Resent Progress in J-PARC LINAC LLRF

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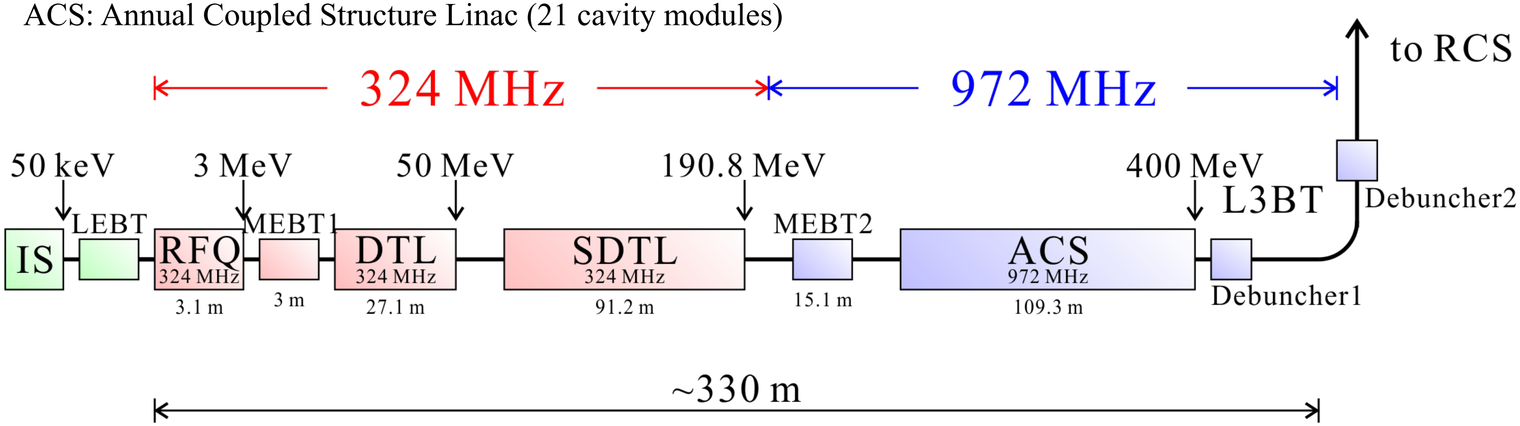
J-PARC LINAC RF Gr.

J-PARC LINAC

- Particles: H^- (negative hydrogen)
- Kinetic Energy: **181 MeV → 400 MeV at 2013**
- Peak Current: **Max 30 mA → 50 mA at 2014**
- Acceleration Frequency: **324 MHz → 324 MHz + 972 MHz at 2013**
- Pulse Width: 500 μs (Beam)[max.], 650 μs (RF)[typical]
- Repetition: 25 Hz (50 Hz)
- Cavity Type normal conducting

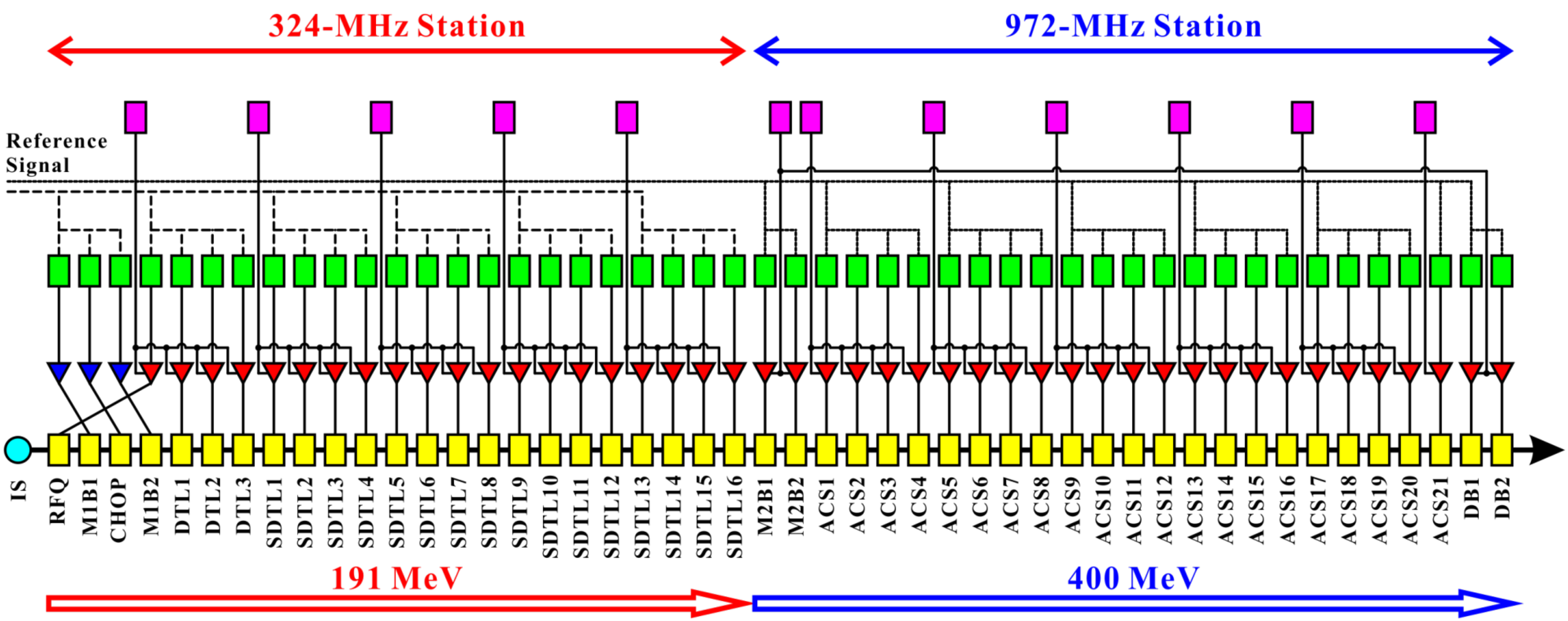
In the low-β section, there are many similarities with the ESS linear accelerator.

IS: H^- Ion Source
RFQ: Radio Frequency Quadrupole Linac
DTL: Drift Tube Linac (3 cavity modules)
SDTL: Separate-type Drift Tube Linac (16 cavity modules)
ACS: Annual Coupled Structure Linac (21 cavity modules)



Required Gradient Stability : ±1% in amplitude, ±1 deg. in phase
→ digital FB & FF : ±0.3% in amplitude, ±0.3 deg. in phase
→ Reference Distribution System : ±0.3 deg. in phase

Overview of RF System



#Components	HVDC PS	LLRF	Klystron	Solid-State Amplifier	Cavity Module
324MHz	5	24	20	4	39
972MHz	7	25	25	0	25

Almost all modules of the 324 MHz system were developed more than fifteen years ago and have been used *since the beginning of the J-PARC linac*. Therefore, it is concerned about increasing the failure rates.

※ One klystron supplies the RF power to two SDTL cavities.
※ One high-voltage power supply drives four klystrons.

cPCI boards (common: 324 MHz and 972 MHz):

- ✓ FPGA board: discontinued
- ✓ DSP board: discontinued
- ✓ CPU board: discontinued, but fungible

Development environment:

- ✓ FPGA: Xilinx ISE Ver 6.2i
- ✓ DSP: TI Code Composer Studio Ver 2.1
- ✓ Host program: Redhat 8.0 gcc compiler Ver 3.2
- ✓ Application: python2.4, wxPython2.6

