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UPGRADE OF THE NewSUBARU CONTROL SYSTEM

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Abstract

A new dedicated electron injector linear accelerator (linac) was constructed for the soft X-ray synchrotron radiation facility, NewSUBARU. The SPring-8 linac was used as the injector at the facility since its operation started. However, the new linac enabled NewSUBARU to operate independently from the SPring-8. The control system of the new linac and the existing storage ring must be constructed as a unified system for seamless operation. The control framework already used for the SACLA/SPring-8 was also used for the NewSUBARU. MicroTCA.4 (MTCA.4), EtherCAT, and GigE vision camera were used for the new linac control. For the storage ring control, the existing VMEbus system (VME) was used with virtually no changes. The open source version of Qt5 was selected to create a graphical user interface program (GUI). Additionally, the design of the new linac is planned to be used in the 3 GeV synchrotron radiation facility project currently under construction in eastern Japan. Similar kind of hardware and control framework will be utilized for the project.

INTRODUCTION

NewSUBARU is a soft X-ray synchrotron radiation facility with a 1.5 GeV electron storage ring having a circumference of 118 m [1]. It was built at the SPring-8 site and shared a linac of SPring-8 as an injector. The NewSUBARU started user experiments in January 2000. SPring-8 is a hard X-ray synchrotron radiation facility with an 8 GeV electron storage ring having a circumference of 1,436 m. It has a 140 m-long 1 GeV linac and an 8 GeV booster synchrotron having a circumference of 396 m as injectors and has been in service for user experiments since October 1997. SACLA is an X-ray free electron laser facility with a 400 m-long 8 GeV linac that was constructed at the SPring-8 site. The SACLA has been in service since March 2012.

In the SPring-8 upgrade project (SPring-8-II), a method for realizing an ultra-low emittance ring was studied. The plan consisted of drastically modifying the SPring-8 storage ring and injecting a low emittance beam of SACLA directly into the ring. This required the existing injectors, the linac, and the booster synchrotron of SPring-8, to be shut down. However, this would further show that NewSUBARU would no longer be operational. Therefore, a new 1 GeV linac had to be built exclusively for NewSUBARU. As it had to be installed in the existing beam transport tunnel, the linac was designed to be compact with a total length of 70 m and used C-band accelerating structures developed at the SACLA [2]. In July 2020, a beam injection from the SPring-8 linac to the NewSUBARU was completed and the installation of the new linac was started. The commissioning of the linac started in February 2021, and two months later, in April, the user experiments at NewSUBARU were resumed. Figure 1 shows the layout before and after the new linac was installed at the NewSUBARU. A picture showing the NewSUBARU building and the new annex building for the new linac is illustrated in Figure 2.

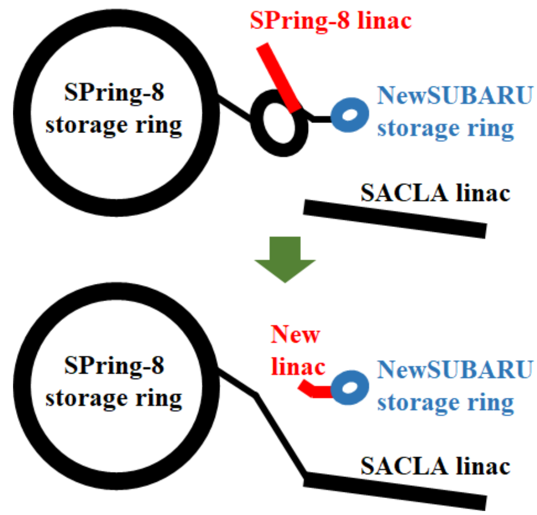

Figure 1: Layout of the NewSUBARU before and after installation of the new linac.

Figure 2: NewSUBARU building and new annex building for the new linac.

Since 1995, MADOCA control framework has been developed and used for the SPring-8 and the SACLA [3]. In 2018, the MADOCA was upgraded for integrated operation of the SACLA and SPring-8 as part of the SPring-8-II [4-6]. Using this new control system, beam injection from the SACLA to the SPring-8 storage ring was started in 2020.

