Development of a LLRF Control System for a Synchrotron at WERC

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MTCA Workshop

Accelerator Facility at WERC - W-MAST

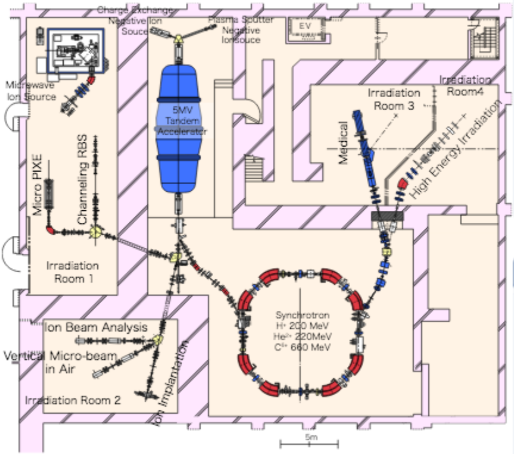


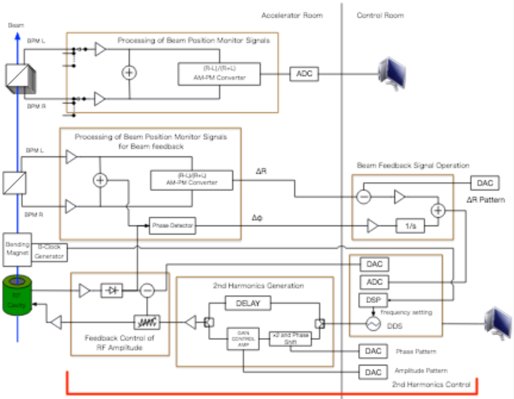
Figure 1: Overview of W-MAST

- 5 MV Tandem Accelerator works as an injector
- Beams from the synchrotron
  - H^+ < 200MeV
  - He^{2+} < 220MeV
  - C^{6+} < 660MeV
- Utilized for medical, biological and material sciences

RF Acceleration

- Untuned RF Cavity using FINEMET core
- Proton 7 MeV → 200MeV Revolution Frequency 1.1 MHz → 5.1 MHz
- Second harmonics to reduce space charge effect

Problems of the Current LLRF Control System



Analog circuits are used in the current system.
Replace with digital circuits
using FPGA(field-programmable gate array).

Figure 2: The Current LLRF Control System

- DDS controlled with a DSP
  - We can not obtain repair parts.
- Feedback controls consits of analog circuits
  - Troubles due to aging
- Phase and amplitude of second harmonics are not feedback controlled.
  - A fine adjust ment is difficult due to unstable frequency characteristics.
- An AM/PM Converter calculates beam position.
  - Calculation results depend on input signal level
  - Troubles due to aging

→ Digital circuit using FPGA

New LLRF Control System Using FPGA Based on MTCA.4

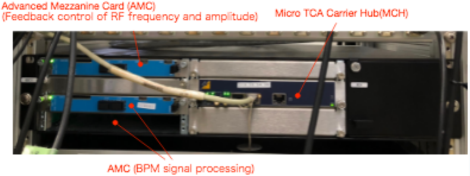


Figure 3: Front view

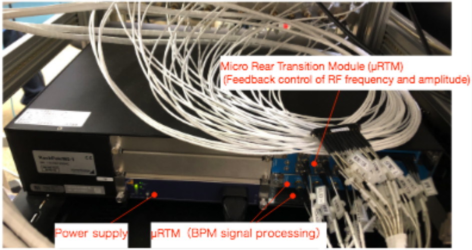


Figure 4: Rear view

- MicroTCA.4 based
- AMC manufactured by Mitsubishi Electric TOKKI Systems
  (AD x8, DA x2) x3
- Xilinx Zinq XC7Z045 :
  FPGA + Arm Cortex-A9
- EPICS IOC on Linux
- Settings and monitorings through EPICS's channel access
- System clock 150 MHz is generated by multiplying 10 MHz from the timing system.

