U.S. DEPARTMENT OF ENERGY
Office of Science

BERKELEY LAB

ALS-U
ADVANCED LIGHT SOURCE

Lattice Correction Studies and Commissioning Simulations for ALS-U

Thorsten Hellert

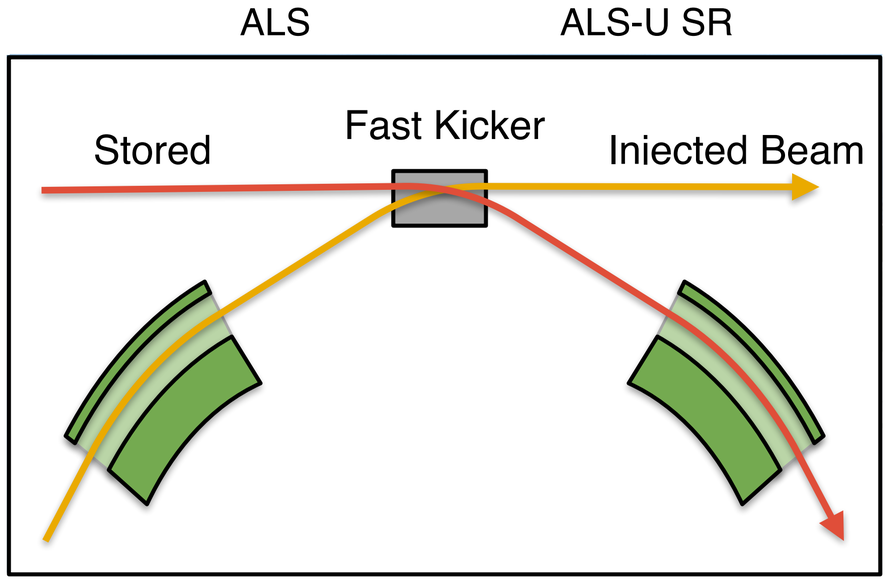
Optics Tuning and Corrections for Future Colliders Workshop
Jun 26-28
CERN

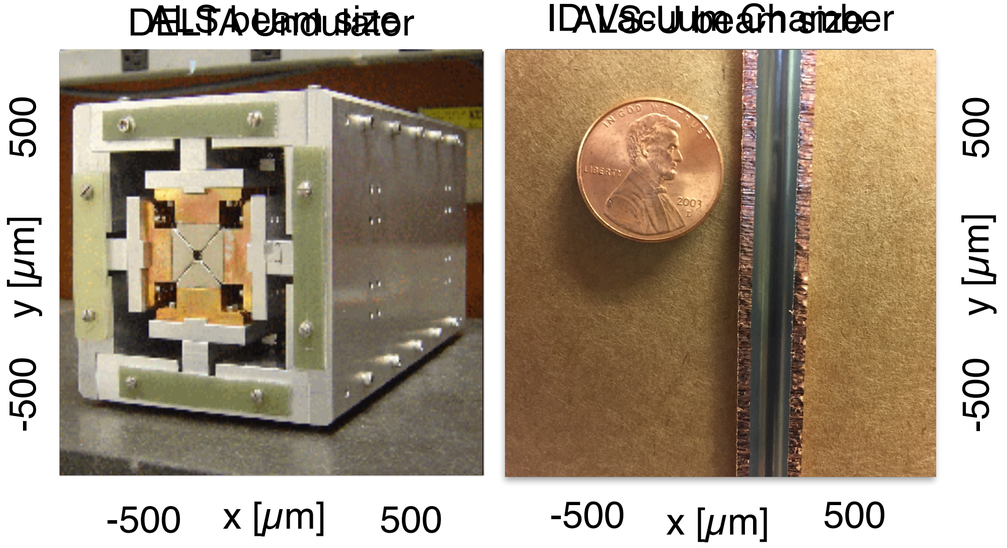
Outline

- Introduction
  - Advanced Light Source Upgrade
  - Toolkit for Simulated Commissioning
- Commissioning Simulations for the ALS-U Storage Ring
  - Orbit errors in sextupole magnets
  - Beam based alignment

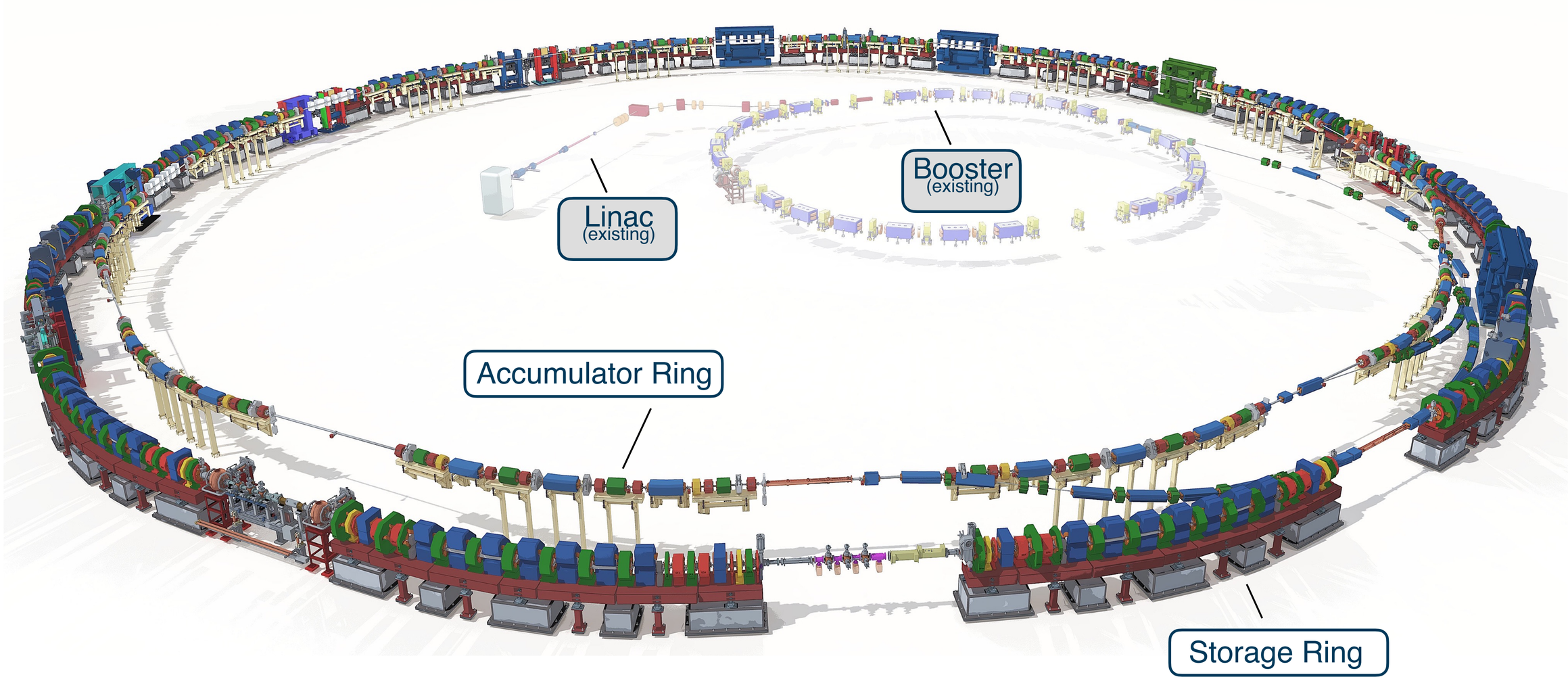
Design Choice of the Advanced Light Source Upgrade

