Karlsruhe Institute of Technology

Institute for Data Processing and Electronics

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

**12th MT ARD ST3 Meeting 2024 Darmstadt**

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 July 2024

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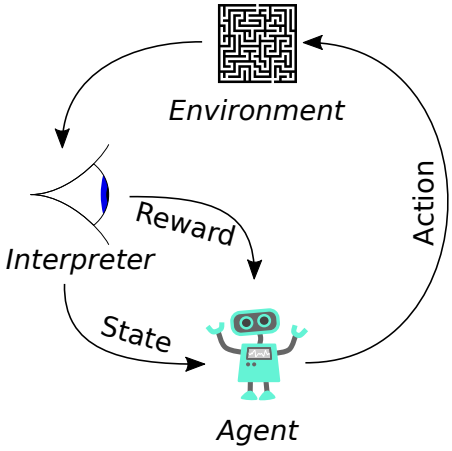
# Motivation



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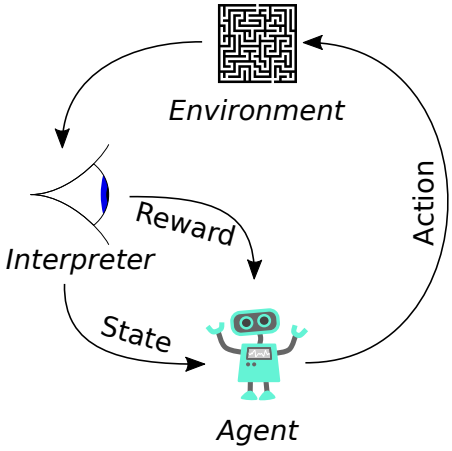


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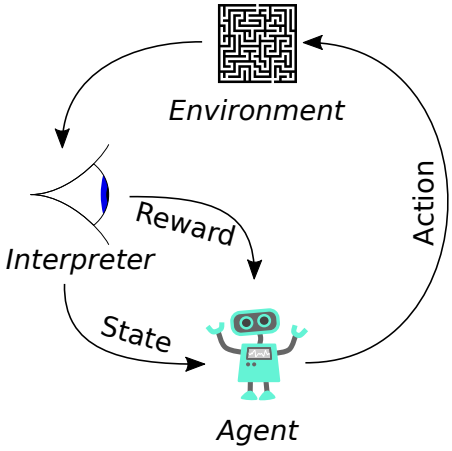


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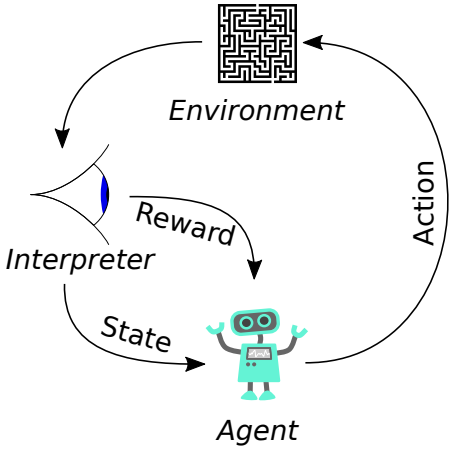


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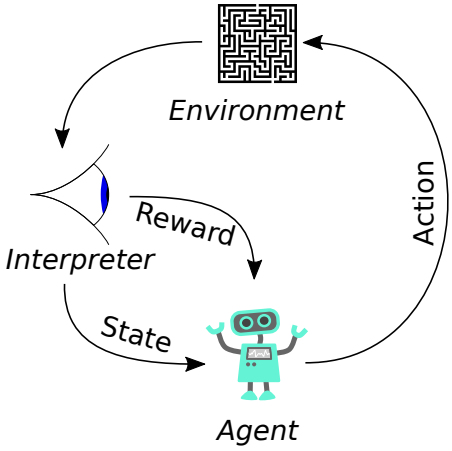


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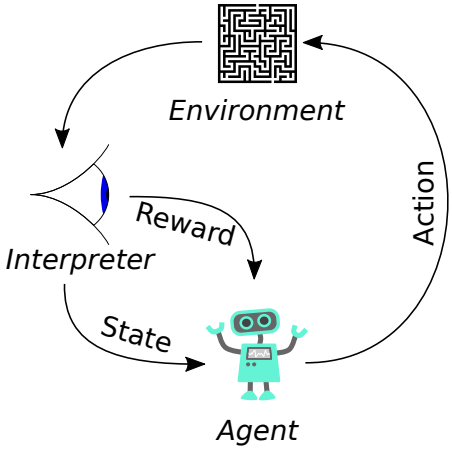


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Timing constrains become relevant!

