Identification of Field Errors with Machine Learning Techniques

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Outline

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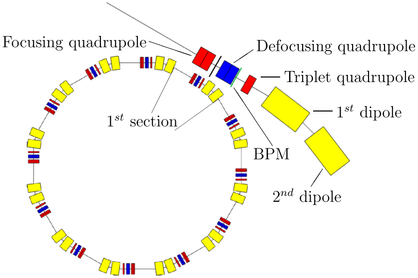
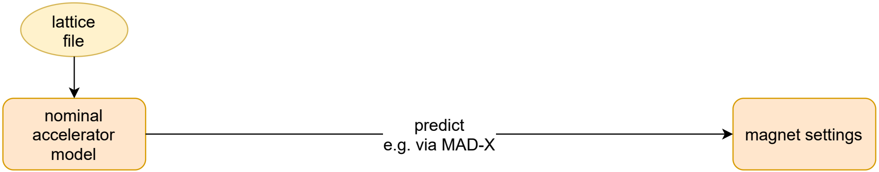
Field Errors

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

    LOCO-algorithm, non-linear tune response matrix



Accelerator Set Up



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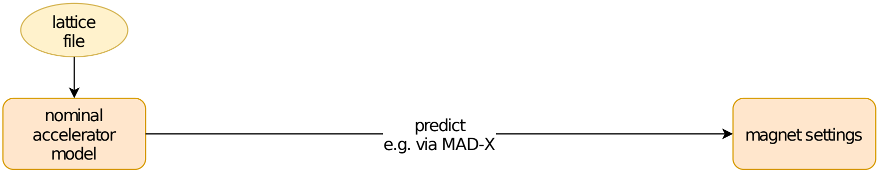
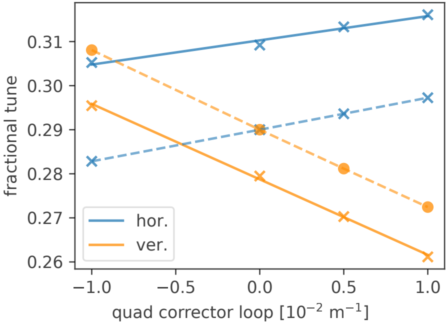


SIS18 measurements
-> tunes show systematic shift
-> quadrupole error present in accelerator



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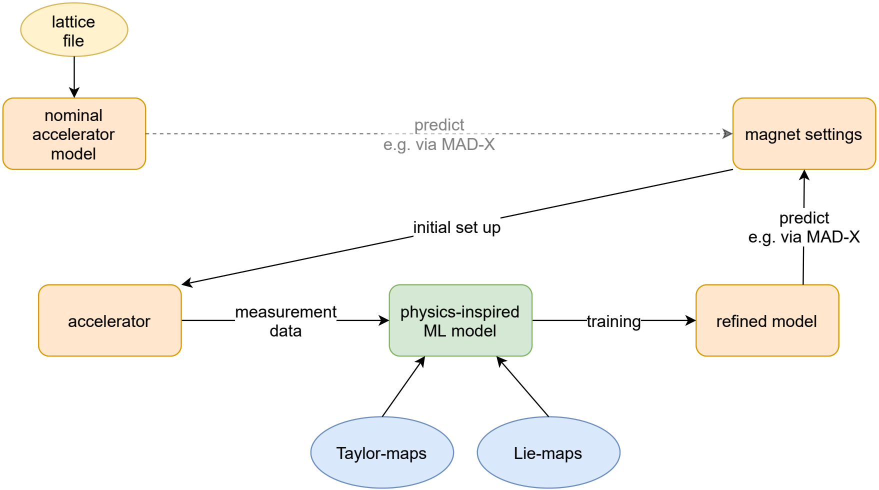


Goal: Identify Field Errors

Goal

- identify field errors from measurements
- support operation of accelerator

approach

1. compare measurements and predictions of accelerator model
2. quantify difference by loss $\mathcal{L}$
3. minimize $\mathcal{L}$ by varying multipole strengths of model

$\Rightarrow$ obtain accurate representation of accelerator
$\Rightarrow$ identify linear & non-linear field errors

