In-house development of waveform digitizers for nuclear physics experiments at RIBF

Nori Kitamura
Center for Nuclear Study, University of Tokyo

December 4, 2024
Streaming Readout Workshop SRO-XII

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in collaboration with H. Baba (RIBF, RIKEN) and the SPADI Alliance

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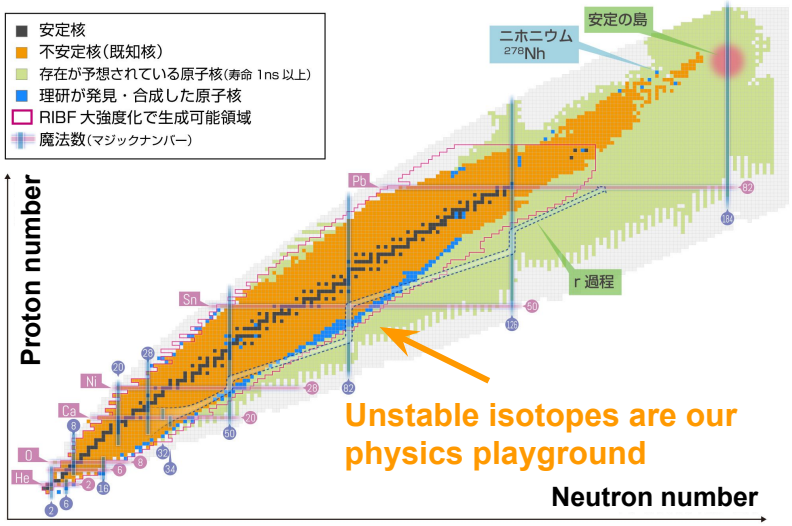
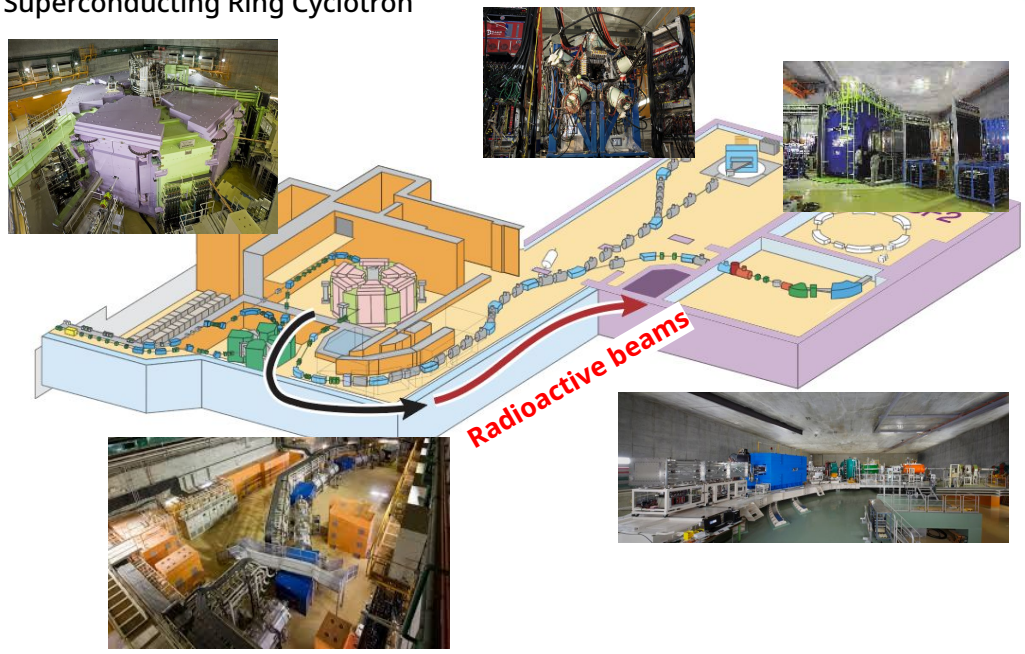
Low-energy nuclear physics experiments at RIBF

- Understanding of exotic nuclear structure in unstable nuclei: *quantum many-body dynamics*
- Emulating synthesis and decay processes of elements in stellar environments
- Finding pathways toward creation of new elements and isotopes



RIKEN RI Beam Factory (RIBF)

Superconducting Ring Cyclotron

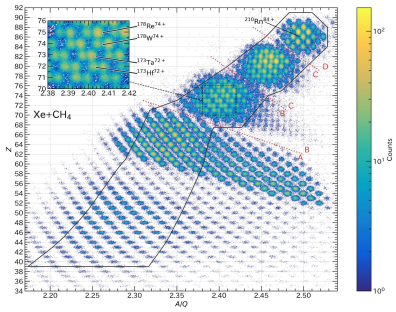


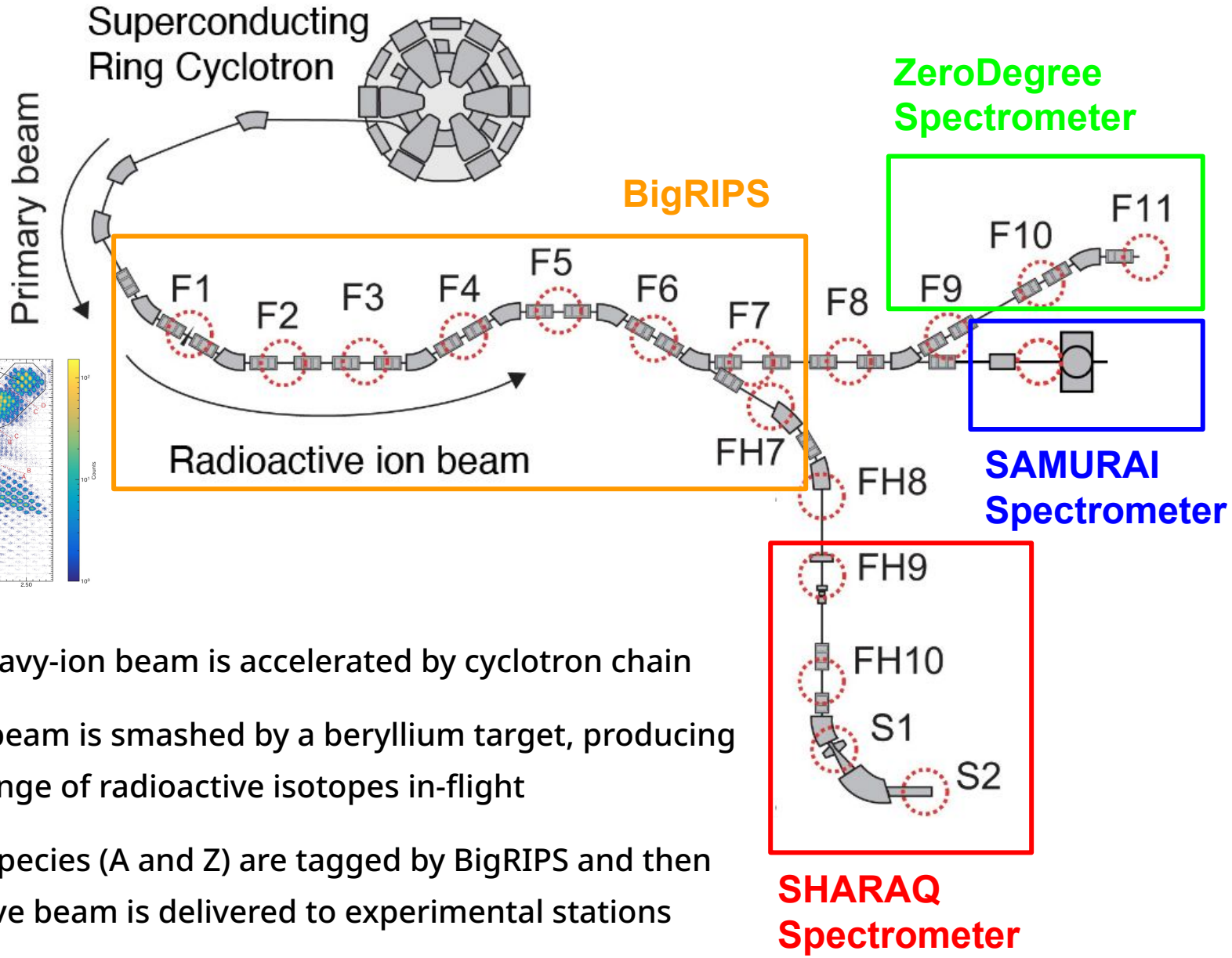
Radioactive isotope separator “BigRIPS”

