Building Accurate Accelerator Models from Physics and Beam-based Measurements

HEP GARD ABP Workshop 2 – WG1

Xiaobiao Huang

4/15/2020

SLAC National Accelerator Laboratory

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

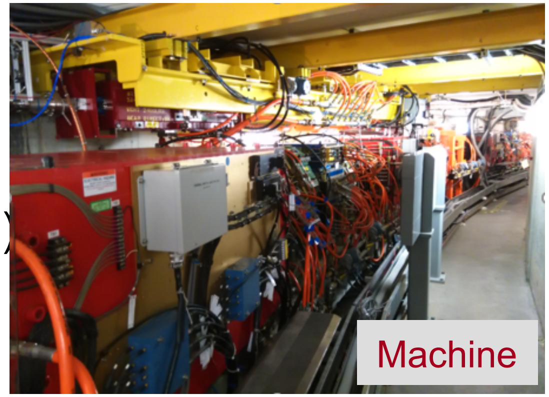
The proposed R&D

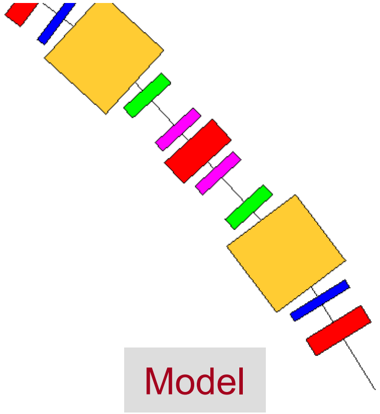
SLAC

- Develop methods to build accelerator models that accurately predict the behavior of the machine and use them for accelerator commissioning and control, design, simulation, and science data analysis.
- Approaches
  - Bottom-up: improving accuracy of modeling of individual elements from physics principles
  - Model calibration with beam-based measurements
    - Effectively extract information from data and use it to adjust the model.
  - Analysis of large operation data sets with advanced machine learning (ML) techniques.

The needs for accurate accelerator models

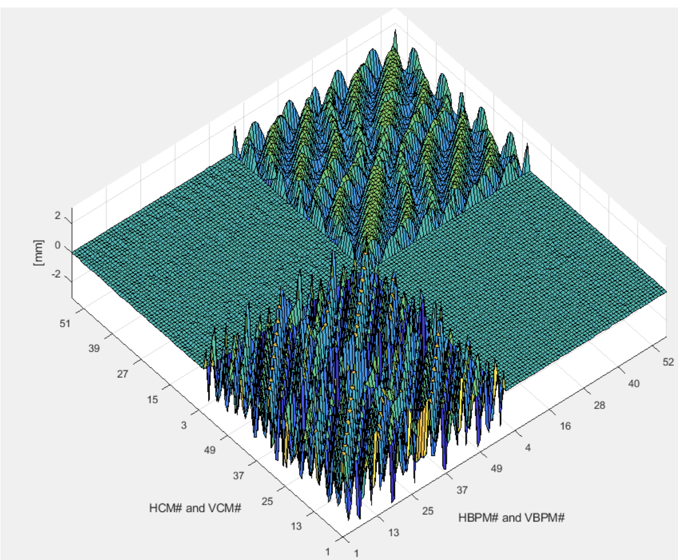
- All accelerators are built with physics/simulation-based design models.
  - Design models are essential, but they can't predict the behaviors of actual machines to the desired accuracy
  - Inaccuracy limits the usefulness of the models
- There are numerous error sources that cause the machine to deviate from the model
  - Omitted effects in the model (e.g., fringe fields, …)
  - Manufactural tolerance
  - Measurement/regulation errors
  - Misalignments
  - Hysteresis
  - Human errors
  - Malfunctions
  - Environmental factors (e.g.,ground motion)
- Calibration is key



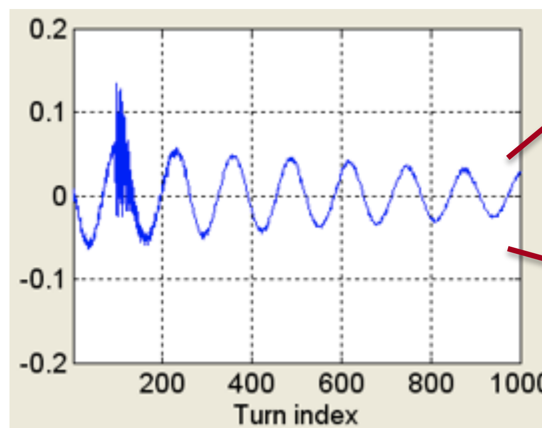


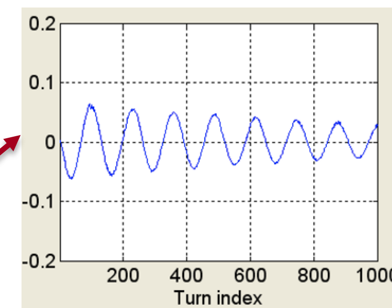
State-of-the-art in model calibration techniques - linear

