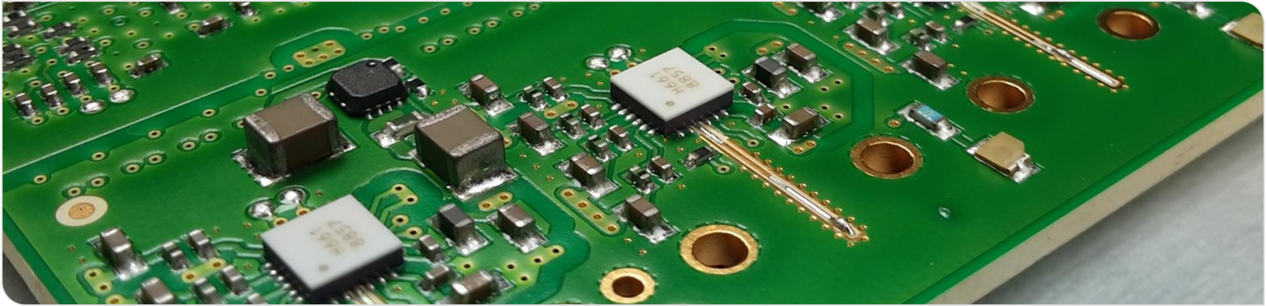
Karlsruhe Institute of Technology

Institute for Data Processing and Electronics

Real-time Reinforcement Learning on FPGA with Online Training for Autonomous Accelerators

Luca Scomparin, Jürgen Becker, Edmund Blomley, Erik Bründermann, Michele Caselle, Timo Dritschler, Andreas Kopmann, Anke-Susanne Müller, Andrea Santamaria Garcia, Johannes L. Steinmann, Chenran Xu | 5-8 March 2024



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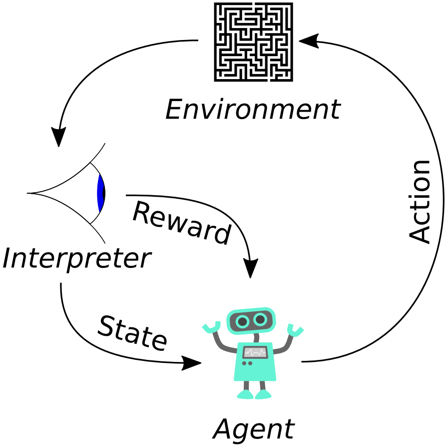
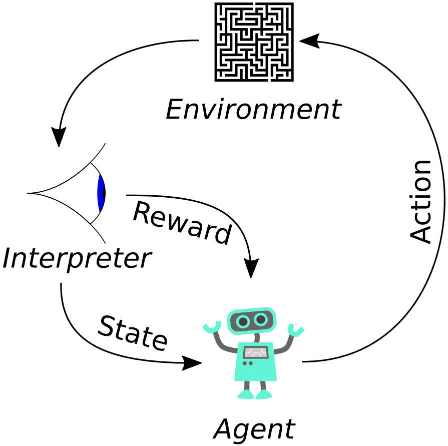

Environment
Interpreter
Reward
Action
State
Agent

Motivation



Usually data-hungry

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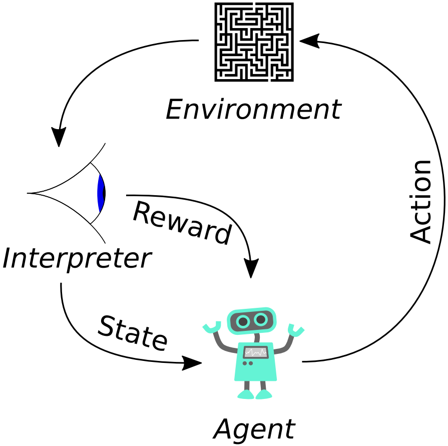

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Great data rate $\rightarrow$ lot of training data

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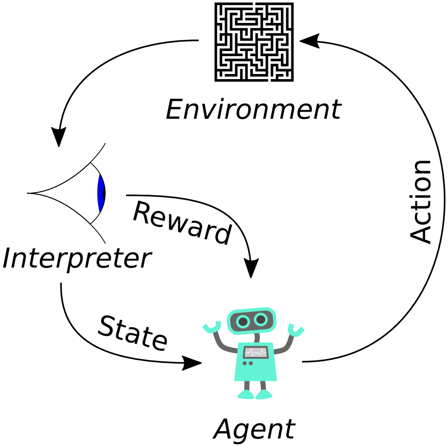

