MD7203: New IR7 optics for improved cleaning and impedance

B. Lindström on behalf of R. Bruce, X. Buffat, R. de Maria, L. Giacomel, N. Mounet, S. Redaelli

Thanks to: D. Mirarchi, S. Fartoukh, M. Solfaroli, R. Tomás, J. Wenninger

4th October 2022 – restricted Machine Protection Panel

Introduction and Motivation

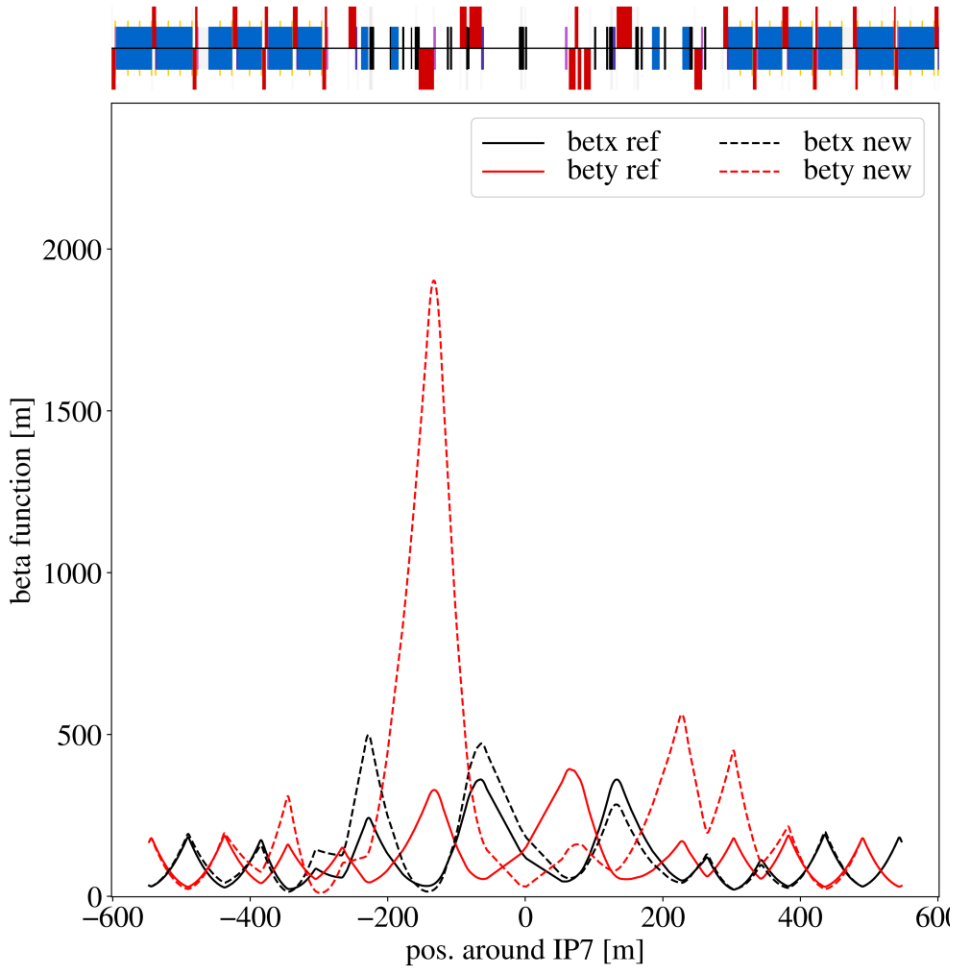
- HL-LHC beam intensity and brightness produces significant challenges:
  - Beam losses in IR7 DS could cause quenches
  - Impedance can cause instabilities
- Beam losses:
  - Initial plan to mitigate them using TCLDs installed between two 11T dipoles
  - 11T dipole availability for HL-LHC is uncertain and a backup strategy must be devised
- Impedance:
  - Low-impedance collimators are introduced in stages (LS2, LS3), but these are not enough and relaxed collimator settings were requested by WP2
  - Further reduction of impedance helps ensure beam stability
  - Impedance reduction could also allow for tighter settings

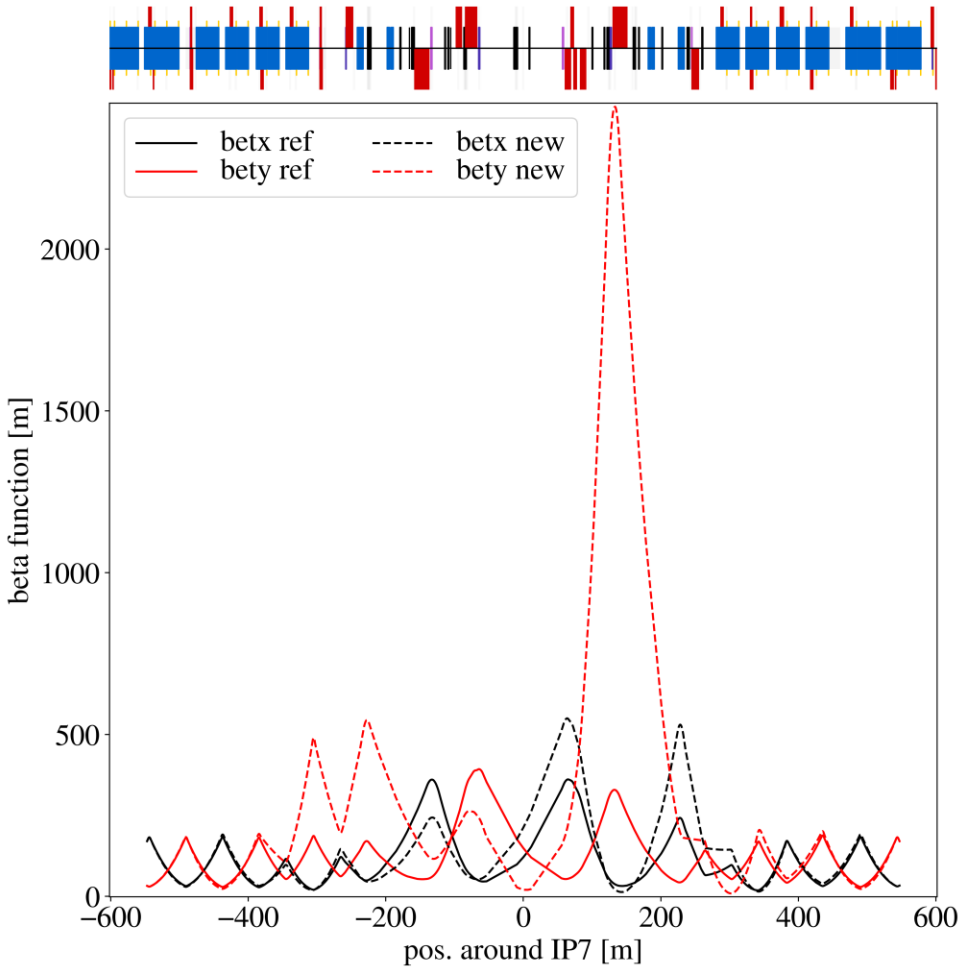
New IR7 optics[1] and collimator setup[2]

- Increase collimator beta functions
  - Larger normalized kicks on scattered particles → larger probability of absorbing them in TCS / TCLAs
  - Larger physical gaps → lower impedance
- Increase single pass dispersion at TCS / TCLAs
  - Increased through optics rematch and orbit bump
  - Off-momentum particles outscattered from TCP are more likely to be intercepted by collimators before reaching the DS
- Asymmetric TCLA settings
  - Improves cleaning performance
  - Gap kept constant – one jaw moves closer and catches dispersive losses
  - Successfully used on TCPs operationally in 2018 ion run
- Single-sided jaw collimators
  - Retract one jaw of selected collimator(s) to reduce impedance further [3]

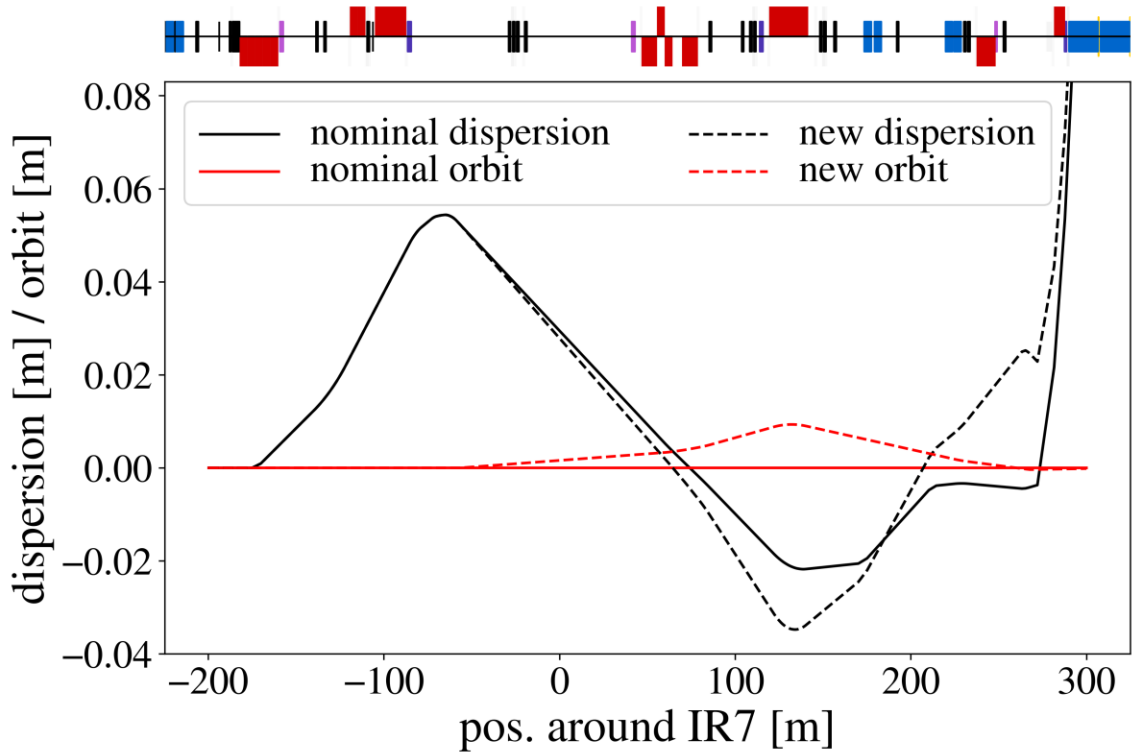
1: R. Bruce et al, https://doi.org/10.18429/JACoW-IPAC2021-MOPAB006
2: B. Lindstrom et al, https://doi.org/10.18429/JACoW-IPAC2022-TUPOTK062
3: D. Kodjaandreev, http://cds.cern.ch/record/2690267

Beta functions





Dispersion

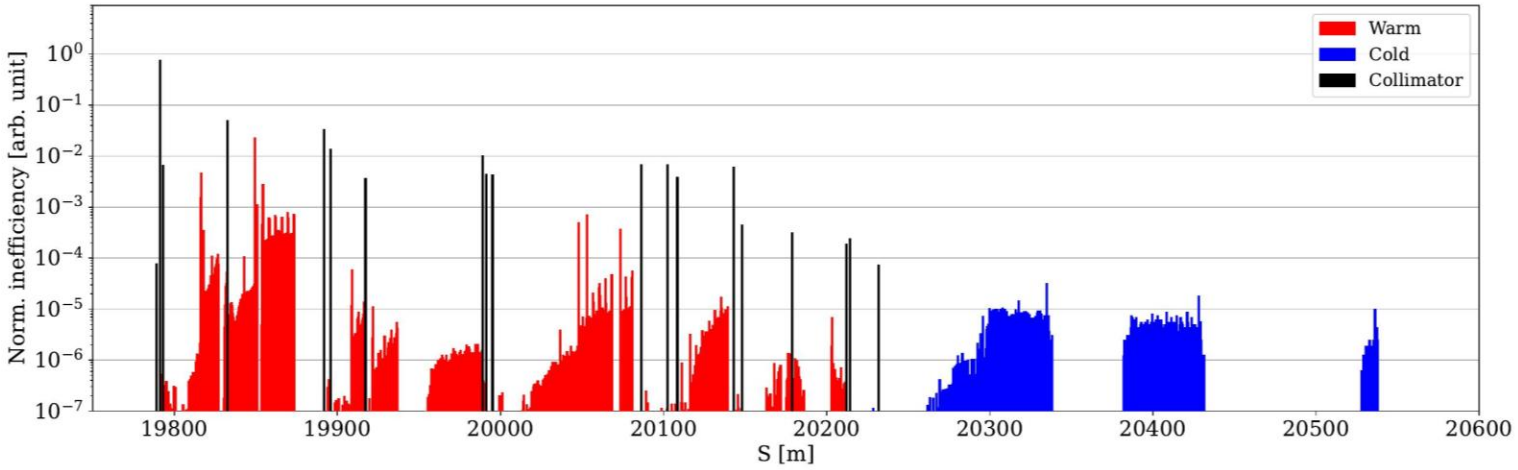


mcbwh.4l7.b1: 34 % of max
mcbch.7r7.b1: 50 % of max
mcbch.9r7.b1: -3.7 % of max

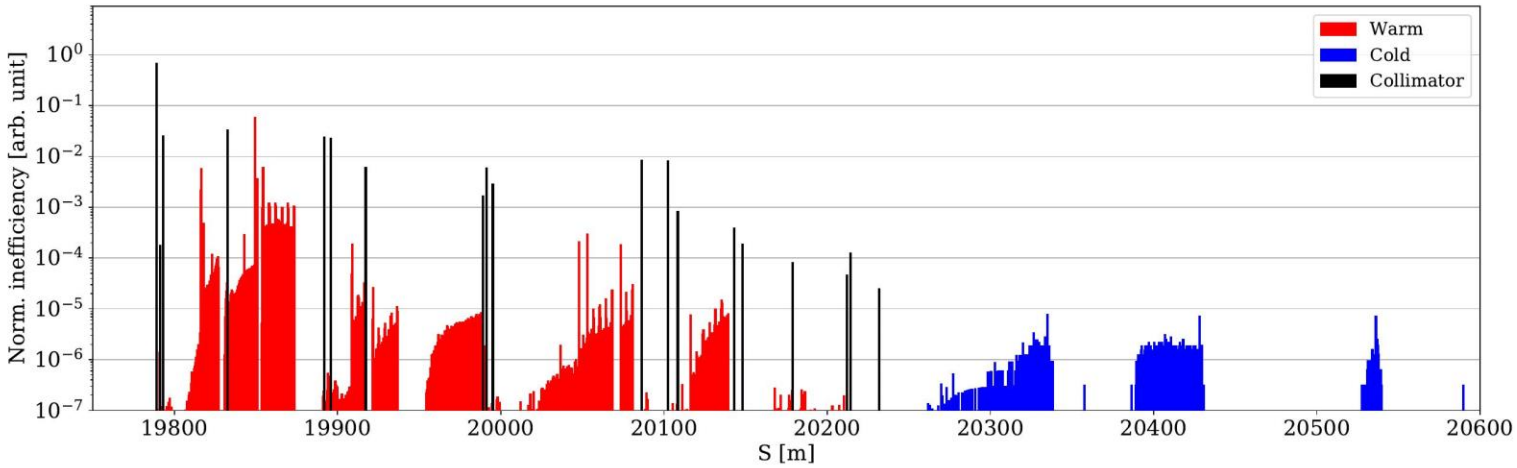
The two large kicks per bump are at locations of small dispersion (0.1-0.2 m), so it should be Ok for the length change of the orbits – Jörg

Loss map comparison (runIV – 20 cm, relaxed)

nominal

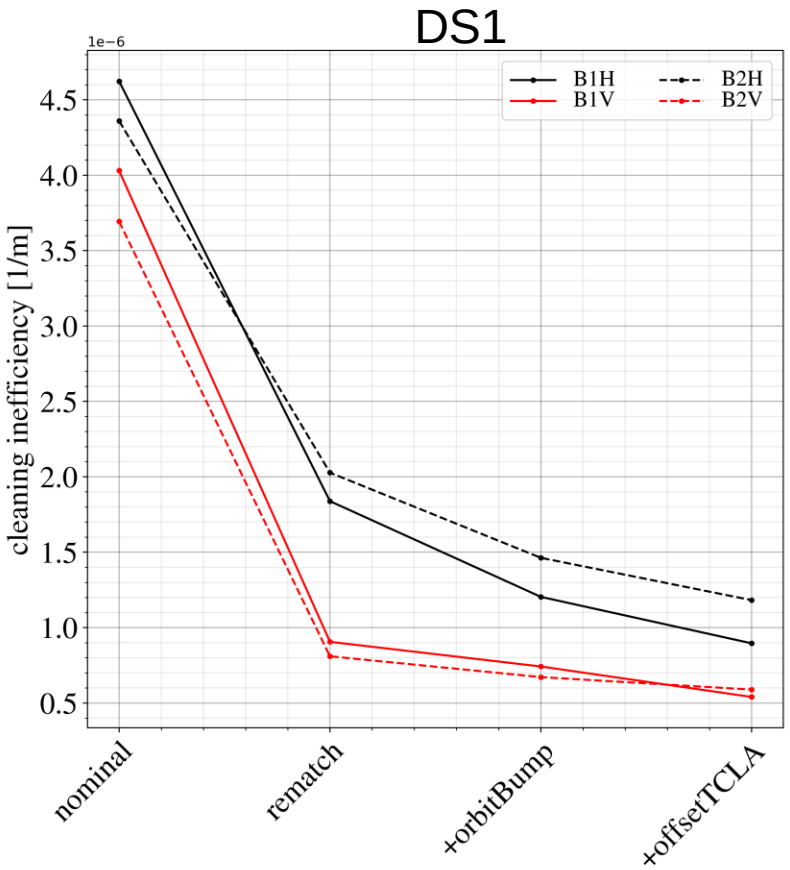


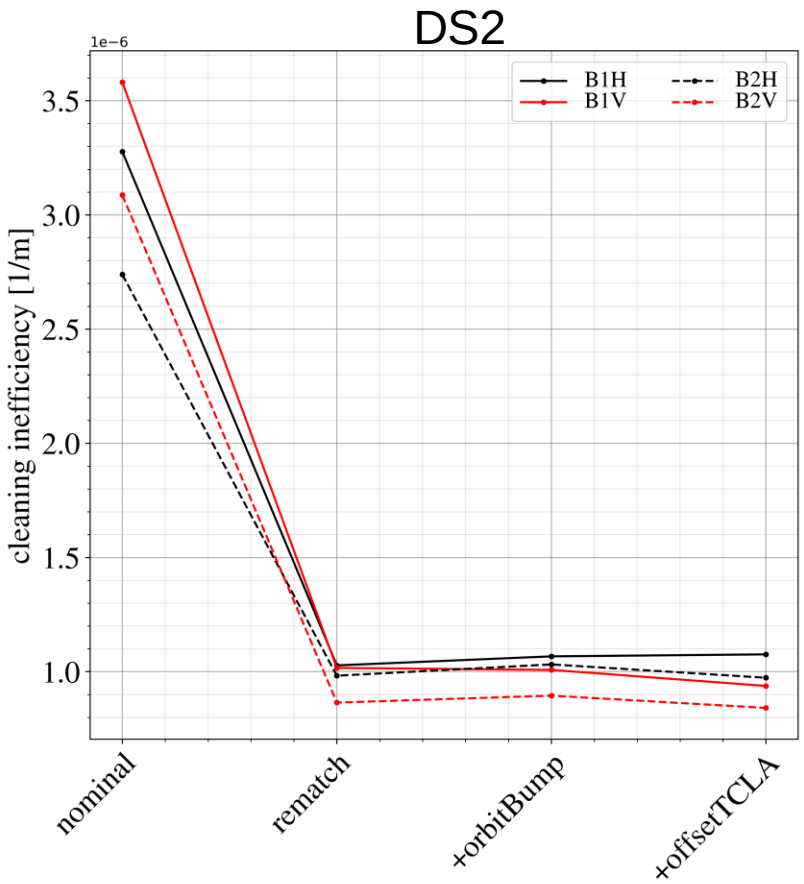
rematched optics + orbitBump + offset TCLA



Loss map comparison (runIV)

- Significant reduction, up to 80 %, in the three main DS clusters





MD plan

- Fill 1:
  - Set up and correct new IR7 optics at FT
  - 6 hours
  - Only pilots – no impedance measurements possible
- Fill 2:
  - Detailed measurements of cleaning performance and impedance
  - 8 hours
  - 2-3 days after Fill 1
- Impedance measurements:
  - Use ADT to kick one nominal and one pilot bunch to see tune shift
  - Lower octupole current until instability is observed as EOF
- Loss maps:
  - Horizontal and vertical loss maps
  - Use ADT to blow-up a pilot bunch completely
- Machine protection:
  - Setup beam (< 3e11 protons)
  - Mask IR7 collimator limits and BPMs, collimators to be moved to new settings
  - Optics will be changed

Machine Protection related concerns

- Aperture in IR7:
  - Nominal: ~41 σ for both beams
  - Rematched optics: 21.2 σ in MQWA.C5L7.B1 / 18.5 σ in MQWA.C5R7.B2
  - Rematched optics+orbit bump: 21.2 σ in MQWA.C5L7.B1 / 17.6 σ in MQWA.E4L7.B2
- Collimator movement:
  - All IR7 collimators need to be moved during optics rematch.
    - Move out to expected positions plus margin prior to optics change
    - Check alignment and then move collimators to nominal gaps
  - TCLA to be offset with a fixed gap. Offset is in the same direction as the orbit perturbation caused by asynch dumps, and remains in the shadow of the TCS.
- MQW higher order modes:
  - MQWA has large b3 and causes optics changes with the orbit bump, although these are ”insignificant” (see next slide for numbers)

MQWA errors with 9.3 mm bump: (1) nominal optics (2) rematched (3) rematched + orbit bump

- (1)
- deltaQ1: +0.0000225
- deltaQ2: -0.000019874
- deltaDQ1: -0.108400794
- deltaDQ2: -0.015907795
- betabeatX: 1.0002538
- betabeatY: 1.0001194
- deltaX: +2.06106818233494e-05
- deltaY: +1.50795259224515e-05

- (2)
- deltaQ1: +0.000024267
- deltaQ2: -0.000014737
- deltaDQ1: +0.127441728
- deltaDQ2: -0.022560443
- betabeatX: 1.0004135
- betabeatY: 1.0002283
- deltaX: +2.8712788989093e-05
- deltaY: +2.7672176230855e-05

- (3)
- deltaQ1: +0.001703098
- deltaQ2: -0.00019679
- deltaDQ1: +0.227847012
- deltaDQ2: -0.043988004
- **betabeatX: 1.0124906**
- **betabeatY: 1.003714**
- deltaX: -6.6821e-5
- deltaY: +9.81098661950715e-05

First fill (optics setup) – 6 hours

- Inject b1/b2, 3 pilots per beam, non-colliding
- Normal ramp to 6.8 TeV, xing bump, remain at FT
- **New IR7 optics:**
  - Drive collimator to more open settings
  - Deploy optics change
  - Check consistency of new optics / corrections
  - Check collimator alignment using BPMs (or BLMs when no BPMs), adjust if necessary
  - Drive collimators to final settings (manually)
  - Measure global aperture
- **Orbit bump:**
  - Open collimator gaps symmetrically to accomodate for bump
  - Apply horizontal 9.3 mm bump
  - Measure global aperture (in case of time)
  - Loss maps if any beam remains

Second fill (measurements) – 8 hours

- Inject b1/b2, 1 nominal + 20 pilots, non-colliding
- Nominal ramp to 6.8 TeV and remain at FT
- Measure tune-shift using ADT
- New IR7 optics:
  - Same procedure as fill 1
  - Measure tune shift
  - H/V loss maps, two per plane per beam
- Asymmetric TCLAs:
  - Move final two TCLAs in b1/b2 +3 sigma
  - H/V loss maps, two per plane per beam
- Orbit bump:
  - Same procedure as fill 1
  - H/V loss maps, two per plane per beam
- Single-sided jaws:
  - Retract one jaw completely of old IR7 collimators
  - Measure tune shift
  - H/V loss maps
  - Decrease octupole current until instability occurs

Thanks for listening and to everyone involved!