The Circuit of New LLRF Control System

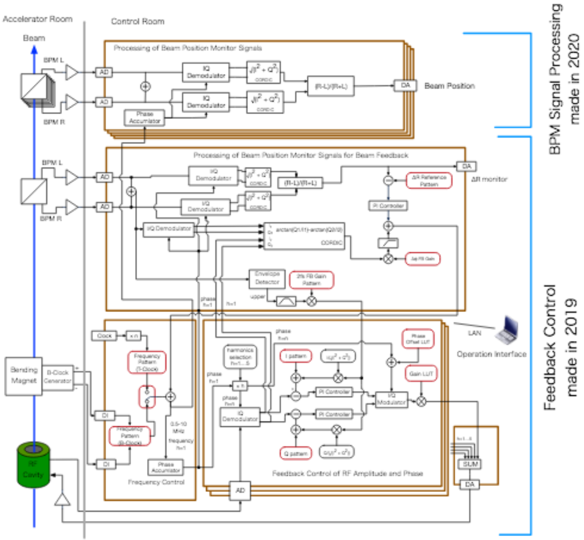


Figure 5: Overview of new LLRF

- RF feedback control and BPM signal processing are integrated
- Control of amplitude and phase through feedback control of I/Q signals
- Multi-harmonics($<$ 5th)
- Update the phase accumurater with B-Clock or T-Clock
  - Used as a reference signal for IQ modulators/demodulators
- Beam position and phase are calculated with I/Q signal detected from BPM signals.
  - Feedback control of horizontal beam position
  - Suppress phase oscillation

Feedback Control of Cavity Voltage

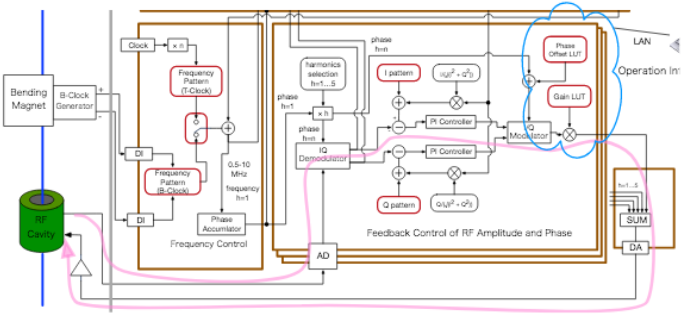


Figure 6: Circuit of feedback control of cavity voltage

1. The cavity voltage signal is converted to I/Q signals with an IQ demodulator.
2. The LPF of the IQ demodulator is important.
3. Compare I/Q signals with each set patterns
4. Obtain a feedback signal through a PI controller
5. RF output is generated with an IQ modulator.

Correction of frequency characteristics of amplitude and phase caused by cables, a cavity and a RF amplifier is required.

→ Gain LUT/Phase Offset LUT
High-order 16-bit data of 34 bit frequency data are used for addressing to the LUT.

Adjustment of a Gain/Phase Offset LUT

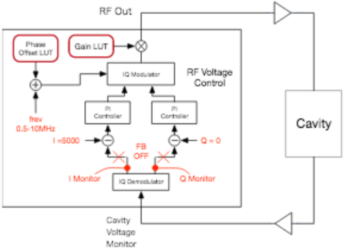


Figure 7: Setup for adjustment of LUTs

1. FB OFF. set Phase Offset LUT to 0. set Gain LUT to 1
2. fundamental harmonics (I,Q)=(5000,0).
3. Obtain I/Q values of 300 points between 0.5 MHz and 10 MHz.
4. Evaluate amplitudes $2\sqrt{I^2 + Q^2}$ and phases arctan Q/I from interpolated IQ values.
5. Adjust LUTs to make amplitude and phases keep constants.

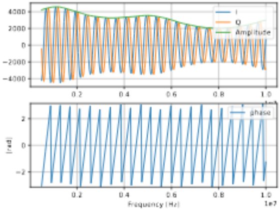


Figure 8: Frequency characteristics of interpolated I/Q values, amplitude and phase before setting LUT.

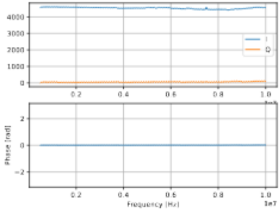


Figure 9: After applying LUT, frequency responses of I/Q values are constants.

Commissioning of Feedback Control of Cavity Voltage

Measurement of Closed Loop Gain

- Optimizing P gain and I gain
- Selection of LPF for IQ demodulator
  - 2 stage Tracking CIC vs Tracking CIC + Leaky Integrator

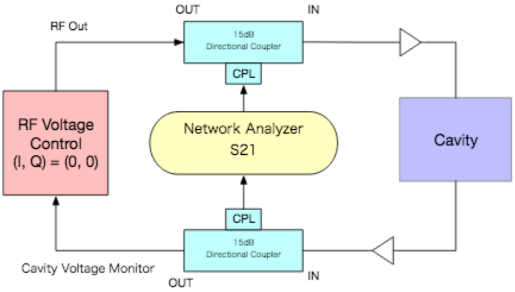


Figure 10: Setup for measurements of closed loop gain.

