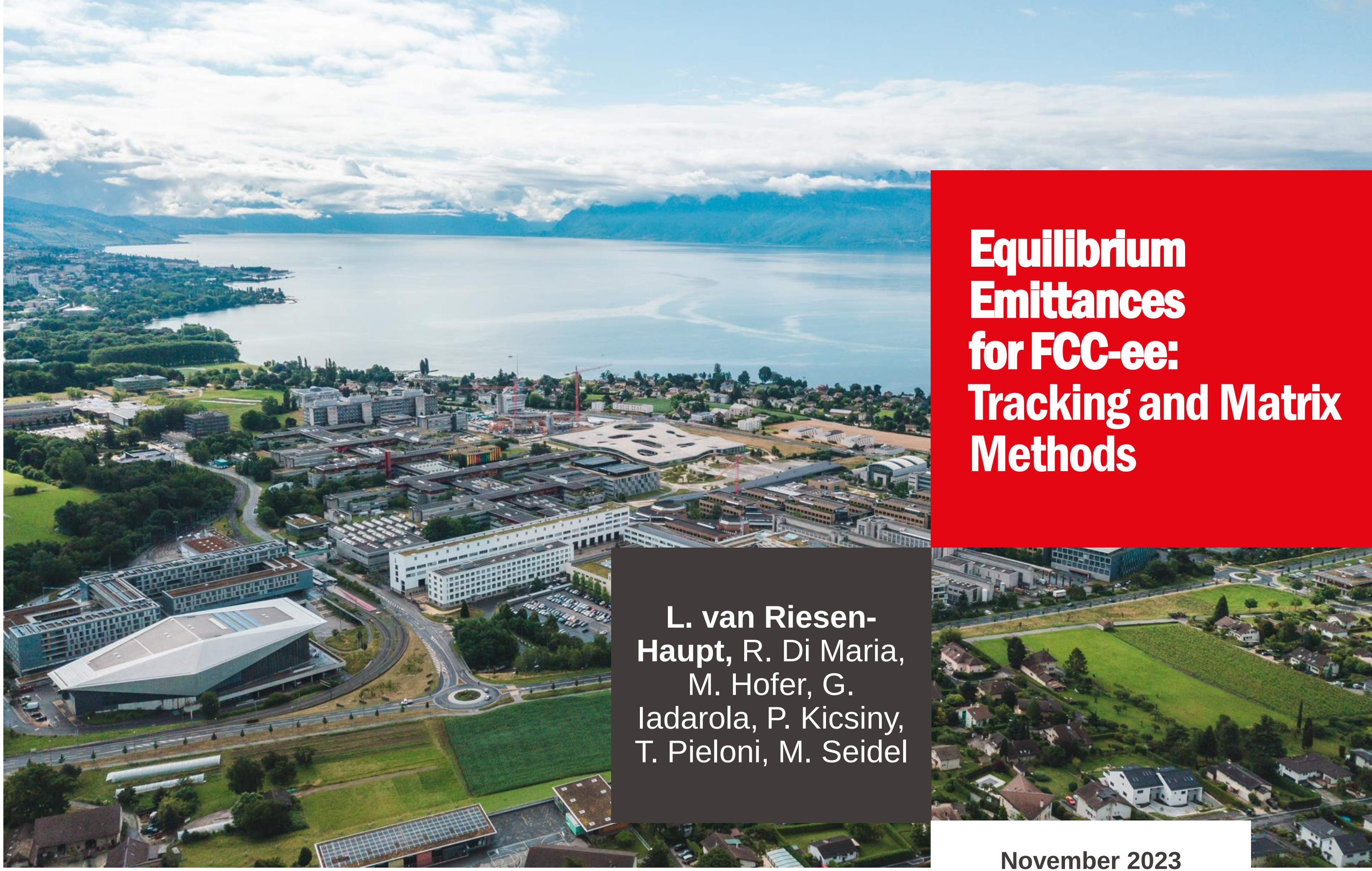

Equilibrium Emittances for FCC-ee: Tracking and Matrix Methods

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Overview

- Introduction to equilibrium emittance simulations and previous efforts
- FCC-ee software framework
- Summary of recent efforts
- Benchmarking equilibrium emittance simulations with lattice errors
- Emittance with relaxed optics

Introduction to equilibrium emittance simulations and previous efforts

Background and Motivation

- Equilibrium **emittance** in lepton machines depends on **balance** between
  - Radiation **damping**
  - Quantum **excitation**
    - Dependant on **dispersion**
- In an **flat error free** machine
  - Horizontal dispersion occurs from bending magnets → **Horizontal emittance**
  - **No vertical dispersion** and zero emittance
- **Vertical dispersion** occurs from
  - Direct **dispersion sources** – e.g. magnet errors and correctors
  - **Coupling** sources – e.g. solenoid or magnet errors
- Precise determination of vertical emittance required in simulation and measurement due to impact on luminosity