AD/DA AMC Board & Digitizer Box

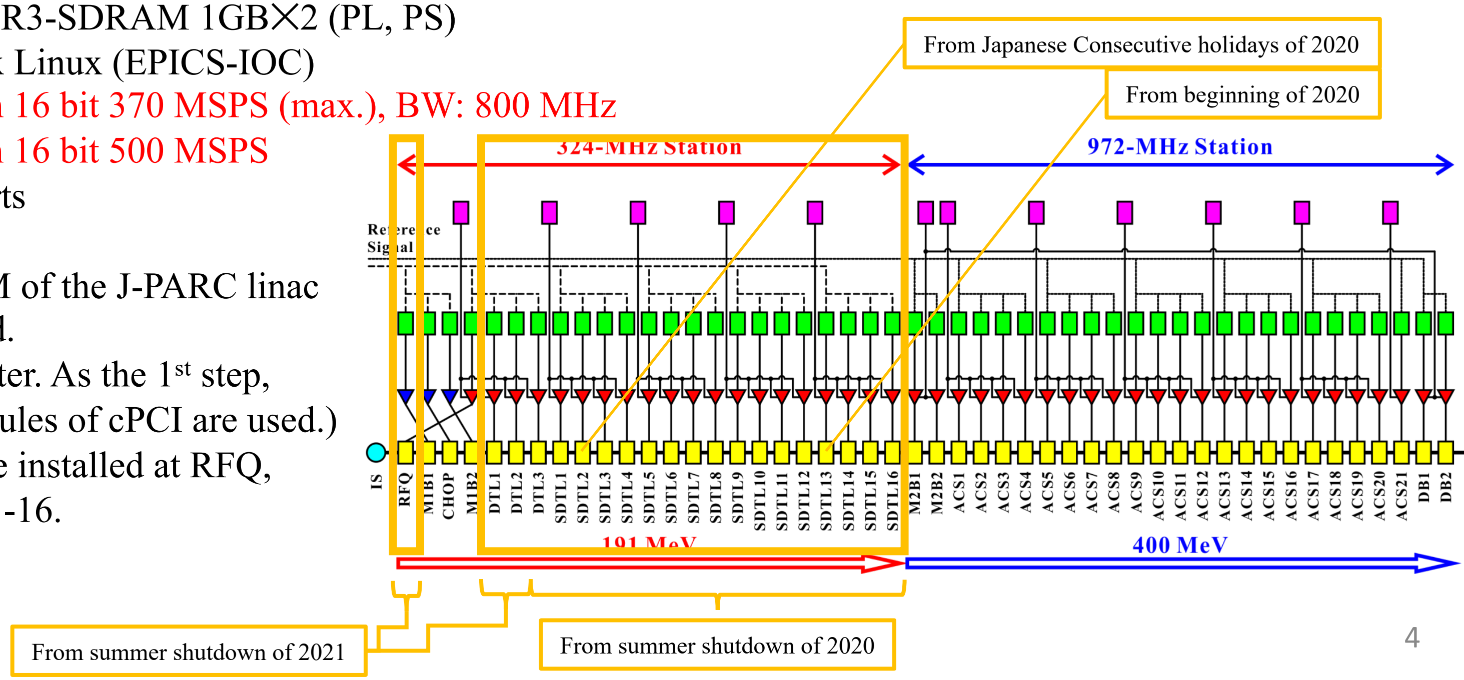
- The AMC board having FPGA, ADC and DAC for DFB and DFF is specialized to use the bus of the μTCA.4 standard.
- On the other hand, the RTM one is temporary. In the 1st stage, the shelf of μTCA.4 with the bus and the RF backplane will not be utilized an ARM on a Zynq FPGA will be used instead of a CPU board.

A/D-D/A signal processing board of AMC produced by Mitsubishi Electric TOKKI Systems Corporation

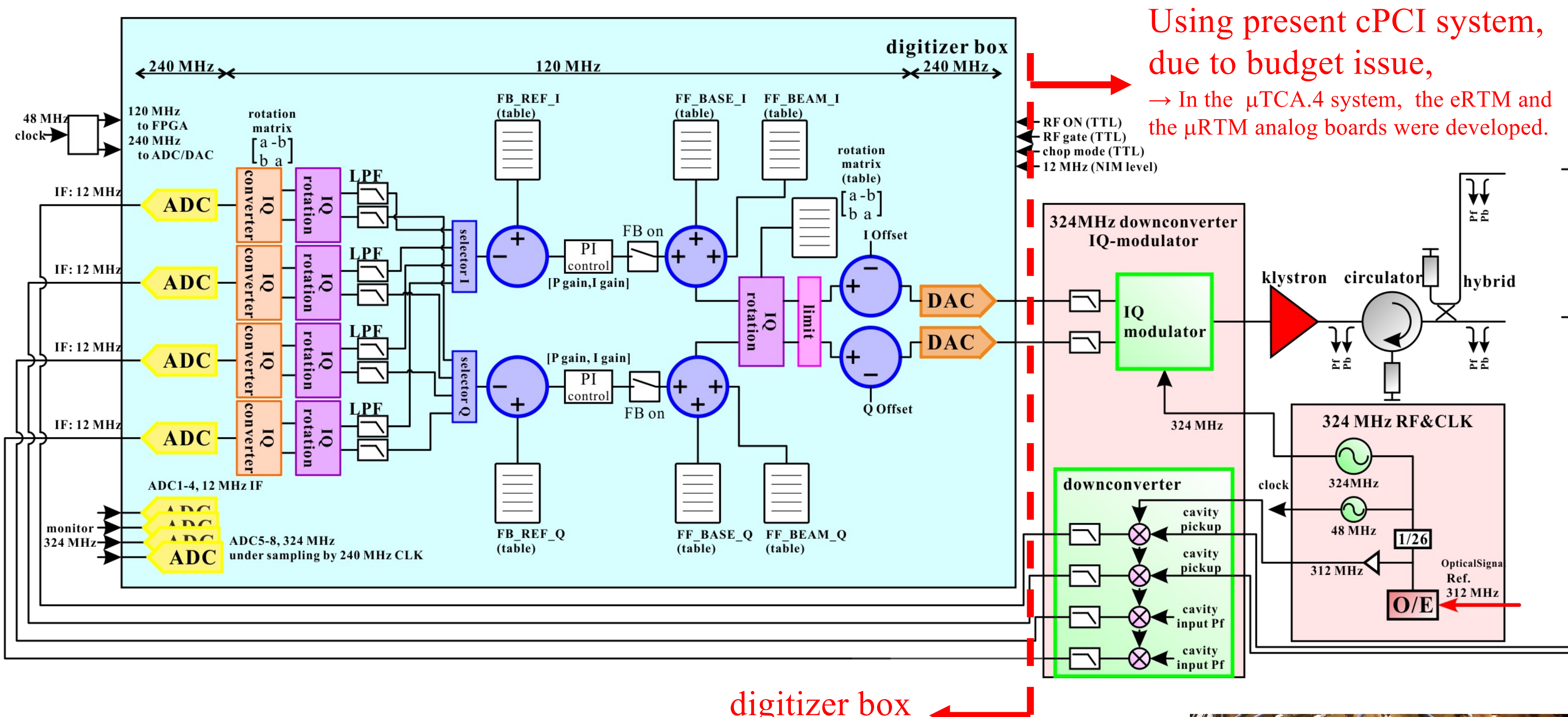
- platform: μTCA.4 AMC
- FPGA: Zynq XC7Z045-1FFG900C, QSPI FLASH-ROM 16MB, SD-card Remote Update
- RAM: DDR3-SDRAM 1GB×2 (PL, PS)
- OS: Xilinx Linux (EPICS-IOC)
- ADC: 8 ch 16 bit 370 MSPS (max.), BW: 800 MHz
- DAC: 2 ch 16 bit 500 MSPS
- SFP: 2 ports

→ The μTCA.4 RTM of the J-PARC linac LLRF is produced.
(Just level converter. As the 1st step, the analogue modules of cPCI are used.)

→ This systems were installed at RFQ, DTL1-3, SDTL01-16.



