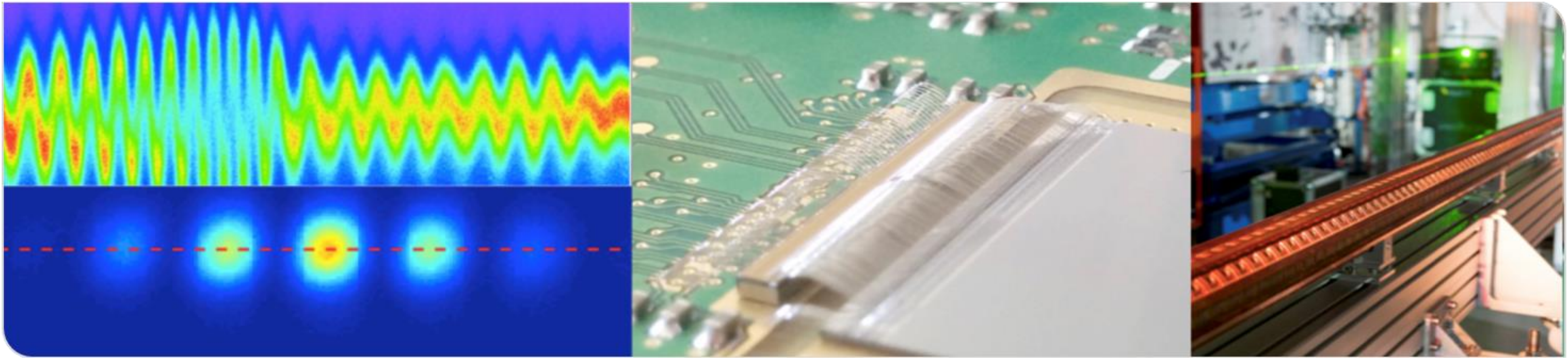
Karlsruhe Institute of Technology

Reinforcement Learning

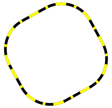
Erik Bründermann, Andrea Santamaria Garcia, Chenran Xu, Niky Bruchon for the KIT accelerator and detector teams



Disclaimer

Examples

- are not representative
- shall inspire overarching concepts

Oversimplifications = **box** or **ring** 

KARA

- Karlsruhe Research Accelerator
  - Storage ring length 110 meters
    - 0.5 GeV to 2.5 GeV
  - At center of KIT Light Source
    - Covering electromagnetic spectrum
      - THz, IR, VIS, UV, X-rays

