Identification of Magnetic Field Errors using Deep Lie Map Networks

TECHNISCHE UNIVERSITÄT DARMSTADT

Overview

Magnetic Field Errors

Deep Lie Map Networks

Experiment in 2022

Proof of Principle Experiment

Conclusion

Magnetic Field Errors

Magnetic Field Errors

- detrimental to machine performance
  - excite resonances
  - reduce dynamic aperture
  - cause beam loss
- many origins
  - magnet fabrication errors
  - misalignments
  - power supply failures

power corrector magnets for compensation

Require location and magnitude of linear & non-linear field errors!

Established Field Error Identification Procedures

Linear **O**ptics from **C**losed **O**rbits (**LOCO**) [1]

- linear machine model from orbit response
- fit model to measured orbit response
- find dipole & quadrupole errors
- widely employed since 1996
- non-linear field errors not covered

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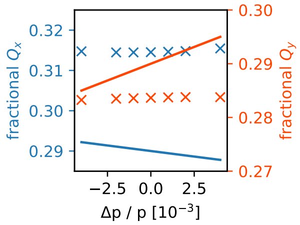
non-linear optics estimation

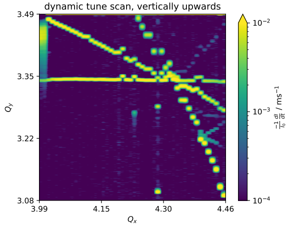
- different approaches demonstrated
  - resonance-driving terms [2]
  - non-linear tune response matrix (NTRM) [3]
- time demanding measurements
- require structured measurement data (e.g. bumps around machine)
- require accurate linear machine model in advance

SIS18 @ GSI

- 216 m long synchrotron, accelerate heavy ions from protons to uranium
- injector of the future FAIR facility / SIS100 synchrotron
- nominal optics model
  - tunes shifted $\Delta Q_{x,y} = 1 \times 10^{-2}$
  - discrepancies in chromaticity $\Delta\xi_x = 0.13$, $\Delta\xi_y = 0.38$
- 3rd order resonances present



solid line: prediction (machine model),
crosses: measurements



Dynamic tunescan in SIS18, vertically upwards.

Motivation

- improved & accurate optics description

  $\Longrightarrow$ step towards digital twin
- efficient on beamtime
- independent from existing linear optics model

Propose: **D**eep **L**ie-**M**ap **N**etworks (**DLMN**) [4]

- identify sextupole errors from trajectory data
- machine-learning based approach

Deep Lie Map Networks

Deep Lie-Map Networks - Identification of Magnetic Field Errors

PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 064601 (2023)

Identification of magnetic field errors in synchrotrons based on deep Lie map networks

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Magnetic field errors pose a limitation in the performance of synchrotrons, as they excite nonsystematic resonances, reduce dynamic aperture, and may result in beam loss. Their effect can be compensated by assuming knowledge of their location and strength. Established identification procedures are based on orbit response matrices or resonance driving terms. While they sequentially build a field error model for

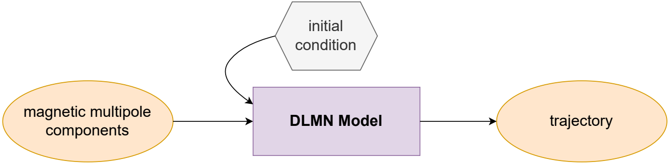
Deep Lie-Map Networks - Identification of Magnetic Field Errors

Deep Lie-Map Networks (DLMN) is a newly developed differentiable tracking code

- differentiability
  - fit simulation model to measurement data
- analogy to deep neural networks
  - use gradient-based optimization algorithms from AI community to *train* accelerator model
- improved accelerator model
  - use for high-fidelity simulation studies
  - support operations, e.g. resonance compensation

Deep Lie-Map Networks - Training Procedure

- fit measured trajectory recorded by BPMs
- vary magnetic multipole components



limiting factors

- observed trajectory subject to BPM noise
- prediction requires initial condition
  $\rightarrow$ precise knowledge of kick required!

