EPFL

CHART

Swiss Accelerator Research and Technology

Beam-beam and optics studies in FCC-ee

T. Prebibaj

In collaboration with:

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EPFL-LPAP Activity Meeting

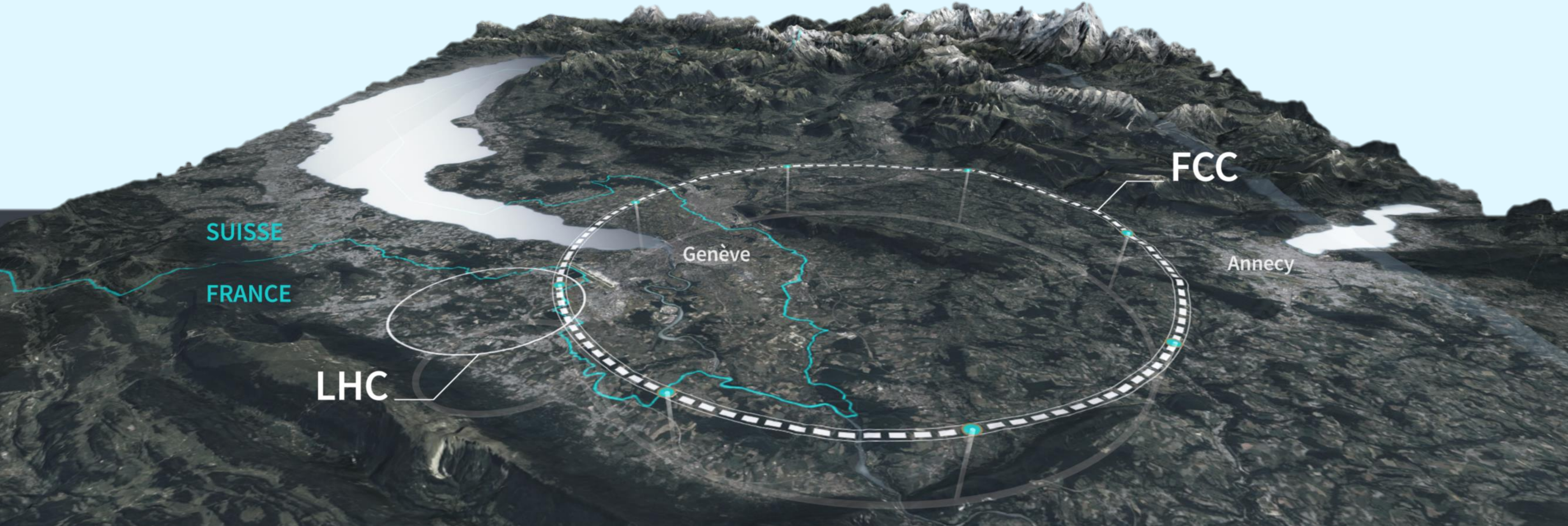
16/04/2026

École polytechnique fédérale de Lausanne

Work supported by the Swiss Accelerator Research and Technology (CHART)

FCC-ee

fcc.web.cern.ch



The Future Circular electron-positron Collider (FCC-ee) is a proposed 90.7 km circumference collider designed to operate at four energies: 45.6 GeV (Z), 80 GeV (WW), 120 GeV (ZH), and 182.5 GeV (ttbar)

Conceptual Design Report published in 2019
Feasibility Study Report in 2025
Decision point expected in 2028.

A very brief overview of relevant beam dynamics concepts

Beam dynamics in FCC-ee

Performance

Beam-beam

Imperfections

Corrections

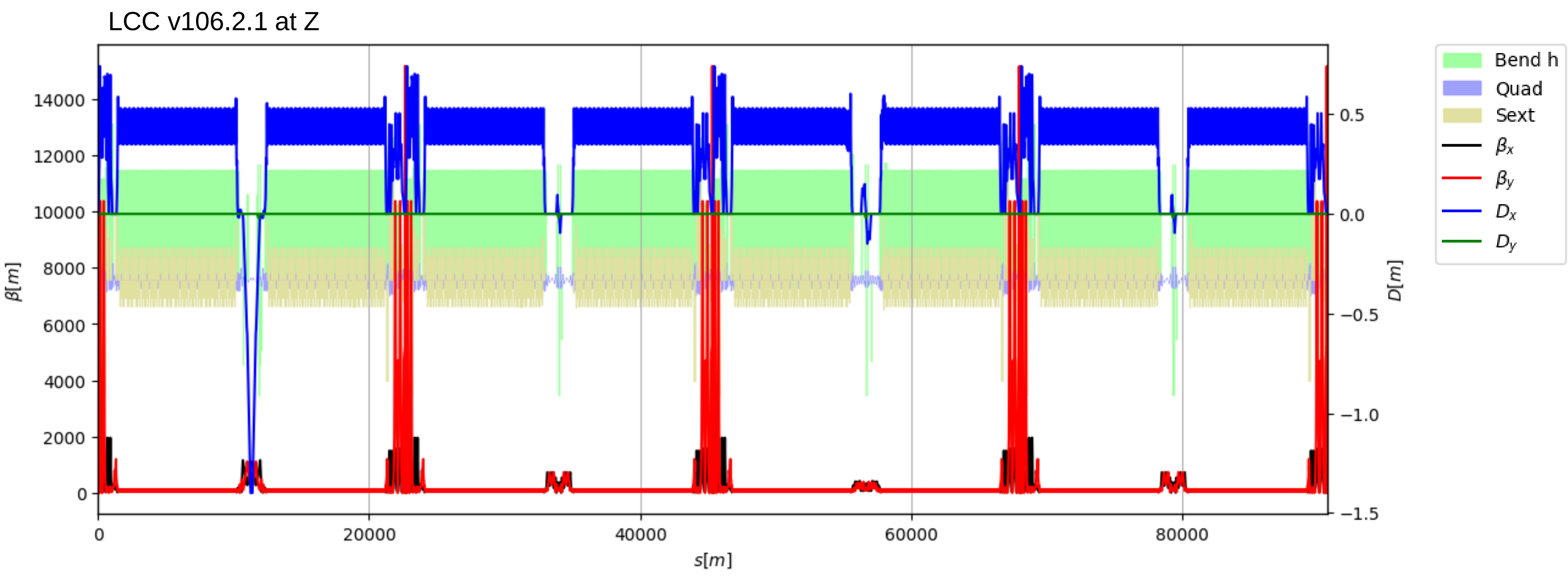
Radiation

Optics

The collider lattice

Collider lattice is fundamental for all systems (e.g. magnets, insertions, …) & performance.

- Two main variants: **GHC** (“Global Hybrid Correction”) by K. Oide and **LCC** (Local Chromaticity Correction) by P. Raimondi.
- A review panel recommended adopting the **LCC optics** as the new baseline (read advantages).



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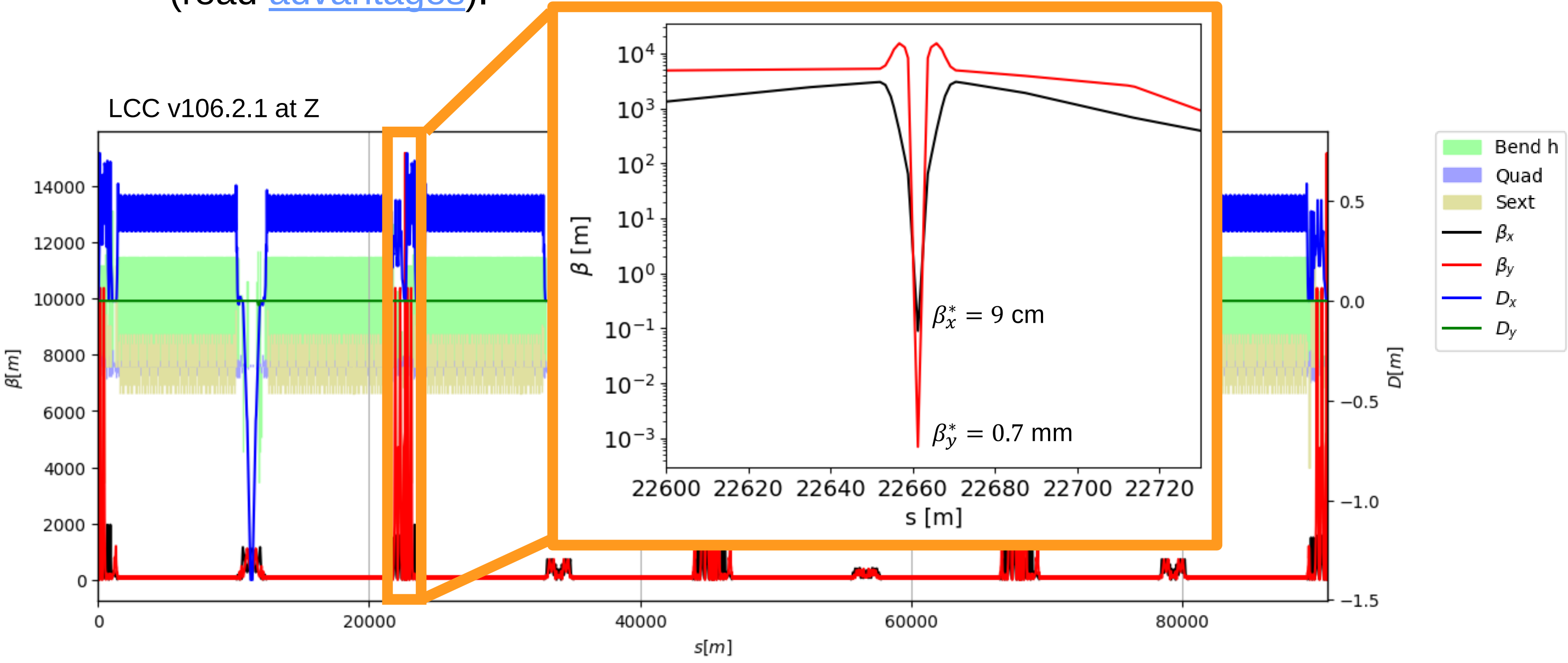

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Synchrotron Radiation

Synchrotron Radiation (SR) power (<50 MW per beam) is the main constraint on beam intensity (or total current I_{tot}).

- SR causes exponential damping of transverse & longitudinal emittances.
- Quantum excitation leads to an **equilibrium emittance** in the horizontal and longitudinal planes and to a very small (but non-zero) vertical emittance.
- In practice, the **vertical emittance is dominated by machine imperfections** that lead to vertical dispersion and betatron coupling.

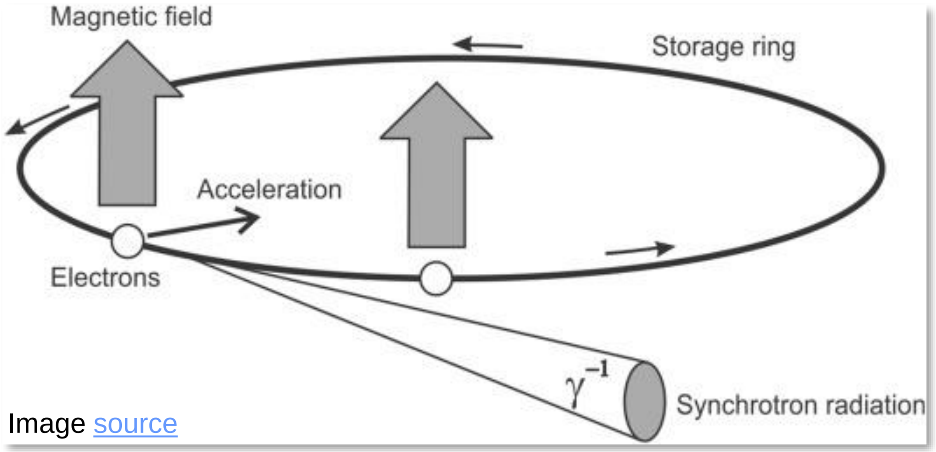

Image source

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Lattice imperfections

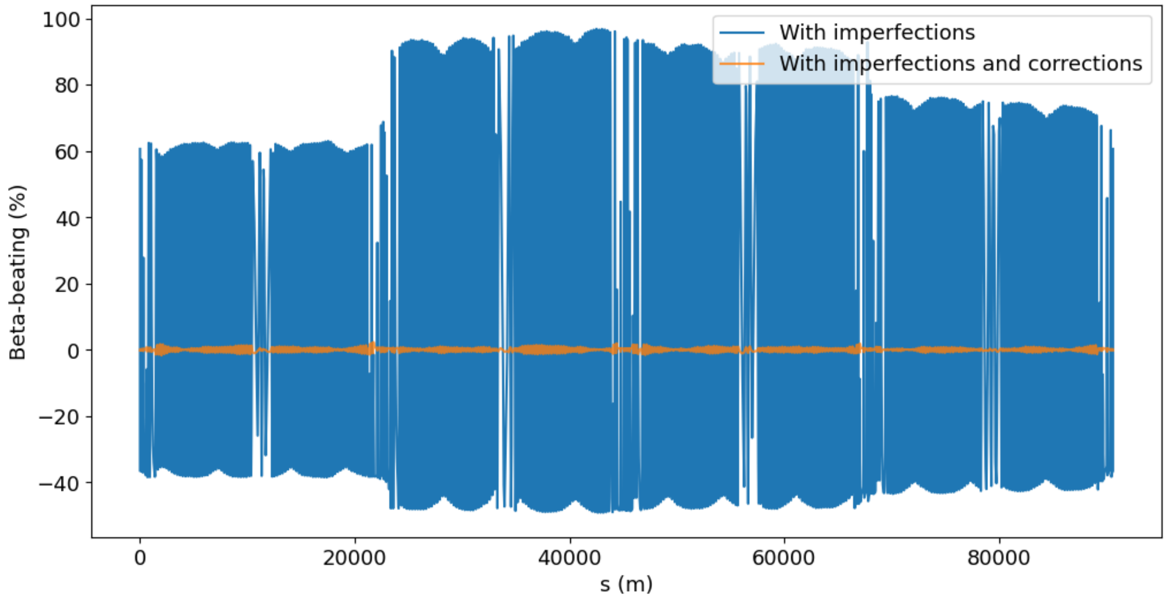
Lattice imperfections give rise to numerous **undesired effects**!