# What is Real-Time?

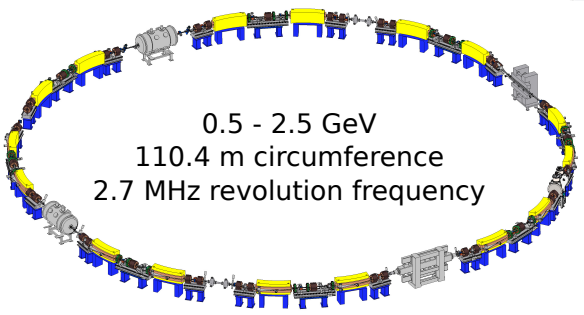
Shin and Ramanathan (1994) identify major components:

> *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!

# Case study: KARA



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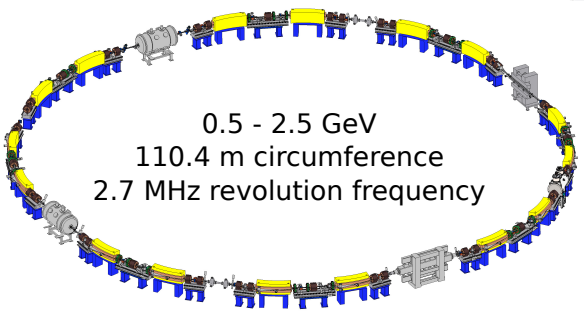
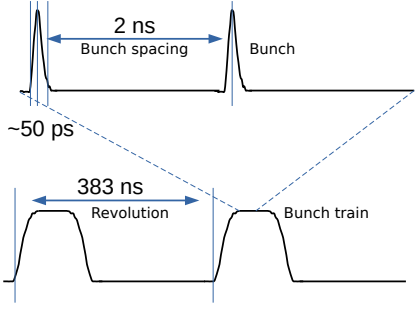



**Example signal**

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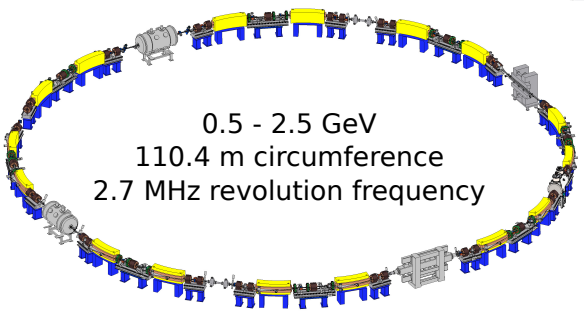


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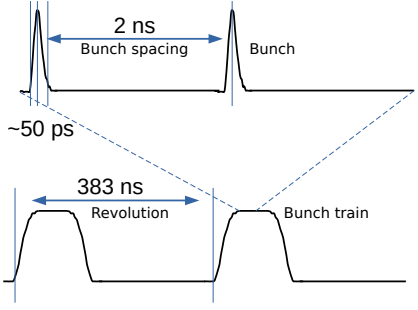
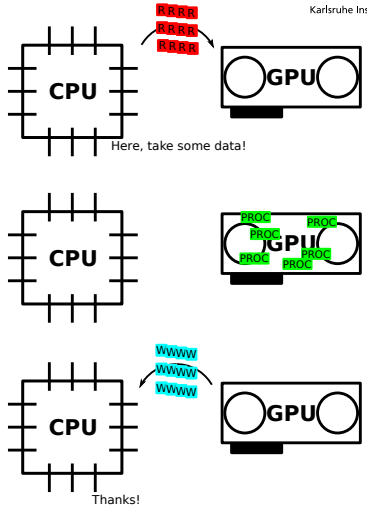



Synchrotron frequency/period $O(10\,\text{kHz} \leftrightarrow 100\,\mu\text{s})$

Huge variety of time scales!

