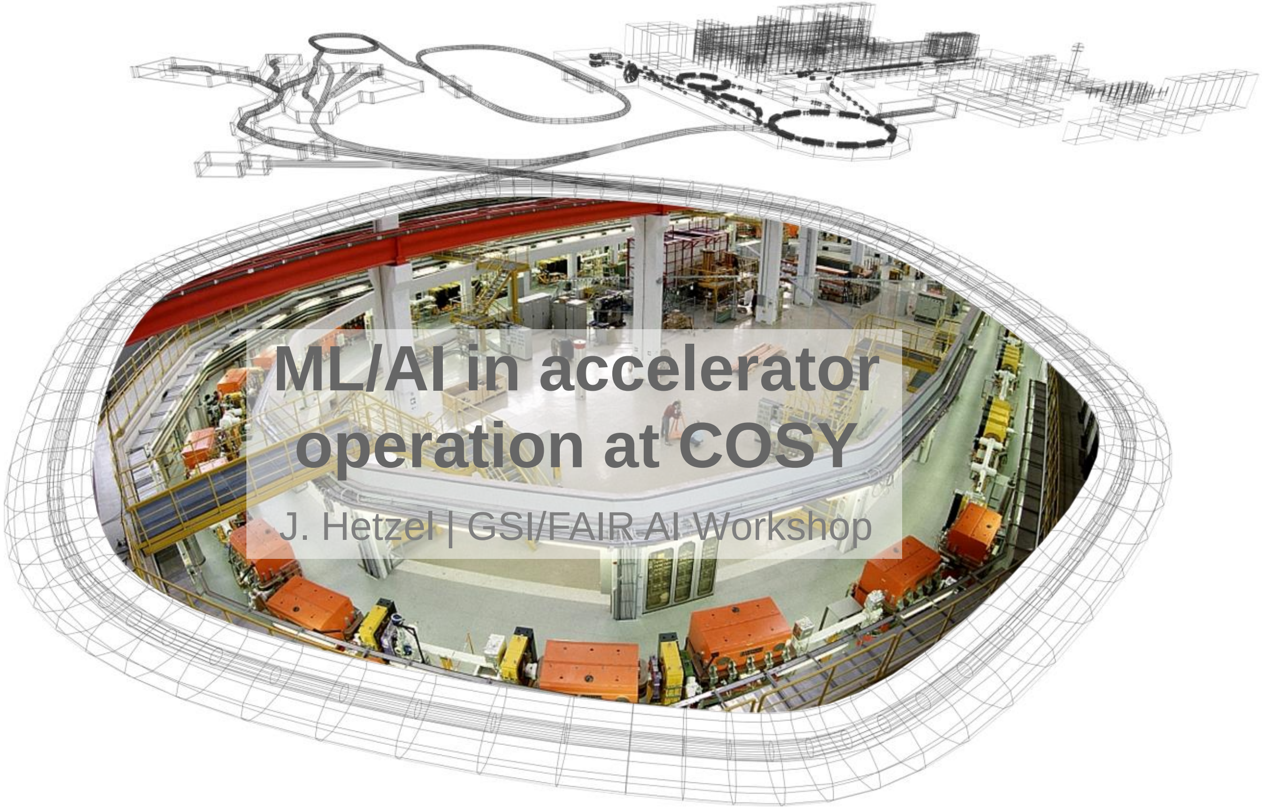
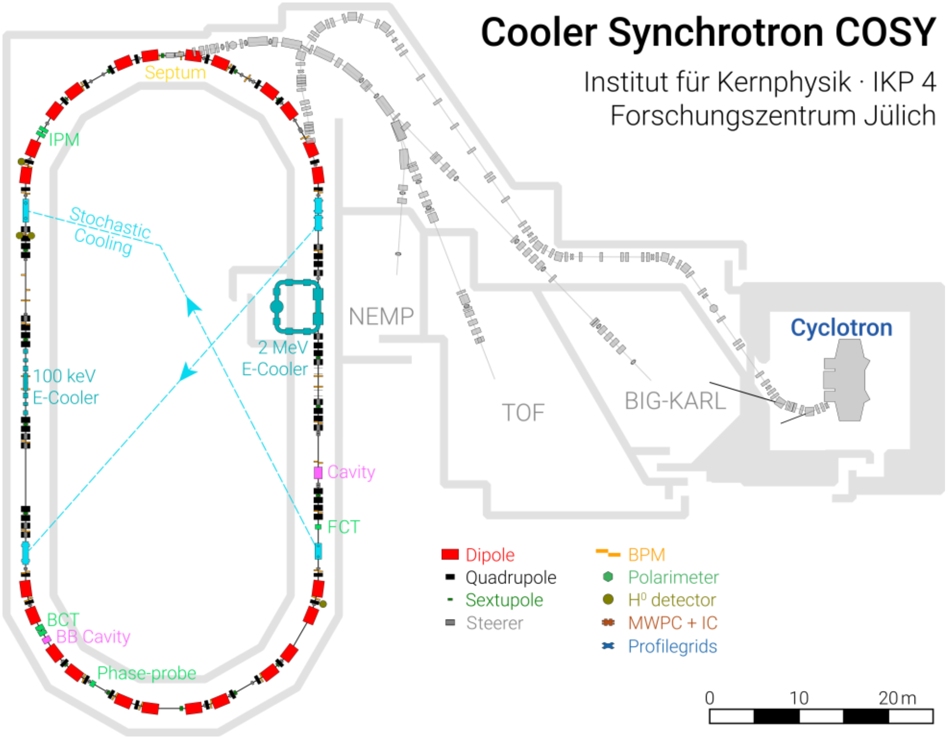


