Machine Learning in Synchrotron Light Sources – Facility Needs

Presented to the Machine Learning Workshop

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U.S. DEPARTMENT OF ENERGY

Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Overview of synchrotron light sources
  - Past and Present
  - Key features: brightness and stability
  - Typical layout and operation requirements
- Present status of machine control, correction, and optimization
  - Deterministic approaches: orbit feedback, optics and coupling correction, etc
  - Heuristic approaches: online optimization
    - Application to nonlinear beam dynamics optimization
- Challenges in existing and future rings
- Summary

Synchrotron Light Sources around the world

There are over 40 synchrotron light sources around the world.

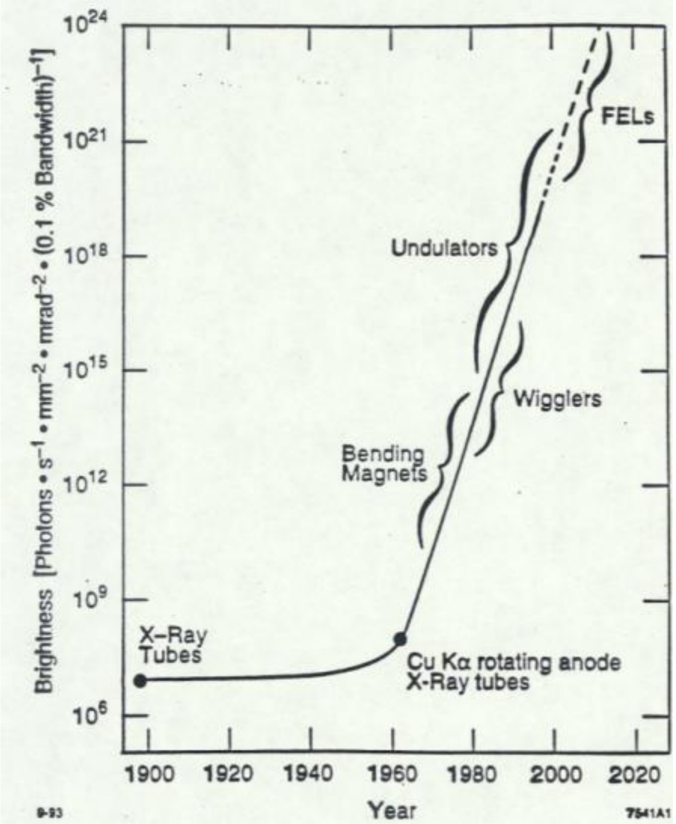
and many more …

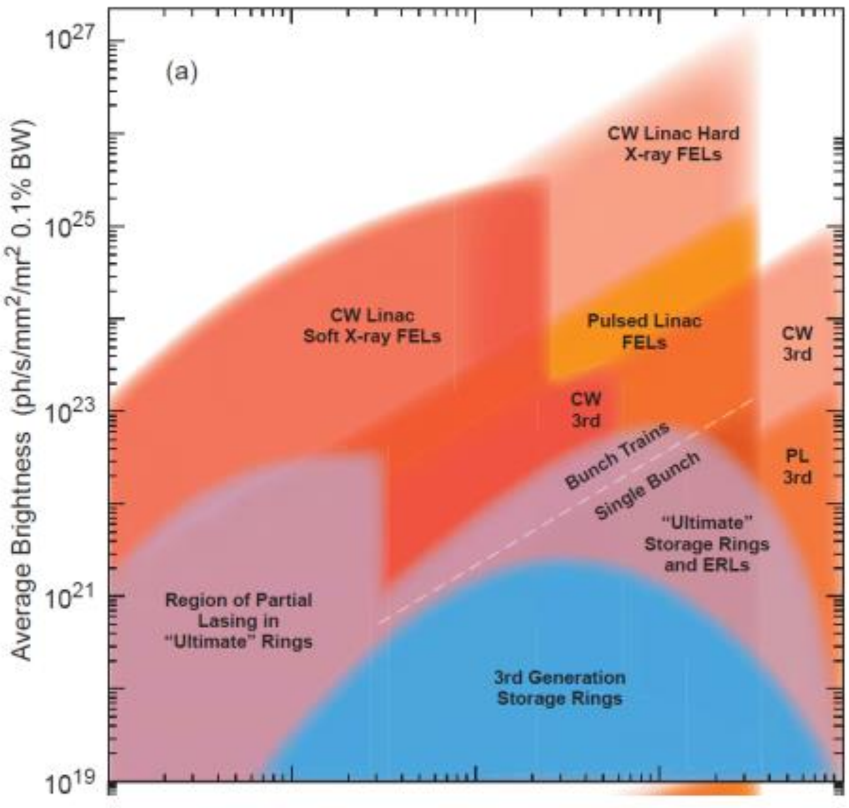
Four generations of synchrotron light sources

- First generation (1970s-1980s): parasitic operation
  - CEA, SPEAR, DORIS, …
- Second generation (1980s): dedicated synchrotron light sources
  - SPEAR2, NSLS, BESSY, Photon Factory, LNLS,MAX-I, …
- Third generation: optimized for high brightness undulator beamlines (1990s-2010)
  - See previous slide
- Fourth generation: MBA lattice, very high brightness (x10-50) (in progress now)
  - ESRF-EBS, APS-U, ALS-U, SPRING-8 Upgrade, HEPS

Spectral brightness

- Spectral brightness is a key performance measure

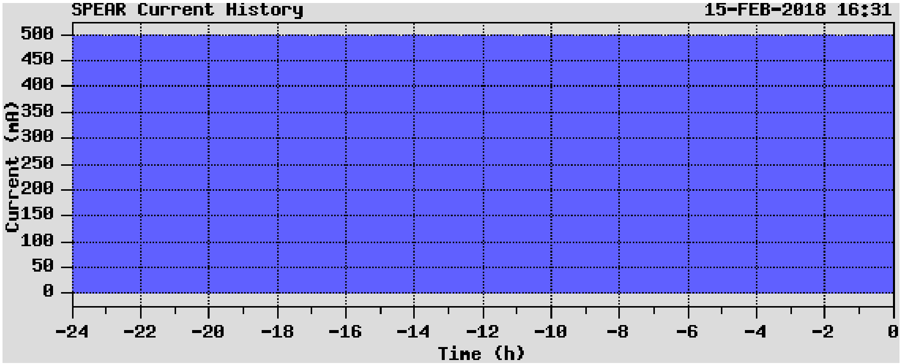




Storage rings serve photon beams with high average flux and high average spectral brightness in a wide energy range to many beamlines.

