# 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

21st September 2022 – 12th HL-LHC Collaboration Meeting

# Introduction and Motivation

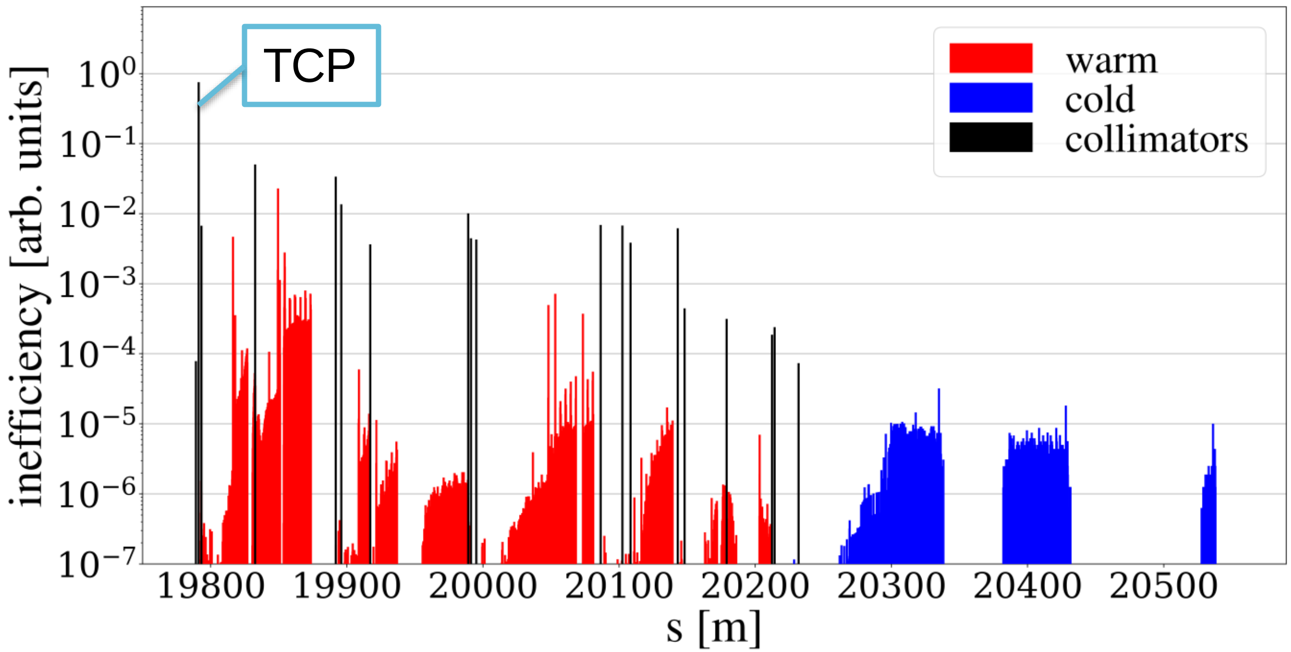
- HL-LHC beam intensity and brightness produces significant challenges:
  - Beam losses in IR7 DS could cause quenches
  - Impedance can cause instabilities
- Beam losses:
  - Initial plan to mitigate them using TCLDs installed between two 11T dipoles
  - 11T dipole availability for HL-LHC is uncertain 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

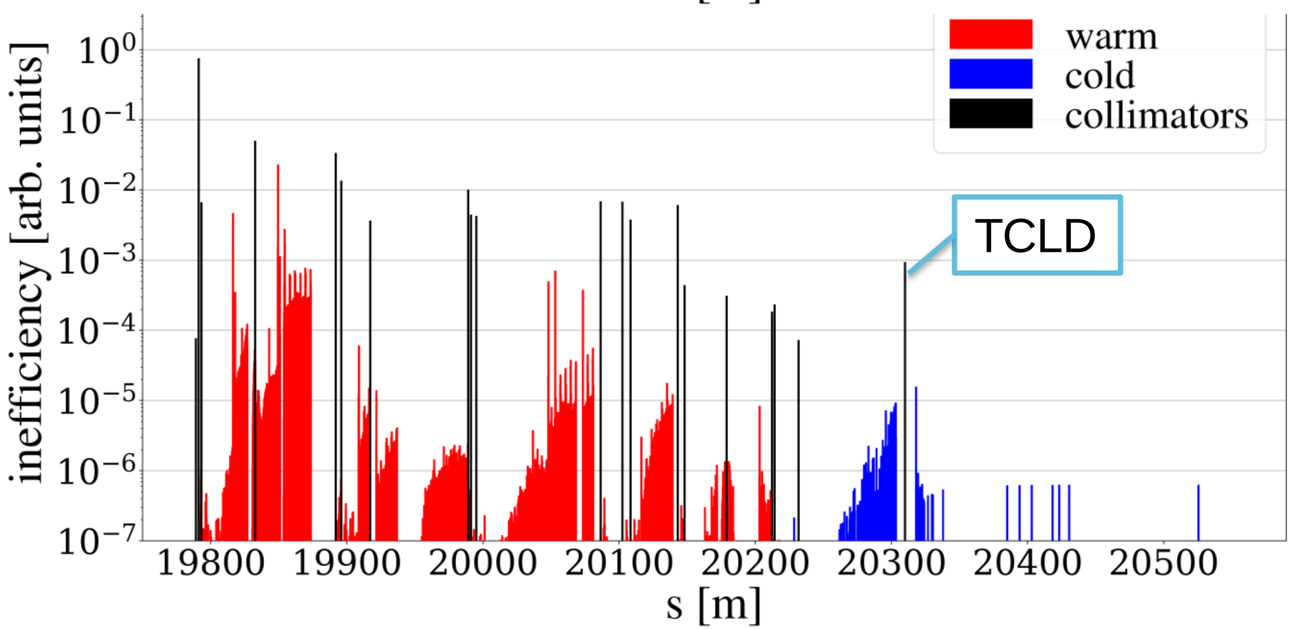
# TCLD in IR7 dispersion suppressor

- 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



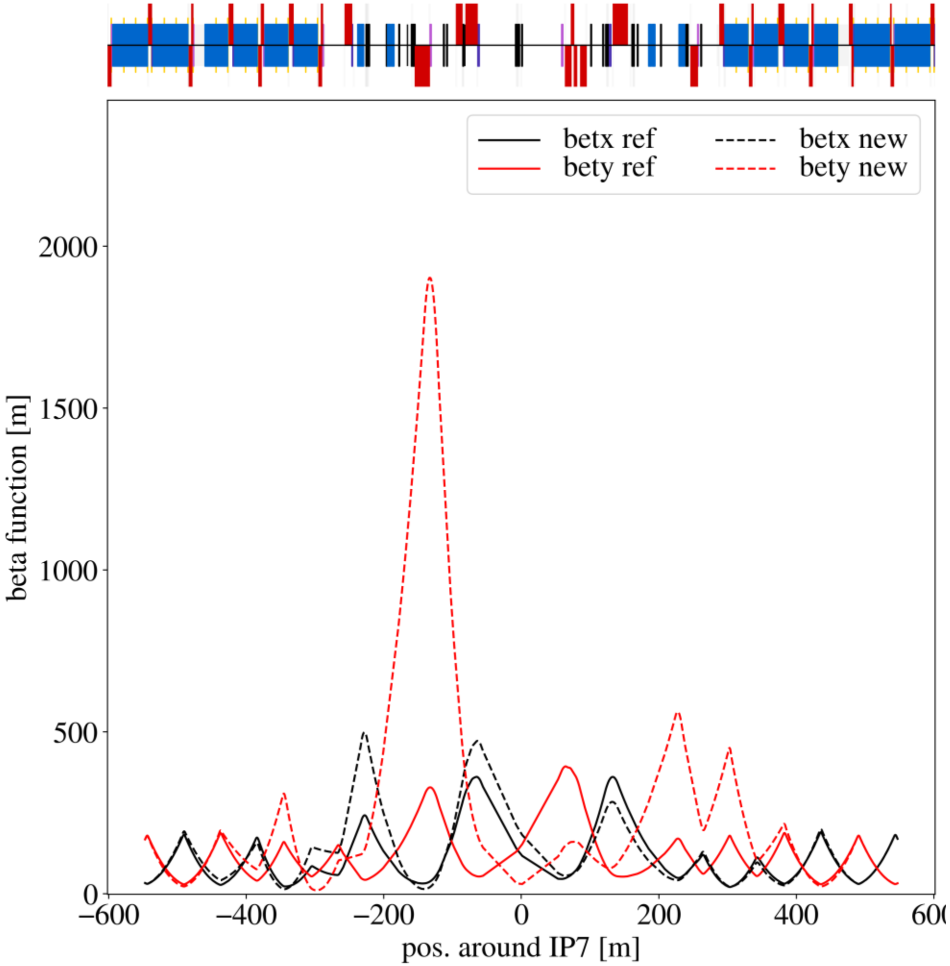



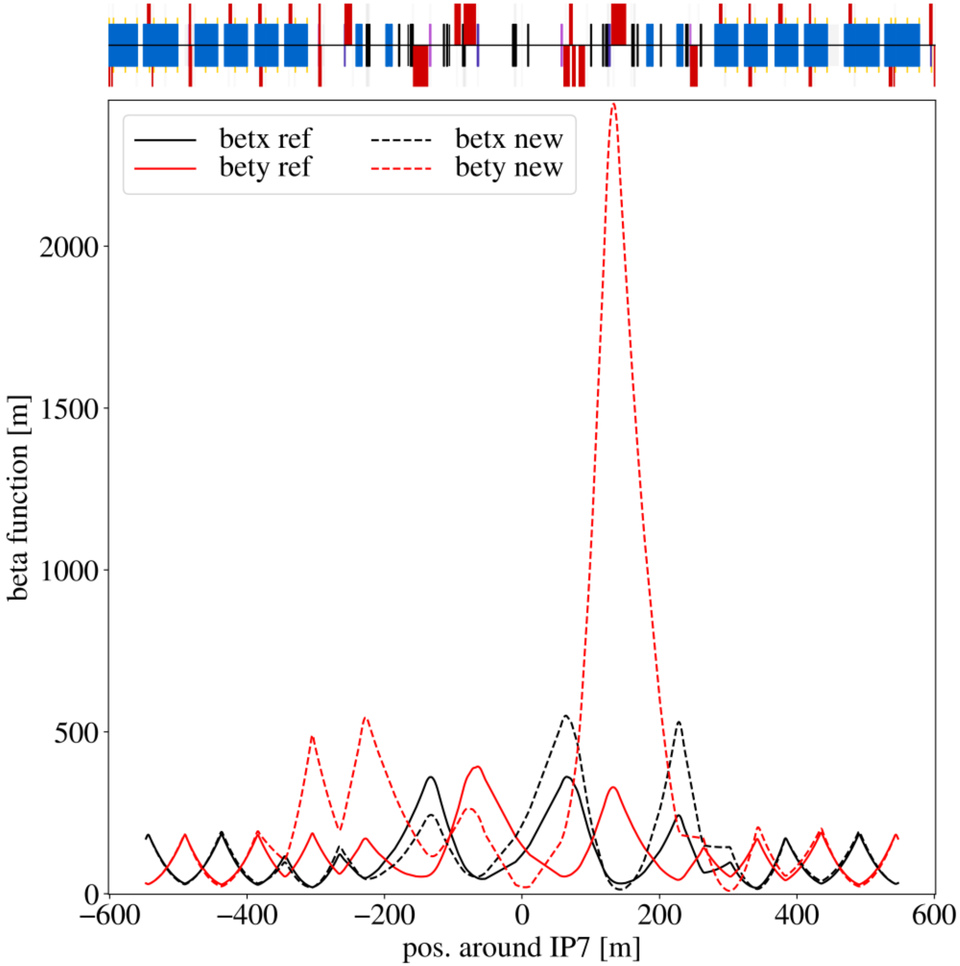
# New IR7 optics[1] and collimator setup[2]

- 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]

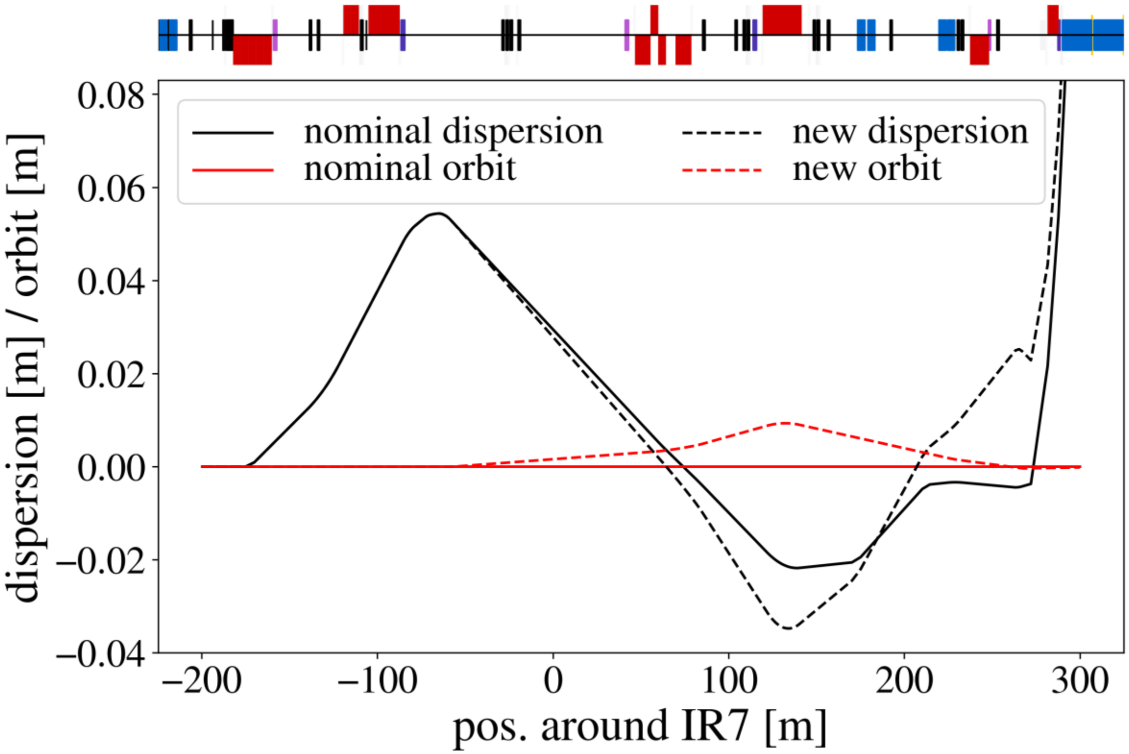
1: R. Bruce et al, https://doi.org/10.18429/JACoW-IPAC2021-MOPAB006
2: B. Lindstrom et al, https://doi.org/10.18429/JACoW-IPAC2022-TUPOTK062
3: D. Kodjaandreev, http://cds.cern.ch/record/2690267

