



Recent Developments of the Toolkit for Simulated Commissioning

Thorsten Hellert

Outline

- **Introduction**
 - Historical Context of Commissioning Simulations
- **Simulated Commissioning Toolkit Design Features**
 - Workflow
 - Error Model
 - Examples
- **Recent Developments**
 - SC to elegant corrected lattice converter
 - pySC
 - Automated startup scripts using MML

Error Analysis in Storage Ring Design - Past and Present

- **Generate Error Ensembles**

- Gradient errors, misalignments, girders, etc.

- **Evaluate Lattice Performance**

- Beta beat, orbit error

- Limit error amplitudes to provide acceptable performance

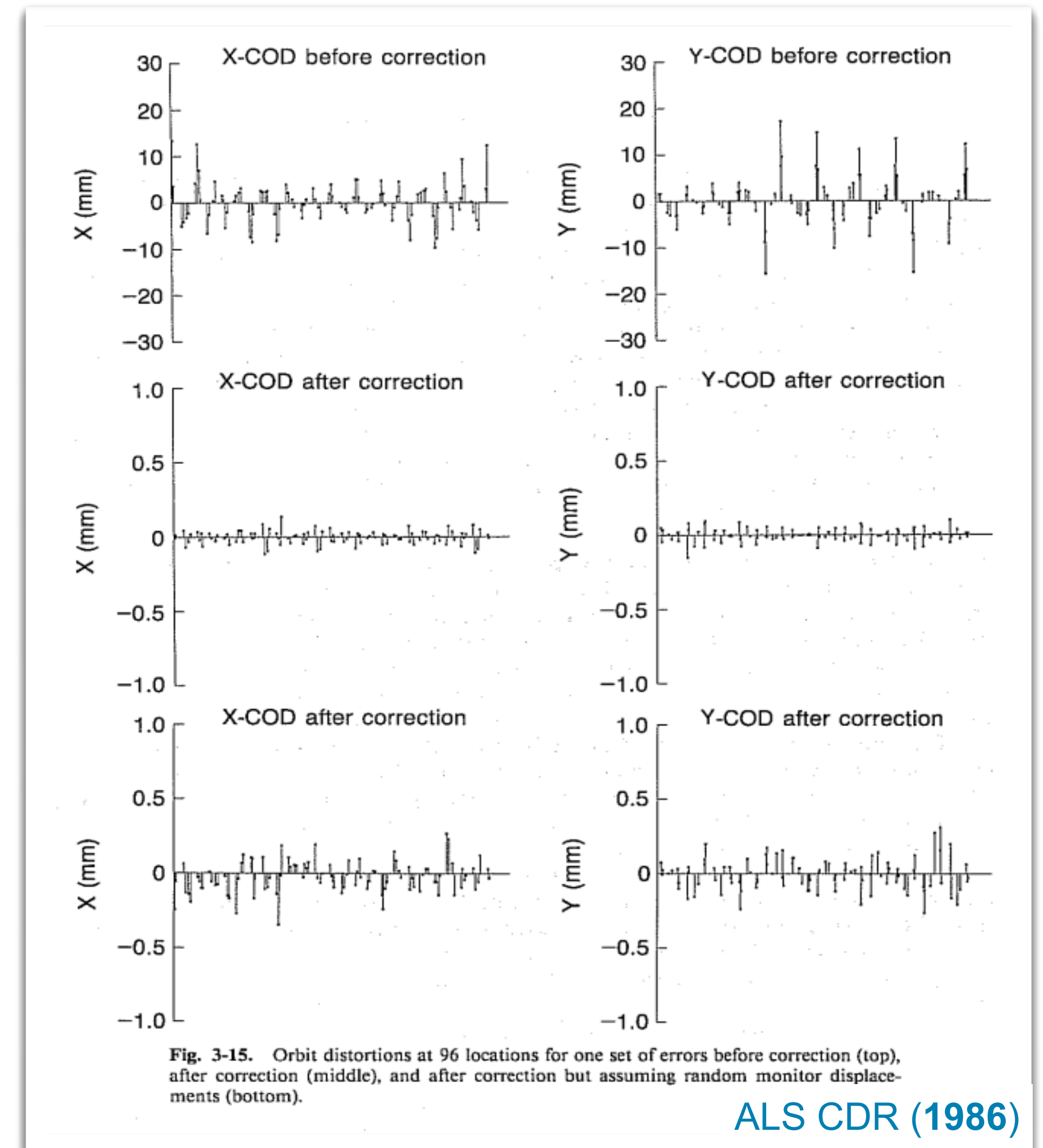
Construction of the DESY Synchrotron, 1961



Error Analysis in Storage Ring Design - Past and Present

Closed Orbit Distortion Before and After Correction for ALS

- **Generate Error Ensembles**
 - Gradient errors, misalignments, girders, etc.
- **Correct Lattice**
 - Closed orbit correction
- **Evaluate Lattice Performance**
 - Beta beat, orbit error
- **Statistical Evaluation**
 - Calculate statistics of lattice performance
 - Limit error amplitudes to provide acceptable performance

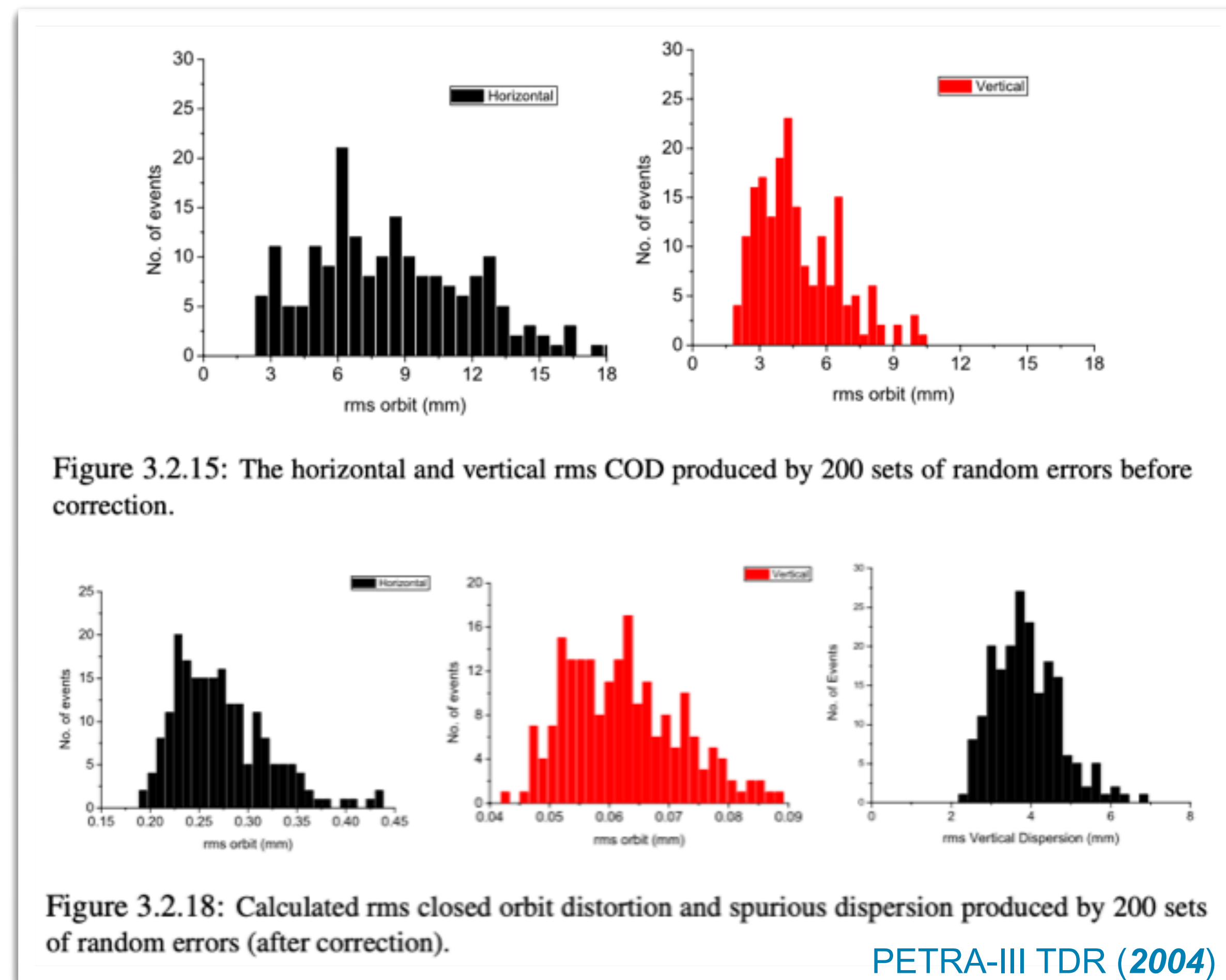


(Magnet misalignments = 150 μ m)

Error Analysis in Storage Ring Design - Past and Present

- **Generate Error Ensembles**
 - Gradient errors, misalignments, girders, etc.
- **Correct Lattice**
 - Closed orbit correction
 - Linear optics correction
- **Evaluate Lattice Performance**
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Closed Orbit Distortion and Dispersion Error for PETRA-III

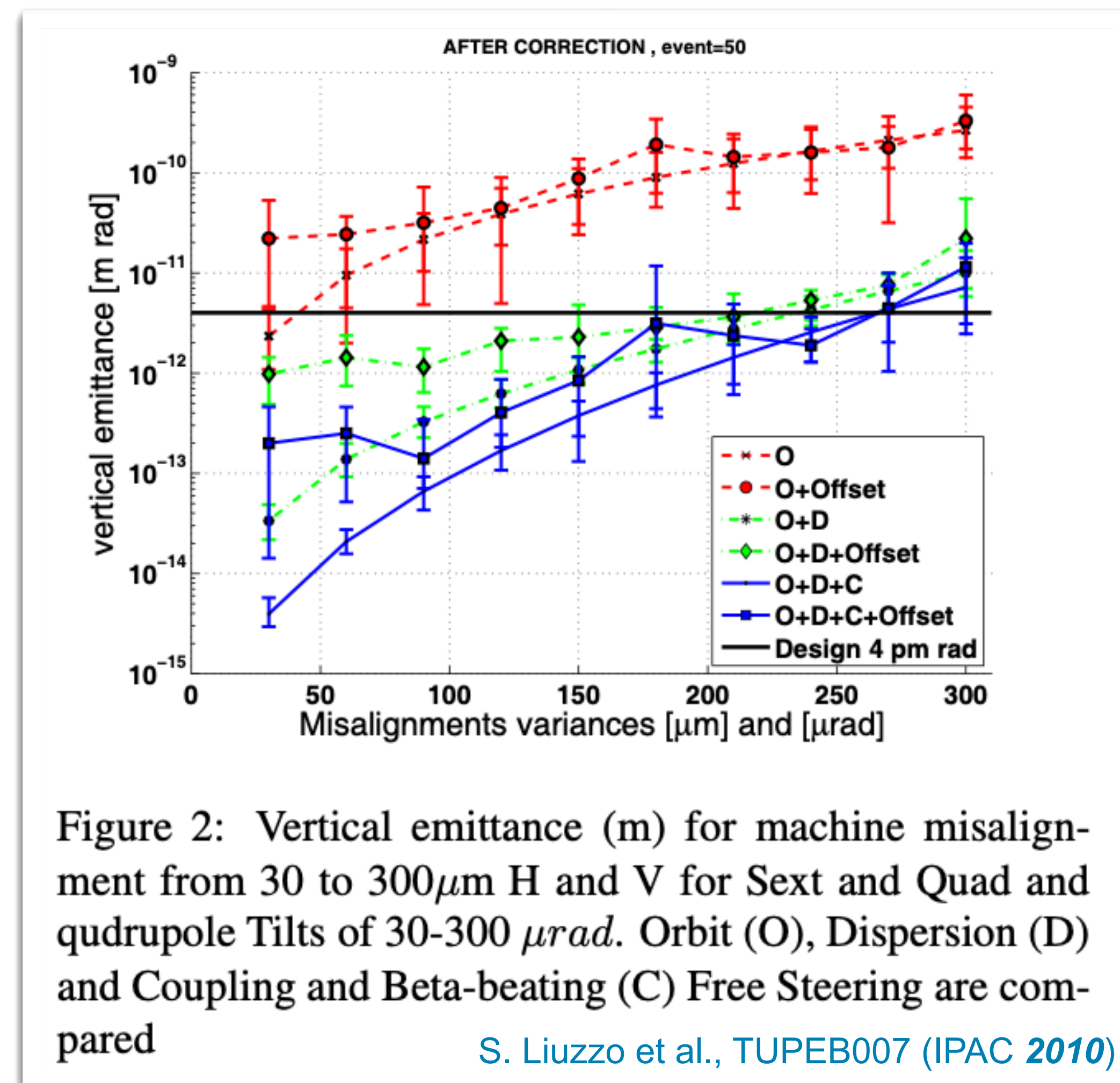


(Magnet misalignments = 250 μ m)

Error Analysis in Storage Ring Design - Past and Present

Dispersion-, Coupling- and Beta-Beat-Free Steering for SuperB

- **Generate Error Ensembles**
 - Gradient errors, misalignments, girders, etc.
- **Correct Lattice**
 - Closed orbit correction
 - Linear optics correction
- **Evaluate Lattice Performance**
 - Beta beat, orbit error
 - Injection efficiency, dynamic aperture, lifetime
- **Statistical Evaluation**
 - Calculate statistics of lattice performance
 - Limit error amplitudes to provide acceptable performance



(Magnet misalignments < 300 μm)

Error Analysis in Storage Ring Design - Past and Present

- **Generate Error Ensembles**

- Gradient errors, misalignments, girders, etc.

- **Correct Lattice**

- ~~Closed orbit correction~~ => *no closed orbit!*
- Linear optics correction

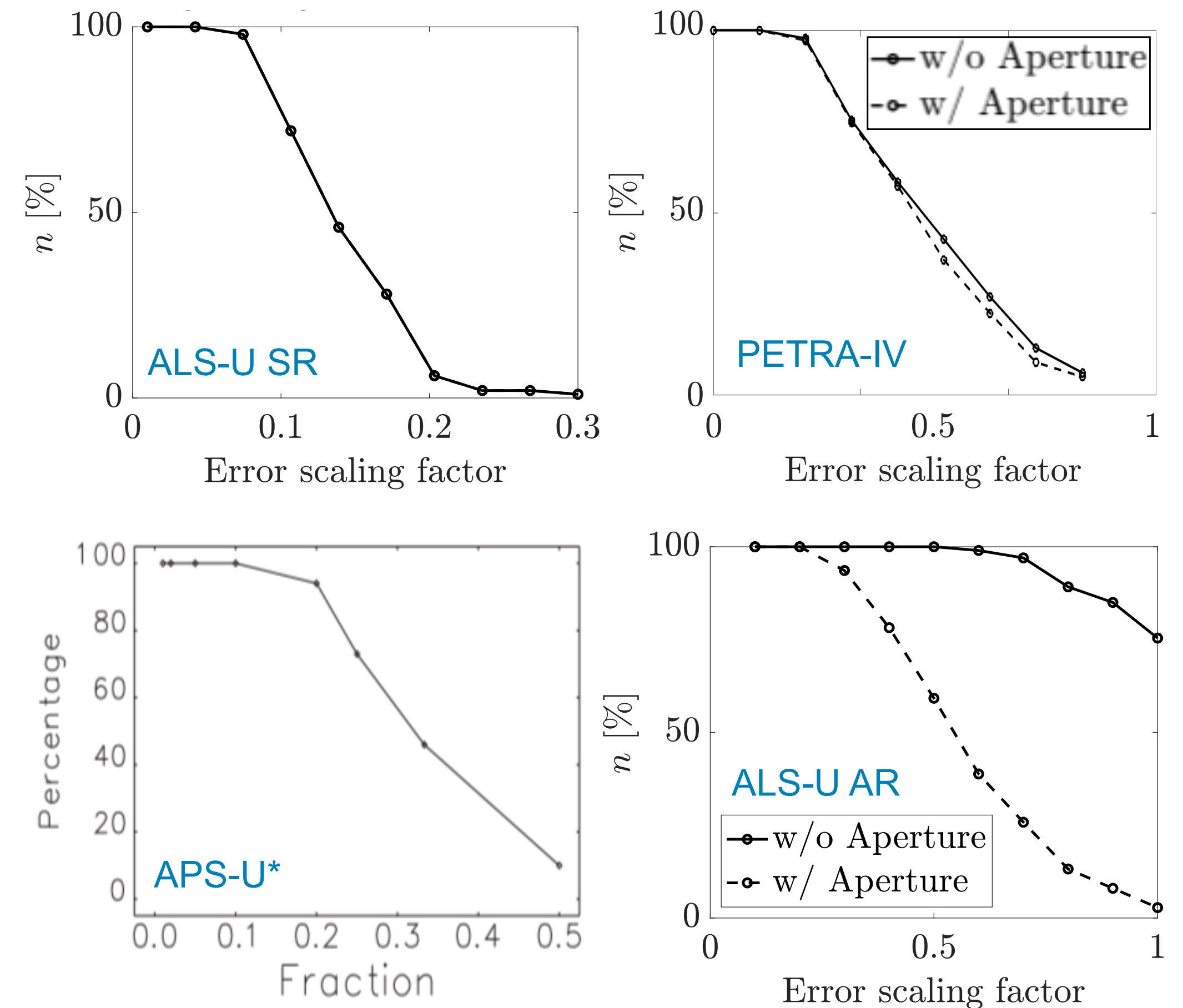
- **Evaluate Lattice Performance**

- Beta beat, orbit error
- Injection efficiency, dynamic aperture, lifetime

- **Statistical Evaluation**

- Calculate statistics of lattice performance
- Limit error amplitudes to provide acceptable performance

Closed Orbit Existence For Increasing Errors



*) V. Sajaev, PRAB 22,040102

Error Analysis in Storage Ring Design - Past and Present

- **Generate Error Ensembles**

- Gradient errors, misalignments, girders, etc.

