

A high-speed MTCA.4- based digitizer system for J-PARC MR

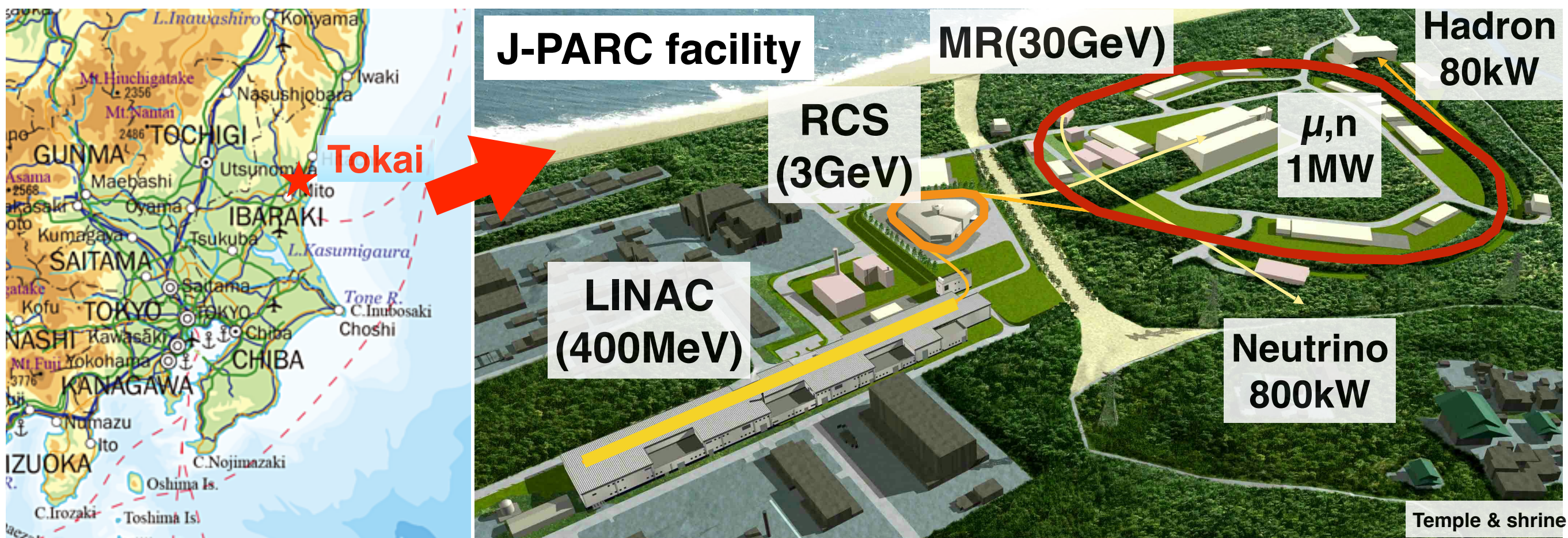
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KEK/J-PARC

2025/Aug./28th(Thu)
MTCA workshop for accelerator and physics in Japan 2025
@KEK

- Introduction of J-PARC and MR
- Requirement for the high-speed digitizer
- MTCA.4-based high-speed digitizer
- Future Prospect
- Summary

(Japan Proton Accelerator Research Complex)