The NewSUBARU has adopted MADOCA as its control system since its introduction. With the construction of the new linac, it was natural to completely shift from the first MADOCA to the upgraded one. To operate the new linac and the existing storage ring together, a file server, the database servers, and the computer networks required further upgrading.

When upgrading an existing facility, the shutdown period must be as brief as possible. To achieve this, advance

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careful preparation and an efficient work plan for the shutdown period are vital. It was expected that changing the VME of the storage ring would require tremendous work, such as, checking the I/O of the equipment. Hence, it was decided to leave the VME mostly unchanged. In contrast, all the servers, networks, and software were upgraded.

This paper reports the upgraded NewSUBARU control system.

EQUIPMENT CONTROL OF THE NEW LINAC

MTCA.4

The RF system of the new linac consists of a gridded RF thermionic gun, a 238 MHz RF cavity, a 476 MHz subharmonic buncher, an S-band accelerating structure, and 16 high-gradient C-band accelerating structures. The low-level RF (LLRF) system of the SPring-8 storage ring was updated from conventional analog circuits to digital circuits using the MTCA.4 in 2016. From then on, the MTCA.4 has been operating for the LLRF system [7, 8]. Additionally, the MTCA.4 was selected for the LLRF system of the new linac.

As a high-speed AD/DA board for IQ modulation and demodulation of the RF signals, the Struck SIS8325 AMC board was utilized. This board had 10-channels of 250 Ms/s 16-bit ADCs, 2-channels 250 Ms/s 16-bit DACs, and an FPGA. For the FPGA logic, the following additional features were implemented along with the original logic: converting the data detected by the ADCs to the IQ signals; collecting the data at a fixed delay time from a master trigger signal of the linac; storing the waveforms in memory banks; and reading them out using a DMA transfer.

For the Rear Transition Modules (RTMs), which are responsible for the RF signal I/O and level adjustment, a newly manufactured Candox 72DSR238A01 direct sampling board was used for 238 MHz and Struck DWC8VM1 down-conversion boards were used for other frequencies.

In 2018, a test bench of a gridded RF thermionic gun, a 238 MHz RF cavity, and a 476 MHz sub-harmonic buncher for the linac was constructed and the operation of the MTCA.4 was tested for them.

The C-band accelerating structure system for the linac was tested in May 2020 to evaluate its performance, including the LLRF system using an MTCA.4. The device control software running on the MTCA.4 CPU was developed in conjunction with the test.

The same SIS8325 AMC boards were used for the readout of the nine beam position monitors (BPMs) and five beam current transformers (CTs).

A newly developed MDT MMETRG01B AMC board was used to transmit a trigger signal. This AMC board had five SFP transceivers (one input and four outputs) on the front panel and was connected to the other boards via optical fibers. A high-speed serial signal with a bit rate of 1 Gbps and 8B/10B encoding was used to transmit the event code that defines when the trigger signals should be output. The delay time of the trigger signal could be set using a 24-bit coarse delay counter with a 238 MHz clock and a 5-bit fine delay counter with 78 ps resolution. The board could handle 16 inputs and 16 outputs with a dedicated level converter connected via a connector mounted on the front panel. Furthermore, eight M-LVDS lines of the MTCA.4 backplane could be used for input and output, and the trigger signals were transmitted to the SIS8325s installed in the same chassis without any additional wiring.

The MMETRG01B was installed in the LLRF section of the storage ring to generate and transmit a master trigger signal. Four MMETRG01Bs were installed in the LLRF sections of the annex building for the new linac to receive the master trigger signal. They were connected using phase-stabilized optical fibers to avoid any temperature drift effects. Table 1 summarizes the AMC modules used in the five MTCA.4.

Table 1: AMC Modules Used in the Five MTCA.4

Host	Target equipment	AMC modules
1	linac master trigger, storage ring injection magnets/monitors trigger	MMETRG01B × 1
2	linac LLRF/HPRF/vacuum of gun, 238, 476	MMETRG01B × 1, AdXMC1573 × 1, SIS8325 x3
3	linac LLRF/HPRF/vacuum of S-band, BPM × 3, CT × 4	MMETRG01B × 1, AdXMC1573 × 1, SIS8325 × 3
4	linac LLRF/HPRF/vacuum of C-band1, C-band2, BPM × 2	MMETRG01B ×1, AdXMC1573 × 1, SIS8325 × 5
5	linac LLRF/HPRF/vacuum of C-band3, C-band4, BPM × 4, CT × 1	MMETRG01B × 1, AdXMC1573 × 1, SIS8325 × 6

The MicroTCA Carrier Hub (MCH) and CPU board used were from N.A.T., and the operating system (OS) was the Ubuntu 16.04 LTS low latency kernel. The MCH had an intelligent platform management interface (IPMI) to monitor the status of each AMC board, air-cooling fan, power supply, and so on, from other servers via a network. We are testing to monitor those monitor values from a Zabbix server.