Equilibrium Emittance Simulations

Fast

Slow

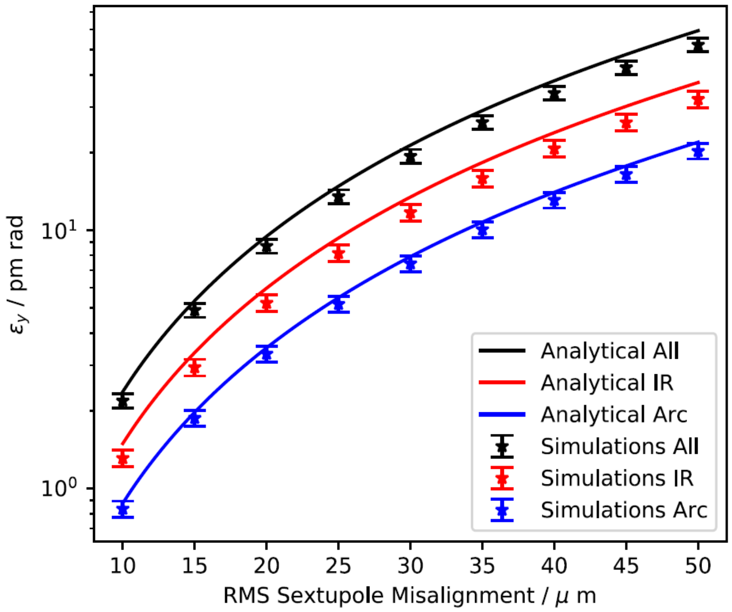
- Various **methods** to compute equilibrium emittances:
  - **Summation methods**
    - Fast approximation in error-free lattices
    - Summations of linear optics functions
    - E.g. radiation integrals
  - **Matrix methods**
    - For coupled motion with errors
    - E.g. “Envelope” method
  - **Tracking**
    - Tracking of particles with radiation damping and quantum excitations
    - Averaging beam sizes over many turns
    - Allows to include other effects such as beam-beam

First estimate

Full picture

Previous Efforts

- Benchmarking and improving MADX
  - Validation of **MADX matrix method** for error free machine
    - By **benchmarking with tracking** studies with MADX and SAD
  - **Validation** of **summation methods** in **MADX** by comparison to matrix methods
    - **Addition radiation integrals** added to MADX
- Efforts to **use summation methods** to **predict** contribution of errors on magnet groups
    - **Compared** against matrix methods



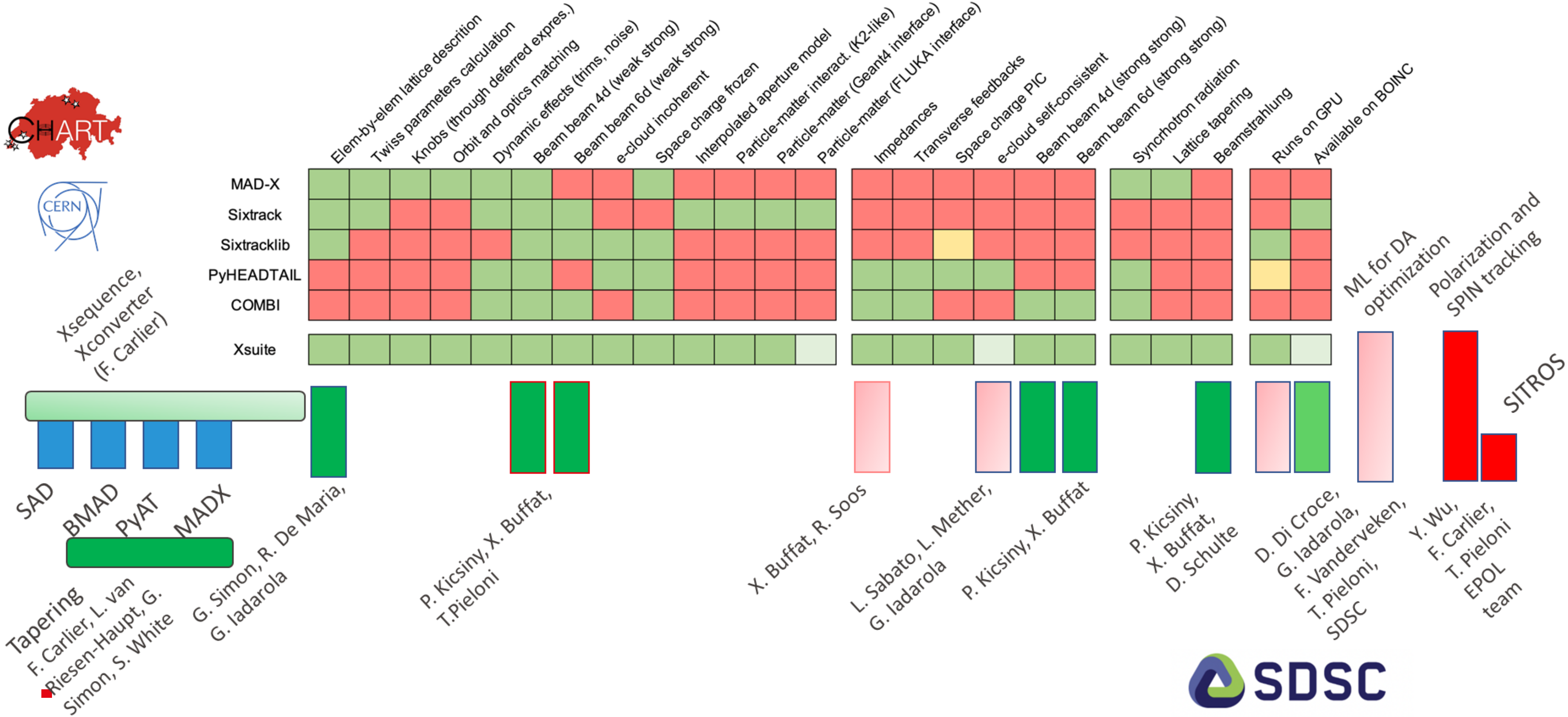
T. Charles et al., **Alignment & stability challenges for FCC-ee**

