Identification of Field Errors with Machine Learning Techniques

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GSI/FAIR

- GSI/FAIR hosts variety of ring accelerators
- SIS100 central accelerator of future FAIR facility
- existing SIS18 will be used as injector

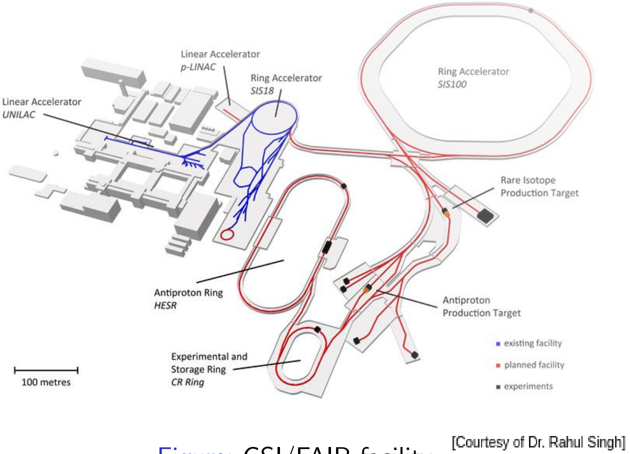
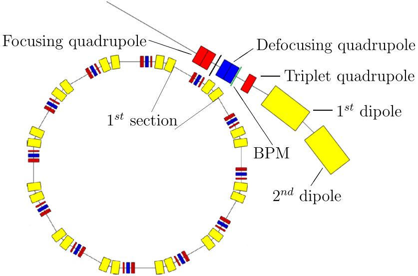


Figure: GSI/FAIR facility.

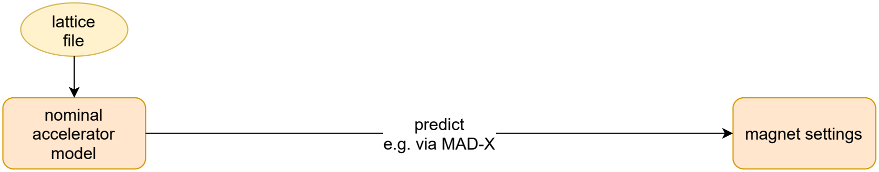
Field Errors

- unwanted multipoles
  - excite resonances
  - reduce dynamic aperture
  - cause beam loss
- mitigation and correction
  - requires type, location and strength
  - compute from accurate model
  - dedicated beam time necessary to find them

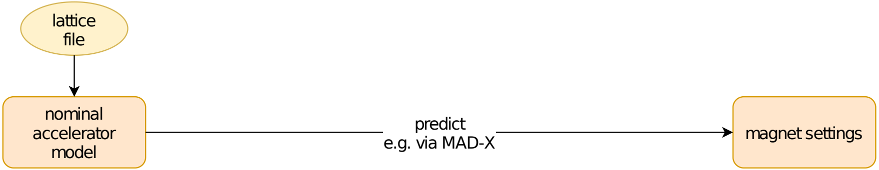
    LOCO-algorithm, non-linear tune response matrix



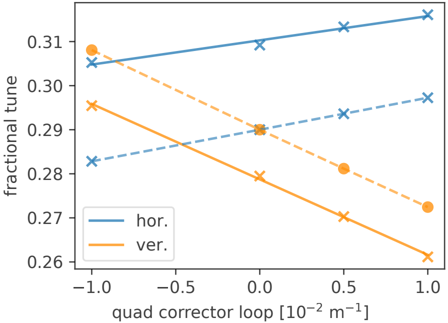
Accelerator Set Up



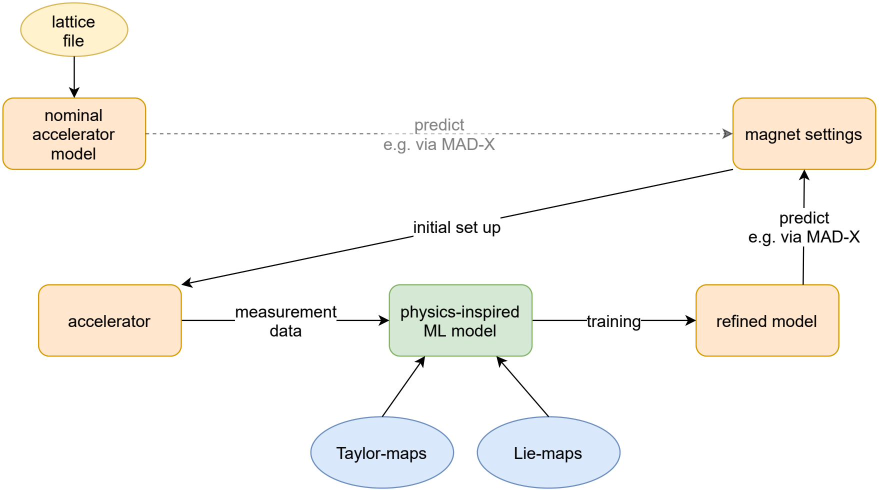
Accelerator Set Up



SIS18 measurements
-> tunes show systematic shift
-> quadrupole error present in accelerator