EtherCAT

The MTCA.4 was used for the devices to treat high-speed wide-bandwidth data, whereas, the EtherCAT was used for relatively slow-speed devices [9].

PLCs were used in high-power RF (HPRF), such as, klystron power supplies and vacuum controllers. The PLCs were controlled using EtherCAT. The Advanet AdXMC1573 XMC EtherCAT master board was mounted on a Vadatech AMC105 PMC/XMC carrier and installed in each MTCA.4 chassis.

Additionally, EtherCAT was also used for magnet power supply control. To reduce the construction cost, a few magnet power supplies were reused that were no longer required at other accelerator in our site. These power supplies had optical remote I/O to connect to an OPT-CC VME board developed at SPring-8 as a field bus in the past. A gateway was prepared for EtherCAT and OPT-CC to accept

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them. All the magnet power supplies were controlled using a PC server with an Advanet AdEXP5712 PCI Express EtherCAT master board.

Eight beam profile monitors were present for adjusting the beam position and shape by watching the screens. Stepper motors were driven to move the screens and adjust their focus. Moreover, the stepper motors were used to move the collimator to adjust the electron beam charge. Their positions were read by resolver counters. A second PC server with an EtherCAT master board was prepared to control the motor controllers and the resolvers.

The number of slaves for six EtherCAT masters is listed in Table 2.

Table 2: The Number of Slaves for Six EtherCAT Masters

Host	Target equipment	Number of slaves
1	linac gun PLC, 238 PLC, 476 PLC, vacuum PLC	4
2	linac S-band PLC, vacuum PLC × 2	3
3	linac C-band1 PLC, C-band2 PLC	2
4	linac C-band3 PLC, C-band4 PLC, vacuum PLC	3
5	linac magnet power supplies	65
6	linac beam profile monitor × 8, collimator, resolver counter	13

GigE Vision Camera

To watch the beam image on the screen of a beam profile monitor, a GigE vision-enabled JAI GO-2400M camera was selected [10]. A PC server was set up and two Neousys Tech PCIe-PoE354at PoE-type network interface boards and a K. K. Rocky RCB-LVDS-TRIG8 trigger input counter board were installed. Eight cameras were directly connected to each port of the PCIe-PoE354at with Ethernet cables. Power supply control via Power-over-Ethernet was also performed. The RCB-LVDS-TRIG8 received the trigger signal and distributed the LVDS standard signal to the eight cameras using an Ethernet cable. Next, the TTL standard signal was input to the camera through the LVDS-TTL translator (RCB-LVDS2TTL).

The Aravis open source library was used for camera control and to read out the image data. The collected image data were stored on an NFS server in the HDF5 format with the associated meta-information such as camera gain and shutter speed.

EQUIPMENT CONTROL OF THE EXISTING STORAGE RING

VME

The storage ring control system consisted of subsystems of RF, magnet, vacuum, monitor, utility, and safety. Each subsystem was controlled using a VME equipped with Solaris 10 OS. As the control equipment for the storage ring was practically unchanged, the same CPU board, I/O board, and chassis were utilized.

A test bench for the RF control was constructed after the shutdown of the NewSUBARU in July 2020. The test bench was prepared to identify the libraries required to transition to a new control system, such as, the gcc4. It was confirmed that the updated equipment control software would work without any challenges. The RF control was chosen for the test because it had the largest number of I/O boards to handle, and only some of them were used in the NewSUBARU.

In the MADOCA framework, the executable files, and the configuration files for the equipment control software running on the VME CPU were placed on a file server. In December 2020, a dedicated file server for the NewSUBARU was installed, and the old mount point was changed to a new one. This allowed easy transfer to the new control system.