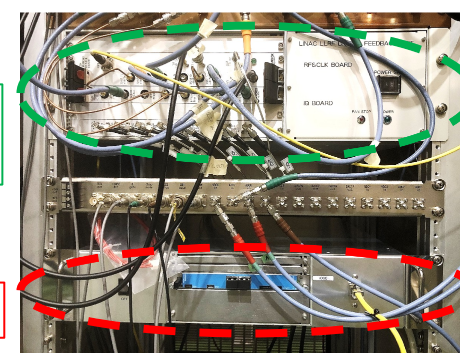
FPGA Block in Digitizer Box



ADC input signal

- ✓ ADC1,2(mixer(IF:12MHz) + IQ sampling(240MHz CLK)): cavity pickup
- ✓ ADC3,4(mixer + IQ sampling): cavity input (Pf)
- ✓ ADC5(direct sampling(240MHz CLK)): 40 W amplifier input
- ✓ ADC6(direct sampling): klystron input (40 W amplifier output)
- ✓ ADC7(direct sampling): klystron output
- ✓ ADC8(direct sampling): neighboring cavity pickup

cPCI analog module
1st step : using the cPCI analog module
2nd step : developing an analog module

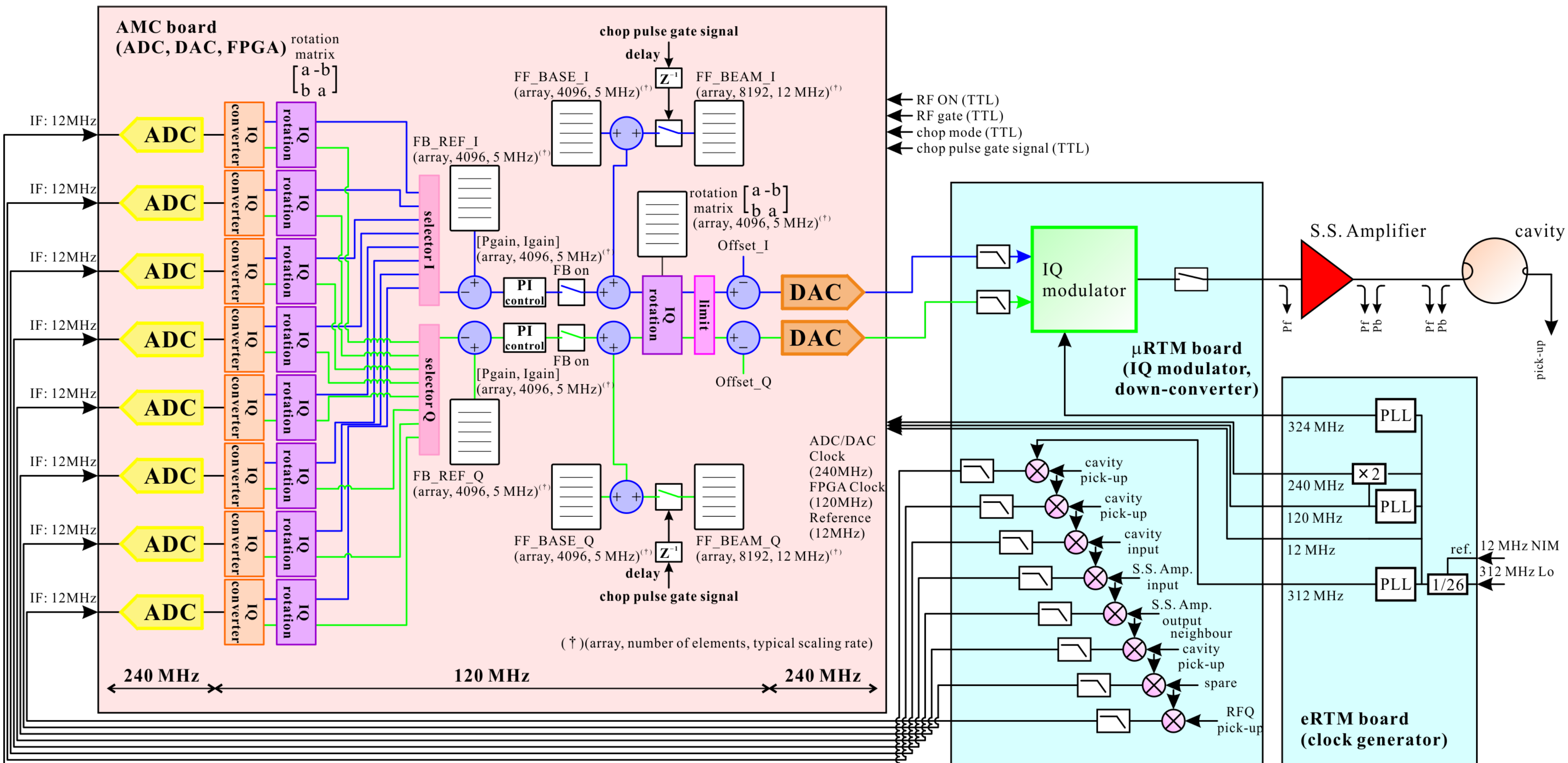


digitizer box

Comparison with cPCI system

- increasing number of elements: 1024 → 4096 (or 8192)
- increasing monitor points: before/after the PI controller, before rotation matrix
- increasing flexibility in table inputs: FB_REF/FF_BASE/PI_GAIN/FF_BEAM/rotation matrix

FPGA Block in μTCA.4 System



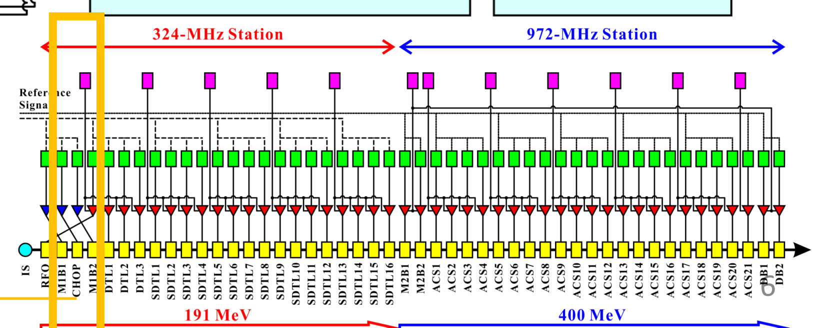
eRTM board : generating 312 MHz (LO), 324 MHz (RF), 12 MHz (reference), 120 MHz (FPGA clock), 240 MHz (ADC clock)

μRTM board : implementing 8 ch down converter, 1 ch IQ modulator

→ 8 ch 12 MHz IF signals input to an AMC board

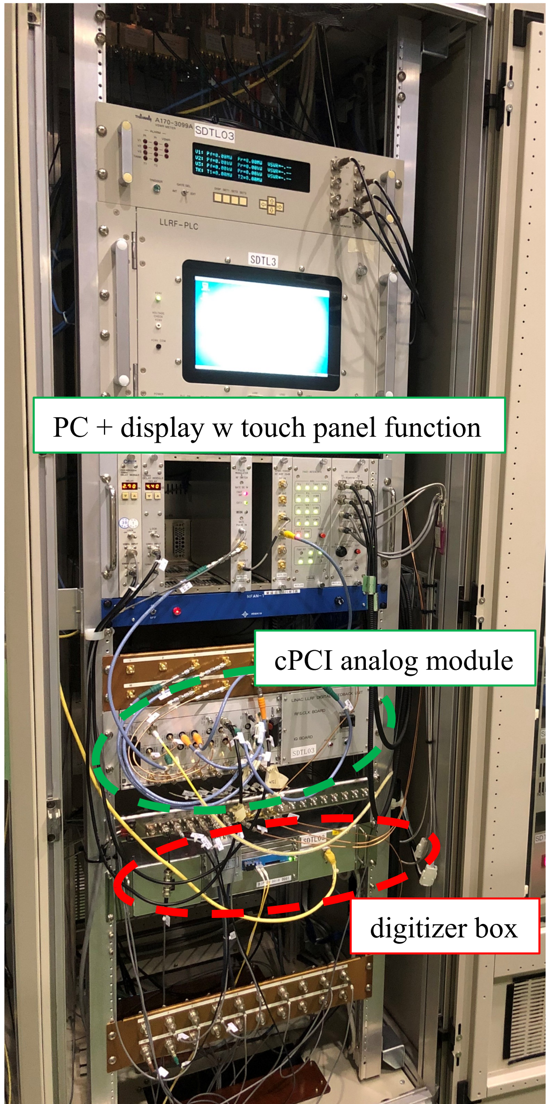
(digitizer box : 4 ch 12 MHz IF, 4 ch 324 MHz RF(direct sampling)