Scale of a single experiment at RIBF

- 10-100 collaborators
- 1-2 weeks of beamtime
- Changes of experimental setup at frequent intervals
- A wide variety of detectors: semiconductor, gaseous, and scintillators
- Number of channels 100-10k

A bit more about RIBF

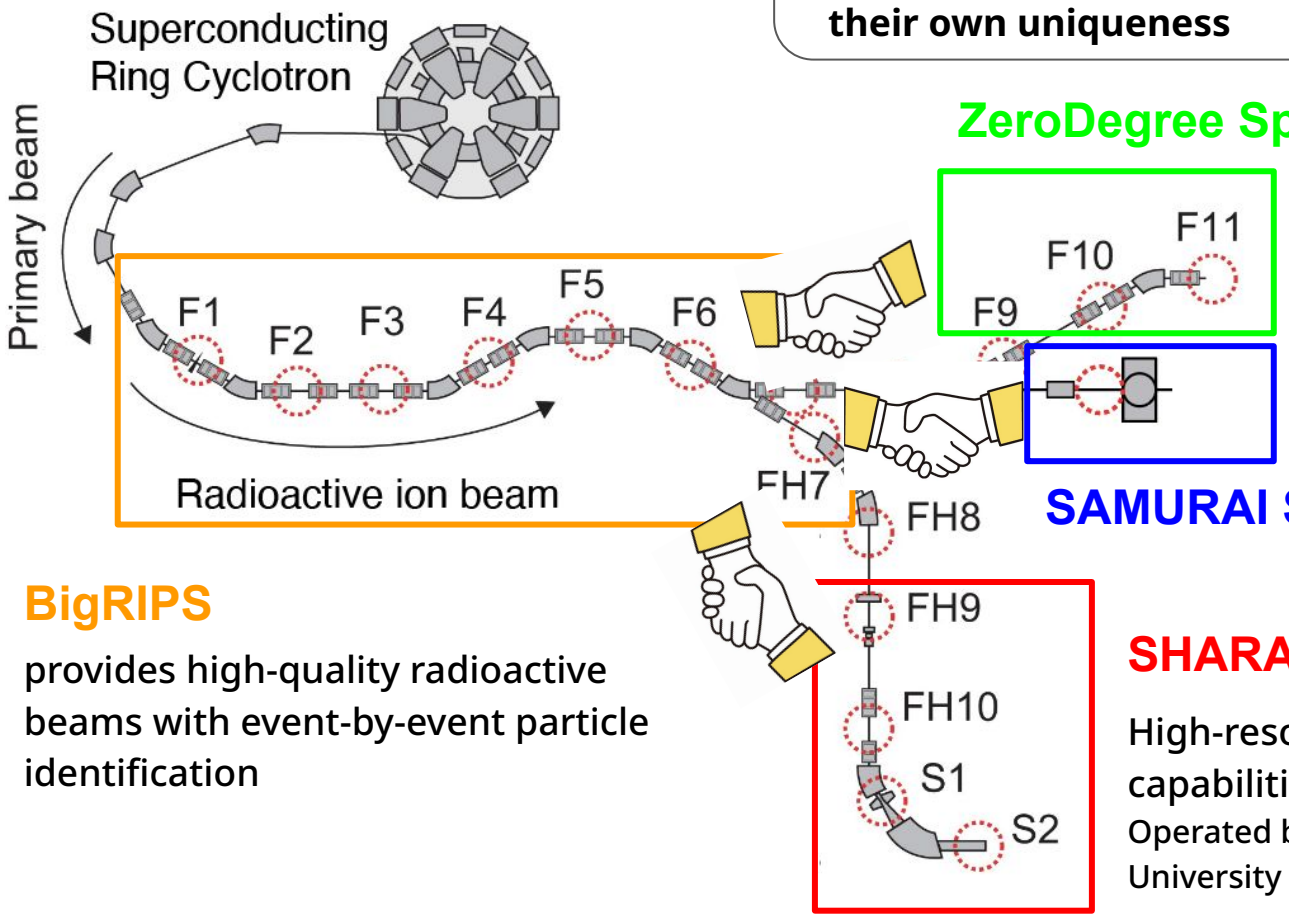




- Stable heavy-ion beam is accelerated by cyclotron chain
- Primary beam is smashed by a beryllium target, producing a wide range of radioactive isotopes in-flight
- Isotope species (A and Z) are tagged by BigRIPS and then radioactive beam is delivered to experimental stations

A bit more about RIBF

Three major experimental stations primarily intended for nuclear reaction studies induced by radioactive isotopes, but they have their own uniqueness



ZeroDegree Spectrometer

Decay studies such as β-γ spectroscopy

Large acceptance and versatil spectrometer

SAMURAI Spectrometer

BigRIPS

provides high-quality radioactive beams with event-by-event particle identification

SHARAQ Spectrometer

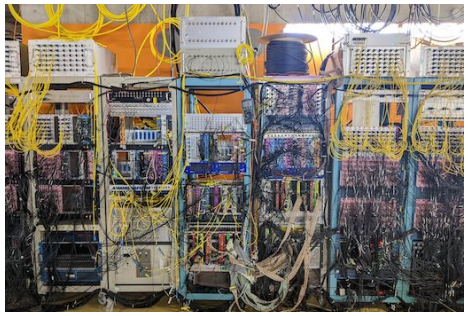
High-resolution and low-energy capabilities

Operated by Center for Nuclear Study, University of Tokyo

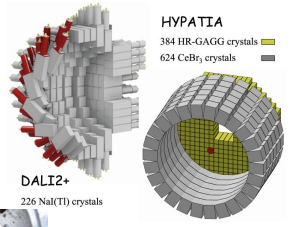
BigRIPS information is always required when running experiments at any of the experimental stations