For the electron charge measurement system, an interrupt register board was added to collect the data synchronized with the injection trigger signal. The synchronized data acquisition software was prepared using the basic functions of the new control system.

CONTROL FRAMEWORK

The new control framework of the NewSUBARU is the same as the one already in use at the SACLA/SPring-8.

In the framework, a system called the MDAQ is provided as the data acquisition software. MDAQ_POL collects data at fixed time intervals of 1 to 10 s; MDAQ_SYNC collects data synchronized with external triggers of 1 to 20 Hz; MDAQ_IMG collects image data when requested with a maximum repetition rate of 1 Hz; and MDAQ_WFM collects waveform data when requested with a maximum repetition rate of 20 Hz. The data collected by MDAQ_POL and MDAQ_SYNC were saved to an online database using the Cassandra database management system for storage. The image data collected by MDAQ_IMG and the waveform data collected by MDAQ_WFM were saved in a file server with an NFS mount, and their meta-information was saved in the online database. The number of registered signals collected by MDAQ_POL, MDAQ_SYNC, MDAQ_IMG, and MDAQ_WFM were 3,616, 729, 8, and 352, respectively.

To ensure that the NewSUBARU control system was completely independent of the SACLA/SPring-8 control system, a new file server, database servers, and a message server (MQTT broker) were installed in designated areas of the NewSUBARU building.

Moreover, the computer networks that connect the NewSUBARU building and the annex building of the linac were newly prepared.

OPERATION GUI

As the new linac was inaugurated, the NewSUBARU control room was fully operational when compared to the previous setup where the SPring-8 linac operation was separate in the central SPring-8 control room. In the new layout of the control room, the number of operator consoles

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was increased from two to six. The OS of the consoles was the SUSE Linux enterprise server 15.

Operational applications such as, accessing the log database and handling control messages are essential for maintaining the operational logic and/or sequence. They are usually in the GUI form. The open source version of the Qt5 was selected to create GUIs. The Qt plug-ins and function libraries were prepared in advance, for instance, message exchanges with child processes, forms, graph platforms, basic figure placement plug-ins, and thread-safe programming samples. For the linac, all the GUIs were newly built. For the storage ring, the old GUIs were all transferred to the Qt-based GUIs. The RF control GUI for the C-band is shown in Figure 3.

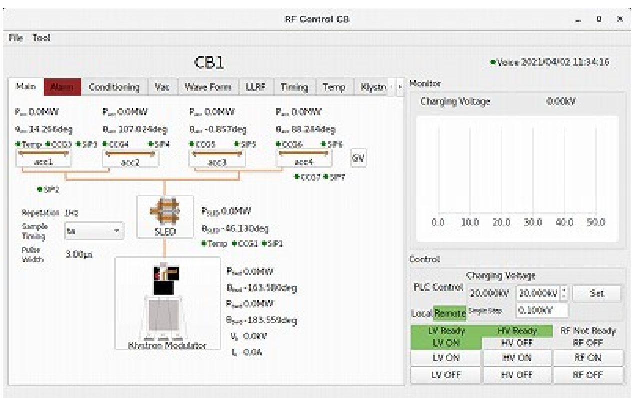

Figure 3: RF control GUI for the C-band.

CONCLUSION

The high-performance dedicated new injector linac has started its operation at the NewSUBARU. This has facilitated the continuation of user experiments after the shutdown of the SPring-8 linac. In addition, the operational flexibility of the NewSUBARU was improved.

To construct the linac, five MTCA.4s were prepared for the RF and monitor, and three PC servers for the magnet power supply and beam profile monitor. Six VMEs of the storage ring were retained with virtually no changes. The maintenance of the VMEs and its replacement may pose a challenge in the future. All the operational GUIs were created using the Qt5. Updating the control system has significantly improved the operation of the NewSUBARU.

Further, the design of the new linac is planned to be used in the 3 GeV synchrotron radiation facility project currently under construction at the Tohoku University campus in eastern Japan [11]. The project plan includes utilizing the same equipment control hardware comprising the MTCA.4, EtherCAT, and GigE camera as well as the same control framework. The project is scheduled to observe its first light in the first half of 2023.

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