- Goal: Diffraction Limited Light Source
  - Brightness increase: $B_{ALS} = 2*10^{19}$ => $B_{ALSU} = 2*10^{21}$
  - Emittance decrease: $\varepsilon_{ALS} = 2000\,pm$ => $\varepsilon_{ALSU} \sim 100\,pm$
- Space Constraint
  - Use of current building and 12-fold symmetry
- Requires Strong Focusing Elements
  - Quadrupole strength: $K_{ALS} \sim 3$ => $K_{ALSU} \sim 15$
  - Sextupole strength: $M_{ALS} \sim 90$ => $M_{ALSU} \sim 800$
- Requires Small Aperture
  - Magnet aperture: $d_{ALS} = 65\,mm$ => $d_{ALSU} = 40\,mm$
  - Undulator aperture: $d_{ALS} = 30\,mm$ => $d_{ALSU} = 6\,mm$
- Requires on-Axis Swap Out
  - Dynamic aperture: $DA_{ALS} = 120\,mm^2$ => $DA_{ALSU} = 3\,mm^2$
- Requires Accumulator Ring
  - Injected beam: $\sigma_{ALS} = 2\,mm$ => $\sigma_{ALSU} = 60\,\mu m$





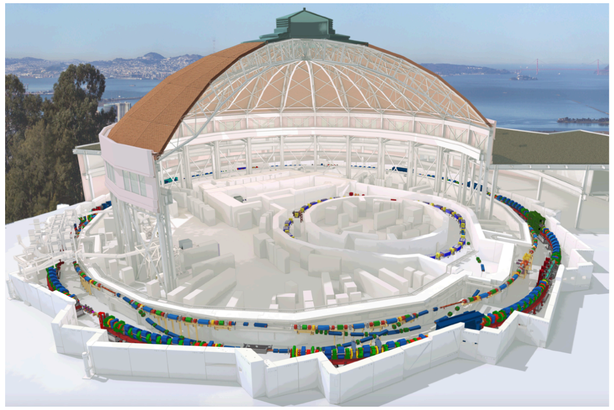
Overview of ALS-U Accelerator Facility



Limited Accessibility of Machine Properties

Power supplies

Operating machine



Diagnostic devices

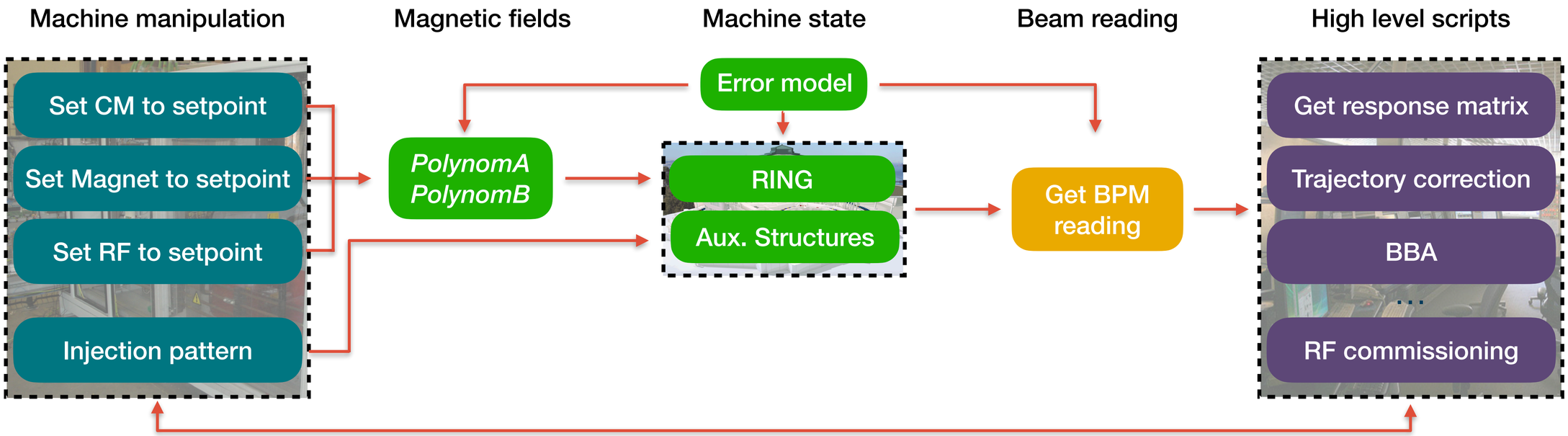
High level controls

Magnetic fields
Particle trajectories
Magnet offsets
…

Limited access!

Setpoints and read back values

Realistic Workflow of Toolkit Important



Set Quad to setpoint

- Compensates bending angle difference by setting horizontal CM
- Checks for CM range (clipping)

Calculate fields

- Calibration errors of all components
- Includes dipole kick from bending angle (set-point & roll)

Auxiliary structures

- Diagnostic errors
- Injected beam trajectory
- Injection pattern

Get BPM reading

- Performs tracking including aperture
- Gets BPM signal from ensemble of particle trajectories