ML/AI in accelerator operation at COSY

J. Hetzel | GSI/FAIR AI Workshop

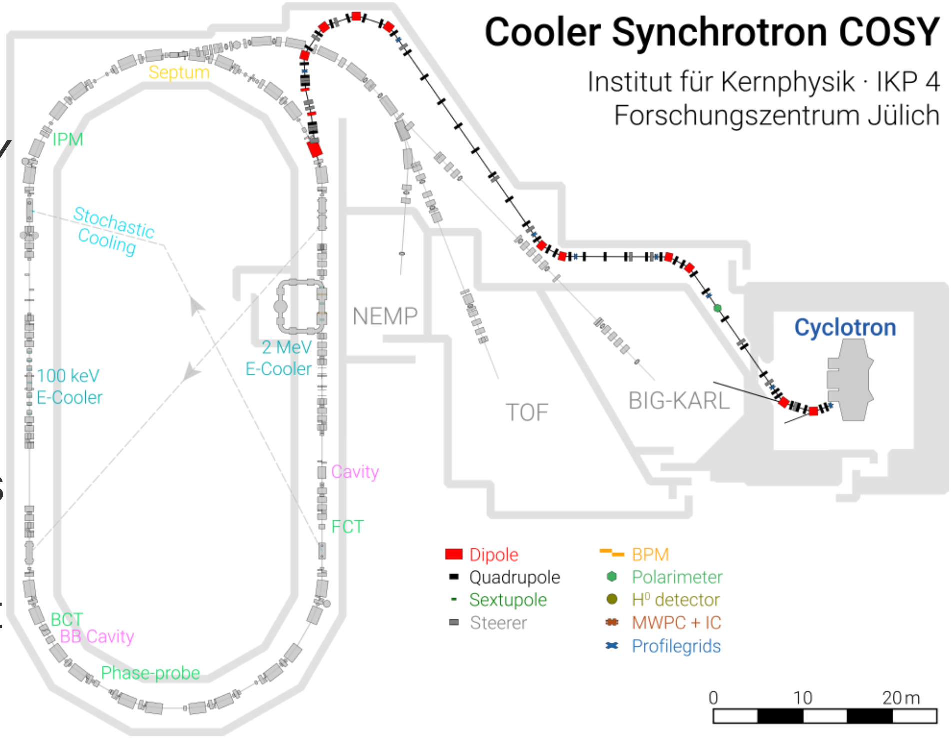
COSY + IBL

- COoler SYnchrotron COSY in Jülich
- Accelerates Protons (& Deuterons) up to T_p =2.7 GeV
- C = 184 m
- Experimental program concluded in 2023
- TransFAIR to GSI