- **Correct Lattice**

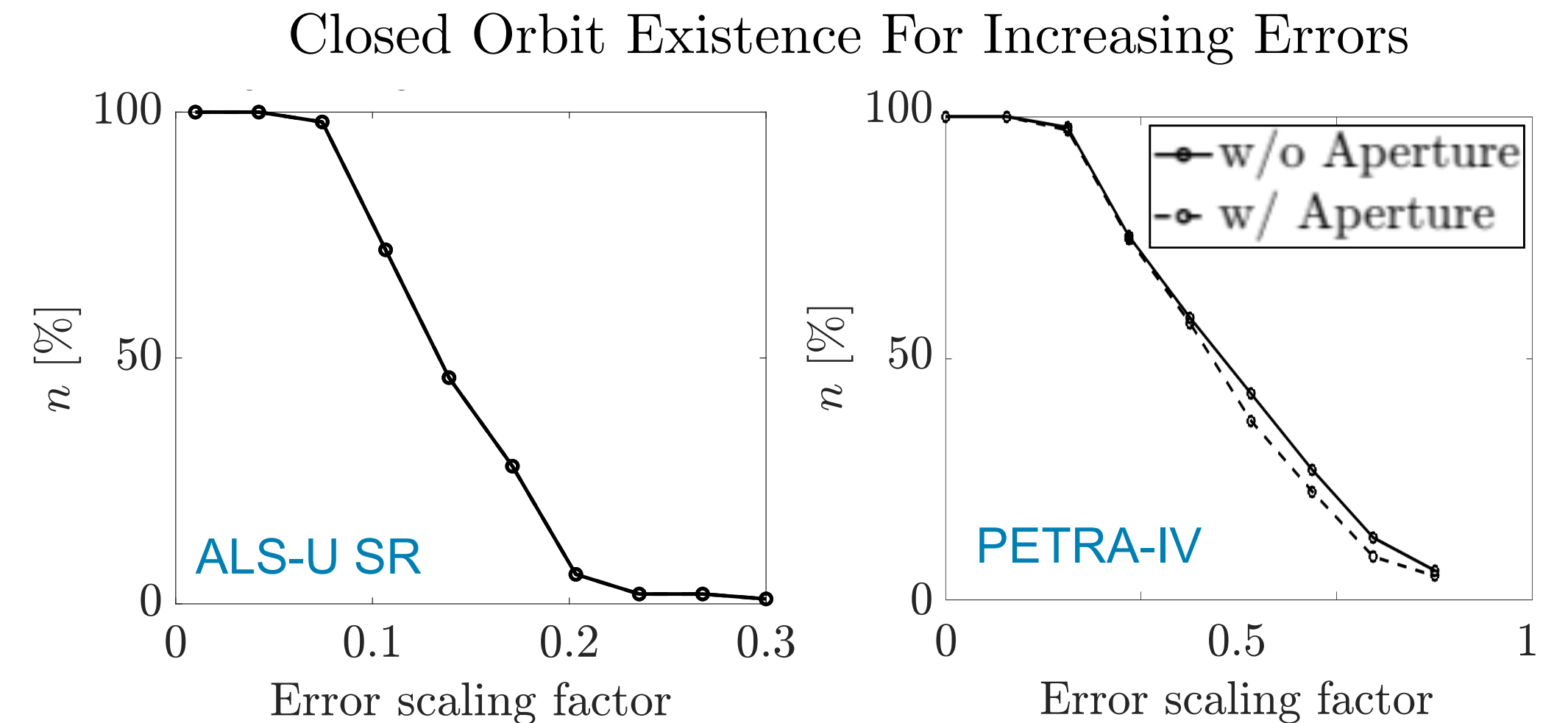
- ~~Closed orbit correction~~ => *no closed orbit!*
- Linear optics correction

- **Evaluate Lattice Performance**

- Beta beat, orbit error
- Injection efficiency, dynamic aperture, lifetime

- **Statistical Evaluation**

- Calculate statistics of lattice performance
- Limit error amplitudes to provide acceptable performance



	Girder to Girder	Magnet to Magnet
ALS-U	30μm/50μm	30μm
APS-U	100μm	30μm
PETRA-IV	100μm	30μm
Diamond-II	150μm	35-50μm
SOLEI-II	50μm	30μm
ALBA II	50-100μm	30μm

Error Analysis in Storage Ring Design - Past and Present

- **Generate Error Ensembles**
 - Gradient errors, misalignments, girders, etc.
- **Correct Lattice**
 - Start to finish commissioning simulation as realistic as possible*
- **Evaluate Lattice Performance**
 - Beta beat, orbit error
 - Injection efficiency, dynamic aperture, lifetime
- **Statistical Evaluation**
 - Calculate statistics of lattice performance
 - Limit error amplitudes to provide acceptable performance

- **Initial Transmission** ALS-U SR
 - 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 and 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

*) V. Sajaev et al., MOPMA010 (2015)

*) S. Liuzzo et al., WEPIK061 (2017)

*) T. Hellert et al., THPMF078 (2018)

Simulated Commissioning Toolkit Design Features

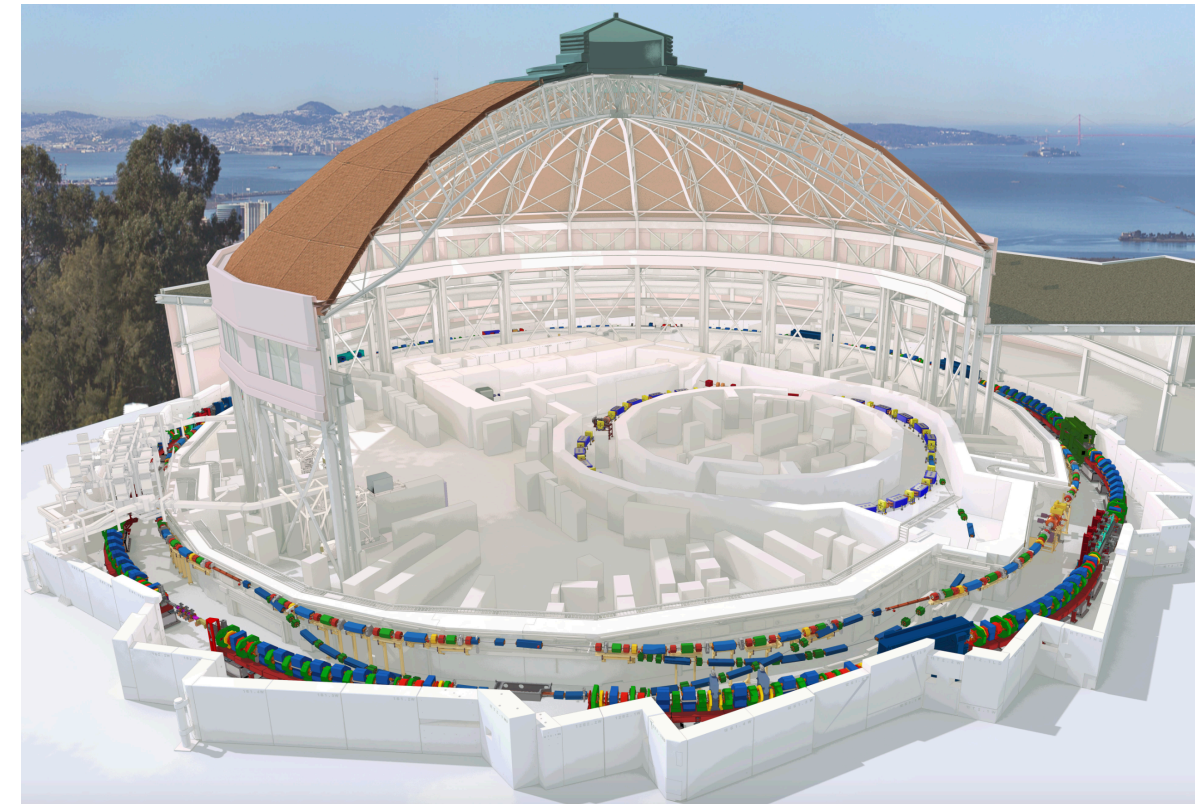


Limited Accessibility of Machine Properties

Power supplies



Operating machine



High level controls



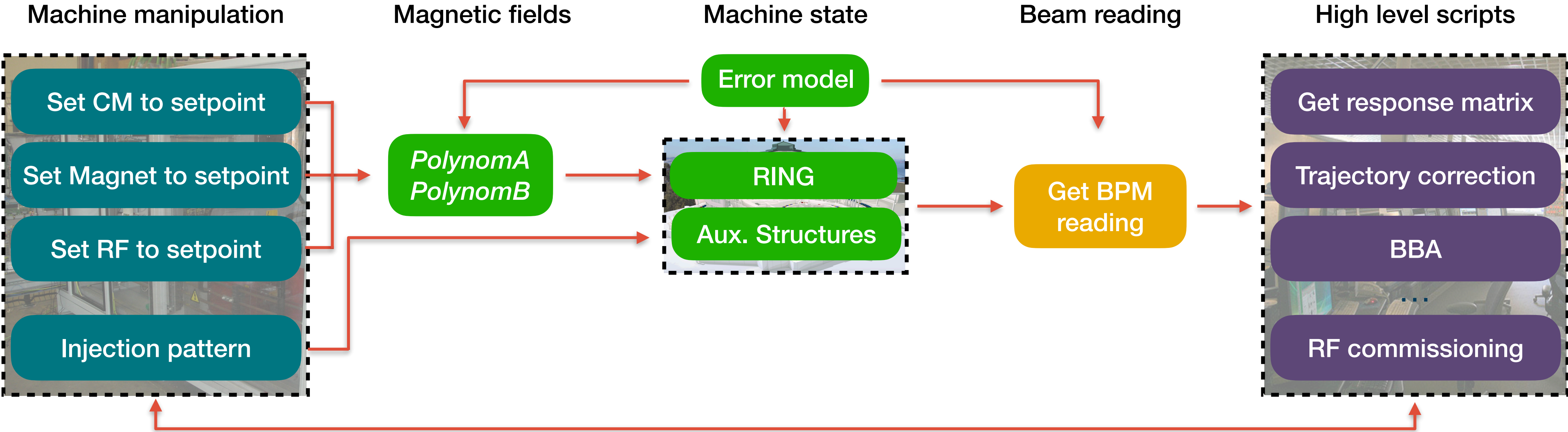
Diagnostics
devices

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
- BPM sum signal
- CM cal. error
- CM roll
- CM / skew-quad limits

- **Support Structure**

- Rafts, Plinths, Sections
- 3D Roll & Offsets

- **Circumference**

- **Higher Order Multipoles**

- Systematic for arbitrary coil excitations
- Random

- **Magnets**

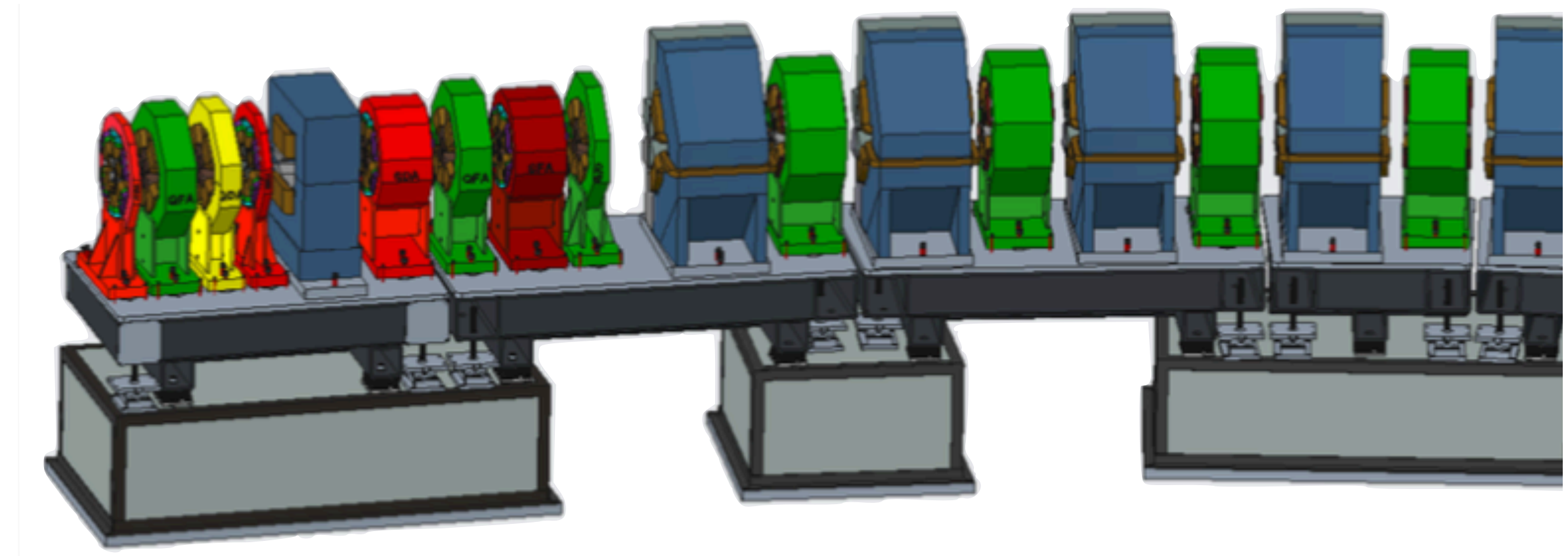
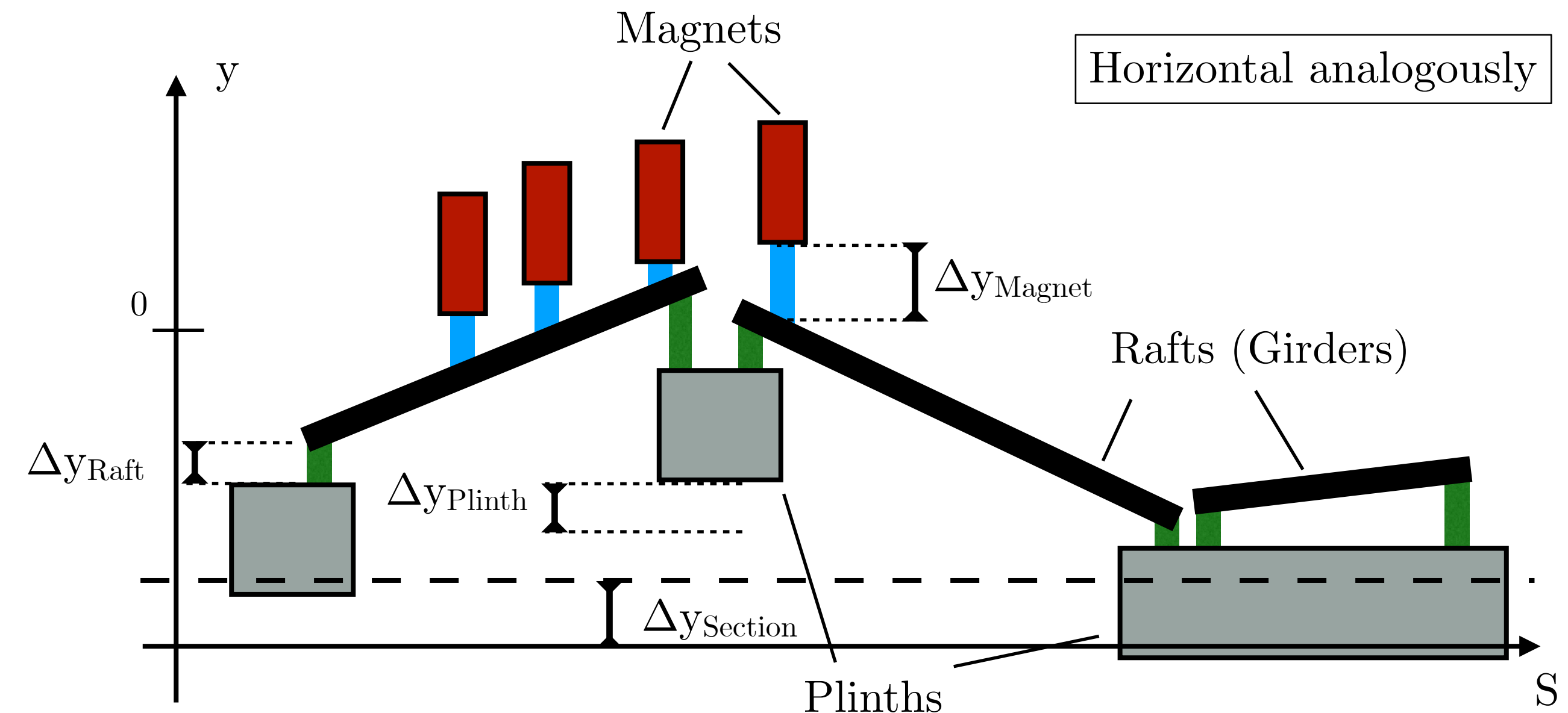
- 3D Offset
- 3D Roll
- Strength
- Calibration