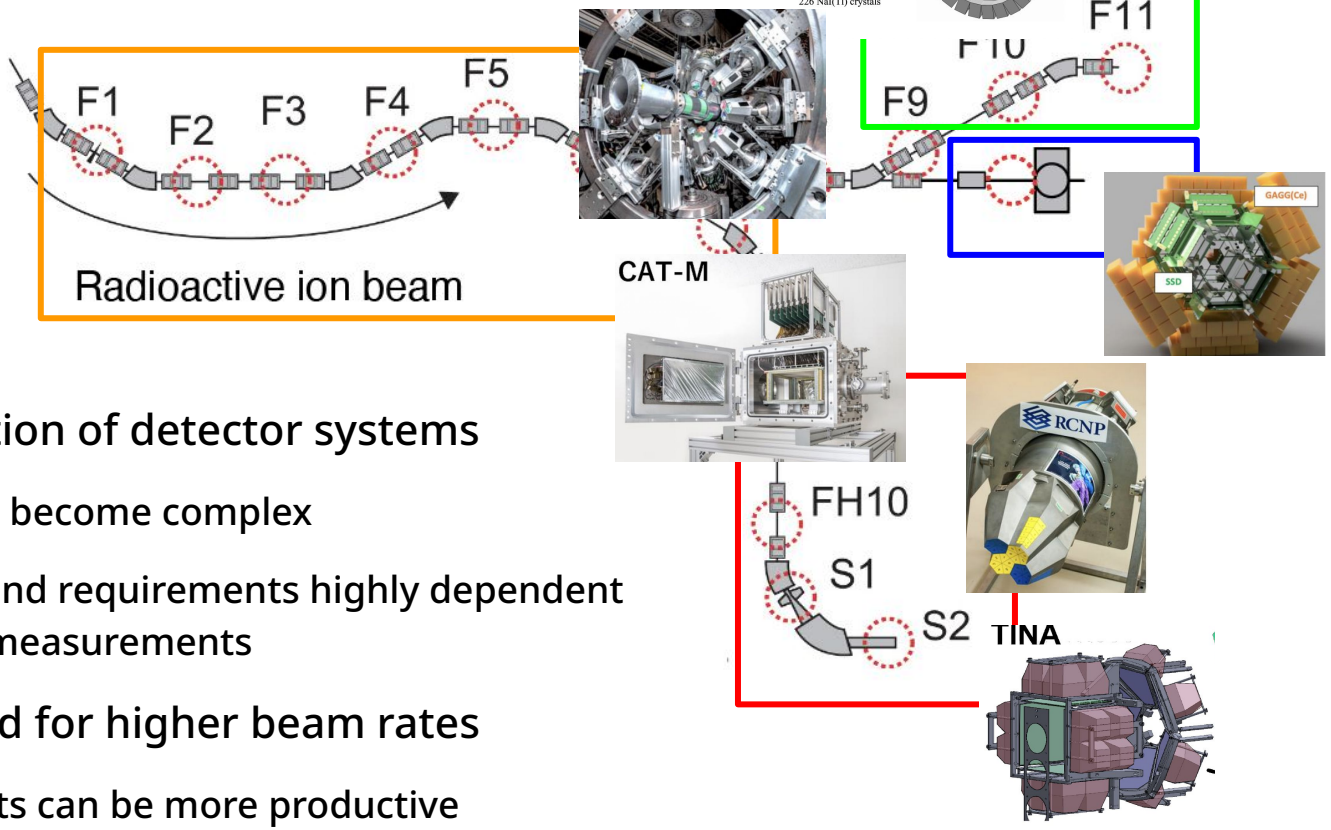
Present DAQ solution at RIBF

- Front-end electronics are (almost) distributed along the beamline
- Heavily relying on *the common-busy global trigger scheme*
- Single-mode optical fibers are used for distributing trigger signals
- Has been successfully used since 2007



What's next?



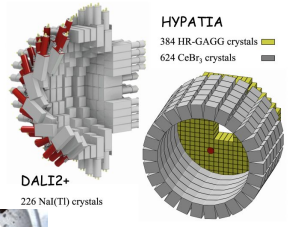


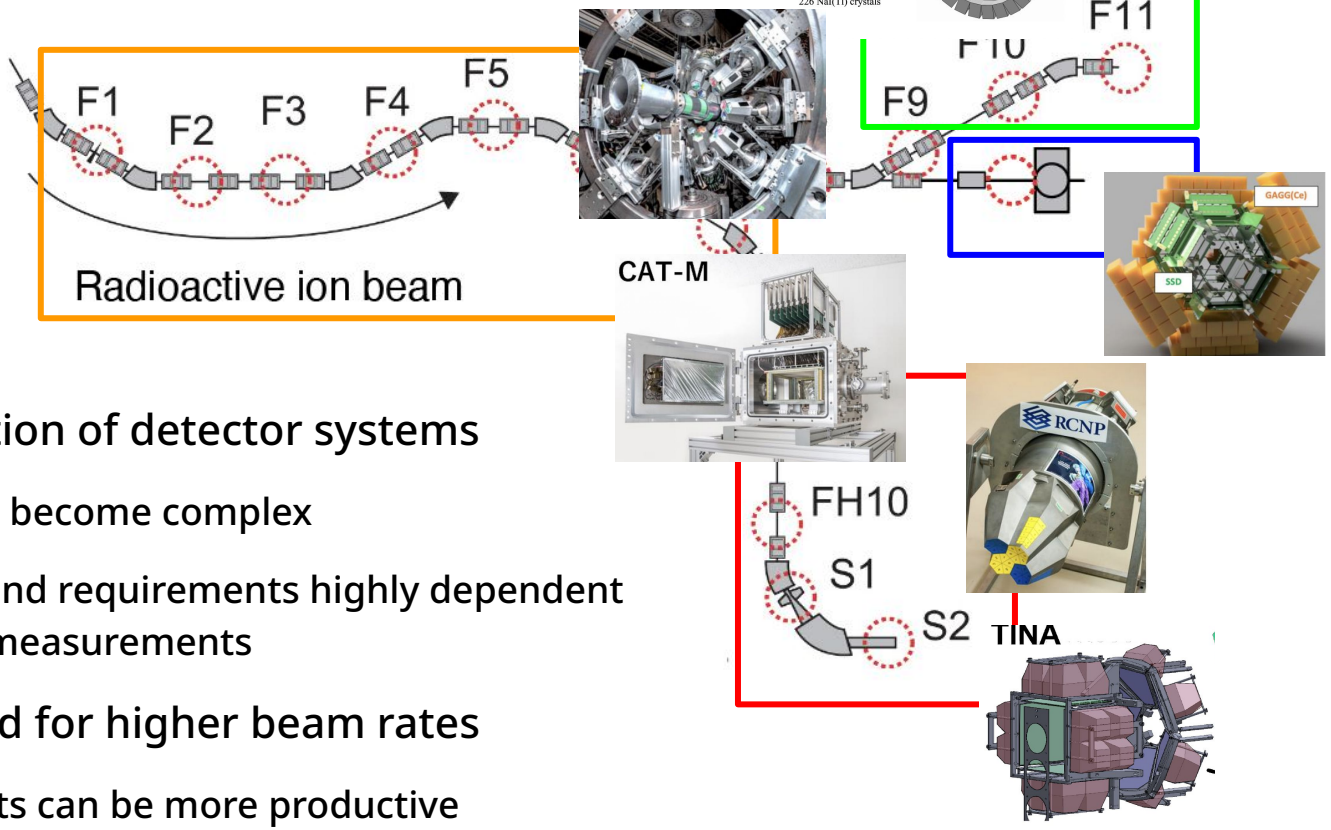
- Continuous evolution of detector systems
  - "User" DAQ has become complex
  - Specifications and requirements highly dependent on the type of measurements
- Increasing demand for higher beam rates
  - Our experiments can be more productive
- We started to hit the limitation imposed by the global trigger scheme

Streaming readout will be the way to go

But we are aware that it's going to be a 5+ year project ;)

What's next?





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Disclaimer: views are my own