Implementation

drift-kick tracking approach

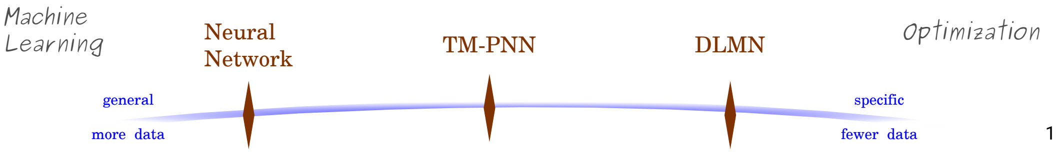
- symbolic differentiation of drifts / kicks w.r.t. phasespace coordinates / magnetic multipole components

reverse mode automatic differentiation

- in contrast to symbolic differentiation
  - removes need to differentiate tracking code as a single expression
- in contrast to finite differences
  - efficient if dim(out) « dim(in)
  - machine precision, no round-off errors
- high-memory usage

- Julia/FluxML implementation 10x faster than Python/PyTorch

Comparison to other Machine Learning Approaches



- sparse data from beam diagnostics
  - ***x*** / ***y*** centroid position once per sector
- no. degrees of freedom » observables
  $\Rightarrow$ ML models prone to overfitting

DLMN

- resembles drift-kick tracking code
  - incorporate nominal optics model
- few degrees of freedom
  - $\equiv$ magnetic multipole components

[1] TM-PNN: [5]

Initial Condition

Excite beam centroid oscillations by fast kicker magnet

- deflect beam in equilibrium state

$$\Delta p_{x,y} = \frac{\int_s B_k ds}{B\rho} \tag{1}$$

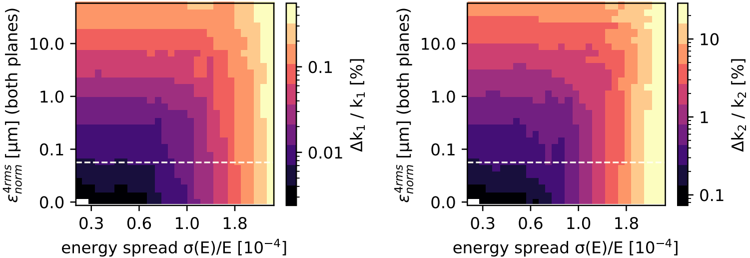
- mismatch rf-frequency w.r.t. ring circumference
  $\hookrightarrow$ effective momentum mismatch δ

initial condition for tracking with DLMN

$$\vec{z}_0 = [D_x\delta, \Delta p_x, D_y\delta, \Delta p_y, 0, \delta]$$

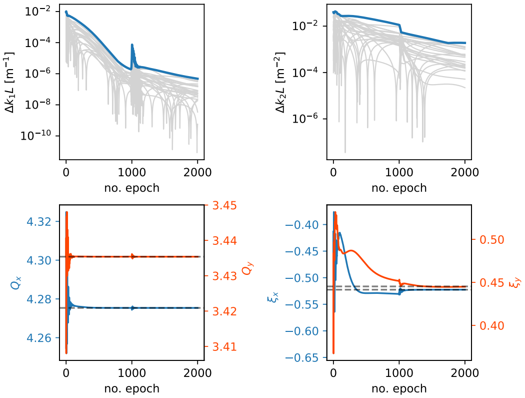
Chromatic & Amplitude Detuning

- motion of beam centroid differs from single particle motion
- detuning limits resolution magnetic field errors
  - beam emittance → amplitude detuning
  - momentum spread → chromatic detuning
- proton beam most suited due to small beam size & momentum spread



Simulated Training Results

Normal distributed quadrupole & sextupole errors



- quadrupole and sextupole strengths converge against those in simulated accelerator
- correct prediction of tunes & chromaticities

Experiment in 2022

Experiment in 2022

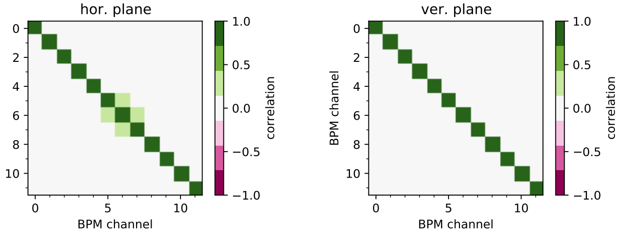
First test of DLMN method to resolve field errors in SIS18

- utilized beam Pb^{65+}
  - disadvantageous due to large beam size
- limited amount of data taken
  - UNILAC failure, BPM failure, QKicker failure
  - only recorded a dozen trajectories
- measurement data taken for
  - corrected chromaticity

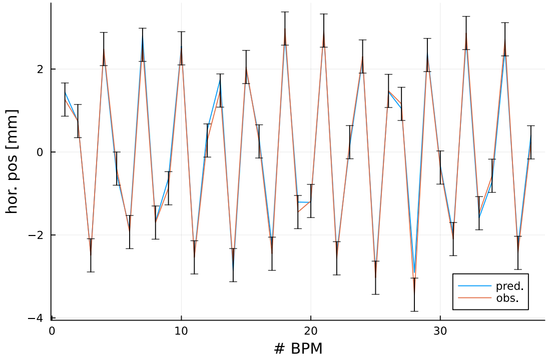
BPM Noise Analysis

Beam-position monitor noise

- normal distributed white noise
- standard deviation
  - horizontal plane $\sigma_x = 170\,\mu m$, $\sigma_y = 80\,\mu m$
- correlation between some BPMs
  ↪ analysis ongoing



