Operation status of MTCA.4 based LLRF control system for the J-PARC MR

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Outline

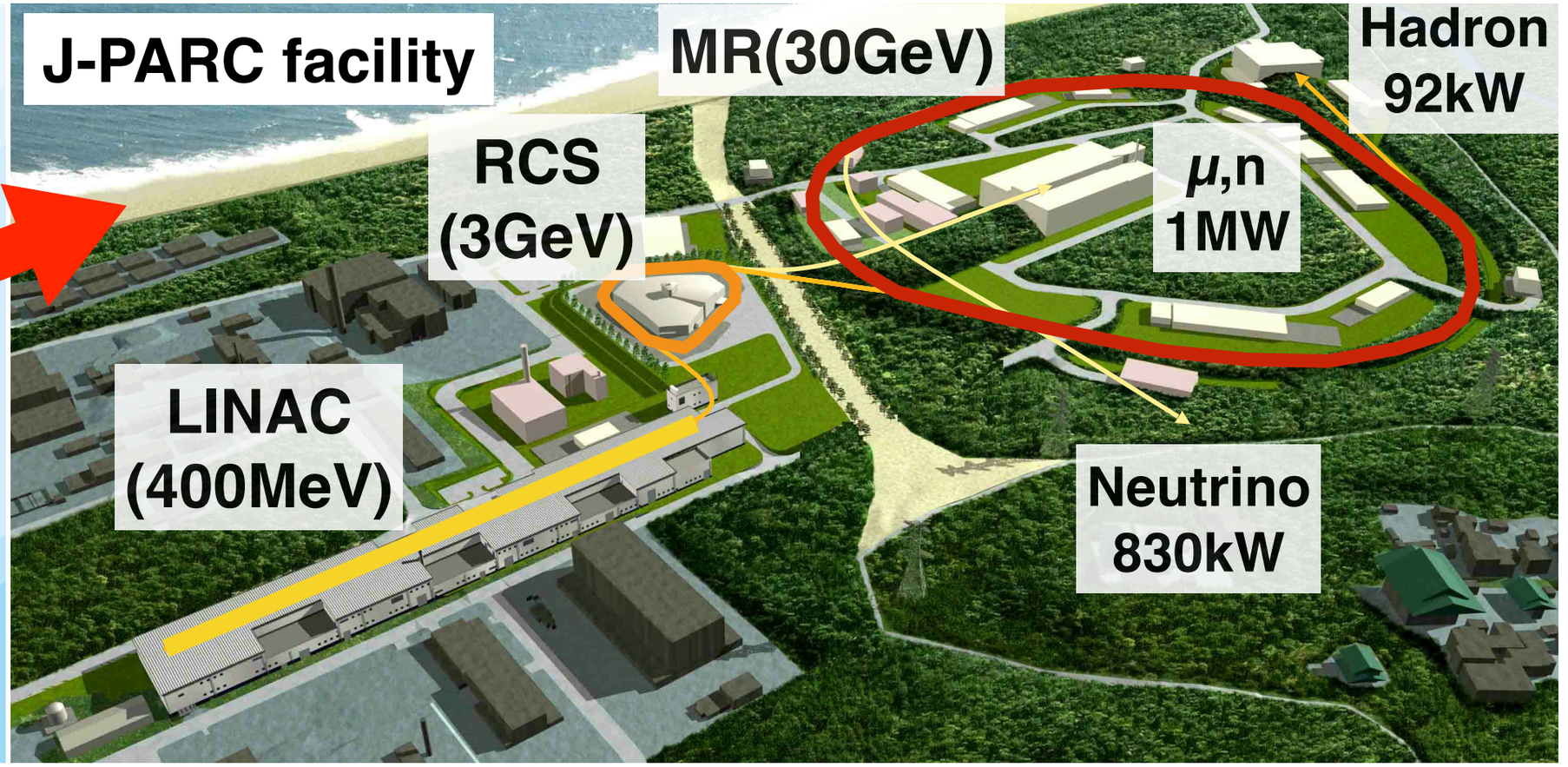
- Introduction of J-PARC and MR RF system
- Requirement for new LLRF system
- MTCA.4-based LLRF control system and its performance
- Technological problem during operation.
- Summary

J-PARC

(Japan Proton Accelerator Research Complex)

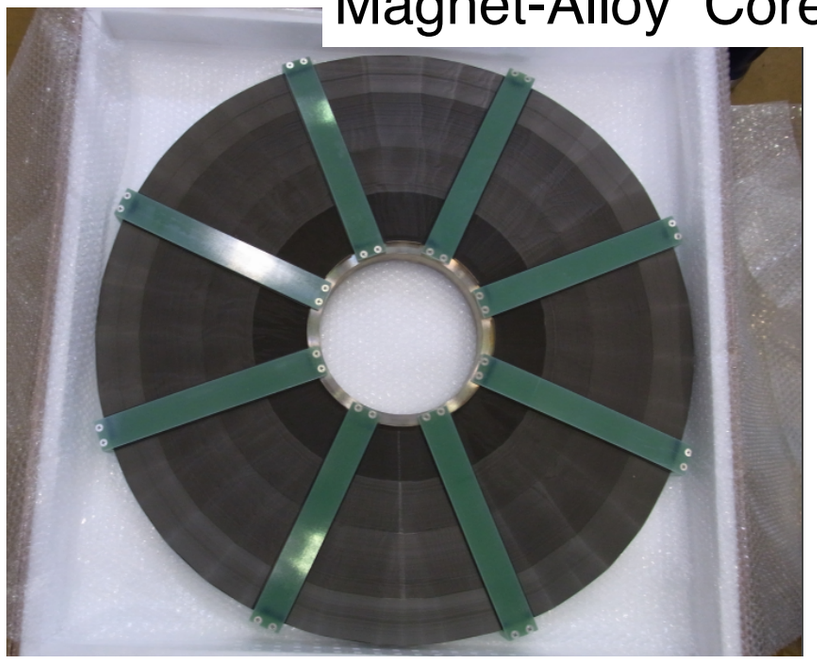
Joint Project between KEK and JAEA

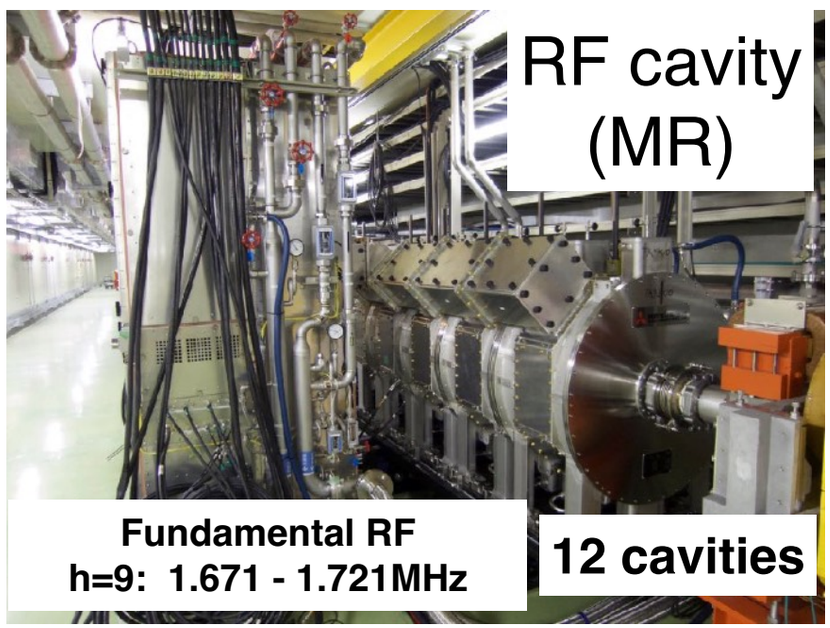
- High intensity Proton Accelerator with a LINAC and two synchrotrons.
- Started the beam commissioning from 2006 and achieved the high intensity proton delivery.
  - **LINAC**: **400MeV** negative hydrogen (**H^-**) with 40mA (25 Hz)
  - Rapid Cycle Synchrotron **(RCS)**: **3 GeV** proton with **1 MW** (25 Hz).
  - Main Synchrotron Ring **(MR)**: **30 GeV** proton with **830 kW** (1.36 s cycle) for ν experiment.