- **RF Errors**

- Phase
- Frequency
- Voltage

- **Injection**

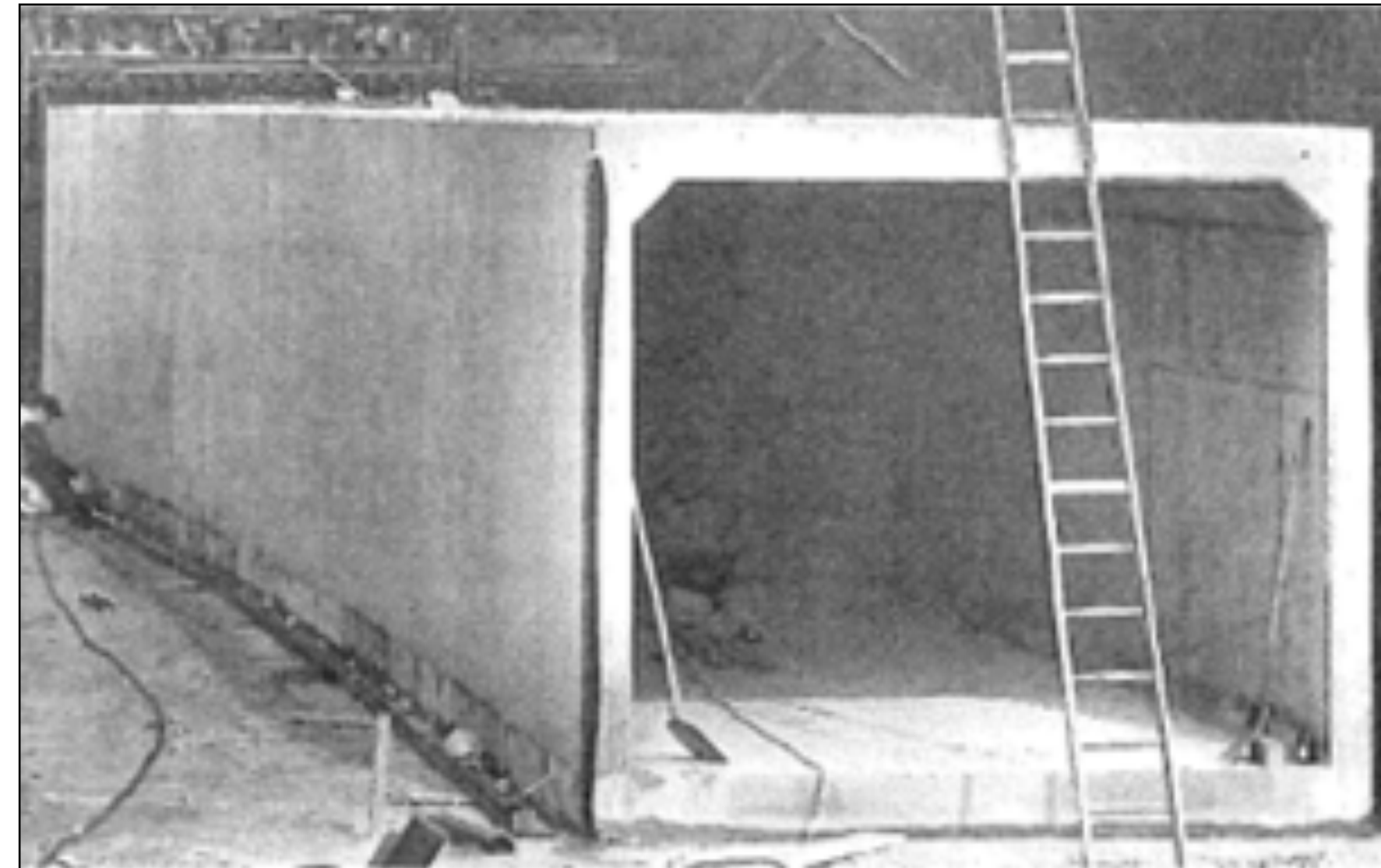
- Static
- Jitter



Large Number of Error Sources Included

Tunnel Cracks for PETRA-IV

- **Diagnostic Errors**
 - BPM offset
 - BPM cal. error
 - BPM noise (TbT/CO)
 - BPM roll
 - BPM sum signal
 - CM cal. error
 - CM roll
 - CM / skew-quad limits
- **Support Structure**
 - Rafts, Plinths, Sections
 - 3D Roll & Offsets
- **Circumference**
- **Higher Order Multipoles**
 - Systematic for arbitrary coil excitations
 - Random
- **Magnets**
 - 3D Offset
 - 3D Roll
 - Strength
 - Calibration
- **RF Errors**
 - Phase
 - Frequency
 - Voltage
- **Injection**
 - Static
 - Jitter



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- CM / skew-quad limits

- **Support Structure**

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- 3D Roll & Offsets

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- Random

- **Magnets**

- 3D Offset
- 3D Roll
- Strength
- Calibration

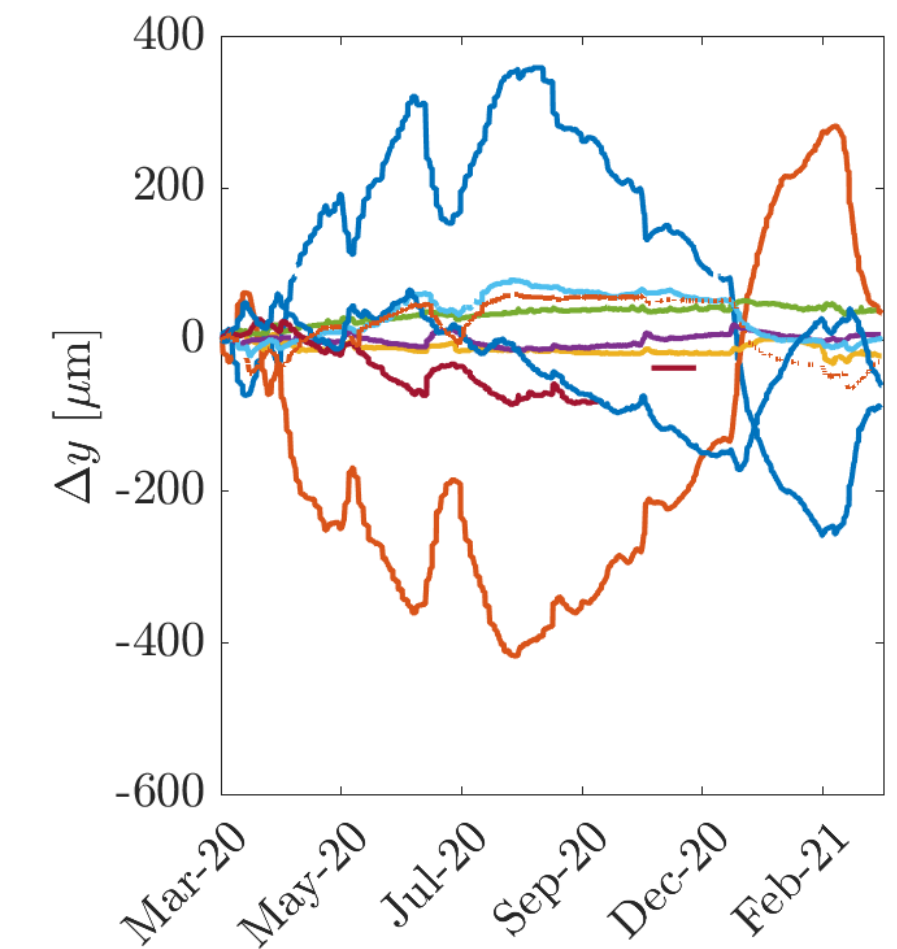
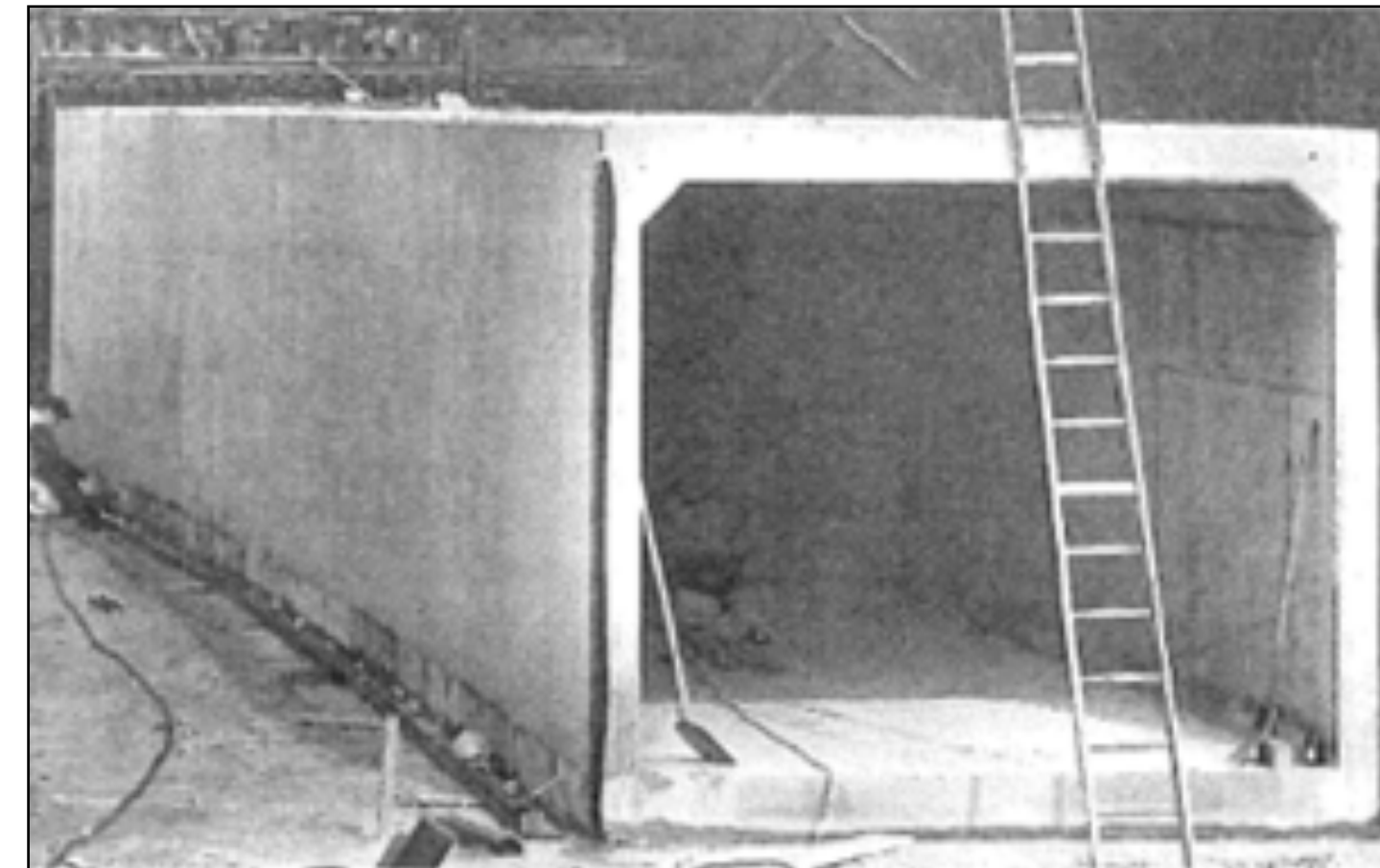
- **RF Errors**