R. Bruce, X. Buffat, R. de Maria, S. Fartoukh, L. Giacomel, B. Lindström, D. Mirarchi, N. Mounet, S. Redaelli, M. Solfaroli, R. Tomás, J. Wenninger

First fill (optics setup) – 6 hours

- B1/B2 1 to 3 pilots
- nominal ramp to FT
- (0): loss maps
- Drive collimators to open settings compatible with new optics + margin
- Change to new IR7 optics
- Check and correct optics
- Check collimator alignment using BPMs (use BLMs when BPMs are not available), drive to nominal sigma gaps in new optics
- (1): loss maps
- (1): aperture measurement
- Drive collimators to open settings compatible with orbit bump, with margin
- Apply horizontal orbit bump of 9.3 mm
- (2): aperture measurement (in case of time)
- (2): loss maps if beam remains

Second fill (measurements) – 8 hours

- B1/B2 20 pilots + 1 nominal (<3e11 protons total)
- nominal ramp to FT
- (0): impedance measurement + loss maps
- Drive collimators to settings found in Fill 1
- Change to new IR7 optics
- Check consistency of new optics
- (1): impedance measurements + loss maps
- Move last two TCLAs B1/B2 by three sigma – constant gap
- (2): loss maps
- Open secondary collimators to accomodate for orbit bump
- Apply orbit bump, 9.3 mm, and drive collimators to nominal settings (with the bump)
- (3): loss maps
- Retract one jaw for TCP.B and old TCSG collimators
- (4): impedance measurements + loss maps
- Decrease octupole current until instability occurs

MD7203 – plan to test mitigation strategies already in RunIII

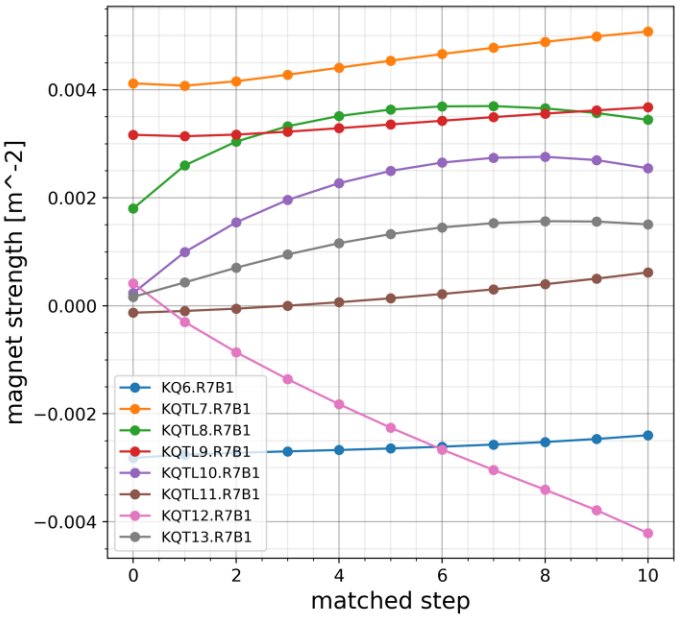
- Relative loss reduction in first DS cluster (avg) compared to reference scenario

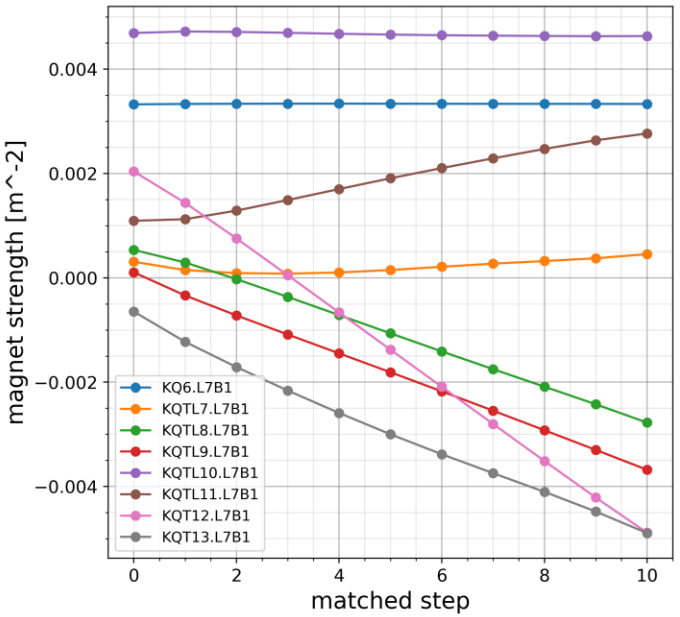
scenario	B1H	B1V	B2H	B2V	impedance	tune shift
(0): reference	1	1	1	1	1	ref
(1): optics rematch	0.56	0.48	0.70	0.44	0.9	1.2e-4*
(2): orbit bump + (1)	0.35	0.39	0.47	0.41	--	--
(3): offset TCLA + (2)	0.23	0.31	0.32	0.32	--	--
(4): single-sided jaws + (1)	0.84	0.56			0.8	2.4e-4*

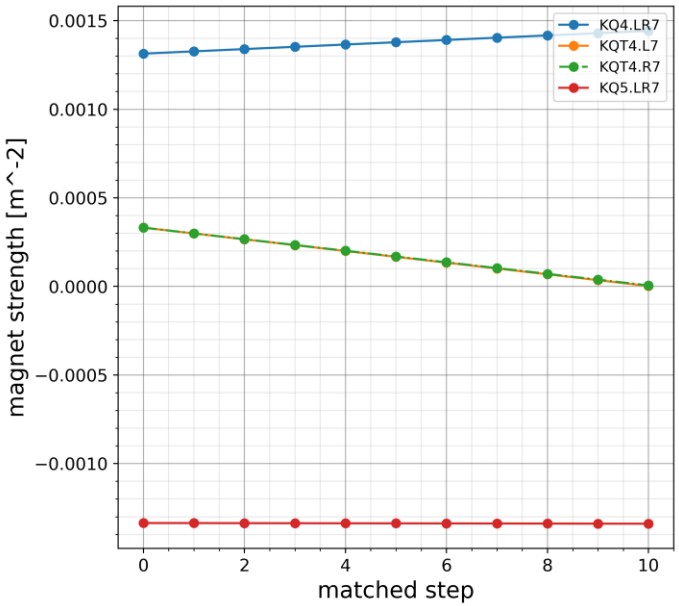
(3) is for maximizing cleaning performance
(4) is for maximizing impedance gain

* tune shift in x, in y it is about half

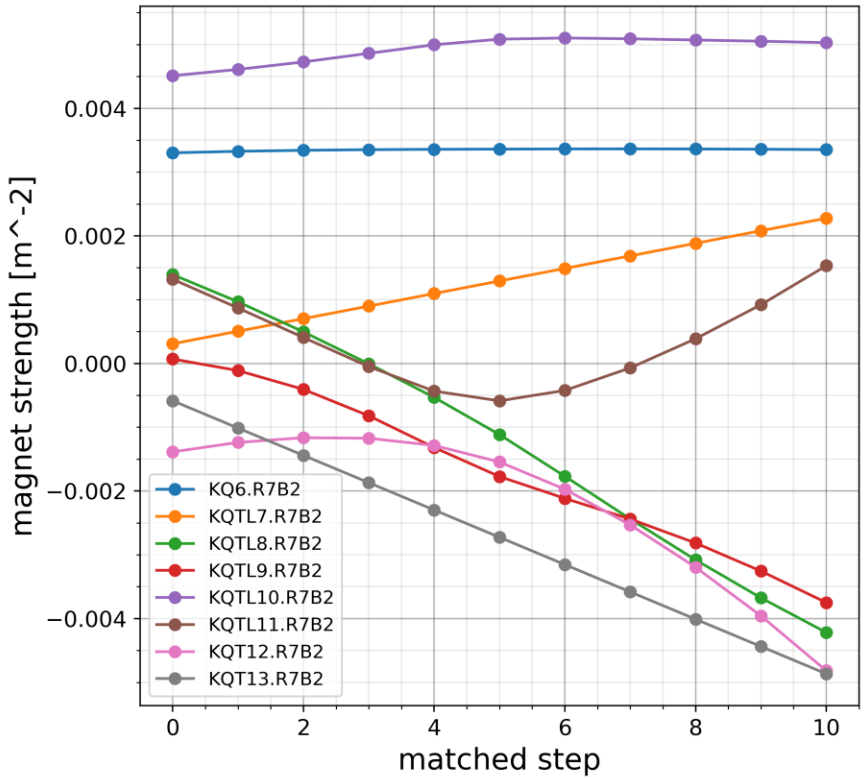
Optics transition

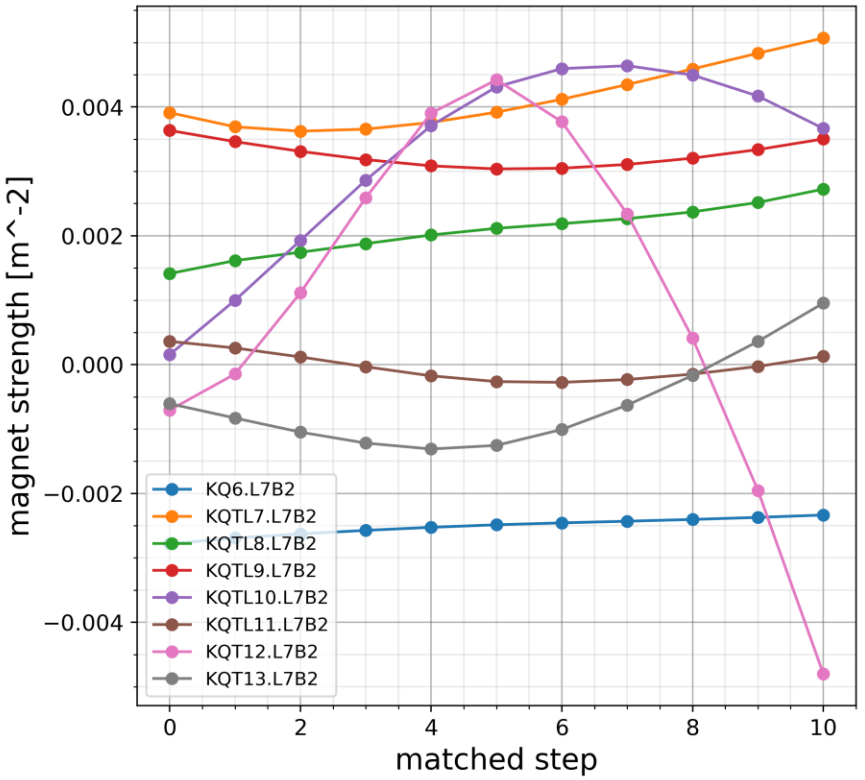






Optics transition





MQ currents

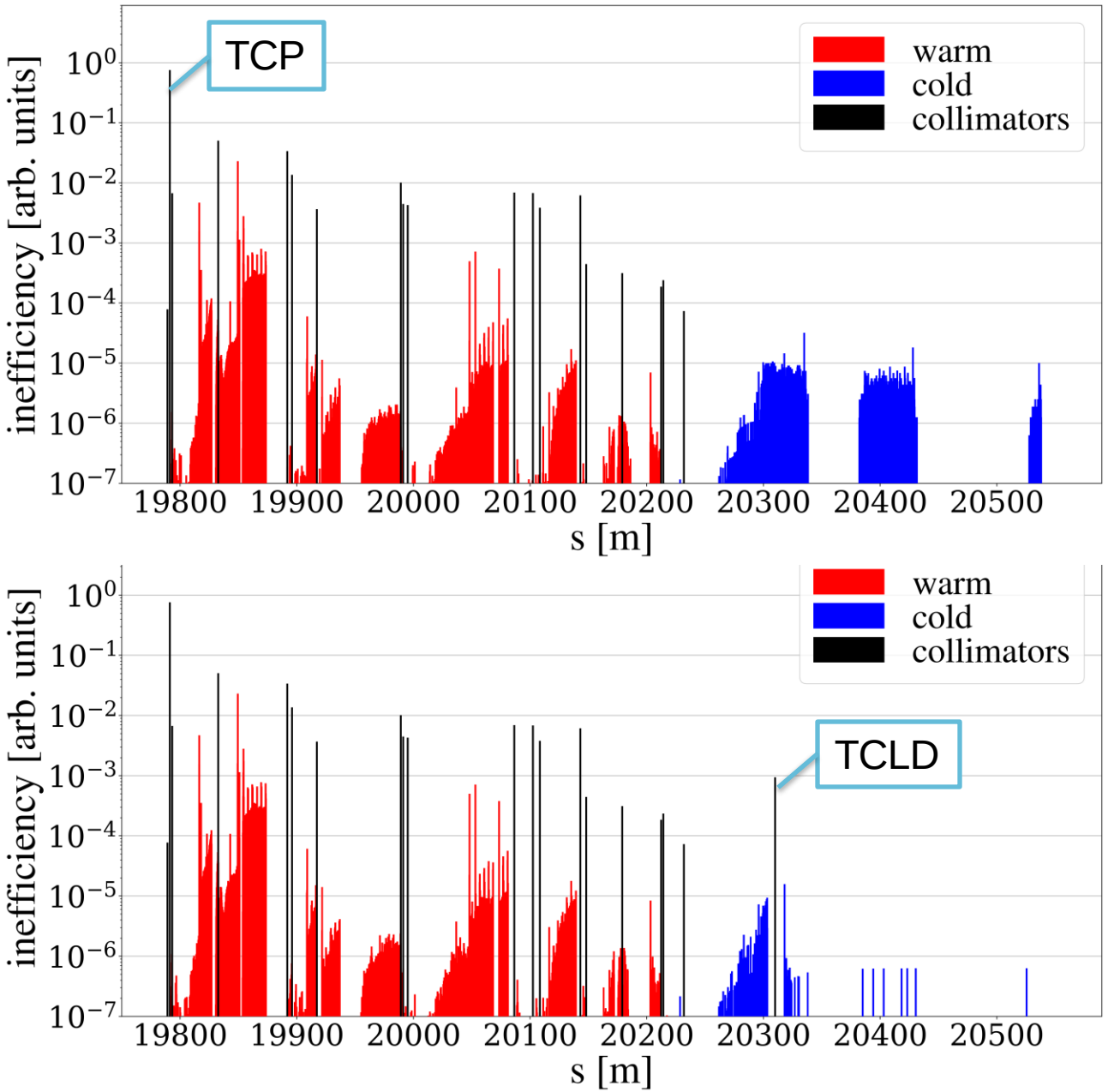
Magnet	Limit	Optics 1
KQT13.R7B2	550	-492
KQT12.R7B2	550	-488
KQTL11.R7B2	550	148
KQTL10.R7B2	550	485
KQTL9.R7B2	500	-361
KQTL8.R7B2	500	-407
KQTL7.R7B2	550	219
KQ6.R7B2	400	306
KQ6.L7B2	400	-213
KQTL7.L7B2	550	489
KQTL8.L7B2	300	263
KQTL9.L7B2	380	338
KQTL10.L7B2	500	353
KQTL11.L7B2	300	12
KQT12.L7B2	550	-486
KQT13.L7B2	550	97

Magnet	Limit	Optics 1	Optics 2
KQT13.R7B1	550	152	23
KQT12.R7B1	550	-426	-479
KQTL11.R7B1	550	60	56
KQTL10.R7B1	550	245	253
KQTL9.R7B1	500	354	369
KQTL8.R7B1	550	332	331
KQTL7.R7B1	550	489	497
KQ6.R7B1	400	-218	-230
KQ6.L7B1	400	304	303
KQTL7.L7B1	550	44	-13
KQTL8.L7B1	200	**-267**	191
KQTL9.L7B1	300	**-355**	-287
KQTL10.L7B1	500	446	477
KQTL11.L7B1	300	266	286
KQT12.L7B1	550	-494	-530
KQT13.L7B1	550	-495	-528

Magnet	Limit	Optics 1
KQ4.LR7	710	706
KQT4.L7	600	1
KQT4.R7	600	3
KQ5.LR7	710	-656

TCLD in IR7 dispersion suppressor

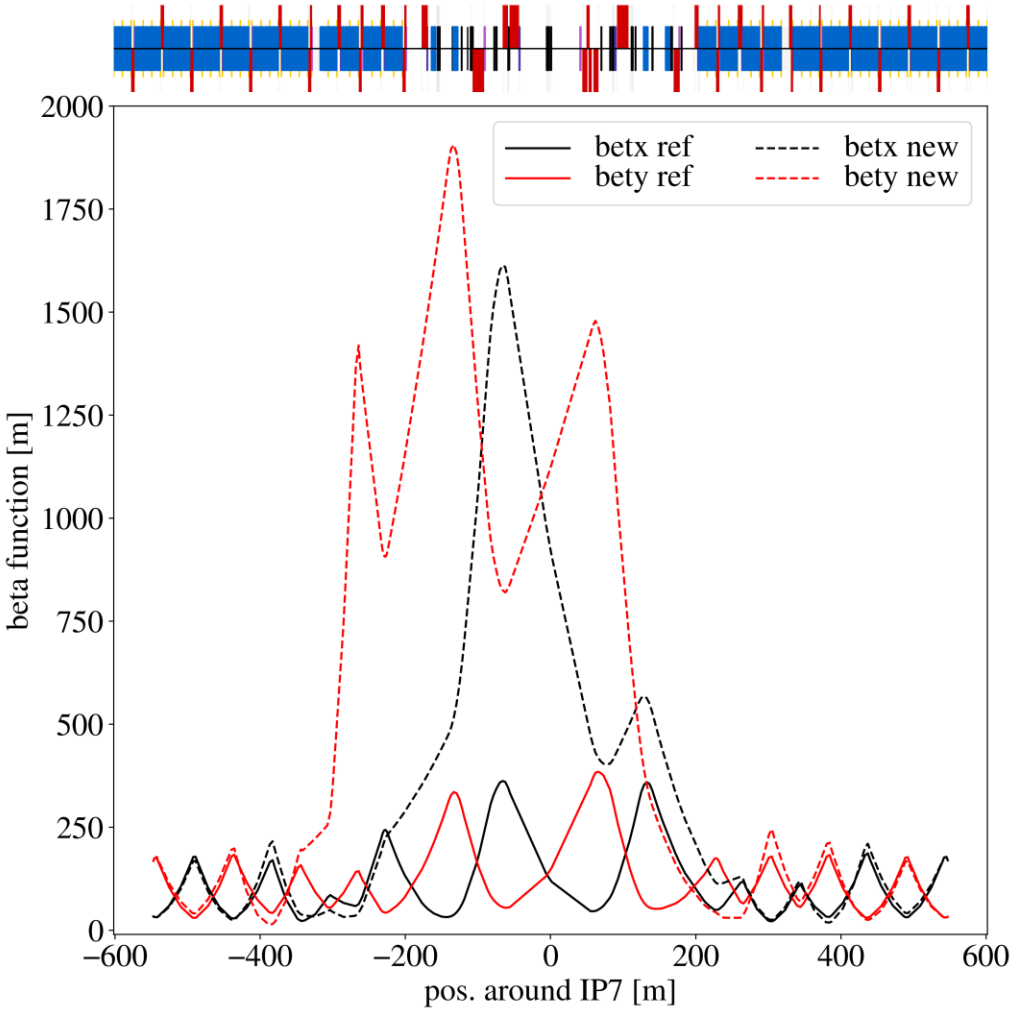
- Planned for RunIII to mitigate quench risk in DS
- Replace one main dipole with two short 11T dipoles
- Production of 11T dipoles delayed – availability for HL-LHC is uncertain
- For ions, DS losses will be mitigated using crystal collimators
- Quench tests needed to conclusively determine necessity of TCLD or other mitigations, for proton operation



