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STATUS OF THE RAON SUPERCONDUCTING LINEAR ACCELERATOR*

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Abstract

RAON, being constructed as the Rare Isotope Science Project (RISP) by the Institute for Basic Science (IBS) since 2011 is a flagship heavy ion accelerator facility in Korea to promote fundamental science and application of isotope nuclei and related science. The installation of the heavy ion accelerator systems including injector, rare isotope (RI) production systems, and experimental systems are currently being progressed toward to commissioning of RAON, while the civil construction of the RAON site in Shindong, Daejeon of Korea, is completed in May 2021. The superconducting LINAC with low energy, so-call SCL3 as the 1st phase will be commissioned on the December of 2021. The overview RAON accelerator facility and status of RISP are provided.

MANUSCRIPTS PROJECT OVERVIEW

The RAON heavy ion accelerator facility is to accelerate both stable and isotope beams up to the power of 400 kW with an energy higher than 200 MeV/u and to produce rare isotopes [1]. The rare isotope (RI) production system of RAON is to have both Isotope Separation On-Line (ISOL) and In-Flight (IF) fragmentation method combined to produce rare isotope beams far from the valley of stability. The construction project for RAON facility, which is located at Shindong area near the city of Daejeon, is progressed with expectation on the commissioning of low energy facilities including injector, SCL3 and KoBRA. The SCL3 (Superconducting LINAC 3) in Fig. 1 is the post-accelerator of ISOL, which is to produce high-intensity and high-quality beams of neutron-rich isotopes with masses in the range of 80-160 by means of a 70 MeV proton beam directly impinging on uranium-carbide thin-disc targets. It accelerates ions or rare isotopes drawn from ISOL up to about 20 MeV/nucleon for low-energy experiments at Korea Broad Acceptance Recoil spectrometer and Apparatus (KoBRA).

The injector system comprises 14.5 GHz and 28 GHz electron cyclotron resonance ion source (ECR-IS), a low energy beam transport (LEBT), a radio frequency quadrupole (RFQ), and a medium energy beam transport (MEBT).

The SCL3 uses two different families of superconducting resonators, i.e., a quarter wave resonator (QWR) and a half wave resonator (HWR). The SCL31 consists of 22 QWRs with geometrical β of 0.047 and resonance frequency of 81.25 MHz. Each QWR cryomodule bears one superconducting cavity. Meanwhile, SCL32 consists of 102 HWRs with 0.12 of β and 162.5 MHz of frequency. All 102 HWRs are installed in two different cryomodules depending on the number of cavities in a cryomodule, where the 13 Type-A cryomodules bear two cavities each as the 19 Type-B cryomodules with 4 cavities each.

The SCL2 accepts a beam with energy 18.5 MeV/u and accelerates it to 200 MeV/u, with two types of single spoke resonators, as SSR1 and SSR2. The SCL2 consists of the SCL21 and the SCL22, each single spoke resonator with geometric β of 0.3 and 0.51, respectively, with same resonance-frequency of 325 MHz. The SSR1 for SCL21 is chosen mainly because it can have a larger beam radius compared to that of HWR without sacrificing accelerating efficiency. Another consideration for SSR is the robust design of mechanical structure and less severe multipaction in principle. They would provide the advantages during beam operation. The numbers of cavities of the SSR1 and the SSR2 is 69 and 150, and the cryomodules bear 3 and 6 cavities, respectively. The SCL2 provides a beam into the in-flight fragmentation (IF) system via a high-energy beam.

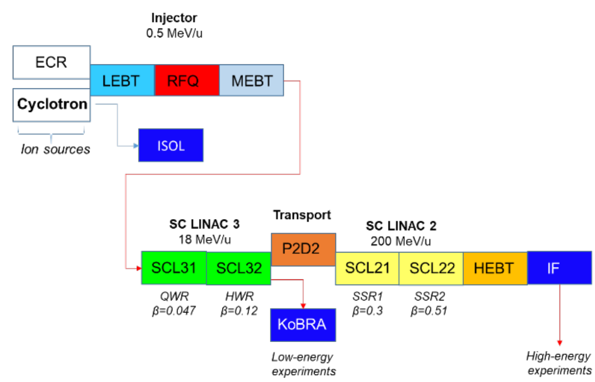

Figure 1: The schematic configuration of RAON complex.