COSY + IBL

- Injection Beam Line IBL
- Transfers particles from Cyclotron JULIC to COSY
- L = 94 m
- T_p= 45 MeV
- Beam controlled by resistive dipoles, quadrupoles and steerers
- Diagnosis Instruments (beam cups & viewers) at several locations



Typical Challenges During Operation

- Lengthy manual optimization of magnet settings to reach necessary performance (e.g. high number of stored particles)
- Drift in beam properties occurs in upstream devices/BLs
- Online model not reliable to needed level
- Automation possible but machine time necessary to test algorithms

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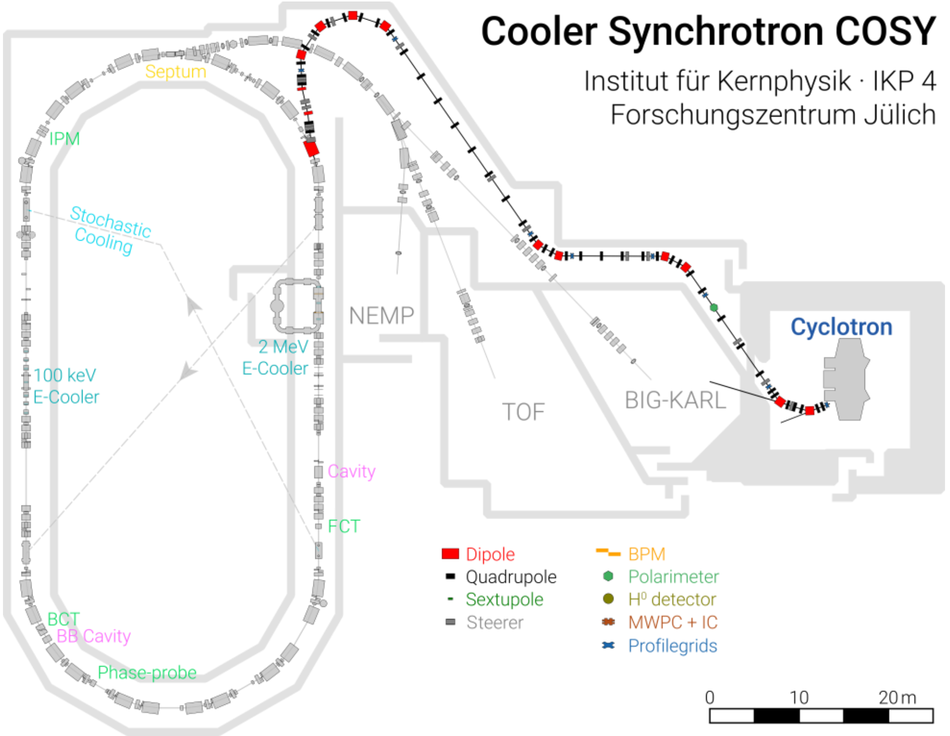