- Orbit & optics distortions (e.g. coupling, beta-beating, …) → emittance increase and/or losses → loss of performance.
- Developing correction schemes to keep these effects under control is a major challenge.
- Lara is working on modelling these imperfections and understanding their impact on performance in presence of beam-beam.

Field type	Imperfection	Error type	Impact
Dipole	Field error	Dipole	Orbit, trajectory, energy
Dipole	Roll	Dipole	Orbit, trajectory
Quadrupole	Field error	Quadrupole	Tune, optics
Quadrupole	Offset	Dipole	Orbit, trajectory
Quadrupole	Roll	Skew quadrupole	Coupling
Sextupole	Field error	Sextupole	Chromaticity
Sextupole	Horizontal offset	Quadrupole	Tune, optics
Sextupole	Vertical offset	Skew quadrupole	Coupling

J. Wenninger, "Linear Imperfections", CAS 2018.

Courtesy of L. Sievert



Performance

Beam-beam

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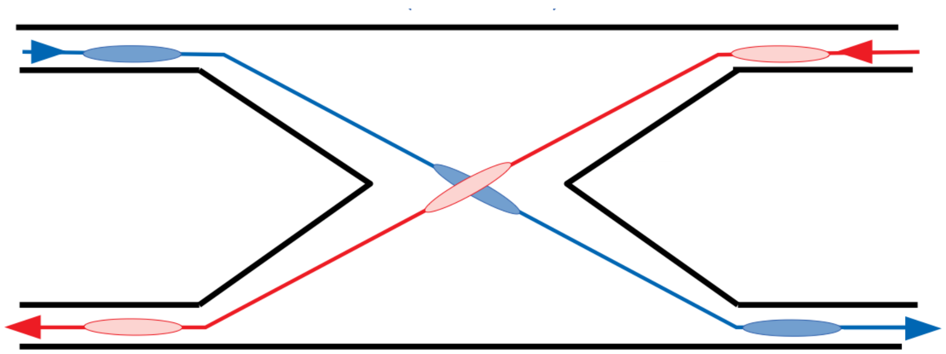
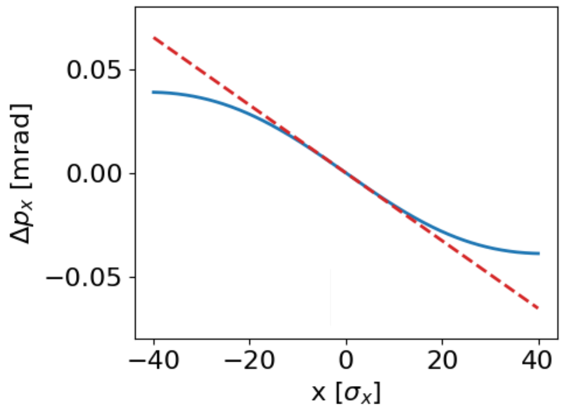
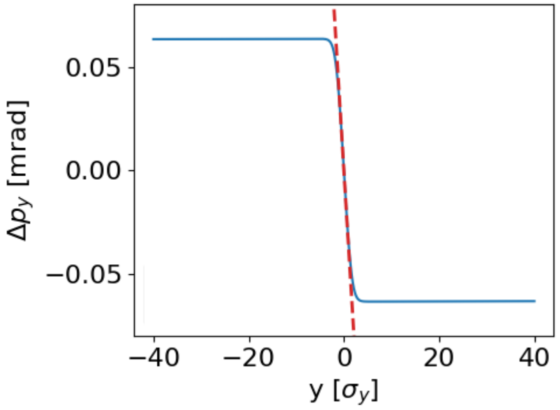
Beam-beam effects

Beam-beam interactions modify key lattice properties (e.g. tunes, beta-beating, …) and can degrade beam quality (e.g. emittance blow-up, instabilities, …).

- **Minimizing these effects is essential for maximizing luminosity.**







Typical for FCC-ee at Z:

$$\xi_x = \frac{N r_e}{2\pi\gamma\epsilon_x(1+\phi^2)} \approx 0.0015$$

$$\xi_y = \frac{N r_e \beta_y^*}{2\pi\gamma\sigma_y\sigma_x\sqrt{1+\phi^2}} \approx 0.09$$

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FCC-ee parameters & performance

Luminosity is given by: $L = \frac{\gamma}{2er_e}\frac{I_{tot}\xi_y}{\beta_y^*}R_G$

Optics / Mode	GHC Z	GHC $t\bar{t}$	LCC Z	LCC $t\bar{t}$
Beam energy E (GeV)	45.6	182.5	45.6	182.5
Circumference C (m)	90658.525		90644.816	
Arc-cell setup	90°/90° long	90°/90° short	52°/45°	99°/77°
Momentum compaction factor α_c (10^{-6})	28.5	7.3	28.6	9.5
Energy Loss per turn W_0 (GeV)	0.039	10.01	0.035	9.01
Beam Intensity N (10^{12} particles)	2400	9.405	2424	9.435
Bunch Intensity N_b (10^{11} particles)	2.02	1.85	2.02	2.20
Number of Bunches	12000	51	12000	43
Horizontal β-function at IP β_x^* (cm)	9	90	9	90
Vertical β-function at IP β_y^* (mm)	0.7	14	0.7	14
Horizontal emittance ε_x (nm)	0.74	1.74	0.70	2.10
Target vertical emittance in collision ε_y (pm)	1.48	1.75	1.40	2.11
Transverse tune Q_x/Q_y	214.16 / 214.20	394.19 / 390.27	194.16 / 170.20	346.13 / 262.27
Chromaticity Q'_x/Q'_y	12 / 5	0 / 0	12 / 5	0 / 0
Harmonic number h at 400 MHz	121200		121200	
Total RF voltage of 400 / 800 MHz (GV)	0.09	2.1 / 9.2	0.09	2.0 / 8.1
Synchrotron tune Q_s	0.031	0.086	0.031	0.111
RF momentum acceptance (%)	1	2	1	2
Bunch length σ_z (non coll./coll.) (mm)	5.4 / 16.3	1.9 / 2.7	5.1 / 16.7	1.9 / 2.8
Rel. mom. spread σ_p (non coll./coll.) (10^{-3})	0.40 / 1.29	1.58 / 2.21	0.39 / 1.34	1.52 / 2.33
Longitudinal damping time τ_z (turns)	1159	18	1297	20
Crab-waist ratio (%)	55	40	55	40
Beam-beam parameter ξ_x/ξ_y (10^{-3})	1.5 / 80	61.2 / 108.9	1.4 / 80	67.1 / 120
Luminosity $\mathscr{L}$ (10^{34} s^{-1}/cm^2)	151	1.54	150	TODO

Parameters from optics comparison report, values may have been updated since then.

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Beam dynamics in FCC-ee

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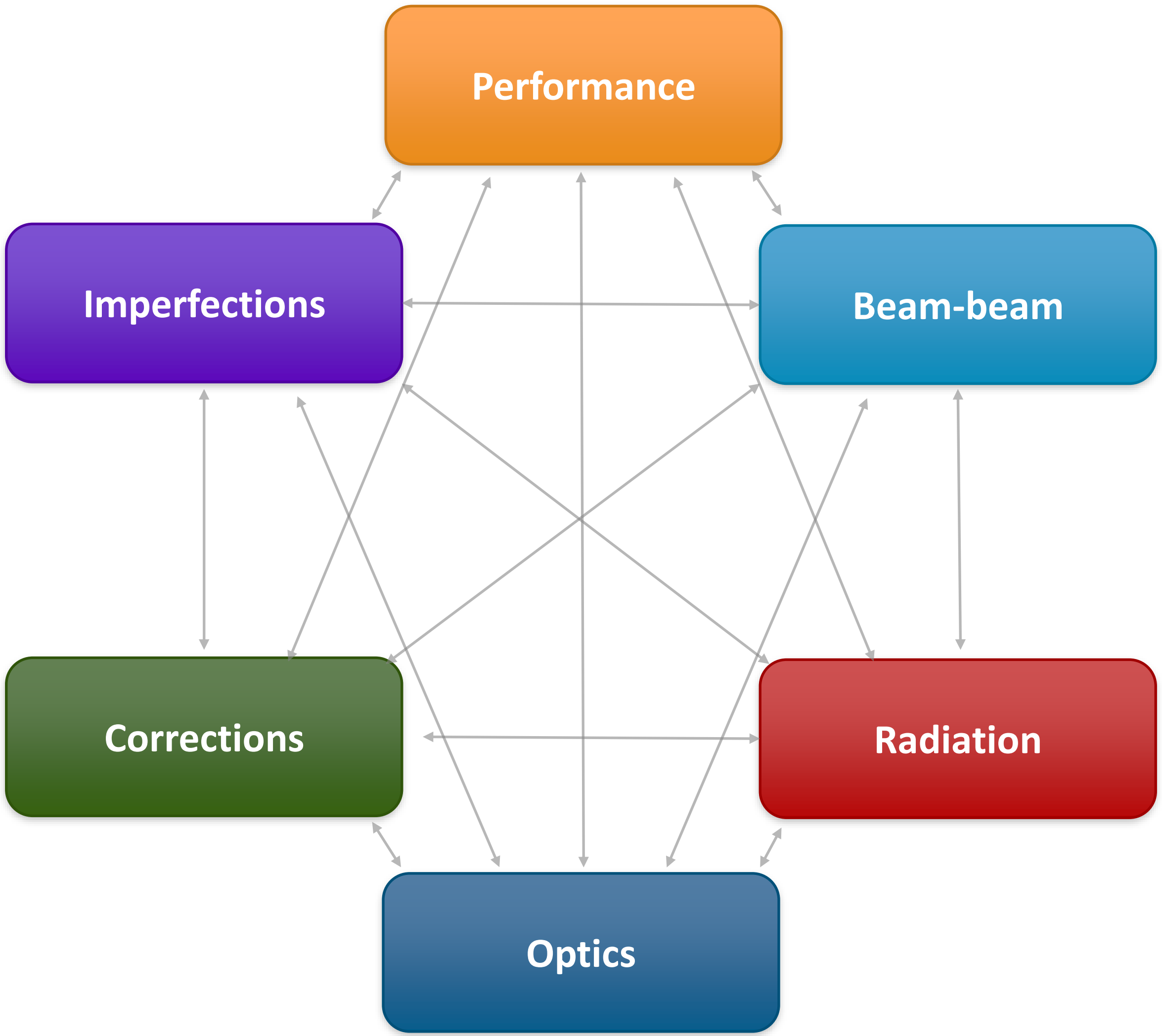
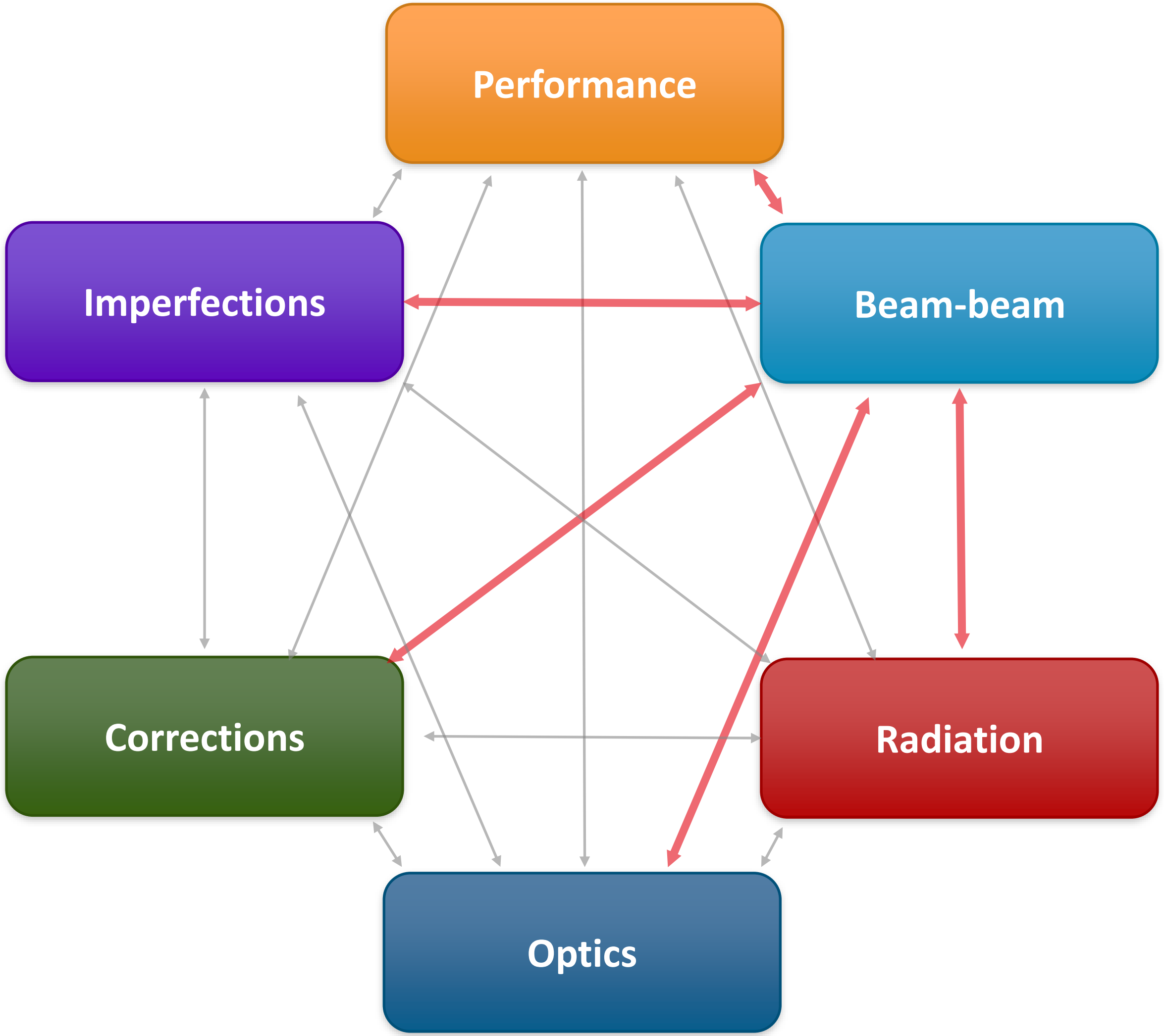


Focus of my studies

Analyze current FCC-ee lattices to **identify sensitivities** to beam-beam forces & machine imperfections.