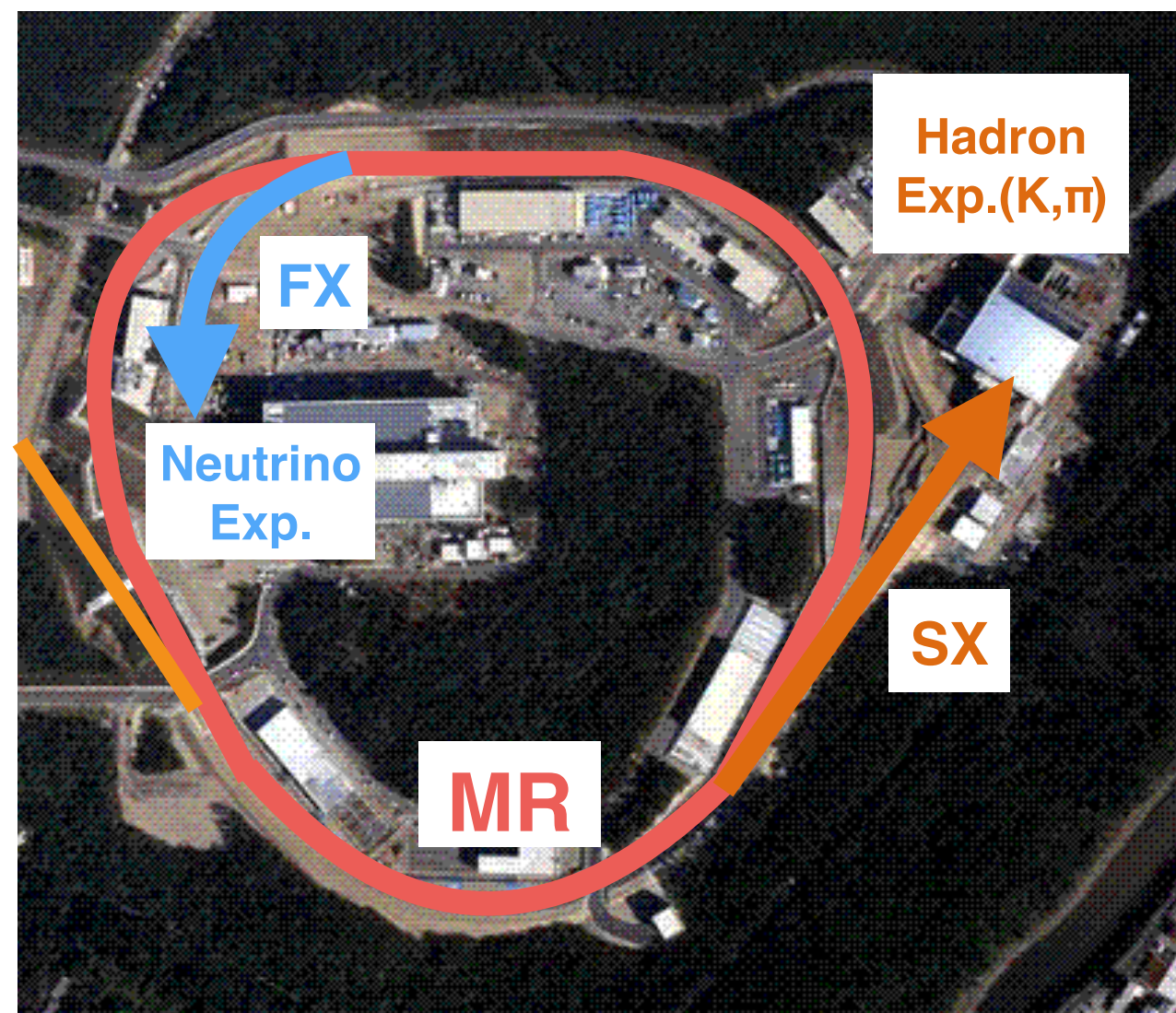
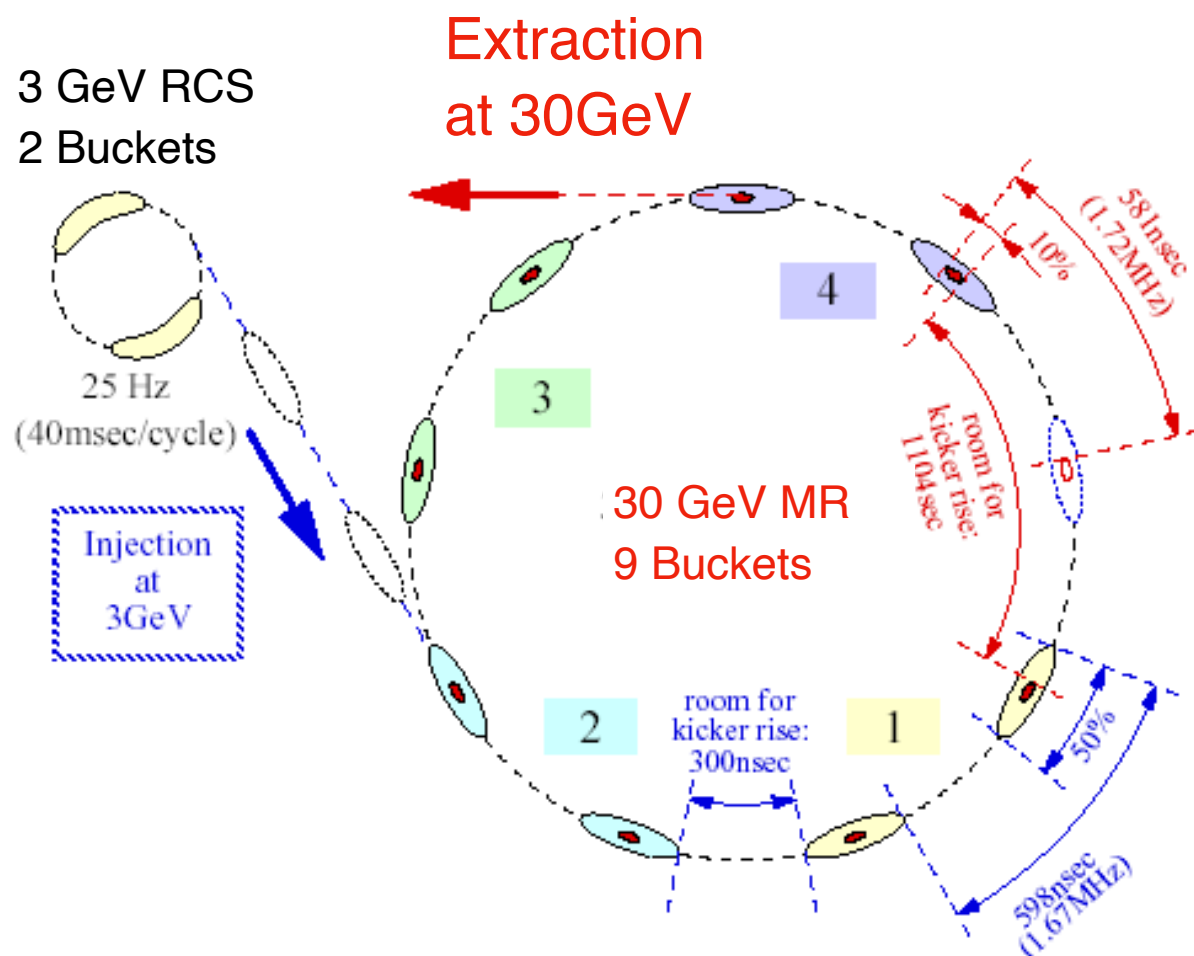
- High intensity Proton Accelerator with a LINAC and two synchrotrons.
 - **LINAC: 400MeV** negative hydrogen (H^-) with 50mA (25 Hz)
 - Rapid Cycle Synchrotron (**RCS**): **3 GeV** proton with **1 MW** (25 Hz) for material and life science (μ and neutrons).
 - Main Synchrotron Ring (**MR**): **30 GeV** proton with **830 kW** (1.36 s cycle) for ν experiment, **92kW**(4.24 s cycle) for Hadron experiment.