Accelerator Set Up

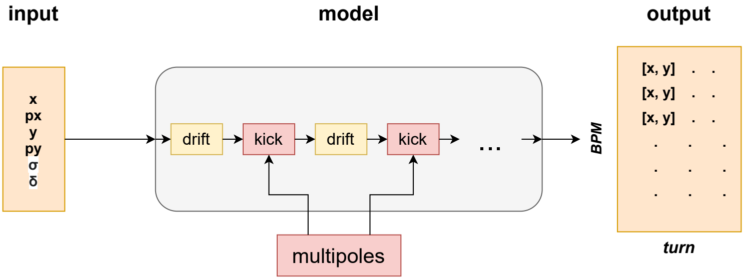


Thin-Lens Model

- treat separable Hamiltonians $H = T + V$ with Lie-algebra
- express phase-space transformations $\mathcal{M}$ via canonical integrators
  - drift-kick scheme, symplectic by design
- maps derived for all major accelerator elements [MF15]

Thin-Lens Model

- understand accelerator model as map $\mathbb{R}^6 \rightarrow \mathbb{R}^{2xKxM}$
  - map initial conditions to K BPM readings for M turns
  - non-linear multi-dimensional optimization problem like artificial neural networks
  - degrees of freedom during training: multipole strengths

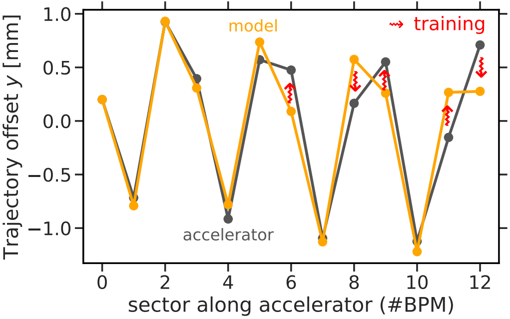


Training Procedure

- minimize discrepancy between prediction and measurement
- compare N trajectories by loss $\mathcal{L}$

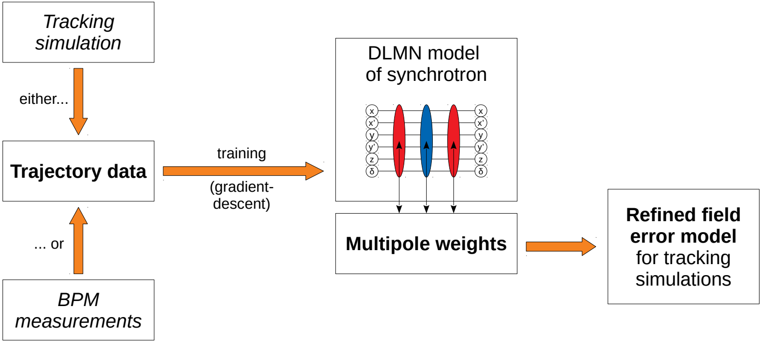
$$\mathcal{L} = \frac{1}{N} \sum_{n}^{N} \sum_{m}^{M_{\text{turns}}} \sum_{k}^{K} \left(\begin{bmatrix} x \\ y \end{bmatrix}_{\text{model}} - \begin{bmatrix} x \\ y \end{bmatrix}_{\text{accelerator}} \right)^2_{m,n,k}$$

- tracking implemented in PyTorch [PGM+19]
  - tools for automatic differentiation
  - implementation of optimization algorithms
  - access to CPUs & GPUs