Outlook – towards better optics

- Skip the phase advance restriction (S. Fartoukh, R. de Maria)

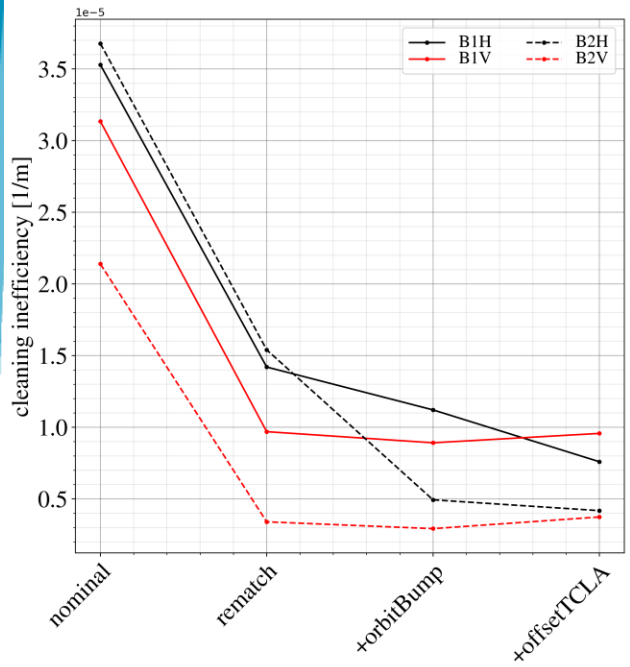
- Impedance goals:
  - Large beta functions at all collimators
- Cleaning performance goals:
  - Optimized phase advances between collimators
  - Large TCP (and possibly TCS) beta functions
  - Large single pass dispersion from TCP to TCS / TCLA
  - Small beta functions at TCLA (and possibly TCS)



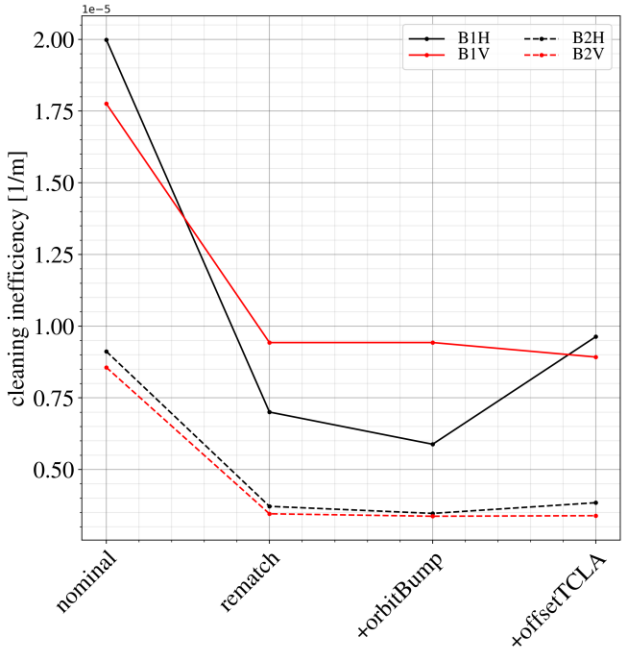
One possibility focused on impedance – up to 70 % improvement in IR7 collimators according to scaling formula

Peak losses in DS clusters

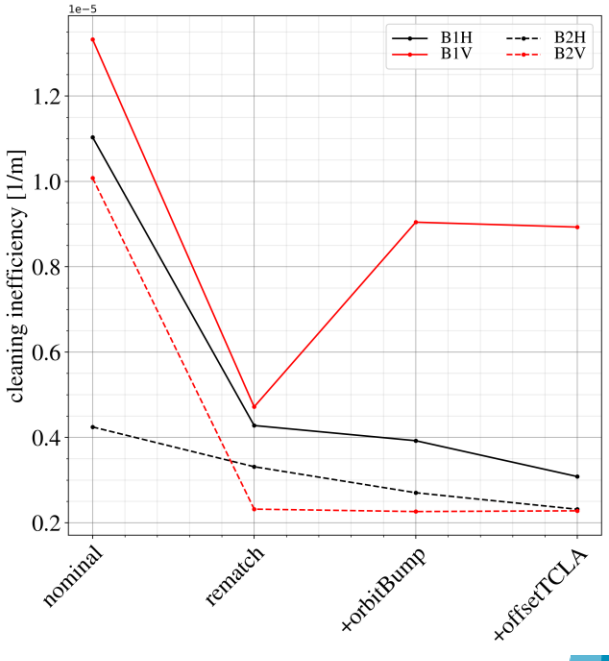
DS1



DS2

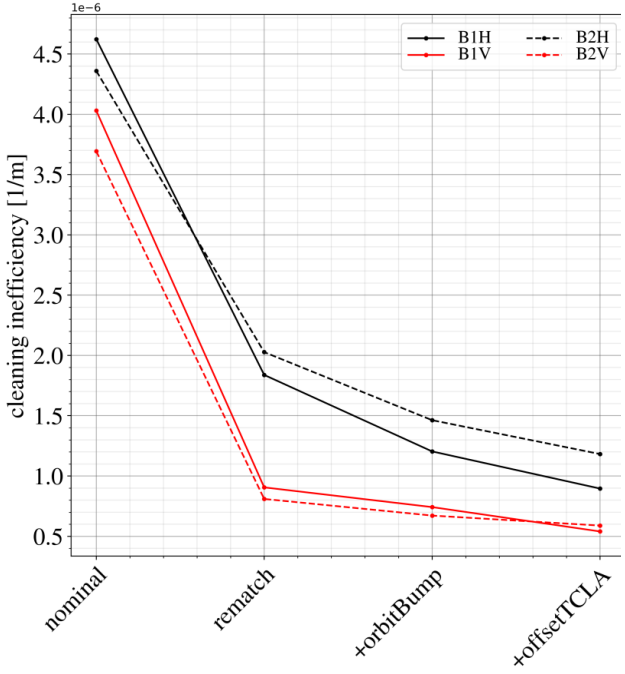


DS3

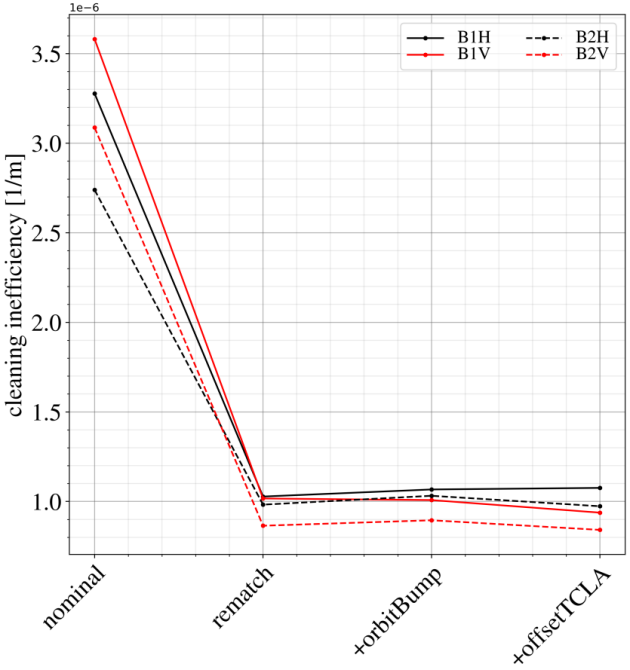


Average losses in DS clusters

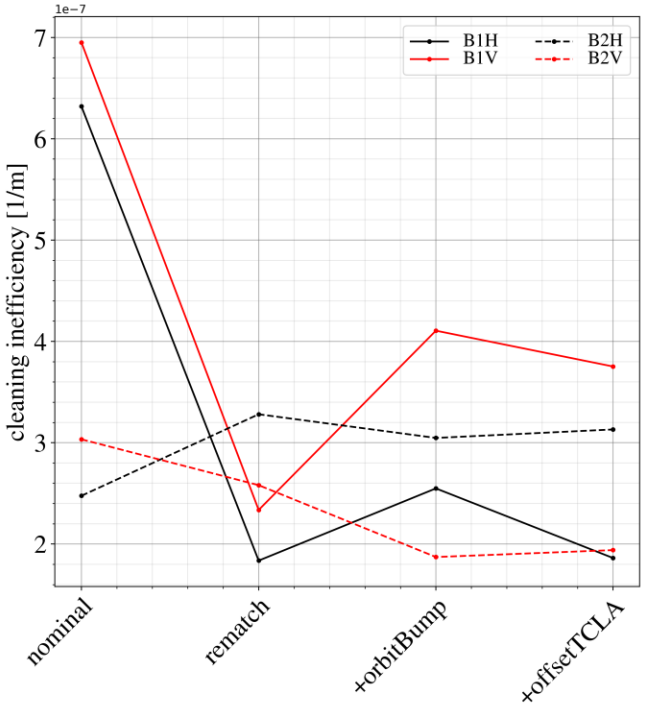
DS1



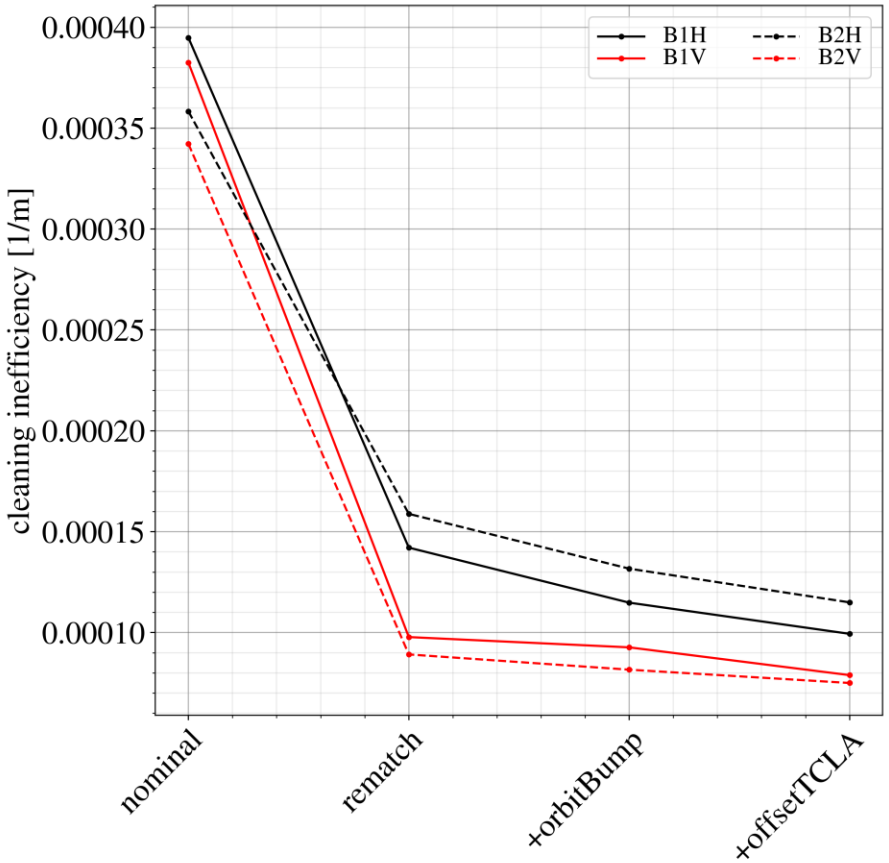
DS2



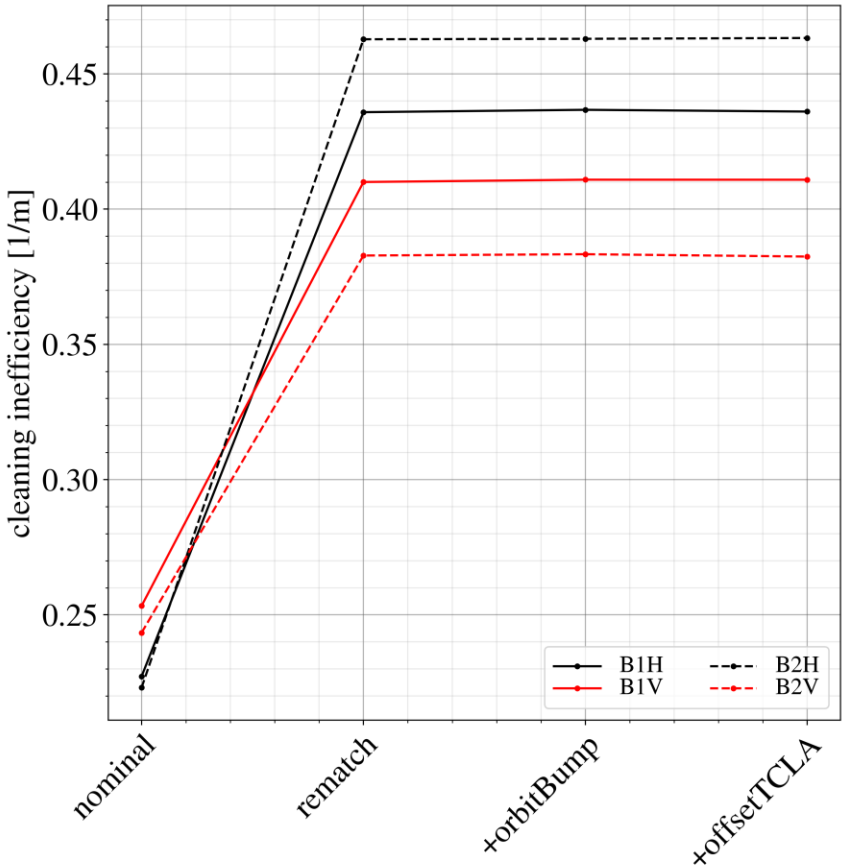
DS3



DS total



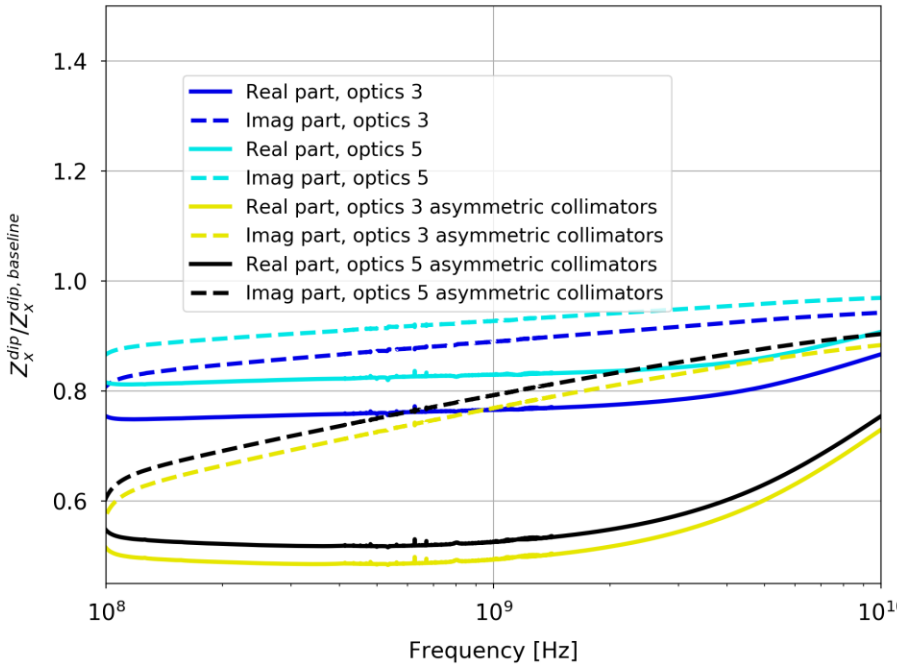
Global cleaning inefficiency



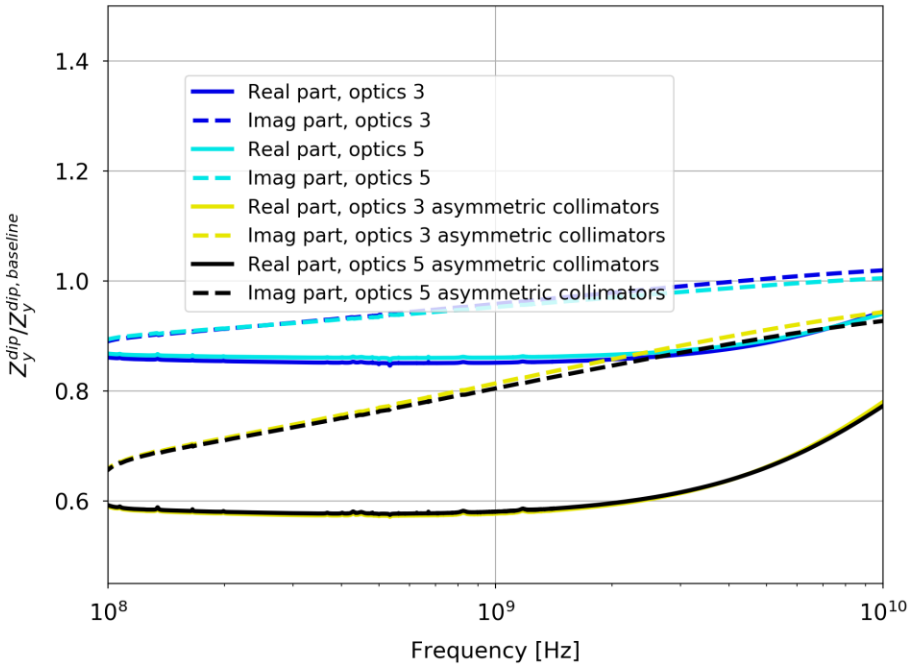
Impedance

- Impedance reduction, with/without asymmetric settings
- Optics 5 is the one proposed for the MD

