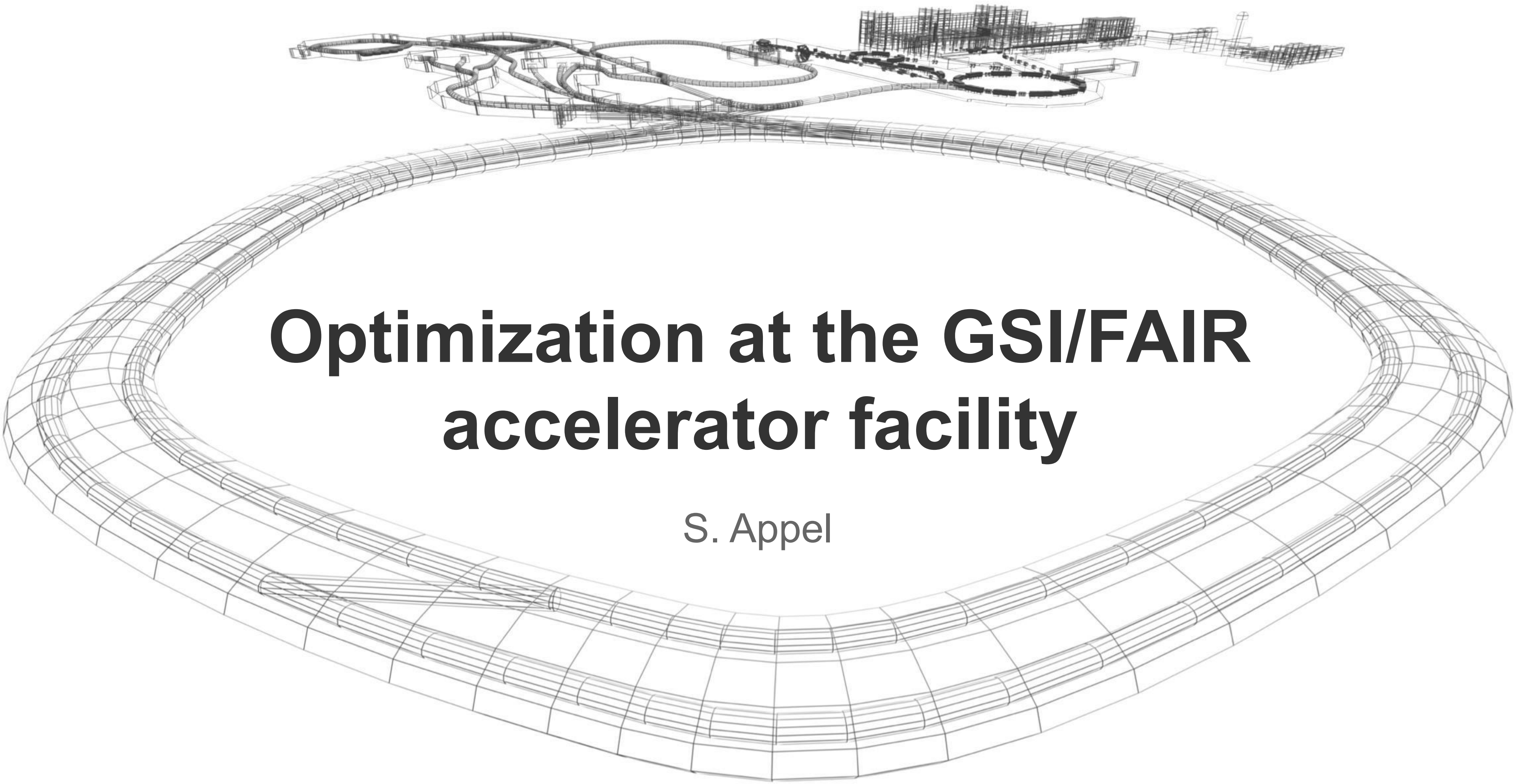


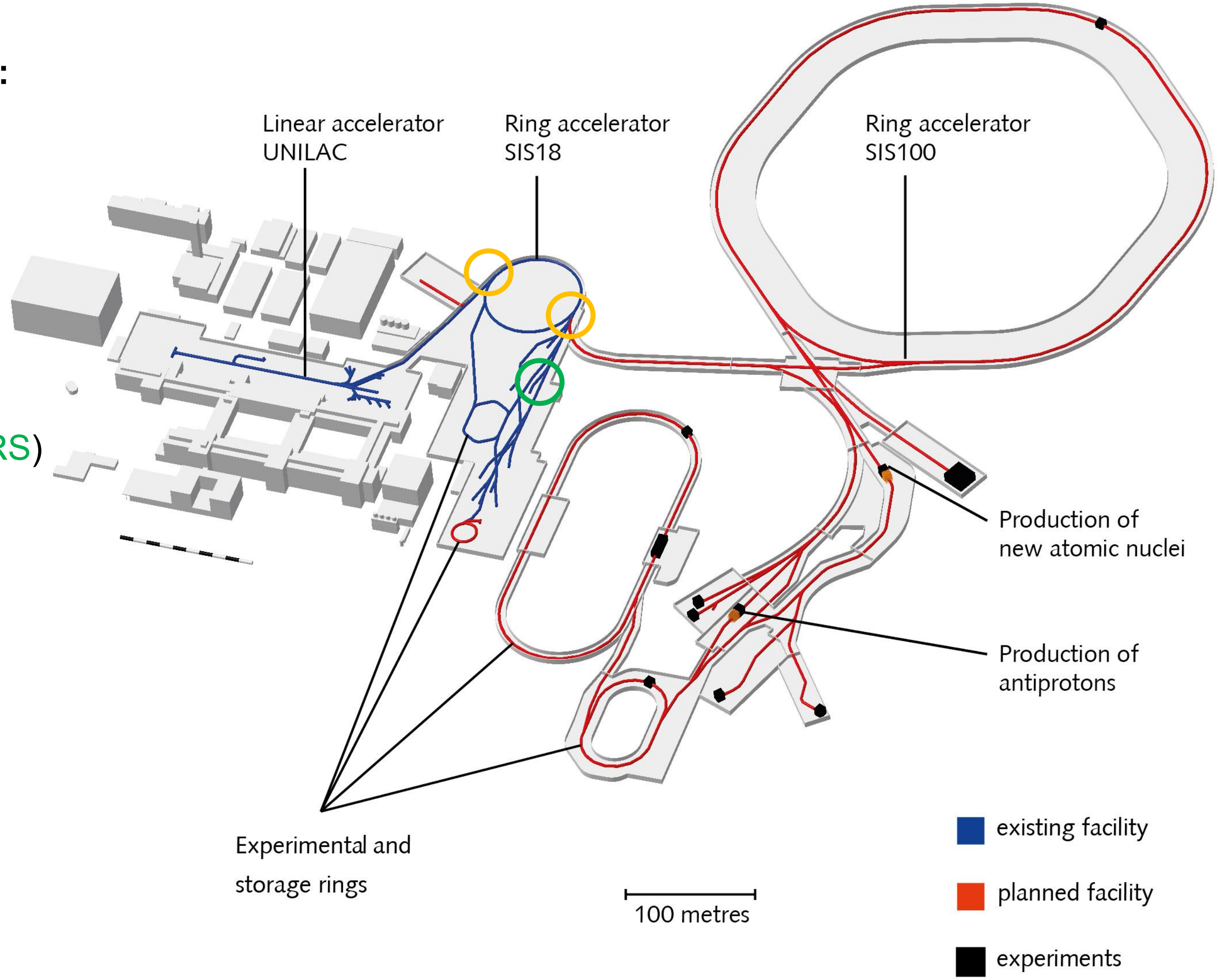
Optimization at the GSI/FAIR accelerator facility

