Design Study of Low-Level RF Control System for CW Superconducting Electron Linear Accelerator in KAERI

Seunghyun Lee [1*], Yujong Kim [1, 2†], In-Ha Yu [3], Myung-Hwan Chun [3], Jaeyong Lee [1], Youngwoo Joo[1, 2], Hyeri Lee [1, 2], Ingyo Jung[1, 2], Moonyoung Han[2] and P. Buaphad [1,2]

[1]Korea Atomic Energy Research Institute, Daejeon 34057, Korea
[2]University of Science & Technology, Daejeon 34113, Korea
[3]Pohang Accelerator Laboratory (PAL), Pohang 37676, Korea

* lsh0810@kaeri.re.kr, †yjkim@kaeri.re.kr

Abstract

Korea Atomic Energy Research Institute (KAERI) has been operating a 20 MeV superconducting RF linear accelerator (SRF LINAC) to conduct research on atom/nuclear reaction using neutron Time-of-Flight (nTOF). It can accelerate electron beams up to 20 MeV with 1 kW continuous wave (CW) operation mode. Unfortunately, this machine has been aged over 15 years that brings about considerably difficulty in normal operation due to the performance degradation of sub-systems. To normalize the operation condition of 20 MeV SRF LINAC, we has been carrying out an upgrade project with replacement and repair of old sub-systems from 2018. This paper describes a design study of Low-Level RF (LLRF) control system to improve the stability and acceleration efficiency of the electric field generated in the superconducting RF cavity structure of 20 MeV SRF LINAC

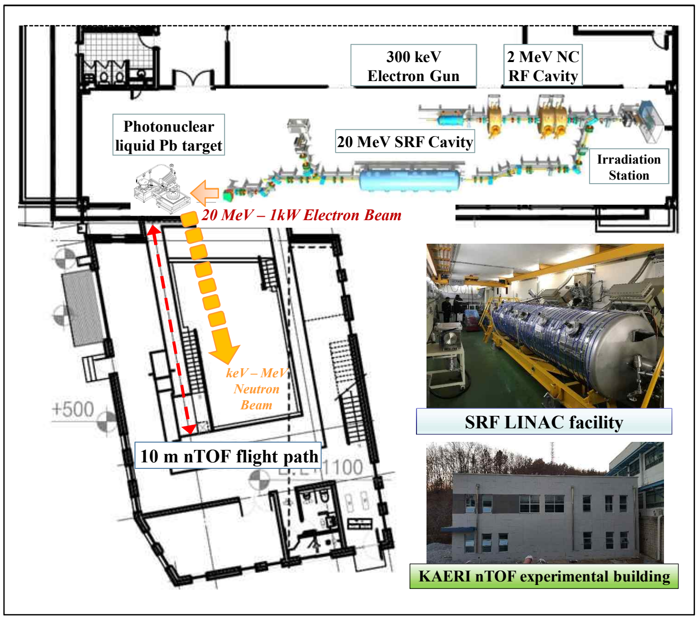
INTRODUCTION

The nTOF method is generally used to measure and verify the neutron cross-section data of major actinides, minor actinides, and photo nuclear reaction library [1]. To produce neutron cross-section data from keV up to MeV range, KAERI nTOF facility was started from early 2016. It will be mainly used to measure nuclear data [2].

To produce neutron beams in nTOF facility, we apply the photonuclear reactions in a target filled with liquid lead (Pb). An incident electron beam produces bremsstrahlung photons, and then bremsstrahlung photons bring about photonuclear chain reaction (γ,n) in the target. It can generate neutrons with a white spectrum [3]. Finally, neutrons go through nTOF experimental building with 10 m flight-path to analyze experiment results. To generate electron beam in KAERI nTOF facility, SRF LINAC is used as an injector. It can accelerate electrons up to 20 MeV kinetic energy with 1 kW continuous operation mode. Two 352 MHz SRF cavities with a cryomodule were fabricated by CERN for the Large Electron-Positron Collider (LEP) facility [4]. To operate those SRF cavities, we installed a RF generator, a Helium refrigerator, a vacuum stage, a control system and a cooling system collaborating Budker Institute of Nuclear Physics (BINP), Russia in 1996.

Unfortunately, a fire accident occurred at 2003, sub-systems of RF generator and Helium refrigerator were broken or malfunctioned. In addition, many components of SRF LINAC outdated due to 15 years operating duration.

To solve those problems, we have been carrying out an upgrade project by replacing or repairing old RF sub-systems since 2018. In this paper, we review RF sub-systems of the SRF LINAC and design a new LLRF system based on digital signal processing to improve beam stability and accelerating efficiency.