Identification of Field Errors

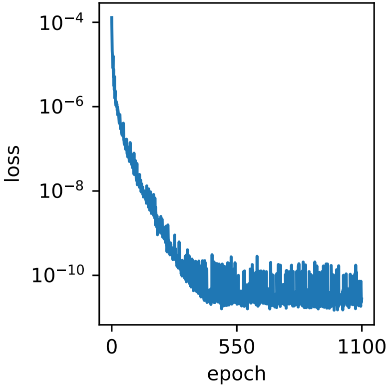
Workflow



Identification of Field Errors

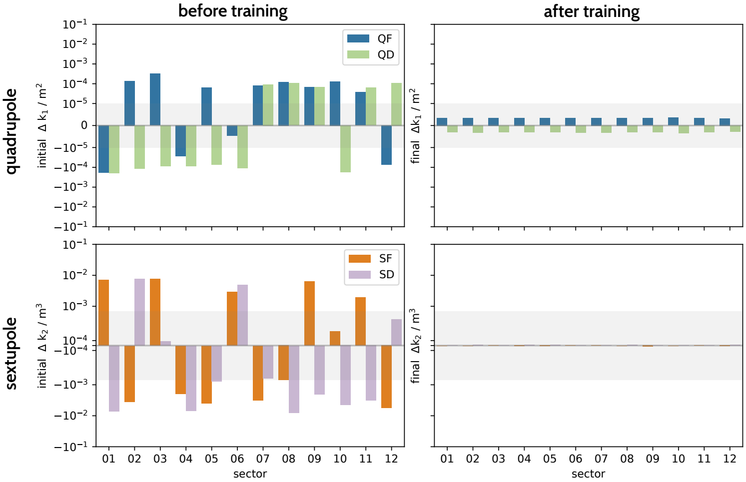
Training Procedure

- 500 simulated trajectories compared over 3 turns
- randomly group training data into mini-batches
- ADAM optimizer, hyperparameters optimized by Gaussian Process



Identification of Field Errors

Results



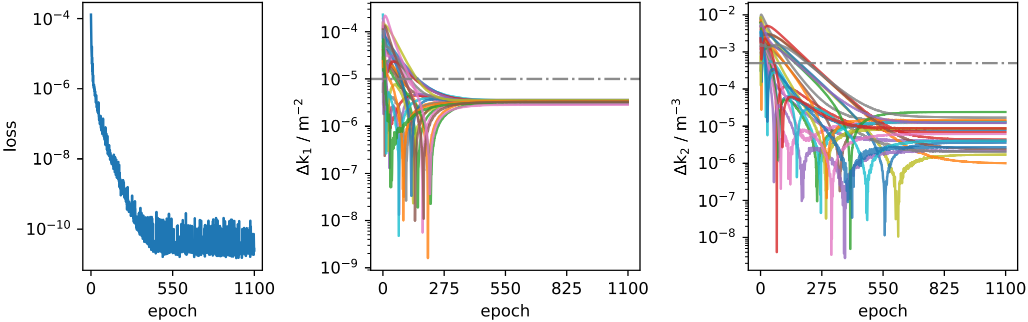
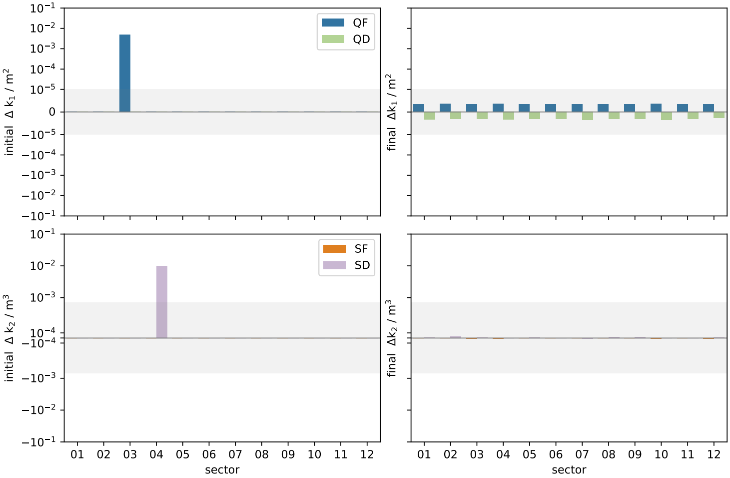


Figure: Evolution of loss (left), quadrupole (middle) and sextupole components (right) during training.