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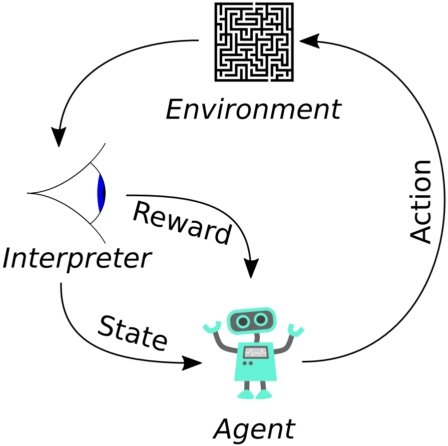

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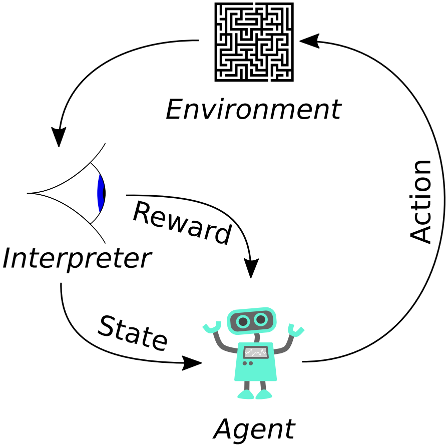

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Timing constrains become relevant!

What is Real-Time?

Shin and Ramanathan (1994) identify major components:

> *Correctness of a computation depends not only on the logical correctness but also on the time at which the results are produced.*

1. "time" is the most precious resource;
2. reliability is crucial;
3. **environment of operation** is an active component.

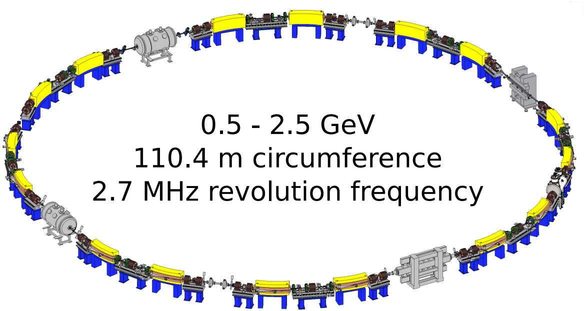
Predictability is fundamental!

Three possible levels/categories:

1. *hard*, catastrophic consequences;
2. *firm*, results produced late not useful;
3. *soft*, later means decreasing usefulness.

Depending on environment, RL can be either one of these!

Case study: KARA



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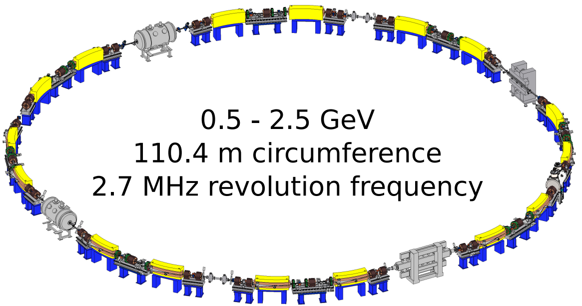
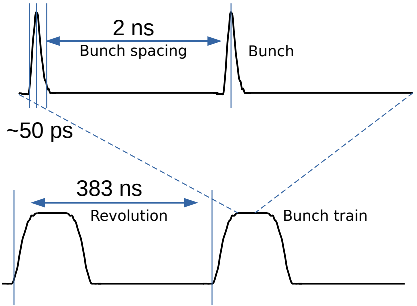


Example signal



Synchrotron frequency/period $O(10\,\text{kHz} \leftrightarrow 100\,\mu\text{s})$

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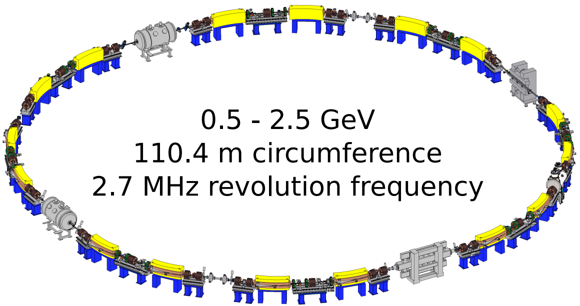