Software Framework

Software Framework and XSuite

- **Multiple codes** exist for different types of studies in the FCC-ee collaboration
  - Even multiple codes and methods for emittance calculations
    - E.g. MADX, SAD and most recently Xsuite
  - Varying degrees of **maturity** and **focus**
  - Used and maintained by **different experts** and **institutions**
- FCC-ee **software framework** aims to
  - Make **interaction** between **different effects**/simulation types possible
  - Work with the community to create **new tools for FCC-ee**
- Many efforts to develop and use **Xsuite** for FCC-ee studies
  - Aims to cover a **wide range** of simulations
  - **Python** based code built with modularity in mind
    - **Many experts** contributing to development
  - Requires **comprehensive benchmarking** studies

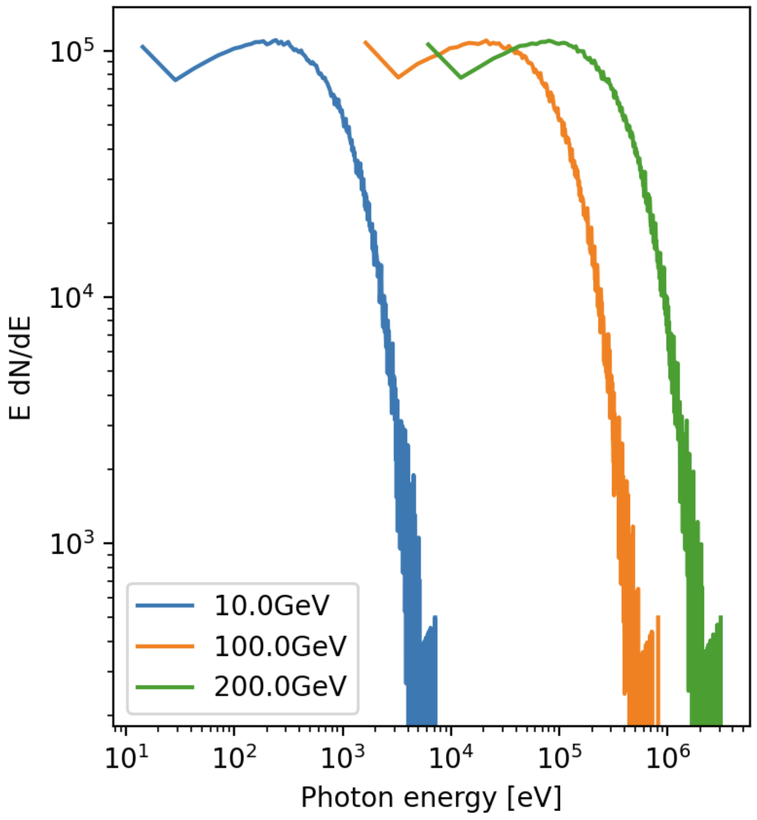
Software Framework and XSuite



Summary of recent efforts in XSuite

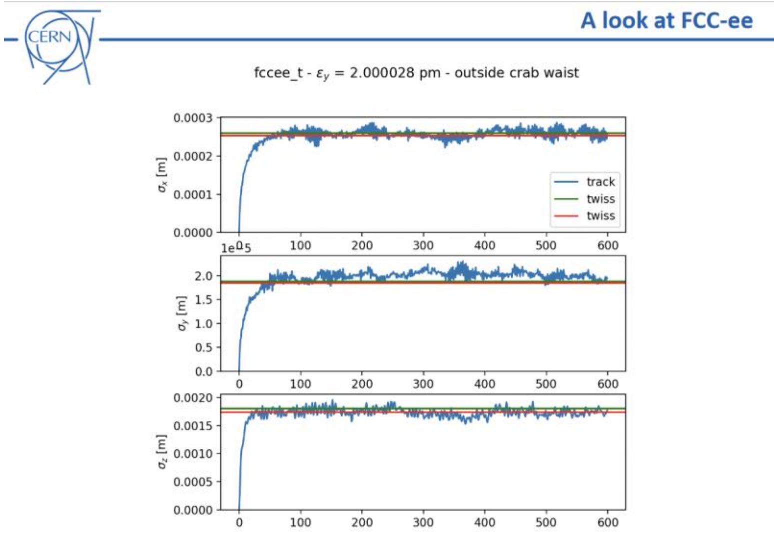
Synchrotron Radiation in XSuite

- **Tracking** feature allows for emittance from tracking
  - Requires **tapered** lattices and accurate **quantum emission**
    - **Benchmark** quantum emission spectrum to **theory**
  - Tracking results of **error-free** lattices benchmarked against **design emittance**
    - Benchmarking of more **complex lattices underway**
- **Recent** addition of **matrix methods**
  - Full **benchmarking underway**



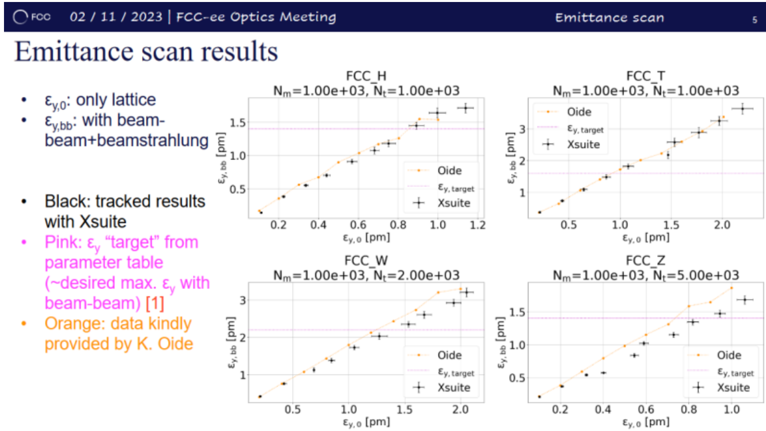
Testing Matrix Methods with Vertical Wiggler

- **Vertical wigglers** offer a simple way of introducing **vertical emittance**
  - **No coupling** between planes
  - **Dispersion bump** closes on itself
  - No alteration of **optics**
- Strong **test** case for robustness of **matrix methods**
  - Currently see **small (few %) deviation** between matrix and tracking
    - **Investigation** whether this is in line with other codes underway
  - More details in talk by G. Iadarola



Vertical Wiggler and Beam-Beam Studies

- Vertical wigglers can be used to introduce "**lattice emittance**" for **beam-beam studies**
  - Understand the effect of **beam-beam blowup**
  - Set targets for "**lattice emittance**"
- Aim to **replicate SAD** simulation by K. Oide using Xsuite
  - Details presented by **P. Kicsiny**
  - Very **good agreement**
- Initially emittance matched in **MADX** and converted
  - **Inconsistencies**, probably due to **definitions** – under investigation
- Instead, wiggler **strengths set** in Xsuite
  - Lattice **emittance** determined from **tracking without beam-beam**