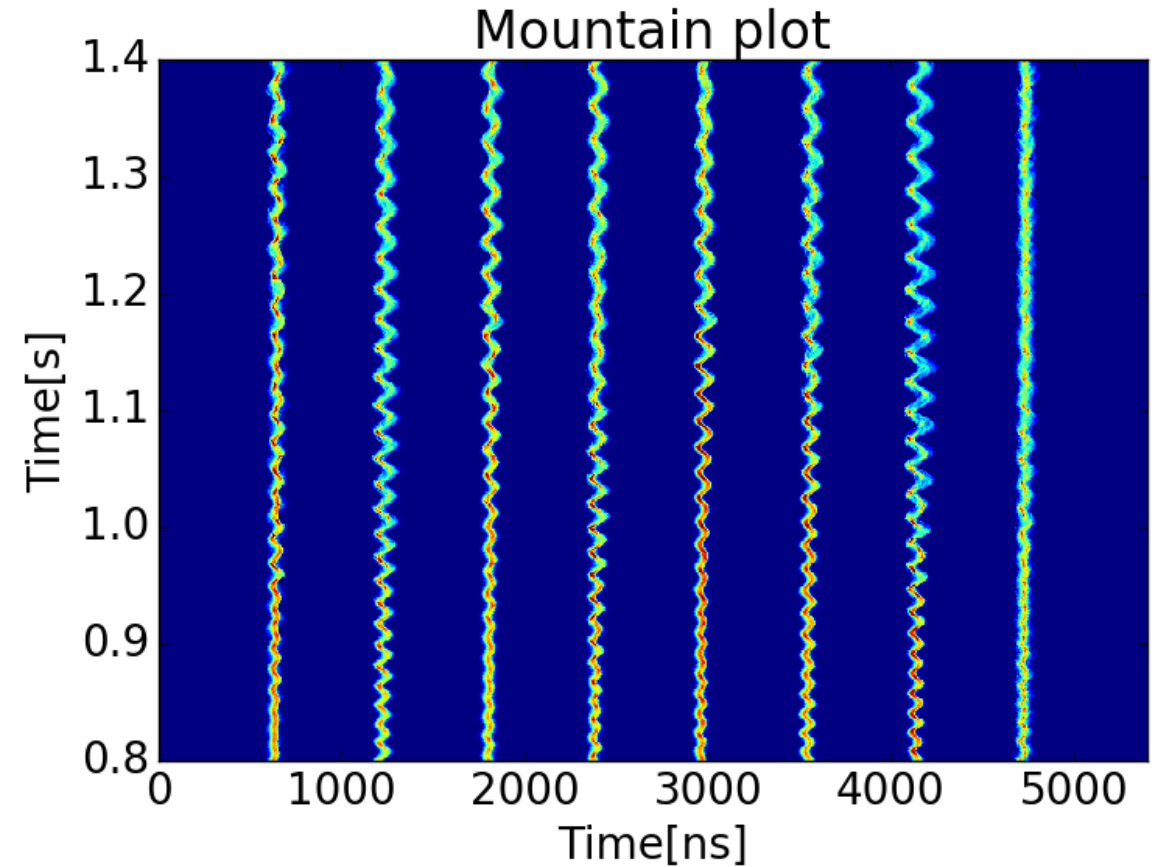
J-PARC Main Ring Synchrotron (MR)

- MR accelerates eight bunches of protons from 3 GeV to 30 GeV.
 - 4 times injection of 2 bunches from RCS
 - Injection period: 140 ms. Acceleration time: 650 ms.
- Two types of beam extraction for experiments.
 - Fast Extraction (FX): 1 Turn Extraction by Kicker
 - Slow Extraction (SX): Multi-turn extraction (~ 2 s).
The beam is debunched by turning the RF off before extraction.

