Application of MTCA.4 with RF Backplane to LLRF and BPM Electronics at SPring-8

H. Maesaka, H. Dewa, T. Fujita, T. Fukui, N. Hosoda, M. Ishii, E. Iwai, M. Masaki, T. Ohshima, S. Takano,

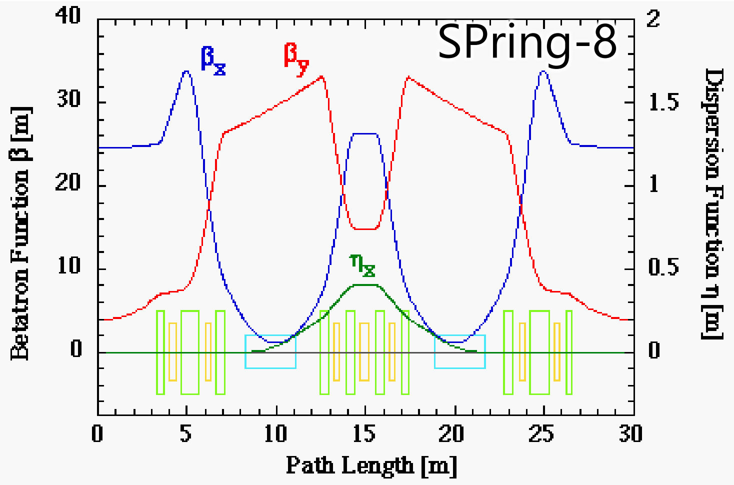
RIKEN SPring-8 Center

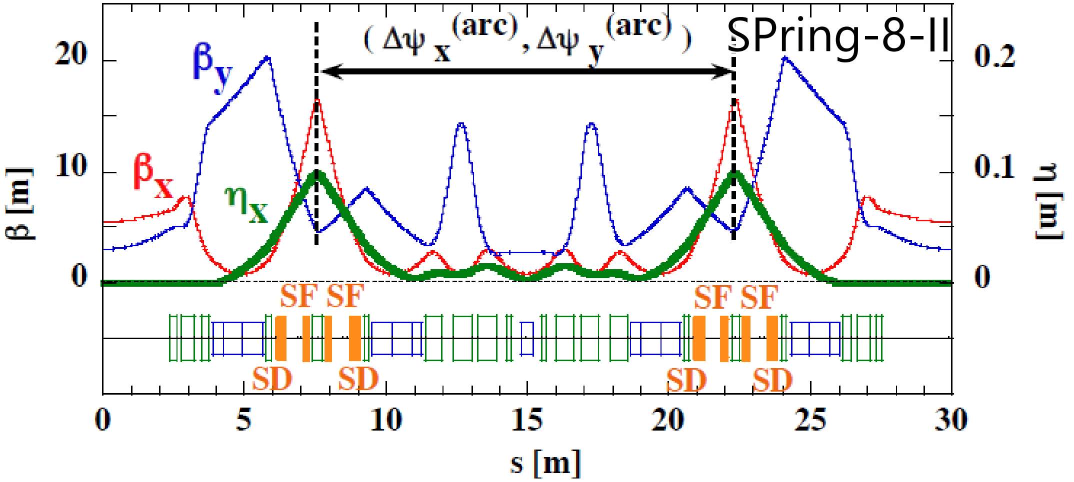
Japan Synchrotron Radiataion Research Institute (JASRI)

December 2nd, 2020

Introduction

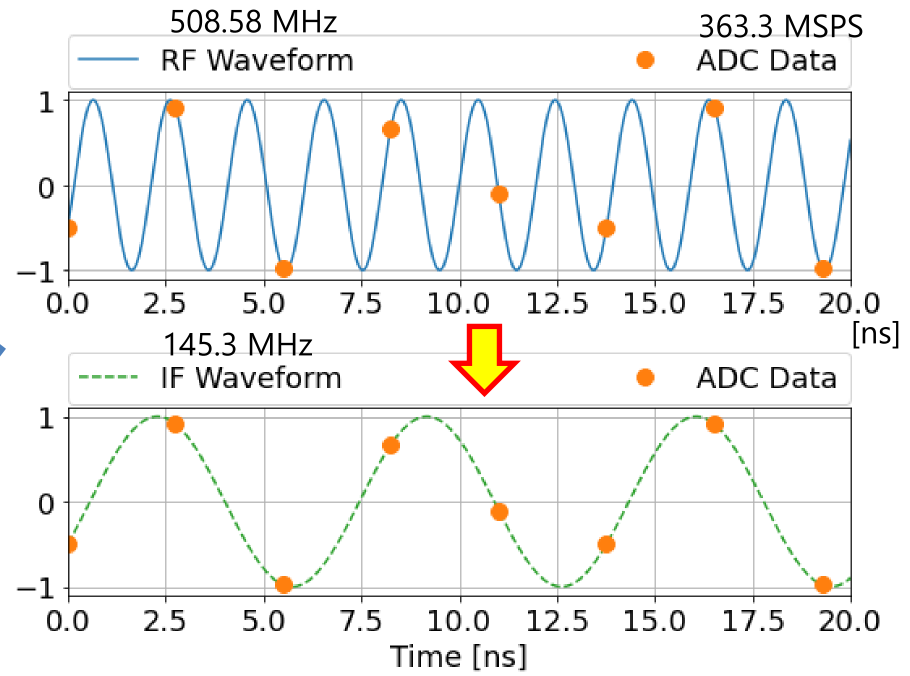
- SPring-8
  - Beam Energy: 8 GeV
  - Lattice: Double-bend acromat (DBA)
  - Natural Emittance: 2.4 nm rad
  - # of cells: 44
  - User service since 1997.
  - Electronics are based on NIM and VME.
- SPring-8 Upgrade Project (SPring-8-II)
  - Beam Energy: 6 GeV
  - Lattice: 5-bend achromat (5BA)
  - Natural Emittance: ~100 pm rad
  - MTCA.4 for high-speed electronics.
    - Low-level RF (LLRF), Beam position monitor (BPM), etc.
  - We started R&D of MTCA.4 ~5 years ago and we are already upgrading these electronics.
- New 3 GeV light source in Japan will also use MTCA.4 for LLRF and beam diagnostic systems.