Synchronized sensor network
Industrial control systems
Advanced control systems

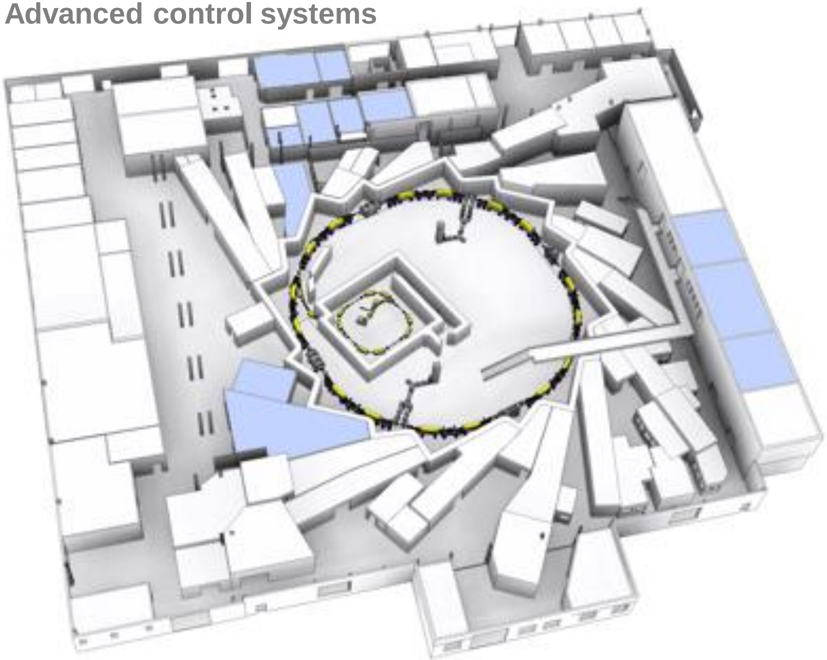
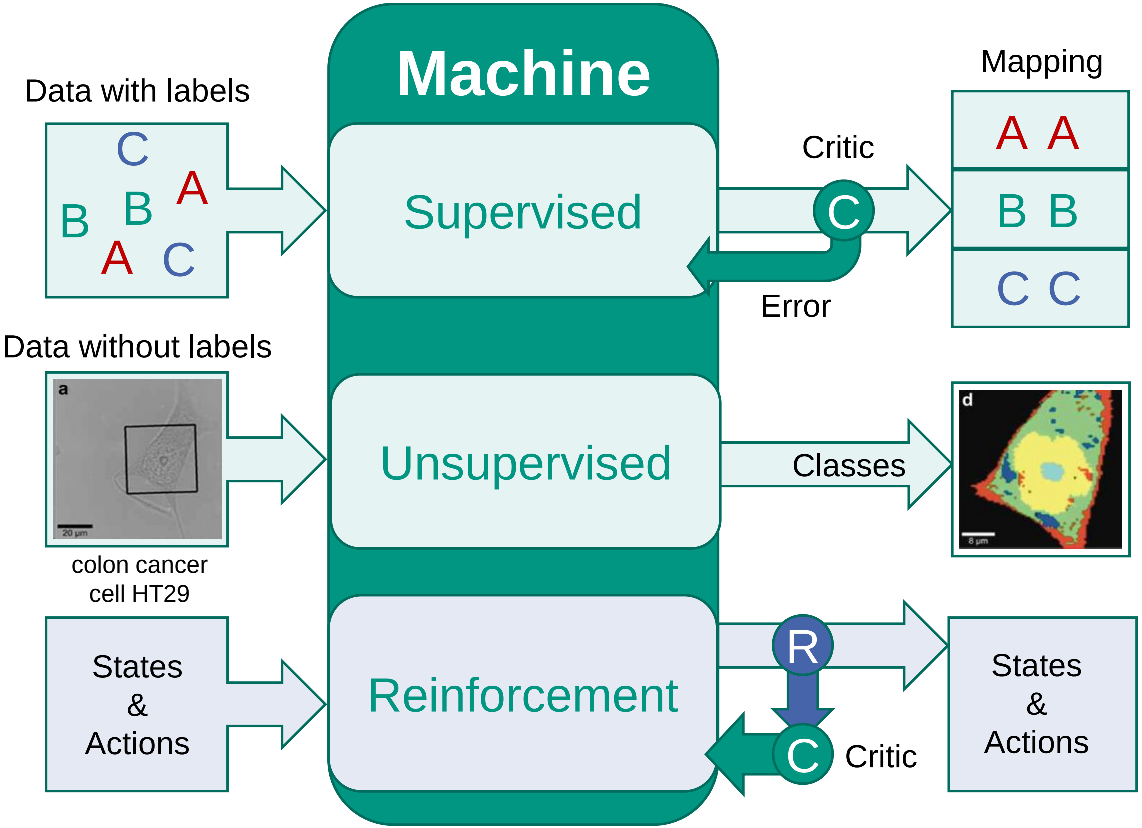


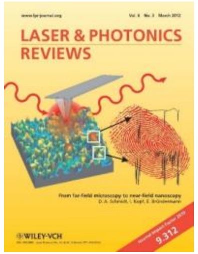
Image: U. Herberger, KIT IBPT www.ibpt.kit.edu/alfa