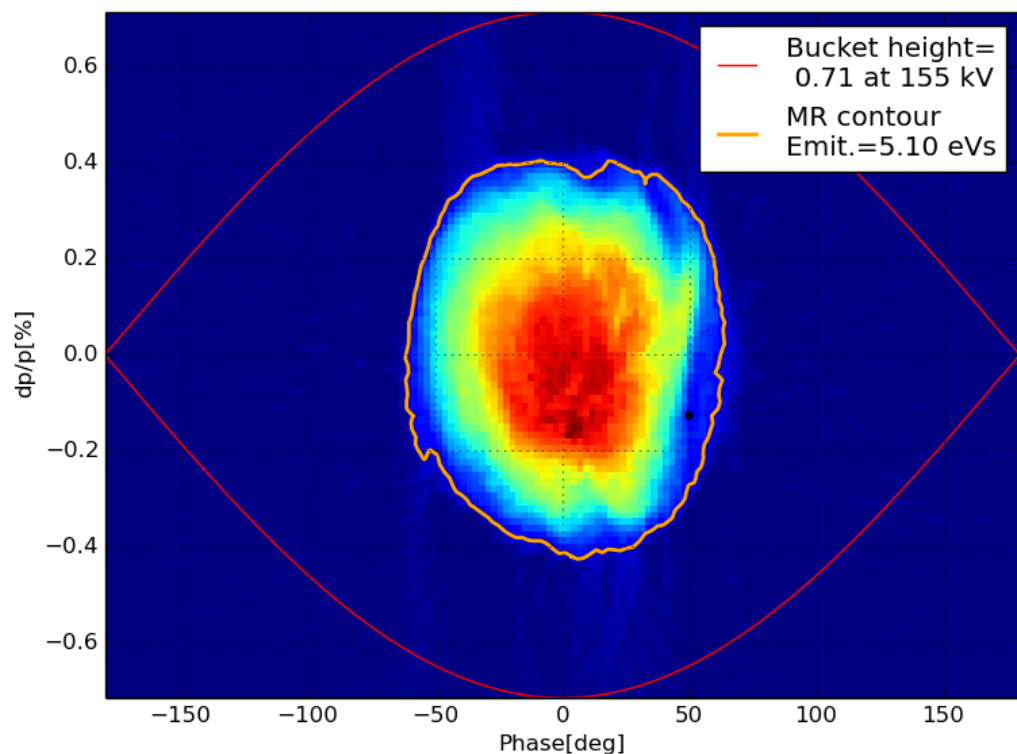
Energy	3~30GeV
Circumference	1567.5 m
#Buckets	9
#bunches	8
Repetition Cycle	1.36 s (FX), 4.24 s (SX)
Acceleration time	650 ms



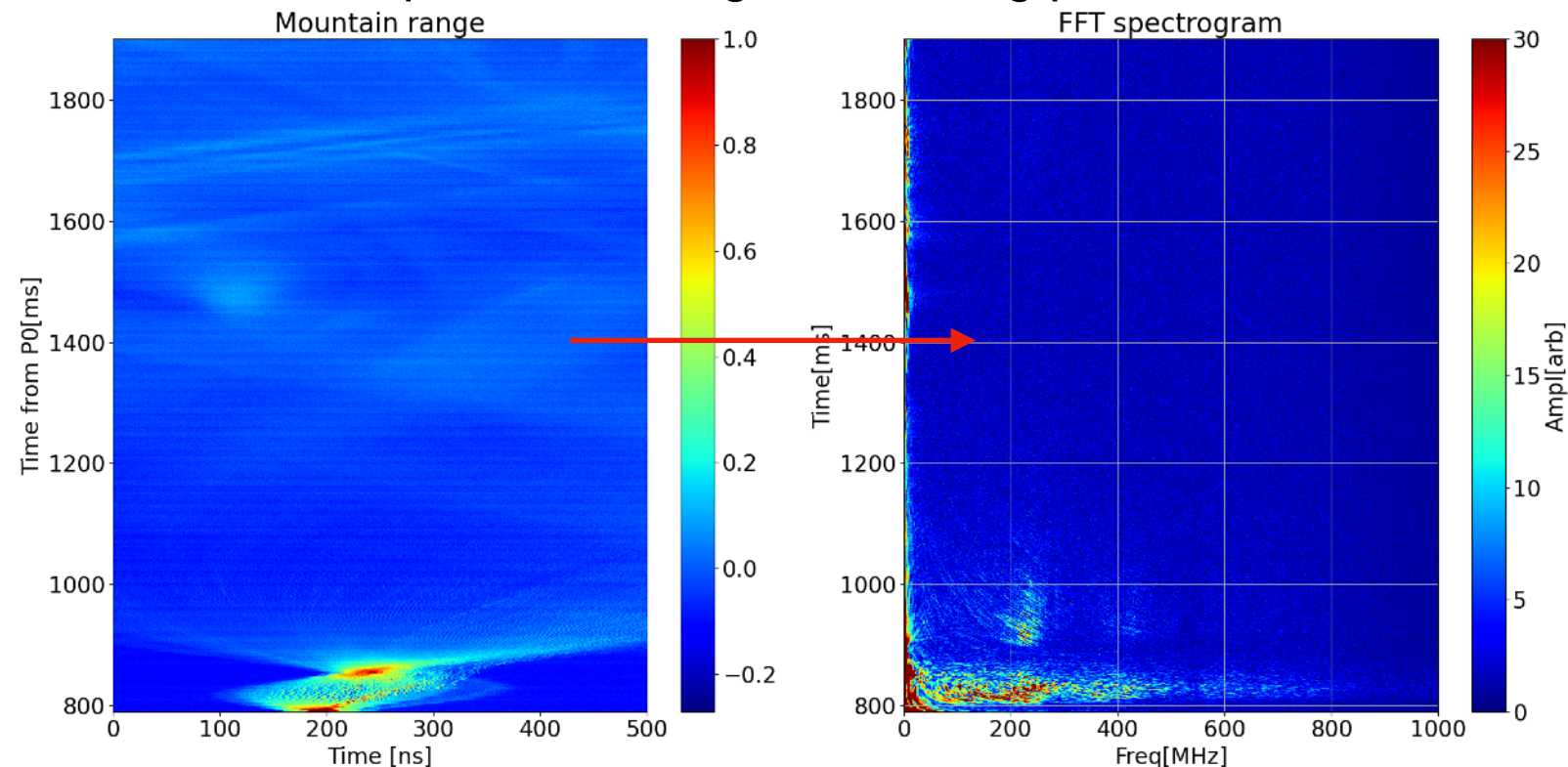
- The waveforms of the beam signals recorded by the oscilloscopes are essential for monitoring and analyzing the beam's longitudinal properties.
 - Motion of the beam bunches
 - Tomography Reconstruction
 - Spectral Analysis by FFT