Equilibrium emittance with lattice errors

Displacement Errors

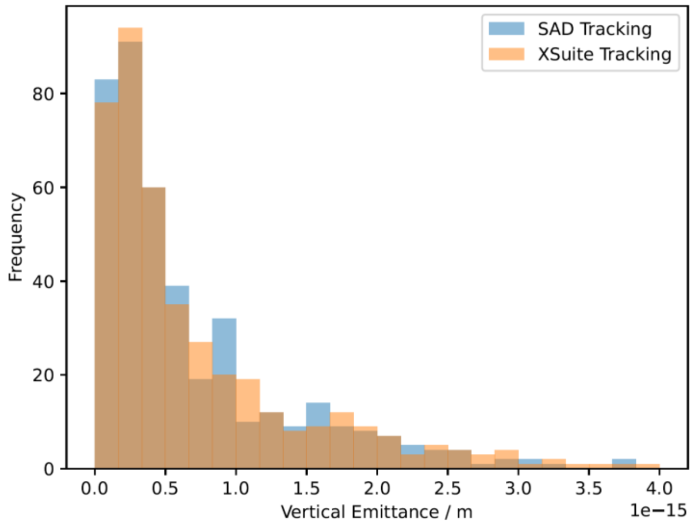
- **Vertical displacement** errors lead to vertical emittance growth
  - Vertical **dispersion** due to misaligned quadrupoles
  - X-Y **coupling** due to misaligned sextupoles
- Big step towards **realistic simulation** of machine
- Check accuracy of different codes
  - **SAD – matrix and tracking**
  - **XSuite – matrix and tracking**
  - **MADX – matrix**
- Once checked could combine with other effects such as beam-beam

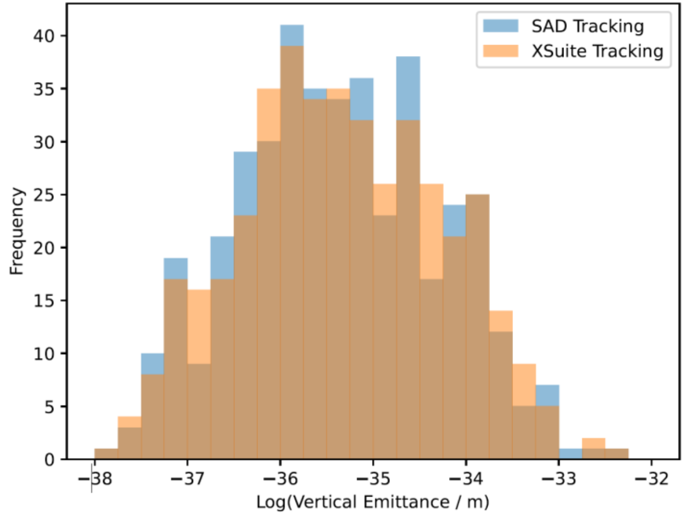
Displacement Errors – Method

- **Compute magnet errors** using python for 500 seeds using modified version of M. Hofer's fccee_xample_error_tracking repository
  - Modified to translate errors to SAD
  - Truncated Gaussian with $\sigma = 2 \times 10^{-9}$ m vertical alignment errors of quadrupoles and sextupoles
- Apply errors to **tt lattices** in all three codes
- Taper lattices using **native tapering** in all three codes
- Compute the emittance using the **matrix methods** provided by all three codes
- **Track** a test particle for 5000 turns in SAD and Xsuite
  - Compute emittance from average beam sizes over 5000 turns

Displacement Errors – Tracking

- **Extremely good agreement** in emittance distribution from 500 seeds
  - Obtained by **tracking in SAD and Xsuite**
- More natural to plot **logarithm** of emittance – normally distributed
  - $Log(\epsilon_{SAD}) = -35.36 \pm 1.07$
  - $Log(\epsilon_{XSuite}) = -35.33 \pm 1.06$
- Also extremely good agreement between emittance obtained from **individual errors** seeds
  - Small disagreement probably due to randomness of **quantum excitation**
  - Disagreement **decreases** with **increasing turns**