# Beta functions



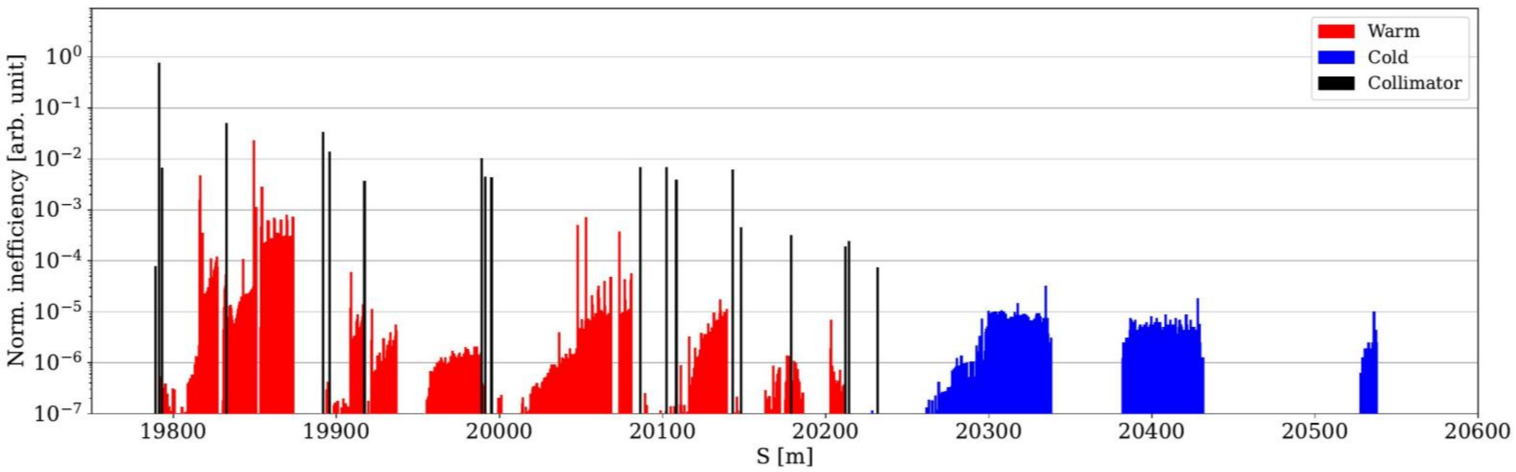
# Dispersion



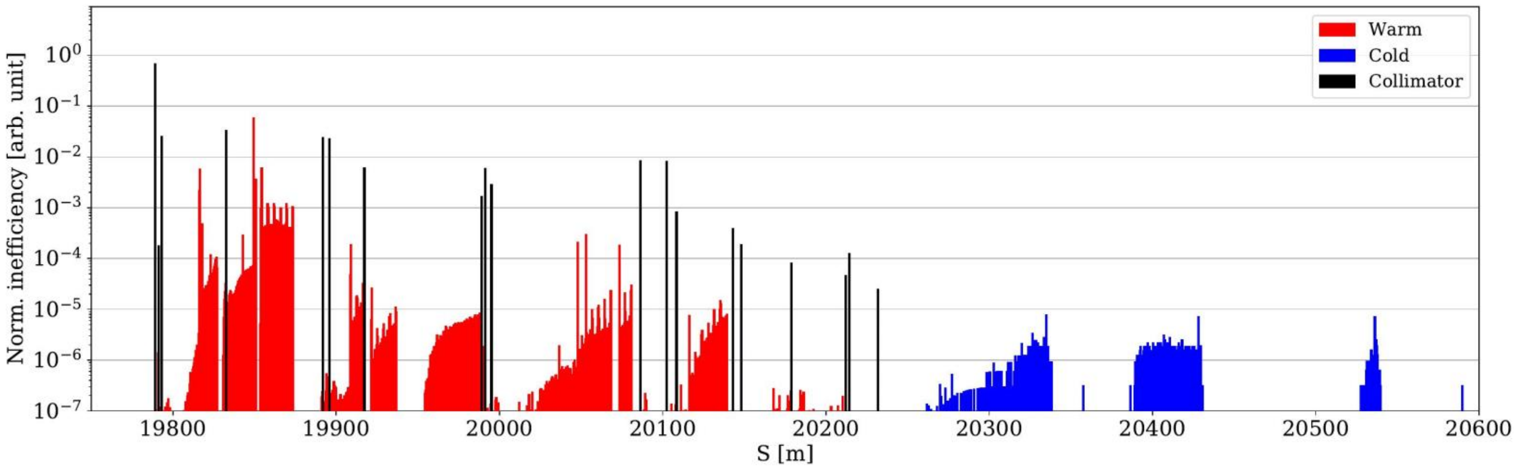

mcbwh.4l7.b1: 34 % of max
mcbch.7r7.b1: 50 % of max
mcbch.9r7.b1: -3.7 % of max

# Loss map comparison (runIV – 20 cm, relaxed)

nominal

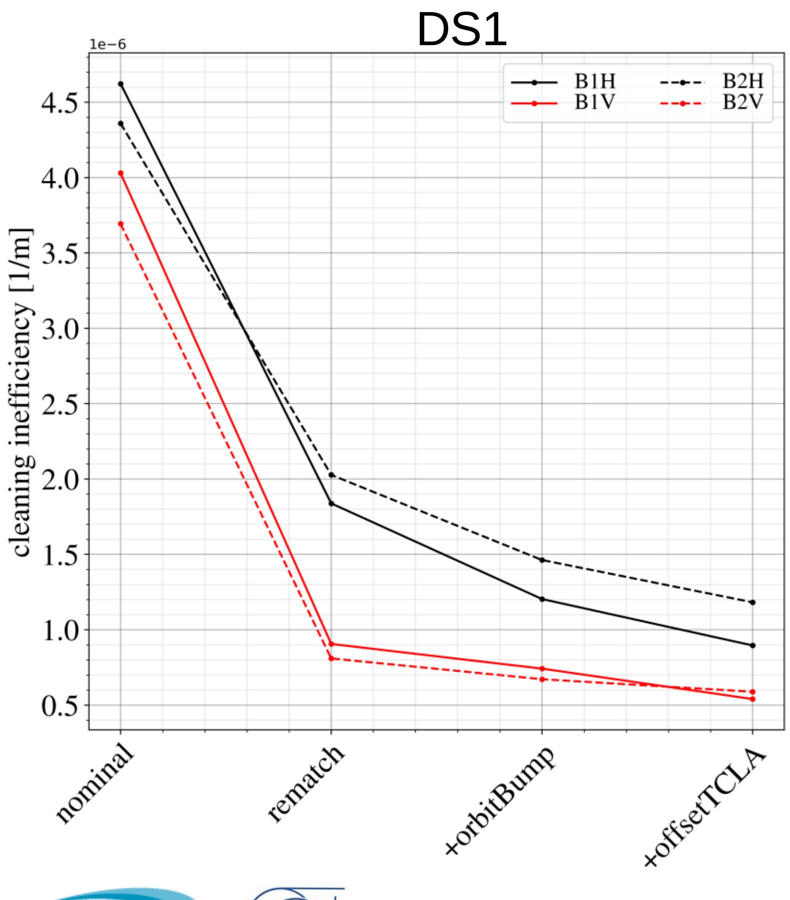


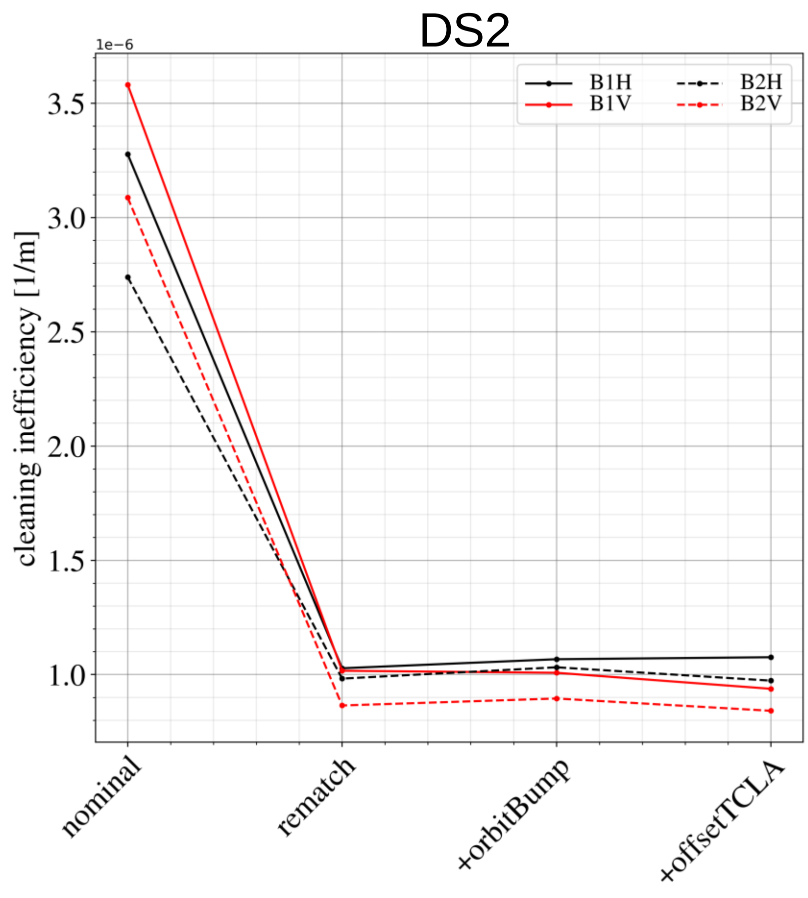

rematched optics + orbitBump + offset TCLA



# Loss map comparison (runIV)

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



# MD7203 – plan to test mitigation strategies already in RunIII

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

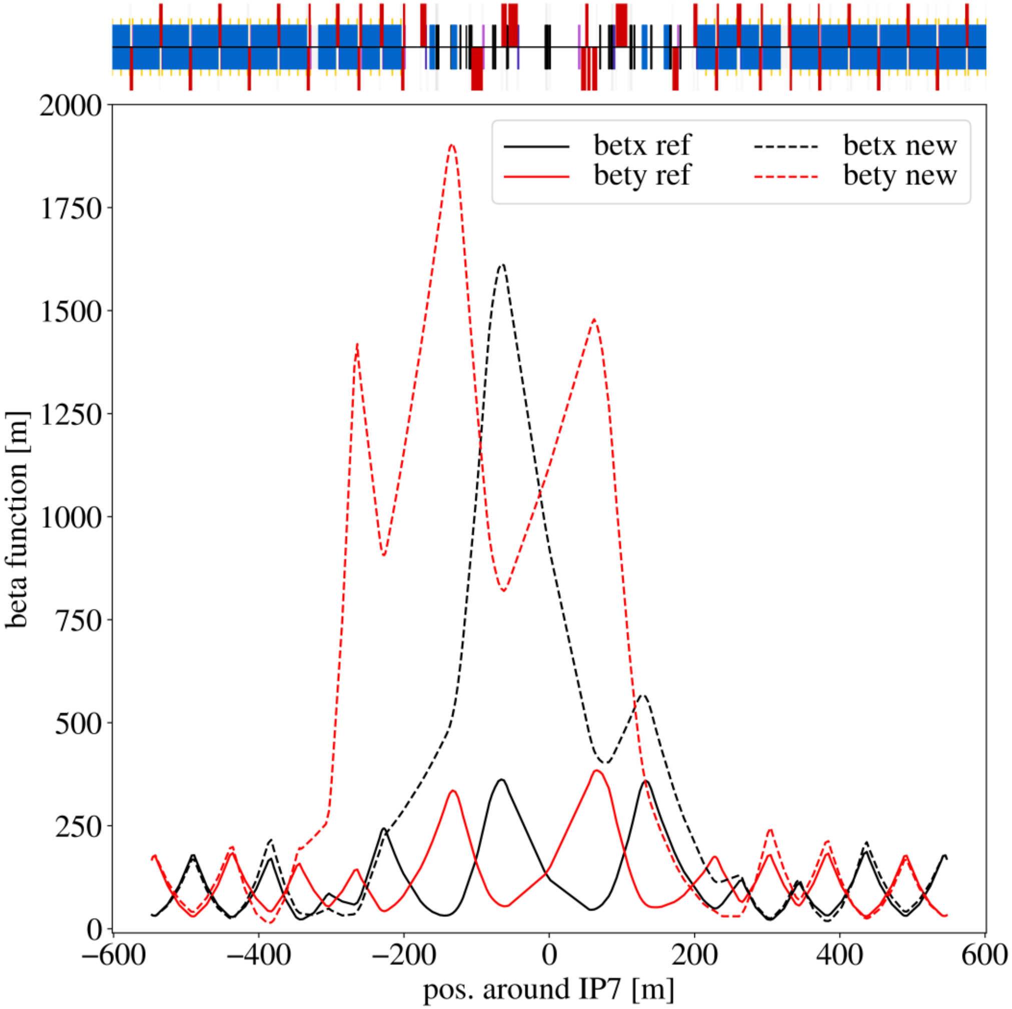
| scenario | B1H | B1V | B2H | B2V | impedance | tune shift |
|---|---|---|---|---|---|---|
| (0): reference | 1 | 1 | 1 | 1 | 1 | ref |
| (1): optics rematch | 0.56 | 0.48 | 0.70 | 0.44 | 0.9 | 1.2e-4* |
| (2): orbit bump + (1) | 0.35 | 0.39 | 0.47 | 0.41 | -- | -- |
| (3): offset TCLA + (2) | 0.23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

# 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

# Summary

- TCLD likely not available
  - → quench tests necessary to conclusively determine the impact of a lacking TCLD on cleaning performance
  - Alternative mitigation strategies must be studied
- Impedance in HL-LHC will risk causing instabilities

- Possible mitigations not relying on new hardware:
  - Rematching IR7 optics with larger beta functions and dispersion – requires transition during ramp due to aperture limits at injection
  - Orbit bumps to produce dispersion
  - Asymmetric TCLAs to catch off-momentum particles
  - Up to **80 %** reduction of DS losses seen in simulations
  - Up to **20 %** improvement of impedance with rematched optics and single-sided jaws

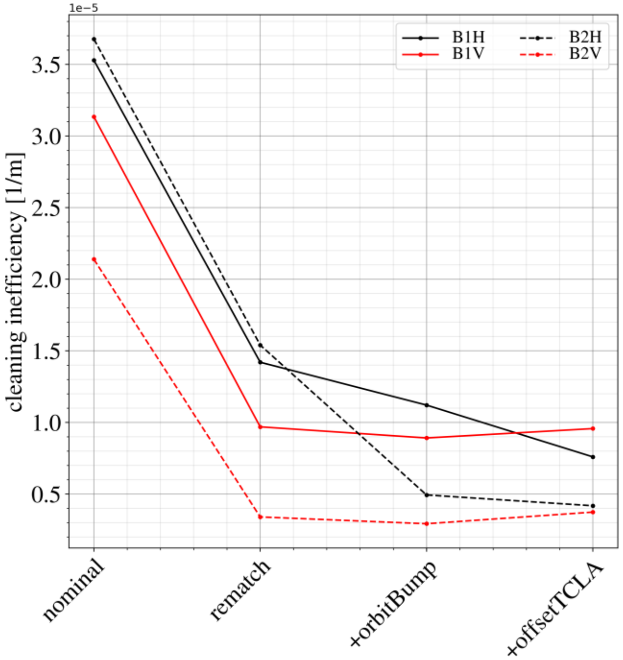
- These mitigation methods will be studied in MD asap

# Thanks for listening and to everyone involved!

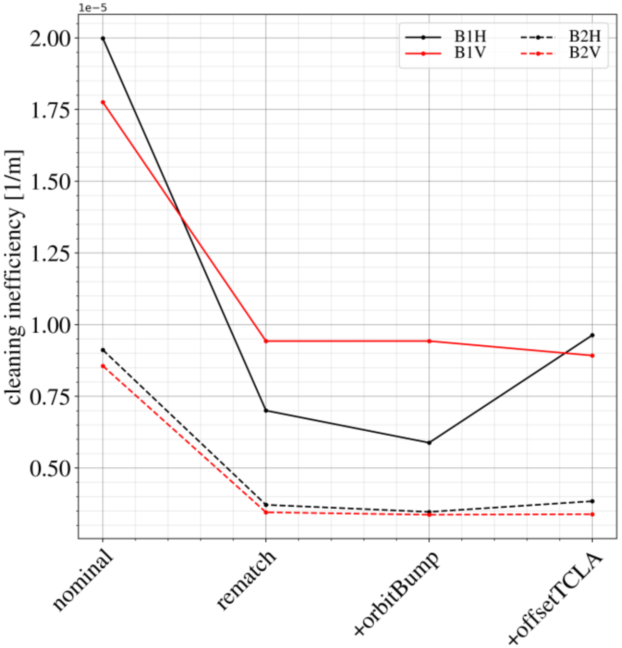
*R. Bruce, X. Buffat, R. de Maria, S. Fartoukh,*
*L. Giacomel, B. Lindström, D. Mirarchi, N. Mounet,*
*S. Redaelli, M. Solfaroli, R. Tomás, J. Wenninger*