According to the project plan, the accelerator part for low-energy accelerator SCL3 and high-energy accelerator SCL2 should be completed in 2021. But it is changed as SCL3 will be commissioned in December 2021, while the plan for SCL2 is under re-scheduling.

PREPARATION OF INJECTOR

The injector [2] as normal conducting accelerator produces ion beam bunches and accelerated to the design beam structure for SCL3 as shown in Fig. 1. The 14.5 GHz, ECR-IS is a compact permanent magnet ion source. The superconducting 28 GHz, ECR-IS, which is dedicated to extract Uranium ion beam, is under performance test. The RFQ accelerates ion beams from proton to uranium from 10 to 500 keV/u through the LEBT. One feature is that this RFQ can accelerate two different charge states, for example, of uranium beams ($^{238}U^{33+}$ and $^{238}U^{34+}$ of 12 pμA) for high-intense ion beams, simultaneously (see Fig. 2). The MEBT is designed to transport and match ion beams to the SCL3. It consists of four 81.25 MHz re-bunching cavities and eleven quadrupoles.

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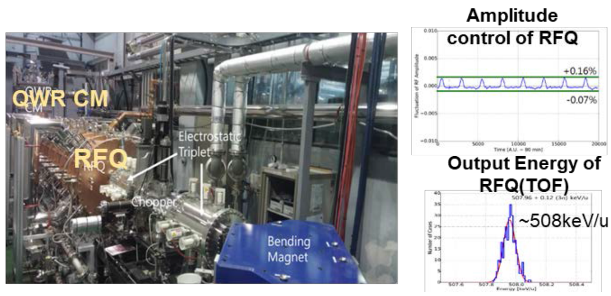

Figure 2: RFQ has been conditioned to 40 kW, possible to accelerator A/q=4.5 beams

The commissioning of injector [3] is being carried out using Argon and Oxygen beam from 14.5 GHz ECR to MEBT and is ready for SCL3 commissioning.

SUPERCONDUCTING ACCELERATORS

Four different SC cavities as shown in Table 1 structure SCL3 and SCL2 as a low-energy accelerator with QWR and HWR and a high-energy accelerator with SSR1 and 2 [4].

SC Cavities

The primary interesting point during the design optimization of SC cavities is the acceleration efficiency to reduce the accelerator cost so that the constraint of peak electric field in the cavity would be forced to be as high as 35 MV/m. The selection of SSR1 with β of 0.3 for SCL21, instead of HWR is also for the higher accelerating voltage with wider bore radius. Table 1 summarizes the parameters of four different SC cavities required for the RAON super conducting LINACs.

Table 1: Design Parameters of RAON SC Cavities [5]

Parameter	Unit	QWR	HWR	SSR1	SSR3
Frequency	MHz	81.25	162.5	325	325
βg		0.047	0.12	0.30	0.51
$L_{eff} = \beta g \cdot \lambda$	m	0.173	0.221	0.277	0.452
Q	10^9	0.24	2.6	3.2	3.2
QR_s	Ω	21	42	98	112
R/Q	Ω	468	310	246	296
E_{acc}	MV/m	6.1	6.5	8.5	8.7
E_{peak}/E_{acc}		5.6	5.0	4.4	3.9
B_{peak}/E_{acc}	mT/(MV/m)	9.3	8.2	6.3	7.2