→ FPGA firmware: μRTM.4 and digitizer box → common

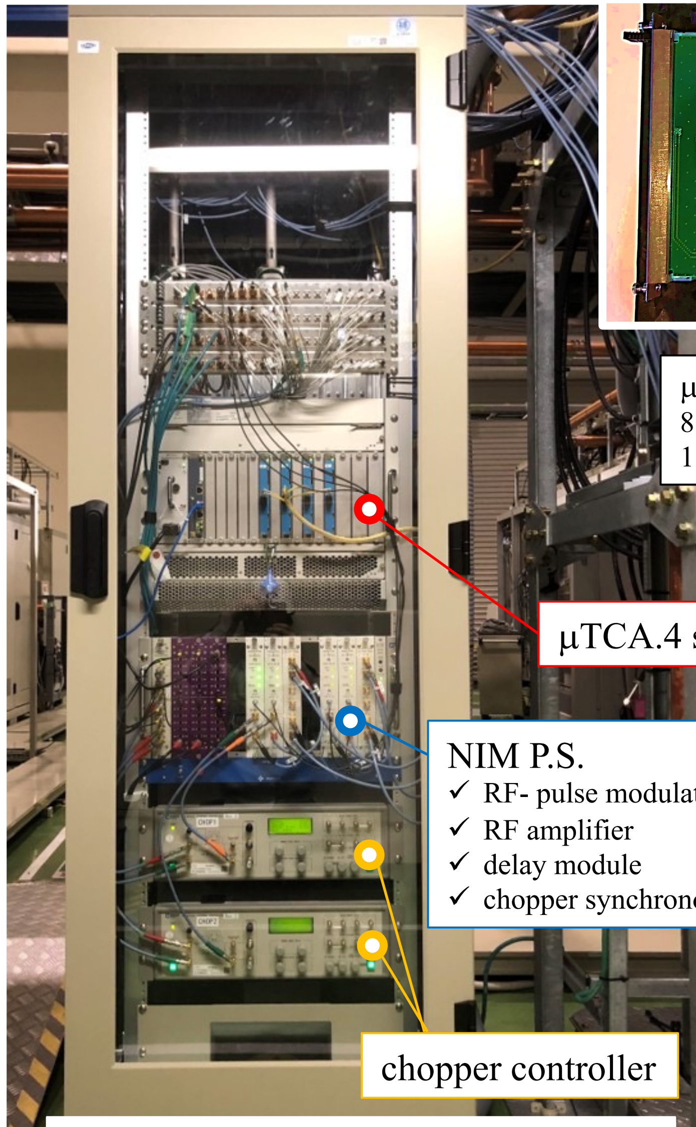


From summer shutdown of 2021
@ MEBT1

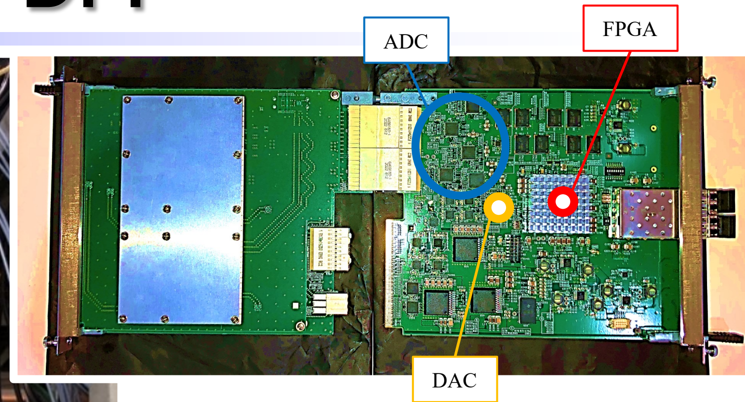
Photos of DFB・DFF



digitizer box + cPCI analog module：
→ @ RFQ, DTL1-3, SDTL01-16



μTCA.4 rack：
→ @ MEBT1 B1, C1, C2, B2
<u>→ constant temperature and humidity in rack</u>



μRTM board
8 ch down-converter
1 ch IQ modulator

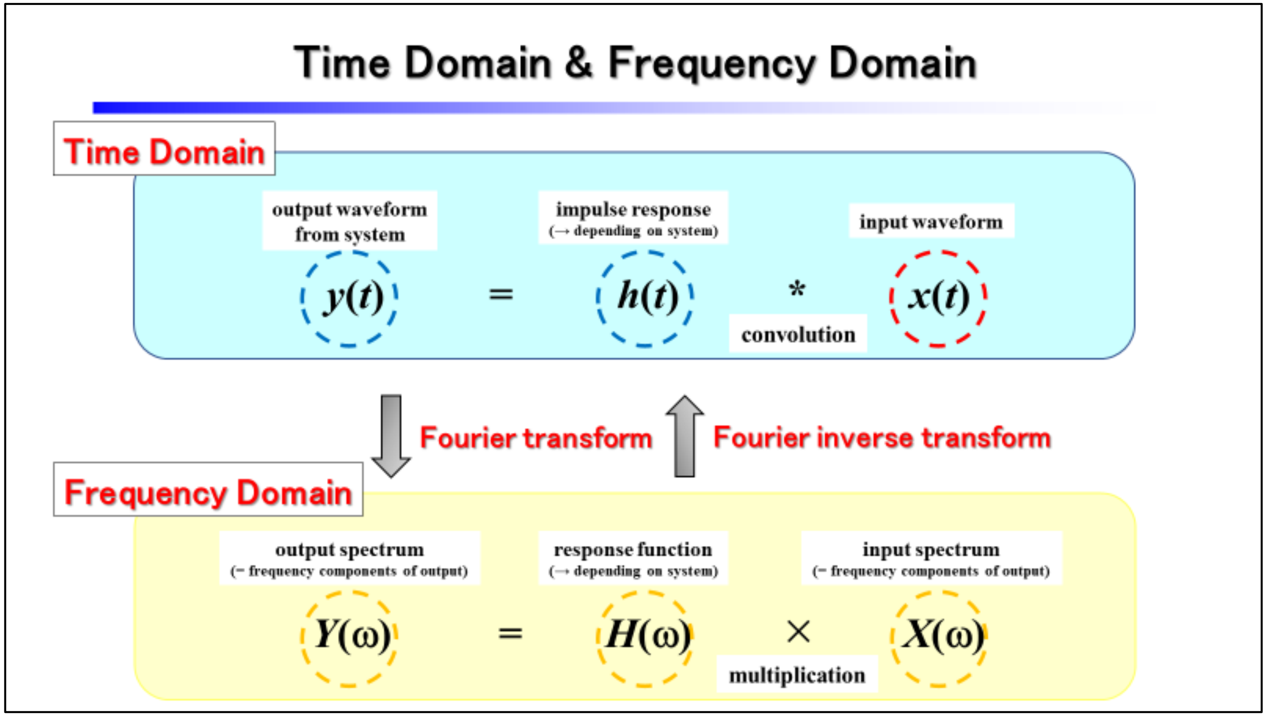
AMC board
FPGA (Xilinx Zynq)
8 ch ADC, 2 ch DAC

consisting of
mezzanine (generator)
carrier (distributor)

eRTM board
input：312 MHz, 12 MHz
output：324 MHz, 312 MHz,
120 MHz, 240 MHz, 12 MHz

Beam Loading Compensation

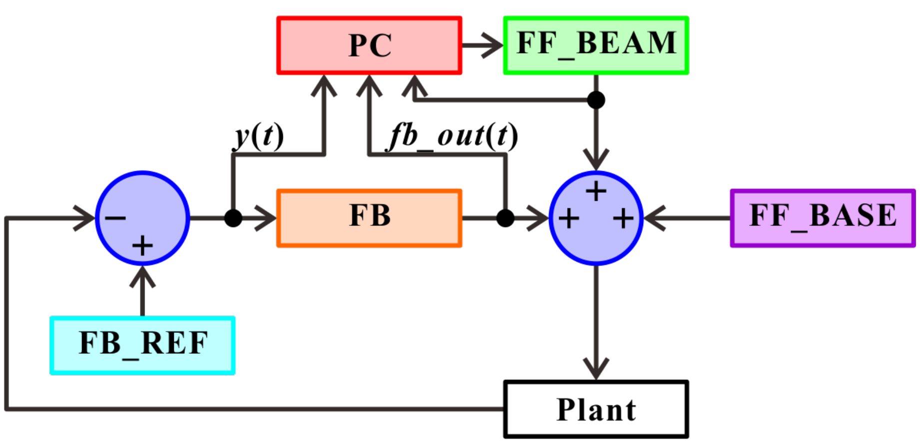
We developed the adaptive beam-loading compensation system calculated in the frequency domain.