J-PARC MR RF system

- J-PARC MR use the wide-band Magnet-Alloy loaded cavity systems.
  - 12 cavities(10 for fundamental RF, 2 for 2nd RF)
  - Beam loading compensation is necessary to achieve high-intensity operation.
- Required Function for Low-level RF (LLRF) control system.
  - **RF common function:**
    - Frequency pattern, Freq. &Phase FB
      - Vector Sum of Cavity Voltage
  - **Cavity Voltage Driver**
    - I/Q pattern generation and FB for Cavity
    - Beam loading compensation



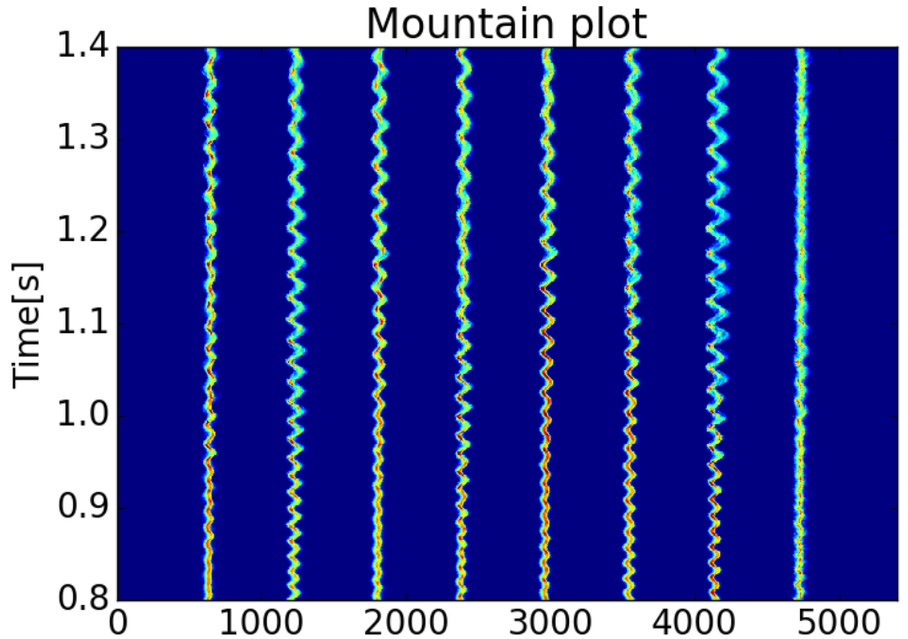


Original LLRF control system for the J-PARC MR

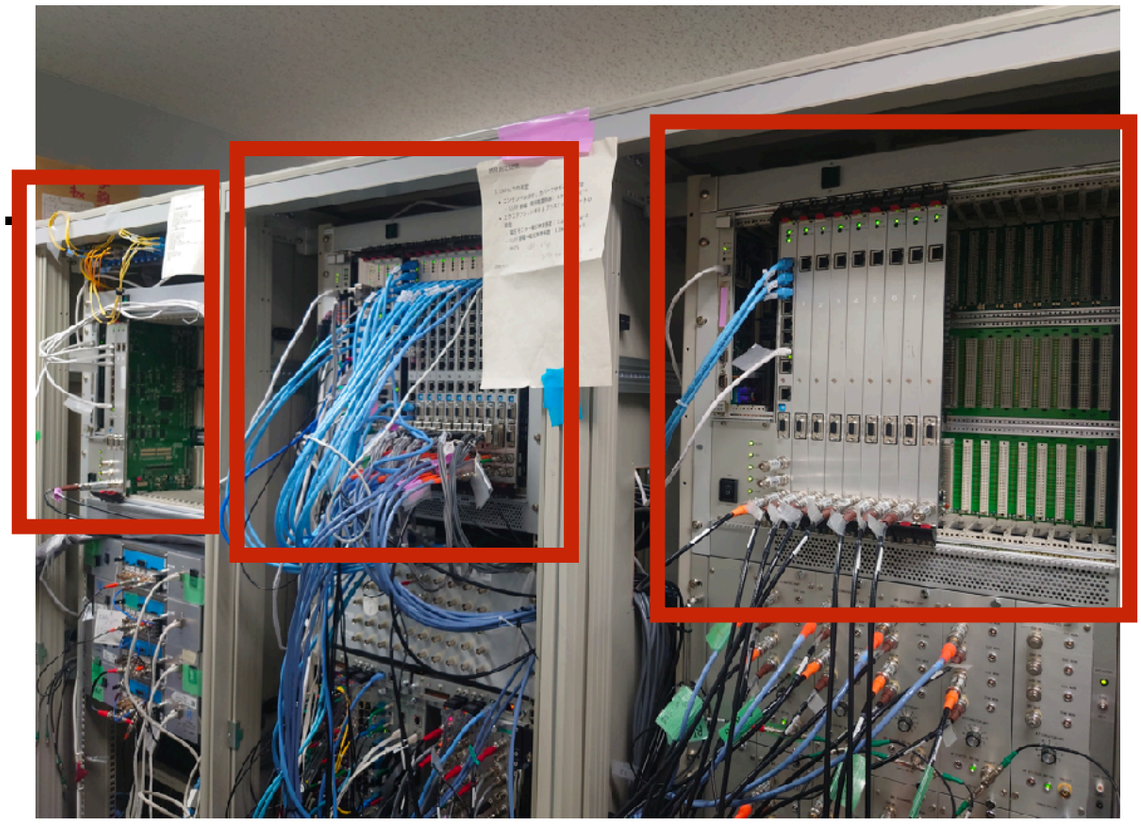
- The original LLRF control system uses the RF FeedForward method for the beam loading compensation.
  - Not perfect enough at the beam power of 500kW (MR), and Coupled Bunch(CB) oscillation was observed.

=> Multi-harmonic vector RF voltage Feedback for the beam loading compensation.

Beam Longitudinal CB oscillation at MR



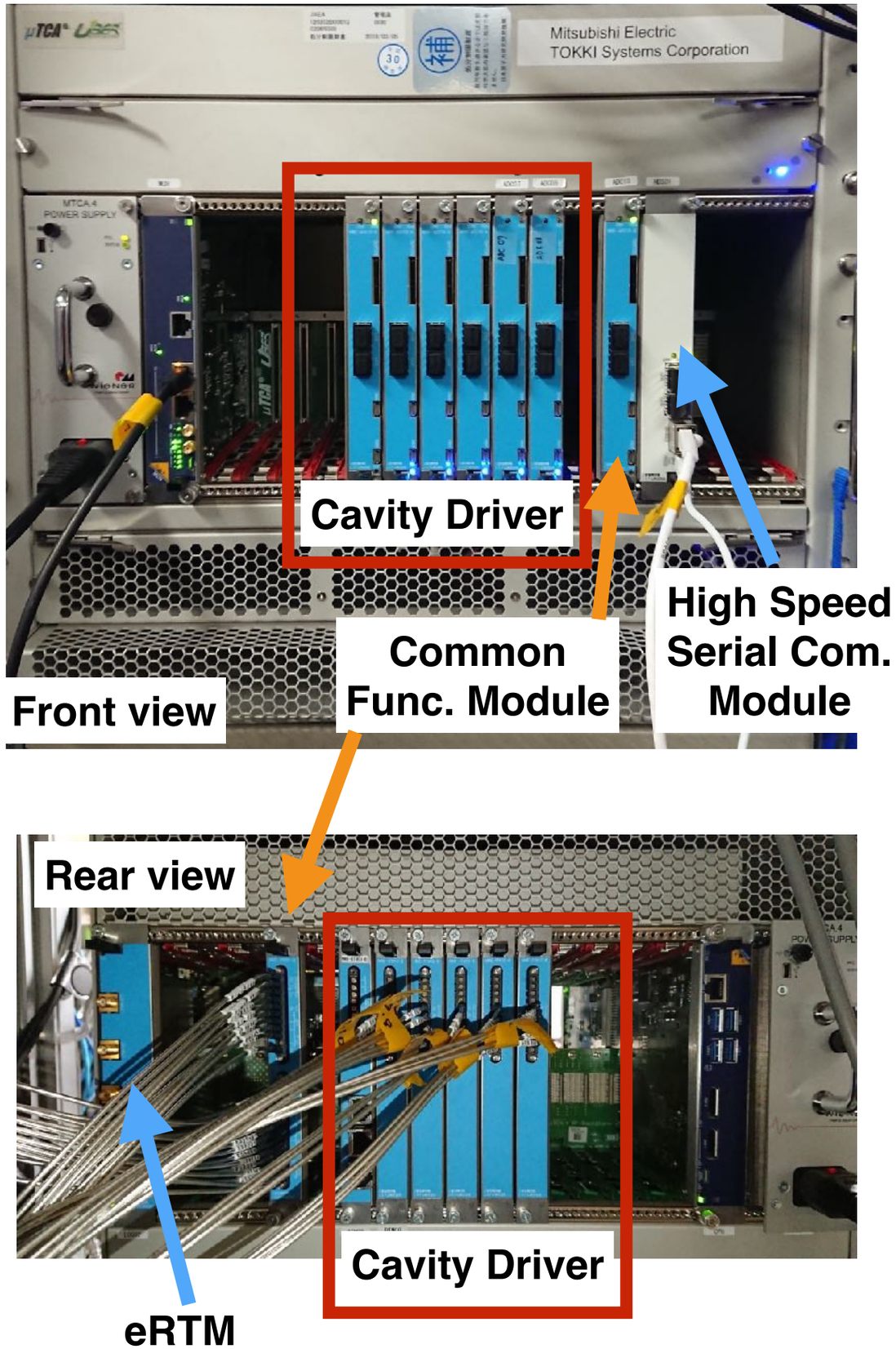
- Original system based on VME
  - Use several racks connected with many cables for data communication.
  - Modules with more than 10years old =Difficulty in maintenance
  - Need more functionalities for higher intensities and stability.