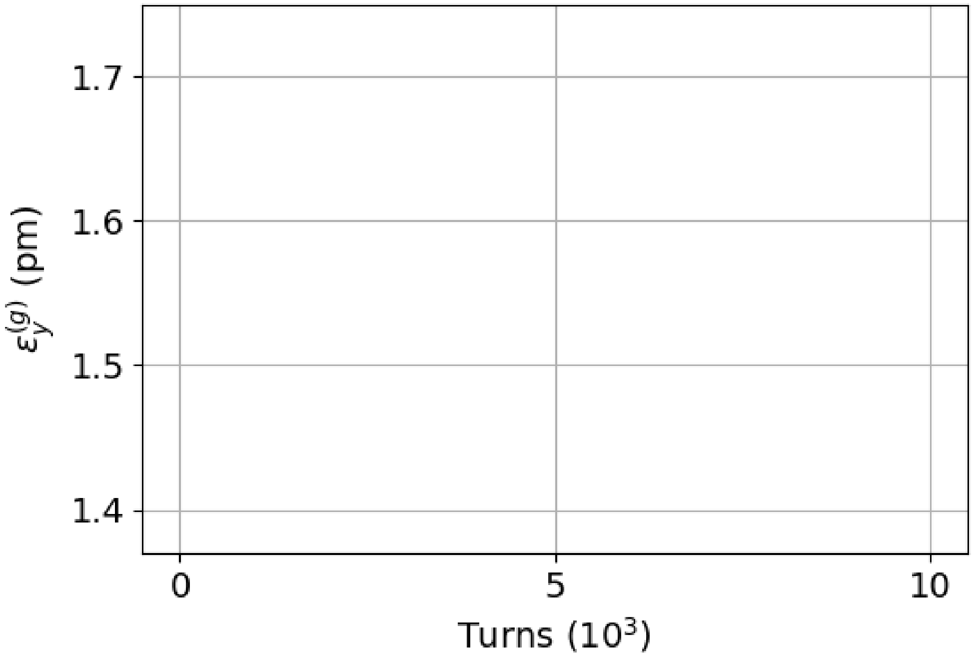
Develop **correction schemes / tuning knobs** for improving beam stability and performance in beam-beam dominated regimes.



Sensitivity of vertical emittance on a lattice with beam-beam

A tracking example without radiation

(i.e. like a proton accelerator)



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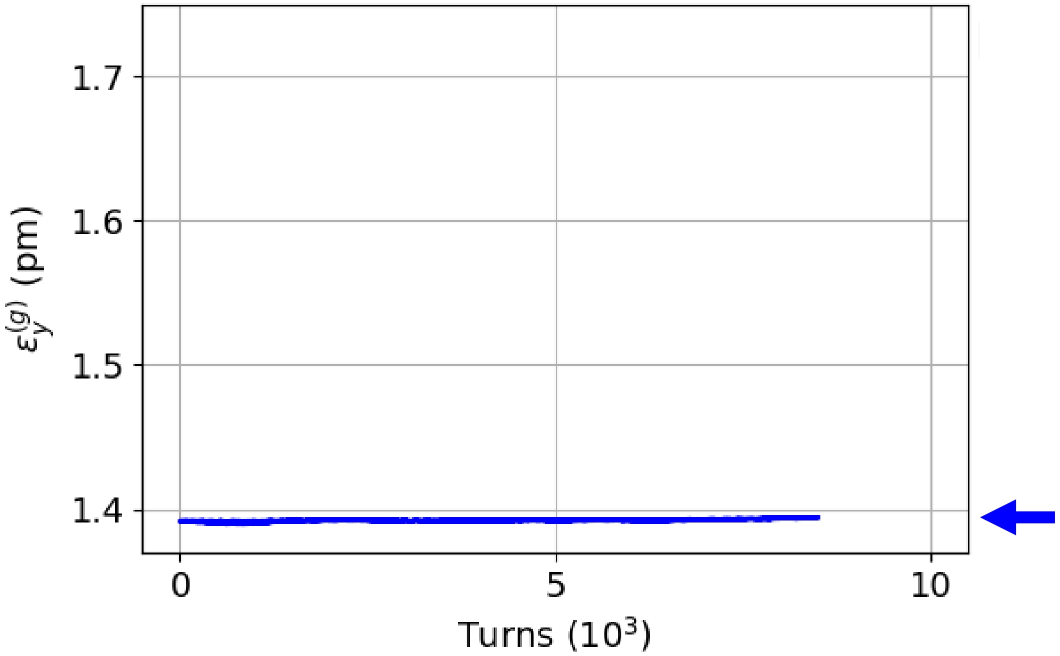
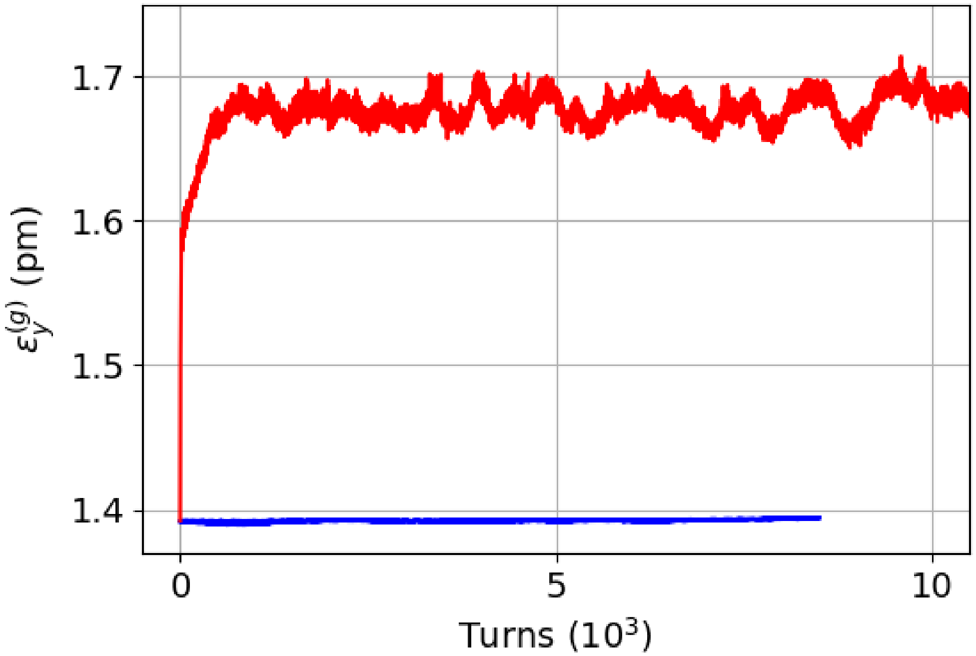


Without beam-beam

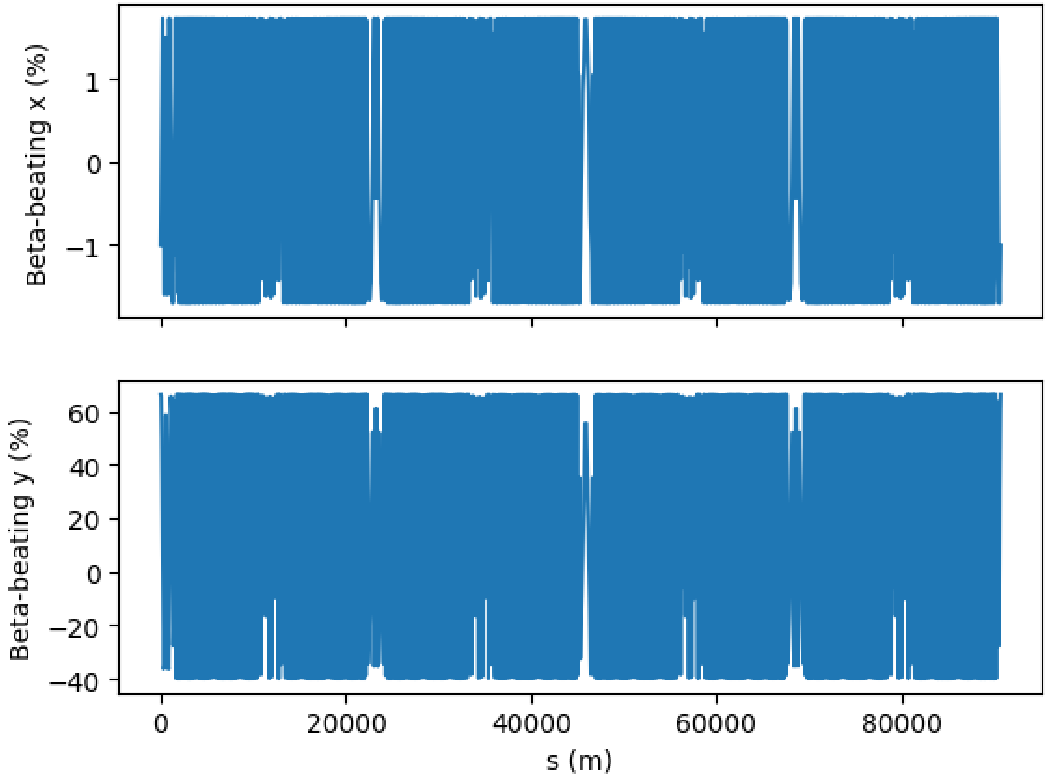
A tracking example without radiation



With beam-beam (only linear): phase space mismatch

Without beam-beam

Beta-beat from beam-beam



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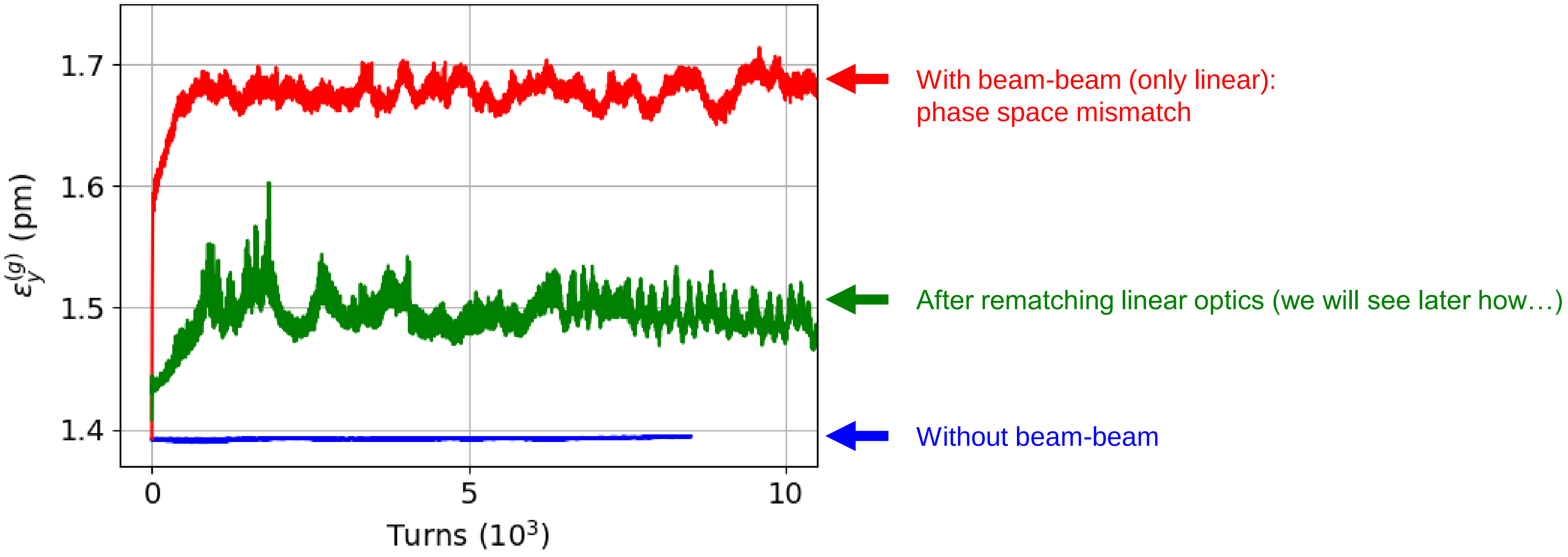
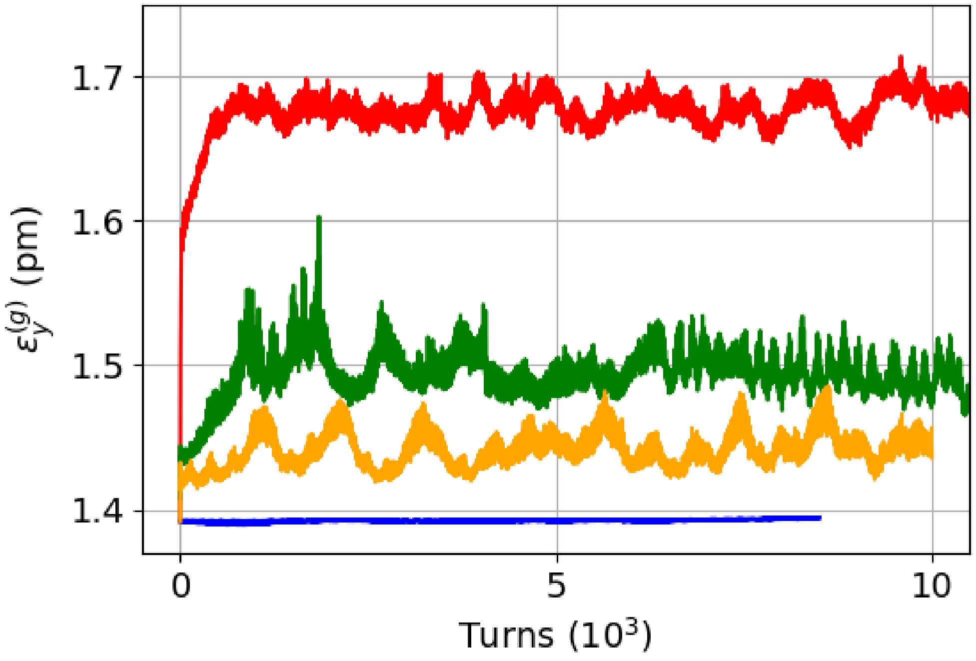
A tracking example without radiation