# Issues of Real-Time AI

- Current ML frameworks have mainly throughput in mind $\rightarrow$ no/little real-time optimization;
- use of batched execution on GPU $\rightarrow$ 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

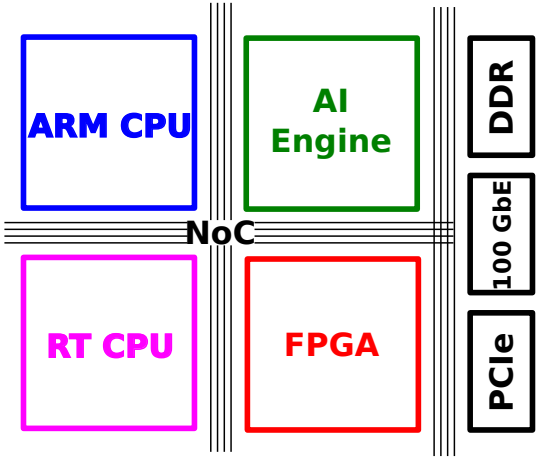
Different computing platforms → different benefits

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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## Experience accumulator

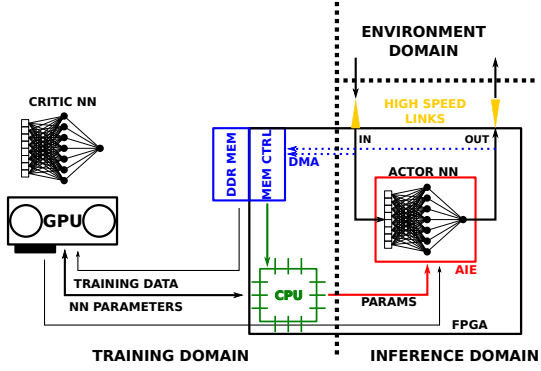
Real-Time inference BUT Offline/Batched training

Pros:

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

Cons:

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



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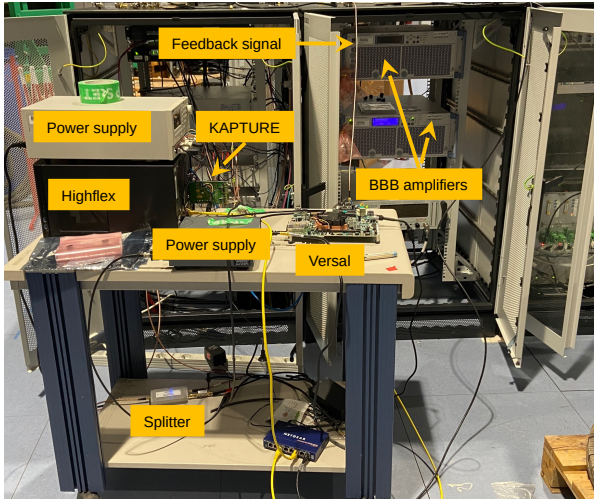
Excite oscillation with kicker, damp it with RL!



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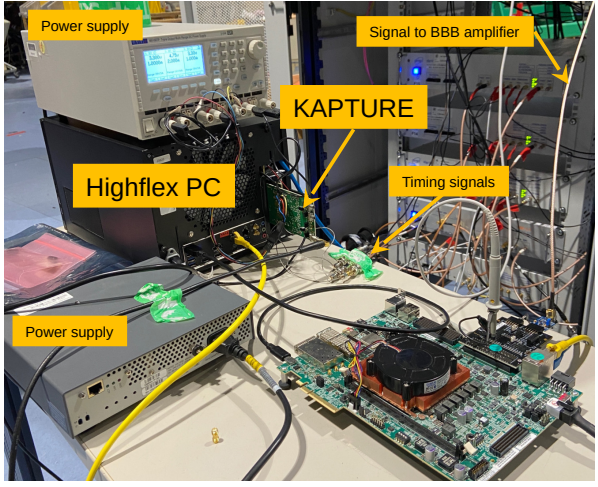