S. Appel

FAIR/GSI

Optimization with numerical optimizers:

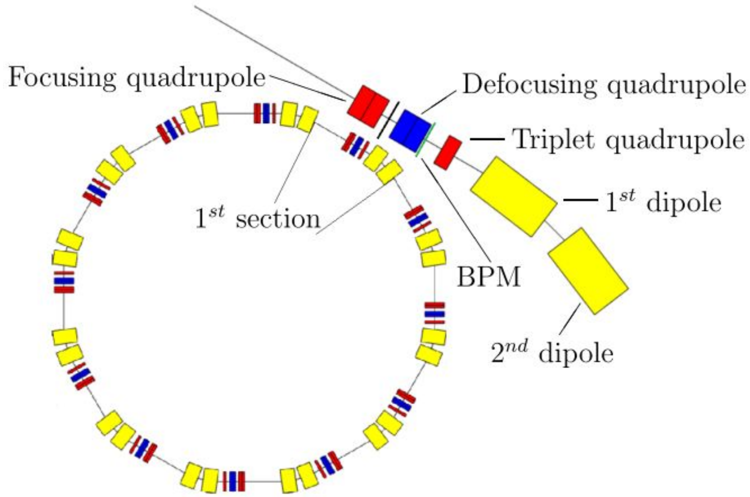
- Multi-turn injection (SIS18)
- Closed orbit correction
  for challenging optics (SIS18)
- Slow extraction (SIS18)
- Beam steering to production target (FRS)
- …

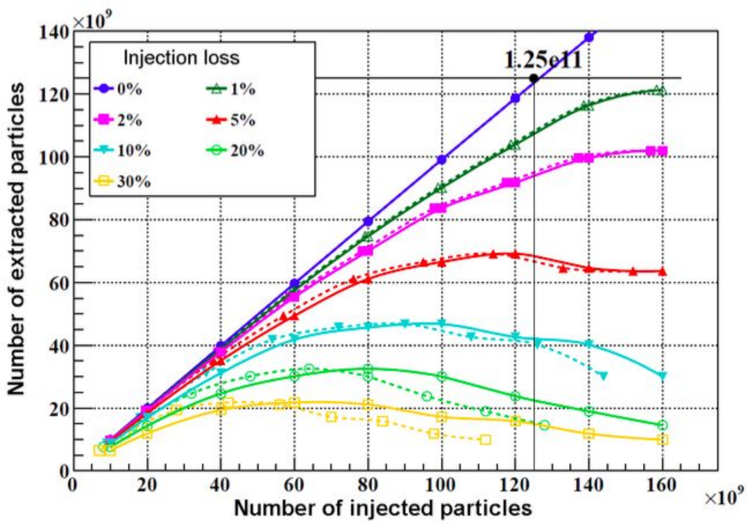


FAIR construction site: October 2023

SIS18 (SchwerIonenSynchrotron)

- Booster for FAIR SIS100 Synchrotron.
- Multi-turn injection into SIS18 is one bottleneck to reach intense beams for FAIR.
- The (incoherent) transverse space charge force is the main intensity limiting effect in the FAIR synchrotrons.
- For intermediate charge state ions, the loss-induced vacuum degradation is another important key intensity-limiting factor.

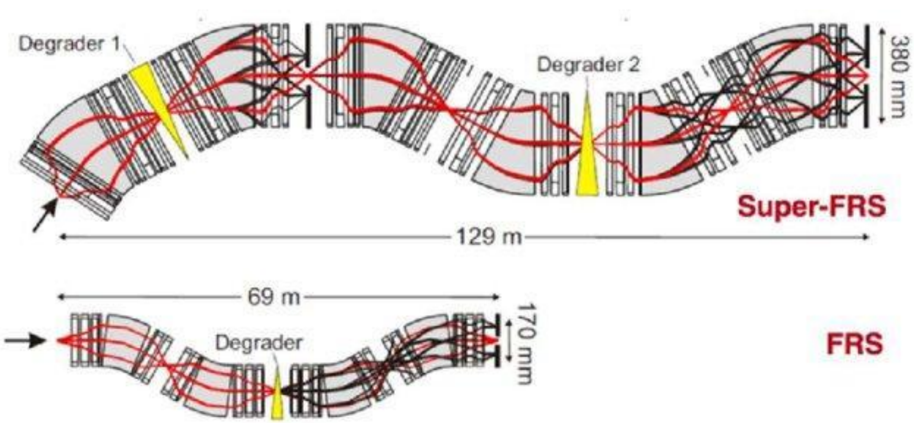




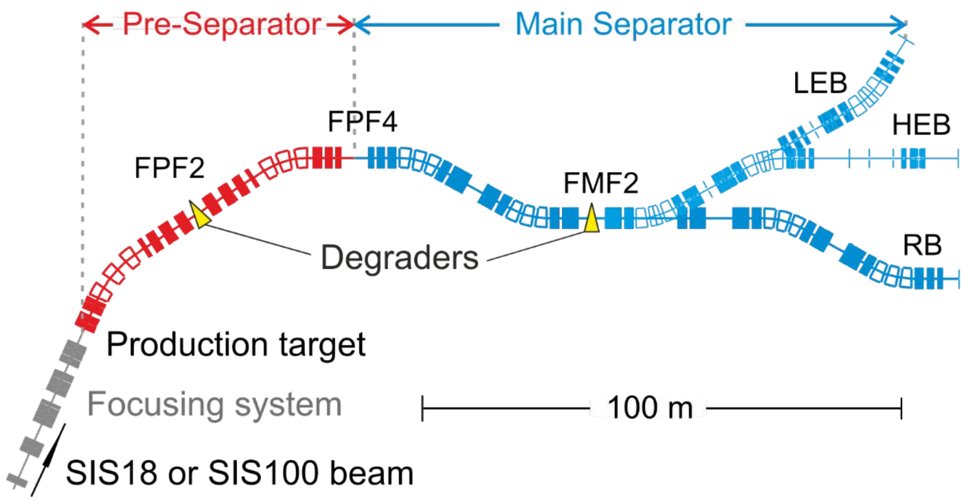
Beam Energy	U : 50-1000 *MeV/u* Ne: 50-2000 *MeV/u* p : 4,5 *GeV*
Particle Number Per Cycle	10^{10} (U^{73}) – 10^{12}(p)
Typical Cycle	3 *s (FAIR 2.7 Hz)*
Extraction	fast: 1 *μs* with compression: 200 *ns* slow: 10-8000 *ms*

FRS (FRagment Separator) and Super-FRS

- Production and investigation of nuclear structure of exotic nuclei.
- characteristics of the high-resolution magnetic spectrometer FRS, exotic nuclei can be produced, separated, identified and eventually stored in a storage ring
- Super-FRS increas of acceptance and complexity (about 4 times more magnets), Gain factors of 1000 (^{12}C) and 7500 (^{132}Sn) can be reached[1].
- Automation of time-consuming tasks will therefore be essential



