MAD-X Benchmarking and Solenoid Models

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Thanks to Rogelio Tomas, Tobias Persson, Helmut Burkhardt, Riccardo De Maria, Katsunobu Oide and the entire FCC Optics Team

Motivations of MAD-X Benchmarking

- Aim to ensure **MAD-X** can **reliably simulate FCC-ee**
  - A lot of MAD-X **users and expertise** in the collaboration
  - MAD-X developed and **maintained in CERN**
  - MAD-X developments strongly **driven by** LHC and **hadron machines**
- Benchmark with **SAD** because
  - Extensively used with **SKEKB** (and developed with it in mind)
    - Largest current lepton collider
  - FCC-ee lattices **designed in SAD** in first iteration
    - Ensure MAD-X simulation represents what design had in mind

Overview of Areas Covered

- **Extensive comparisons between MAD-X and SAD**
    - Linear optics, amplitude and momentum detuning (presentation)
    - Emittance (presentation) and radiation integrals (presentation)
    - On axis and tilted solenoid (presentation)
- **Tapering Implementation in MAD-X**
    - Implemented since version 5.06
    - Optics in good agreement with SAD results (presentation)
    - Able to get correct emittance from tracking
- **Dynamic Aperture Studies**
    - Computation of dynamic aperture without radiation in PTC (presentation)
- **Input for future code development at CERN**
    - Input for MAD-NG development (presentation)

Emittance in Tapered Lattices

- Previously **MAD-X's emit** module did not work in **tapered lattices**
  - Due to lack of **stable longitudinal motion**
- Stability can be achieved by **matching the phase of the cavities** whilst tapering
- Can **compare** the obtained values to
  - **SAD**
  - MAD-X results in un-tapered lattices at 1 GeV and **scaled** by energy squared

Lattice	Energy	ϵ_x @ 1 GeV	Scaled ϵ_x	Tapered ϵ_x	Design Report ϵ_x
Z	45.6 GeV	1.30×10^{-5} nm	0.27 nm	0.27 nm	0.27 nm
WW	80 GeV	1.30×10^{-4} nm	0.83 nm	0.83 nm	0.84 nm
ZH	120 GeV	4.35×10^{-5} nm	0.63 nm	0.63 nm	0.63 nm
tt	182.5 GeV	4.35×10^{-5} nm	1.45 nm	1.45 nm	1.46 nm