horizontal

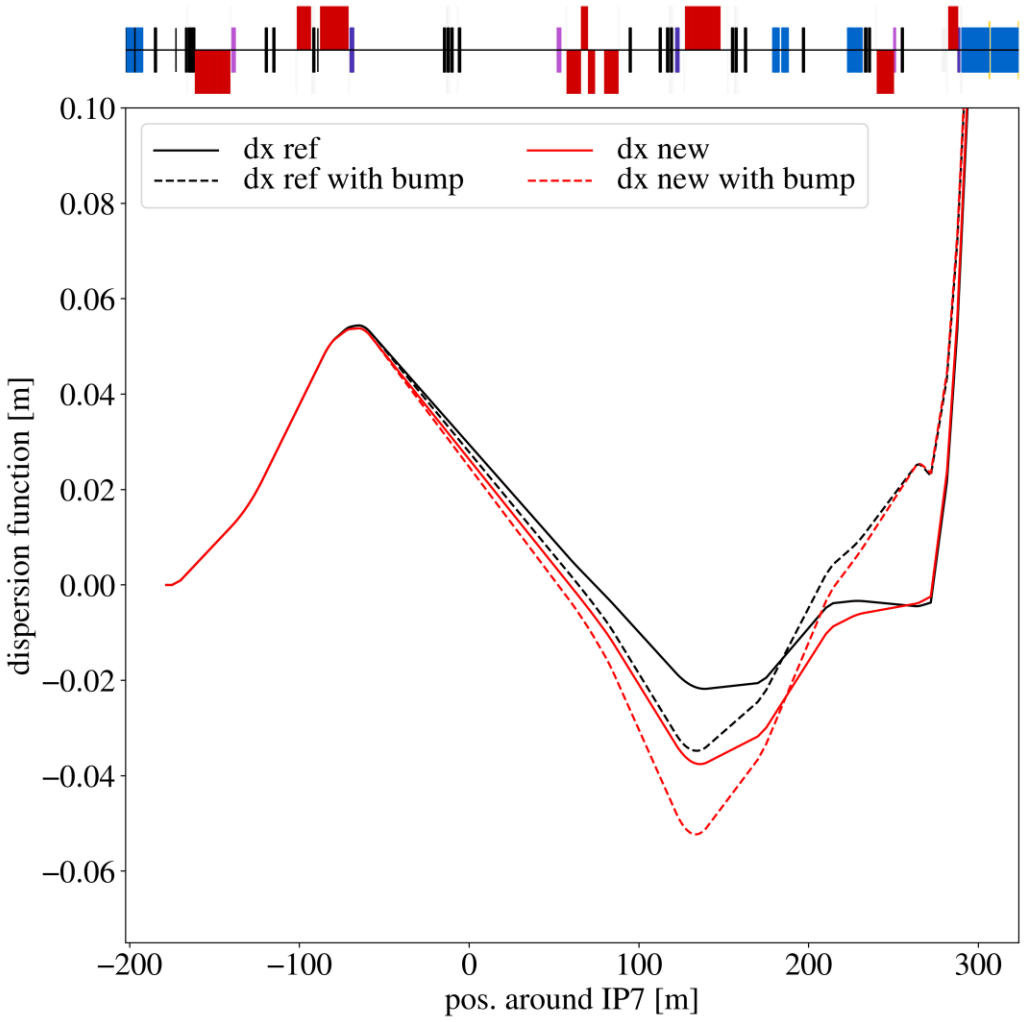


vertical

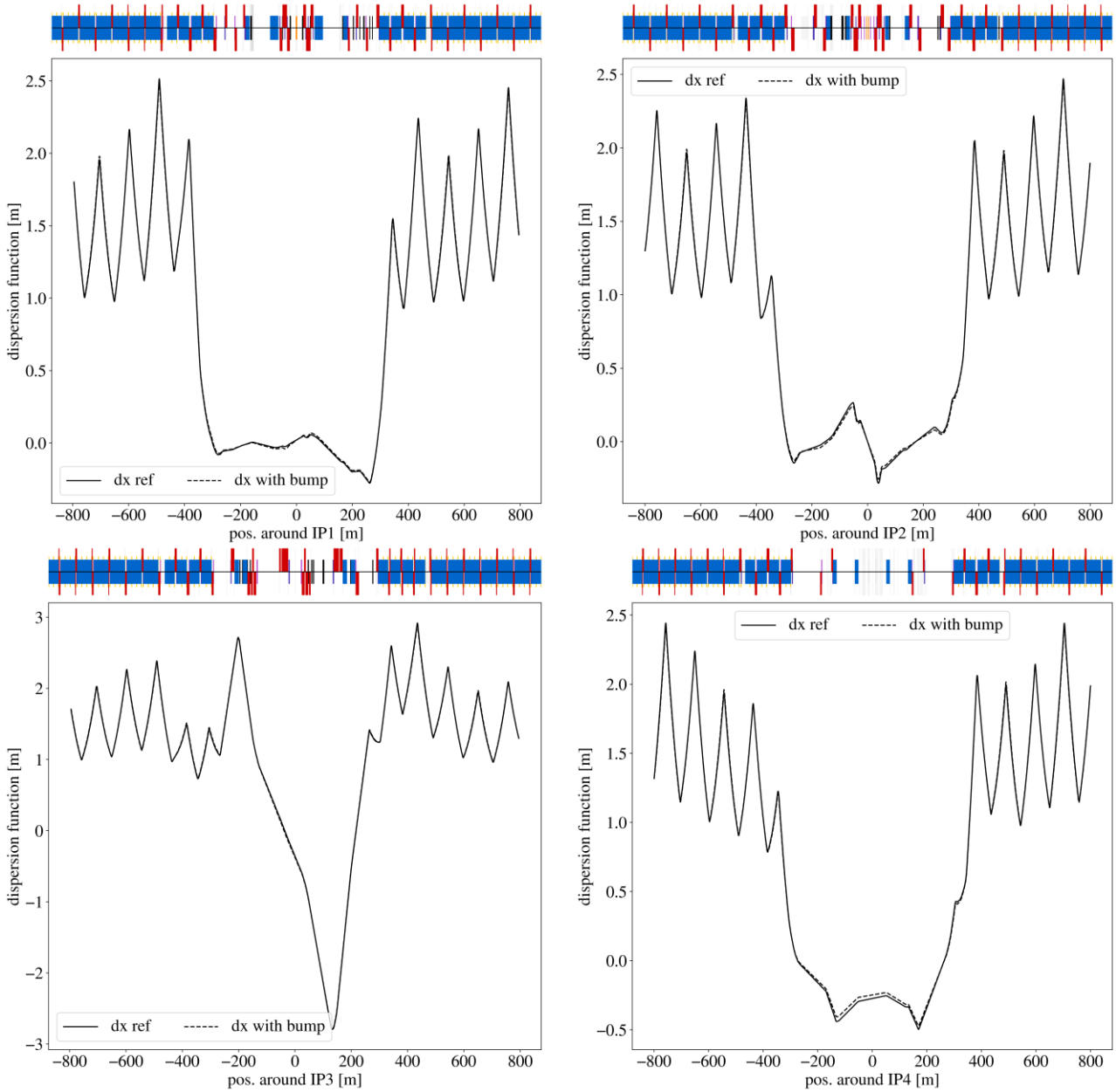


L. Giacomel

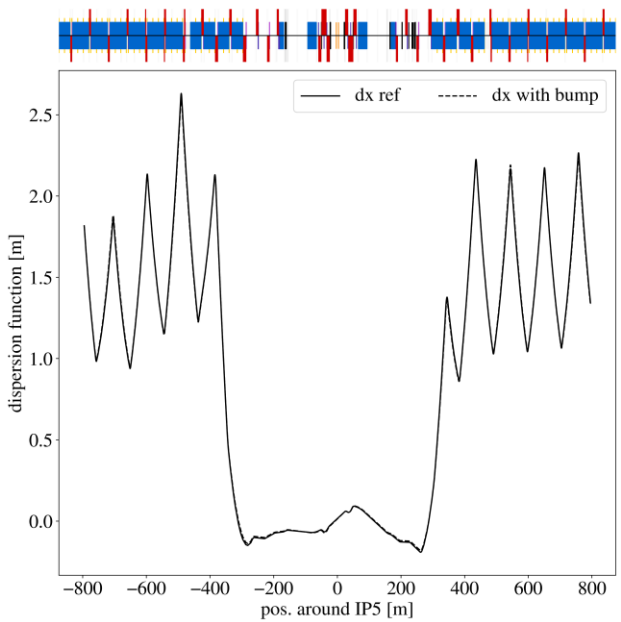
Single pass dispersion

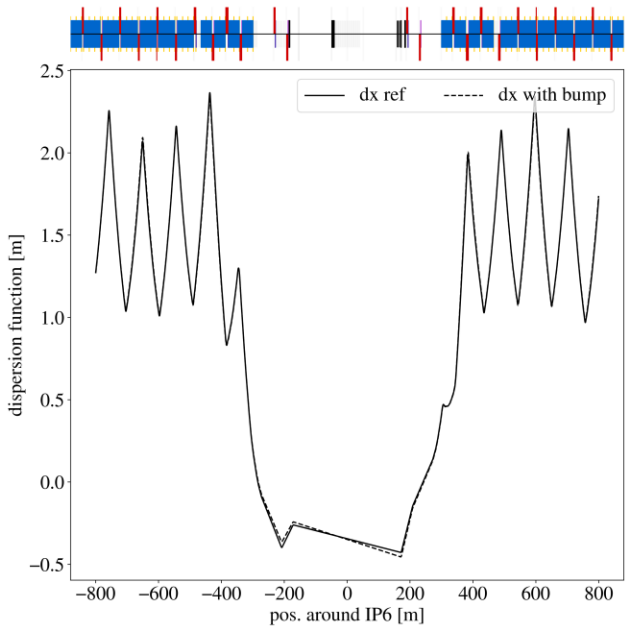


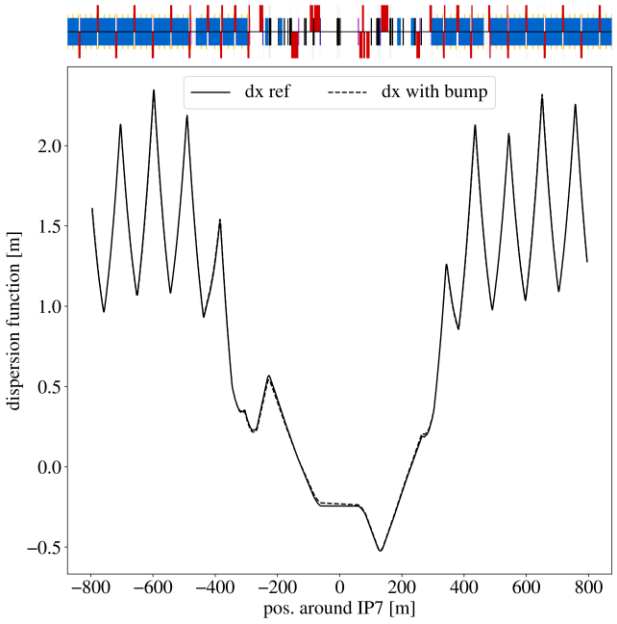
Orbit Bump – Global Dispersion

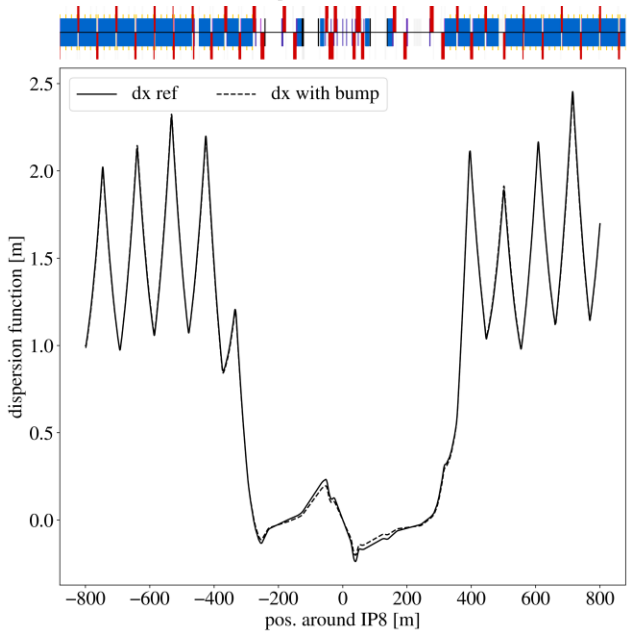


Orbit Bump – Global Dispersion



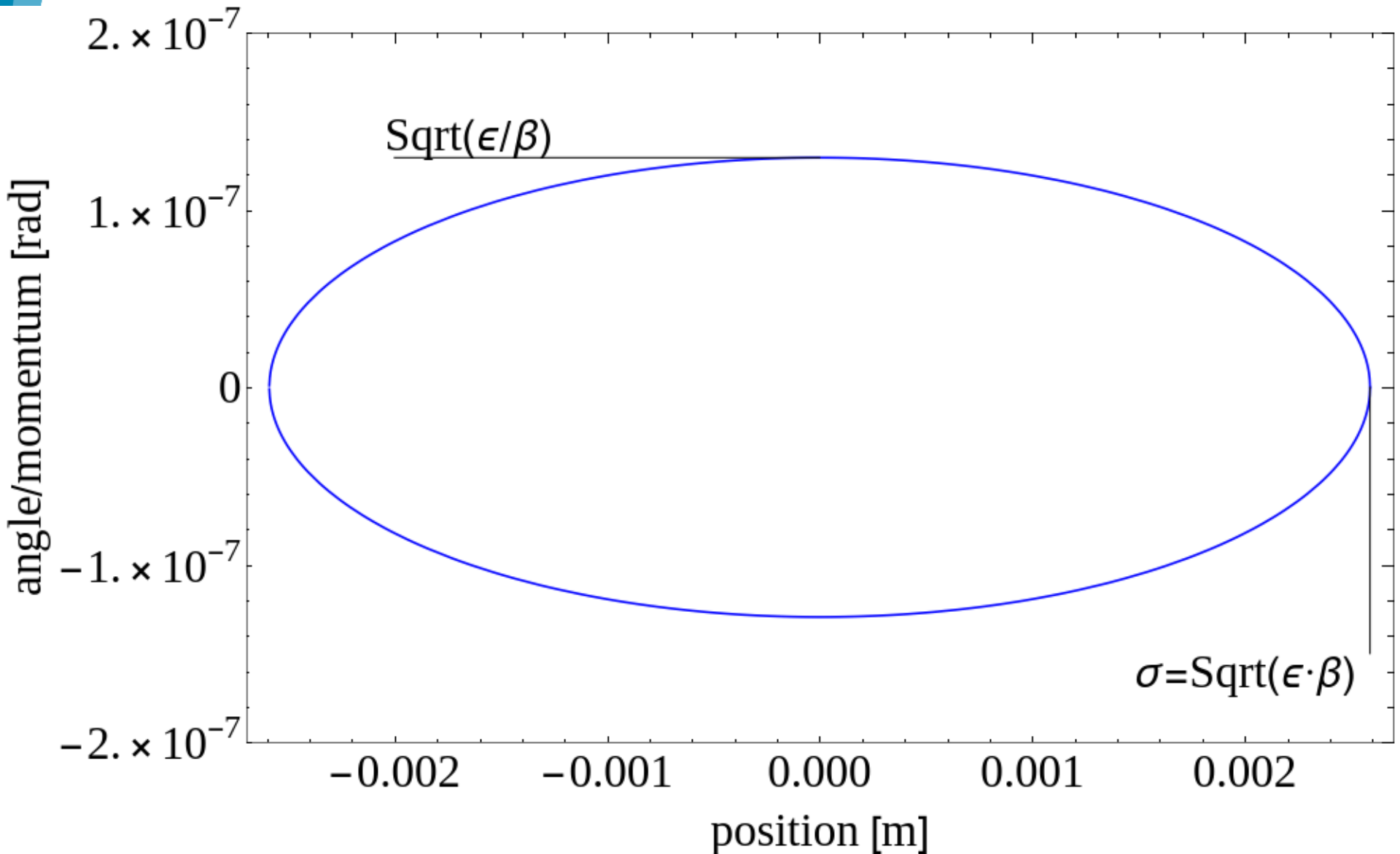






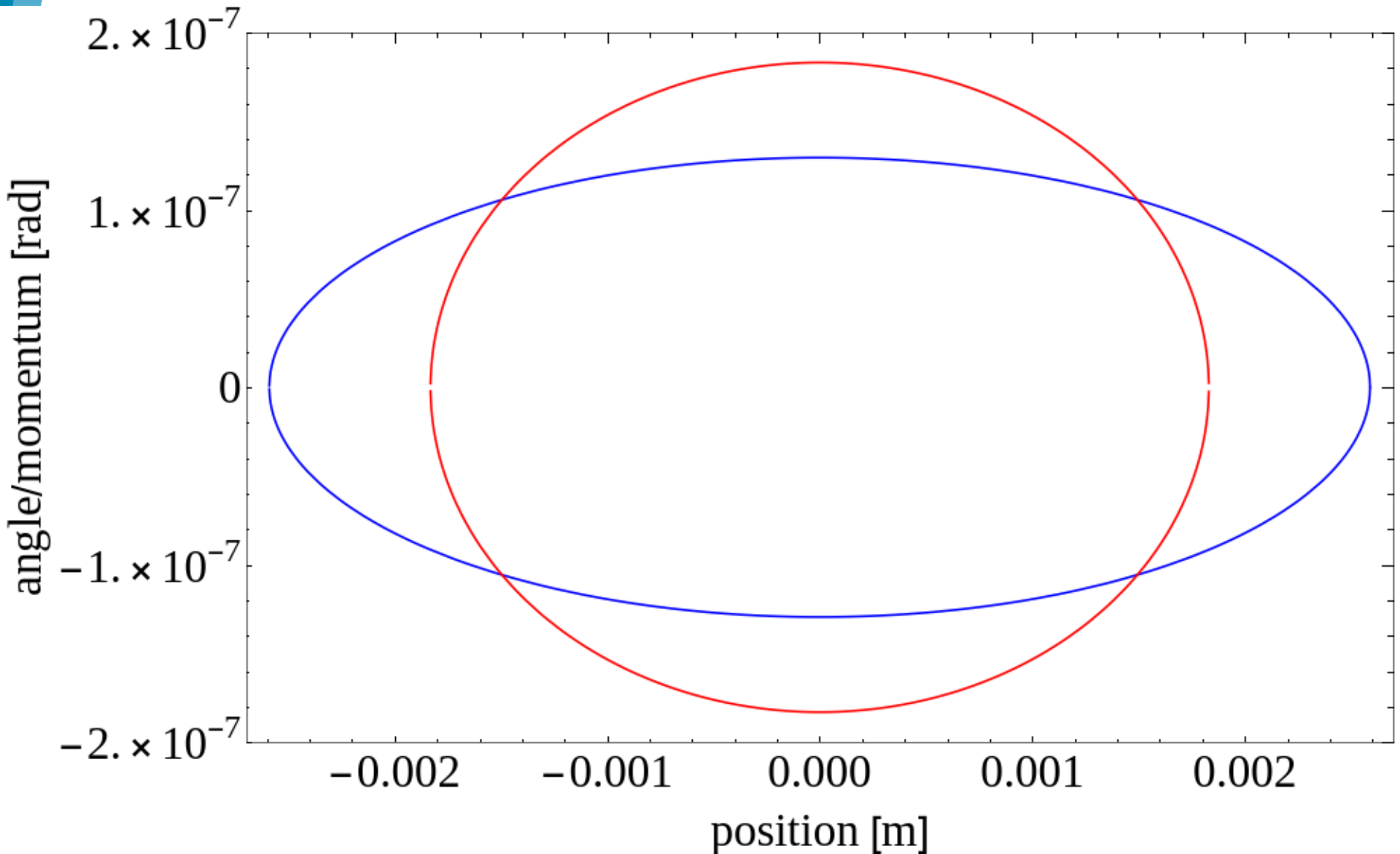
Beam sensitivity to perturbations

Constant area: $\pi \cdot \epsilon$



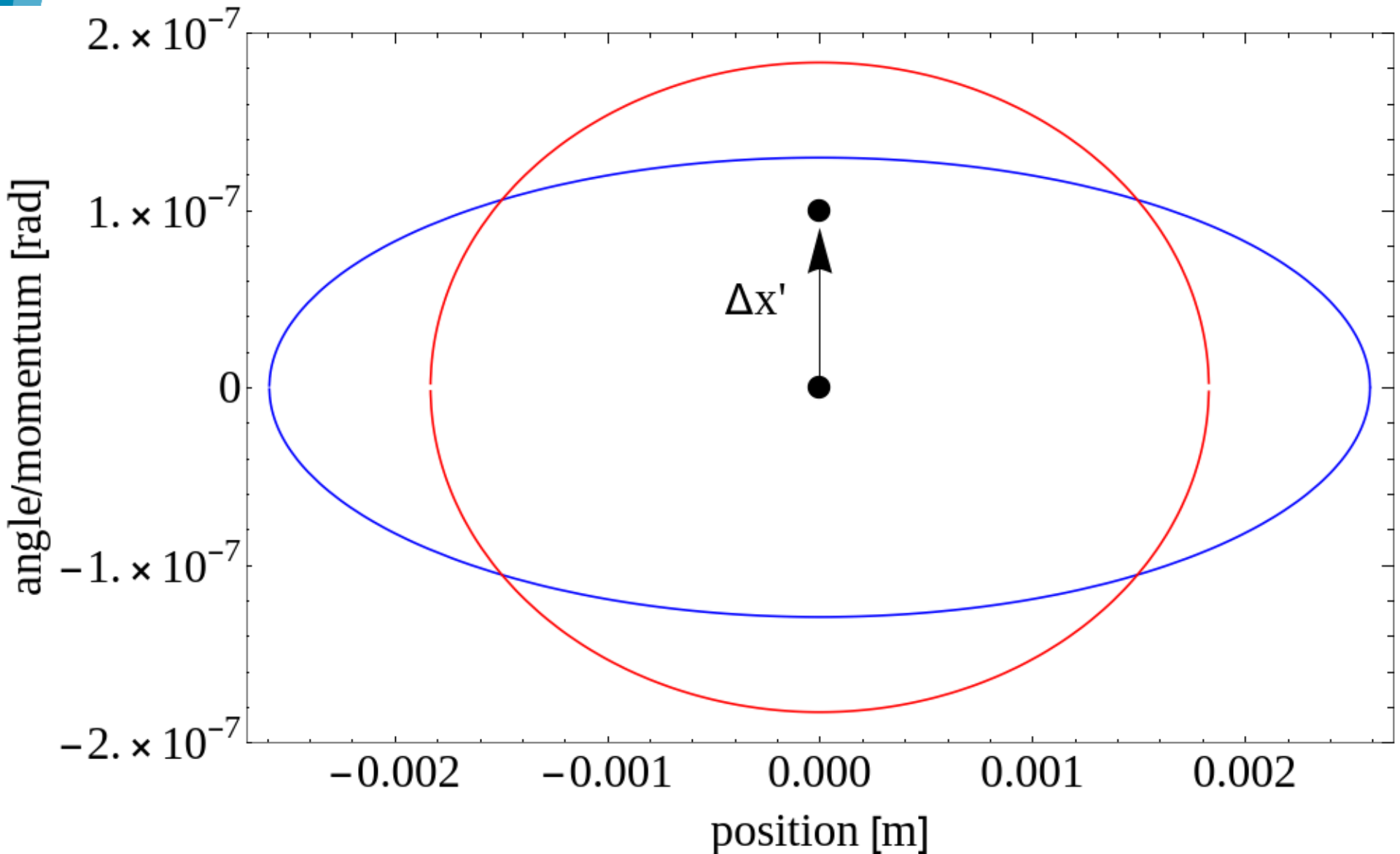
Beam sensitivity to perturbations

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



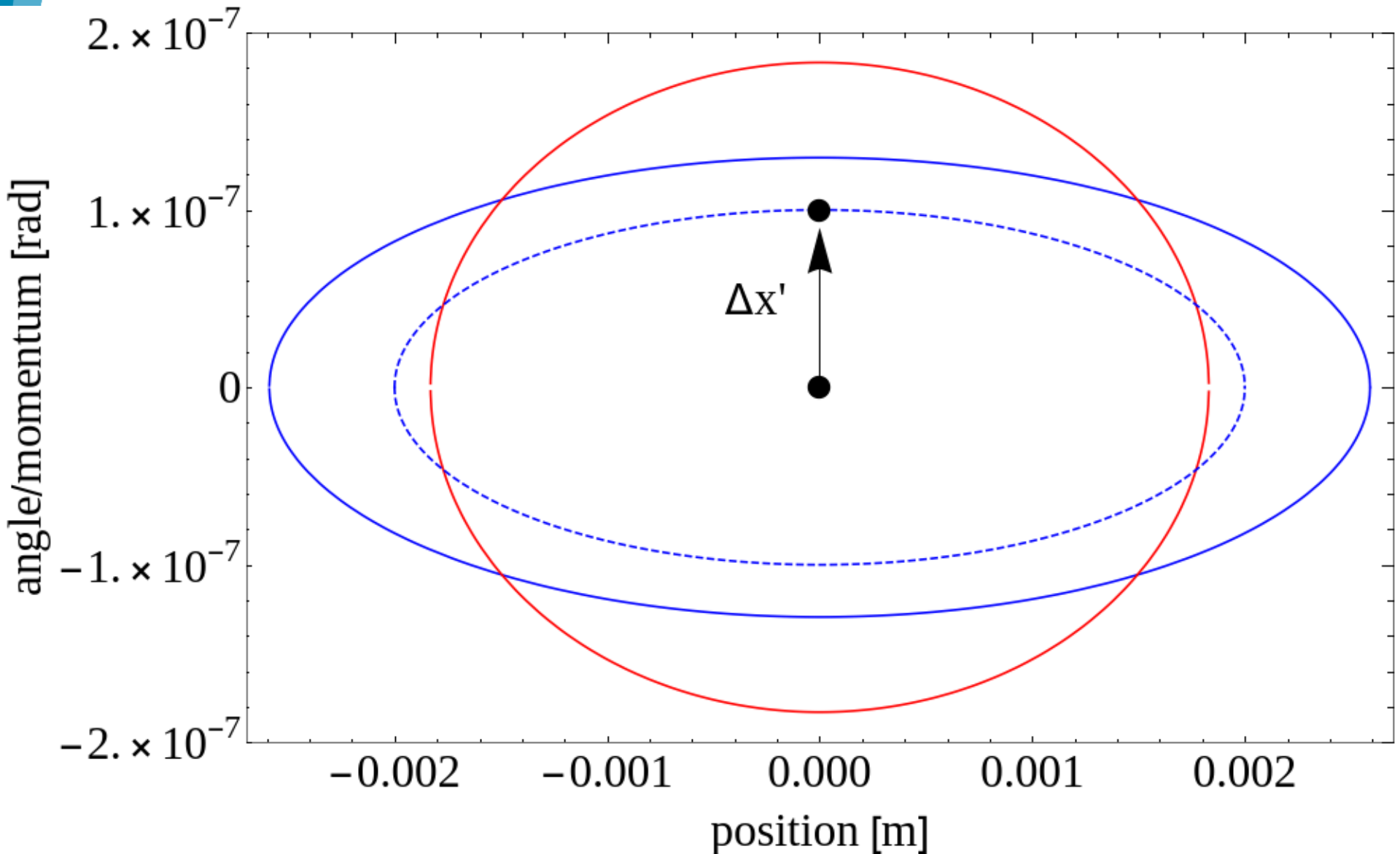
Beam sensitivity to perturbations

A particle receives a kick



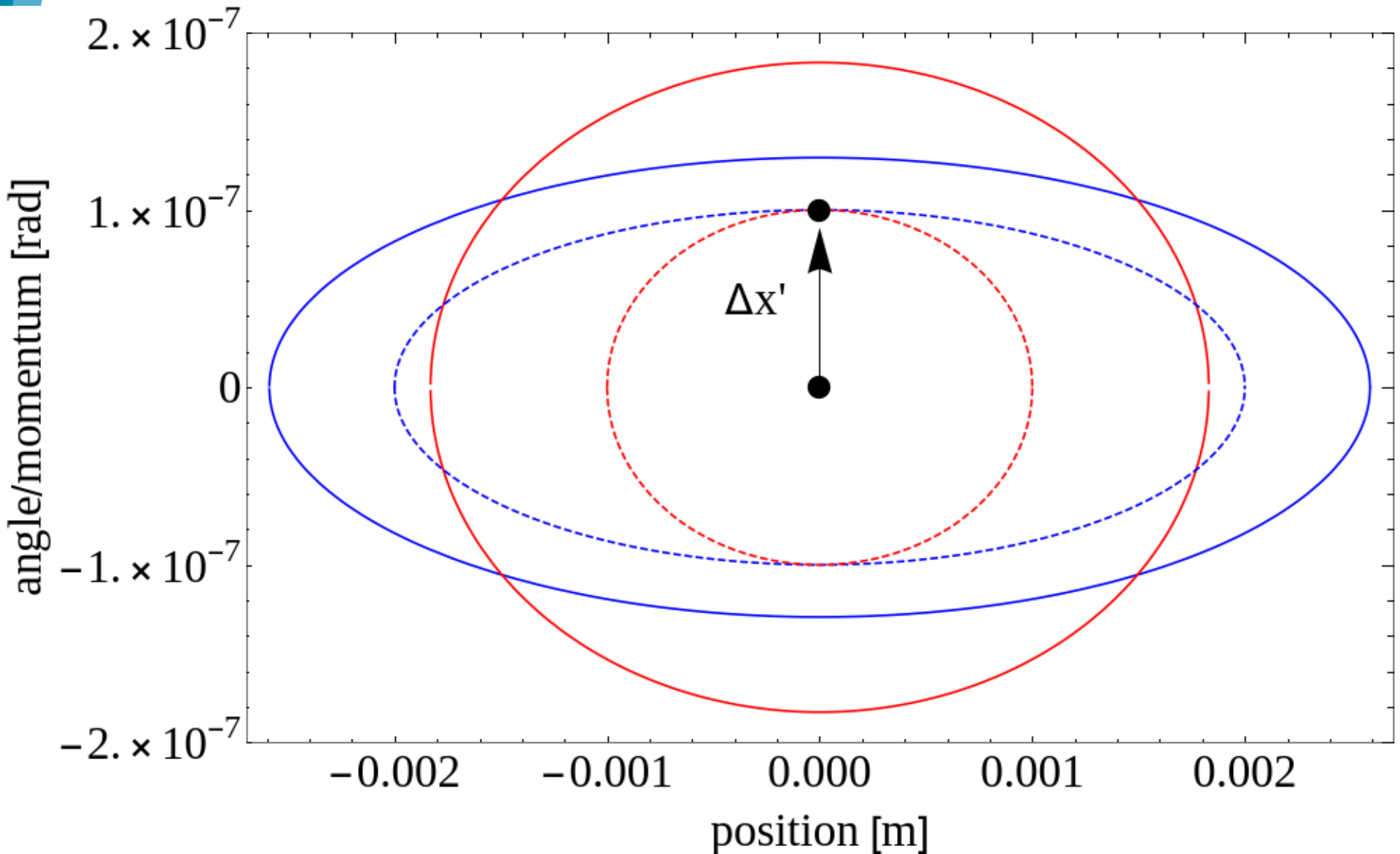
