HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

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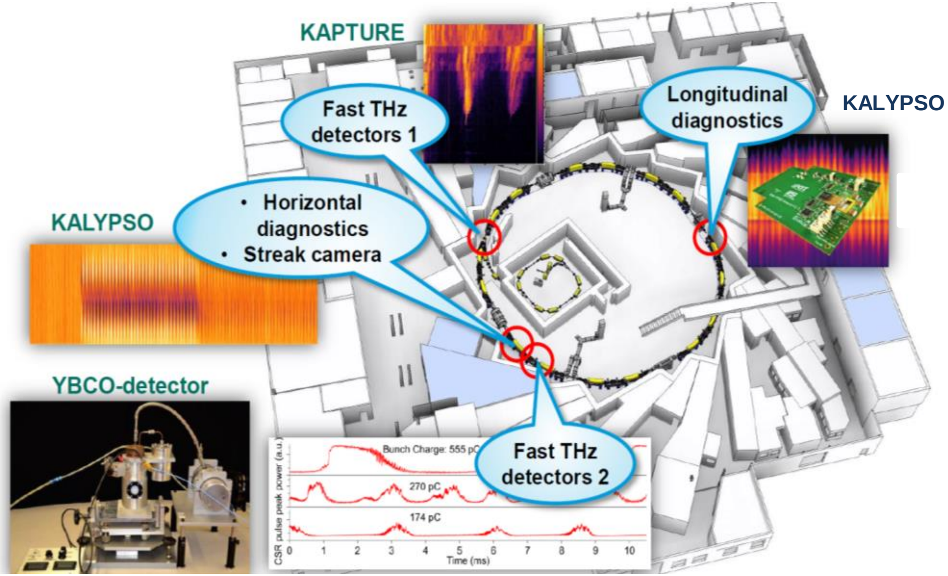
Accelerated Deep Reinforcement Learning for Fast Feedback of Beam Dynamics at KARA

Beam Physics

Accelerator Facilities at KIT

Karlsruhe Research Accelerator (KARA)

- Electron storage ring and synchrotron light source
- KARA: one of the 1st to offer short bunch down to few millimeters, which enables to study the microbunching instability
- Advanced custom detectors developed for a real-time resolved phase space tomography:
  - *KAPTURE*: for bunch-to-bunch measurement of THz beam
  - *KALYPSO*: for both longitudinal and horizontal bunch profiles



Caselle M., et al. KAPTURE-2. A picosecond sampling system for individual THz pulses with high repetition rate. JINST (2017), DOI: 10.1088/1748-0221/12/01/C01040

Rota, L., Caselle M., et al. KALYPSO: Linear array detector for high-repetition rate and real-time beam diagnostics. NIM A (2018), DOI: https://doi.org/10.1016/j.nima

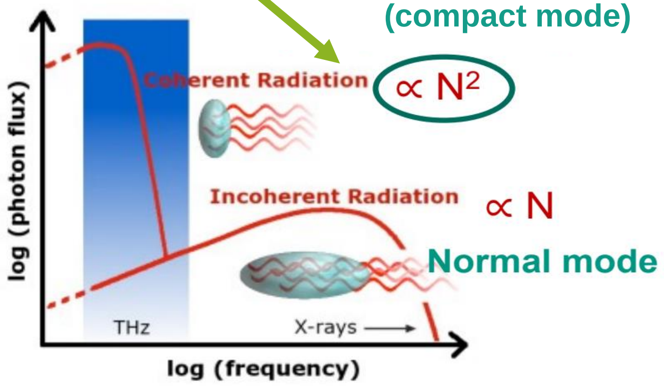
Kehrer B., et al. Synchronous detection of longitudinal and transverse bunch signals at a storage ring. *Phys. Rev. Accel. Beams (2018),* 102803

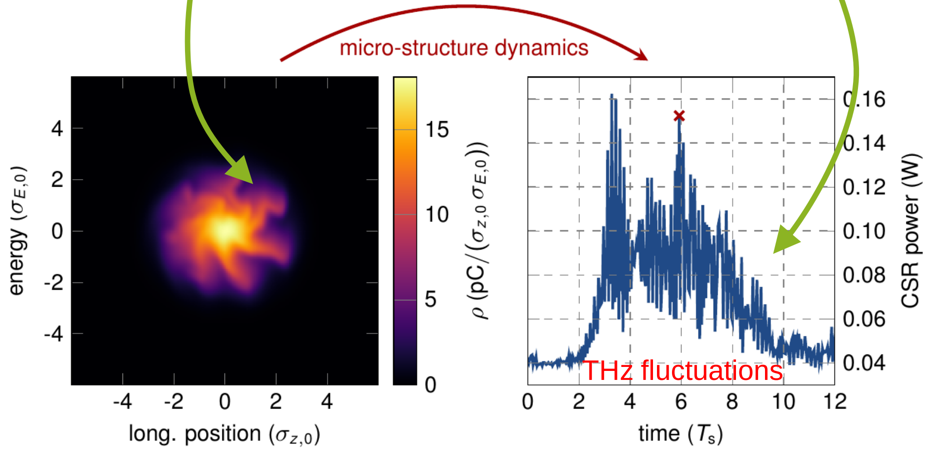
Coherent Synchrotron Radiation (CSR)