A tracking example <u>without</u> radiation



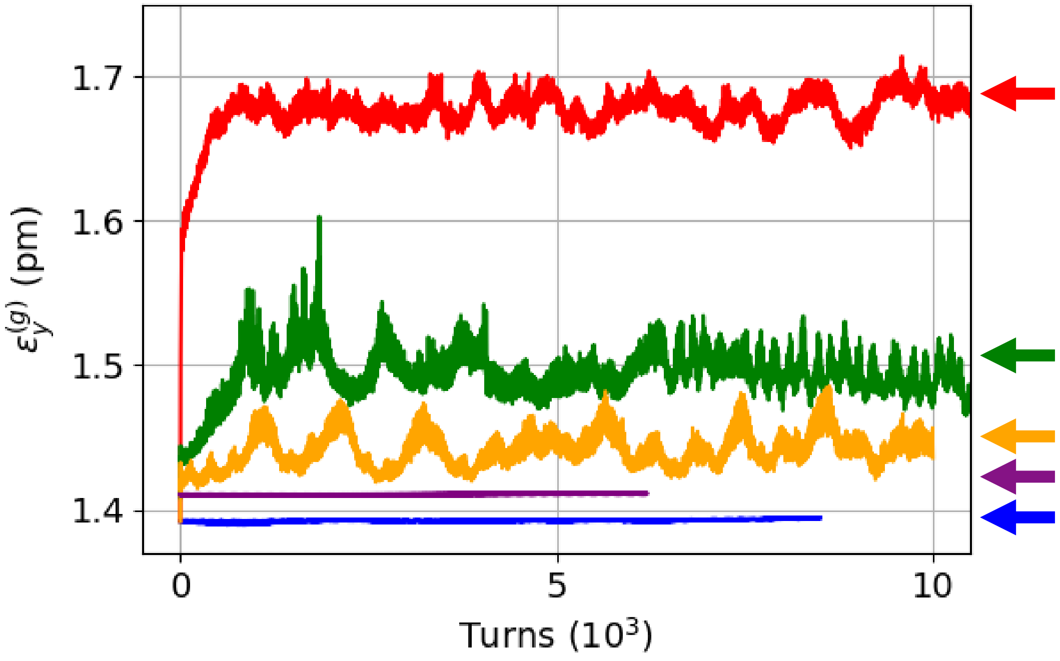
With beam-beam (only linear): phase space mismatch

After rematching linear optics (we will see later how…)

Removing off-momentum dependence (by forcing a monochromatic beam…)

Without beam-beam

A tracking example without radiation



With beam-beam (only linear):
phase space mismatch

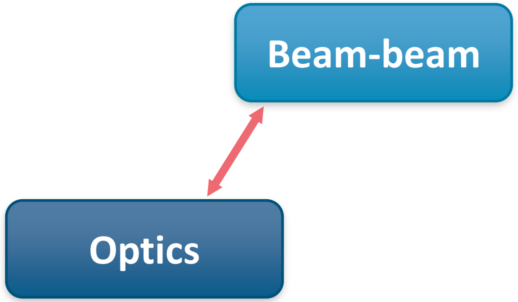
After rematching linear optics (we will see later how…)

Removing off-momentum dependence (by forcing a monochromatic beam…)

Removing strong non-linear elements (crab sextupoles)

Without beam-beam

- Strong linear optics distortions from beam-beam would lead to a phase space mismatch.
- Non-linear properties of the lattice are not negligible on the beam emittance.

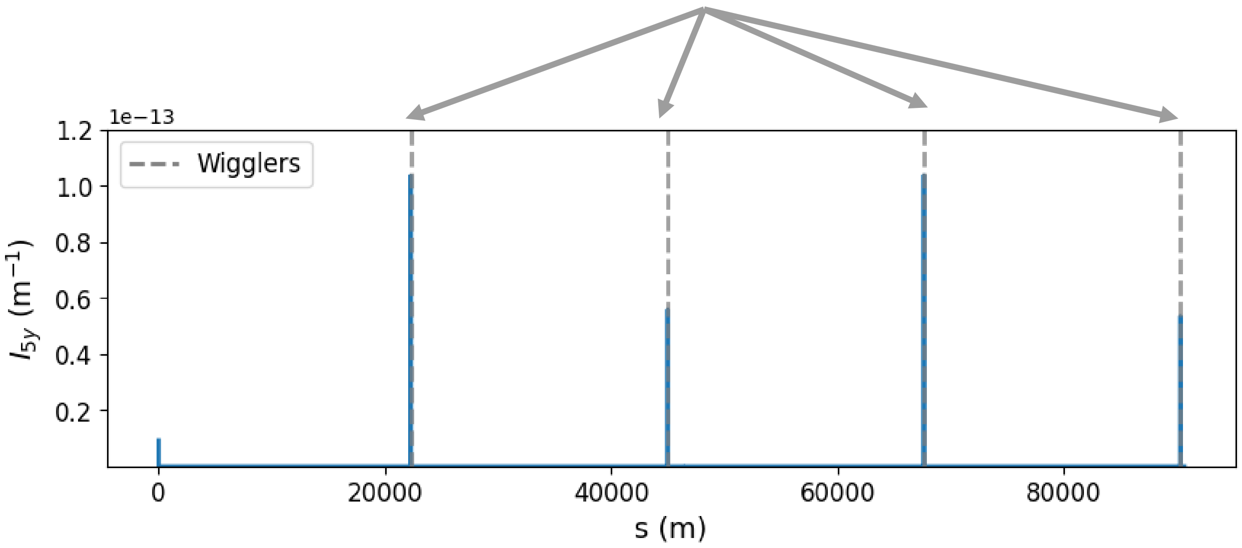


A tracking example **with** radiation

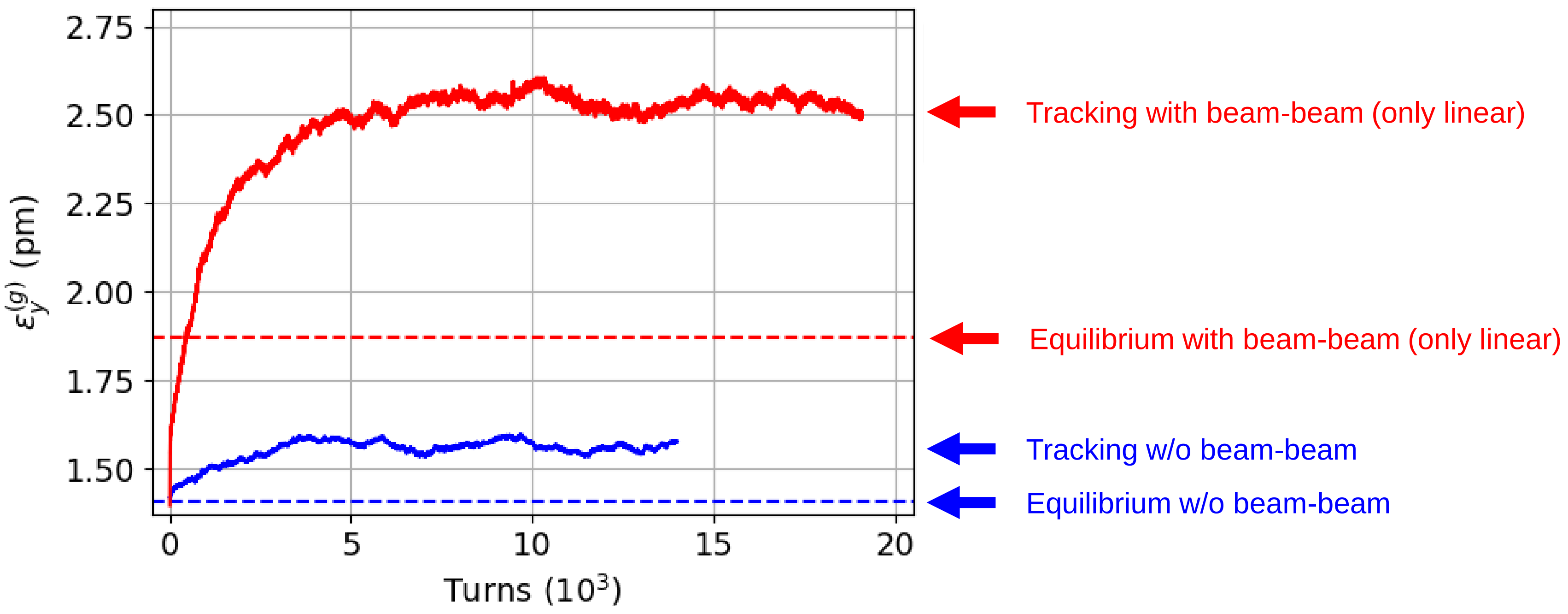
Beam emittance ↔ equilibrium emittance

$$\epsilon_y = C_q \gamma_0^2 \frac{I_5}{j_y I_2}, \qquad I_5 = \oint \frac{\mathcal{H}_y}{|\rho^3|} ds\,, \qquad I_2 = \oint \frac{ds}{\rho^2}$$

Emittance source in ideal lattice: four **vertical wigglers** distributed around the lattice

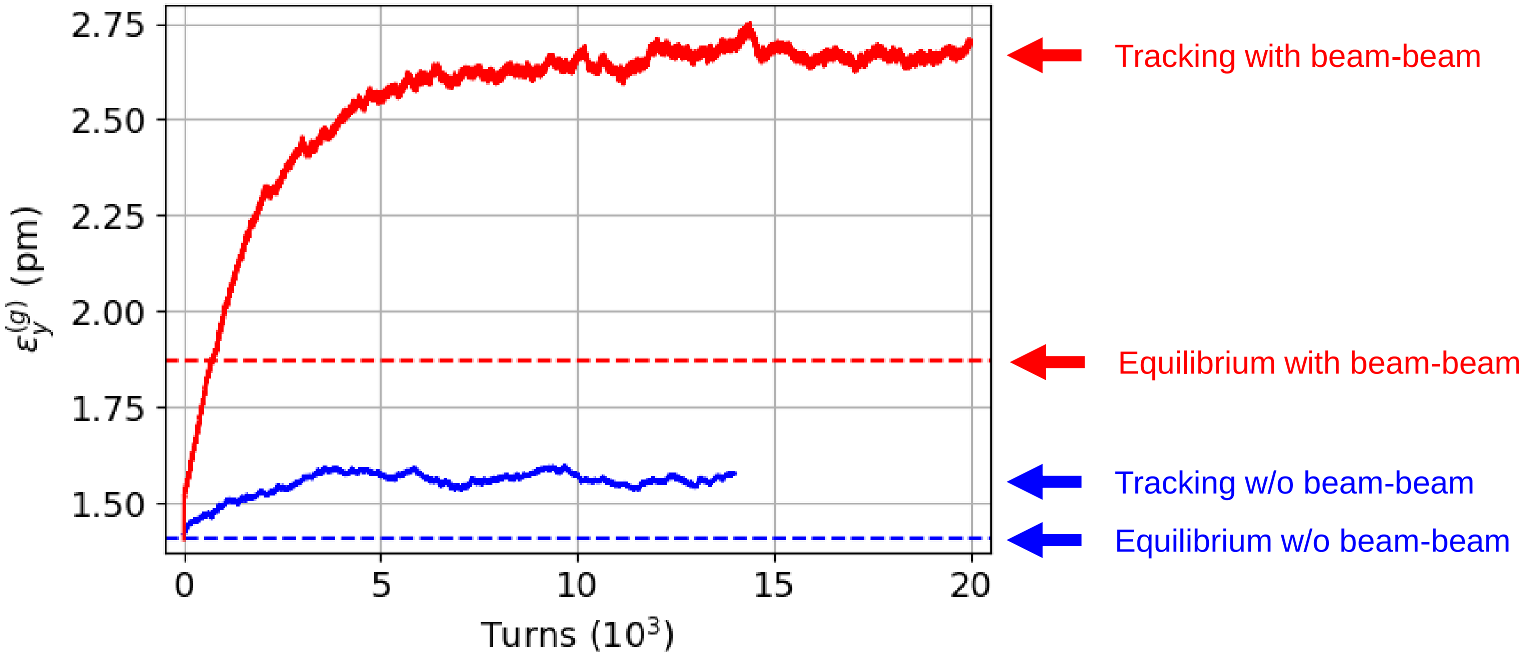


A tracking example with radiation

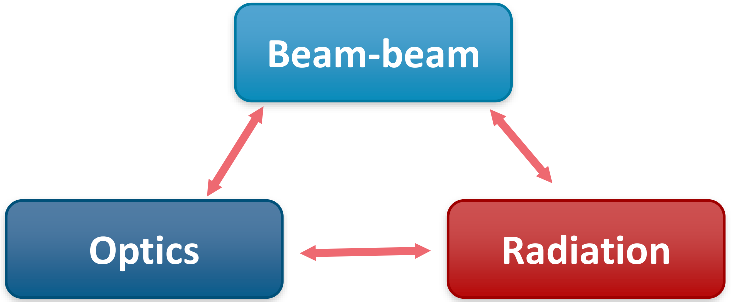


- Strong linear optics distortions from beam-beam lead to different equilibrium emittance.
- Non-linear properties of the lattice are not negligible to equilibrium emittance.