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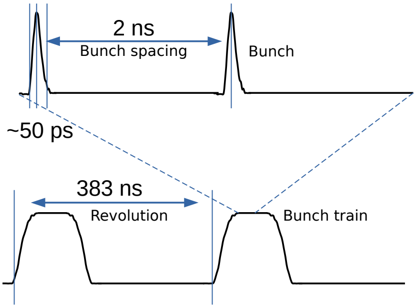
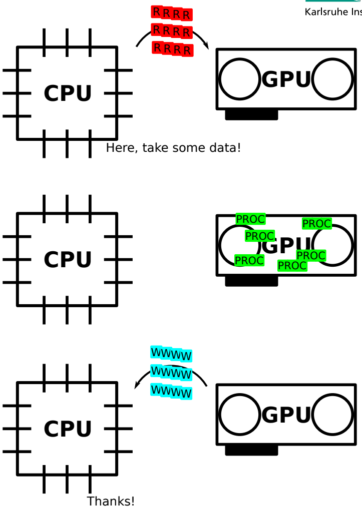


Synchrotron frequency/period $O(10\,\mathrm{kHz} \leftrightarrow 100\,\mu s)$

Huge variety of time scales!

Issues of Real-Time AI

- Current ML frameworks have mainly throughput in mind → no/little real-time optimization;
- use of batched execution on GPU → not optimal for latency;
- conventional computing hardware not meant for low-latency real-time;
- it still works great for latency in the millisecond range!



Heterogeneous platforms

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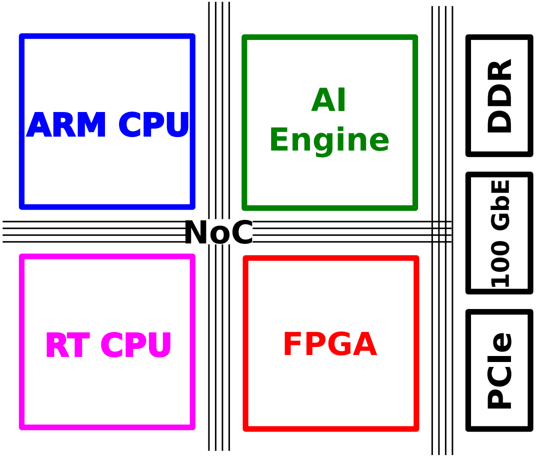
Different computing platforms → different benefits

Heterogeneous combine CPUs, FPGAs and "GPUs"

An example, AMD Versal:

- combines FPGAs and ARM CPUs;
- AI Engine array for heavy multiplication workloads;
- Network-on-Chip interconnect;
- high-speed interfaces.

These computation unit work in synergy and share memory!



The KINGFISHER RL platform

Experience accumulator

Real-Time inference BUT Offline/Batched training

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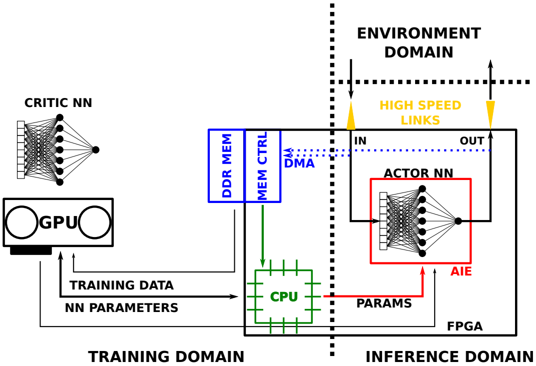
Pros:

+ "easy" real-time;
+ can use complex training algorithms;
+ can use GPUs and other accelerators;
+ training time reward definition™.

Cons:

- data inefficient;
- actor design is critical;
- training overhead.



First test: betatron oscillations

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Start simple $\rightarrow$ test all components together

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- Easy to frame as Markov Decision Process
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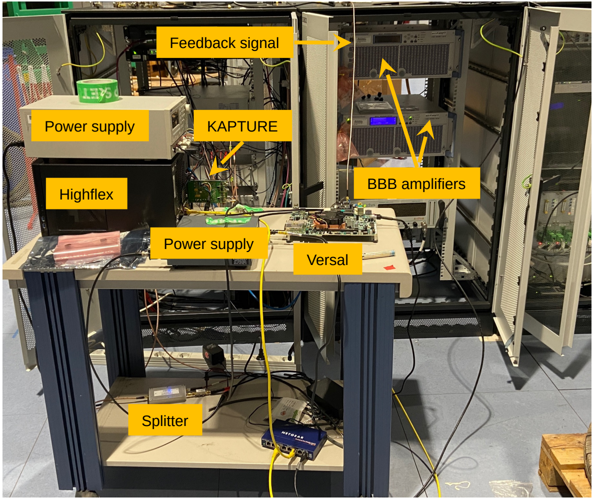
Excite oscillation with kicker, damp it with RL!