Micro-bunching instability

- Coherent synchrotron radiation (CSR) is generated when the wavelength of the emitted radiation is in the order of magnitude of the bunch length.
- High-power THz radiation → **interesting for user →**

Issue: substructures appear (fast dynamics) → **CSR power fluctuates**



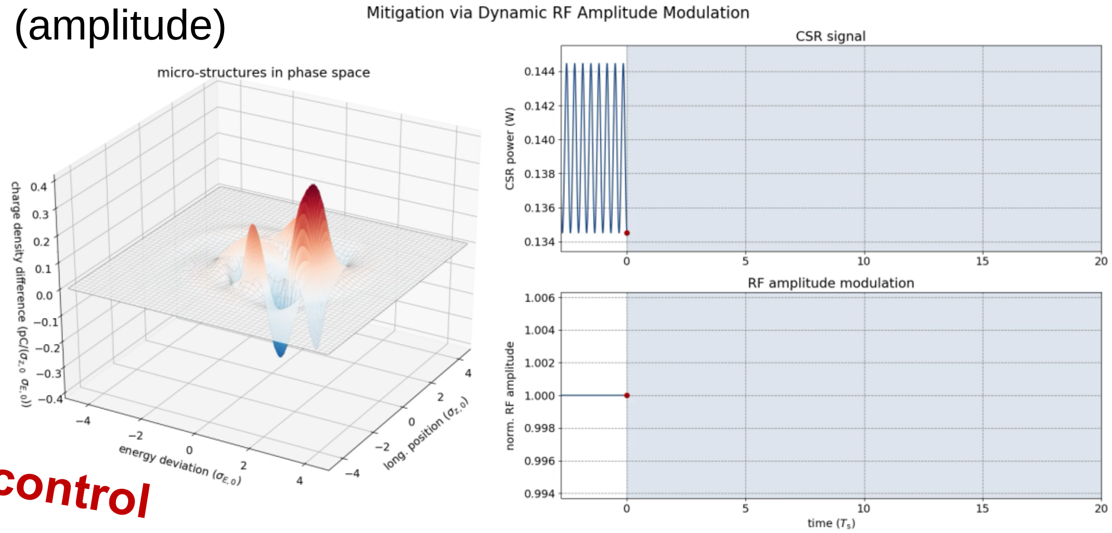


➢ CSR fluctuations **limit the use of the THz light** in experiments

Coherent Synchrotron Radiation (CSR)

Tailor the power output for usage in THz experiments

- The CSR self-interaction contributes to the effective potential that the beam is subjected to, and is continuously changing during micro-bunching dynamics
- **GOAL:** CSR stabilization with **high average** (power) and **low variance**
- **IDEA:** modulating the RF voltage (amplitude)
- **Solution:**
  Manual control



We need dynamic real-time control

Video Courtesy of Tobias Boltz from KIT-IBPT

Complex beam physics requirements

Special hardware and processes

Karlsruhe Institute of Technology

- Complex and nonlinear dynamics in longitudinal / transverse bunch profiles formally described by a nonlocal nonlinear partial differential **Vlasov fokker planck** equation

- Experimental requirements are:
  - Direct sampling of “each” THz beam with a time resolution of few picoseconds @ 1 GPulse/s, very long observation time (hours)
  - High performance data acquisition readout card, continuous data streaming and processing of all pulses acquired @ data throughput which exceeds 100 Gb/s
  - Advanced beam control ➔ by Machine Learned algorithms (ML)

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- Experimental requirements are:
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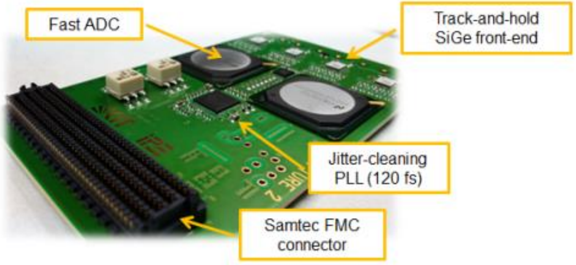
  - High performance data acquisition readout card, continuous data streaming and processing of all pulses acquired @ data throughput which exceeds 100 Gb/s ➔ **HighFlex**
  - Advanced beam control ➔ by Machine Learned algorithms (ML) ➔ **Reinforcement Learning on FPGA**