Cryomodules

The two LINACs have five types of cryomodules with four different kinds of cavities. The design of cryomodules is based on the standard design configuration of 2 K/4 K SC LINACs with insulation vacuum, thermal shield, and magnetic shield. The 2K modules for HWR, SSR1 and SSR2 bear a 4 K subcooled helium reservoir, a heat exchanger and Joule-Thomson expansion valve in each cryomodule, leading to the case that the 2 K environment for cavities is made in the module itself. While the QWR cryomodule is operated at 4.5 K with the simpler design. The thermal shield of QWR is cooled by 40K helium gas, meanwhile thermal intercepts of HWR, SSR1 and SSR2 are by 40 K and 4.5 K shields to minimize the thermal load. The cold mass, including the cavity string, coupler and tuner, is installed on a strong back. The estimated thermal loads of the SC LINACs are summarized in Table 2. The dynamic and the static loads are taking 70% and 30% of the total budget of the thermal load, receptively.

Table 2: Estimated Thermal Load for Each SC LINAC

Period	SCL2	SCL3	Total (W)
Dynamic (W)	6,023	1,274	7,297
Static (W)	1,265	650	1,915
Sum (W)	7,288	1,924	9,212

The independent two cryoplants serve the LINACS operation. The cryoplant with 4.2 kW @4.5 K cool capacity for SCL3 cools 22 QWR and 33 HWR cryomodules. The other plant with 13.5 kW for SCL2 does 1 HWR, 23 SSR1 and 25 SSR2 modules and the superconducting magnets in the IF zone. Estimated from Table 2, the capacity margins are reserved sufficiently by considering the uncertainty. The capacity of two cryoplants was also taken into consideration of the future expansion of SCL2 and another installation of so-called SCL1, which was pushed to the future plan.

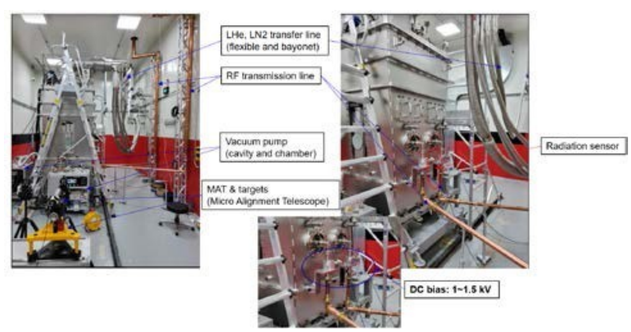

Figure 3: HT Setup of HWR Cryomodule in Test Bunker.

SRF Test Facility

Total 335 SRF cavities with 104 cryomodules in RAON accelerate heavy ion and proton beams to the target for various experiments. The all performance tests for cavities and cryomodules such as cavity vertical test (VT), module horizontal test (HT) and coupler conditioning and test are implemented by IBS staffs at two SRF test facilities. They are independently operating, one is on-site, the Shindong campus and the other is in the Munji campus which is 20 km apart from RAON site. In both facilities, VT pits, HT bunkers shown in Fig. 3, ISO class 4 7 cleanrooms, chemical polishing (BCP) system, high-pressure rinsing (HPR) system, high- and low-temperature furnaces and a helium liquefier are furnished. Throughput of two SRF test facilities is the bottle neck to cover all the cryomodules in the given milestone.

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Cavity Preparation

The RAON cavities are TEM mode, of which mechanical structure is more complicated than that of TM mode i.e., an elliptical cavity. Nevertheless, the basic recipes of surface treatment would be similar to that of an elliptical cavity. However, the detail parameters and procedures are adapted to RAON's own recipe, shown in Fig. 4 [6]. For the mass production, the industry constructed a dedicated facility for the necessary treatment, but cavities failed in VTs with simple causes are re-treated by using the on-site facility.

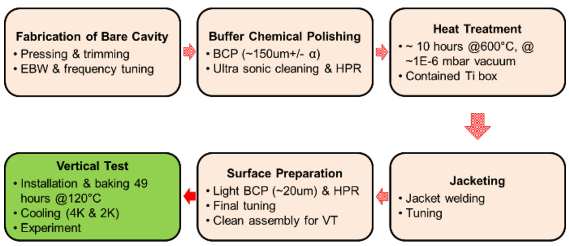

Figure 4: Procedure of Cavity Preparation.

