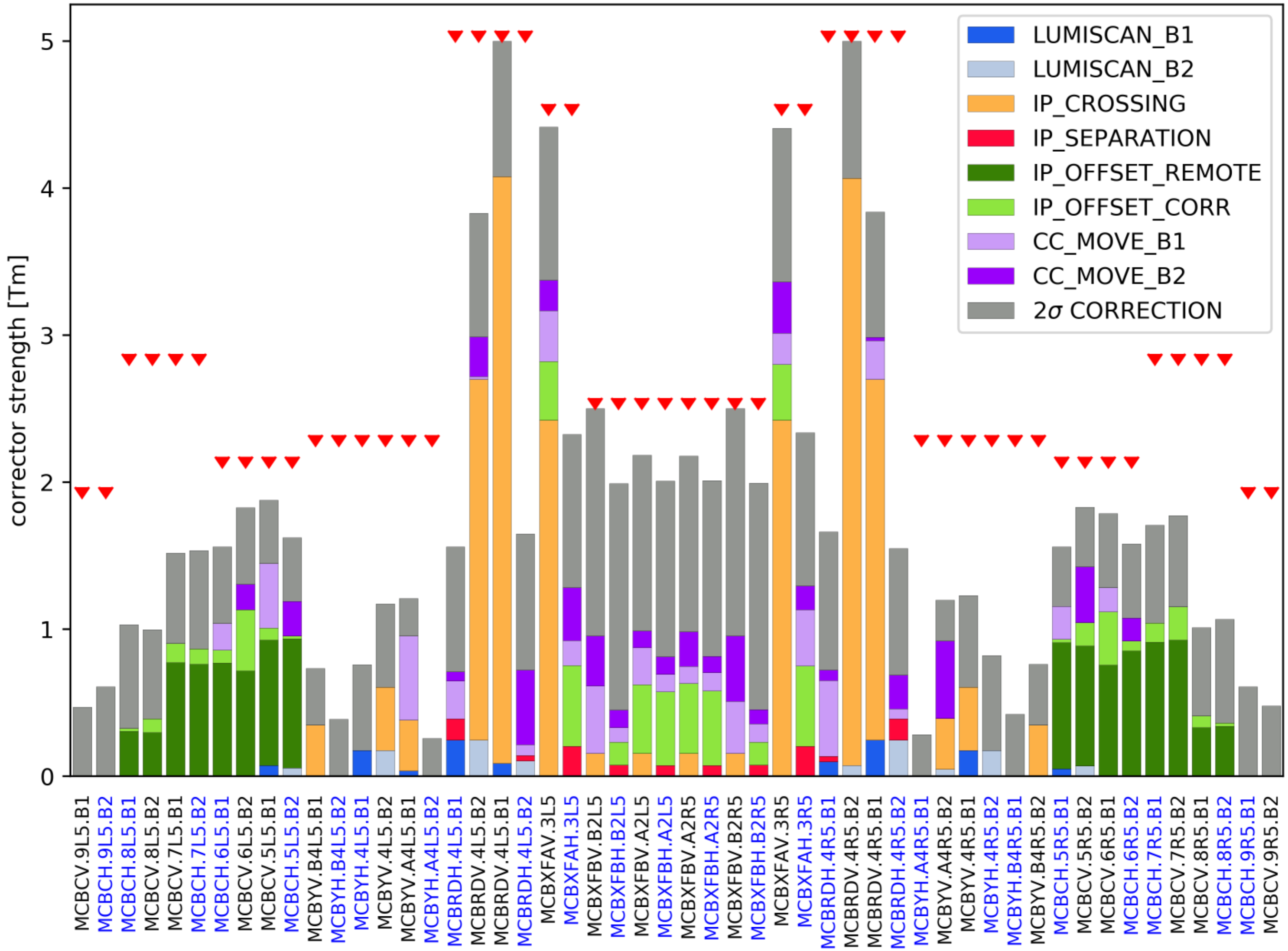
Flat optics: Available "aperture" for orbit

- **Slightly less aperture, touching in a few points.**
  - **Still well compatible with expected residual orbit (<1 mm 2*r.m.s.)**



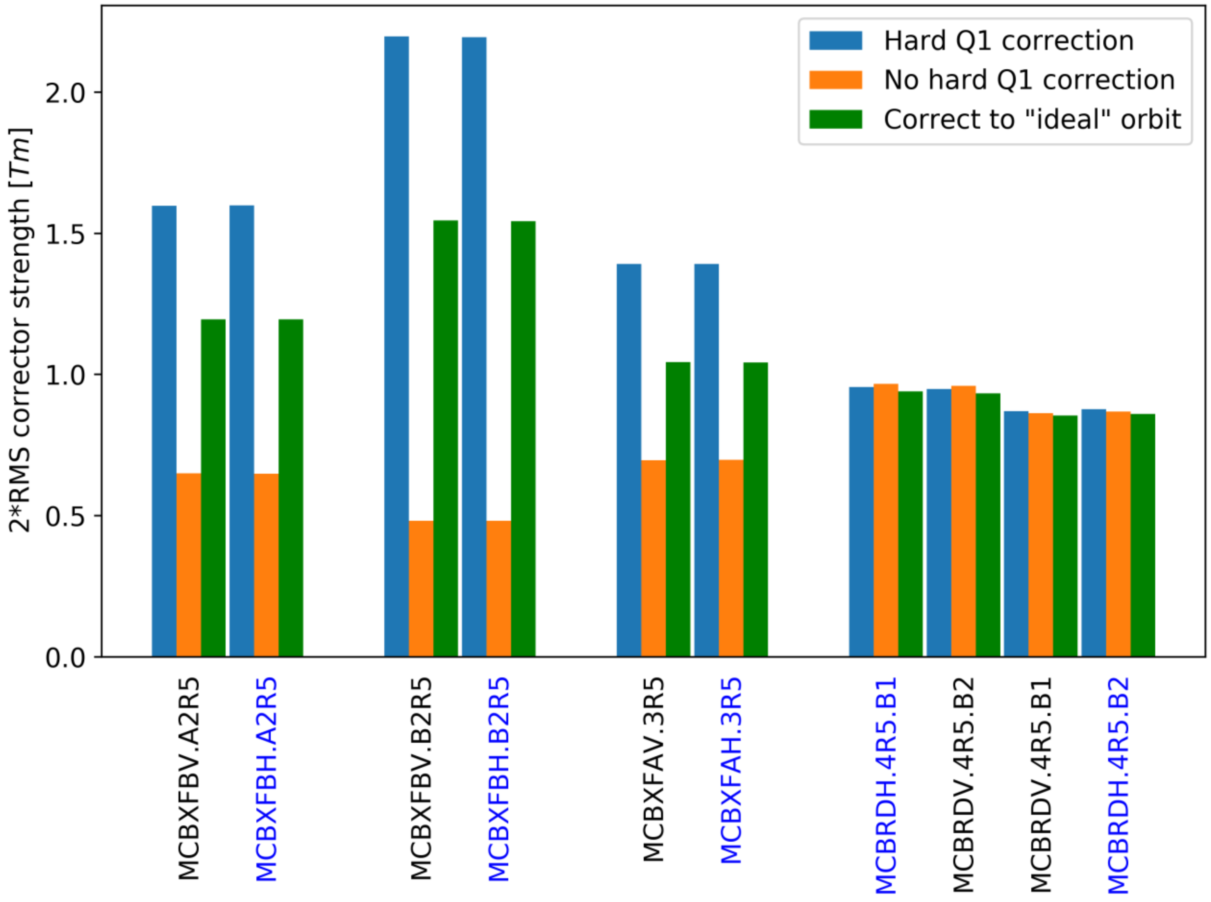
Orbit Corrector Budget

Corrector budget – complete up to Q9



Corrector strength expenditure for correction

- Comparison between orbit corrector budget use for different correction strategies in the triplet:
  - “Hard Q1 correction” = overcorrection at Q1 BPM
  - **“Correct to ideal orbit” = orbit correction at ideal orbit at Q1 BPM**
  - “No hard Q1 correction” = simple orbit correction like in the arc.



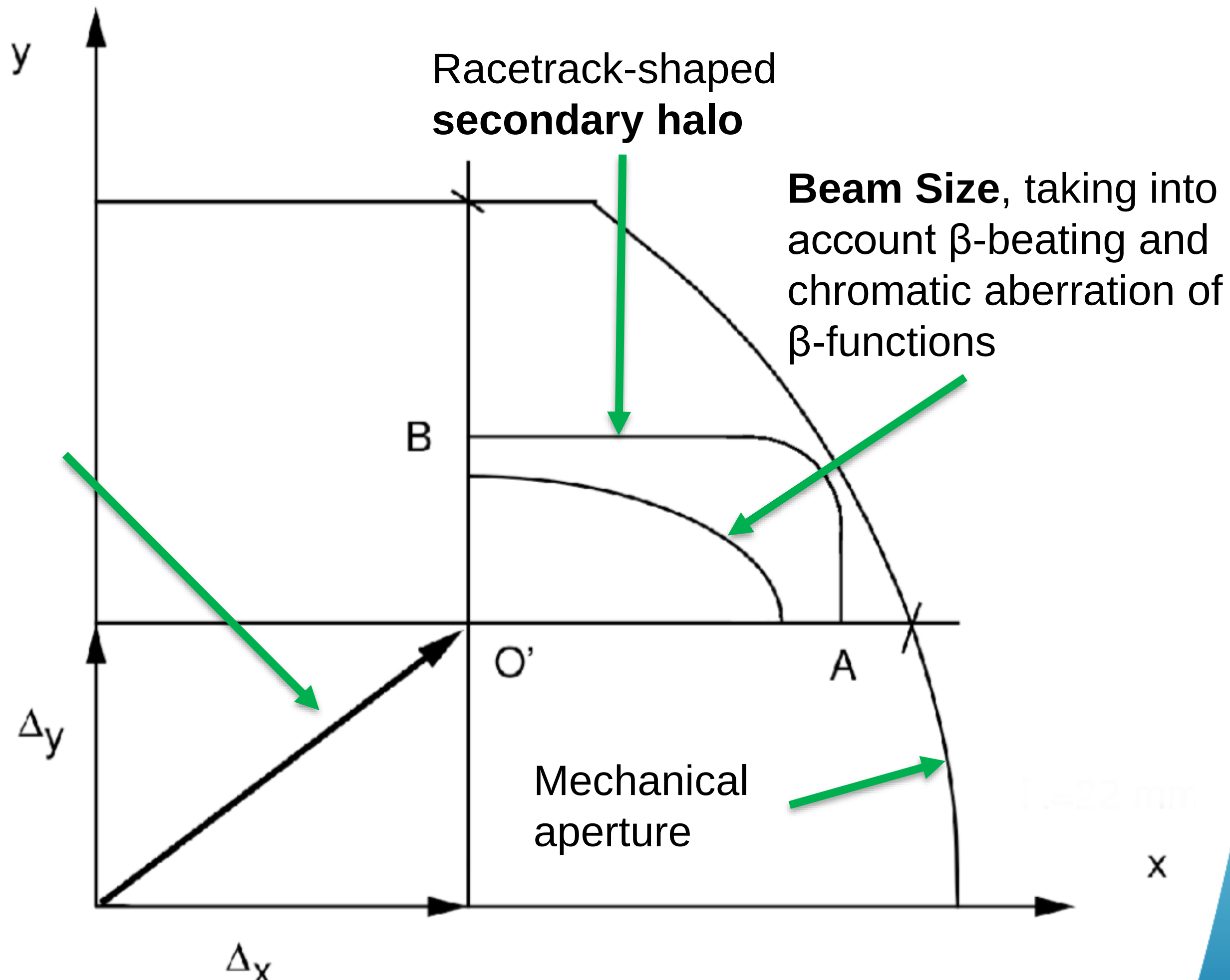
Apertures and Failures

Aperture considerations: how to compute?

