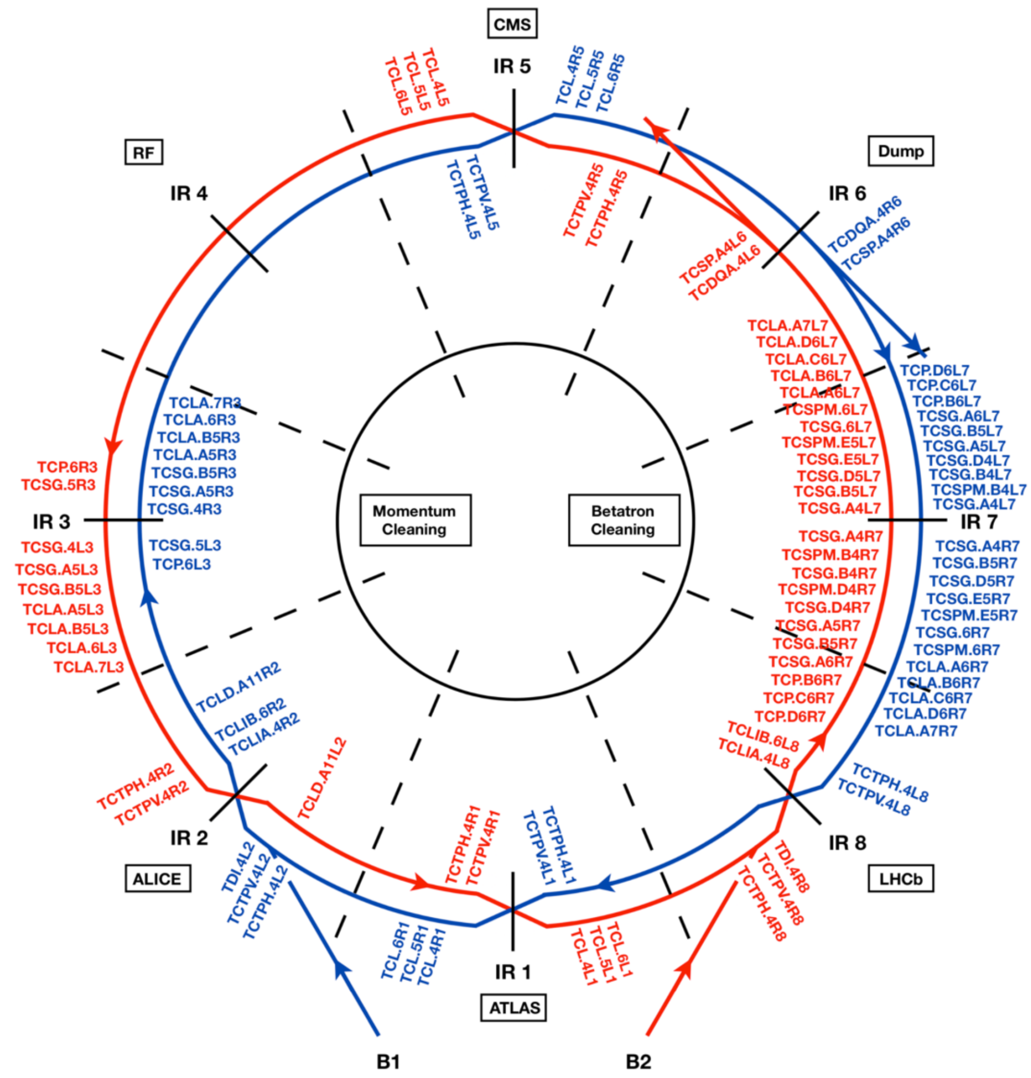
Mitigating collimation impedance and improving halo cleaning with new optics and settings strategy of the HL-LHC betatron collimation system

B. Lindström, R. Bruce, X. Buffat, R. de Maria, L. Giacomel, P. Hermes, D. Mirarchi, N. Mounet, T. Persson, S. Redaelli, R. Tomás, F.F. Van der Veken, A. Wegscheider