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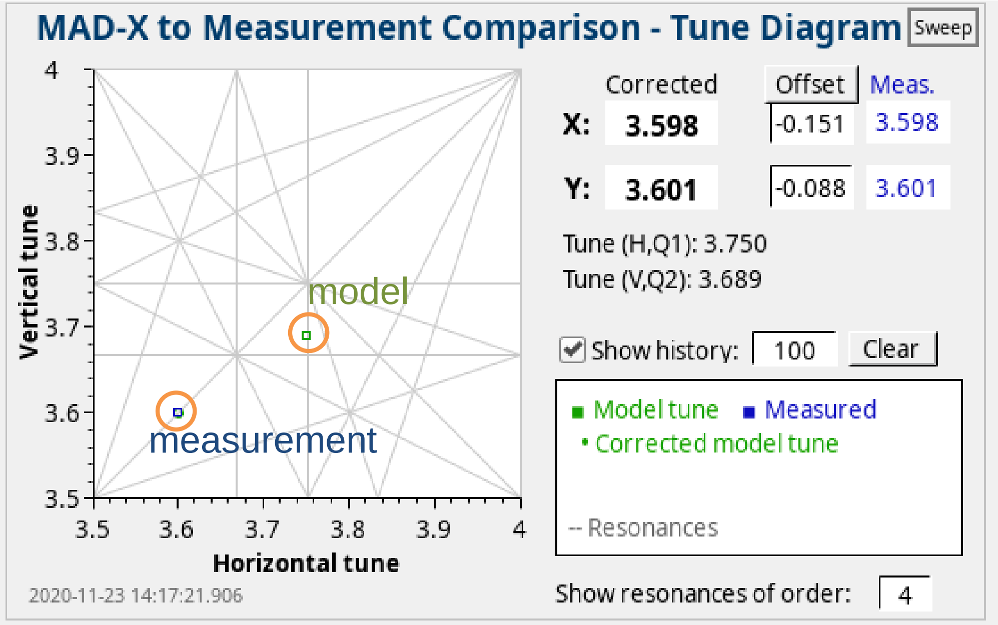

! But: Good agreement in prediction of relative changes!

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- Can we do better?

- YES!

(we did!)

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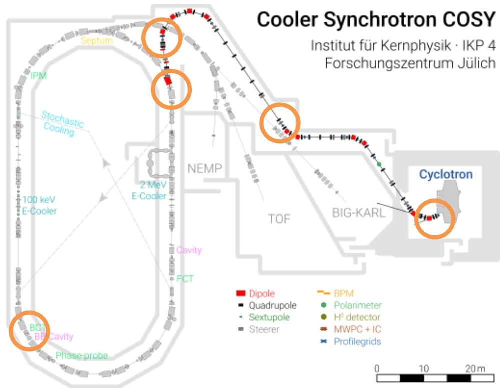
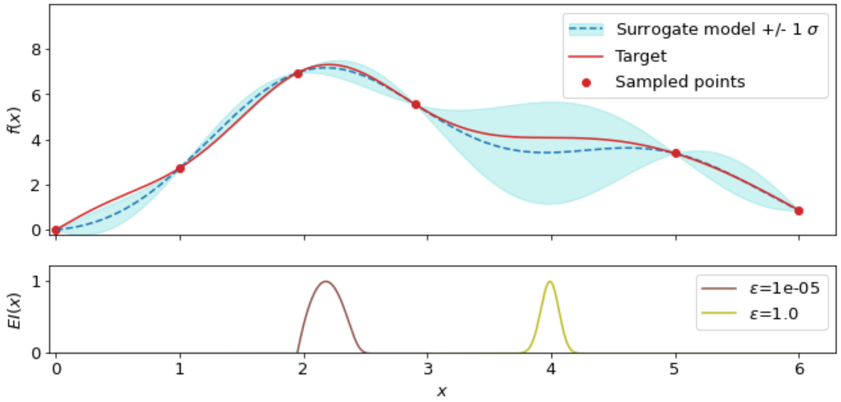
- Automated Optimization incl. **Bayesian Optimization**
- **Reinforcement Learning** to restore beam at injection point
- Optimization of model prediction with **Genetic Algorithm**
- Basic **digital IBL** for offline testing