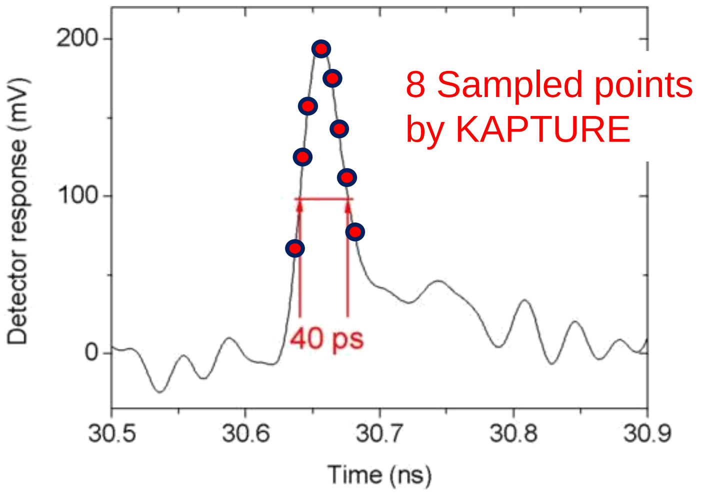
KAPTURE version 2

Ultra-fast sampling-system for ultra-fast detectors

- Karlsruhe Pulse Taking Ultra-fast Readout Electronics (KAPTURE) is an ultra-wideband readout electronics for ultra-fast Terahertz detectors



Terahertz detector pulse



M. Caselle et al., JINST 12 C01040 (2017)

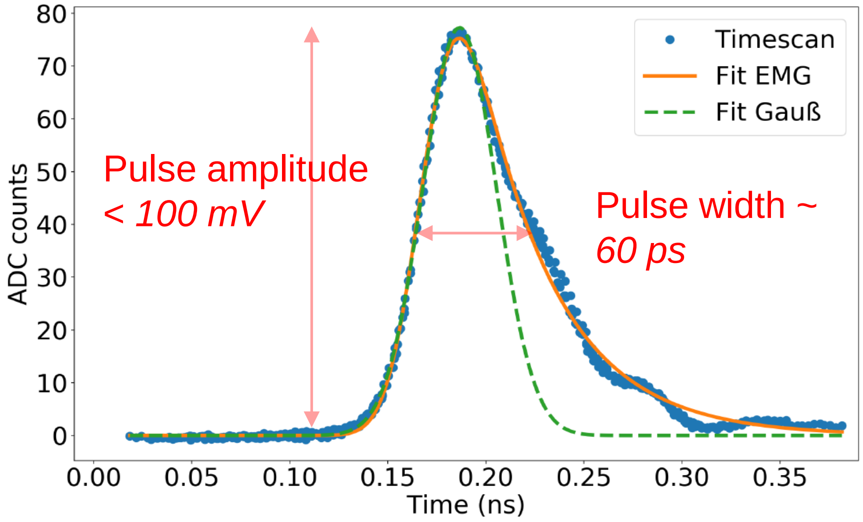
- Sampling time of 3 ps, local sampling frequency > 300 GS/s
- Up to 1 GHz pulse repetition rate
- Pulse amplitude (mV) and arrival time (ps) accuracy
- Real-time pulse sampling for long observation time

Designed for bunch-to-bunch acquisition of the THz coherent synchrotron radiation

KAPTURE-2 (performance)

Ultra-fast sampling-system for ultra-fast detectors

- Local sampling frequency > 300 GS/s with a pulse rate of 1 GPulse/s
- Commissioning to *KARA*



J.L. Steinmann et al. doi:10.18429/JACoW-IPAC2019-WEPGW017

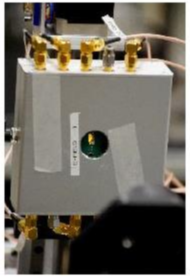
- Fast sampling of THz detector pulse by KAPTURE-2
- Gaussian and an exponentially modified Gaussian (EMG) curves are fitted by GPU
- Excellent SNR

KAPTURE-2 – Recent highlight

Courtesy: M. Brosi, KIT
DOI: 10.5445/IR/1000120018

Shot-to-shot measurement of CSR at different spectral ranges

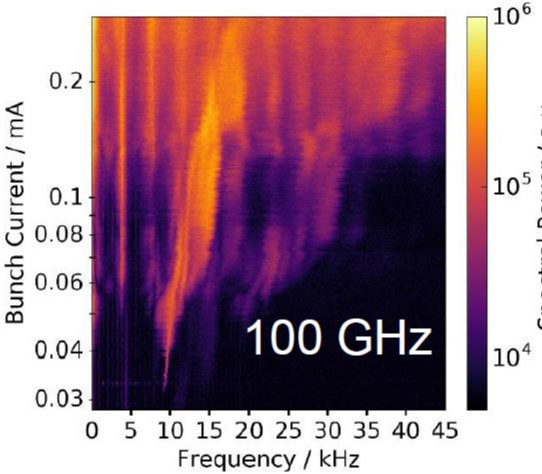
- On-chip THz spectrometer (TU Dresden, N. Neumann):
  - 1.4 mm x 2.4 mm
  - 8 antennas 50 GHz - 700 GHz (~10% relative bandwidth)
  - Connected to Schottky diode detector elements
- KAPTURE2 in 8 channel mode for parallel readout