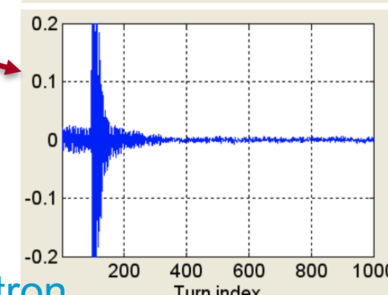
- Linear optics and coupling
  - LOCO (orbit response matrix)
  - Methods using turn-by-turn BPM data (MIA, ICA, SBST, RDT, direct fitting, etc)
  - All using least-square fitting technique to uncover errors
  - Prone to overfitting



Orbit response matrix contain optics and coupling information







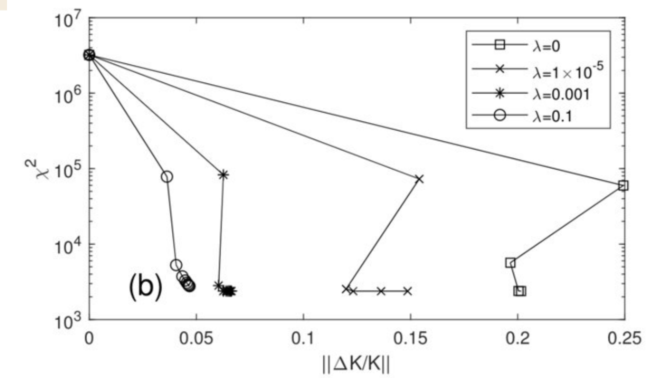
Separating synchrotron and betatron motion in turn-by-turn BPM data w/ ICA.

Linear optics correction – cont'd

- Constrained fitting is critical

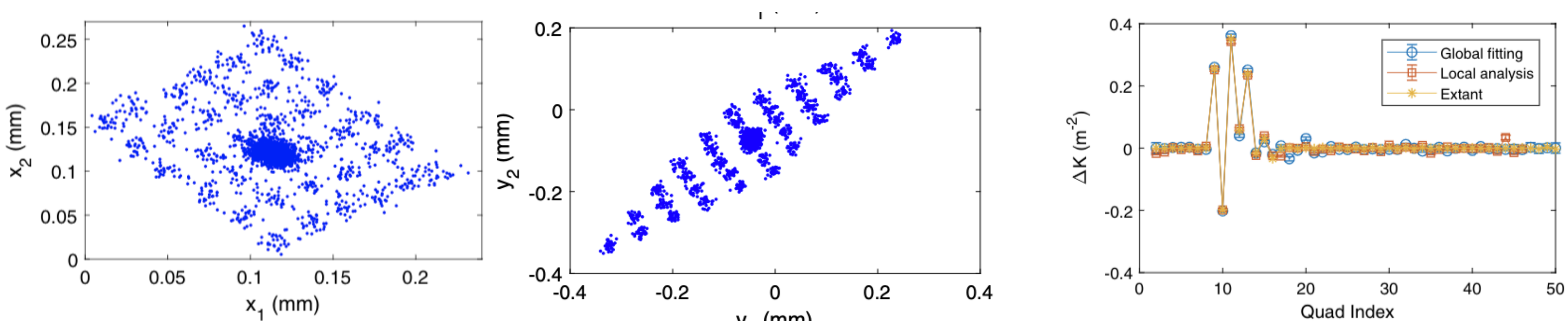
$$\chi_c^2 = \sum_{ij} \frac{1}{\sigma_{ij}^2}(R_{ij}^{\text{meas}} - R_{ij}^{\text{model}})^2 + \frac{1}{\sigma_K^2}\sum_{i=1}^{N_q} w_i^2 \Delta K_i^2,$$

The weight of the penalty terms affects the fitting results, but with small impact to the final chi2.