=> MTCA.4 as next platform!

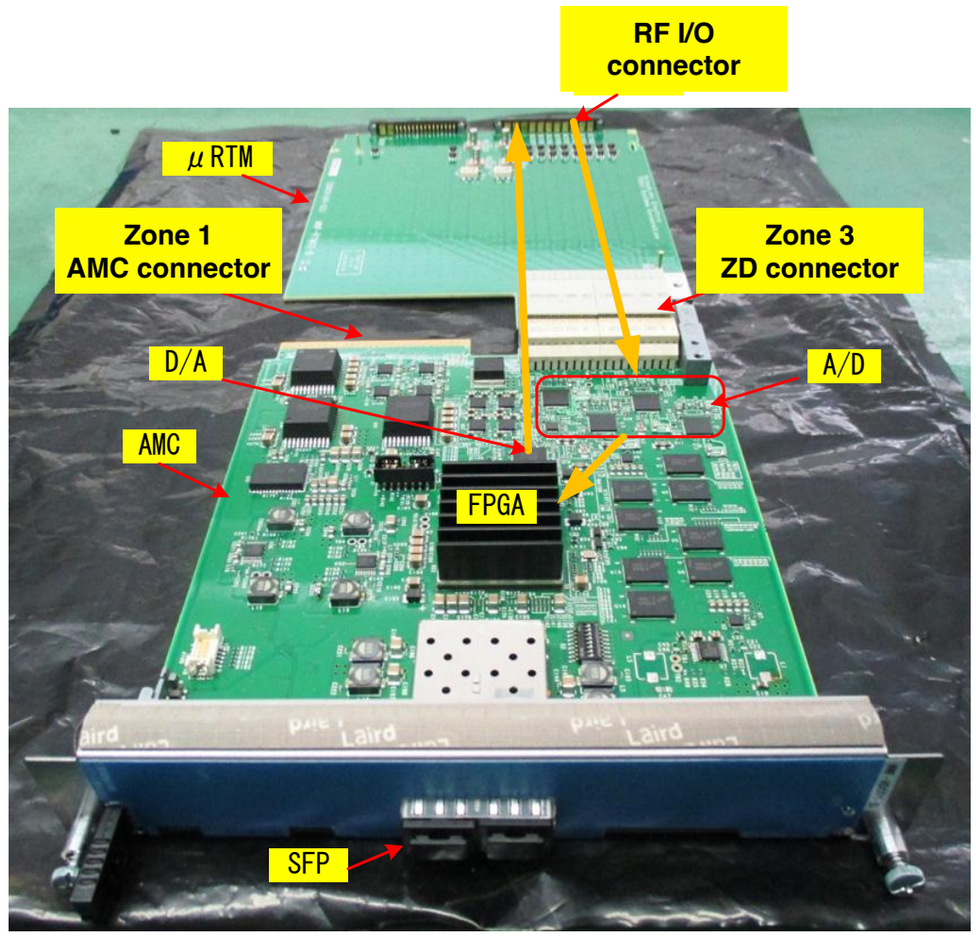
New LLRF control system Configuration

- MTCA.4 shelf with DESY RF backplane
  - AMC/RTM for each function
    - **Common Function module** for Freq. management and beam FB.
    - **Cavity Driver module** for cavity gap voltage FB control.
    - **eRTM** for system clock generation and distribution via RF backplane
- Special MCH:
  High Speed Serial Communication module (HDS)