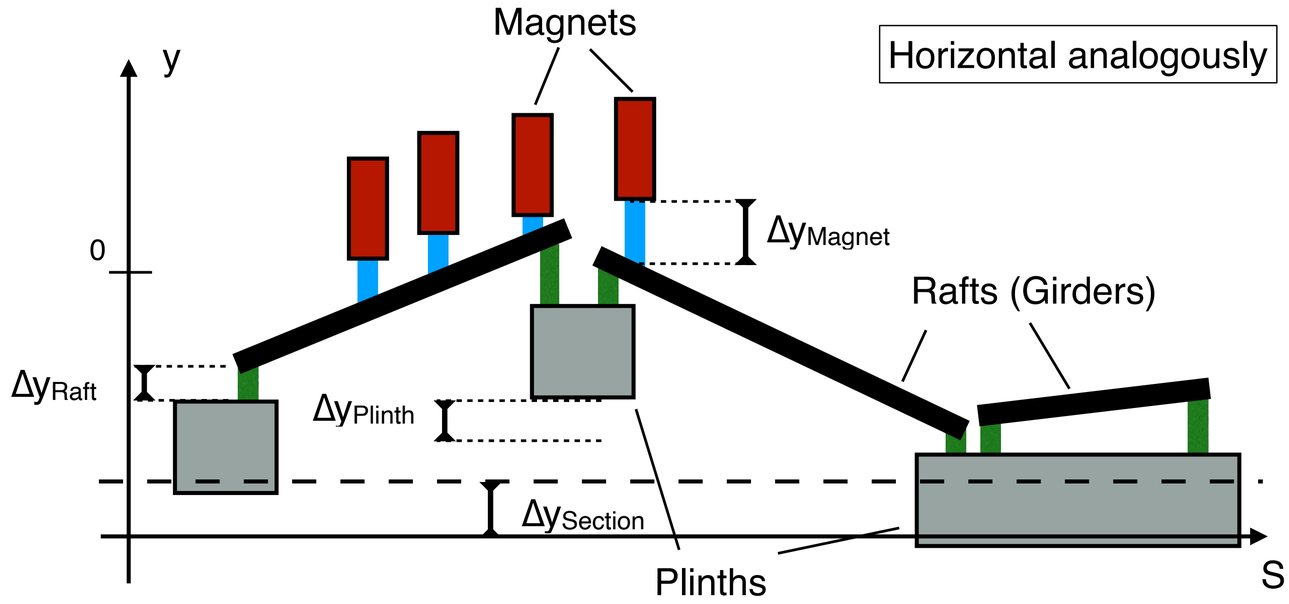
High level

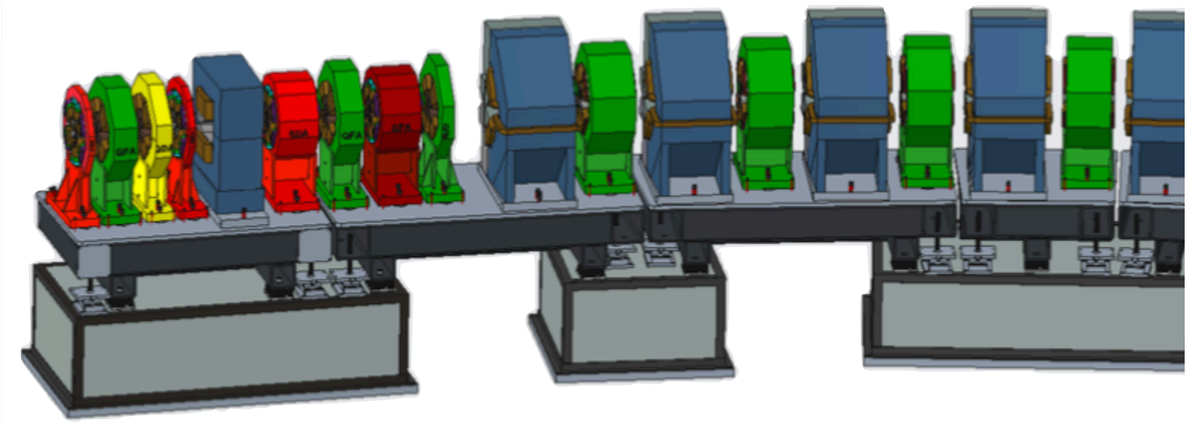
- High level functions use only BPM and setpoints as input
- High level functions write only setpoints

Large Number of Error Sources Included

- Diagnostic Errors
  - BPM offset
  - BPM cal. error
  - BPM noise (TbT/CO)
  - BPM roll
  - CM cal. error
  - CM roll
  - CM / skew-quad limits
- Support Structure
  - Rafts, Plinths, Sections
  - 3D Roll & Offsets
- Circumference
- Higher Order Multipoles
  - Systematic
  - Random

- Magnets
  - 3D Offset
  - 3D Roll
  - Strength
  - Calibration
- RF Errors
  - Phase
  - Frequency
  - Voltage
- Injection
  - Static
  - Jitter





Easy Accessibility For New Users: Manual & Example Scripts

ALSU-AR Paper

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 100702 (2019)

Toolkit for simulated commissioning of storage-ring light sources and application to the advanced light source upgrade accumulator

Thorsten Hellert, Philipp Amstutz, Christoph Steier, and Marco Venturini
Lawrence Berkeley National Laboratory, Berkeley 94720, California, USA

(Received 23 July 2019; published 10 October 2019)

We present a new accelerator toolbox (AT)-based toolkit for simulating the commissioning of light-source storage rings. The toolkit provides a framework for supporting high-level scripts to represent with

ALSU-SR Paper

PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 110701 (2022)

Lattice correction and commissioning simulation of the Advanced Light Source upgrade storage ring

Thorsten Hellert, Christoph Steier, and Marco Venturini
Lawrence Berkeley National Laboratory, Berkeley 94720, California, USA

(Received 16 February 2022; accepted 26 September 2022; published 15 November 2022)

The ALS-U is the upgrade of the existing Lawrence Berkeley National Laboratory Advanced Light

Online Manual

https://sc.lbl.gov

Table of Contents

- Introduction
  - Initialization
  - Error Source Definition & Registration
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  - SCgetModelDispersion
  - SCgetModelRING
  - SCgetModelRM
  - SCgetOrds

SC Manual

T. Hellert – thellert@lbl.gov

Please check the release notes for code changes.

Introduction

Realistic simulations of the operation of a complex machine like an accelerator not only require a good model of the beam dynamics, but also have to acknowledge the fact that only incomplete information about the actual machine state is available during operation, due to the many unknowns in the machine geometry, the magnetic fields and the beam-diagnostic systems. The `SC` toolbox addresses this issue by making clear distinctions between machine parameters that are accessible during operation and the parameters that go into the beam dynamics simulation of the machine, e.g. by implementing a transfer-function, relating magnet setpoints to the actually realized magnetic fields.

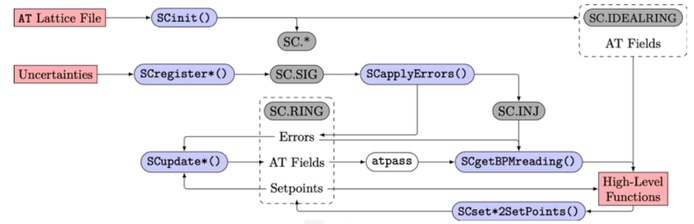


Figure 1. Schematic drawing of the workflow of the `SC` toolkit.

Typical usage of the `SC` toolbox follows the steps

- Initialization of the `SC` core structure
- Error source definition & registration
- Generation of a machine realization including errors
- Interaction with the machine

which are described in the following. Thereafter we describe the definition of error sources, followed by a usage example for a complete correction chain and a list of all implemented functions.

Initialization

In a first step, the user initializes the toolbox by calling SCinit with the AT lattice of his or her machine as input. This sets up a matlab-structure, usually assigned the variable name `SC`, with which nearly all subsequent functions of the toolbox interact. Within this central structure all relevant information about the machine and the error sources is stored.

Error Source Definition & Registration

In the next step, the user registers elements like magnets, BPMs or cavities including all error sources they would like

Toolkit Webpage

Toolkit for Simulated Commission

We present the *Toolkit for Simulated Commissioning* (SC), which allows
as diligently treating beam diagnostic limitations. Please have a look at th
Accumulator Ring including all files and error defenitions can be found h
SC uses the Matlab-based *Accelerator Toolbox* (AT), which can be downlo

Manual

This is the manual.

Source

git repository
Full ALS-U Accumulator Ring example
Full ALS-U Storage Ring example

Git Repository

master ▾ SC / applications / ALSU_SR /

ThorstenHellert Custom ID pass method for r

..

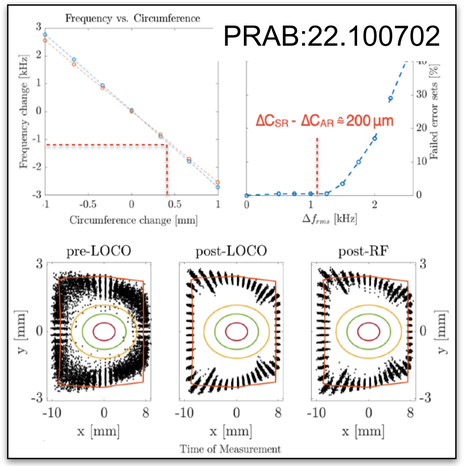
- IDLibrary
- Multipoles
- Studies
- lattices
- calcLatticeProperties_ALSU_SR.m
- crawlClusterJob.m
- getBPM2QuadPairing_ALSU_SR.m
- locoTH.m
- locoresponsematrixFull.m

Annotated Scripts

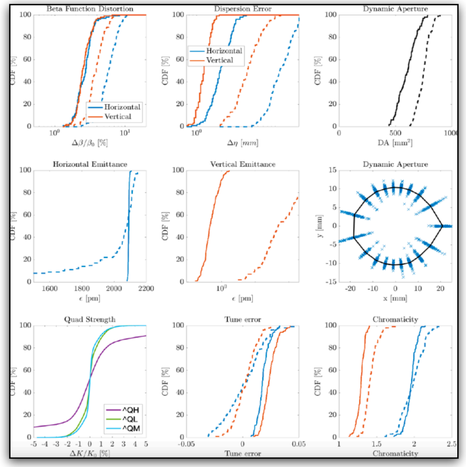
```
% Initialize toolkit
SC = SCinit(RING);

% Register ALSU-SR
[SC,BPMords,CMords] = register_ALS
% Save ideal SC state for ID compe
results.SCrefID = SC;
% Save BPM and CM ords used in orb
results.BPMords = BPMords;
results.CMords  = CMords;

% Define apertures
SC.RING = setApertures_ALSU_SR(SC.
```

Toolkit Used in Design Process at Various Laboratories

ALS-U (*T. Hellert*)



