DEVELOPMENT OF A MICROTCA.4-BASED FEEDBACK SYSTEM FOR ENVIRONMENTAL PHASE COMPENSATION OF THE BEAM-MONITOR REFERENCE AT J-PARC LINAC

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Abstract

In the J-PARC LINAC, the beam monitor and LLRF systems operate with independent RF references. The LLRF system at 312 MHz and 960 MHz incorporates active environmental compensation to enhance stability. However, the 324 MHz beam-monitor RF reference lacks such functionality, resulting in humidity-dependent phase drift. To improve environmental long-term stability, we have developed a feedback-based reference compensation system implemented on a MicroTCA.4 platform. The system takes the 324 MHz beam-monitor reference from the SSA output and down-converts it to 12 MHz on the MicroRTM, enabling IF-phase measurement in the ADC**s** and fast feedback computation in the FPGA. The feedback-corrected I/Q signals drive the IQ modulator on the MicroRTM to regenerate a stabilized 324 MHz reference, which drives SSA and is redistributed to monitor stations, enabling real-time compensation of environmental phase drift with minimal additional hardware. The system is integrated into the existing LLRF infrastructure at MEBT1, achieving full synchronization, compact installation and cost-effective operation. Long-term studies demonstrated suppression of humidity-induced phase fluctuations and improved reference stability, contributing to enhanced beam-monitor reliability and supporting future high-power beam upgrades at J-PARC. This paper presents the system design, FPGA implementation, and long-term measurements characterizing humidity-induced drift and the stabilized performance with feedback.

INTRODUCTION

The linear accelerator (LINAC) at the Japan Proton Accelerator Research Complex (J-PARC) accelerates a 50 mA H^- beam to a final energy of 400 MeV for injection into the rapid cycling synchrotron (RCS), as illustrated in Fig. 1 [1,2]. The LINAC is equipped with various beam diagnostics devices, among which fast current transformers (FCT**s**) play a key role in beam phase measurements [3] used for phase scans during commissioning [4–6].

The LINAC employs separate RF reference systems for low-level RF (LLRF) control and beam diagnostics. The LLRF system operates at 312 MHz and 960 MHz, based on a down-conversion and intermediate-frequency (IF) sampling scheme [7], and uses a phase-stabilized optical distribution scheme maintained in a temperature- and humidity-controlled environment to ensure high phase stability as part of the original LLRF design [8, 9]. In the legacy cPCI system, the beam diagnostics reference is derived from the LLRF RF&CLK board (324 MHz) and fed to a semiconductor amplifier (SSA), then distributed via coaxial cables to the LINAC monitor systems through directional couplers. This configuration provides synchronization with the LLRF system but was not designed with active environmental compensation, and has been successfully used for commissioning measurements over long-term LINAC operation (Fig. 2a).

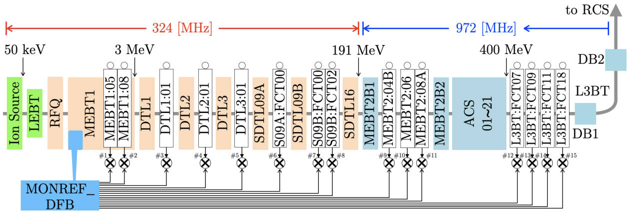

Figure 1: Layout of the J-PARC LINAC highlighting relevant sections and FCT locations used for phase measurements. The symbols ⊗ denote analog phase detectors.

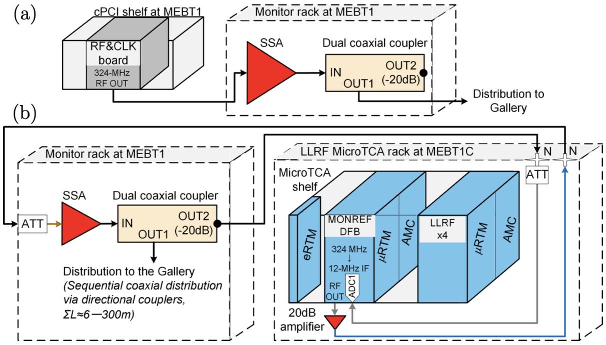

Figure 2: Schematic of the monitor RF reference generation system: (a) conventional configuration without feedback; (b) upgraded MicroTCA.4-based configuration with feedback.

