Collimator MD results

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Thanks to: S. Fartoukh, M. Solfaroli, R. Tomás, J. Wenninger, MD coordinators, LHC OP, OMC team

14th HL-LHC Collaboration Meeting, Genoa – 7th – 10th October 2024

Collimation MDs in 2024

- Proton studies:
  - Halo measurements (population, diffusion, removal)
    - P. Hermes, https://indico.cern.ch/event/1421594/contributions/5978493/
    - C.E. Montanari, https://indico.cern.ch/event/1421594/contributions/6017978/
  - B1 quench test with protons
    - Scheduled for MD5
  - Impedance and stability limits / models
    - L. Giacomel, https://indico.cern.ch/event/1421594/contributions/5979671/
    - X. Buffat, https://indico.cern.ch/event/1421594/contributions/6017980/
  - Crystal characterization and energy ramp
  - Study of Run4 commissioning scenarios
    - A. Donadon, https://indico.cern.ch/event/1421594/contributions/6017977/
  - New optics for the collimation insertions
- Ion MDs:
  - Crystal collimation quench test
  - Collimation with different crystal settings

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  - **New optics for the collimation insertions ← focus of this talk**
- Ion MDs:
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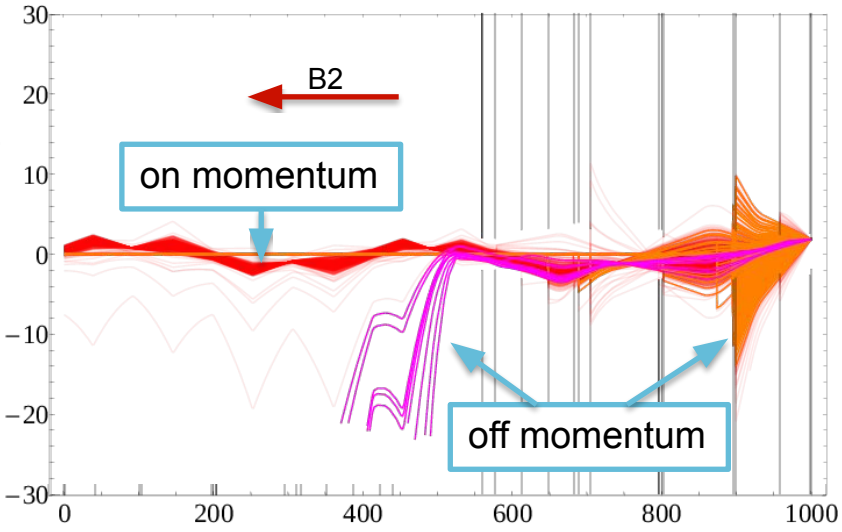
Why new collimation optics?

- HL-LHC beam intensity and brightness produces significant challenges:
  - Beam losses in IR7 DS could cause quenches
  - Impedance can cause instabilities
- Beam losses:
  - ~~Mitigate them using TCLDs installed between two 11T dipoles~~
    - Alternative strategy for risk mitigation
- Impedance:
  - Low-impedance collimators introduced (LS2, LS3),
  - Relaxed collimator settings
  - Further reduction of impedance
    - Baseline ok for impedance, but some uncertainty
    - Crab cavity impedance a potential issue
    - Provides more freedom for collimator settings (keep ”tight” TDR settings)
- Strategy:
  - IR7: Use new optics with improved cleaning and impedance
    - Keep collimator settings in sigma
  - IR3: relax collimator settings, or use new optics
    - For impedance, **only if needed**
    - HW upgrade potential alternative

New IR7 optics[1,2]

Extensive campaign:

- Source of DS losses
- Impedance from individual collimators
- Analytical studies
- Optimization and matching in MADX / XSuite
- Tracking and beam loss simulations



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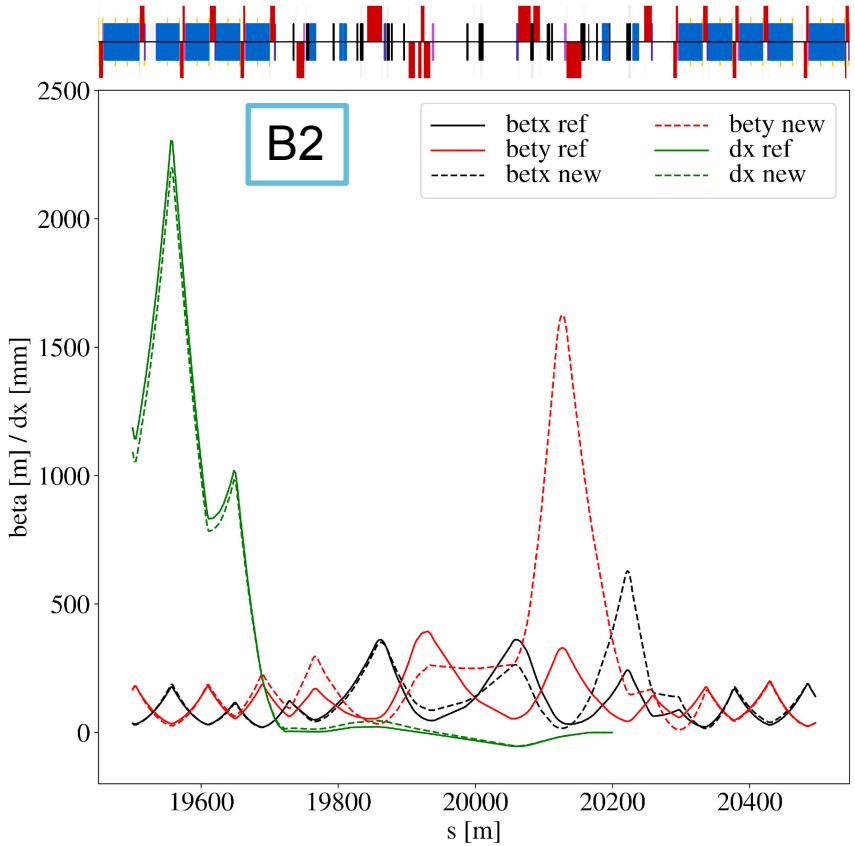

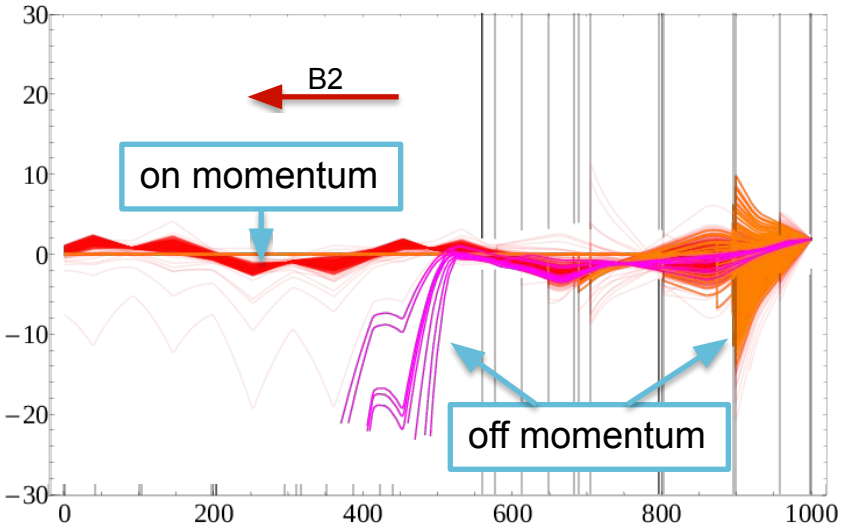

- Increase collimator beta functions
  - Larger normalized kicks on scattered particles → more intercepted by secondary collimators
  - Larger physical gaps → lower impedance
- Increase single pass dispersion from TCP
  - Increased through optics rematch
  - Orbit bump also considered for testing
  - Off-momentum particles scattered by TCP more likely intercepted by collimators

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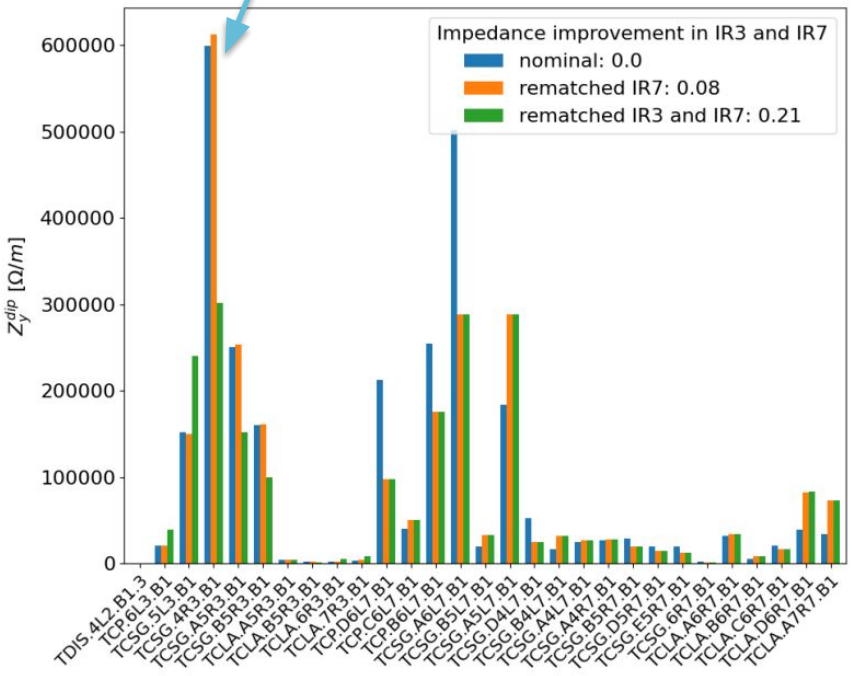
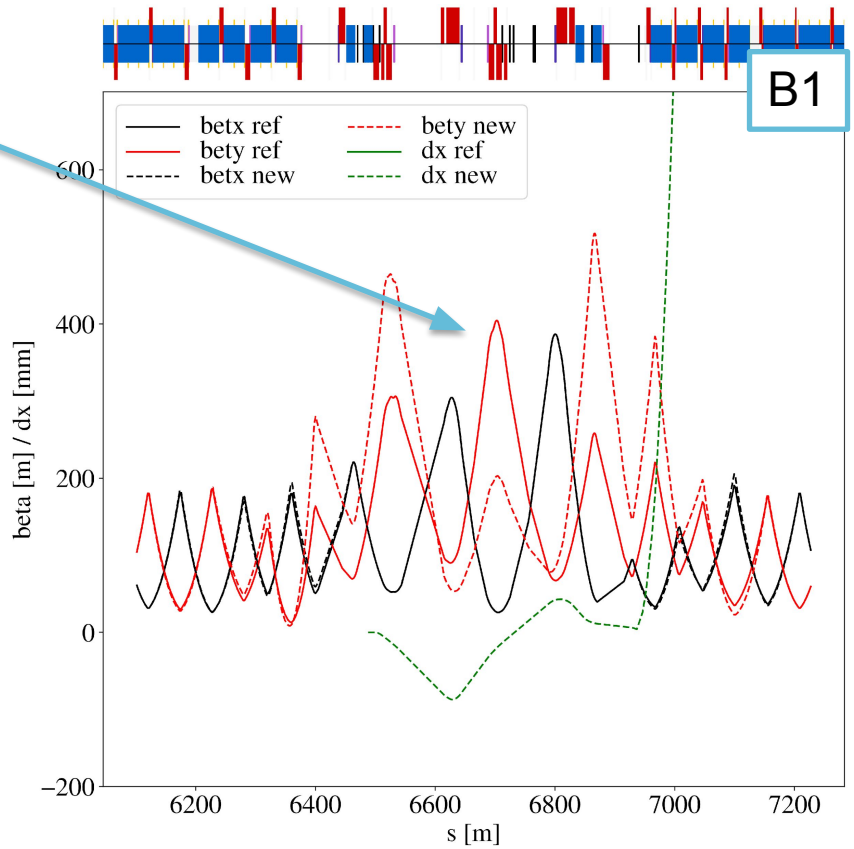
New IR3 optics

- With IR7 mitigated, one collimator in IR3 biggest contributor to impedance
  - small horizontal gap
  - large vertical beta function



L. Giacomel



- IR3 mostly horizontal collimators, and vertical impedance scales with bety
- Idea: reduce problematic vertical beta function, while keeping horizontal plane unchanged

Variants considered and tested in MD

- MD7203: New IR7 optics for improved cleaning and impedance
  - Proposed by WP5, 3 years ago as proof of concept
  - Only IR7 changed
  - FT only, real cycle requires combined ramp & desqueeze
  - Scheduled in 2022 and 2023, but suffered from machine availability
  - 2024-05-16 – successfully tested main objectives!

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  - Proposed by WP2
  - New optics whole machine, integrated IR3 and IR7 optics in cycle
  - Feasibility assessment of IR3 / IR7 desqueeze during ramp
  - 2024-06-06 / 2024-06-08 / 2024-06-24 / 2024-09-29

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- MD11843: Collimation performance with HL-LHC settings
  - Comparison of 2024 collimator settings and HL-LHC tight and relaxed
  - Comparison of 2024 optics, IR7 squeeze only and complete HL cycle optics
  - 2024-09-29

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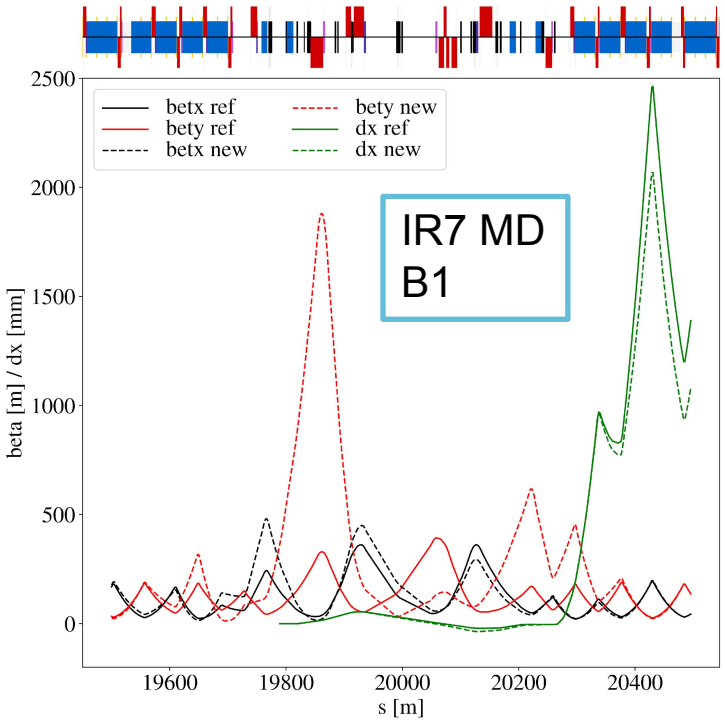
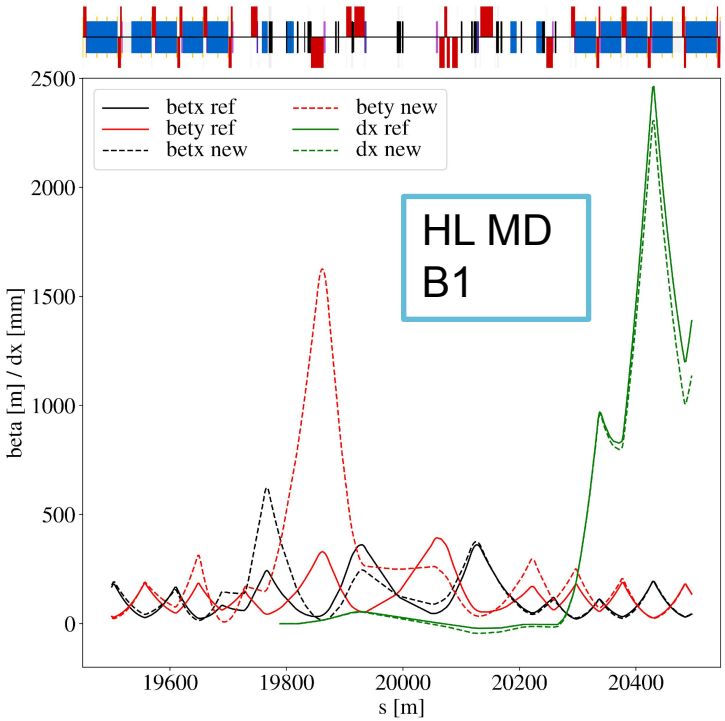
Optics differences

