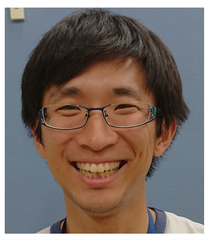

MTCA.4 based LLRF control system for the J-PARC MR

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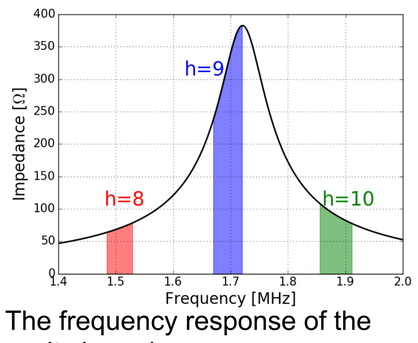
J-PARC MR High Power Upgrade toward 1.3MW

- Main Ring (MR) accelerates protons from 3 GeV to 30 GeV.
  - MR delivers 2.66 × 10^{14} ppp (515 kW) as of April 2021.
- RF system uses MA-loaded cavity with Q=22 →**Beam loading**

Table 1: Operation parameters of the J-PARC MR and the RF system for the fast extraction

energy	3–30 GeV
repetition period	2.48 s
accelerating period	1.4 s
accelerating frequency f_{RF}	1.67–1.72 MHz
revolution frequency f_{rev}	185–191 kHz
harmonic number h_{RF}	9
number of bunches N_b	8
maximum rf voltage	300 kV
fundamental harmonic cavities	9
second harmonic cavities	2
Q-value of rf cavity	22



The frequency response of the cavity impedance.

MR High Power upgrade scenario

- 750 kW upgrade: Faster MR cycle to achieve higher power with smaller # of protons.
- 1.3 MW upgrade: Faster MR cycle and more protons to achieve 1.3 MW

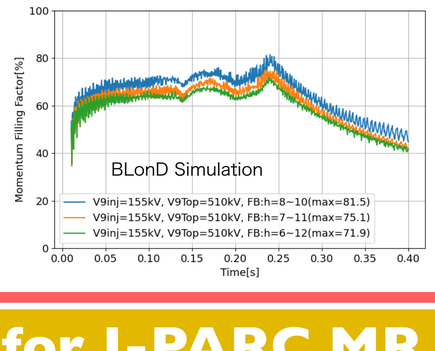
	MR Cycle	Acceleration Time	#of protons	Beam Power	Peak RF	#Cavity for h=9
~2021	2.48s	1.40s	2.6x10^{14} ppp	500kW	310kV	7
750kW upgrade	1.36s	0.65s	2.1x10^{14} ppp	750kW	510kV	9
1.3MW upgrade	1.16s	0.58s	3.3x10^{14} ppp	1.3MW	600kV	11

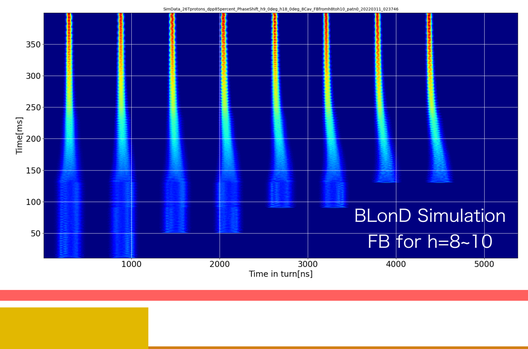
Required Upgrade to the RF system

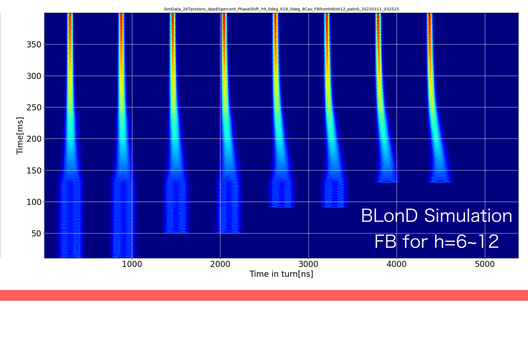
- Faster MR cycle
  - Requires higher RF voltage to accommodate faster ramping rate. →More RF cavity.
- More protons -> More beam loading
  - Requires beam loading compensation for many harmonics to suppress the Coupled Bunch Oscillation. → **New LLRF control system.**

Requirement for the beam loading compensation

- In addition to h=8~10, the cavity impedance of h=6,7,11,12 can be source of coupled bunch oscillation.
- Compensation of beam loading for h=6~12 is a key to achieve keep smaller momentum filling factor with smaller RF voltage during acceleration.