← This is the general principle between the time domain and the frequency domain.

In the time domain, the output waveform is calculated to use the convolution between the input waveform and the impulse response.
On the other hand, in the frequency domain, the output spectrum is calculated to use the multiplication between the input spectrum and the response function.

If we know the response function, we can easily obtain the input spectrum.

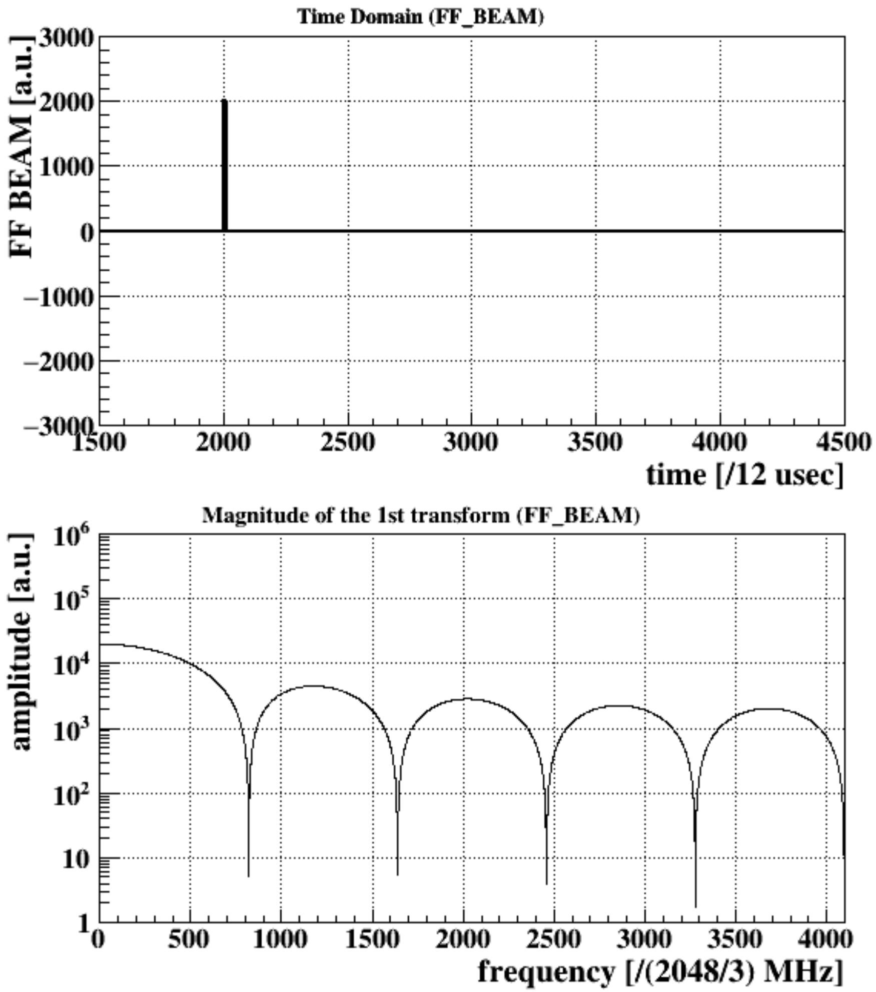


FF_BEAM + *fb_out(t)* † : input waveform
y(t): diff. bw output waveform and FB_REF
→ we can calculate the "ideal" input waveform. It means the "ideal" FF_BEAM can be calculated.

†FF_BASE: fixed tables, no considering.

Response Function

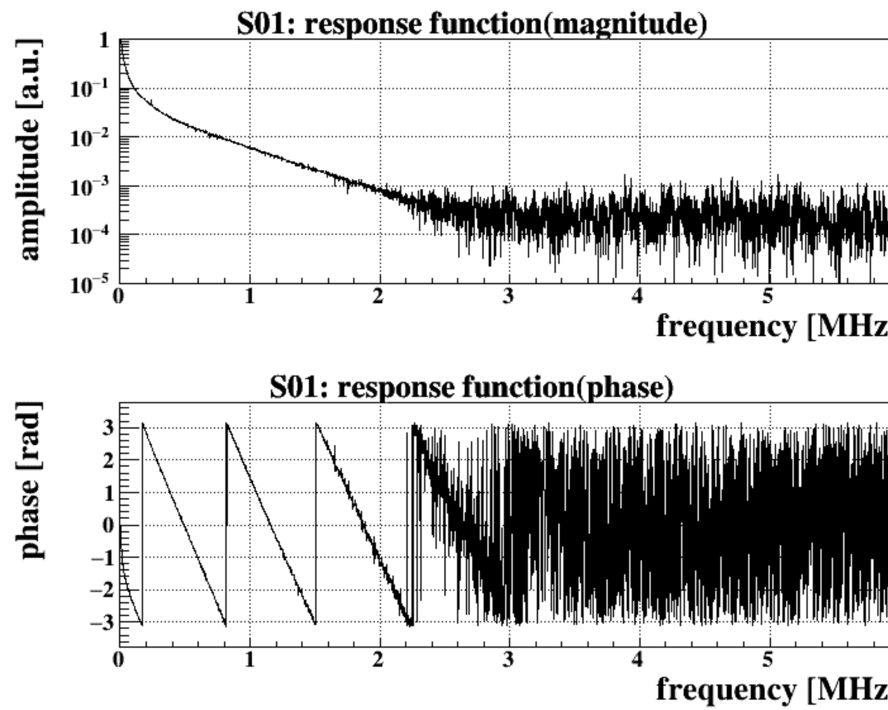
This method requires the response function to be measured in advance. The response function is calculated by analyzing the response to inputs with various pulse widths, which have various frequencies.



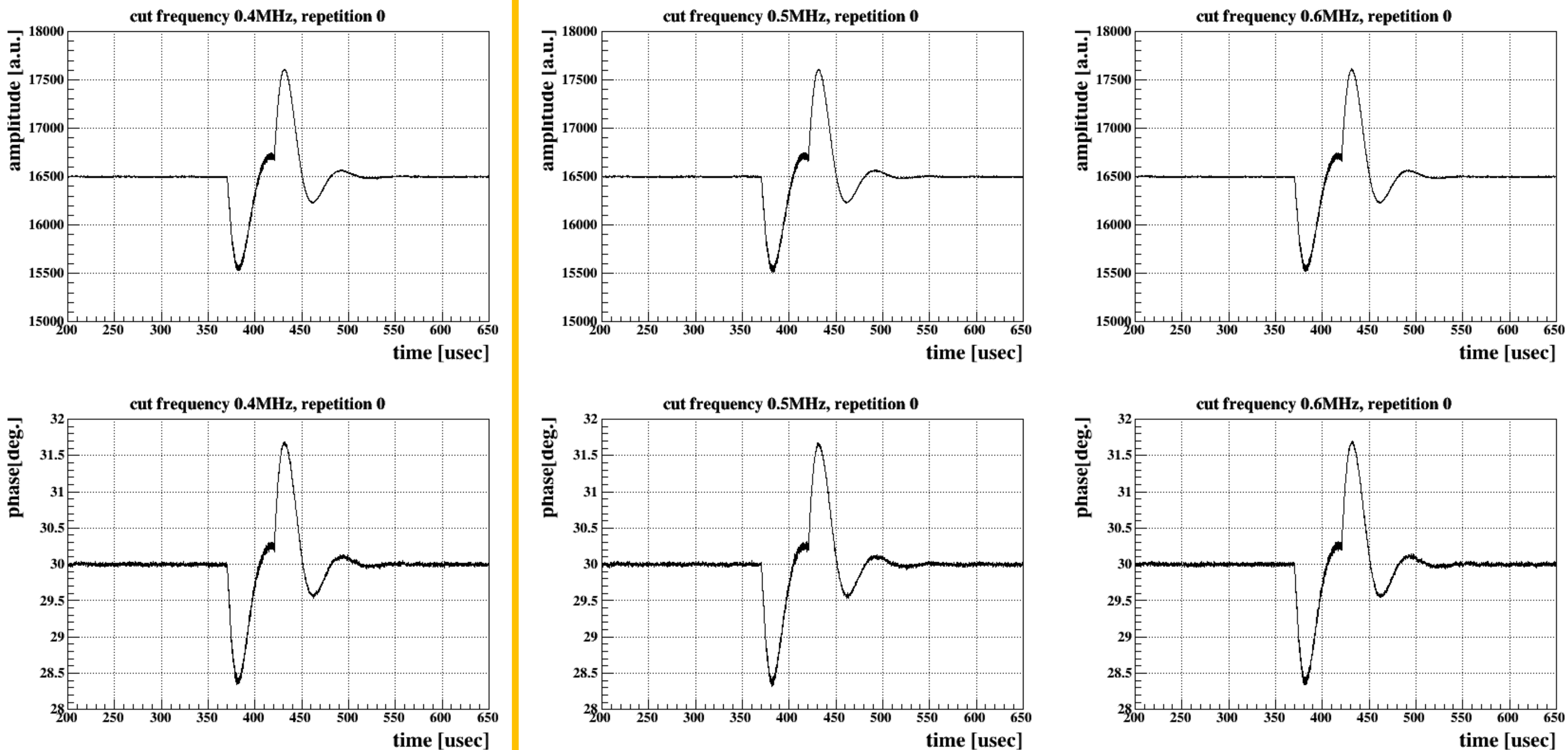
input signals (upper: time domain, lower: frequency domain)