- IR7 MD: first tested version of new optics
- HL MD: multiple improvements in IR7
  - Larger TCP beta functions
  - Improved dispersion
  - Smaller peak beta function
  - Impedance optimized for LS3 collimators
  - Performance limited by max current in some trim quads

(e.g. MQTL8.L7B1,
200 A vs nom. 550 A)





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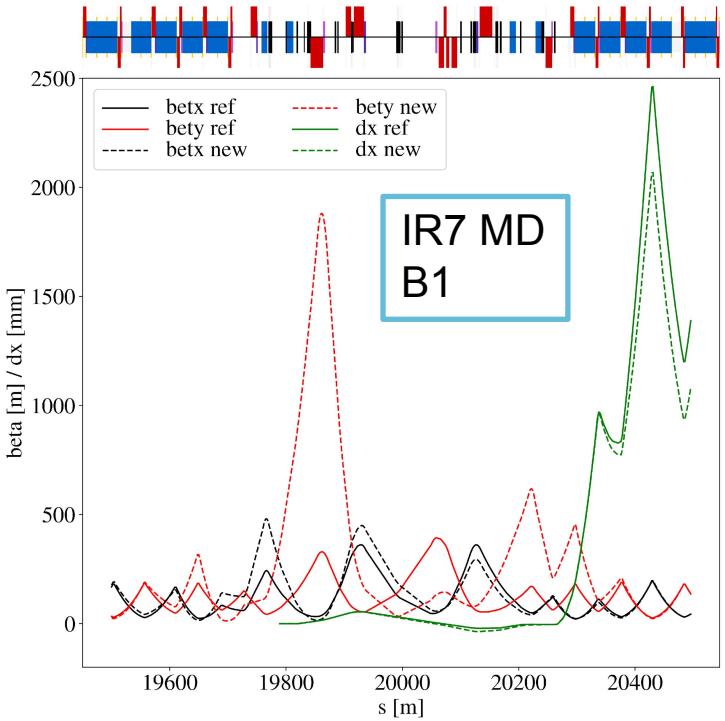
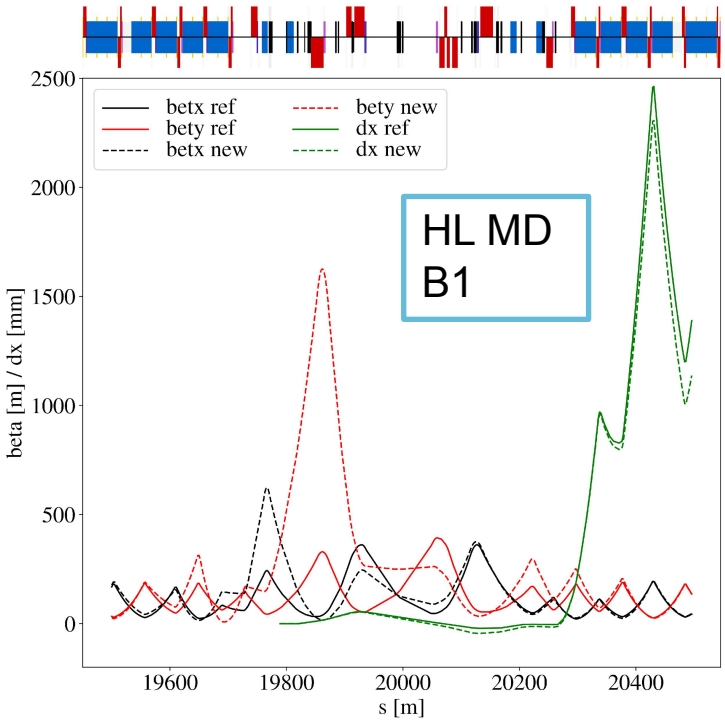
Both could be adapted to normal RunIII ramp and used operationally

(e.g. MQTL8.L7B1, 200 A vs nom. 550 A)





MD results

Loss maps

Betatron:

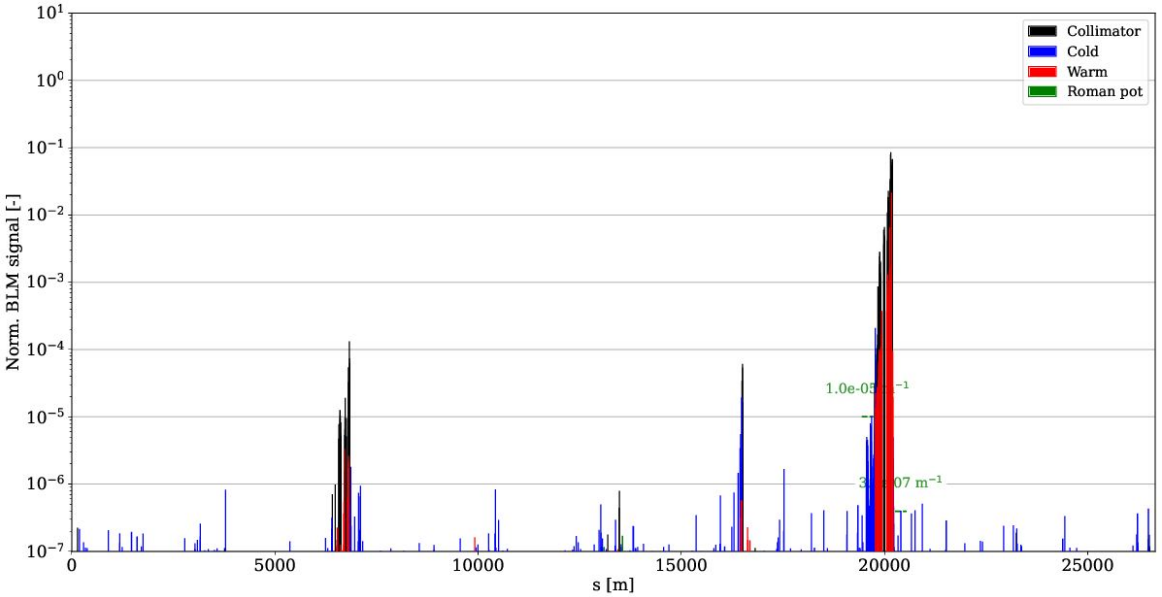
- During combined ramp & squeeze, FT and 41 cm

Off momentum:

- At inj and FT

Asynchronous dump:

- Next MD...



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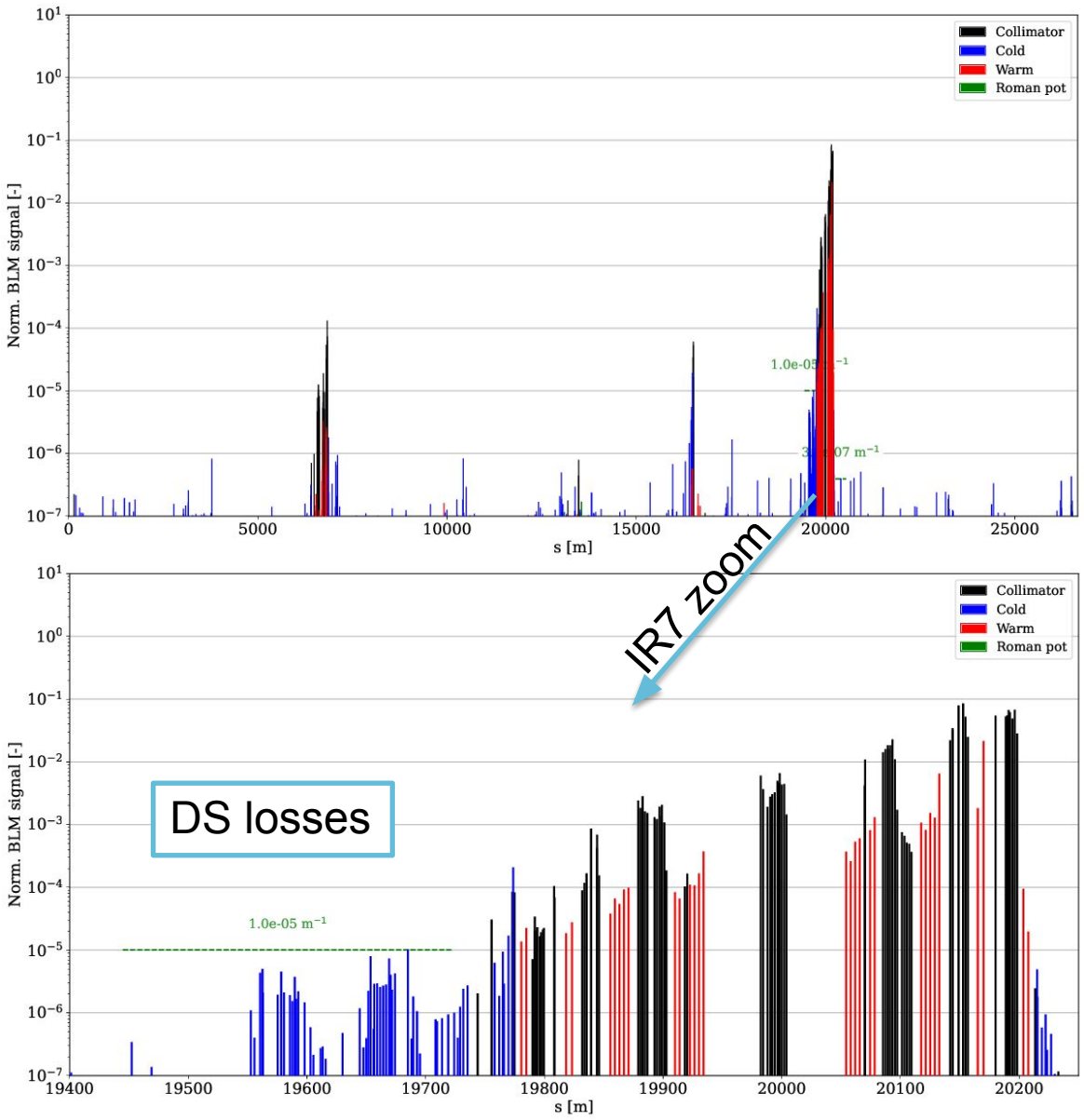

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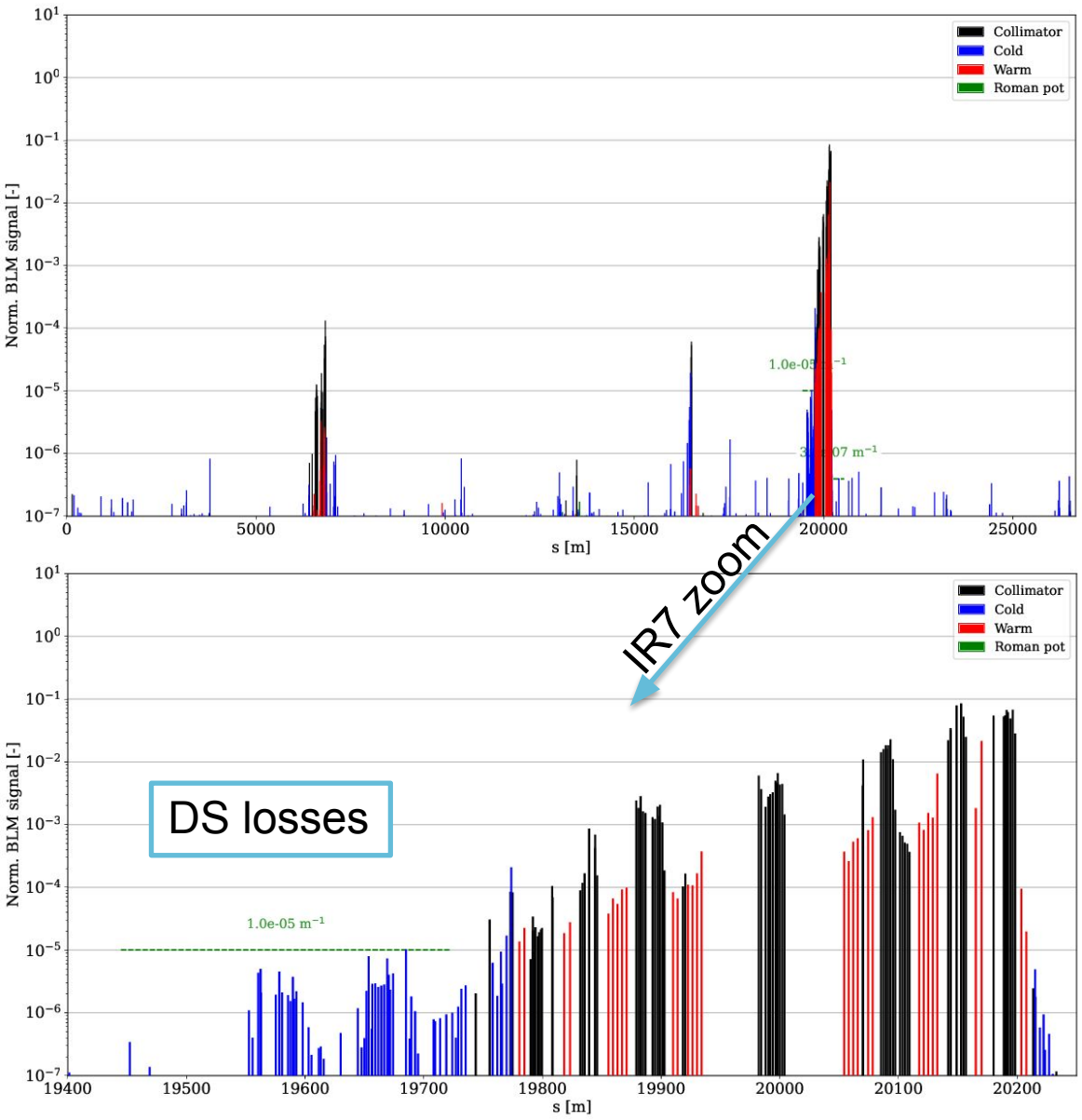
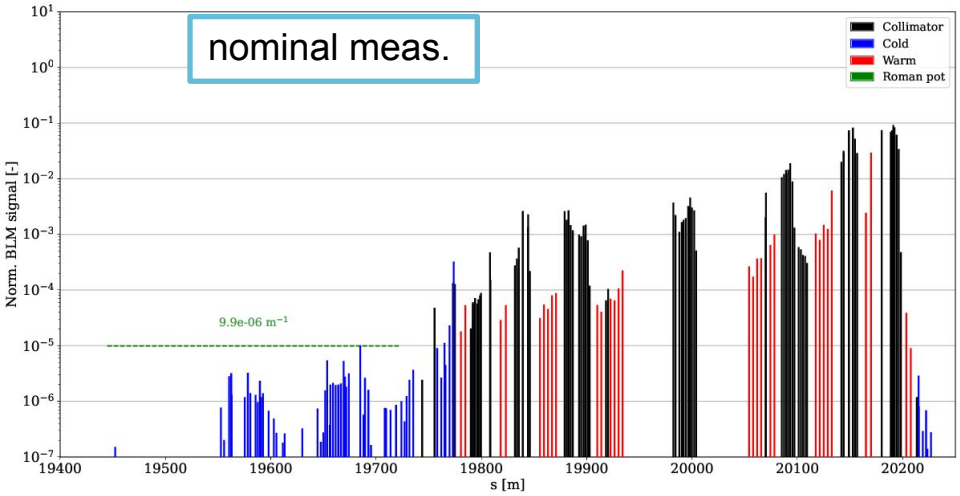
Observables:

- Collimator hierarchy
- DS leakage
- TCT losses
- IR3 / IR7 balance
- No unexplained spikes



B2H losses (FT – HL MD)