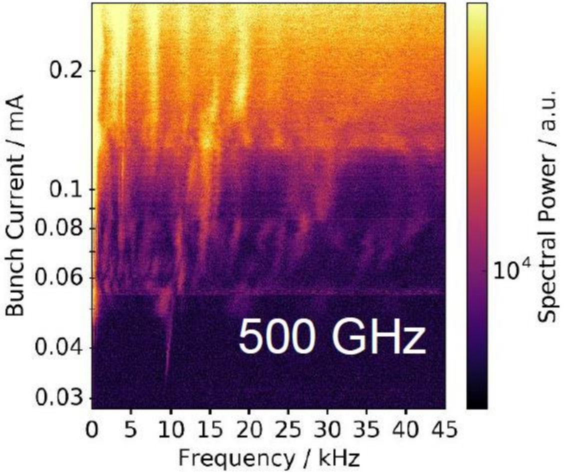


Insight into the long. dynamics

- Micro-structures on long. phase space lead to fluctuations in emitted CSR power
- Similar fluctuation pattern in different spectral ranges
- Differences in relative strength of fluctuation frequencies

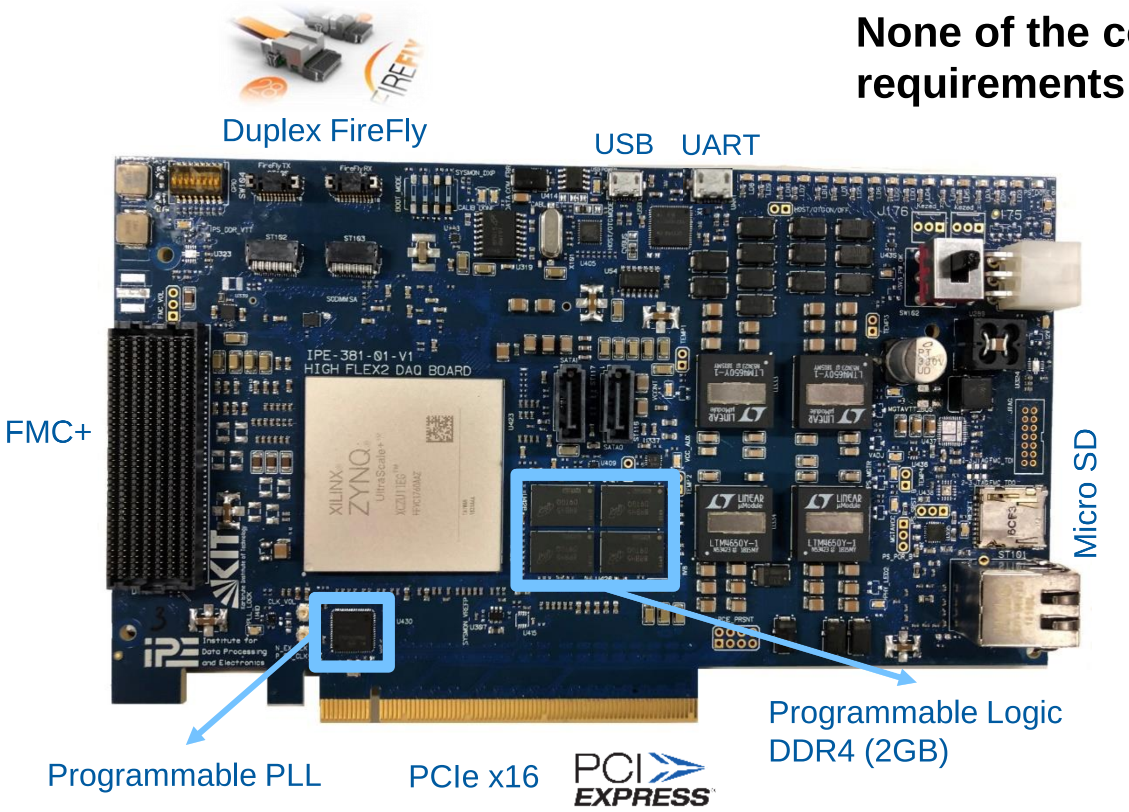
⇒ Dynamic changes in the shapes of the micro-structures





Hardware for Dynamic Real-time control

HighFlex version 2



None of the commercial read-out cards fulfill our requirements

We developed HighFlex-2, a customized read out card based on Xilinx Zynq Ultrascale+ MPSoC