Reconstructed distribution by Tomography



Spectrum during debunching process



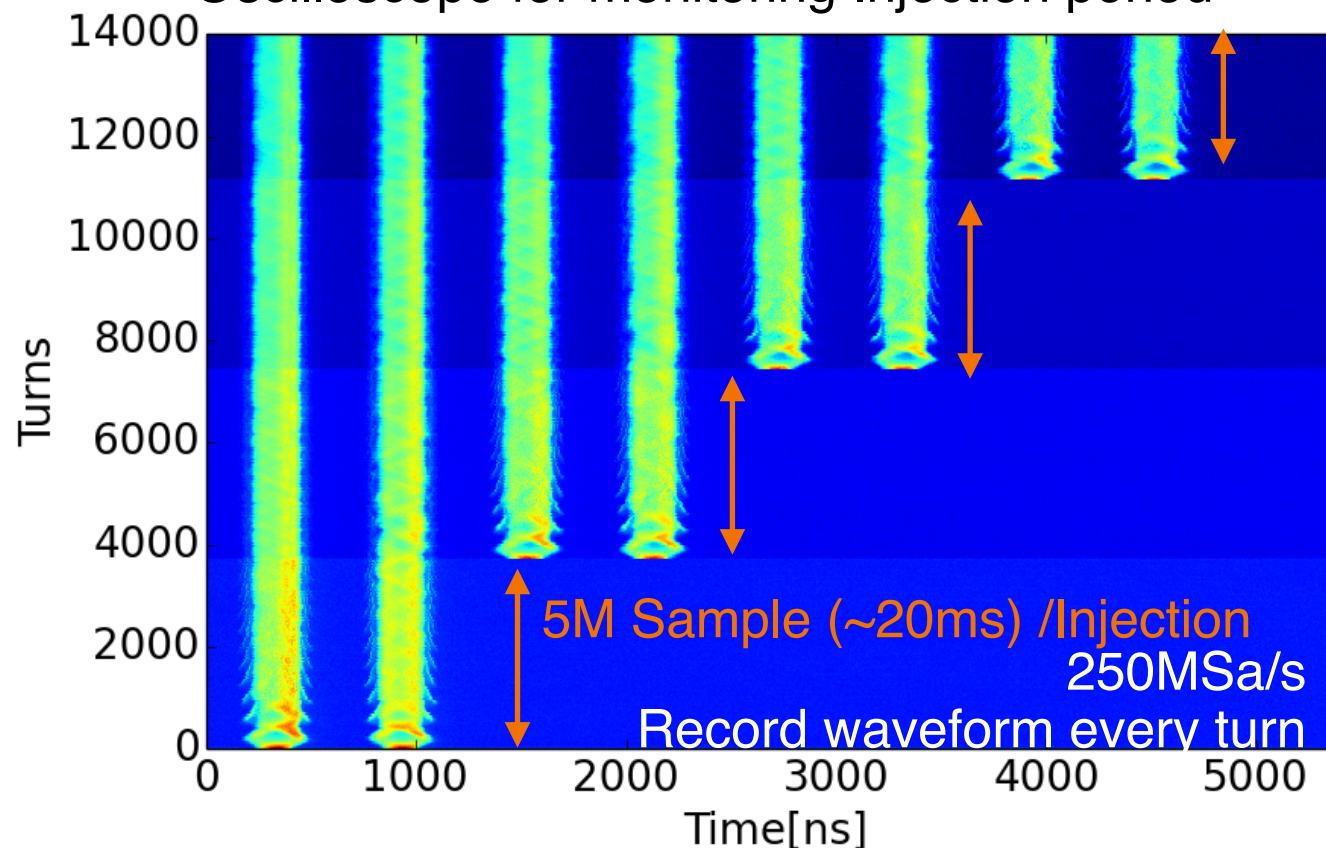
Current situation @J-PARC MR

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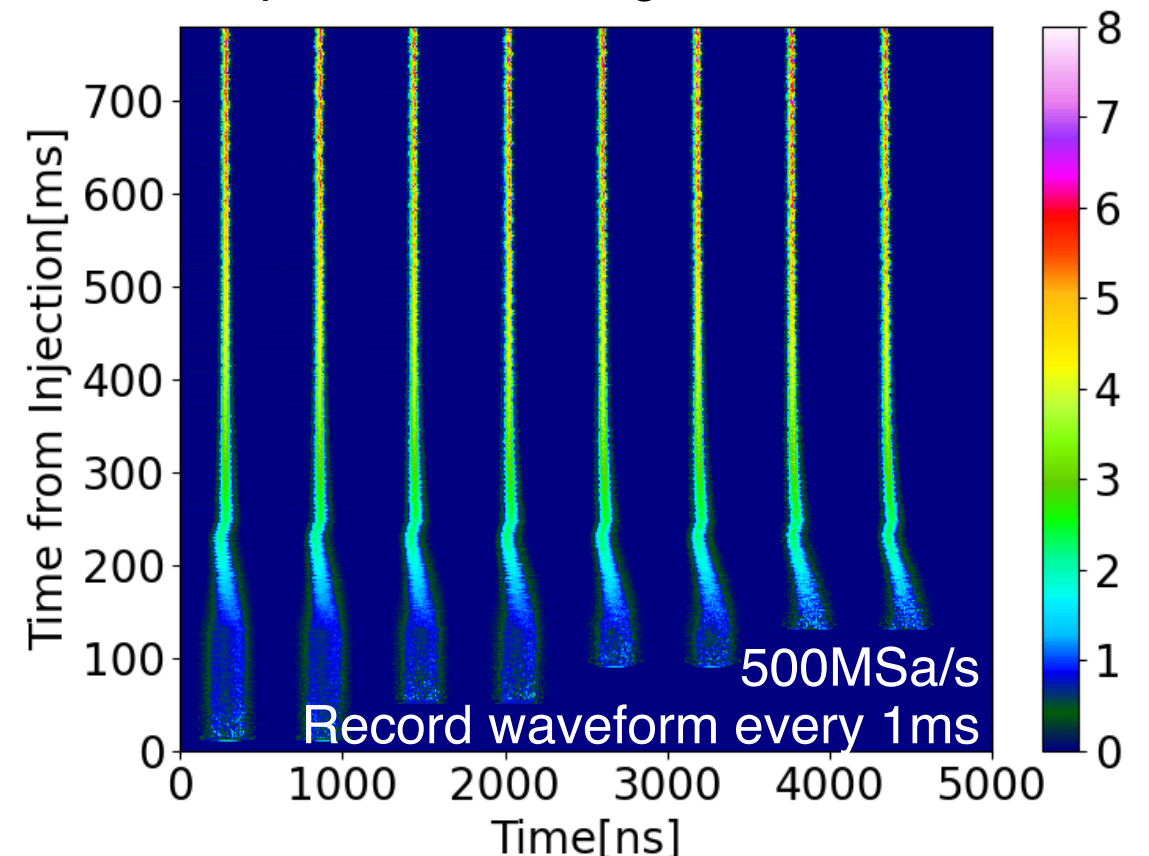
- Oscilloscopes are used to record the waveform of the beam signal.
- Memory on the oscilloscopes: 10~20M samples
 - **Not long enough to store all waveforms for the whole acceleration period.**
- Two oscilloscopes are used with different recording intervals.
- Data readout via VXI11 protocol over Ethernet. **Not Fast enough for ~1Hz cycle.**
- **Oscilloscopes cannot acquire and process the data at ~1Hz.**

Need FASTER digitizer!!!

Oscilloscope for monitoring Injection period



Oscilloscope for monitoring whole the acceleration



Requirement for new digitizer

- Required specs.
 - Sampling speed faster than 500MSa/s.
 - Analog bandwidth >500MHz for the spectral analysis.
 - Memory:1~2GByte to store the waveform for the whole acceleration period.
 - Readout interface faster than VXI11 via ethernet.
 - A compact and stand-alone system is preferred.
- **A high-speed MTCA digitizer AMC with a small MTCA chassis as a solution!**

MTCA.4-based high-speed digitizer system for J-PARC MR

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- 1U MTCA chassis with high-speed digitizer AMC module.
- Digitizer: Teledyne SP Device ADQ14
 - 14bit, 1GSa/s, 700MHzBW, 4ch input, 2GB memory.
- Vadatech MTCA chassis VT816 (Ubuntu Linux)
 - Embedded MCH with CPU (Intel Xeon E3-1125)
 - Fast readout via PCIeexpress bus in the MTCA backplane.