Beam stability

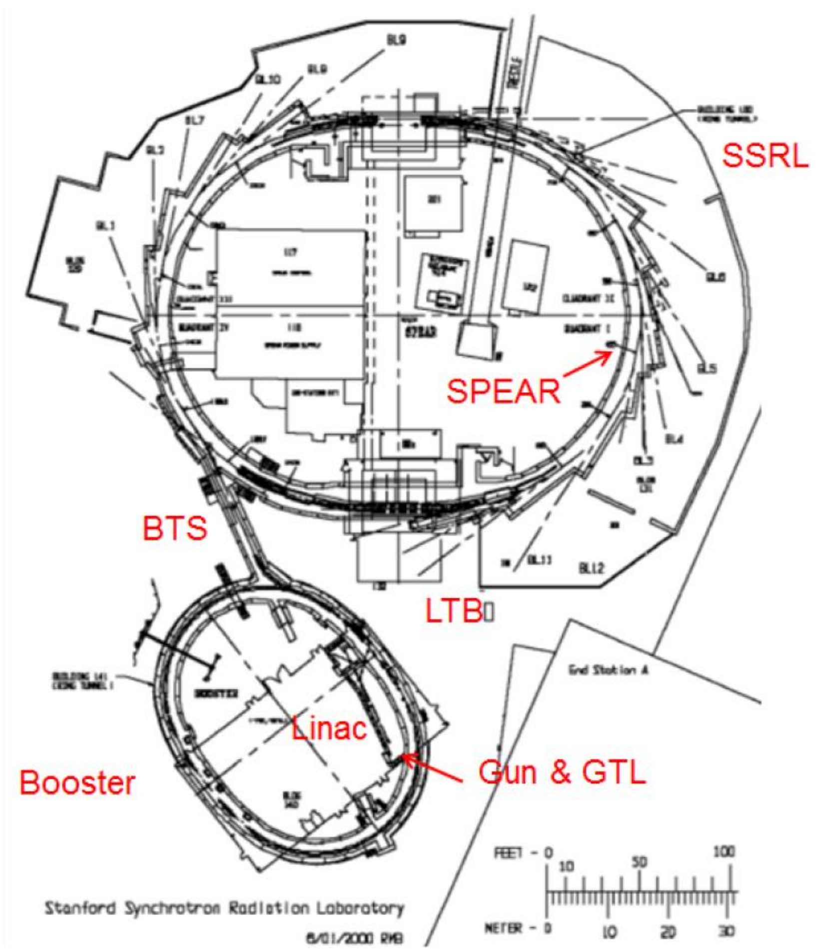
- Storage ring beam orbit is highly stable
  - Within ~ 5 um in 1-200 Hz frequency range (and is typically averaged out).
  - Within ~1 um over a short period of time (~1 hr)
  - Within ~10 um over a day (diurnal ground motion)
  - Feedback on photon beam position monitor data can stabilize the beam
- With top-off fill, photon beam flux is very stable



SPEAR3 with 5-min fills, beam current variation is <1.5%.

- Injection transients and insertion device gap changes can perturb the beam, but are usually under control.

A typical light source complex



An undulator

Operation Requirements

- Personnel and equipment safety
  - Typically through engineering and administrative measures.
- High flux or brightness
  - Mostly determined through design, not runtime variables
- Radiation safety – minimize radiation
  - Low injection loss
  - Long beam lifetime
  - Reduce unexpected beam dumps
- High reliability/availability – minimize unexpected down time
- High photon beam stability
  - Stable orbit
  - Stable linear optics and coupling
  - No collective instability
  - Reduce injection transients

How do we do business today?

Deterministic and Heuristic approaches are used to control and optimize beam conditions.

Deterministic approaches:

- Feedbacks to regulate individual elements (RF, magnet power supplies, etc)
- Feedbacks with beam data (orbit, tune, bunch-by-bunch positions, etc)
- Feedforwards to compensate known perturbations (e.g., insertion device gap changes)

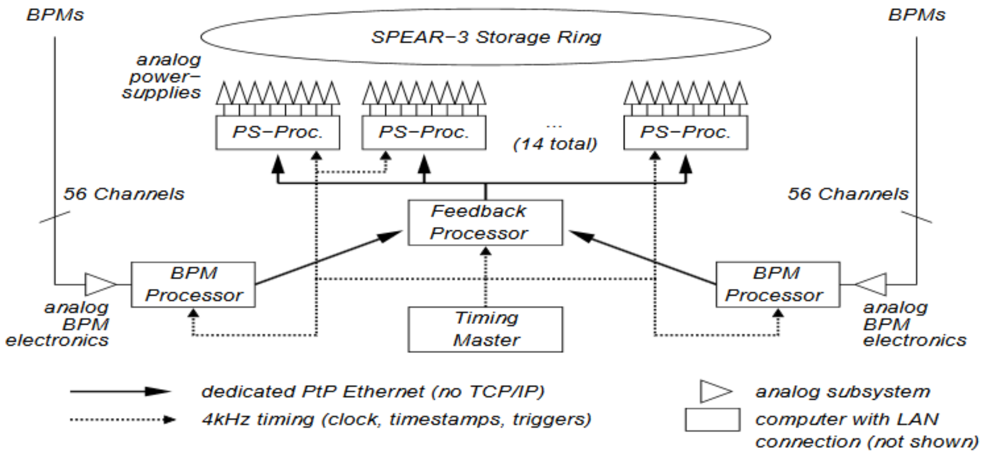
Heuristic approaches:

- Manual machine tuning
- Automated machine tuning

On the storage ring we typically rely on deterministic approaches as tuning is usually not allowed during operation (only allowed during machine studies).