← The input signals of various pulse widths have various frequency components. By analyzing each output, the response function can be calculated.

SDTL01 calculated response function

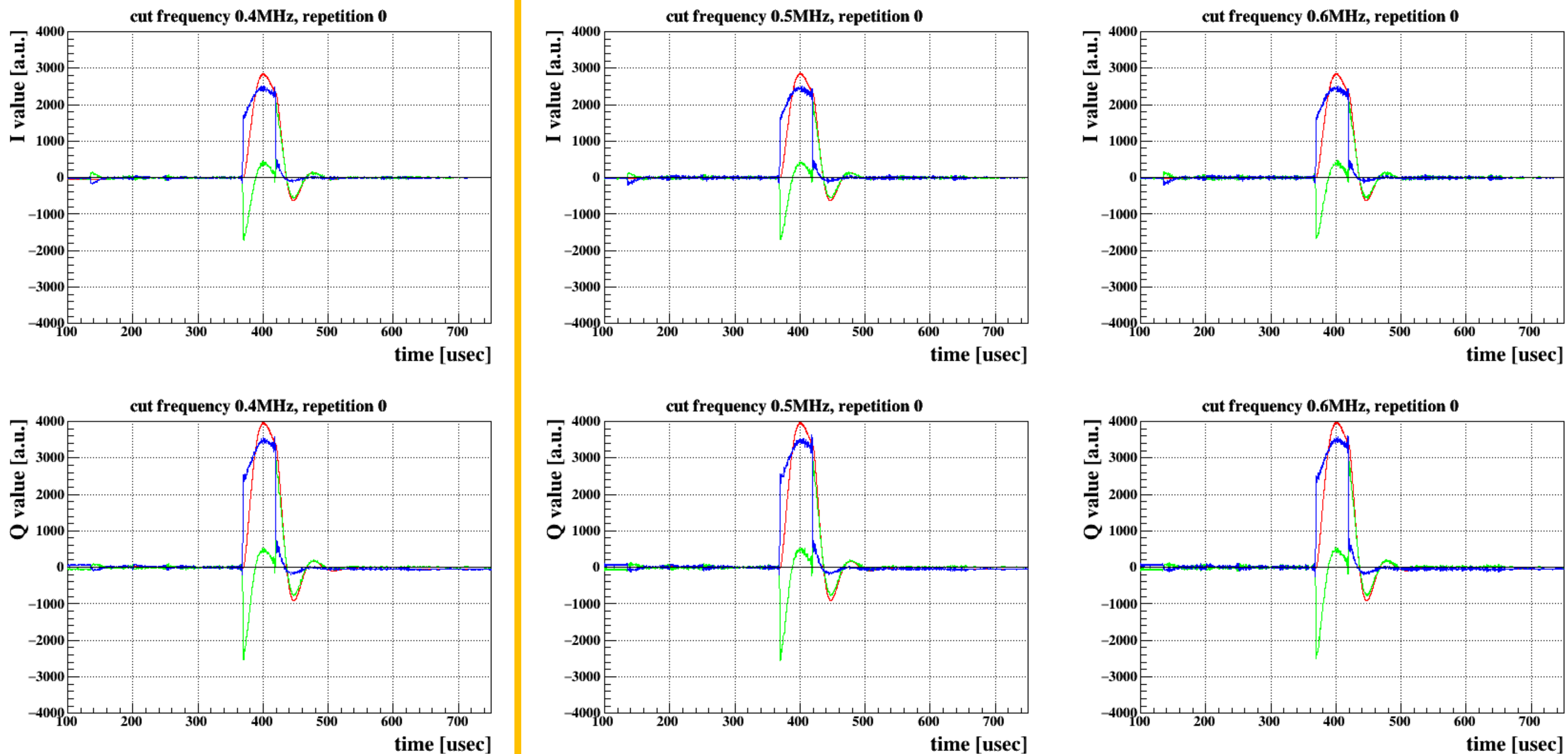


Improved Amplitude & Phase Stabilities



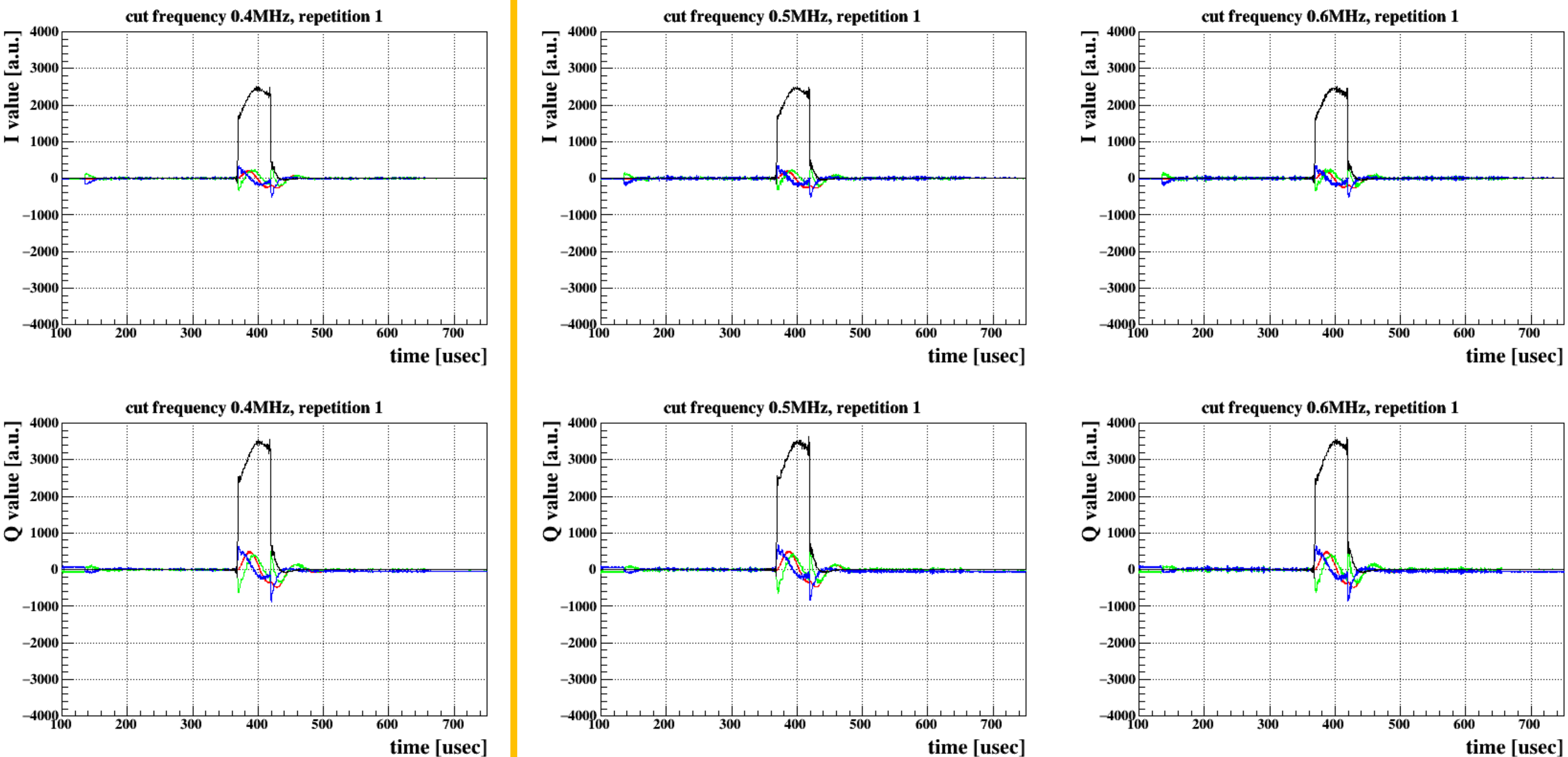
NO clear difference in cut frequency at 0.4 MHz, 0.5 MHz, and 0.6 MHz.
→ The 0.4 MHz cut frequency was adopted in the DFF system of the J-PARC LINAC.