- Close feedback loop
- Set (I,Q) = (0, 0)
- Apply disturbances with S21 mode of a network analyzer.
- Observe suppression of the disturbance at the set frequency by the feedback control.

Measurements of Closed Loop Gain

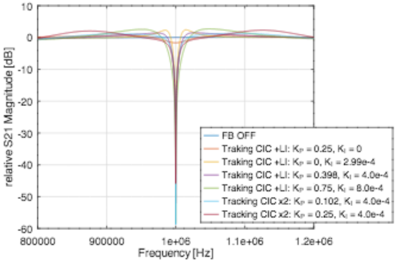


Figure 11: Comparison of closed loop gains at 1 MHz.

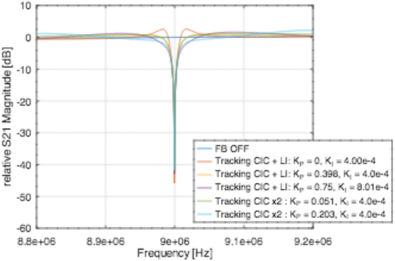


Figure 12: At 9 MHz.

- Sharp valley (supression of the disturbance) at the set frequency
  → Confirmed operation of feedback control
- Suppression of better than 40 dB by applying I gain.
- (P, I) = (0.398, 4e-4) for wider valley and smaller unwanted enhancement around the valley.
- In the case of 9 MHz and 2 stage Tracking CIC, increasing P gain increases unwanted enhancement around the valley.
  → Tracking CIC + Leaky Integrator is selected.

Measurement and Simulation of Open Loop Gain

Confirm measurements of closed loop gain by comparison with simulations

→ Evaluate delay of the system by comparison between a measurement and a simulation of open loop gain

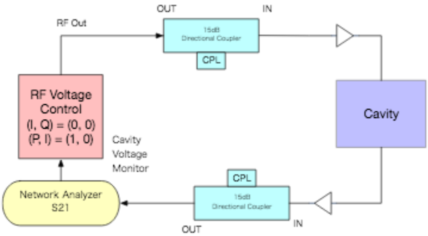


Figure 13: Setup for measurements of open loop

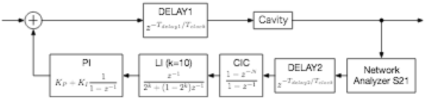


Figure 14: Simulation model of open loop.

Adjust $T_{delay1} + T_{delay2}$ so that the simulation matches the measurement.

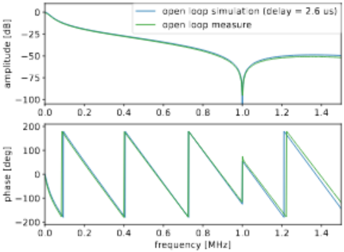


Figure 15: Comparison between the measurement and the simulation.

$$T_{delay1} + T_{delay2} = 2.6\mu s$$

Simulation of Closed Loop Gain

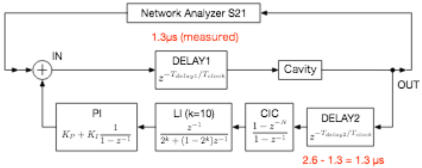


Figure 16: Simulation model of closed loop.

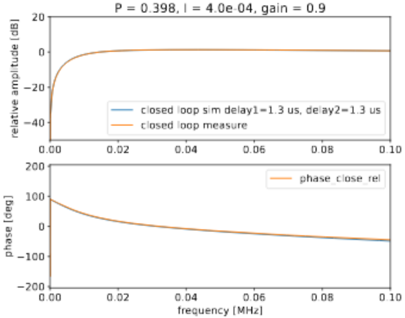


Figure 17: Simulation and Measurement of the closed Loop gain at base band.

The simulation agrees with the measurement well.

Step Response

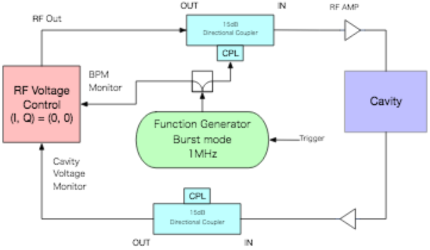


Figure 18: Setup for measurements of step response

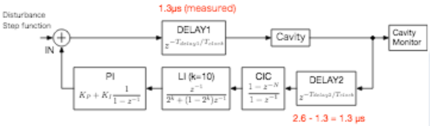


Figure 19: Simulation model of step response.