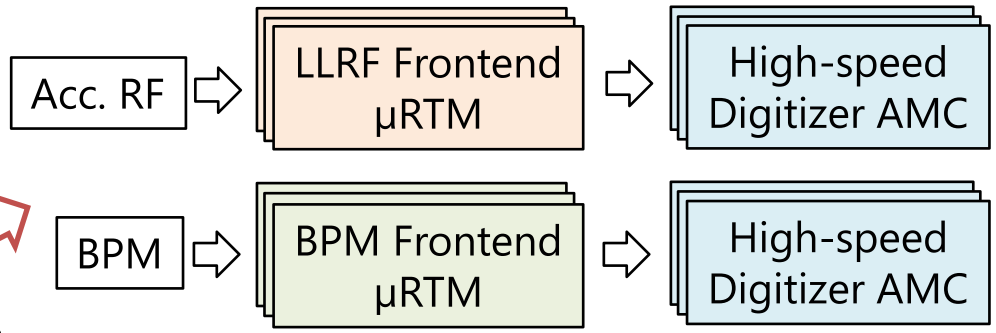


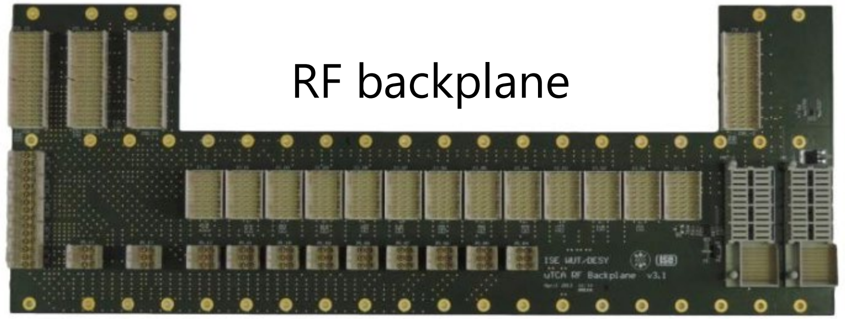


Design Concept

- LLRF and BPM electronics must detect acceleration RF signals precisely.
  - Acceleration RF frequency: 508.58 MHz
- Under-sampling scheme was chosen for RF detection.
  - The circuit is simpler than down-conversion scheme.
  - Drifts of active RF components can be reduced.
    - Mixers, LO generators, etc.
  - Sampling frequency (f_S): 363.3 MHz = 508.58 x 5 / 7
  - Intermediate frequency (f_{IF}): 145.3 MHz = 508.58 x 2 / 7
  - Digital down-conversion from IF to IQ baseband in the FPGA on the digitizer.
  - Required resolution (10 MHz BW):
    - Amplitude: 60 dBc = 1×10^{-3}
    - Phase: 0.1 degree
- MTCA.4 can be one of the best choices for the new system.
  - A common digitizer AMC can be used.
  - The individual RF front-end circuit for each system can be incorporated into a μRTM.
  - The RF backplane provides rigid transmission lines and reduces wiring.