Streaming readout will be the way to go

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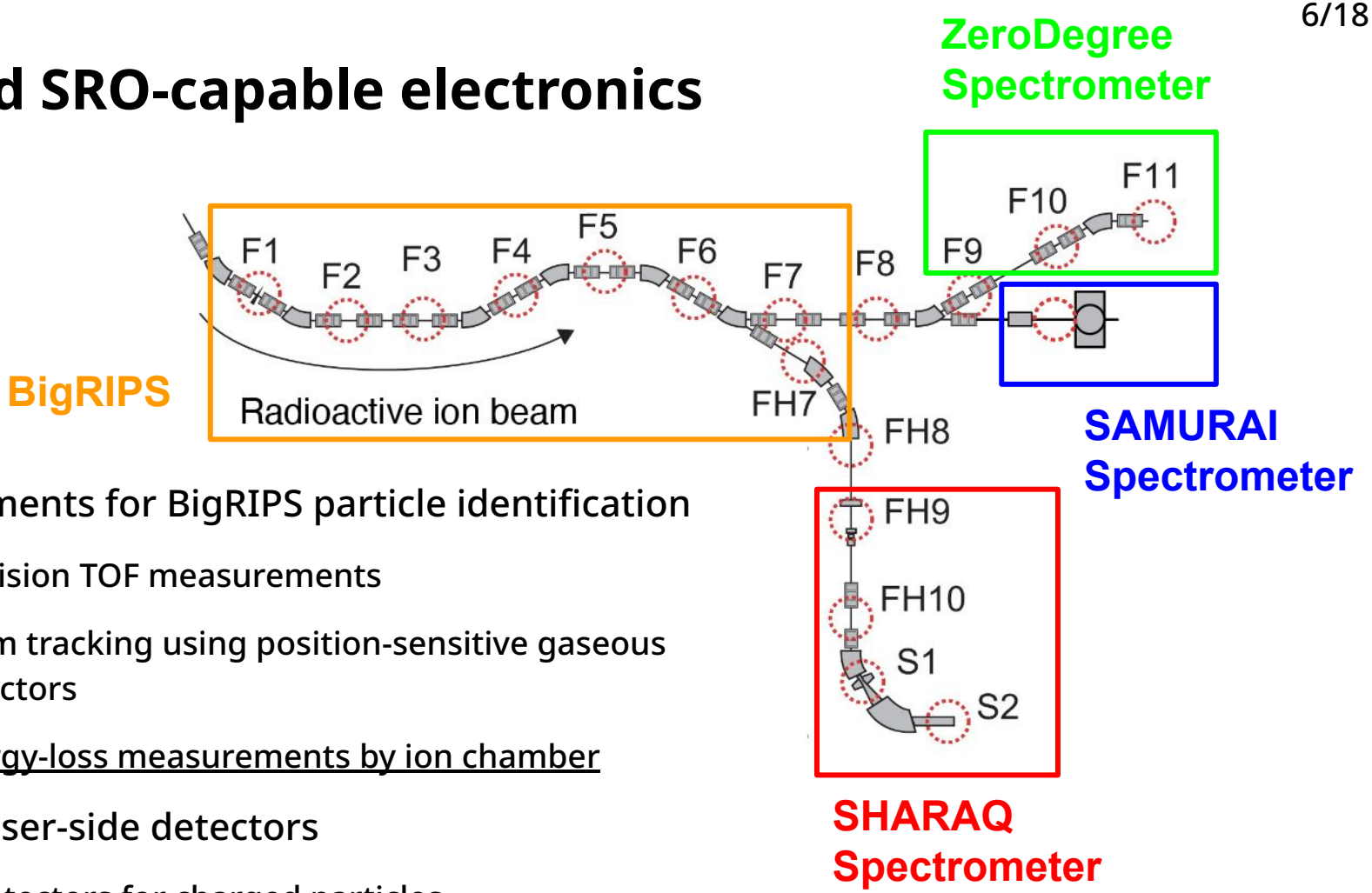
We need SRO-capable electronics



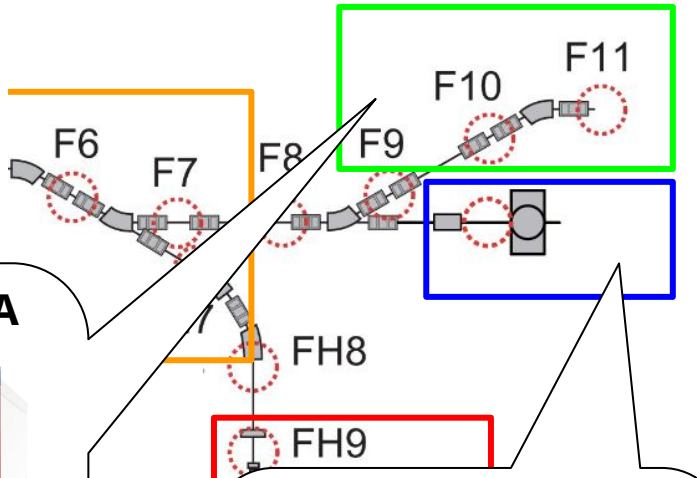
- Requirements for BigRIPS particle identification
  - precision TOF measurements
  - beam tracking using position-sensitive gaseous detectors
  - energy-loss measurements by ion chamber
- Typical user-side detectors
  - Si detectors for charged particles
  - Ge or organic scintillators for gamma rays

At present, we often combine TDC, QDC, and peak-sensing ADC

These need to be SRO-ready → waveform digitizers

Use of waveform digitizers at RIBF

- Acceptance of full digital electronics is slow in low-energy nuclear physics community in Japan
- But some groups at RIBF stated to adopt waveform digitizers

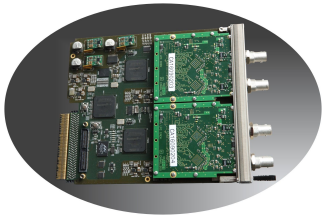


XIA LLC

CAEN SpA

Commercial products

FASTER electronics



Developed at LPC Caen

Our approach: in-house development of waveform digitizer HW, FW, and SW

Justifications:

- Need for *flexible & non-bulky* platform with wide R&D degrees of freedom
- Coherence with RIBF's existing systems guarantees smooth transition into SRO

We want a simple, lightweight, transparent waveform digitizer system

and we want it to be cost effective!

In-house development of digitizers

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- Need for *flexible & non-bulky* platform with large R&D degrees of freedom
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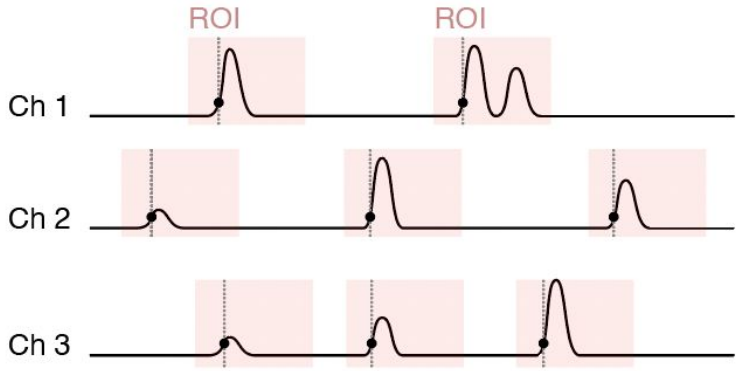
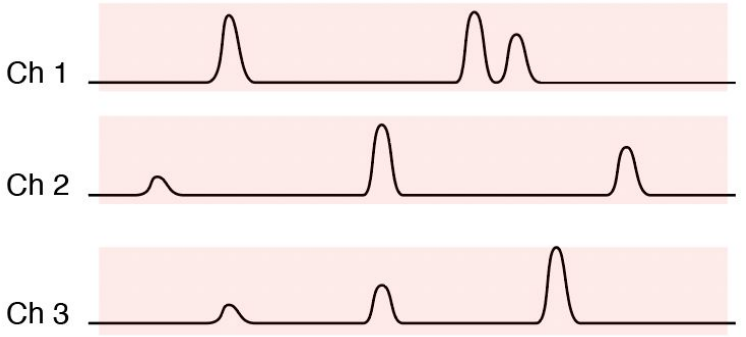
Phase 1 implementation of waveform digitizers in the SRO context

- All channels are self-triggered and free-running



Phase 2 implementation would be continuous, full streaming of raw waveforms

- Overall data rates exceeding 1 Tbps pose real challenges



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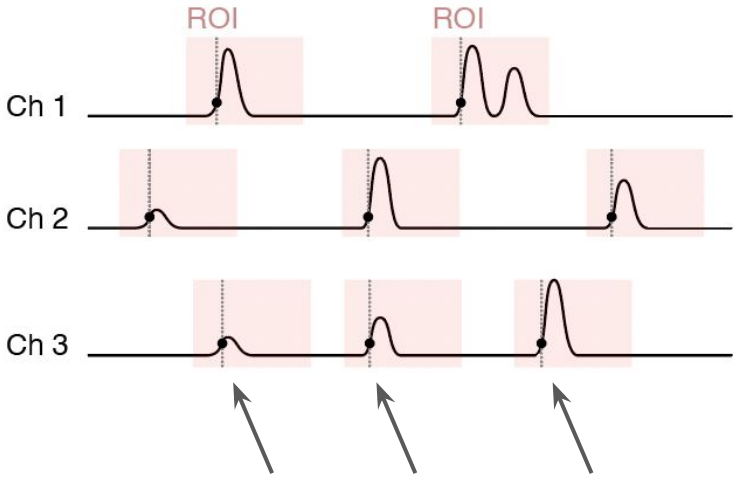
Phase 1 implementation of waveform digitizers in the SRO context