Calculated FF_BEAM



red : calculated from FB
green : calculated from ADC
Blue : adding to next FF_BEAM
Black : previous FF_BEAM

Calculated FF_BEAM



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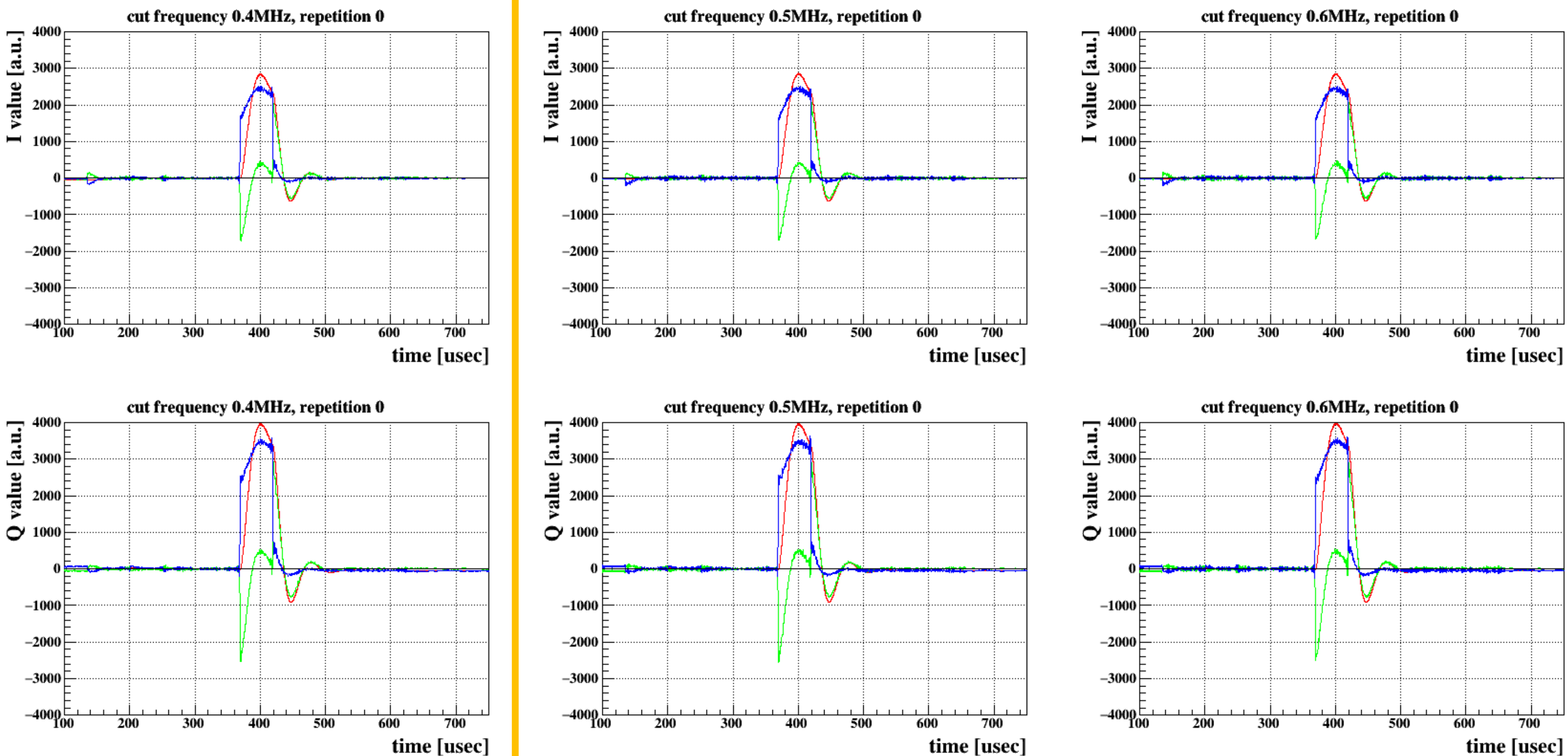
Calculated FF_BEAM



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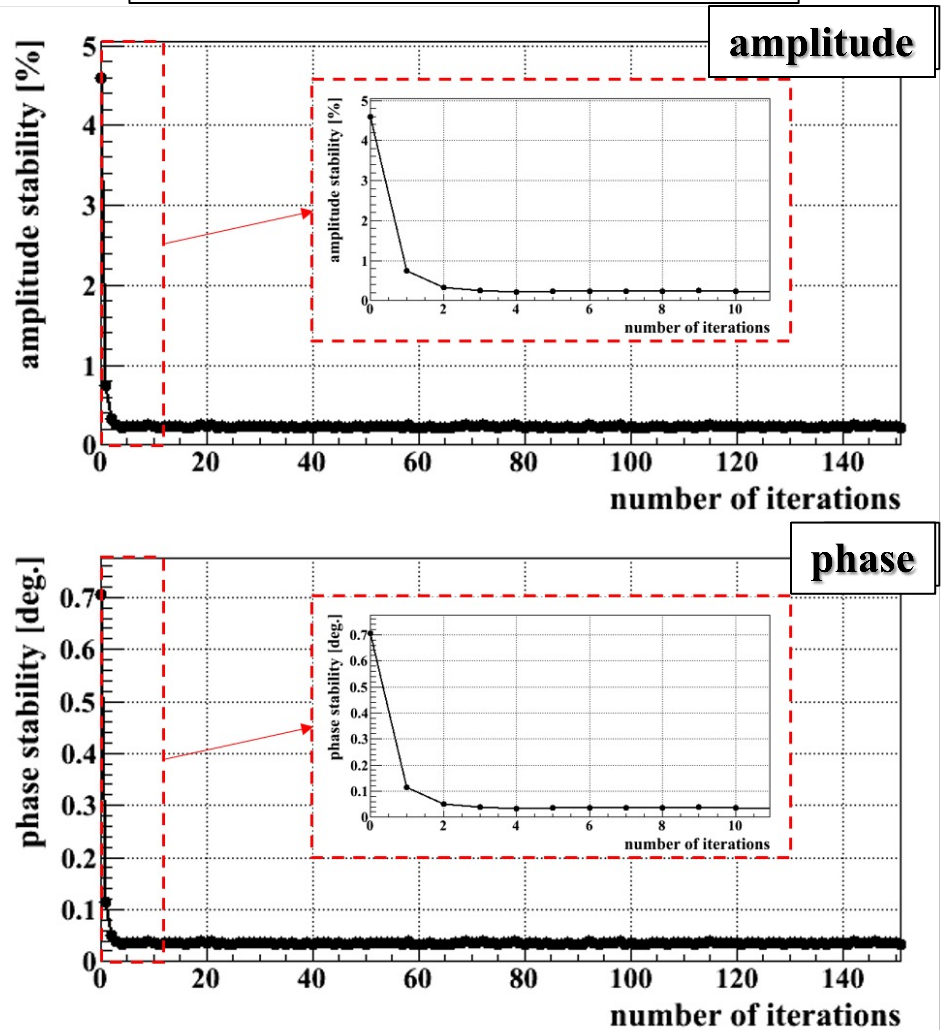
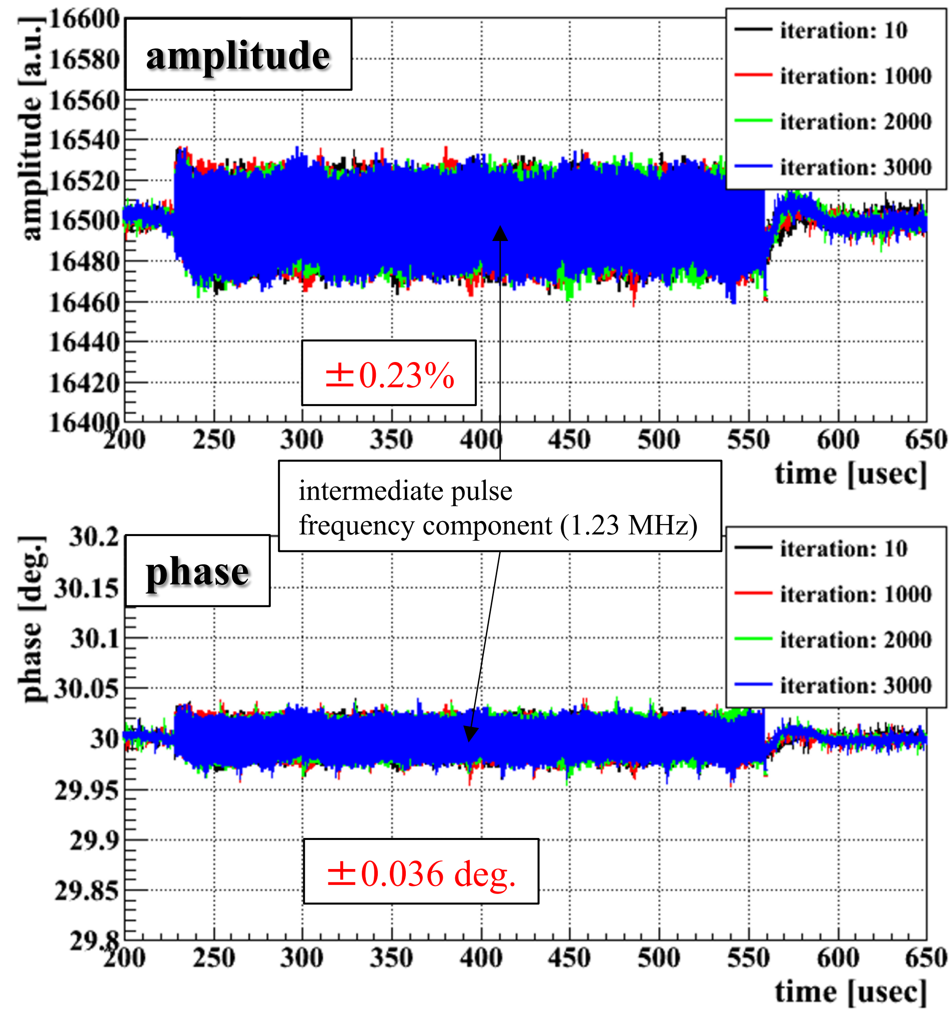
Interactive Effect: Stability