A tracking example <u>with</u> radiation

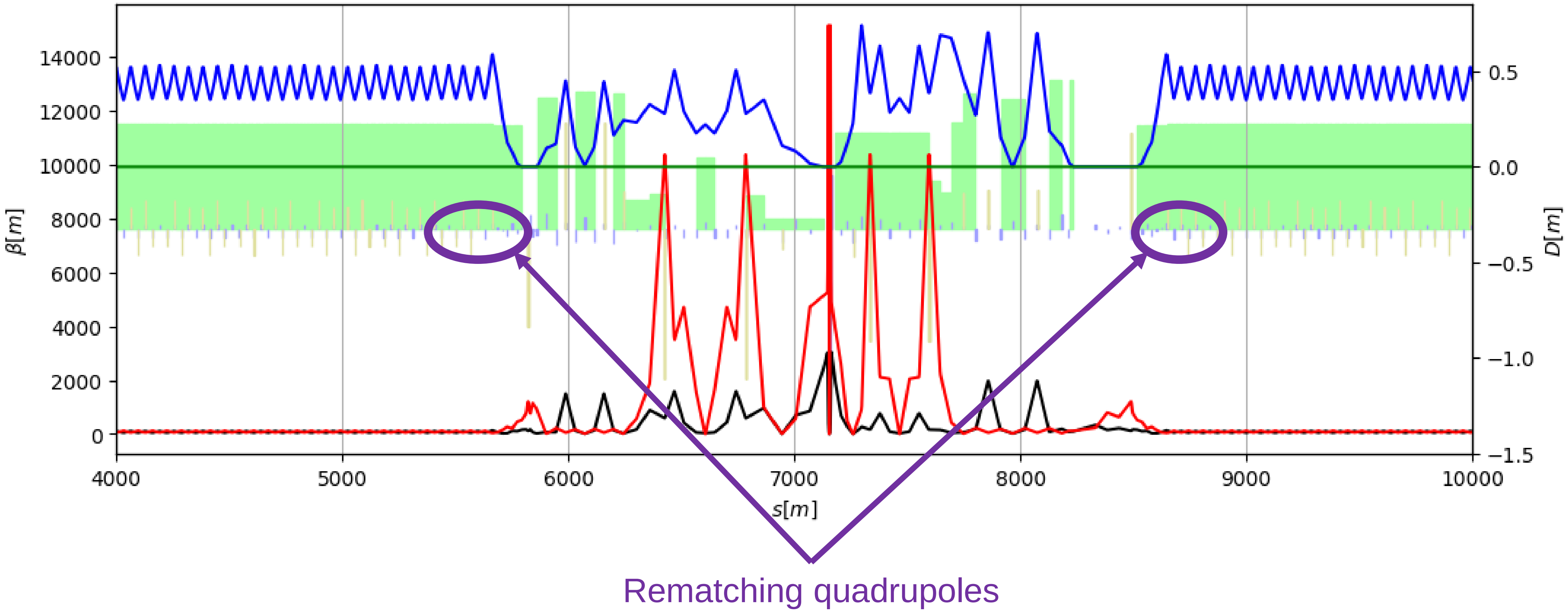


- Strong linear optics distortions from beam-beam lead to different equilibrium emittance.
- Non-linear properties of the lattice are not negligible to equilibrium emittance.
- **Non-linear contribution of beam-beam** and beamstrahlung (BS) are also not negligible.



An example of a tuning knob with beam-beam

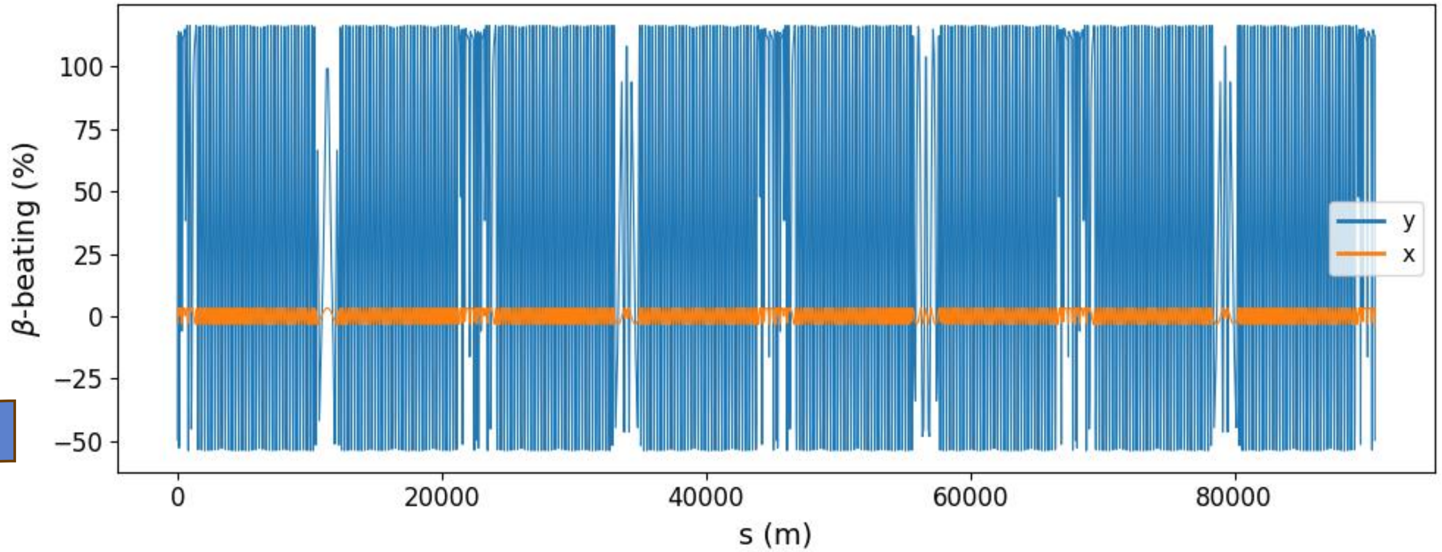
Rematching linear optics

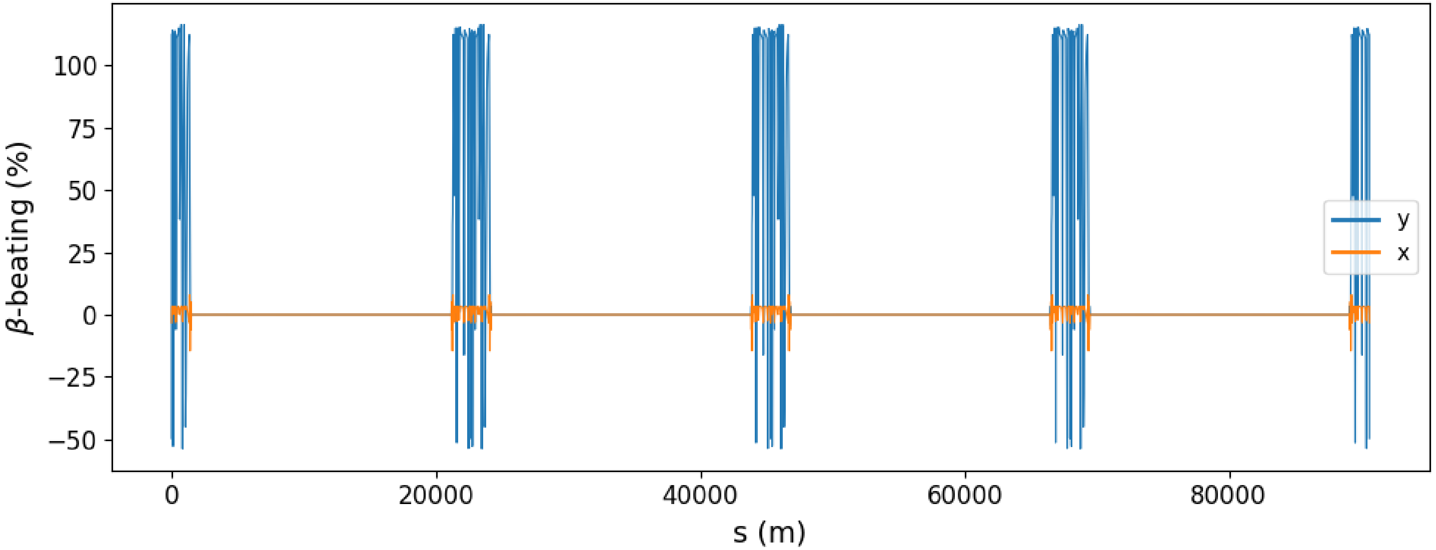


Rematching linear optics

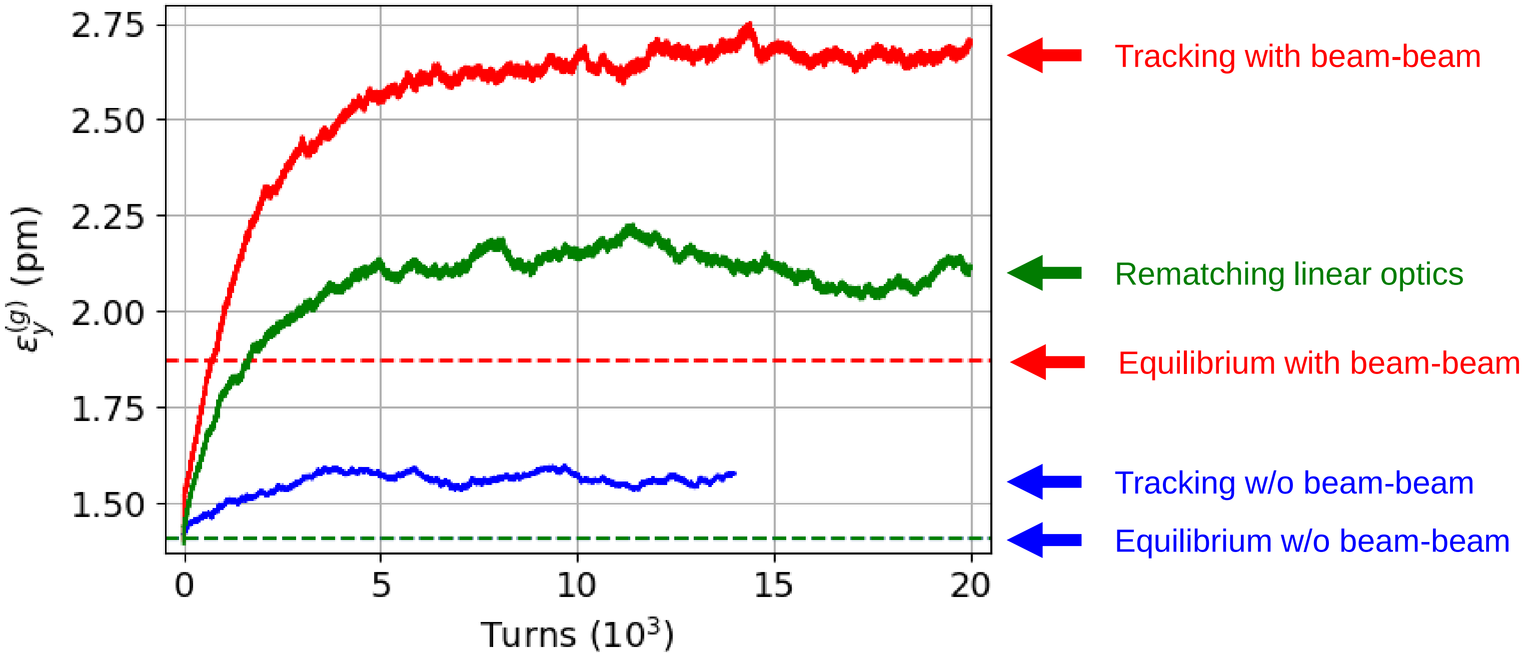
Rematched lattice:

- Optics distortions compensated in arcs and technical insertions.
- Maintained additional focusing induced by beam-beam at IPs ("dynamic β*")