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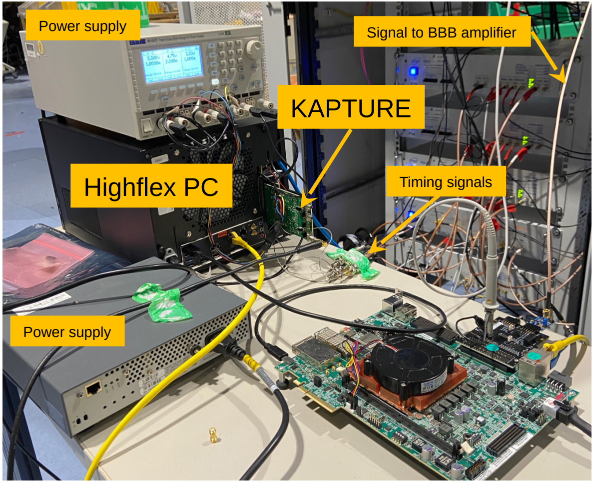

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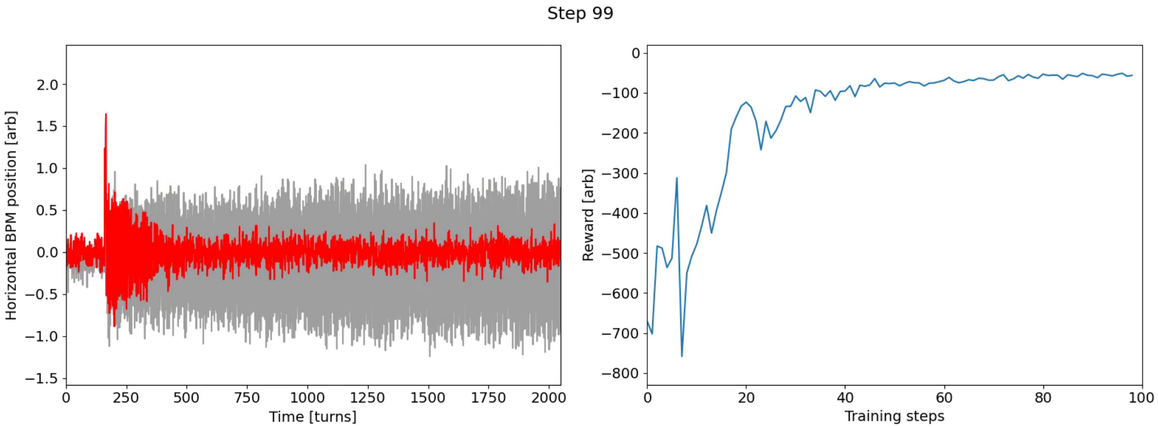

Reward with L1 norm, L2 norm and tanh. 2.7 MHz action rate!

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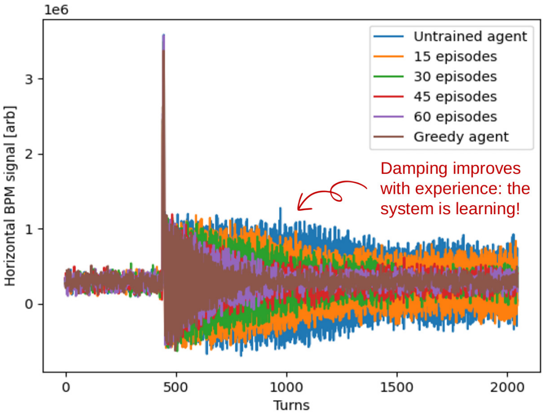
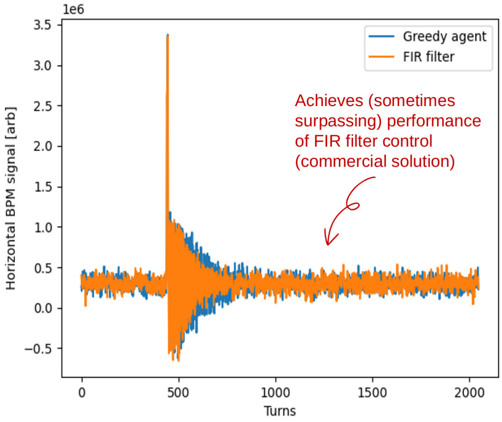
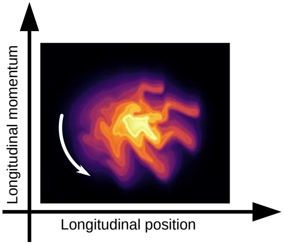




Hard problem: Microbunching Instability

Unstable coherent synchrotron radition (THz) production

- Self-interaction of bunch with emitted radiation
- Nonlinear dynamics, several timescales/frequency components
- Main timescales: $O(10\,\mu s)$, $O(10\,\mathrm{ms})$, with $T_s = O(100\,\mu s)$
- Expensive to simulate!