Tuning on the injector can be done between fills. This has become less convenient as frequent top-off fills are implemented and will be impossible for future rings with swap-out injection.

Orbit feedback – SPEAR3 FOFB as an example



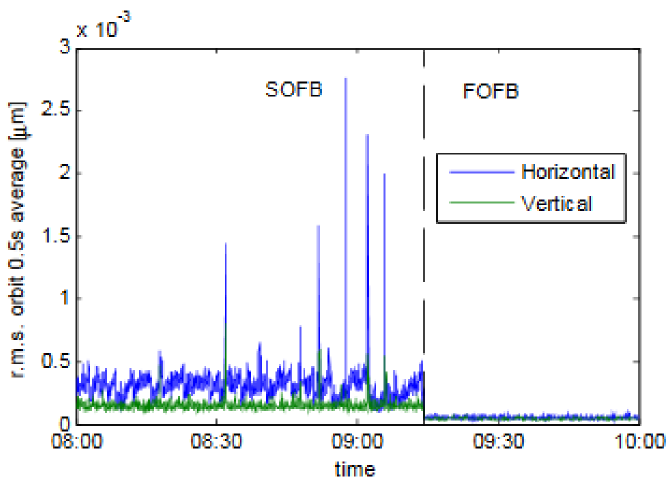
SPEAR3 fast orbit feedback system architecture

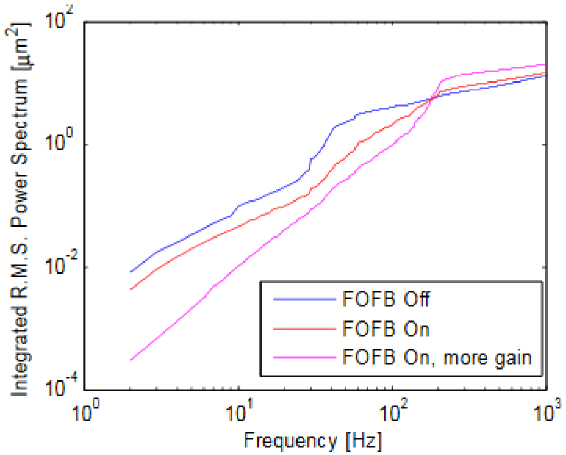
$$\Delta\bar{x} = R\Delta\bar{\theta} \qquad R = USV^T$$

$$\Delta\bar{\theta} = VS^{(-1)}U^T\Delta\bar{x}$$

A PI feedback loop for each eigen-mode.

A. Terebilo, T. Straumann, EPAC'06, THPCH102

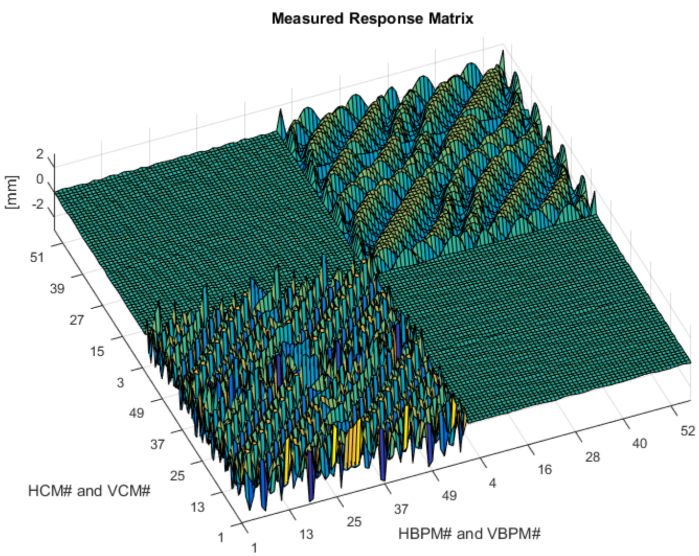


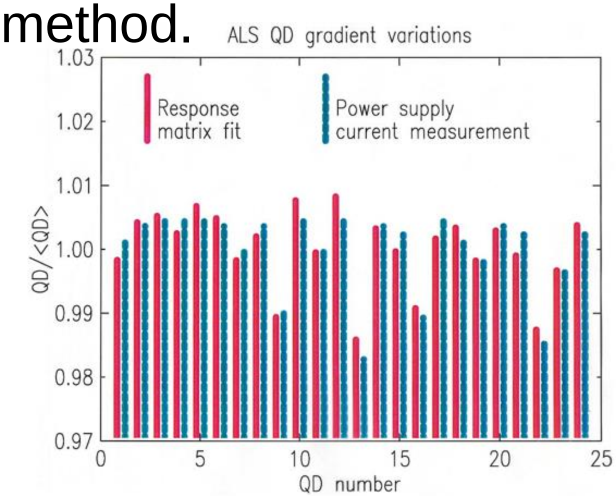


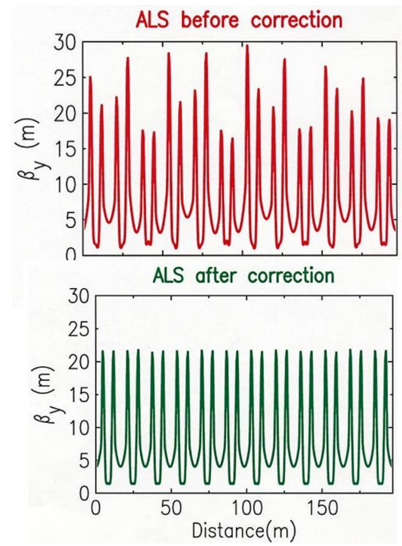
Fast orbit feedback meets the operation needs in orbit stability.