Beam sensitivity to perturbations

Particle traces out ellipse in phase space



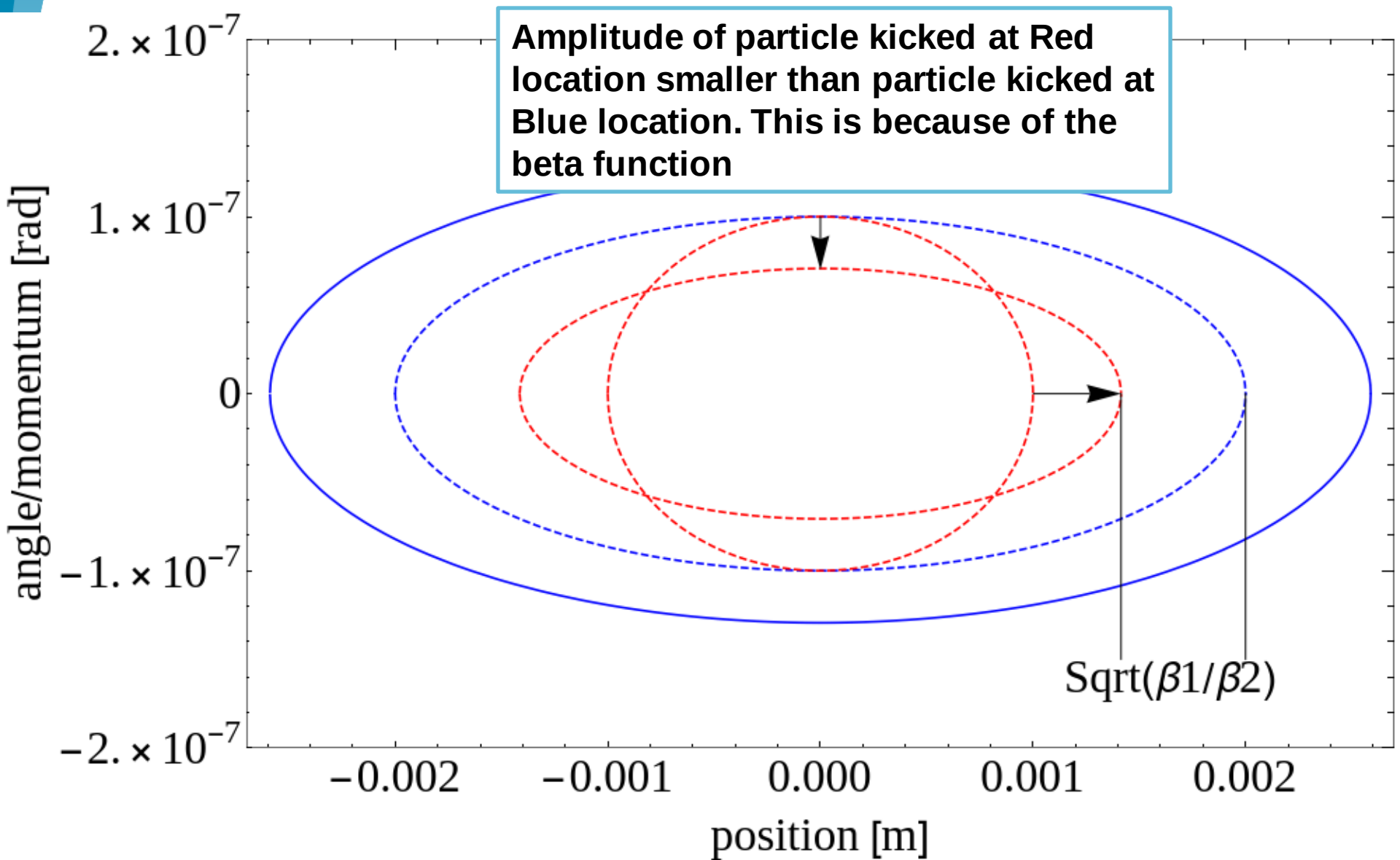
Beam sensitivity to perturbations

Particle at other location traces out different ellipse



Beam sensitivity to perturbations

Observe Red particle at Blue location, transforms the ellipse

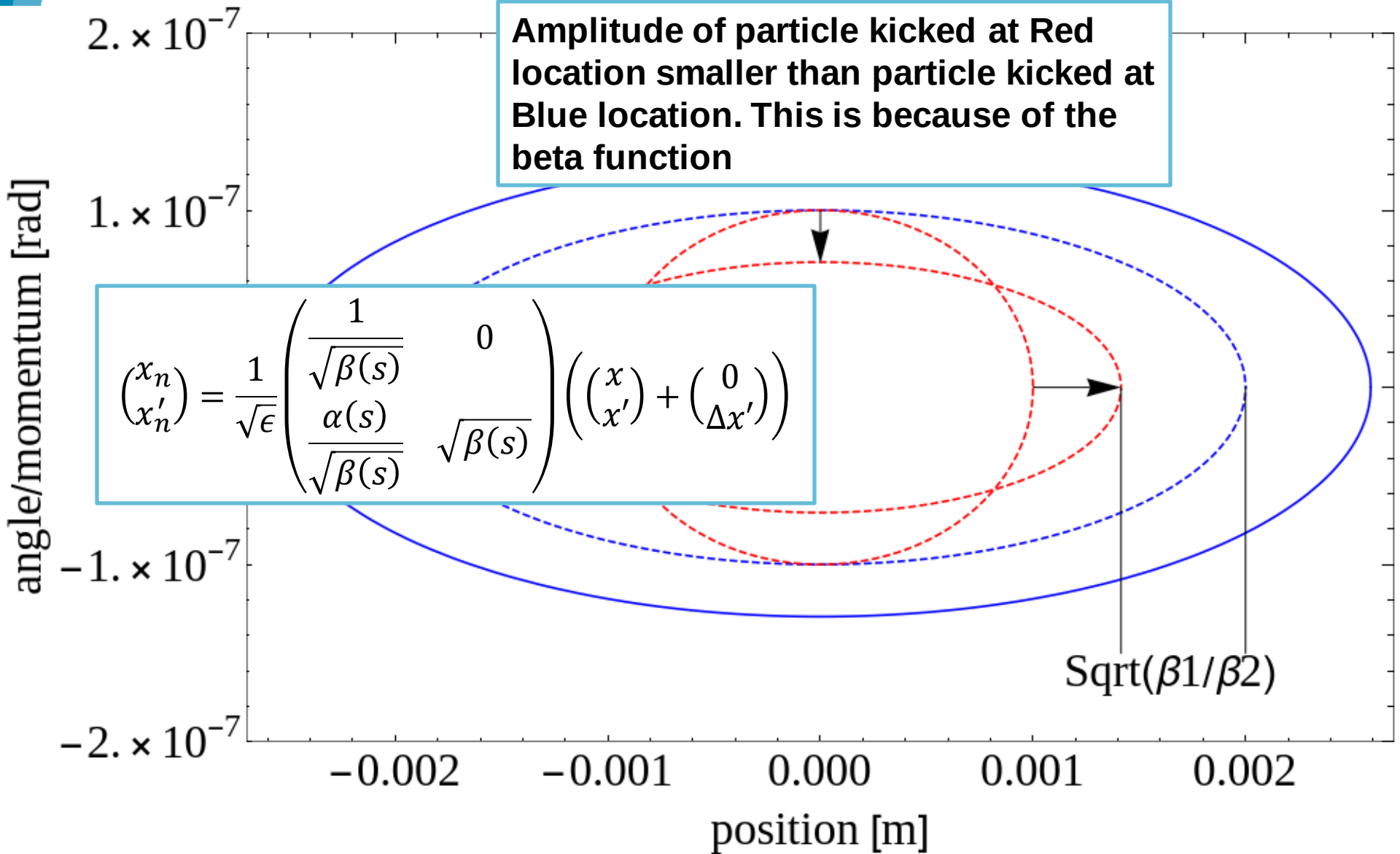


Beam sensitivity to perturbations

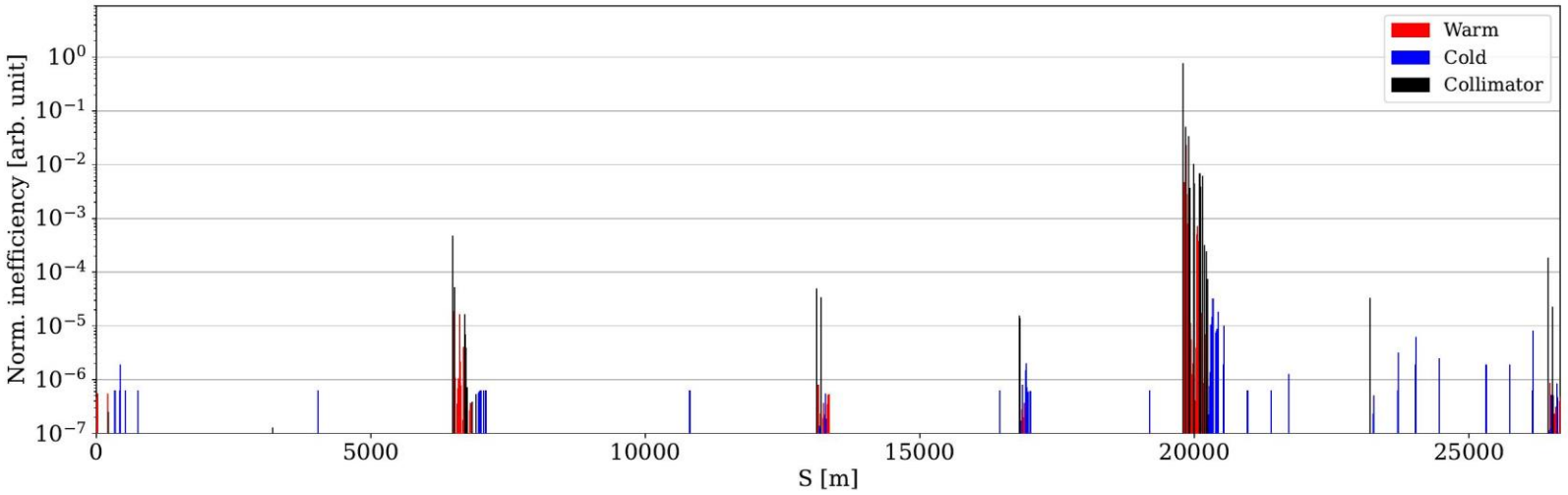
Observe Red particle at Blue location, transforms the ellipse

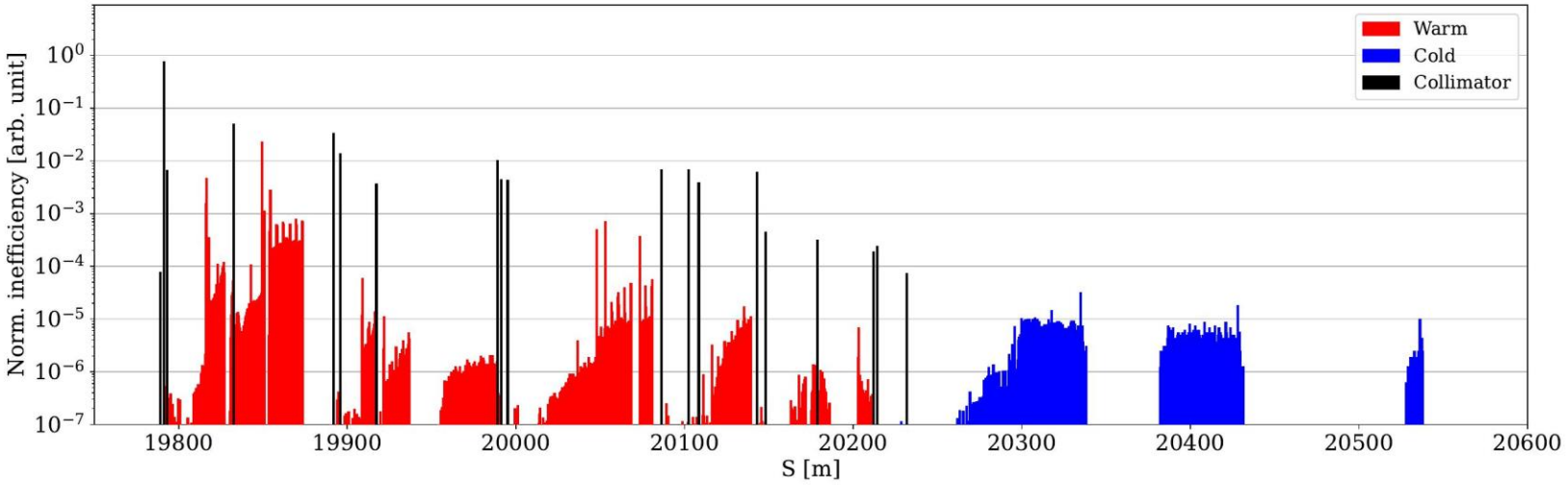
Amplitude of particle kicked at Red location smaller than particle kicked at Blue location. This is because of the beta function

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

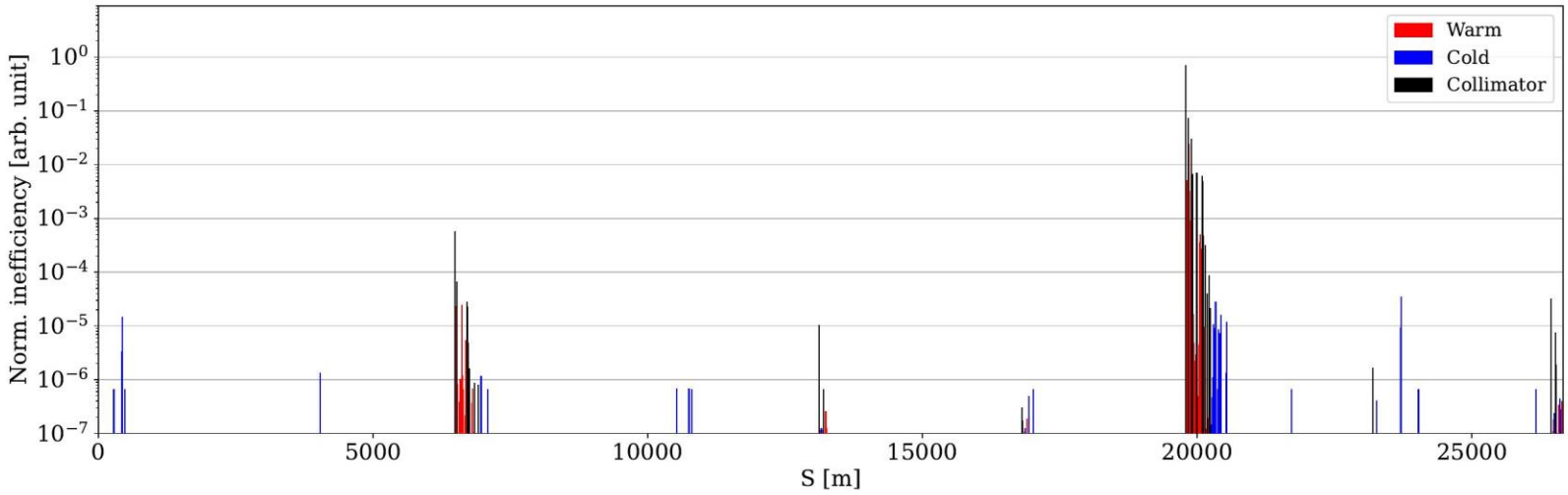


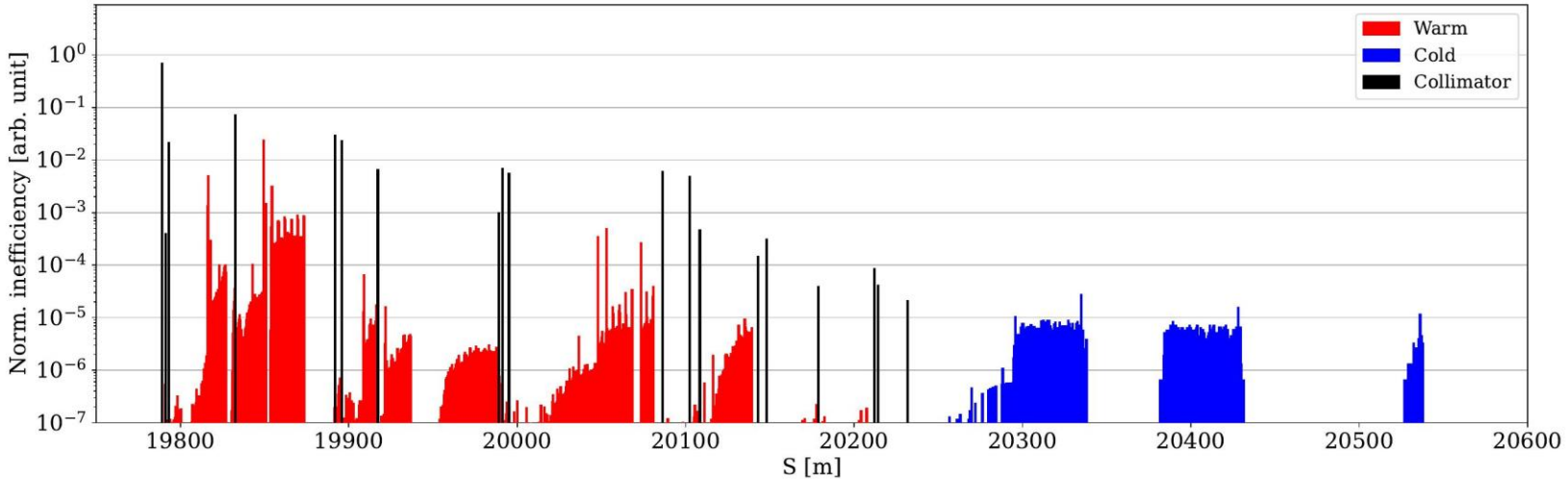
B1H – 20 cm – relaxed settings – no TCLD (ref)