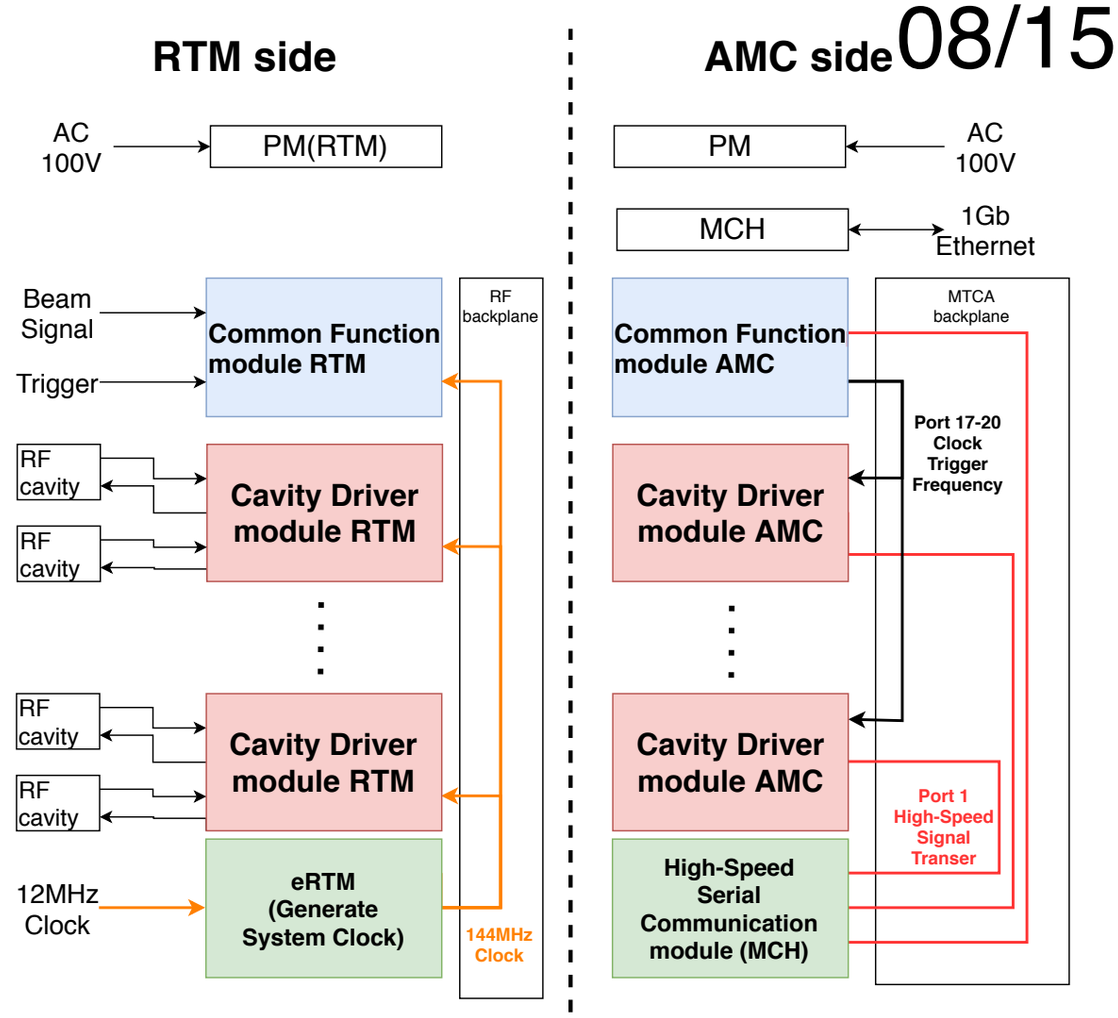
Hardware: AMC/RTM

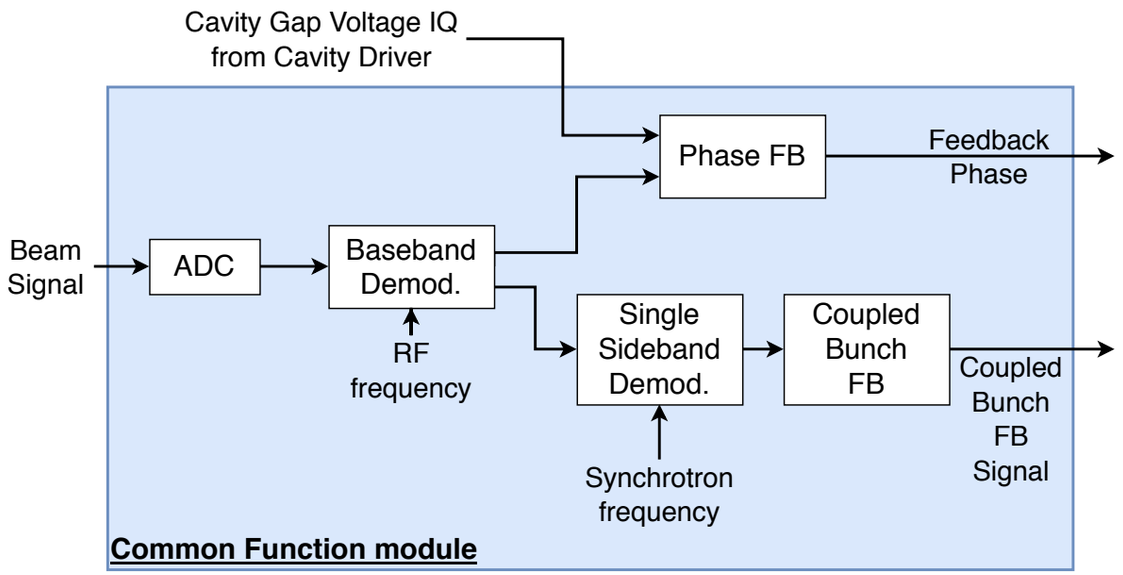
- Developed by MEDS Co., Ltd.
- AMC:
  - 8 ch. ADC and 2ch. DAC.
  - EPICS-IOC running on embedded Linux on Zynq.
  - Clock, trigger distribution and high speed serial communication via MTCA backplane (Zone1).
- RTM:
  - Used for signal transition from/to the RF cavities and the other accelerator control systems.
  - Different design for Common Function module and Cavity Driver module.



LLRF control system functionalities

- Single MTCA.4 shelf for one synchrotron.
- System Clock (144MHz) from eRTM is distributed via RF backplane.
- Common Function Module