Learning



- Prognosis
- SAFETY
- …

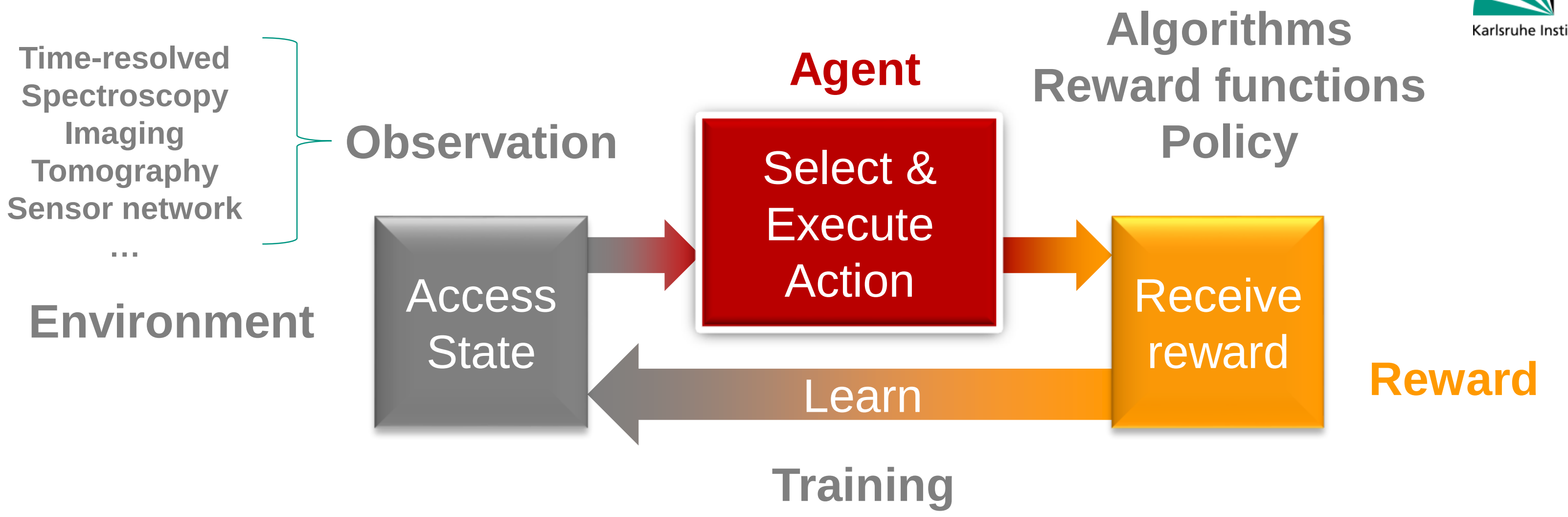
k-means
hierarchical cluster analysis
(HCA)
& segmentation



- Games
- Robotics
- Autonomous operation
- …

D. A. Schmidt, I. Kopf, E. Bründermann, A matter of scale: from far-field microscopy to near-field nanoscopy, Laser & Photonics Reviews 6(3), 296-332 (2012). DOI: https://dx.doi.org/10.1002/lpor.201000037