- Can correct optics, corrected beta beating can reach below 1% level
- But in many cases cannot locate exact error sources

- Global linear optics fitting has been extended to long linacs



LCLS trajectory scan data are used to fit the linear optics

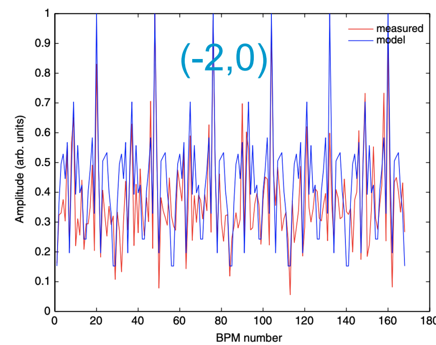
T. Zhang et al, PRSTAB 21, 092801 (2018)

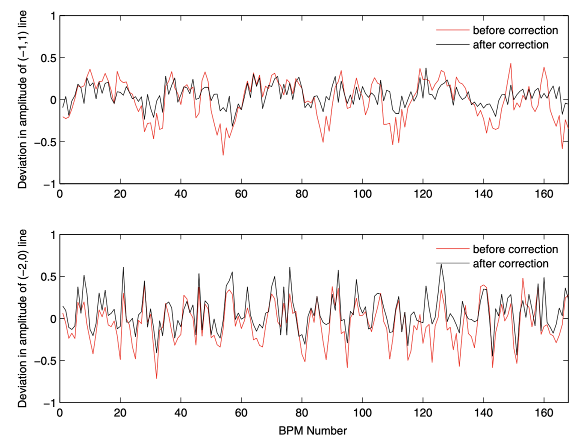
Correction of storage ring nonlinear dynamics

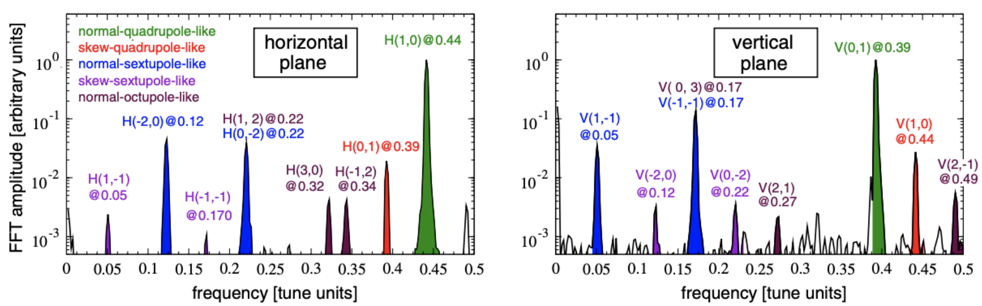
- Nonlinear dynamics correction
  - Based on comparison of nonlinear lattice parameters: chromaticity and high-order chromaticity, tune shifts w/ amplitude, RDTs

$$h_x^-(N) = \sqrt{2I_x}e^{i(2\pi\nu_x N+\psi_{x_0})} - 2i\sum_{jklm} j f_{jklm}(2I_x)^{(j+k-1)/2} \times (2I_y)^{(l+m)/2} e^{i[(1-j+k)(2\pi\nu_x N+\psi_{x_0})+(m-l)(2\pi\nu_y N+\psi_{y_0})]}$$

R. Bartolini et al, PRSTAB 11, 104002 (2008)
RDT correction at Diamond







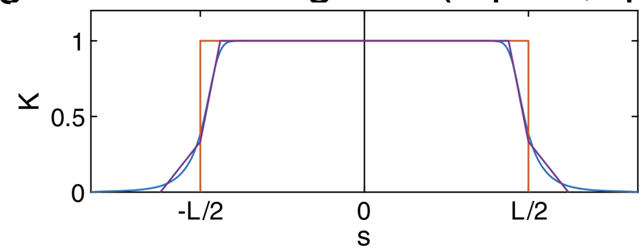
A. Franchi, et al PRSTAB 17, 074001 (2014).
RDT correction at ESRF

  - Very difficult to do; and have not resulted in a routine that consistently improve machine performance.

Correction may need to extend to higher orders

Component 1: modeling the physical processes more accurately

- Improving modeling of individual components
  - Fringe fields in magnets (dipole, quadrupole, sextupoles)



Including of quadrupole fringe fields in modeling codes make a big difference in linear optics.

M. Borland, et al, PRSTAB 22, 114601 (2019)

TABLE IV. Changes of lattice parameters when the quadrupole fringe field is turned off in the APS-U lattce, calculated with ELEGANT and AT.