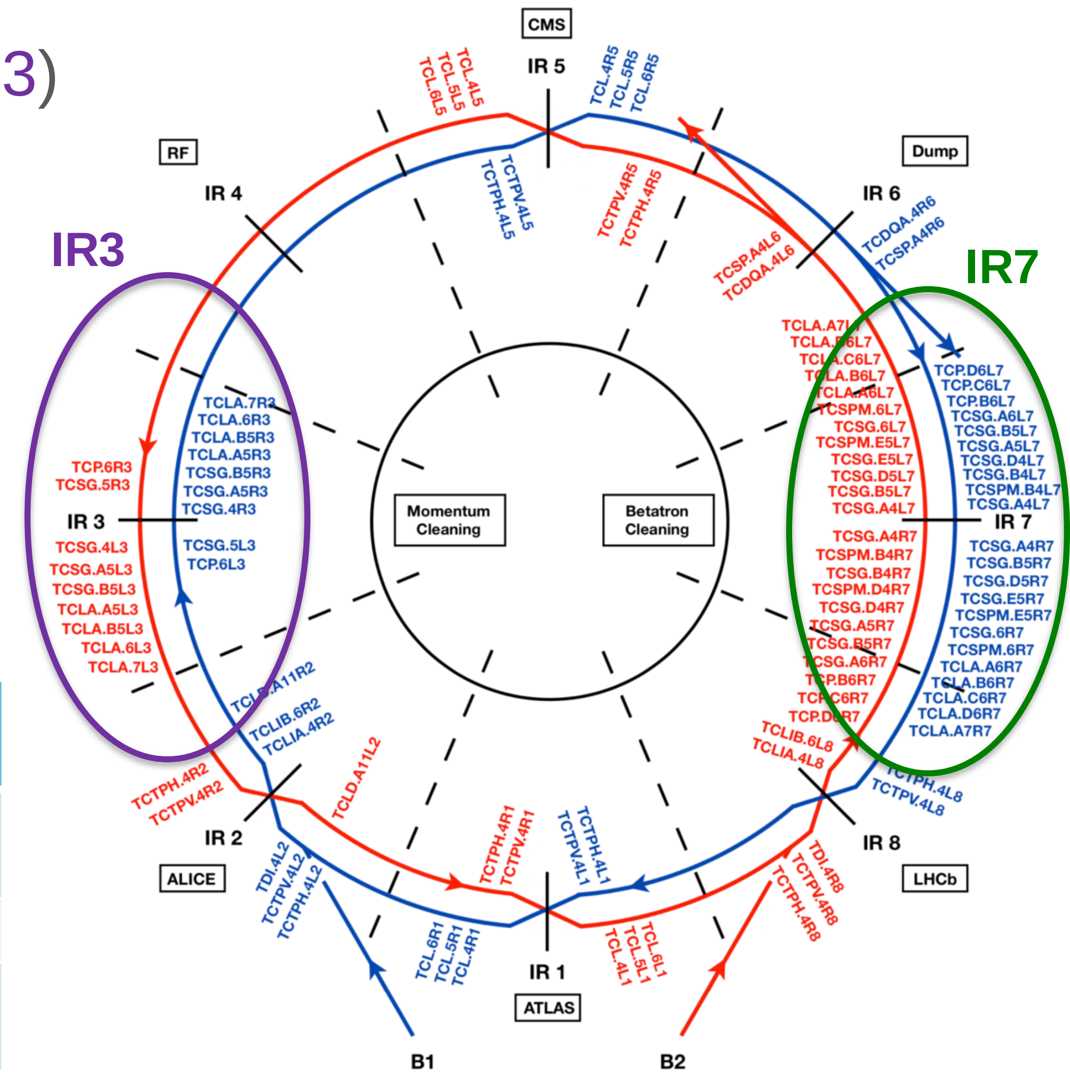
10th October 2023 – HB'23

Collimation insertions in LHC



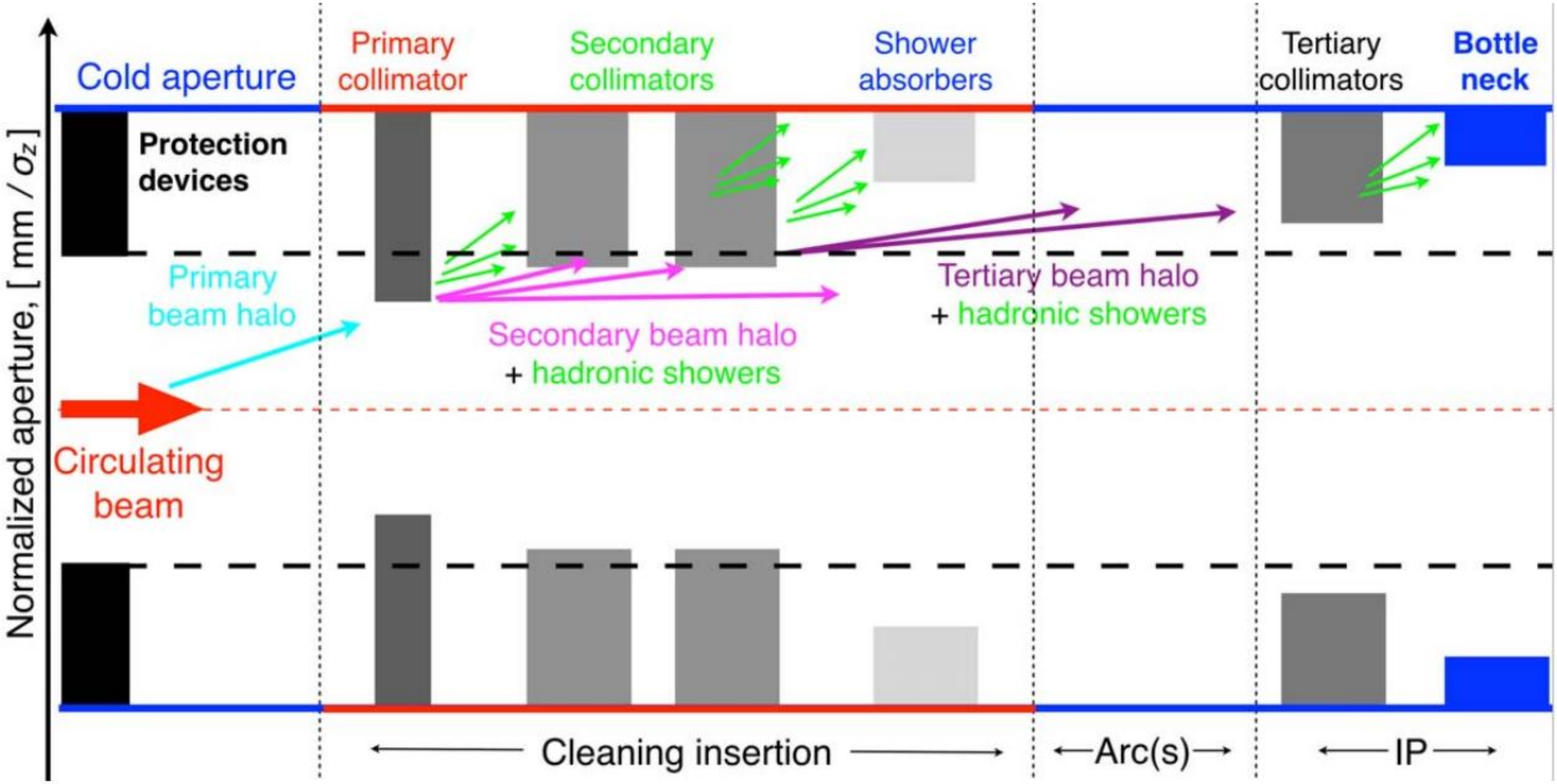
Collimation insertions in LHC

- Momentum cleaning (IR3)
  - Particles with large momentum offsets
- Betatron cleaning (IR7)
  - Particles with large betatron amplitudes



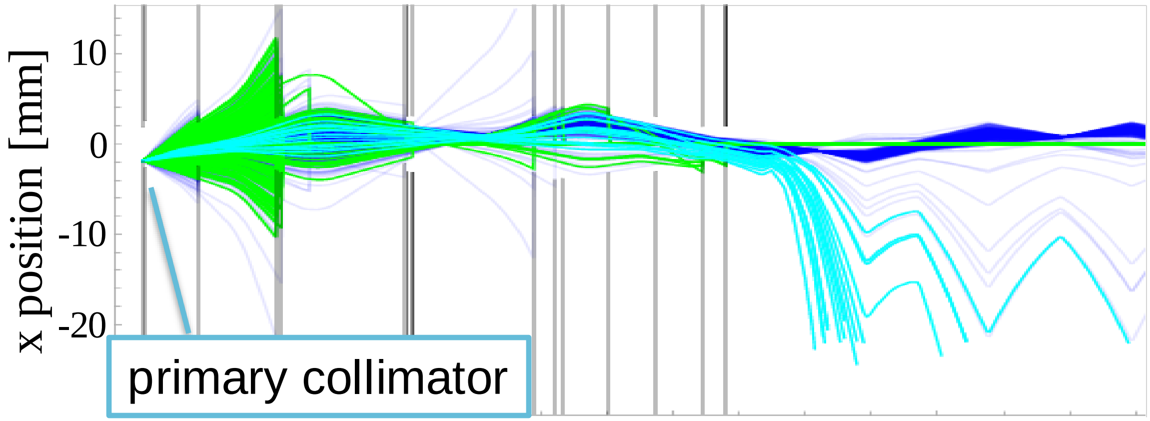
	2023	LHC design	HL-LHC design
Bunch intensity [p+]	1.4-1.6	1.15	2.3
Energy [GeV]	6800	7000	7000
Stored beam energy [MJ]	410	362	678

Multi-stage Collimation



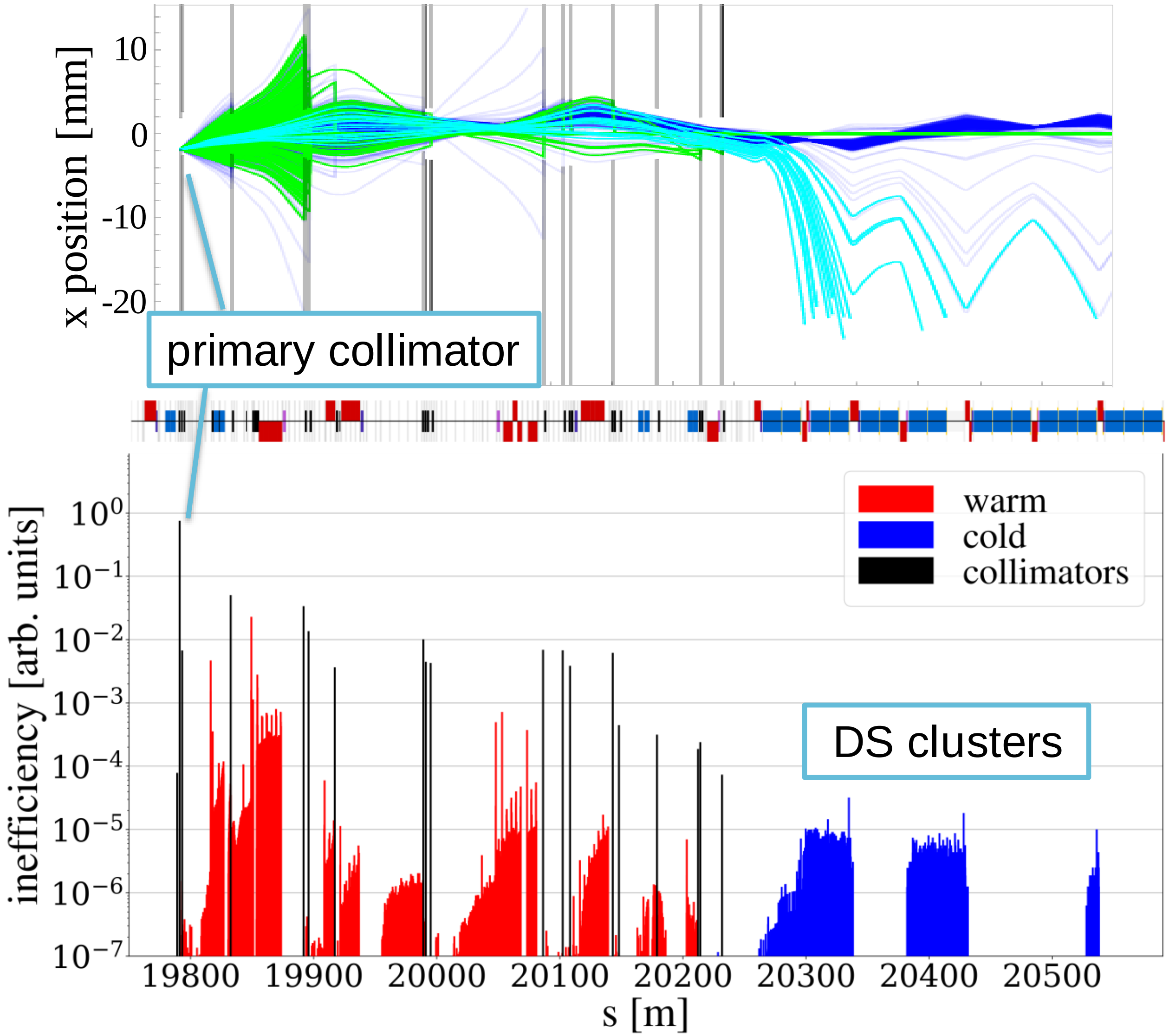
Leakage of collimator losses

- Particles leak out of collimator insertion



Leakage of collimator losses

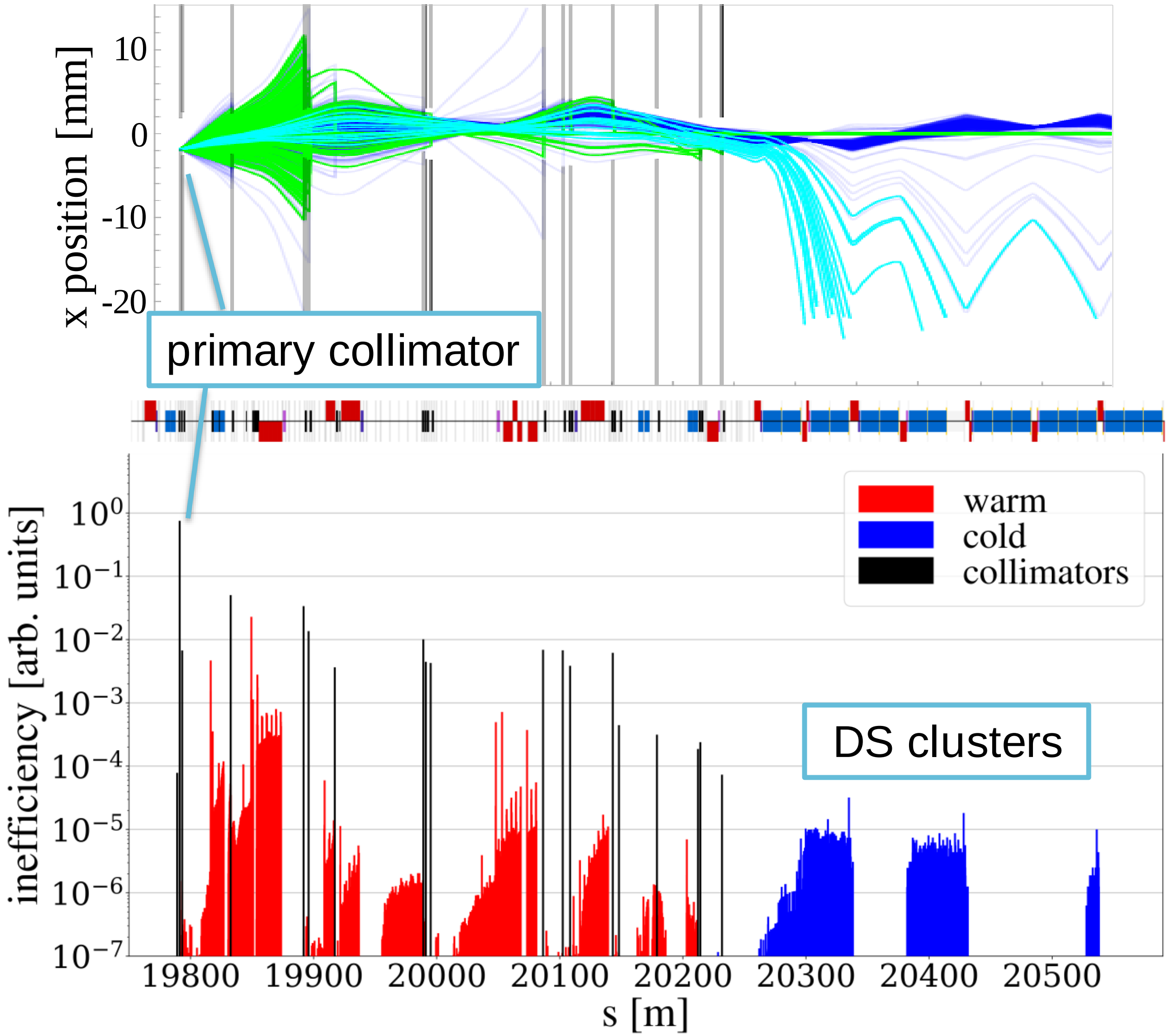
- Particles leak out of collimator insertion
- Particles with large momentum offsets (>~0.2 %) lost in Dispersion Suppressor
- Critical for cleaning performance due to quench risk