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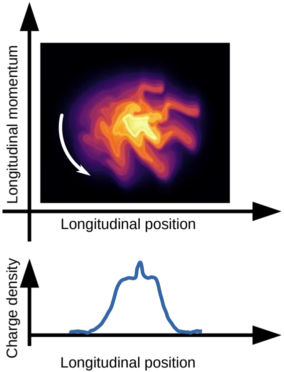

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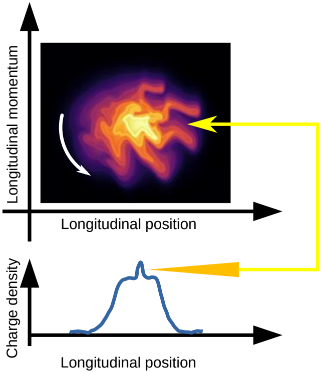

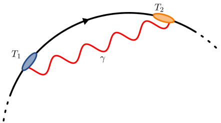

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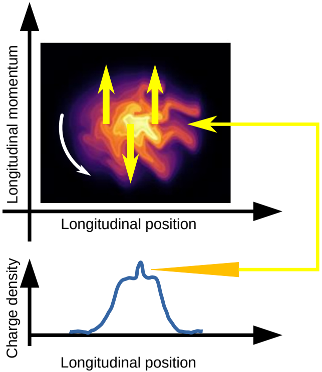

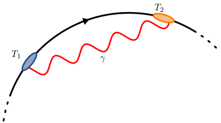

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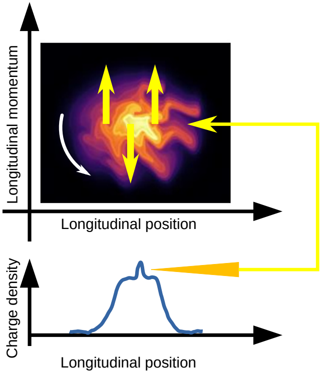
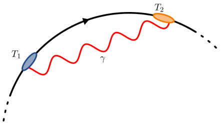
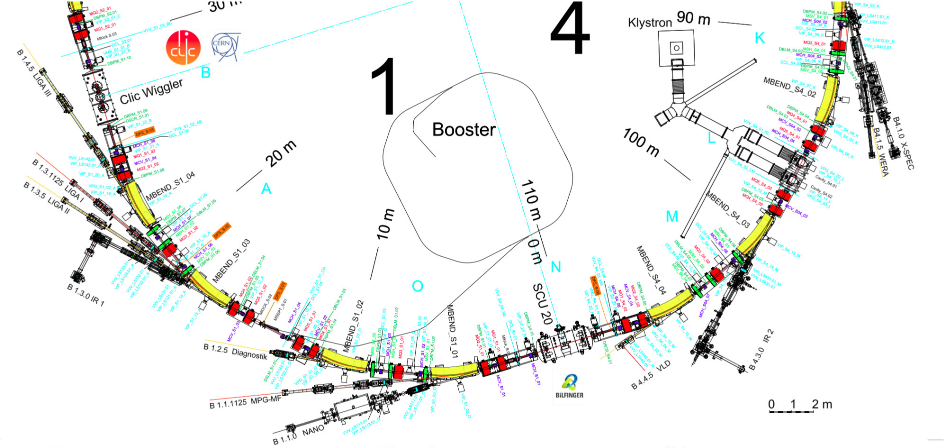
Perfect candidate for real time RL!





Hardware implementation



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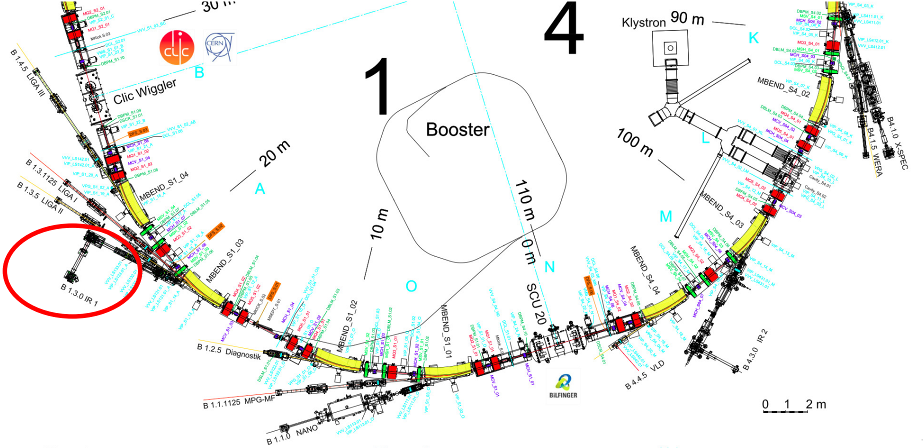