Trouble in the integration...

- We had some troubles during the integration of AMC and chassis.
 - Compatibility issue between AMC and chassis
 - The hot-swap switch could not change the status of ADQ14. (Stay off)
 - MCH cannot identify the FRU information of ADQ14.
 - These features of ADQ14 worked correctly with the nVent small chassis.
 - It turned out that the FRU information stored in ADQ14's MMC device locator record did not fully comply with IPMI standards.
 - After the firmware fix by Teledyne, ADQ14 worked successfully with VT816.
 - **I truly appreciate the kind support from LHS, Vadatech, and Teledyne SPD.**
- Installation of the X Window system in the Linux OS on VT816.
 - At first, we tried to install them on AlmaLinux, but the X Window System did not work properly, probably due to the graphics driver compatibility (Silicon Motion 750 (SM750)).
 - Instead, we installed them on Ubuntu, and everything worked fine.

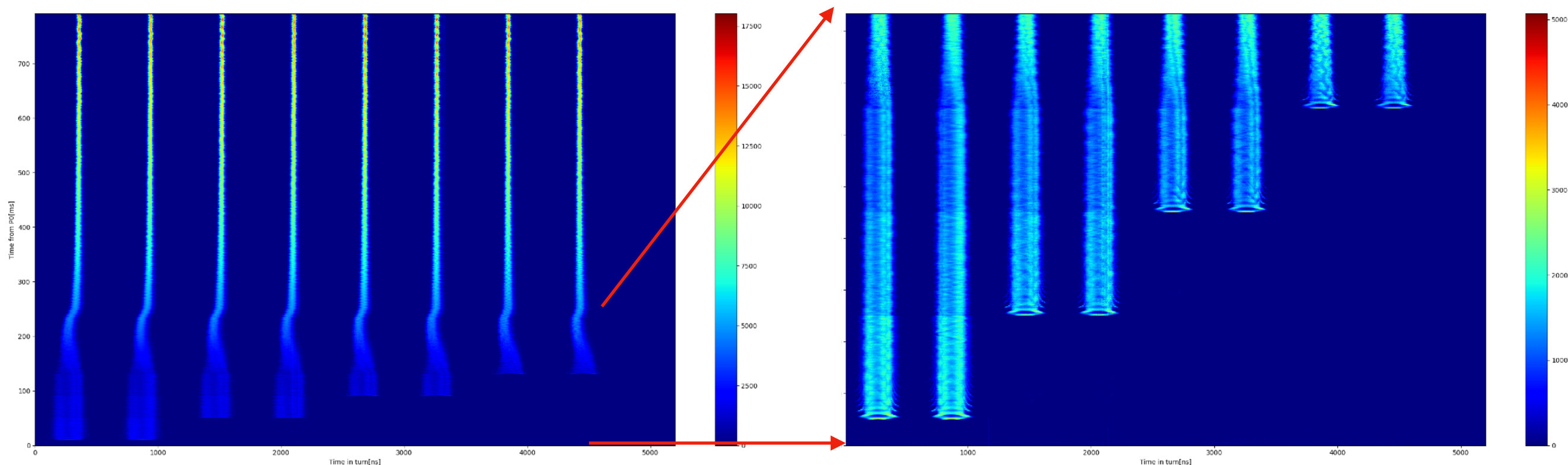
Data acquisition method

- Information required for the analysis: Waveform slice for each turn.
- Easiest way for acquisition: Record single long waveform using the beam cycle start timing as a trigger for the acquisition.
- **Issue: Offline slice reconstruction from single long waveform (>1M Sample) requires the revolution clock data and long time to process.**
- Solution in the case of the J-PARC MR:
Acquisition with fixed number of samples using the revolution clock as a trigger.
 - Fixed sample acquisition is valid since the change of revolution frequency of the MR is only 3% and the MR has one empty bucket.
 - Shortest revolution period is chosen as a record length to ensure the recording for all turns since the trigger arriving during acquisition is discarded.
 - Waveform slices for each turn are stored in the memory as an array of the waveforms with fixed number of samples. Easy to reconstruct.