  - Frequency pattern management, Trigger/Clock distribution via MTCA backplane
  - Beam Feedback
    - Baseband demodulation for Phase FB, Sideband demodulation for Coupled Bunch FB for MR.





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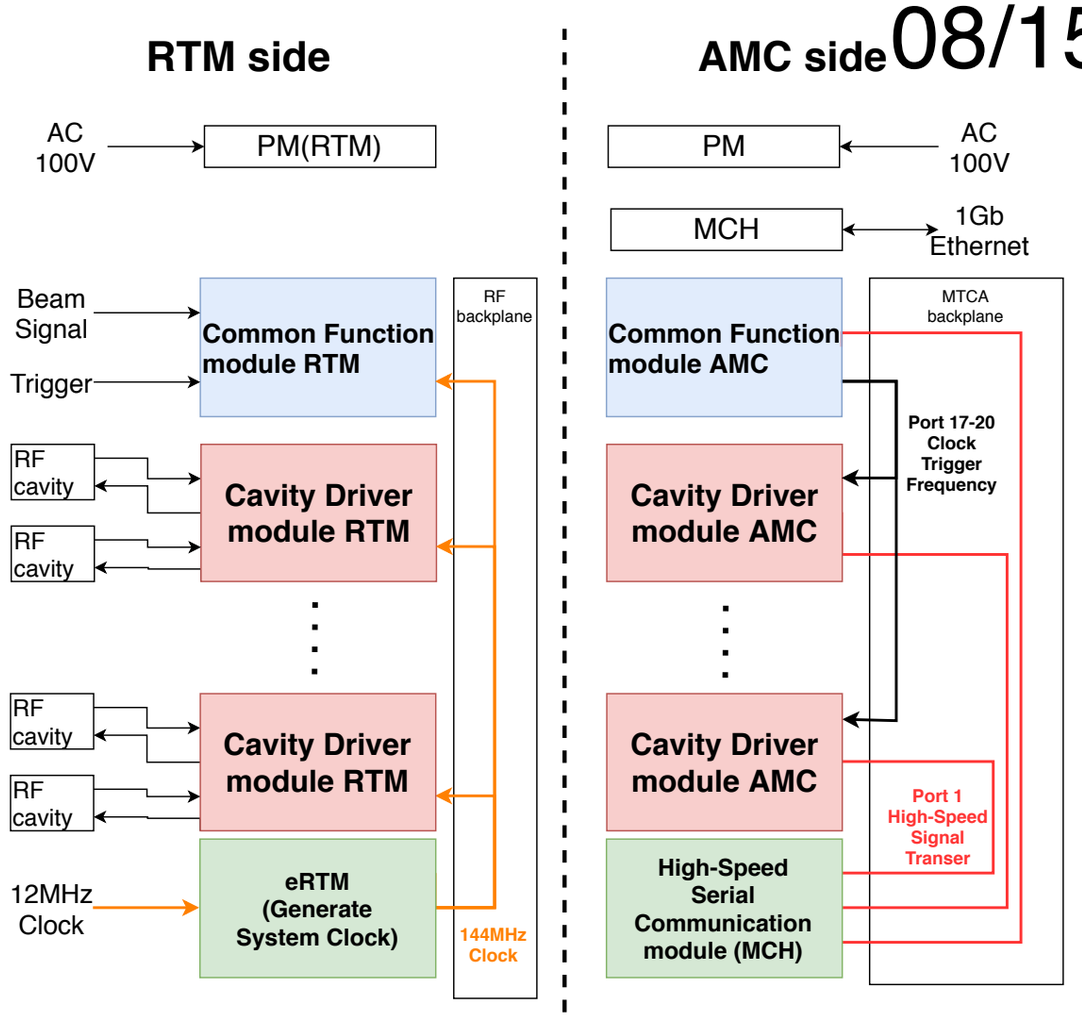
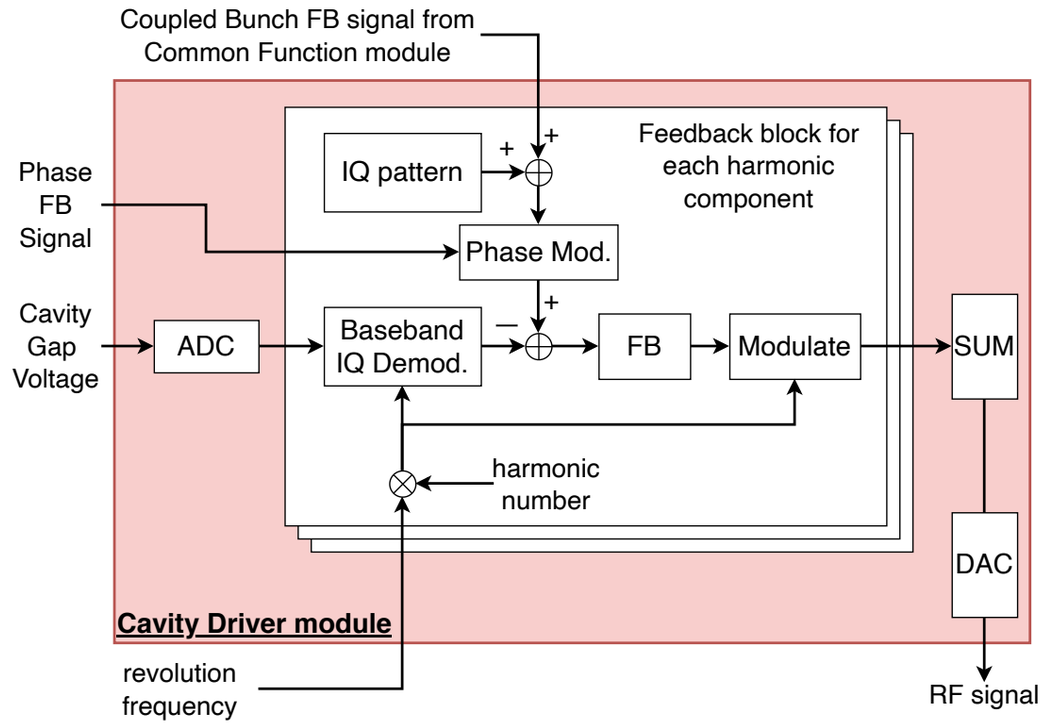
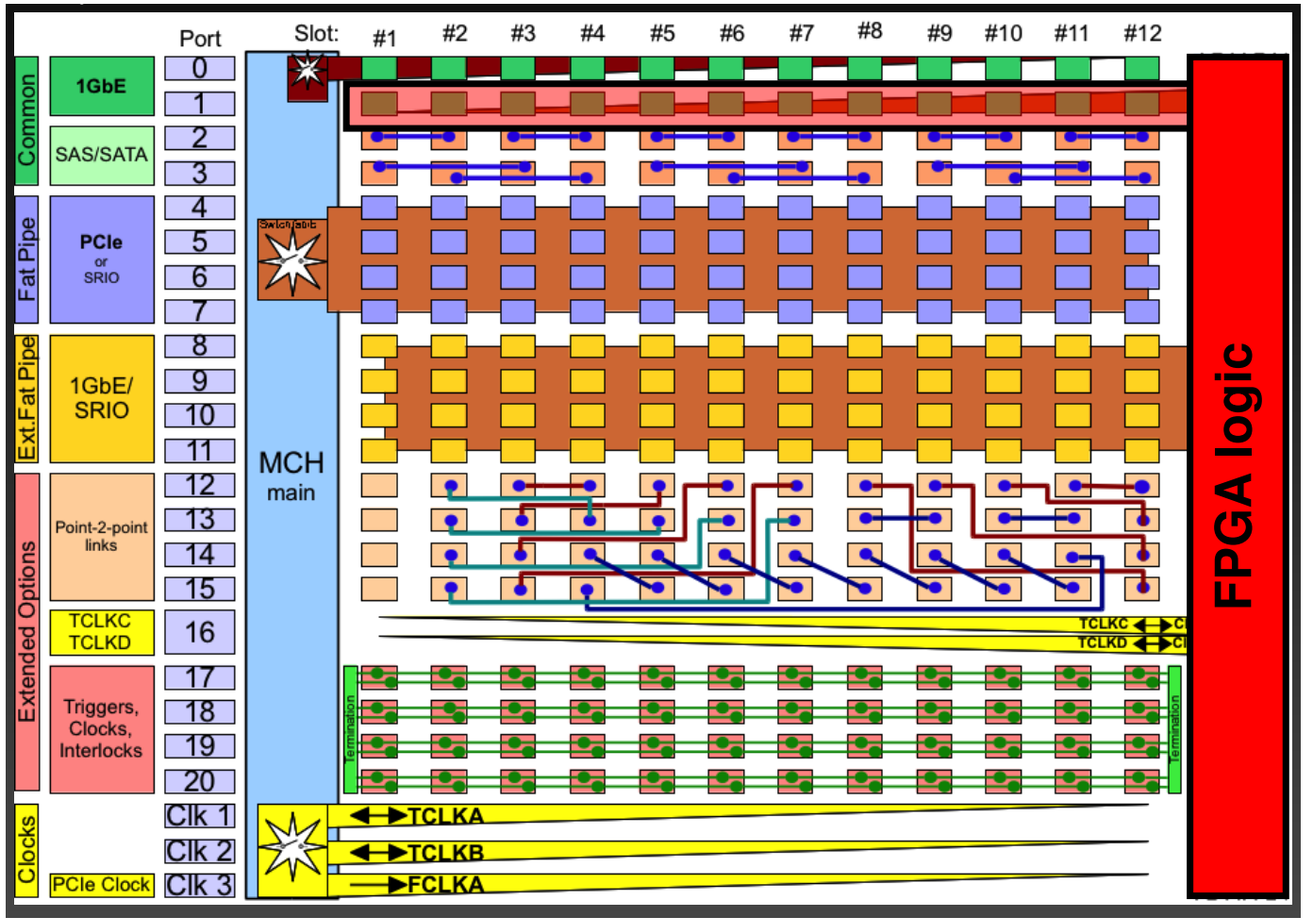
  - Beam Feedback
    - Baseband demodulation for Phase FB, Sideband demodulation for Coupled Bunch FB for MR.
- Cavity Driver Module
  - 1 AMC/RTM for 2 cavities
    - Total 5~6 modules for 9(MR) or 12(RCS) cavities.
  - Multi-harmonic Vector IQ FB for cavity voltage.
  - Coupled-Bunch Feedback signal as a set point of the voltage feedback(MR).