Reinforcement learning



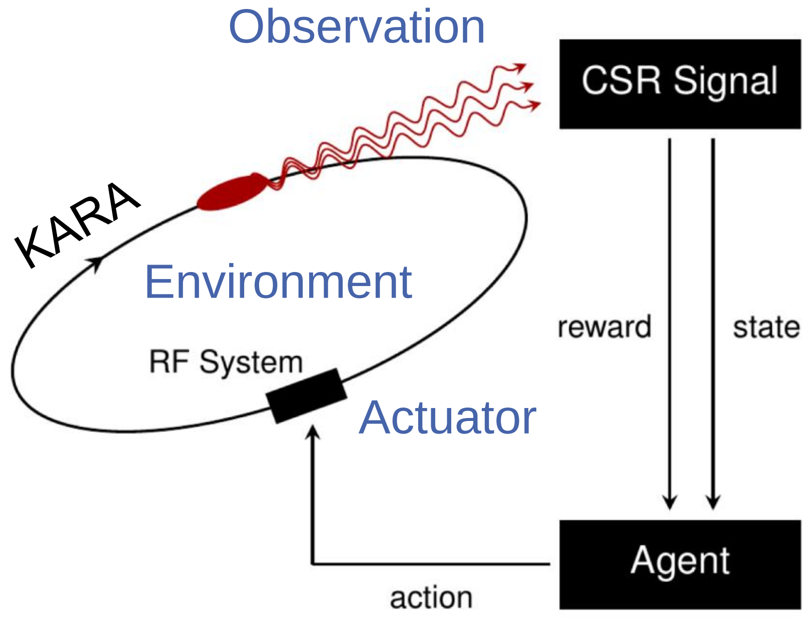
Data preparation
Calibration

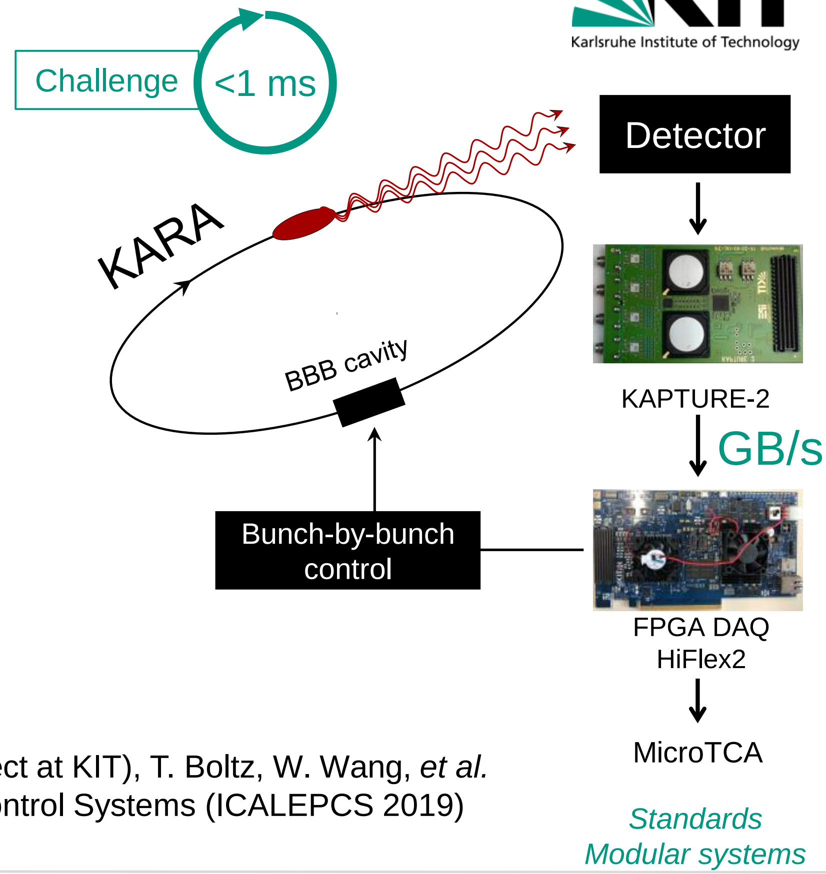
Modeling

System design

Deployment

Reinforcement learning for radiation control





Accelerating Machine Learning for Machine Physics (an AMALEA-project at KIT), T. Boltz, W. Wang, *et al.*
Proc. 17th Int. Conf. on Accelerator and Large Experimental Physics control Systems (ICALEPCS 2019)
DOI: https://doi.org/10.18429/JACoW-ICALEPCS2019-TUCPL06

More details see …

Accelerated Deep Reinforcement Learning for Fast Feedback of Beam Dynamics at KARA

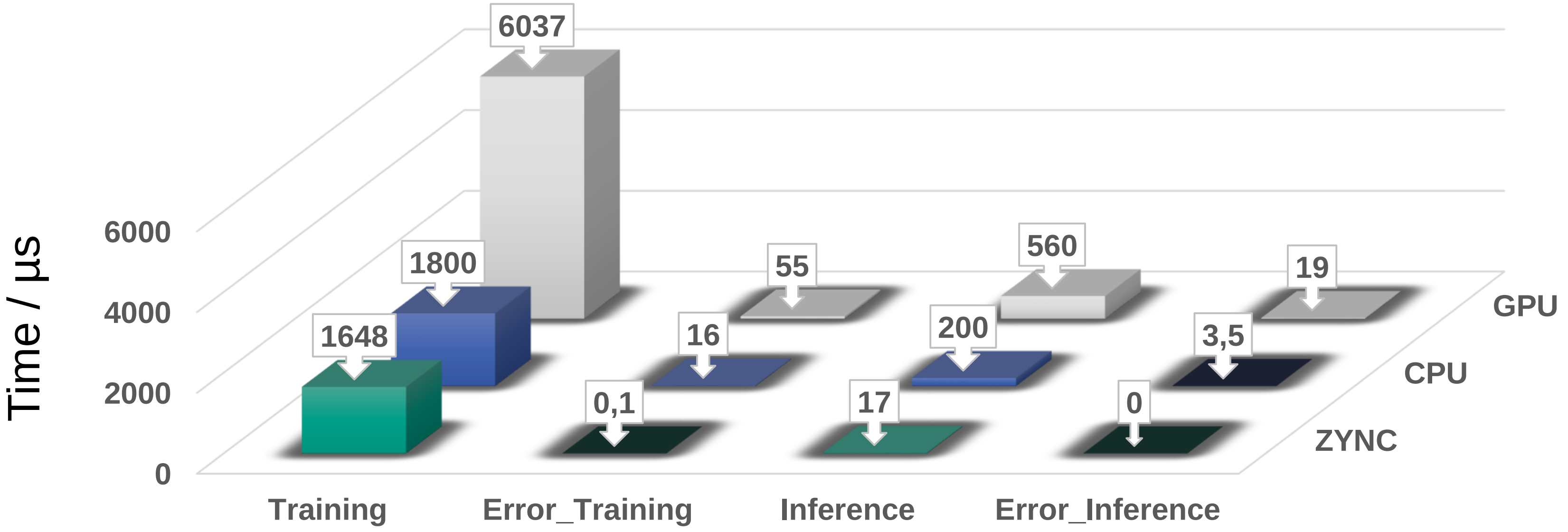
W. Wang, M. Caselle, T. Boltz, E. Blomley, M. Brosi, T. Dritschler, A. Ebersoldt, A. Kopmann, A. Santamaria Garcia, P. Schreiber, E. Bründermann, M. Weber, A.-S. Müller, Y. Fang
in *IEEE Transactions on Nuclear Science*.pp. 1-7, (2021).
DOI: https://dx.doi.org/10.1109/TNS.2021.3084515