STATUS OF SLC3, LOW-ENERGY LINAC

All components of SCL31 including QWR cryomodules, focusing magnets, beam positioning monitors, vacuum systems and RF systems are installed in the accelerator tunnel and are under preparation for beam commissioning. Meanwhile the components of SCL32 are installing with parallel work such as horizontal tests of HWR cryomodules, until coming October. The SCL32 preparation for beam commissioning is also forced to go together with installation by the elaborate scheduling in order to start the beam commissioning in the coming December.

Table 3: VT Acceptance Rate of QWR

Period	1st	2nd	>3rd	total
# of VTs	19	10	3	32
*Accepted	9	7	2	18
Acceptance(%)	47	70	66	56

QWR Cryomodules

All the fabrication process of the QWR cryomodules and procedure of surface preparation were setup basically during the prototyping. At the beginning a lot of time was spent to find the sources of performance failures or degradation and to clear out them. The major causes of VT failure were the multipacting (MP) in the power coupler, the premature field emission (FE), the vacuum leakage, nonoptimization of VT RF circuit and cryogenic system and also human errors due to less-experience. It took about one years to find proper remedies of MP and FE. The coupler MP was mitigated by the change of cleaning & assembly method, as adopting a solution that the RF flowing surface was decontaminated with HPR. To erase the premature FE by the particle contamination the quality and procedure control of BCP, HPR and cavity string assembly was kept to the extremely severe level. Also the assembly procedure for vertical test was improved to prevent a particle intake. With these jobs the acceptance rate from QWR VTs is 56%, shown in Table 3.

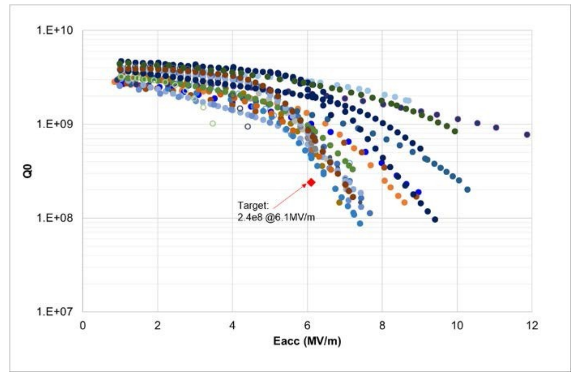

Figure 5: VT Result of QWR Cavities.

All 22 certified cavities as shown in Fig. 5 were furnished to 22 cryomodules which were passed through the HTs. The major parameters checked were the thermal load, the frequency deviation against helium pressure fluctuation, df/dp, where f is frequency in MHz and p is helium pressure in mbar, the Lorentz-force-detuning (LFD) in Hz/(MV/m)². Figure 6 shows the module's performance.

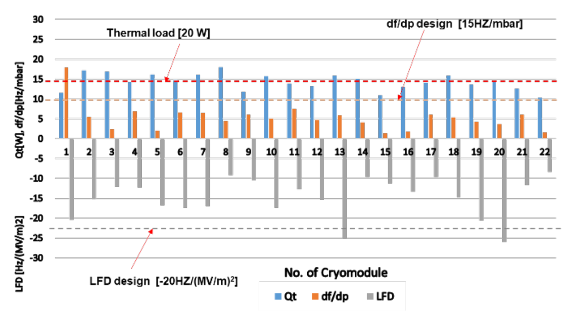

Figure 6: HT Results of QWR Cryomodules.

The installation of SCL3 is completed including the connection between cryomodules and cryogenic valves.