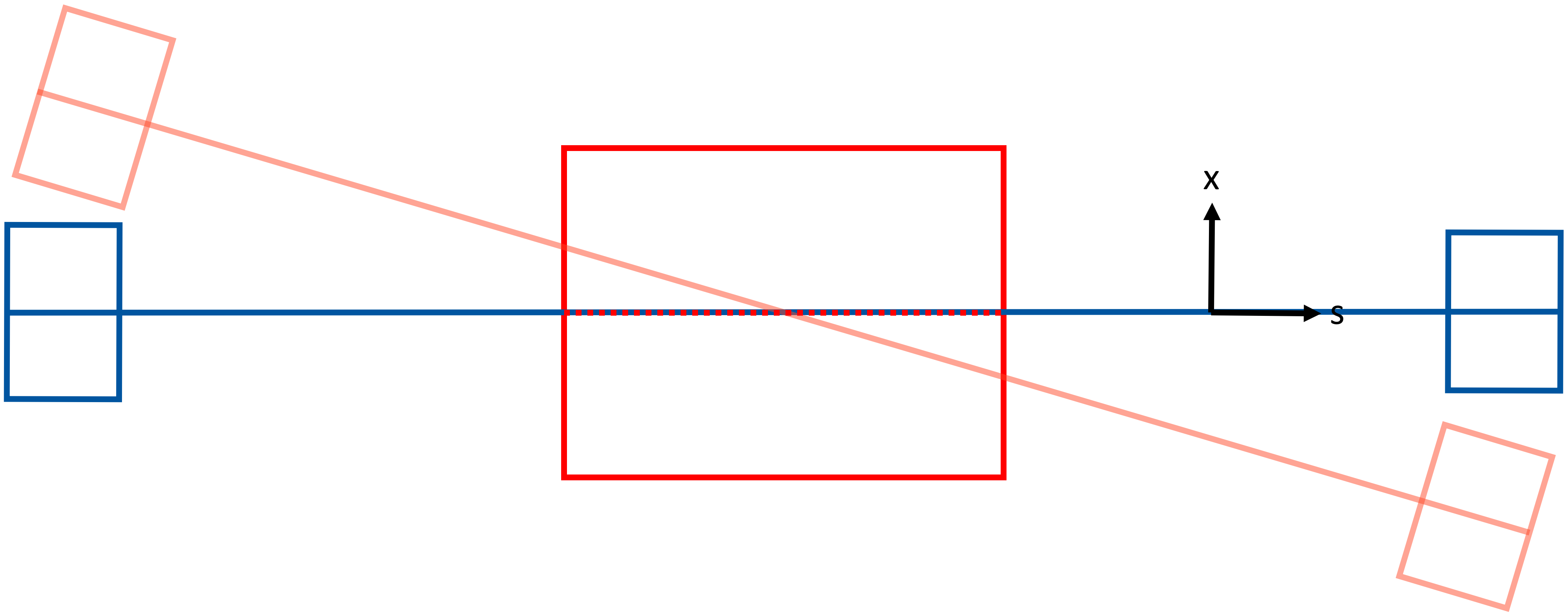
Tilted Solenoid for Optics Calculations

- Require a solenoid definition that can accurately reflect the **optics effects**
  - On-axis **solenoid field**
    - E.g. local coupling
  - **Dipolar field** from tilt
    - E.g. orbit bump and radiation effects
- Need to understand the **geometric implications** of the solenoid
  - E.g. in **SAD** solenoid defines **reference orbit** – similar to bending dipoles
- Aim is not to produce the most accurate simulation of the solenoid but one that captures **the effects most crucial to optics simulations**
  - See talk by **H Burkhardt** for other approach

Tilted Solenoid Strategies

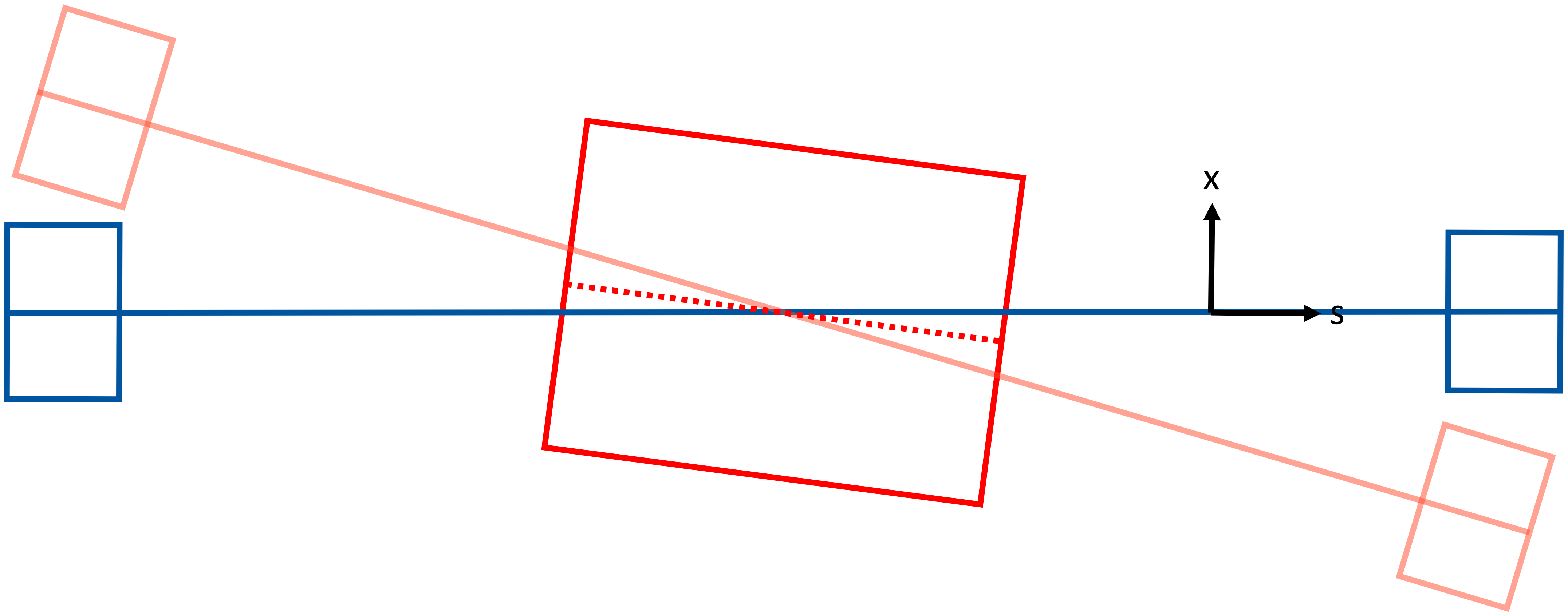
Method	Benefits	Drawbacks
Misalignment of Solenoid Implemented like alignment errors	• Very simple • No need to change lattice file	• Not SAD layout • Radiation in solenoid currently not correct