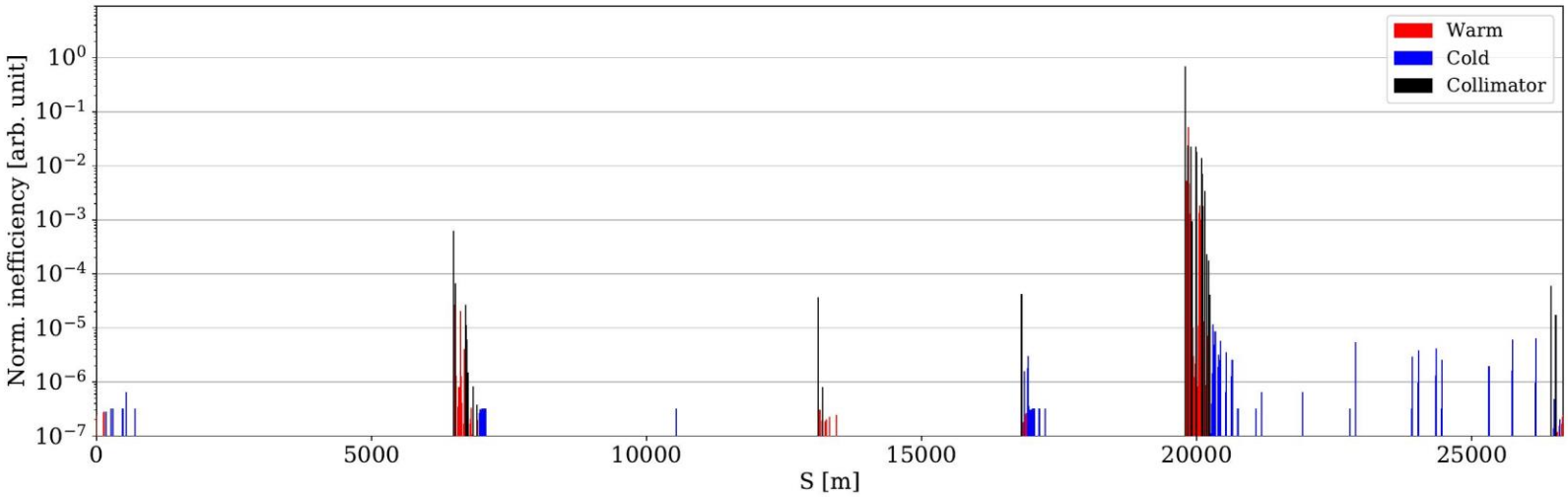


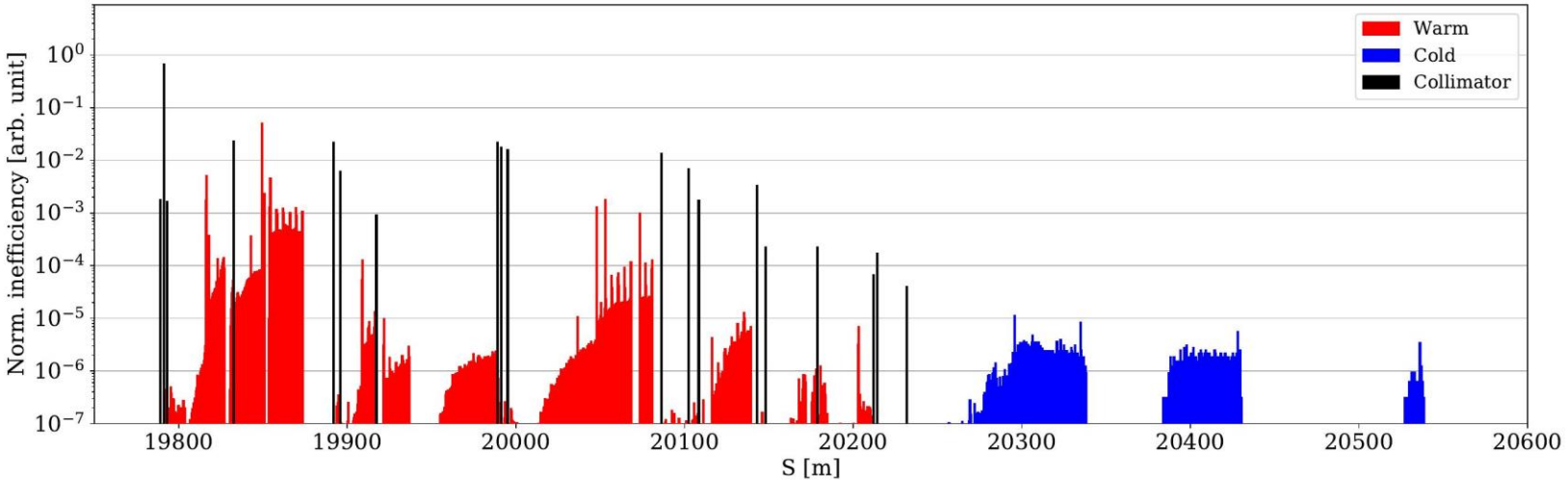
B1V – 20 cm – relaxed settings – no TCLD (ref)



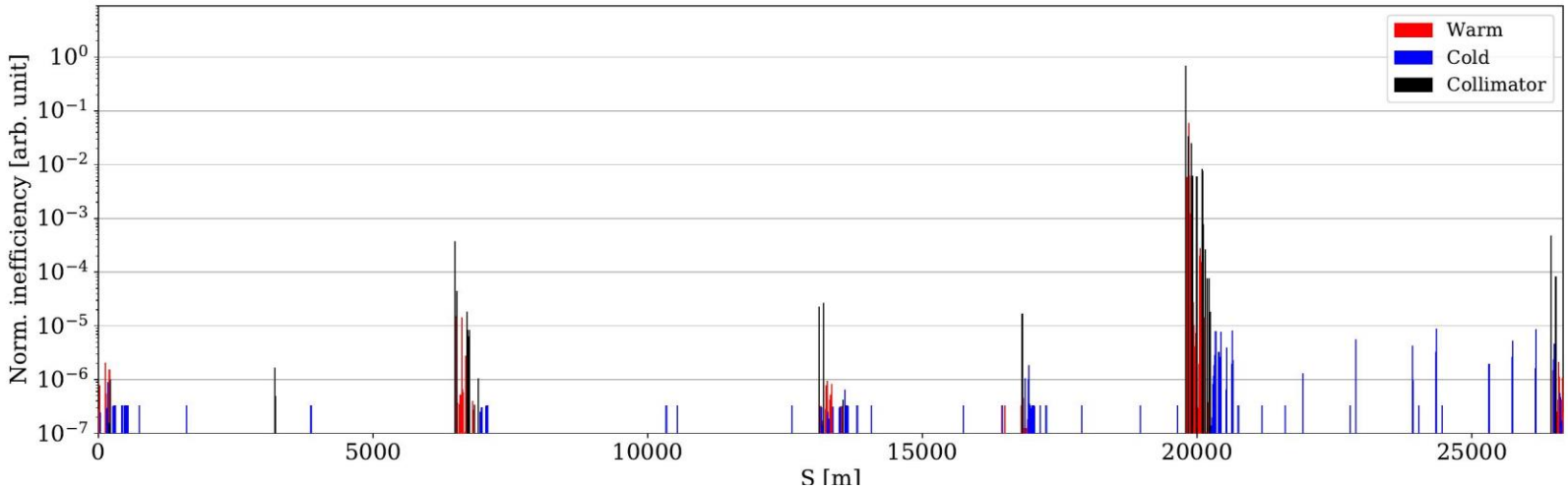


B1H – rematch


Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
5000
10000
15000
20000
25000
S [m]


Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
19800
19900
20000
20100
20200
20300
20400
20500
20600
S [m]

B1V – rematch


Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
10^{0}
10^{-1}
10^{-2}
10^{-3}
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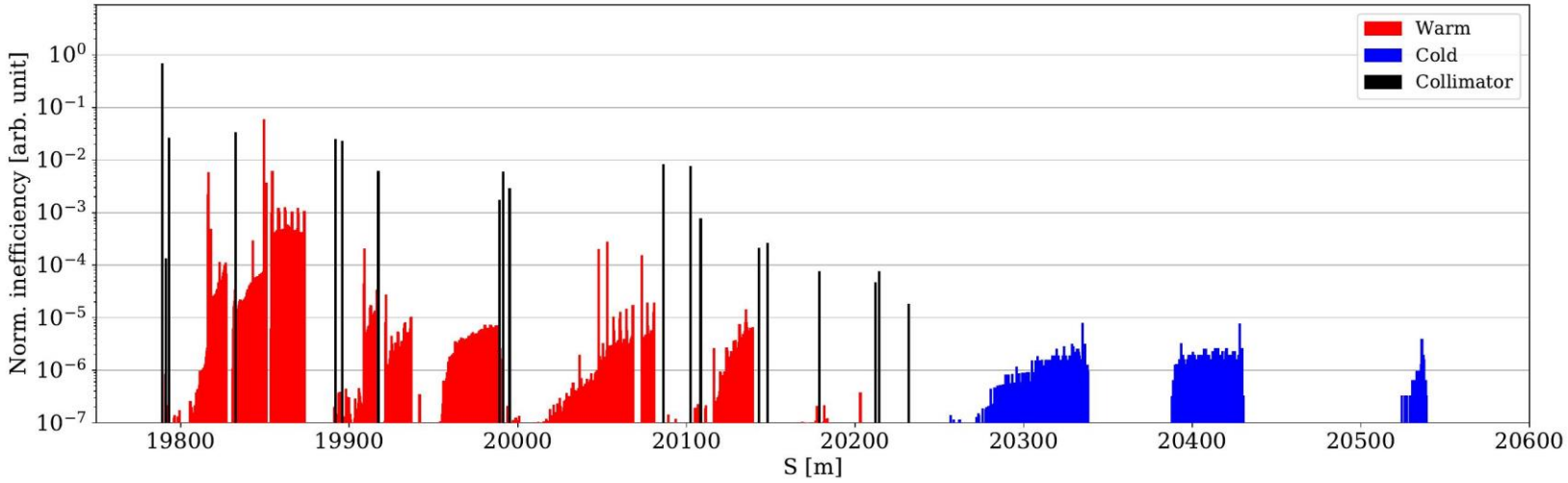
10^{-5}
10^{-6}
10^{-7}
0
5000
10000
15000
20000
25000
S [m]


Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
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19900
20000
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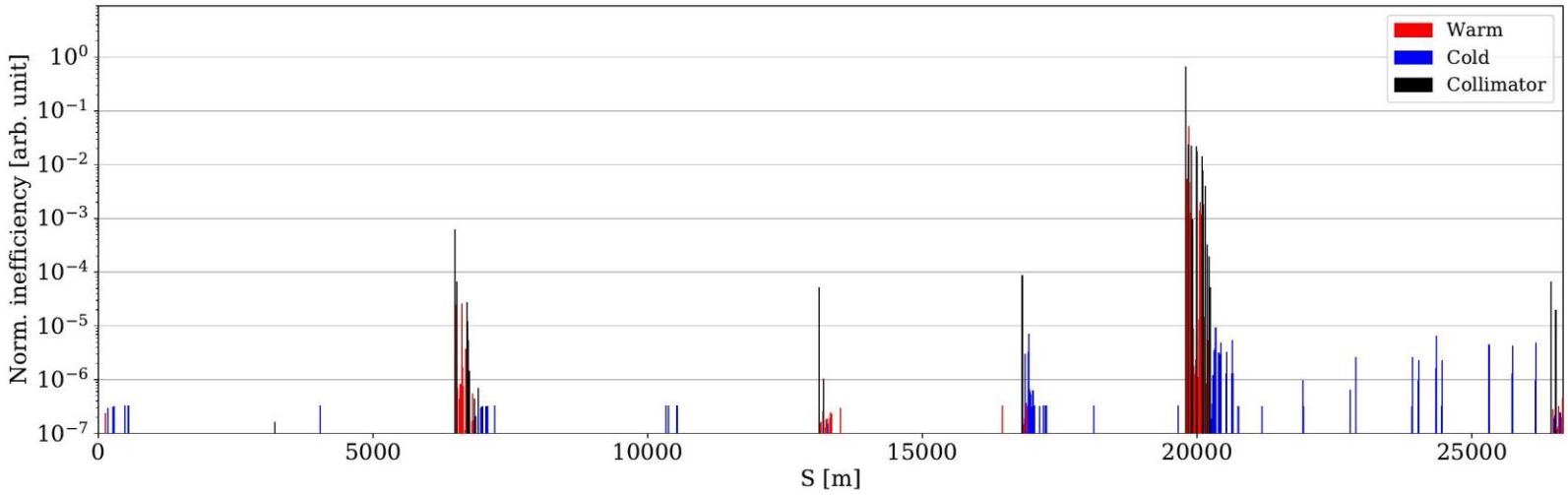
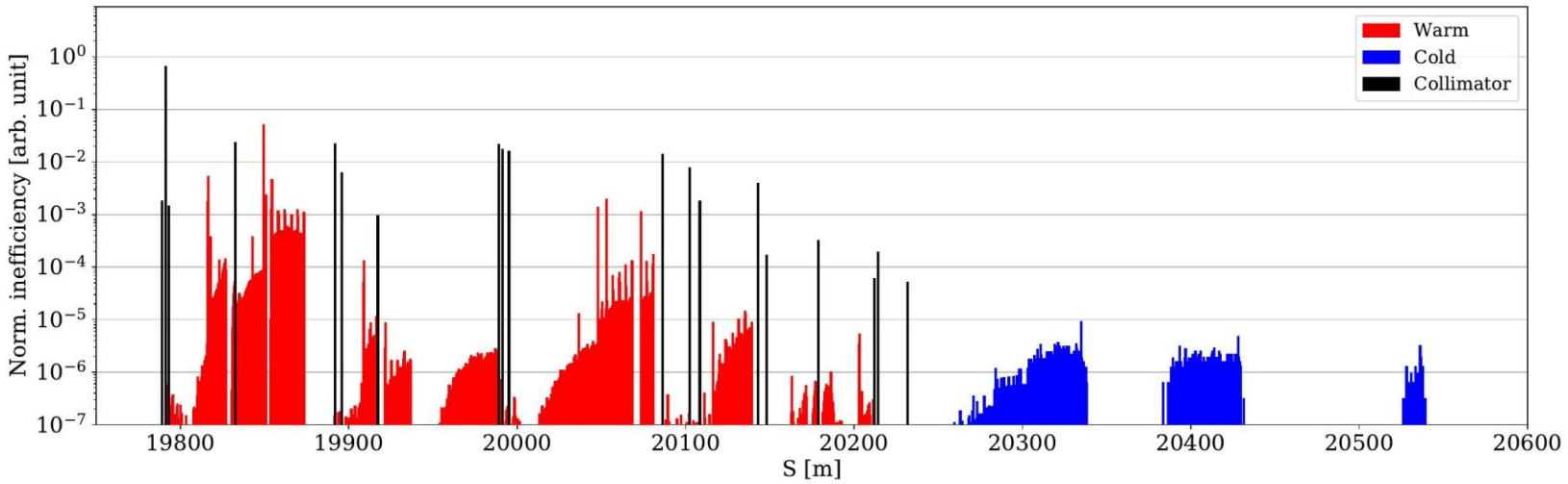
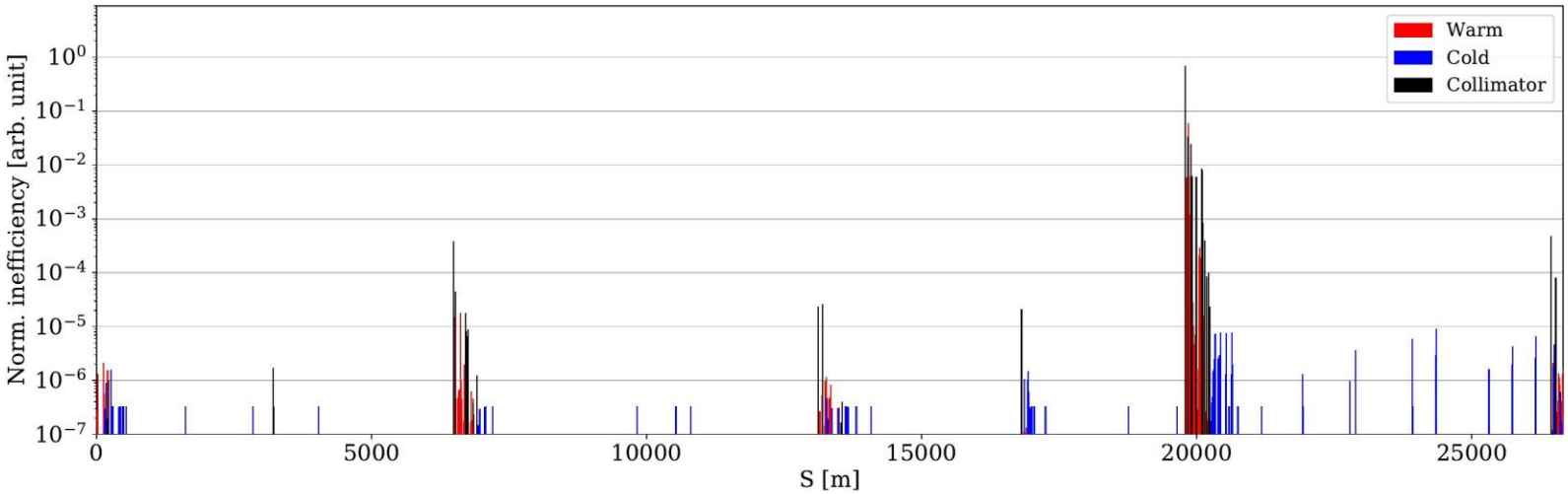
20200
20300
20400
20500
20600
S [m]