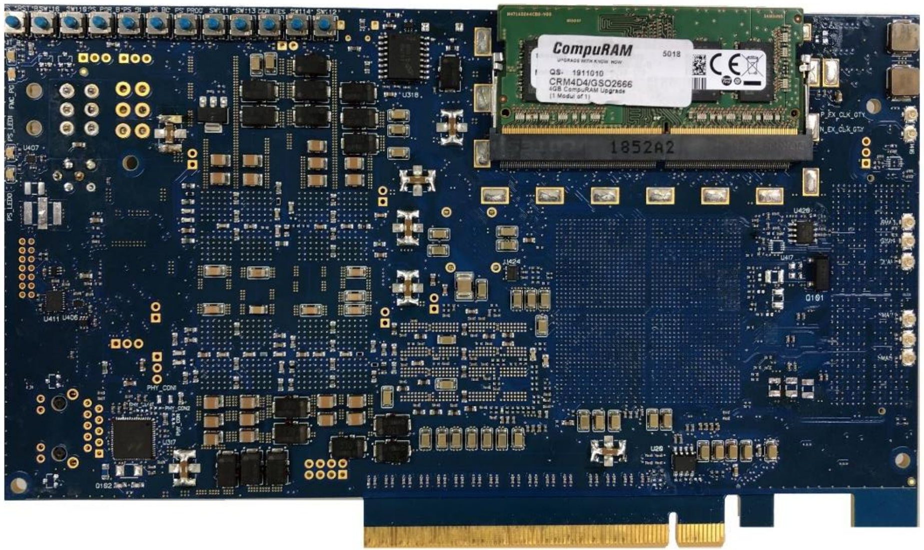
FEATURES

- 12 duplex FireFly data link (336 Gbps)
- PCIe Gen 3 and Gen 4 (240 Gbps)
- DDR4 Chips for Programmable Logic (PL)
- Ethernet, SD, USB for PS

Hardware for dynamic real-time control

HighFlex-2

PS ARM DDR4 (4GB SODIMM)



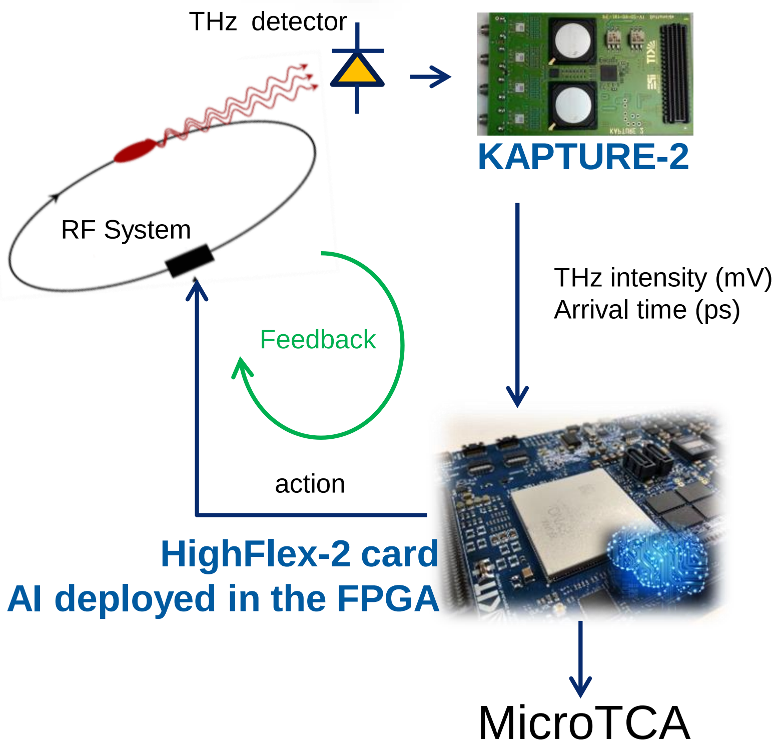
- Team work done at IPE
  - Schematic, layout, production
- Printed Circuit Board (PCB)
  - 22 layers
  - MEGTRON 6 dielectric material
- HighFlex-2 is a sophisticated and high-end board
- Many applications within and beyond beam diagnostics

Zynq architecture is an optimized Hardware-platform for machine learning algorithms!

Control of the complex beam with ML

Machine Learning toward Autonomous Accelerators

- Closed feedback loop at KARA:
  - **Detection** of signals with THz detectors and KAPTURE @ 500 MPulse/s
  - **Data processed** by Reinforcement Learning on FPGA
  - **FPGA action** as special RF signal modulation is sent to the kicker cavity
- **Goal**: total latency of control feedback loop ***<< 1 ms***
- **Target applications**: KARA, FLUTE, ARES and more
- **Status**: first beam control on FPGA developed within *AMALEA* → will continue in ACCLAIM (Helmholtz Innovation fund)