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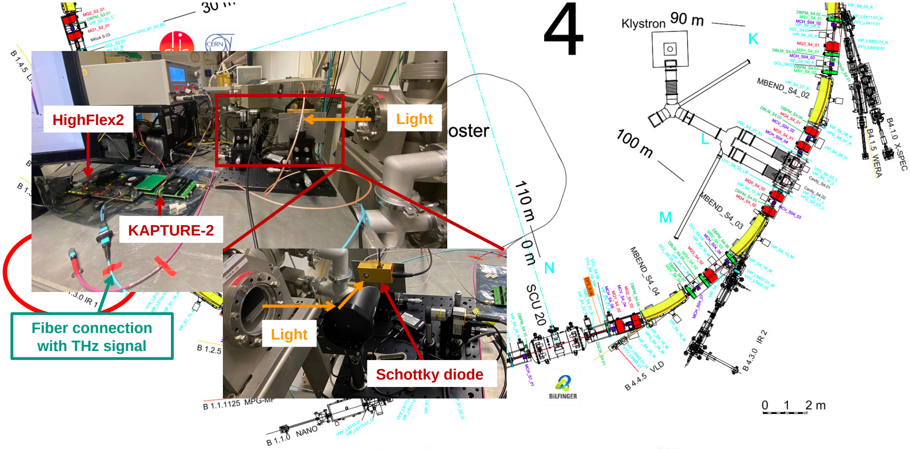

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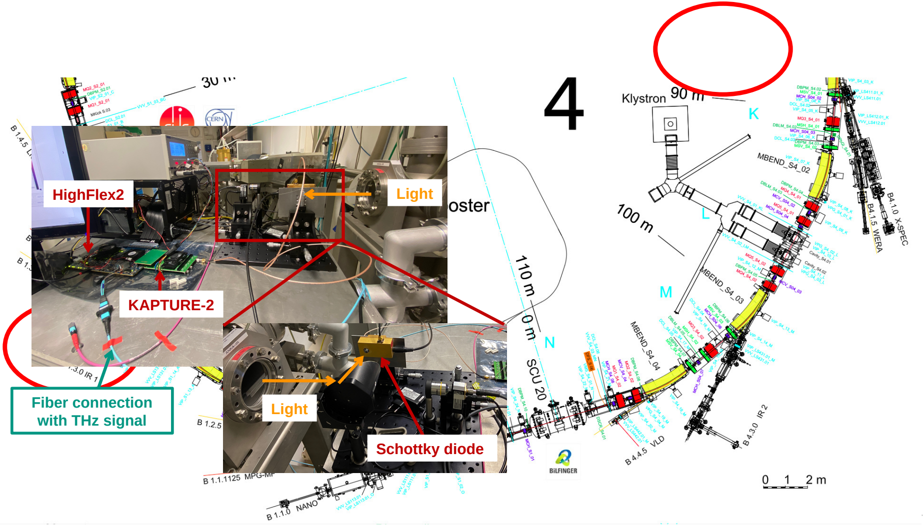

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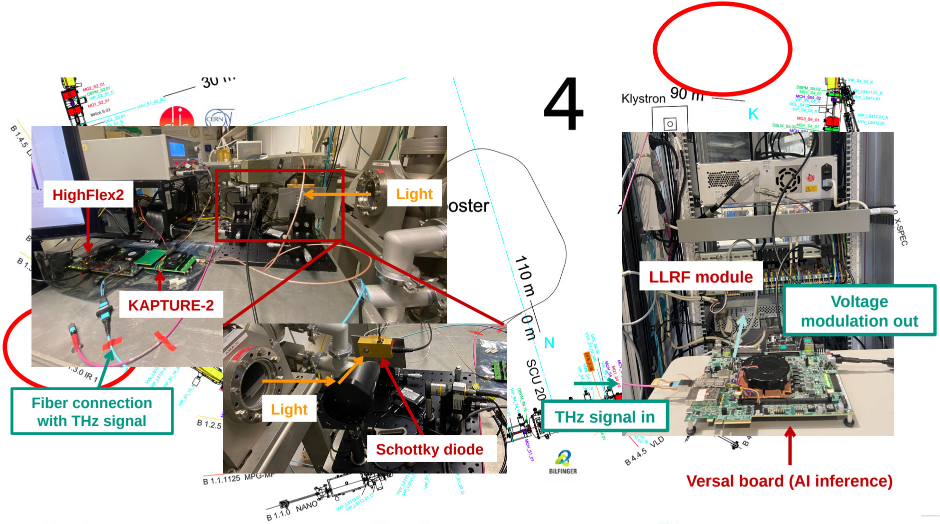