- Present baseline for aperture computation (CERN-ACC-2017-0051)

Orbit tolerances, including:

- Closed orbit deviation **(x_{co} = 2 mm);**
- Mechanical alignment tolerance **(Δ_{al});**
- Beam screen alignment **(Δ_{ba});**
- Cold bore alignment **(Δ_{cb});**
- Off-momentum component (**$D\delta_p$;** taking into account dispersion beating)



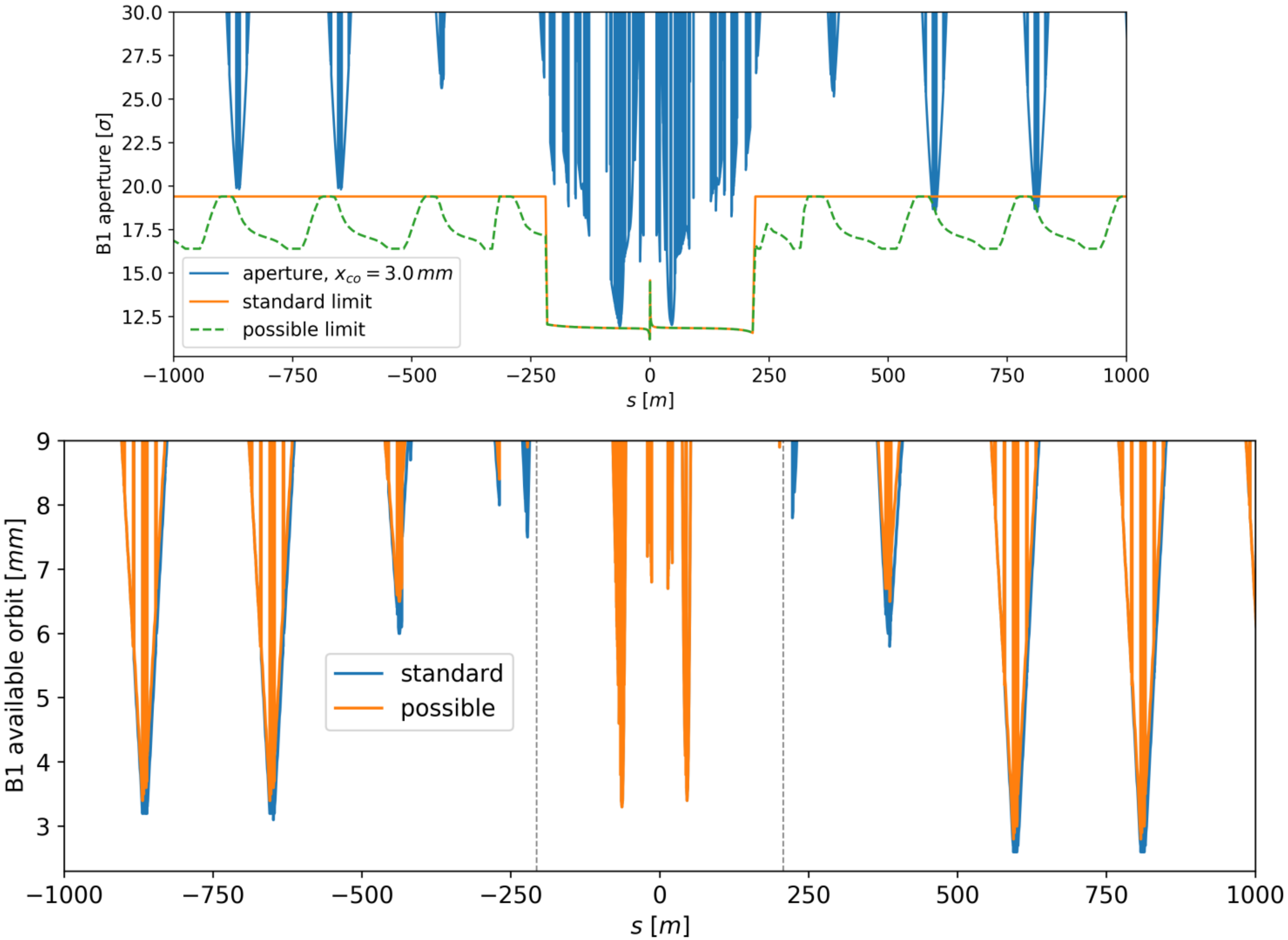
Aperture considerations: how to compute?

- Present baseline for aperture computation (CERN-ACC-2017-0051) assumes:

Parameter	Injection Note (Example)	Top energy Note (Example)	Description
Halo(s)	6 σ	6 σ	Primary and secondary halo extensions
ε_n	2.5 (2.5) μm	2.5 (2.5) μm	Normalized emittance.
dPMax	8.6e-4 (8.6e-4)	2e-4 (2e-4)	"Bucket edge at the current beam energy." **-> to be set to 0 for TWISS_DELTAP != 0**
x_{co}	2 (2) mm	2 (2) mm	Max closed orbit deviation - radial
k_β	1.05 (1.05)	1.1 (1.1)	β beating
f_{arc}	0.14 (0.14)	0.1 (0.1)	Relative parasitic dispersion (scaling from arc to local dispersion) (DPARX/DPARY in MAD-X)
δ_p	8.6e-4 (6e-4?)	2e-4 (2e-4?)	Momentum offset used to compute off-momentum β beating by executing 3 separate Twiss $-\delta_p$; 0; $+\delta_p$
σ_p	(4.5e-4)	(4.5e-4*sqrt(450/7000))	Beam energy spread, used in beam definition **-> not being used by aperture calculation**
Interval	n.a. (1.0)	n.a. (1.0)	Approximate length in meters between measurements.
SPECIF	(12.6)	(14.6)	Aperture spec, for plotting only.
VMAXI	(30)	(30)	??

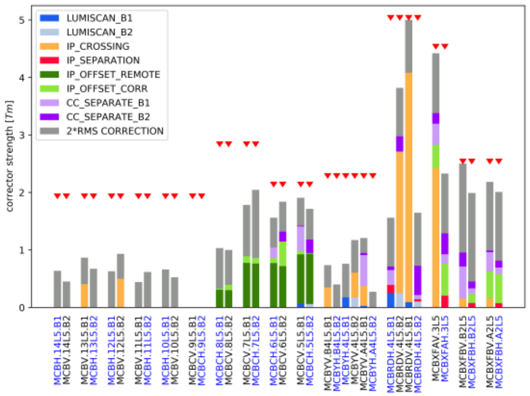
Aperture B1 comparison (round optics)

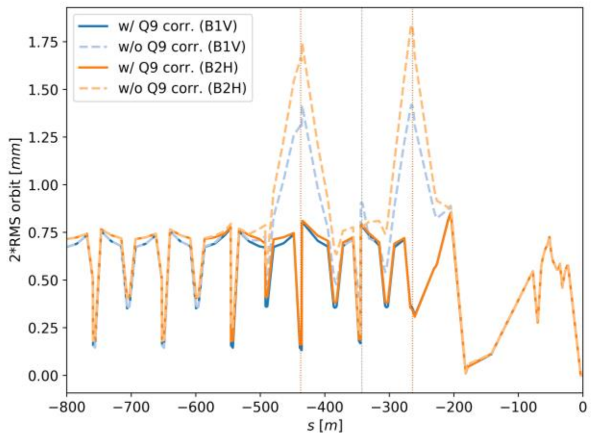
- Using CERN-ACC-2017-0051 as aperture limit also in the arc