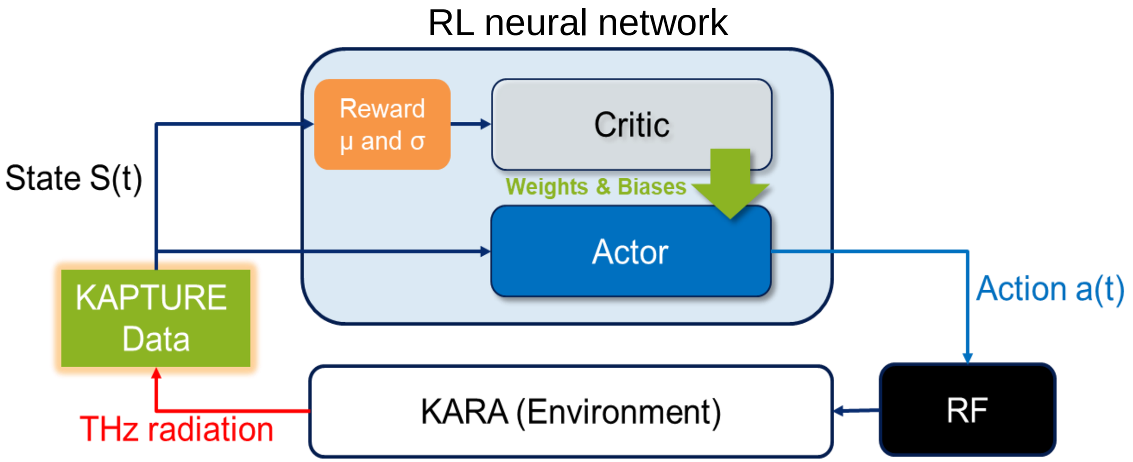
Reinforcement Learning (RL)

Goal-directed learning from interaction with an environment

- RL algorithms are capable to learn purely from interaction with a real environment
- The RL interacts with the environment to maximize the reward, ➔ CSR stabilization with high average (power) and low variance
- No pre-existing set or training (labelled) data are necessary

The Critic neural network updates both weights and biases in order to maximize the reward (self-learning)

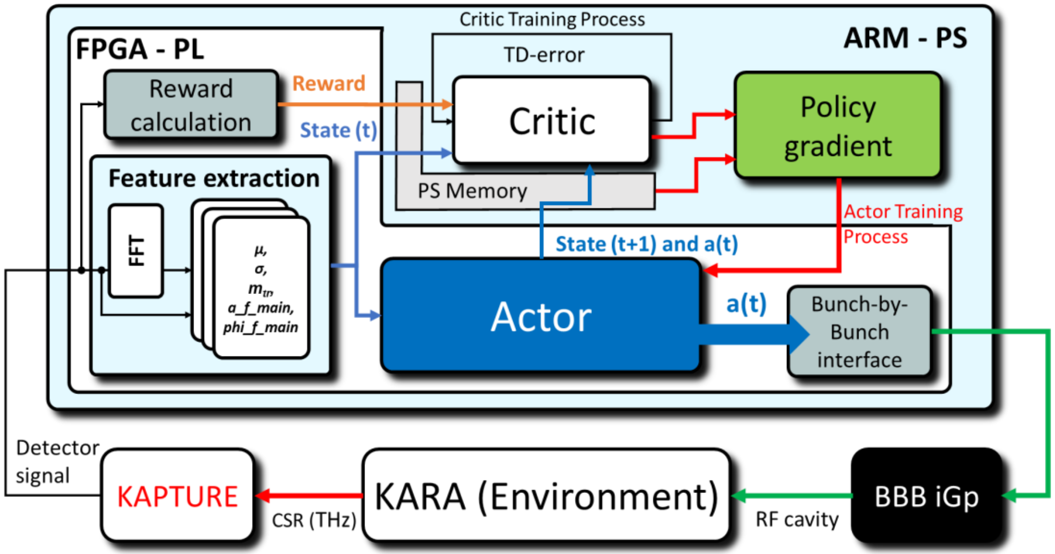
The same RL algorithm can be applied in various applications



Hardware implementation

Reinforcement Learning on modern programable device

Deep Deterministic Policy Gradient (DDPG)



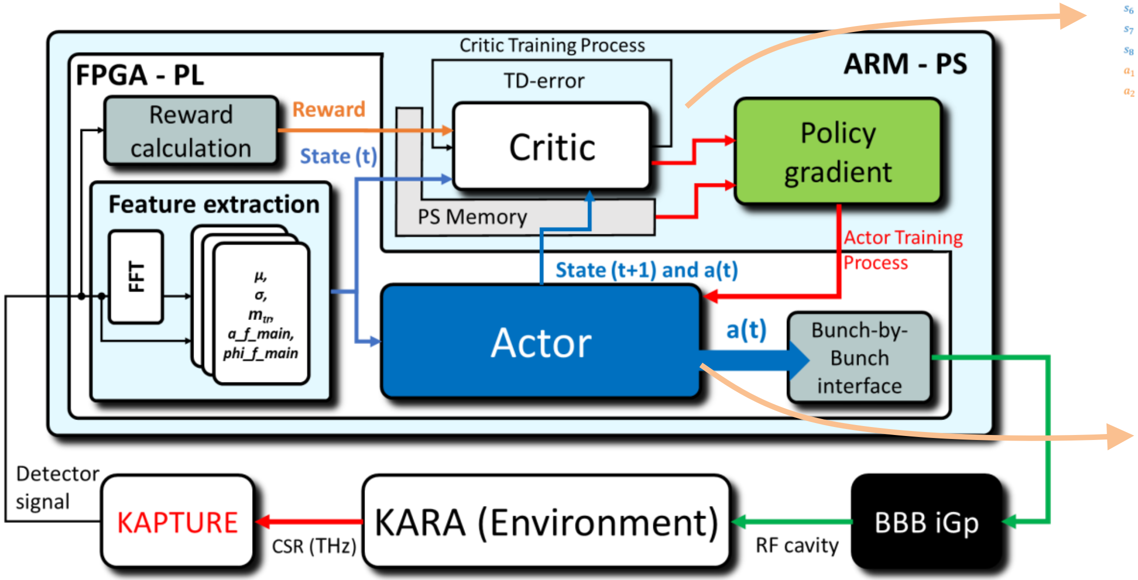
- Using DDPG to control micro-bunching instability at KARA
- The training is located on ARM for a fast and flexible training
- The inference is located on FPGA for a fast and real-time control