- Phase
- Frequency
- Voltage

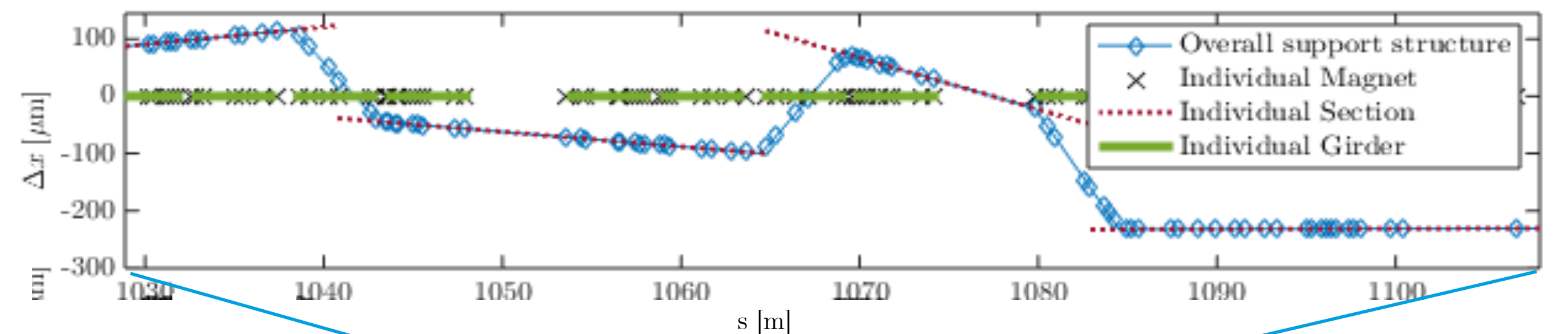
- **Injection**

- Static
- Jitter

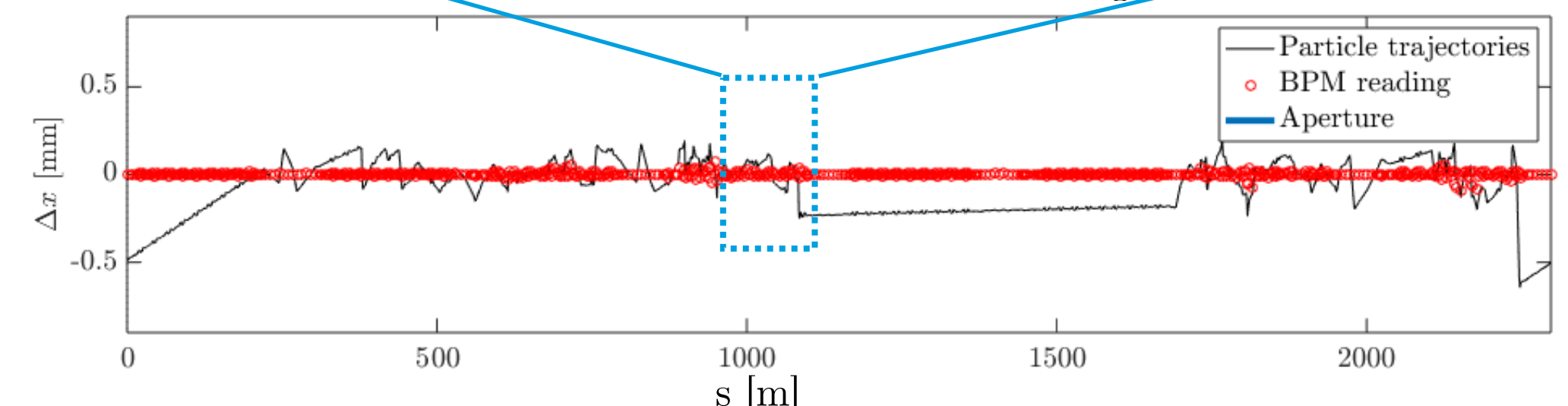
Tunnel Cracks for PETRA-IV



Horizontal Offset of Accelerator Components

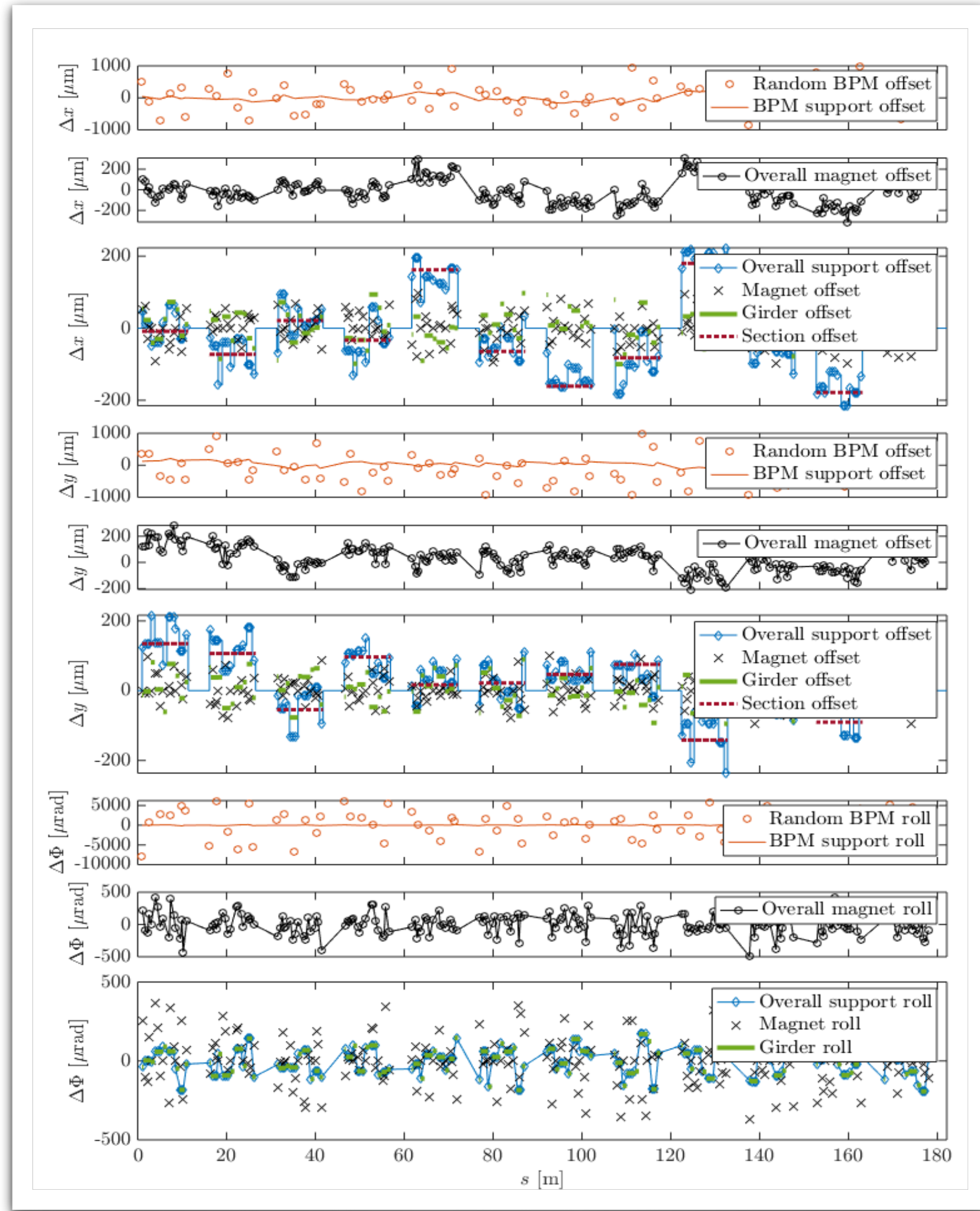


Closed orbit and BPM readings

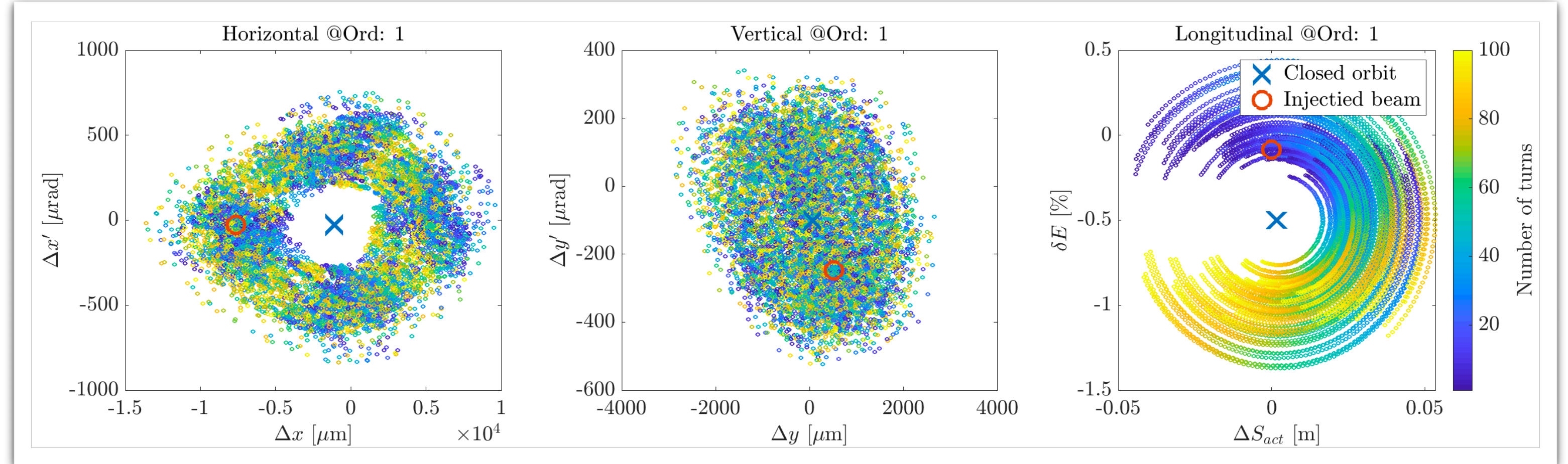


Various Visualization Tools for Easy R&D

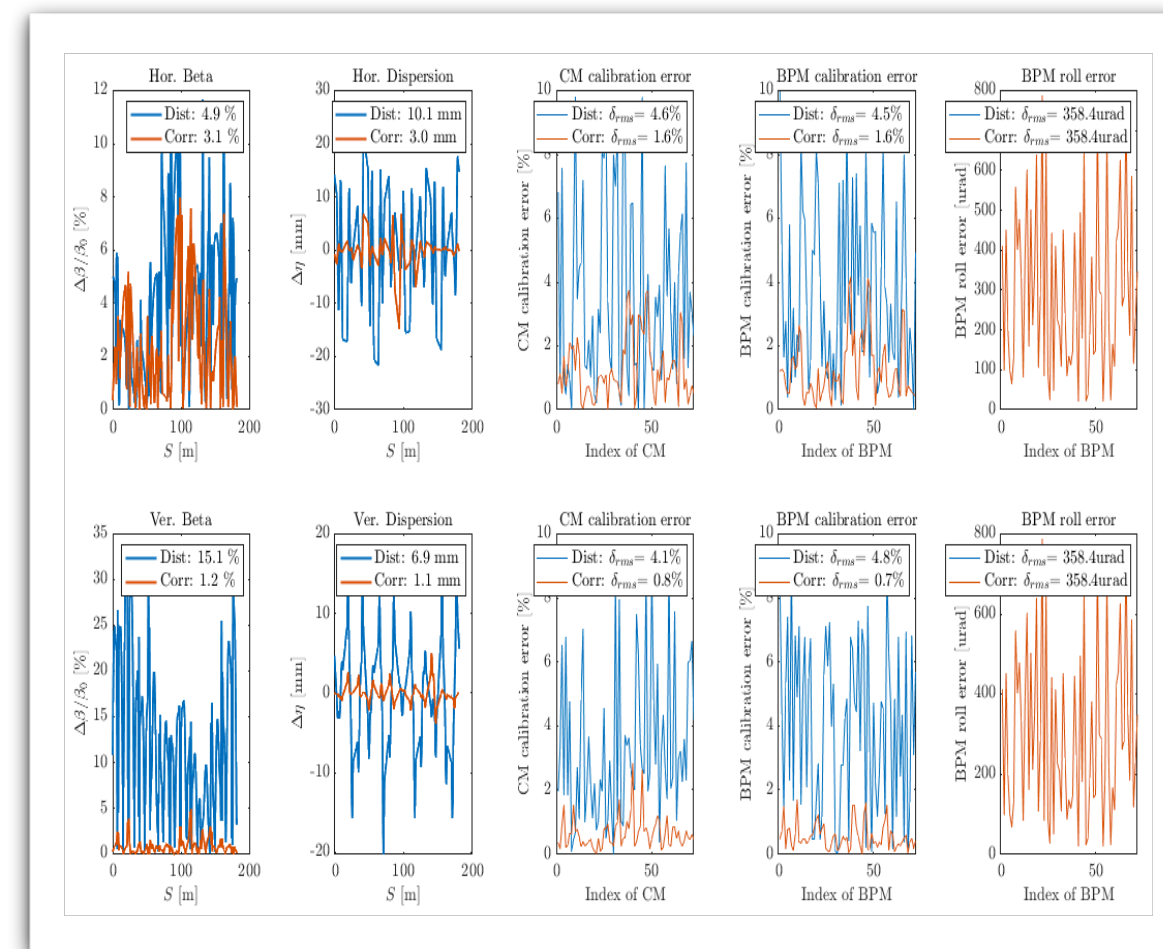
Misalignments



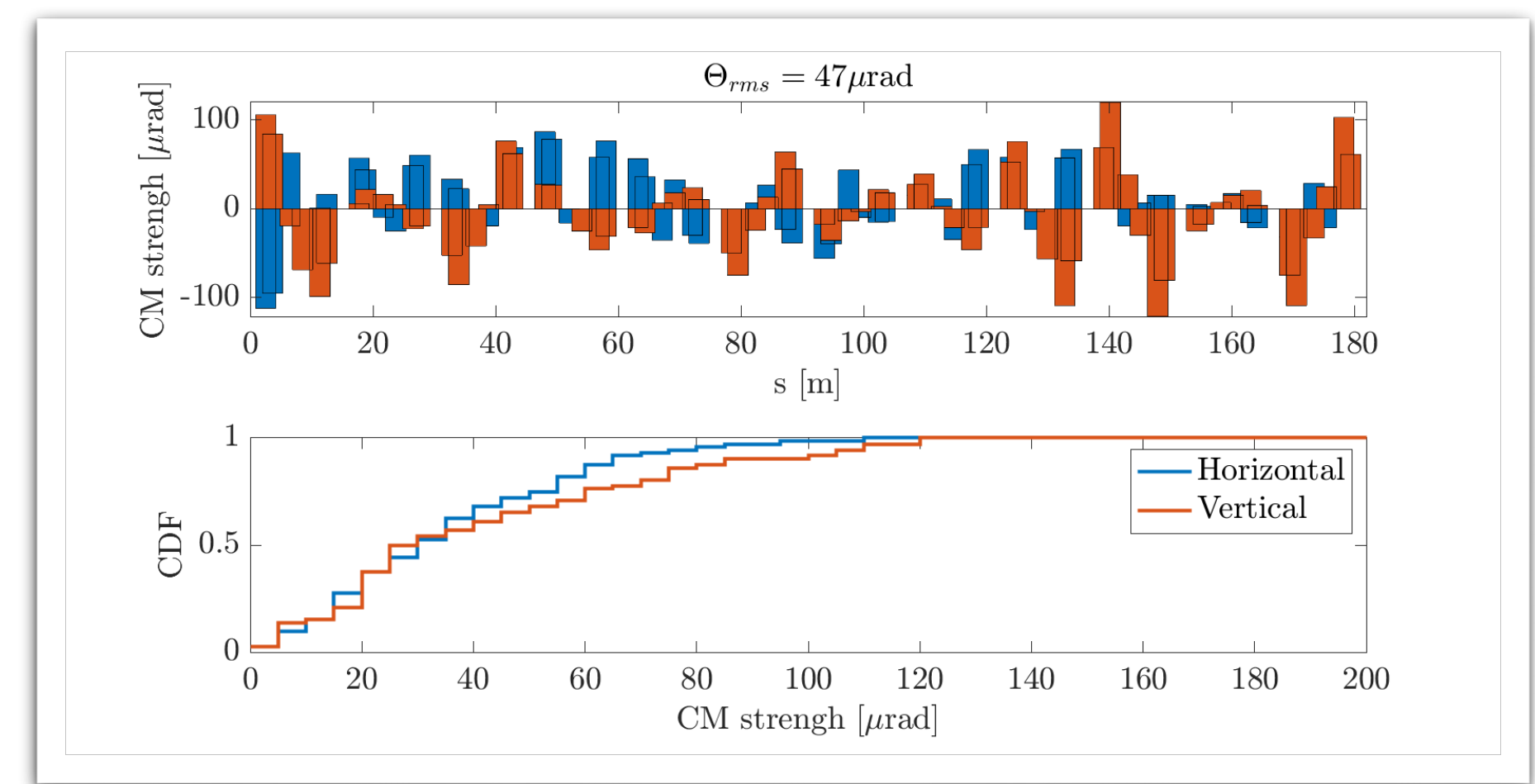
Turn-by-turn Phase Space



LOCO Status

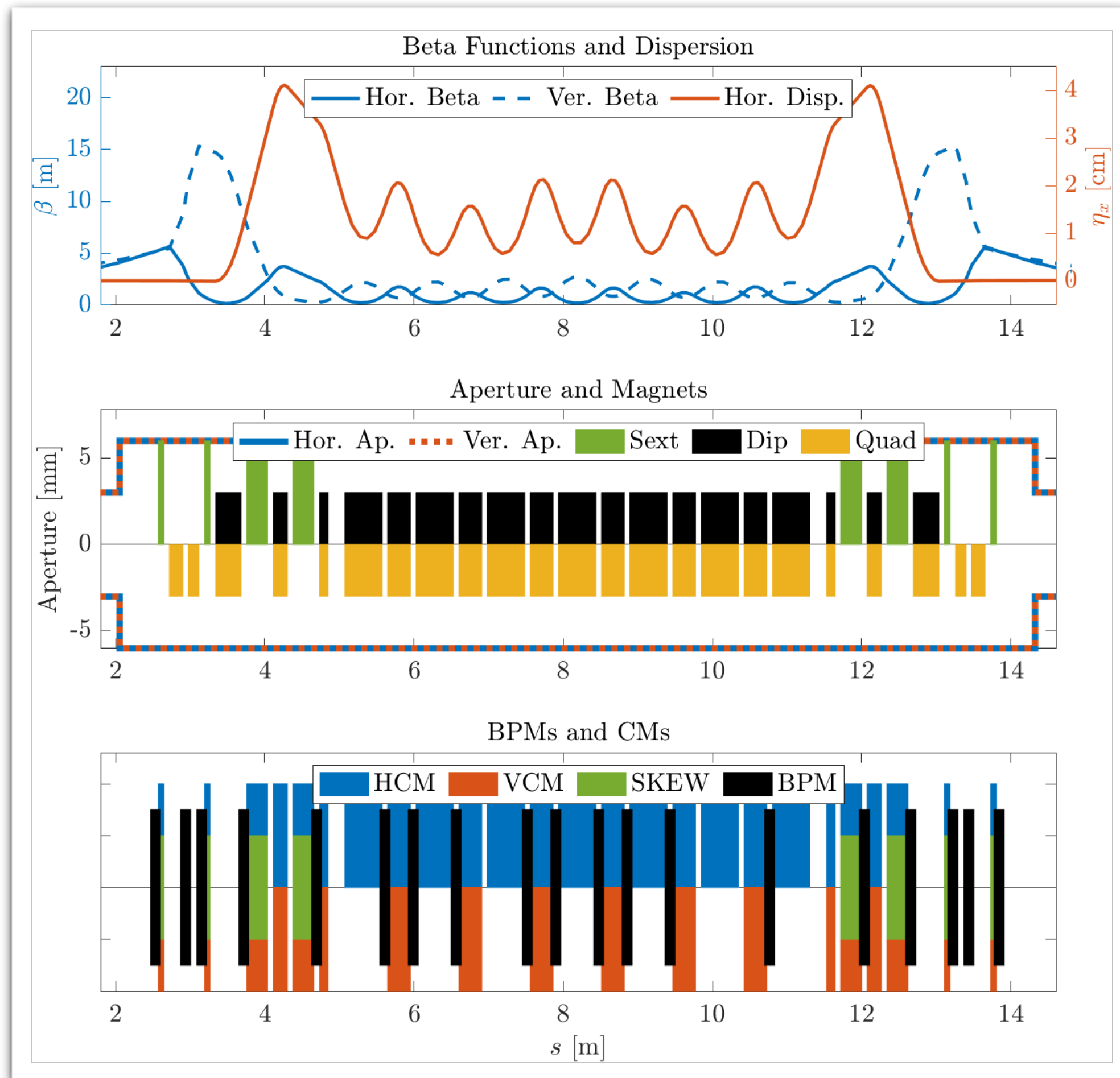


Corrector Strength

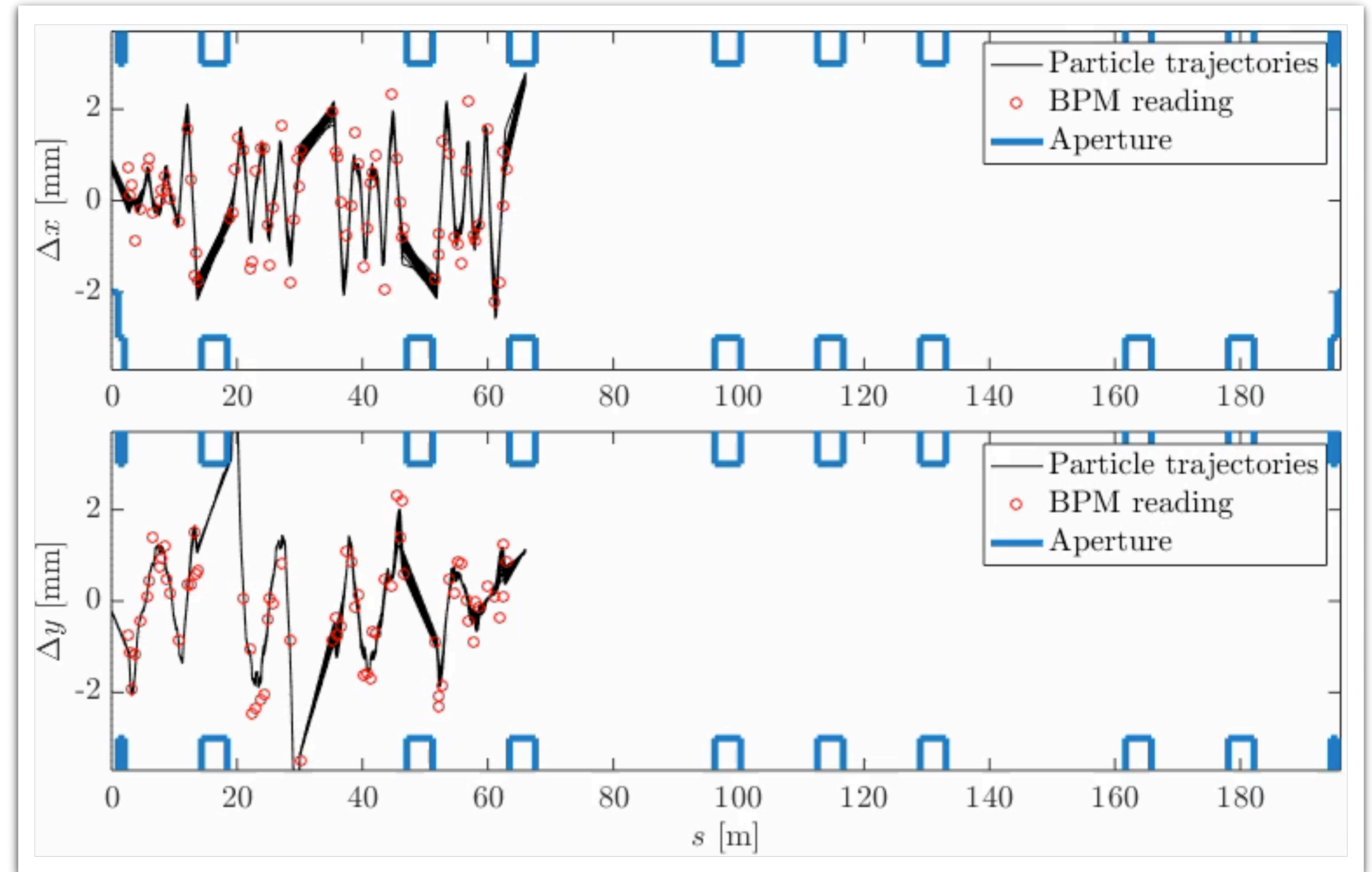


Various Visualization Tools for Easy R&D

Lattice and Element Registration in Toolkit



Trajectories/Orbit and BPM Readings



Easy Accessibility For New Users: Manual & Example Scripts

- Detailed Description of Code and Example Workflows:
 - Comprehensive toolkit manual
 - Each function given with examples
 - Full annotated correction chain for both ALS-U Accumulator and Storage Ring online

Online Manual

Table of Contents

- Introduction
- Initialization
- Error Source Definition & Registration
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- Setup enviroment
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- SCgetBeamTransmission
- SCgetCMSetPoints
- SCgetDispersion
- SCgetModelDispersion
- SCgetModelRING
- SCgetModelRM
- SCgetOrds

<https://sc.lbl.gov>

SC Manual

T. Hellert – hellert@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

Git Repository

Annotated Scripts

Toolkit for Simulated Commissioning

We present the *Toolkit for Simulated Commissioning* (SC), which allows as diligently treating beam diagnostic limitations. Please have a look at the [Accumulator Ring](#) including all files and error defenitions can be found [here](#). 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](#)

master SC / applications / ALSU_SR /

ThorstenHellert Custom ID pass method for n

..