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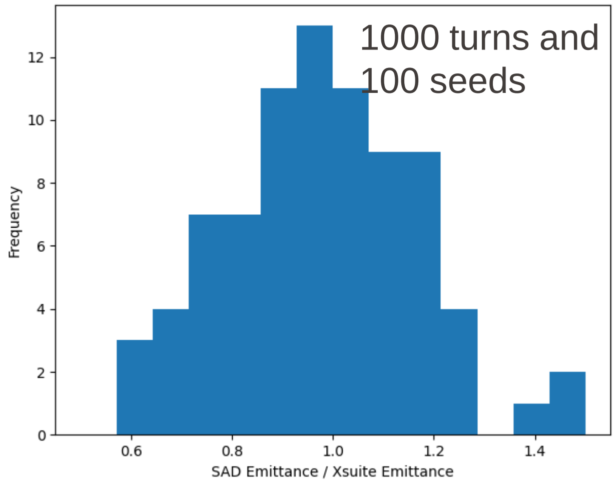
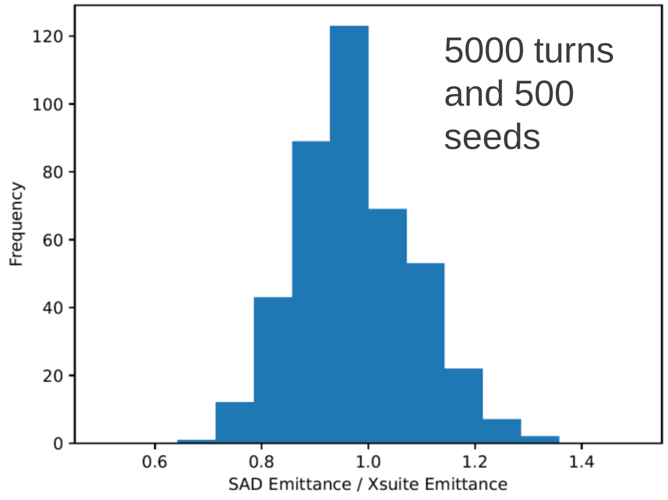
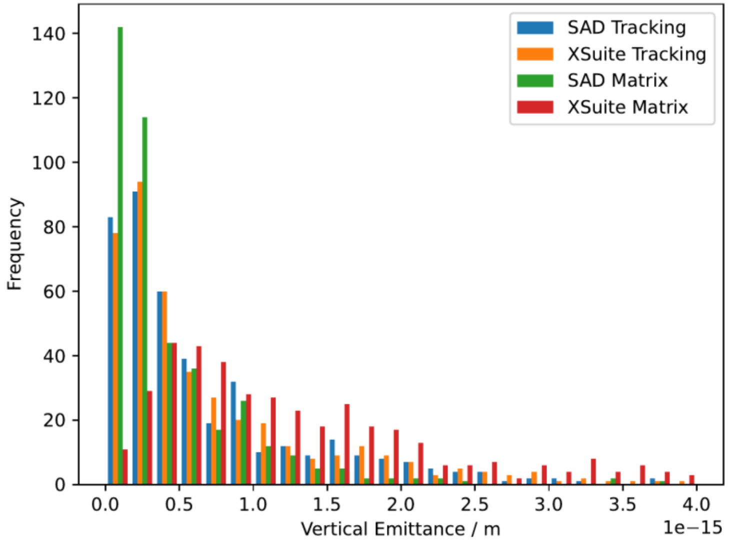