- All channels are self-triggered and free-running
  → need for trigger generation scheme optimized for detectors
- Increased data rates will be problematic under high counting rate and/or noisy conditions



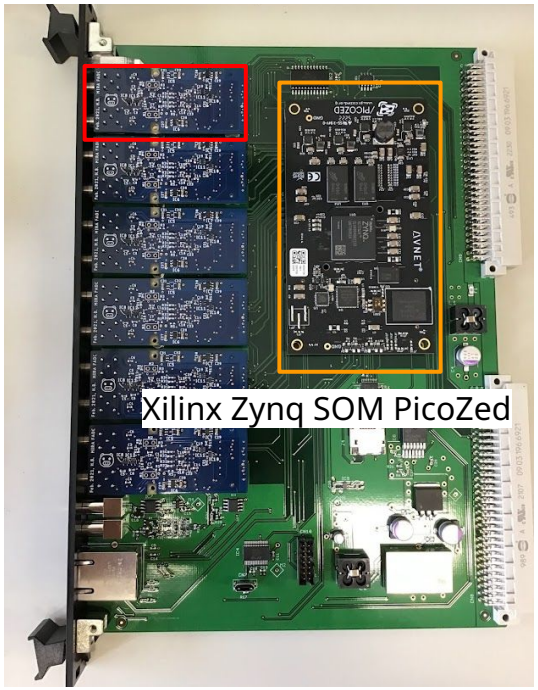
Waveforms captured around self triggers
Events can be built afterwards

→ **Real-time waveform processing on FPGA, effectively enabling data reduction**

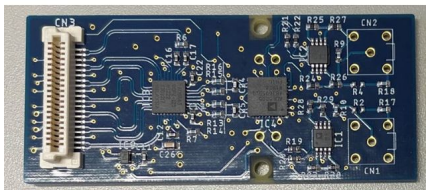
Commercial digitizers have this ability, but we want it to be highly customizable and implemented in a transparent way

In-house development of digitizers: hardware

- High-res digitizer board “MIRA” developed by H. Baba at RIBF
- Specs: 125 Msps, 14 bit resolution, 12 channels/board
  - Originally developed for the readout of Si detectors, ion chamber, and scintillator array



Daughterboard
AD9645 125 Msps 14 bit
dual pipelined ADC
combined with AFE



x6

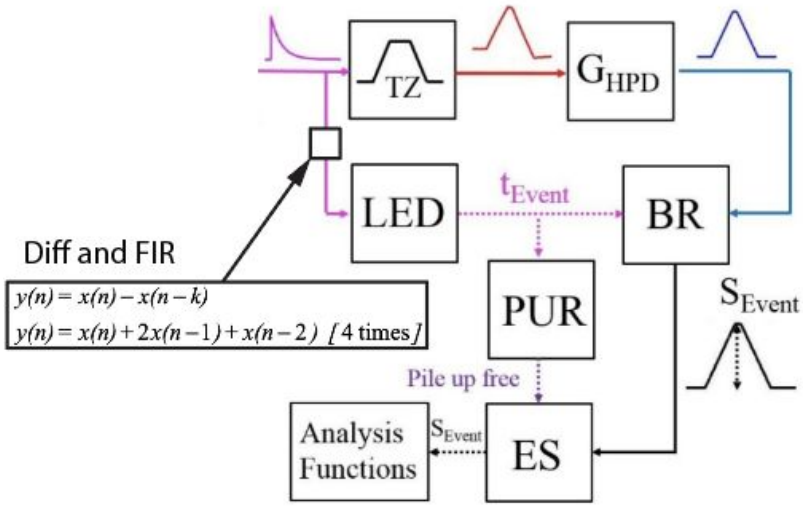
Raw data stream from ADC
20 Gbps in total

- Equipped with 6 ADC daughterboards, resulting in 12 channels in total
- Waveform processing by PicoZed 7020 and data transfer via 1GbE
- Mother board in VME6U form factor, power supplied through the backplane connector but no VME communication, however general-purpose LVDS is supported

In-house development of digitizers: firmware

- **Fast filter** used for generating ch-wise self triggers
- **Trapezoidal filter** (Jordanov filter) for precision energy measurements
- **Gated summation** as a QDC replacement

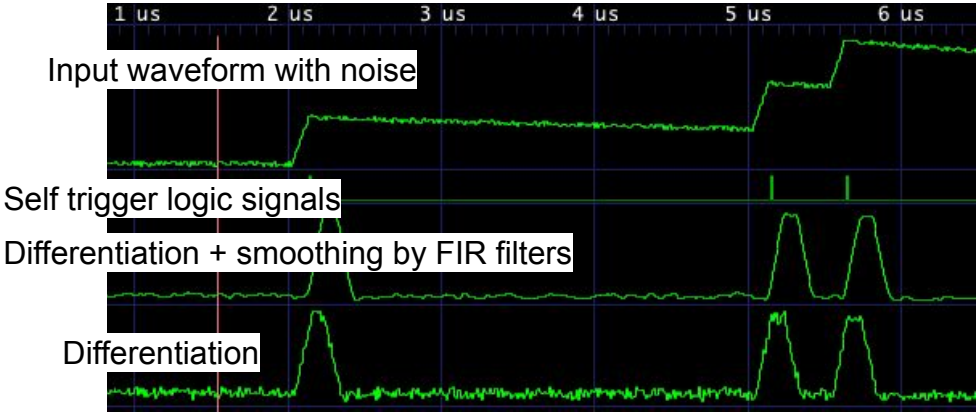
  plus, sub-sampling timing (S. Takeshige et al.)

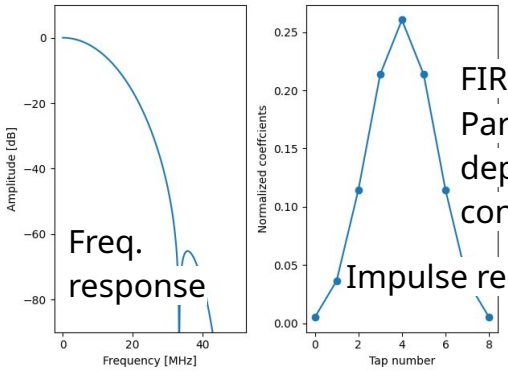


Based on

https://ieeexplore.ieee.org/document/8532908

HDL simulations for fast filter implementation





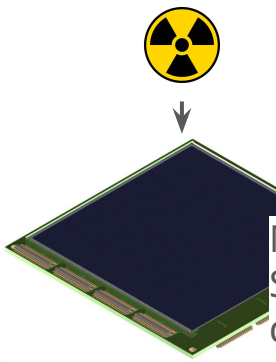
FIR filter used for smoothing
Parameters can be adjusted depending on the actual noise conditions