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

```

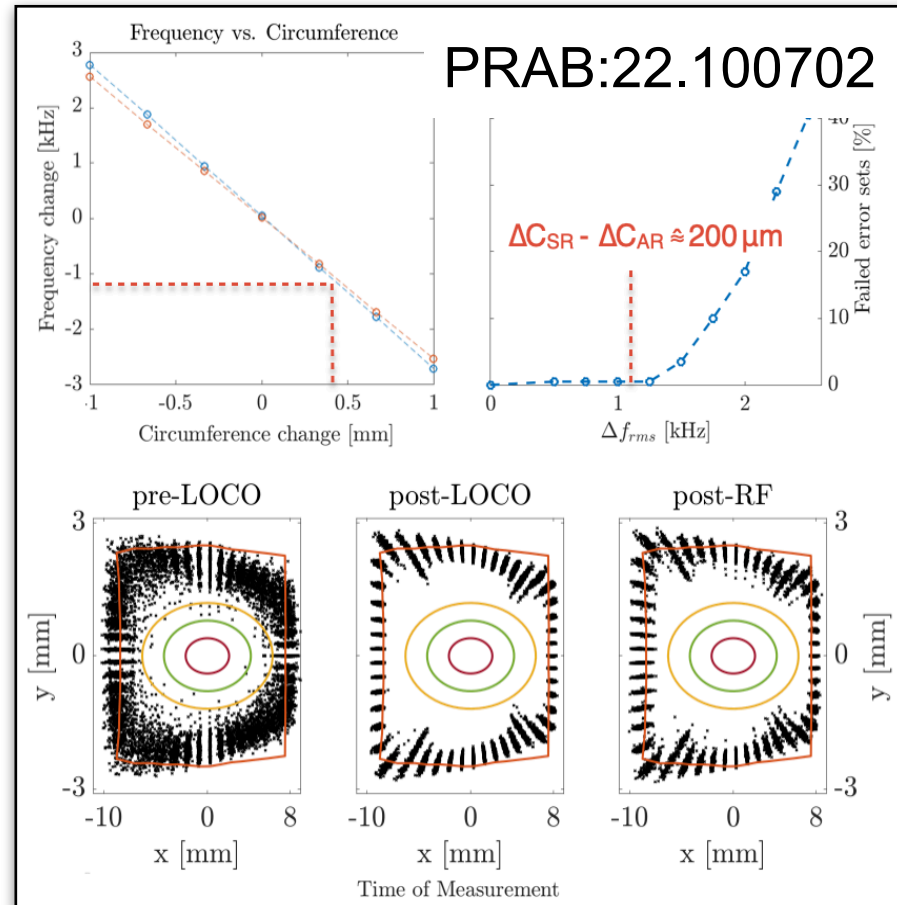
% Initialize toolkit
SC = SCinit(RING);

% Register ALSU-SR
[SC, BPMords, CMords] = register_ALSU_SR(SC, BPMords, CMords);
% Save ideal SC state for ID computation
results.SCrefID = SC;
% Save BPM and CM ords used in orbit calculation
results.BPMords = BPMords;
results.CMords = CMords;

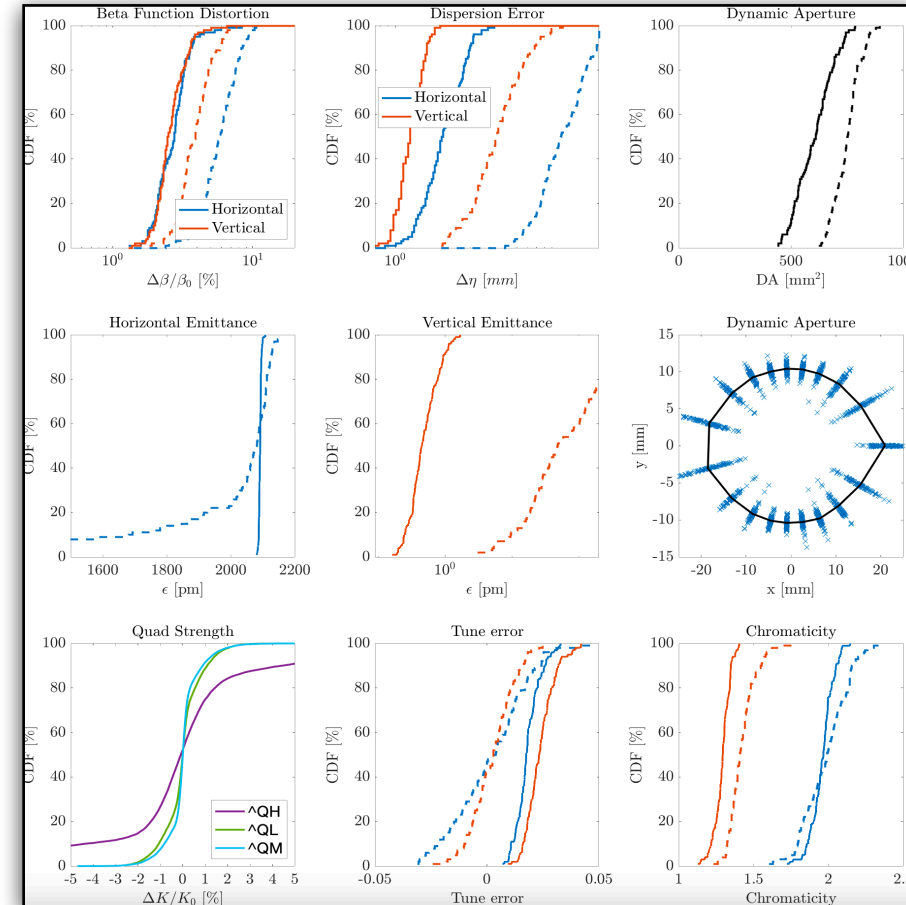
% Define apertures
SC.RING = setApertures_ALSU_SR(SC, BPMords, CMords);
    
```


Toolkit Used in Design Process at Various Laboratories

ALS-U (*T. Hellert*)



NLSL-II (*A. Khan*)



Diamond-II (*H. Chao*)

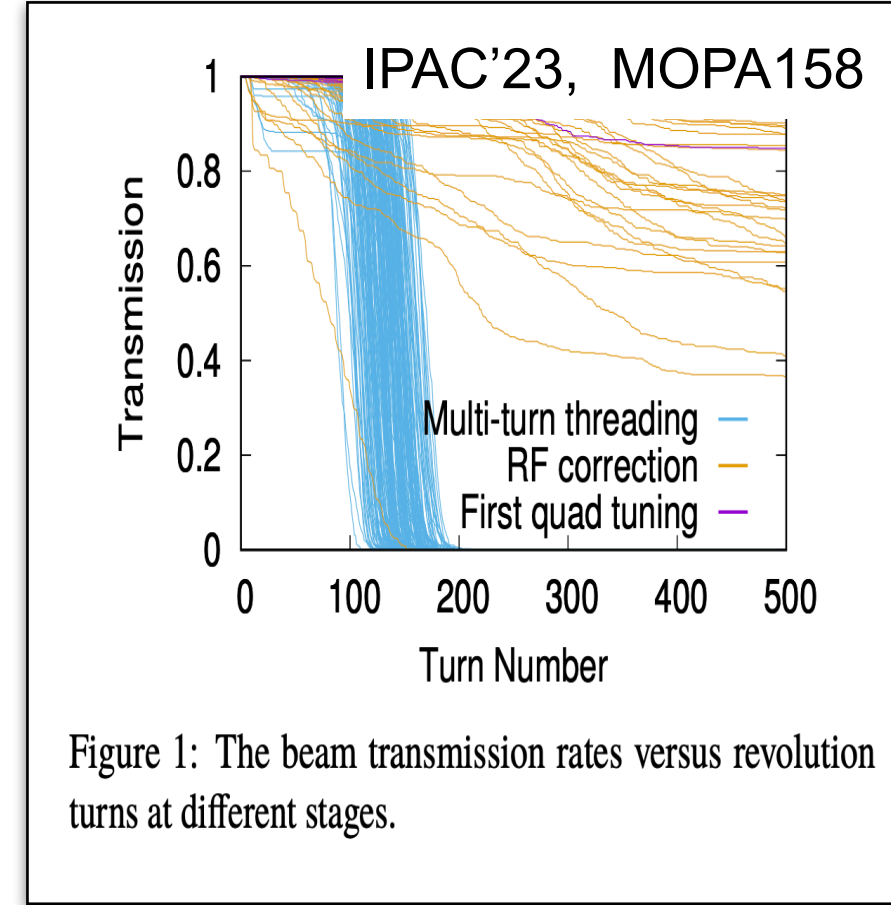
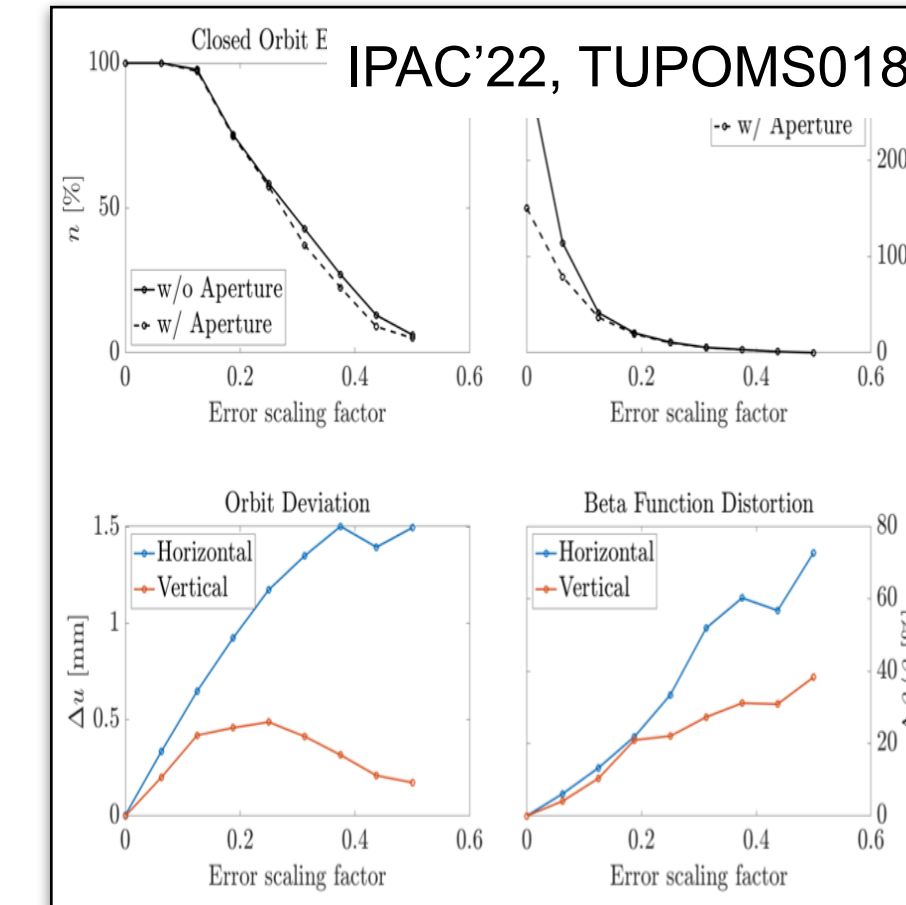


Figure 1: The beam transmission rates versus revolution turns at different stages.

PETRA IV (*T. Hellert*)



ALBA-II (*Z. Marti Diaz*)

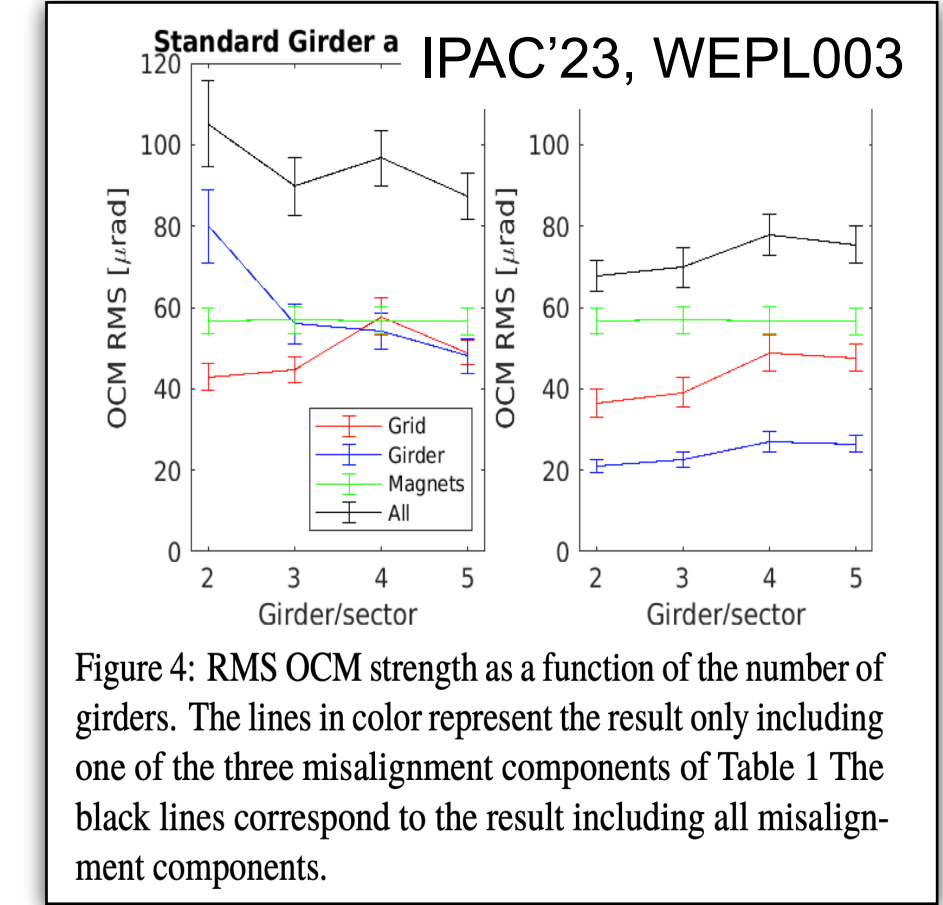
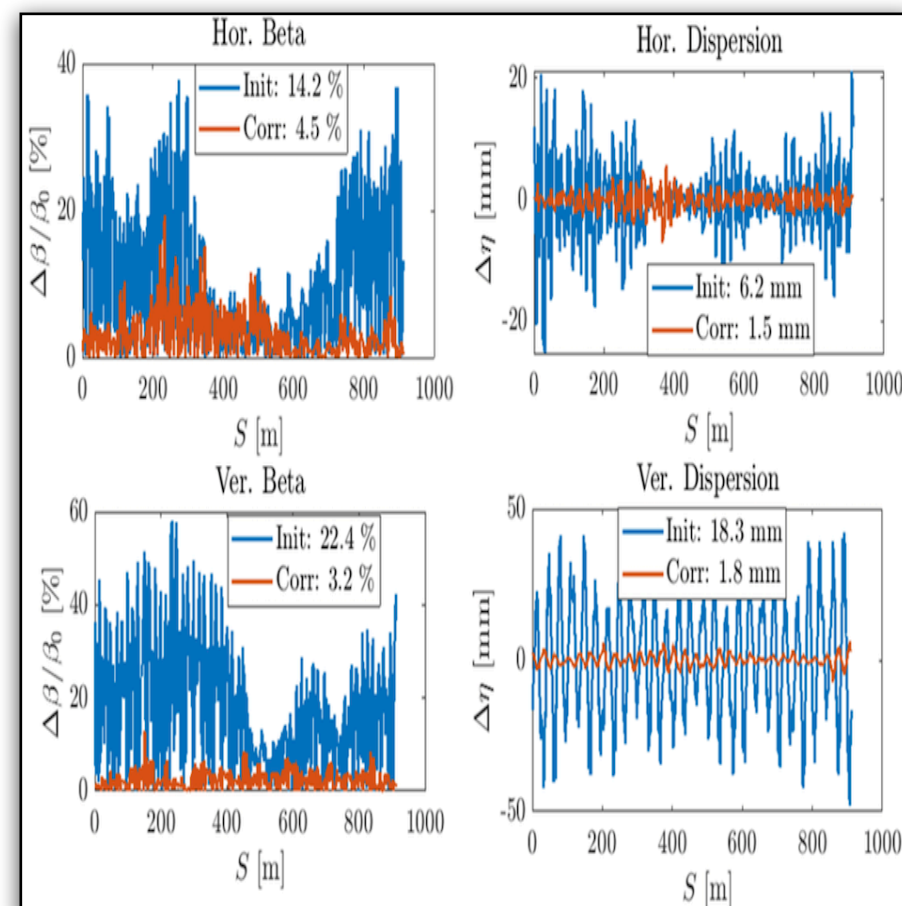
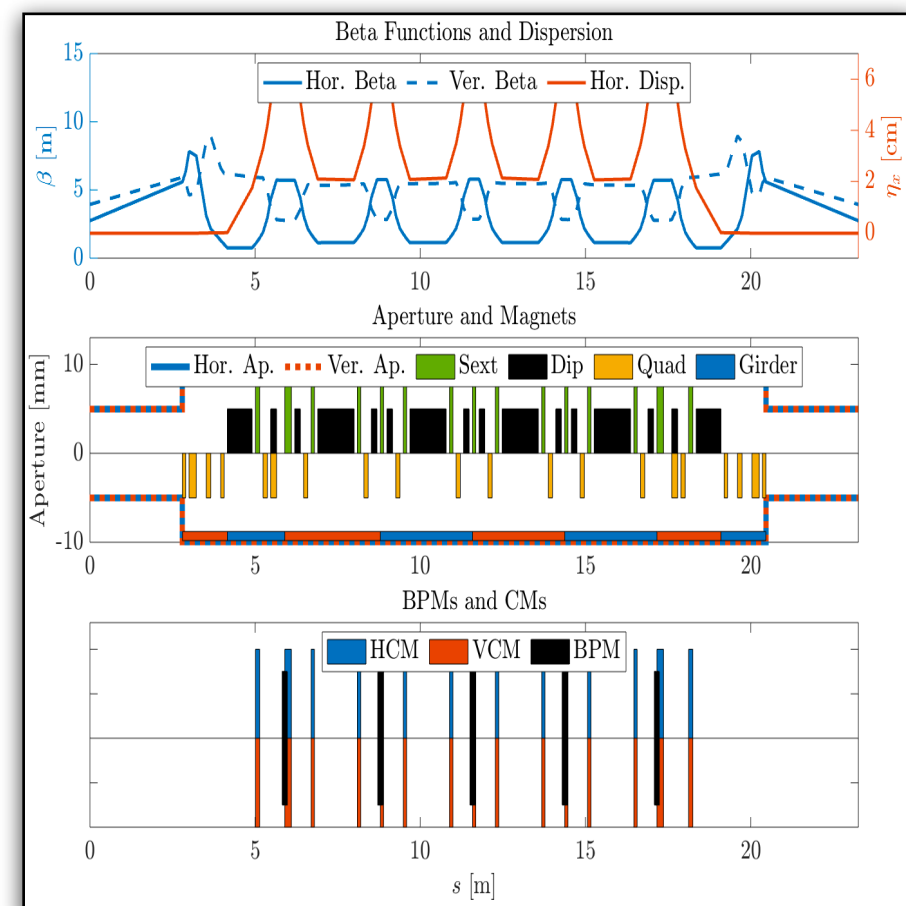


Figure 4: RMS OCM strength as a function of the number of girders. The lines in color represent the result only including one of the three misalignment components of Table 1 The black lines correspond to the result including all misalignment components.