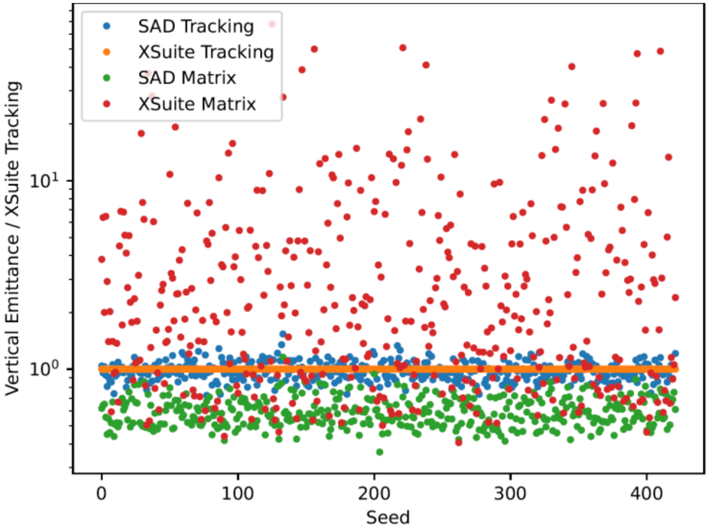


Ratio between tracked SAD and Xsuite emittance using identical errors

Displacement Errors – Matrix Methods

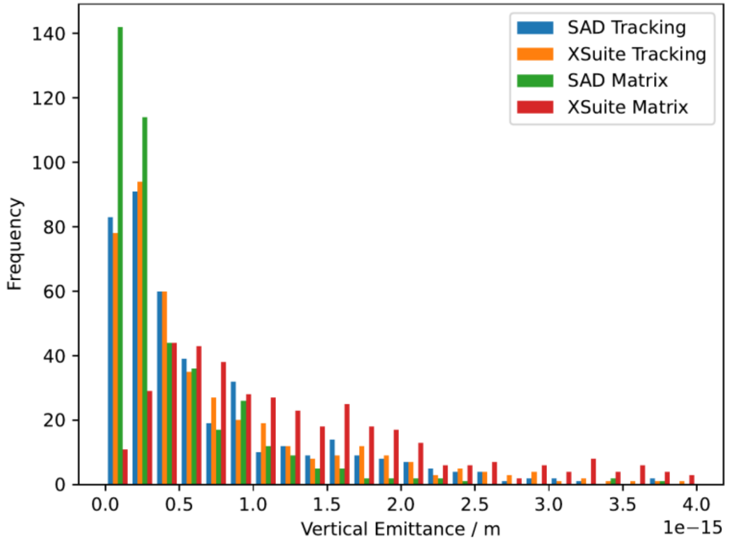
- **Matrix methods** from the **two codes** show similar distributions as tracking
  - **Not as close** as the tracking results in both codes
    - $Log(\epsilon_{SAD}) = -35.36 \pm 1.07$
    - $Log(\epsilon_{Suite}) = -35.33 \pm 1.06$
    - $Log(\epsilon_{SAD\_matrix}) = -35.86 \pm 1.00$
    - $Log(\epsilon_{Suite\_matrix}) = -34.47 \pm 0.90$
  - SAD seems to underestimate, Xsuite overestimate
- **Similar** trends seen for **individual seeds**

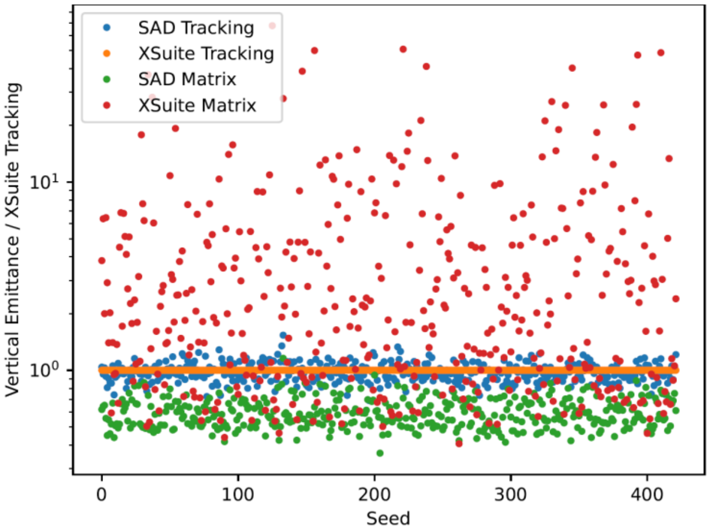




Displacement Errors – Matrix Methods

- **MADX** emit module only gave sensible numbers for **very few seeds** and the lattice **without errors**
  - This could be linked to the **tapering** implantation
  - Past studies relied on performing it at **1GeV** and **scaling** up with energy