NSLS-II (*A. Khan*)



Diamond-II (*D. Amorin*)

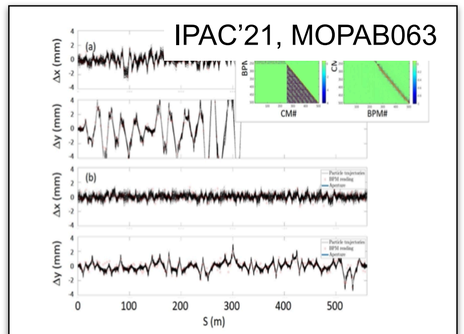
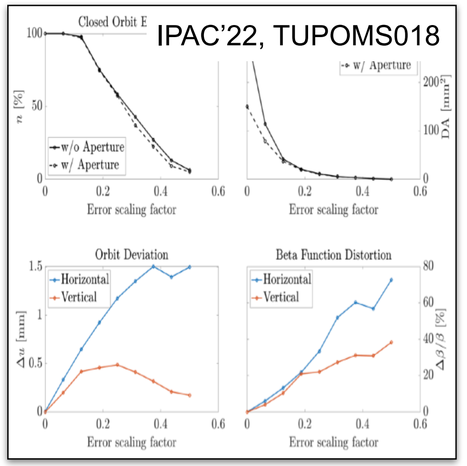


Figure 3: First turn threading in the Diamond-II SR. (Top) initial attempt with total loss of the beam, (bottom) 1st turn transmission completed with beam ready for a 2-turn threading. Inset: 1-turn RM and its pseudo-inverse.

PETRA IV (*T. Hellert*)



ALBA-II (*Z. Marti Diaz*)

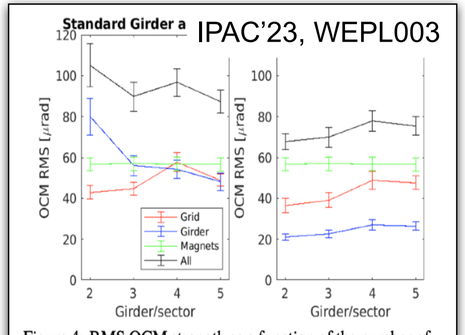
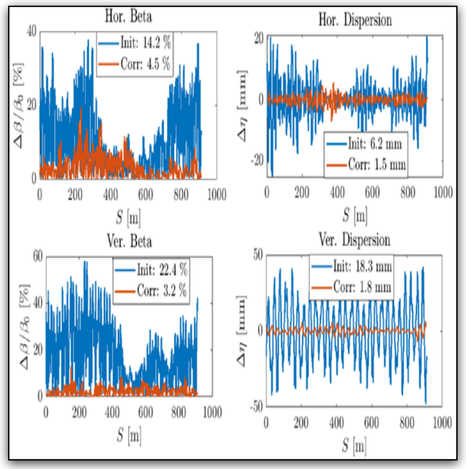


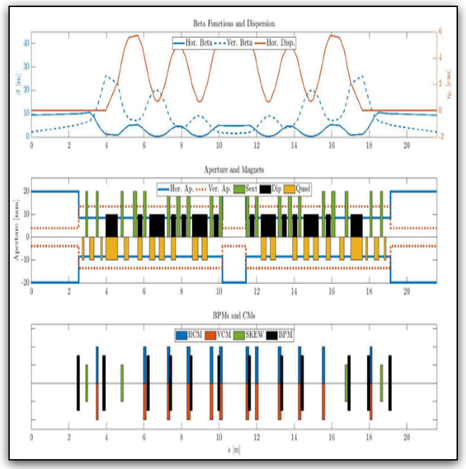
Figure 4: RMS OCM strength as a function of the number of girders. The lines in color represent the result only including one of the three misalignment components of Table 1 The black lines correspond to the result including all misalignment components.

HBSRS (*S. Prakash*)

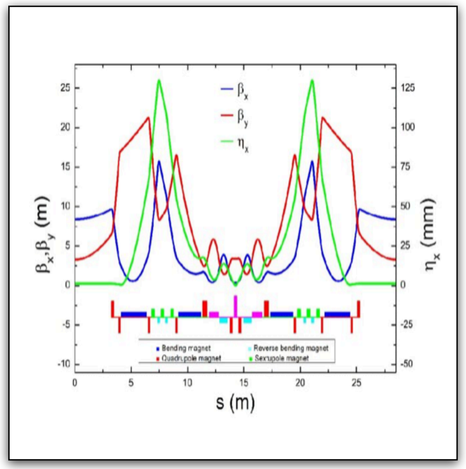


BESSY III (*P. Goslawski*)

Elettra 2.0 (*S. Dastan*)



Korean 4GSR (*J. Kim*)



SOLEIL U (*O. Garcia*)

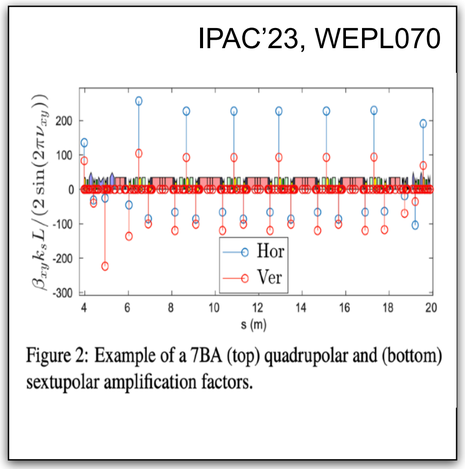


Figure 2: Example of a 7BA (top) quadrupolar and (bottom) sextupolar amplification factors.

Commissioning Simulations for the ALS-U Storage Ring

Error Analysis by Start to Finish Commissioning Simulations

- Commissioning Simulations Carried out for all Subsystems:
  - Booster-to-Accumulator Transfer Line
  - Accumulator Ring
  - Storage Ring
  - Accumulator-to-Storage Ring Transfer Line
  - Storage Ring-to-Accumulator Transfer Line
- Specific Errors and Perturbations:
  - Misalignments from sectors, plinths and rafts
  - Dynamic multipoles from (corrector-)coil excitations
  - Septa leakage fields
  - Pulsed elements stability and pulse shape
  - Differential circumference change between AR/SR with locked RF frequency
  - Planar undulators and EPUs

