AN UPDATED LLRF CONTROL SYSTEM FOR THE TLS LINAC

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Abstract

The amplitude and phase of the RF field at the linear accelerator (LINAC) decides the beam quality. To study and to improve the performance of the LINAC system for Taiwan Light Source (TLS), a new design of a low-level radio-frequency (LLRF) control system was developed and set up for the TLS LINAC. The main components of the LLRF control system are an I/Q modulator, an Ethernet-based arbitrary waveform generator, a digital oscilloscope and an I/Q demodulator; these are essential parts of the LLRF feed-forward control. This paper presents the efforts to improve the LLRF control system. The feasibility of the RF feed-forward control will be studied at the linear accelerator of TLS.

INTRODUCTION

The beam quality of a 50-MeV linear accelerator (LINAC) is determined by the flatness of the RF field amplitude and phase. Both parameters depend primarily upon the performance of the klystron modulator and the beam-loading effects. A well-tuned pulse-forming network is not achieved easily but is essential to produce an effective microwave pulse for the linear accelerator. To eliminate tedious tuning of the pulse-forming network, a RF feed-forward system might be another, and alternative, solution to improve the performance. Not only beam-loading effects can be compensated but also the effects of slow drift due to various causes can be removed with a RF feed-forward control [1-3]. The feasibility of RF feed-forward control was studied recently at the linear accelerator of Taiwan Light Source. The efforts will continue as R&D topics to study the control algorithm and the RF control hardware development. Improvement of the operational performance of the injector to support top-up operation of TLS requires further exploration.

LINAC SYSTEM

The pre-injector of TLS consists of a 140-kV thermionic gun and a 50-MeV linear accelerator system of traveling-wave type. A synoptic view of the pre-injector is shown in Fig. 1. The microwave system was composed of a multiplier that generates 2998 MHz from 499.654 MHz, a 1-kW GaAs solid-state RF amplifier, and a high-power klystron amplifier. The high-power klystron is powered with a 80-MW modulator based on a pulse-forming network (PFN). The PFN is charged with a switching power supply. An analogue I/Q modulator is placed in front of the GaAs amplifier to control the amplitude and phase of the RF field fed into the linear accelerator. An analogue I/Q demodulator is used to detect the RF signal from the outlet of the linear accelerator.

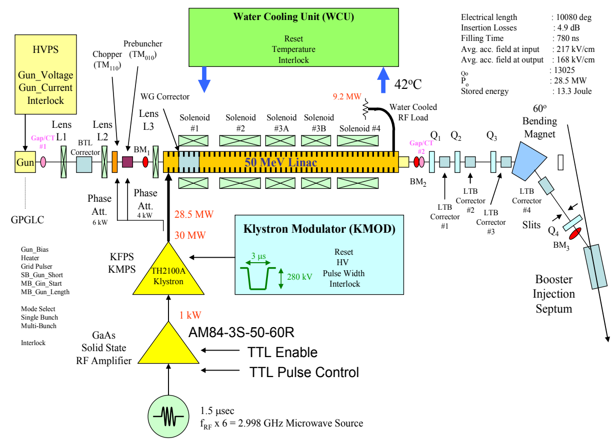

Figure 1: Synoptic of the 50-MeV linear accelerator system at TLS.

DESCRIPTION OF THE LLRF SYSTEM

Overview

A functional block diagram of the low-level RF system for the linear accelerator of TLS is shown in Fig. 2. This system consists of a clock generator, an arbitrary waveform generator (AWG), an analogue-type I/Q modulator, a GaAs solid-state RF amplifier, a high-power klystron and a klystron modulator, an analogue-type I/Q demodulator and a digital oscilloscope.

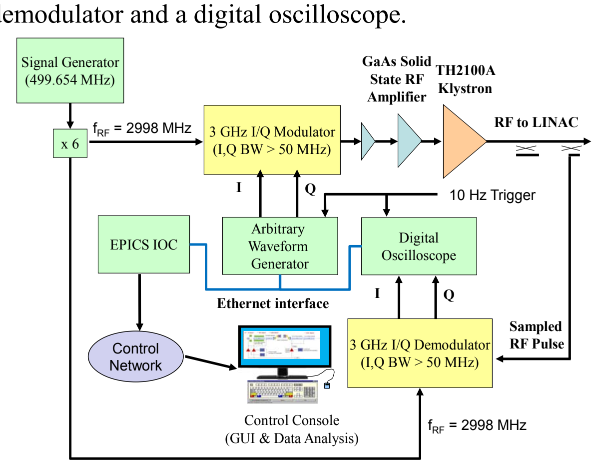

Figure 2: Block diagram of the updated low-level RF system for the 50-MeV linear accelerator; it is a feed-forward-enable system.

The arbitrary waveform generator serves to generate an in-phase (I) and a quadrature-phase (Q) control waveform as an input to the I/Q modulator. The pickup RF signal at the LINAC output is detected with the I/Q demodulator to

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obtain in-phase and quadrature-phase (I and Q) components of the RF field. The RF amplitude and phase are acquired with a simple calculation from the I and Q signals. The AWG and oscilloscope are connected to the EPICS-IOC via a private Ethernet. The AWG and the oscilloscope can be accessed in the EPICS environment [4].