# Peak losses in DS clusters

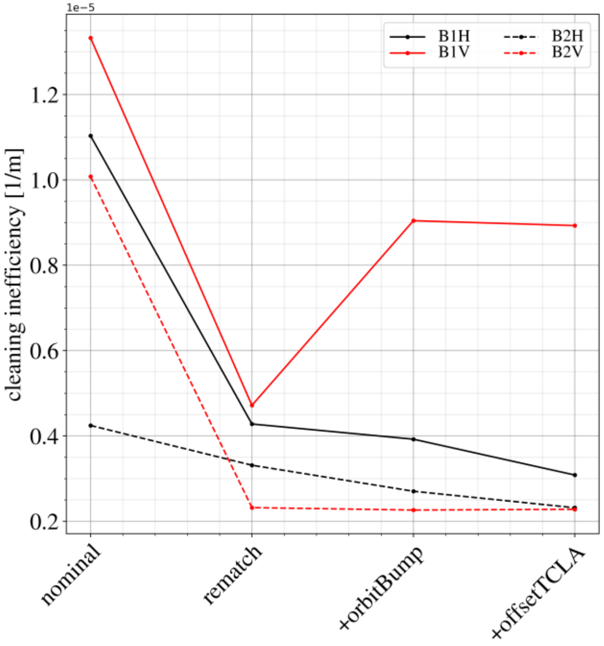
DS1




DS2

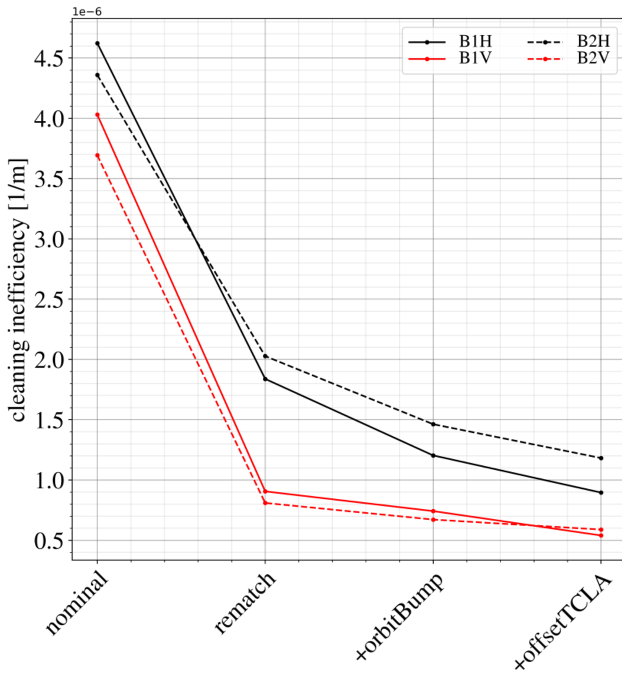



DS3

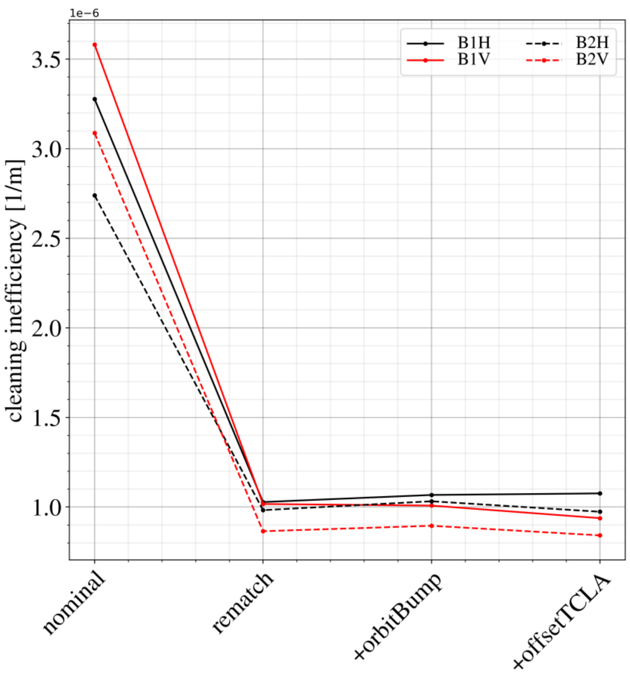


# Average losses in DS clusters

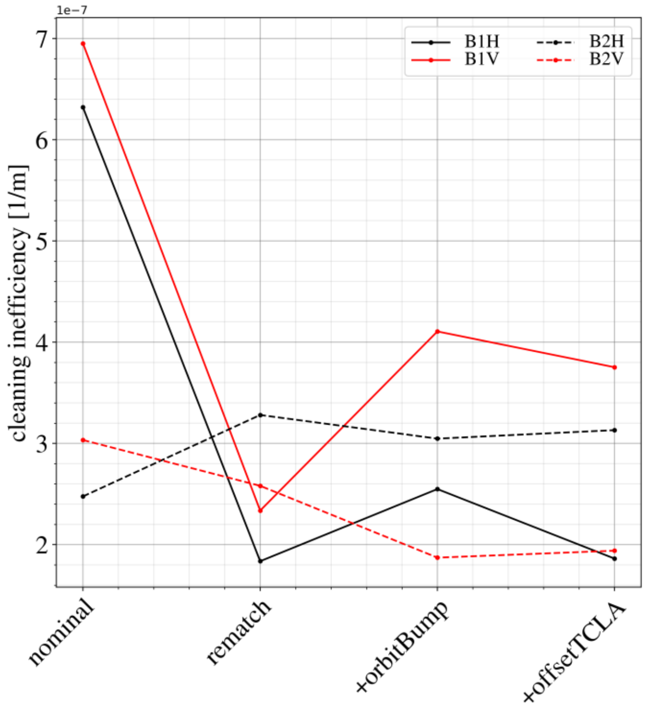
DS1



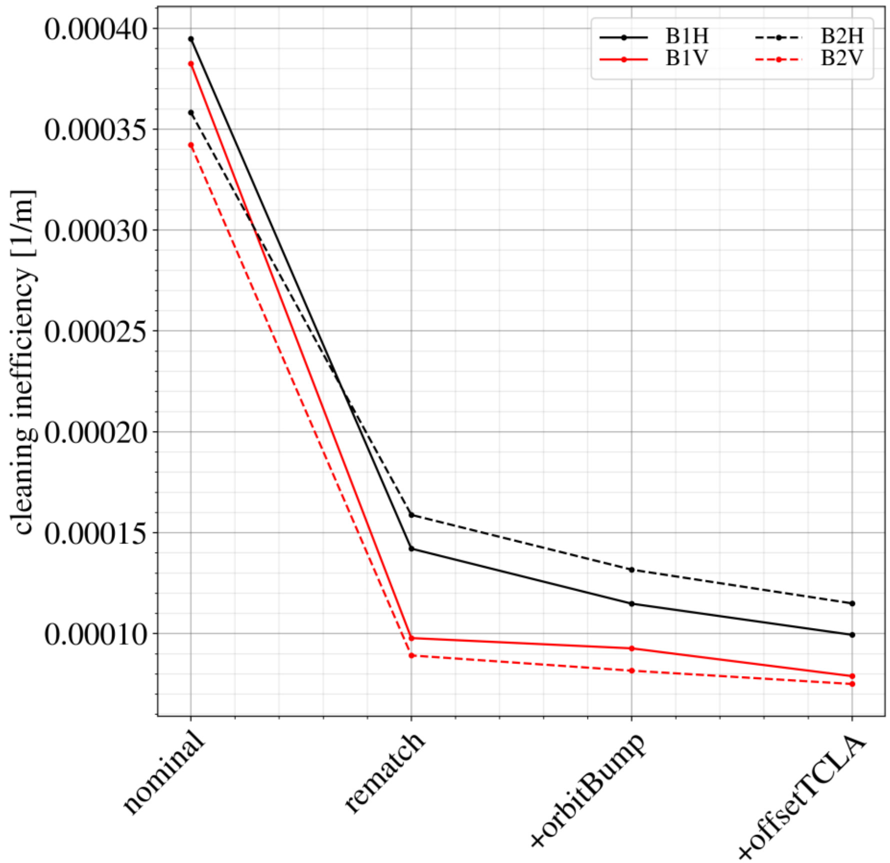

DS2



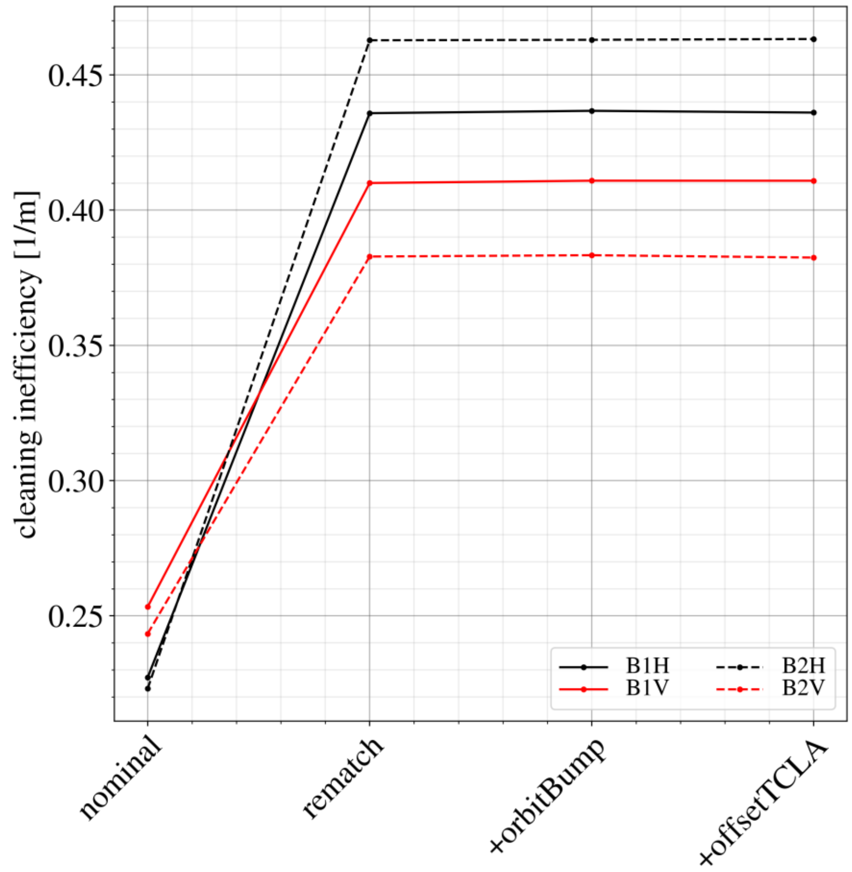

DS3



DS total



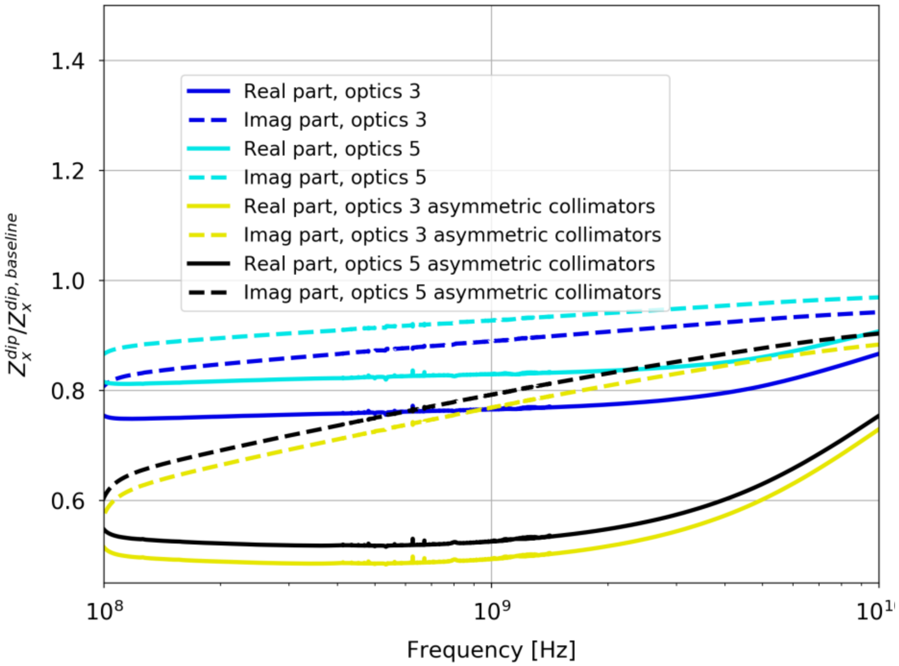

Global cleaning inefficiency



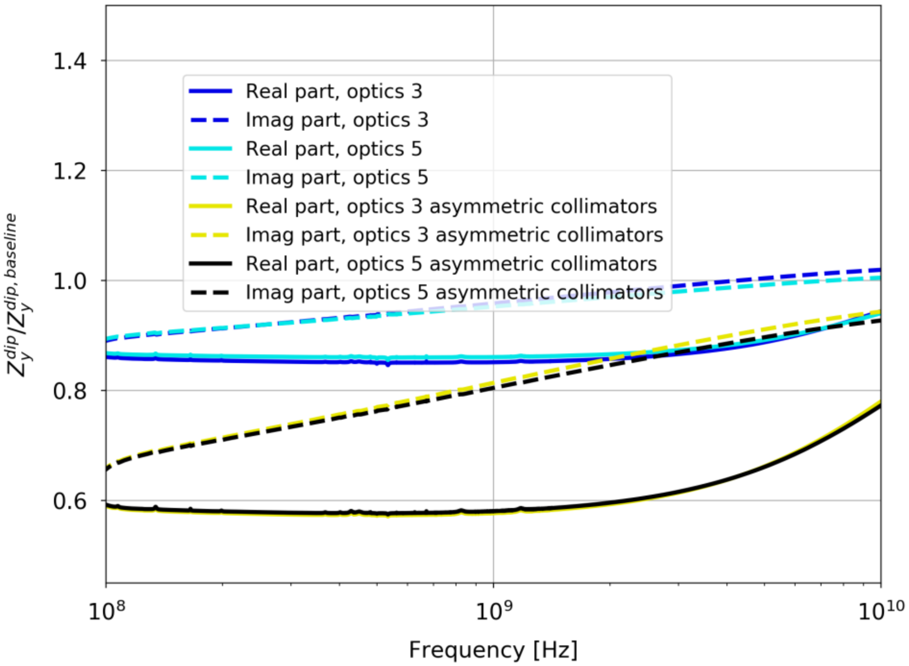
# Impedance

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

horizontal

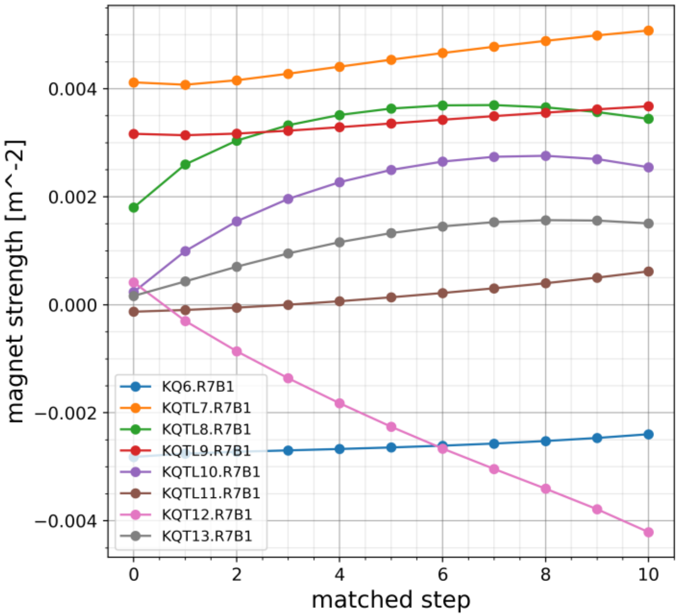


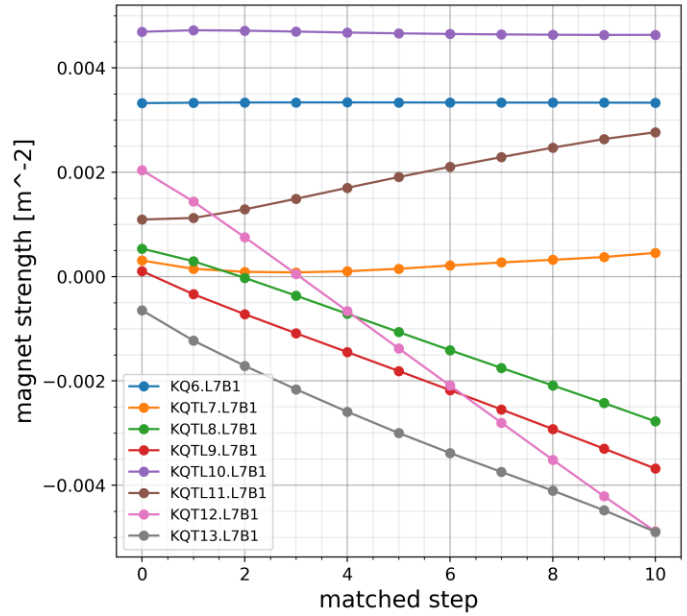

vertical

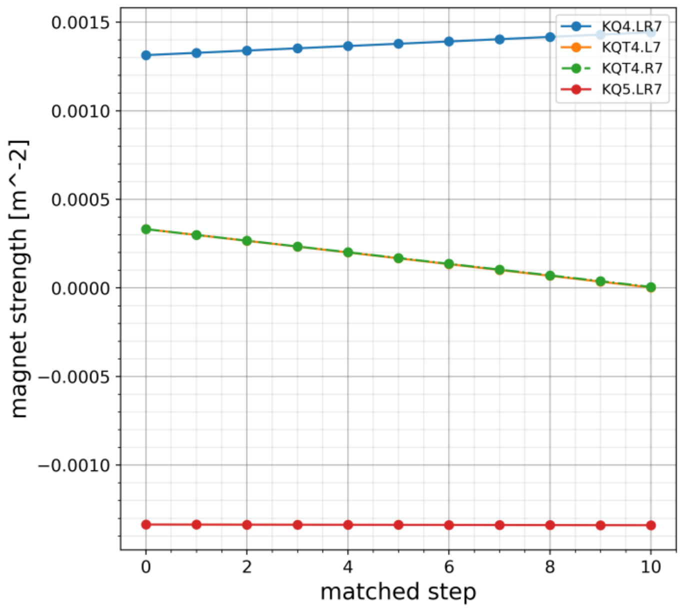



L. Giacomel

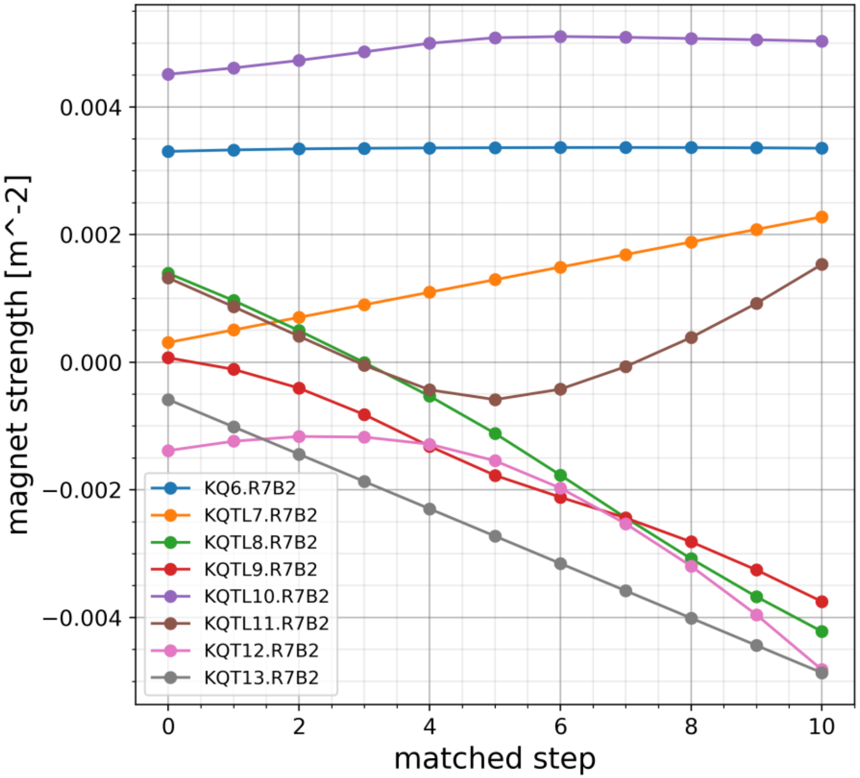
# Optics transition (tentative for b1)

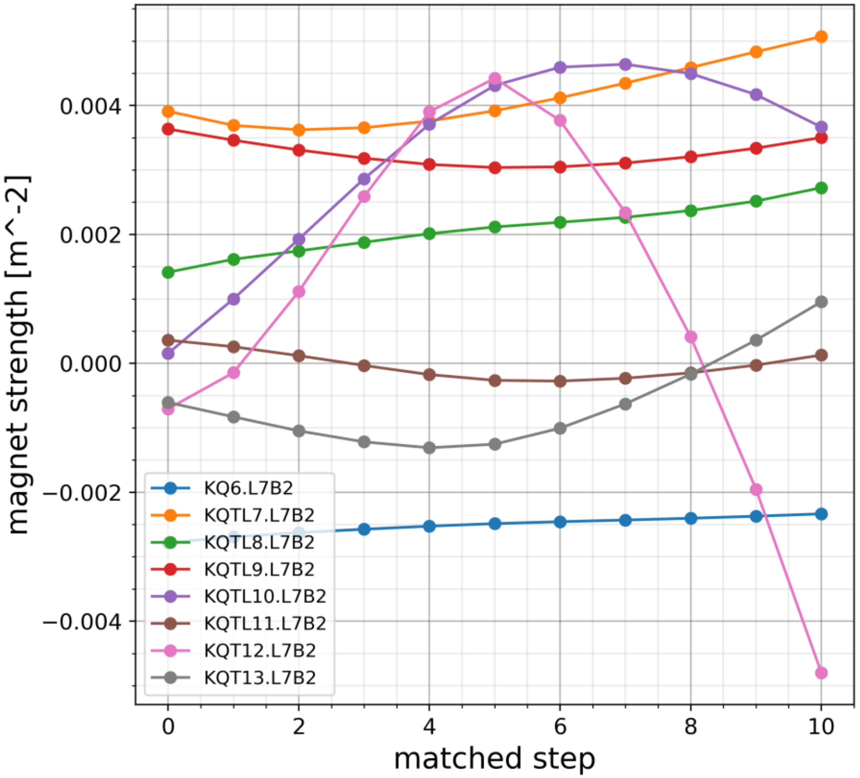


# Optics transition



# 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 |

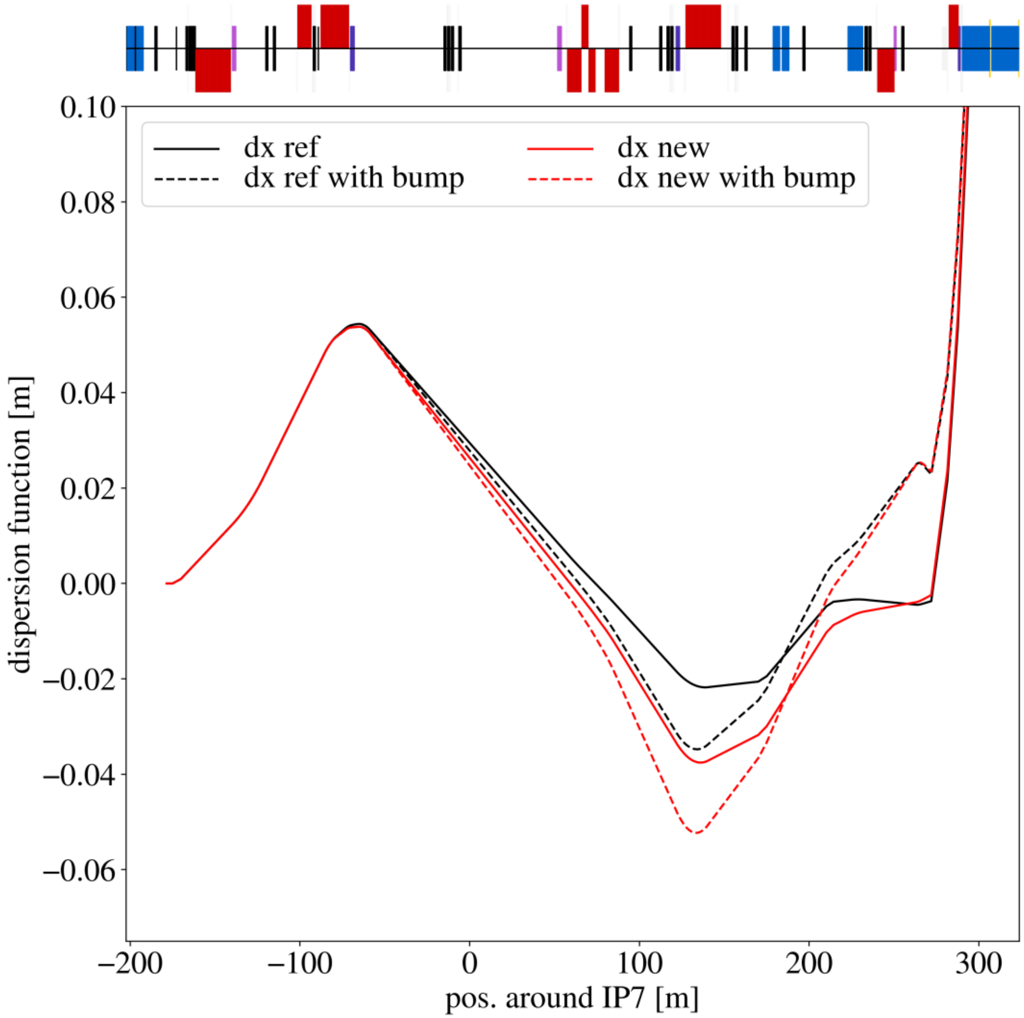
| Magnet | Limit | Optics 1 |
|---|---|---|
| KQ4.LR7 | 710 | 706 |
| KQT4.L7 | 600 | 1 |
| KQT4.R7 | 600 | 3 |
| KQ5.LR7 | 710 | -656 |

# 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

# Single pass dispersion



# 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, drive to nominal sigma gaps in new optics
- (1): loss maps
- (1): aperture measurement

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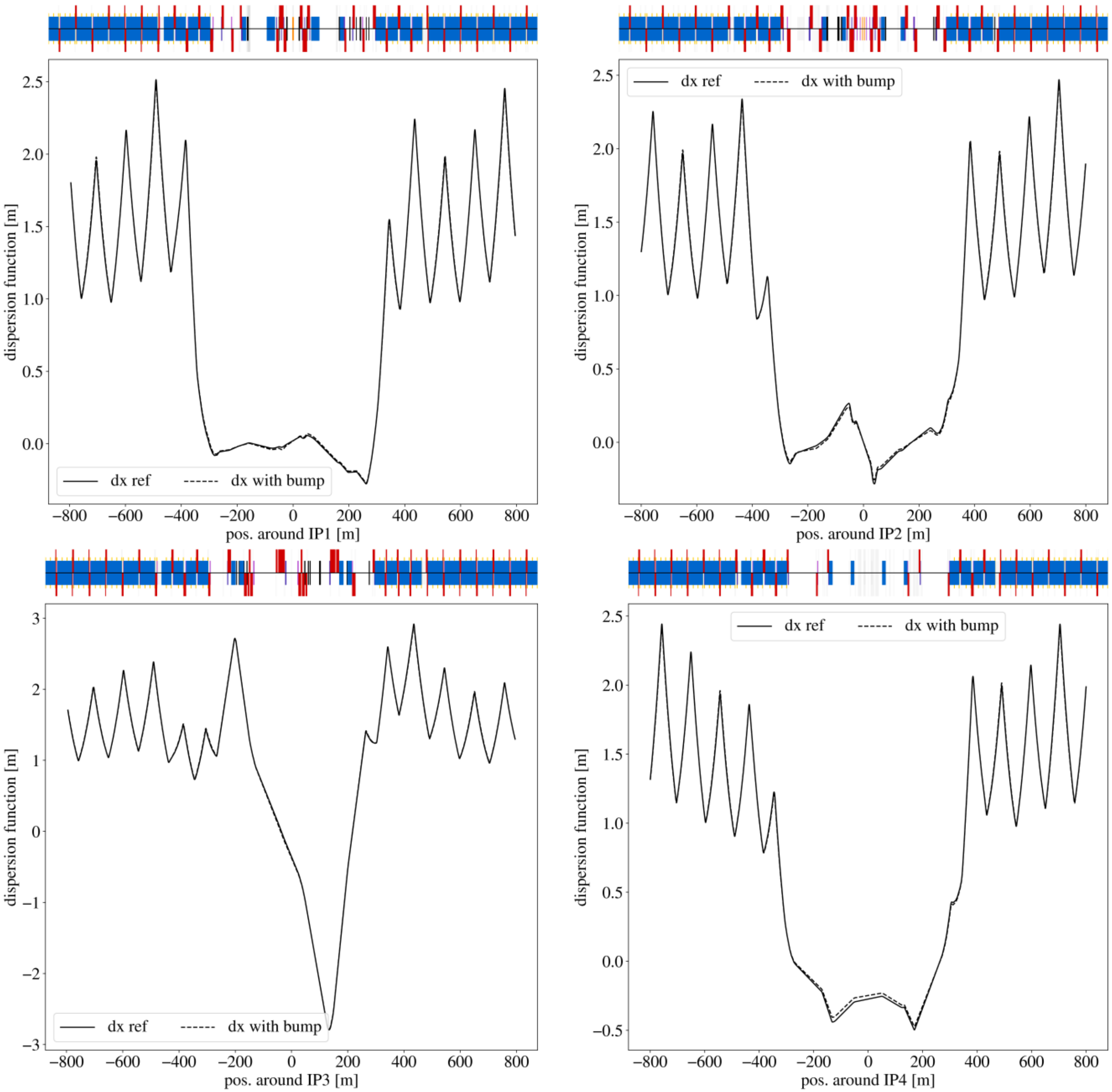
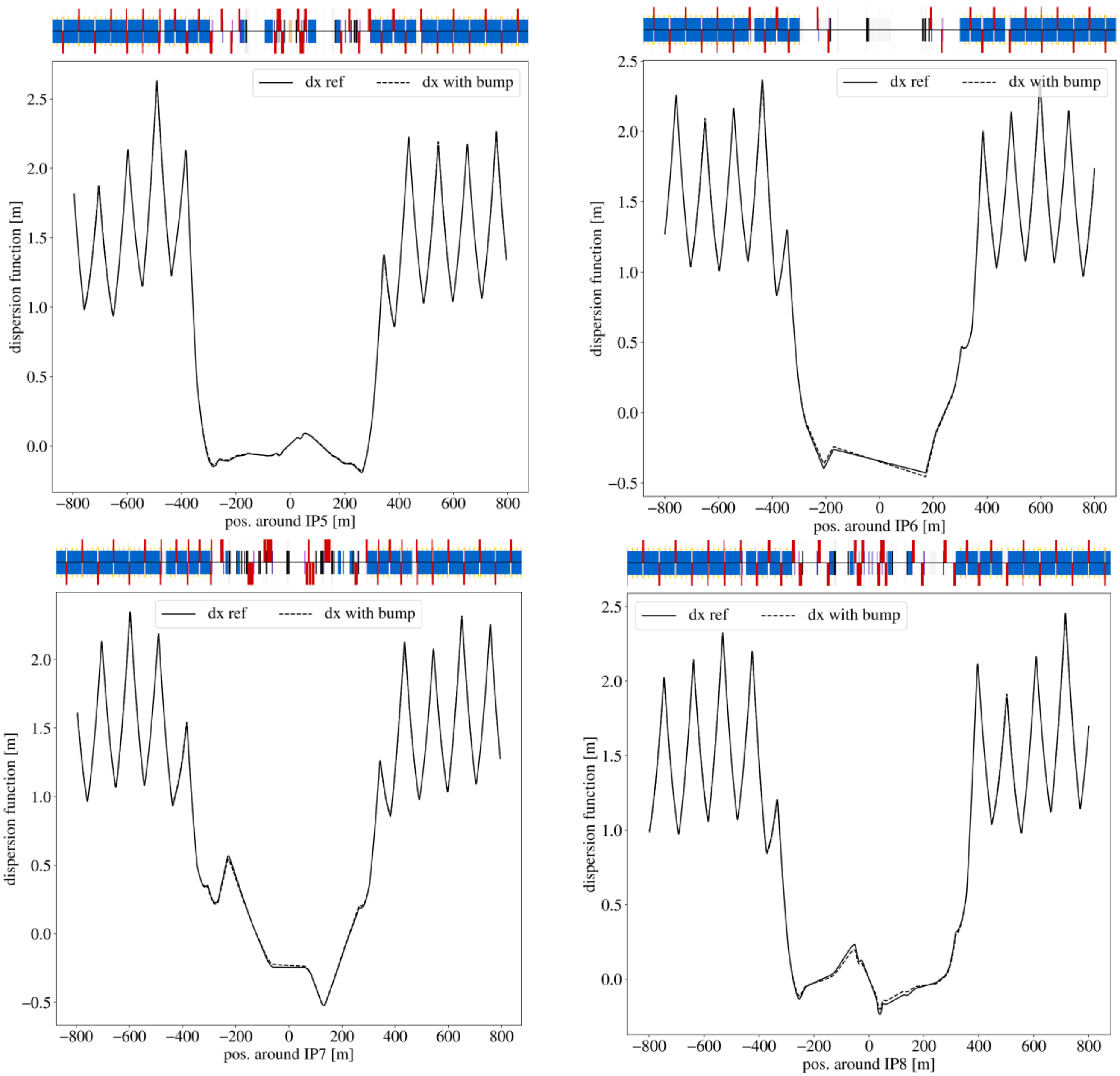
# Second fill (measurements) – 8 hours