Neural network architecture

- Deep deterministic policy gradient (DDPG)
- 4 layers each with 64 units
- Actor fully-connected dense layer neural network on FPGA
- Critic network and training policy located in ARM processor

Performance and latency

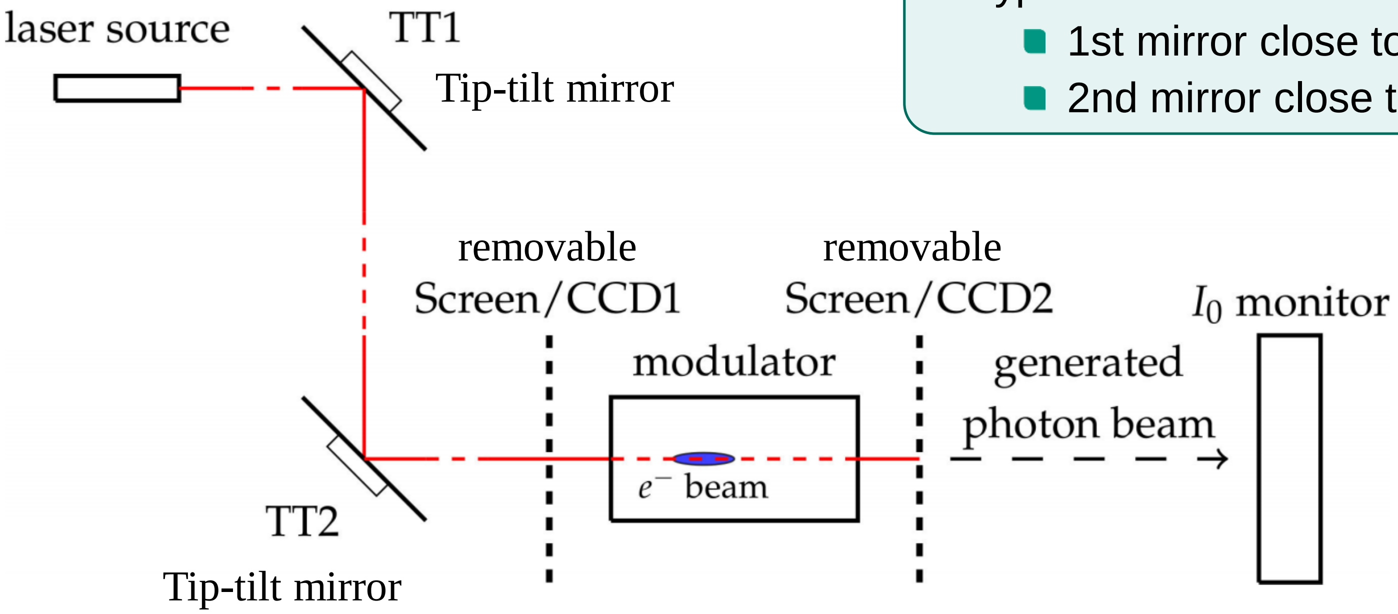
Proposed RL compared with Keras*-RL implemented on CPU and GPU



Accelerated Deep Reinforcement Learning for Fast Feedback of Beam Dynamics at KARA, W. Wang, M. Caselle, T. Boltz, E. Blomley, M. Brosi, T. Dritschler, A. Ebersoldt, A. Kopmann, A. Santamaria Garcia, P. Schreiber, E. Bründermann, M. Weber, A.-S. Müller, Y. Fang in IEEE Transactions on Nuclear Science.pp. 1-7, (2021), in *IEEE Transactions on Nuclear Science*. DOI: https://dx.doi.org/10.1109/TNS.2021.3084515