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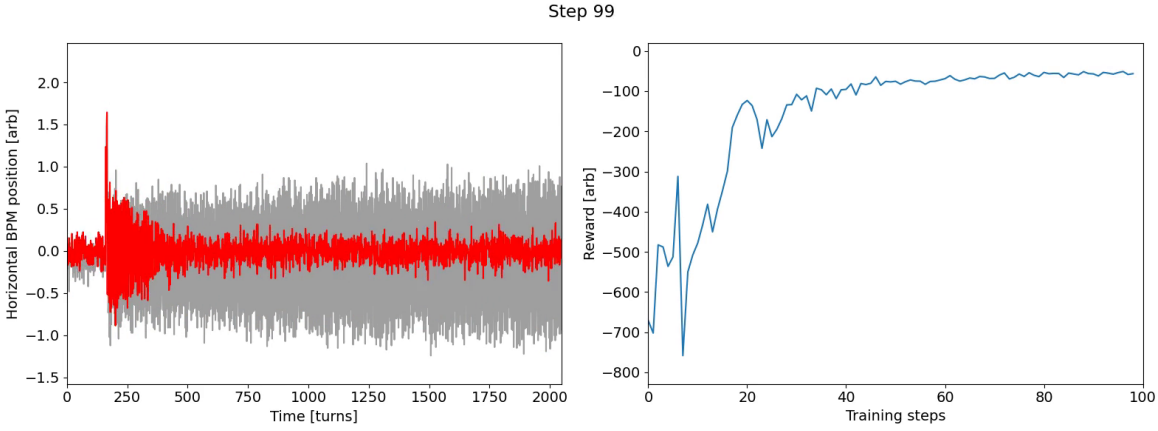


Reward with L1 norm, L2 norm and tanh. 2.7 MHz action rate!

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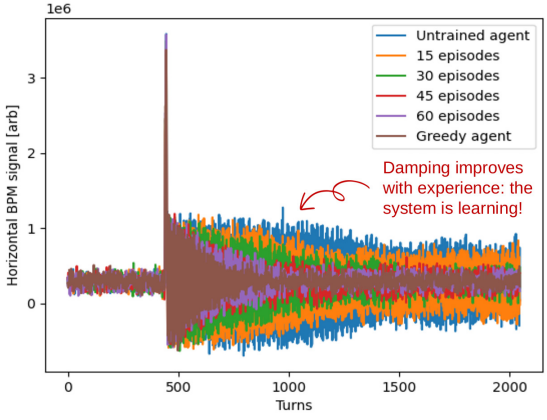
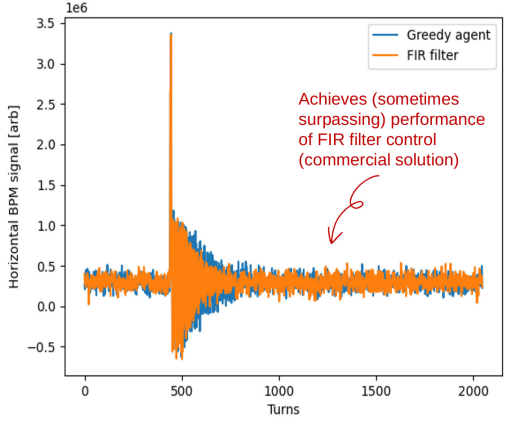
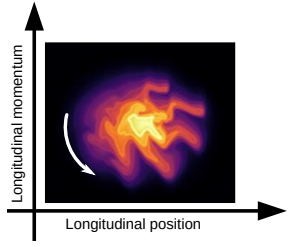


# Hard problem: Microbunching Instability

Unstable coherent synchrotron radition (THz) production

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



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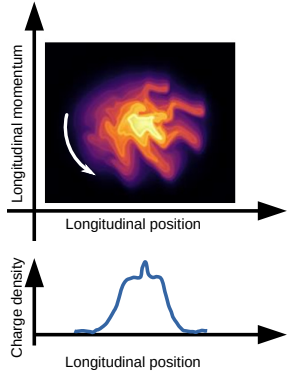

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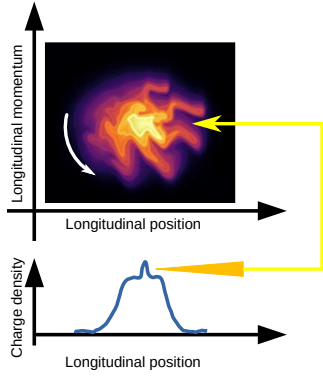