- 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

# Orbit Bump – Global Dispersion

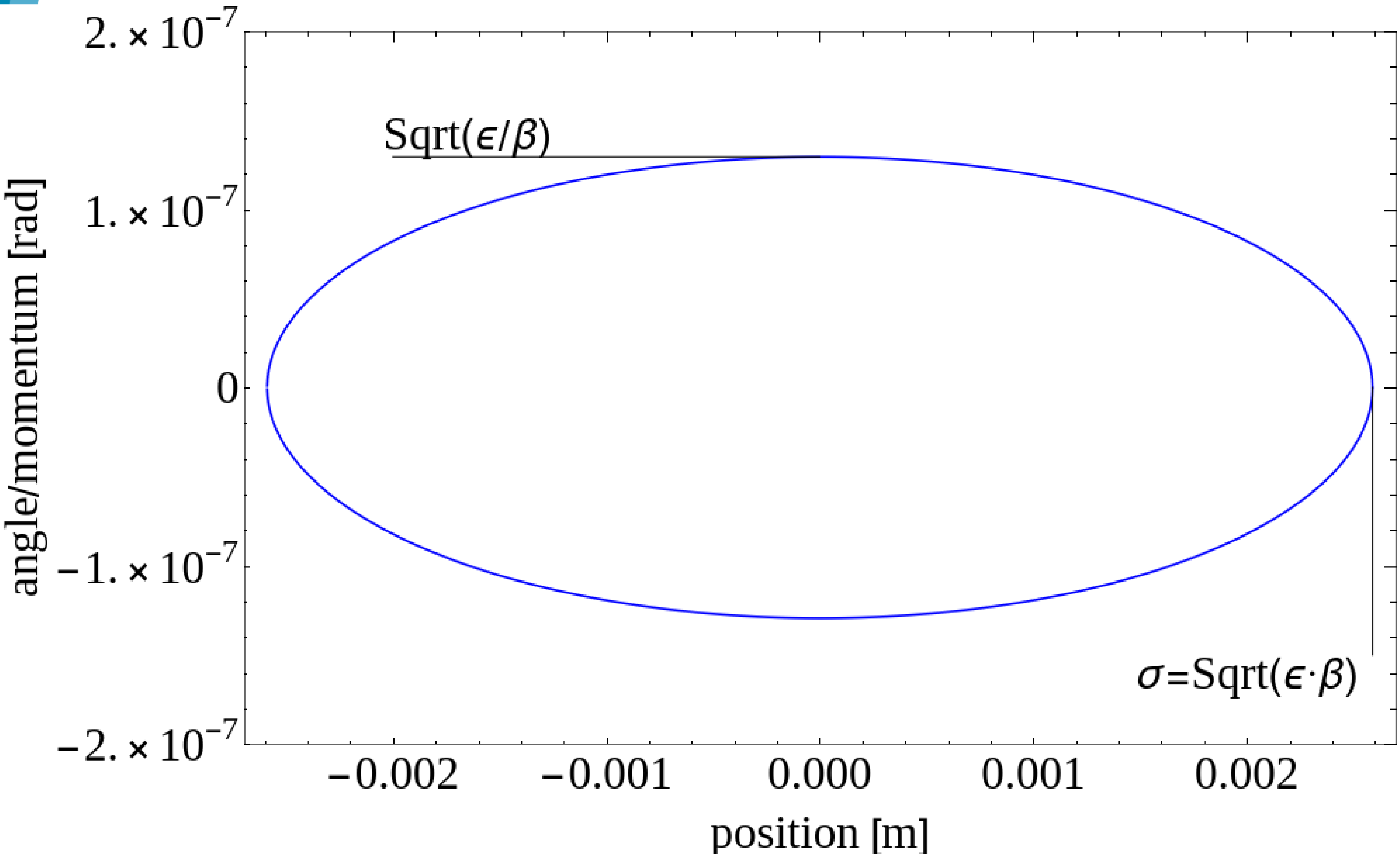


# Orbit Bump – Global Dispersion



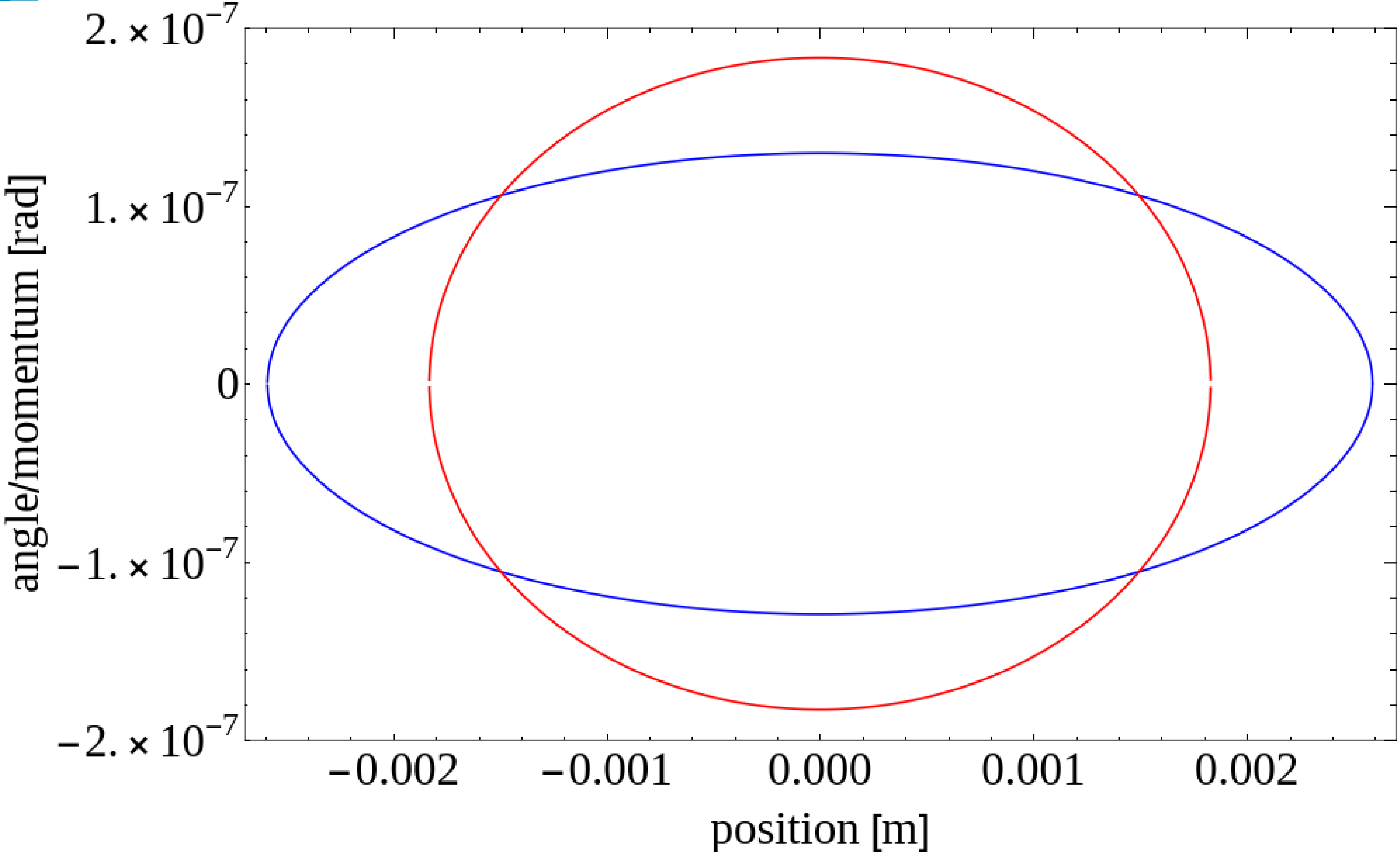
# Beam sensitivity to perturbations

Constant area: $\pi \cdot \epsilon$



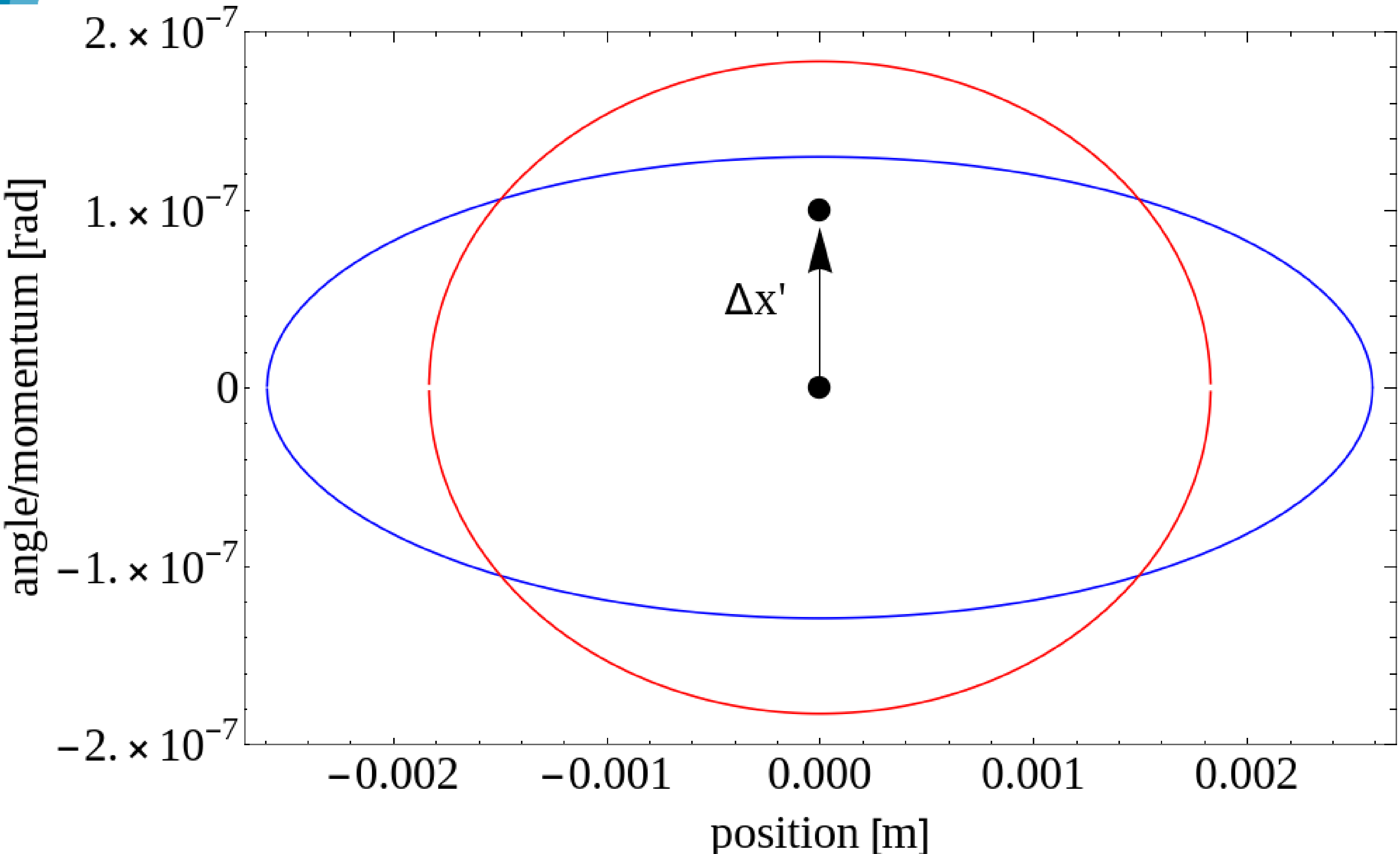
# Beam sensitivity to perturbations

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



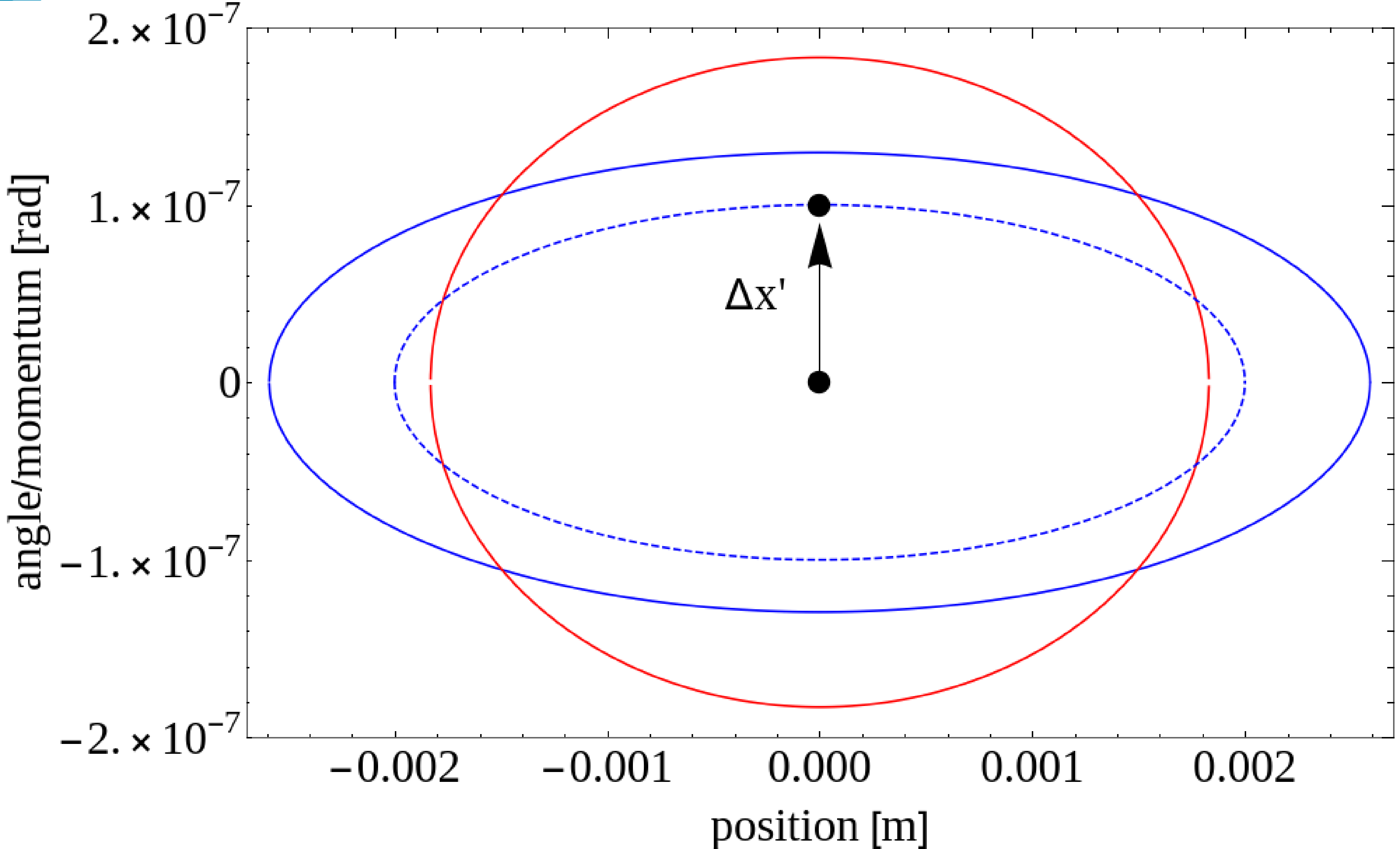
# Beam sensitivity to perturbations

A particle receives a kick



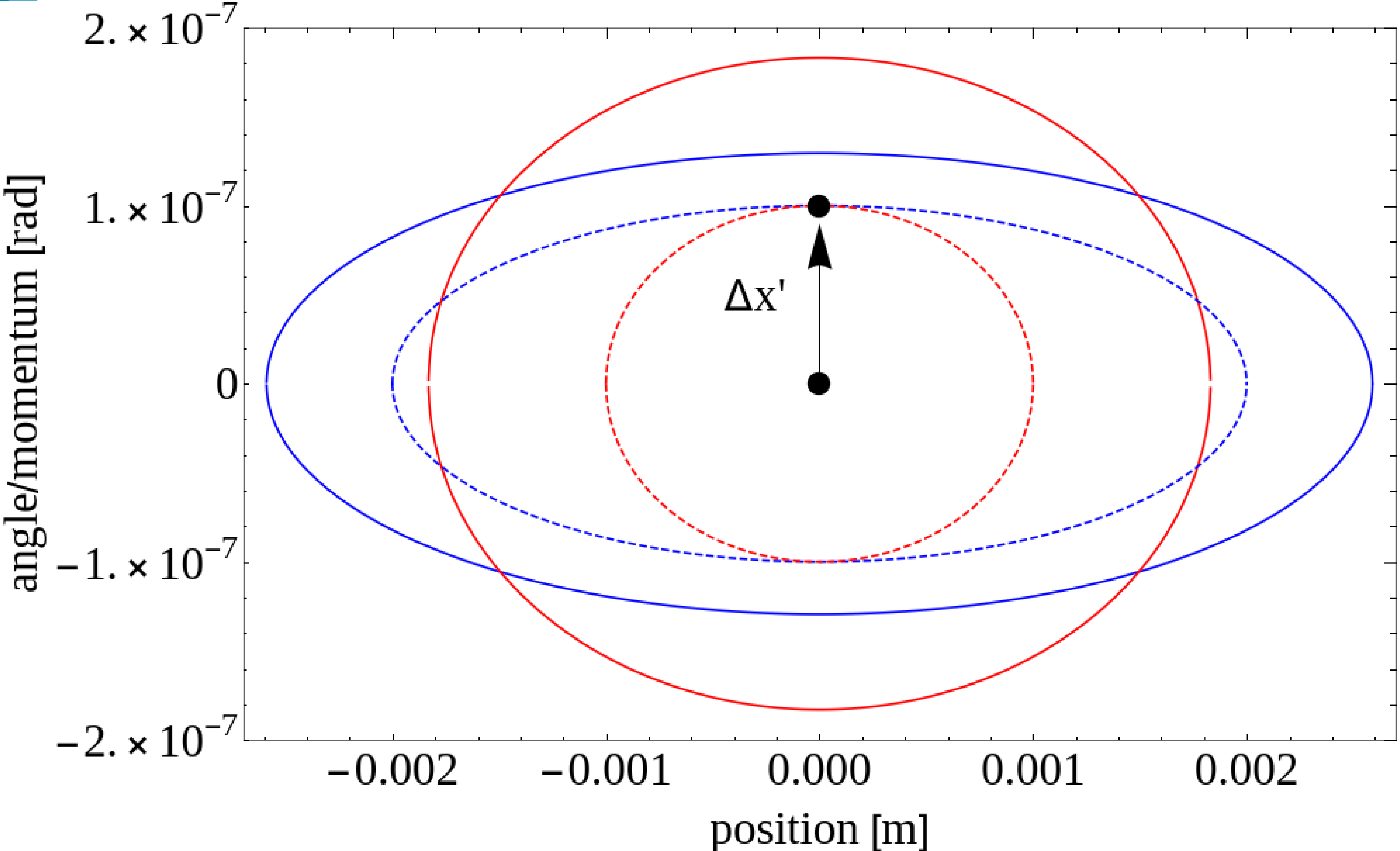
# Beam sensitivity to perturbations

Particle traces out ellipse in phase space



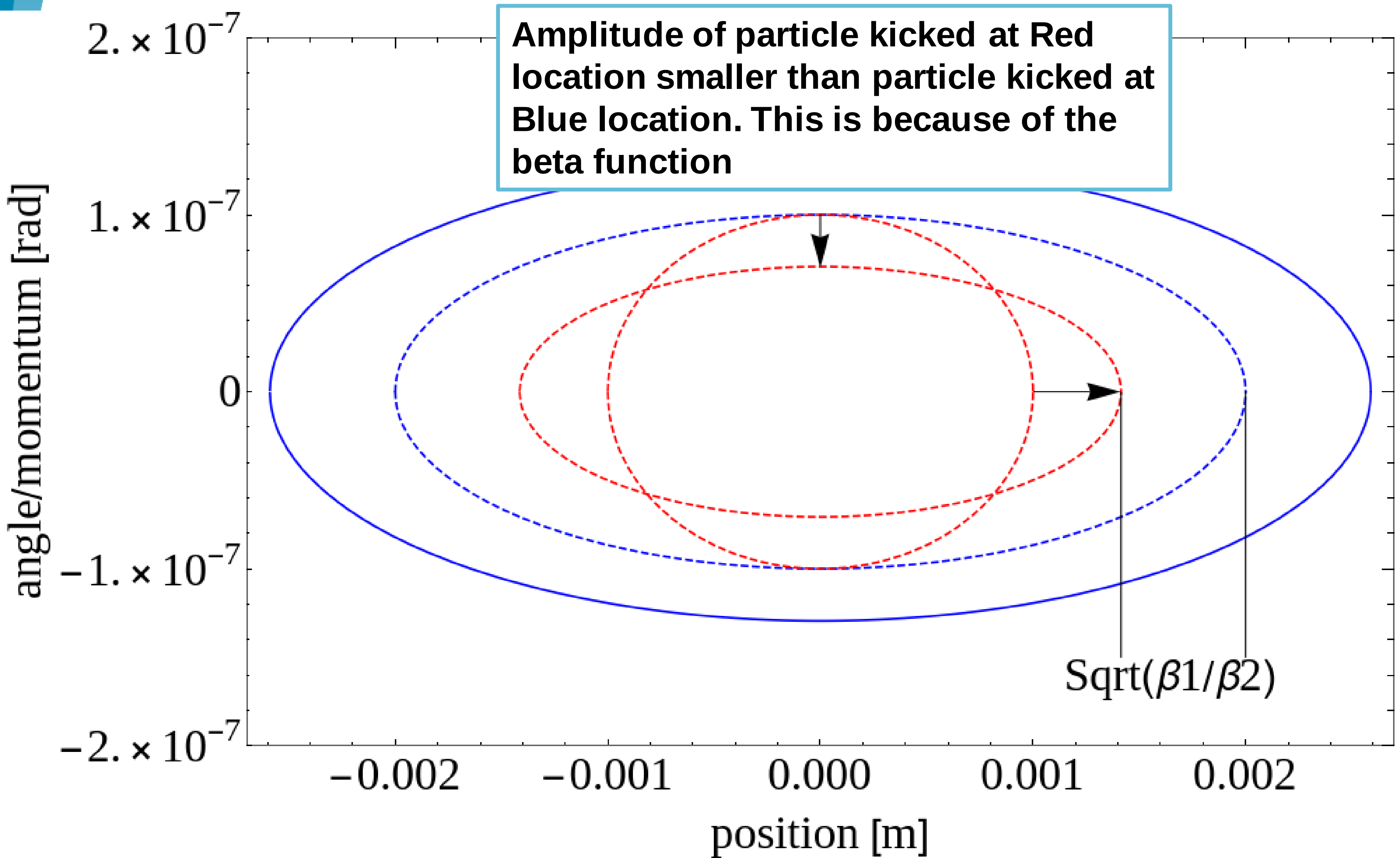
# Beam sensitivity to perturbations

Particle at other location traces out different ellipse