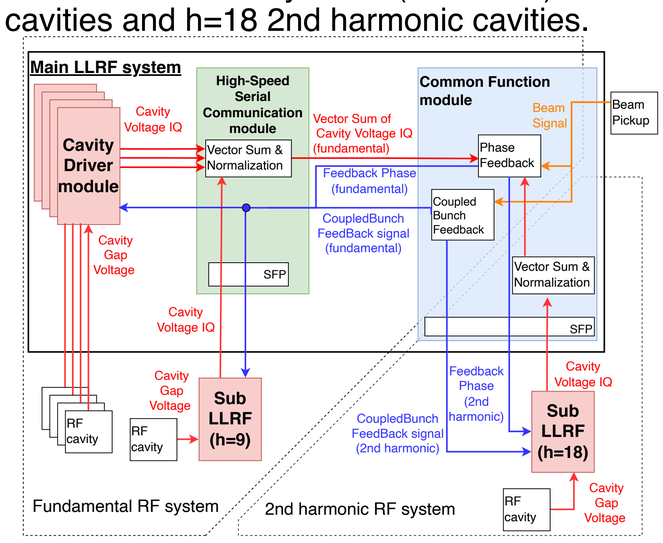




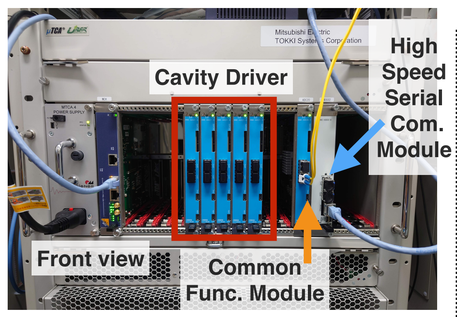


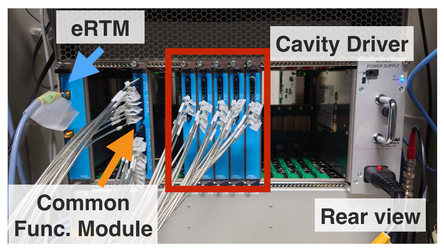
New LLRF control system for J-PARC MR

- Based on MTCA.4 standard
- Two LLRF control systems (Main/Sub) for h=9 Acc. cavities and h=18 2nd harmonic cavities.

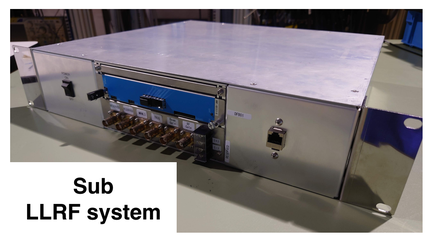


- **Main system:**
  - LLRF control system for h=9 cavities. (9 cavities located at RF station for Acc.)
  - MTCA.4 shelf with DESY RF backplane
  - AMC/RTM for each function
    - **Common Function module** for Freq. management and beam FB.
    - **Cavity Driver module** for cavity gap voltage FB control.
  - eRTM for system clock generation and distribution via RF backplane
  - Special MCH:High Speed Serial Communication module





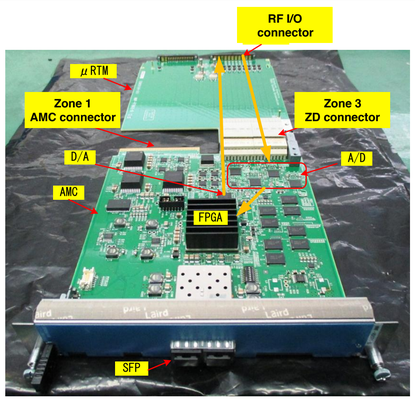
- **Sub system:**
  - LLRF control system for h=18 cavities (2 cavities at RF station)
  - 2U MTCA.4 shelf.
  - Cavity Driver module with clock/ trigger/Freq. management function.
  - Communication with main system via optical fiber.



Sub LLRF system

Hardware

- Developed by MEDS(Mitsubishi).
- **AMC** with 8ch. ADC, 2ch DAC and Zynq FPGA.
  - EPICS-IOC running on the embedded LINUX in Zynq CPU
- **RTM:** customized for each function



Common Function Module

- Frequency pattern management, Trigger/Clock distribution via MTCA backplane
- Beam Feedback
  - Baseband demodulation for Phase FB
  - Sideband demodulation for Coupled Bunch Monitoring/FB.