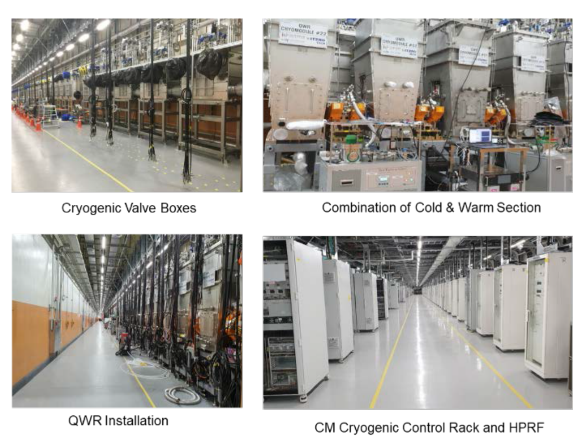

Figure 7: SCL31 Installation in Tunnel & Gallery.

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The preparation of beam commissioning is on-going such as vacuum works, checking RF systems and module cryogenic control system, flushing the cryogenic lines and preparing RF control and monitoring systems. The detail work list and schedule are organized, but time line is forced to be mismatched by the unexpected errors in the tunnel. Figure 7 shows the installation of SCL31.

HWR Cryomodules

The production and VT of 102 HWR cavities are completed and 34 HWR cryomodules are also assembled. All 15 HWR-A cryomodules which has 2 cavities each, and 10 HWR-B cryomodules which has 4 cavities each, out of 19 are accepted through HTs.

The main issues from cavities qualification were also multipacting from power couplers and field emission in cavities as QWRs. The recipe of surface preparation was slightly modified compared to that of QWR cavities in the way that every movable coupler for VTs were cleaned part by part by HPR and re-assembled before the new clean assembly for VT. In the other hand the temperature of cavity baking was increased 150°C not 120°C, as temperature sensors were positioned on the He vessel outer wall, not on the Nb cavity body. With these two primary remedies, another minor improvement during a cavity preparation and a VT made the total acceptance as 78%, 102 with 130 VT trials as shown in Fig. 8.

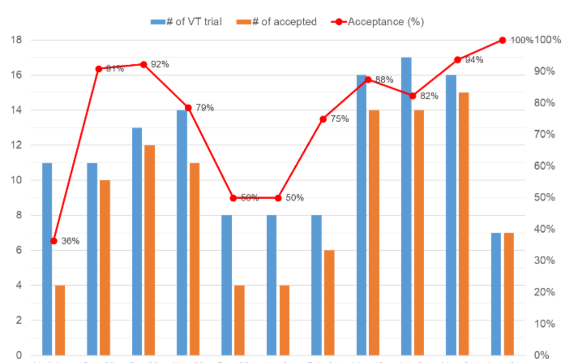

Figure 8: Acceptance Rate of HWR VTs.

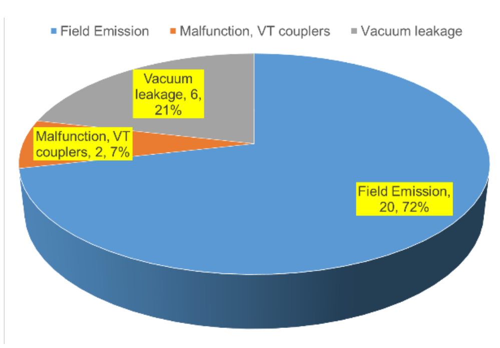

Figure 9: Cavity Limitation during VTs.

As shown in Fig. 8 the acceptance became worse, resulted to 50% November 2020 to February 2021. It was revealed as the changing the cavity manufacturer according to contract with bi-vendors made the different preparation quality. By the investigation, the management procedure of TOC (total organic contents) of the HPR water and clean room and clean assembly were improved. Another increasing baking temperature up to 180°C would contributes high acceptance. Figure 9 shows the main trouble of cavities VT was field emission (72%) and vacuum leakage (21%) during VTs. As shown in Fig. 10, quality factor Q0s are scattered widely which is from the less optimized preparation mentioned above as poor TOC control and clean room management and immature skill of cavity preparation and power processing during VTs.