# Beam sensitivity to perturbations

Observe Red particle at Blue location, transforms the ellipse

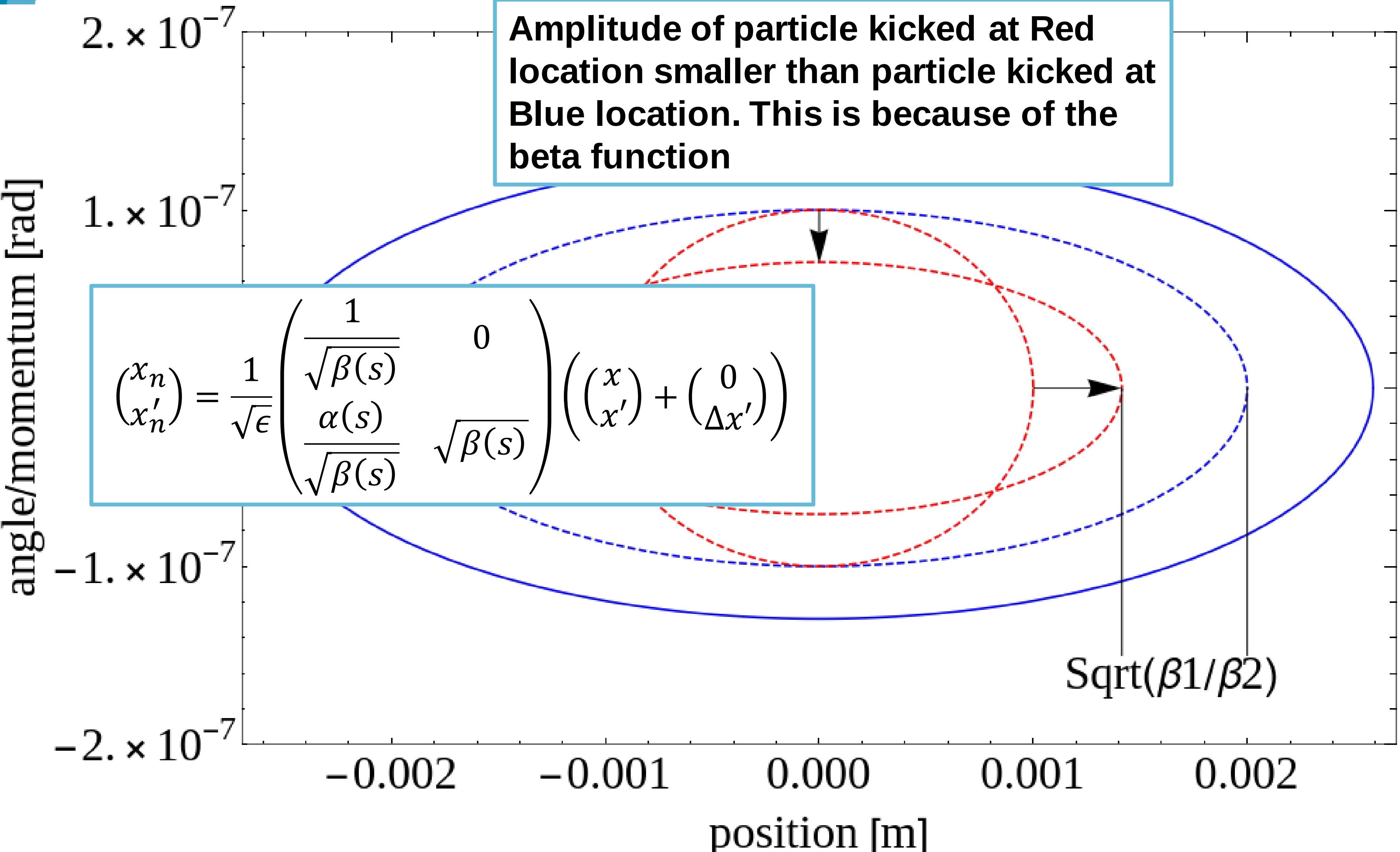


# Beam sensitivity to perturbations

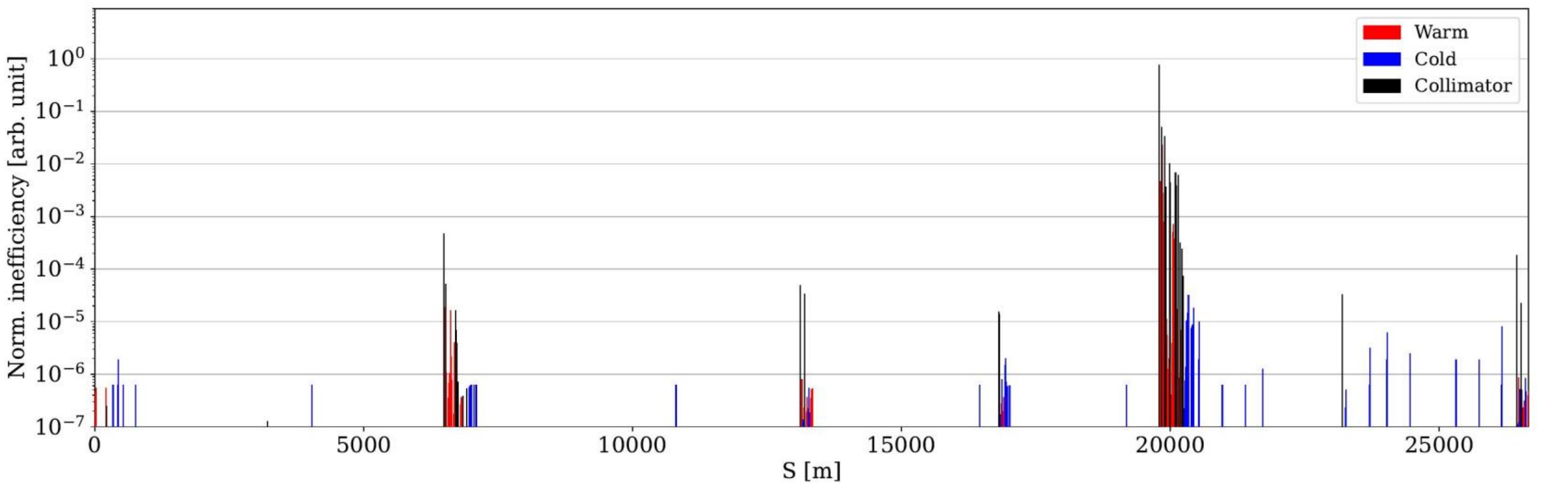
Observe Red particle at Blue location, transforms the ellipse

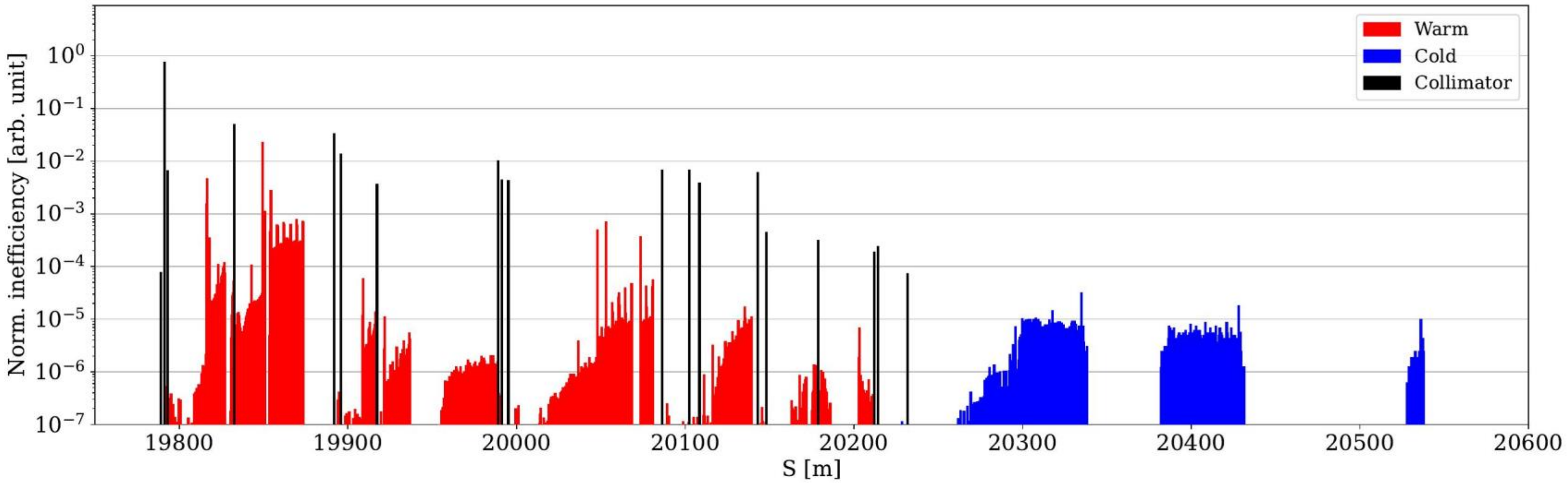
**Amplitude of particle kicked at Red location smaller than particle kicked at Blue location. This is because of the beta function**

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

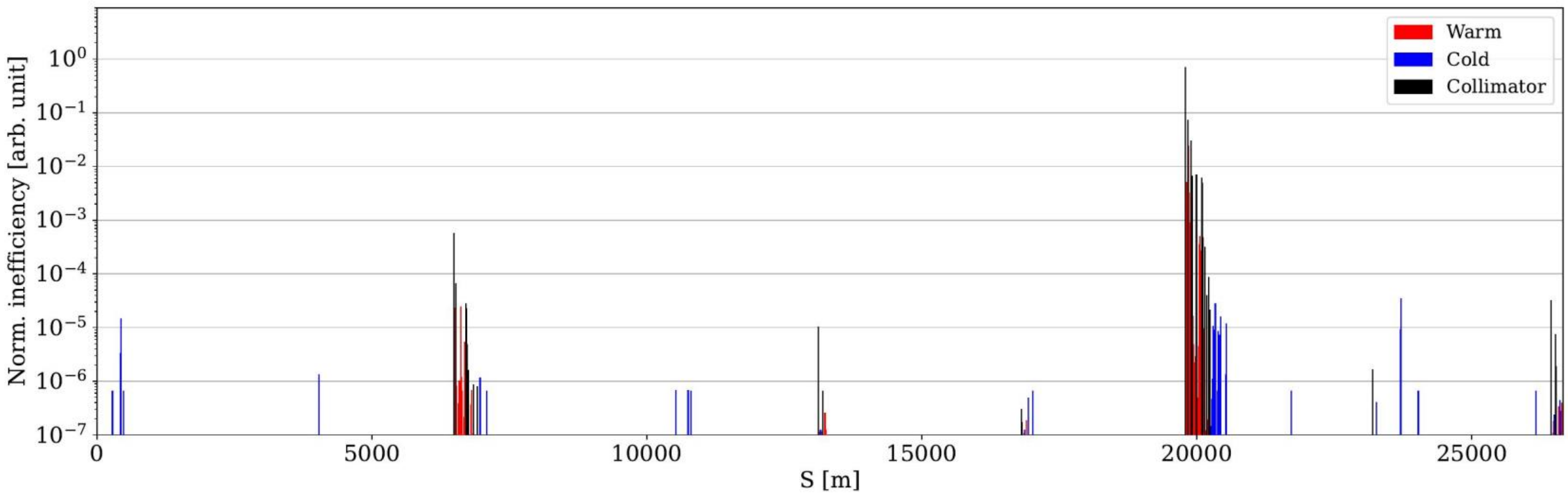


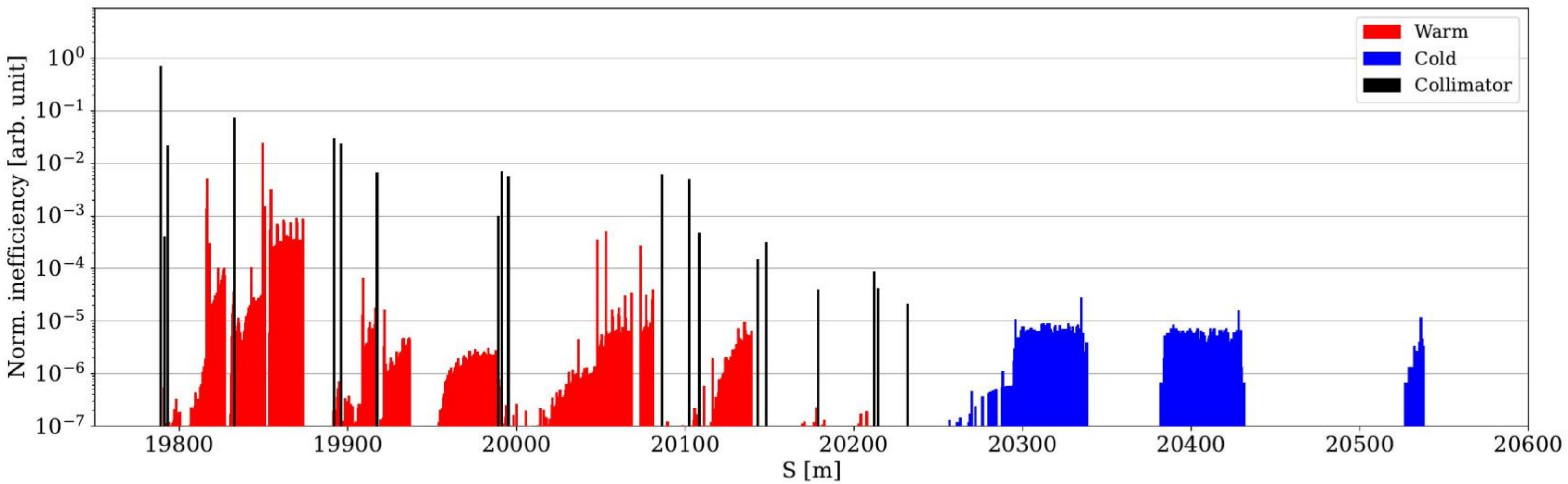
# B1H – 20 cm – relaxed settings – no TCLD (ref)



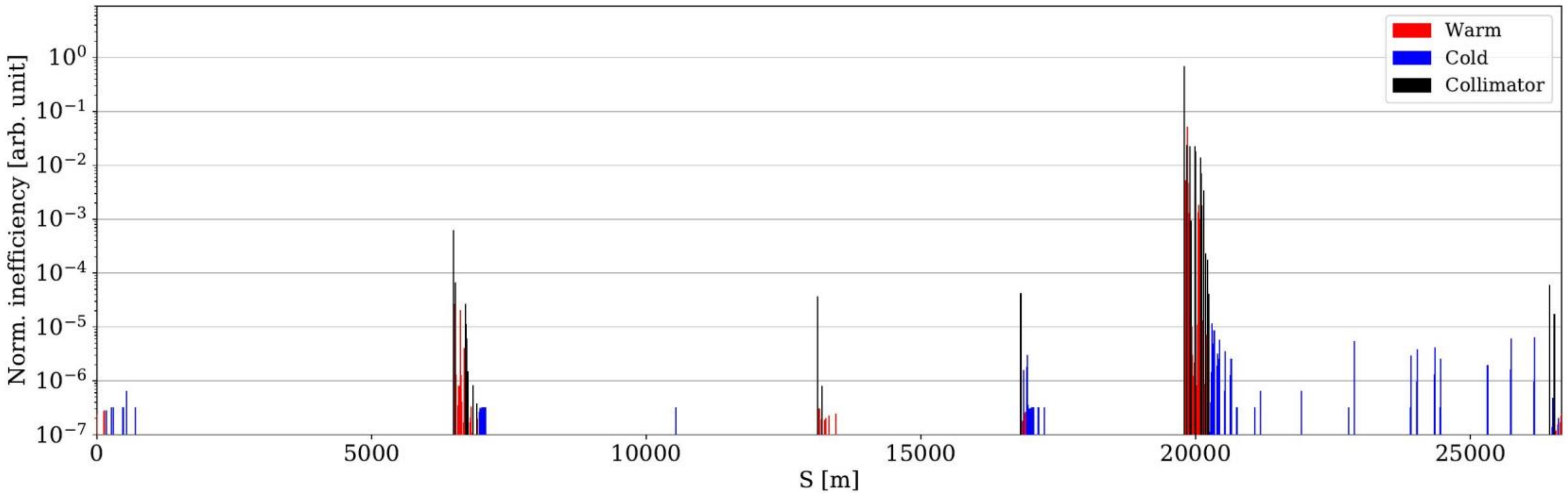



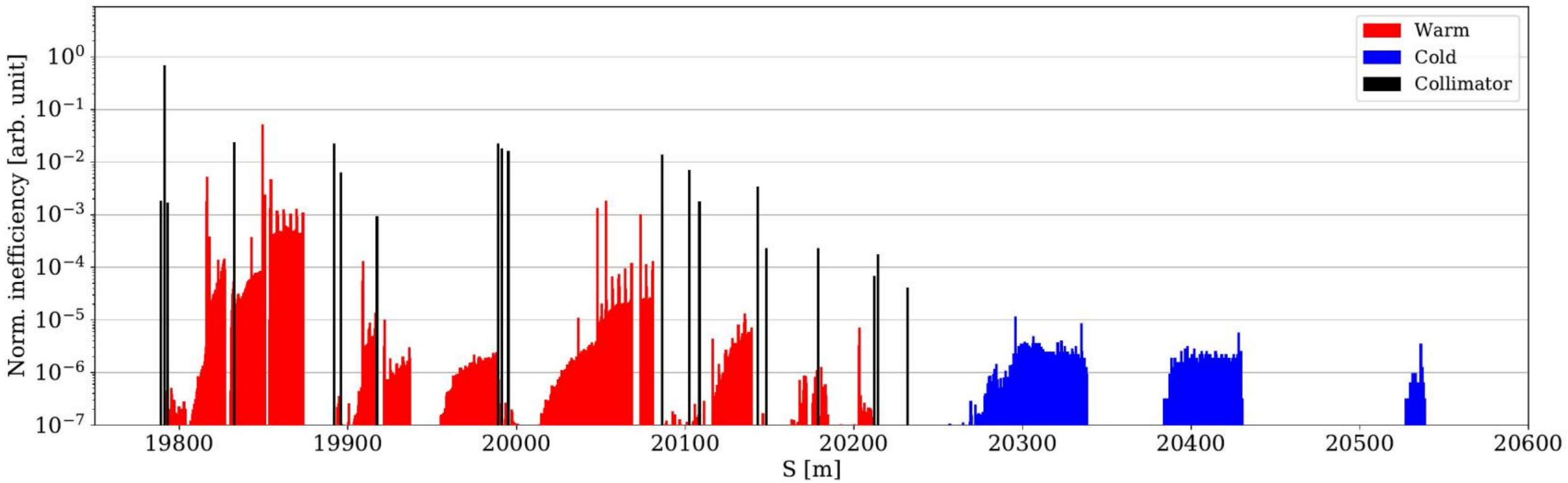
# B1V – 20 cm – relaxed settings – no TCLD (ref)