Super-FRS layout:

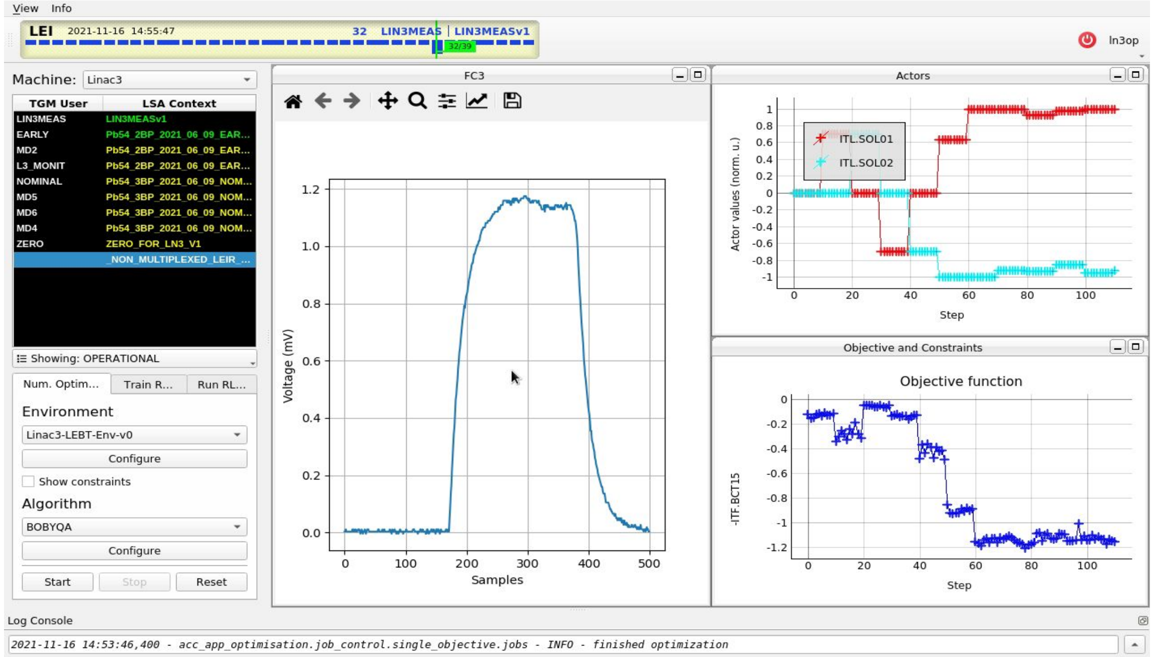


[1]H. Simon et al., EMIS XVIII workshop, 2018.

GeOFF at GSI

Generic Optimization Frontend & Framework (GeOFF) is a widely used framework for testing automation at CERN

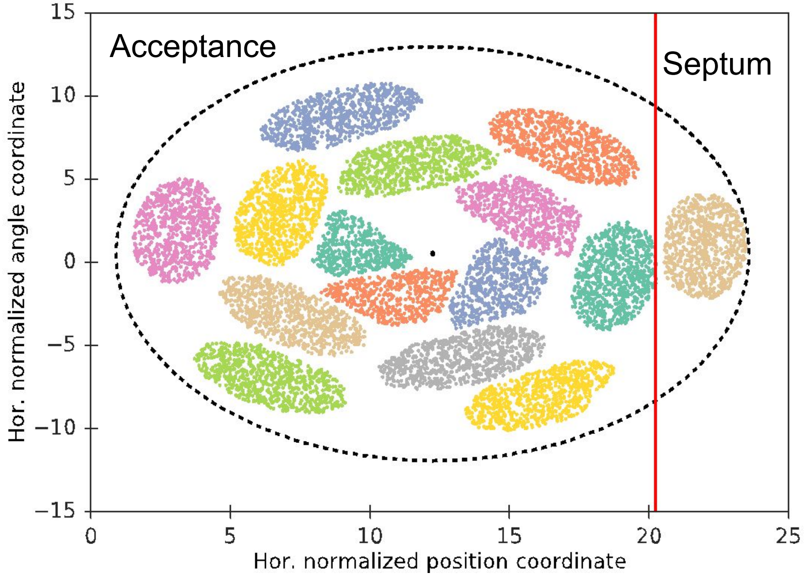
- Python-based framework with use of pjlsa
- lists, configures and runs optimization problems
- standardized interfaces and adapters for various packages via Common Optimization Interfaces
- Optimization problem formulated in standard interfaces
- Class contains logic for live plotting, data logging, and communication with LSA, FESA and the Device Access system

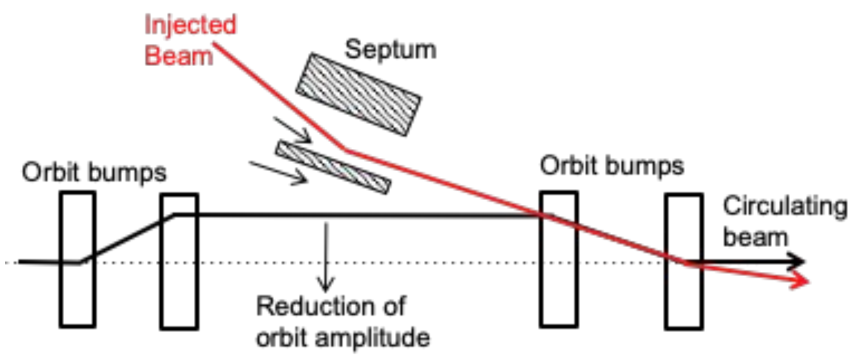


- Adaption of code quickly and on-the-fly during shift: Flexibility of framework made this easy

Multi-Turn-Injection

- MTI has to respect Liouville's theorem: Injected beams only in free space
- Gain factor should be as high as possible to reach the space charge limit
- Injection loss should be as low as possible to avoid loss-induced vacuum degradation
- Objective: Minimize beam loss for given number of injection with five parameters
- MTI model has been implemented in Xsuite[1] for fast tracking
- Xsuite support CPUs and GPUs
- Testing RL optimization with SCL + MPC, see poster