Misaligned Tilted Solenoid



Machine Frame

Misaligned Tilted Solenoid



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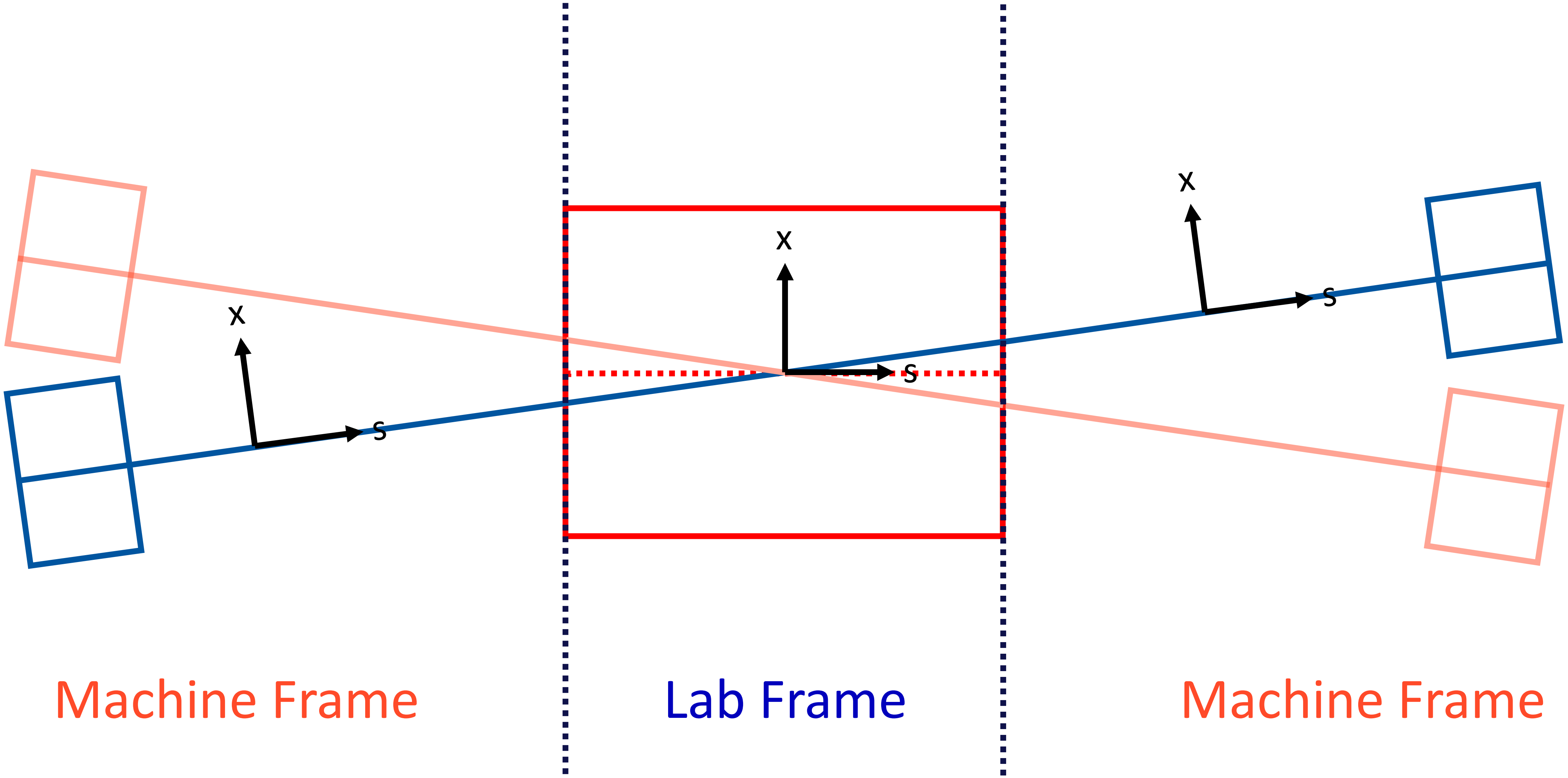
Tilt through change of coordinate system Rotations and translations at solenoid entrance/exit	• Exact replication of SAD layout • Exact agreement with SAD β, α, μ and horizontal dispersion	• Completely new lattice file from new translator • Rotation (currently) causes strange vertical dispersion • EMIT does not currently work

Change of Coordinate System



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SAD-like Implementation of Tilted Solenoid

- **Redefine co-ordinate system** at **entrance and exit** of solenoid region
  - Known “tilt” at entrance
  - Zero orbit at exit
- Exact co-ordinate transformation at solenoid exit **dependant on closed orbit**
  - **SAD determines this internally** during closed orbit search
  - In **MAD-X** this can be achieved by **matching transformations**
- Features to test:
  - Optics due to solenoid and due to tilt
  - Orbit in both planes
  - Vertical dispersion due to tilted solenoid field