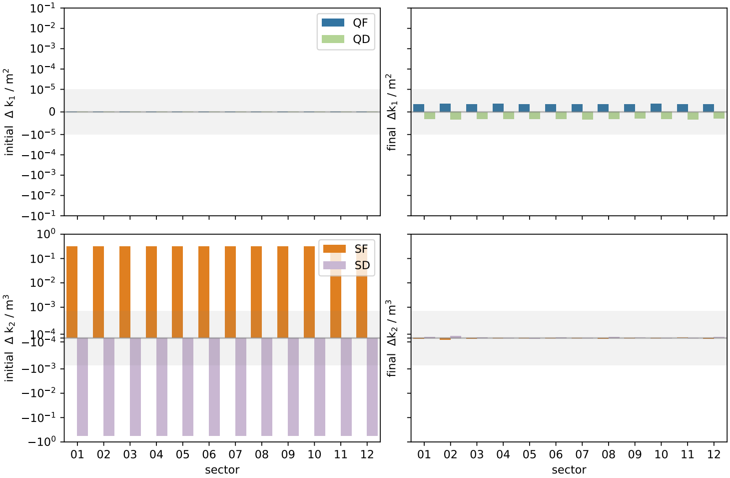
Thin-lens Model

Results



Thin-lens Model

Results

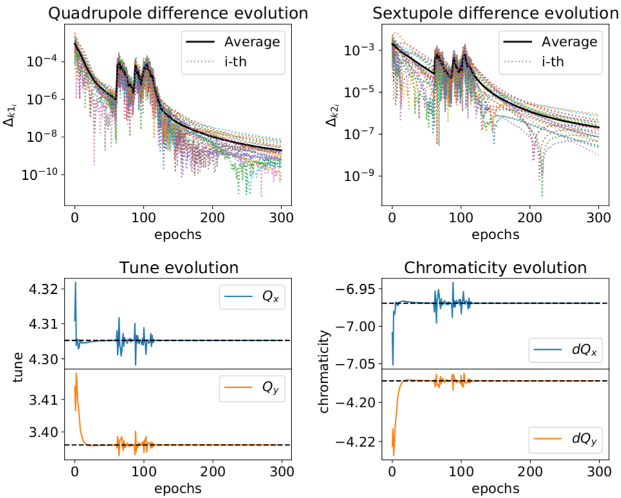


Identification of Field Errors

Results

training successfully applied to

- isolated gradient / sextupole errors
- distributed errors
- chromaticity correction scheme



[Results by Sabrina Appel]

Conclusion

approach

- model accelerator based on thin-lens approximation & Lie-algebras
- canonical integrators expressed in terms of automatic differentiation
- 6D particle tracking implemented in PyTorch ML framework

outcome

- identify isolated & distributed multipole errors
- correctly reproduce physical observables

  like beta-functions, tunes, chromaticities
- physical interpretation of model parameters as multipole strengths at any stage

Outlook

- train on SIS18 experimental data
  - study influence w.r.t. BPM measurement noise
  - compare to results obtained by Non-linear Tune Response Matrix [PF11]
  - leverage for resonance compensation
- study hyper-parameter optimization
  - speed
  - meta-learning
- investigate uniqueness of solution
- extend loss by additional quantities like phase advance

End

Thank you for your attention!

[Gra08] Paul Grannis. Particle accelerators - herding and hurrying cats, 2008.

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[PF11] A Parfenova and G Franchetti. Experimental benchmarking of nonlinear tune response matrix with several controlled sextupolar errors. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 646(1):7–11, 2011.

References II

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[Sca95] Walter Scandale. Dynamic aperture. In *AIP Conference Proceedings*, volume 326, pages 52–97. American Institute of Physics, 1995.

Physics-inspired Neural Networks

- exploit domain knowledge to construct network architecture
- replace layers by Taylor-maps $\mathcal{M}(\vec{z}) = \vec{z} + W_1\vec{z} + W_2\vec{z}^2 + \ldots$

$$\vec{z} = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}; \quad \vec{z}^2 = \begin{bmatrix} z_1^2 \\ z_1 z_2 \\ z_2^2 \end{bmatrix}; \quad \vec{z}^3 \begin{bmatrix} z_1^3 \\ z_1^2 z_2 \\ z_1 z_2^2 \\ z_2^3 \end{bmatrix}$$

- describe accelerator as concatenation $\mathcal{M}_{\text{accelerator}} = M_k \circ M_{k-1} \circ \ldots \circ M_1$

Taylor-maps

- represent transformations in 6D-phase space
- weight matrices W_k can be calculated by Truncated-Power-Series-Algebra
- or be obtained beam dynamics, e.g. affiliated from MAD-X, elegant, ...
- Quadrupole

$$\mathcal{M}_{\text{quad}} = W_1 \vec{z} = \begin{bmatrix} \cos\left(\sqrt{|k|}L\right) & \frac{\sin\left(\sqrt{|k|}L\right)}{\sqrt{|k|}} \\ \sqrt{|k|}\sin\left(\sqrt{|k|}L\right) & \cos\left(\sqrt{|k|}L\right) \end{bmatrix} \tag{1}$$

Thin-Lens Model

thin-lens approximation

- treat separable Hamiltonians $H = T + V$ with Lie-algebra
- express phase-space transformations $\mathcal{M}$ via canonical integrators

$$\mathcal{M}(\vec{z}) = e^{-L:H:} = e^{-L:T+V:} \approx \Pi_{i=0}^{n} e^{-Lc_i:T:} e^{-Ld_i:V:} + \mathcal{O}(L^{n+1})$$
$$= \Pi_{i=0}^{n}(1 + c_i L : -T :)(1 + d_i L : -V :) + \mathcal{O}(L^{n+1})$$

- symplectic by design
- maps derived for all major accelerator elements [MF15]