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OPERATION EXPERIENCE OF THE SUPERCONDUCTING LINAC AT RIKEN RIBF

N. Sakamoto*, H. Imao, O. Kamigaito, T. Nagatomo, T. Nishi,
K. Ozeki, K. Suda, A. Uchiyama, K. Yamada,
RIKEN Nishina Center, Wako, Saitama, Japan

Abstract

Construction and hardware commissioning of the RIKEN superconducting linac (SRILAC) [1] based on 10 SC-QWRs (Superconducting Quarter-Wave-length Resonators) (73 MHz, C.W.) was completed in the end of 2019 and beam acceleration test was succeedingly conducted in January 2020 for the first time. After beam commissioning in the end of FY2019 [2], user service was started. So far argon and vanadium ions were accelerated to the energy from 4.2 to 6.3 MeV/u. In the user-service phase one of the most important issues for superconducting cavity (SC) is how to preserve their original performance, such as acceleration gradient, Q_0, field emission (FE), radiation onset voltage and so on. Recently the average beam power reached 1 kW. It is becoming more important to keep the beam losses at SCs as small as possible. In this paper operation history, control of the beam losses, and radiation monitoring are reported.

RILAC UPGRADE AT RIKEN

The RIKEN Heavy-Ion Linac (RILAC) [3] upgrade was performed to allow it to further investigate super-heavy elements. The new element Nh was synthesized by bombarding a ^{209}Bi target with an intense ^{70}Zn^{14+} beam with an energy of 5 MeV/u accelerated by the RILAC, which was upgraded by adding a booster linac comprising six DTLs. The SRILAC was introduced by replacing the latter four DTLs of the booster linac as shown in Fig. 1 so that ions (A/q=6) are accelerated to 6.5 MeV/u [4]. This upgrade corresponds to an increase of the total acceleration voltage by 14 MV.

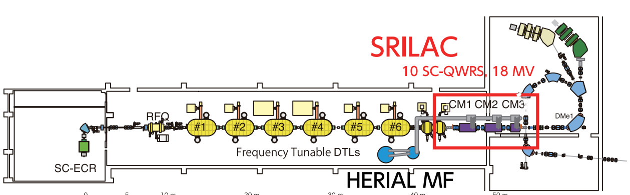

Figure 1: Layout of RILAC and SRILAC.

Construction of the SRILAC started in the middle of FY2016 and installation to the accelerator cave was finished in the end of FY2018. First cool-down with He refrigerator was successfully performed in October 2019 and radio-frequency (RF) commissioning was succeedingly made [5]. On January 28, 2020, ^{40}Ar^{13+} beam was successfully accelerated with to 6.2 MeV/u for the first time. Due to the vacuum leak from the coupler ceramic window of SC05, beam commissioning was accomplished using 9 SCs. After acceleration tests, additional NEG pumps and high pumping-speed Ion-pumps were installed to improve the vacuum pressure of MEBT to several times 10^{-8} Pa during a long-term shutdown due to COVID-19. From June 2020, after the shutdown, user beam-service restarted. By choosing the number of SCs and their gap voltages, the beams with energy from 4.2 MeV/u to 6.3 MeV/u were accelerated. Beam power was being slightly increased reached 1 kW keeping the MEBT vacuum level below 1×10^{-7} Pa and in this year.

* nsakamot[at]ribf.riken.jp

SUPERCONDUCTING LINAC BOOSTER

The SRILAC consists of three cryomodules (CMs) and a beam transport line connecting CMs. Design parameters are summarized in Table 1.

Table 1: Design Parameters of SRILAC

Parameters	Value
Frequency (MHz)	73.0 (c.w.)
$E_{\rm inj}$ (MeV/u)	3.6
$E_{\rm out}$ (MeV/u)	6.5
Maximum gap voltage (MV)	2.4
Synchronous phase (°)	-25
Number of cavities	10
Cavity type	QWR(TEM)
$\beta_{\rm opt}$	0.078
TTF	0.9
$R_{\rm sh}/Q_0$ (Ω)	579
G	22.4
$E_{\rm acc}$ (MV/m)	6.8
$E_{\rm peak}/E_{\rm acc}$	6.2
$B_{\rm peak}/E_{\rm acc}$ (mT/(MV/m))	9.6
Operating temperature (K)	4.5
Target Q_0	1×10^9
$Q_{\rm ext}$	$1 - 4.5 \times 10^6$
Amplifier output (kW)	7.5
Beam current (μA)	~100

Three Cryomodules host 10 SC-QWRs. The SC-QWRs are made from pure Nb sheets with a residual resistivity ratio of 250, and their inner surfaces are processed by buffered chemical polishing (BCP1) with 100 μm, annealing at 750°C for 3 h, light etching (20 μm, BCP2), and 120°C baking for 48 h. The operating temperature is 4.5 K, not 2 K, and all the cavities achieved fairly large Q_0 that exceeded the target value of 1×10^9 at an $E_{\rm acc}$ of 6.8 MV/m in the cavity