Outline

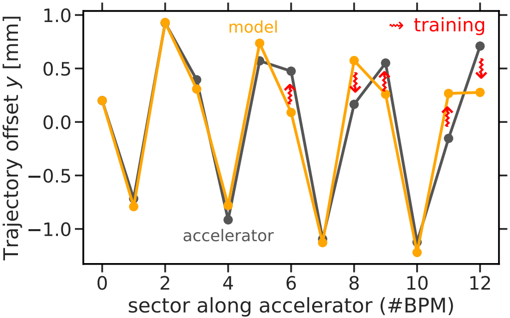
Field Errors

Identification with Machine Learning Techniques

Model Systematic Deviations

Measurement Systematic Deviations

Loss



loss $\mathcal{L}$

- quantify difference of trajectories
- measurements: observe motion of beam centroid with BPMs

$$\mathcal{L} = \sum_{N_{\text{turns}}} \sum_{N_{\text{BPM}}} \left(\frac{1}{\hat{\sigma}} \begin{bmatrix} x \\ y \end{bmatrix} \bigg|_{\text{measurement}} - \frac{1}{\hat{\sigma}} \begin{bmatrix} x \\ y \end{bmatrix} \bigg|_{\text{model}} \right)^2 \quad (1)$$

$\hat{\sigma}$ normalization factor $\propto \text{var}(x), \text{var}(y)$

Accelerator Model

self-implemented tracking code with automatic differentiation

- based on drift-kick approximation, 6D tracking
- concatenation of differentiable maps
  - enable differentiation of whole tracking model w.r.t. multipole strengths
  - compute $\frac{\partial \mathcal{L}}{\partial k_{i,j}}$ with $k_{i,j}$ i-th multipole of j-th magnet

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- single particle tracking
- features
  - exact drifts, no truncation
  - transversal magnetic fields up to arbitrary order
  - linearized dipole edges
- benchmarked against MAD-X, SixTrackLib

Analogy to Artificial Neural Networks (ANNs)

similarities to artificial neural networks

- concatenation of simple, non-linear maps
- optimization of some scalar loss over training set
- large amount of tunable parameters
- well suited for automatic differentiation
  - stochastic gradient descent

$\Rightarrow$ use gradient based algorithms designed to train ANNs

$\Rightarrow$ identify linear & non-linear field errors

Application to SIS18 in Simulations

Presentation of Problem

goal: locate order & strength of field error

- hide field errors in accelerator
  - quadrupoles
  - sextupoles
  - octupoles
- training robust against additional deviations?
  - finite integration order of magnets
  - hide multipoles in accelerator not captured by training

goal: locate order & strength of field error

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  - quadrupoles
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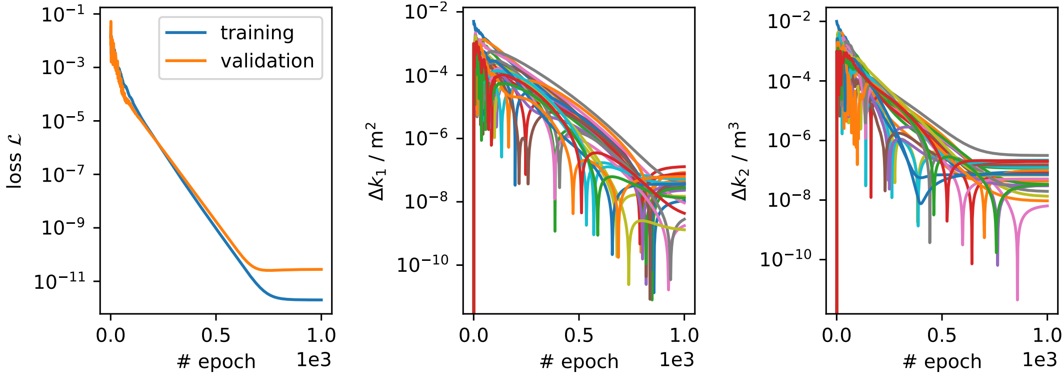
- training robust against additional deviations?
  - finite integration order of magnets
  - hide multipoles in accelerator not captured by training
- learning parameters
  - k_1, k_2, k_3
  - at two locations per cell

    $\Rightarrow$ 72 free parameters
- training data set
  - 18 trajectories for different initial conditions

Application to SIS18 in Simulations

Results

exemplary training run



$\Rightarrow$ no overfitting

$\Rightarrow$ resolution: quadrupole errors $\propto 10^{-7}\,\mathrm{m}^{-2}$, sextupoles $\propto 10^{-6}\,\mathrm{m}^{-3}$

Application to SIS18 in Simulations

Overview

- successful identification of field errors in simulations
- possible to identify
  - quadrupoles
  - sextupoles
  - octupoles