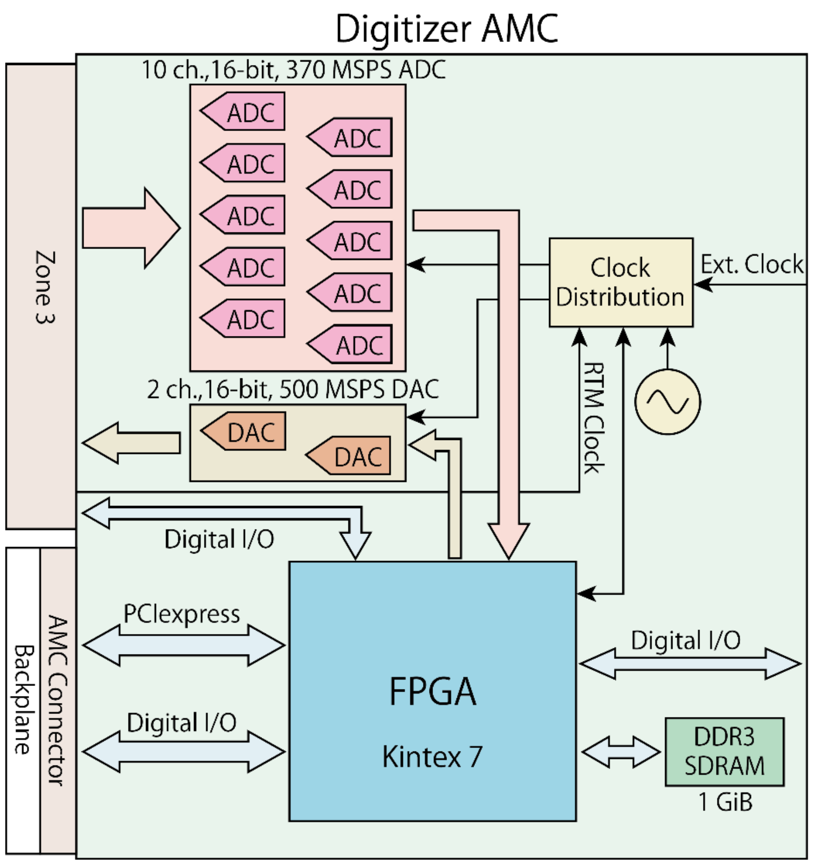




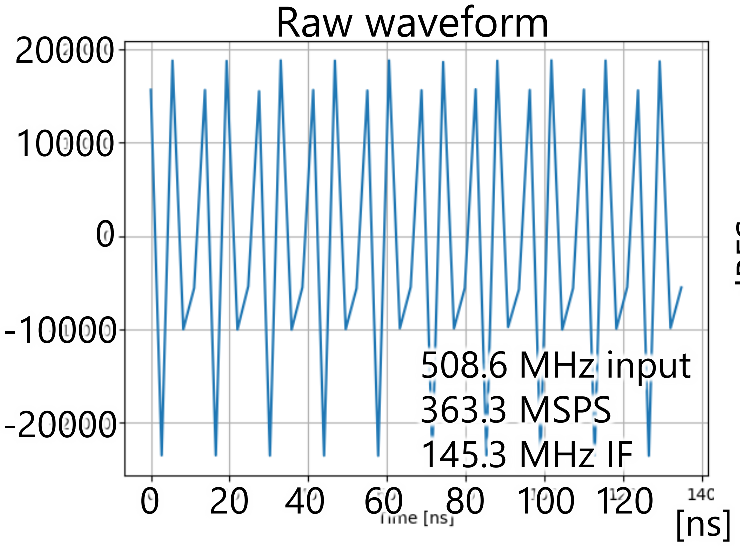


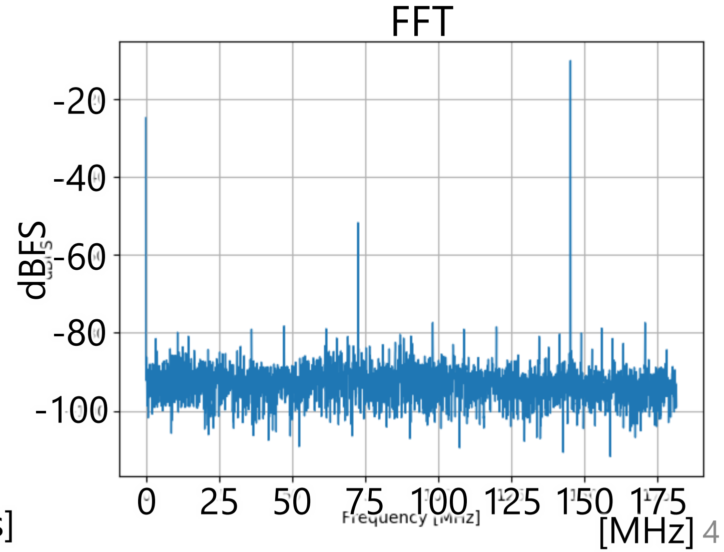
Digitizer AMC

- ADC x 10 ch.
  - 370 MSPS max., 16-bit
  - ADC16DX370
- DAC x 2 ch.
  - 500 MSPS max., 16-bit
  - AD9783
- FPGA: Kintex7 (XC7K480T)
- On-board RAM: DDR3-SDRAM 1 GiB
- ADC performance
  - Noise level (182 MHz BW):
    –69.9 dBFS (No input)
    –51.7 dBc (508.6 MHz input)
    - Larger noise than ADC datasheet for 509 MHz input due to clock jitter.
  - Amplitude resolution (10 MHz BW):
    –64.9 dBc ~ 5.6 x 10^{-4} (508.6 MHz)
  - Phase resolution (10 MHz BW):
    0.058 deg. (508.6 MHz)