I/Q Modulator and Demodulator

In this section, the I/Q modulator and demodulator are described briefly. Figure 3 shows a block diagram of the I/Q modulator and demodulator. The I/Q modulator mixes the I signal with the RF-carrier sine wave, and mixes the Q signal with the same RF-carrier sine wave at a phase offset 90º, as shown in Fig. 3, upper part.

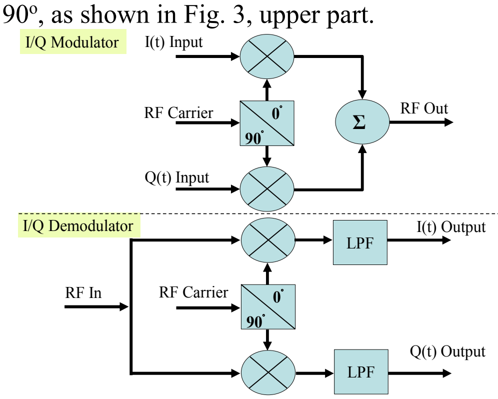

Figure 3: Block diagram of the I/Q modulator and demodulator for the low-level RF system.

The two signals are combined into the output signal, of which the amplitude and phase can be represented with a new vector; it can be derived from the I signal and the Q signal. On simultaneously controlling the two control voltages applied to the I and Q signals, we obtain an output signal with an arbitrary amplitude, phase and pulse length. One 250-MHz programmable AWG (33522A) is used to control the I and Q signals; the generator has resolution 16 bits in the LLRF system. The RF output from the I/Q modulator is expressed in Eq. (1). The in-phase component I(t) and quadrature-phase component Q(t) signals from Eq. (2) and Eq. (3) are used to control the amplitude and phase of the RF output.

$$A(t)\sin(\omega t+\theta(t)) = I(t)\sin(\omega t)+Q(t)\cos(\omega t) \quad (1)$$

$$I(t) = A(t)\cos\theta(t) \quad (2)$$

$$Q(t) = A(t)\sin\theta(t) \quad (3)$$

The phase and amplitude of the RF signal are reconstructed with an I/Q demodulator. The RF signal is split; two equal signals are then separately mixed with an RF carrier signal (phase offsets 0° and 90°). A digital oscilloscope (DSO9024H, resolution 12 bits) is used to read I and Q signals. We thus obtain simultaneously the amplitude *A(t)* and phase *θ(t)* of the RF signal according to the following equations:

$$A(t) = \sqrt{I^2(t)+Q^2(t)} \quad (4)$$

$$\theta(t) = \arctan(Q/I) \quad (5)$$

The reconstructed amplitude and phase signals from Eq. (4) and (5) are used to monitor the amplitude and phase of LINAC RF. The lower part of Figure 3 shows a block diagram of the I/Q demodulator.

EPICS Waveform Support for LLRF System

A high-resolution oscilloscope and an arbitrary waveform generator (resolution 16 bits) are used for observing and producing I and Q signals of the LLRF control system. One dedicated EPICS IOC was set up to implement EPICS support and communicates with the oscilloscope and arbitrary waveform generator via an Ethernet interface. To implement the EPICS support of Ethernet-based instrument devices, one workstation computer is set up the EPICS environment as the EPICS IOC. The StreamDevice and ASYN driver are required, and are employed to communicate with the oscilloscope and the arbitrary waveform generator through the Ethernet interface [5]. A protocol file that defines all required functions with Standard Commands for Programmable Instruments (SCPI) commands for communication with instrument devices has been created for the StreamDevice. The ASYN driver supports TCP or VXI-11 for communication with message-based instrument devices. The related records of the EPICS database have been created with a link to the StreamDevice. The channel access (CA) client with OPI applications or lab-CA client with a MATLAB program can be used to access PV from a CA server that acquires data from a database of the EPICS IOC. A block diagram of the software architecture is shown in Fig. 4.

The 500-point waveform data of I and Q are acquired with the dedicated EPICS IOC; the rate of waveform updating is satisfied with 10 updates/s. The amplitude and phase of the LINAC RF setting/reading PV are derived from the MATLAB application in every 100 ms as shown in Fig. 4.

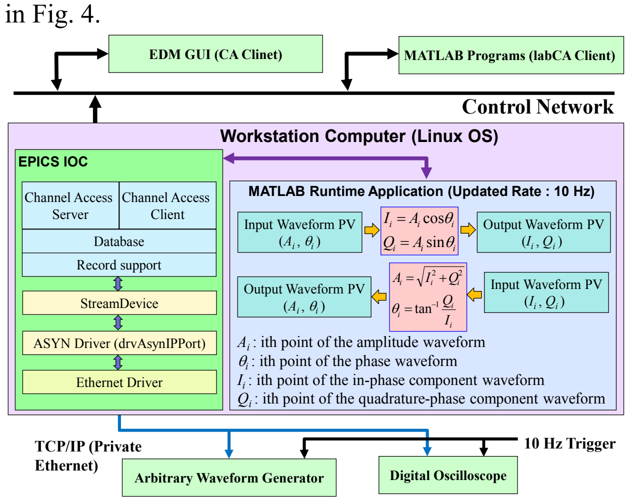

Figure 4: Software block diagram of the building EPICS support of an arbitrary waveform generator and a digital oscilloscope for LLRF control.