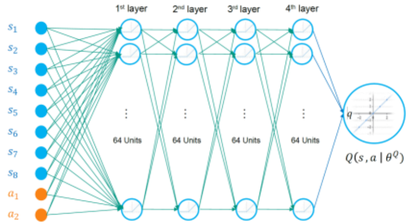
RL Framework developed for a easy deployment of RL algorithms on an FPGA

Hardware implementation

Reinforcement Learning on modern programable device

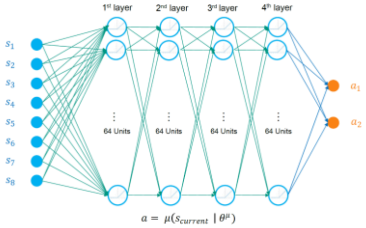
Deep Deterministic Policy Gradient (DDPG)





Critic

Critic neural network and the policy gradient are implemented as bare-metal application on ARM processor



Actor

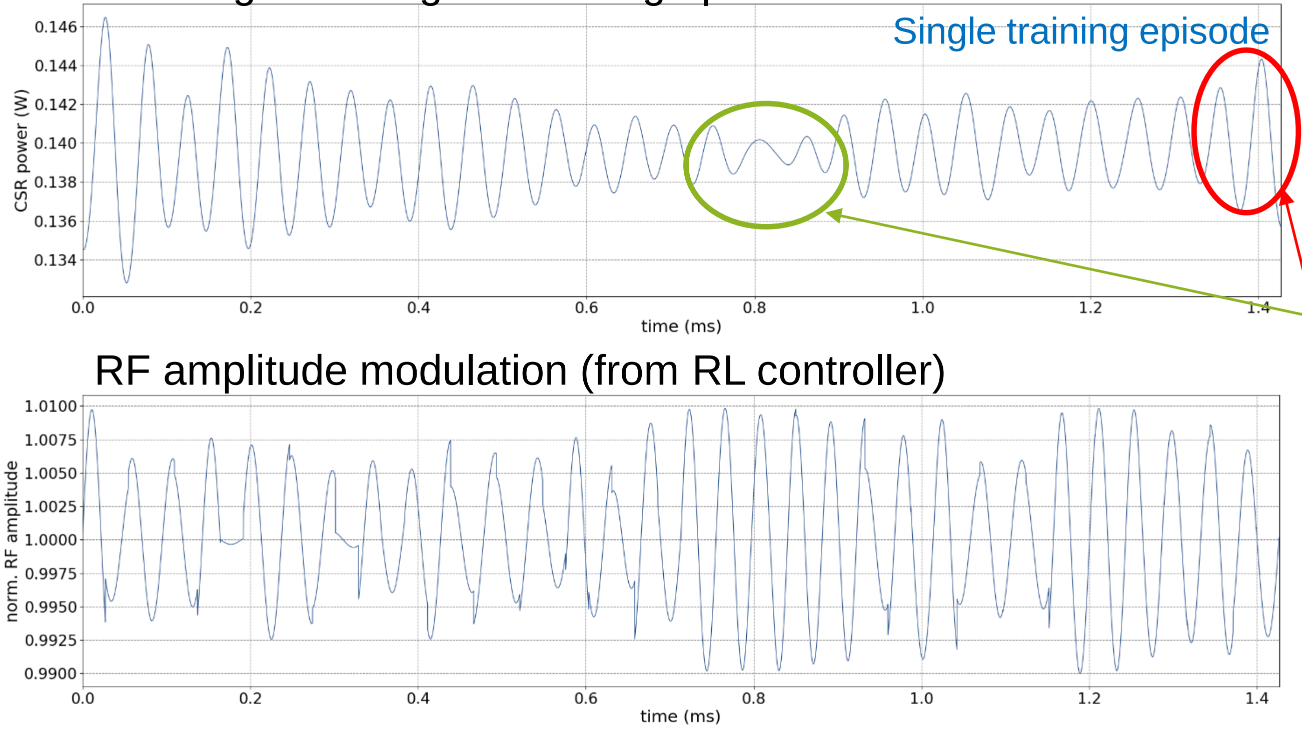
Actor consists of four fully-connected dense layers, each layer consists of 64 neurons using a rectified linear unit (ReLU) as activation function in **FPGA**