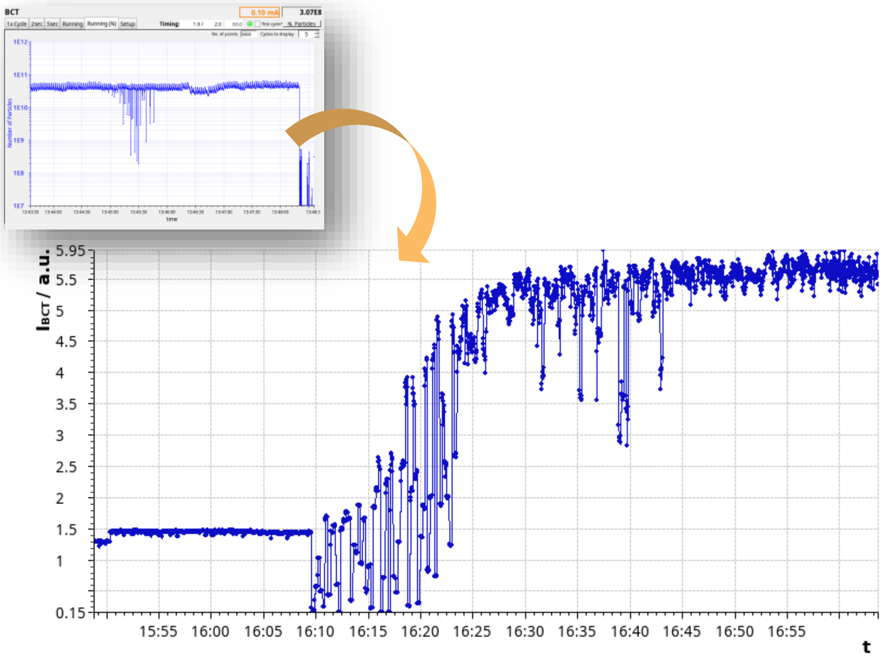
Bayesian Optimization BO





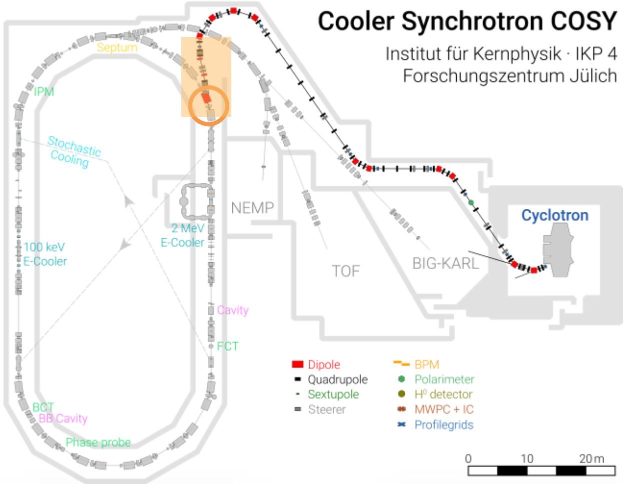
- Goal: Optimize Beam Current
- „Knobs“: Strength of Quadrupoles and Steerers @ IBL
- BO able to manipulate all knobs at once
- Generate surrogate model
- evaluation of surrogate model gives next setting (exploration: minimize uncertainties, exploitation: high beam current)
- Run simulation in parallel to reject settings with guaranteed losses

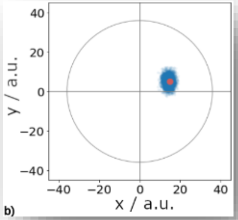
Bayesian Optimization



- Runs Automatic
- Improvement in setup-time
- Improvement in transferred intensity (all particles reach end of IBL)
- Implementation allows operators to chose target and magnets in optimization
- Regular use at COSY for Machine Development (preparation for beam times)
- Paper: A. Awal et al., 2023, *JINST* 18, P04010