DLMN Fit of Measured Trajectory



mean absolute error

$$M = \frac{1}{N} \sum_{i}^{N} |\Delta x_i| + |\Delta y_i|$$

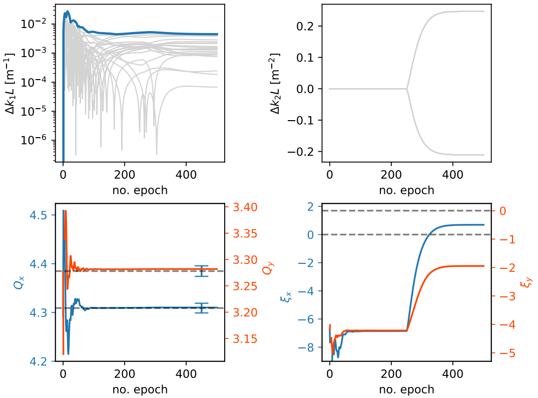
- expectation due to BPM noise

$$\mathrm{E}[M] = 210\,\mu\mathrm{m}$$

- after training

$$M_{\mathrm{fit}} = 204\,\mu\mathrm{m}$$

Training Results on Measurement Data: Systematic Sextupole Degrees of Freedom



model at natural chromaticity trained on SIS18 with corrected chromaticity $\xi_{x,y} = 0$

- good reproduction of tunes
- chromaticities corrected towards corrected chromaticity
- families of focusing / defocusing sextupoles assigned correctly
- trainig data consists of four measured trajectories only

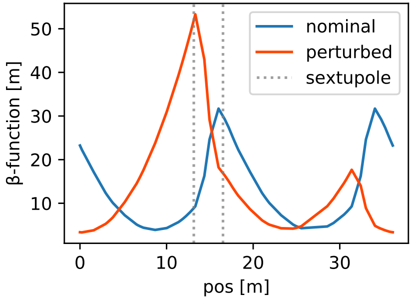
Proof of Principle Experiment

Proof of Principle Experiment

Goal

Compensate 3rd-order resonance using DLMN

- drive resonance by two lattice sextupoles
  - artificial non-linear field error
- perturb β-functions
  - need to adapt linear optics model in parallel
- use DLMN to calculate corrector strengths



Lessons learned from 2022 Experiment

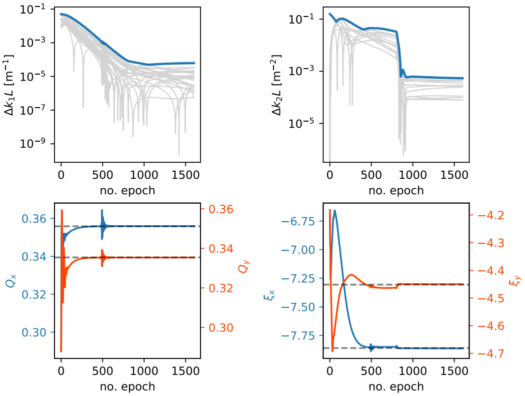
- automated data collection
  - reduce measurement uncertainty on trajectories by enhanced statistics
  - aim to decrease by one order of magnitude standard error

$$\hat{\sigma}_{\bar{x}} = \frac{\sigma_x}{\sqrt{n}}$$

- proton beam available
  - reduced momentum spread
  - smallest emittances available @SIS18

$\Longrightarrow$ reduced chromatic & amplitude detuning

Simulated Results



- quadrupole and sextupole strengths converge against those in simulated accelerator
- correct prediction of tunes & chromaticities
- β-functions reproduced

Conclusion

Conclusion

- DLMN is a new approach to identify magnetic field errors
- identify linear & non-linear errors in parallel
- accurate optics model $\Rightarrow$ step towards digital twin
- first application to measurement data very promising

Outlook

Experimental demonstration of the DLMN method
planned for proton run this winter

- enhanced data collection & statistics
  $\Rightarrow$ improved resolution of field errors
  $\rightarrow$ cross-check to alternative approaches
- proton run
  $\Rightarrow$ beam properties more suited for DLMN proof-of-principle
- python bridge to control system
  - more efficient use of beamtime
  - more extensive data-logging

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End

Thank you for your attention!