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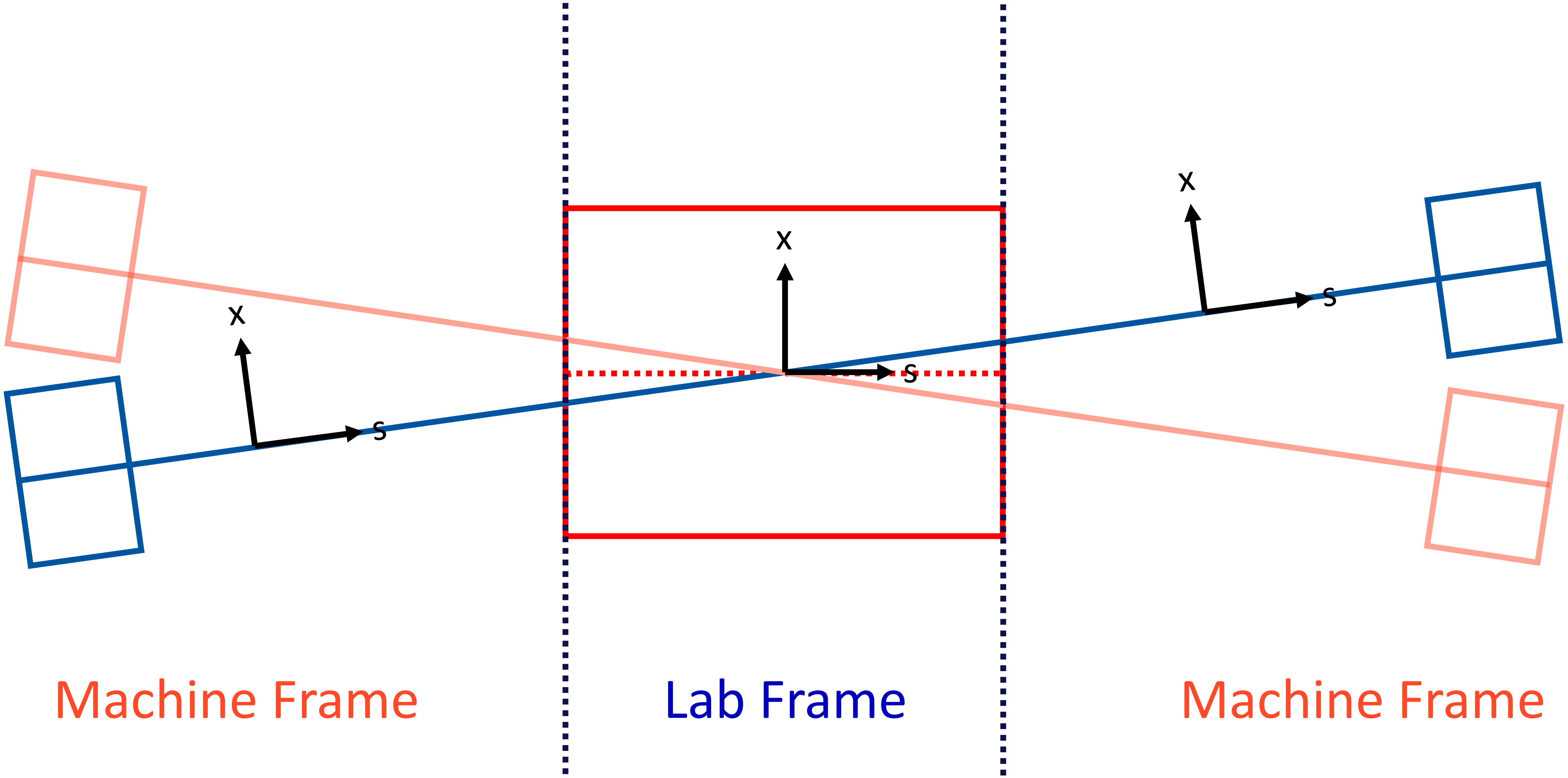