Outline

Steps Towards Application at Accelerators

steps towards training with measured data

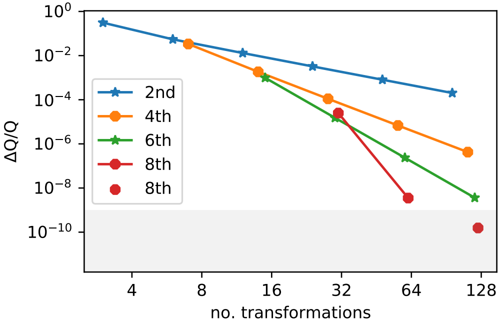
model systematic deviations

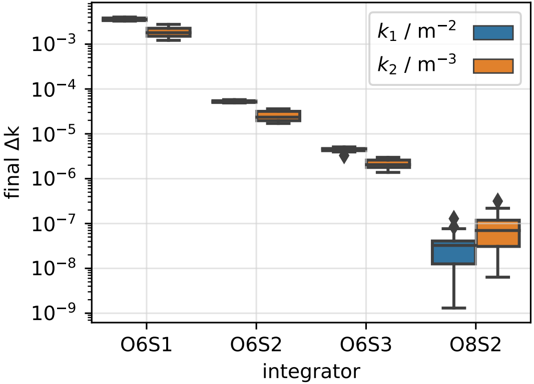
1. resolution of multipoles?
2. effect of uncaptured non-linearities?
3. influence of working point?

1) Possible Resolution of Field Errors

symplectic integrator of finite order

- tradeof between accuracy and speed

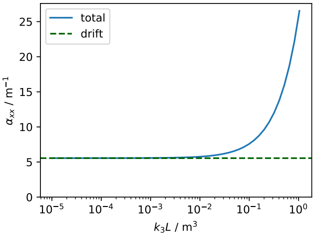


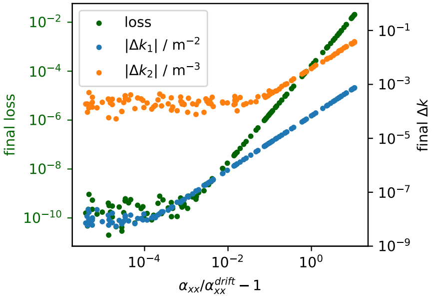


⇒ possible to resolve field errors with sufficiently fast model

2) Effect of Additional Field Errors

training possible if additional unconsidered non-linearities present?
train k_1, k_2, hide unconsidered octupole error in SIS18

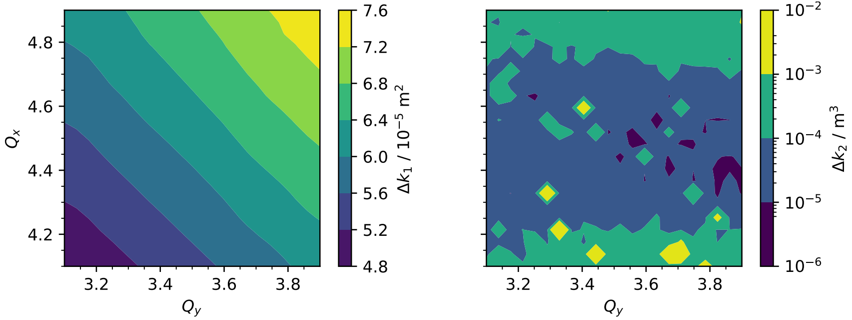




$\Rightarrow$ unconsidered octupole: resolution still feasible

(errors in SIS18: $\Delta k_1 \propto 5 \times 10^{-3}\,\mathrm{m}^{-2}$, $\Delta k_2 \propto 10^{-2}\,\mathrm{m}^{-3}$)

3) Influence Working Point on Training



⇒ no significant effect on quadrupole resolution

⇒ sextupole resolution accecptable for application to SIS18

(errors in SIS18: $\Delta k_1 \propto 5 \times 10^{-3}\,\mathrm{m}^{-2}$, $\Delta k_2 \propto 10^{-2}\,\mathrm{m}^{-3}$)

Outline

Steps Towards Application at Accelerators

steps towards training with measured data

model systematic deviations

1. resolution of multipoles?
2. effect of uncaptured non-linearities?
3. influence of working point?

measurement systematic deviations

1. how to obtain initial condition from measurements?
2. represent centroid motion by single particle motion?
3. training possible with finite BPM resolution?

model does particle tracking $\Rightarrow$ require initial condition

get x, y from BPMs, how to get p_x, p_y?