    - Shown to be in good agreement with SAD matrix module
    - This is not practical for tracking
    - **Aim to replicate this** to check matrix methods
  - **Further exploration underway**





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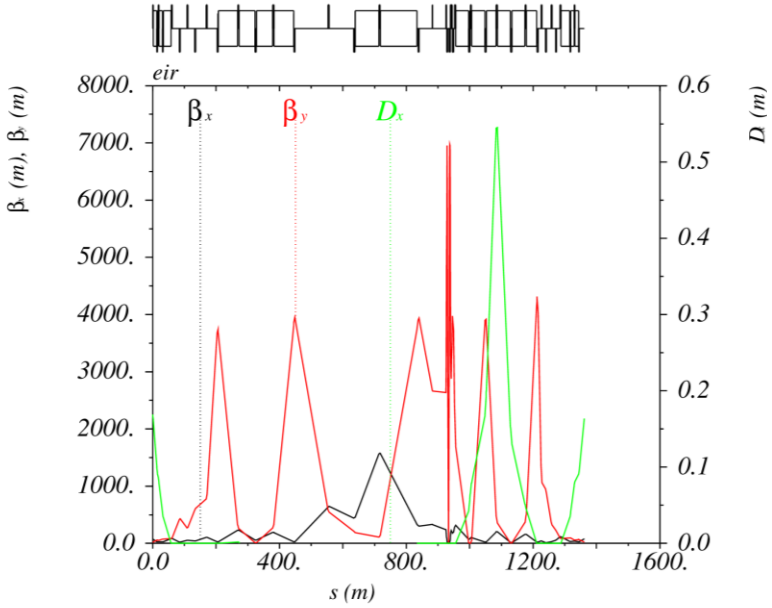
Next Steps

- **Improve** and further **benchmark XSuite**
  - **Investigate** behaviour of **newly implemented Xsuite matrix method** to determine possible improvements
  - Explore **different kinds of errors** and benchmark between tracking codes
- Use tools to **study properties** of the machine
  - Provide **reference sample cases** a starting point for other point to facilitate complimentary studies by **collaborators**
  - Launch studies that compute emittance from **beam-beam and full lattice errors**
  - Develop and build on existing tools to **correct machine** and **tune emittance** with **realistic errors**