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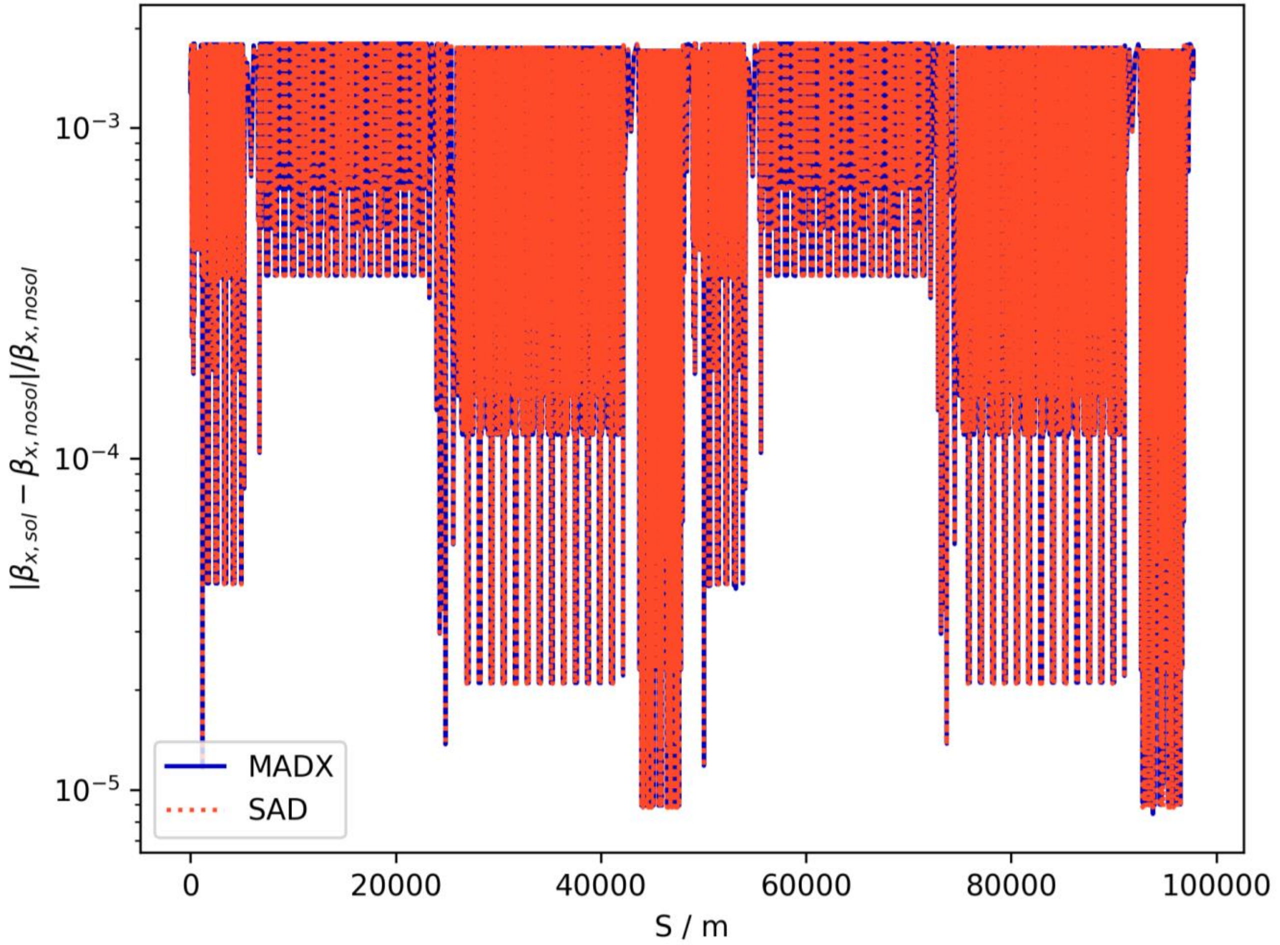
Change in Optics due to Solenoid

- Solenoid field **set to 0T and 2T**
  - **Change in optics**
- Check if change in optics is the **same in both codes**
- **Very good** agreement
  - Significantly larger beating than due to conversion



β-beating due to turning on tilted solenoid obtained using MAD-X and SAD

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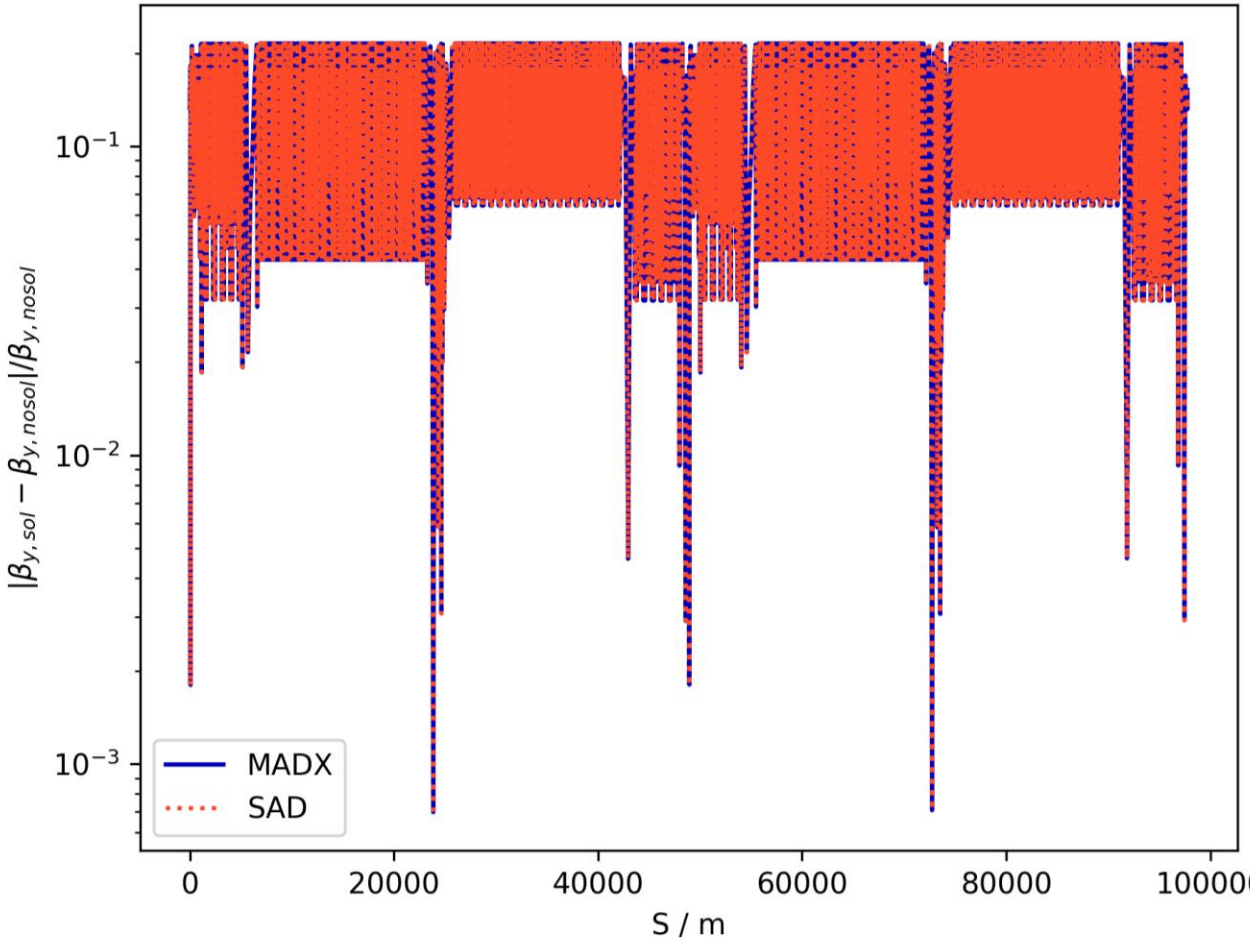
  - Especially in the **y plane**