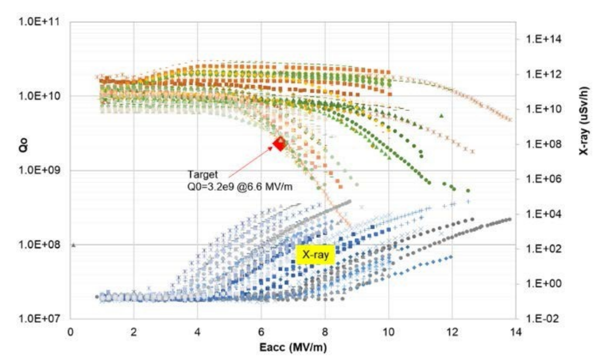

Figure 10: VT Results of HWR Cavities.

The production of HWR cryomodules are completed. At present, all 15 HWR-A cryomodules and 10 HWR-B cryomodules out of 19 are accepted through HTs. Figure 11 shows the HT of HWR A cryomodules, with nominal values such as thermal load of 14.1 W @ 6.5 MV/m at 2 K and df/dp of 15 Hz/mbar.

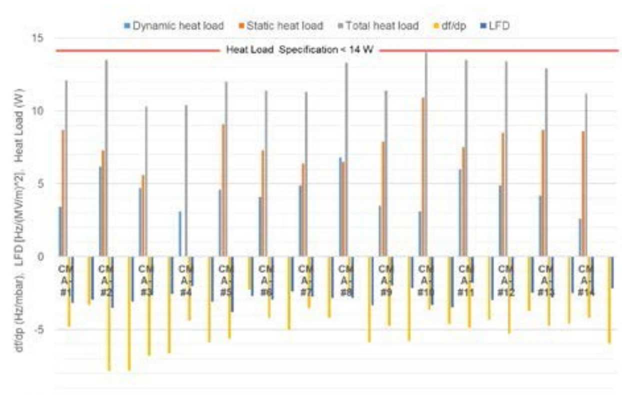

Figure 11: HT of HWR-A Cryomodules.

The HTs of HWR-B cryomodules are on-going as completion of 10, but 6 series of HT trials during last 2 months were failed. It is found out as the changing procedure of cavity string after VTs would result to particles intake into cavity, such way that the post HPR after VTs was omitted about cavities reached to high Q0 in order to save module assembly

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times. After recovering the original string procedure, FE was cleared through the trial HT. Figure 12 shows the assembly process of HWR B cryomodule in the manufacturer's workshop.

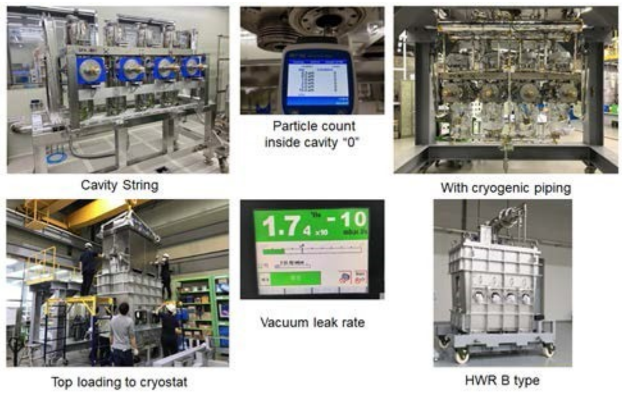

Figure 12: Assembly process of HWR-B Cryomodule.

The cryomodules which are accepted from HTs are to be installed one by one in the tunnel. All the installation works of SCL3 and preparation of pre-commissioning will be completed by coming October. The cooldown of SCL3, first QWR then HWR will start on the early November this year. Through the months long pre-commissioning of SRF system, SCL3 with ISOL will be integrated and commissioned late 2021. Figure 13 shows SCL3, installing HWR-B with cryogenic valve box connection.

Figure 13: Installation work of HWR-B. Waiting for remaining 9 cryomodules.