Emittance with Relaxed Optics

Relaxed Optics

- **Relaxed optics** aim to increase β^* in order to reduce β in the rest of the IR
  - **Matching scripts** for this produced and in optics repository
  - **No rematching of sextupoles**!
- Previously shown that errors on **IR magnets** have a **disproportionately large impact** on emittance
  - **Investigation** whether relaxed optics could tune emittance
- Simulation with **100 seeds** with and without relaxed optics



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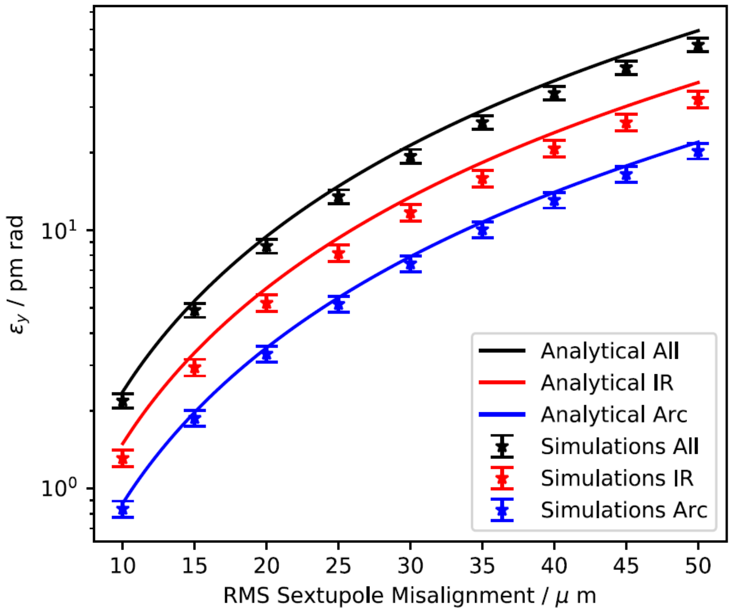
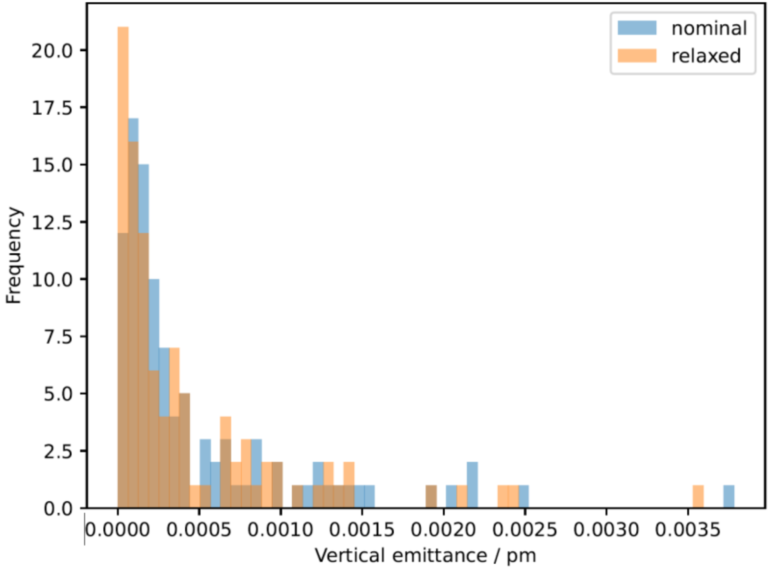


Relaxed Optics Emittance

- **Tracking** with quantum excitations **not possible** due to non-adjusted **sextupoles**
  - Even **without errors**
  - Even when **sextupoles** uniformly **scaled** to match chromaticity
- Simulations performed using **SAD and matrix methods**
- **No significant improvement** in vertical emittance
  - $Log(\epsilon_{nominal}) = -36.3 \pm 4.4$
  - $Log(\epsilon_{relaxed}) = -36.5 \pm 4.4$



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Summary

- Study of vertical emittance and tuning critical to the performance of the machine
  - Multiple methods and tools exist to determine and tune the emittance
- Three most commonly used tools tested against each other
  - Xsuite tracking in excellent agreement with established methods
    - Opens the door for broader studies in the spirit of the software framework
  - Further benchmarking to understand limitations in all codes
- First studies of emittance with relaxed optics performed
  - Further work needed to understand shortcomings
  - Other studies to be done – e.g. dynamic aperture

WORK SUPPORTED BY THE SWISS ACCELERATOR RESEARCH AND TECHNOLOGY (CHART)