Recent observations have revealed that the Monitor RF reference signal is susceptible to environmental effects, particularly humidity-induced phase drift in the klystron gallery, leading to degradation of long-term phase measurement stability. To address this issue, we leverage existing LLRF infrastructure by implementing a feedback-based RF reference compensation system, referred to as MONREF_DFB, within same MicroTCA.4 shelf using a μRTM and an AMC-based digitizer, replacing the legacy cPCI-based platform. The

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modules share reference clock, power supply, and communication infrastructure, enabling synchronized operation with the LLRF system and real-time correction of RF reference phase and amplitude. In the upgraded configuration (Fig. 2b), the RF reference signal is generated directly from the µRTM RF output and amplified by the SSA. The directional coupler output (OUT1) is distributed to each RF station, while the coupled output (OUT2) is fed back to digitizer ADC, forming a closed-loop feedback system for stabilization. This paper presents the development and implementation of the MONREF_DFB system and demonstrates its effectiveness in suppressing environmental phase drift, thereby improving the reliability of beam diagnostics in the LINAC and supporting enhanced RF stability.

FIRMWARE

The 324 MHz RF signal from OUT2 of the Monitor SSA is down converted to a 12 MHz intermediate frequency (IF) and digitized by a 16-bit ADC operating at 240 MHz, employing oversampling. The system operates in continuous-wave (CW) mode, as the Monitor RF reference is distributed as a CW signal. The digitized signal is processed in the FPGA to extract I/Q components, enabling phase and amplitude monitoring of the RF reference. The FPGA implements I/Q conversion, calibration, filtering, and feedback/feedforward control, as illustrated in Fig. 3.

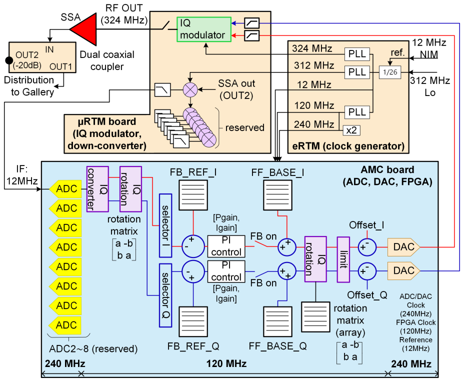

Figure 3: Firmware architecture of the MONREF_DFB system implemented on the MicroTCA.4 platform.

The core feature of the firmware is a feedback-based RF reference stabilization scheme implemented within the FPGA. The measured I/Q signals are compared with reference values generated from EPICS-configured parameters ($A_{\mathrm{FB\_REF}}$, $\theta_{\mathrm{FB\_REF}}$), and the resulting error is corrected using a digital PI controller. In parallel, a feedforward table ($\mathrm{FF}_{\mathrm{BASE}}$), defined by EPICS-configured amplitude and phase settings, generates the corresponding I/Q waveforms.

The combined feedback and feedforward signals are converted to DAC outputs, which drive an IQ modulator to generate 324 MHz RF for the SSA, thereby forming a closed-loop system for real-time stabilization of the Monitor reference. Detailed implementation of digital feedback and signal processing architecture can be found in Refs. [7, 10]. Related FPGA-based LLRF and MicroTCA.4 control architectures have been reported at other accelerator facilities [11–16].

RESULTS

Long-term Measurements

At FEEDBACK OFF (Fig. 4a), the Monitor RF reference phase directly follows environmental variations in the klystron gallery. The ADC phase exhibits clear humidity-dependent drift, showing strong correlation with the gallery relative humidity. A humidity variation of ≈21.00 %Rh results in a phase deviation of about 1.32 deg, where $\Delta\phi = \phi_{\mathrm{ADC}} - \langle\phi_{\mathrm{ADC}}\rangle$ denotes the ADC phase deviation relative to its mean value over the measurement period.