Leakage of collimator losses

- Particles leak out of collimator insertion
- Particles with large momentum offsets (>~0.2 %) lost in Dispersion Suppressor
- Critical for cleaning performance due to quench risk

- β* reduction requires tight collimator settings
- Min. collimator gap at top energy ~1 mm



HL-LHC challenges

- Protons per bunch increase:
  - 1.15e11 (design) → 1.4e11 (now) → 2.3e11 (HL)
- Impedance scales with bunch charge
  - → **beam lifetime decreases, instabilities**
  - Collimators main source of impedance (low conductivity and tight gaps)
- Collimator leakage scales with beam intensity (assuming same lifetime)
  - → **increased quench risk**
- Limitations mainly from Betatron Collimation (IR7)

Mitigations

Impedance

- Replace collimators with low-impedance materials
- →Primary: Mo-graphite (instead of CFC)
- →Secondary: Mo-coated Mo-graphite / Cu-coated graphite

Mitigations

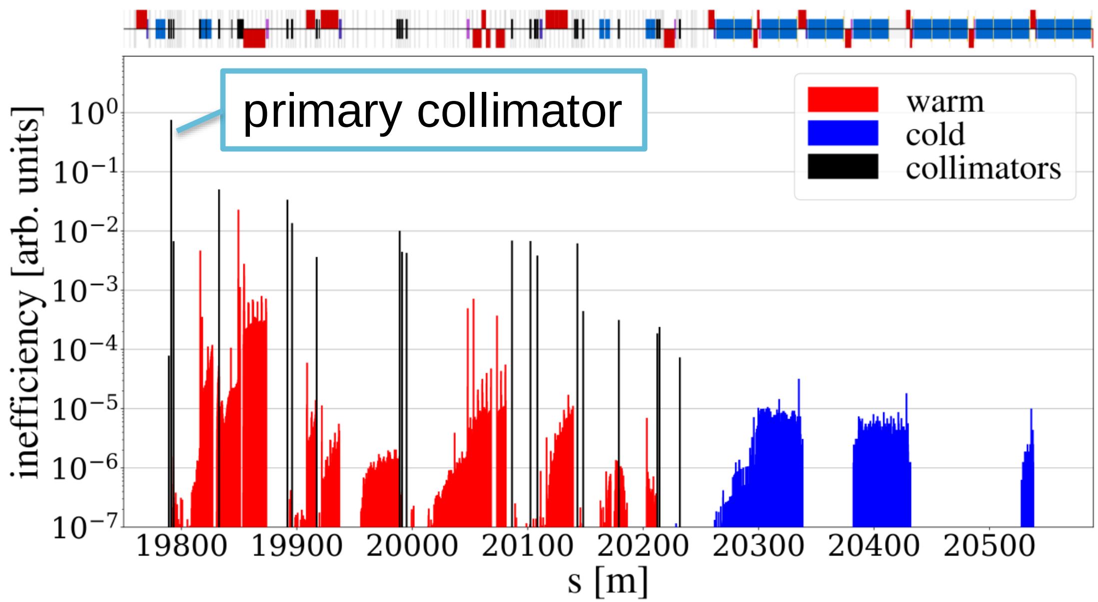
Impedance

- Replace collimators with low-impedance materials
- →Primary: Mo-graphite (instead of CFC)
- →Secondary: Mo-coated Mo-graphite / Cu-coated graphite
- **Concern still remains** (e.g. crab cavity impedance)

Mitigations

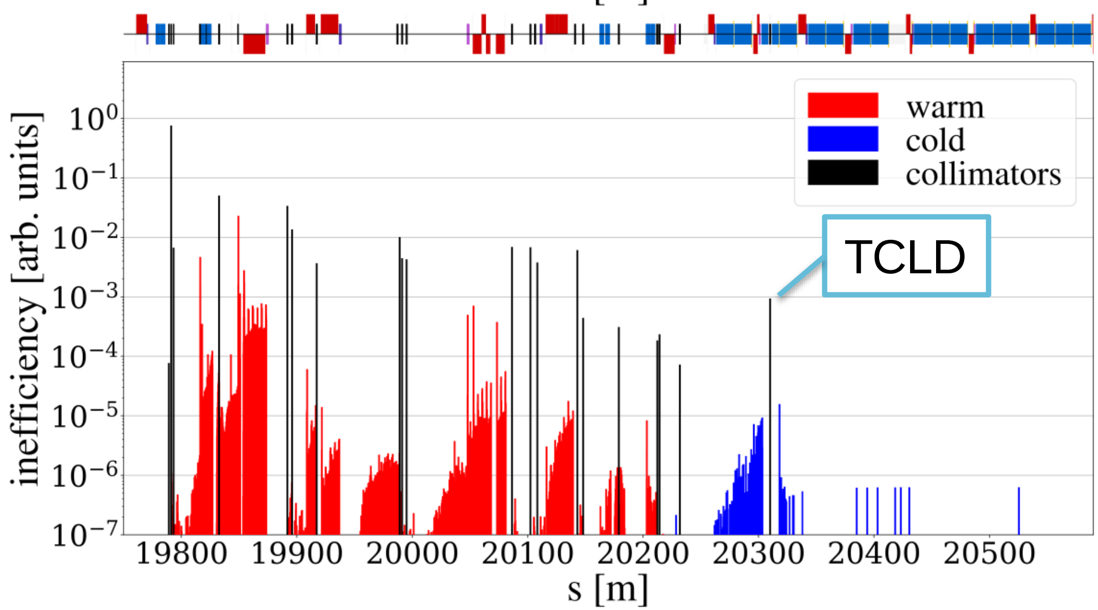
Impedance

- Replace collimators with low-impedance materials
- →Primary: Mo-graphite (instead of CFC)
- →Secondary: Mo-coated Mo-graphite / Cu-coated graphite
- **Concern still remains** (e.g. crab cavity impedance)



Beam Losses

- Replace one arc dipole (8.33 T) with two shorter dipoles (11T)
- Install a collimator in the gap