RL problem definition

Environment $\rightarrow x_i$ Coherent Sychrotron Radiation power each turn

Initial approach

$$O = \{\mu_{\text{CSR}}, \sigma_{\text{CSR}}, m_{\text{trend}}, A_{\text{FFT max}}, f_{\text{FFT max}}, \Delta_\theta\}$$

$$A = \{A_{\text{mod}}, f_{\text{mod}}\}$$

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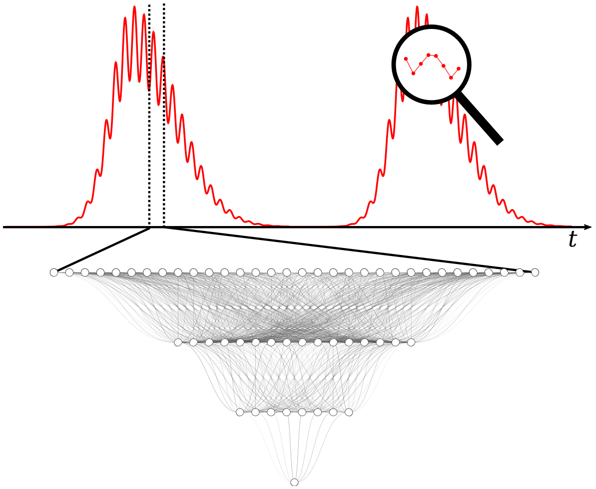
Reward is observation based and varies at runtime

Agent design

- 64 samples input into network
- Sampling rate affects network time-span
- Filter signal $\rightarrow$ remove high-frequency components
- Drop samples $\rightarrow$ network "sees" more time



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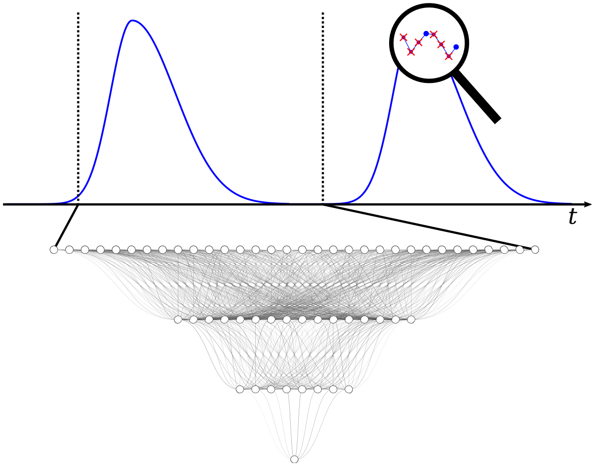

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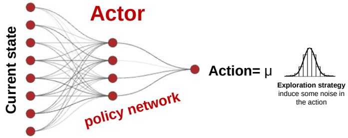
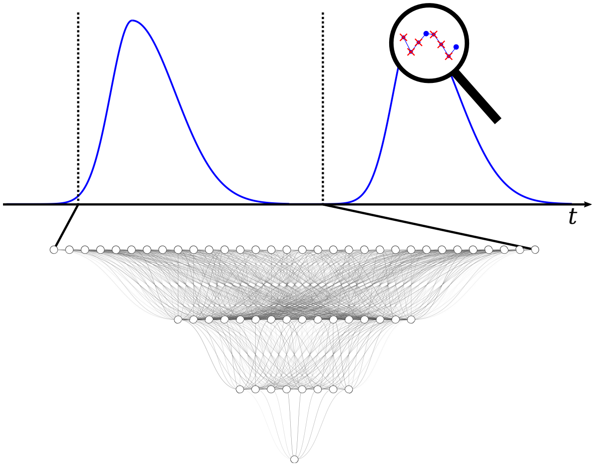
Agent output chooses mean of gauss distribution