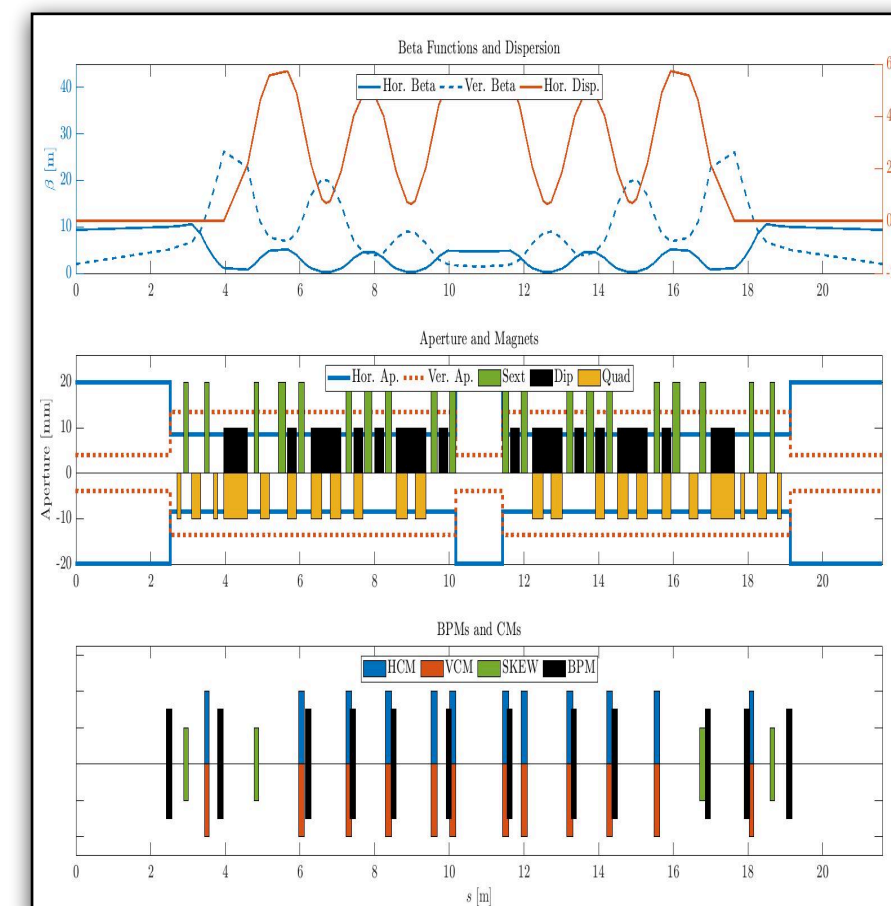
HBSRS (*S. Prakash*)



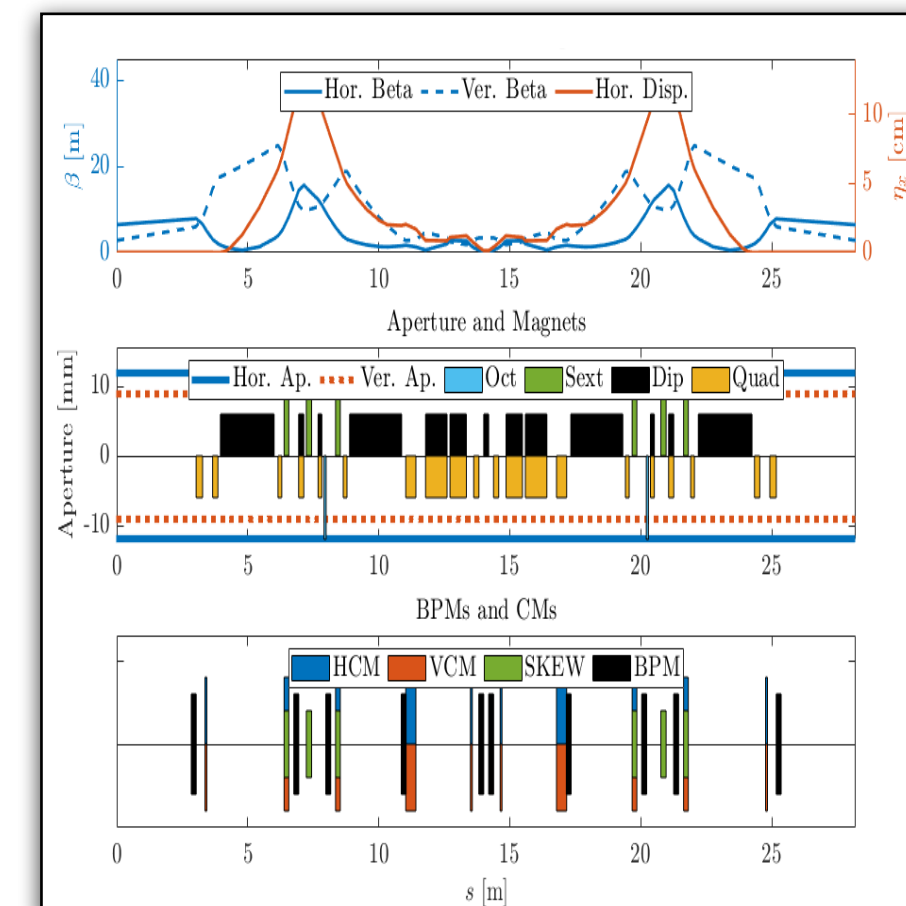
BESSY III (*B. Kuske*)



Elettra 2.0 (*S. Dastan*)



Korean 4GSR (*J. Kim*)



SOLEIL U (*O. Garcia*)

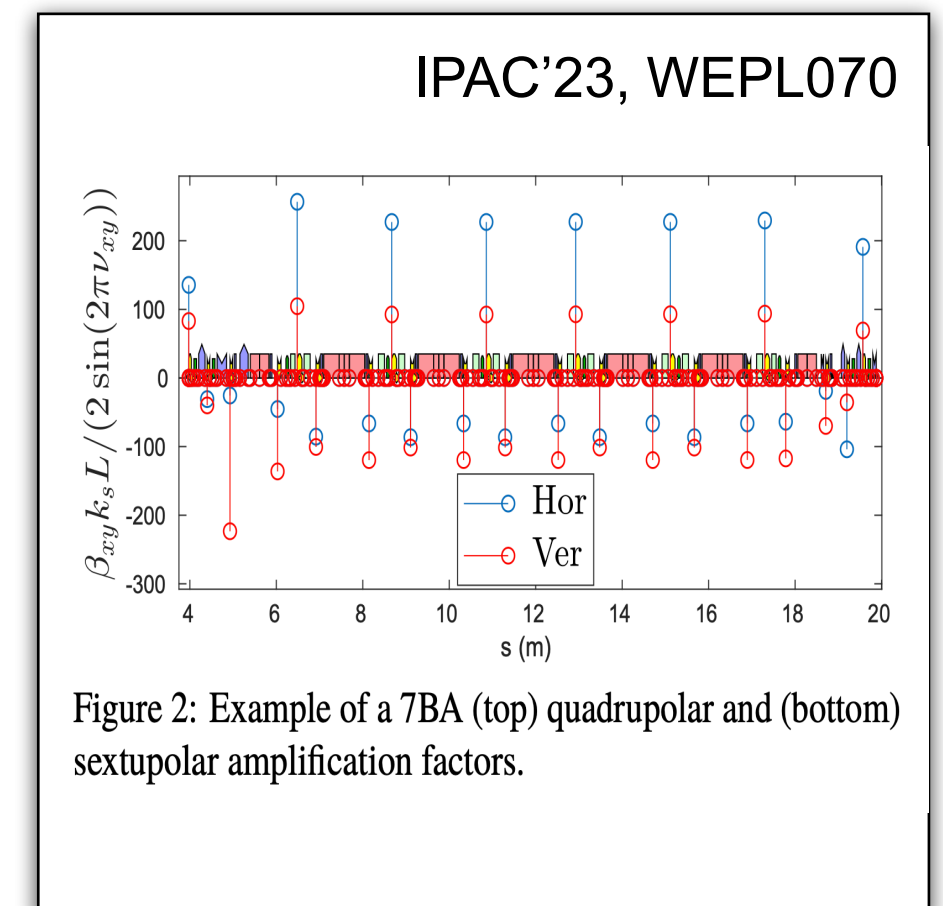
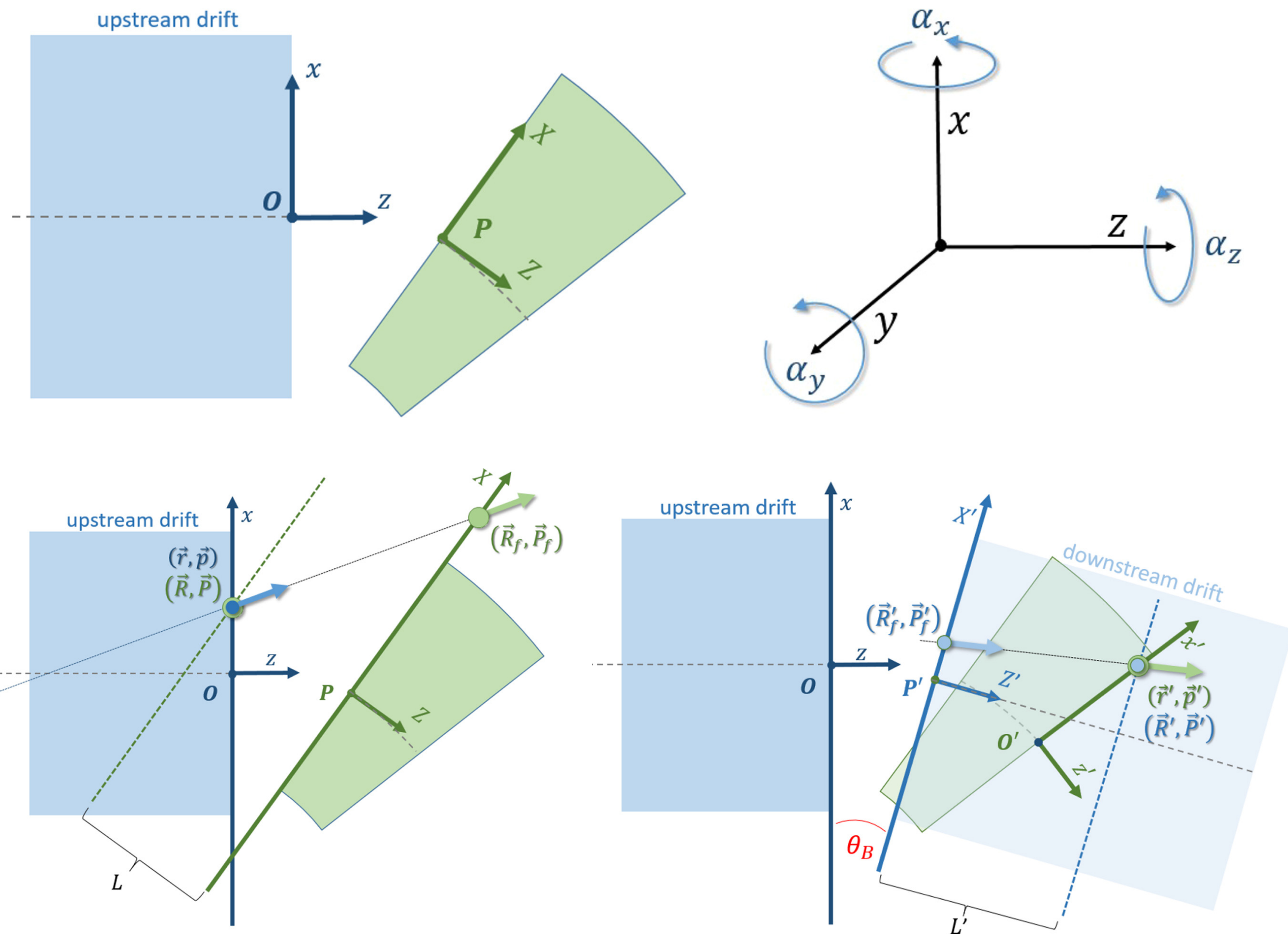
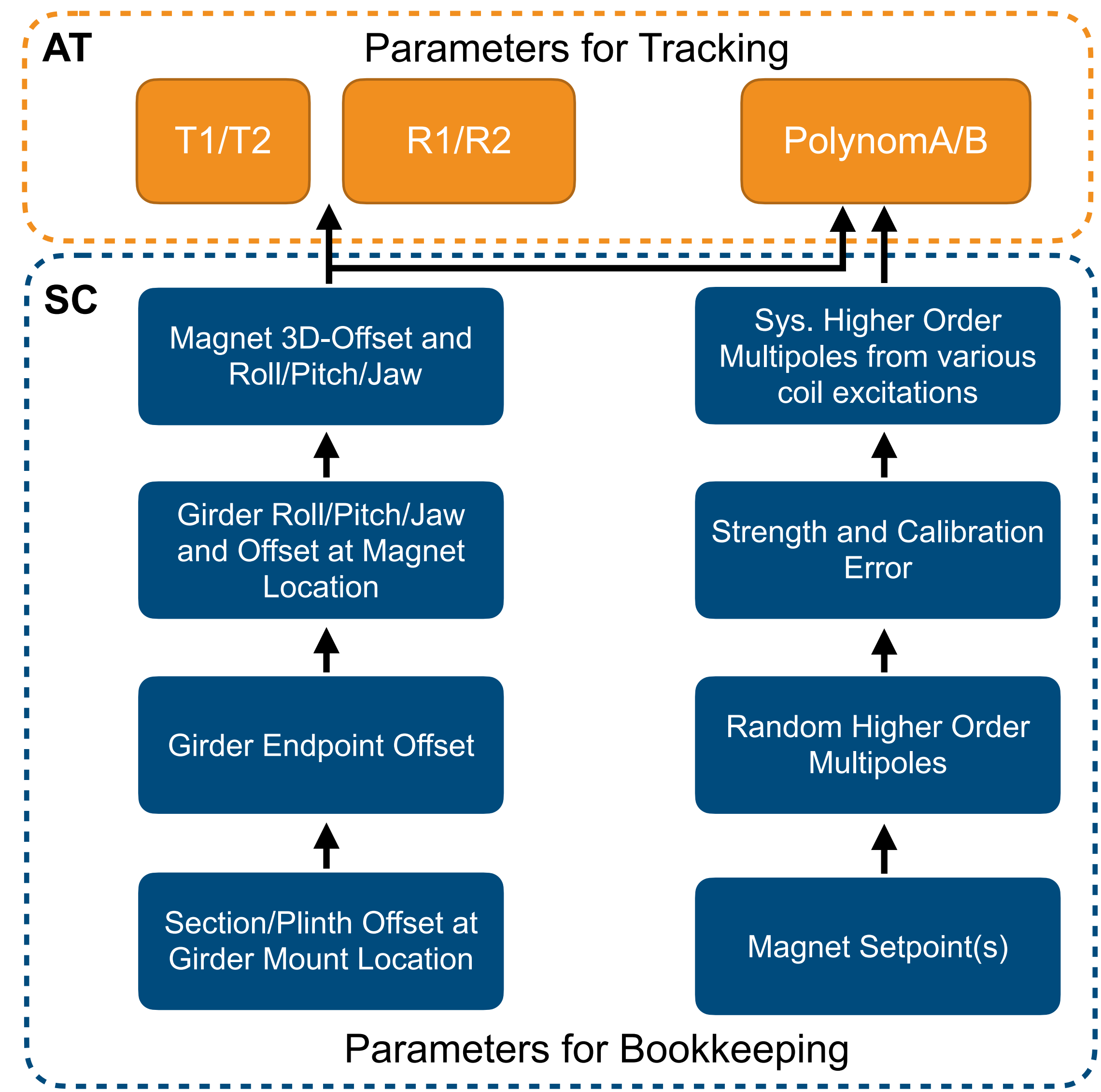


Figure 2: Example of a 7BA (top) quadrupolar and (bottom) sextupolar amplification factors.