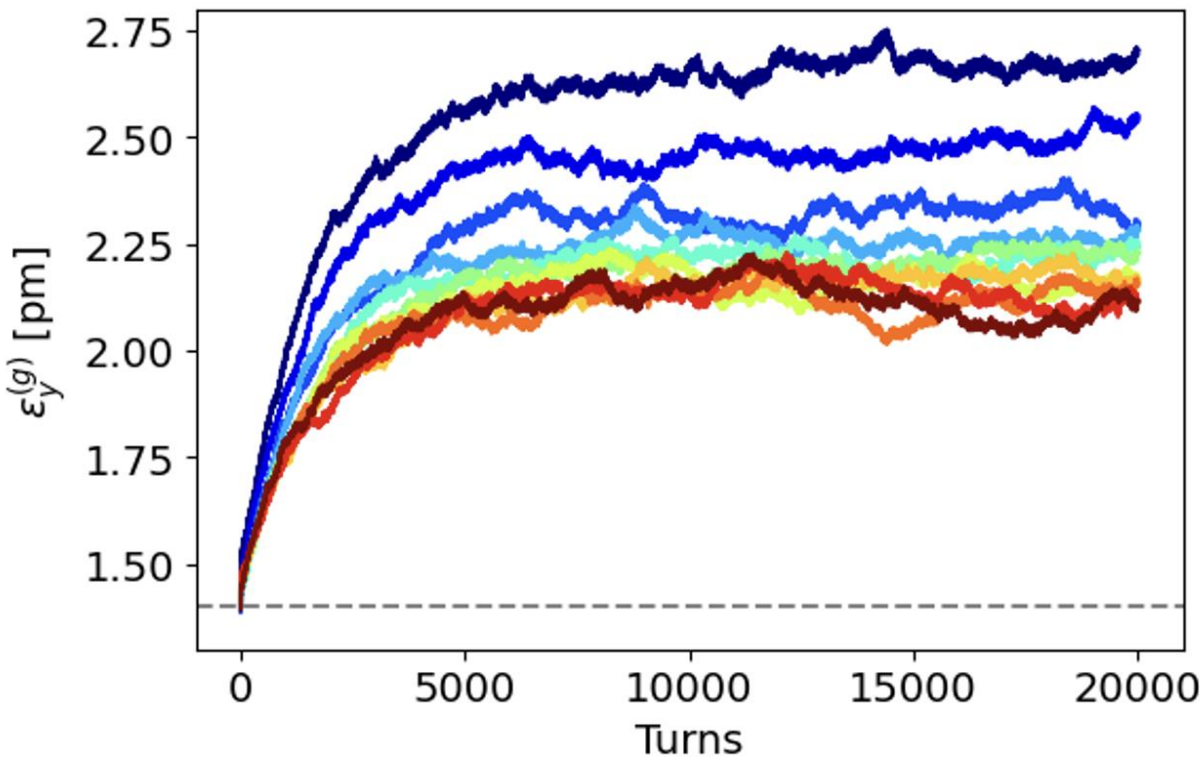


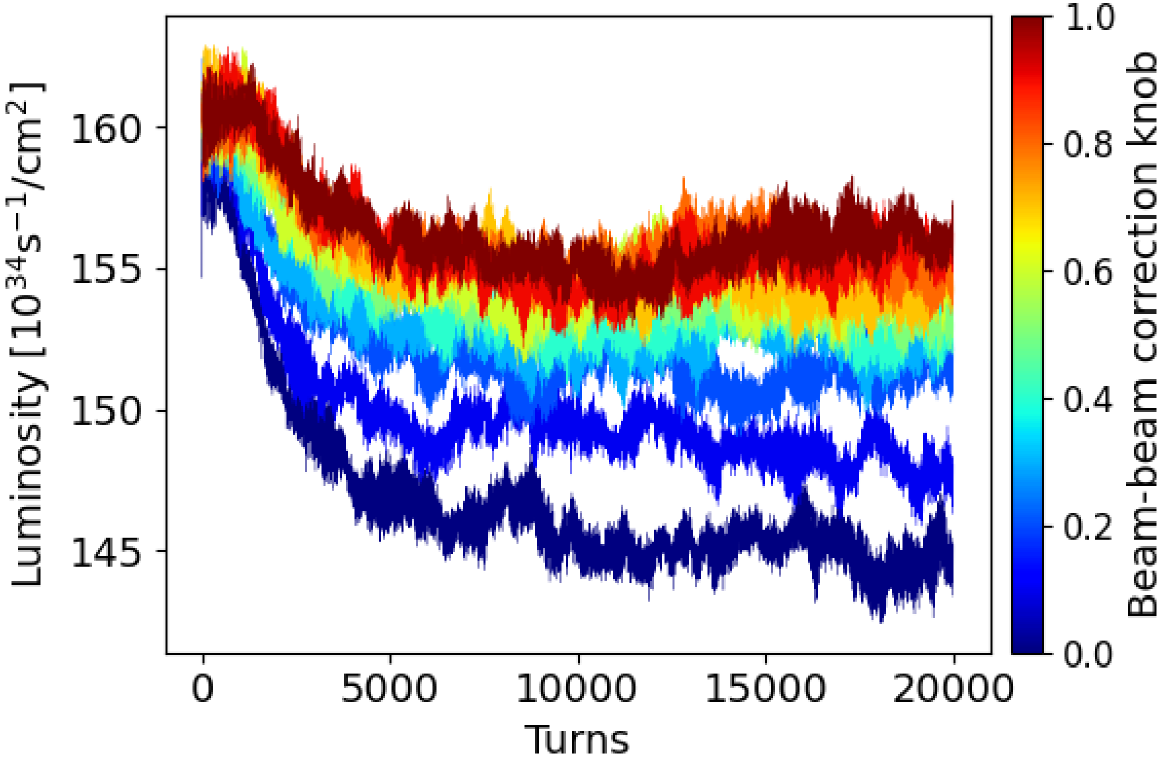


Reducing vertical emittance blow-up



Tuning-knob and luminosity





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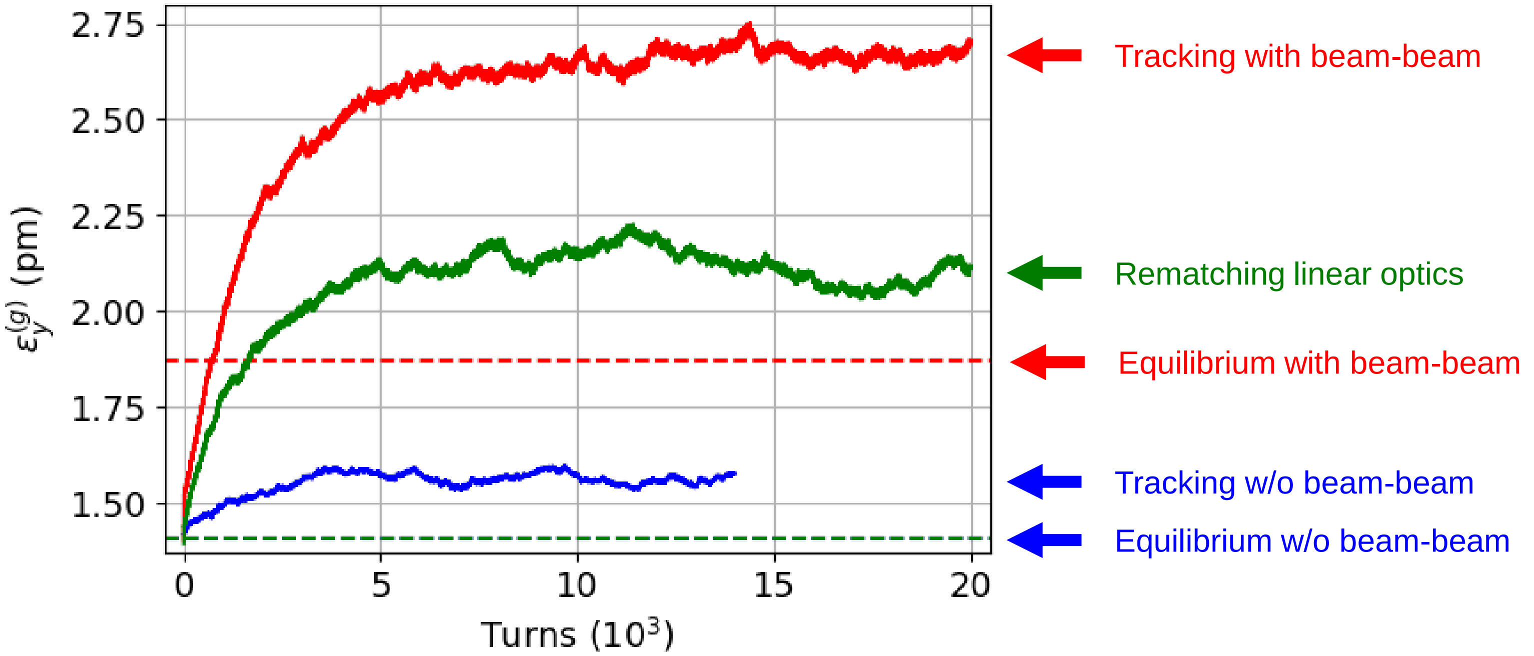
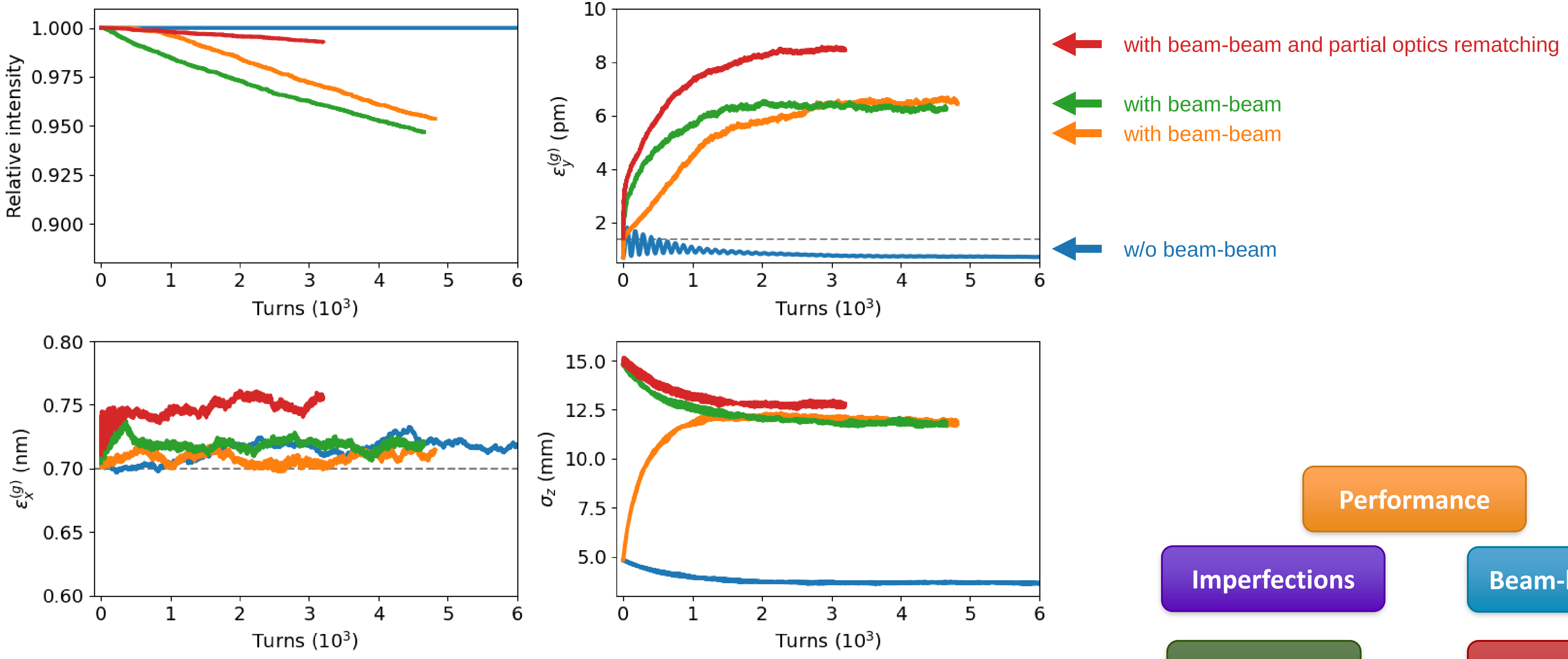


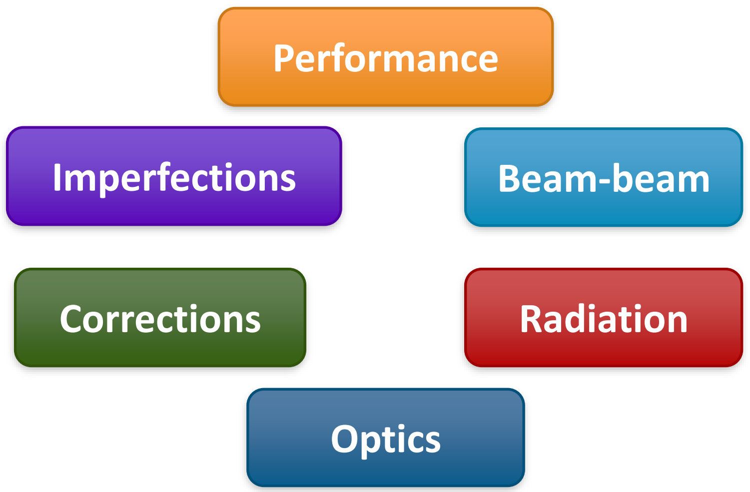
Some considerations:

- Beam-beam forces are very non-linear → optics distortions are amplitude dependent → correcting the zero-amplitude optics leads to overcorrection of higher amplitudes → some intermediate correction?
- Rematching the non-linear properties?
- So far: ideal lattice with “fake” emittance sources (vertical wigglers). What will matter in a lattice with lattice imperfections?

Lattices with imperfections and beam-beam

Tracking in lattices with imperfections (in progress…)





Summary & Outlook

Summary & Outlook

Vertical emittance blow-up in the ideal lattice with beam-beam

- Multiple effects contribute to emittance growth in tracking with beam–beam, even in an ideal lattice.
- How much we want to control these effects in practice?

Tracking tuned lattices with beam-beam

- Initial exploratory tracking simulations with “quasi-strong” beam-beam.
- Plan to study/understand source of losses and emittance increase (as in the ideal lattice) and propose potential mitigations.