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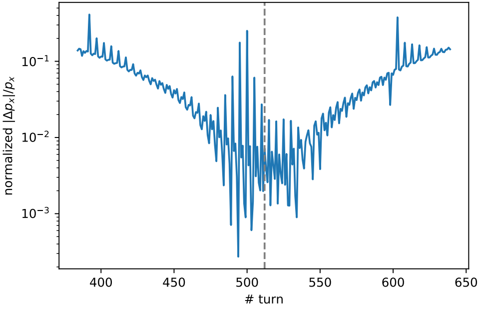
get x, y from BPMs, how to get p_x, p_y?

Hilbert transform

- applies $\pm\frac{\pi}{2}$ phase shift to signals
- use to obtain transversal momenta in normalized phase space coordinates
- requires precise knowledge of twiss parameters



1) Recovery of Initial Condition

Leverage Kickers

model does particle tracking $\Rightarrow$ require initial condition
get x, y from BPMs, how to get p_x, p_y?

Hilbert transform

- applies $\pm\frac{\pi}{2}$ phase shift to signals
- use to obtain transversal momenta in normalized phase space coordinates
- requires precise knowledge of twiss parameters

alternative: kick beam

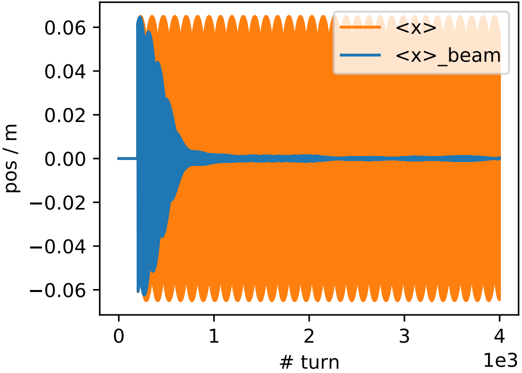
- beam at rest
  $[x, p_x, y, p_y] = [0, 0, 0, 0]$
- kick beam $\rightarrow$ set momenta
- requires precise knowledge of kicker field

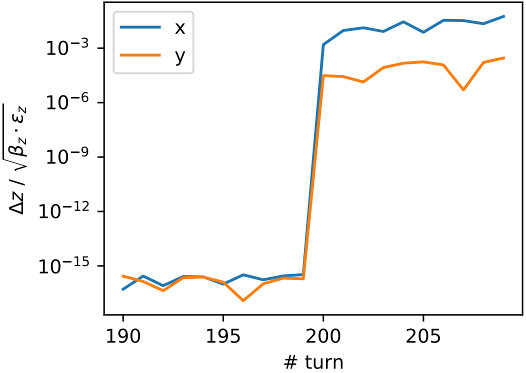
2) Effect of Decoherence on Training

How good can single-particle motion represent bunch motion?

- decoherence: particles oscillate with different tunes $\nu \Rightarrow$ beam debunches
  - effect on training resolution?
- two mechanisms
  - amplitude detuning: $\nu_z \to \nu_z(J_z)$
    detuning $\propto \epsilon_x$, ϵ_y
  - chromatic detuning: $\nu_z \to \nu_z(\delta)$
    detuning $\propto \sigma_E$

How good can single-particle motion represent bunch motion?





difference in bunch motion and single particle motion after kick

2) Effect of Decoherence on Training

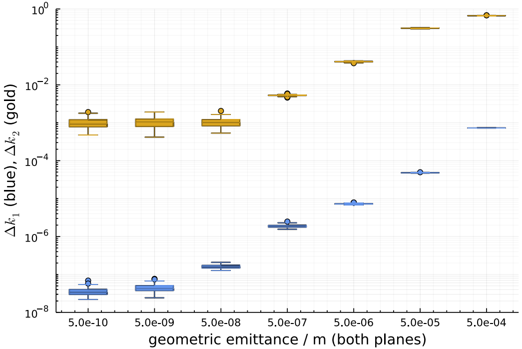


Figure: Resolution vs. geometric emittance.