Linear optics and coupling correction

- Correction of linear optics has significant impact to operation performance (on injection efficiency and beam lifetime)
- LOCO (linear optics from closed orbit) has been the most successful optics and coupling correction method.







J. Safranek, Nucl. Inst. and Meth. A 388 (1997) p. 27
See also papers on LOCO in ICFA Newsletter 44 (2007)

- LOCO Data taking has been expedited with AC excitation of correctors

W. Cheng, et al, IPAC2016
X. Yang, PRAB, 20, 054001 (2017)

Over fitting in optics correction

- LOCO fits response matrix to the lattice model to uncover lattice errors. Over fitting can be a serious problem.
  - The fitted quadrupole errors can be unrealistically large

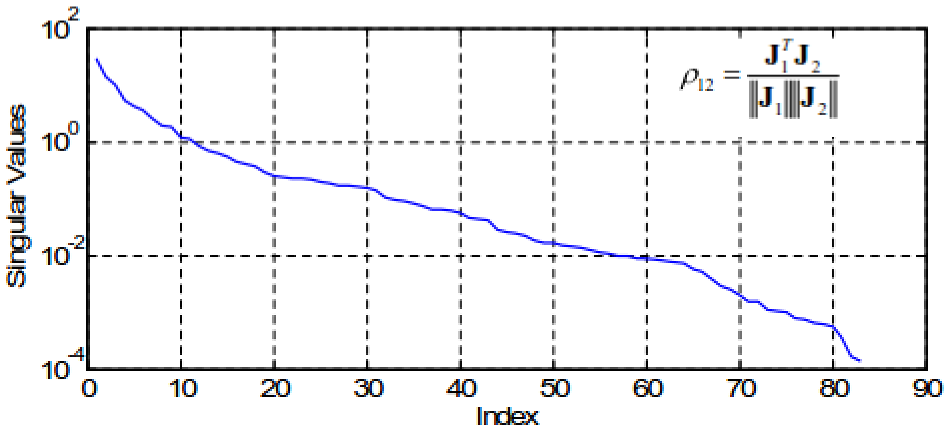
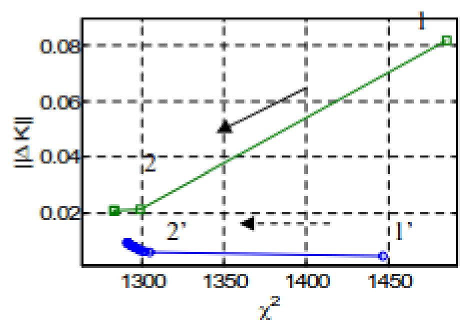


Figure 2: singular values of the correlation matrix of SPEAR3 quadrupoles.

The fitted errors tend to drift in the less constrained (small S.V.) direction to seek small χ^2 reduction on the order of noise level.

  - Adding artificial constraints has been successful in providing solutions for optics correction.

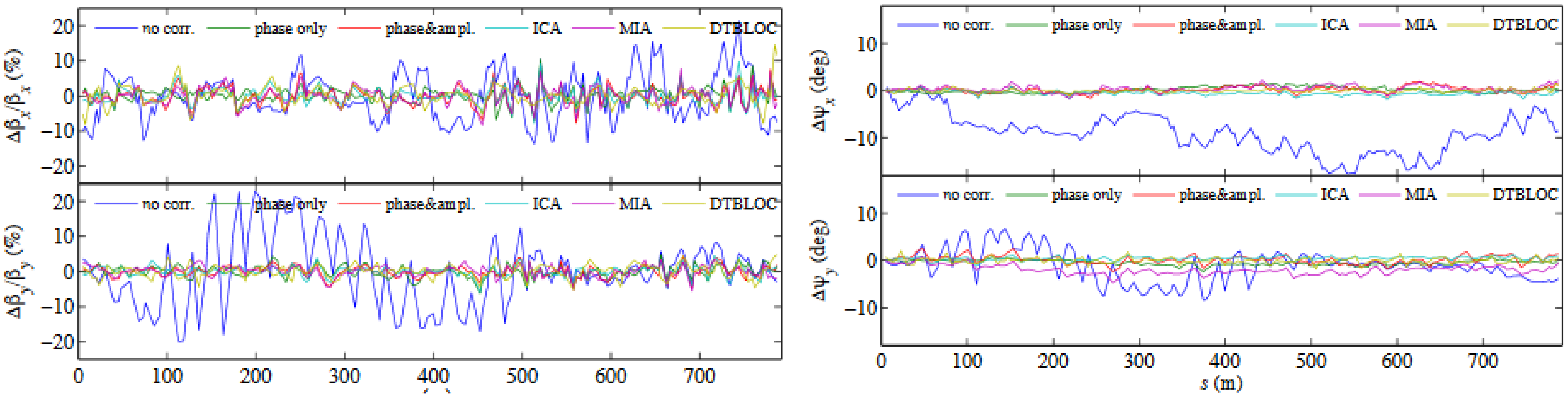
$$\chi^2 = \sum_{i,j} \frac{(M_{\mathrm{mod},ij} - M_{\mathrm{meas},ij})^2}{\sigma_i^2} + \frac{1}{\sigma_{\Delta K}^2} \sum_k w_k^2 \Delta K_k^2$$



X. Huang, et al, PAC05
X. Huang, et al, ICFA Newsletter 44 (2007)

Turn-by-turn BPM data for optics and coupling correction

- Simultaneous turn-by-turn BPM data contain information about optics errors (betatron phases and beta function)
  - 3-BPM and N-BPM methods — P. Castro, et al, PAC'93; A. Langner et al, PRSTAB 18, 031002 (2015)
  - Model Independent Analysis — J. Irwin, et al, PRL 82, 1684 (1999); C.-x Wang et al, PRSTAB 6, 104001 (2003)
  - Independent Component Analysis — X. Huang, et alPRSTAB, 8, 064001 (2005)
- Optics correction by fitting the lattice model
  - Using optics errors — X. Huang, PRSTAB, 8, 064001 (2005); M. Aiba, et al, PRSTAB, 12, 081002 (2009); X. Shen et al, PRSTAB 16, 111001, (2013); X. Yang, X. Huang, NIMA, 828, 97 (2016).
  - Can also fit turn-by-turn data directly. — X. Huang, PRSTAB, 13, 114002 (2010);