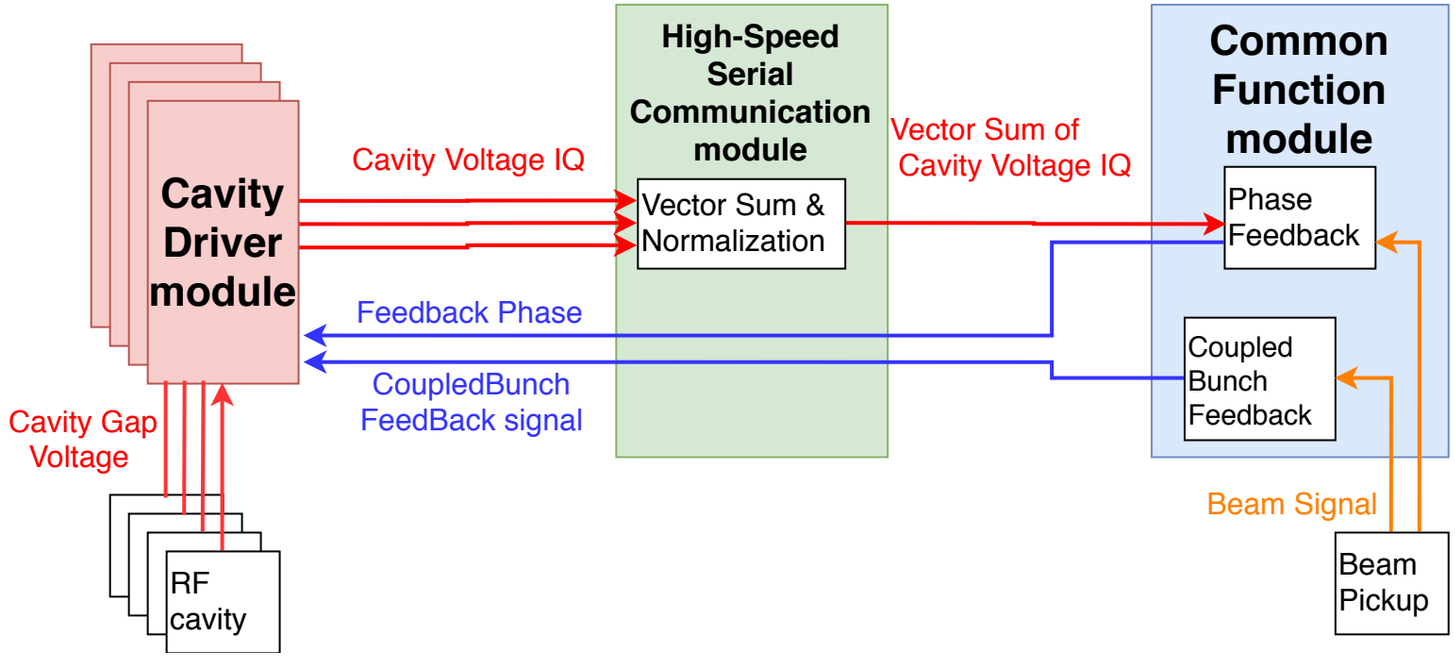




High-speed Serial communication via MTCA backplane

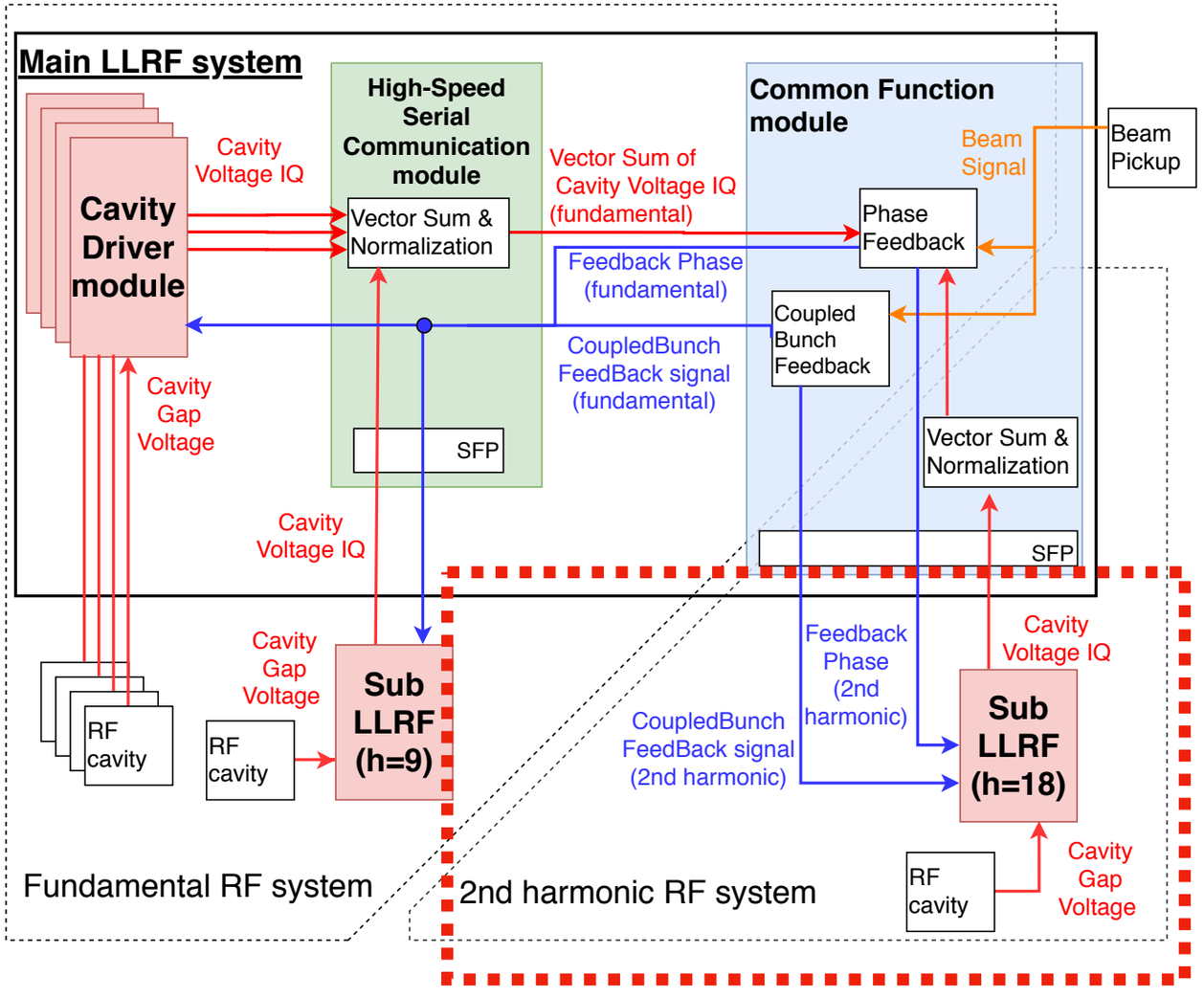
- Use **Port1** in MTCA backplane as a high-speed serial communication path.
  - Xilinx Aurora is used as data format.
- Special MCH2 “High speed Serial communication module (HDS)” as a data accumulator and distributer.
- Cavity Driver module → HDS →Common Function module
  - Cavity Voltage IQ signals are summed and normalized at HDS.
- Common Function module→HDS →Cavity Driver
  - Phase FB signal
  - CB feedback signal for MR (sidebands of beam signal)





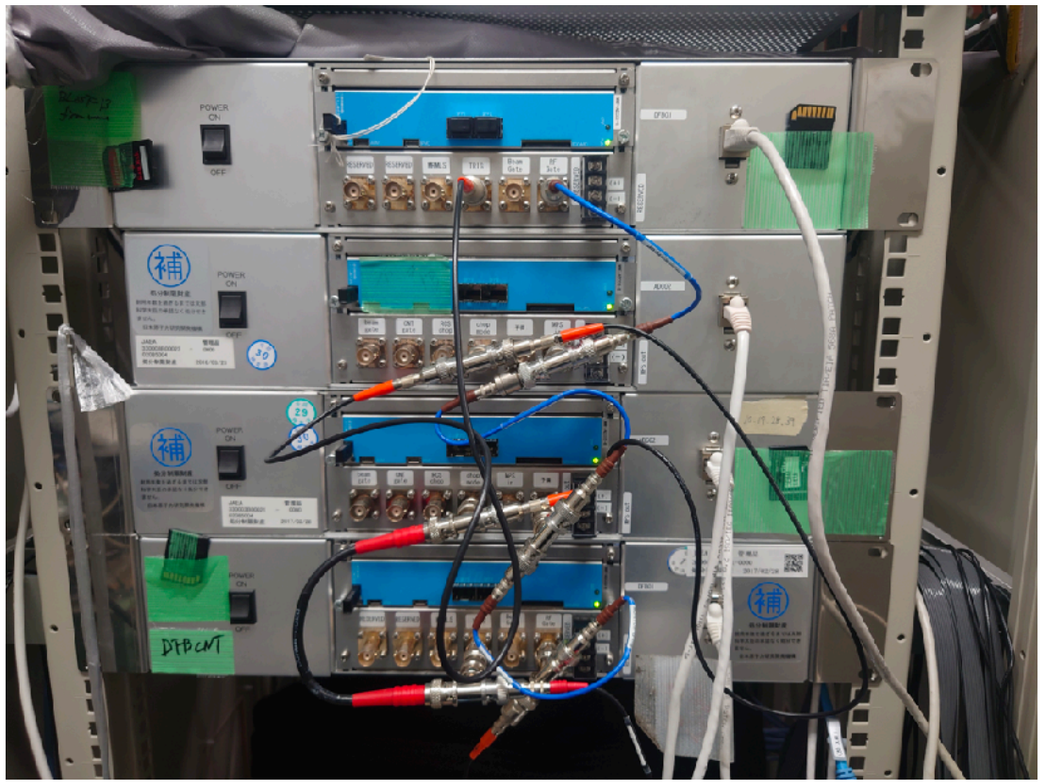
Sub LLRF system for 2nd Harmonic Cavities.

- 2nd RF cavities locate in different RF station. -> Need separate LLRF system.
- 2U BOX with a pair of the cavity driver module (AMC/RTM) for 2ndRF cavities.
  - Self Management of Clock/Trigger/Frequency.
  - For beam FB information,
    use SFP ports on AMC as high-speed serial communication port.