Storage Ring Correction Chain

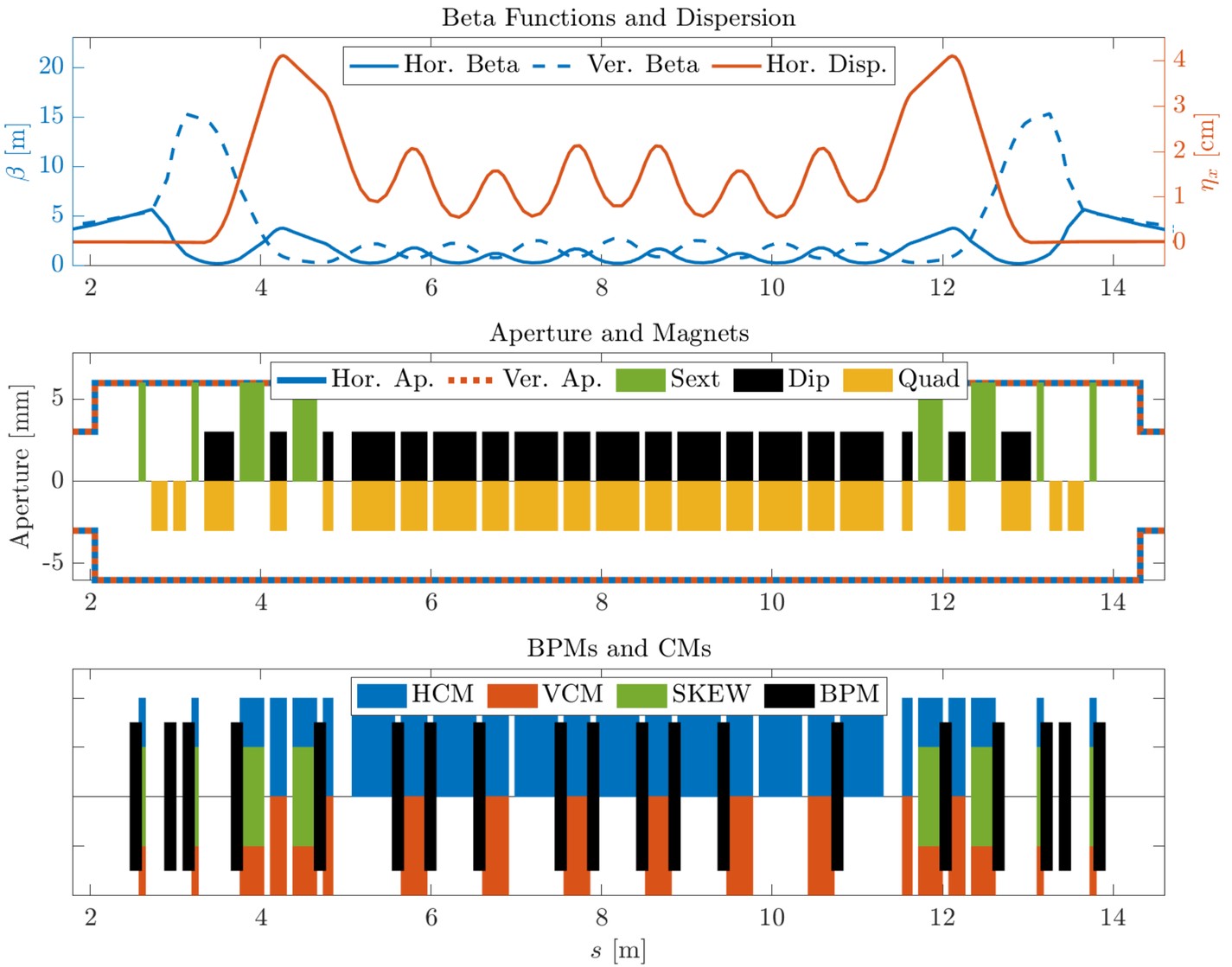
- Initial Transmission
  - Achieve first turn transmission
  - 2-turn trajectory correction
- Multi-Turn Transmission
  - Trajectory based BBA
  - Static injection error correction
- Sextupole Ramp-Up
  - In loop with 2-turn trajectory correction
- Achieve Beam Capture
  - RF phase correction
  - RF frequency correction
  - Tune scan
- Linear Optics Correction
  - Beam based alignment
  - Closed orbit correction
  - LOCO based optics correction
- ID Compensation
  - Close IDs and include kick maps
  - Global optics correction
  - Evaluation of lattice properties

Error Amplitudes for ALS-U Commissioning Simulations

- Magnet errors
  - Magnet offset = 35 μm
  - Sector offset = 100 μm
  - Raft offset = 30 μm
  - Raft roll = 100 μrad
  - Magnet roll/pitch/jaw = 200 μrad
  - Magnet long. offset = 200 μm
  - Magnet strength = 1E-3
  - Magnet calibration = 1E-4
- Static injection errors
  - Δx = 500 μm
  - Δx' = 200 μrad
  - Δy = 500 μm
  - Δy' = 200 μrad
  - ∂E = 0.1 %
- Diagnostic errors
  - BPM offset = 500 μm
  - BPM cal. error = 5%
  - BPM noise (TbT) = 30 μm
  - BPM noise (CO) = 1 μm
  - BPM roll = 4 mrad
  - CM cal. error = 5%
  - CM roll = 0.2 mrad
- Circumference
  - ΔL = 0.2 mm
- Injection jitter
  - Δx = 10 μm
  - Δx' = 10 μrad
  - Δy = 1 μm
  - Δy' = 0.5 μrad
  - ∂E = 0.01 %
  - Δϕ = 0.1°
- RF errors
  - Δf = 0.1 kHz
  - ΔV = 0.5 %
  - Δϕ = π/2
- Higher order multipoles
  - Systematic from primary coils
  - Systematic from corrector coils
  - Random from primary coils

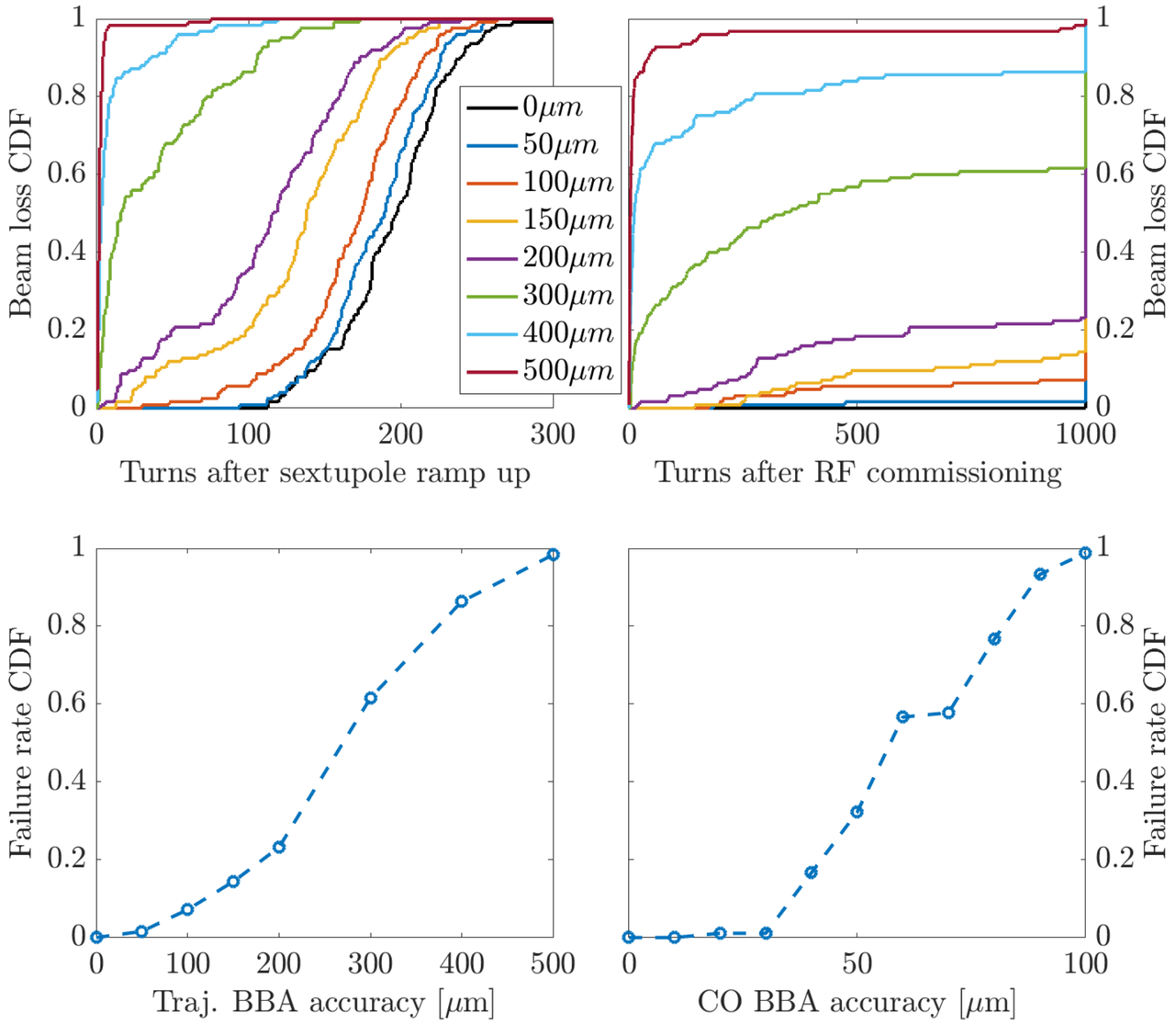
BPM/CM Layout Guided by Commissioning Simulation