Cavity Driver Module

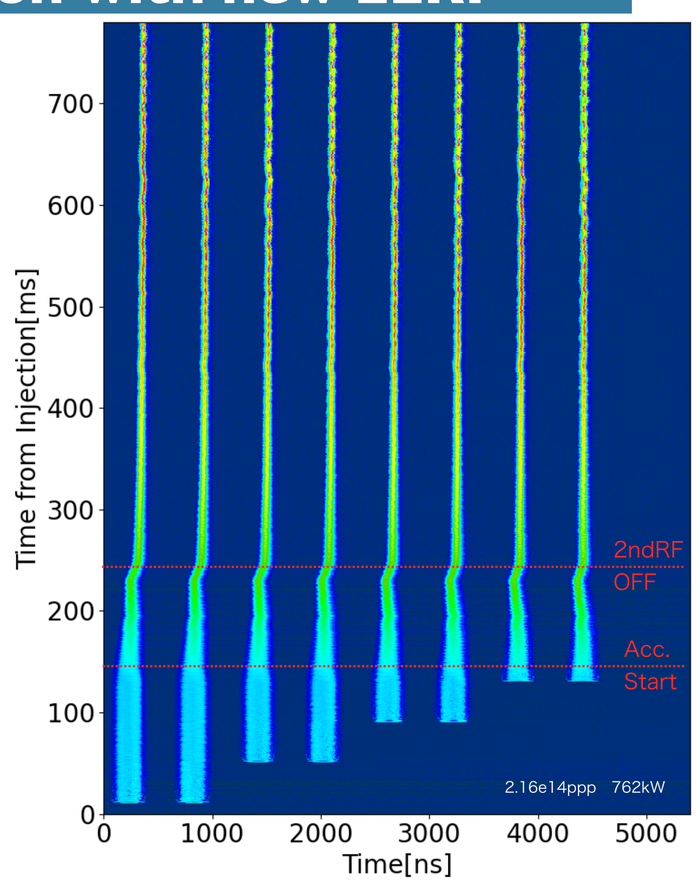
- Multi-harmonic Vector IQ FB for cavity voltage.

Data communication

- Collect Cavity RF voltage IQ data to calculate Vector Sum of Cavity Voltage
- Distribute Beam FB signal via MTCA backplane at main system.
- Send/Receive 2nd harmonic information via optical fiber.

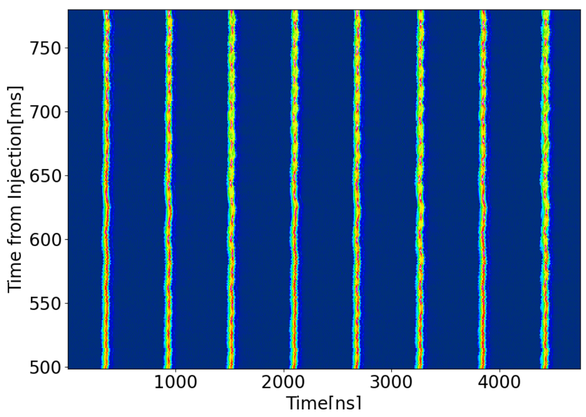
30-GeV Acceleration with new LLRF

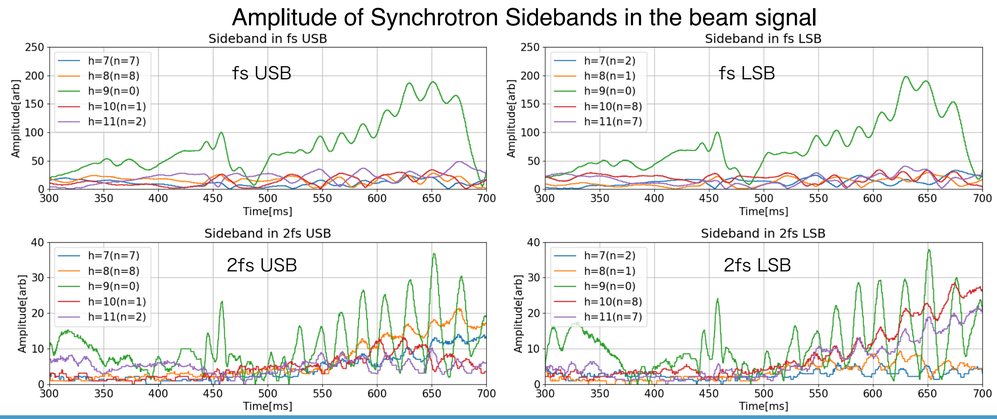
- Full LLRF control system was replaced to new system in 2021
- In April 2023, protons were successfully accelerated to 30GeV with 1.36 s cycle.
  - Peak RF voltage: 450kV(h=9) 110kV(h=18)
  - Beam Phase FB for h=9
  - Voltage FB control for
    - h=6~12 in the cavity for fundamental harmonics.
    - h=15~21 in the cavity for second harmonics.
- 2.16x10^{14} ppp = 760kW beam can be accelerated without longitudinal loss.
- Small dipole oscillation of mode n=0(h=9) remained after beam phase FB.
  - Tuning phase FB is underway.



Coupled Bunch Oscillation

- Small dipole CB oscillation
  - Mainly in h=9 (mode n=0)
  - CB oscillation in the neighbor harmonics is well suppressed.
- Small quadruple CB oscillation was observed during acceleration.
  - 2fs sideband for mode n=7,8 (h=7,8,10,11) can be seen.
    - Remaining cavity wake voltage can be source.





Summary and outlook

- **We developed a new MTCA.4 based LLRF control system for J-PARC MR.**
- **Full LLRF control system was installed and fully replaced the original LLRF system in 2021.**
- **Protons were successfully accelerated to 30GeV with faster operation cycle under new LLRF system in April 2023.**

25 October 2022, LLRF2023, Lahan Select Gyeongju, South Korea

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