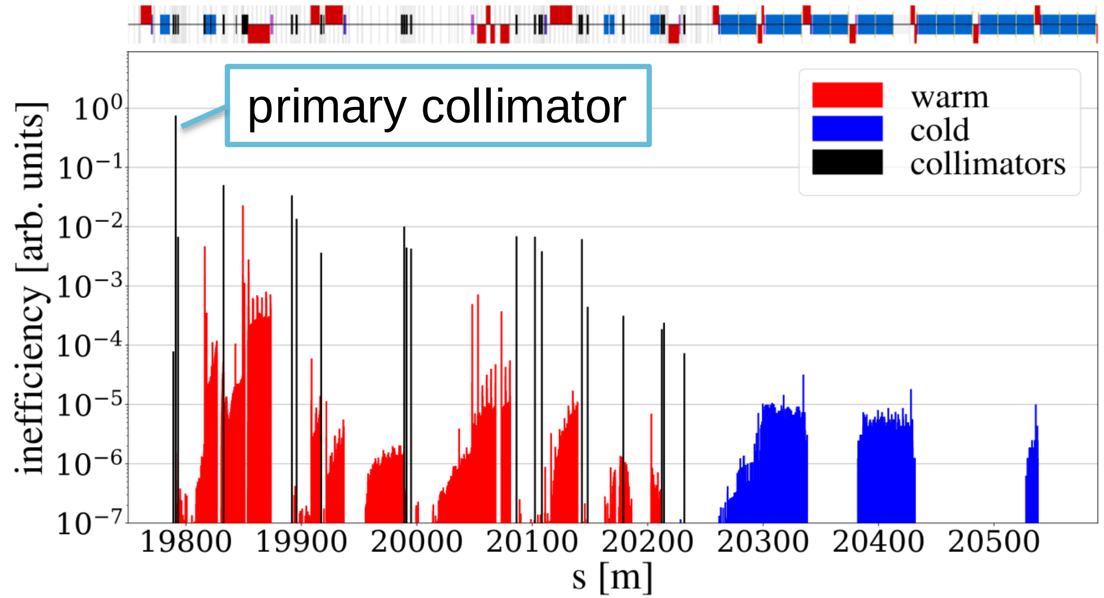
Mitigations

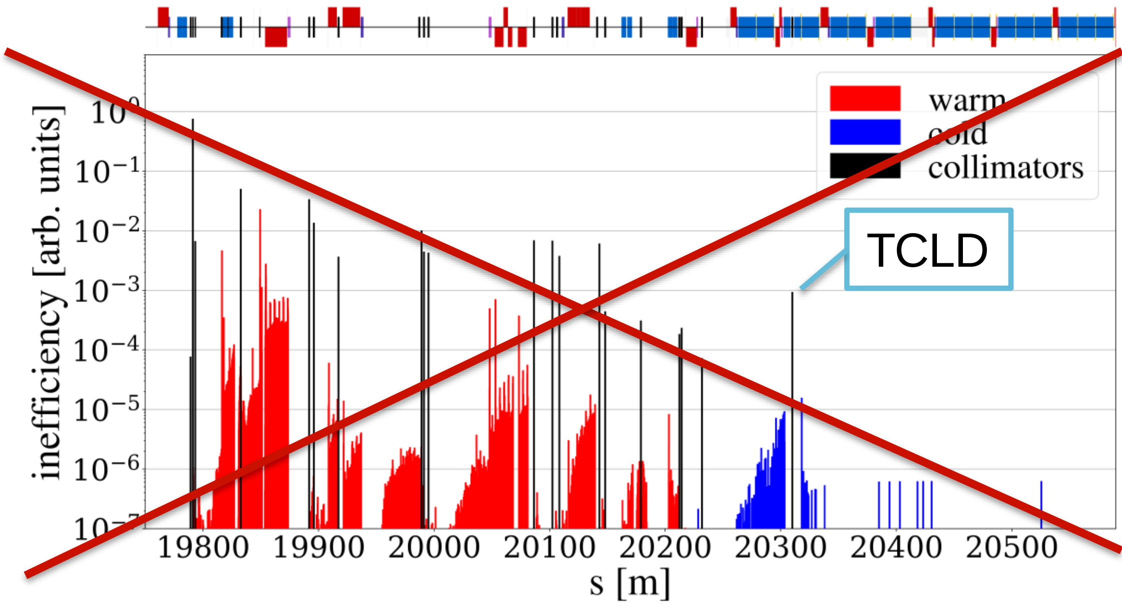
Impedance

- Replace collimators with low-impedance materials
- →Primary: Mo-graphite (instead of CFC)
- →Secondary: Mo-coated Mo-graphite / Cu-coated graphite
- **Concern still remains** (e.g. crab cavity impedance)

Beam Losses

- Replace one arc dipole (8.33 T) with two shorter dipoles (11T)
- Install a collimator in the gap
- **Descoped** from baseline due to 11T dipole production difficulties
- n.b. ion collimation is instead mitigated by crystal collimators





What else can we do?

Change the optics in IR7 to mitigate both impedance and collimation leakage!

Focus on LHC here, but approach can be generalized to other multi-stage systems

Impedance

- Resistive wall impedance:

$$Z_{\perp}^{dip}(\omega) = \frac{(\mathrm{sgn}(\omega) + j)(Z_0 L \delta_0 \mu_r)}{2\pi a^3} \cdot \sqrt{\frac{\omega_0}{|\omega|}}$$

gap between jaws,
depends on beta function
(collimator settings are
defined in sigma)

skin depth,
depends on material conductivity

More details: L. Giacomel et. al., THBP40, this conference
N. Mounet et. al., THA1C1, this conference

Impedance

- Resistive wall impedance:

$$Z_{\perp}^{dip}(\omega) = \frac{(\mathrm{sgn}(\omega) + j)(Z_0 L \delta_0 \mu_r)}{2\pi a^3} \cdot \sqrt{\frac{\omega_0}{|\omega|}}$$

gap between jaws,
depends on beta function
(collimator settings are
defined in sigma)

skin depth,
depends on material conductivity

Effective impedance,
e.g. horizontal collimator:

$$\beta_x Z_{\perp}^{dip}(\omega) \propto \frac{\beta_x}{\sqrt{\beta_x}^3} = \beta_x^{-\frac{1}{2}}$$

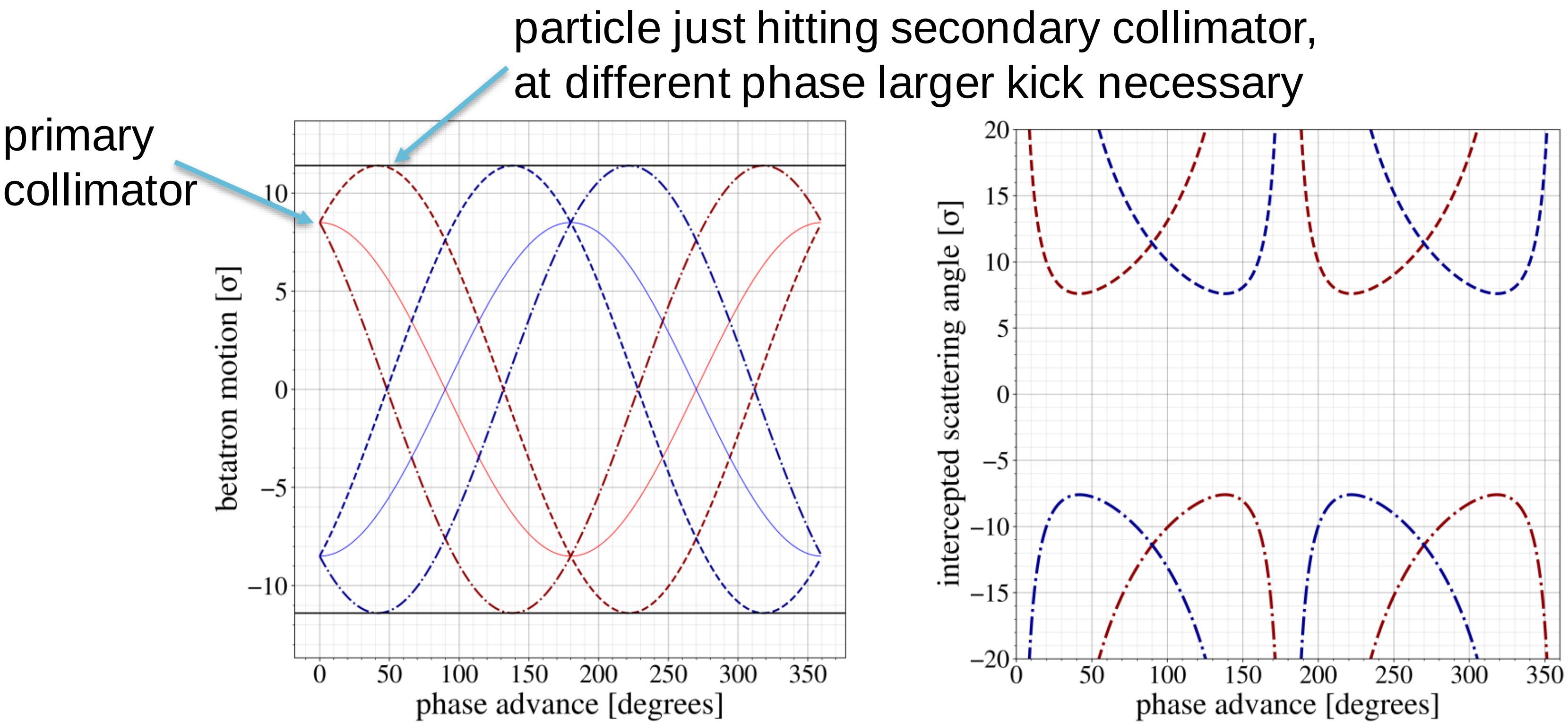
$$\beta_y Z_{\perp}^{dip}(\omega) \propto \frac{\beta_y}{\sqrt{\beta_x}^3}$$

Increasing beta functions opens up collimator gaps

More details: L. Giacomel et. al., THBP40, this conference
N. Mounet et. al., THA1C1, this conference

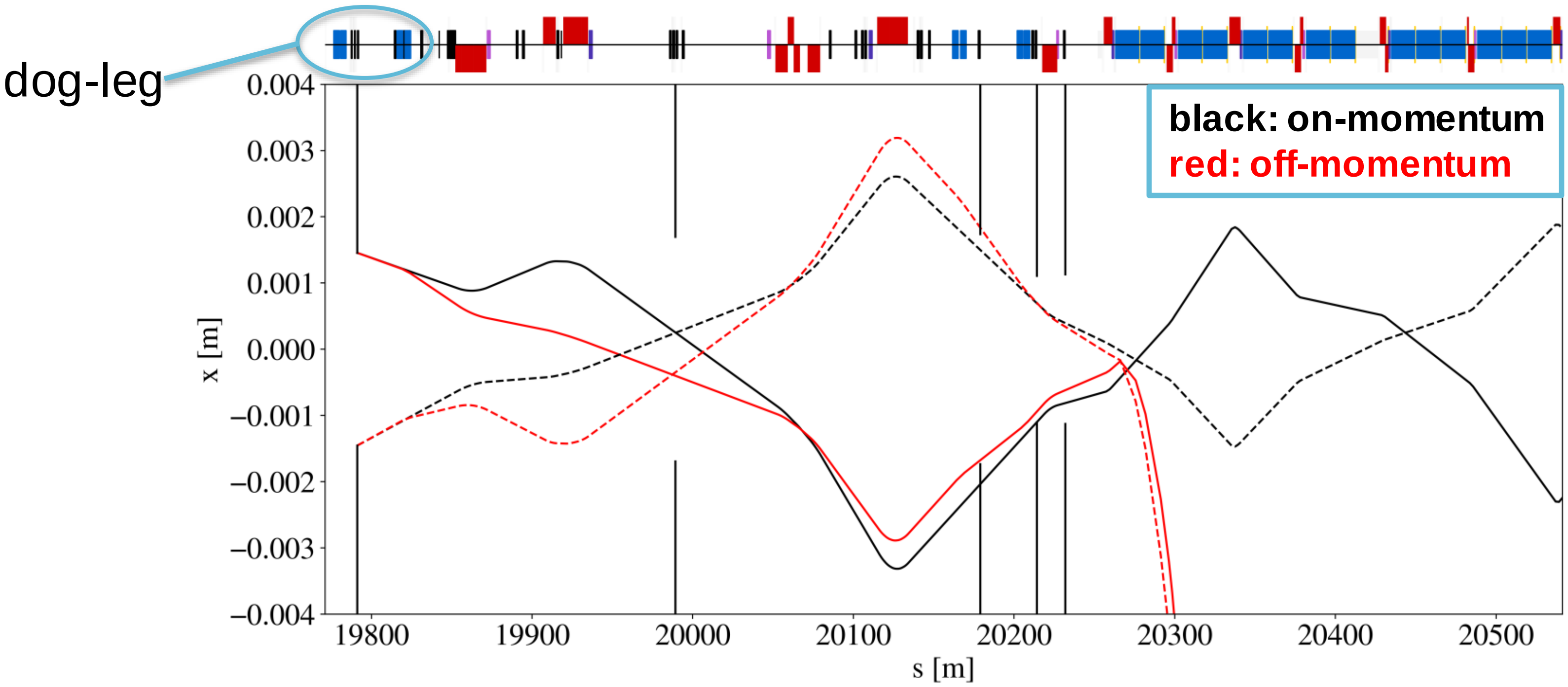
Collimator cuts (1/2)