- 9 Arcs (+3 with Superbends) with Each:
  - 19 BPMs (suitable for TBT evaluation)
  - 25 hor.corrector magnets (CM)
  - 18 ver. corrector magnets
  - 17 BPMs and 16 CMs used for orbit correction
  - 8 skew quadrupole correctors
- All CMs Embedded in Other Magnets
  - H/V CMs in all sextupoles
  - HCMs in all dipoles (except BEND1)
  - VCM limits: ±0.8 mrad (quad) / ±0.4 mrad (sext)
  - HCM limits: ±0.8 mrad (quad) / ±0.4 mrad (sext) + 5% of corresponding magnet bending angle (combined function magnets!)
- Normal- and Skew Quadrupoles Embedded in Sextupole Magnets
  - Skew limit: 0.1 m^{-2}
  - Normal limit: 0.26 m^{-2}



Importance of BPM Offsets During Commissioning

- Errors included in all runs:
  - RF, Injection, Diagnostic
  - Sys. multipoles, magnet strength and roll errors
  - Girder/Magnet offset
- Errors varied in all runs:
  - Simulated trajectory/orbit BBA accuracy
- Findings:
  - Beam transmission with sextupoles at 500µm initial BPM offset virtually zero
- Conclusion:
  - Reliable BBA procedure based on 2 turn transmission required to store beam
  - Stored beam BBA accuracy of <50um required to allow for successful correction chain



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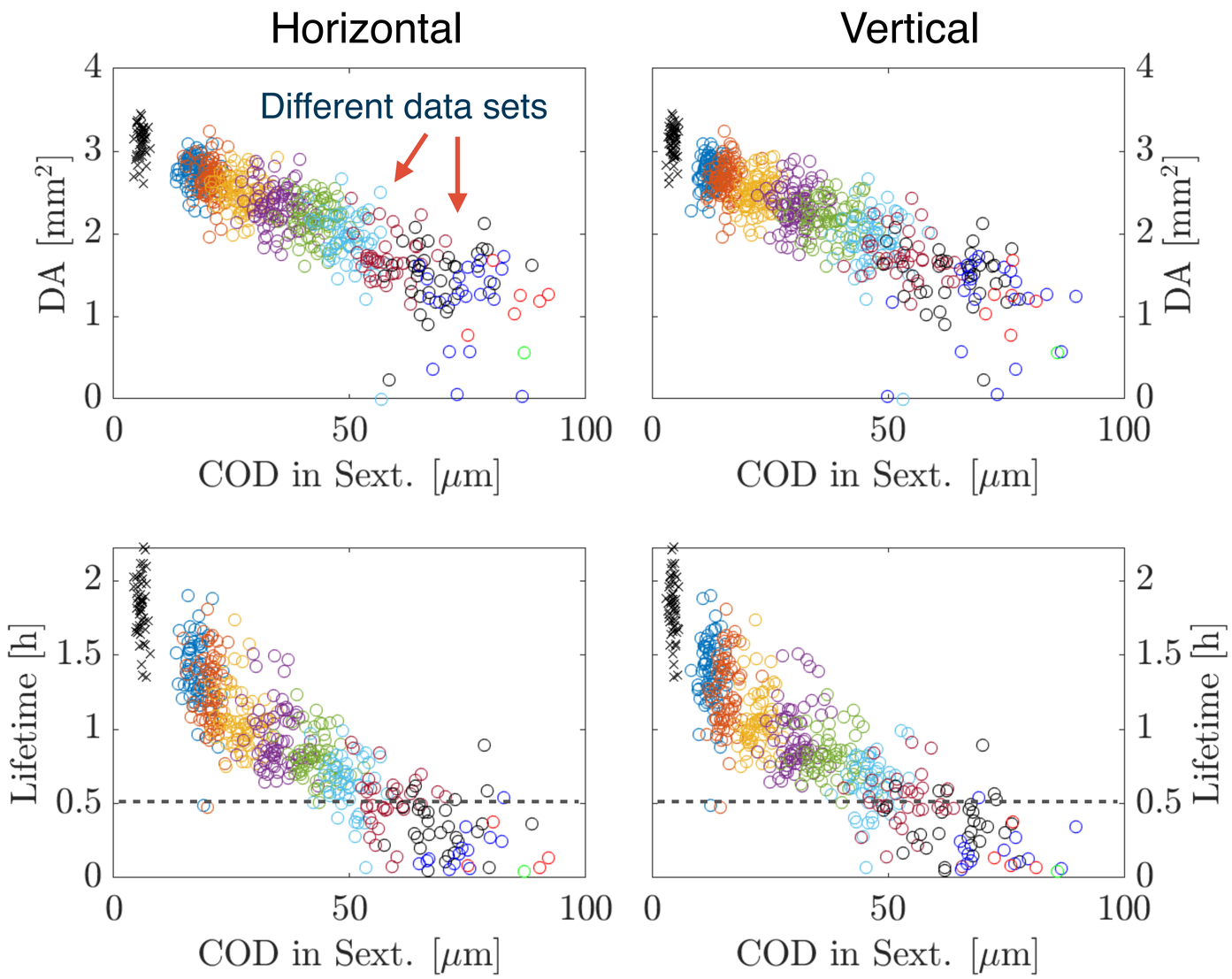
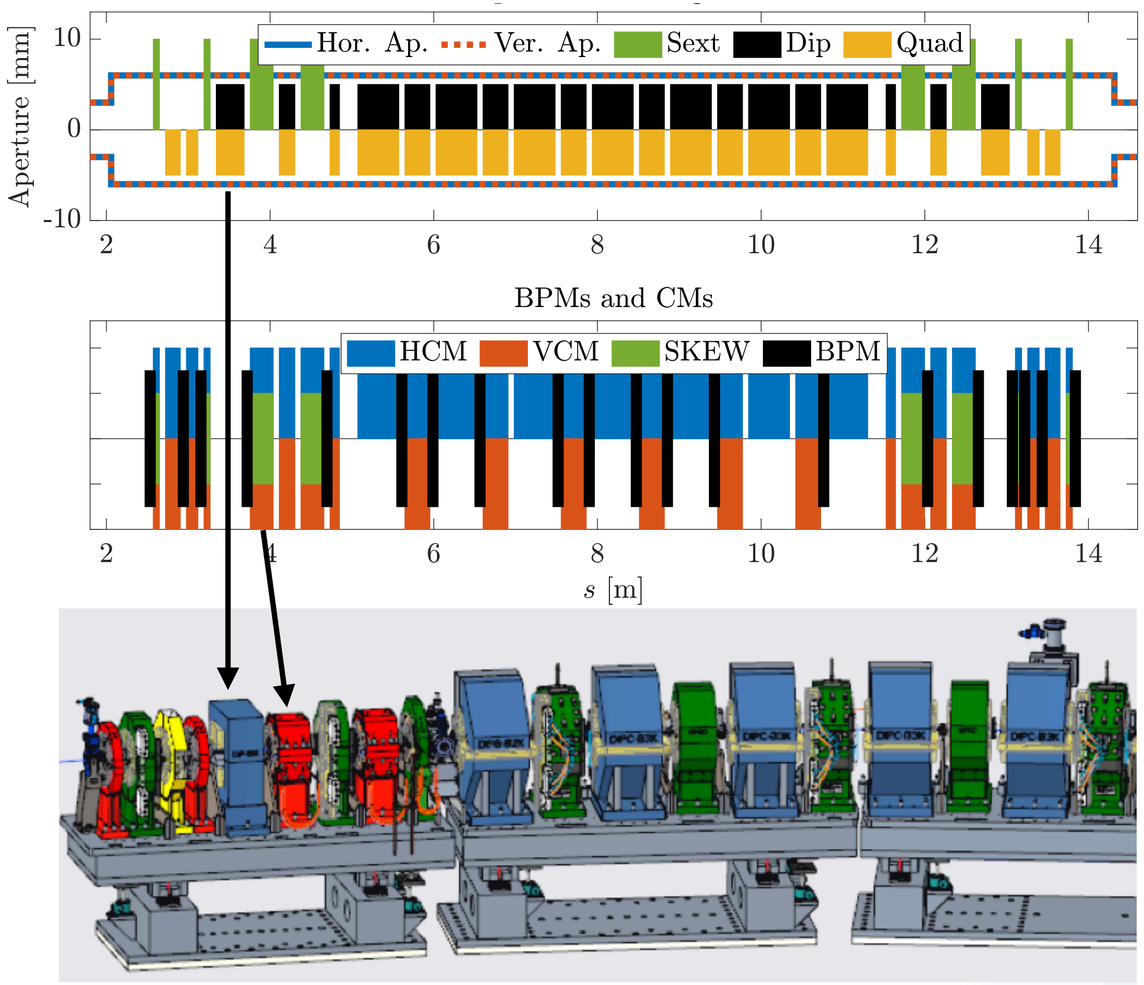
- Errors varied in all runs:
  - Girder/Magnet offset
  - Simulated stored beam BBA accuracy
- Findings:
  - Correlation between pre-LOCO closed orbit deviation (COD) in sextupole magnets and post-LOCO performance
  - Lifetime virtually zero above COD of 50 µm rms
- Conclusion:
  - Small COD in sextupoles most crucial for lattice performance