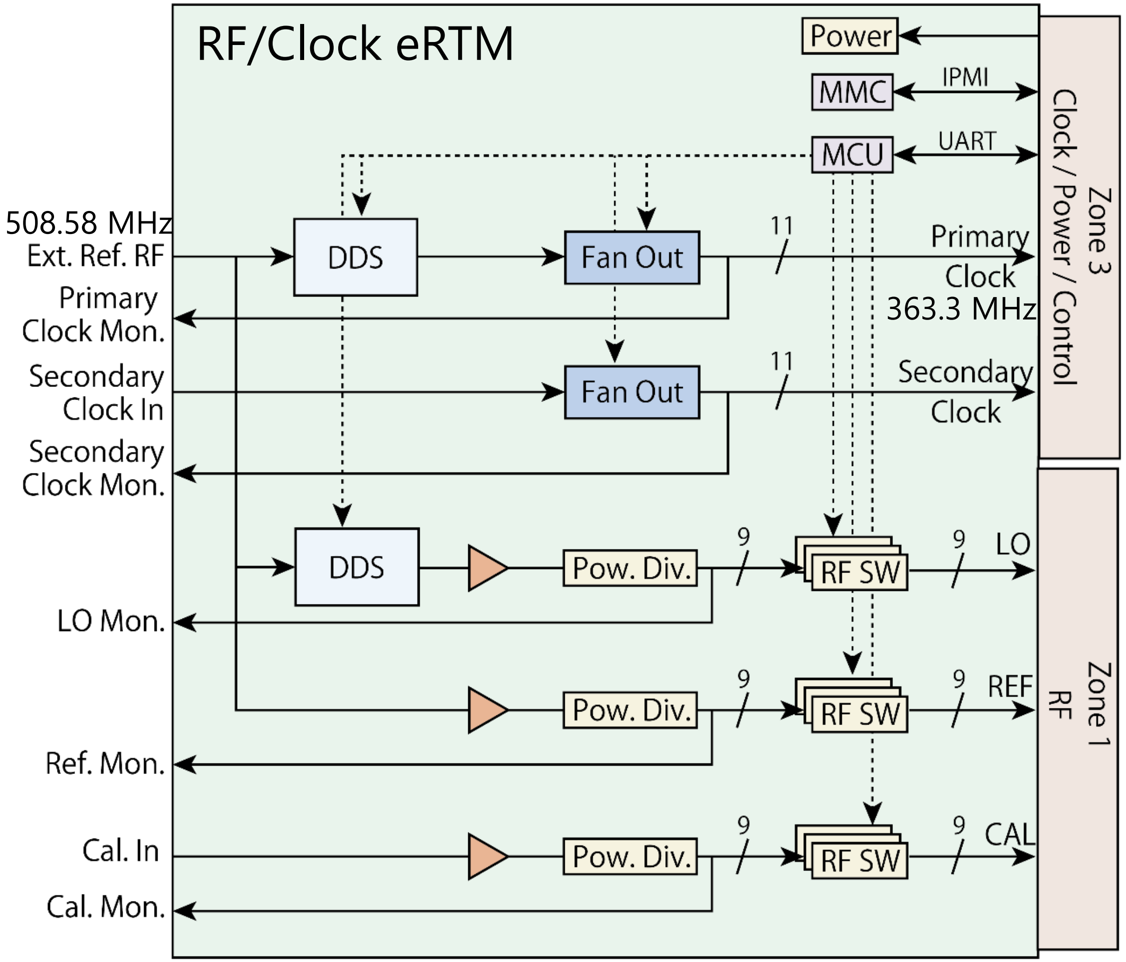
Made by Mitsubishi Elec. Tokki Systems



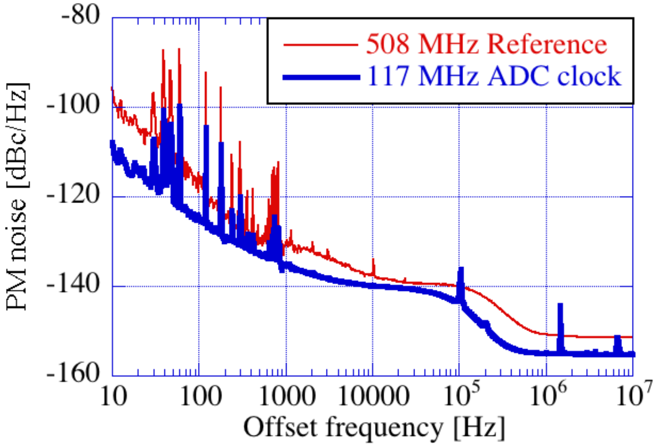


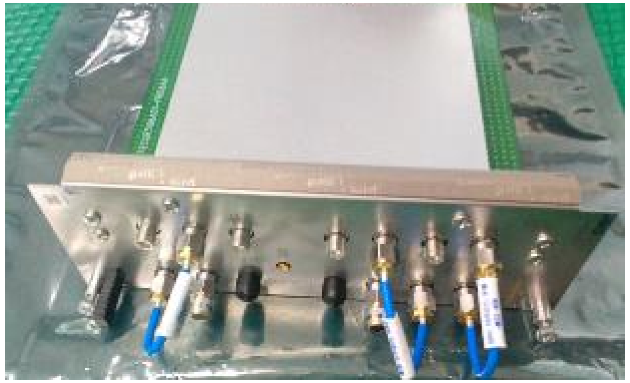
RF/Clock eRTM (extended RTM)

- The primary clock and LO signal are generated by direct digital synthesizer (DDS).
  - AD9914
  - Up to 500 MHz.
- The two clocks and three RF signals (LO, REF, and CAL) are distributed to μRTMs through the RF backplane.
  - Clock: 11-way fan out
  - RF: 9-way power divider
- All the outputs can be turned on and off.
- The DDS frequency and output switches are controlled by using UART through LVDS data lines of the RF backplane.
  - Operability confirmed with NAT-MCH-RTM-BM-FPGA.
- The MMC (IPMI) also works well with NAT-MCH-PHYS80 and NAT-RPM-AC600.



Phase noise data
Additive jitter is less than 100 fs.