All calculated amplitudes and phases of the LINAC RF are formed to a waveform array and saved in the dedicated PV; specific EDM pages are created to show the amplitude and phase of the LINAC RF as in Fig. 5. To support both the existing TLS control system and the developing EPICS environment, the client consoles were set up with an EPICS environment to access the upgraded subsystems via a PV channel access from the dedicated IOC.

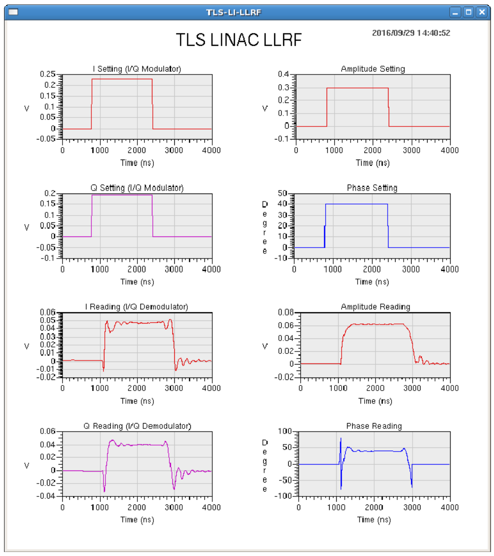

Figure 5: GUI pages for observation of the amplitude and phase waveform of the LINAC RF field.

PERFORMANCE OF THE LINAC RF FIELD

To study the performance of the LINAC RF system, the amplitude and phase of the LINAC RF field are recorded to observe the stability of the LINAC RF field. The upper part of Fig. 6 shows that the variational amplitude of the LINAC RF field is about ± 0.3 % during 100 s; the lower part of Fig. 6 shows more clearly the drift pattern of the amplitude without correction.

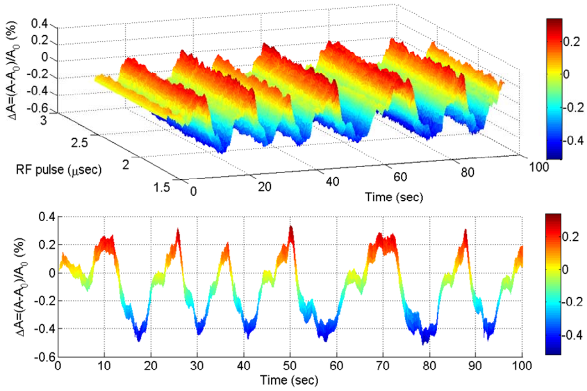

Figure 6: Variational amplitude of the LINAC RF field. A denotes amplitude; $\Delta A = (A\text{-}A_0) / A_0$ is the amplitude drift.

The phase drift of the LINAC RF field is about ± 0.4° during 100 s without correction, shown in Fig. 7. To cure the amplitude and phase drifts of the LINAC RF output, RF feed-forward control might be a solution to achieve improved performance. Apply RF feed-forward control can improve the flatness of the amplitude and phase of the RF field.

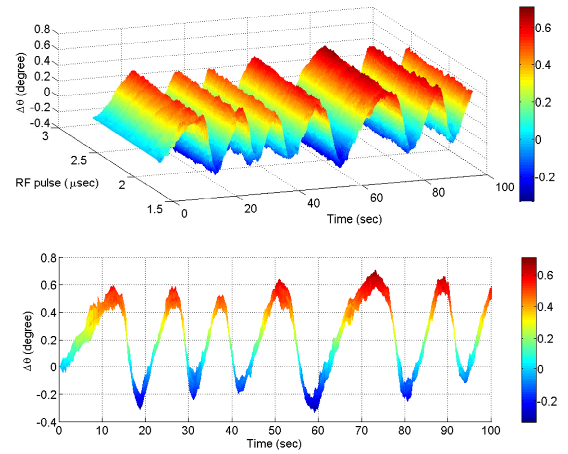

Figure 7: Measurement of the RF phase from the LINAC output without correction. θ is the phase; $\Delta\theta = \theta - \theta_0$ is the phase drift. The upper part describes that the phase variation of the LINAC RF field is about ± 0.4° during 100 s; the lower part shows clearly the drift pattern of the phase.

SUMMARY

A preliminary test run of the updated LLRF control system has been performed at the 50-MeV linear accelerator of TLS. Various EDM pages for varied purposes were created for the operation of the LINAC LLRF system. These implementations and improvements are still in progress. The drift and flatness of the amplitude and phase of the linear accelerator RF pulse will be improved after correction. Several correction algorithms of the RF feed-forward control will be studied. Efforts to improve the feed-forward control algorithm, RF electronics and data acquisition are continuing. Apply RF feed-forward correction is in plan. The beam quality of the LINAC, in terms of its energy spectrum, is also continuing to be improved.

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