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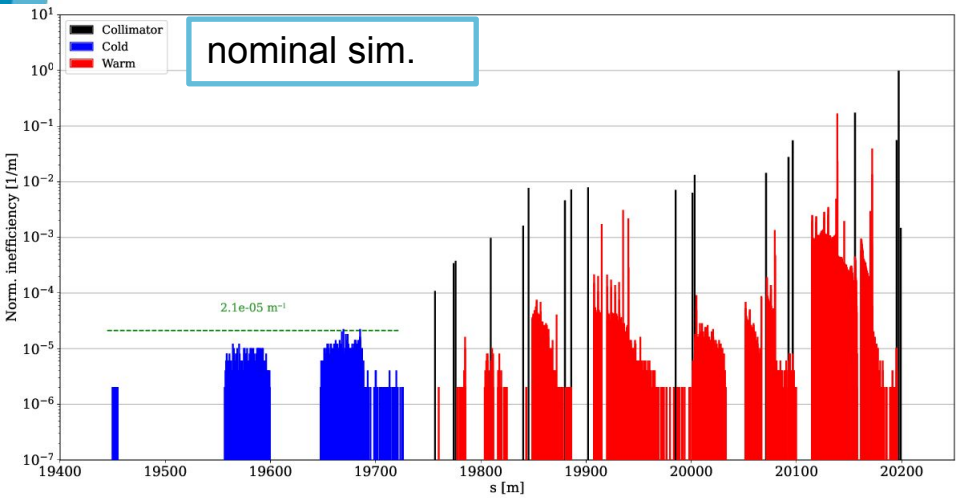

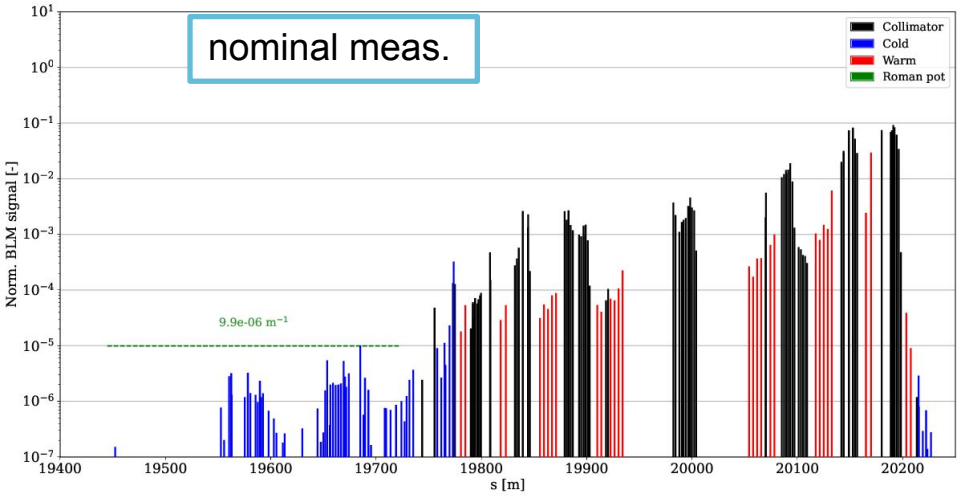

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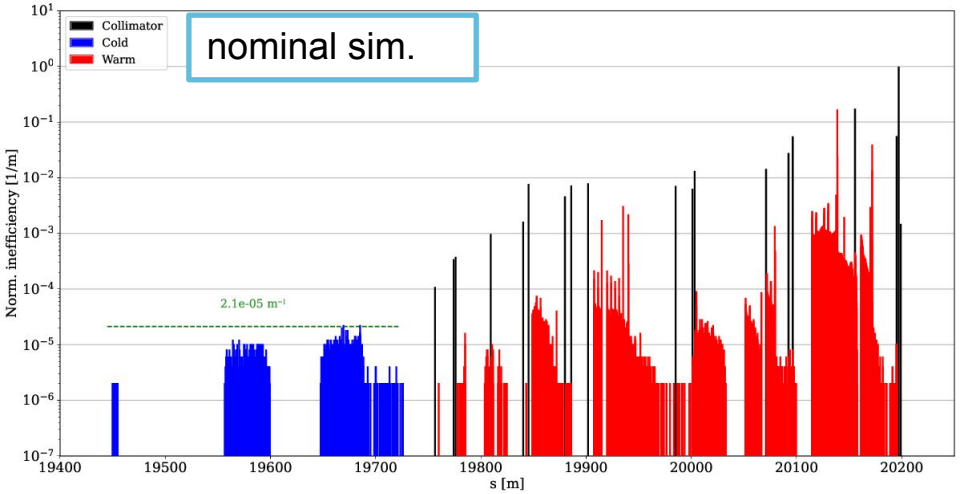
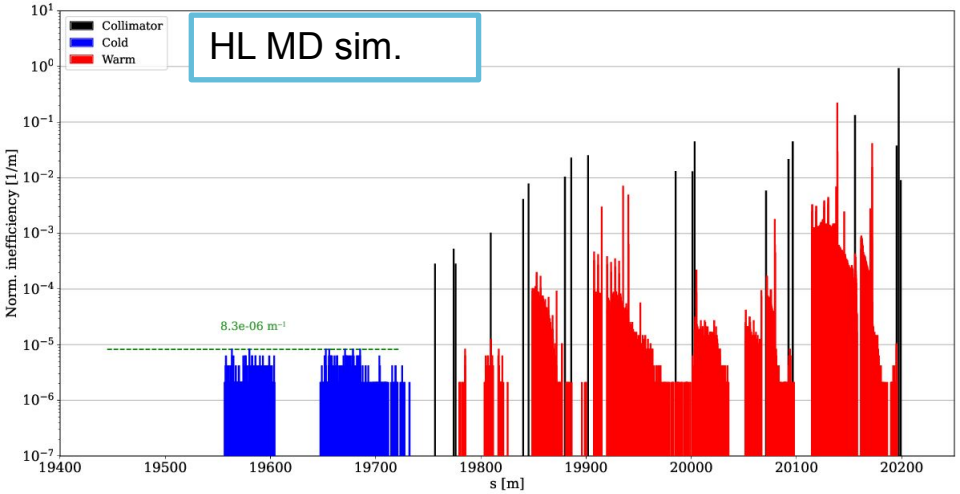
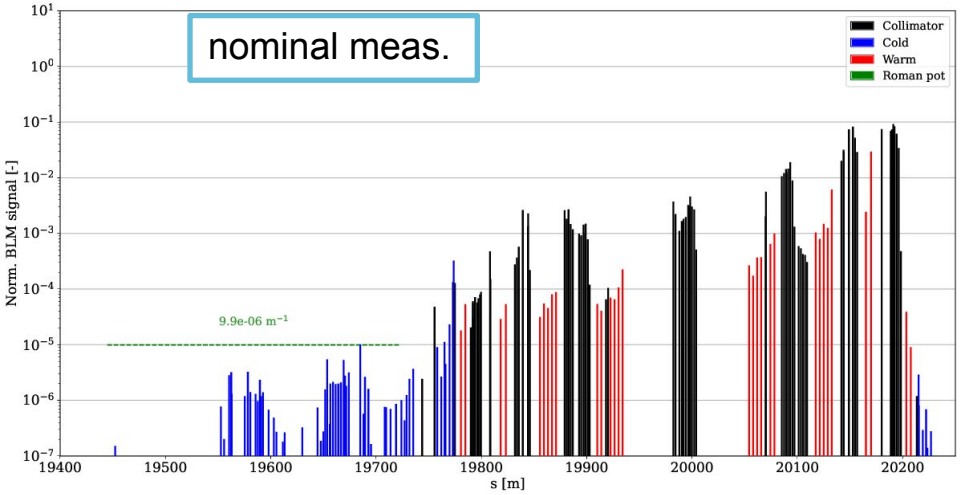
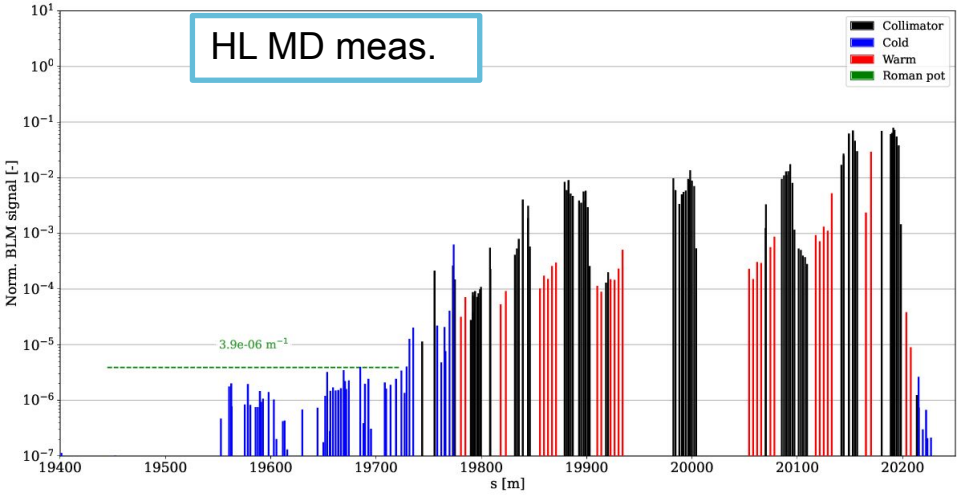
- Simulated 61 % improvement – measured 61 % *(σ=7.4 %)*









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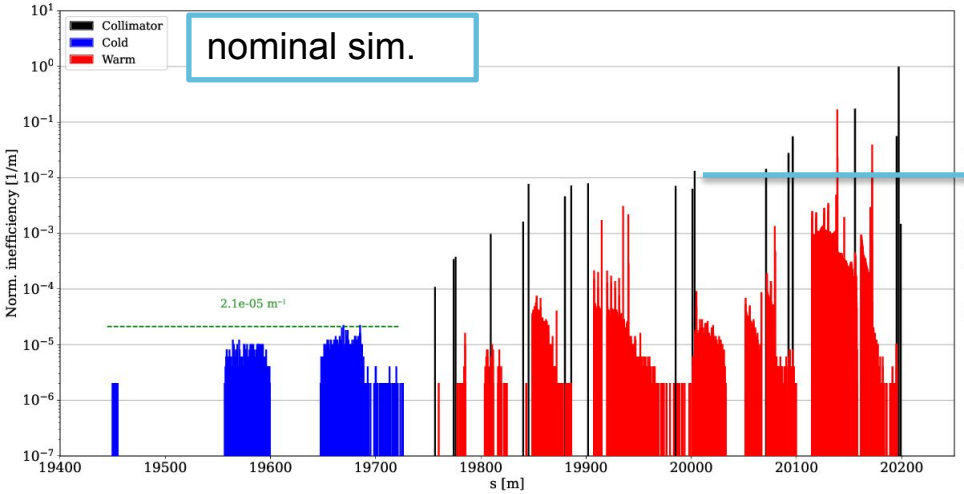
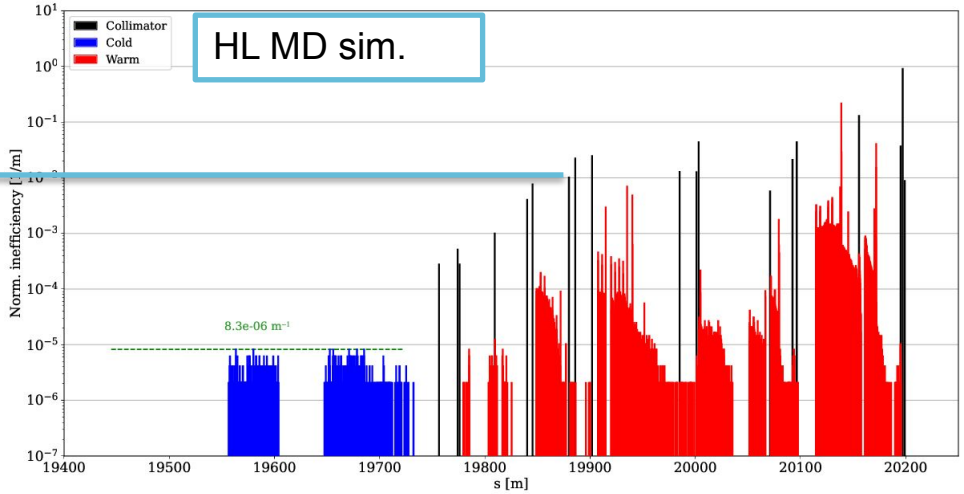
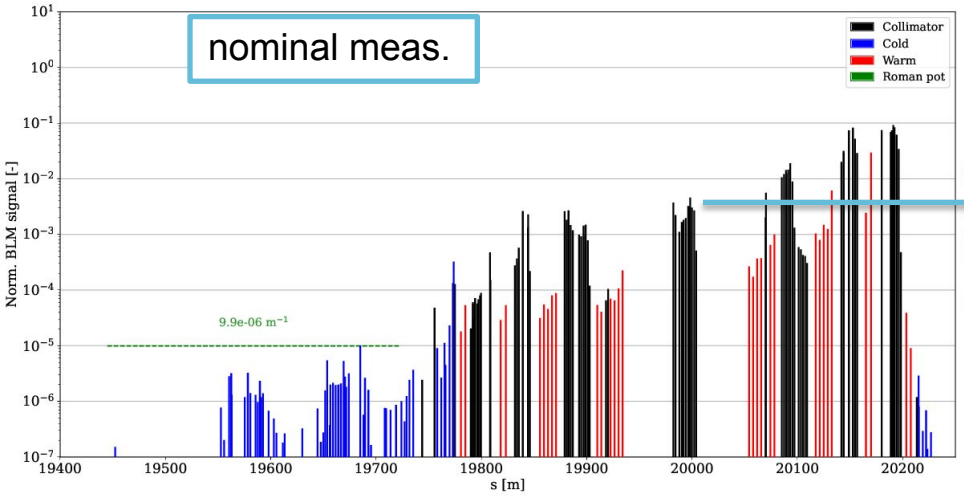
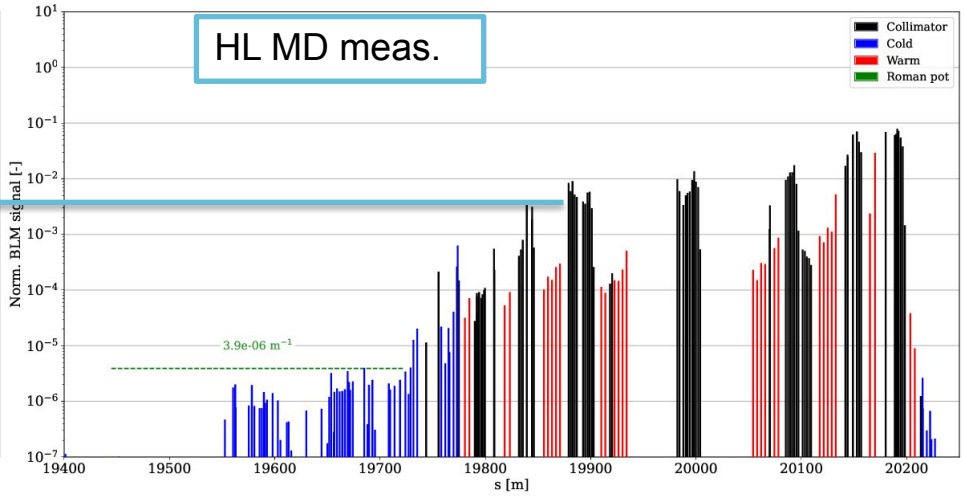
- Secondary stages catch more losses – less leakage to DS