In addition, temperature variations introduce short-term transient phase perturbations. A rapid temperature change of ≈0.60 °C produces a phase excursion of about 0.40 deg, superimposed on the humidity-driven trend. Since no corrective action is applied at FEEDBACK OFF, the observed ADC phase drift represents the intrinsic environmental sensitivity of the Monitor RF reference path. This behavior establishes the baseline for evaluating the effectiveness of the feedback compensation. The temperature-induced phase perturbations appear as short-duration deviations, whereas humidity induces a dominant long-term drift.

At FEEDBACK ON (Fig. 4b), the ADC phase remains stable over time, demonstrating effective suppression of humidity-induced drift. The DAC phase (corresponding to the SSA input) tracks humidity variations and provides the required compensation. Specifically, a 20.00 %Rh peak-to-peak humidity variation results in an approximately 1.30 deg peak-to-peak DAC phase adjustment, maintaining a constant Monitor RF reference phase.

Compared to the FEEDBACK OFF case (≈0.63 deg/10.00 %Rh sensitivity), the ADC phase variation at FEEDBACK ON is suppressed to within ±0.04 deg, despite similar humidity fluctuations. This corresponds to more than an order-of-magnitude reduction in phase variation. Using the LLRF RF reference, whose dedicated distribution system provides significantly higher environmental stability, as a baseline, it is confirmed that the stand-alone 324 MHz Monitor RF reference exhibits inherent humidity-dependent phase drift. The implemented feedback system successfully compensates for this effect, and stable FEEDBACK ON operation has been maintained during LINAC operation.

Beam Study Results

A beam-based evaluation was conducted to verify the impact of Monitor RF reference phase on measured beam phase. The nominal operating conditions were set to the feedback and feedforward amplitudes $A_{\mathrm{FB\_REF}} = A_{\mathrm{FF\_BASE}} = 16500$ (arb. units) and phases $\theta_{\mathrm{FB\_REF}} = \theta_{\mathrm{FF\_BASE}} = 30$ deg. The amplitude was fixed, while the reference phase was intentionally varied by ±1 deg, ±2 deg, ±3 deg, and ±10 deg, with the cavity-RF fields maintained stable by LLRF system.

Beam phase measurements were performed using the beam monitor digitizer (BMONDIG) [17] at multiple locations along the LINAC. The FCT signals were processed