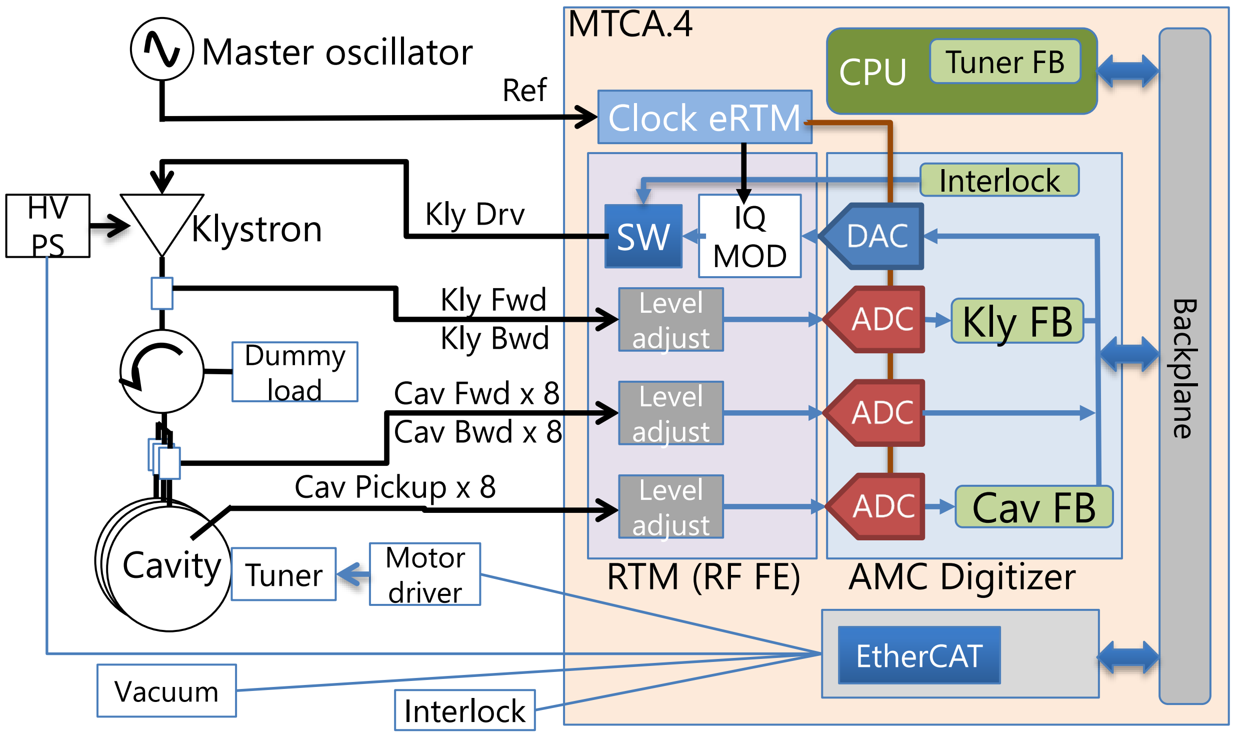


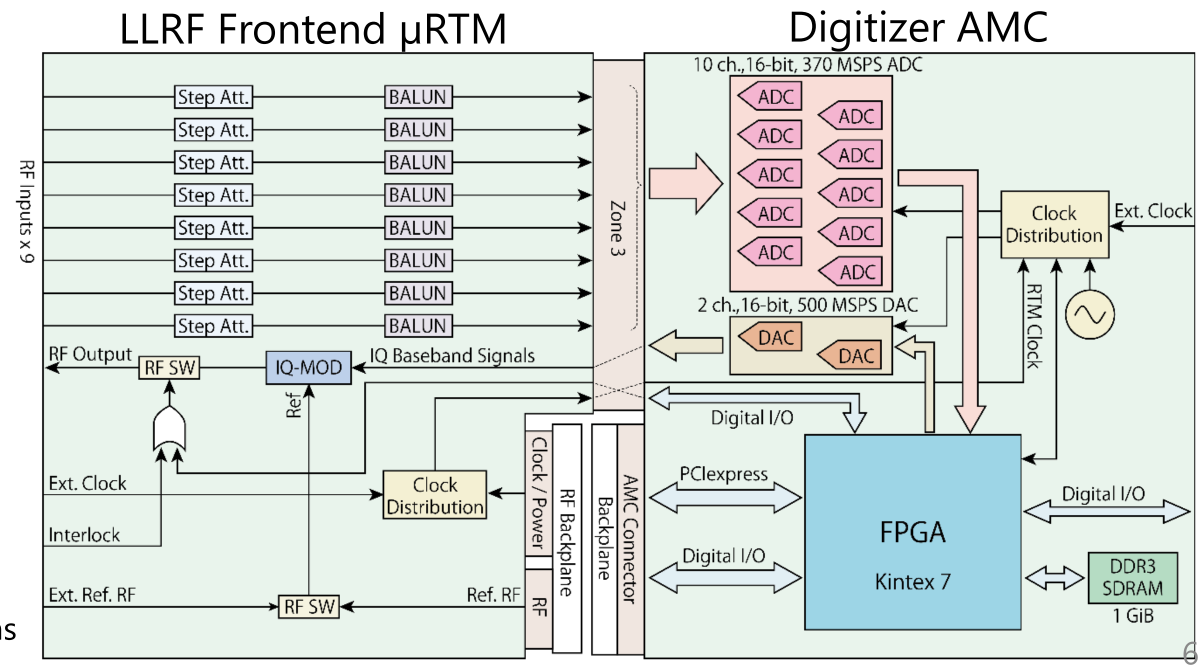
Two-slot wide

Made by Candox Systems

LLRF System

- An acceleration RF signal is generated by an IQ vector modulator on a µRTM.
  - Baseband signals are given by DACs on the digitizer.
- RF signals from high-power components are directly digitized by ADCs after level adjustment by step attenuators on the µRTM.
- IF data from ADCs are digitally down-converted in the FPGA.
- The klystron forward signal and the vector sum of the cavity pickup signals are fed back to DAC for the stabilization of the amplitude and phase.
- The RF switch is turned off when a machine protection interlock signal is detected.
  - Waveforms at such an event can be recorded.
- We have replaced the electronics for all the four RF stations with the MTCA.4 system.