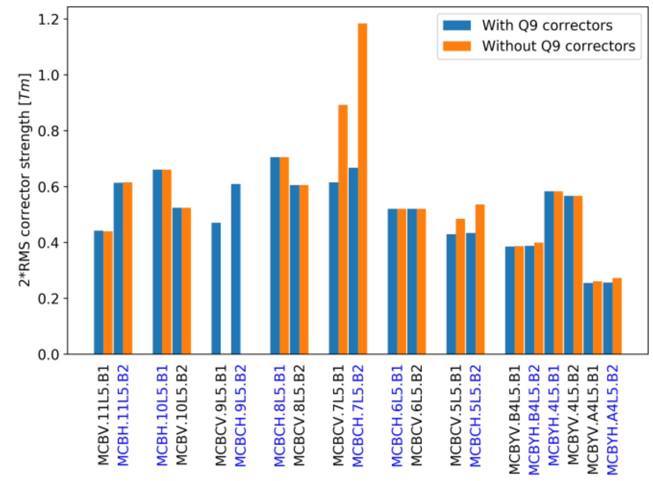


Full case for failures of Q9 orbit correctors

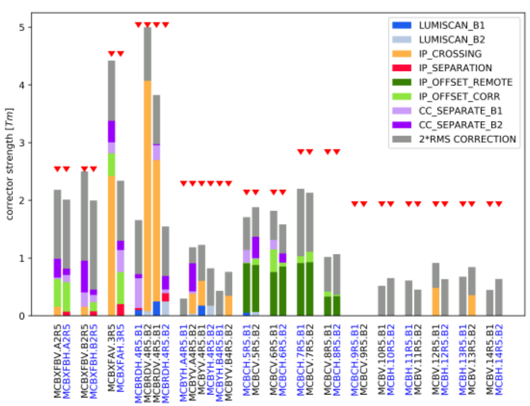
Nominal/failure case around Q9 Left H/V

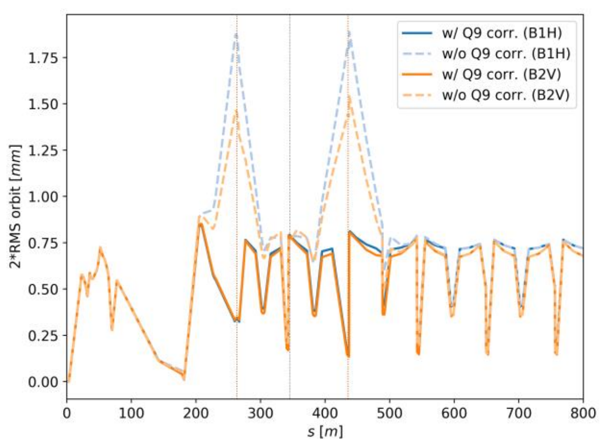


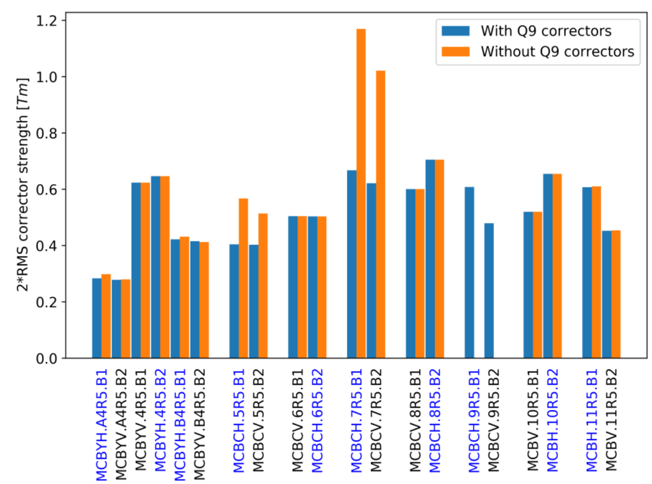




Nominal/failure case around Q9 Right H/V

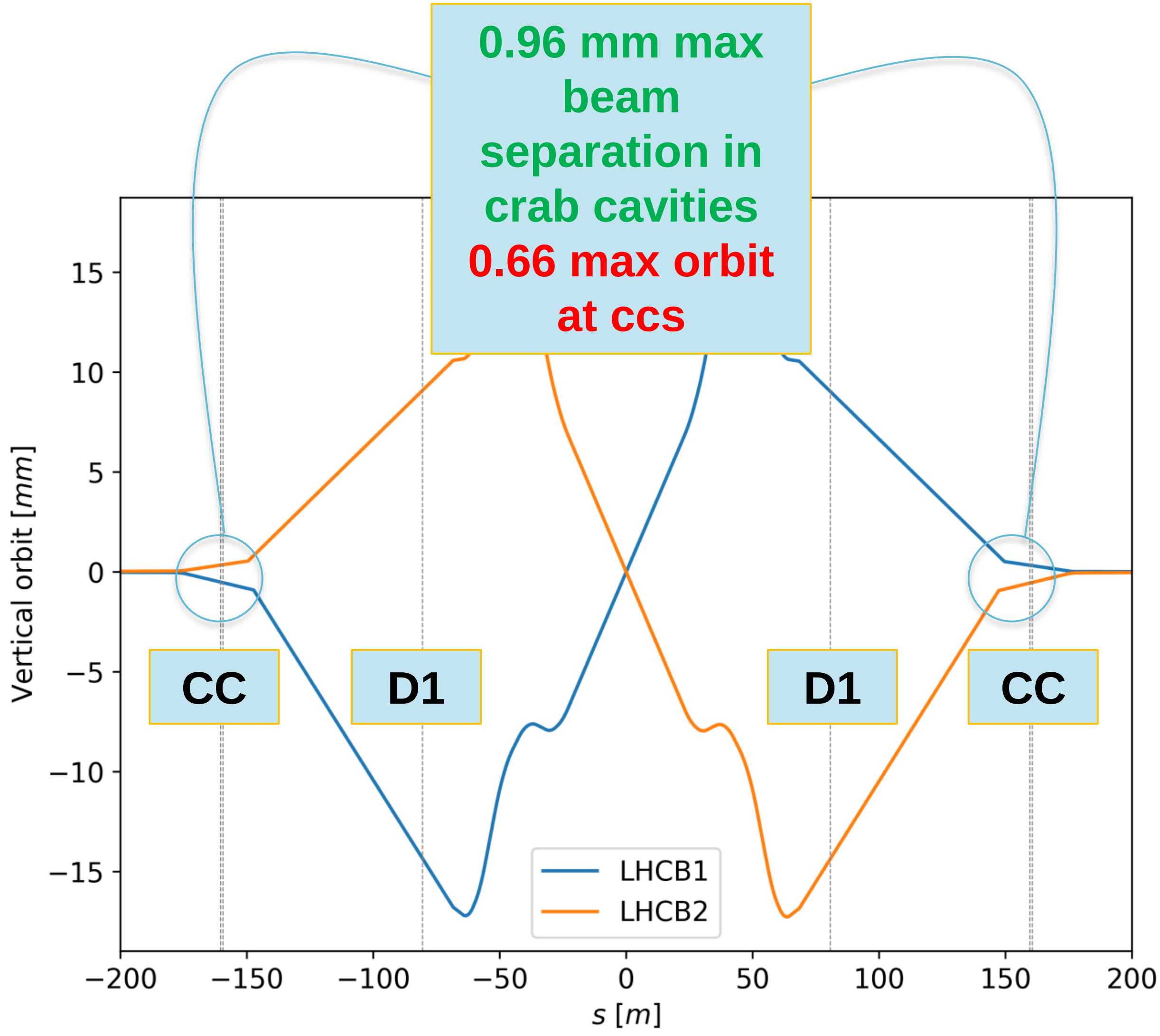




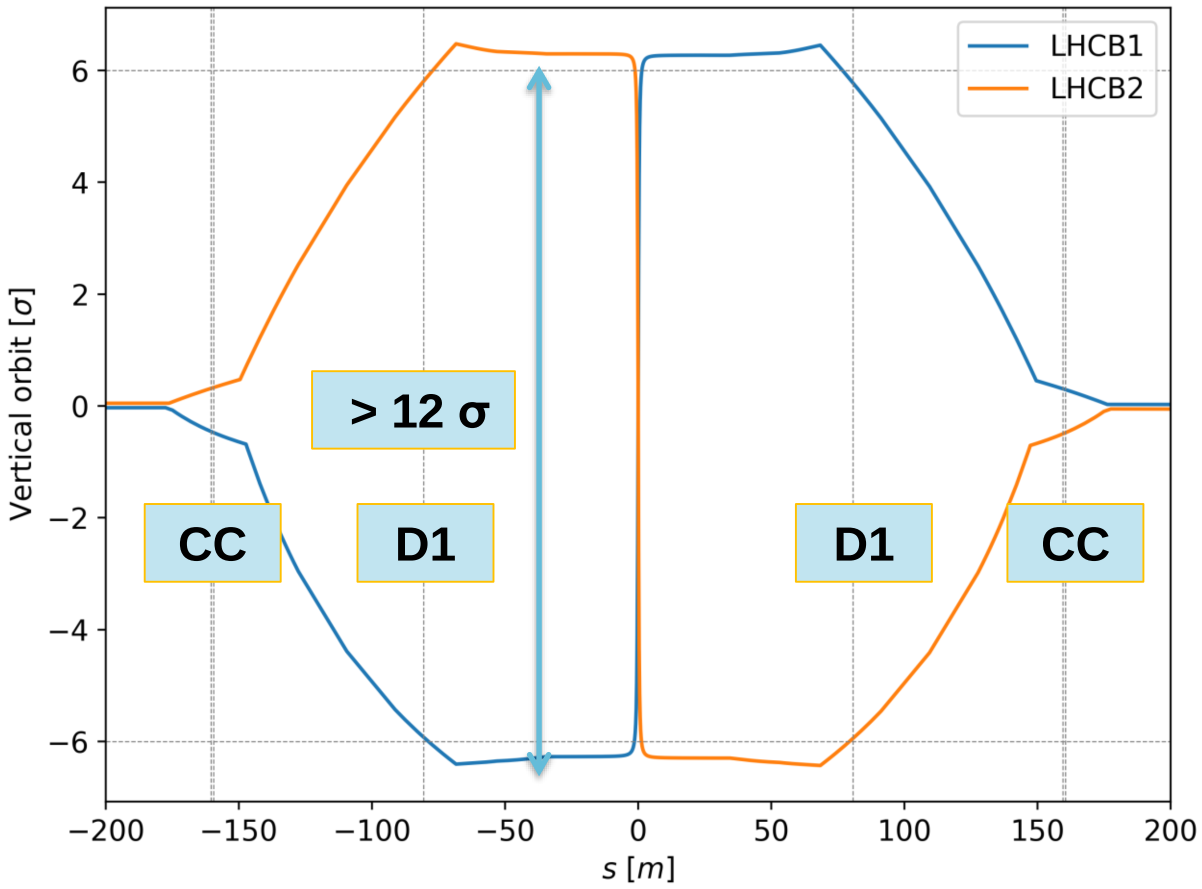