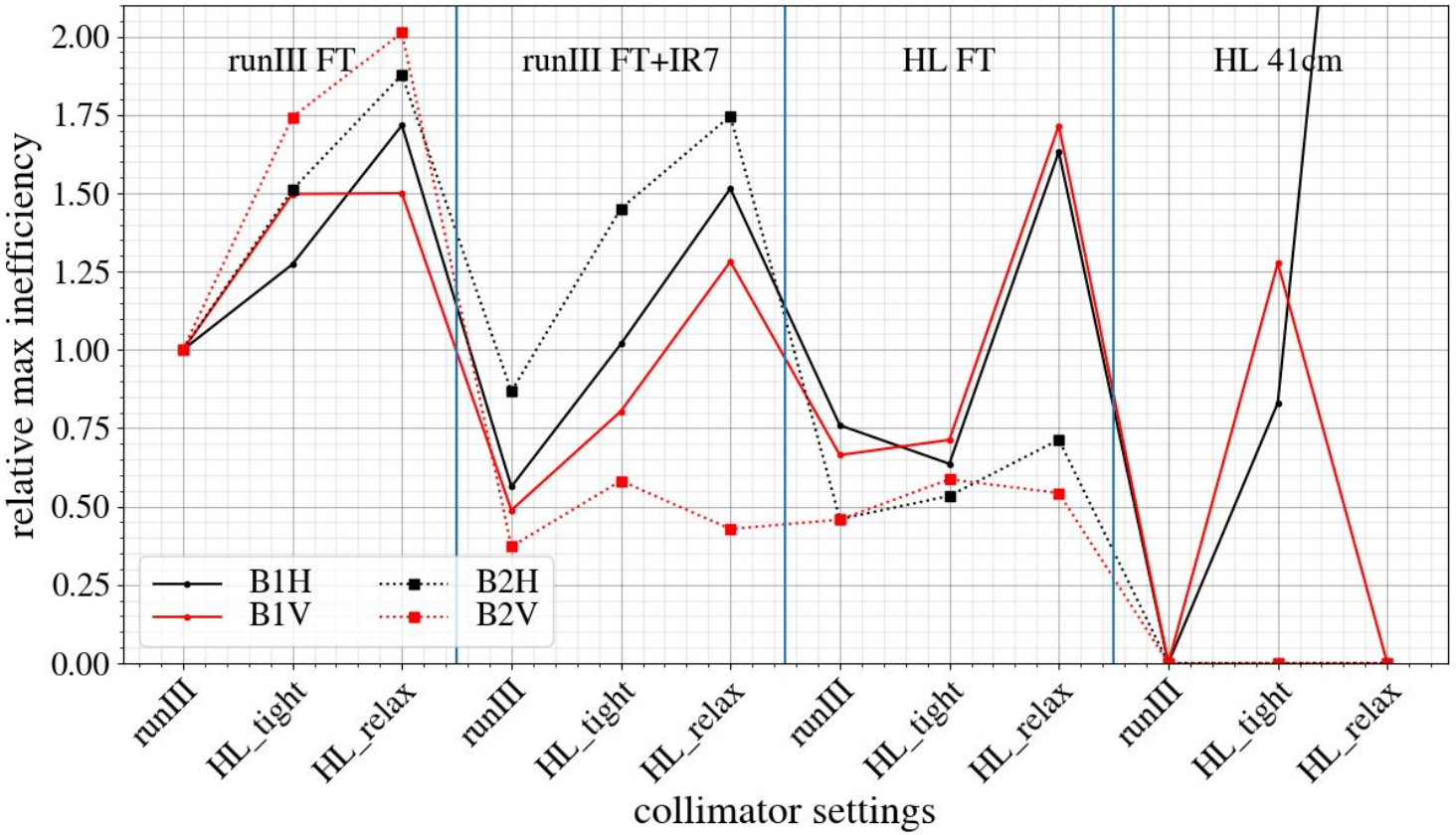






Summary of DS betatron cleaning

- Significant worsening with relaxed settings (estimate only ~7 % worse than tight)
- Optics at HL 41 cm not corrected, and TCTs not aligned, loss maps not reliable
- In general, significant improvement due to new optics!
- Detailed analysis of last MD / collimator settings by **A. Donadon** ongoing*



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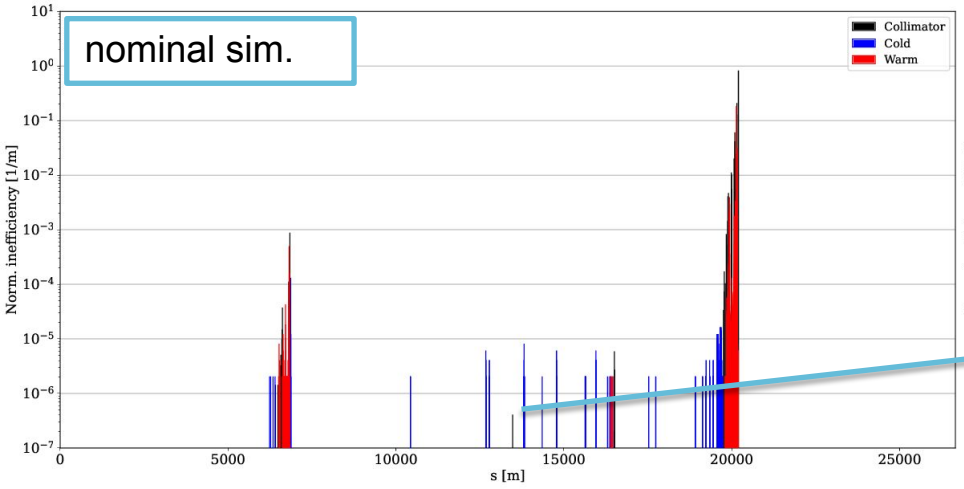
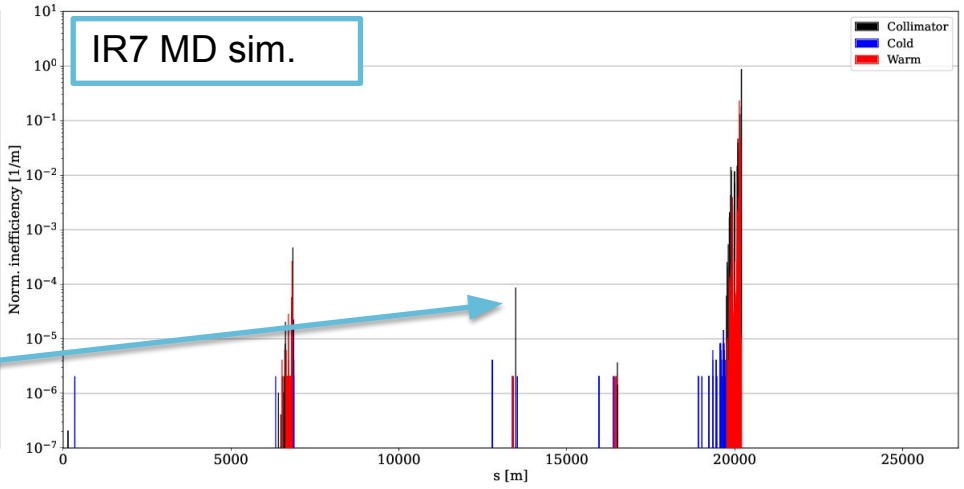
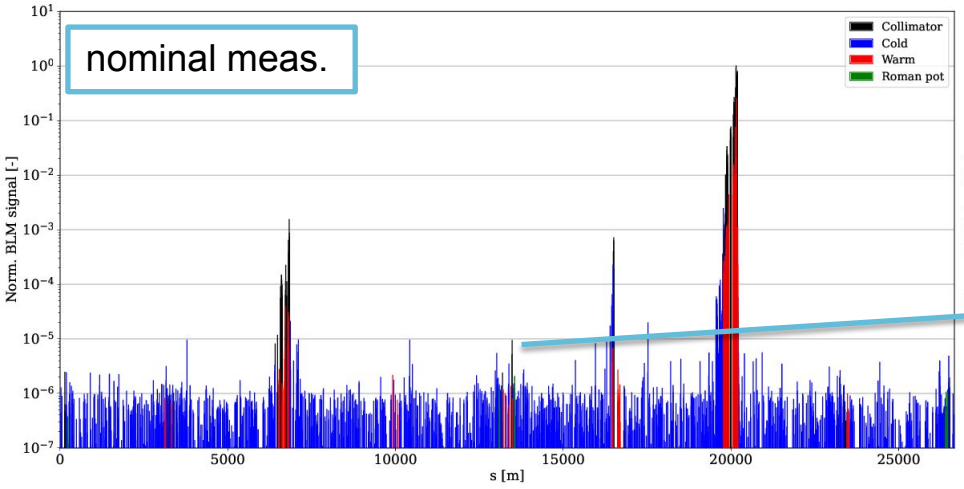
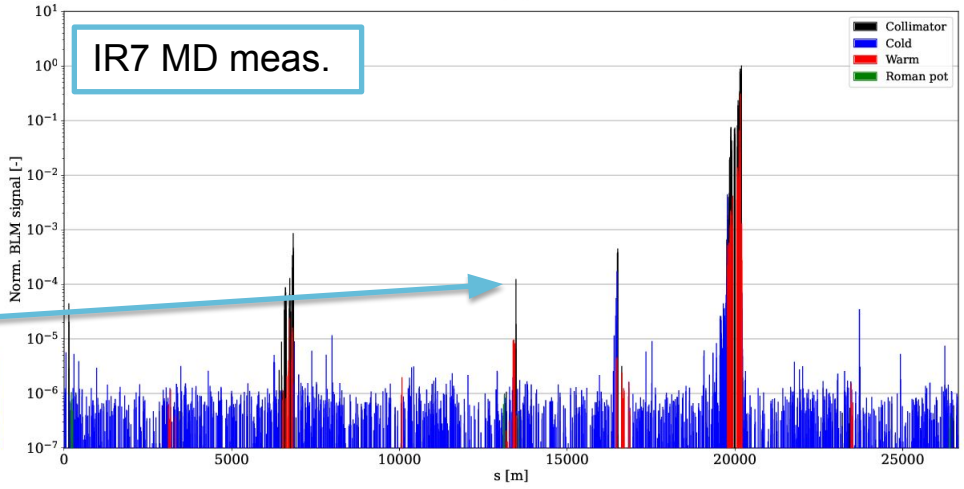
TCT losses – B2V

- Increase of TCT losses
- TCT power load and detector background should be evaluated
- Can be mitigated with phase advance from TCP to TCT
- n.b. TCTs at 18 sigma, go to 8.5 sigma during levelling



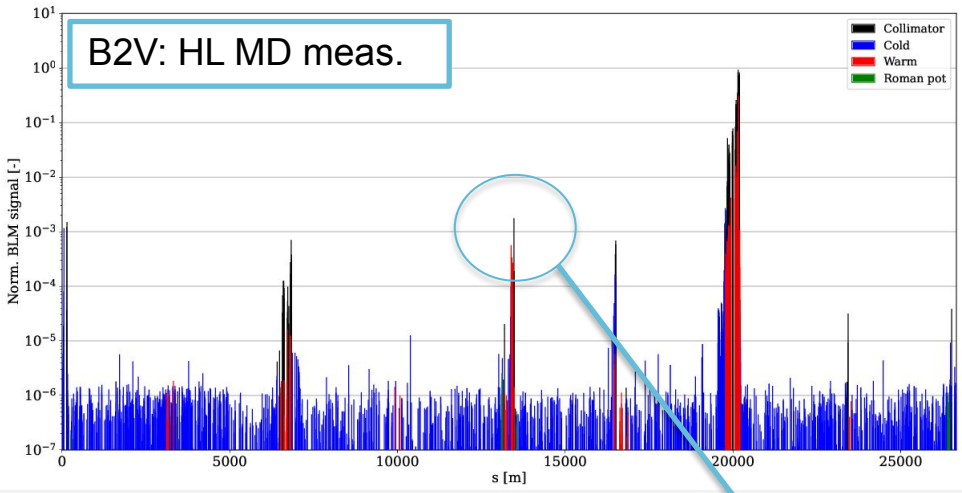


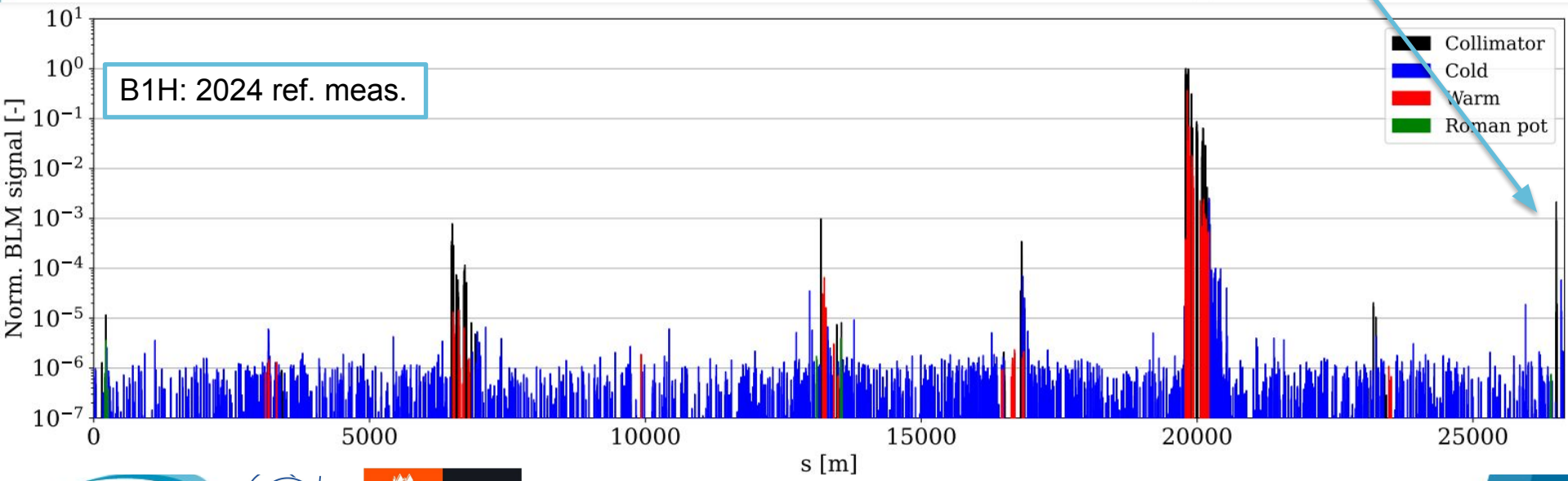




Tight TCT settings

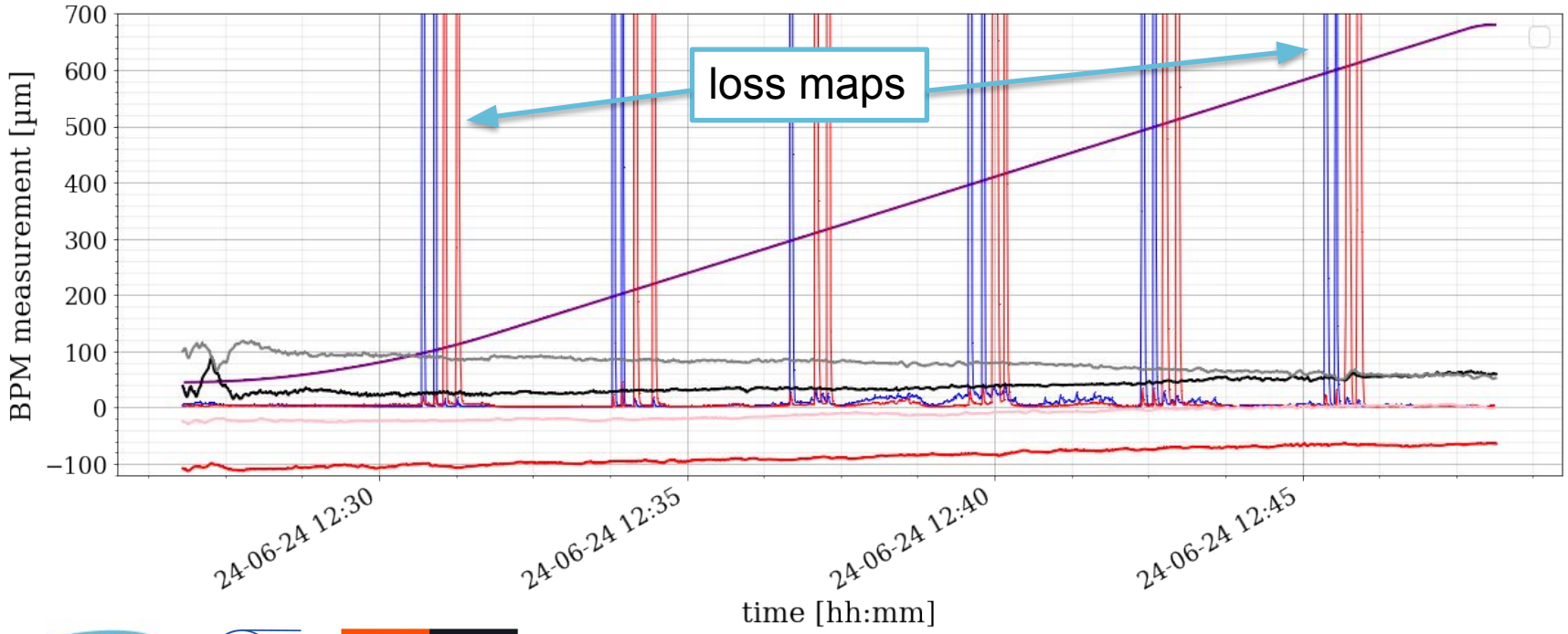
- Worst TCT losses in 2024 operation IR1 for B1H
- Similar to HL MD optics
  - Only B2 measurements with tight TCT
- Phase advance not yet optimized in the MD optics
- In HL, TCTs in cell 6 as well