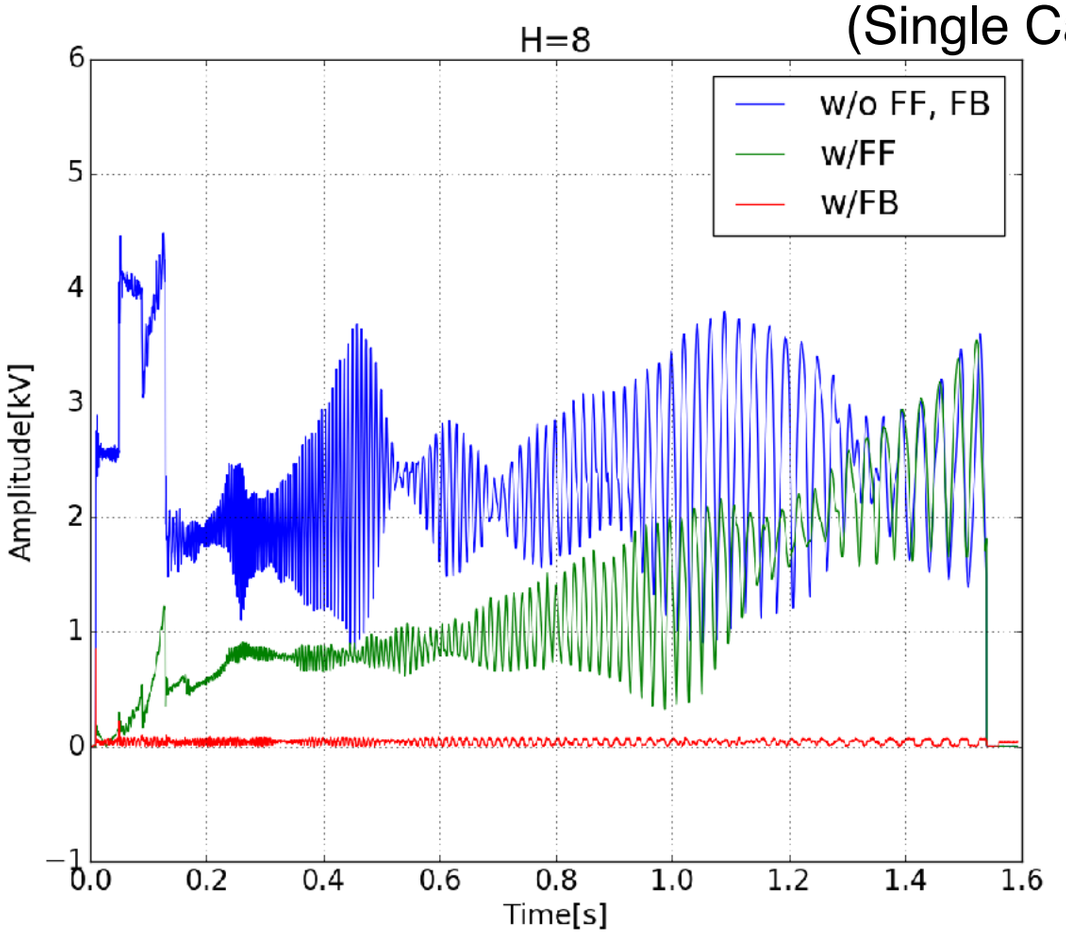


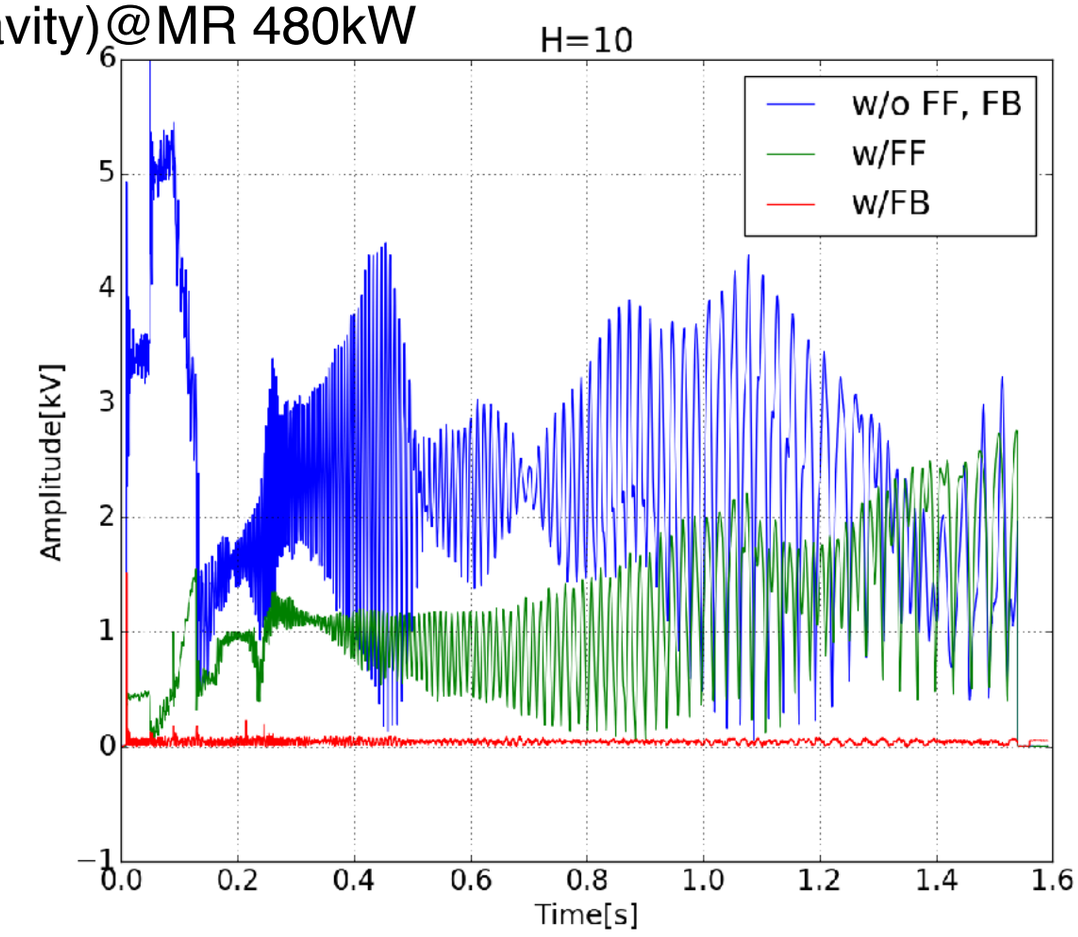
Performance Evaluation with prototype module at MR.

- Before the development of new LLRF system for MR, prototype system is installed in 2019.
- The performance of the beam loading compensation was evaluated with single cavity.
  - Cavity Voltage FB system suppressed wake voltage for h=8,10 down to less than 0.1kV



Detected Cavity Voltage (Single Cavity)@MR 480kW



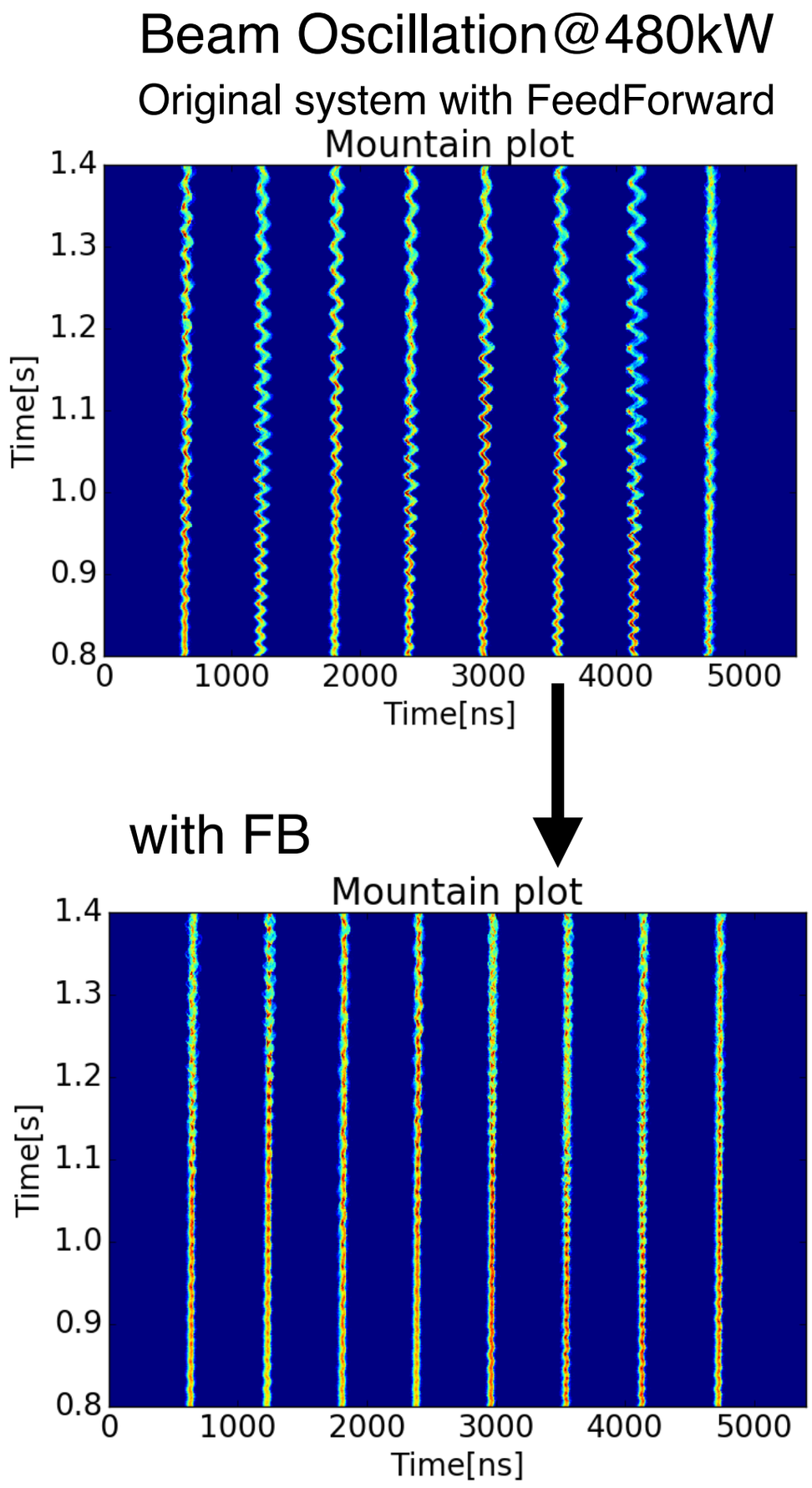


Effect of wake voltage suppression on the CB oscillation at MR

- Enabled cavity voltage FB control for h=8, 10 in all cavities with the prototype system.
  - h=9 component was controlled by original LLRF system.
- No significant beam oscillation with FB thanks to powerful beam loading compensation for h=8,10.