* open-source software library provides Python interface for artificial neural networks. Keras acts as an interface for TensorFlow library. Keras - Wikipedia

FERMI FEL seed laser alignment set-up scheme



- Typical recommendation for a simple setup
  - 1st mirror close to source
  - 2nd mirror close to target

Basic Reinforcement Learning Techniques to Control the Intensity of a Seeded Free-Electron Laser, Niky Bruchon *et al.*, Electronics 2020, 9, 781, DOI: https://doi.org/10.3390/electronics9050781

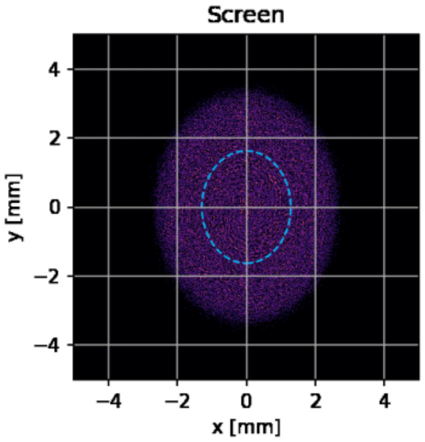
Focusing of a beam

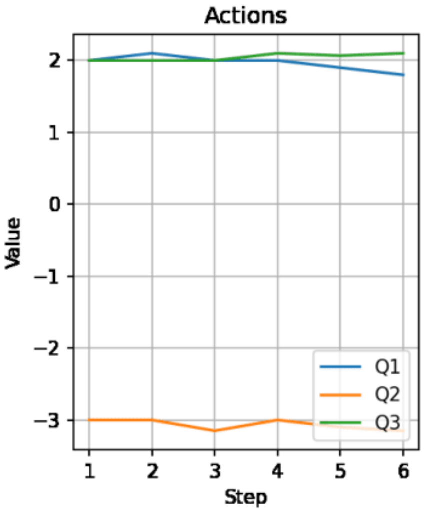
Allow optimization both by RL agent and traditional optimizers

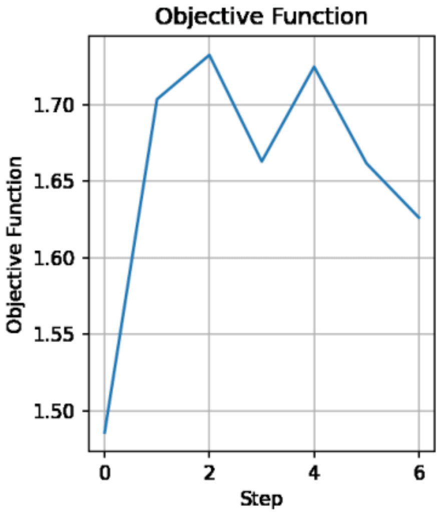
First tests using scipy Nelder-Mead optimizer

Objective = $\max(\sigma_x, \sigma_y)$

Actuators = $[Q_1.k_1, Q_2.k_1, Q_3.k_1]$





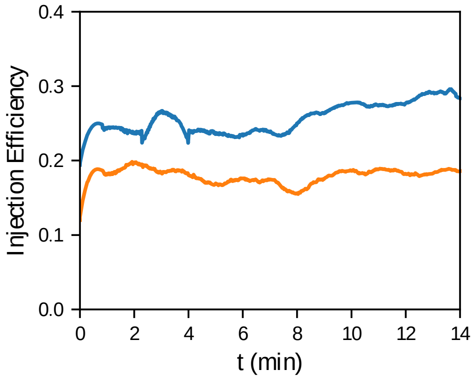


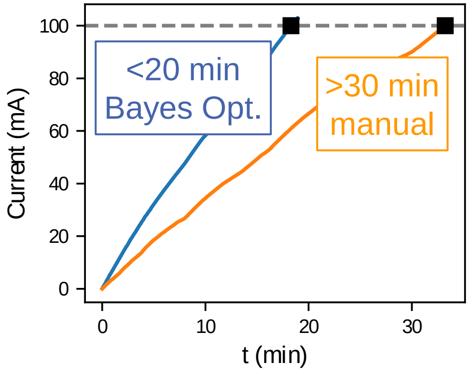
OpenAI Gym environment
to ease sharing between facilities