SC -> ELEGANT Corrected Lattice Converter



M. Venturini and T. Hellert: 'Particle dynamics and misaligned lattice elements in accelerators', NIM-A 1044:167487, 2022



SC -> ELEGANT Corrected Lattice Converter

- AT/elegant
 - SC allows for easy error model- and correction chain setup
 - Elegant allows for more advanced tracking studies than AT
- Corrected Lattice Converter
 - Set up errors and correction chain with SC
 - Convert final lattice to elegant
 - Perform e.g. collective effects studies
 - Preliminary converter available on SC webpage

12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
 ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB119

COMPARISONS BETWEEN AT AND ELEGANT TRACKING*

G. Penn[†], T. Hellert, M. Venturini
 Lawrence Berkeley National Laboratory, Berkeley, CA, USA

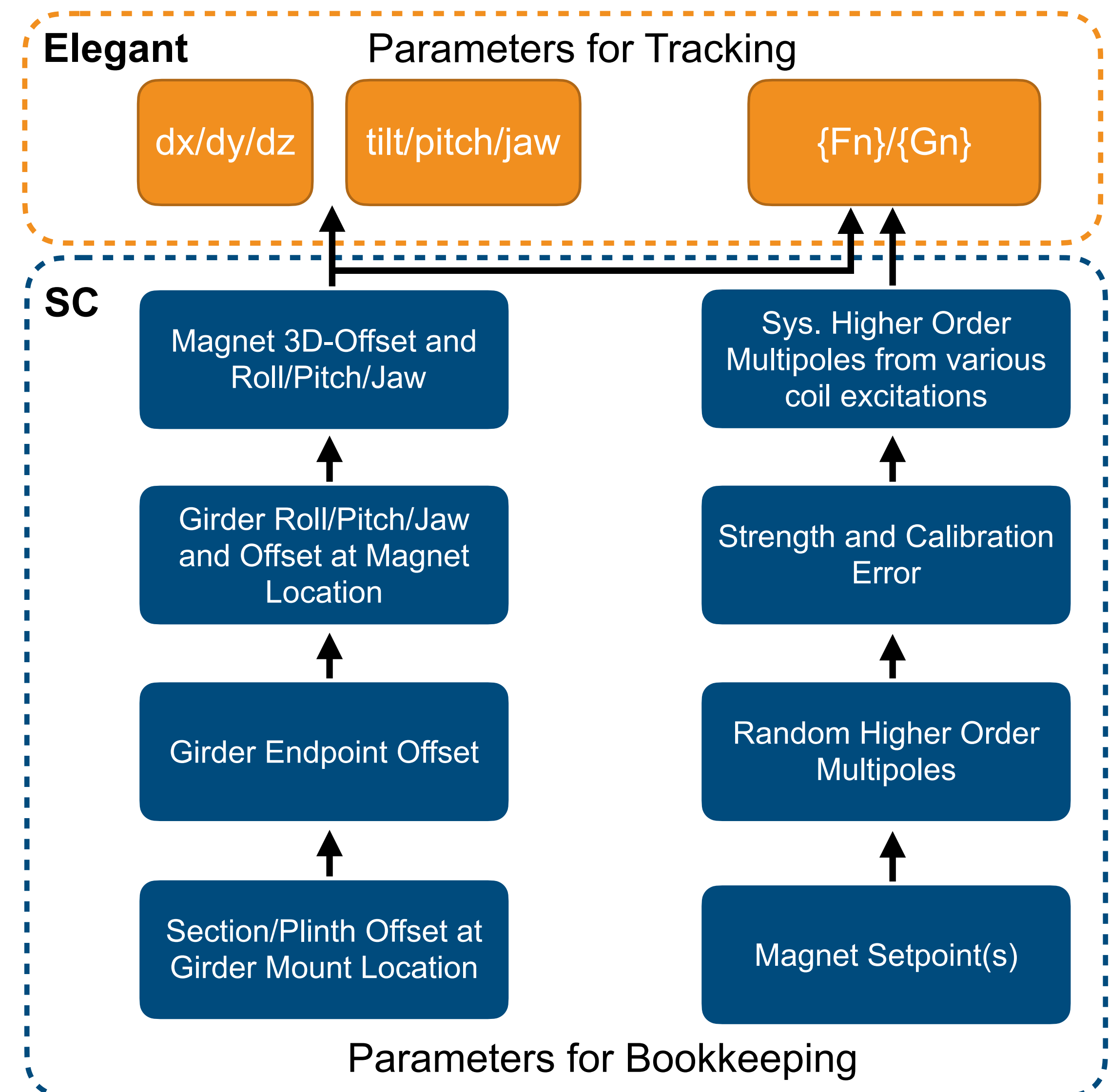
Abstract

The simulation codes elegant [1] and Accelerator Toolbox (AT) [2] are both in common use for the study of particle accelerators and light sources. They use different software platforms and have different capabilities, so there is a strong motivation to be able to switch from one version to another to achieve different goals. In addition, it is useful to directly compare results for benchmarking studies. We discuss differences in tracking methods and results for various elements, and explore the impact on simulations performed with lat-

Recently, there has been work by developers of elegant and SC to implement consistent models for misalignments based on concepts from [4], which has facilitated the translation tool. This work also relies on previous comparisons, for example [5], which includes work by X. Huang to implement tracking in AT that is more accurate and similar to that of elegant. However, this code is not yet in the standard AT repository and is not included in the results shown below.

TRACKING COMPARISONS

G. Penn et al., MOPAB119, IPAC'21



pySC - A Python Implementation of the SC Toolkit

- Choice of Matlab Implementation of SC
 - ALS(-U) is/will be operated with *Matlab Middle Layer* (MML)
 - Matlab based implementation of ALS-U commissioning allows for straight forward experiments at ALS
 - However: cost of Matlab licenses often prevents full utilization of HPC clusters for parallelization of commissioning simulation
- Python Allows for more Advanced Code Development
 - Object based implementation of the SC toolkit
 - Unit tests integration in source control
 - Maximum parallelization possible
 - Open source accessibility for all laboratories
- pySC Development Status
 - Code translation underway since March'23 in DESY/ESRF/LBNL cooperation
 - First major overhaul of the SC toolkit since its publication
 - Significant improvements compared to original implementation
 - Expected publication of pySC at ICALEPS'23 by Lukas Melina*

Advertisement: AT workshop at ESRF in October 2023

Accelerator Toolbox Workshop

Oct 2 – 3, 2023
ESRF
Europe/Paris timezone

Enter your search term

Overview

Timetable

Contribution List

Registration

Practical information

Participant List

LOC

✉ at-workshop-loc@esrf.fr

The objective of the Accelerator Toolbox workshop is to bring together international scientists to exchange ideas and discuss best practices about use of the [accelerator toolbox code](#) (matlab or python) for beam dynamics in charged particle accelerators.

The workshop programme consists of plenary talks and poster presentations.

The agenda will include (but is not limited to) presentations of:

- recent upgrades of the software
- experience of use for simulations: commissioning, DA, Injection efficiency and lifetime, impact of ID gaps on optics, losses & collimation, injection, optics design, optics matching, etc...
- experience of use of AT in control room: MML, Pytac, digital twins, etc..
- use of AT for collective effects studies
- discussion on code status, maintenance and priority for future developments

Please propose topics for presentation using this survey: [AT workshop SURVEY](#)

All topics that participants would like to discuss will be addressed either as talks or as poster presentations.

An international Scientific Board will support the LOC in the selection and organization of all proposed contributions.

Students and non experts are most welcome. A session of training to use matlab/python AT with real life examples will take place if a sufficient number of people show interest.

Remote attendance at the w

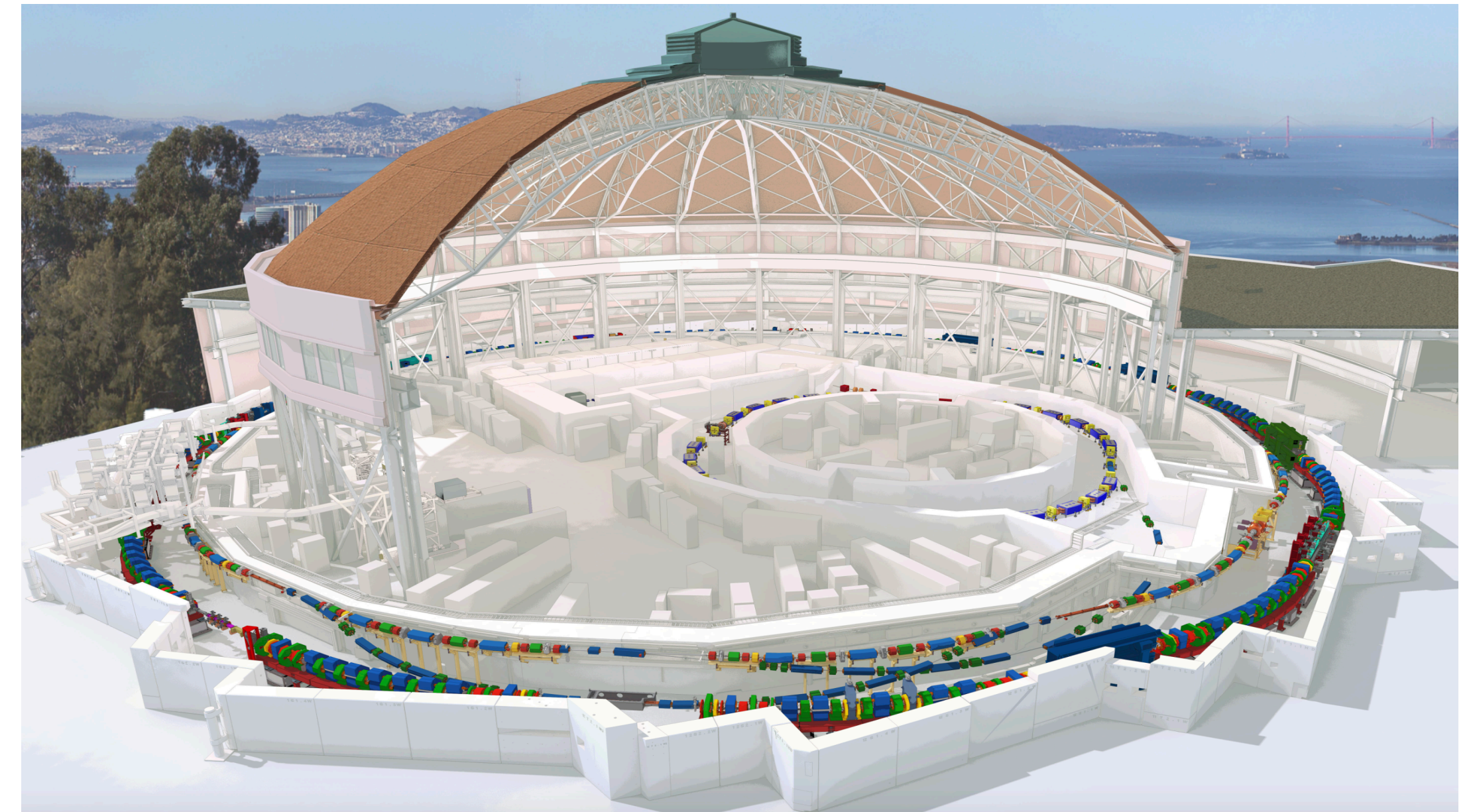
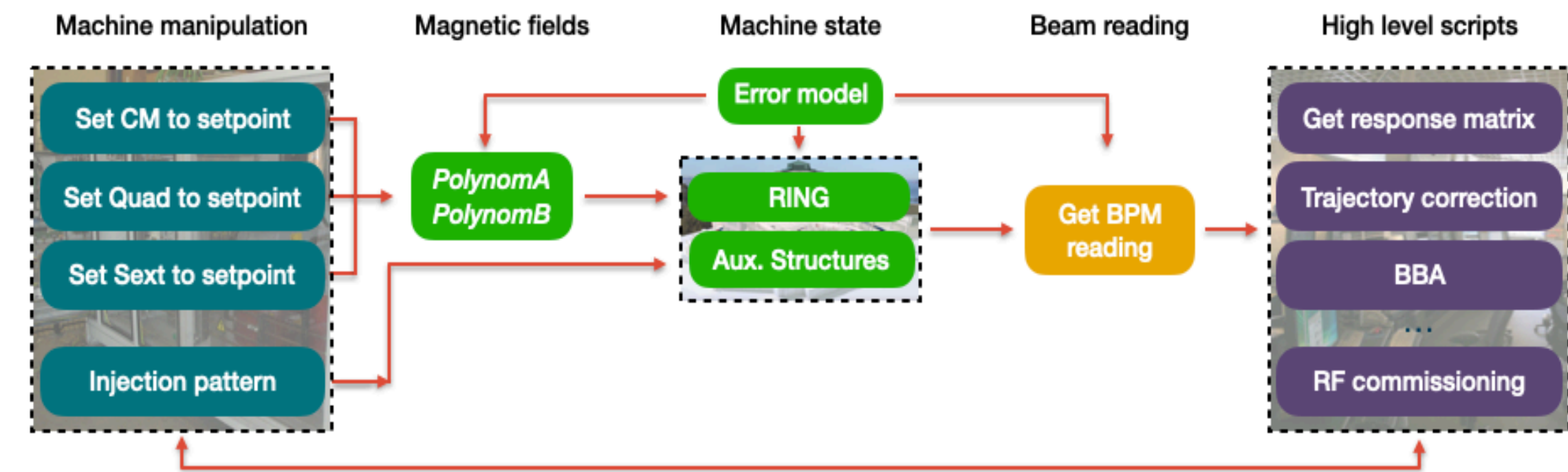
LOC
Simone Liuzzo (ESRF)

<https://indico.esrf.fr/event/93/>

*) L. Malina et al: “Python library for simulated commissioning of storage-ring accelerators” to be presented at ICALEPS 2023

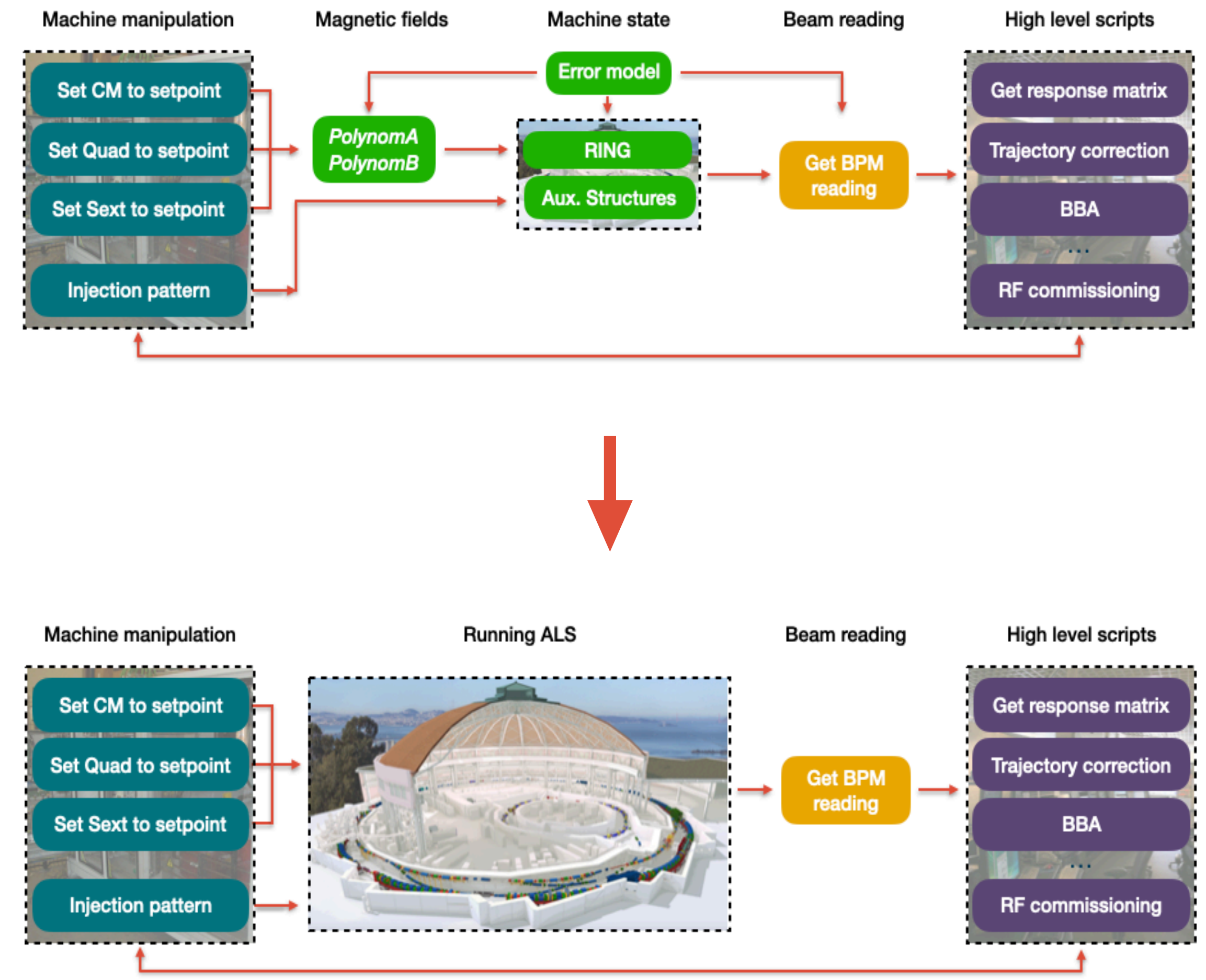
Automated Startup and Commissioning Tests at ALS

- Automated startup and commissioning scripts will be essential for ALS-U
 - Lattice too non-linear to achieve stored beam with conventional methods
 - Scheduled commissioning time for AR and SR very short compared to the operational complexities
- SC Toolkit developed for simulated commissioning and error analysis studies
 - Comprehensive automated lattice correction tools to get from first injection to stored beam
 - Workflow mimics machine operation from the control room