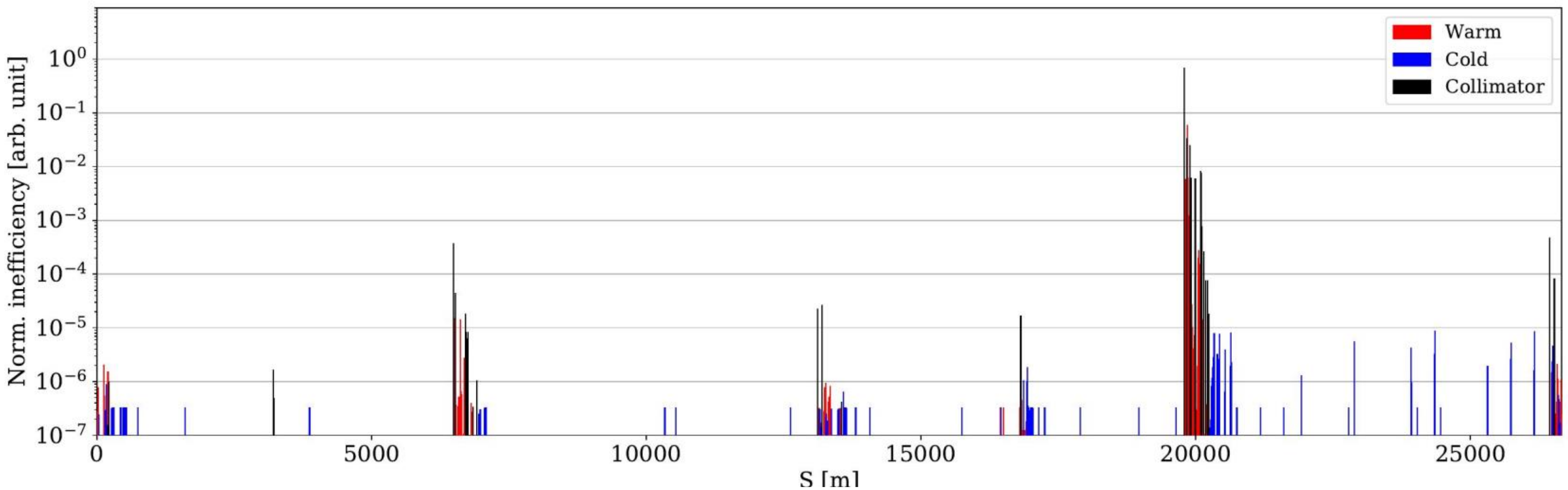



# B1H – rematch


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]
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0
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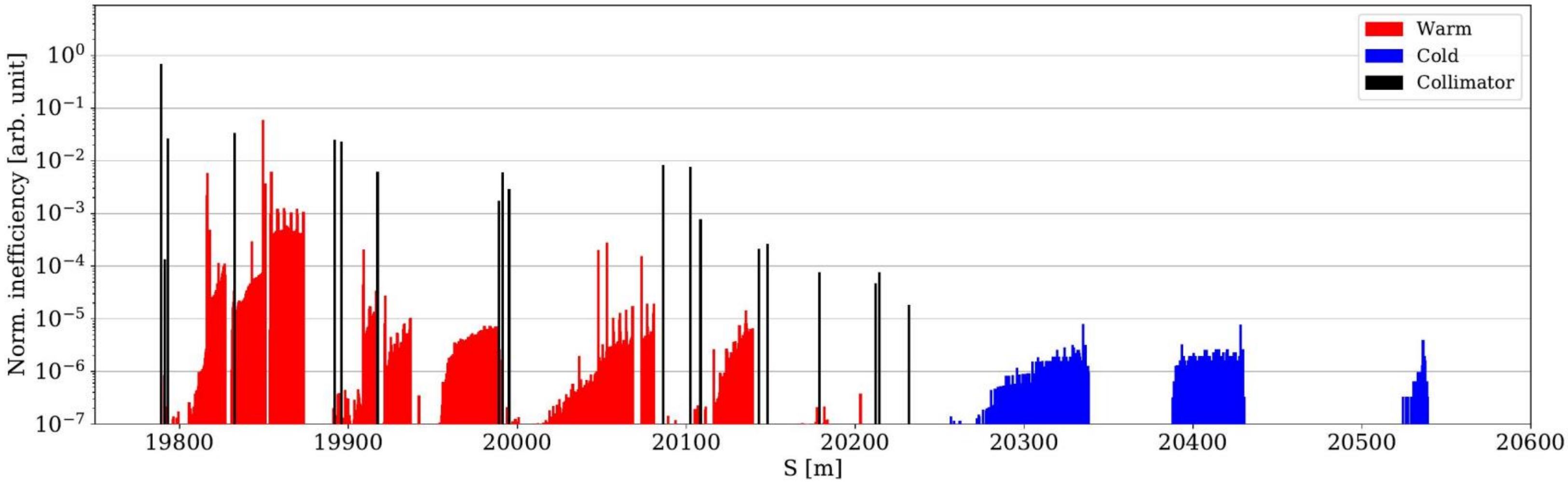
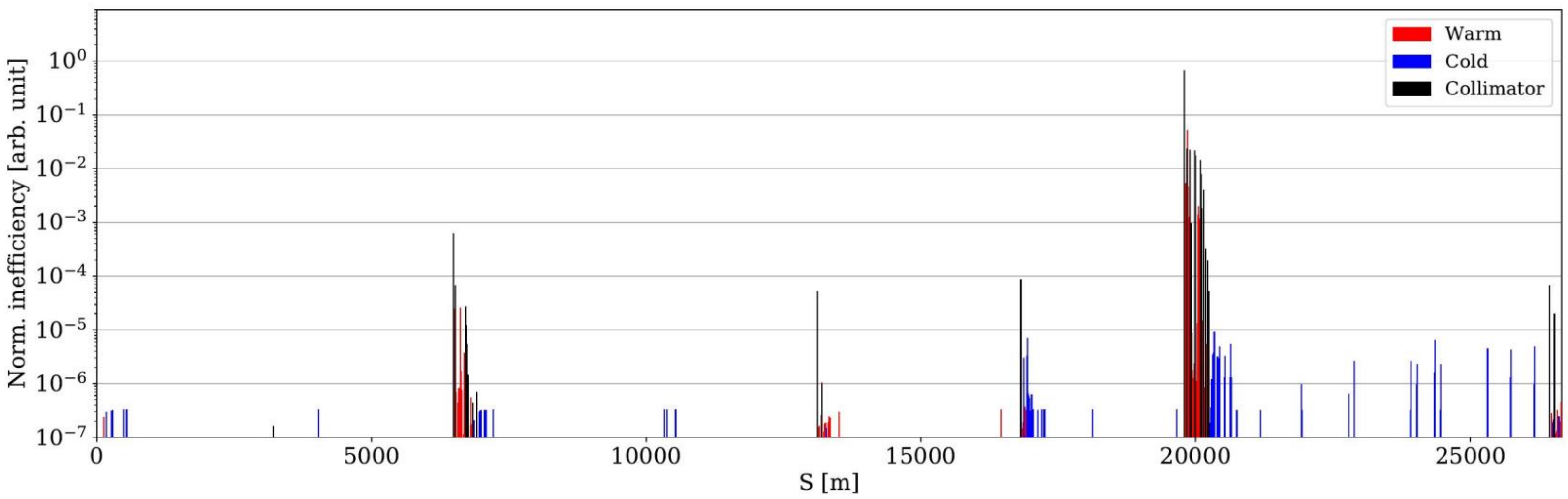
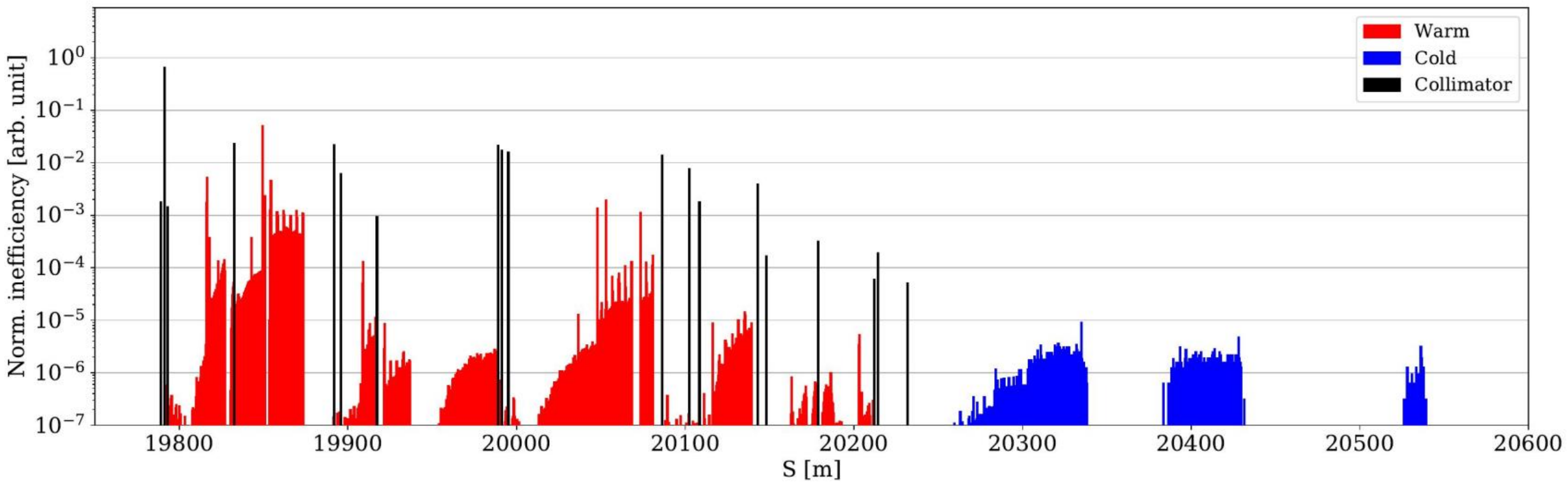
15000
20000
25000
S [m]

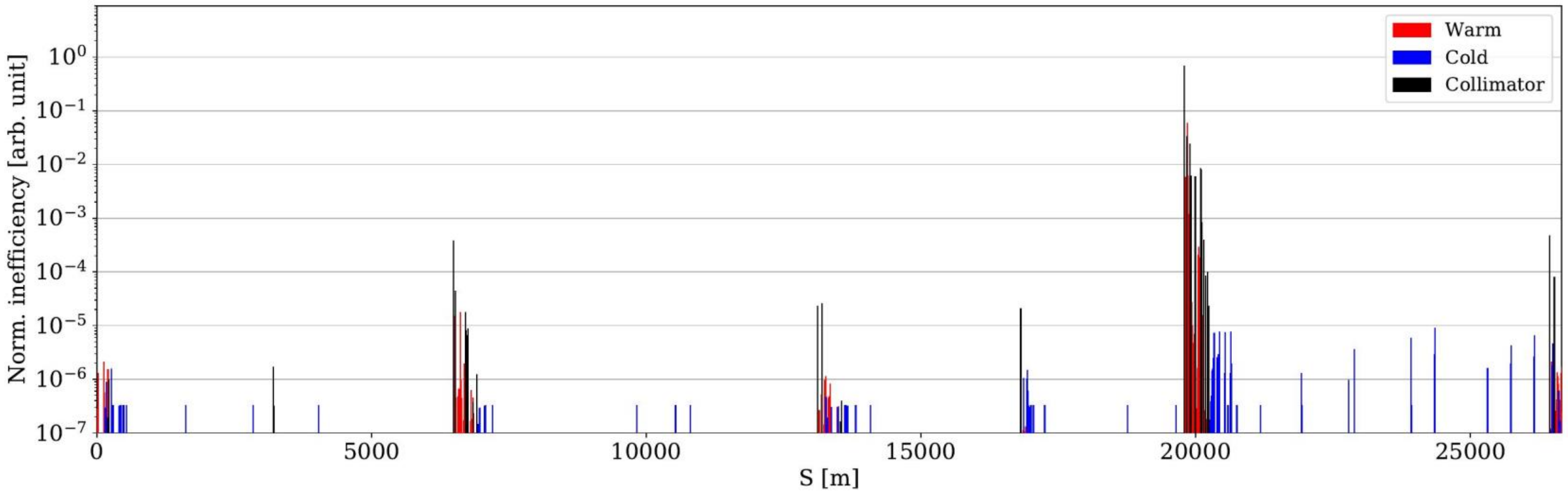

Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
19800
19900
20000
20100
20200
20300
20400
20500
20600
S [m]