Knobs

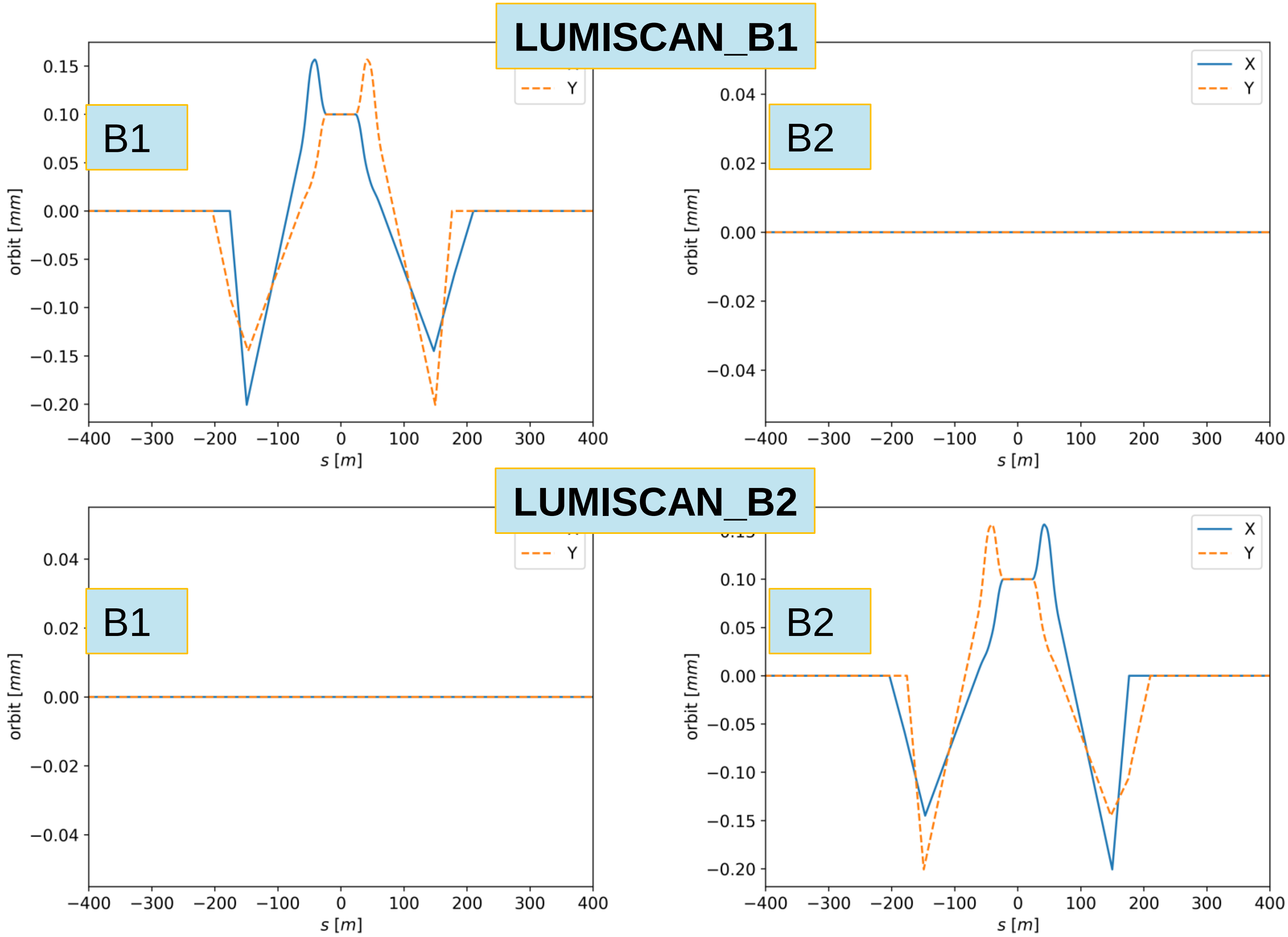
Crossing knob



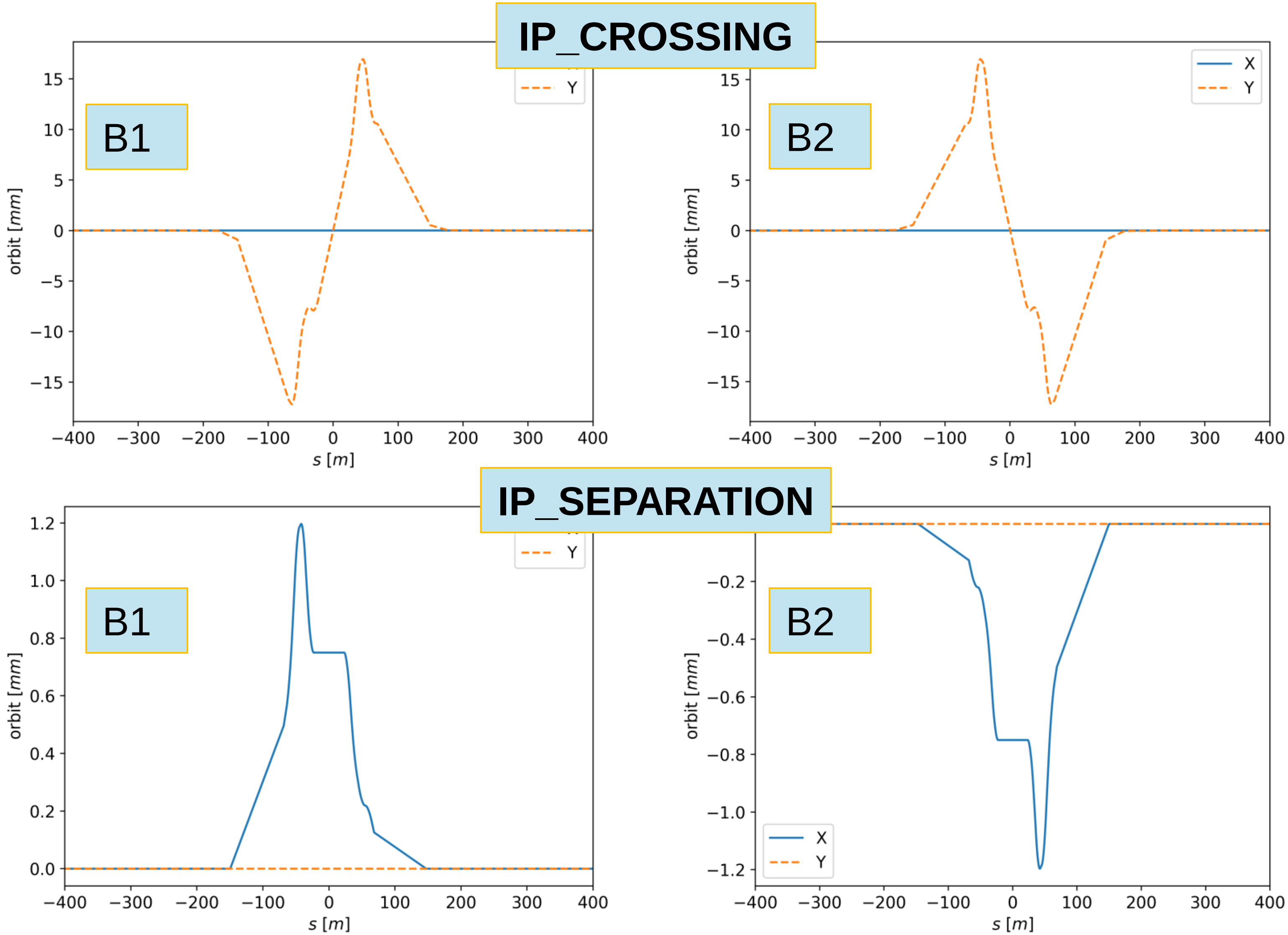
Crossing knob (in beam sigmas)



Knob orbits

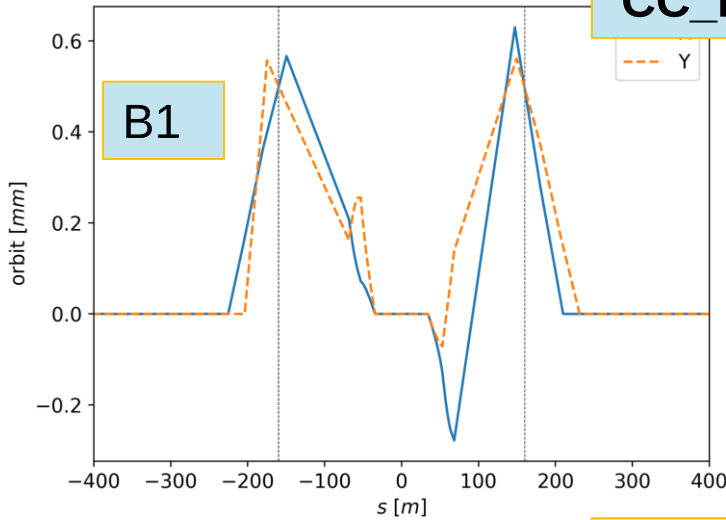

LUMISCAN_B1
B1
B2
LUMISCAN_B2
B1
B2
X
Y
orbit [mm]
s [m]
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
0.04
0.02
−0.02
−0.04
−400
−300
−200
−100
0
100
200
300
400