- Particles are scattered from both jaws of primary collimator
- Betatron kick to hit secondary collimator:
  - (i) relative settings in units of beam size σ
  - (ii) phase advance
- Normalized kick $\Delta x'[\sigma] \propto \sqrt{\beta_x}$



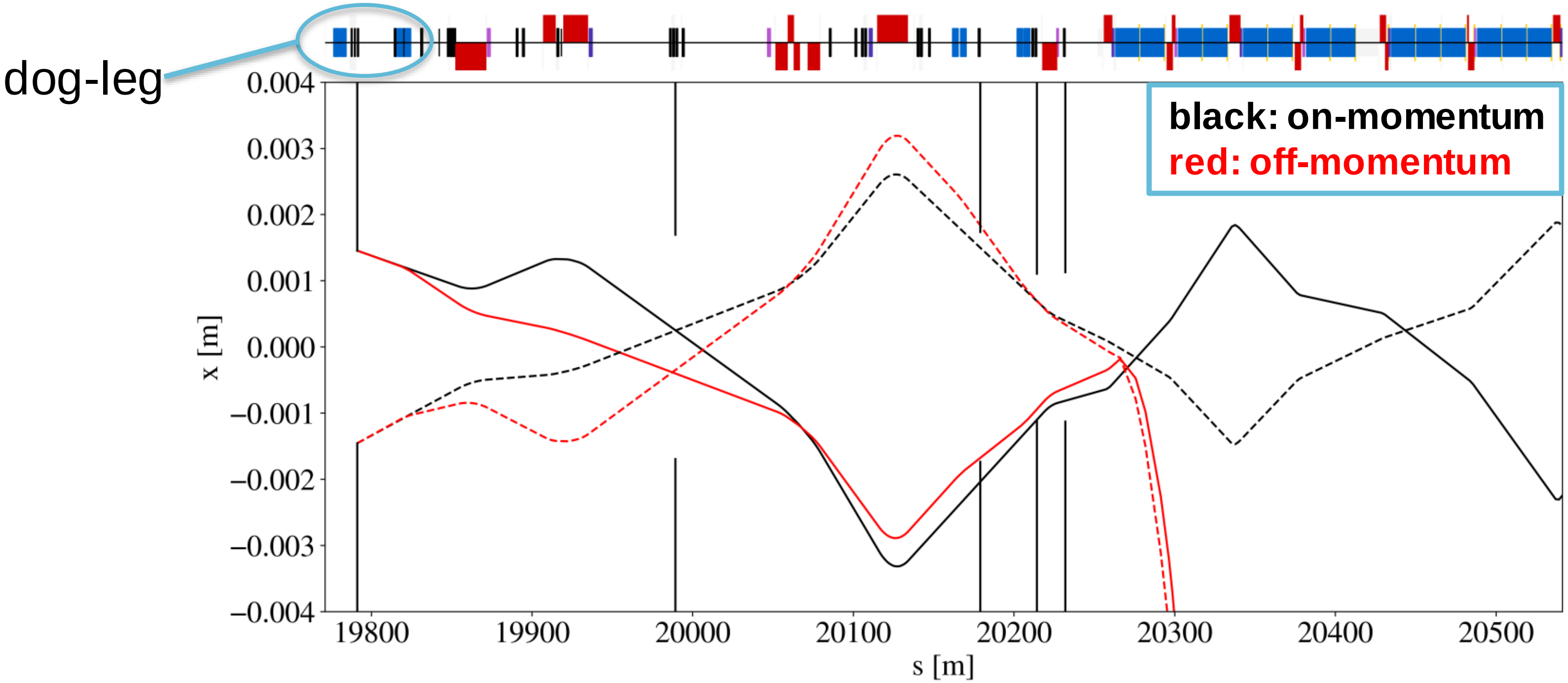
Collimator cuts (2/2)

- Single-pass dispersion generated by dog-leg dipoles
- Shifts collimator cuts (pos or neg)
  → causes off-momentum particle to leak or be intercepted



Collimator cuts (2/2)

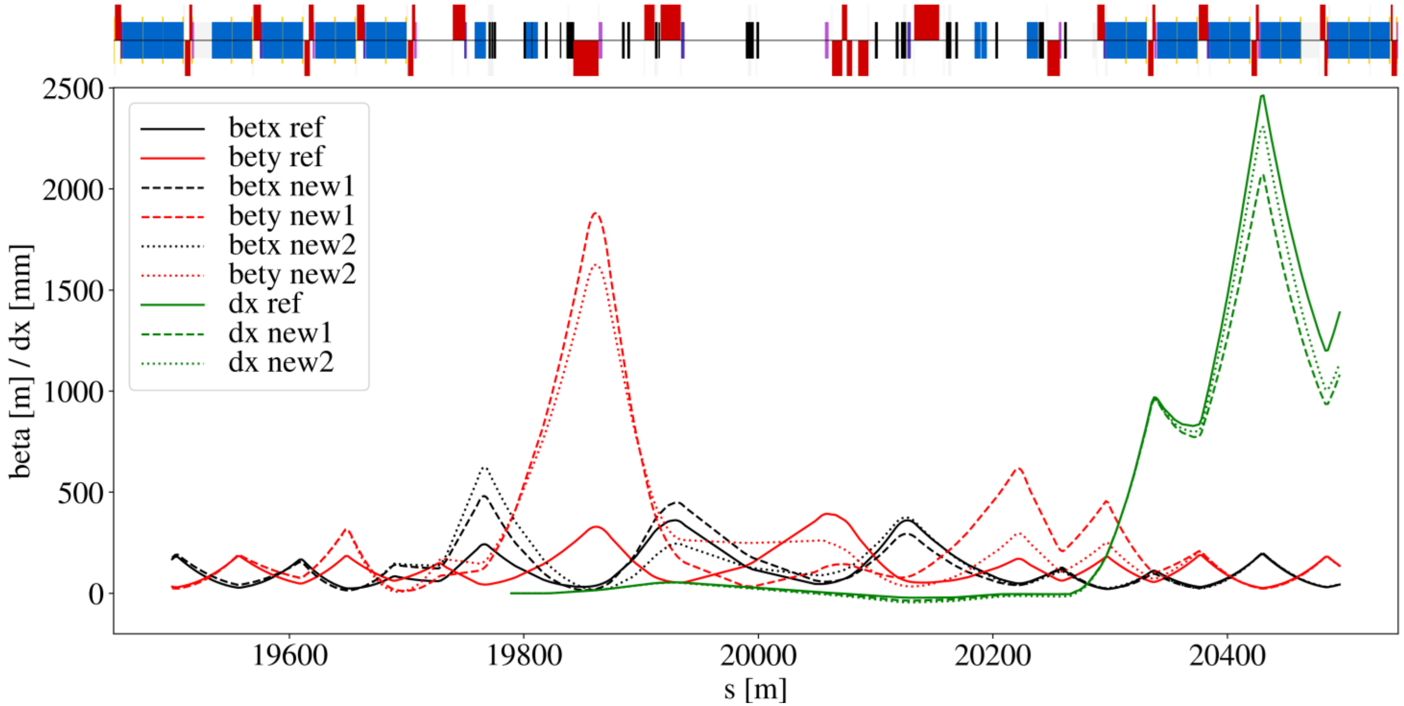
- Single-pass dispersion generated by dog-leg dipoles
- Shifts collimator cuts (pos or neg)
  → causes off-momentum particle to leak or be intercepted



Increase beta functions at primary collimators and single pass dispersion at secondary collimators