High Power RF System (HPRF)

A solid state power amplifier (SSPA) is adapted as the high power source of LINACs. The required power of unit cavity in SCL3 is 4 kW CW as not big scale, so that a SSPA provides several advantage compared to other source such as klystron and IOT [7]. A water cooling can remove the dissipated power from the RF components stably. Table 4 describe the characteristics of SSPA for QWR and HWR. The only difference between QWR and HWR is frequency. The power margins of them are as big as 30%, which is considered as phase mismatch depending on the cavity during beam operation.

Table 4: Specification of SSPA for QWR/HWR

Parameters	**Unit**	**Value**
Frequency range (QWR/HWR)	MHz	QWR: 81.25±1 HWR: 162.5±1
Power (CW and pulse)	kW	4 kW @ 0 dBm input
I/O impedance	O	50
Gain linearity	dB	<6 (–20 dB range) <3 (–10 dB range)
Input return loss	dB	<–20
Stability - Phase	degree	1
Stability Power	%	1

All HPRF systems for SCL3 are equipped in the gallery, shown in Fig. 7 and are under unit tests so-call site acceptance test. The typical results of stability without cavity is shown in Fig. 14.

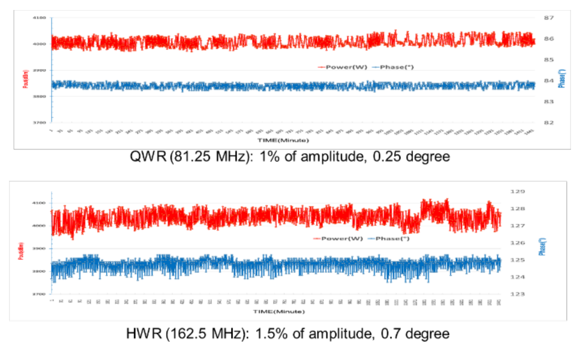

Figure 14: Long-term (∼1 day) Stability from unit SSPA.

Low-Level RF System (LLRF)

A digital LLRF system by using FPGA is base architecture to control the amplitude and phase as precise as low 1% and 1°, respectively. The LLRF systems govern RF feedback, interlock, protection, quench detection, monitoring, DAQ and SRF operation system including OPI, connecting each other by EPICS protocol. It also includes a pulse conditioning system for a power coupler and a cavity. The schematic scheme of SCL3 LLRF is shown in Fig. 15.

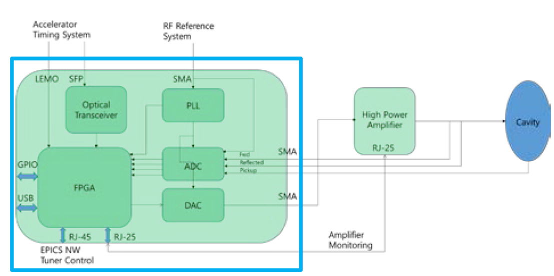

Figure 15: Diagram of SCL3 LLRF.

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All the hardware such as a control rack loaded control board, signal/network cables are ready in the gallery. The OPI with HMI is under preparation, two different HMI – one for a LLRF expert the other one for an ordinary operator from the central control room of SCL3. Still we are running for the SRF pre-commissioning (SRF commissioning without beam) such as

- RF integrated test with LLRF and HPRF through dummy water load
- Noise removing and/or avoiding methodology
- Tuner functional test (phase lock) during each module HT, ongoing
- Commissioning integrated SRF system without beam
- Beam commissioning

The tuner and power coupler are certified to support LLRF performance during each horizontal test of cryomodules in the test bunker. Also the same procedure will be repeated as the SRF pre-commissioning in the tunnel. As shown in Fig. 16 the RF feedback system gives well behavior during 1 hour long.

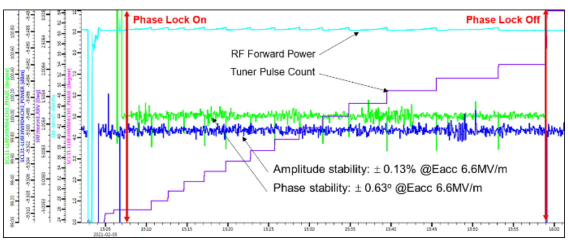

Figure 16: Feedback Performance of HWR LLRF.