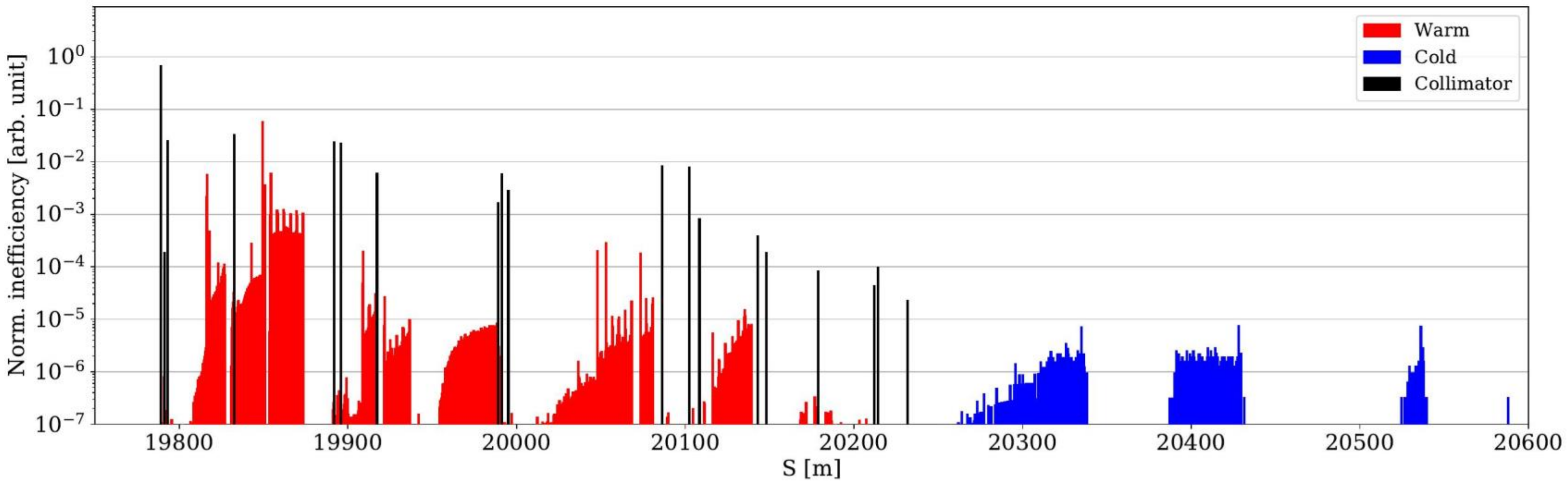
# B1H – rematch + orbit bump



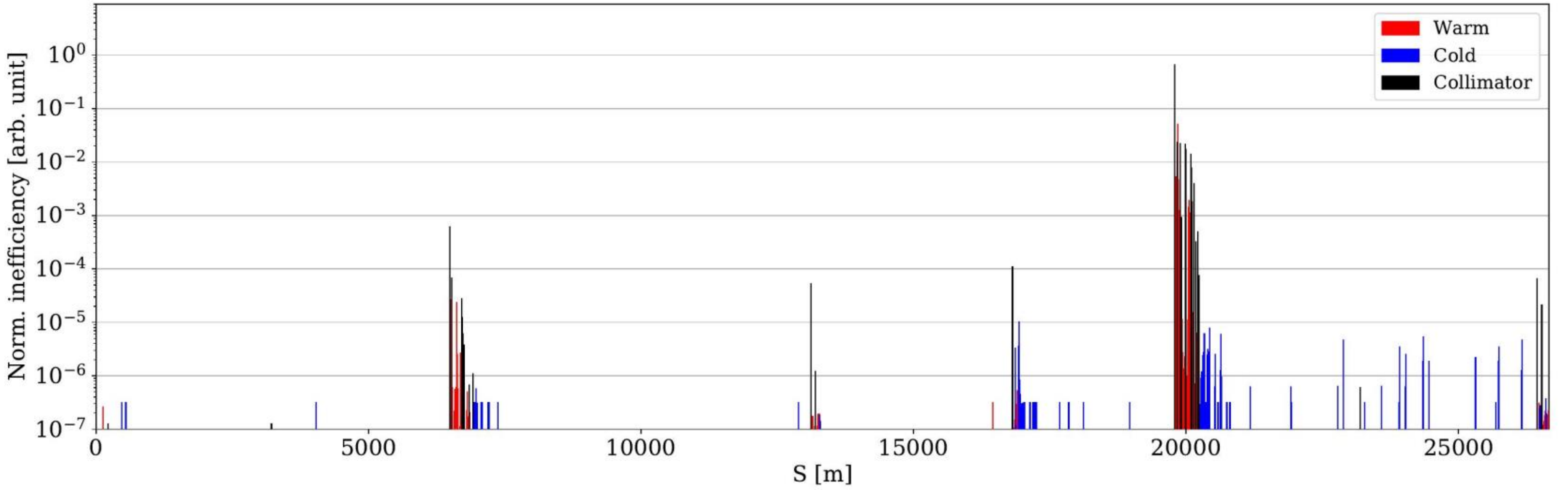



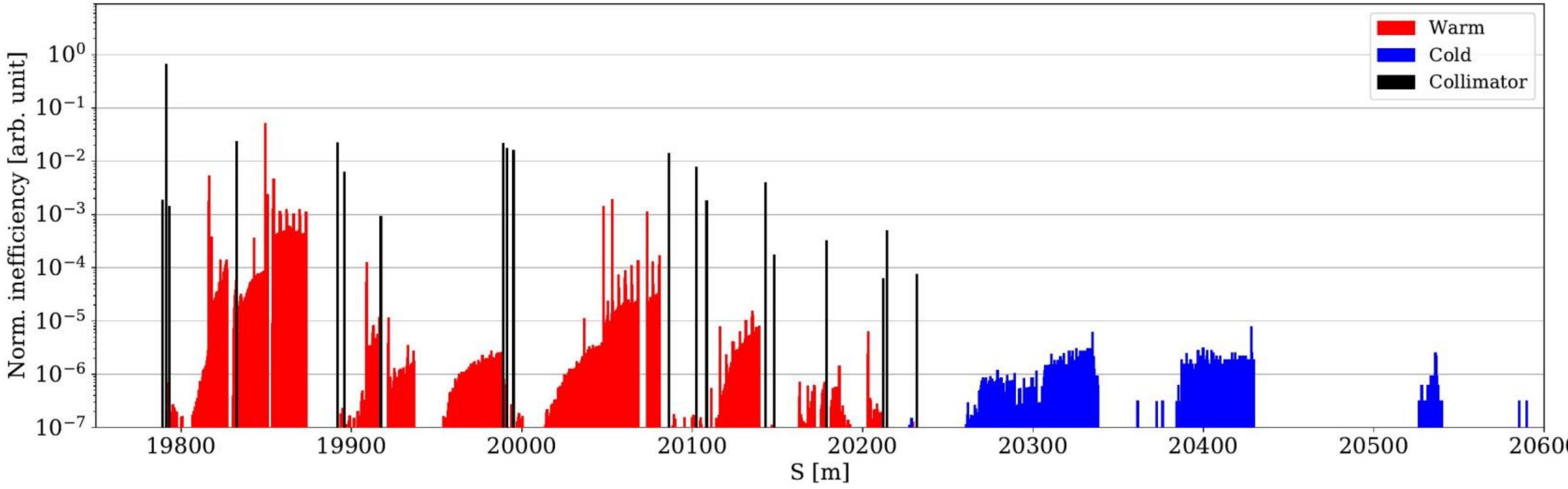
# B1V – rematch + orbit bump



# B1H – rematch + orbit bump + TCLA offset 3 sigma

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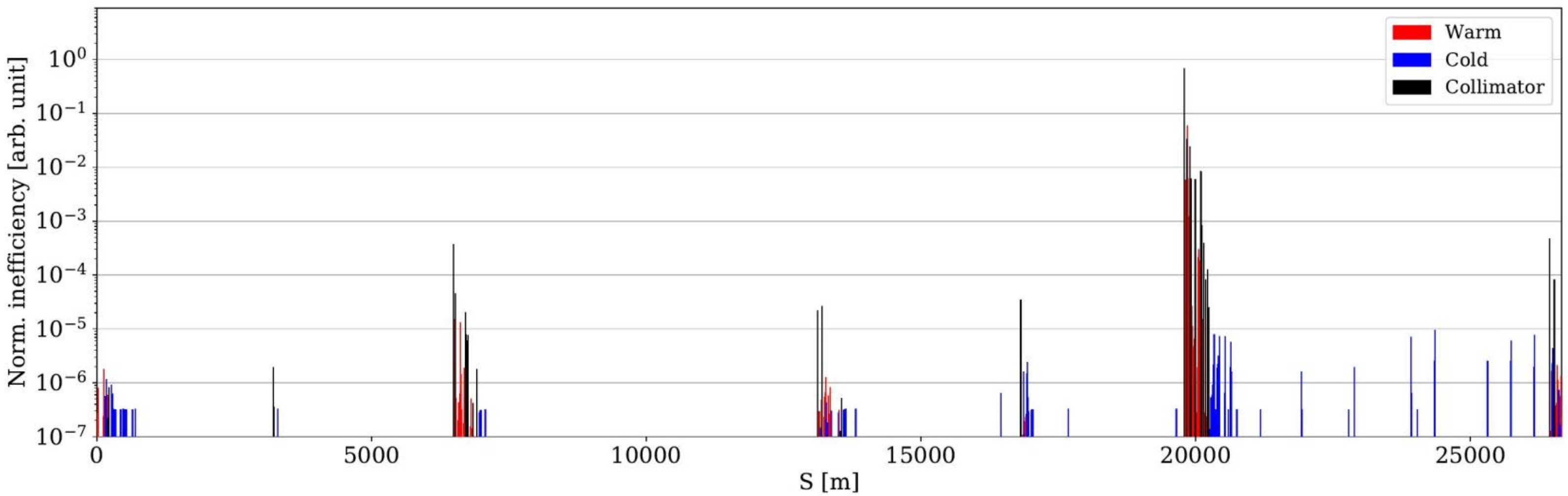
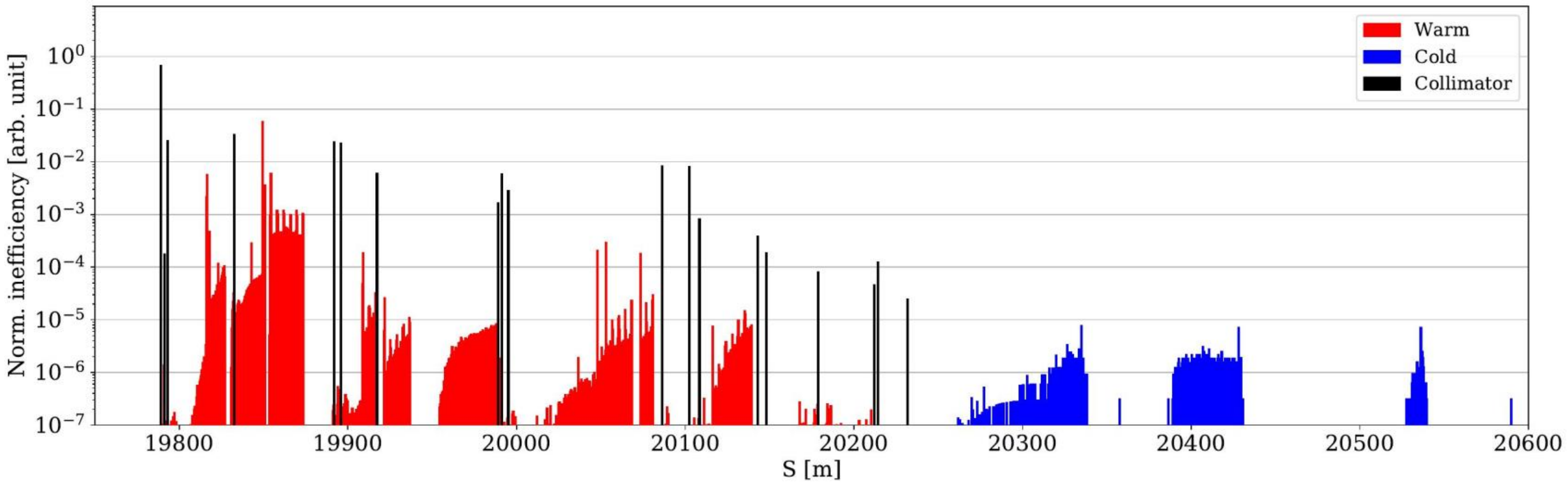
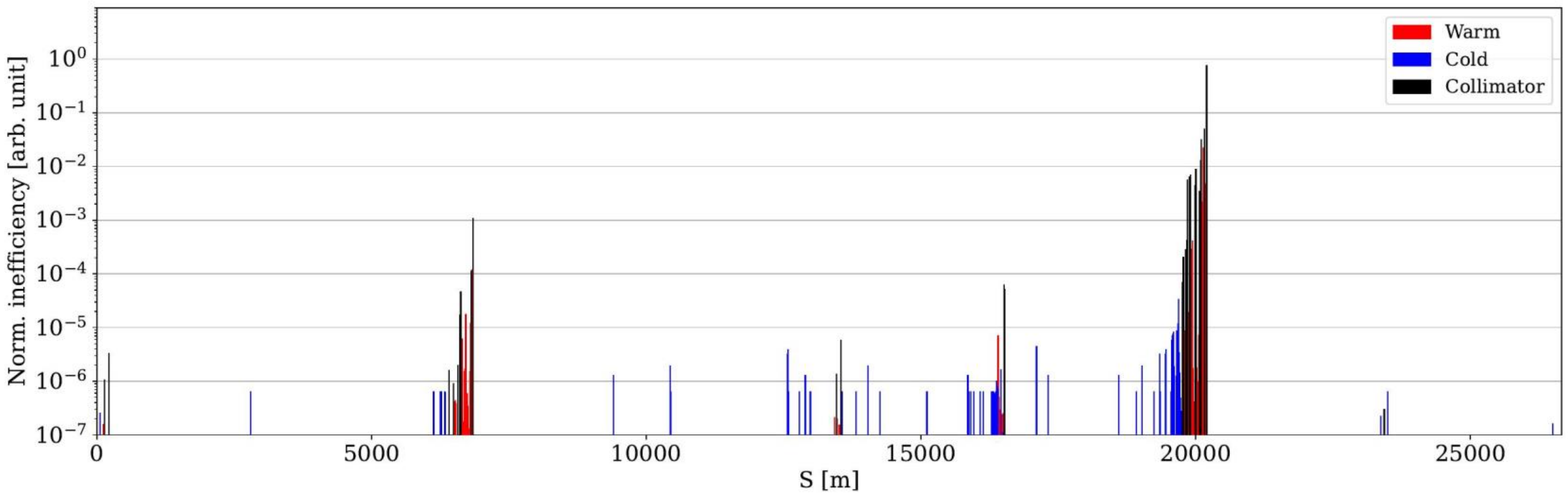
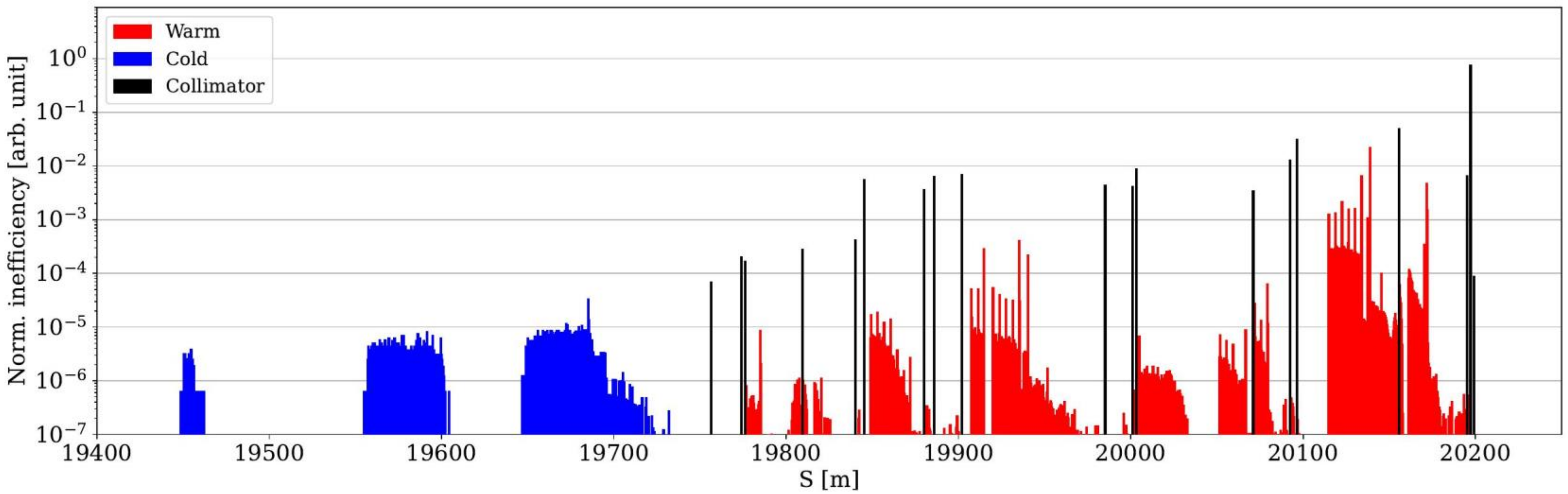
# B1V – rematch + orbit bump + TCLA offset 3 sigma



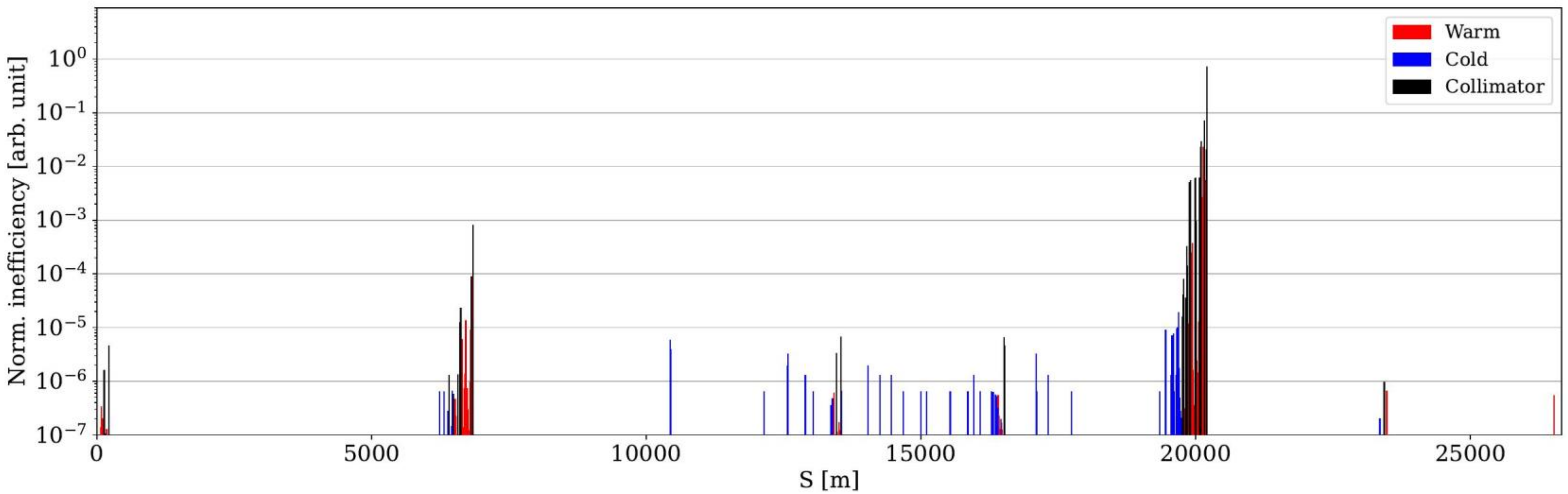



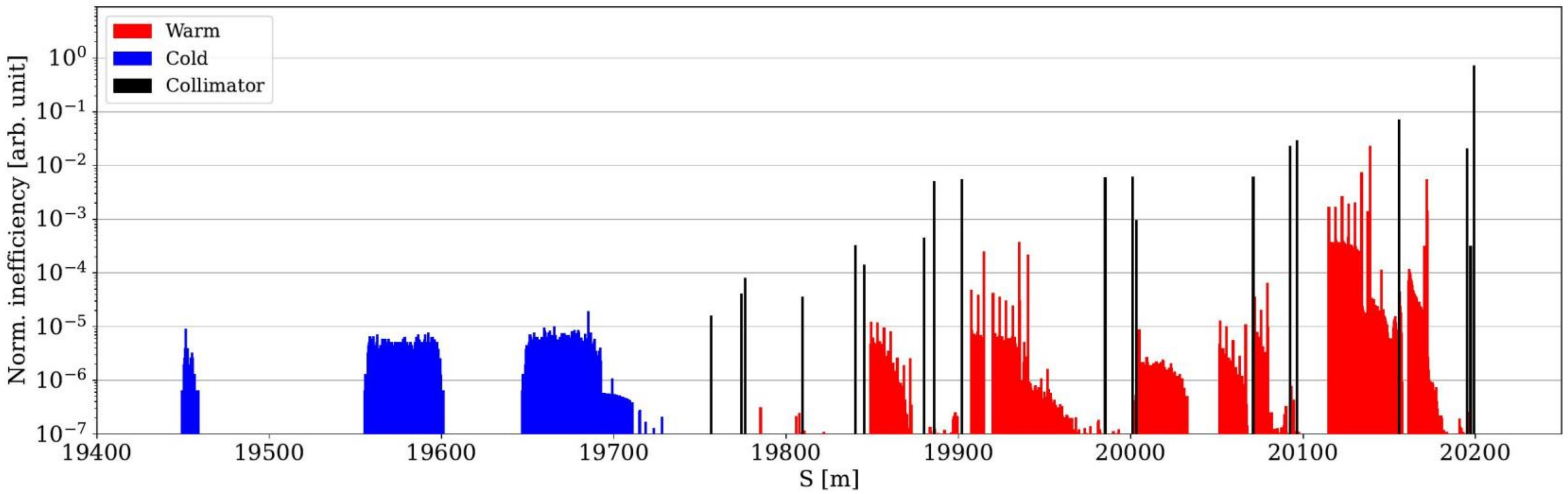
# B2H – 20 cm – relaxed settings – no TCLD (ref)



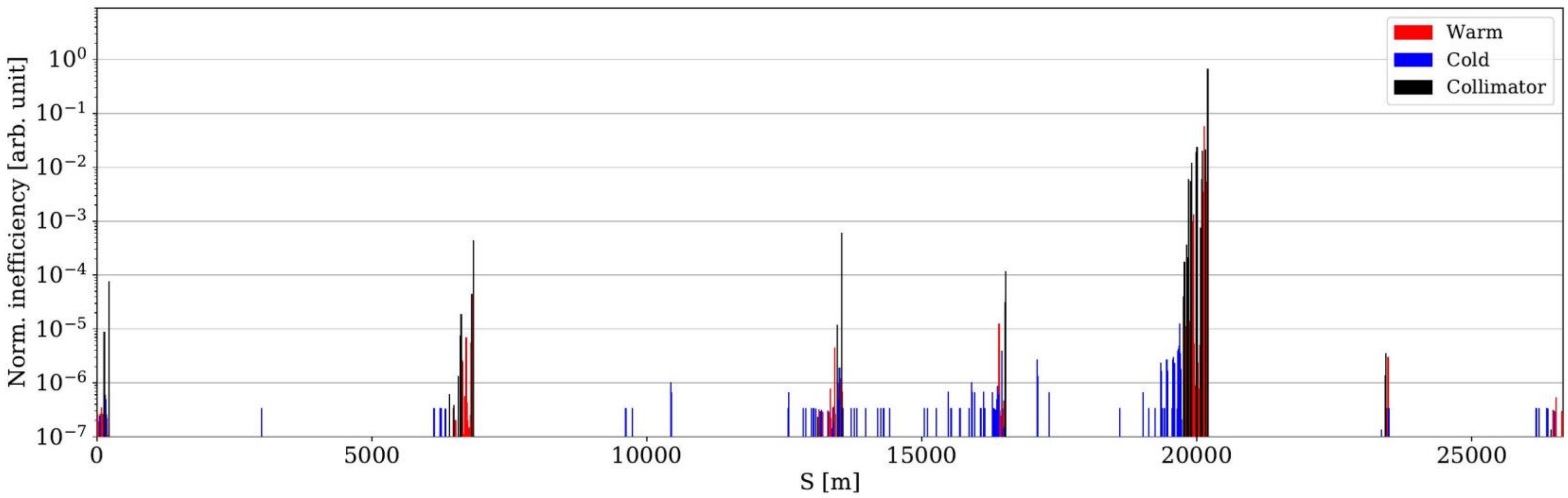



# B2V – 20 cm – relaxed settings – no TCLD (ref)

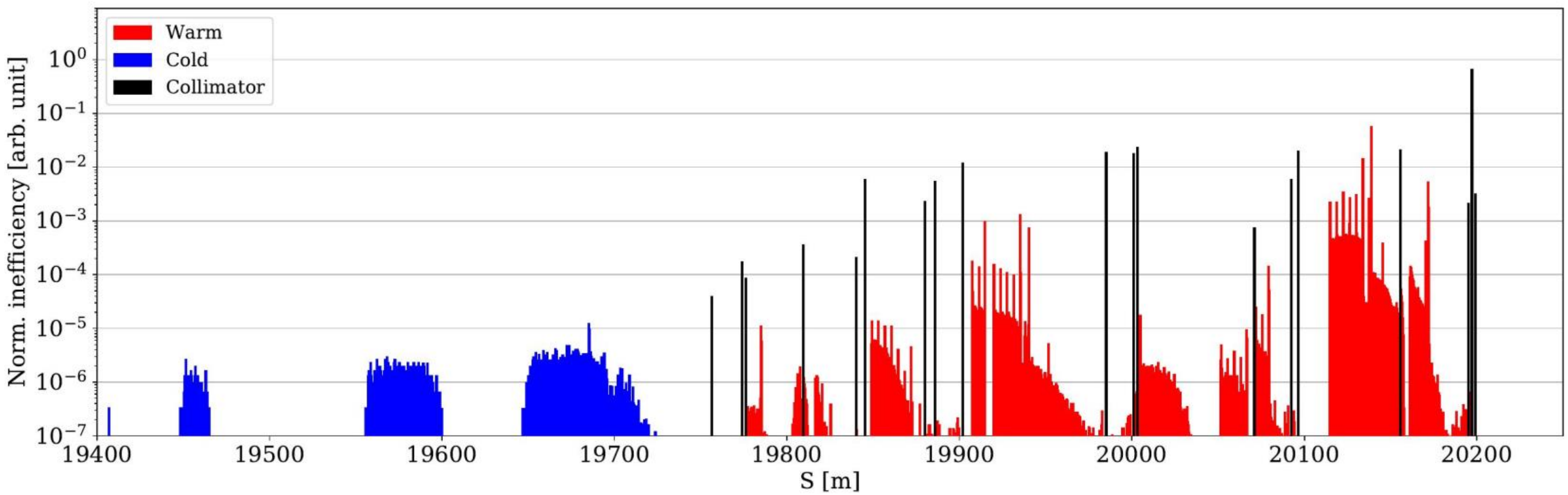


# B2H – rematch

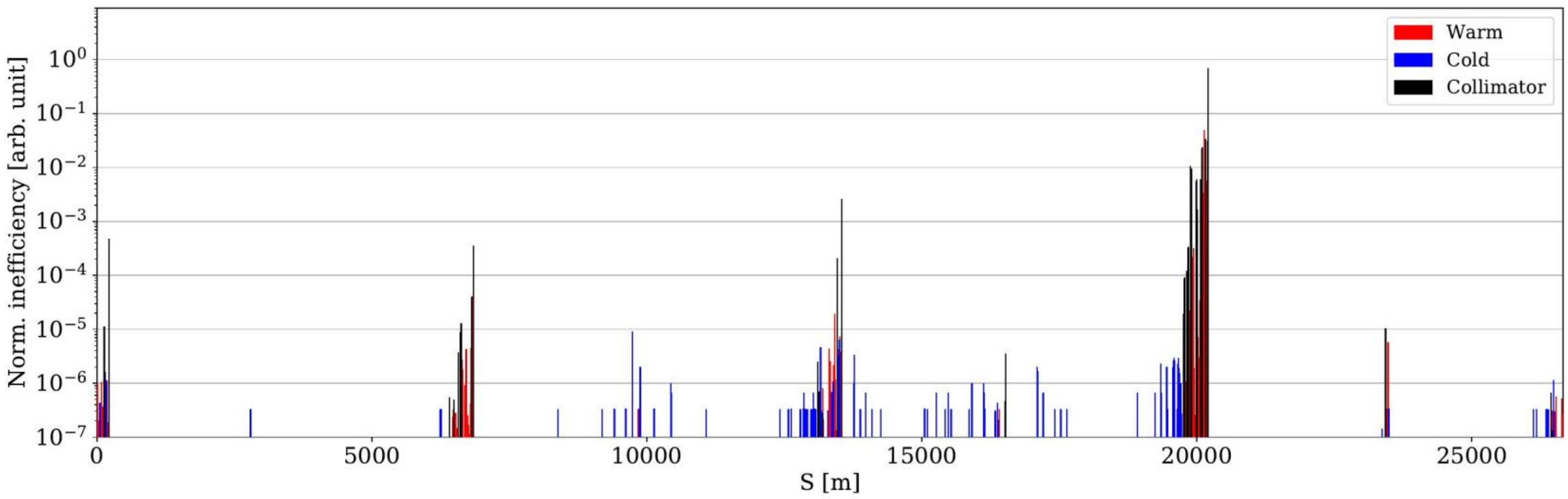


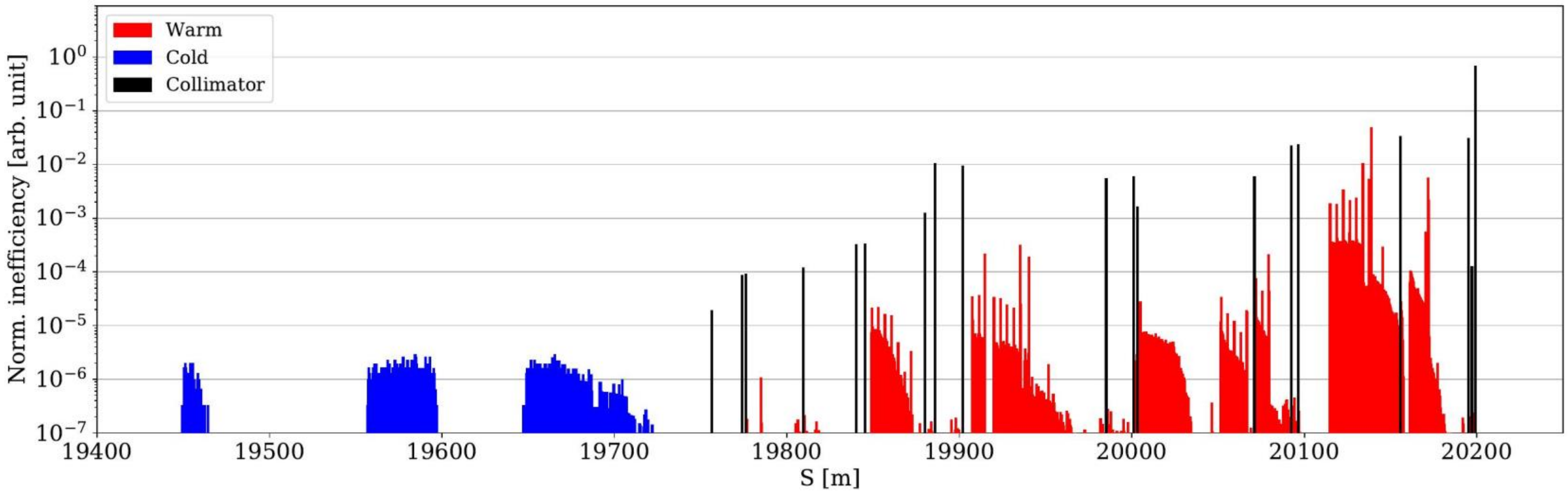
Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
S [m]
0
5000
10000
15000
20000
25000