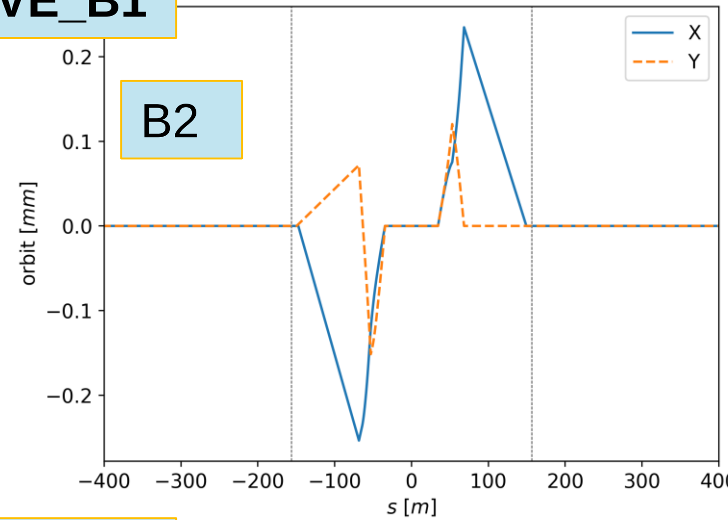
Knob orbits


IP_CROSSING
B1
B2
orbit [mm]
s [m]
X
Y
IP_SEPARATION
B1
B2
orbit [mm]
s [m]
X
Y

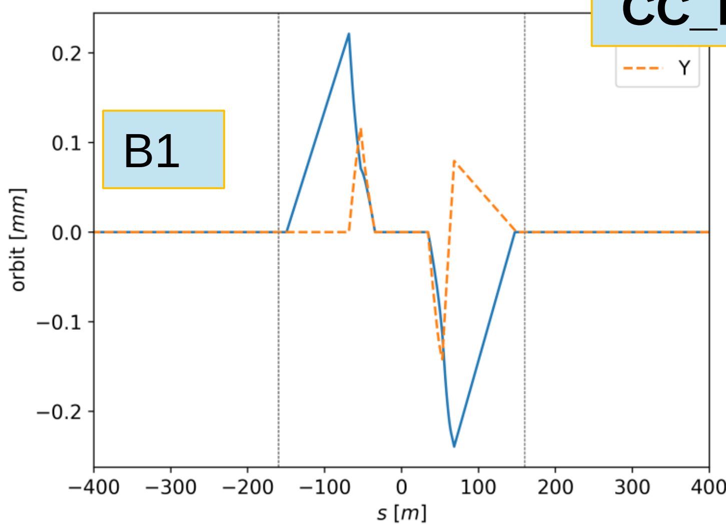
Knob orbits

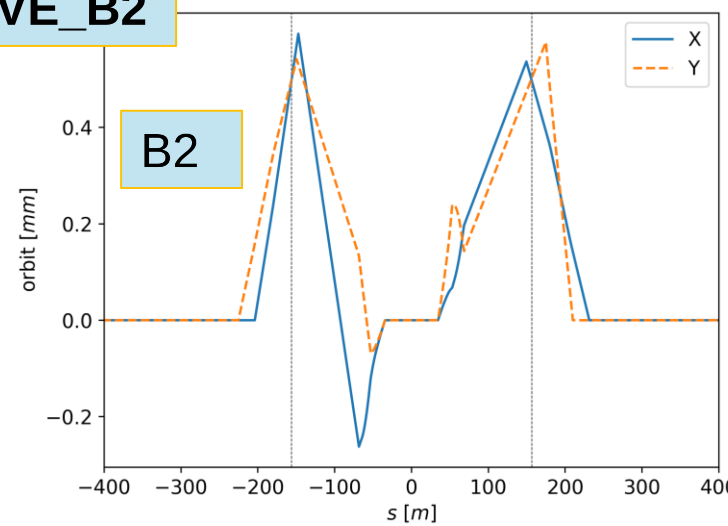
CC_MOVE_B1





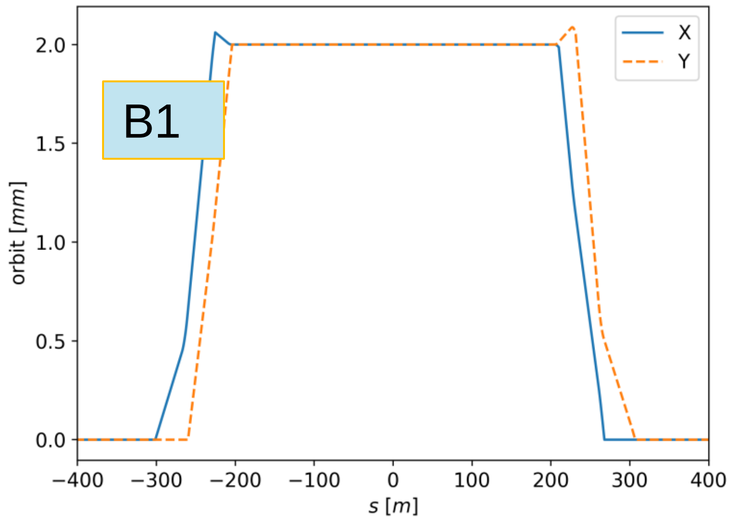
CC_MOVE_B2

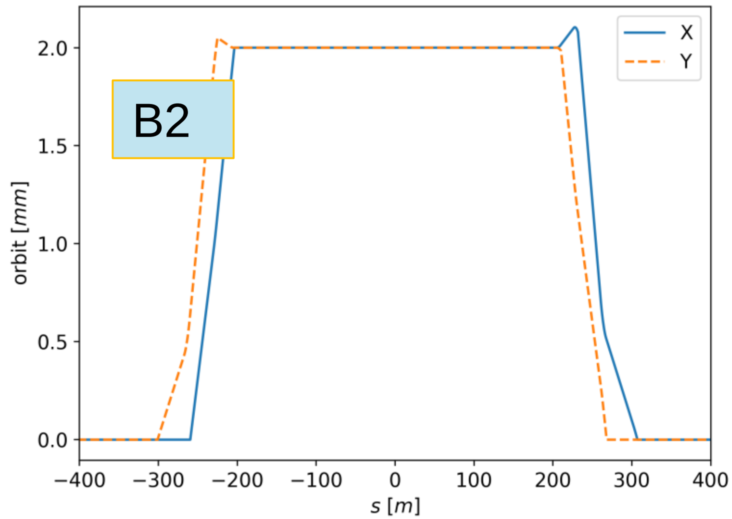




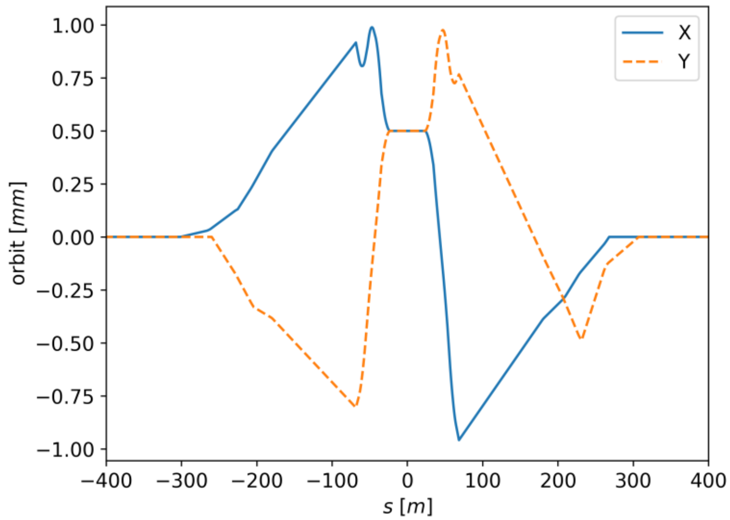
Knob orbits

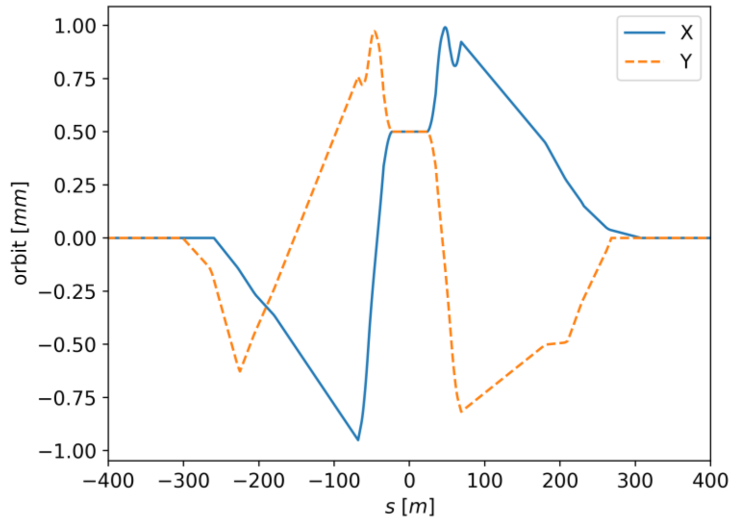
IP_OFFSET_REMOTE





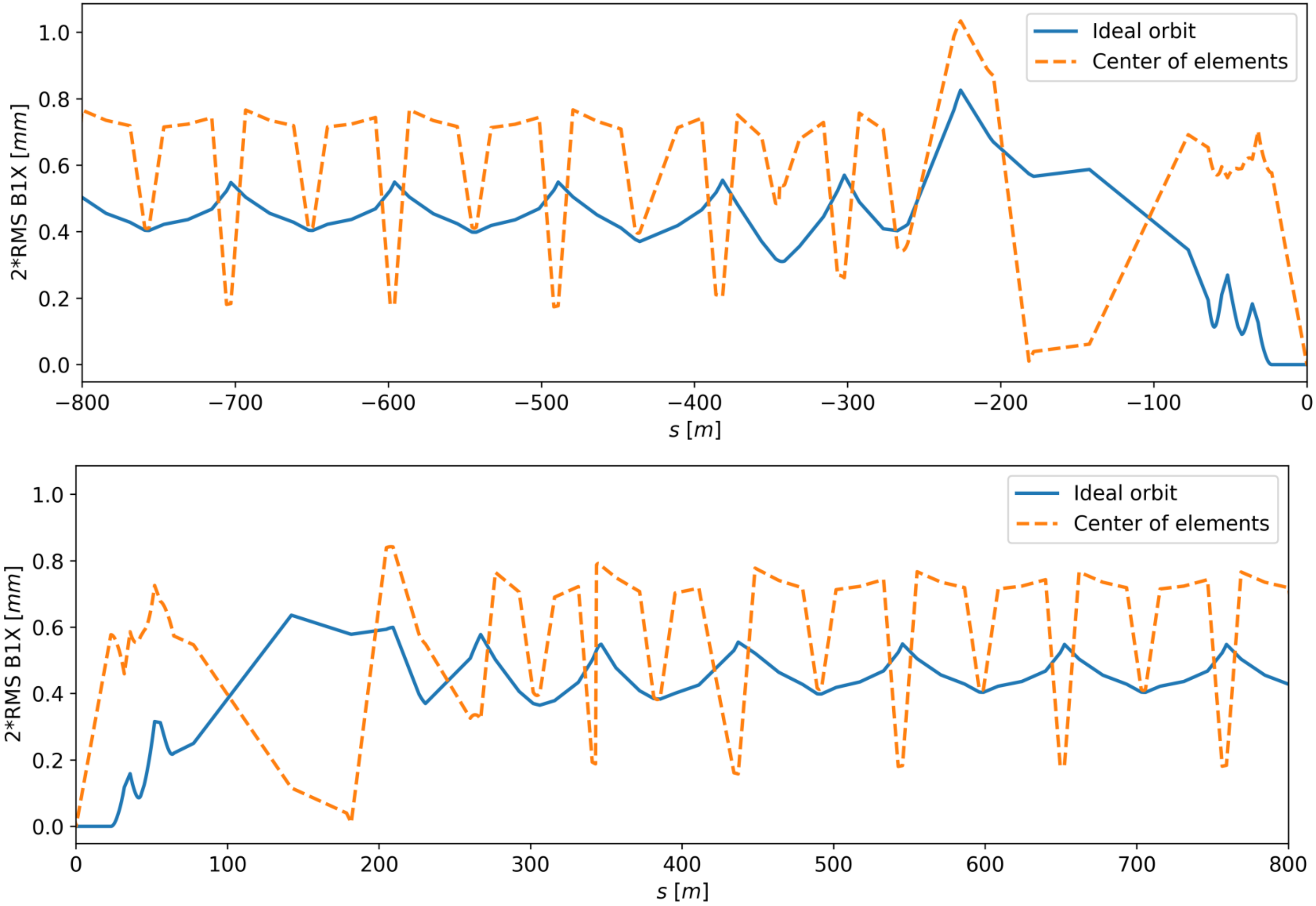
IP_OFFSET_CORR





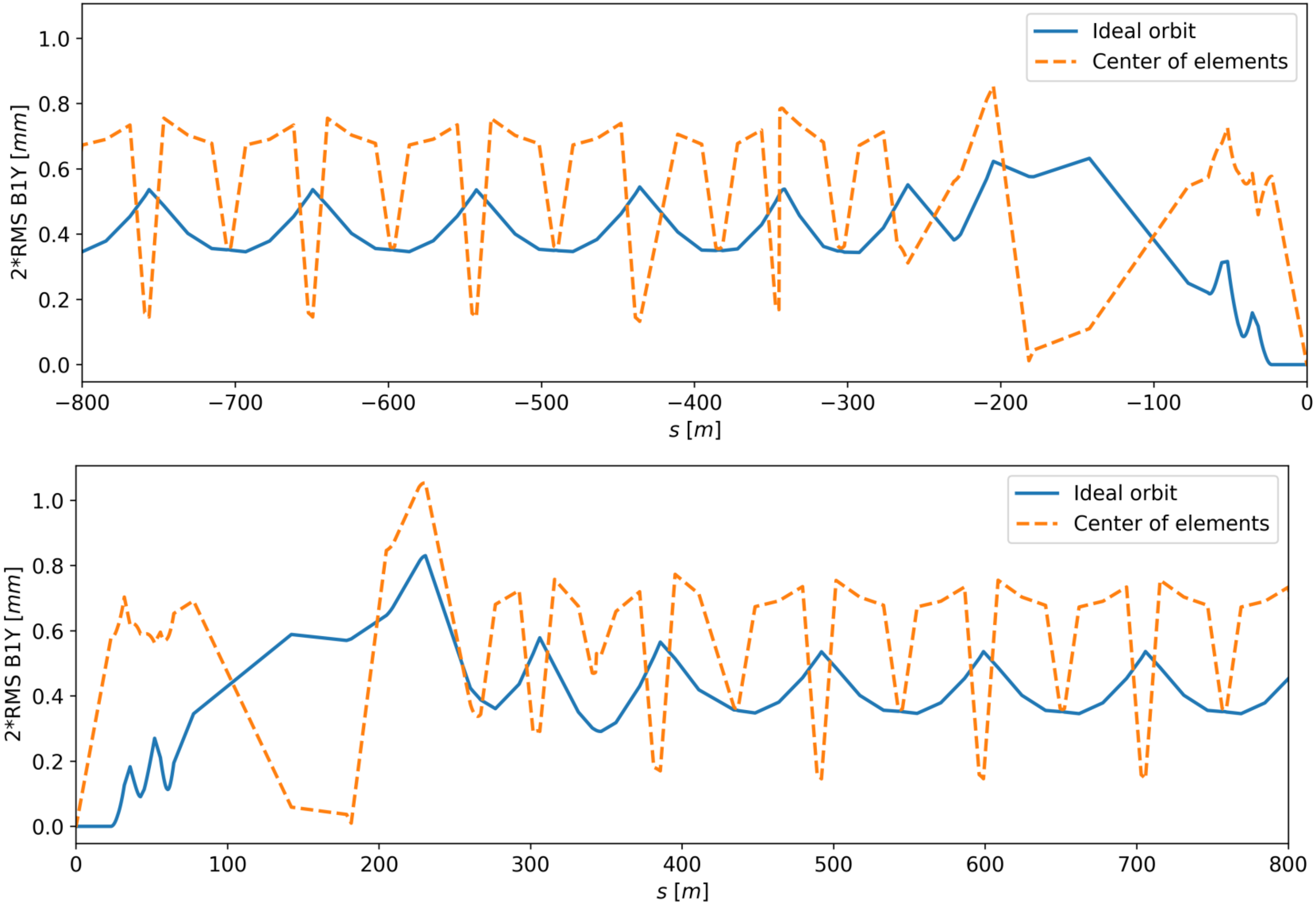
Residual orbit B1X

- **BPMs move with nearby magnet** + “strong” correction to get **beam at ideal IP**