Optics rematch and constraints

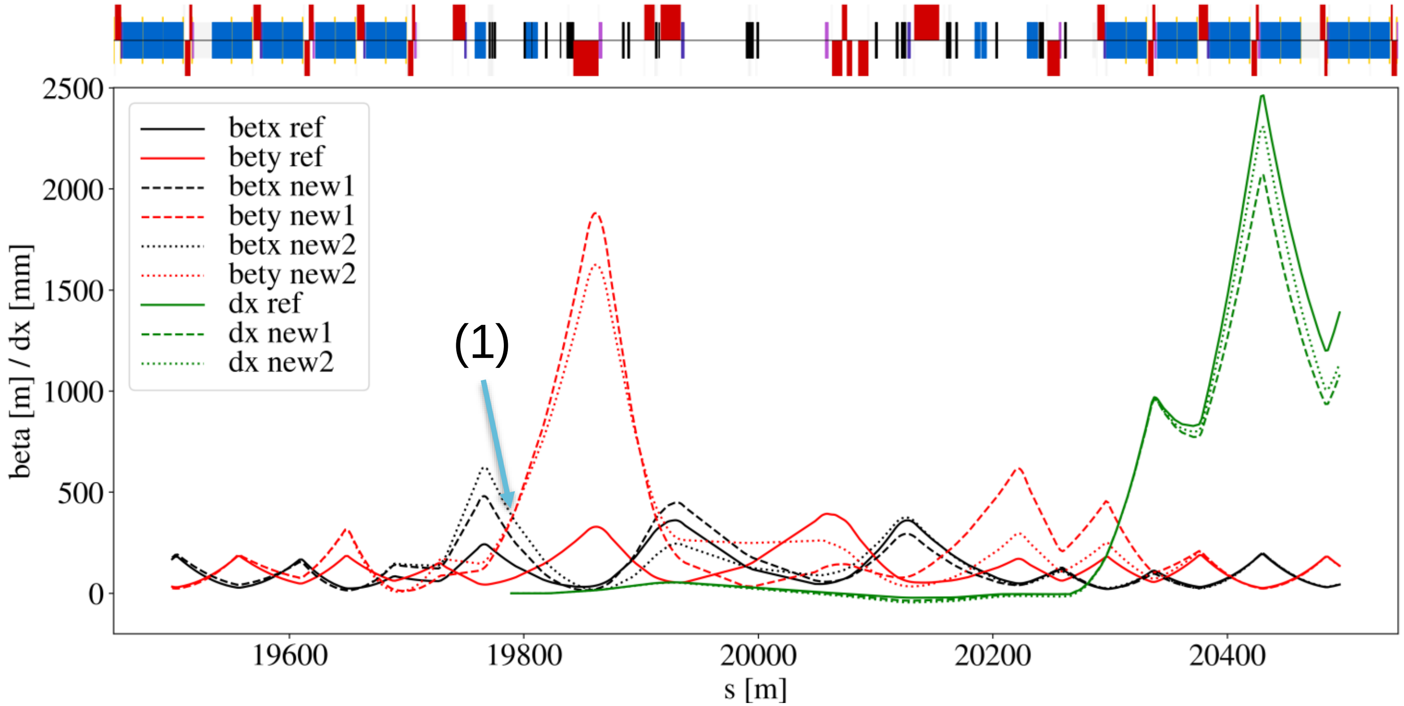
- Used **Xsuite*** for matching
- Quadrupoles (individual and common for b1/b2) up to cells 13
- Constraints:
  - Optics are matched to the arcs
  - Peak beta function kept reasonably small (aperture, field errors)



***G. Iadarola, Xsuite: an integrated beam physics simulation framework, this conference**

Optics rematch and constraints

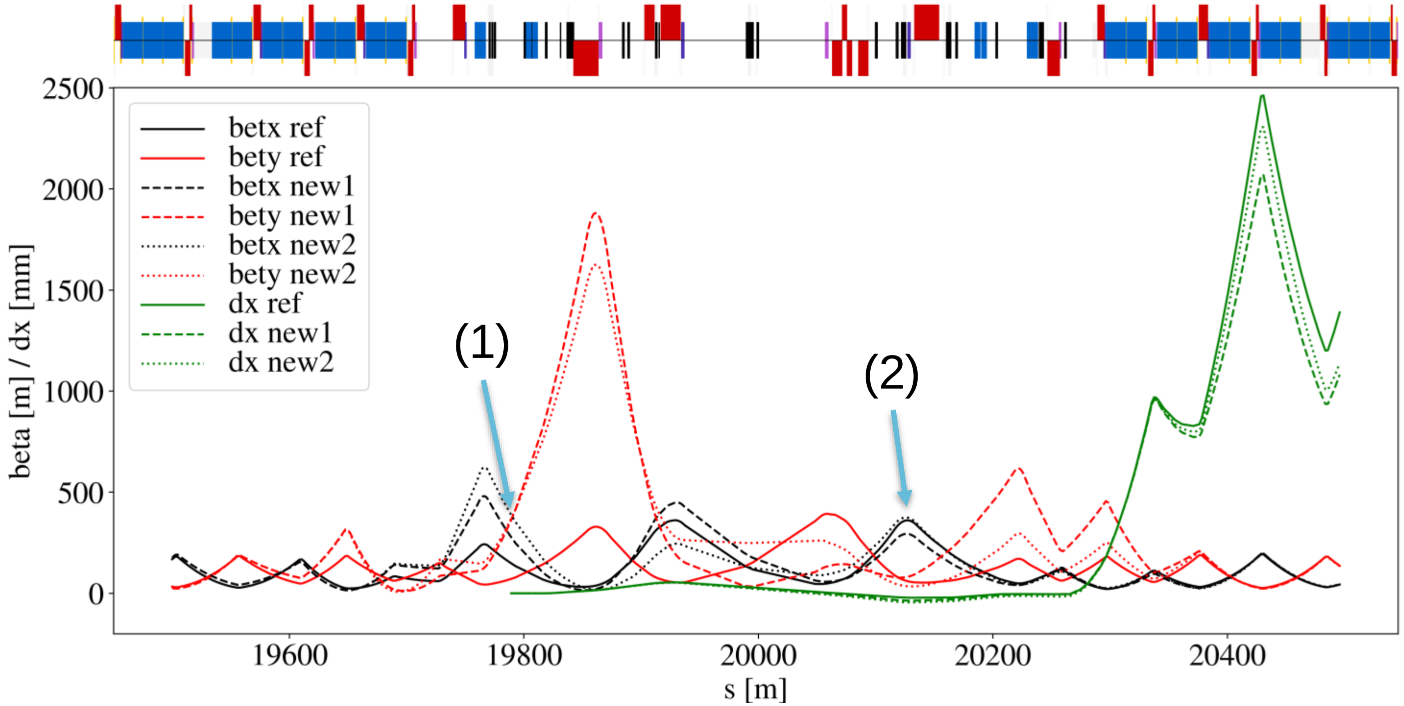
- Used **Xsuite*** for matching
- Quadrupoles (individual and common for b1/b2) up to cells 13
- Constraints:
  - Optics are matched to the arcs
  - Peak beta function kept reasonably small (aperture, field errors)
- Goals:
  - (1) Large betx/bety at primary collimators – **cleaning impedance**



***G. Iadarola, Xsuite: an integrated beam physics simulation framework, this conference**

Optics rematch and constraints

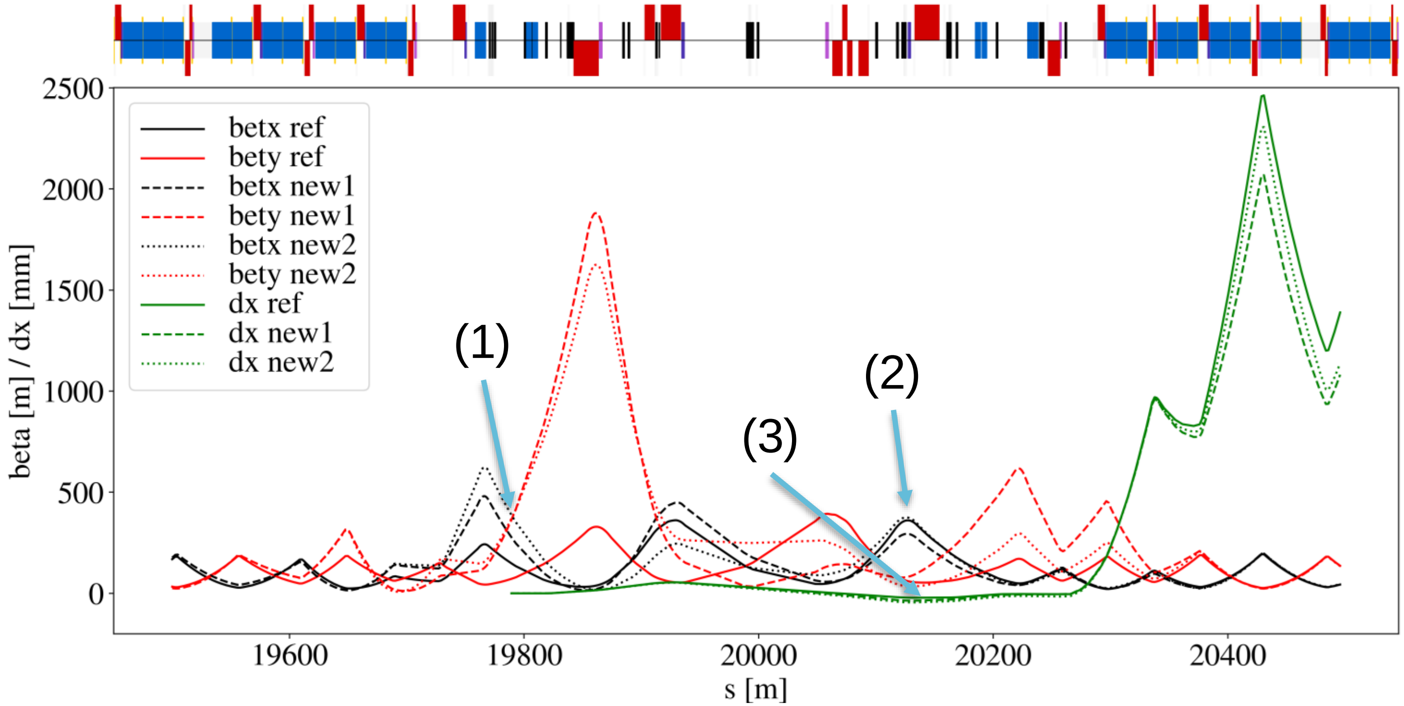
- Used **Xsuite*** for matching
- Quadrupoles (individual and common for b1/b2) up to cells 13
- Constraints:
  - Optics are matched to the arcs
  - Peak beta function kept reasonably small (aperture, field errors)
- Goals:
  - (1) Large betx/bety at primary collimators – **cleaning impedance**
  - (2) Small betx at secondary collimators and absorbers – **cleaning impedance**



*G. Iadarola, Xsuite: an integrated beam physics simulation framework, this conference