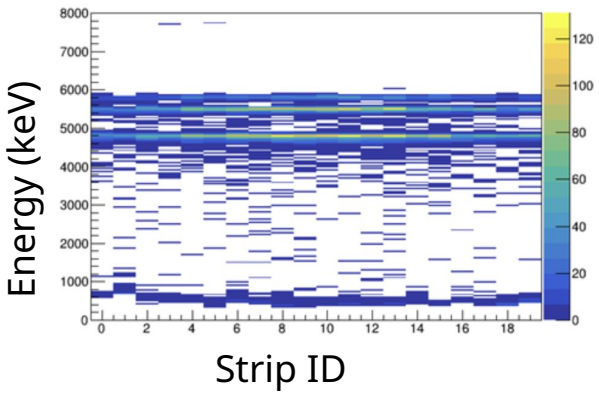
Firmware testing and characterization

Readout tests using a Si strip detector with an alpha source

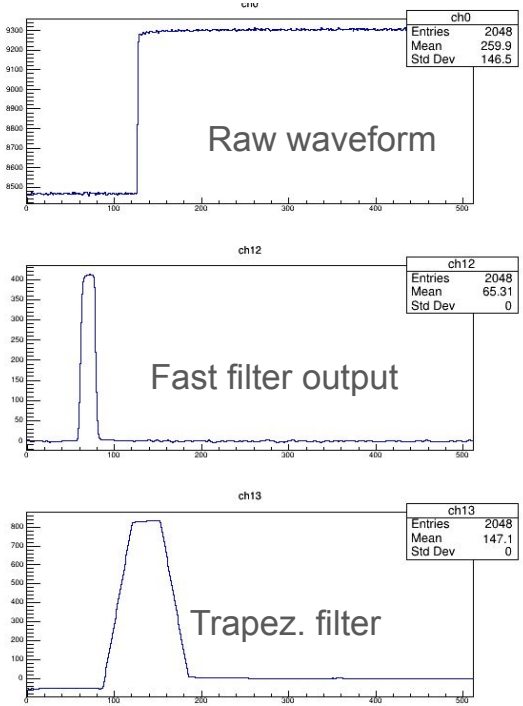
- Trigger generation using the fast filter
- Trapezoidal filtering for energy calculation, baseline and flattop are captured

Mixed alpha source



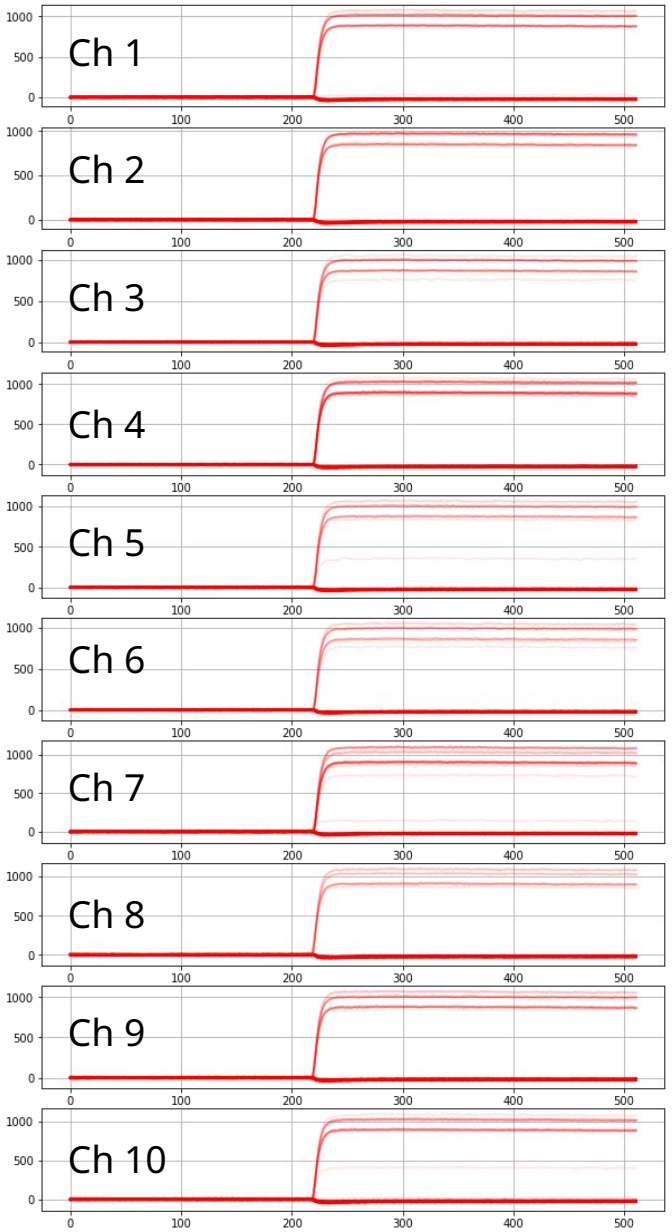


Single event example



Courtesy of H. Baba & S. Takeshige

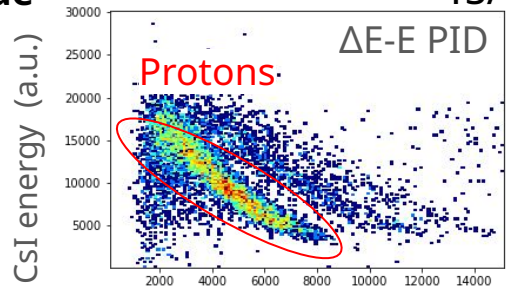
Captured raw waveforms

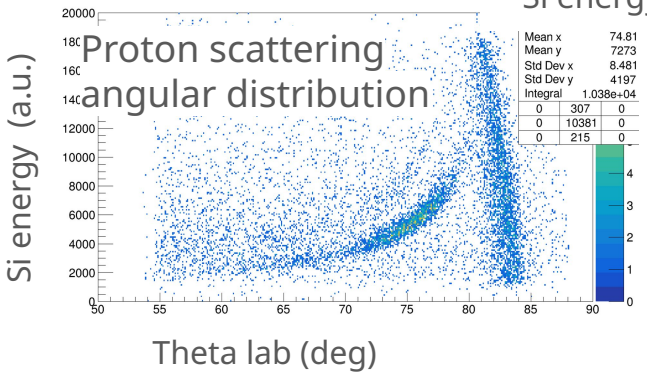


Digitizer commissioning at RIBF

March, May and November, 2024

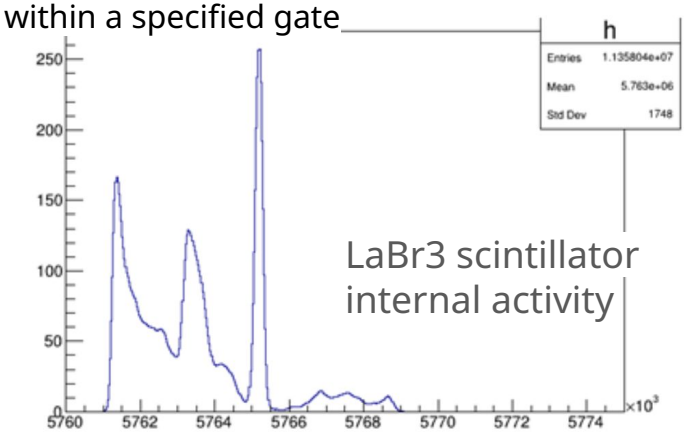
- Proton elastic scattering measurements
- Readout of Si strip (ΔE) and CsI (E)
- Trigger generation and energy measurement have been commissioned
- Triggering rate was not too high



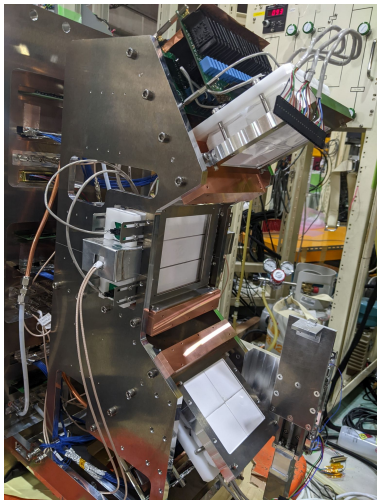


Gated summation (QDC) has also been tested

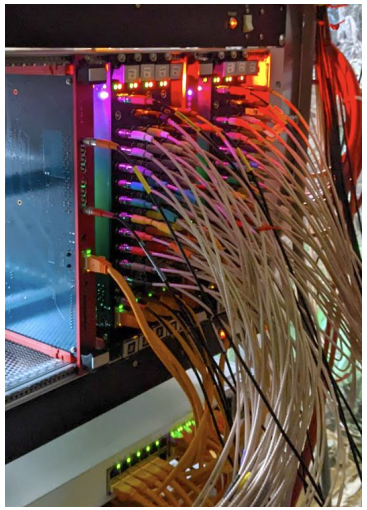
Simple integration of waveform within a specified gate