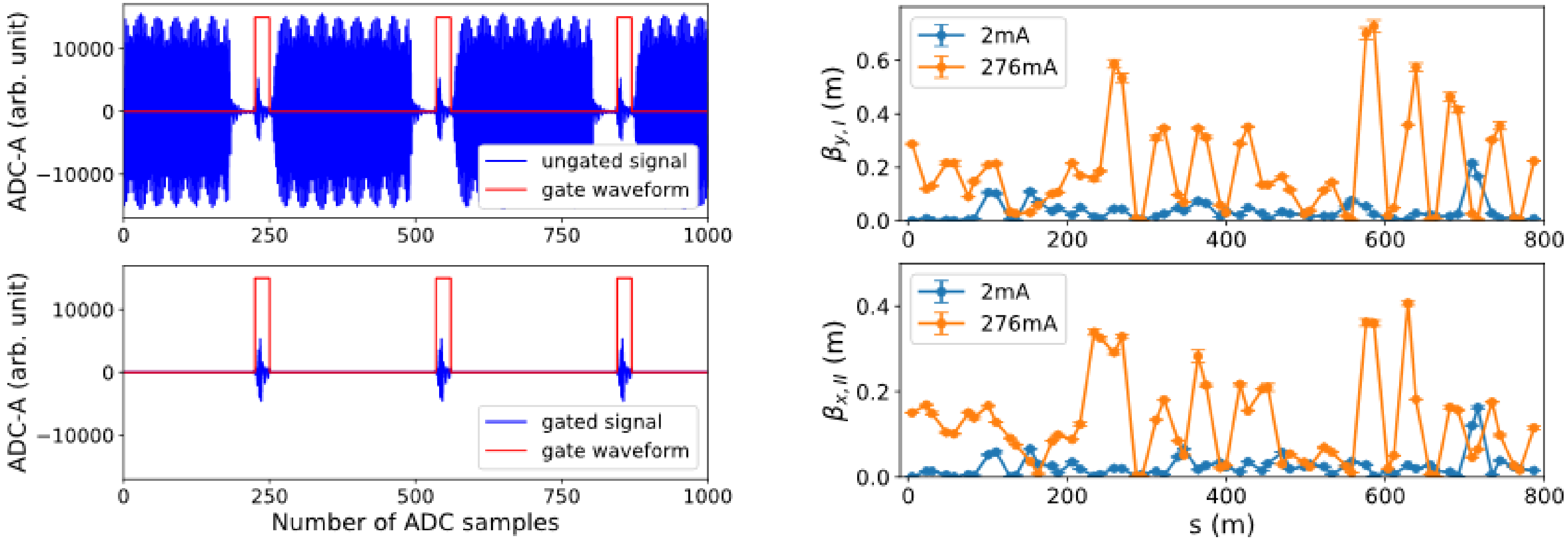


Comparison of optics correction results.

V. Smaluk, et al, IPAC2016, THPMR008

Transparent optics correction

- Storage ring optics drift with time and get perturbed by configuration changes (e.g., ID gap changes)
  - Turn-by-turn data during injection transients can be used for optics monitoring and correction.
  - Using bunch-by-bunch feedback and gated BPM data acquisition, a small bunch train can be used for optics monitoring and correction. Y. Li, et al, PRAB 20, 112802 (2017)



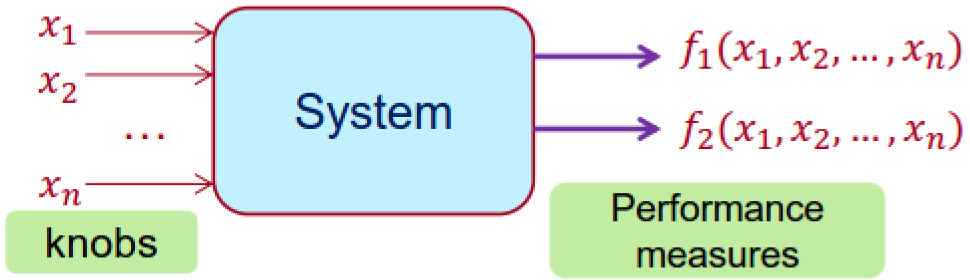
Optics and coupling correction generally meets the operation needs.

Nonlinear beam dynamics correction

- The push for lower emittance puts stress on nonlinear beam dynamics – dynamic aperture (DA) and local momentum aperture (LMA) get smaller.
- Errors in the lattice cause deviation of nonlinear beam dynamics behavior from the design. Restoring DA and LMA is crucial for low emittance rings.
- Beam based correction of nonlinear beam dynamics has been attempted, but no reliable method has been established.
  - Fit nonlinear tune shifts (chromatic and geometric)
    - R. Bartolini et al, PRSTAB 14, 054003 (2011)
  - Fit nonlinear RDTs –
    - R. Bartolini et al PRSTAB 11, 104002 (2008)
    - A. Franchi, et al PRSTAB 17, 074001 (2014).
    - J. Bengtsson, R. Bartolini, et al PRSTAB 18, 074002 (2015).
  - No clear causal relationships between DA/LMA and observed NL behavior (tune shifts and RDTs)

Online optimization as a general approach

- Beam based correction (BBC): deriving errors from measurements for correction.
  - Need ample diagnostics to sample the system status.
  - This approach is basically regression (supervised learning) in machine learning.
- Beam based (online) optimization (BBO): adjust the knobs while observing the performance.
  - This is a form of reinforcement learning.