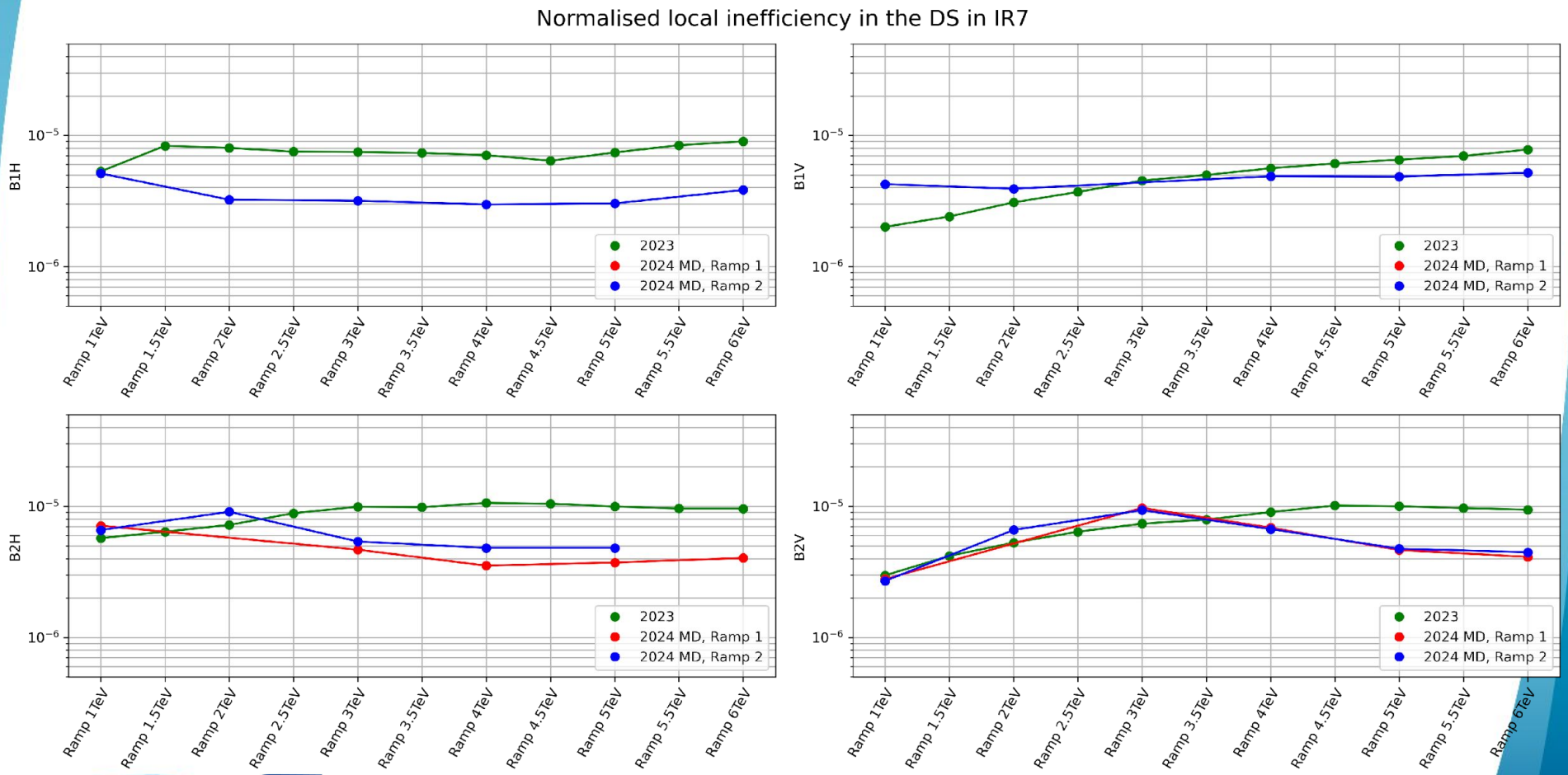
Losses during ramp

- Changing optics in IR7 during ramp not done before
  - Spurious loss spikes at collimators?
- Ramp with tight settings and single indiv:
  - Orbit well controlled and optics corrected
  - Similar lifetime to normal ramps
  - No significant loss spikes noted
- Follow-up with trains required for further validation



Cleaning during ramp

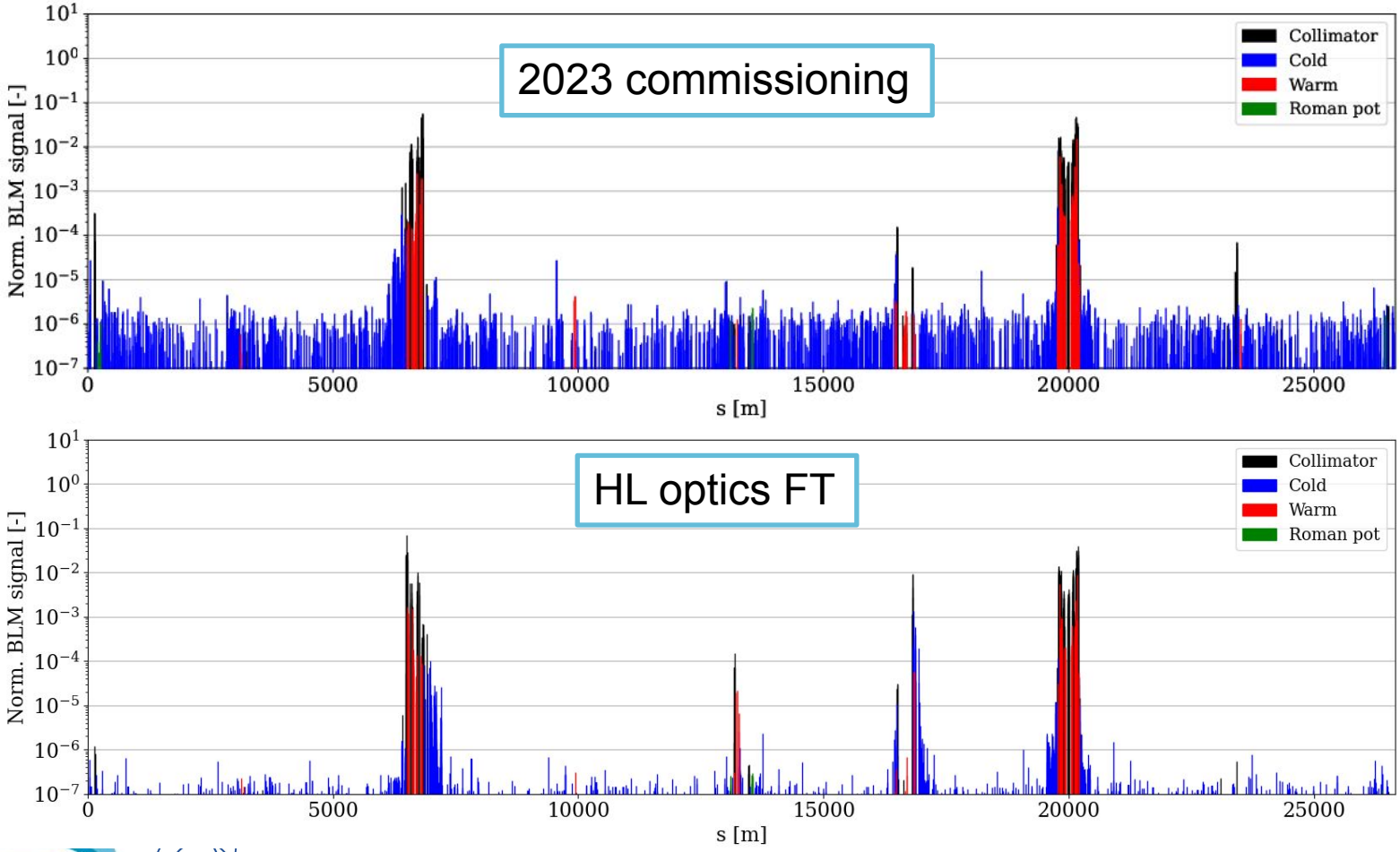
- No issues observed in betatron loss maps
- DS cleaning starts improving around 3 TeV as IR7 squeeze kicks in



N. Triantafyllou

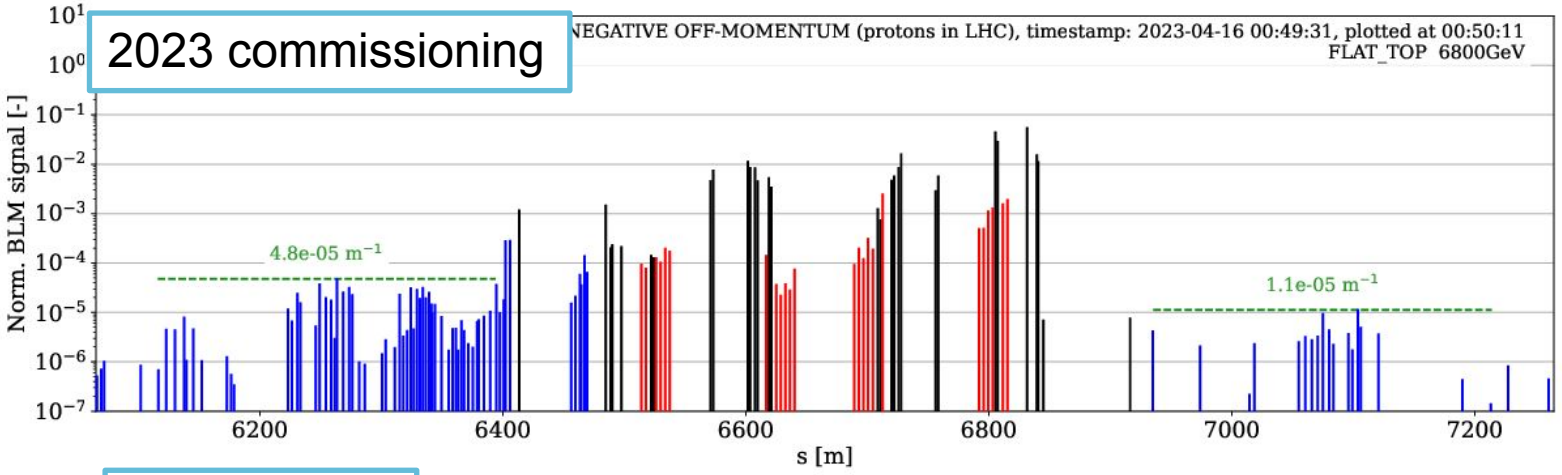
Off-momentum loss maps

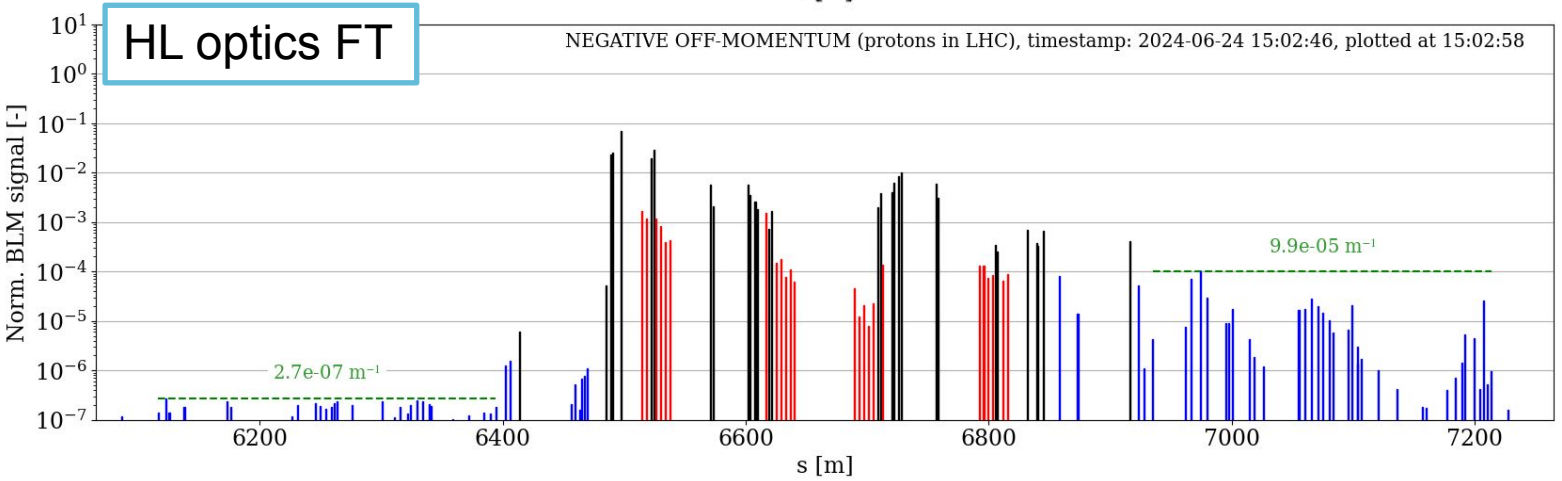
- Could only do negative
- Similar balance IR3 / IR7 and TCT losses
- Large increase in IR6, possibly due to new optics and different TCDQ setting



Off-momentum loss maps

- Worse IR3 DS losses, but still lower than positive reference
- Hierarchy looks good
- Need to repeat loss maps and also do positive, at smaller beta* as well



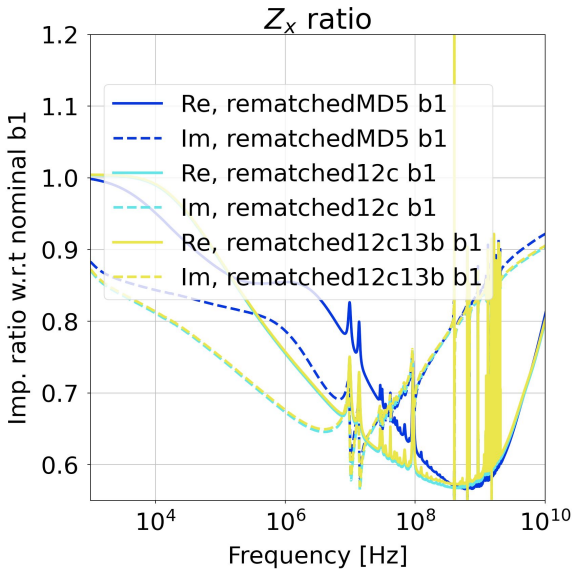


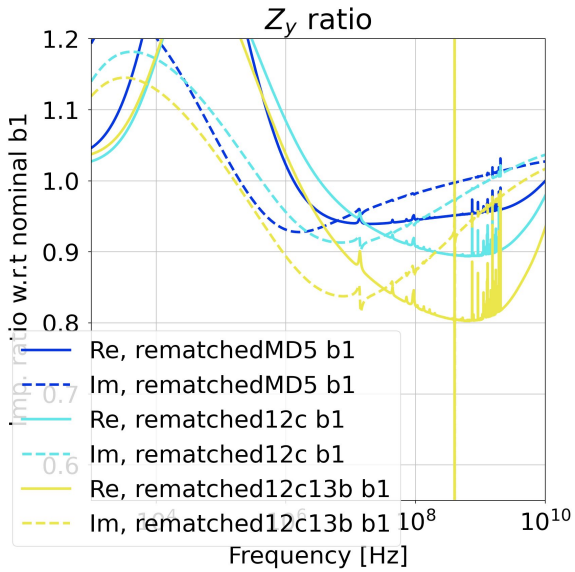
Impedance

- Expecting > 40 % gain in x and 10-20 % in y in HL-LHC*
- MD results:

	B1H	B1V	B2H	B2V
IR7 MD	4 %	26 %	33 %	19 %

- B1H signal too noisy, was unable to measure it also in other MDs not related to IR3/IR7 optics