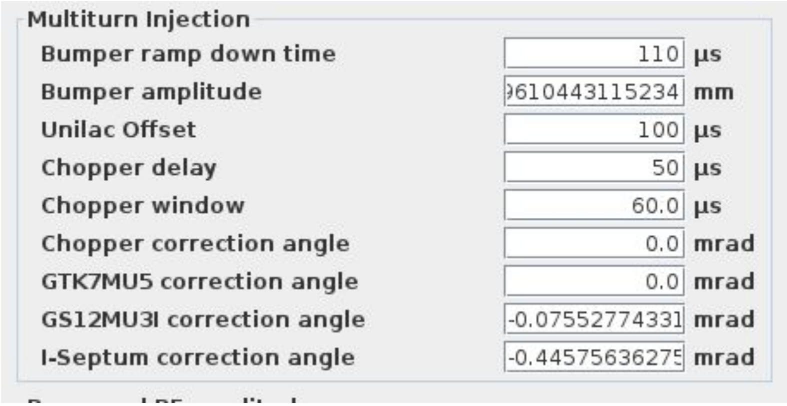


[1]https://xsuite.readthedocs.io/en/latest/

Automation of Multi-Turn Injection

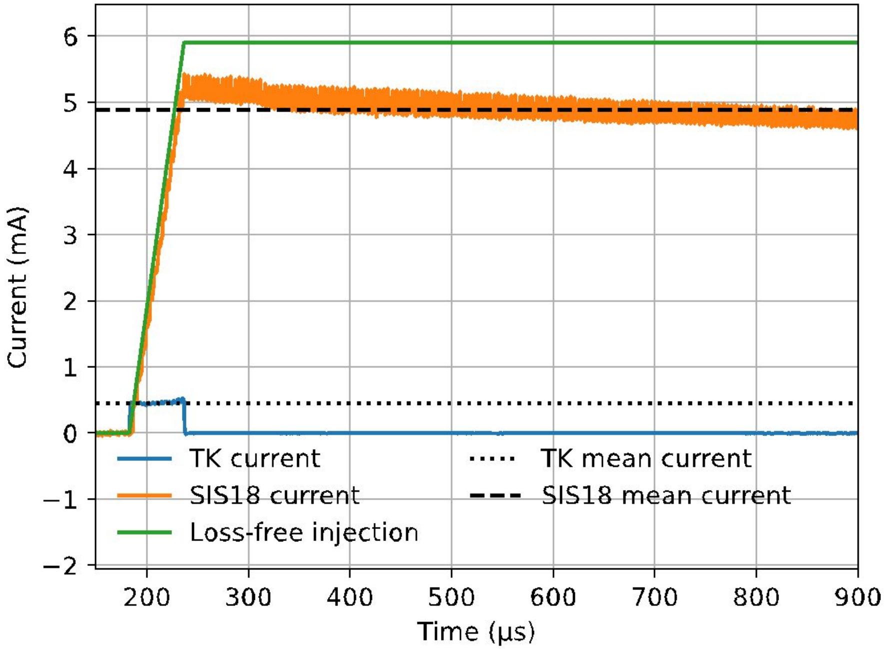
- **Usually,** MTI is optimized manually with varying success
- **Idea**: Automated optimization of MTI
  - with numerical optimizer (Py-BOBYQA)
  - by using GeOFF and Python bridge
  - Goal: low loss injection over many turns

injection variables to be modified by numerical optimizer



Multiturn Injection

Bumper ramp down time	110	µs
Bumper amplitude	610443115234	mm
Unilac Offset	100	µs
Chopper delay	50	µs
Chopper window	60.0	µs
Chopper correction angle	0.0	mrad
GTK7MU5 correction angle	0.0	mrad
GS12MU3I correction angle	-0.07552774331	mrad
I-Septum correction angle	-0.44575636275	mrad



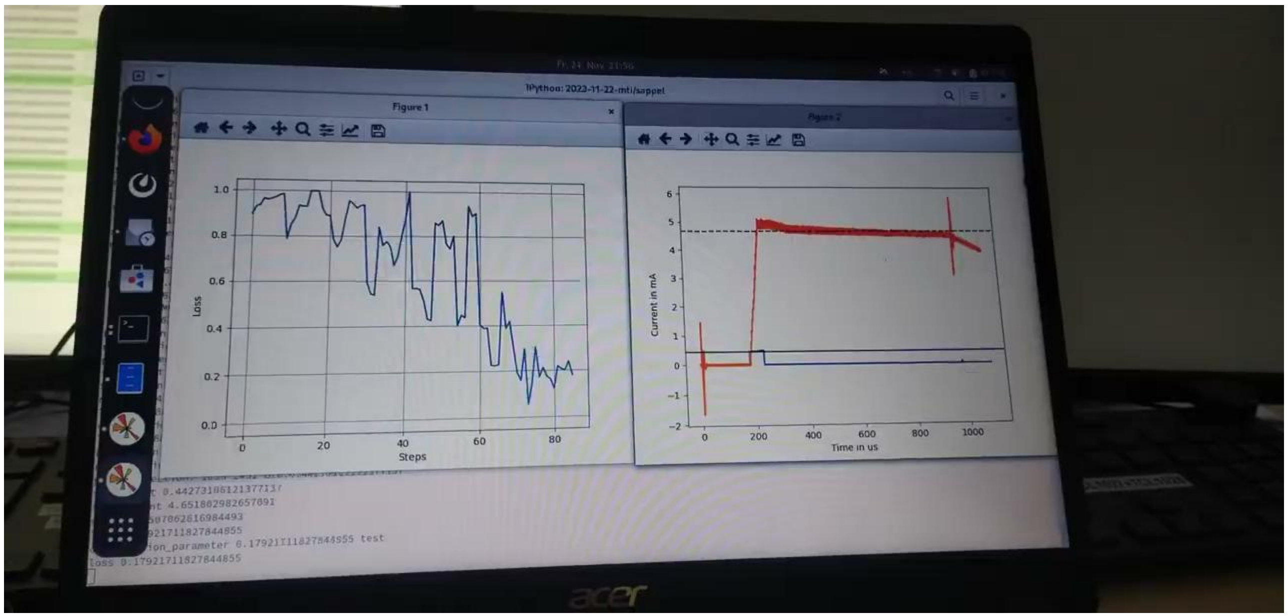
Loss definition:

- *Loss = (ideal current– SIS18 mean current) ÷ ideal current*
- *ideal current = mean TK current × expected number of injections*
- *Expected number of injections = Chopper window ÷ SIS18 rel. time*

Sabrina Appel (GSI), Nico Madysa (GSI)

Automation of Multi-Turn Injection

- With the Python bridge fully automated multi-turn injection optimization can be performed in about 15–20 min.
- The loss could be reduced from 40 % to 15 % using five optimization parameter.



Usage of GeOFF in a scripting context, with the terminal window in the background, and continuously updating figures for monitoring in the foreground.

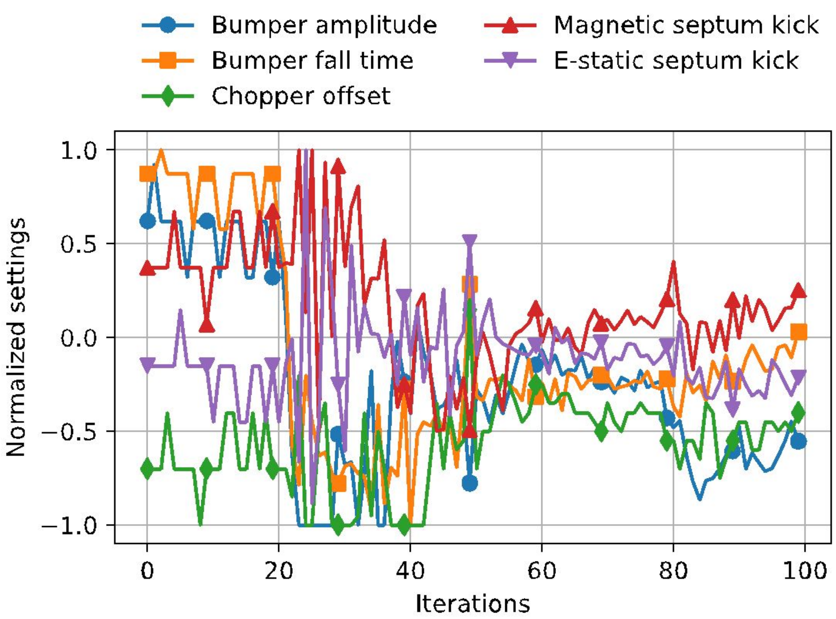
Sabrina Appel (GSI), Nico Madysa (GSI)