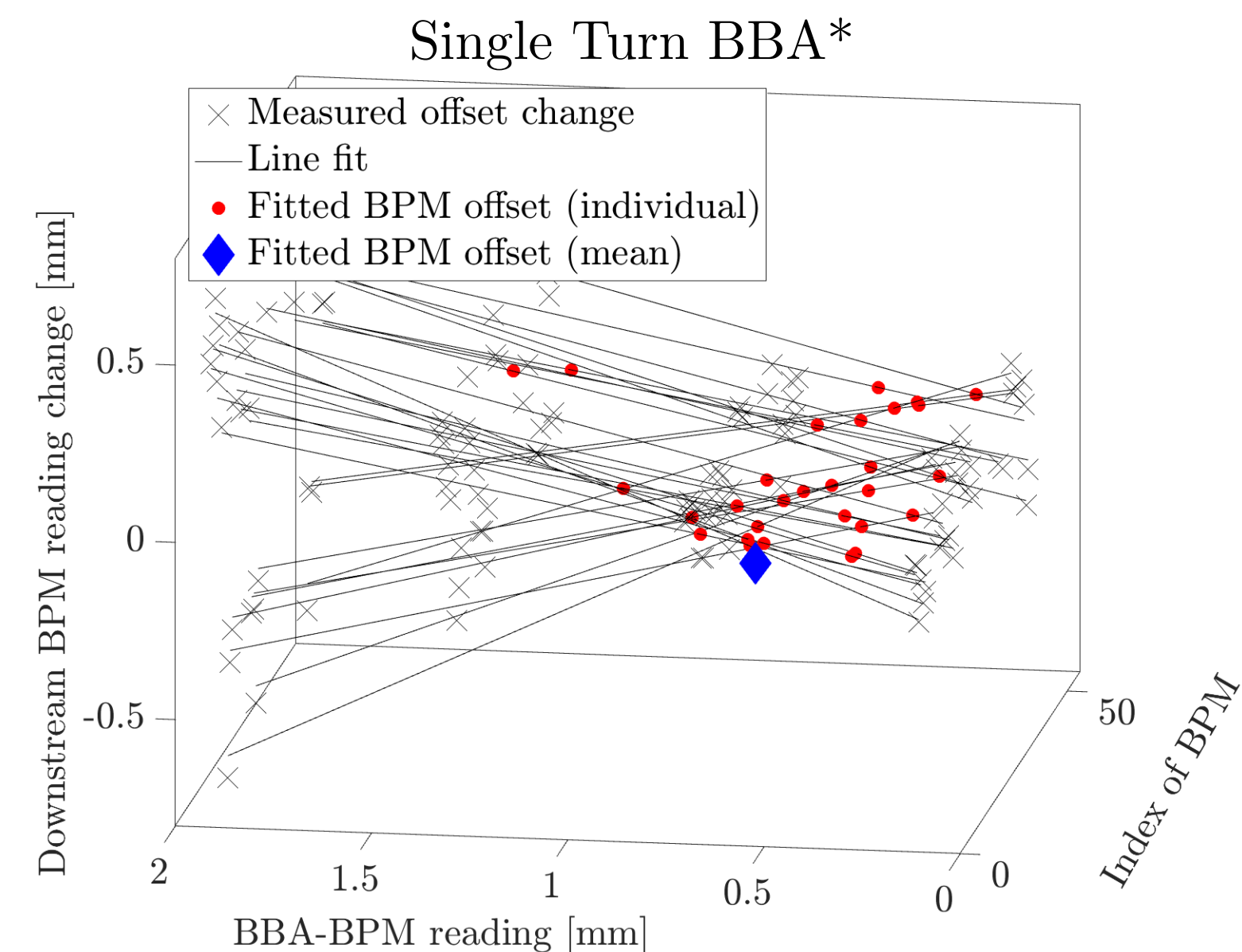
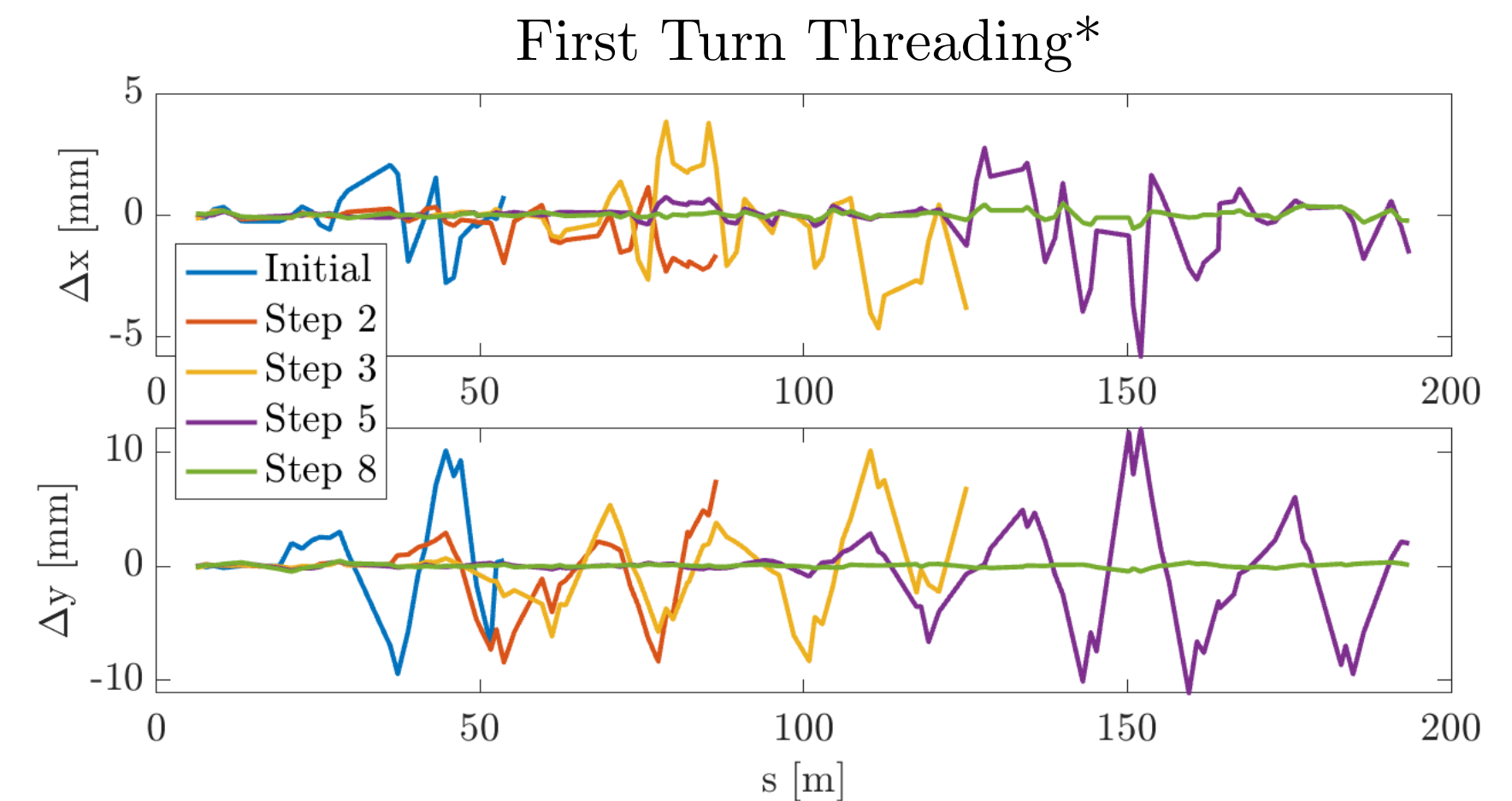
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 - Lattice too non-linear to achieve stored beam with conventional methods
 - Scheduled commissioning time for AR and SR very short compared to the operational complexities
- SC Toolkit developed for simulated commissioning and error analysis studies
 - Comprehensive automated lattice correction tools to get from first injection to stored beam
 - Workflow mimics machine operation from the control room
- Integrating SC Toolkit into the control system
 - ALS and ALS-U operated with MML, toolkit written in Matlab
 - ALS lattice very similar to ALS-U AR lattice



Automated Startup and Commissioning Tests at ALS

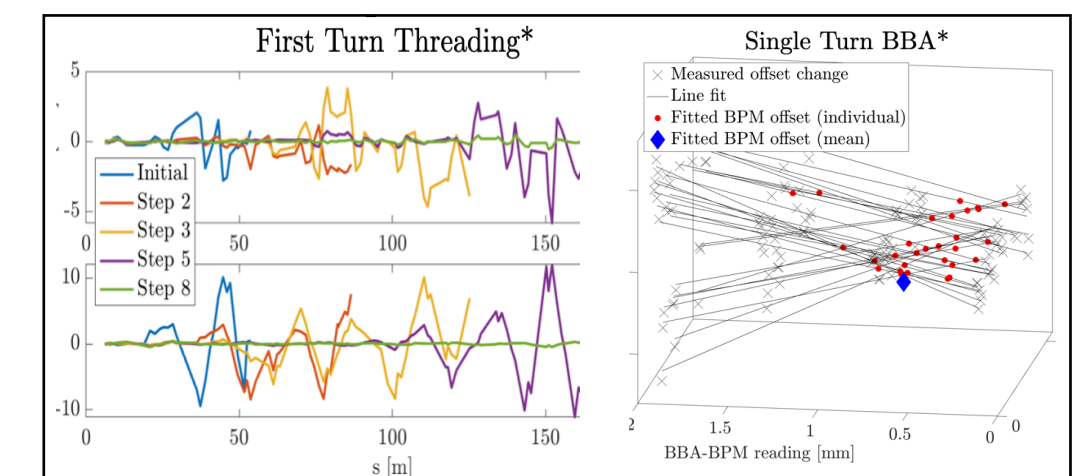
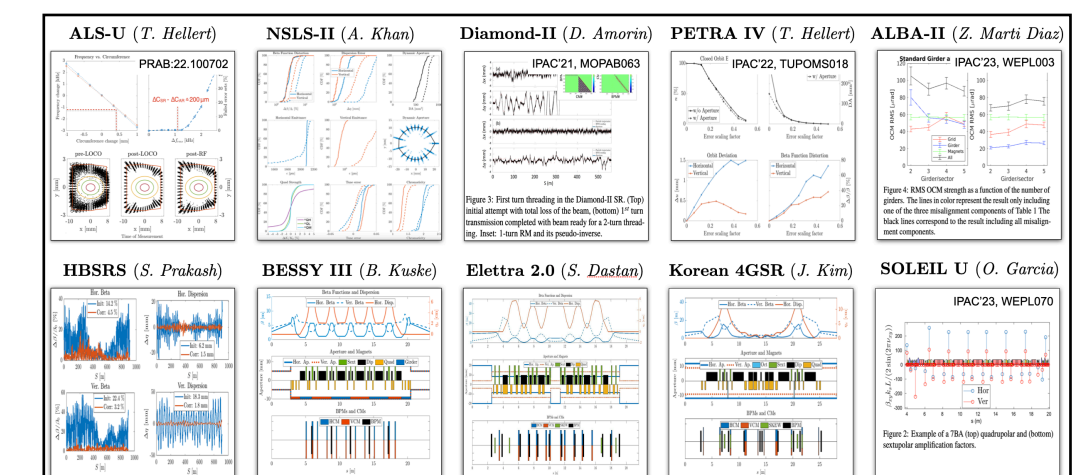
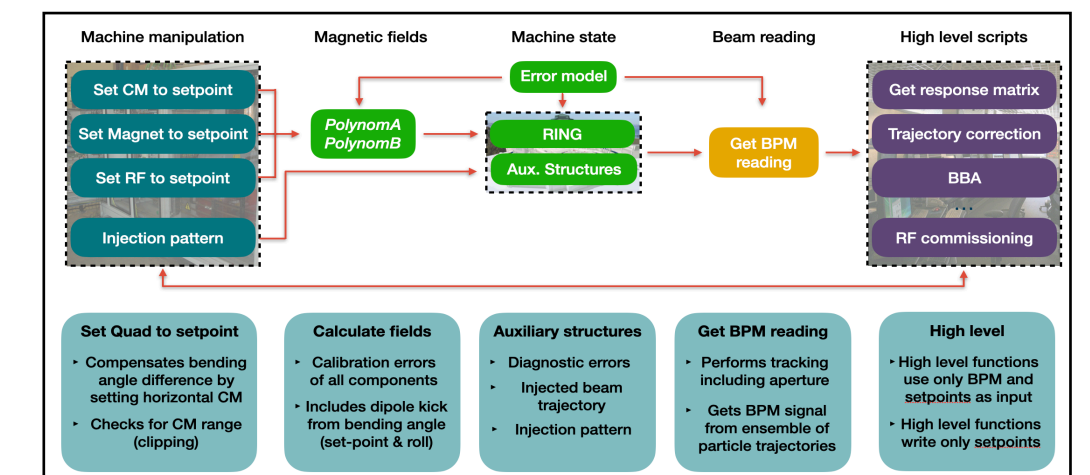
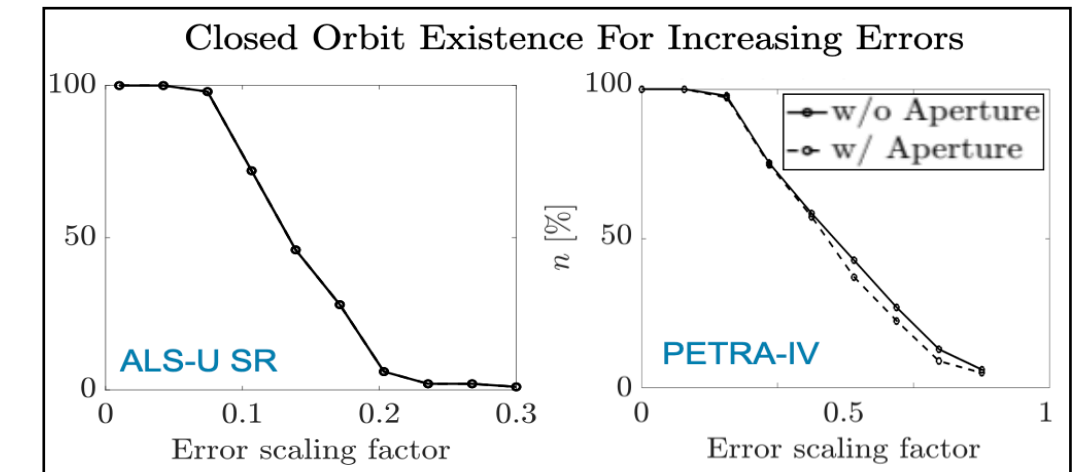
- Automated startup and commissioning scripts will be essential for ALS-U
 - Lattice too non-linear to achieve stored beam with conventional methods
 - Scheduled commissioning time for AR and SR very short compared to the operational complexities
- SC Toolkit developed for simulated commissioning and error analysis studies
 - Comprehensive automated lattice correction tools to get from first injection to stored beam
 - Workflow mimics machine operation from the control room
- Integrating SC Toolkit into the control system
 - ALS and ALS-U operated with MML, toolkit written in Matlab
 - ALS lattice very similar to ALS-U AR lattice
- Experimental commissioning tests and code development at ALS in progress
 - First turn threading
 - Multi-turn trajectory/orbit control
 - Single turn beam based alignment



*) T. Hellert et al.: MOPM010, IPAC'23

Summary

- Commissioning Simulations are Essential for the Design of Future Storage Ring Light Sources
 - Challenging lattice of future light sources
 - Tolerances studies must include commissioning process
 - Simulation must reflect reasonable information flow
- Development of Commissioning Simulation Toolkit
 - High fidelity error model
 - Realistic workflow
 - Comprehensive documentation
 - Wide range of application successfully demonstrated at multiple machines
- Several Code Developments Underway
 - SC to elegant corrected lattice converter
 - Python implementation (pySC)
 - Automated startup and commissioning scripts by integrating the SC toolkit into the MML control system



References

- S. Liuzzo et al: “Lattice Tuning and Error Setting in Accelerator Toolbox”, in Proc. IPAC'17, Copenhagen (2017) <https://doi.org/10.18429/JACoW-IPAC2017-WEPIK061>
- V. Sajaev: “Commissioning simulations for the Argonne Advanced Photon Source upgrade lattice”, PRAB 22.040102 (2019) <https://doi.org/10.1103/PhysRevAccelBeams.22.040102>
- T. Hellert et al: “Lattice correction and commissioning simulation of the Advanced Light Source upgrade storage ring” PRAB 25.110701 (2022) <https://doi.org/10.1103/physrevaccelbeams.25.110701>
- T. Hellert et al: “Toolkit for simulated commissioning of storage-ring light sources and application to the advanced light source upgrade accumulator”, PRAB 22.100702 (2019) <https://doi.org/10.1103/PhysRevAccelBeams.22.100702>
- Z. Martí et al: "ALBA-II first tolerance studies", in Proc. IPAC'23, Venezia (2023) <https://doi.org/10.18429/jacow-ipac2023-wepl003>
- O. Blanco-García et al: "Status of the SOLEIL II robustness studies", in Proc. IPAC'23, Venezia (2023) <https://doi.org/10.18429/jacow-ipac2023-wepl070>
- H. Chao et al: "Update of Diamond-II storage ring error specifications and commissioning simulations", in Proc. IPAC'23, Venezia (2023) <https://doi.org/10.18429/jacow-ipac2023-mopa158>
- T. Hellert et al: “Error Analysis and Commissioning Simulation for the PETRA-IV Storage Ring” in Proc. IPAC'22, Bangkok (2022) <https://doi.org/10.18429/JACoW-IPAC2022-TUPOMS018>
- G. Penn et al: “Comparisons Between AT and Elegant Tracking”, in Proc. IPAC'21, Campinas (2021), <https://doi.org/10.18429/JACoW-IPAC2021-MOPAB119>
- M. Venturini et al: “Particle dynamics and misaligned lattice elements in accelerators”, NIM-A 1044:167487 (2022), <https://doi.org/10.1016/j.nima.2022.167487>
- L. Malina et al: “Python library for simulated commissioning of storage-ring accelerators”, to be presented at ICALEPS 2023
- Accelerator Toolbox Workshop, 2-3 October 2023, ESRF, <https://indico.esrf.fr/event/93/>