Optics rematch and constraints

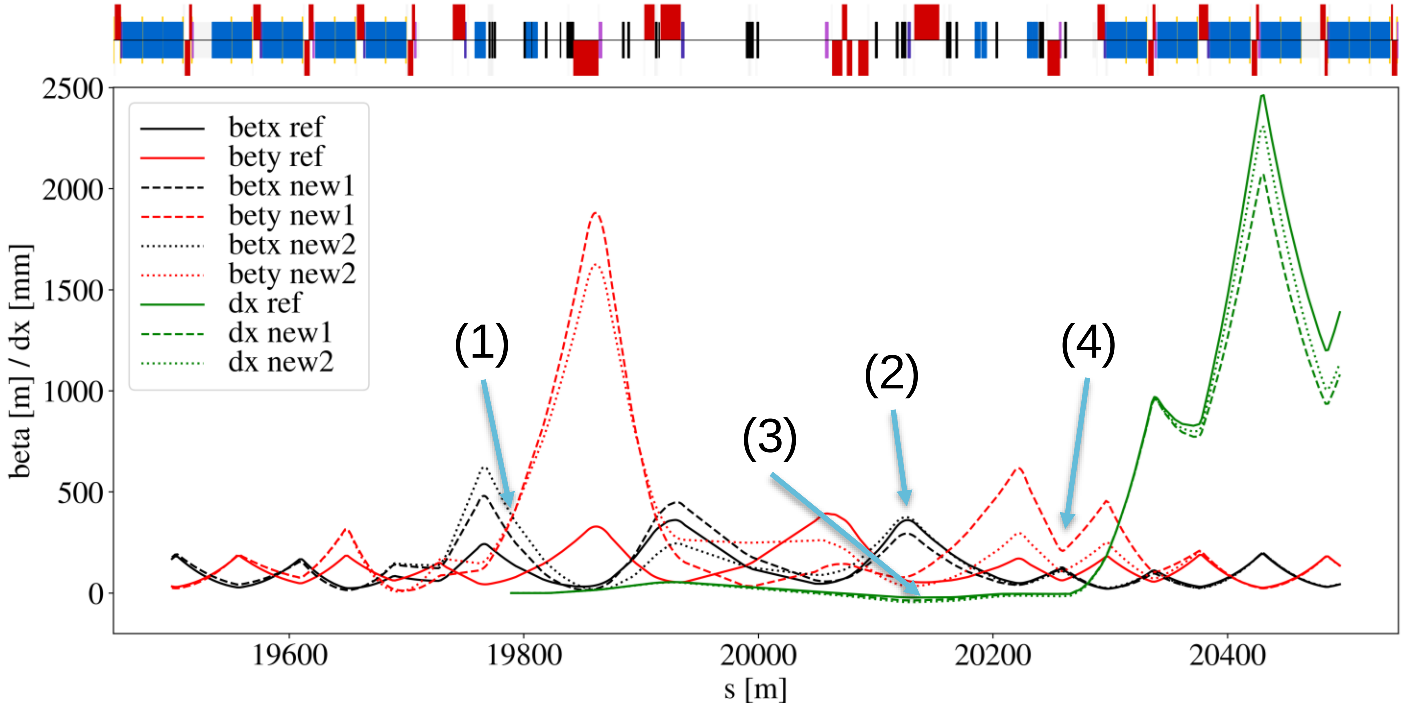
- Used **Xsuite*** for matching
- Quadrupoles (individual and common for b1/b2) up to cells 13
- Constraints:
  - Optics are matched to the arcs
  - Peak beta function kept reasonably small (aperture, field errors)
- Goals:
  - (1) Large betx/bety at primary collimators – **cleaning impedance**
  - (2) Small betx at secondary collimators and absorbers – **cleaning impedance**
  - (3) Increase single-pass dispersion – **cleaning** ~~impedance~~



*G. Iadarola, Xsuite: an integrated beam physics simulation framework, this conference

Optics rematch and constraints

- Used **Xsuite*** for matching
- Quadrupoles (individual and common for b1/b2) up to cells 13
- Constraints:
  - Optics are matched to the arcs
  - Peak beta function kept reasonably small (aperture, field errors)
- Goals:
  - (1) Large betx/bety at primary collimators – **cleaning impedance**
  - (2) Small betx at secondary collimators and absorbers – **cleaning impedance**
  - (3) Increase single-pass dispersion – **cleaning** ~~impedance~~
  - (4) Small beta function in orthogonal plane of collimators – ~~cleaning~~ **impedance**



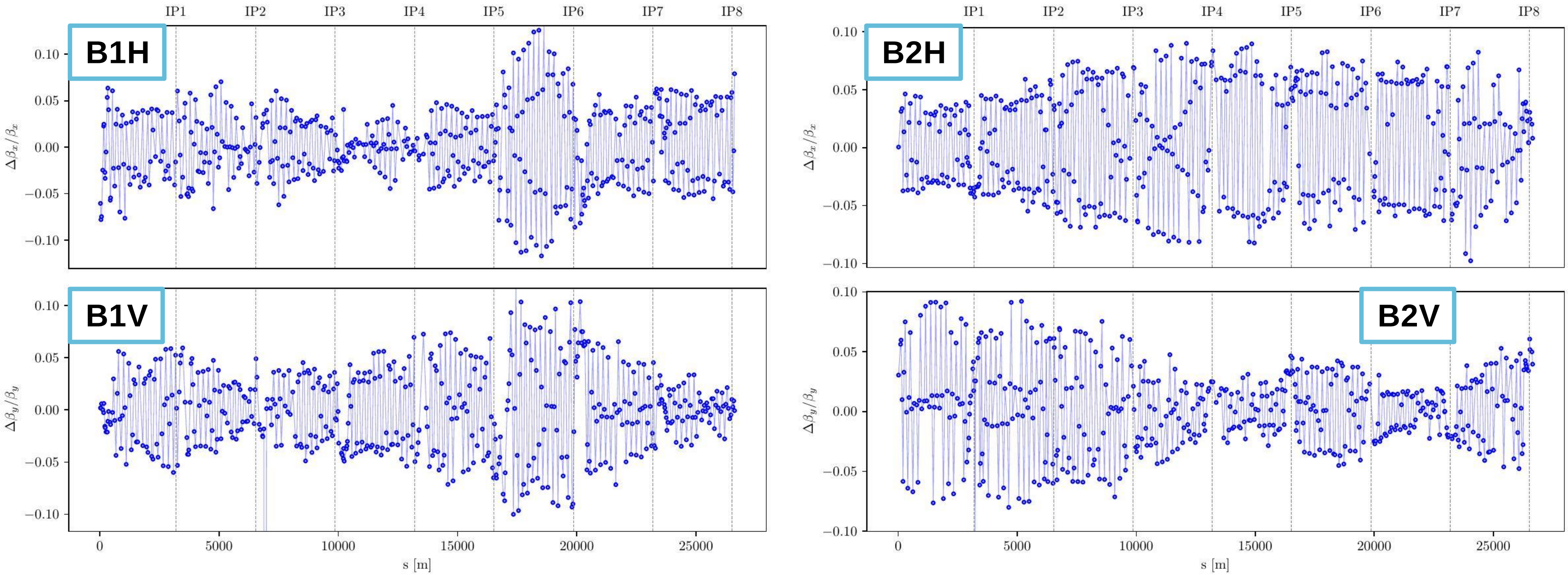
*G. Iadarola, Xsuite: an integrated beam physics simulation framework, this conference

Experiment – optics

- Initial test in 2022, suffered from machine availability issues
  - Commissioned the optics at top energy
    - Aperture not compatible at injection energy
      → transition during ramp if deployed operationally

Experiment – optics

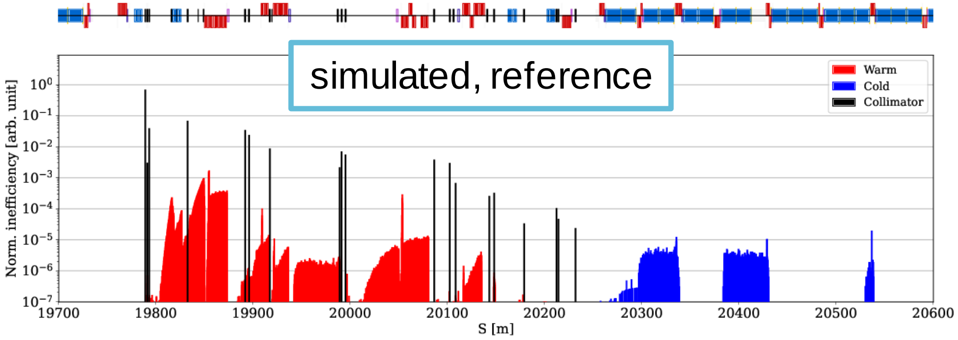
- Initial test in 2022, suffered from machine availability issues
  - Commissioned the optics at top energy
    - Aperture not compatible at injection energy
      → transition during ramp if deployed operationally
- Optics measurement showed small beta-beating in IR7 (< 7 %)
  → no corrections needed