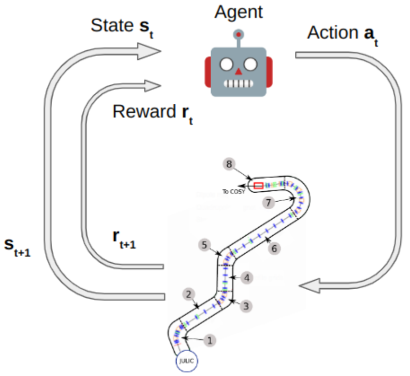
Reinforcement Learning

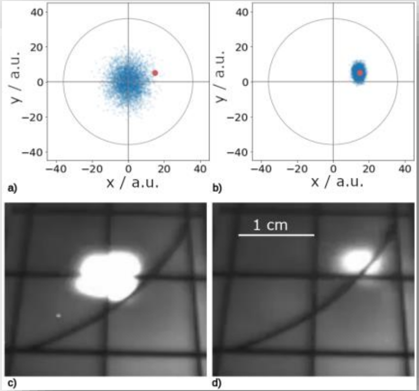


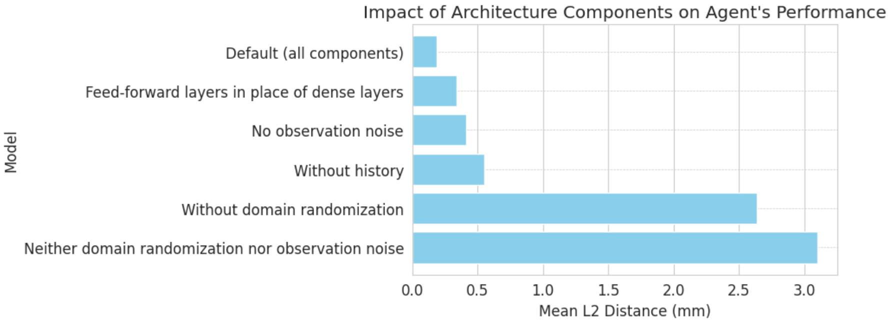


- Challenge: Easy way to compensate for drifts in upstream devices (e.g. cyclotron)
- Optimal phase space distribution for injection known
- Live image of beam distribution at injection point available (sadly only 2 of 4 dimensions!)
- use elements in last section of IBL to restore good distribution

Reinforcement Learning



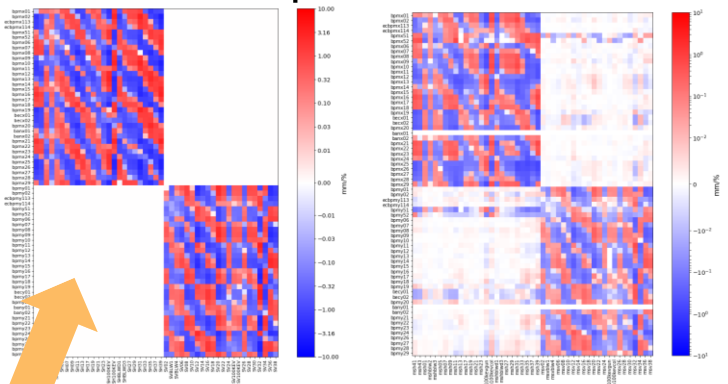




- Reinforcement agent: observe state (magnet settings and live image) and take action, gain reward
- Trained on model and applied on COSY (sim-to-real)
- Study on agents architecture vs. performance
- Reaches operator level, but faster
- Publications:
  - A. Awal et al., arxiv.2406.12735, submitted to PRAB (in review)
  - PhD Thesis of A. Awal