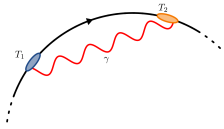

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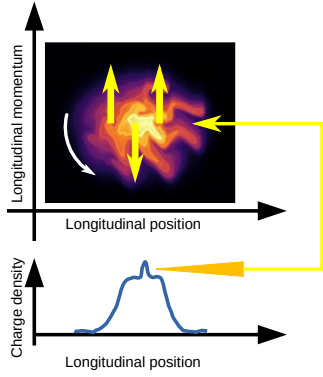


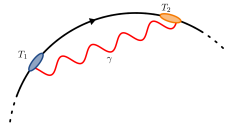

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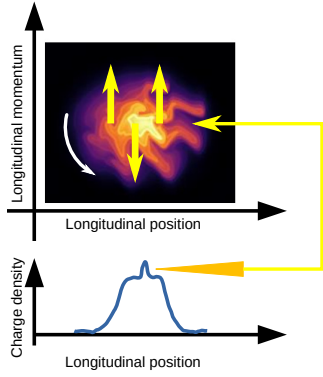
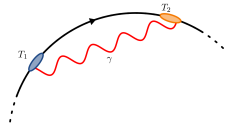
Perfect candidate for real time RL!



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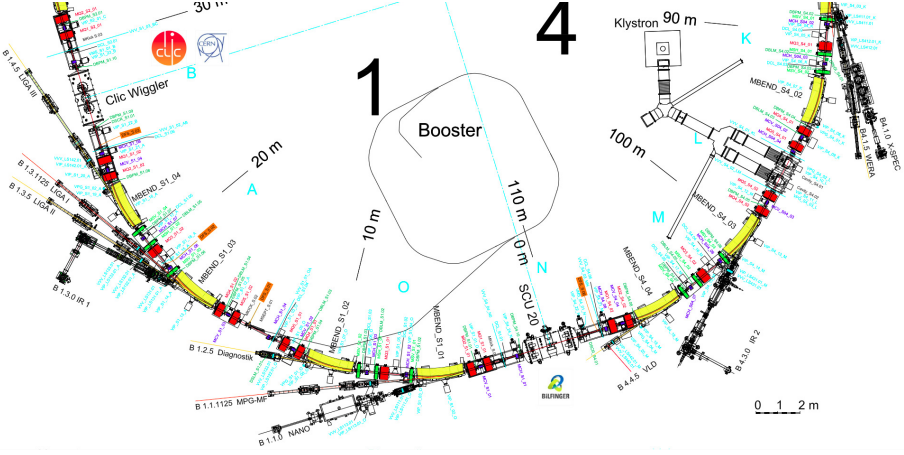

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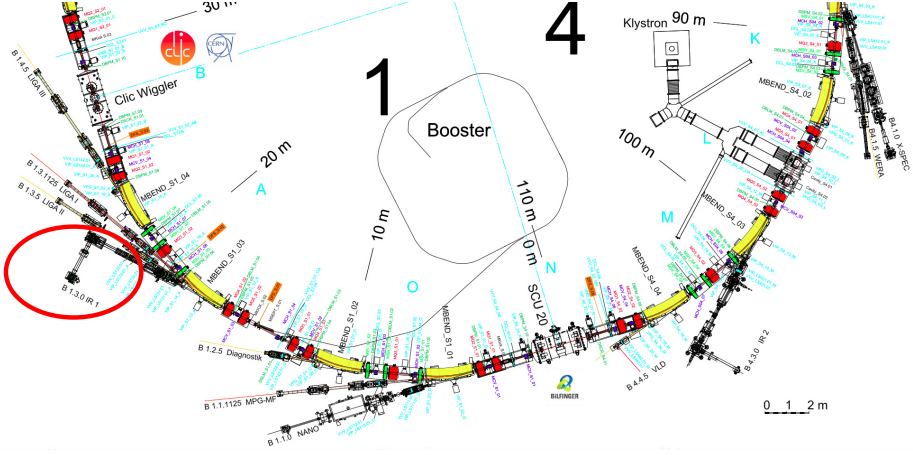