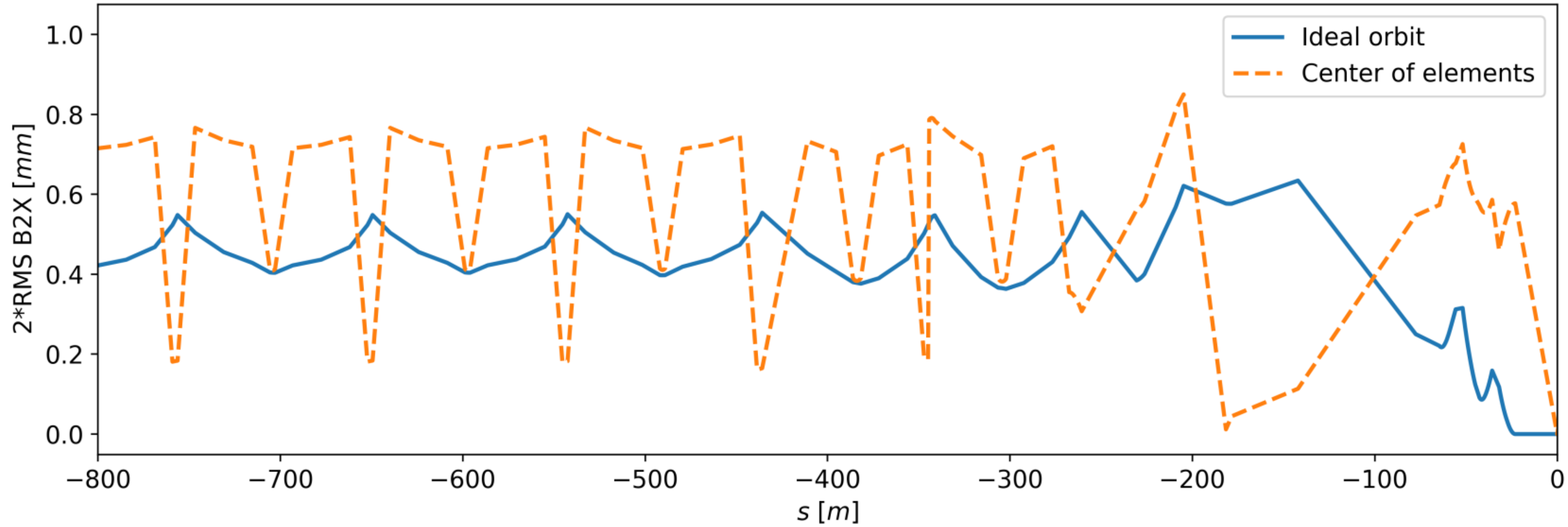
Residual orbit B1Y

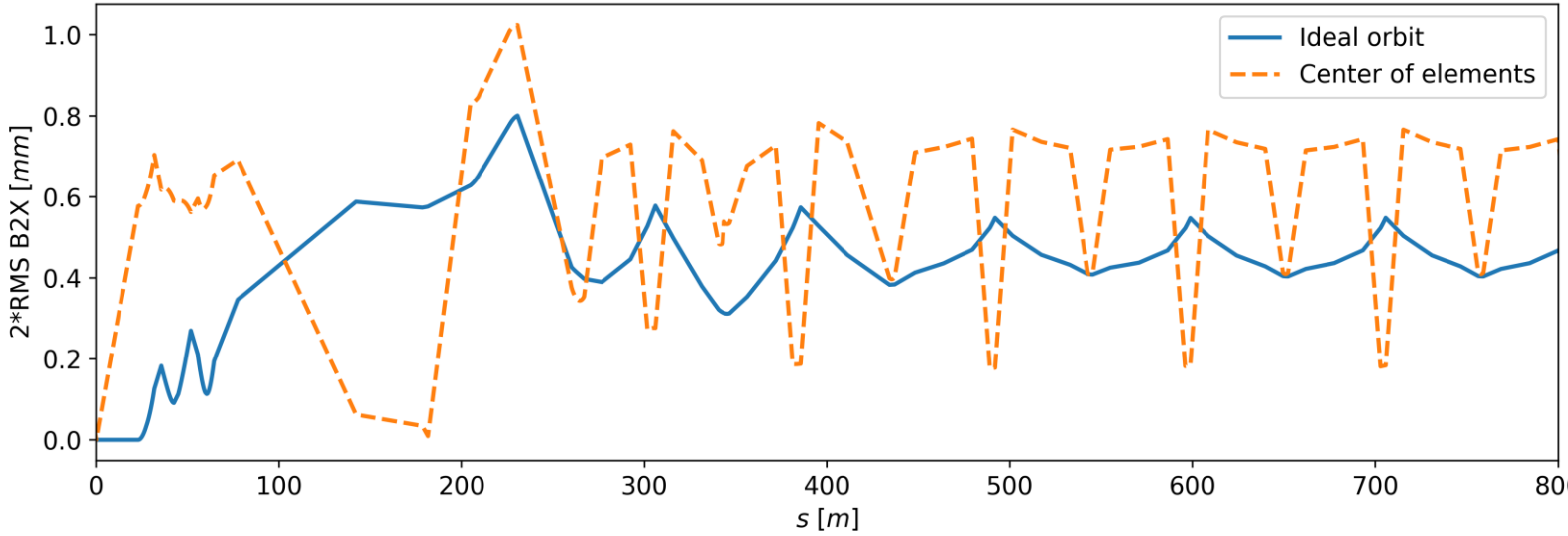
- **BPMs move with nearby magnet** + “strong” correction to get **beam at ideal IP**



Residual orbit B2X

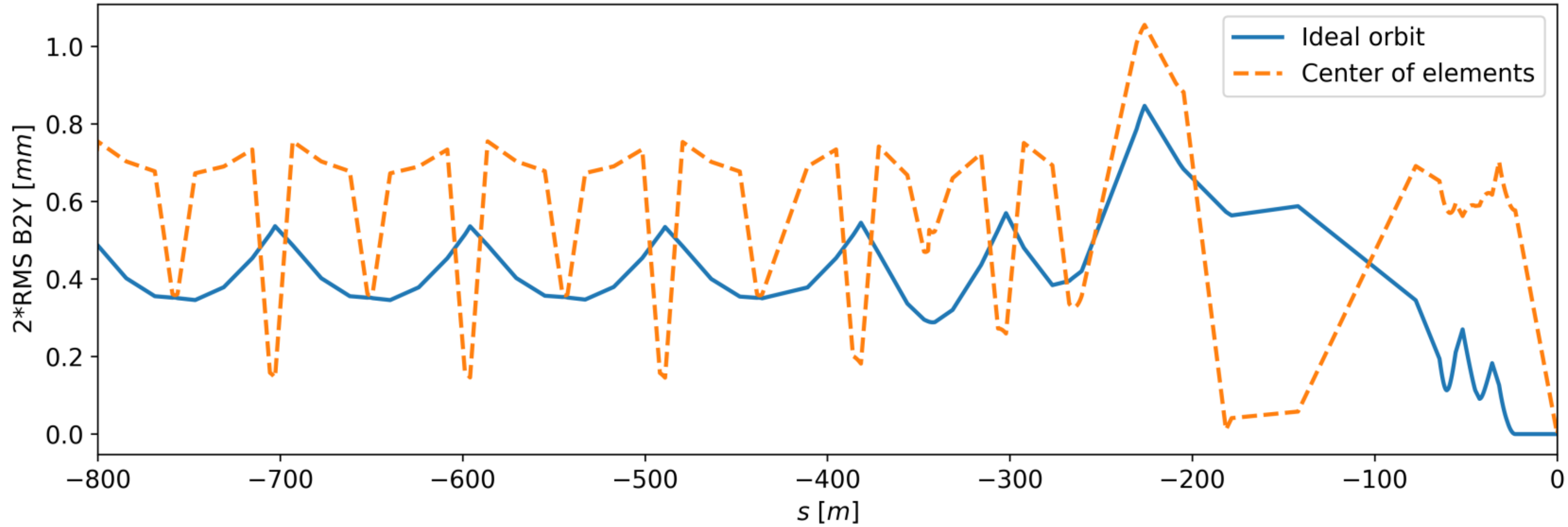
- **BPMs move with nearby magnet** + “strong” correction to get **beam at ideal IP**

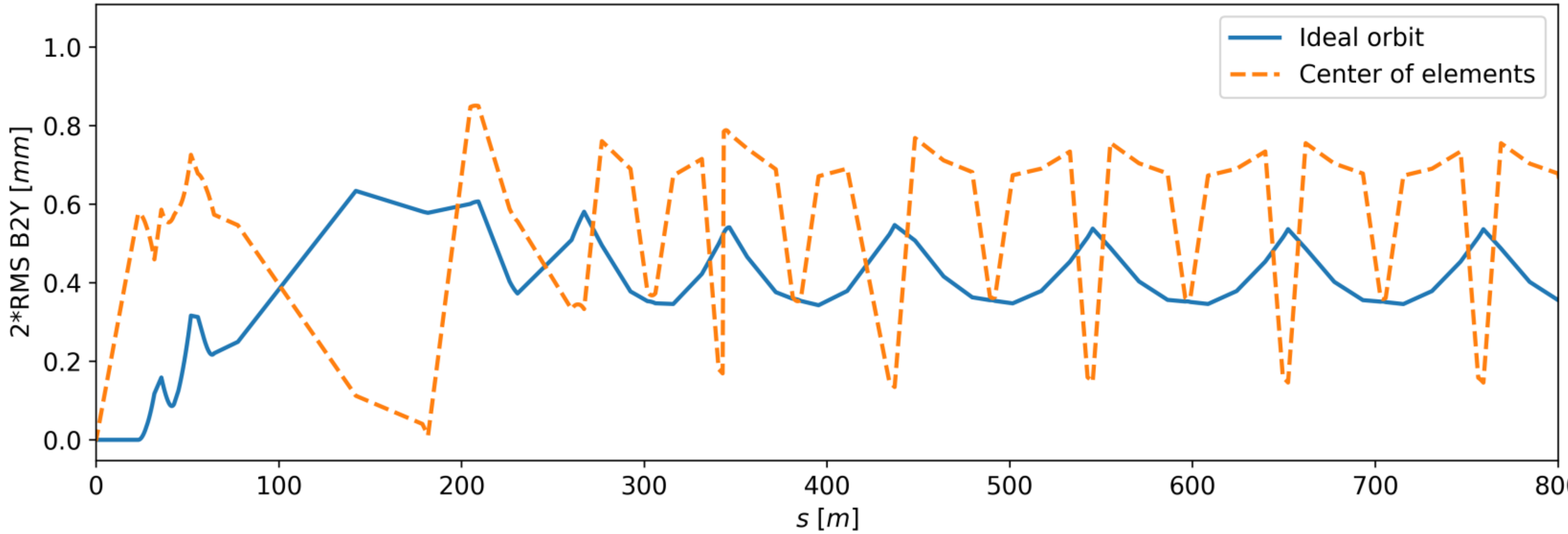




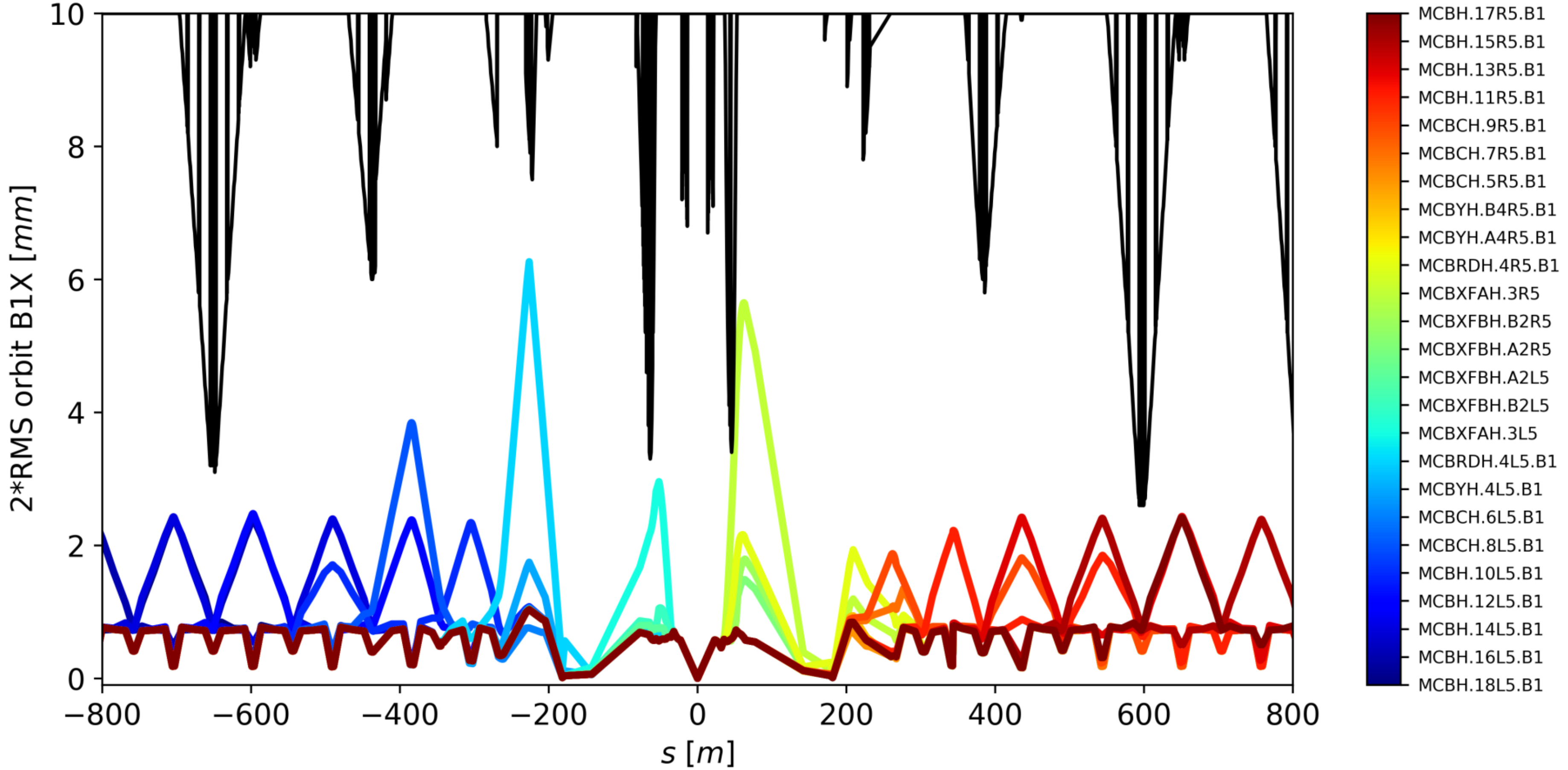
Residual orbit B2Y

- **BPMs move with nearby magnet** + "strong" correction to get **beam at ideal IP**