Beam Based Alignment Challenges

- BBA Chalenges:
  - All but 2 quadrupole families are combined function magnets
  - No suitable quadrupole for BPMs adjacent to sextupole magnets
- Detailed Study of BBA Possibilities Performed:
  - **Regular BBA on quadrupoles**
  - Using main sextupole coils with stored beam
  - Using **quadrupole trim coils in sextupoles** with trajectories (2 turn) & **with stored beam**
  - Assumed K values for quadrupole trim coils: +/- 0.26 m^{-2}



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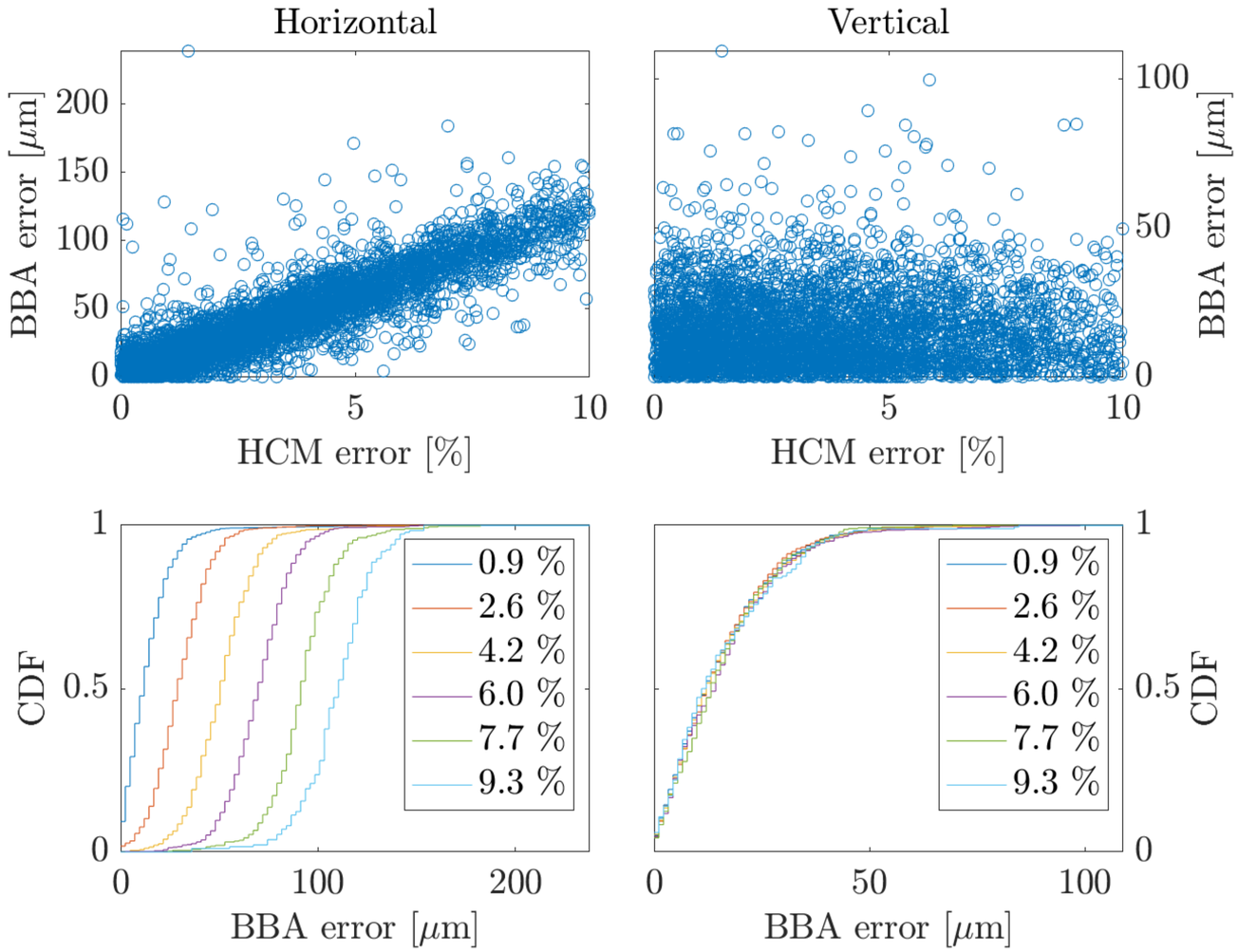
  - Assumed K values for quadrupole trim coils: +/- 0.26 m^{-2}
- Challenge with Combined Function Quadrupoles:
  - HCM trim coil exercised in order to correct for dipole change
  - Dipole compensation compromised by calibration errors of main quadrupole coil and HCM
  - HCM calibration error correction depends on optics correction accuracy
  - Optics correction depends on orbit correction accuracy
  - Orbit correction depend on BBA accuracy