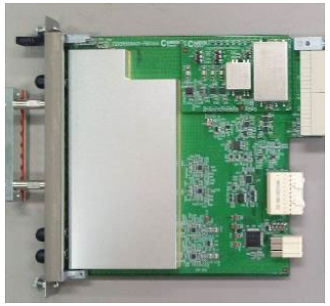




Front

Rear

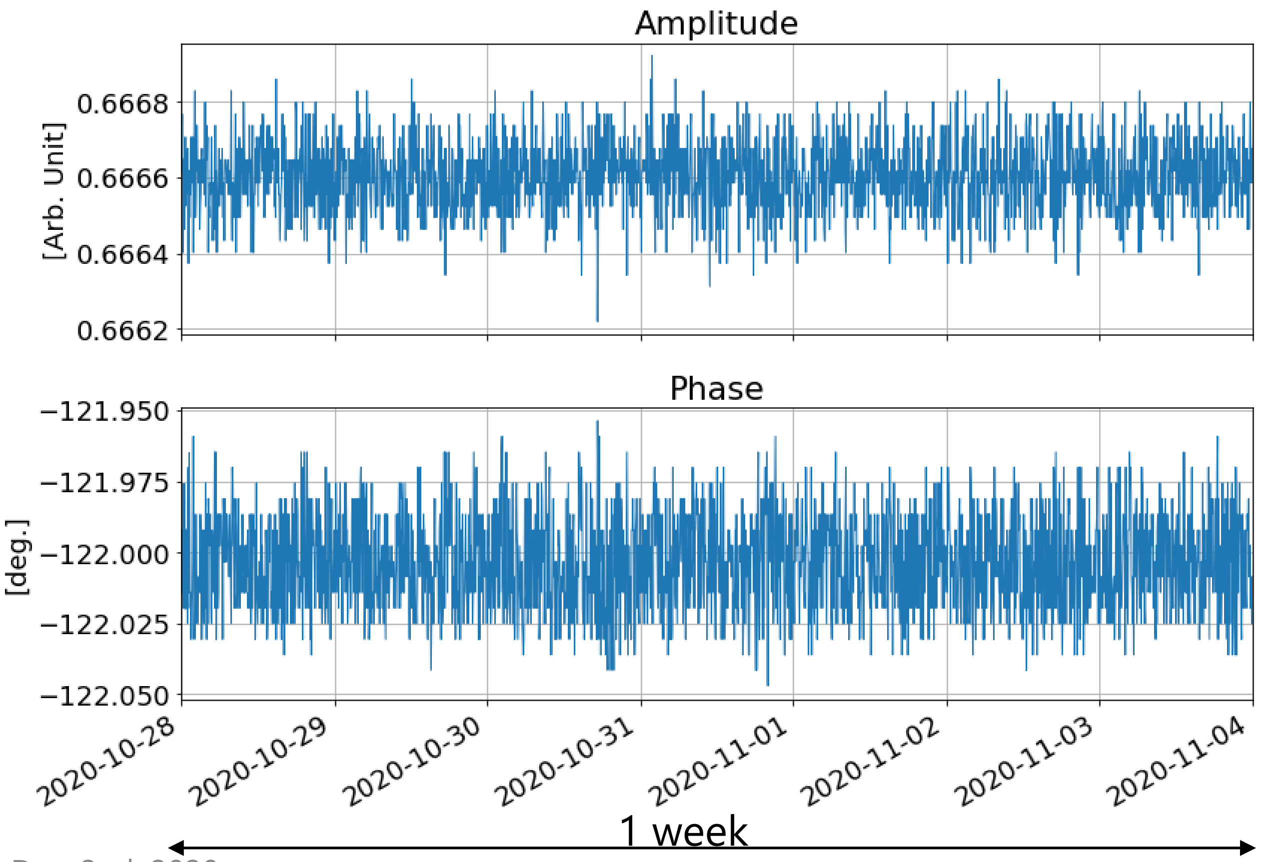
LLRF µRTM



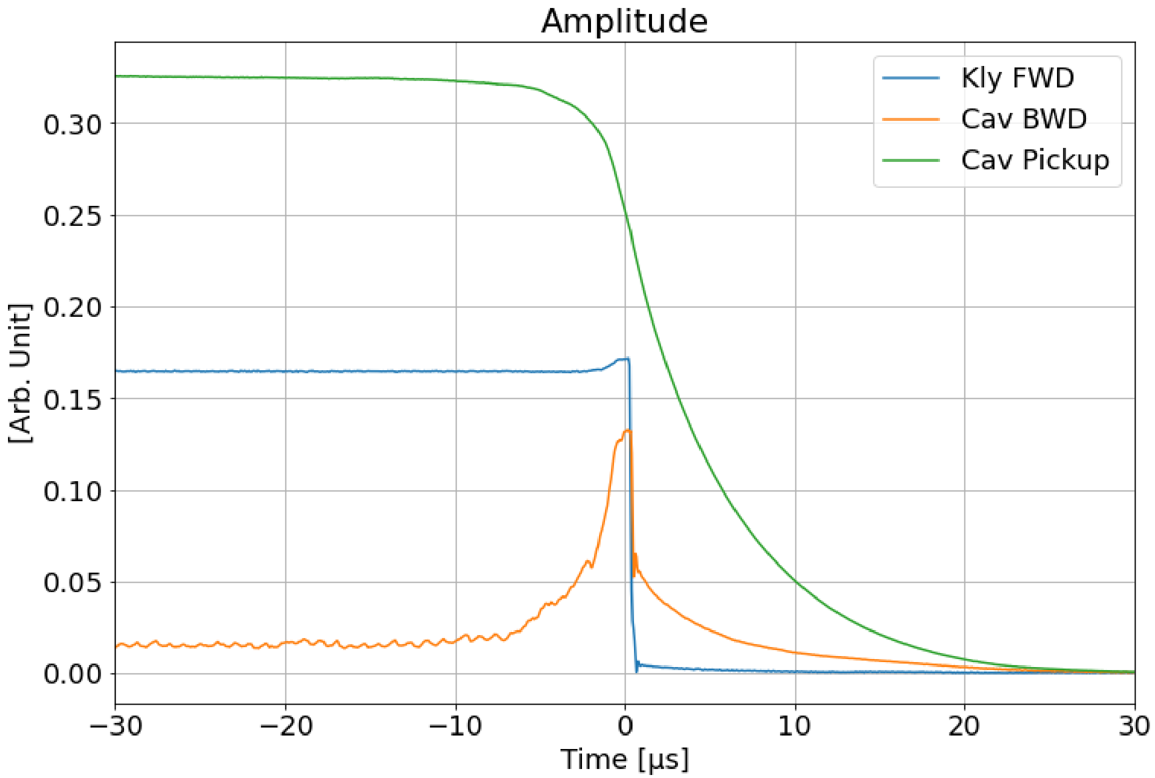
Made by Candox Systems

LLRF Performance

- Stability of the vector sum data
  - 1-week data
  - Amplitude: 1.4 x 10^{-4}
  - Phase: 0.017 deg.
  - (within the feedback loop)



- Waveform data in case of a breakdown in a cavity.
  - The backward power from the cavity began to increase about 6 μs before SW off.
  - This interlock was triggered by over-voltage of the cavity backward signal.
  - These waveforms are quite useful for postmortem analysis.