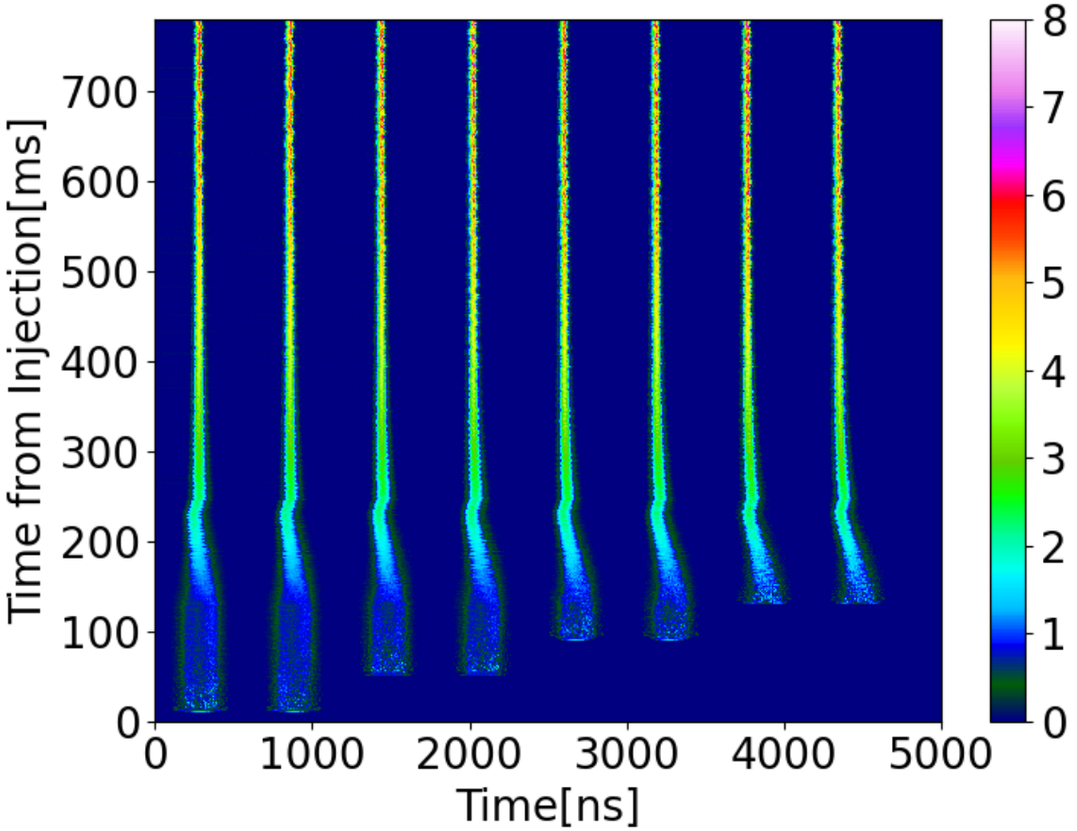
- Used for the user operation since 2020.
  - achieved the user operation with 515kW at Apr. 2021.

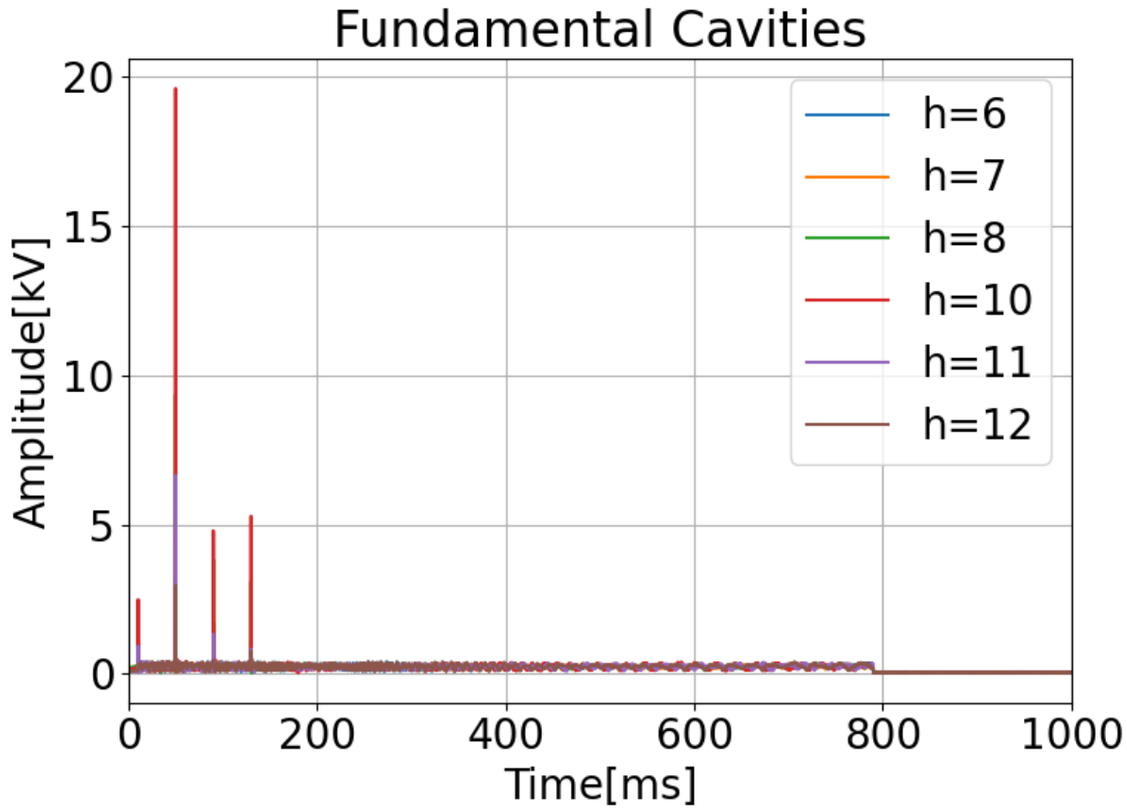
- New LLRF control system for MR is installed to MR in JFY2021 during the 1-year long shutdown for the MR high-power upgrade.



High power upgrade with new LLRF system

- The operation cycle of the J-PARC MR was shortened to 1.36 s from 2.48s to achieve higher beam power since 2022.
  - To achieve stable beam acceleration with a faster cycle,
    FB control for the cavity voltage is enabled for h=6~12 (fund. RF) and h=15~21 (2ndRF).
- In May 2025, the proton beam was delivered to the experiment
  with an intensity of 2.35×10^{14} ppp = 830 kW without longitudinal instability.
  - Wake voltage was well suppressed by the LLRF system.
  - No strong CB oscillation seen even in the case of power with 950 kW during beam study.





Technical problem during the operation…

- Overheat of the AMC in the small crate.
  - Racks for the LLRF for the 2nd RF are located in the Power Supply room.
    - Too hot in the summer season.
  - The FPGA clock becomes unstable, and the FPGA losses sync with the ADC at the end.
    - Temporarily fixed by open the roof of the 2U MTCA crate and putting the powerful fan on the top to cool the chips.
- The EPICS process suddenly dies while the FPGA logics keep working.
  (2~3 times/year)
    - Need to restart the EPICS process and reconfigure the LLRF parameters.
- MTCA Power supply failure.. (Only once)

Conclusion

- MTCA. 4-based LLRF systems have been developed for J-PARC MR.
  - The multi-harmonic vector RF voltage control function is implemented in AMC to control the cavity RF voltage.
- A prototype of the new LLRF system for the MR was installed in 2019 and has contributed to the stable 500kW operation since 2020.
- A new LLRF system for the MR was installed in JFY2021.
- The new system has been in operation since 2022 and contributes to the stable 830kW beam operation after the high-power upgrade of the J-PARC MR.