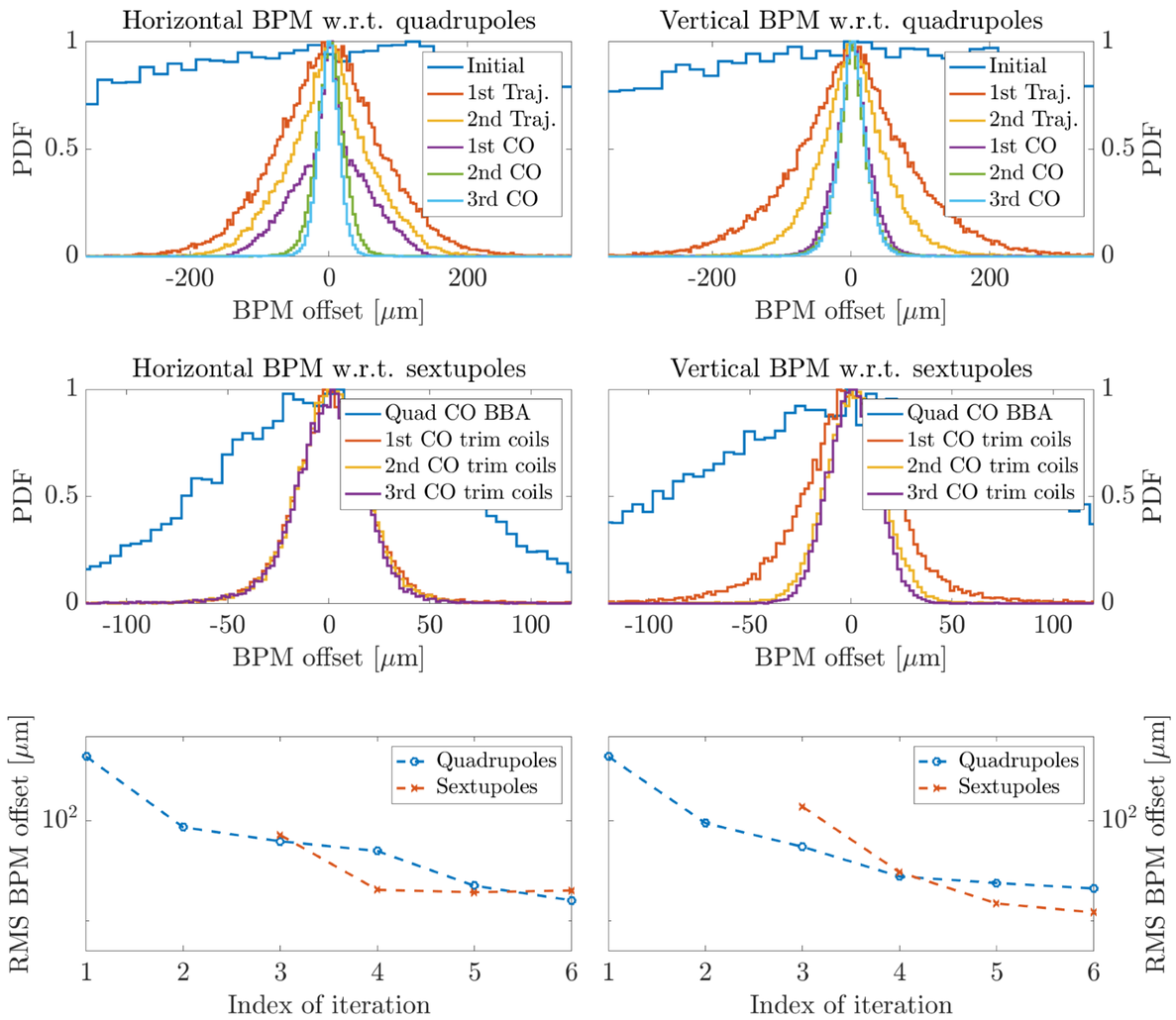


Correction Chain for ALS-U SR Commissioning

- Initial Transmission
  - Achieve first turn transmission
  - 2-turn trajectory correction
- Multi-Turn Transmission
  - Trajectory based BBA
  - Static injection error correction

  ← 2 Iterations
- Sextupole Ramp-Up
  - In loop with 2-turn trajectory correction
- Achieve Beam Capture
  - RF phase correction
  - RF frequency correction
  - Tune scan
- Linear Optics Correction
  - Beam based alignment
  - Closed orbit correction
  - LOCO based optics correction

  ← 3 Iterations
- ID Compensation
  - Close IDs and include kick maps
  - Global optics correction
  - Evaluation of lattice properties



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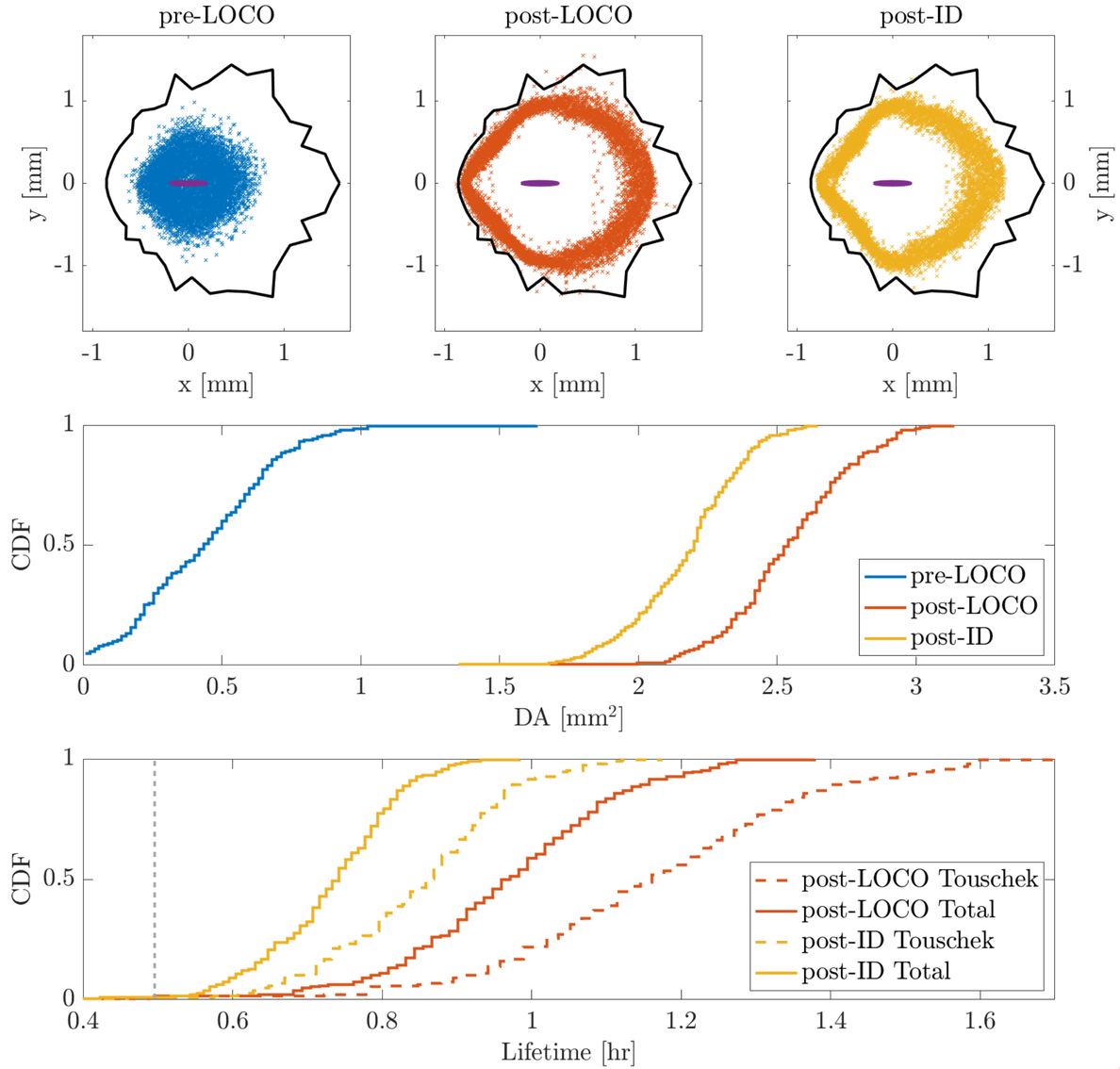

Summary

- Advanced Light Source Upgrade
  - 9 bend achromat lattice with 70pm-rad emittance
  - Very fast commissioning process required
- Development of Commissioning Simulation Toolkit
  - Commissioning simulations are key for the design of future storage rings
  - Wide range of application successfully demonstrated at multiple machines
- High Sensitivity of ALSU-SR Performance on Misalignments
  - Single turn beam based alignment procedure required to store beam
  - Orbit errors in sextupole magnets must be limited to ~30µm
- Effective Correction Chain Established
  - BBA on combined function quadrupoles
  - Quadrupole trim coils on sextupole magnets
  - Performance requirements achieved