Genetic Algorithm GA for Better Model Predictions

Orbit Response Matrices

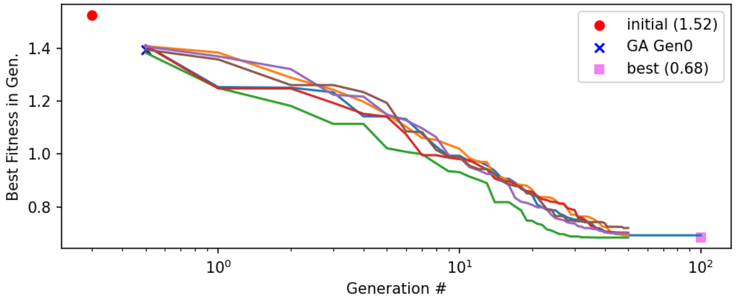


Model − Measurement

	Generation 1					Generation 2			
Δx	0.7 mm	0.8 mm	0.1 mm	...	0.6 mm	0.7 mm	0.7 mm	0.8 mm	...
Δy	0.4 mm	0.6 mm	0.3 mm		0.6 mm	0.4 mm	0.45 mm	0.6 mm	
Δs	0.2 mm	0.2 mm	0.5 mm		0.4 mm	0.2 mm	0.2 mm	0.21 mm	
...	...			...	...				...
Δϕ	9 mrad	5 mrad	1 mrad	...	3 mrad	9 mrad	5 mrad	9 mrad	...
	0.57	0.33	0.32		0.13	0.57	0.854	0.412	

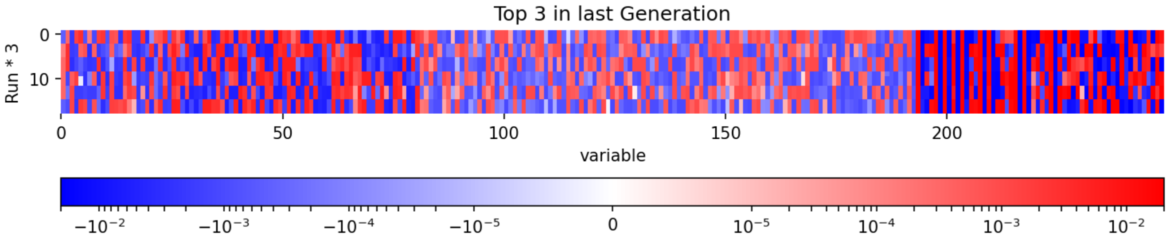
- Agreement of model and COSY optimized with Orbit response matrices (measurements for different settings available, easy to simulate)
- Free parameter: displacements and rotations magnets in COSY
- GA initialized randomly, settings (individuals) with better agreements (model to measurement) more likely to contribute to next generation
- Next gen: Mix of settings of successful individuals of recent gen + random variation
- Repeat until convergence

Genetic Algorithm for Better Model Predictions

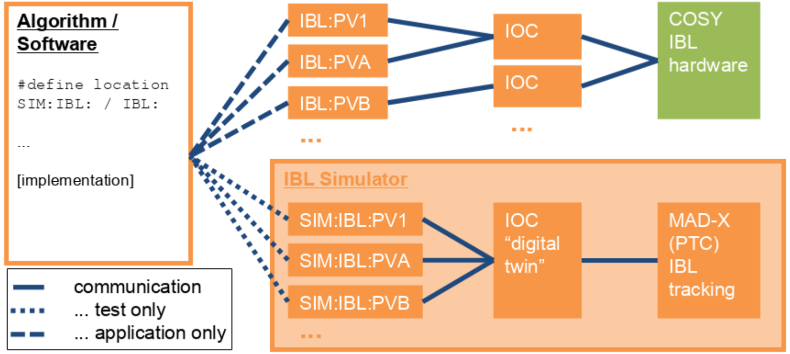


Results:

- Better agreements of ORMs achieved
- But: disagreement of results of different runs (correlations)
- Still: Better predictions of online model reached, although true source still unidentified



Digital IBL



- Software version of IBL
- Mimics central properties of elements (e.g. ramping time of power supplies, noise, jitter)
- Simulation of beam with MAD-X
- Beam instrumentation is simulated based on beam simulation
- Simulations triggered in real time (one simulation every two seconds)
- Same interface as control system (both EPICS)
- runs locally at PC of software developers ⇒ independence from beam times

Conclusion

- Accelerator operation benefits from usage of AI methods!
  - Faster set up times
  - Fast recovery of beam properties possible (independently of upstream)
  - Better model predictions
- Gain independence from machine availability with suitable simulations of whole machine (including physics, element behavior and control system).
- Reliable measurement of quantities for optimization essential!

Special thanks:

- A. Awal, I. Bekman, R. Gebel, J. Pretz
- CosyLab
- IKP-4, COSY Supervisor Team