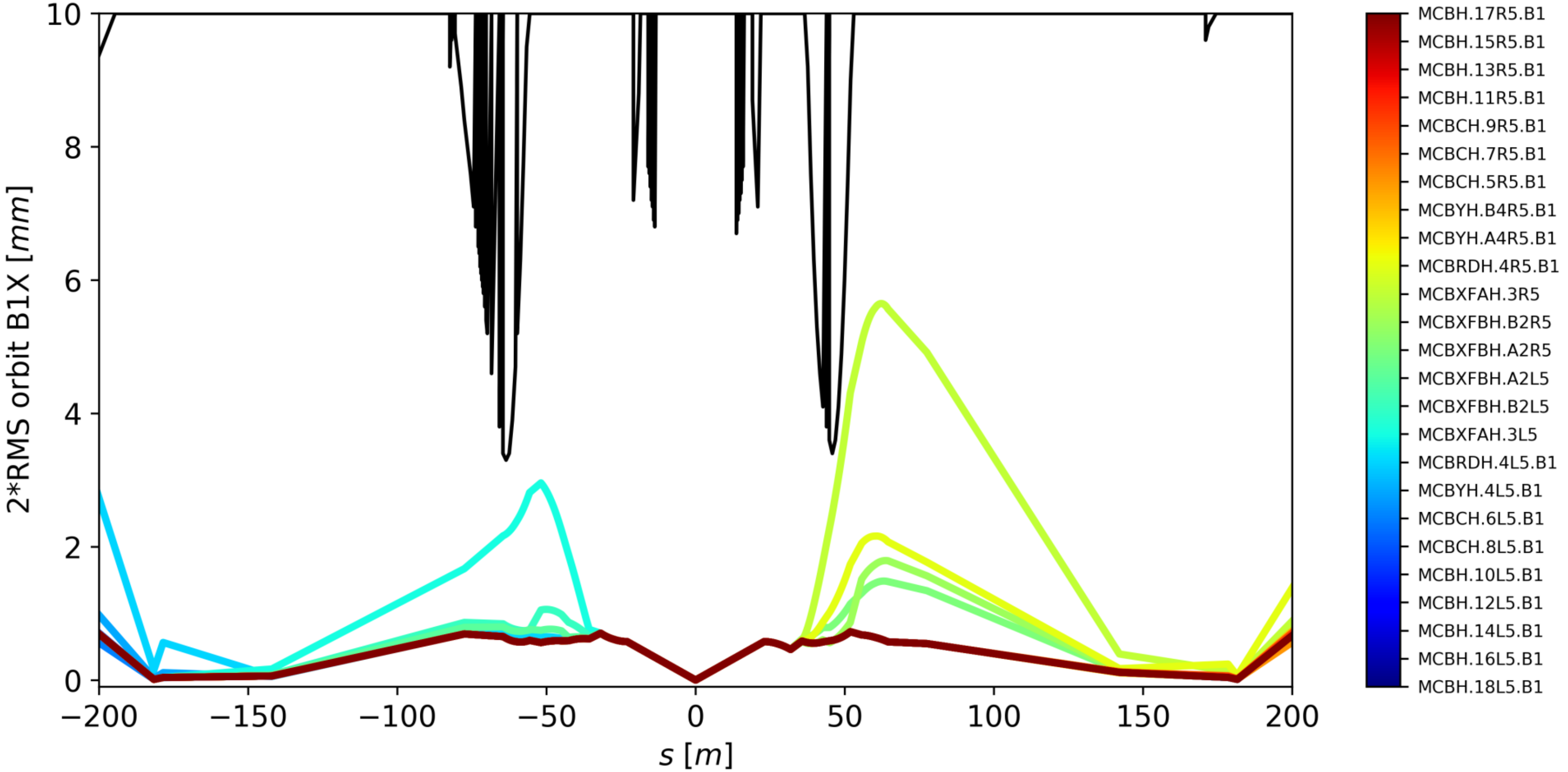




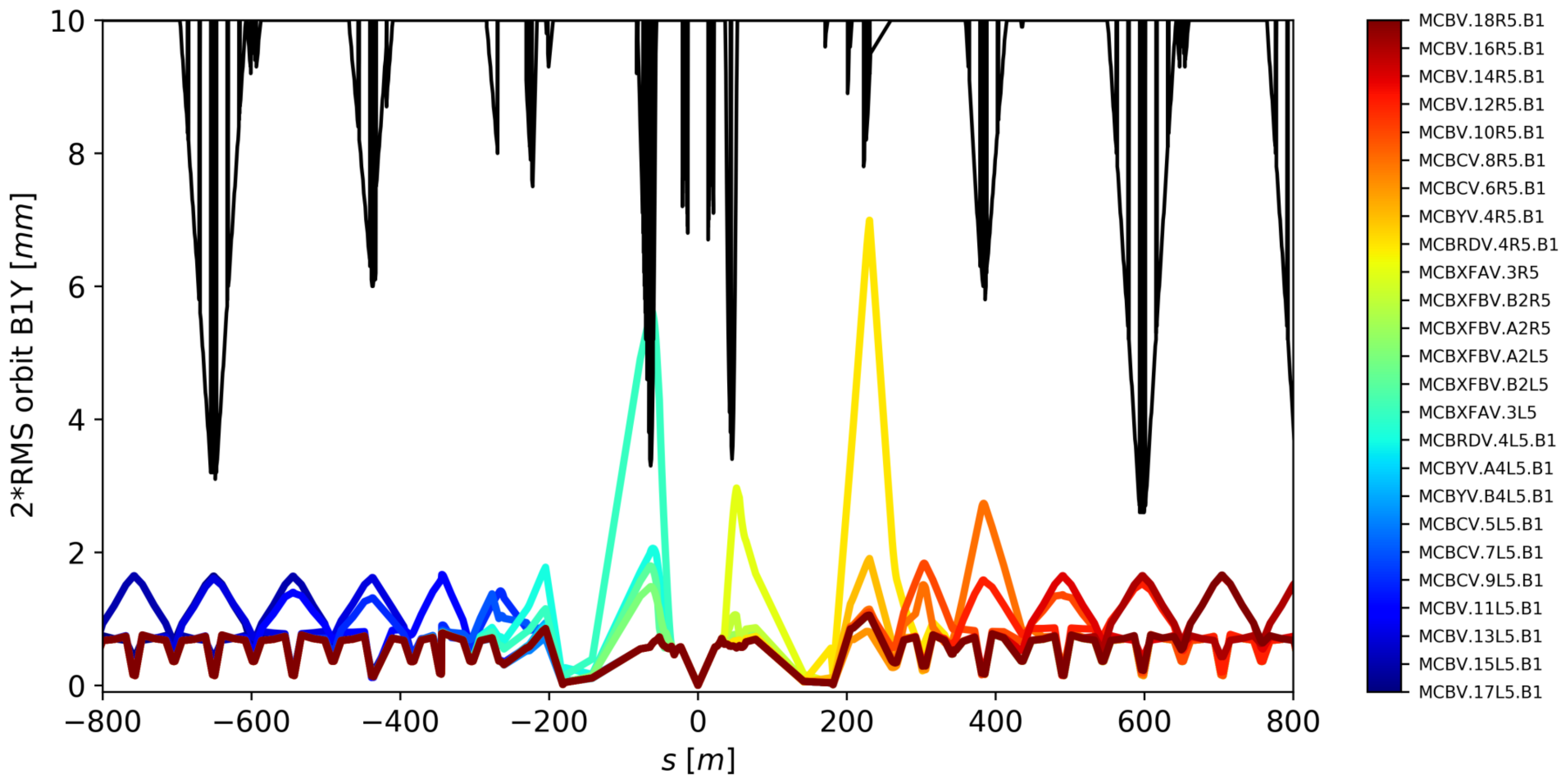
Failure scenario: B1X



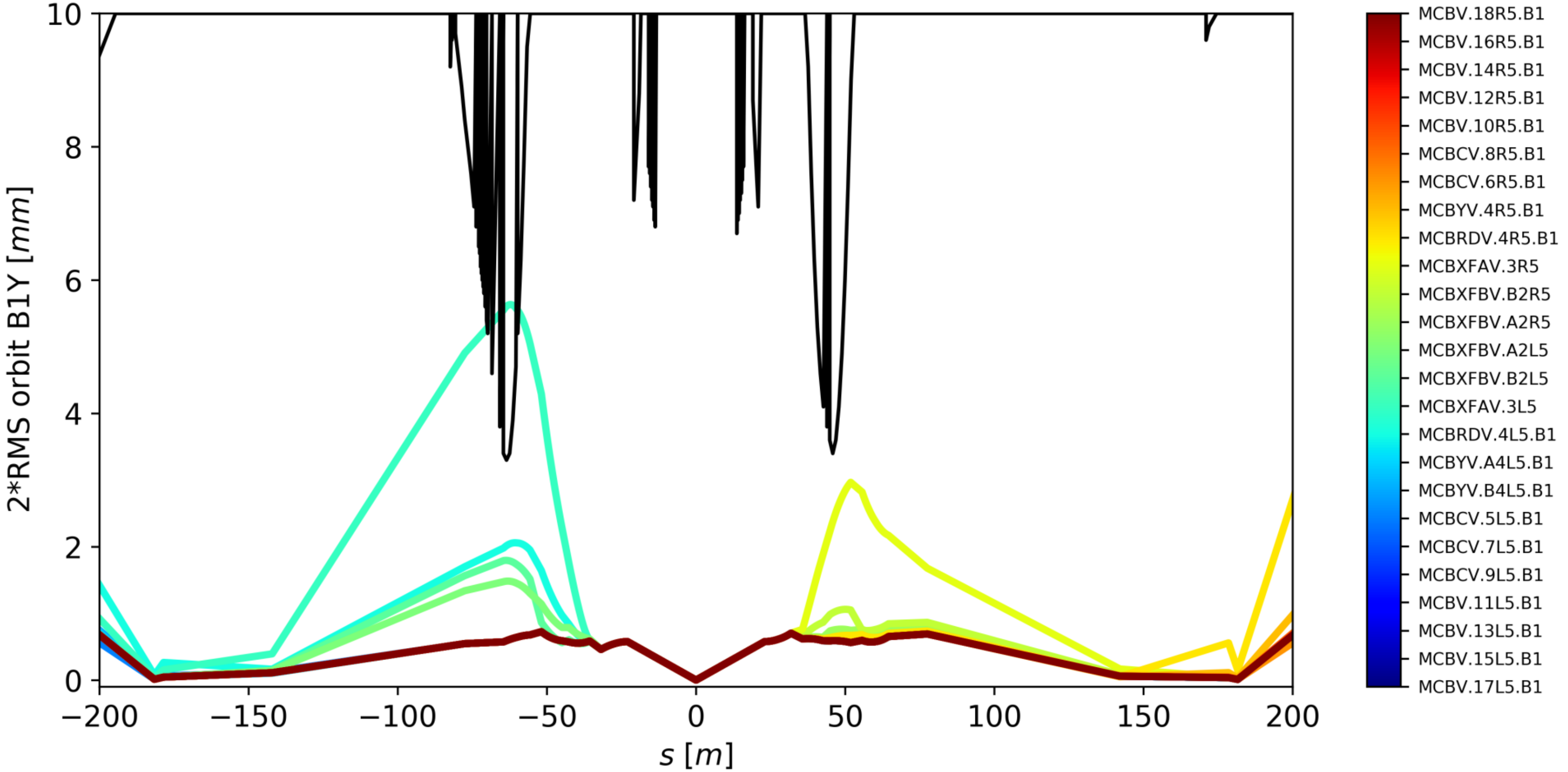
Failure scenario: B1X (zoomed)