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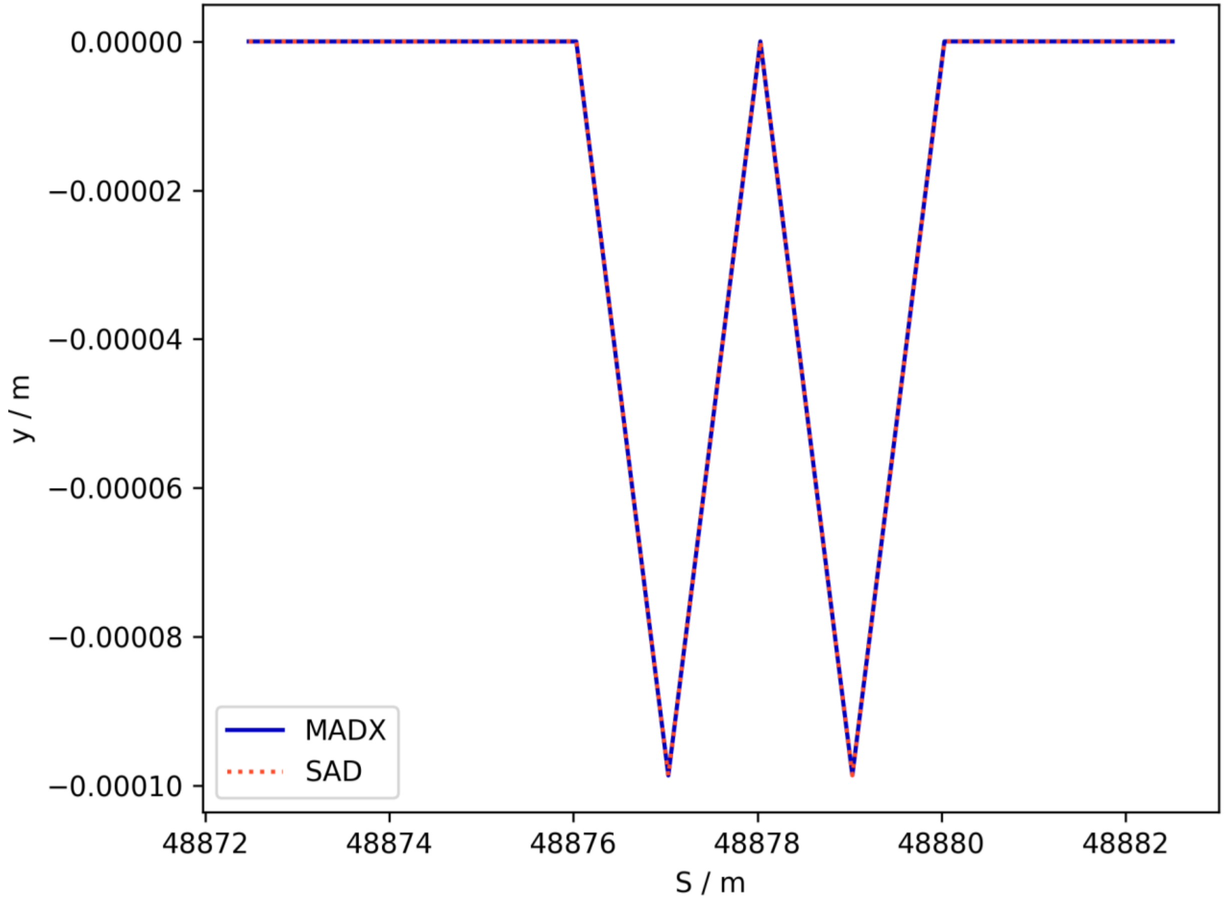
Orbit Bump