* L. Giacomel, https://indico.cern.ch/event/1421594/contributions/5979671/

Summary of observables

- Fractional change new optics compared to reference
- DS improved in all cases

	B1H		B1V		B2H				B2V			
	IR7 MD		IR7 MD		IR7 MD		HL MD		IR7 MD		HL MD	
	sim	meas	sim	meas	sim	meas	sim	meas	sim	meas	sim	meas
DS1	**0.44**	**0.63**	**0.33**	**0.60**	**0.57**	**0.81**	**0.36**	**0.42**	**0.40**	**0.36**	**0.40**	**0.44**
TCT1	**3.06**	1.04	2.71	**3.59**	(0)	**3.78**	1.05	1.23	(inf)	1.90	(inf)	0.61
TCT2	(0)	2.92	(0)	1.08	(0)	1.16	(0)	1.38	(0)	0.98	(0)	0.64
TCT5	0.99	2.45	(0)	1.15	15.8	**7.89**	2.55	**3.79**	(217)	**3.71**	1.07	0.86
TCT8	(206)	**21.0**	(269)	**13.8**	(0)	1.11	(0)	1.56	(0)	0.96	(inf)	0.77
IR3 vs IR7	1.14	1.57	0.89	0.80	0.50	0.84	0.35	0.56	0.54	0.56	0.50	0.45

- Meas. $\sigma = 0.074$
- Numbers in () not reliable due to very low absolute losses
- *Note: Above measurements are for 2024 FT collimator settings, tight and relaxed settings will be presented in detail at a later time by **A. Donadon***

Conclusions

- Very promising results on cleaning performance
  - DS leakage cut by 19 - 61 % in all cases (2024 coll. settings)
  - Simulations generally agree well with measurements
    - Some outliers to be understood, e.g. relaxed settings
  - TCT losses increase but can be likely be mitigated
    - phase advance constraint already planned for HL optics
- Significant reduction of impedance by 19 – 33 %
  - B1H could not be measured
- IR7 Aperture > 28 sigma

- Outlook:
  - Redo loss maps (ATS squeeze, relaxed settings)
  - Redo off-momentum loss maps (verify IR3 optics do not degrade cleaning)
  - ASD (necessary for trains)
  - Trains in combined ramp and squeeze (verify no losses in ramp)
  - Aperture measurement of arcs with large ATS factor
  - Cross-check (potential) increase of background with experiments

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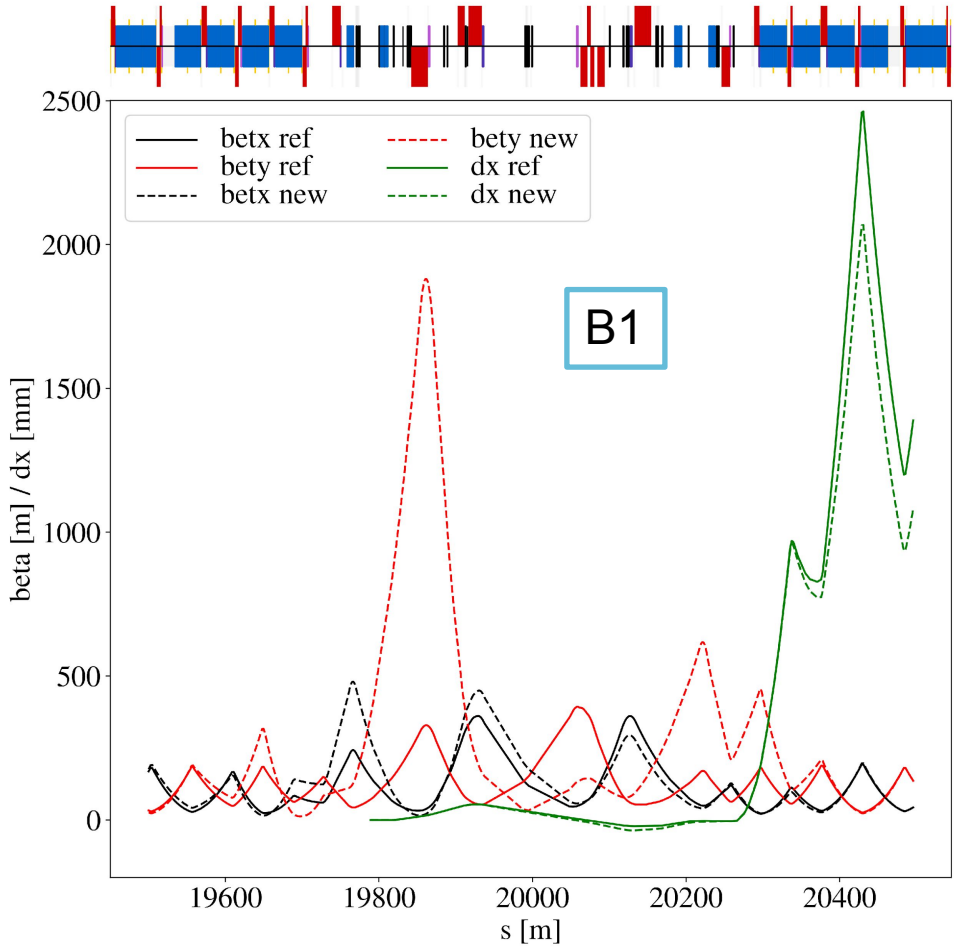
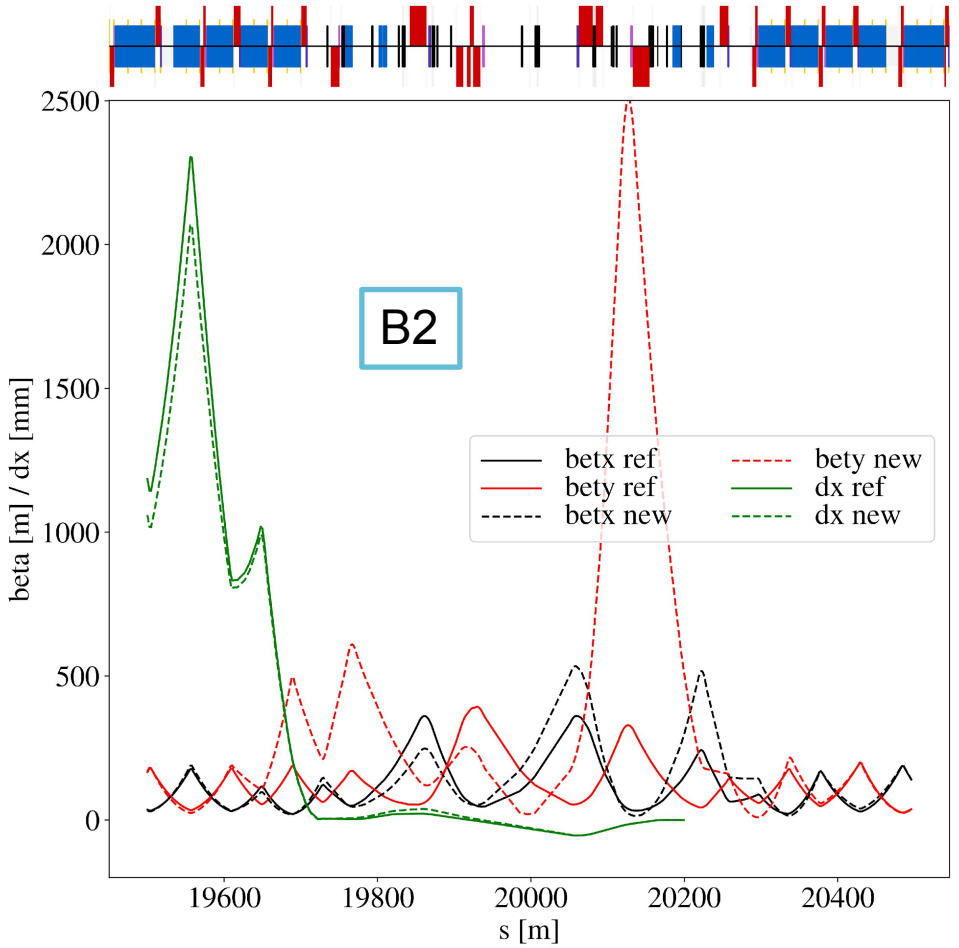
Goal: Fully validate operational feasibility of new optics before LS3

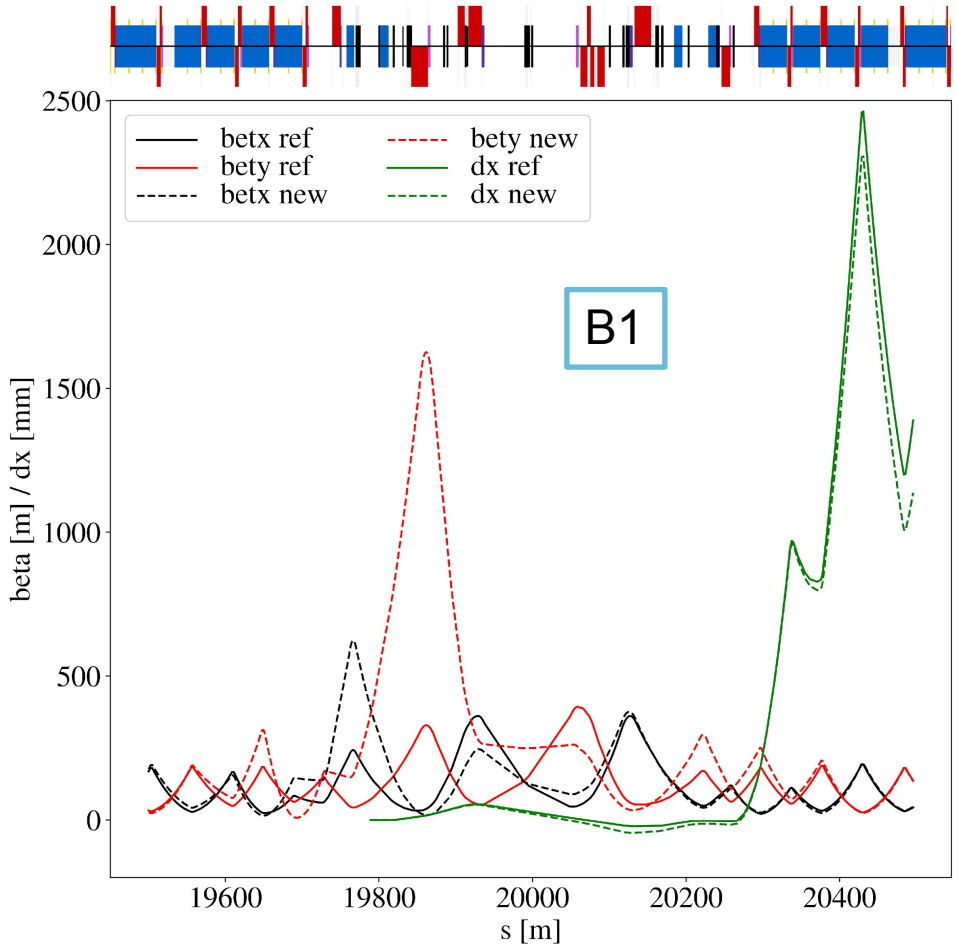
Thanks a lot for your attention!

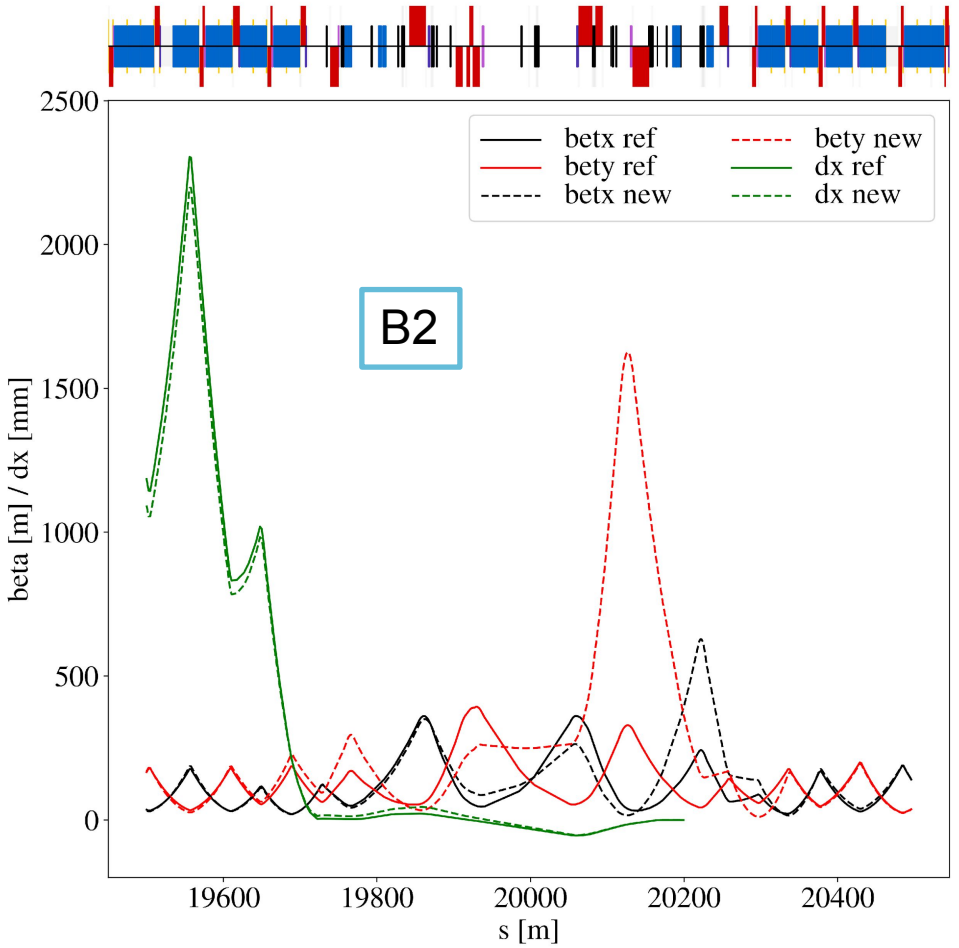
IR7 MD optics (reMD5)



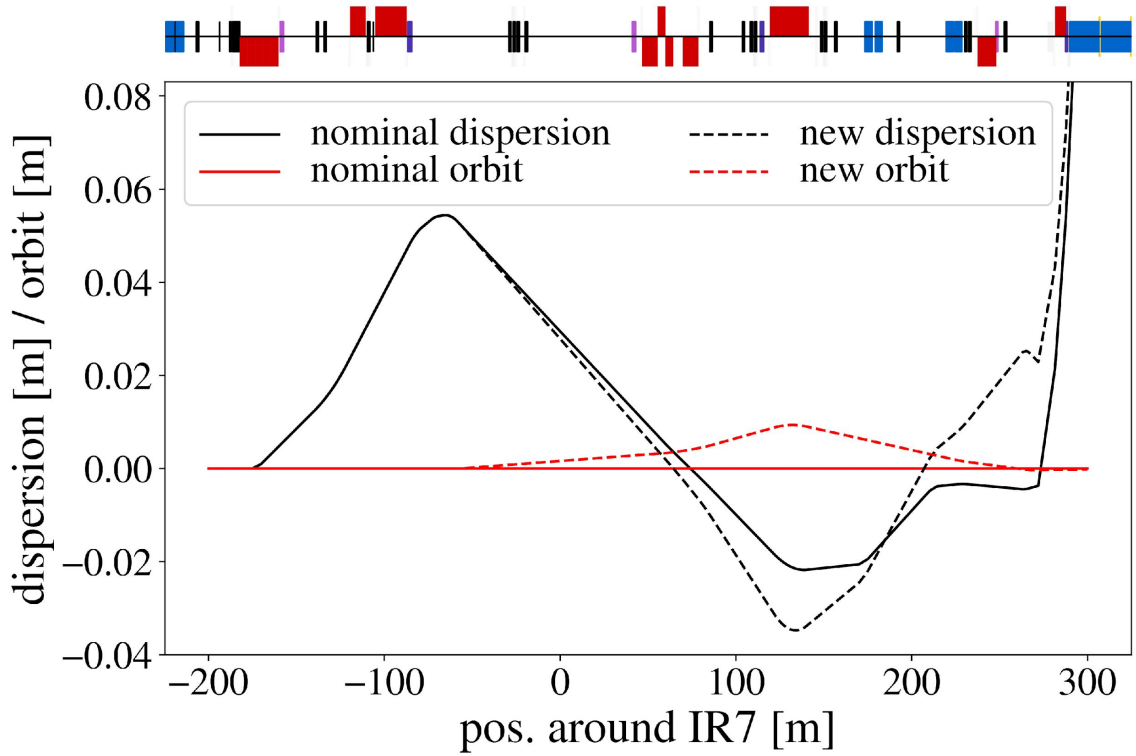


HL MD optics (re12c)