Parameter	ELEGANT	AT
Horizontal tune, $\Delta\nu_x$	0.0579	0.0582
Vertical tune, $\Delta\nu_y$	0.1360	0.1374
Chromaticity, $\Delta\xi_x$	−0.0071	−0.0688
Chromaticity, $\Delta\xi_y$	0.6184	0.4942
Horizontal tune, $\Delta\nu_x$ ($\delta_p = 0.04$)	0.1022	0.0690
Vertical tune, $\Delta\nu_y$ ($\delta_p = 0.04$)	0.1792	0.1754
Horizontal tune, $\Delta\nu_x$ ($x = y = 2$ mm)	0.0738	0.0735
Vertical tune, $\Delta\nu_y$ ($x = y = 2$ mm)	0.1407	0.1415

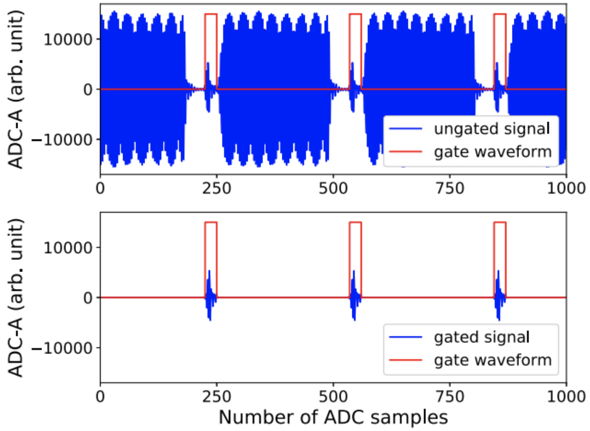
  - Non-conventional magnets, insertion devices, impedanes, other E&M fields

- It is desirable to have a standard modeling code that is thoroughly verified and benchmarked.
- The modeling code should also be fast for simulation of long term dynamics.

Component 2: fast, non-invasive, and accurate linear optics model calibration

SLAC

- Fast, non-invasive optics measurements allow tracking of changes due to environmental drifts.
  - Turn-by-turn BPM data taking is fast; small excitation
  - Gated BPM signal combined with special fill patten



Optics measurement at NSLS2 with gated BPMs.
Y. Li, et al, PRSTAB 20, 112802 (2017)

- Improving optics calibration accuracy with large data sets and advanced algorithms
  - Reduce overfitting
  - Determine and reach the optics accuracy for reliable nonlinear dynamics control.
  - Statistical methods such as Bayesian inference could be explored for information recovery.

Component 3: nonlinear dynamics calibration and correction

- Identify the measurable features that are related to nonlinear beam dynamics performance – dynamic aperture and local momentum aperture
  - High order RDTs? Is it possible?
- Develop methods for the measurements of these features
- Determine the diagnostics requirements for the measurements.
- Demonstrate the measurements on real accelerators
- Are there enough knobs to correct these features?

Desirable outcome, impact, and ABP mission alignment

SLAC

- The desirable outcome is powerful new methods that can be used to obtain precise accelerator models that correspond to operation conditions.
- The potential impact
  - Save tuning time in commissioning and operation
  - More relaxed accelerator design requirements
  - Higher operational performance (e.g., injection efficiency, lifetime)
  - Higher science output (reaching higher luminosity, more time for science, …)
- How does it fit into the GARD ABP missions
  - Advance physics of accelerators and beams to enable future accelerators
  - Guide and help to fully exploit science at the GARD beam facilities and operational accelerators.
  - Educate and train future accelerator physicists.
- How can it fail? What can go wrong with this idea?
- Is it testable? What facility?

Grand Challenges and key milestones

SLAC

- This proposal/idea addresses all 4 grand challenges:
  - #1 (beam intensity): How do we increase beam intensities by orders of magnitude?
  - #2 (beam quality): How do we increase beam phase-space density by orders of magnitude, towards quantum degeneracy limit?
  - #3 (beam control): How do we control the beam distribution down to the level of individual particles?
  - #4 (beam prediction): How do we develop predictive “virtual particle accelerators”?
- What are key milestones on the way to address Grand Challenges?
  - 1: demonstrating significantly better agreement in linear optics between model and measurements with improved modeling code development (up to the level of random errors)
  - 2: determining the required linear optics accuracy for reliable nonlinear dynamics control and demonstrating the level of accuracy in experiments.
    - Specify diagnostics requirements
  - 3: demonstrating nonlinear dynamics correction that consistently improve performance.

HEP mission and Synergies

- Relevance with respect to HEP mission
  - Intensity frontier: - achieving high bunch charge in rings
  - Energy frontier: hadron – for required DA and lifteime on large hadron rings
  - Energy frontier: lepton
  - Colliders and accelerators beyond Standard Model
- Synergies with BES and NP
  - BES storage ring light sources have the same requirements for accurate accelerator modeling.
  - NP rings are similar (RHIC and EIC)
  - Linacs also need modeling improvement (LCLS)
  - Method development can be done and tested on BES rings.
  - Method can also be developed and tested on HEP rings (IOTA) and applied to BES and NP rings.