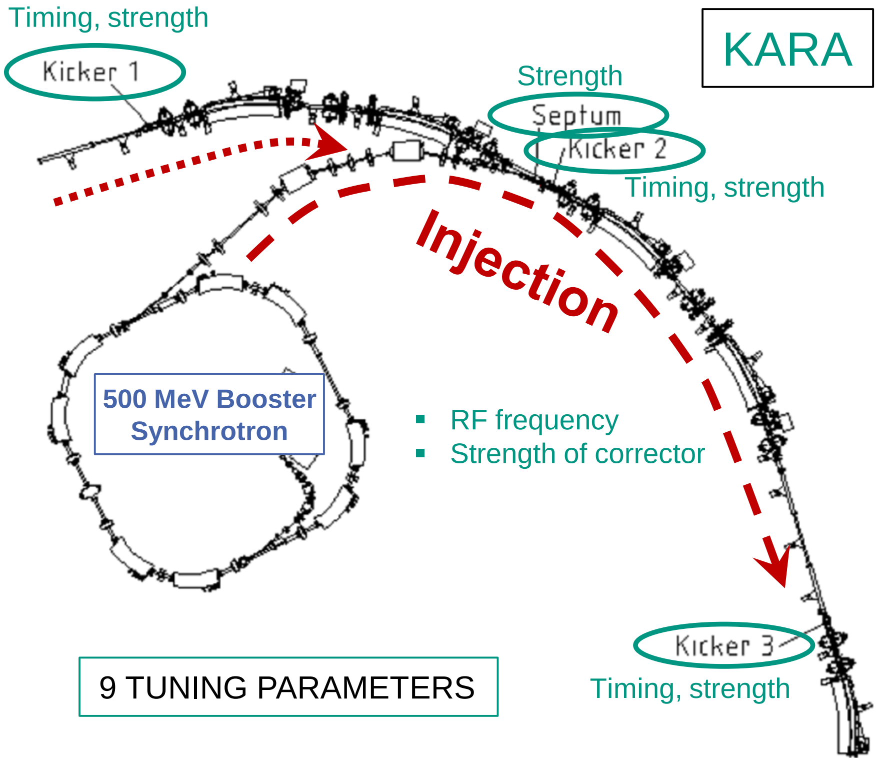
Courtesy of Chenran Xu, KIT

Inject electrons twice faster

- **Goal**
  - improve injection rate
- Manual trial-and-error tuning
  - time consuming
  - depends on operator's experience
  - may get stuck in a local optimum



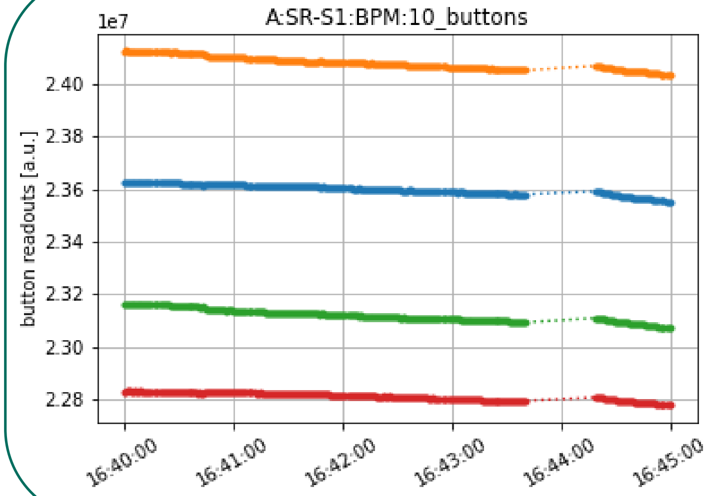




Chenran Xu, Master thesis, KIT, to be published
https://indico.desy.de/event/28167/contributions/93869/attachments/63231/77117/2020-12-17_AMALEA_FinalMeeting_SANTAMARIA_export.pdf

Diagnosis and prognosis

12.04.2021: restart of firmware



Missing data in 4-channel readout of beam position monitor

Courtesy of Niky Bruchon, KIT

Deployment

Karlsruhe Institute of Technology

Goal

- Solutions shall be transferable
- Independent of platform
  - From PC to Cluster to HPC

Challenge

- Dependencies easily break

Measures

  - Containers (docker, singularity, …)
  - Virtualization (virtual machines, …)

Control System Virtualization at Karlsruhe Research Accelerator, W. Mexner, B. Aydt, D. Hoffmann, E. Bründermann, E. Blomley, M. Schuh, A.-S. Müller, S. Marsching, Proc. 17th Int. Conf. on Accelerator and Large Experimental Physics control Systems (ICALEPCS 2019). DOI: https://doi.org/10.18429/JACoW-ICALEPCS2019-MOMPL009

Guiding (teaser) questions

Disclaimer:
No attempt to be complete!