New digitizer in operation at J-PARC MR

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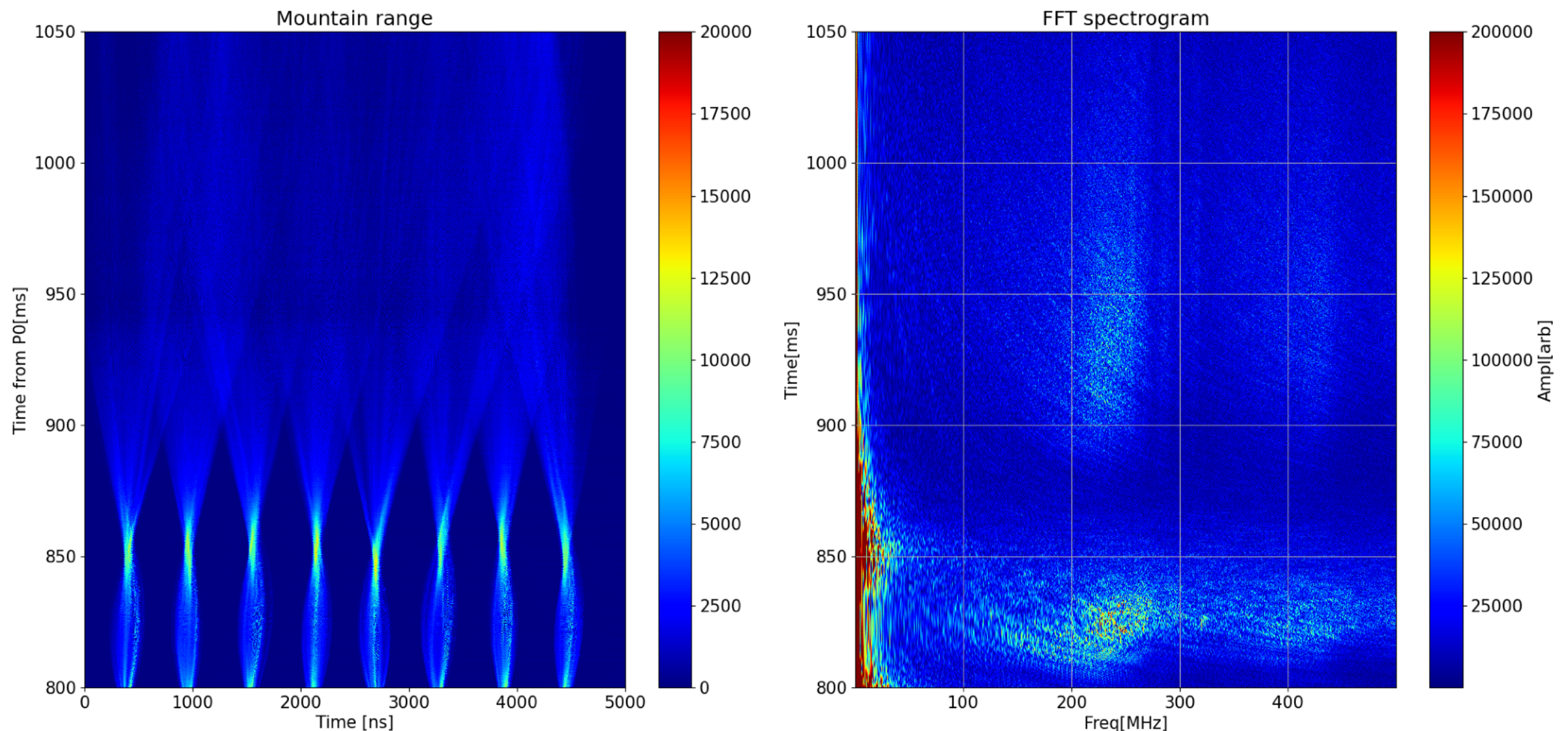
- The new digitizer is installed in the J-PARC MR and has been operating since November 2024.
- Successfully recorded the waveform of beam signal for the whole accelerating period (790ms) with 1GSa/s.
- Just started the operation by recording single-shot data by the script.
 - Automatic data acquisition for continuous beam operation is under preparation.



FFT analysis

- With an oscilloscope, the waveform of only one bunch can be recorded with 1GSa/s, and can be analyzed by FFT. Dynamic range: 8-bit.
- A new digitizer with a large memory can achieve FFT analysis with eight bunches for the whole acceleration period.
- Better sensitivity can be achieved thanks to the wider dynamic range(14-bit).

Spectrum during debunching process (recorded by ADQ14)



Future Prospect

- Automatic data acquisition via EPICS.
- Peer-to-peer data transfer to the GPU.
 - ADQ14 supports direct memory transfer to the GPU.
 - Faster analysis can be done by a GPU
 - Online analysis, such as FFT and Tomography reconstruction.
 - Input for the Machine Learning.
- GPU in the MTCA system???

GPU on AMC?

- If we can have GPU modules in the MTCA system, it will give higher computing performance....but.
- No AMC module with a GPU is currently available.
 - Is it due to the available power per AMC? (80W)
- Two possibilities.
 - Installing a GPU on the AMC carrier, such as Vadatech AMC104.
 - Some GPU cards can operate within 80W limit.
 - NVIDIA RTX A1000 (50W), L4(72W)
 - No confirmation for peer-to-peer transfer...
 - Connect the PCI-Express bus of the MTCA backplane to the external PC with a high-performance GPU.

Vadatech AMC104



Summary

- Waveforms recorded by oscilloscopes or digitizers are essential for monitoring the longitudinal property of the beam.
- A high-speed digitizer with a large memory is required for the J-PARC MR to record the waveform for the whole acceleration period.
- The Teledyne SPD ADQ14 AMC with Vadatech VT816 chassis is chosen as a new digitizer platform.
- After resolving technical issues during the integration process, the new digitizer started operating in the J-PARC MR in November 2024.
- Integration with GPU is under consideration.