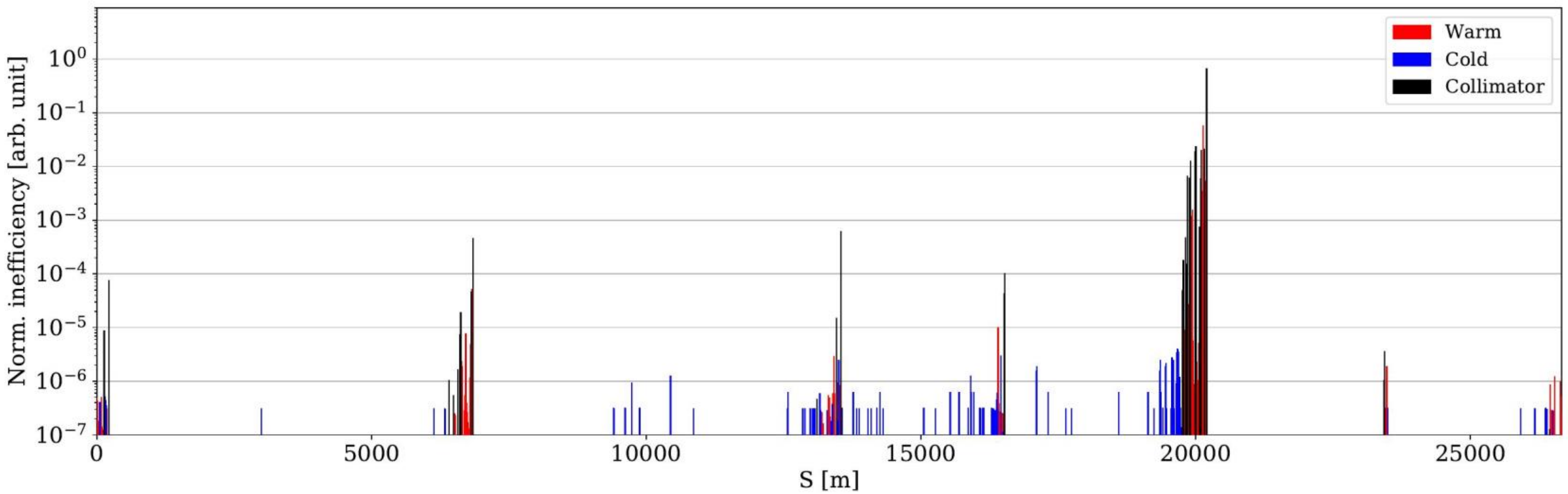
Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
S [m]
19400
19500
19600
19700
19800
19900
20000
20100
20200

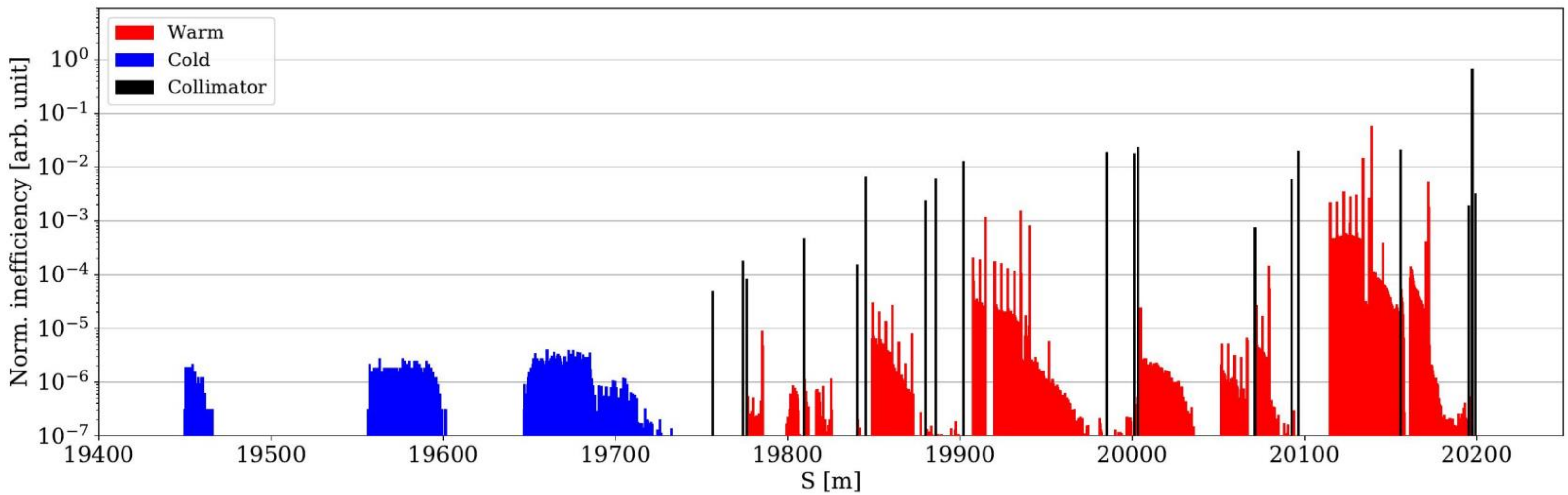
# B2V – rematch


Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
S [m]

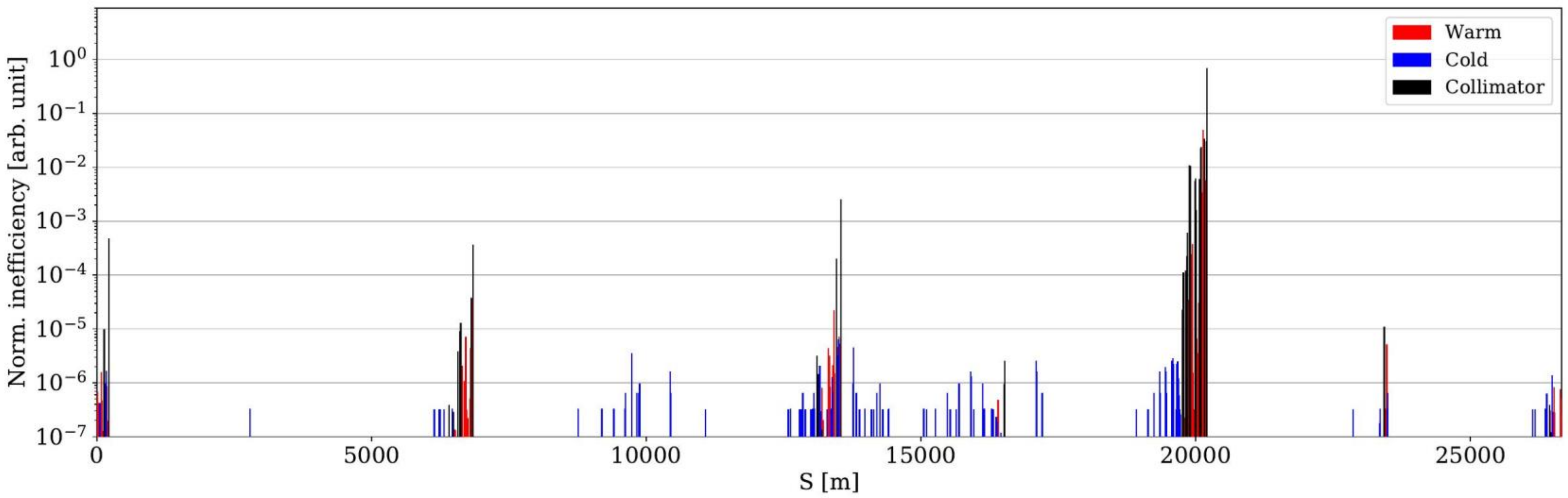

Warm
Cold
Collimator
Norm. inefficiency [arb. unit]
S [m]

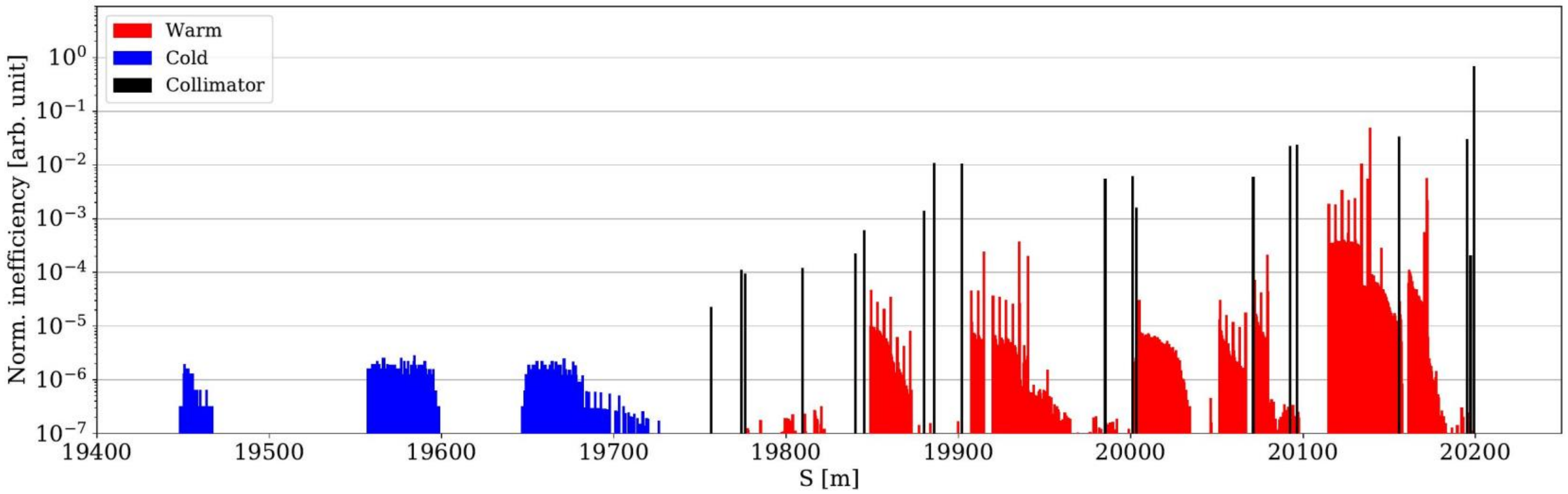
# B2H – rematch + orbit bump



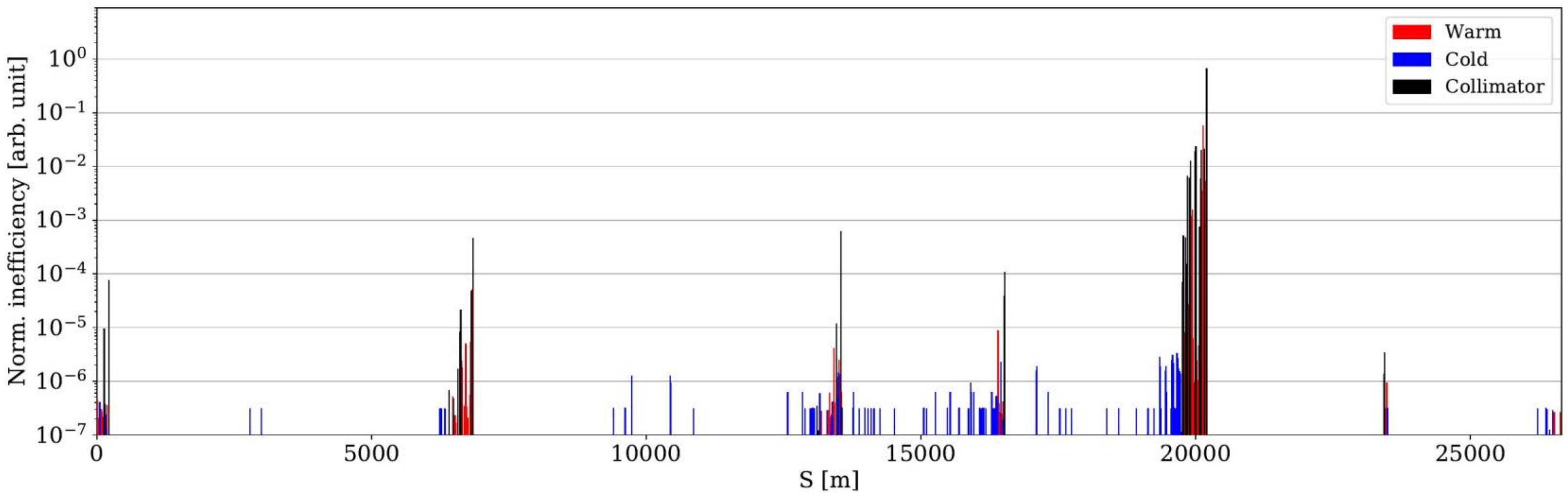



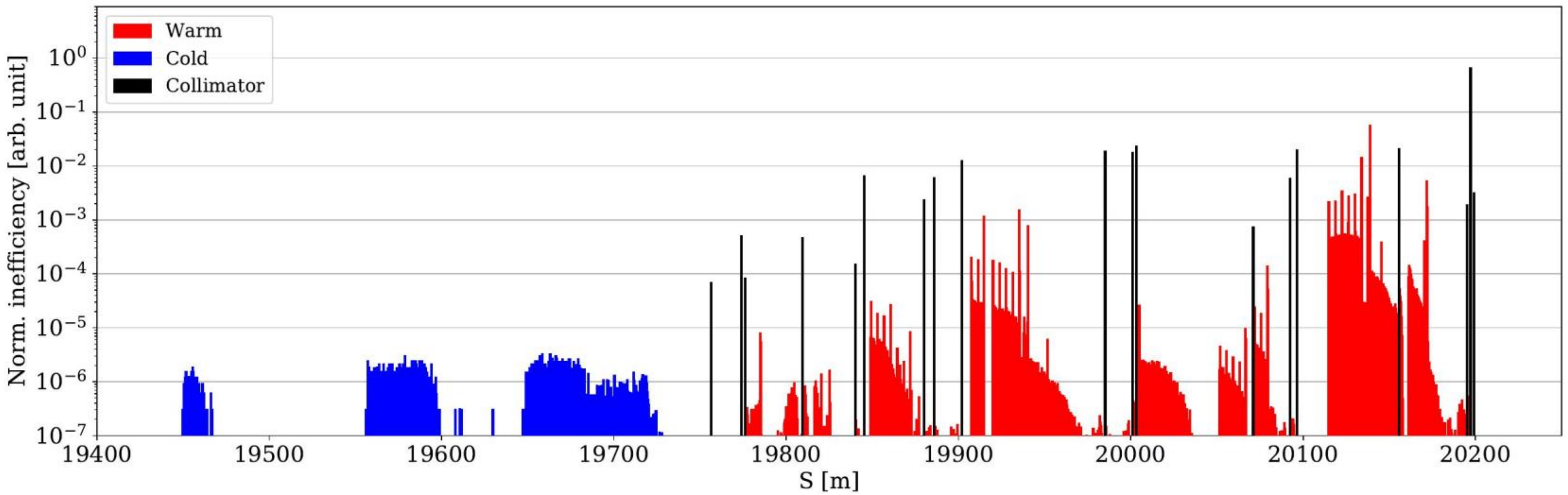
# B2V – rematch + orbit bump



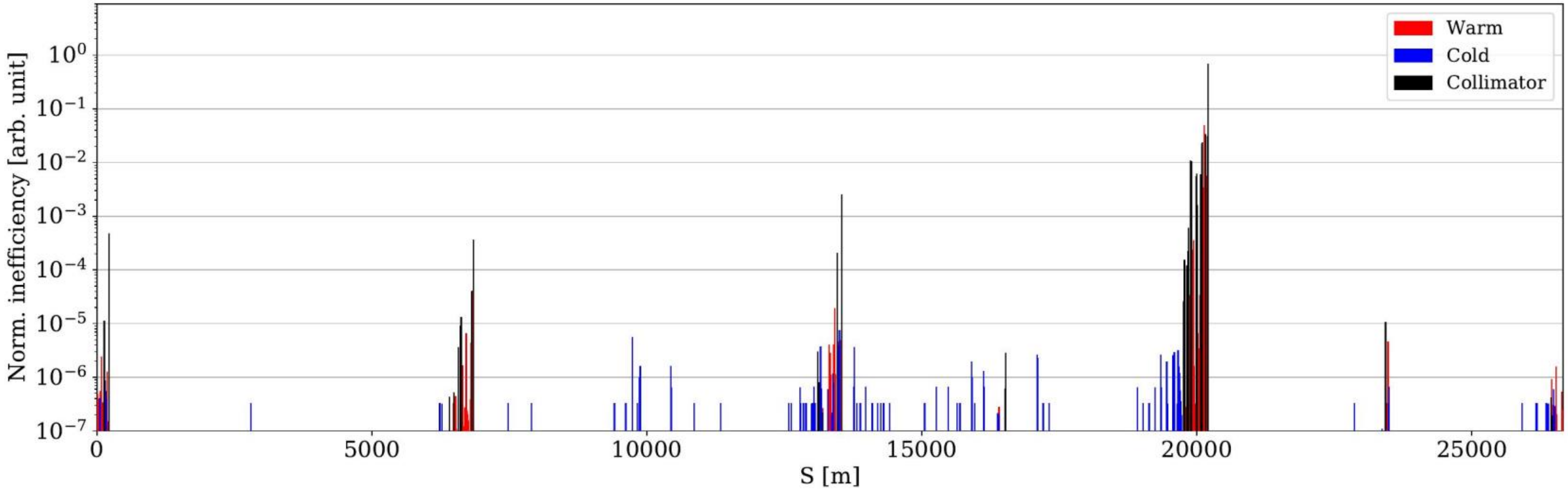



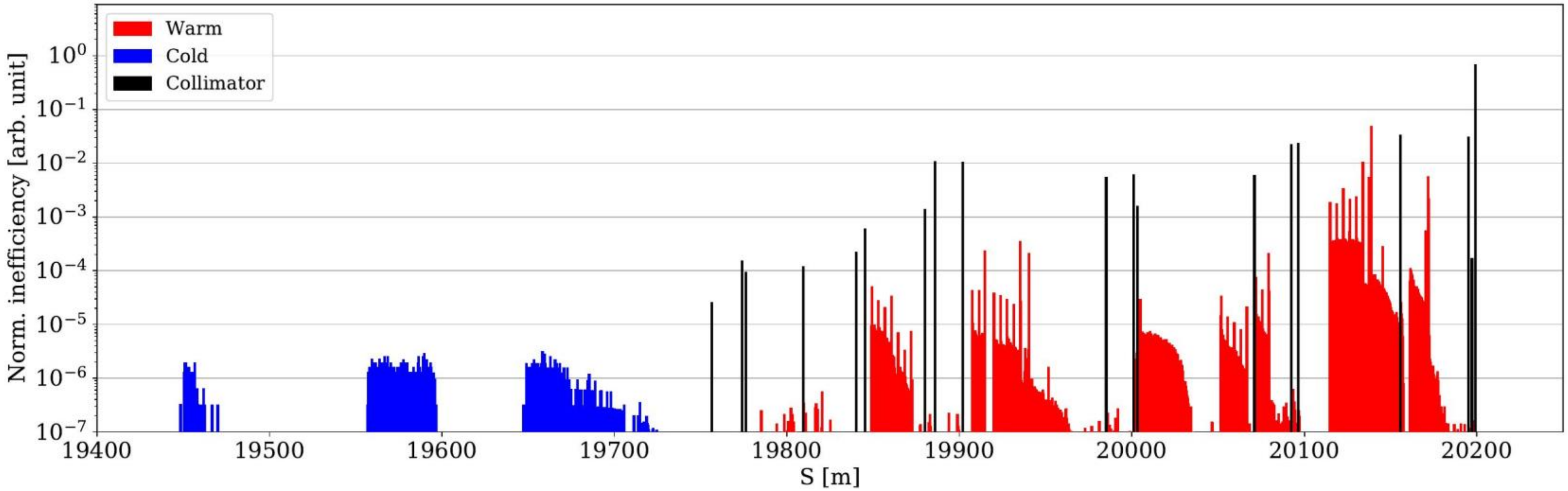
# B2H – rematch + orbit bump + TCLA offset 3 sigma



# B2V – rematch + orbit bump + TCLA offset 3 sigma

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