STATUS OF CRYOGENIC SYSTEM

The cryogenic cooling system for RAON is separated two parts with semi-independent operation, as SCL3 and SCL2 has their own cryoplants with common connection between them through a distribution box. If one would be out of service the other can support to maintain the cold temperature neighbor LINAC. A smaller cryoplant with capacity of 4.2 kW as the equivalent heat load @4.5 K. is for cooling SCL3. While a larger cryoplant with capacity of 13.5 kW is for cooling mainly SCL2 and IF separator (LTS and HTS magnets). The SCL2 cryoplant is also being designed to supply the helium flows to SCL3, SCL2, and IF separator, simultaneously when the RAON accelerator operates with low RF powers. For the LINACs and IF separator, the required helium flows from cryoplants are 4.5 K subcooled He for cavities cooling and 40 K thermal shields as shown in Fig. 17. The return lines serve 4K very low pressure (VLP) from cavities, 5-8 K from cavities, 60K from thermal shields, and warm He return. Both the cryoplants have capacity margin about 50% of estimated heat loads [8].

Prototyping tests of QWR and HWR valve boxes for the thermal and hydraulic checks were performed and then all valve boxes for SCL3 were installed and connected to the cryomodules, except 9 HWR-B modules which wait for the performance tests. In order to minimize risks for SCL3 commissioning and to optimize control logic of cryogenic distribution and superconducting systems, simulation models with control logic are being developed and all designed components and control logic will be checked by a dynamic simulation.

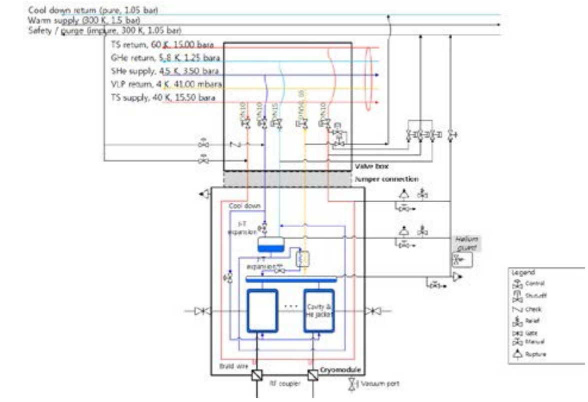

Figure 17: Conceptual P&ID of HWR-A cryomodule.

All the components of two cryoplants are installed (Fig. 18). SCL2 cryoplant starts the commissioning with completion target of in the coming October. Meanwhile SCL3 plant is under safety inspection by Korean Certification Agency. With these situation the cryoplant 2 will serve the cooldown SCL3 for beam commissioning in December, 2021.

Figure 18: Cold Boxes for SCL2 (right) and SCL3 (left).

All the other cryogenic components such as a helium recovery system, a cryogenic distribution system and valve boxes are on the processing of decontamination and cleaning for preparing cooldown the SC cavities, of which will start in the middle of coming November.

SUMMARY AND FUTURE PLAN

The installation of low-energy LINAC, SCL3 is under way to the beam commissioning, which will start in the December, 2021. Then the primary works of beam commissioning including KoBRA pre-commissioning will be done in the first half in 2022 and the KoBRA main commissioning plan with a selected experiment starts in September, 2022.

The high-energy LINAC, SCL2 is still under prototyping stage. Now part of manpower from superconducting RF division care the prototyping R&D. Already there are some progress in the R&D, so that the prototyping will be completed in 2021. The planning for a pre-production of SCL2

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cryomodules during two years 2022–2023 is organized and approved by the Korean central government. With the result of pre-production achievement, new planning of SCL2, so-called Project Phase 2 will be realized and be proposed to the government with construction target during 5 years, 2024-2028.

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