Number of Iterations & Stabilities



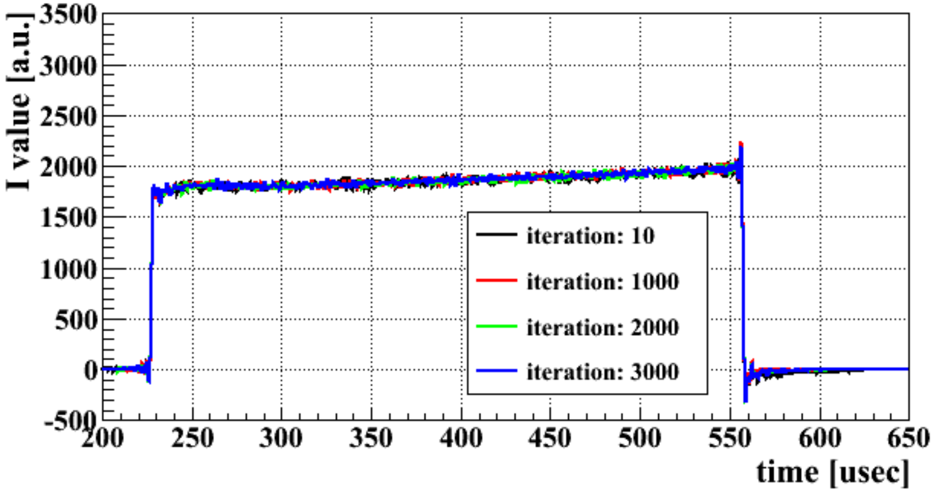
RF waveform



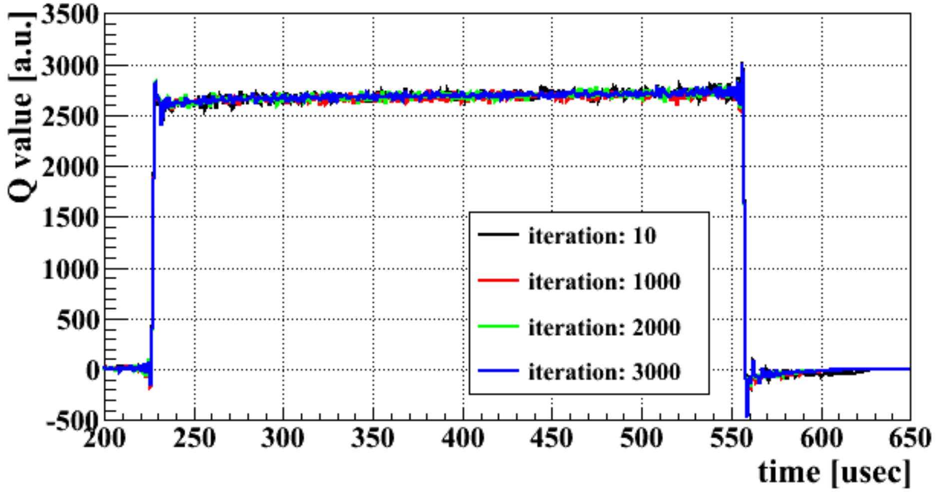
The requirement for the RF system (±1% in amplitude, 1 deg. in phase) is satisfied in one trial.
The stabilities convergence to optimum values after a few trials.

Interactive Effect: Divergence

FF_BEAM：I



FF_BEAM：Q



There is no accumulation of extra values at all for FF_BEAM after 3000 iterations.
No divergence is expected even after an infinite number of iterations.

Summary

- We developed the next generation DFB and DFF system based on the μTCA.4 AMC board. 20 digitizer boxes were installed at RFQ, DTL, and SDTL. The μTCA.4 system was utilized at MEBT1 to control the RF fields of four RF sources (two bunchers and two choppers). These systems are working very well without serious problems.
- We developed the adaptive beam-loading compensation system calculated in the frequency domain. In this method, we can obtain the result to meet the requirement for the RF system (±1% in amplitude, 1 deg. in phase) in one trial. In addition, the stabilities convergence to optimum values after a few iterations. There is no accumulation of extra values at all for FF_BEAM after 3000 iterations. No divergence is expected even after an infinite number of iterations.

Answers of Subject for Discussions

RF

- LLRF implementation and operations, e.g., some beam information given beforehand?
  Of cause, it is an important information. We use FF_BEAM to compensate the beam loading to keep the constant field gradient in the cavity. If the beam condition changes, the beam loading will naturally fluctuate. Then, the compensation system cannot correctly work.
- How to manage RF parameters (changing duty factor or it's always the same?)
  In the J-PARC LINAC, the RF pulse widths and the repetition are fixed. We do not prefer to change the cavity heat load.
- How detuning and blanking are handled?
  NO. We do not consider the blanking. It is difficult for RCS to accept the beam changing the characteristics (energy, emittance, and position) without adjustment.
- Conditioning and beam operations in parallel?
  NO. In the startup of the summer shutdown of J-PARC LINAC, the beam commissioning is started after the cavity and coupler conditioning is perfectly completed.

Blanking: not sending rf to a specific cavity, or range of cavities without detuning them for certain pulses