BPM Electronics

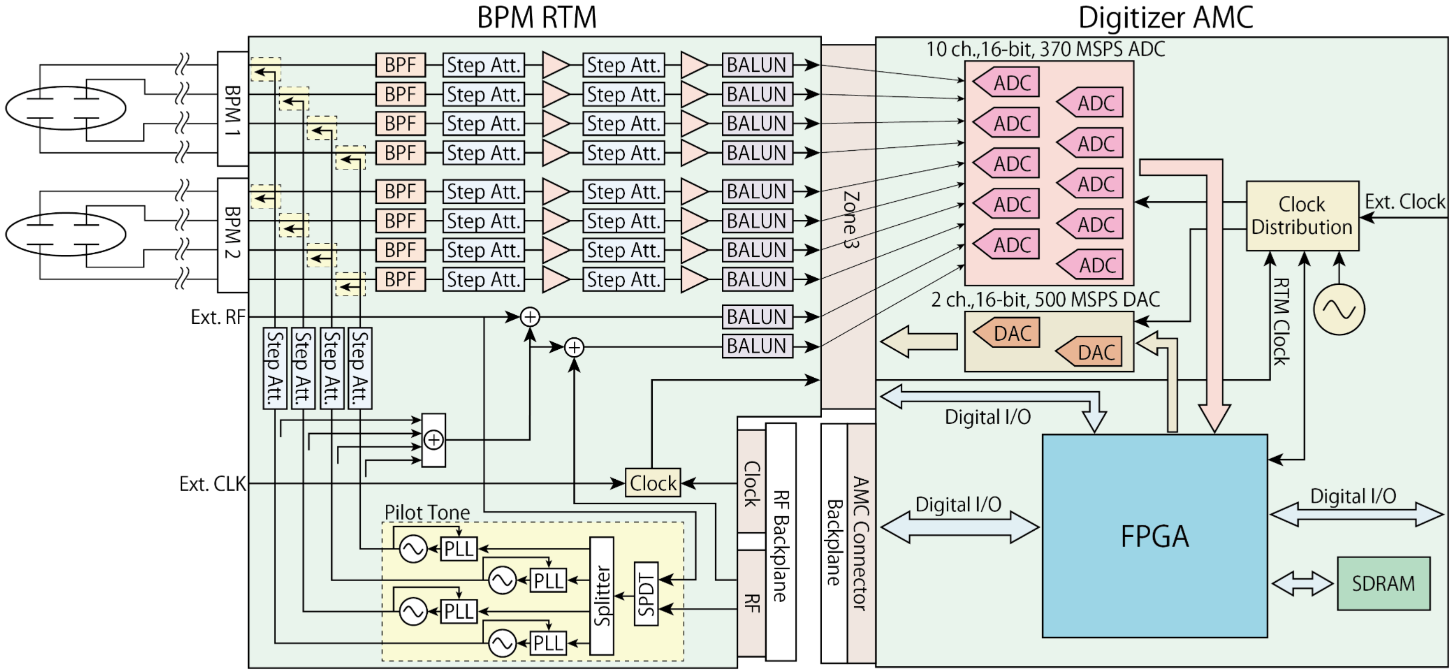
- Two BPM inputs per board.
  - (4-ch. BPM) x 2 + (2 ref. inputs) = 10 inputs
- 508.58 MHz signals are extracted by SAW band-pass filters (~10 MHz BW).
- The signal level is adjusted by step att. and amplifiers.
  - Attenuation: 0 – 63 dB, Gain > 40 dB
  - Input signal level
    - 100 mA uniform filling: –6 dBm
    - 0.1 nC single bunch: –53 dBm
- Pilot tone generators for gain calibrations.
- FPGA Firmware
  - Digital down-conversion
  - Beam position calculation

$$X = \sum_{i=0}^{7}\sum_{j=0}^{7-i} k_x^{ij}\Delta_x^i\Delta_y^j, \qquad Y = \sum_{i=0}^{7}\sum_{j=0}^{7-i} k_y^{ij}\Delta_x^i\Delta_y^j$$

$$\Delta_x = (V_1 - V_2 - V_3 + V_4)/(V_1 + V_2 + V_3 + V_4)$$

$$\Delta_y = (V_1 + V_2 - V_3 - V_4)/(V_1 + V_2 + V_3 + V_4)$$

  - Four kinds of data.
    - COD mode, 10 Hz slow data
    - COD mode, 10 kHz fast data
    - COD mode, Turn-by-turn data (209 kHz for SPring-8)
    - Single-pass mode (turn-by-turn)
- We are testing the new BPM electronics with 4 BPMs in the present SPring-8 storage ring.
  - The present BPM electronics will be gradually replaced with the MTCA.4 system.



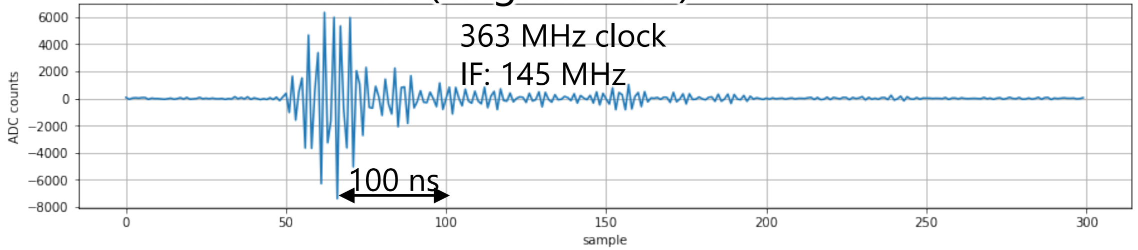
Made by Candox Systems

Front

Rear

BPM Performance

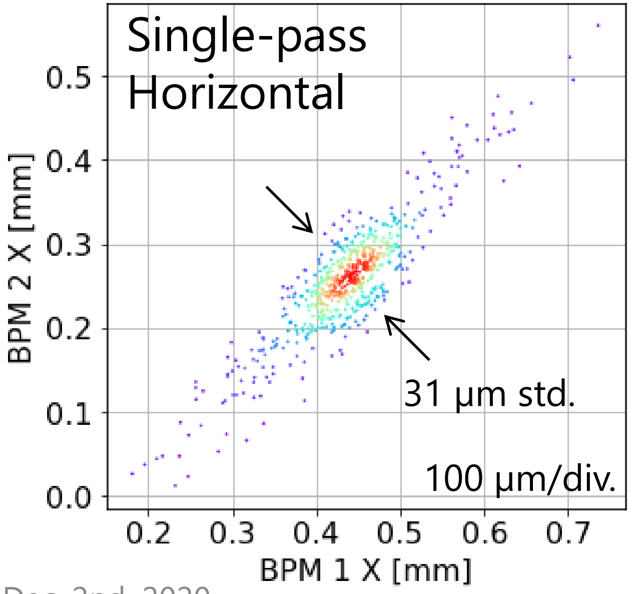
Raw IF waveform (single bunch)