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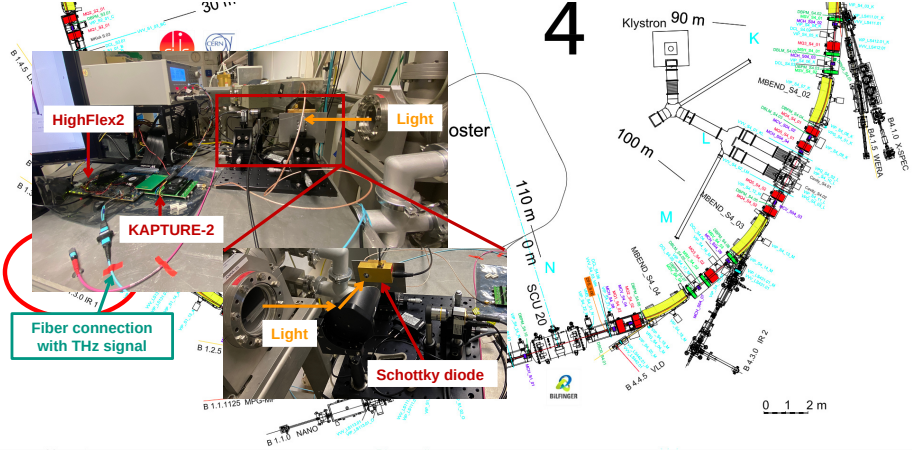

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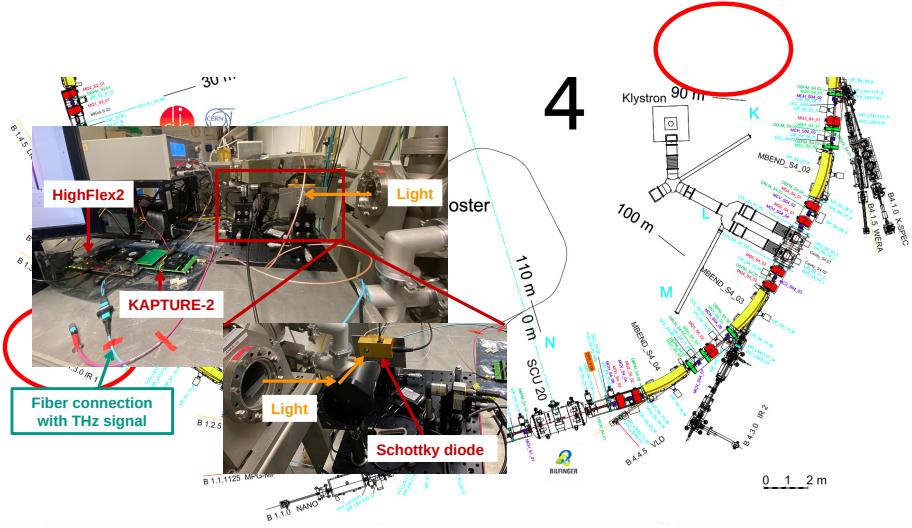

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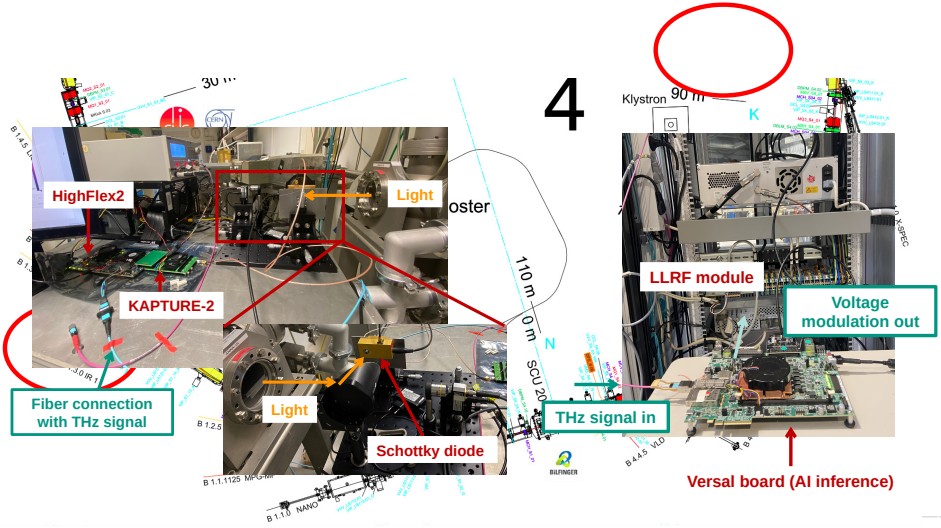