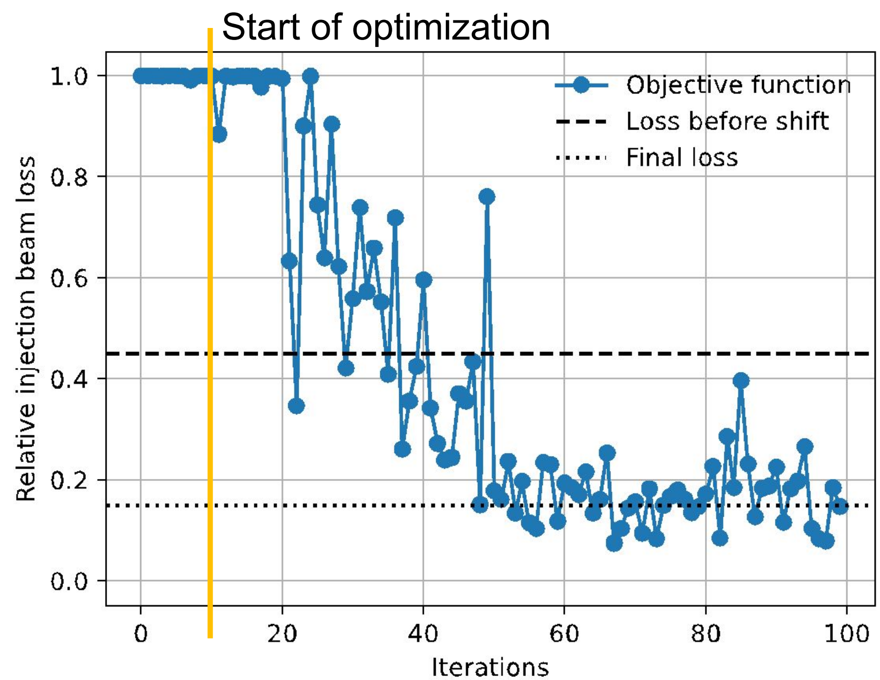
Automation of Multi-Turn Injection

- Using five optimization parameters.
- It ran for **100** iterations, which took about **19 minutes**.
- **Loss could be reduced from 40 % to 15 %.**
- Optimum was found, even though beam was fully lost in the beginning.

Multiturn Injection

Parameter	#	Value	Unit
Bumper ramp down time	1	110	µs
Bumper amplitude	2	)610443115234	mm
Unilac Offset		100	µs
Chopper delay	3	50	µs
Chopper window		60.0	µs
Chopper correction angle		0.0	mrad
GTK7MU5 correction angle		0.0	mrad
GS12MU3I correction angle	4	-0.07552774331	mrad
I-Septum correction angle	5	-0.44575636275	mrad

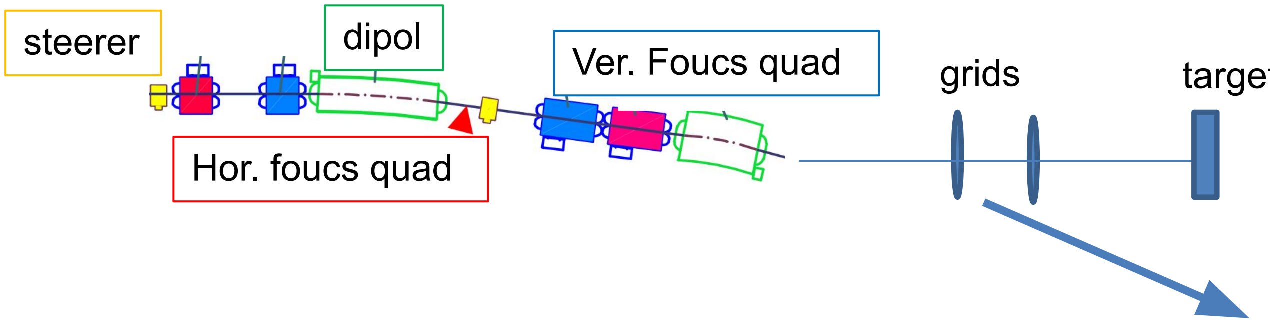


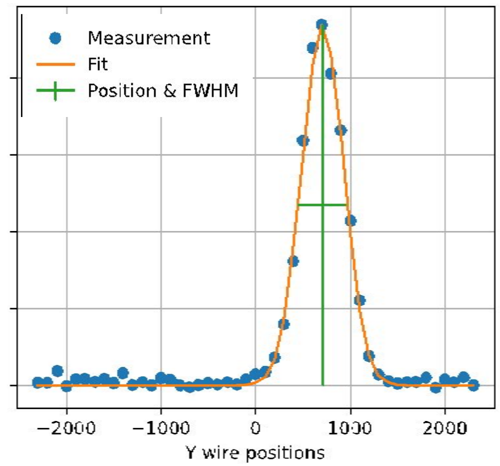


Sabrina Appel (GSI), Nico Madysa (GSI)

FRS: Automatic online steering

Objective Functions:
Misplacement or distance to the beam target using to two grids in front of the target





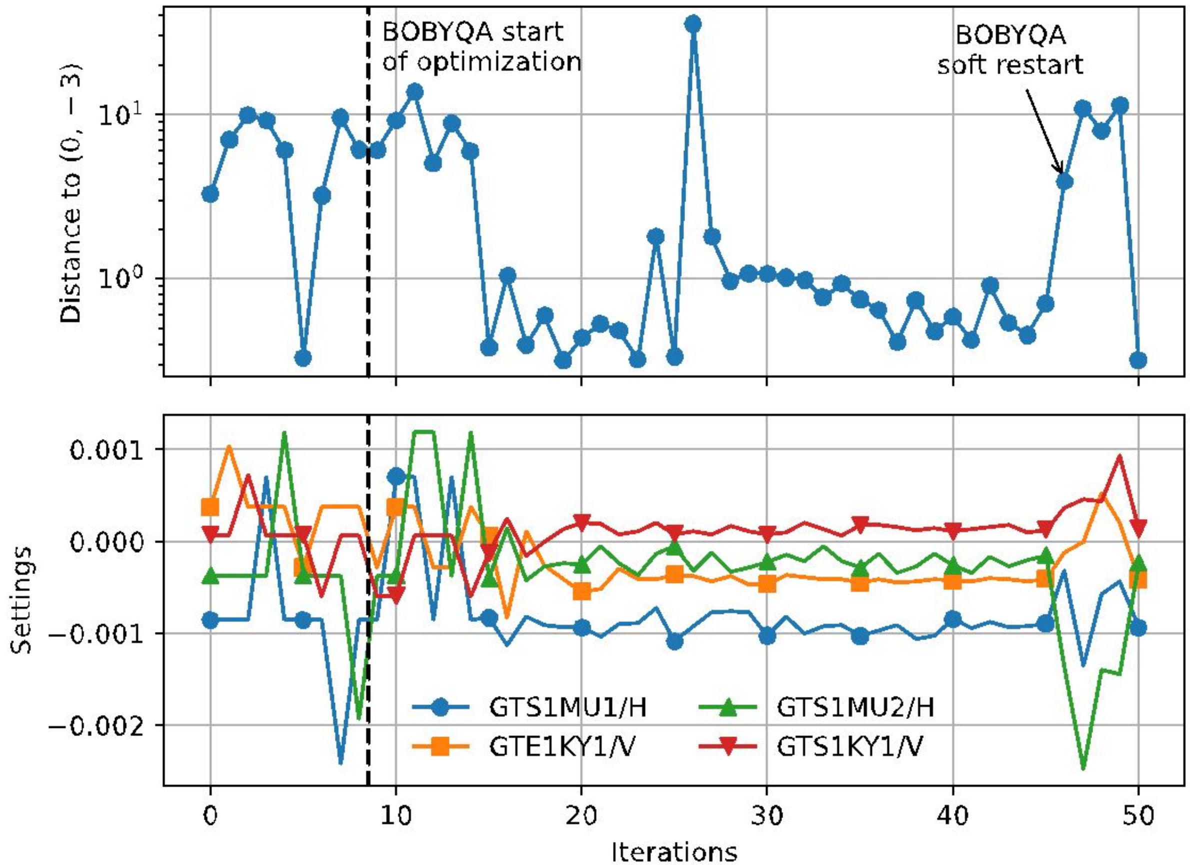
Limitation/time condition:

- Bandwidth multiplexer: multiple shots were necessary to acquire X/Y-grids
- “Bad shots”: analysis class cloud not perform reliable analysis of grids
- Slow extraction: SIS18 cycle length

S. Appel, E. Kazantseva, N. Madysa and S. Pietri (all GSI)

FRS: Automatic online steering

Proof of principle:
Online beam steering in **50 iteration** and took **18 minutes**.



S. Appel, E. Kazantseva, N. Madysa and S. Pietri (all GSI)

Idea of Bayesian Optimization (BO) based closed orbit correction

BO-based closed orbit correction:

Probability distribution (Gaussian Process) acts as a surrogate model

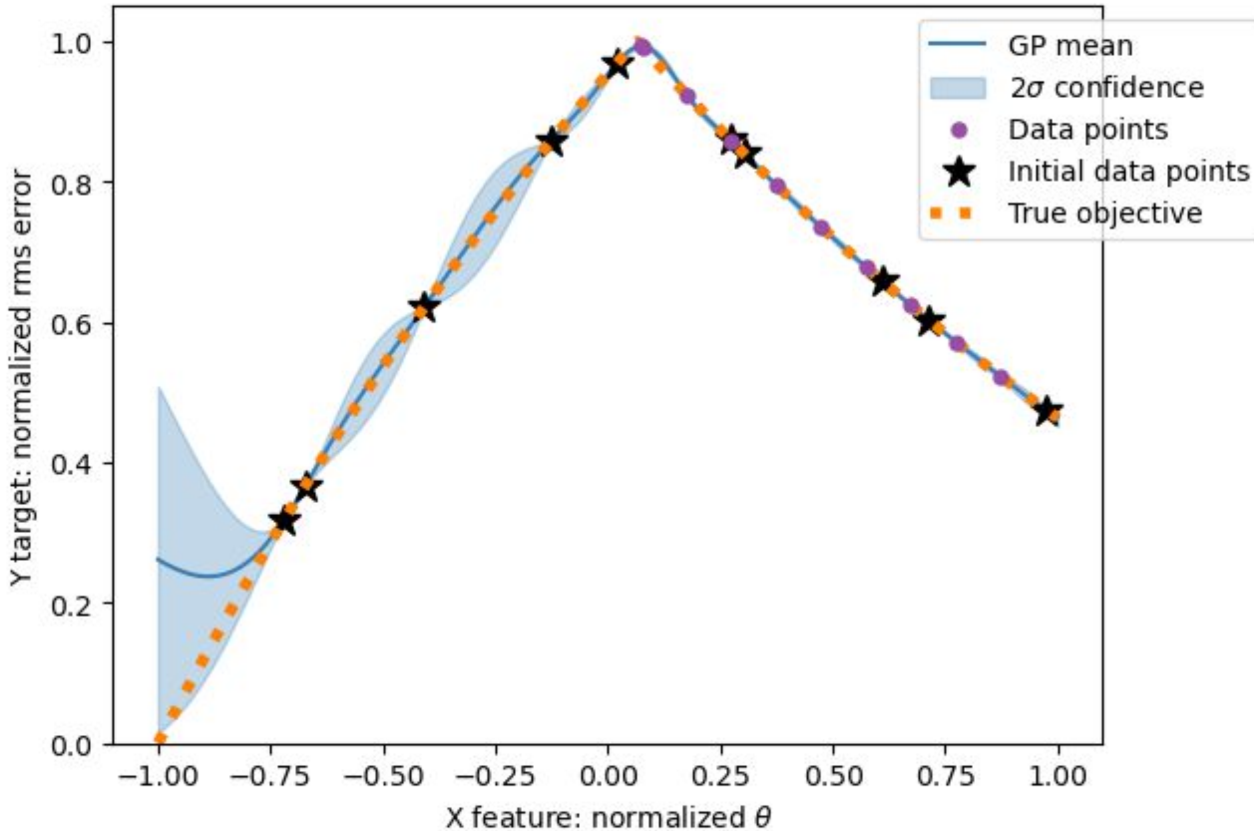
Described by mean function and the covariance function or kernel (currently using a Matern kernel, next step: physics-informed kernel)

Objective function: RMS deviation at BPMs

Next most promising evaluation point: Optimizing acquisition function (Upper Confidence Bound)

V. Isensee, MSc thesis 2023, Methods of Closed-Orbit Correction in Synchrotrons"

Simulation of the correction of a FODO cell (noise free):



V. Isensee (TU Darmstadt), C. Caliari (TU Darmstadt), A. Oeftiger (GSI)

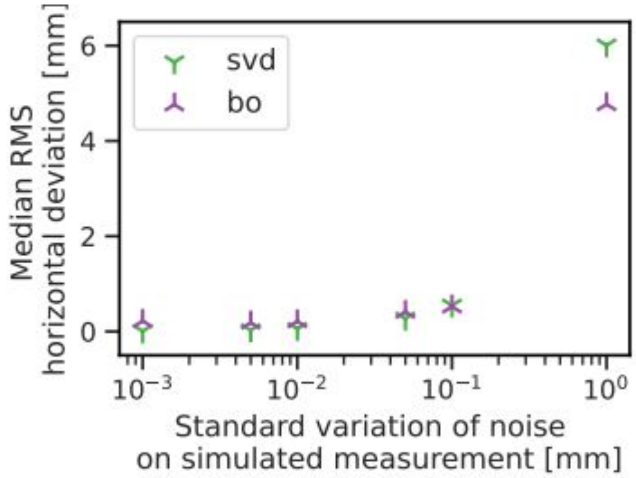
Challenging scenario at the experiment

Challenges due to:

Nonlinearities introduced by the chromaticity correction with sextupoles

BPM Noise

Simulated influence of Noise on BPMS:
For higher noise level BO achieves better results than SVD



Asymmetric optics:

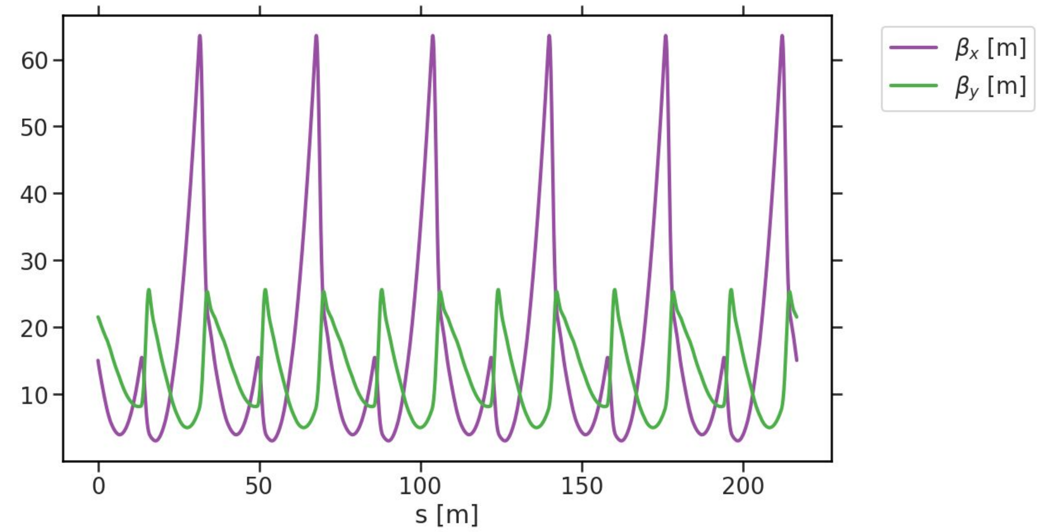
Optical setting to shift the transition energy, called sigma optics

Superperiodicity reduced from S=12 to S=6

Can cause standard closed orbit correction methods to fail

(see:
B. Franczak, K. Blasche and K. H. Reich, "A Variable Transition Energy Lattice for SIS 12/18," in IEEE Transactions on Nuclear Science, vol. 30, no. 4, pp. 2120-2122, Aug. 1983)

Simulated Betafunctions in sigma optics scenario:



V. Isensee (TU Darmstadt), C. Caliari (TU Darmstadt), A. Oeftiger (GSI)

BO-based correction for challenging machine optics

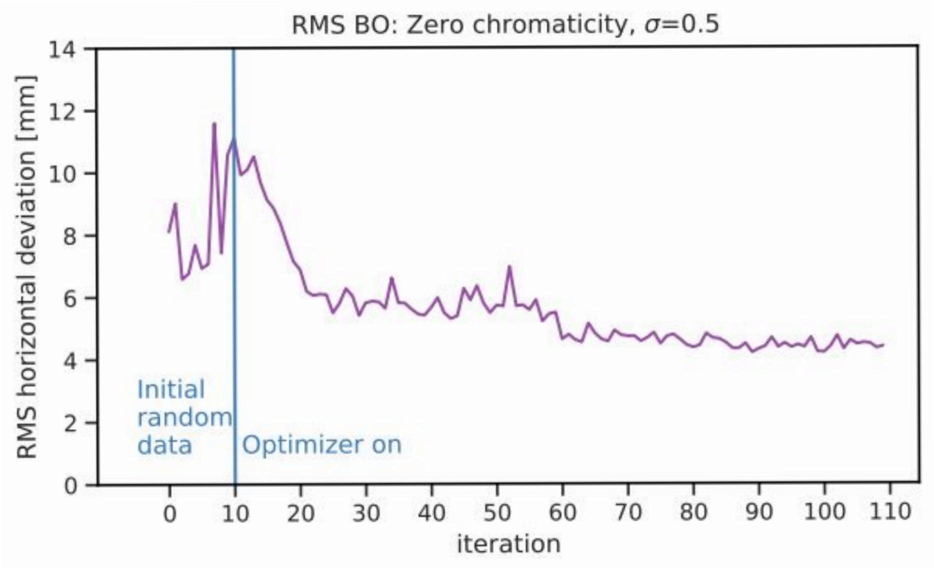
Results of BO-based correction:

Sigma optics with sigma value = 0.5

Random data needed for initialization

RMS of horizontal deviation converges

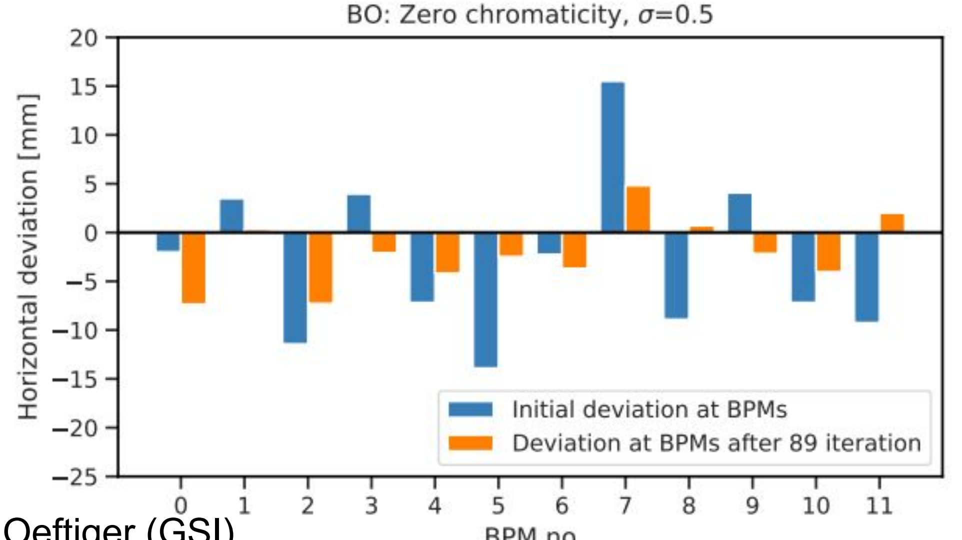
BO-based correction found result, where the standard methods (SVD) fails



Best found closed orbit:

Trained surrogate model, including a hyperparameter for noise, which can be reused

→ Basis for physics-informed kernel: BO with orbit model in between BPMs



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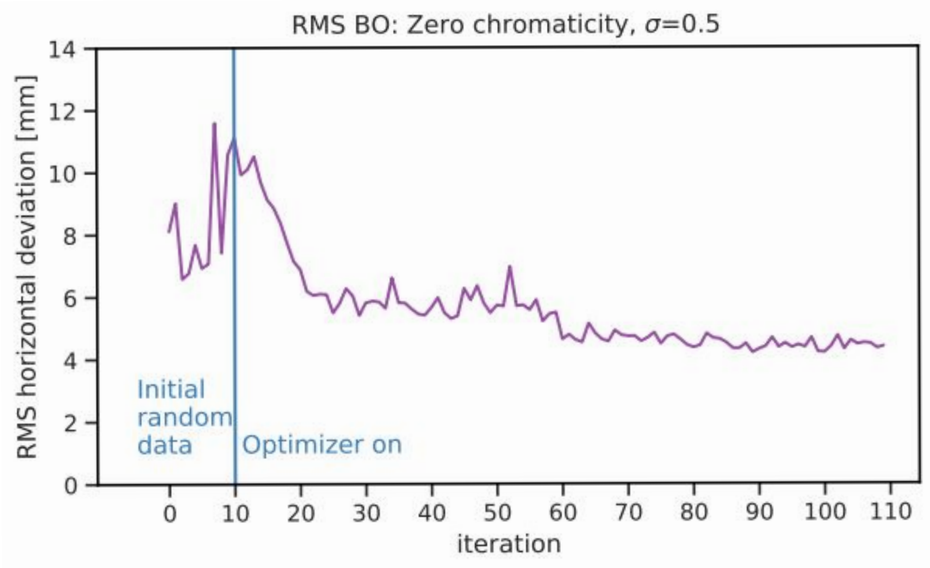