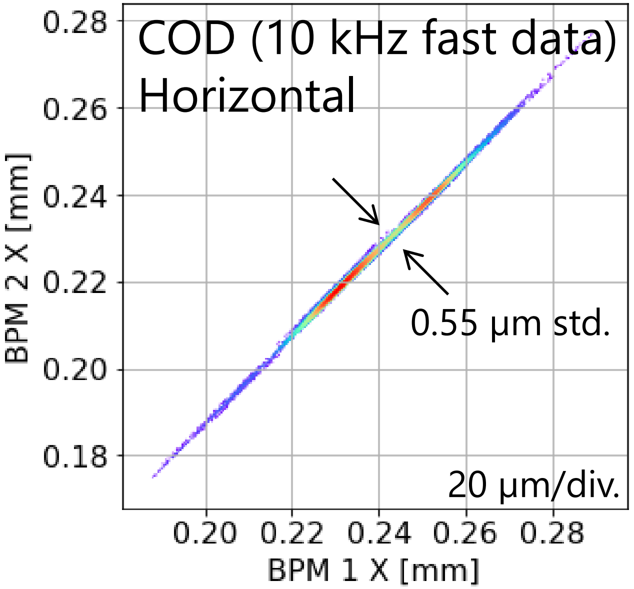


BPM Resolution

- Single pass: 22 μm (0.13 nC)
- COD (fast data): 0.39 μm (30 mA, 2 kHz BW)

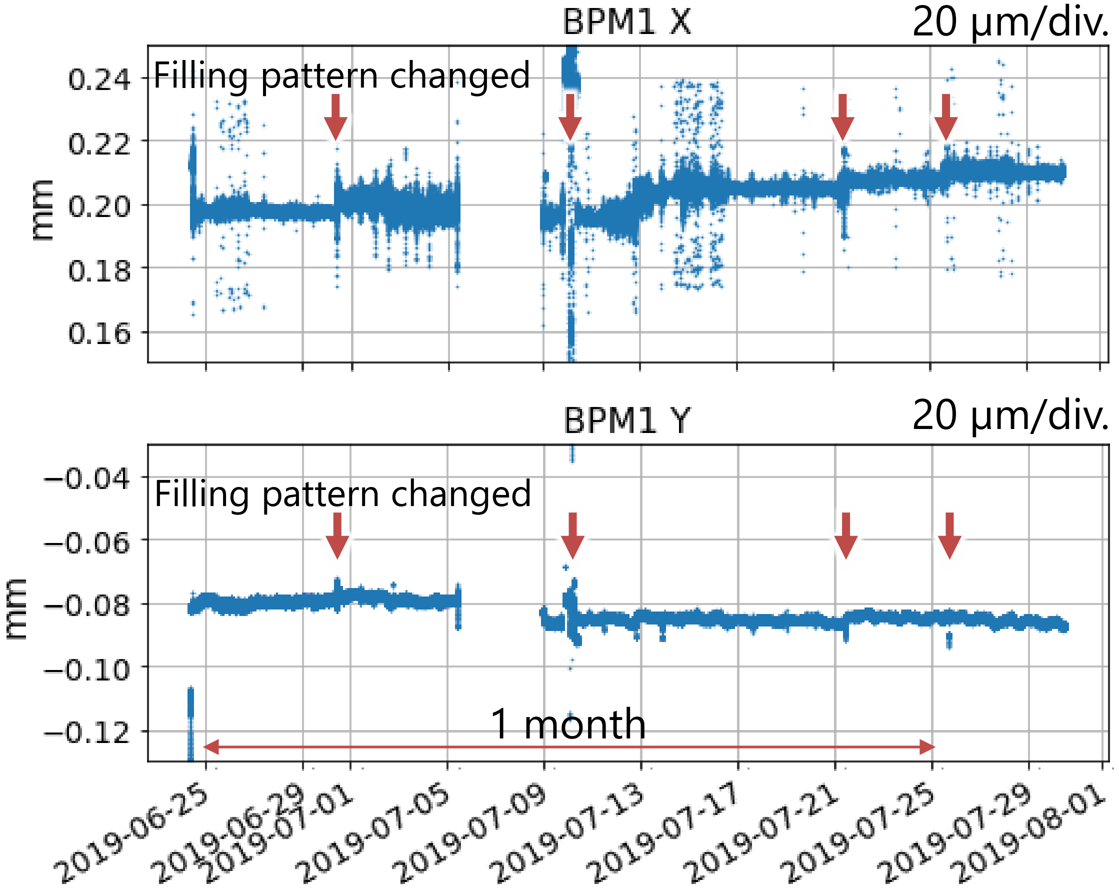
Beam orbit was intentionally shaken for these measurements.





Long-term stability

- The beam orbit was stabilized by the present BPM system.
- Beam position data from the MTCA.4 system was stable within 10 μm for more than 1 month.



Summary

- We have developed MTCA.4 LLRF and BPM electronics for the SPring-8 upgrade project.
  - RF backplane is used for RF and clock distribution.
- High-speed digitizer AMC
  - 370 MSPS, 16-bit, 10-ch. ADCs and 2-ch. DACs
  - Under-sampling scheme to detect 508.58 MHz RF signals.
- RF/Clock distribution eRTM
  - DDCs for primary clock and LO generation.
  - This eRTM can distribute three RF signals (LO, REF, CAL) and two clock signals.
- RF Frontend μRTMs
  - LLRF: 9 RF inputs with step attenuators and 1 vector modulator output.
  - BPM: 2 BPM inputs with SAW filters, step attenuators, and 40 dB amplifiers.
- LLRF system
  - RF detection, RF generation, ALC and PLL feedbacks, etc. are working well.
  - We completed the replacement of the LLRF system for all the four RF stations.
- BPM electronics
  - BPM calculations for single-pass and COD modes are successfully implemented.
  - Sufficient position resolutions and long-term stability were confirmed.