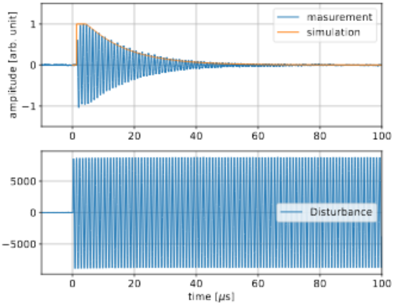


Figure 20: Comparison between the measurement and the simulation of step response. $(K_P, K_I) =$ (0.398, 4e-4)

- Settle down to zero without oscillation.
- The simulation agrees with the measurement well.

Processing of Beam Position Monitor Signals

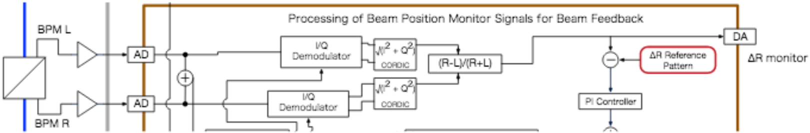


Figure 21: Circuit of BPM signal processing.

- Diagonal cut rectangular electrode
- Evaluate amplitude of R/L signals $2\sqrt{I^2+Q^2}$ after I/Q demodulation
- Beam position : $(R-L)/(R+L)$
    - Feedback control of beam position with RF frequency
- Detect phase oscillation with phase difference between RF and BPM signals.
    - Suppress phase oscillation.

Off-beam Commissioning of BPM Signal Processing (1)

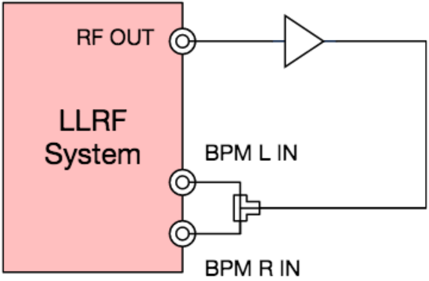


Figure 22: Setup of commissioning for BPM signal processing

- Input same signals to BPM R と BPM L
- Sweep frequency (0.8-6.25MHz)
- Comparison LPF for IQ demodulator
  - 2 stage Tracking CIC
  - Tracking CIC + Leaky Integrator (k = 10)

Off-beam Commissioning of BPM Signal Processing (2)

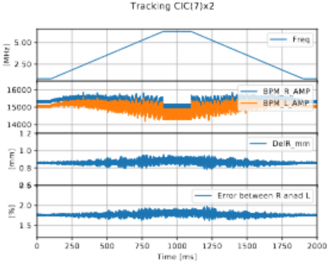


Figure 23: Stability of operation result of BPM signal with 2 stage Tracking CIC.

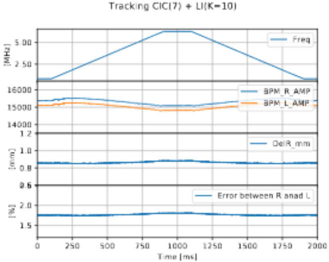


Figure 24: In the case of Tracking CIC + Leaky Integrator

- $\sim$0.1 % of drift of ΔR.
- The fluctuation is large in the case of 2 stage Tracking CIC.
- Since the pass band is wide, the influence of noise may be appearing.
- Tracking CIC + LI is selected.

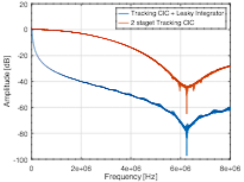


Figure 25: Comparison of frequency responses for $f_{rev} = 6.25$MHz

Simulation of Detection of Phase Oscillation

- A sum signal of BPM R and BPM L is used.
- Check ability to detect phase oscillation when Tracking CIC + Leaky Integrator is used as LPF.

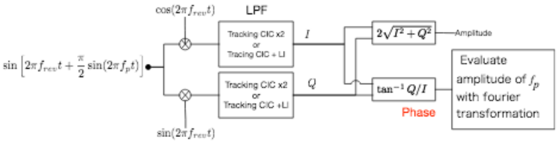


Figure 26: The simulation model for detection of phase oscillation

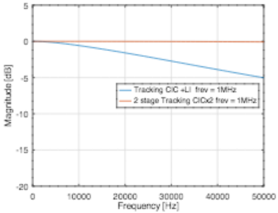


Figure 27: Frequency response of the circuit to detect phase oscillation.

- -2dB attenuation in frequency domain (< 2kHz) of phase oscillation is enough small.
- It may be possible to detect phase oscillation.