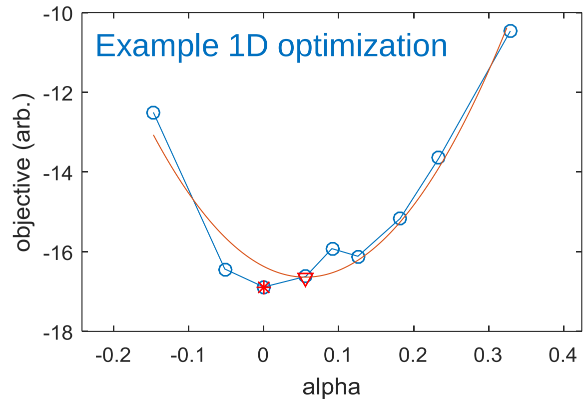
See X. Huang presentation at NAPAC-16 for more discussion of BBC and BBO.

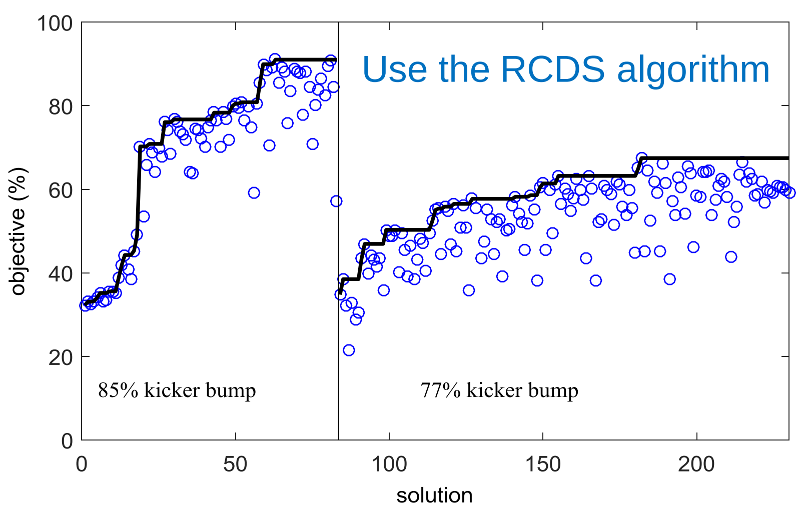
Development of online optimization algorithms

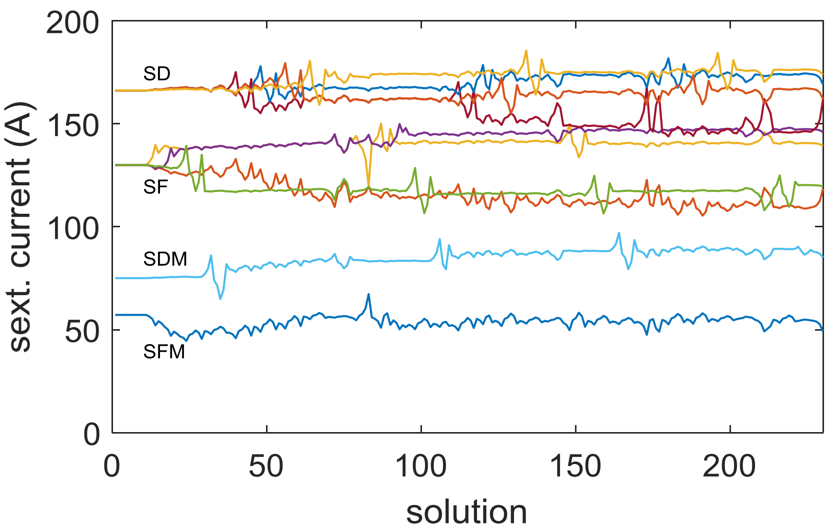
- Early attempts of automatic tuning implemented 1-D scan and downhill simplex methods L. Emery et al, PAC2003
- At SPEAR3, we did a series of exploration of online optimization algorithms.
  - The robust conjugate direction search (RCDS) method was invented to effectively search the parameter space in presence of noise
    X. Huang, J. Corbett, J. Safranek, J. Wu, NIMA 726 (2013) 77
  - Genetic algorithm (GA) has been tried on the machine
    K. Tian, J. Safranek, Y. Yan, PRSTAB 17, 020703 (2014)
  - Particle swarm optimization (PSO) was tested and found to be effective
    X. Huang, J. Safranek, PRSTAB 18, 084001 (2015)
  - Extremum Seeking (ES) has been tested and found to be able to track time varying perturbation.
    A. Scheinker, X. Huang, J. Wu, IEEE Trans. Contr. Sys. Tech. vol 26, no 1 (2018) 336-343

Online optimization of nonlinear beam dynamics

- Use 8 combined sextupole knobs (out of 10 sextupole families) to improve injection efficiency.
- Started from flat sextupole pattern (old nominal).
- Reduced kicker bump to 85% first, injection efficiency came back quickly.
- Kicker bump reduced to 77% for second run.
- Took about 55 min total.