Dispersion

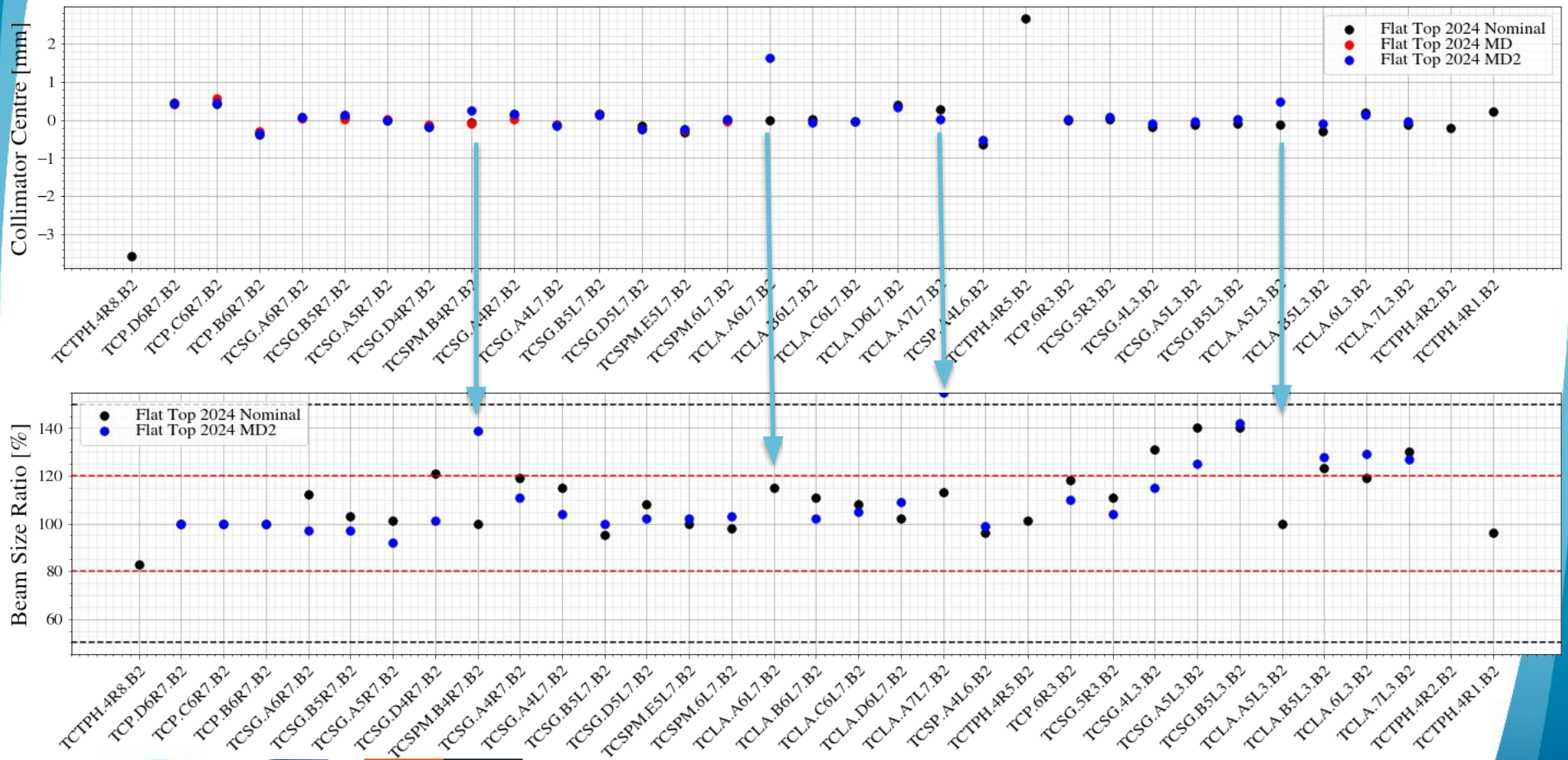


mcbwh.4l7.b1: 34 % of max
mcbch.7r7.b1: 50 % of max
mcbch.9r7.b1: -3.7 % of max

The two large kicks per bump are at locations of small dispersion (0.1-0.2 m), so it should be Ok for the length change of the orbits – Jörg

Collimator centers

- Excellent agreement of collimator centers between MD optics and nominal
  - No change expected, but critical to check that OFB updated properly to new cycle
- A few outliers, likely caused by erroneous loss spike detection during alignment



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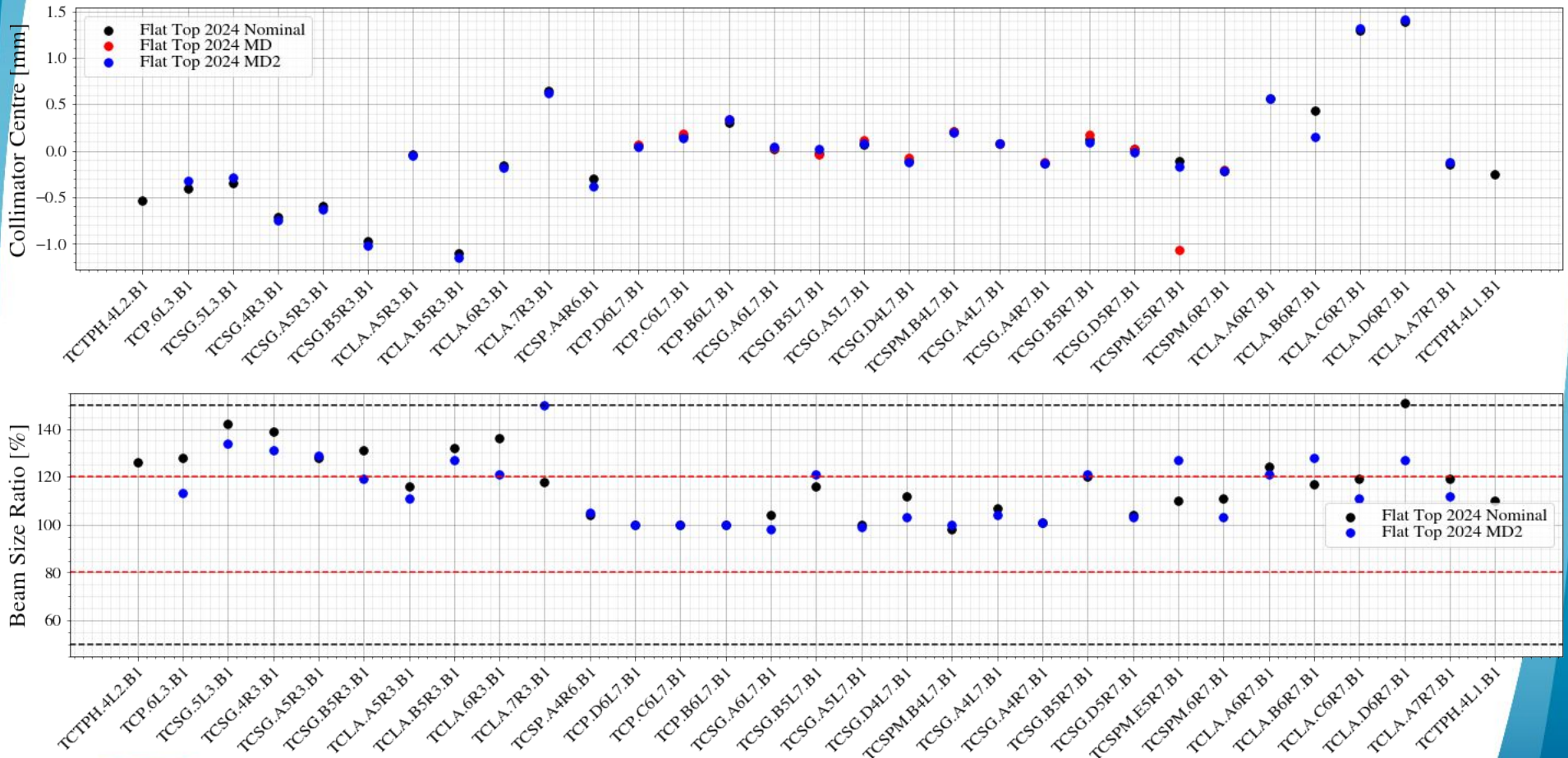
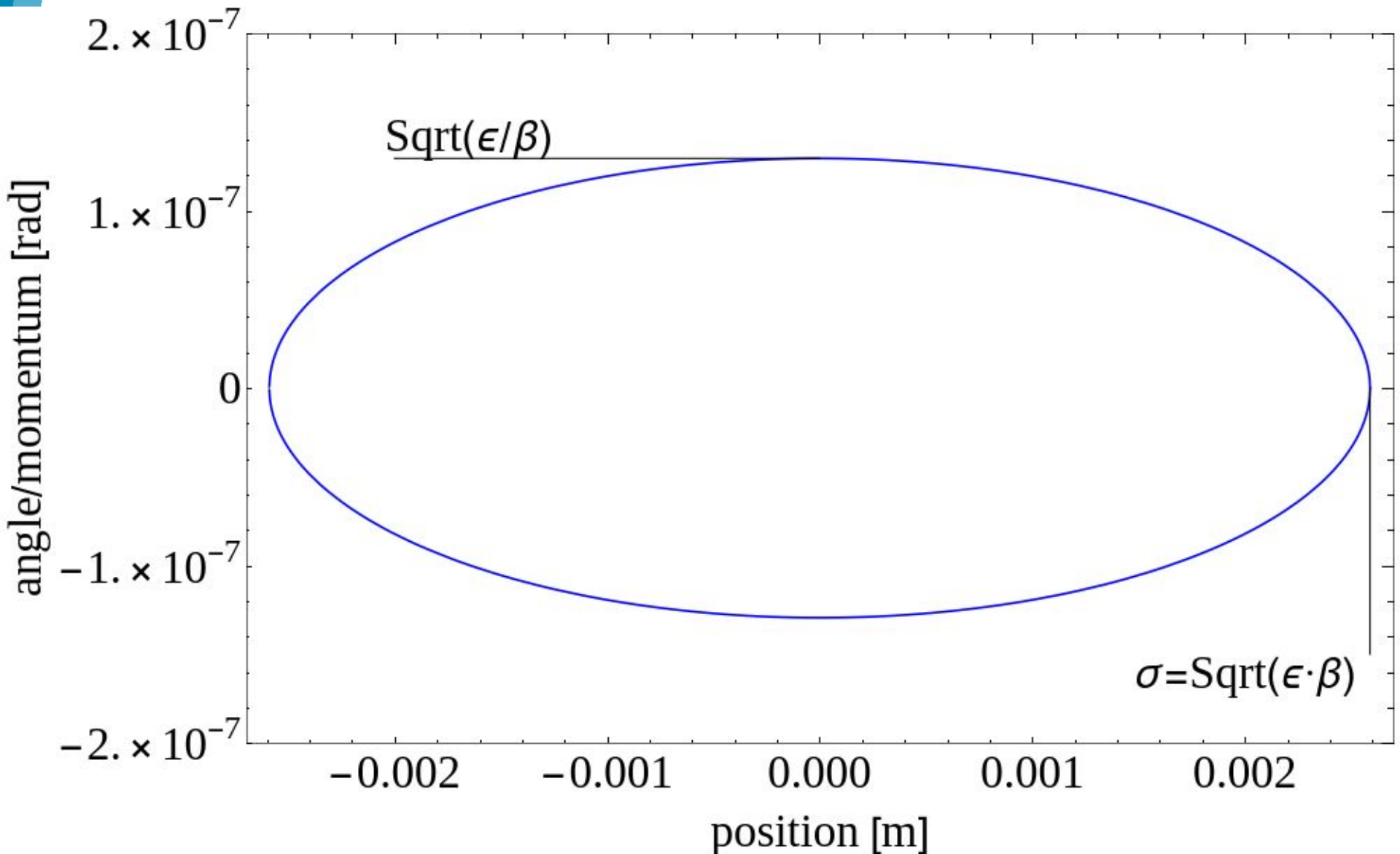