# RL problem definition

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

## Initial approach

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

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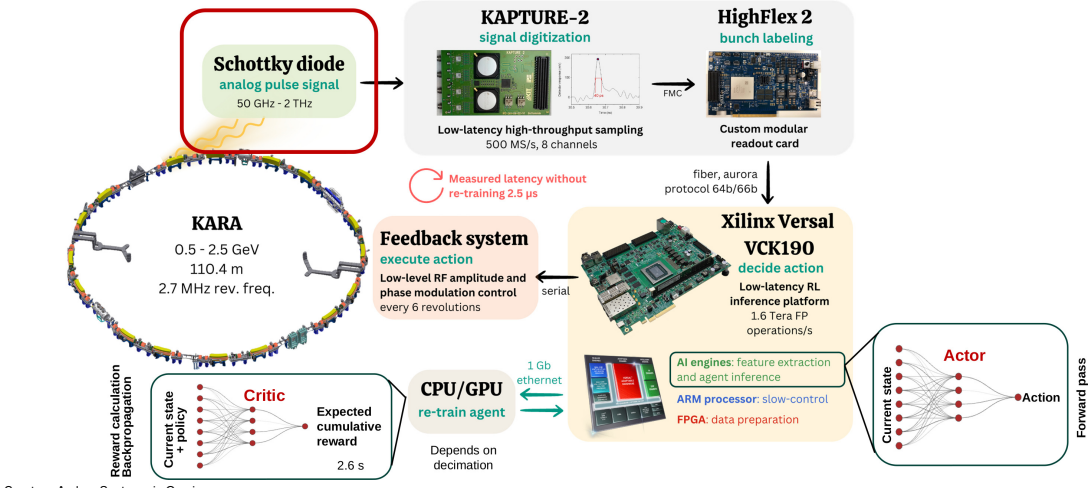
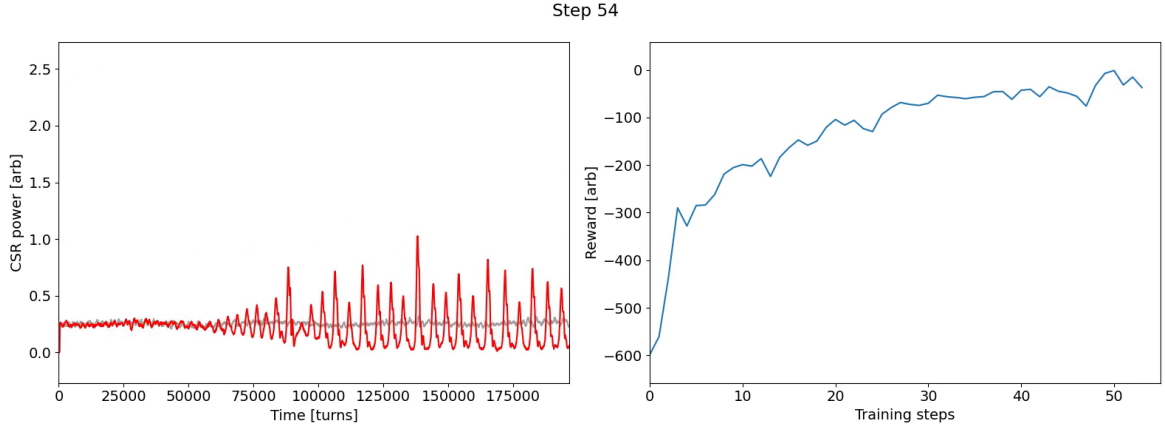
Reward is observation based and varies at runtime

# System schematic




Courtesy Andrea Santamaria Garcia

# In action




Reward with L2 norm from average

# Conclusion

- First online training purely on accelerator
- $\mu s$ 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!