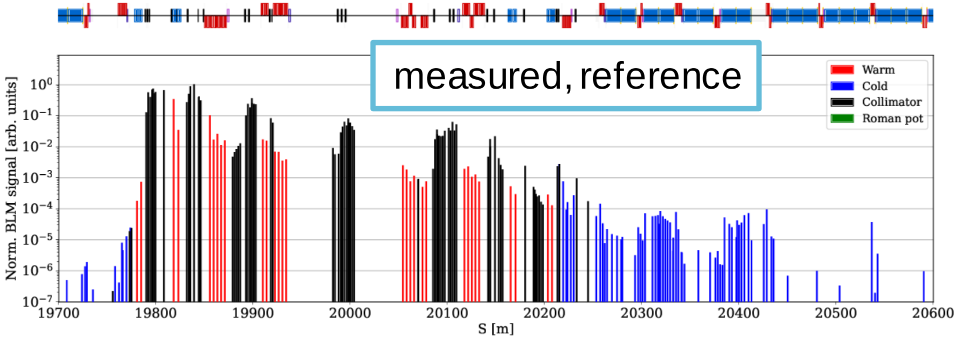


No issues observed with the optics

Experiment – cleaning

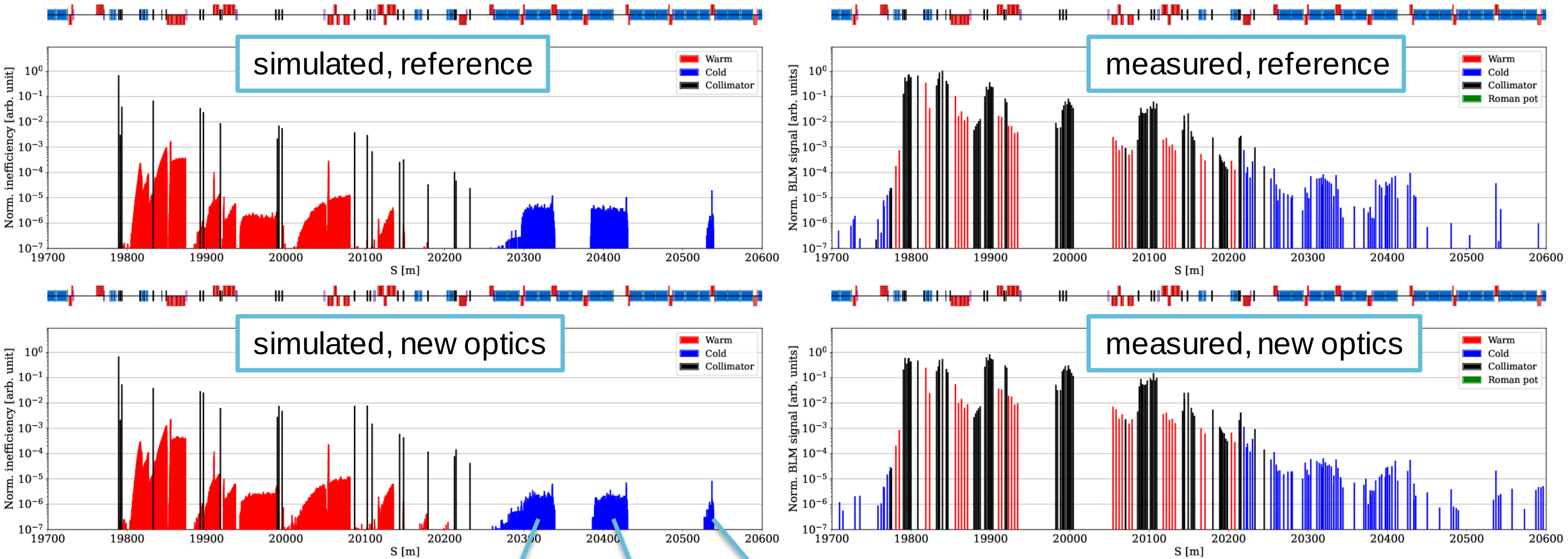
- Collimator cleaning performance measured for beam 1 (vertical)
- Transverse damper excites single bunch → losses on primary collimator





Experiment – cleaning

- Collimator cleaning performance measured for beam 1 (vertical)
- Transverse damper excites single bunch → losses on primary collimator

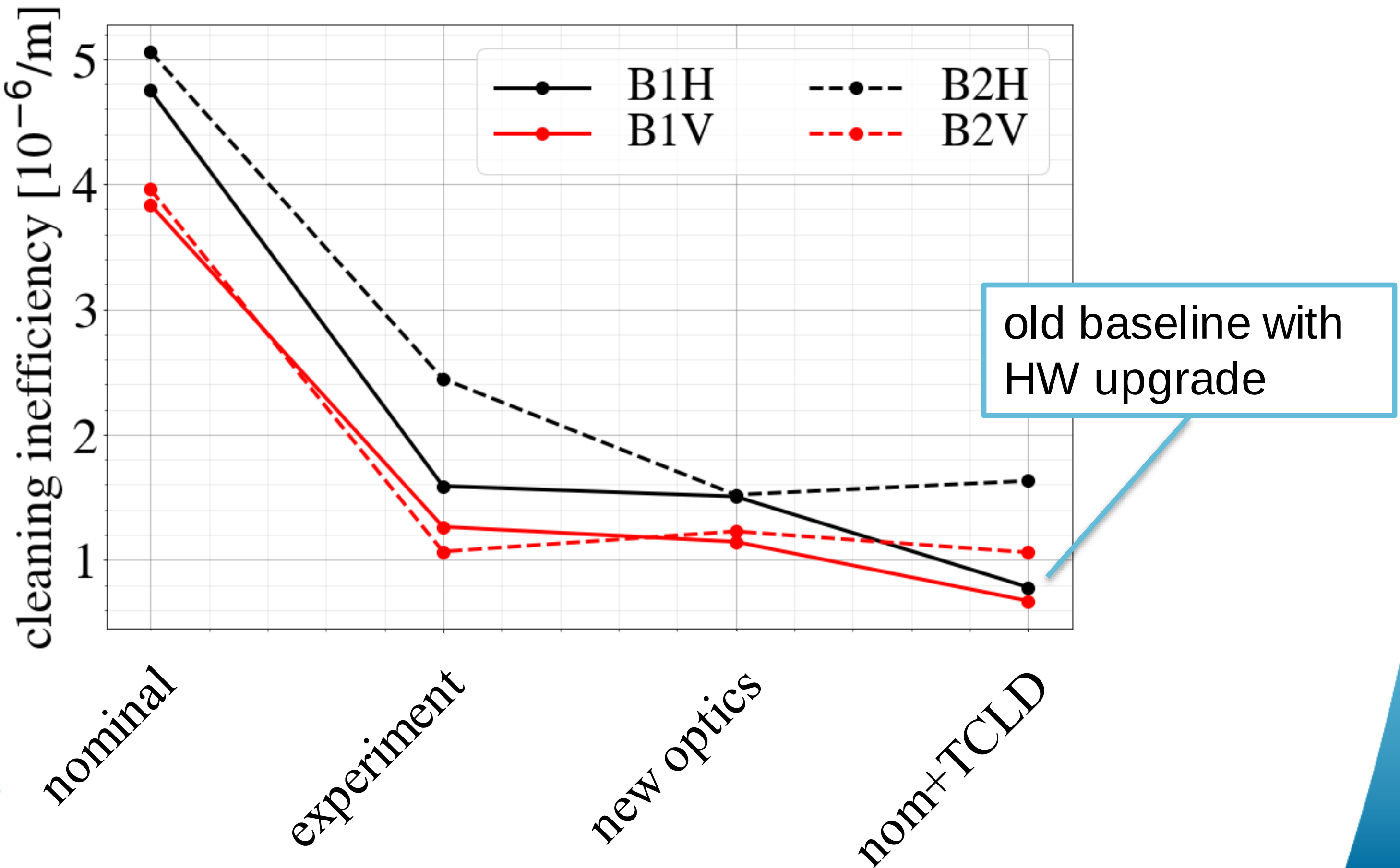


Simulated loss reduction: 0.58 – 0.62 – 0.35
Measured loss reduction: 0.64 – 0.72 – 0.47 (±0.05)
Follow-up measurements scheduled

Measurements support simulation results

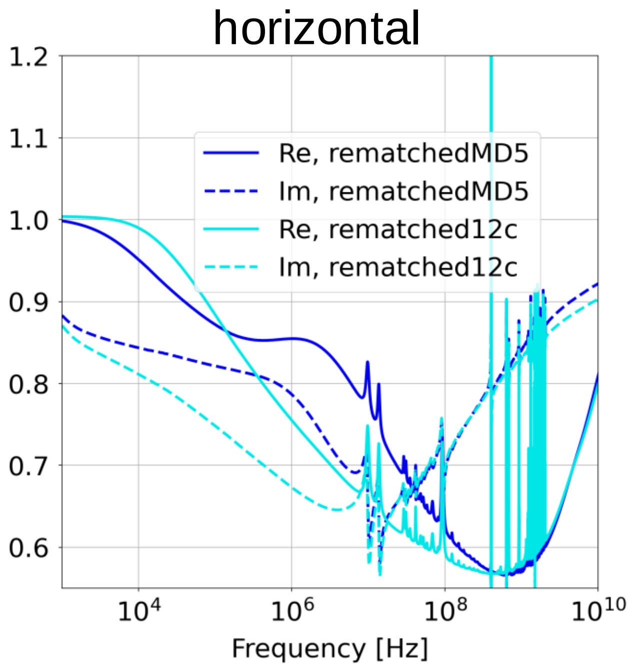
HL-LHC cleaning – simulated

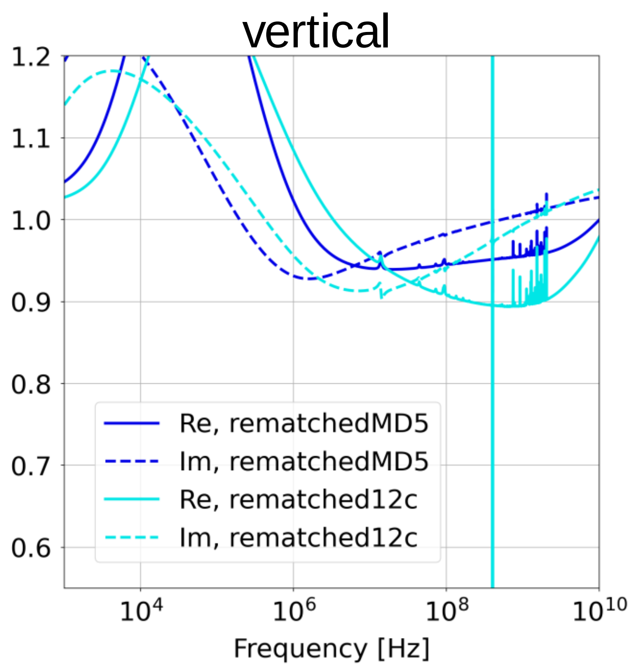
- Improved optics further for HL-LHC
- Average losses in first cluster
  - Similar to nominal optics with TCLD



HL-LHC impedance – simulated

- Main interest in the ~1 GHz frequency range
  - 45 % improvement in x
  - 10 % improvement in y
- Octupole threshold reduced by ~52 A
- Further reduction in y elsewhere is under study





Summary

- Two critical challenges in HL-LHC
  - Leakage of losses from collimators
  - Impedance of the collimators
- New optics design to mitigate both
  - DS losses reduced by up to 70 %
  - Impedance reduced by 45 % in H, 10 % in V
  - Octupole threshold reduced by ~52 A
- Measurements:
  - DS losses measured in one case – confirm simulation results
  - Impedance measurements are scheduled
- New optics will be implemented in HL-LHC baseline (as of HLLHCV1.6 optics)
- Operational deployment before end of current Run 3 under consideration