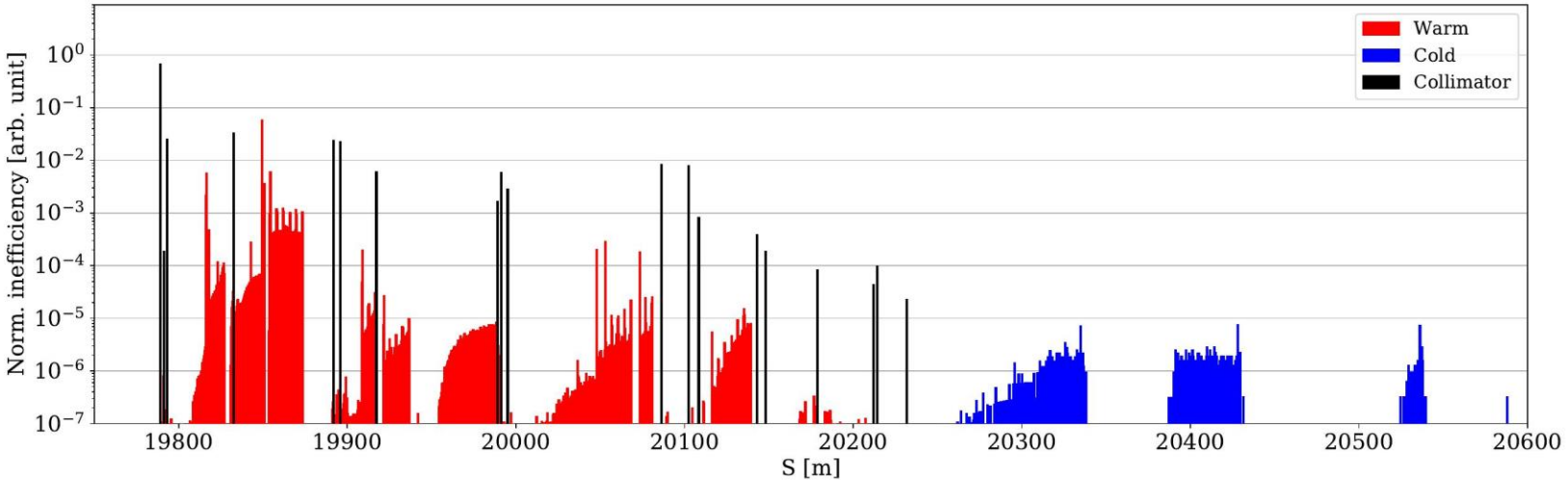
B1H – rematch + orbit bump



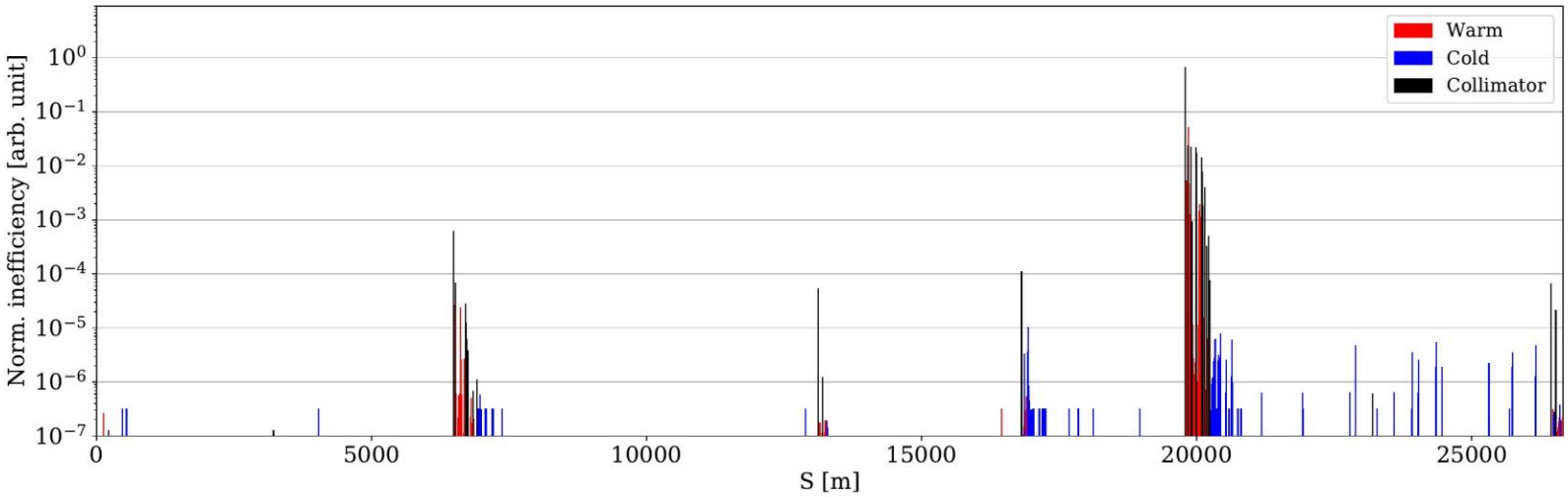


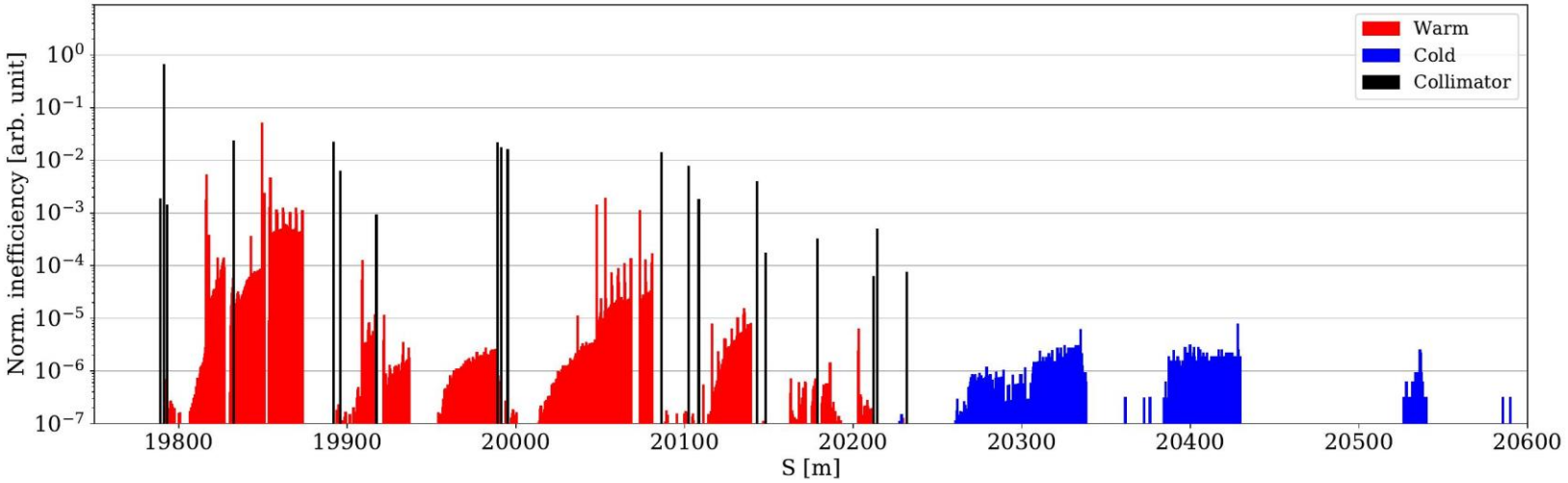
B1V – rematch + orbit bump



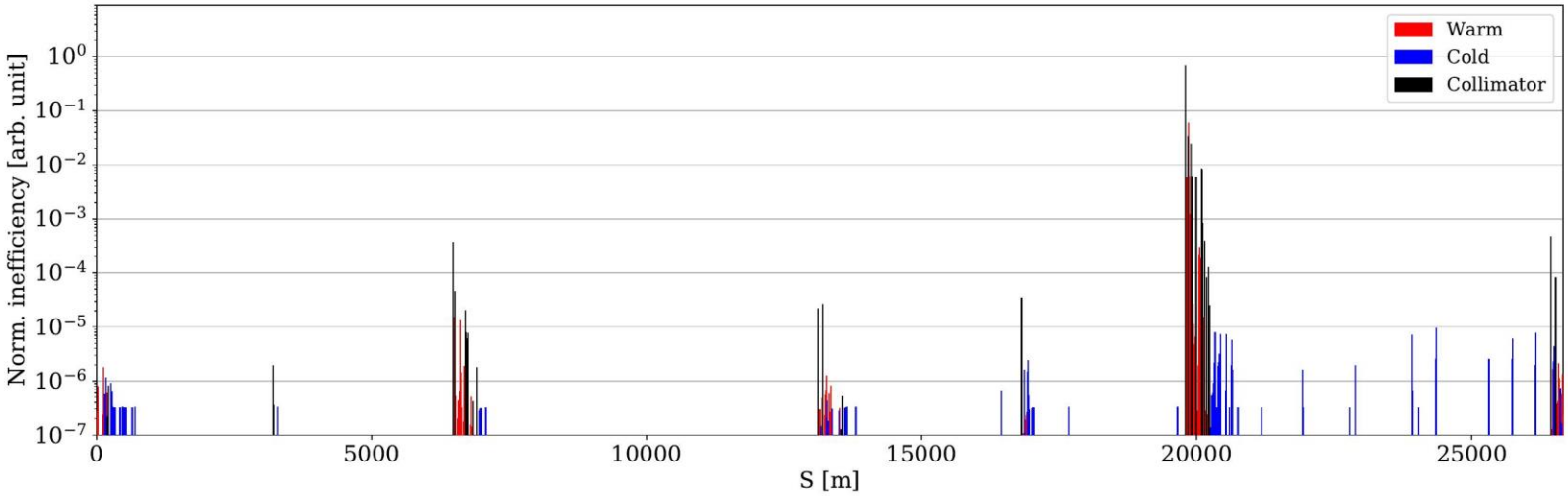


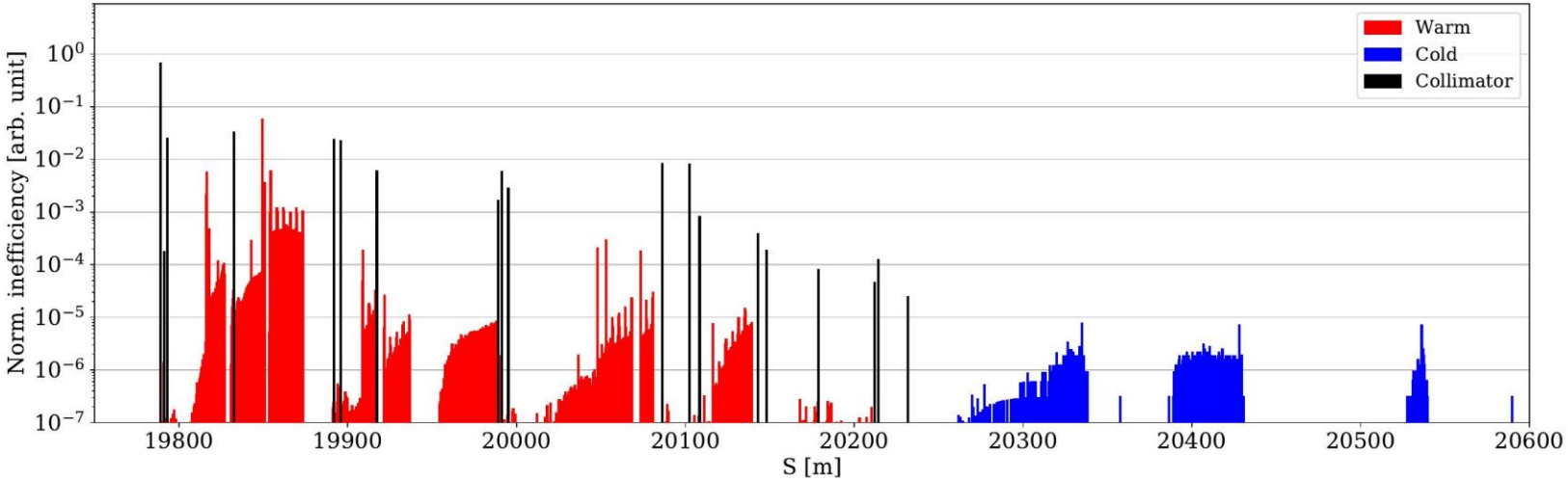
B1H – rematch + orbit bump + TCLA offset 3 sigma



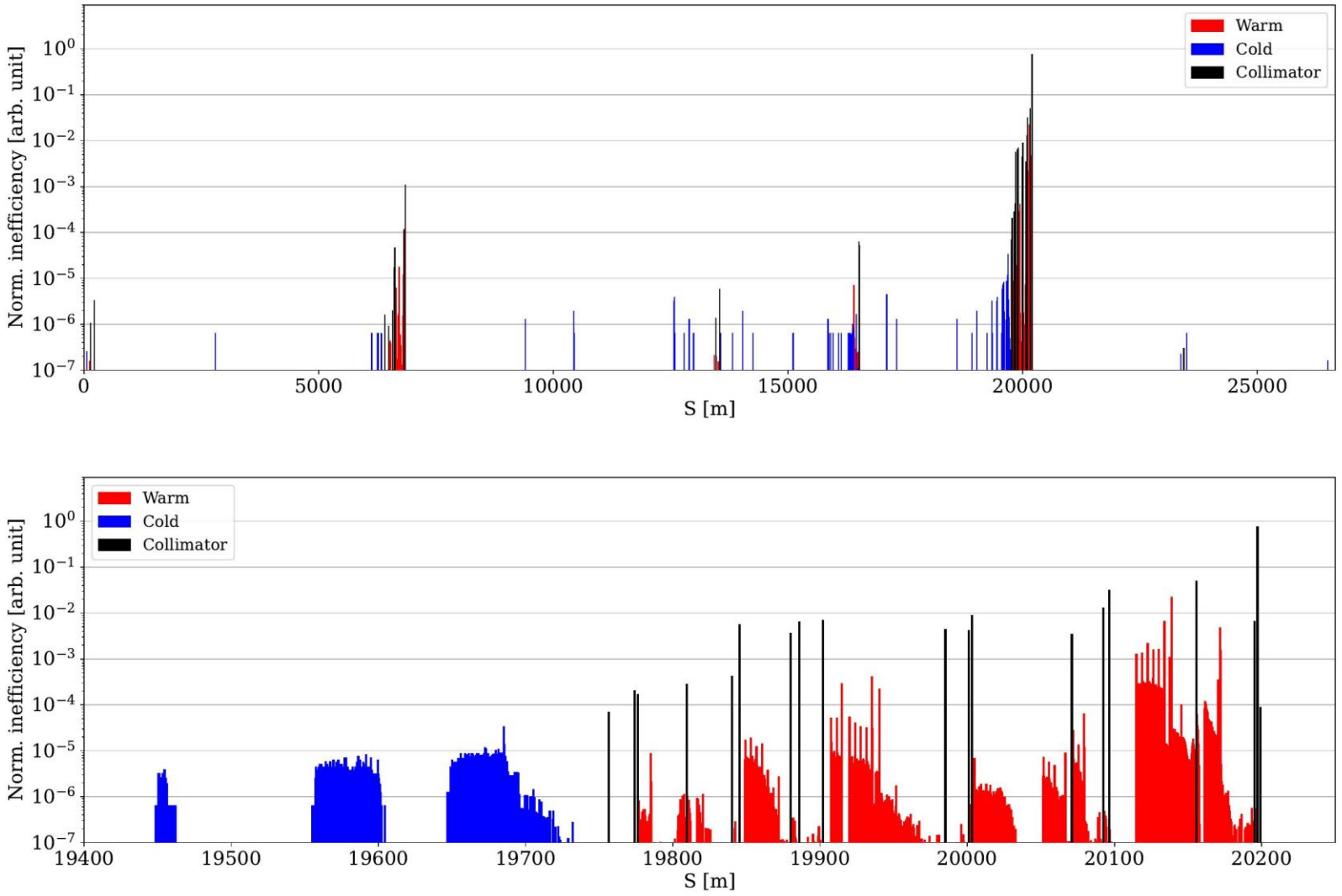


B1V – rematch + orbit bump + TCLA offset 3 sigma

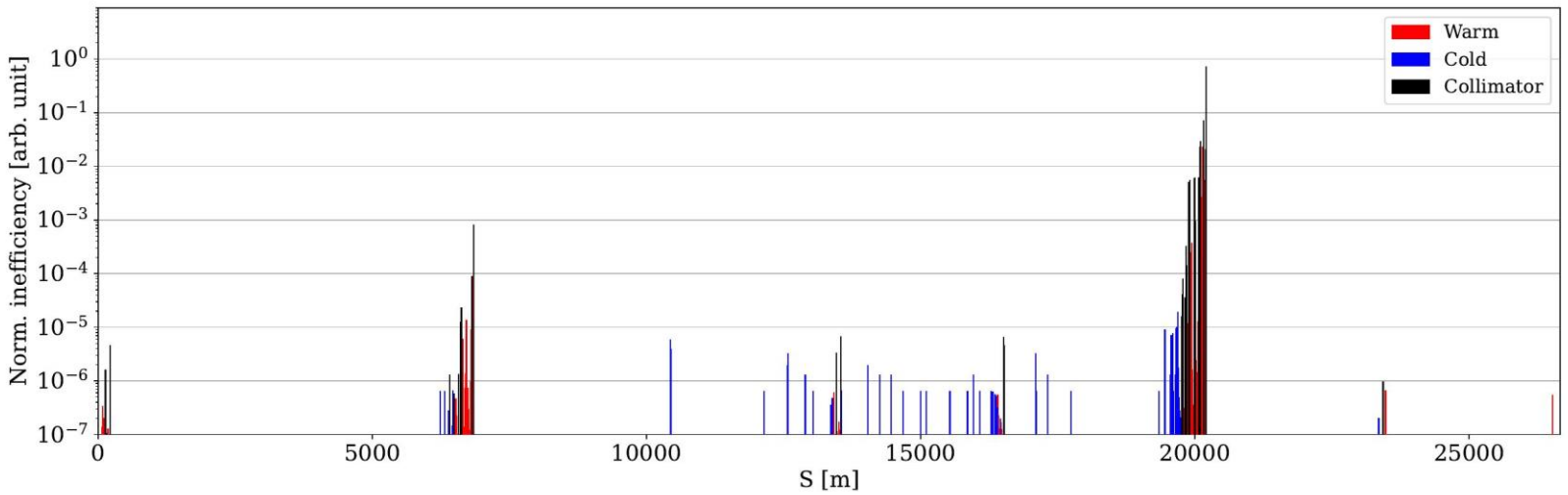


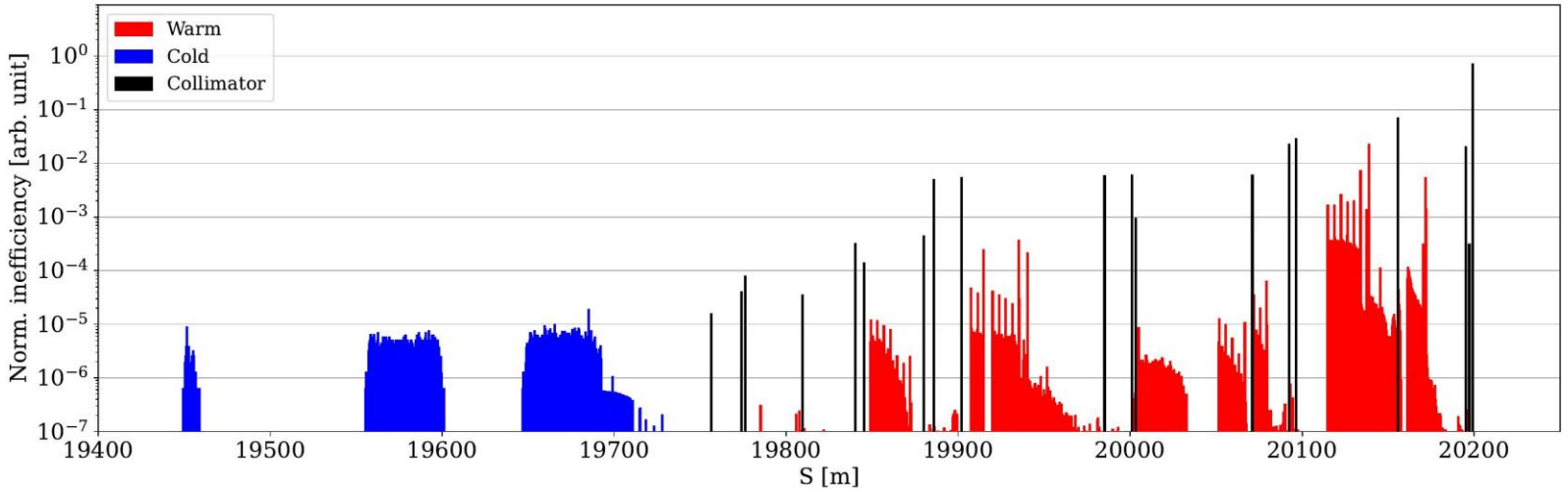


B2H – 20 cm – relaxed settings – no TCLD (ref)

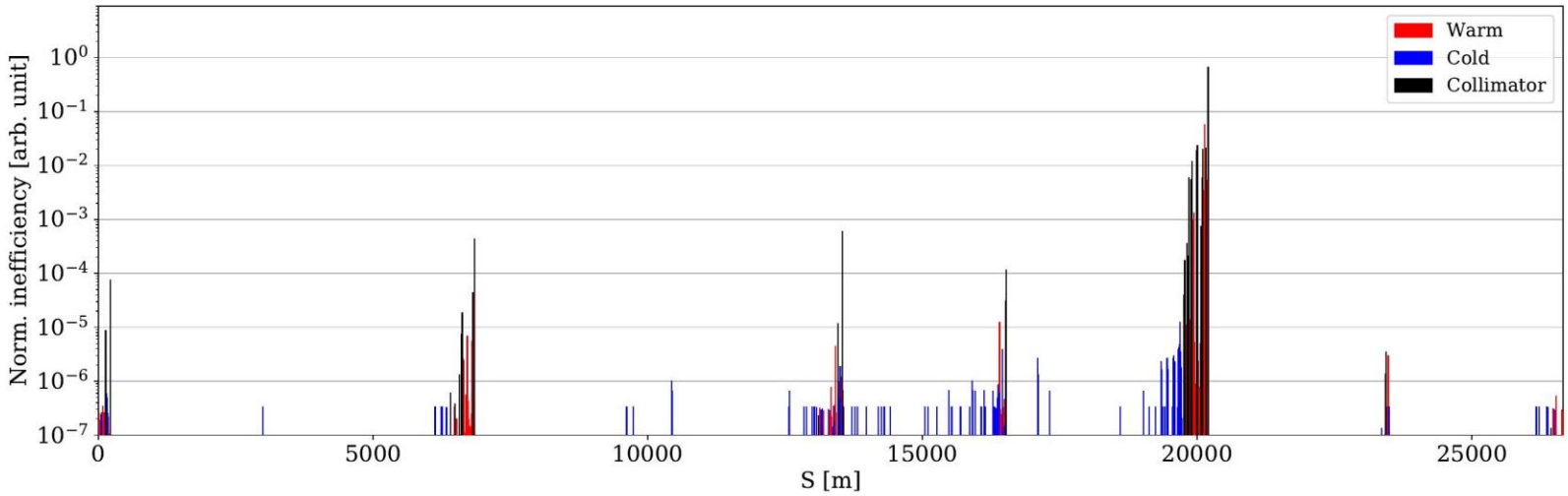


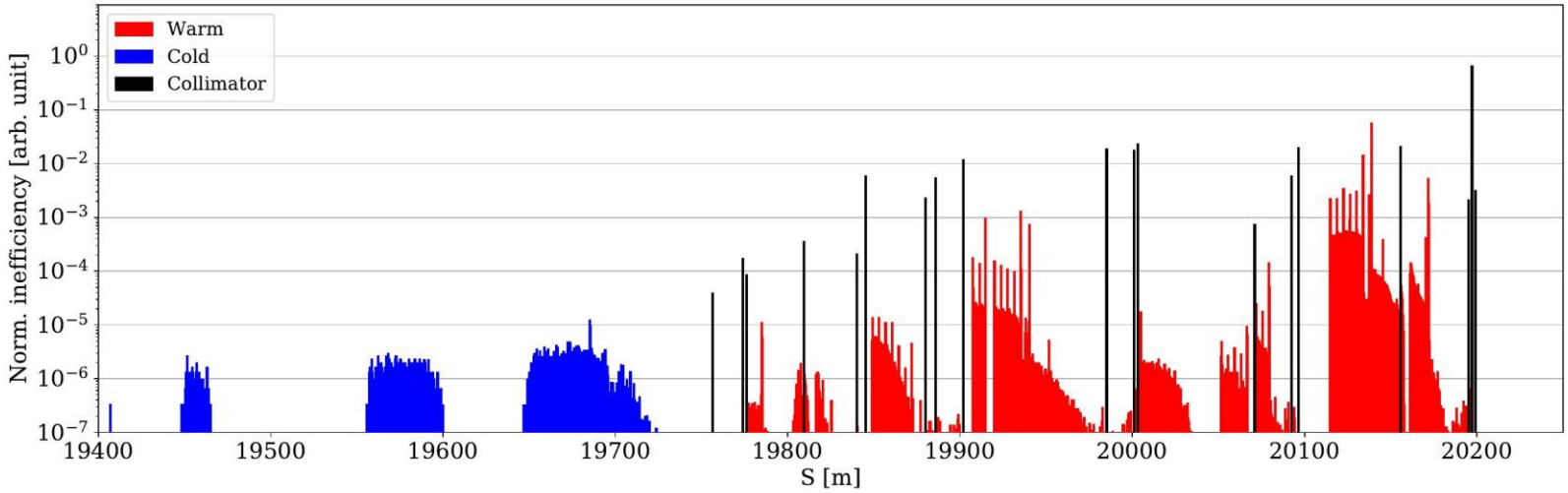
B2V – 20 cm – relaxed settings – no TCLD (ref)