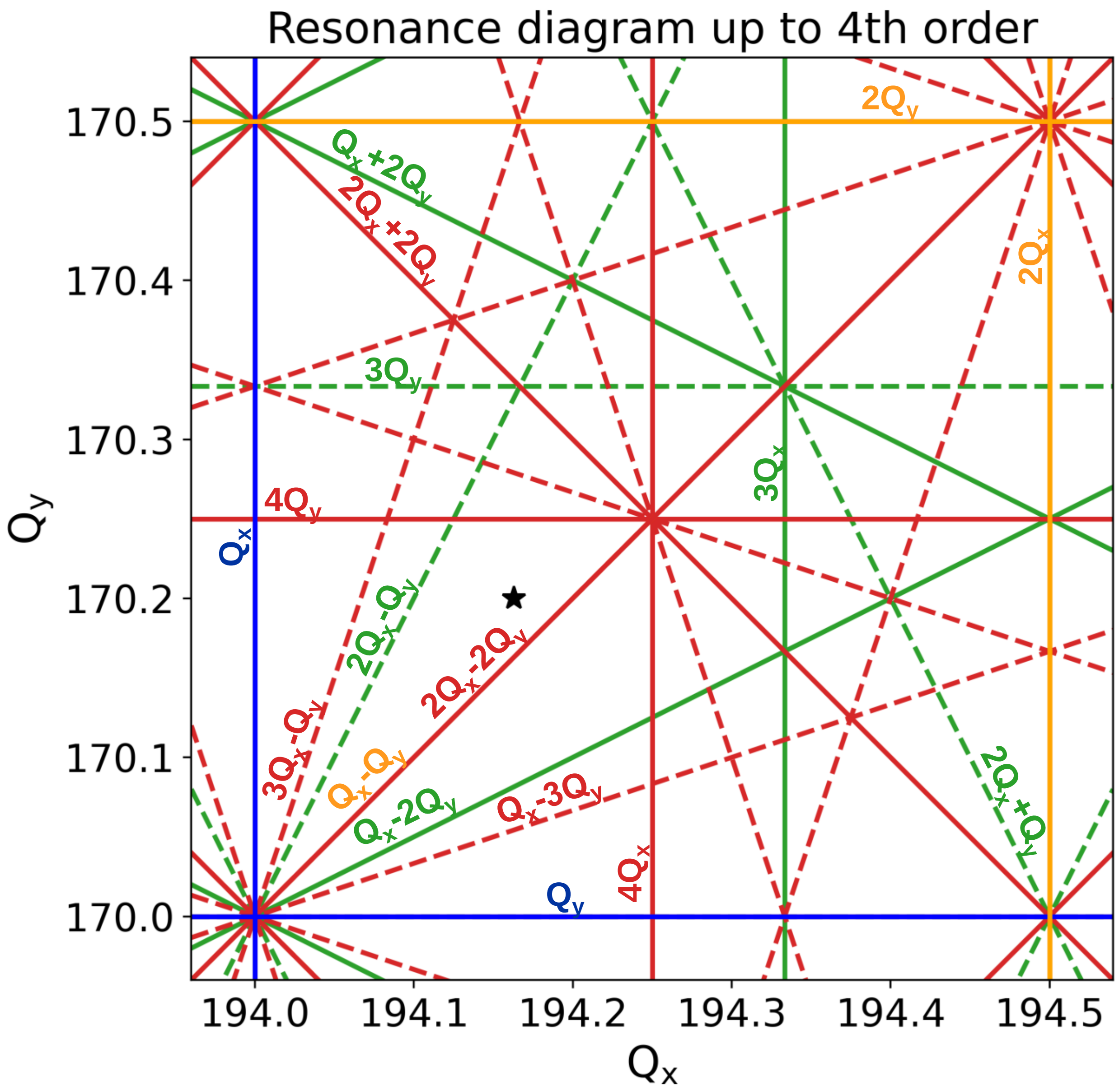
RDT sensitivity scans with beam-beam (in backup slides)

- Ongoing work towards understanding which RDTs drive performance with beam-beam and how to compensate them.

Thank you for your attention!

Backup

Beam-beam and RDT scans



RDTs:

- 3rd order normal: f1020, f1011, f1002, f3000, f2100
- 3rd order skew: f0030, f0012, f2010, f2001, f1110
- 4th order normal: f4000, f3100, f2020, f2011, f2002, f1120, f0040, f0031
- 4th order skew: f3010, f3001, f2110, f2101, f1021, f1012, f1030, f1003
- …

1st order resonances
2nd order resonances
3rd order resonances
4th order resonances

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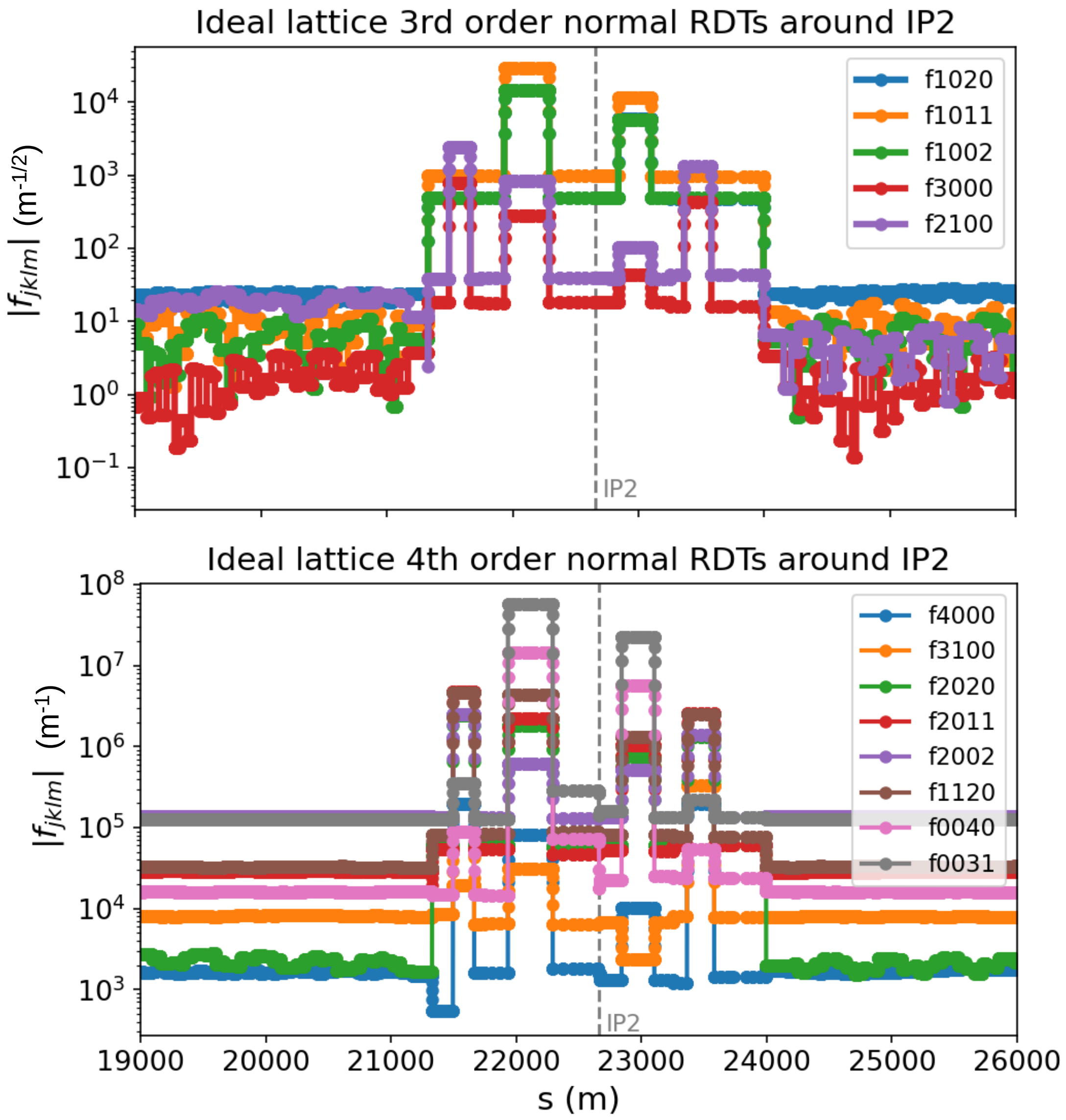
RDTs of ideal lattice



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- …

"Agnostic" approach:

- Change individual RDTs either locally (e.g. at IPs) or globally
- Track with beam-beam and see impact on performance (lifetime, emittance, lumi, …)

Changing a single RDT

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- 3^{rd} order normal: f1020, f1011, f1002, f3000, f2100
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Changing a single RDT

Standard (truncated) SVD:

- Build linear response matrix R with large number of individually powered correctors: $\Delta f = R\,\Delta k$
- Define a target RDT change: $\Delta f_{target} = a f_0$
- Invert using truncated SVD: $\Delta k = R^{-1}\Delta f_{target}$
- While it minimizes $\left\| R\Delta k - \Delta f_{target} \right\|^2$, it leads to cross-talk between RDTs.

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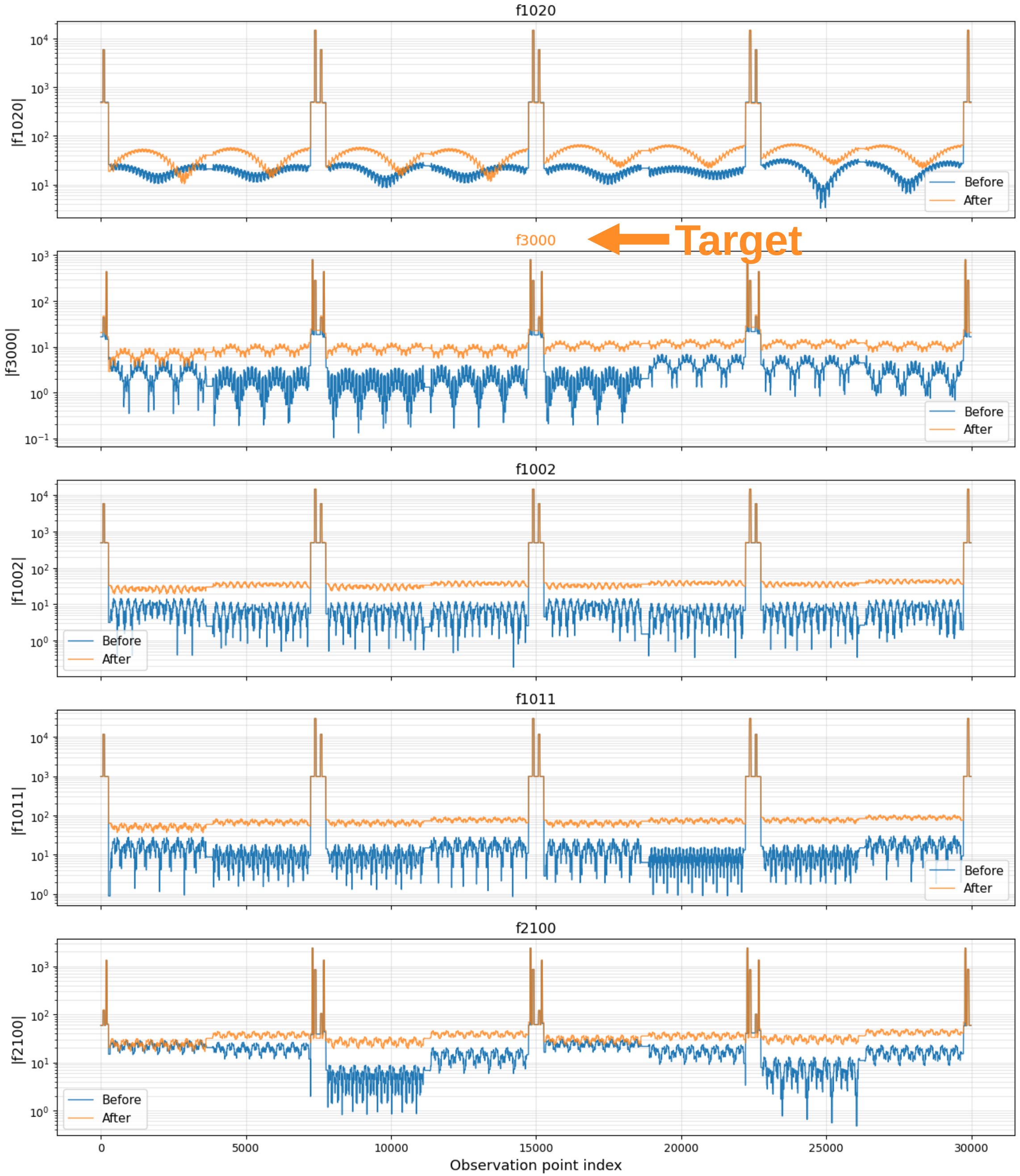

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- While it minimizes $\left\|R\Delta k - \Delta f_{target}\right\|^2$, it leads to cross-talk between RDTs.