QDC data = uncalibrated energy



Si-CsI telescope array for proton elastic scattering measurements



Number of channels ~100

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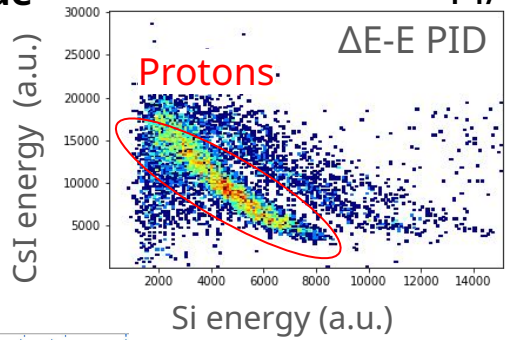
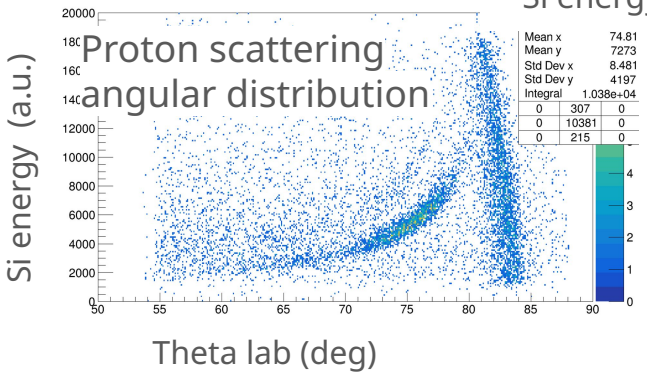
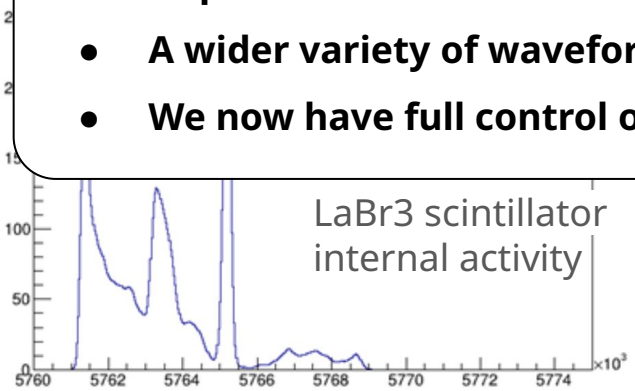




Gated summation (QDC) has also been tested

Simple integration of waveform with ...

- **Implementation of elementary waveform processing on digitizer FPGA**
- **A wider variety of waveform filters will be implemented**
- **We now have full control over processing algorithm**



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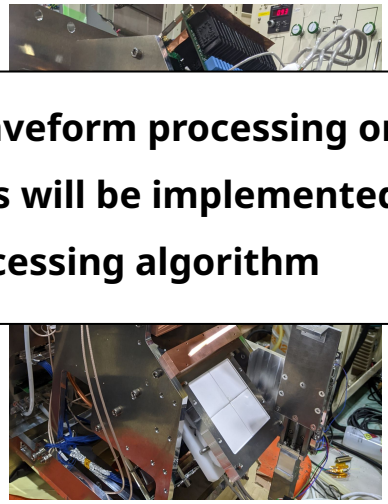

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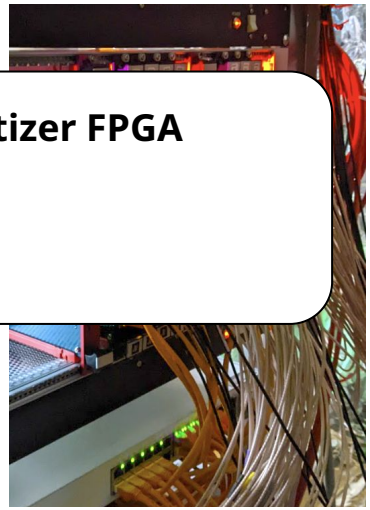
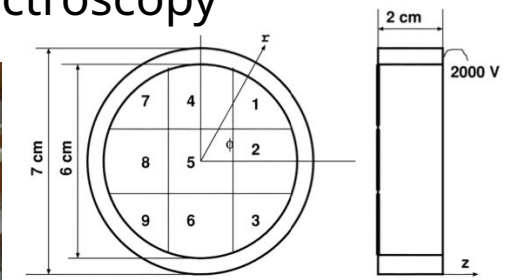


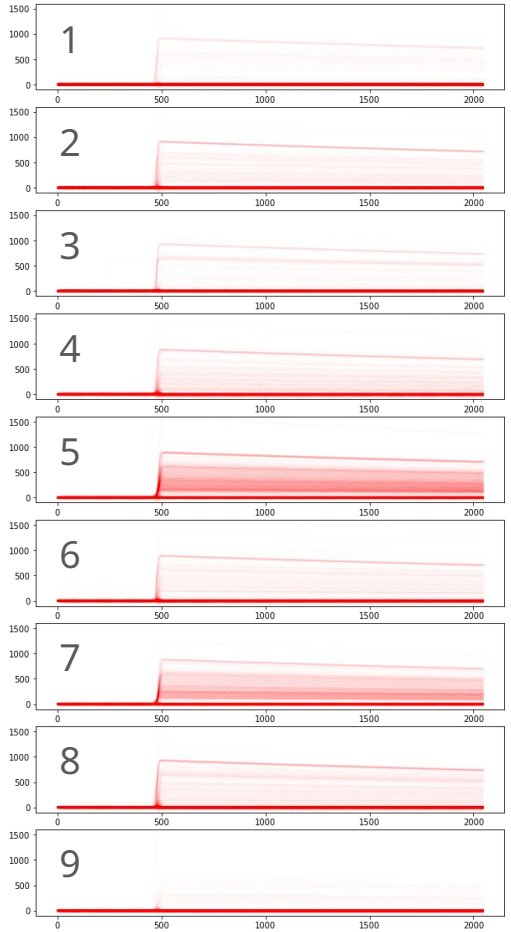
Number of channels ~100

Possible application to segmented Ge detector readout

Position-sensitive Ge array “GRAPE”
designed for gamma-ray spectroscopy

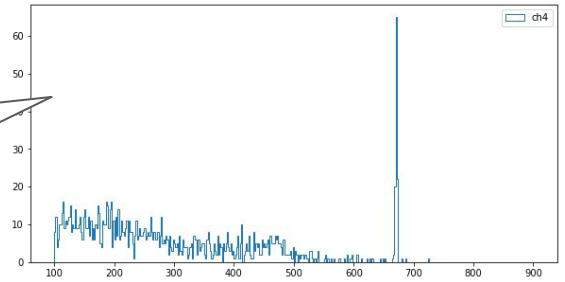


Two Ge crystals in a single cryostat and nine-fold segmentation for each



Analysis of captured waveforms enables 3D gamma-ray hit position reconstruction
essential for Doppler correction of gamma rays