RL hardware implementation results (I)

CSR behaviour and amplitude modulation to RF cavity

CSR signal during the training episode

RF amplitude modulation (from RL controller)



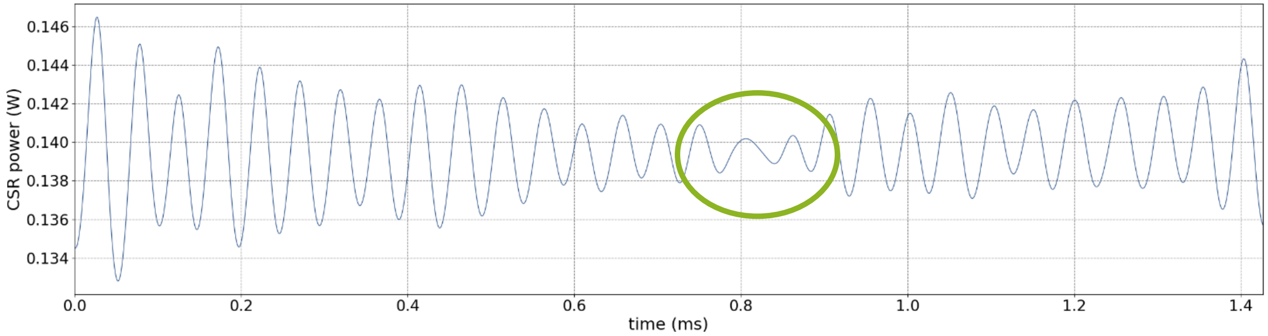
RL on FPGA

RL start to learn how control the CSR fluctuation

RL stop because the received reward is very low

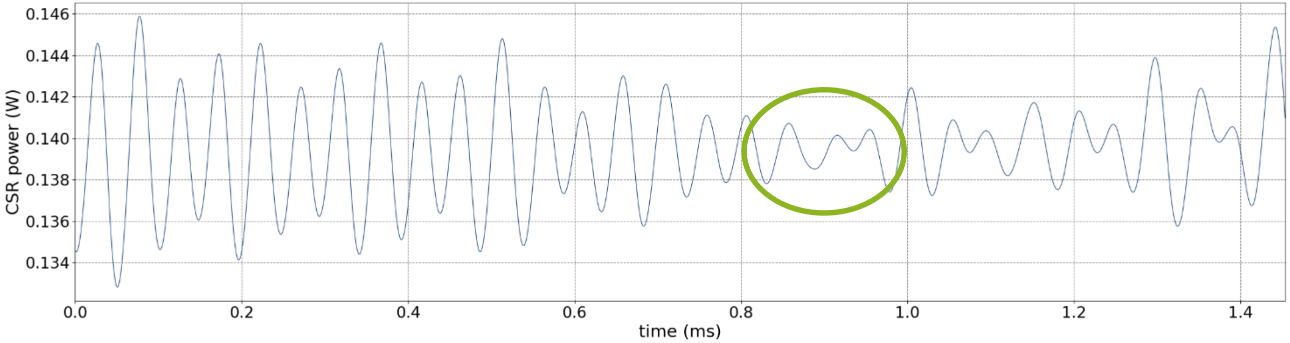
RL hardware implementation results (II)

Comparison between hardware and Keras implementation



RL on FPGA

HighFlex 2



Software implementation

Keras

CPU/GPU

The hardware implementation generates the similar behavior compared to Keras

RL hardware implementation results (III)

Time performances of the Inference and training phases

Karlsruhe Institute of Technology

- Comparison between the KIT- RL controller on ZYNQ and the software implementation deployed on CPU and GPUs

Problem	CPU	GPU	HighFlex2	
Inference	200 µs	557 µs	**17 µs**	**FPGA**
Training	1800 µs	6037 µs	**1648 µs**	**ARM**

- The inference deployed in FPGA is extremely fast
- FPGA is the natural interface to detector and actor
- Optimized code on Zynq ARM has acceptable performance for RL during the training

HighFlex-2 is an optimized platform for Reinforcement Learning

Conclusions

- Very challenging topic: High-dimensional, nonlinear (collective), fast beam dynamics in femtosecond time scale
- Control of the longitudinal bunch profile for stabilization and automatic start-up
- Could be transferred for real-time optimization of plasma accelerators and their laser systems
- Control-feedback-system and algorithms could be transferred to two similar facilities (ARES and FLUTE)
- Fast ML inference deployed in FPGA
- Design of custom readout cards optimized for AI applications
- Excellent agreement between hardware and software (Keras-RL) implementations
- Deep Deterministic Policy Gradient as demonstrated very low latency of 17 µs, which well satisfied the KARA requirement