A more “weighted SVD” :

- Split R into target & non-target RDT parts: $R = \begin{bmatrix} R_t \\ R_{nt} \end{bmatrix}$
- Solve a weighted least squares:
  $\min_{\Delta k} \left\|R_t\Delta k - \Delta f_{target}\right\|^2 + A\|R_{nt}\Delta k\|^2 + B\|\Delta k\|^2$
- A suppresses cross-talk of non-target RDTs
- B limits corrector strengths
- Reduces to standard SVD solution when A=B=0

RDTs:

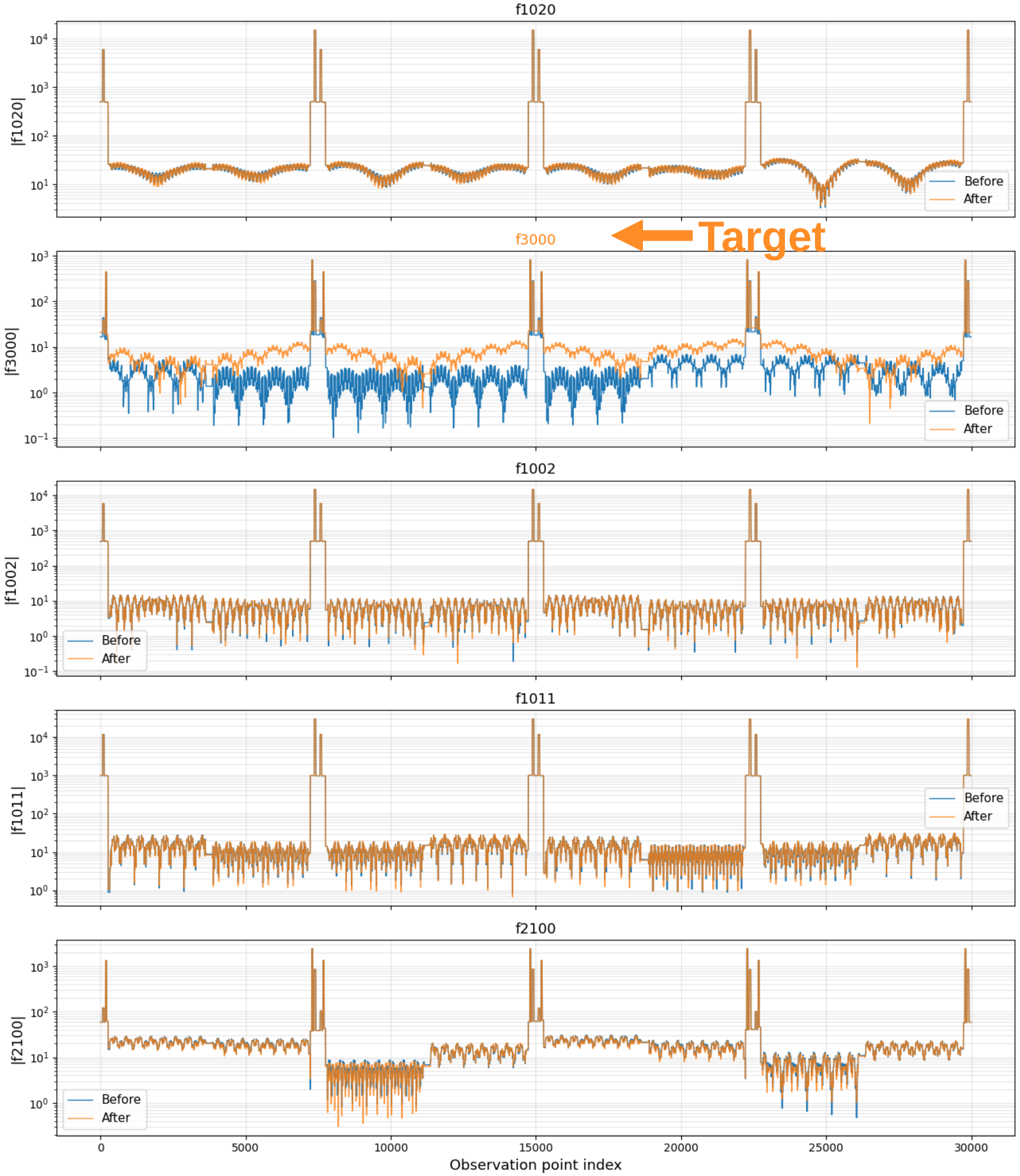
- 3^{rd} order normal: f1020, f1011, f1002, f3000, f2100
- 3^{rd} order skew: f0030, f0012, f2010, f2001, f1110
- 4^{th} order normal: f4000, f3100, f2020, f2011, f2002, f1120, f0040, f0031
- 4^{th} order skew: f3010, f3001, f2110, f2101, f1021, f1012, f1030, f1003
- …

“Agnostic” approach:

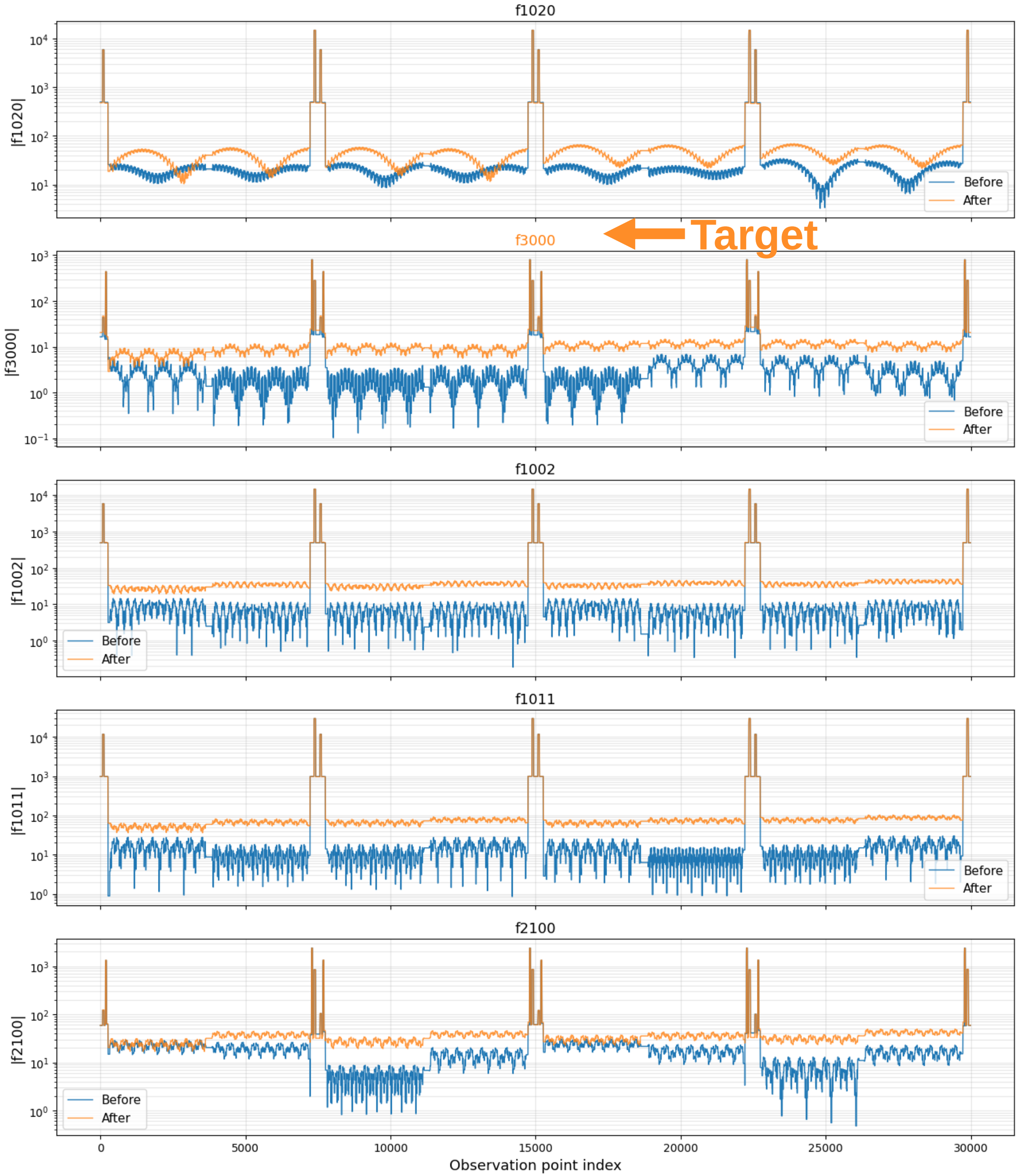
- Change individual RDTs either locally (e.g. at IPs) or globally
- Track with beam-beam and see impact on performance (lifetime, emittance, lumi, …)

Example: changing f3000 by +25%

“Weighted” SVD



Standard (truncated) SVD



Changing a single RDT

Standard (truncated) SVD:

- Build linear response matrix R with large number of individually powered correctors: $\Delta f = R\,\Delta k$
- Define a target RDT change: $\Delta f_{target} = a f_0$
- Invert using truncated SVD: $\Delta k = R^{-1}\Delta f_{target}$
- While it minimizes $\left\|R\Delta k - \Delta f_{target}\right\|^2$, it leads to cross-talk between RDTs.

A more "weighted SVD" *:

- Split R into target & non-target RDT parts: $R = \begin{bmatrix} R_t \\ R_{nt} \end{bmatrix}$
- Solve a weighted least squares:
  $\min_{\Delta k} \left\|R_t\Delta k - \Delta f_{target}\right\|^2 + A\|R_{nt}\Delta k\|^2 + B\|\Delta k\|^2$
- A suppresses cross-talk of non-target RDTs
- B limits corrector strengths
- Reduces to standard SVD solution when A=B=0

RDTs:

- 3rd order normal: f1020, f1011, f1002, f3000, f2100
- 3rd order skew: f0030, f0012, f2010, f2001, f1110
- 4th order normal: f4000, f3100, f2020, f2011, f2002, f1120, f0040, f0031
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- …

"Agnostic" approach:

- Change individual RDTs either locally (e.g. at IPs) or globally
- Track with beam-beam and see impact on performance (lifetime, emittance, lumi, …)

*Need to make sure tunes, chroma, second order dispersions, higher order RDTs, … remain unperturbed.

Tracking

- Xsuite
- LCC 106.1.0 at Z
- Tapered lattice, no imperfections
- Quantum radiation + beamstrahlung, no Bhabha scattering
- Weak-strong beam-beam: strong beam initialized with equilibrium lattice emittances and 251 slices.
- 8000 particles tracked for 8000 turns
- Monitoring in RF sections (dispersion-free)
- Artificial aperture at 20σ in both transverse plane (LimitRect) and at the bucket length (LongitudinalLimitRect).

RDTs:

- 3rd order normal: f1020, f1011, f1002, f3000, f2100
- 3rd order skew: f0030, f0012, f2010, f2001, f1110
- 4th order normal: f4000, f3100, f2020, f2011, f2002, f1120, f0040, f0031
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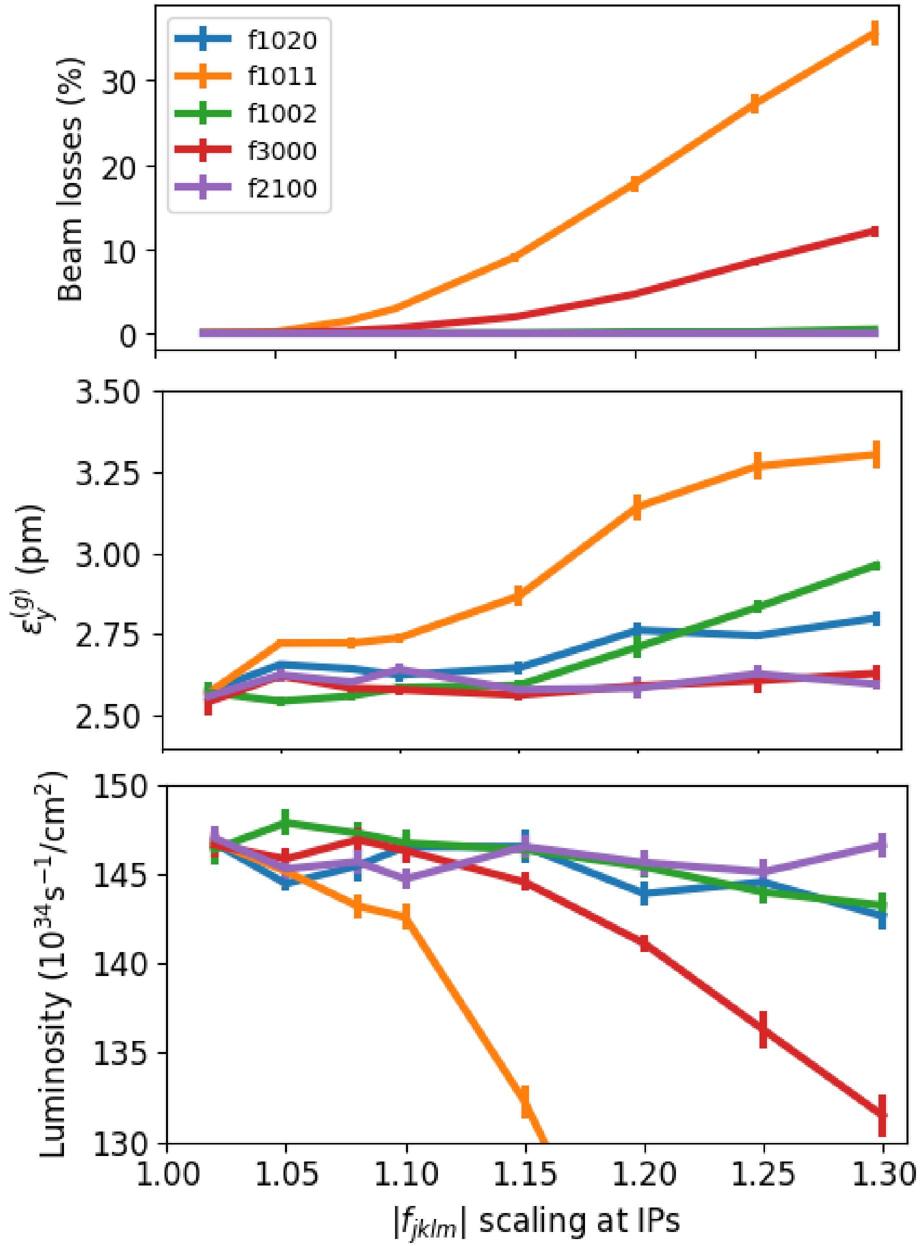
- …

“Agnostic” approach:

- Change individual RDTs either locally (e.g. at IPs) or globally
- Track with beam-beam and see impact on performance (lifetime, emittance, lumi, …)

RDT scans with beam-beam

3rd order normal



RDT scans with beam-beam

Even with an agnostic/numerical approach, one can:

- Rank relative importance of individual RDTs with beam-beam (e.g. f1011<f3000<f1002)
- Quantify their impact on observables (e.g. f3000 causes mainly losses).

Caveats:

- Difficult to disentangle local RDT effects (e.g. IP geometric aberrations) from global effects (e.g. losses)
- Single-RDT scans are not fully isolated due to coupling to higher-order RDTs

Outlook / potential directions:

- Understand why specific RDTs drive performance with beam-beam
  - Resonance excitation?
  - coupling to higher-order terms (e.g. 2nd-order dispersion)
- Can the numerical scans guide us to specific corrector configurations?

Also work in progress!

3^{rd} order normal