< Overview of KAERI nTOF Facility>

SYSTEM OVERVIEW

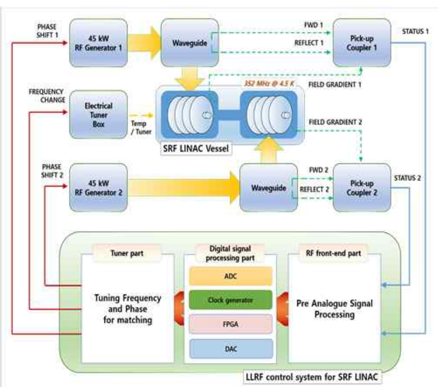


Table 1: Operating parameters of SRF LINAC

Parameter	Value
Resonating frequency	352 MHz
Power transmit (P_{RF})	45 kW
Maximum Accelerating Energy	20 MeV
Beam current (I_b) @ CW mode	1 mA
Operating temperature	4.5 K
Cavity type	Nb coated Cu
Number of cell	4-cell in 1 cavity
Q-factor (Q_0)	3.4×10^9 @ 6 MV/m
Characteristic Impedance (r/Q)	500 Ω
Standing Wave Ratio (SWR)	< 1.1

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DESIGN OF LLRF CONTROL SYSTEM

Proposed LLRF control system is classified into three parts: RF front-end part, digital signal processing part, and tuner part.

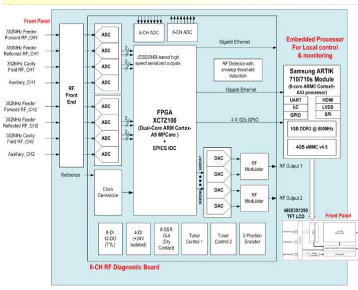
RF front-end part work for not only receiving, but also reprocessing transmit signals from RF generator to RF cavity. Input signals of RF front-end are forward power, reflect power and accelerating electric field in general. Digital signal processing part generally consists of an Analogue-Digital Converter (ADC), a clock-generation module, a Field Programmable Gate Array (FPGA) as logic board, and a Digital-Analogue Converter (DACs). Digitized sampling data go into FPGA board to compute operation frequency and power transmit level. To compare transmit signal and detecting signal, FPGA board derives output command to change operating parameters of RF system. Finally, tuner part adjusts tuning rods to change operating frequency, or shifts phase value to match reference power level.

Table 2: LLRF system requirement parameter

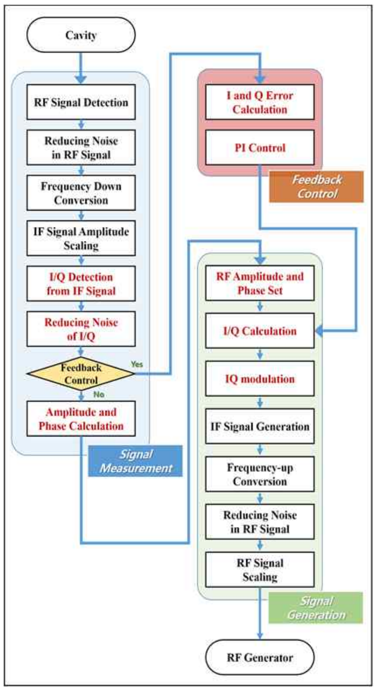
Parameter	*Value*	*Note*
Center Frequency	352 MHz	f_0
Bandwidth	~ 100 kHz	Δf_{3dB}
Phase Control Stability	≤ 0.1 deg	RMS
Amplitude Control Stability	< 0.1%	RMS
Phase Acceptance	± 50~80°	
Dynamic range	> 20 dB	Nominal Gradient Range
Set Point Resolution	≤ 0.1%, 0.1 deg	SNR Digital Resolution
Thermal Stability	± 0.05 dB	10℃< T<40℃

METHOD AND MATERIALS

Detection signals from SRF LINAC is processed in RF front-end and ADC module by IQ sampling method. To convert frequency to handle in FPGA, we use digital down convertor at an intermediate frequency in a traditional heterodyne scheme. Pick up signals from direction coupler or RF cavity are processed in FPGA with proportional plus integral (PI) algorithm [5]. To generate output signal, IQ demodulation process will be run to convert analogue operation command. To develop LLRF control system, we design architecture of digital LLRF. It consists of two ADC modules, one FPGA module, one clock generator, one Digital Input (DI)-Digital Output (DO) module, and one DAC module with Experimental Physics and Industrial Control System (EPICS) Input/Output Controller (IOC) [6].



< Design Architecture of Digital LLRF Bard >



< Flow-chart of Digital Signal Process in LLRF >

RESULTS AND DISCUSSION

We introduced KAERI nTOF facility and SRF LINAC system. To evaluate performance, we proposed conceptual design of LLRF control system based on digital signal processing. It has advantages to increase beam stability and acceleration efficiency for CW mode in superconducting accelerator. In the future, we will accomplish design optimization to improve performance. Finally, we will fabricate whole system and conduct performance evaluation to verify operating result data and compare to the design characteristics.

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