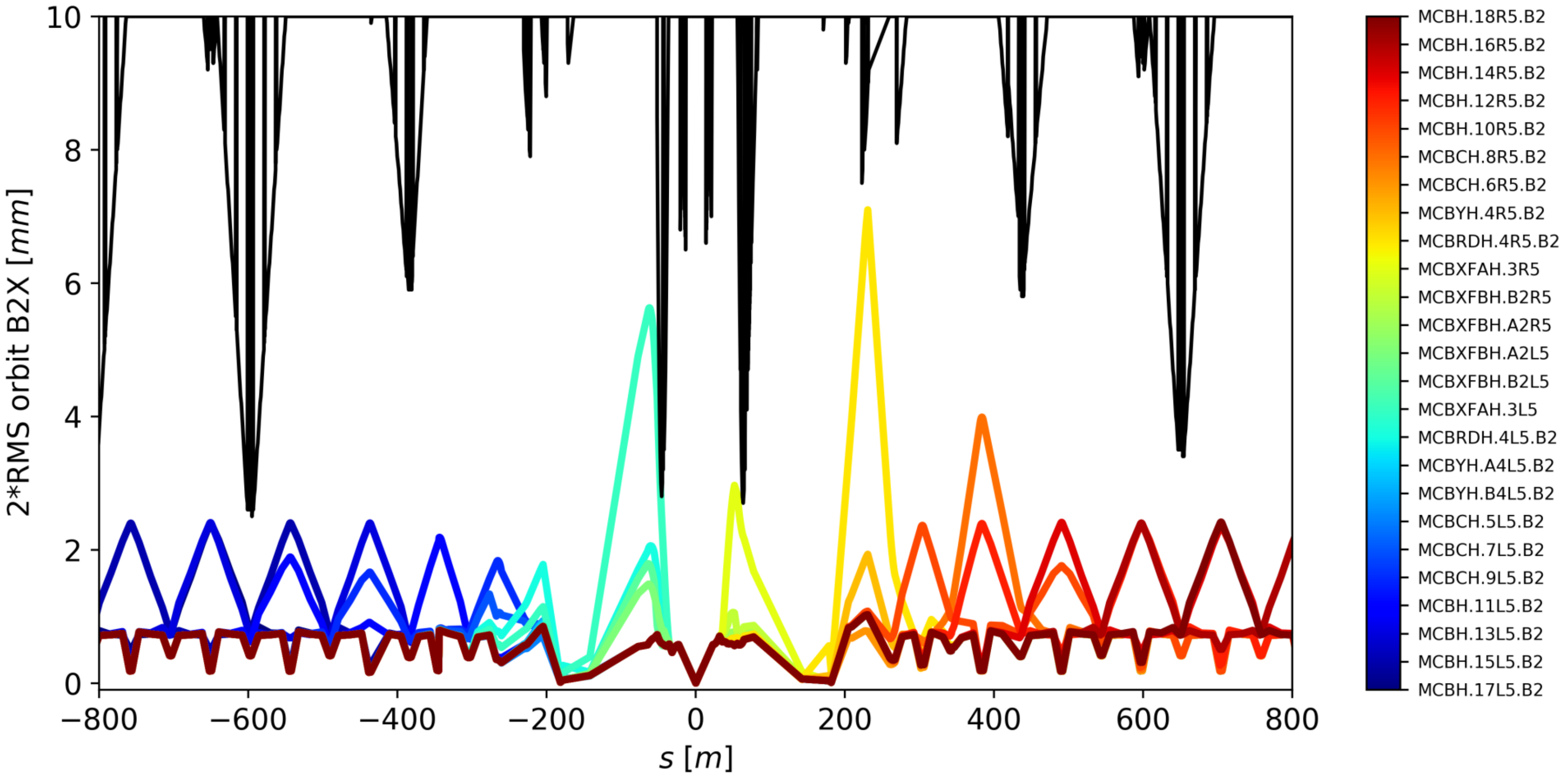
Failure scenario: B1Y



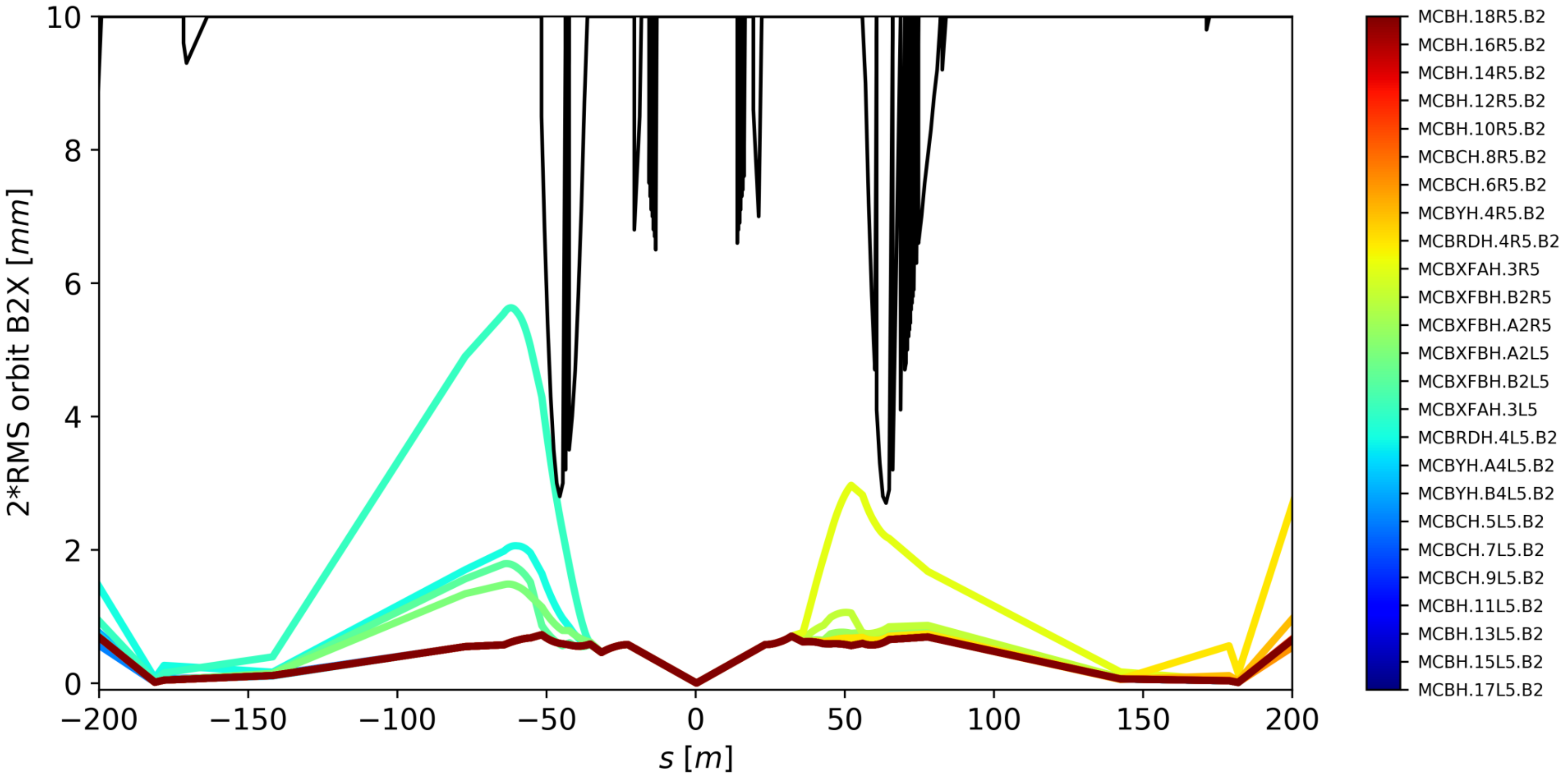
Failure scenario: B1Y



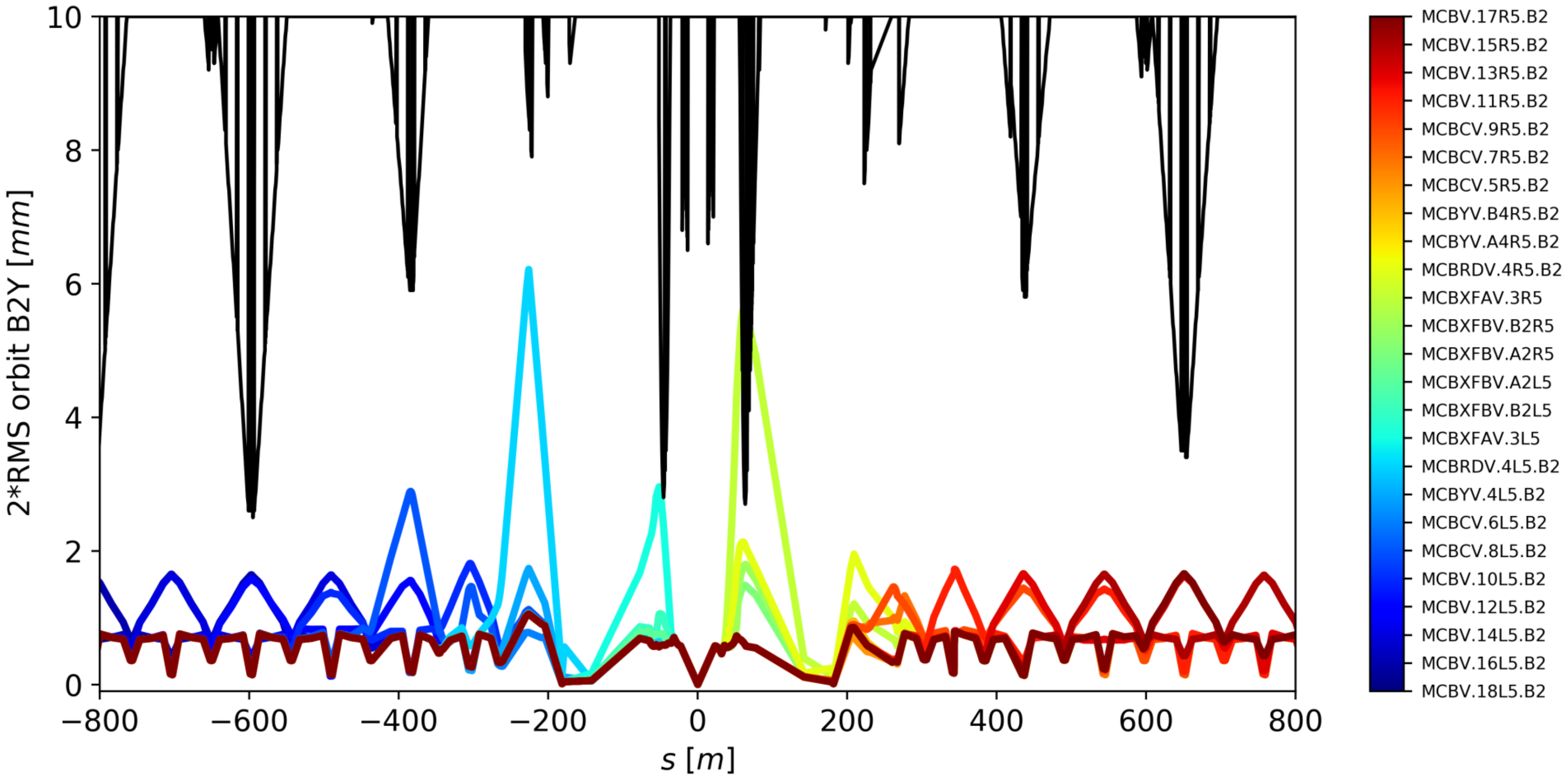
Failure scenario: B2X



Failure scenario: B2X



Failure scenario: B2Y



Failure scenario: B2Y (zoomed)