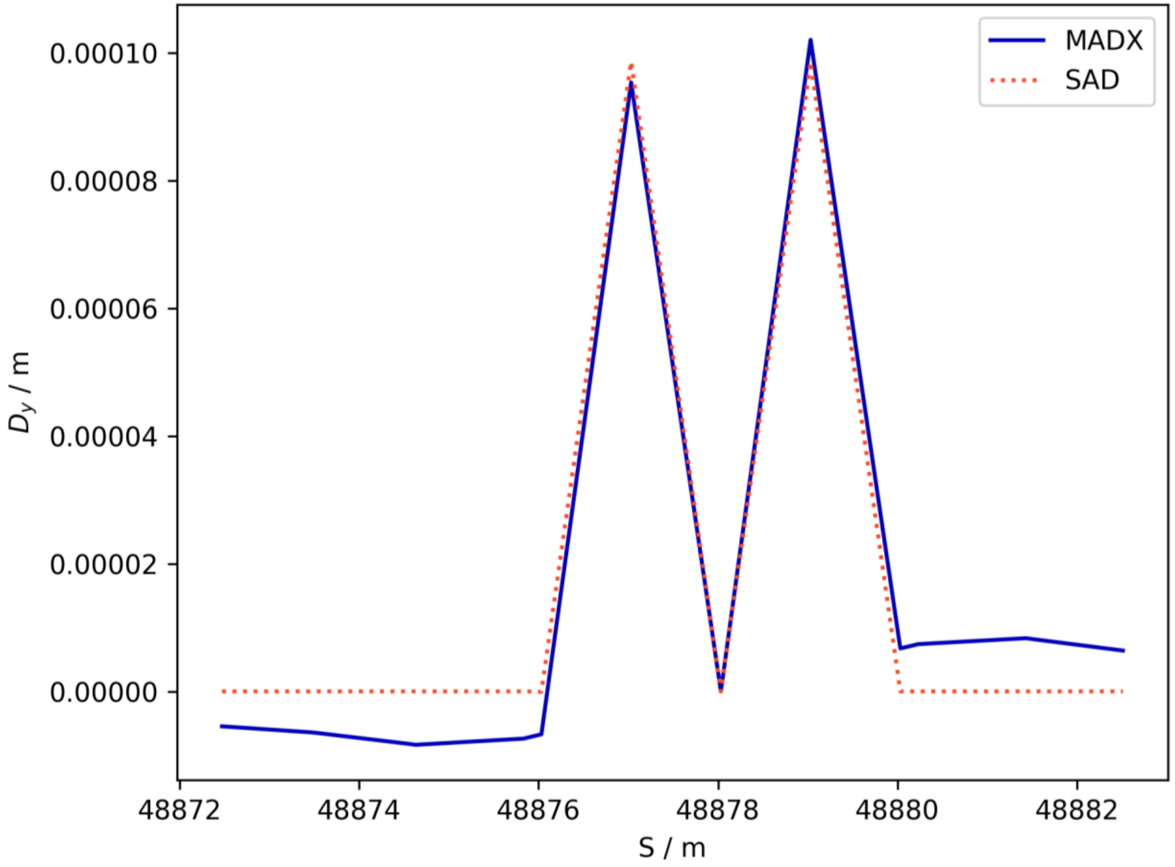
- Check whether the **vertical orbit** behaves as desired
- Zoomed in plot **around the second IP** (48878 m)
  - **2 m solenoid and two 1 m anti-solenoid** around IP
- NOTE:
  - Convention is to return to “Machine Frame” at IP
  - Hence **zero orbit at IP**
- **Very good** agreement



Vertical orbit bump due to tilted solenoid in FCC-ee

Vertical Dispersion

- Expect a **vertical dispersion** bump in solenoid
  - Caused by vertical **dipolar field** due to tilt
  - **Cancelled by anti-solenoid**
  - Important for **vertical emittance**
- Currently transformation causes unphysical dispersion in MAD-X
  - Plot obtained using a **fix provided by T. Persson**
  - **Ongoing work…**