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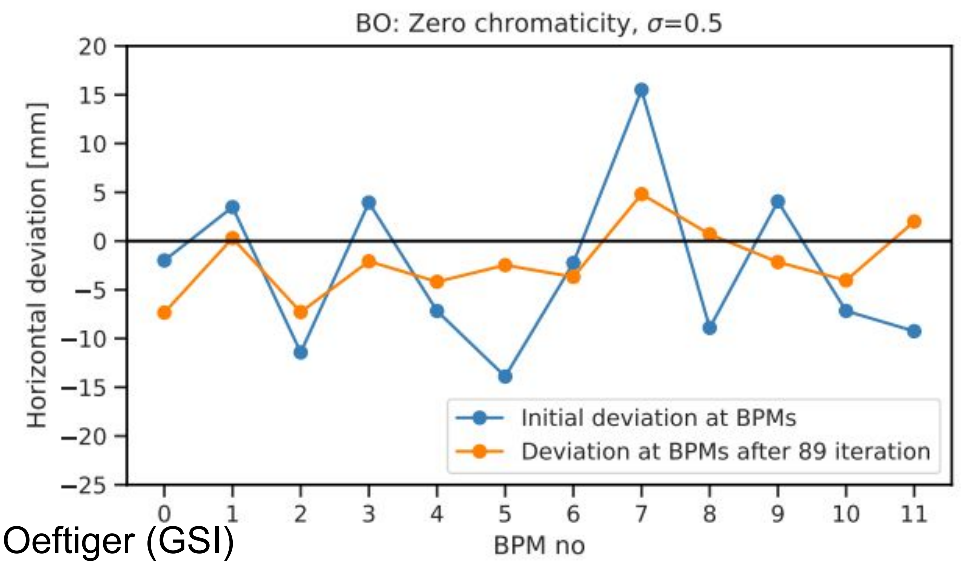


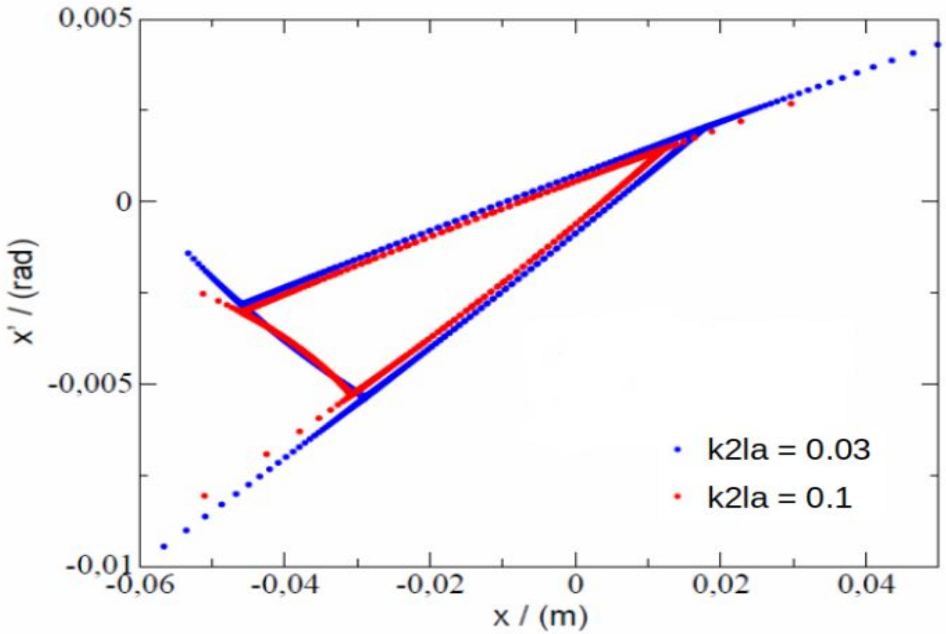
V. Isensee (TU Darmstadt), C. Caliari (TU Darmstadt), A. Oeftiger (GSI)

Optimization of slow extraction from SIS18

- Slow extraction (typ. 1 to 10 s) based on interplay of many parameters
- Very important for the fix target experiment (production of rare isotopes, compressed matter)

Slow Extraction by Tune sweep:

- Excitation of 3rd integer resonance with sextupoles.
- Shrinkage of separatrix due to quadrupole ramp.
- Sextupole strengths are characterized by amplitude and phase.
- Large amplitude results in lower particle loss due to transit from beam extraction channel in large steps.
- Phase affects orientation of triangle, thus, determines particle loss.



Olha Kazinova, TU Darmstadt
Stefan Sorge, GSI

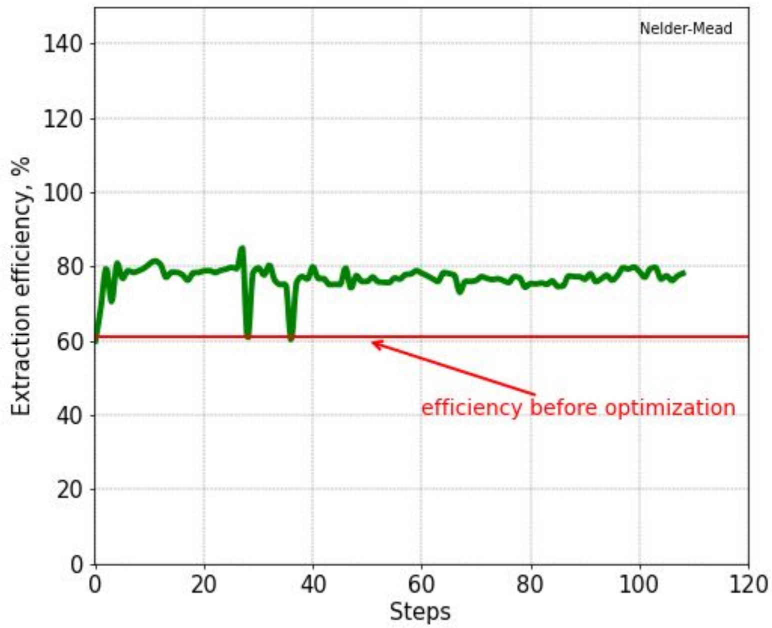
Optimization of slow extraction from SIS18

Maximizing extraction efficiency

$$p_{\text{eff}} = \frac{N_{\text{ex}}}{N_{\text{circ}}}$$

Extracted particles

Particles in circulating beam



Variables used for optimization:

sextupole amplitude $(k_2L)_a$ and phase φ which define strengths of the resonances sextupoles by

$$(k_2L)_{n_{\text{period}}} = (k_2L)_{\text{a}} \sin\left(2\pi\frac{n_{\text{period}}-1}{N_{\text{period}}} + \phi_{\text{sx}}\right)$$

 Extraction efficiency could be increase from from 60 % to 80 %.

Olha Kazinova, TU Darmstadt
Stefan Sorge, GSI

- Thank you for your attention.
- Questions?