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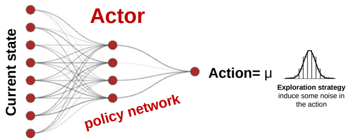
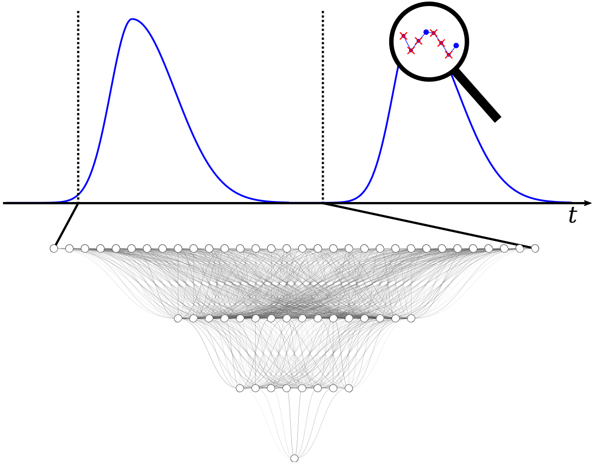
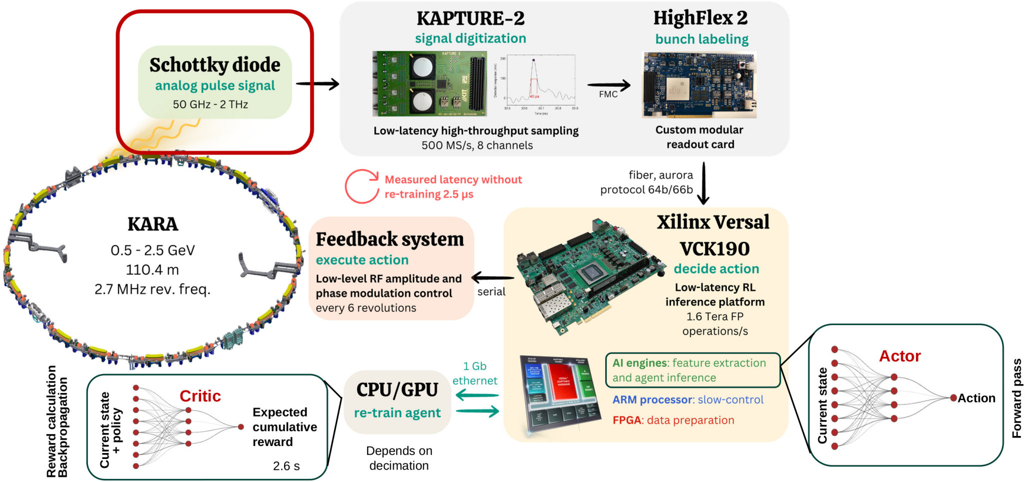




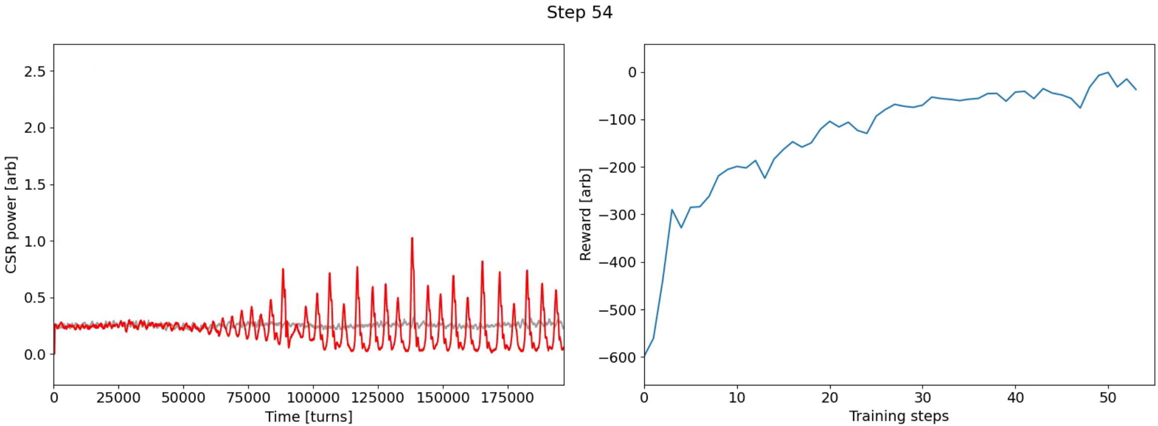
Possibility of cumulative action

System schematic



Courtesy Andrea Santamaria Garcia

In action



Reward with L2 norm from average

Conclusion

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- First online training purely on accelerator
- μs Real-Time RL is a viable option
- Its performance is problem dependent
- FPGAs and Heterogeneous platforms are the key
- Hardware aware problem design is fundamental

Sounds interesting? Let’s find more applications!