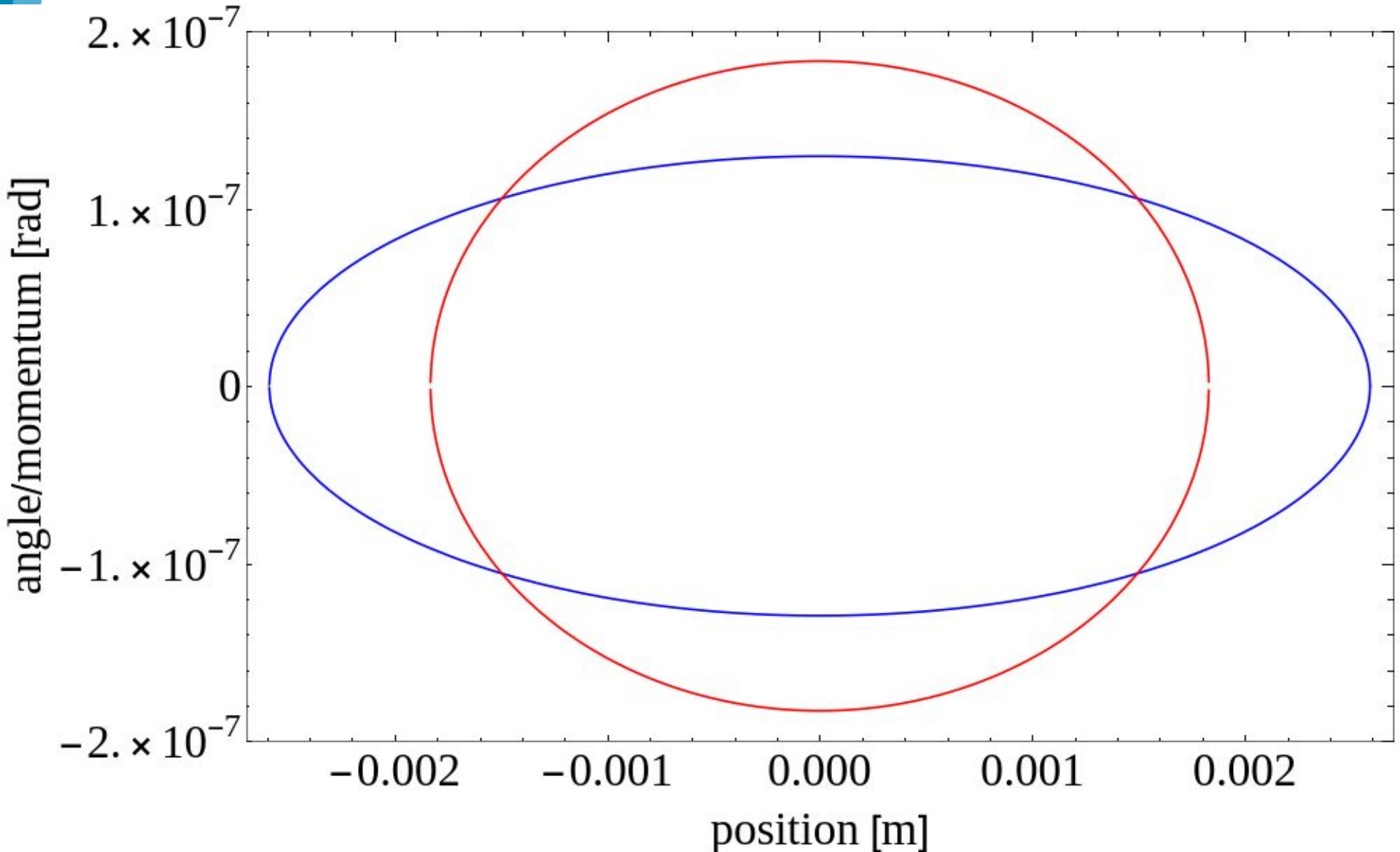
Beam sensitivity to perturbations

- Constant area: $\pi \cdot \epsilon$



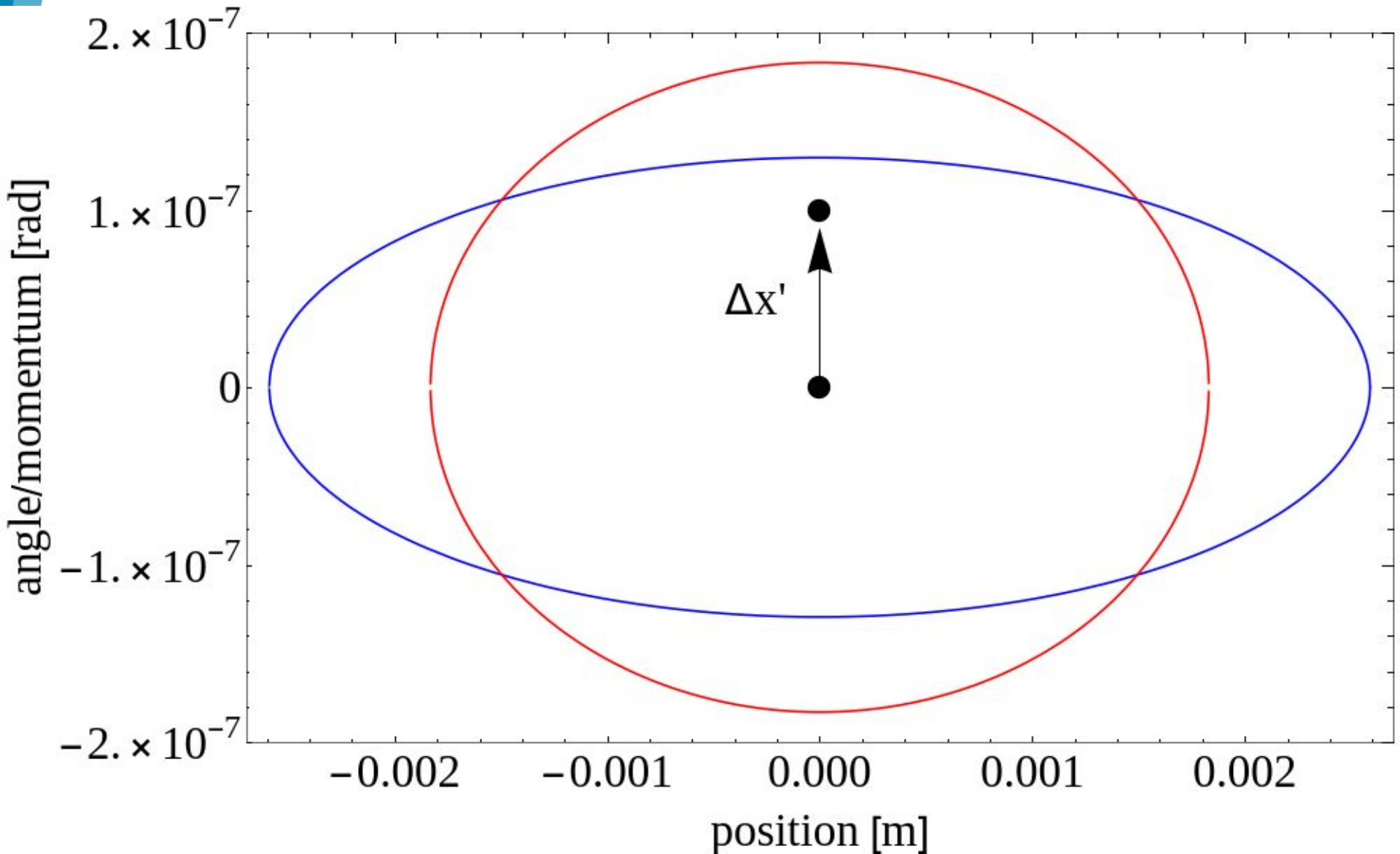
Beam sensitivity to perturbations

Ellipse at location with smaller beta function, area is the same



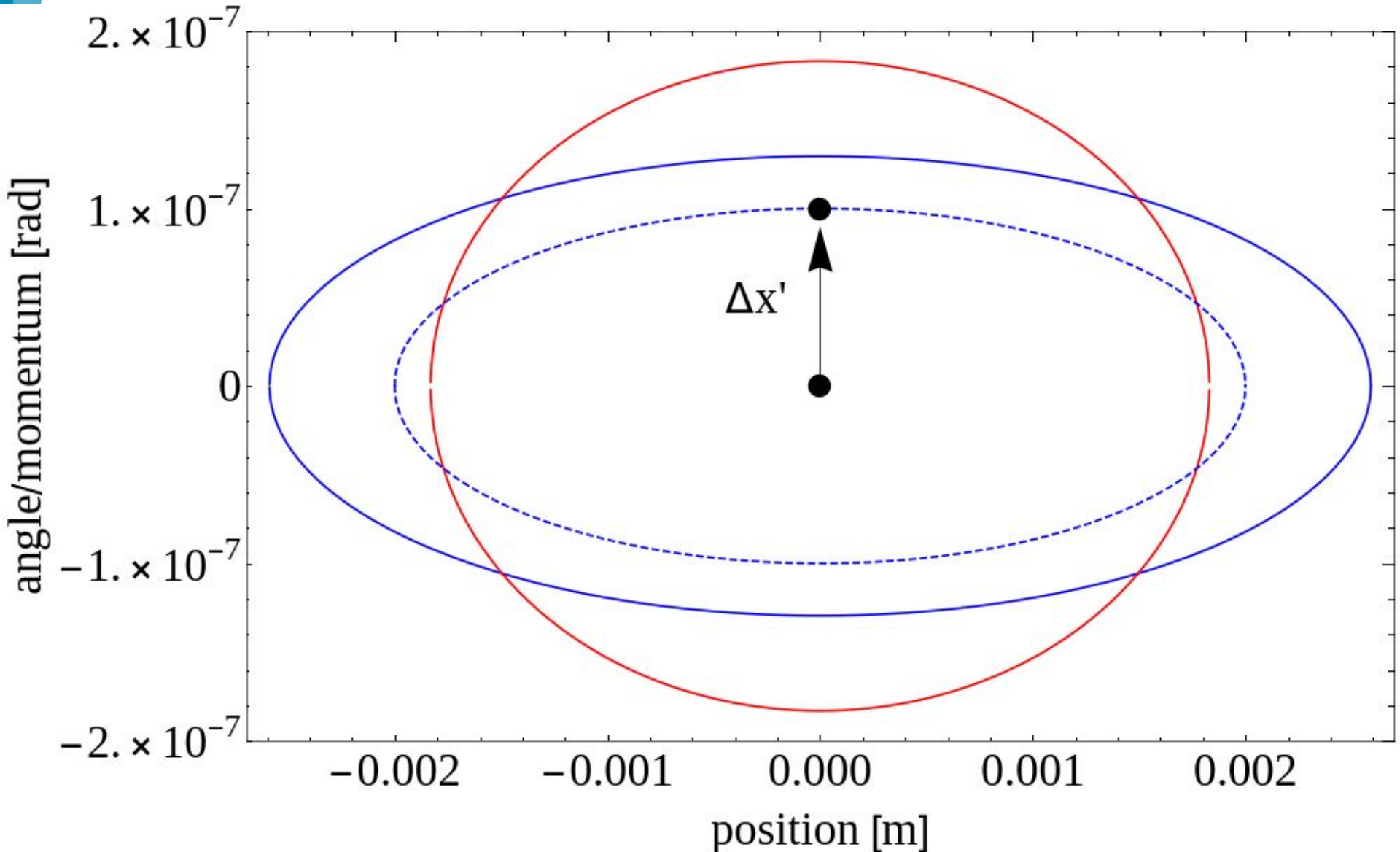
Beam sensitivity to perturbations

A particle receives a kick



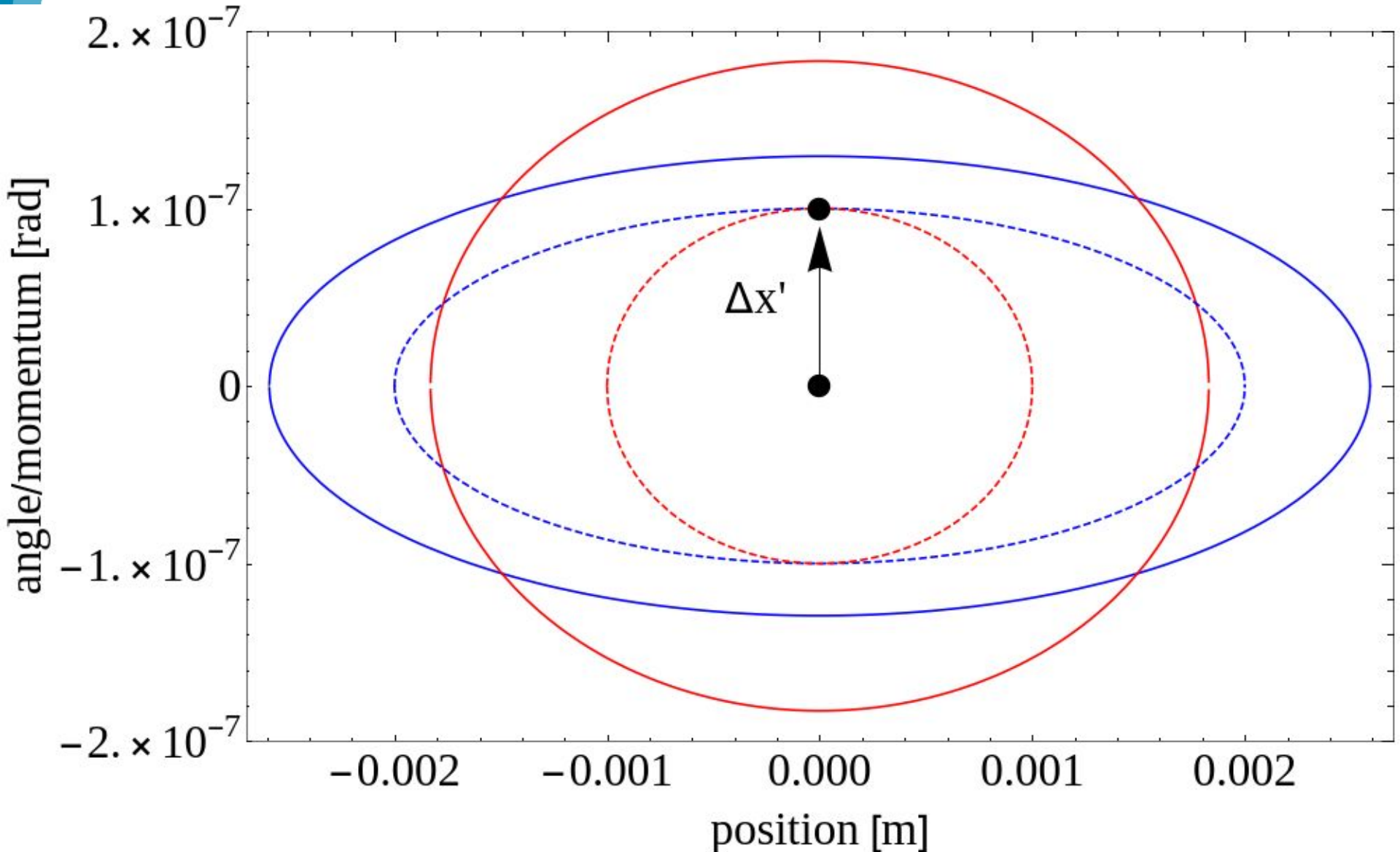
Beam sensitivity to perturbations

Particle traces out ellipse in phase space



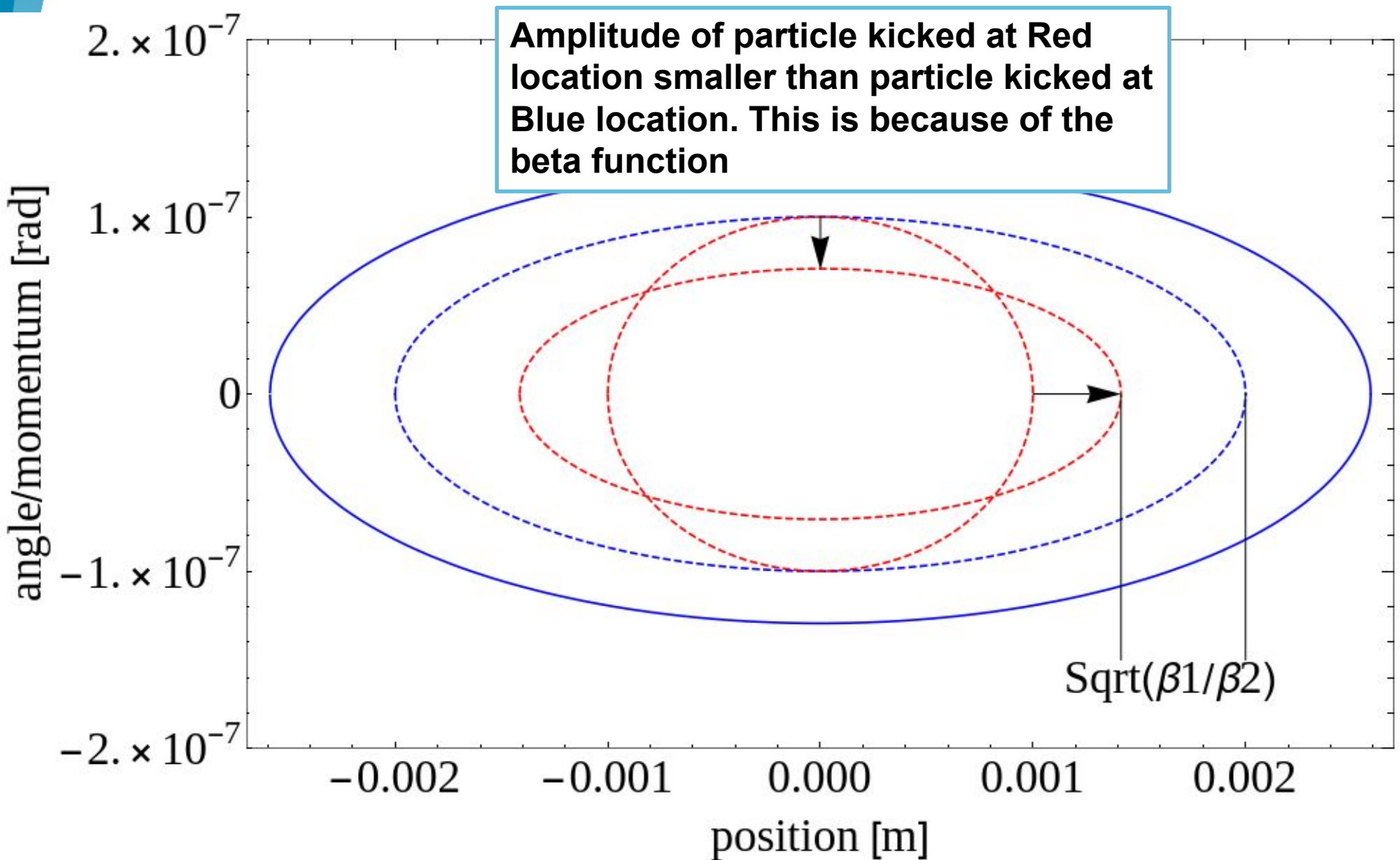
Beam sensitivity to perturbations

Particle at other location traces out different ellipse



Beam sensitivity to perturbations

Observe Red particle at Blue location, transforms the ellipse



Beam sensitivity to perturbations

Observe Red particle at Blue location, transforms the ellipse

Amplitude of particle kicked at Red location smaller than particle kicked at Blue location. This is because of the beta function

$$\begin{pmatrix} x_n \\ x_n' \end{pmatrix} = \frac{1}{\sqrt{\epsilon}} \begin{pmatrix} \frac{1}{\sqrt{\beta(s)}} & 0 \\ \frac{\alpha(s)}{\sqrt{\beta(s)}} & \sqrt{\beta(s)} \end{pmatrix} \left(\begin{pmatrix} x \\ x' \end{pmatrix} + \begin{pmatrix} 0 \\ \Delta x' \end{pmatrix} \right)$$