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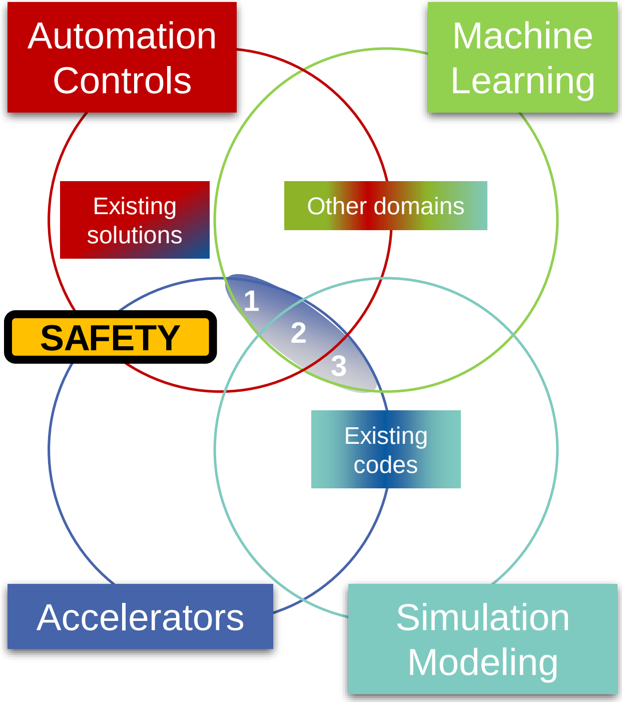

- Where do accelerators profit from ML and ML-guided research?
- Where are break-even points to conventional approaches?
- Can a common understanding/language/taxonomy* be found?
- Can ML improve efficiency and replace tedious/cumbersome tasks?
- Are ML-algorithms transferable? Can they be standardized/easy to use?
- Is ML fast enough for fast-feedback and control tasks?
- What about safety-critical applications, if the ML-decision-process is complex?

Accelerator Operations from components (RF, magnets, lasers, …) to facility, Simulation, Modeling, Data Analysis, Physics and Engineering Experiments, …

- *Level of digitalization/automation heterogeneous (within and between facilities)*
  - Teaser Keywords (*no specific order*): remote control, industrial control systems, specialized codes, industrial and advanced diagnostics, fast feedback systems, data archiving and management, virtualized servers, network infrastructure, …
- Beam and plasma dynamics, acc. physics codes**, accelerator and optics modelling, …

Examples:

1 - accelerator optimization (tuning, correction), autonomous operation
2 - virtual diagnostics, digital twins, anomaly detection, forecasting
3 - surrogate models, time-efficient parameter scanning, optics design

Borders blurred. For Autonomous Accelerators a confluence of it all?

* EU taxonomy for sustainable activities
** Accelerator physics codes - Wikipedia

References and projects

- Helmholtz Innovationspool project ACCLAIM (2021-2023)
  - Accelerating science with artificial intelligence and machine learning
  - Coordinators: M. Zepf, HIJ; F. Gaede, DESY.
  - https://indico.desy.de/event/30694/
- Helmholtz AI „ML toward Autonomous Accelerators“ (2020-2022)
  - Coordinator, PI: A. Eichler, DESY; PI: E. Bründermann, KIT.
- Evaluate the “Impact of machine learning on accelerator R&D”
  - ARD Status and Plans slide 7+8
  - https://indico.desy.de/event/29414/contributions/100337/
- Presentations
  - https://indico.desy.de/event/28167/contributions/93869/attachments/63231/77117/2020-12-17_AMALEA_FinalMeeting_SANTAMARIA_export.pdf
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  - https://indico.desy.de/event/30438/contributions/104968/attachments/66590/82578/2021-06-25_ACCLAIM.pdf
- Action Plan ErUM-Data Community Meeting Jan 2021
  - https://indico.desy.de/event/28330/timetable/#20210118.detailed