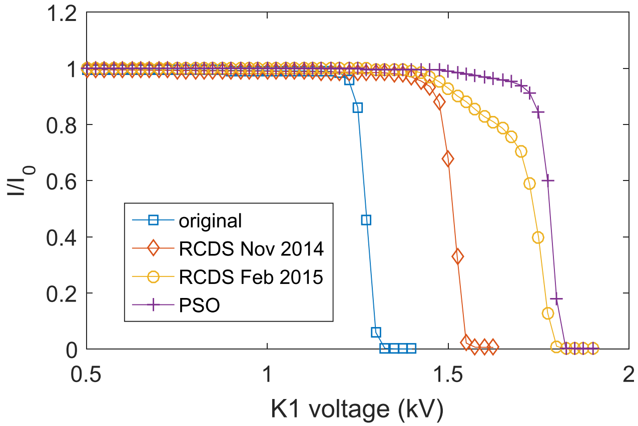


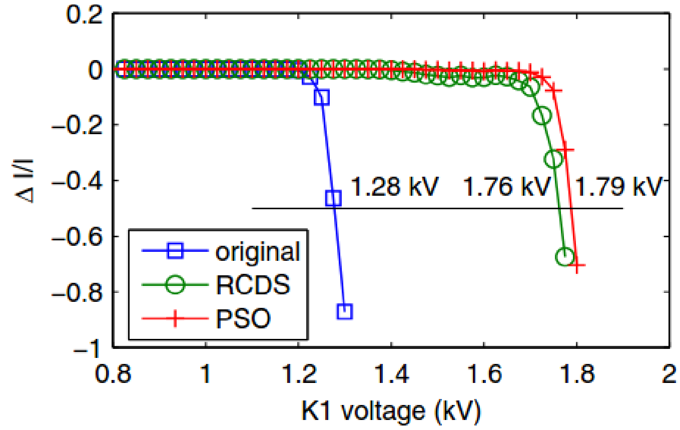


Experiment on the SPEAR3 storage ring

Dynamic aperture improvement

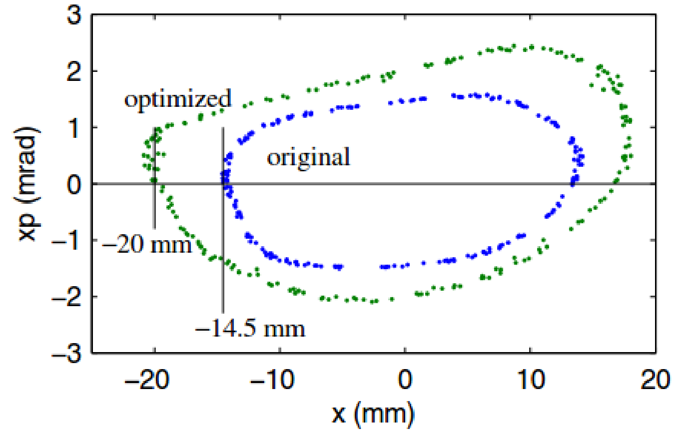
- Dynamic aperture is measured by kicking the stored beam with a kicker until beam is lost.





The kicker voltage is converted to kick angle and used in tracking to find out the dynamic aperture.

Dynamic aperture was increased from 15 mm (original) to 20 mm.



Optimization did not change chromaticity nor momentum aperture.

Beam lifetime optimization

- At ESRF, RCDS has been applied to substantially improve beam lifetime by tuning sextupole knobs.

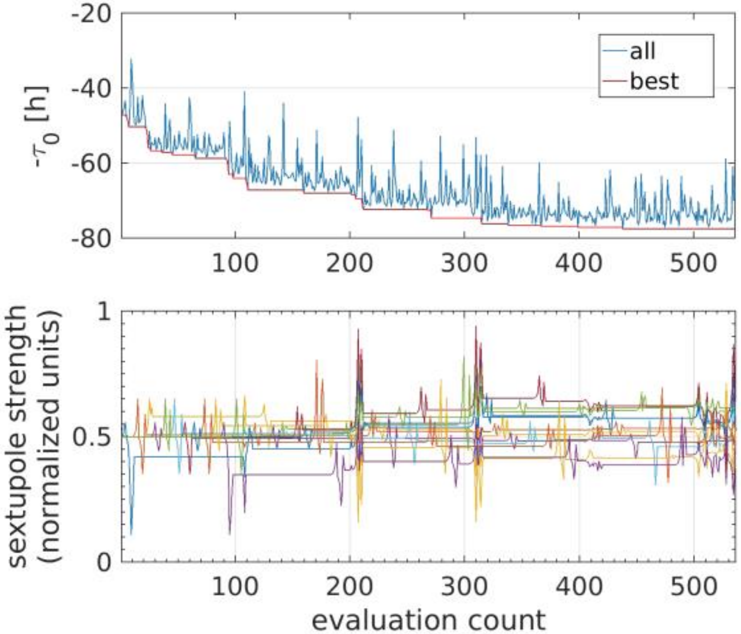
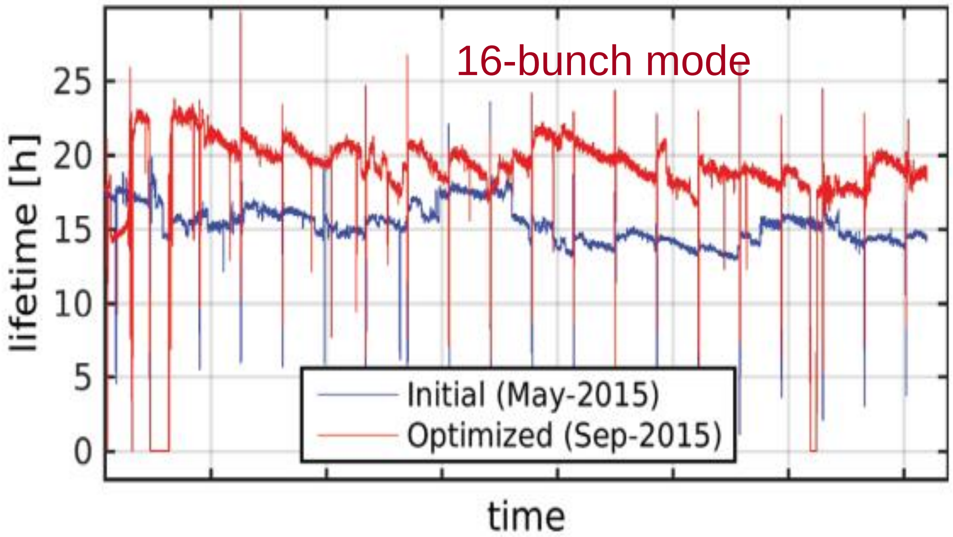


Figure 2: Optimization of lifetime using 12 sextupole correctors in 7/8+1 mode.