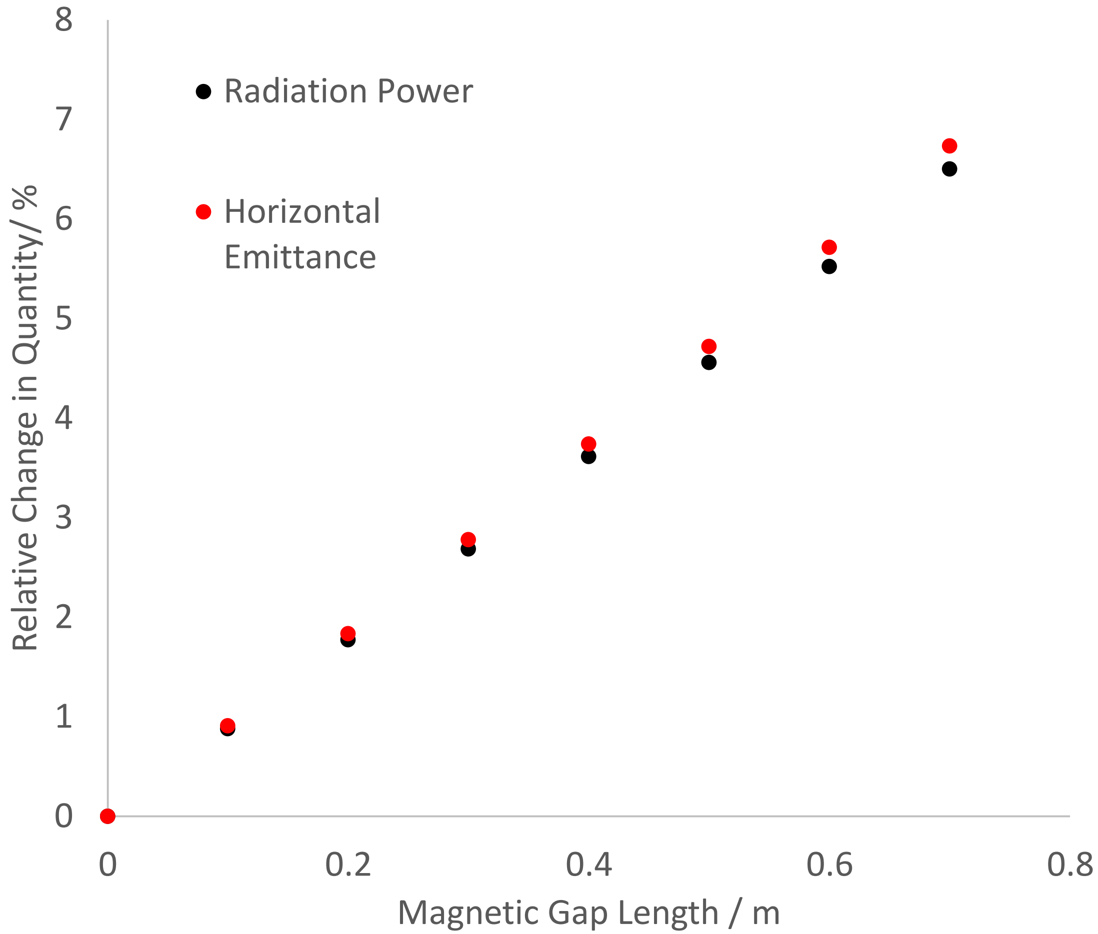
Vertical dispersion due to solenoid/anti-solenoid pair

Magnet Splitting Study

- Get a first idea of how magnetic gaps will affect machine performance
- First estimate of the impact of a more “realistic” lattice
  - Based on first estimates of hardware restrictions
    - Maximum magnet length about 10 m
    - Separation between magnets about 30 cm (about 3%)
- Implementation in SAD
  - Replace magnets that are longer than 10 m with equivalent sequences
    - Made of dipoles and drifts
    - Same overall length and angle
- Used tt 217 lattice

Preliminary Splitting Results

- Impact of dipole splitting with **10 m length** and **30 cm gaps**
  - **No significant impact** on linear optics and overall geometry
    - Geometry shifts by a **few cm** at most
    - IP **β-beating** of $\mathbf{0.01}$ % **and** $\mathbf{10^{-4}}$ % in the vertical and horizontal plane
    - Very low **dispersion beating**
  - About **3% increase** in **radiation** and **beam emittance**
- **Linear behaviour** in both **emittance** and total **radiated power** for different lengths of magnetic gaps.



Conclusions

- Continuous efforts to **benchmark MAD-X** modules against SAD
  - E.g. **emittance** in **tapered** lattices
- Efforts to simulate the **optics effects** due to **tilted solenoid**
  - **Different possibilities** to simulate solenoid
  - Promising **“SAD-like”** implementation
    - Reproduces SAD **layout** and **optics** features
    - Some limitations due to **element definitions**
  - **Complementary** to more precise simulation for MDI etc.
- First iteration of study on impact on **magnet splitting and gaps**
  - **Negligible** effect on **optics** and **layout**
  - Predictable effect on **radiation and emittance**

EPFL

Many thanks for your attention!

Questions welcome!

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