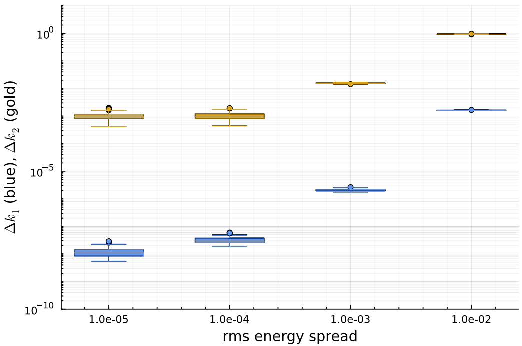


Figure: Resolution vs. rms energy spread.

amplitude detuning

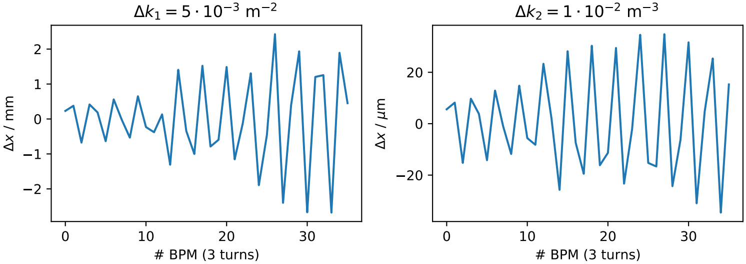
chromatic detuning

(errors in SIS18: $\Delta k_1 \propto 5 \times 10^{-3}\,\mathrm{m}^{-2}$, $\Delta k_2 \propto 10^{-2}\,\mathrm{m}^{-3}$)

3) Resolve Influence of Multipoles with BPMs

How much does centroid motion change over 3 turns?

kick beam and track centroid with / without field error



resolution of BPMs $\sim$10 µm

$\Rightarrow$ resolve influence of gradient errors

$\Rightarrow$ effect of sextupole errors close to BPM resolution

Conclusion

successful identification of field errors in simulations

- quadrupole, sextupole, octupole
- robust against
  - uncaptured non-linearities
  - chosen working point
  - finite integration order of magnets
- convergence affirmed by multitude of simulations
- no overfitting

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training on real measurement data

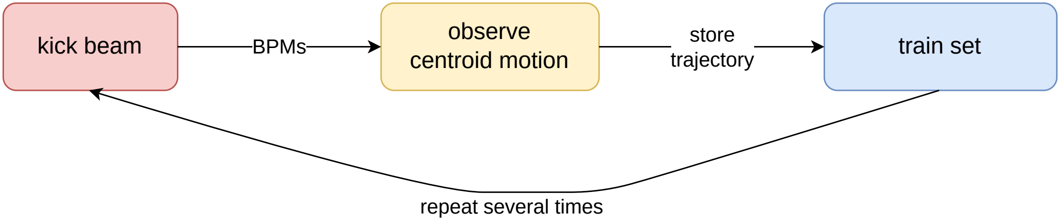
- control initial conditions by kickers
- require 18 shots of synchrotron to create training data set
- representation of bunch centroid by single particle
  - resolution of multipoles affected
- finite resolution of BPMs
  - identify gradient errors in SIS18
  - sextupole errors close to resolution limit

End

Thank you for your attention!

References I

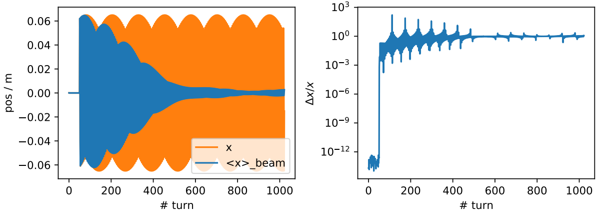
Training Set



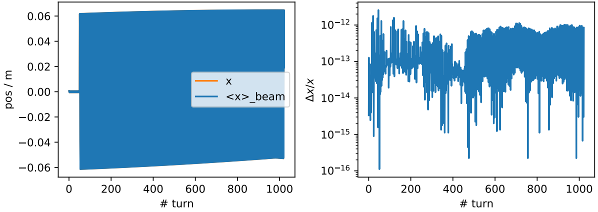
- ground truth to be fitted by model
- kick beam horizontally & vertically
- typical size of train set: 18 trajectories

Detuning in presence of Exact Drifts

- study detuning caused by exact drifts
- compare motion of beam centroid to centroid particle
- beam parameters
  - geo. emittance $\epsilon_x = \epsilon_y =$34 µm
  - monoenergetic beam, $\sigma_E = 0$



(a) Linear lattice with **exact** drifts.



(b) Linear lattice with **linear** drifts.