Objective function: $$\tau_0 = \tau \frac{I}{I_0} \frac{BL(I_0)}{BL(I)} \frac{\sigma_{y,0}}{\sigma_y}$$

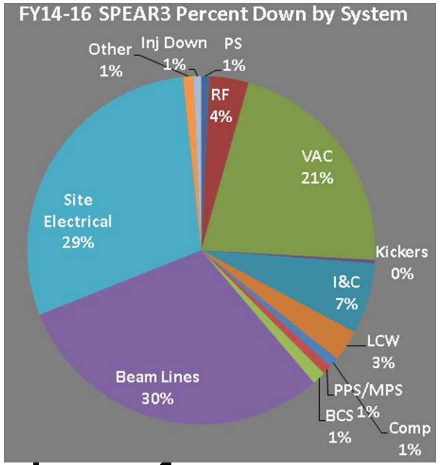
S. Liuzzo, et al IPAC 2016

- Recent experiment at SPEAR3 gained 30% in beam lifetime for an upgrade lattice using sextupole knobs. K. Wootton, X. Huang

Challenges in existing storage rings

- Reduce downtime
  - Upgrade/replace components with vulnerability
  - Quick identification and resolution of failures.
  - Quick recovery

  Can ML mine the history data to identify failing components and identify failure causes?



- Maintain performance during operation w/o interference to users
  - Deterministic approaches (feedback and feedforward) can be used if causes of the performance drop are known. But sometimes that is not clear.

  Can ML build inexplicit model of various diagnostics data to discover error sources and suggest corrections?

Challenges in future diffraction limited storage rings

- Next generation storage rings pose severe challenges in the commissioning phase and in operation.
  - There is no accumulation for swap-out rings – may deal with very weak (quickly decaying) beam at the beginning.
  - May need to correct optics before storing beam (initial errors may be too large to store beam)
  - Beam dynamics is very nonlinear. There are many strong error sources (many more strong magnets). Beam dynamics behavior may be far from design. Need global optimization.
  - Need to optimize dynamic aperture and momentum aperture simultaneously.
  - Undulators substantially affect beam parameters (since bending magnet radiation will be relatively weak). Need accurate scheme for compensation.

Can ML help in coming up with solutions, e.g.,
Beam based correction with less and noisier data?
More efficient beam based optimization methods for multi-objective, global optimization?

Summary

- Synchrotron light sources are very successful scientific research instruments with a strong presence and a bright future.
- Deterministic approaches of beam control and correction had a long history of development and generally meet the operation requirements.
- Online optimization has seen significant development in recent years. An important application to storage ring nonlinear is beam dynamics optimization.
- Beam based correction and beam based optimization can be seen as sub-categories of machine learning.
- Machine learning could potentially benefit storage rings in improving reliability and stability and help deal with future challenges in DLSR.

Slide from Anke-Susanne Müller (IBPT)

ML options for KARA at KIT

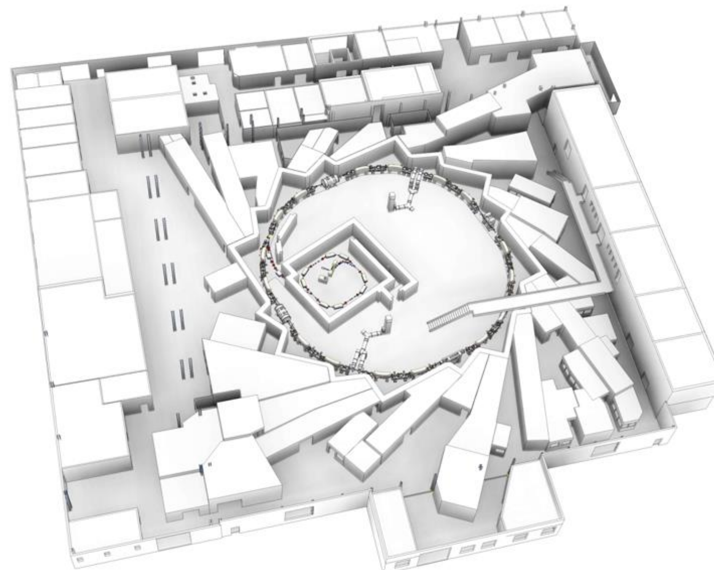
Karlsruhe Institute of Technology

Motivation (generic):

- cost efficiency
- faster turn-around times
- optimize personnel-intensive processes

Application areas:

- data analysis:
  sensor network of high-data throughput beam diagnostics devices
- optimization of operation modes
- advanced feedback



KARA
light source & accelerator test facility (wide parameter range: energy, bunch length, ...)

SLAC, February 2018

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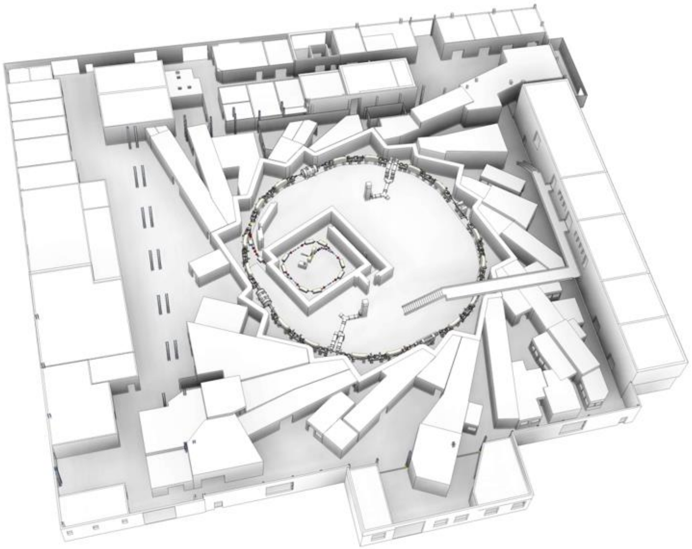

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