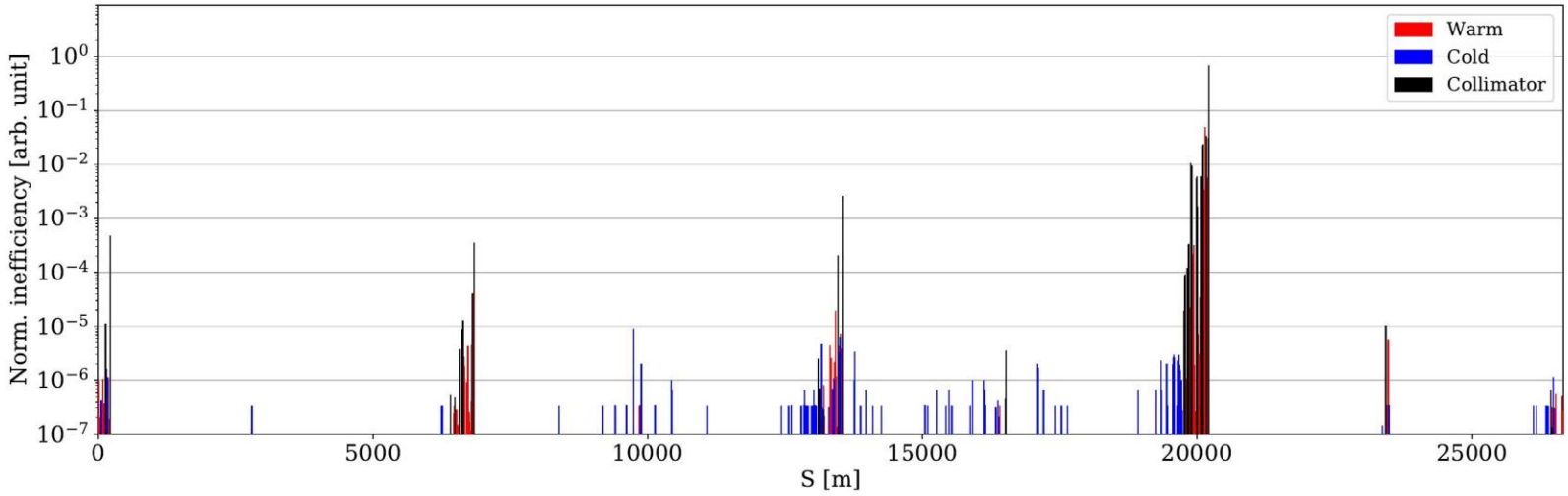


B2H – rematch


Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
5000
10000
15000
20000
25000
S [m]


Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
19400
19500
19600
19700
19800
19900
20000
20100
20200
S [m]

B2V – rematch


Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
10^{0}
10^{-1}
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10^{-3}
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5000
10000
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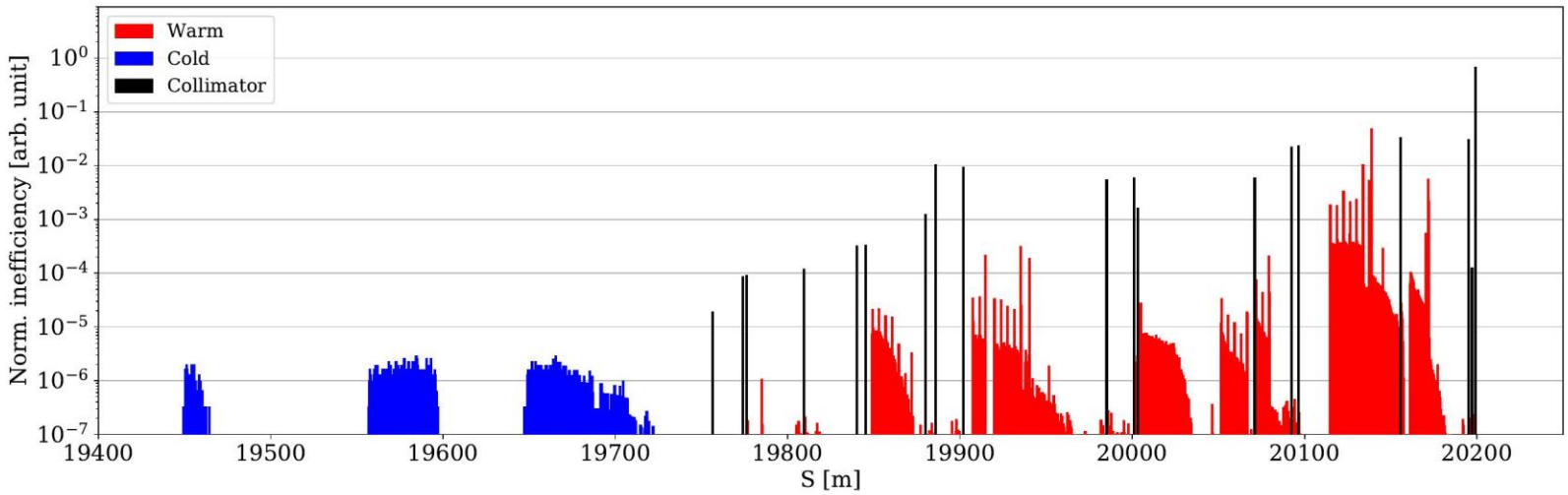
25000
S [m]


Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
10^{0}
10^{-1}
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10^{-5}
10^{-6}
10^{-7}
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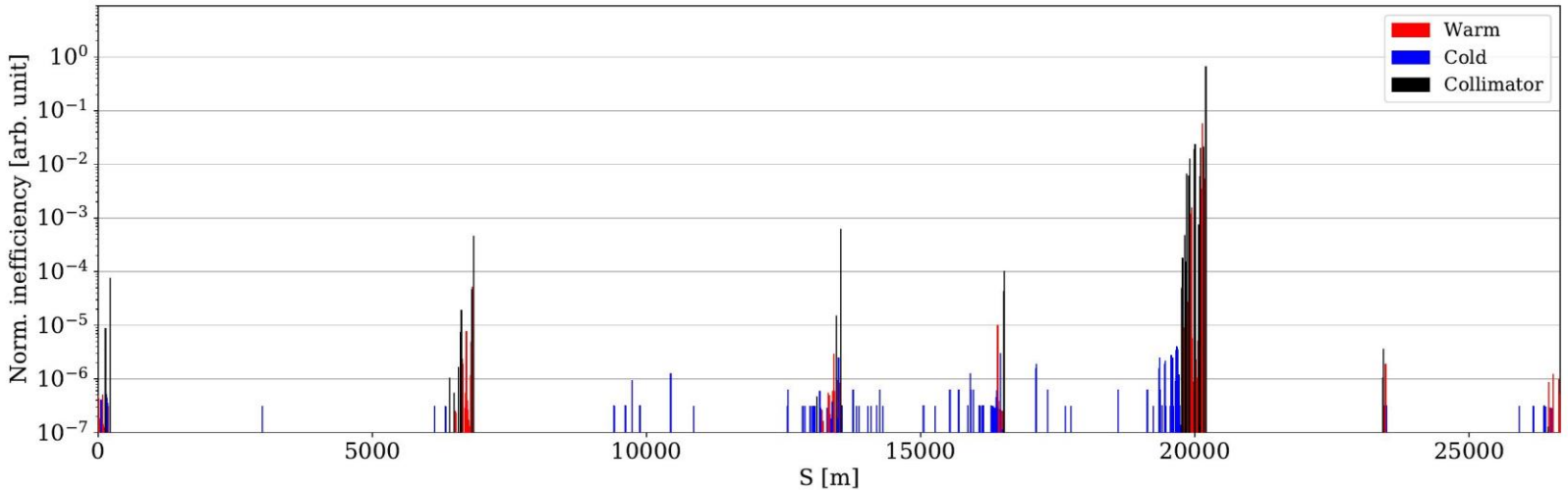
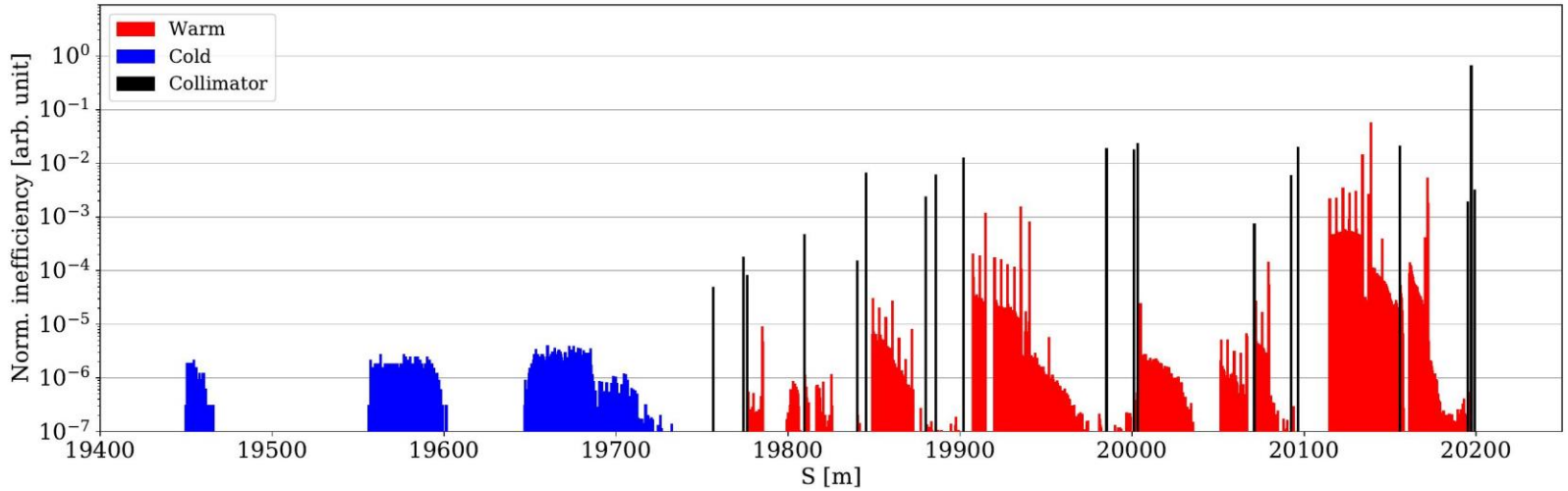
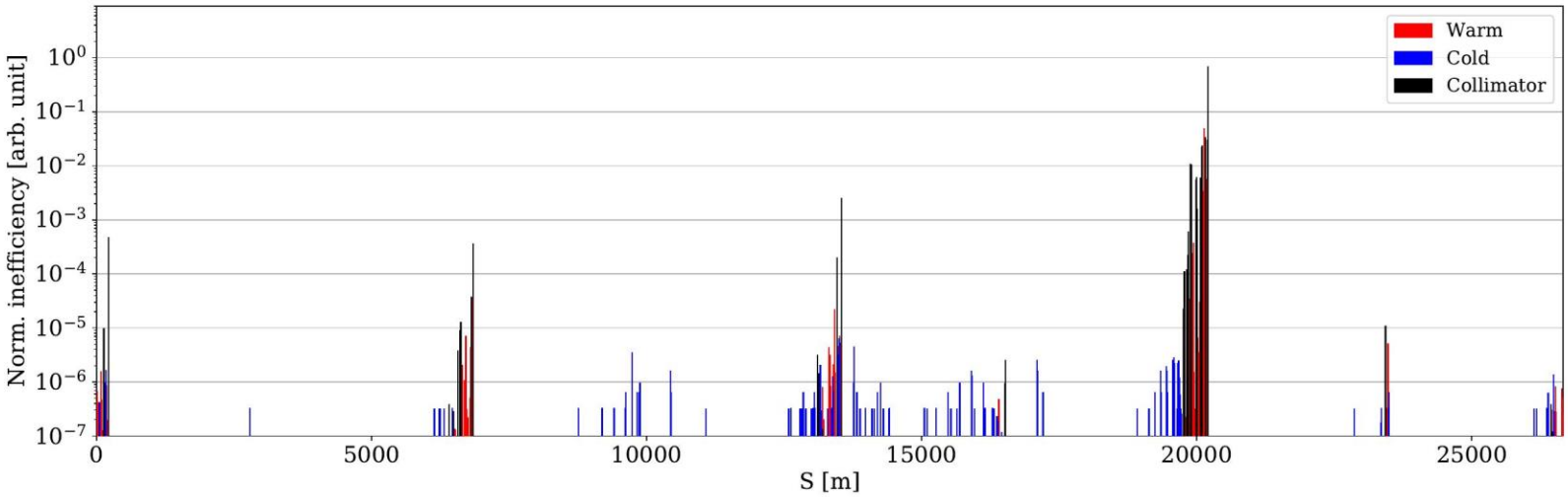
19600
19700
19800
19900
20000
20100
20200
S [m]

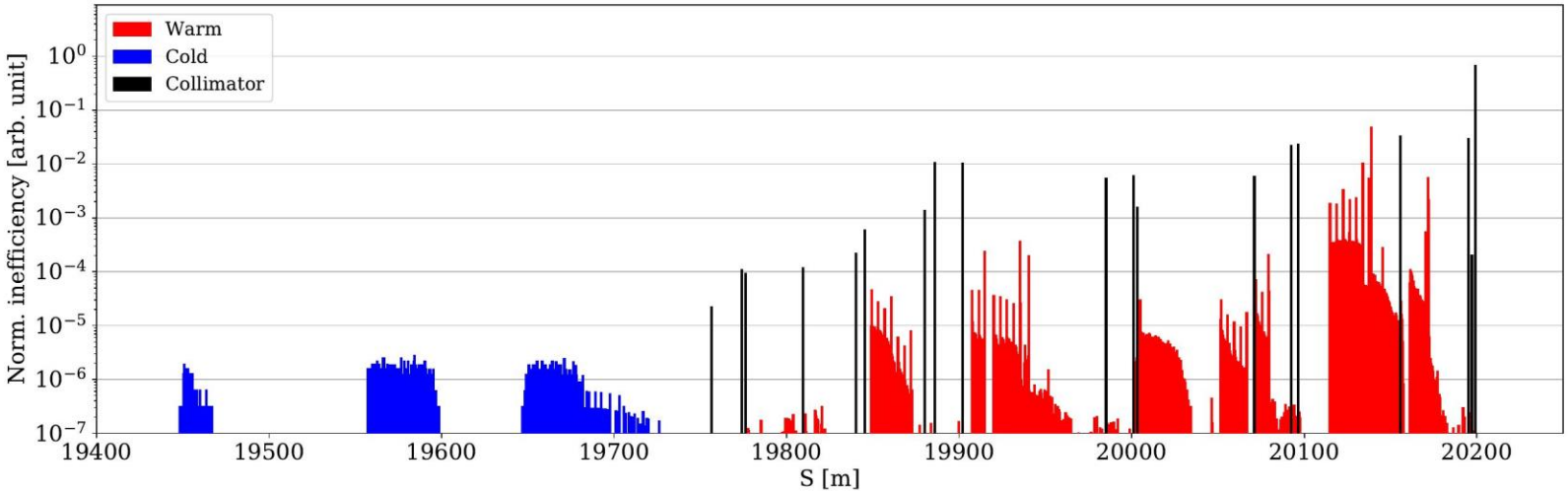
B2H – rematch + orbit bump



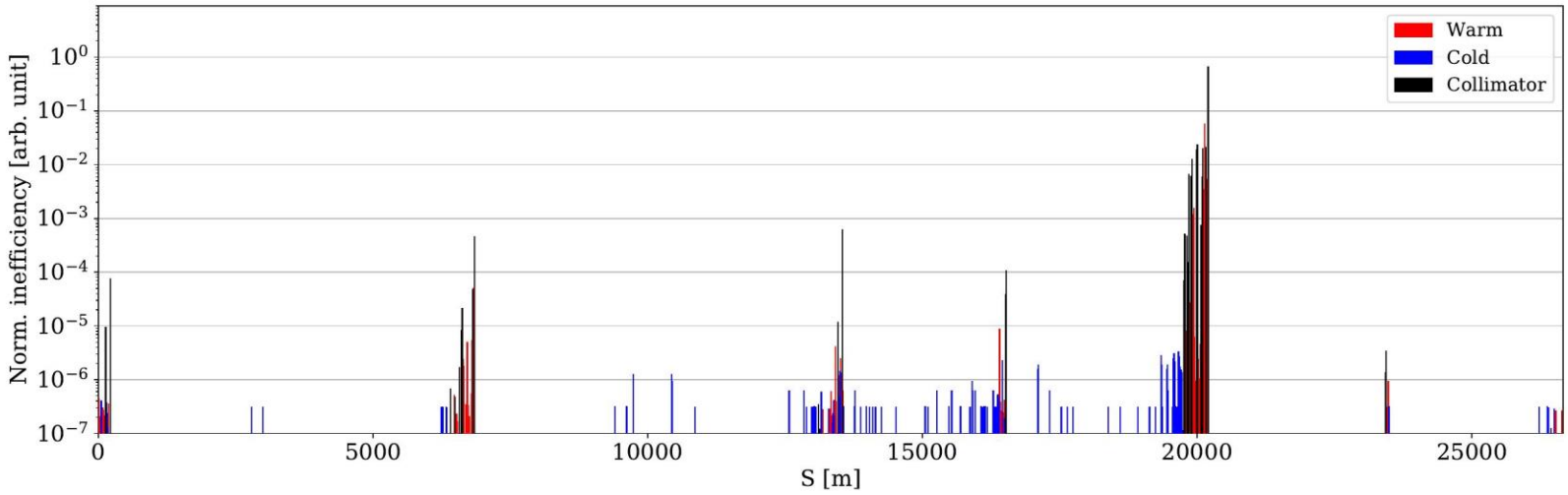


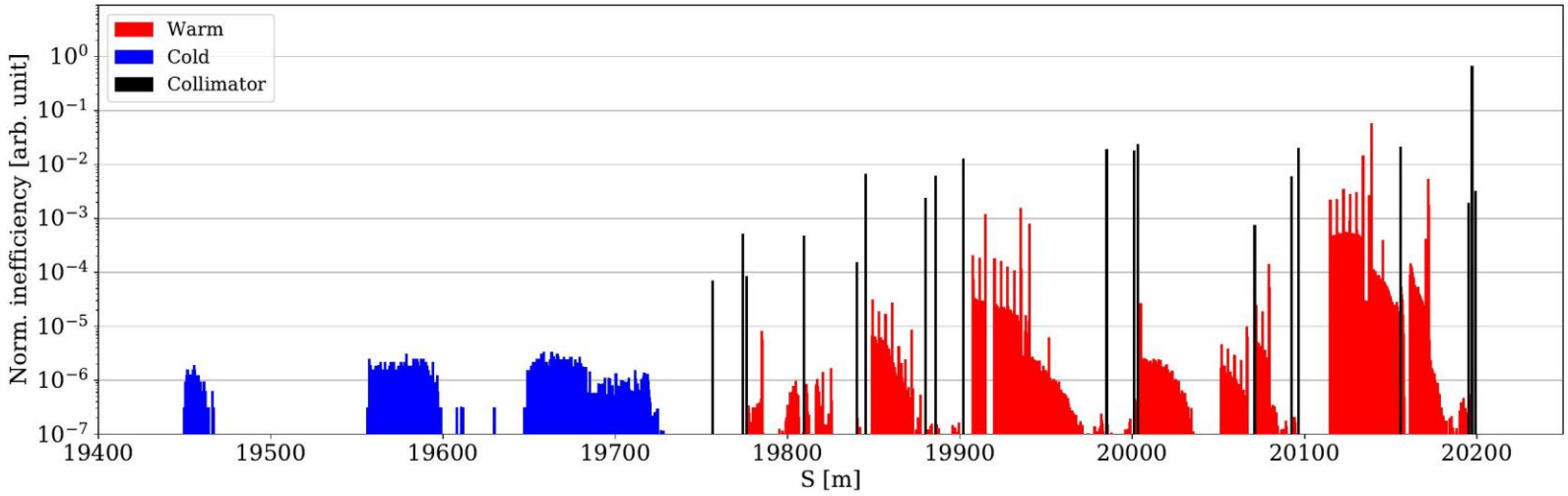
B2V – rematch + orbit bump





B2H – rematch + orbit bump + TCLA offset 3 sigma





B2V – rematch + orbit bump + TCLA offset 3 sigma