Summary

- New LLRF Control system based on MTCA.4 is under development.
- Off-beam commissioning are preformed.
  - Phase offset/gain LUT
  - Measurements of closed loop gain and PI gain search
  - step response
  - Comparisons between simulations and measurements show good agreements
  - Selection of LPFs in the IQ demodulator for BPM signal processing.

Future Plan

- VCO is replaced to fix instability of clock.
  - By the way, the system clock is changed to 300 MHz.
- Development of operation interfaces
- Beam Commissioning.

Tracking CIC Filter

CIC Filter

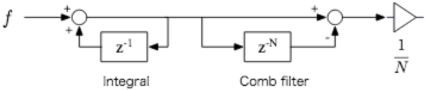


Figure 28: The circuit of CIC

$$H(z) = \frac{1 - z^{-N}}{1 - z^{-1}} \quad (1)$$

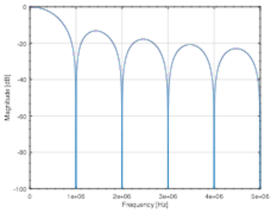


Figure 29: Frequency characteristics of CIC filter. Periodic notches occur.

Tracking CIC Filter

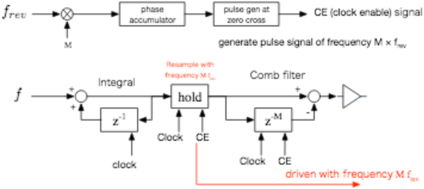


Figure 30: The circuit of tracking CIC filter

- Notces at $f = hf_{rev}$.
- Frequency of notch follows hf_{rev}.
- Harmonics other than selection can be effectively removed.

Leaky Integrator

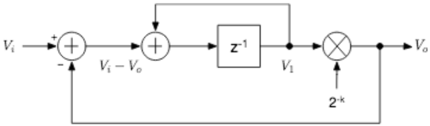


Figure 31: Circuit of leaky integrator

$$H(z) = \frac{2^{-k}z^{-1}}{1-(1-2^{-k})z^{-1}} \quad (2)$$

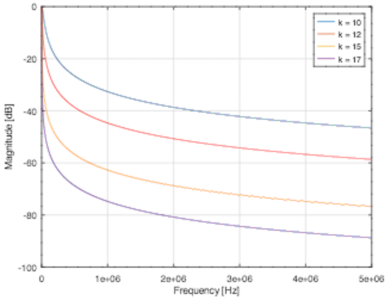


Figure 32: Frequency characteristics of leaky integrator (k = 10)

LPF with small number of operations.

AM/PM COnverter

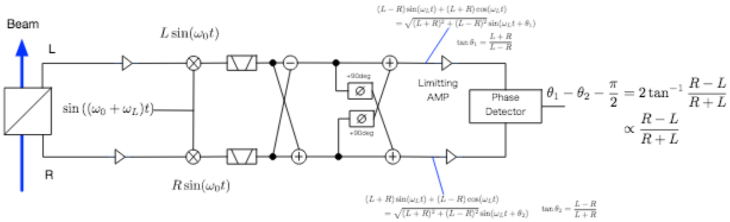


Figure 33: Circuit of AM/PM converter to process BPM signals.

- AM/PM converter evaluate horizontal beam position form BPM signals.
  - Convert difference of amplitudes to phase difference which is detected by phase detector.
- The calculation result changes, when the input signal level changes (Fig. 34) .
  - It seems that error of output of the phase detecter increases if the signal level is too small or too large.

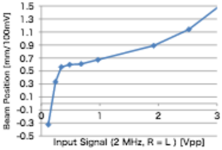


Figure 34: Varying input signal level of sine wave of 2MHz.

Updating Frequency

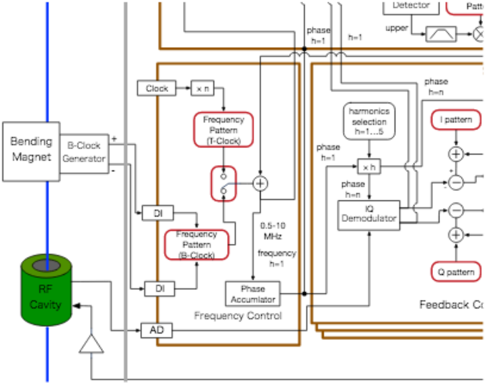


Figure 35: Frequency control part

- Frequency update can be selected :
  - B-Clock Number of pulses propotional to change of a BM.
  - T-Clock Periodic clock synchronized with the timing system.
- Update the phase accumurater with B-Clock or T-Clock
- Used as a reference signal for IQ modulators/demodulators