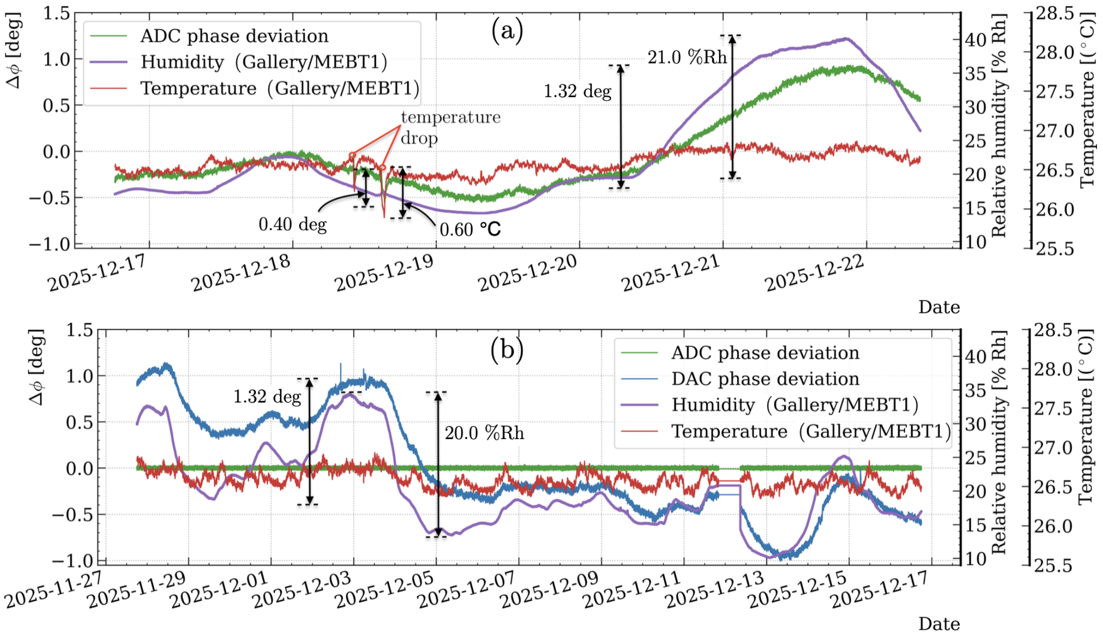

Figure 4: Long-term measurements under (a) FEEDBACK OFF and (b) FEEDBACK ON. The ADC phase shows humidity-dependent drift at FEEDBACK OFF, while stable phase is maintained at FEEDBACK ON via DAC compensation. The gap that appears between Dec. 11 to Dec. 13 corresponds to a temporary interruption of data acquisition.

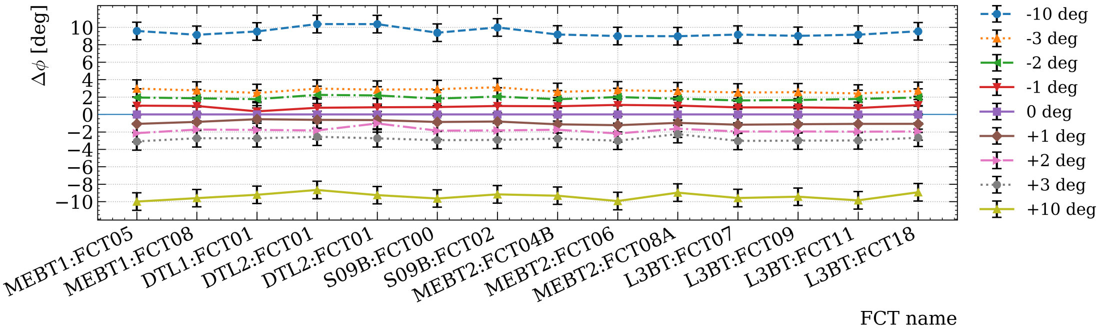

Figure 5: Beam phase response to intentional variation of the Monitor RF reference phase. Applied phase offsets (±1 deg, ±2 deg, ±3 deg, ±10 deg) produce corresponding shifts in measured beam phase at multiple FCT locations, demonstrating consistent phase propagation. Error bars indicate the FCT phase measurement accuracy (≈1 deg).

using analog phase detectors referenced to the stabilized 324-MHz Monitor RF signal generated by the MONREF_DFB system, with an accuracy of approximately 1 deg [4, 18].

The measurements were performed at multiple stations along the LINAC, including MEBT1, DTL, SDTL, MEBT2, and L3BT sections. The results show that intentional changes in the Monitor RF reference phase produce corresponding shifts in the measured beam phase across all FCT locations (see Fig. 5). The observed beam phase variation closely follows the applied reference phase change, confirming the critical importance of a stable Monitor RF reference for beam diagnostics.

CONCLUSION

Our feedback-based RF reference compensation system makes a novel contribution by enabling synchronized operation and real-time correction of phase and amplitude, thereby improving Monitor RF reference stability and supporting stable LINAC operation. Addressing humidity-dependent long-term phase drift observed in the conventional Monitor RF reference at the J-PARC LINAC, the proposed system suppresses phase variations by more than an order of magnitude. Long-term measurements show that the conventional system exhibits a sensitivity of ≈0.63 deg/10.00 %Rh while with feedback the phase variation is reduced to within ±0.04 deg under similar environmental conditions. The DAC phase tracks environmental variations, providing effective compensation and maintaining stable reference conditions.

Phase variations in Monitor RF reference produce proportional offsets in FCT-measured beam phase, as confirmed at multiple locations along LINAC (Fig. 4). The implemented feedback system suppresses these variations, enabling beam diagnostics stability comparable to that of the LLRF system.

ACKNOWLEDGMENTS

The authors thank the LINAC commissioning group members for their invaluable assistance and Dr. Akihiko Miura (JAEA) for valuable discussions on beam diagnostics.

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