Offline GRAPE readout test using a radioactive source



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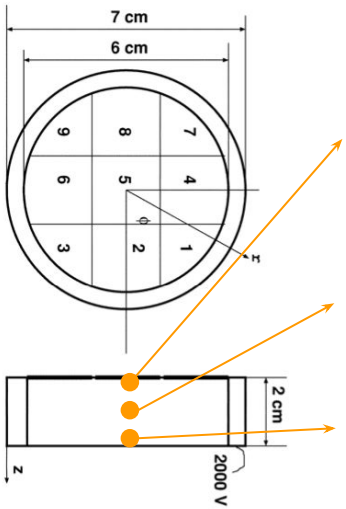
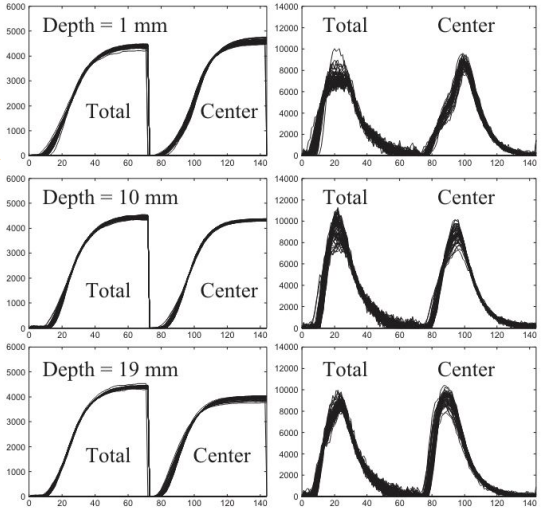
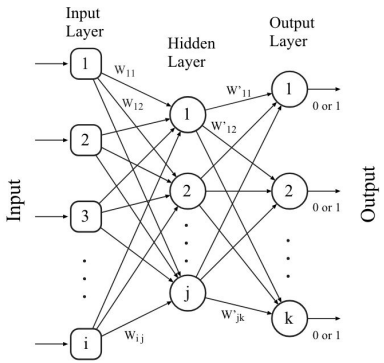
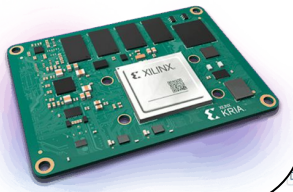




Pulse shape changes depending on the hit position
Application of a NN approach: exploratory work by Fukuchi+ 2003

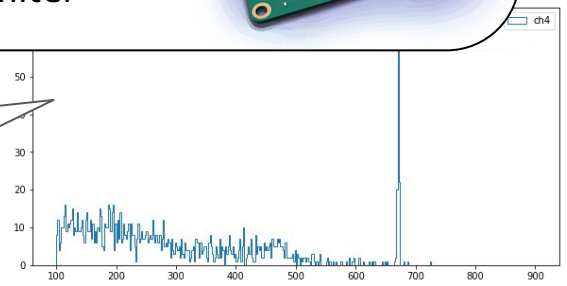


Binarized Neural Network can be implemented on FPGA



Output: 3d position (x,y,z) and energy from trapezoidal filter

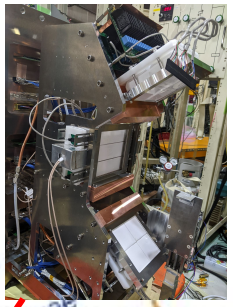
Offline GRAPE readout test using a radioactive source



Prospects: deployment of our digitizers at RIBF

Si+CsI telescope array

Scintillator array



Dedicated ultra high rate pulse processing

Multi-sampling ion chamber

Possible implementation of ML methods on FEE

Ge array

Si+CsI(Tl)

Distribute waveform digitizers to various experimental stations, and then migrate into SRO

Sub-ns time synchronization among them will be accomplished by White Rabbit or MIKUMARI

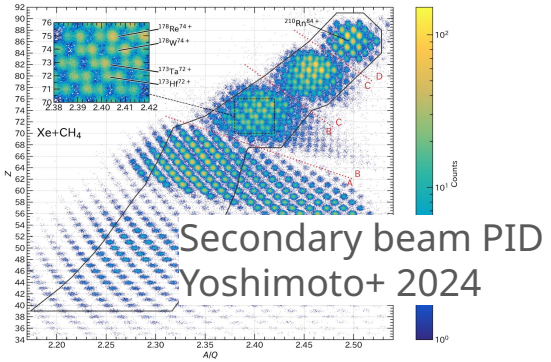
Summary

- **Waveform digitizers will serve as main workhorses in low-energy nuclear physics experiments at RIBF**
- We initiated in-house development of simple, lightweight waveform digitizers
  - Coherence with RIBF's existing systems guarantees smooth transition into SRO
  - Driven by need for flexible & non-bulky platform with wide R&D degrees of freedom
- Implementation of basic waveform processing
  - Successfully commissioned in experiments performed in 2024
  - Development of high-rate tolerant algorithms is underway
  - Some prospects of ML-based real-time waveform processing on FPGA
- Developments toward SRO, including sub-ns time synchronization among different FEE locations, are a next milestone

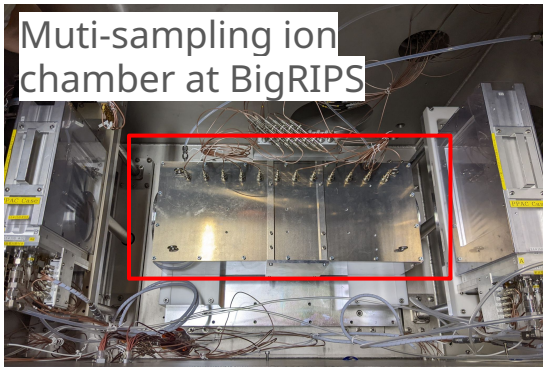
Digitizer commissioning at RIBF

June, 2024

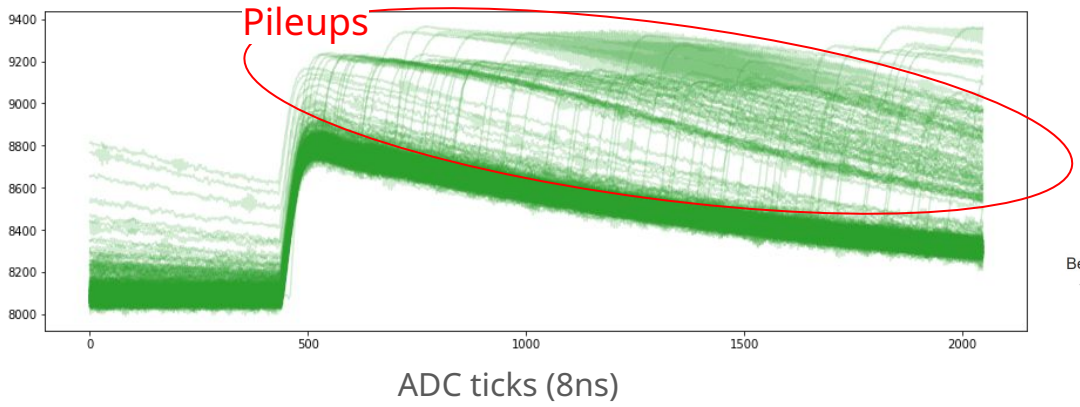
- ΔE measurements by muti-sampling ionization chamber are essential for beam particle identification
- Our digitizer was used for the readout test
- Recorded waveform data that will be used for developing high-rate (>100kcps) tolerant firmware



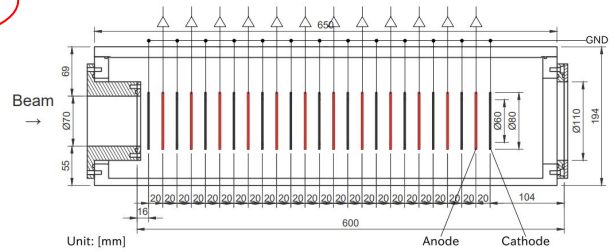
Secondary beam PID
Yoshimoto+ 2024



Muti-sampling ion chamber at BigRIPS



ADC ticks (8ns)



- **Implementation of elementary waveform processing on digitizer FPGA**
- **A wider variety of waveform filters will be implemented**
- **We have full control over processing algorithm**

Stolen from S. Mandal's talk (today)

Multi-layer perceptron (MLP)

- Composed of two fully connected layers of perceptrons (16 neurons in hidden layer, 2 neurons in output layer)
- Will be used for:
  - Regression: Amplitude and/or time of arrival estimation
  - Classification: Pulse shape detection (for particle ID or pileup detection)
- Each perc
  - Multiplic -bit) with weights
  - Additior
  - Applicat function (ReLU) for hidden layer neurons only