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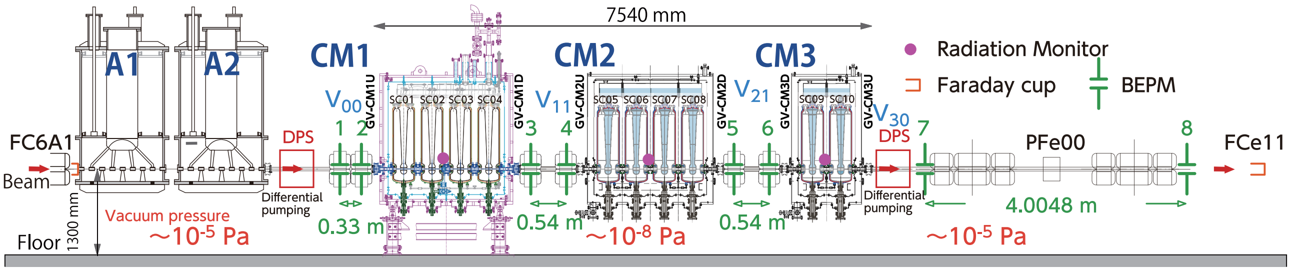

Figure 2: Layout of the cryomodules, beam transport lines, and diagnostics of the SRILAC section.

performance test [1, 4]. Note that no emission was observed during the performance tests of the bare cavities.

The gap length of the cavity is optimized for β=0.078 particles with a transit time factor (TTF) of 0.9. The maximum gap voltage is 2.4 MV, which corresponds to an acceleration gradient E_{acc} of 6.8 MV/m with a synchronous phase of -25°. Each cavity with a local magnetic shield of μ-metal is contained within a He vessel made of pure Ti. The power coupler (PC) with a single warm-window is designed with a function of tunable coupling so that a Q_{ext} range from 1×10^6 to 4.5×10^6 can be achieved by a change of the insertion distance of its antenna [6].

In the phase of user beam-service one of the most important issues is how to preserve the original cavity performance. Layout of the SRILAC is shown in Fig. 2. All-metal-gate-valves (VAT) are installed at the both end of CMs. Since the all-metal-gate-valves are not particle-free, operation speed is slowed as much as possible by lowering compressed air of the pneumatic valves to reduce the number of generated particle. The number of opening/closing times of the gate-valves attached to the beam ports of the CMs have been recorded. In case of emergency a pair of fast-closing valve (VAT) isolates the SRILAC section. RT Quadrupole magnets and non-destructive diagnostics, Beam-Energy and Position Monitors (BEPMs), are adopted in the MEBT (Fig.!3). Newly developed three-stage differential pumping systems

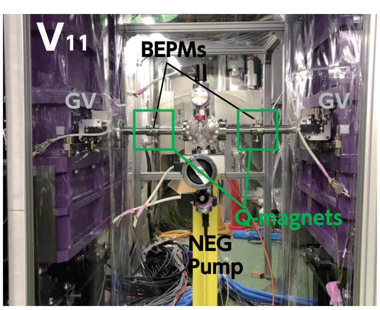

Figure 3: Installation of a beam pipe with a pair of BEPMs and a pump station was performed using a local clean booth.

(DPS) [7]are introduced to prevent gas flow from existing room-temperature section.

Beam energy was measured by TOF using a pair of BEPMs and transmission efficiency measured with the Faraday cups of FC6A1 and FCe11 indicated in Fig. 1 was 100 %. Elaborate beam tuning was performed so as to minimize beam losses keeping vacuum pressure of MEBT (V_{00},V_{11},V_{21},V_{30}) below 1×10^{-7} Pa. Typical vacuum pressure at MEBT with/without beam is summarized in Table 2.

Table 2: Typical Vacuum Pressure Levels of MEBT

Beam	$\mathbf{V_{00}}$ [Pa]	$\mathbf{V_{11}}$ [Pa]	$\mathbf{V_{21}}$ [Pa]	$\mathbf{V_{30}}$ [Pa]
On	3.1E-8	5.2E-8	4.6E-8	4.6E-8
Off	1.5E-8	1.9E-8	2.6E-8	2.2E-8

OPERATION EXPERIENCES

Operation history since the first beam-acceleration test is shown in Fig. 4. In the figure cyan block indicates when CMs

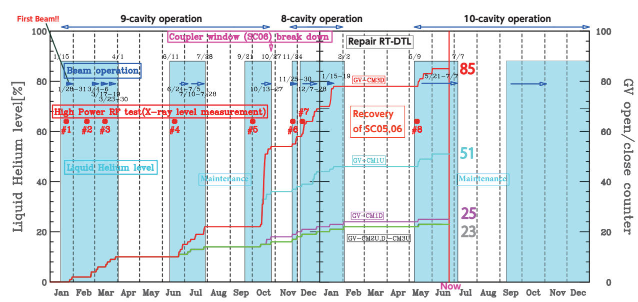

Figure 4: Operation history since the first beam-acceleration test .

were filled with liquid helium. So far beam operation was conducted for 11 times. The beam power was about 100 W in the beginning and recently reached 1 kW. Beam operation started with nine cavities as mentioned above. In October 2020, vacuum leakage from the RF window of the SC06 PC occurred during a user beam-service. Then evacuation port was installed replacing coaxial power-line and the outer area of the broken ceramic window was evacuated. Then user beam-service restarted in November 2020 with eight cavities and continued to January 19, 2021.

This year, during a long term shutdown due to RT DTL trouble, evacuation chambers attached to the PC port were replaced by coaxial lines equipped with a vacuum window and vacuum port [6]. It worked well and 10-cavity operation started from June 2021.

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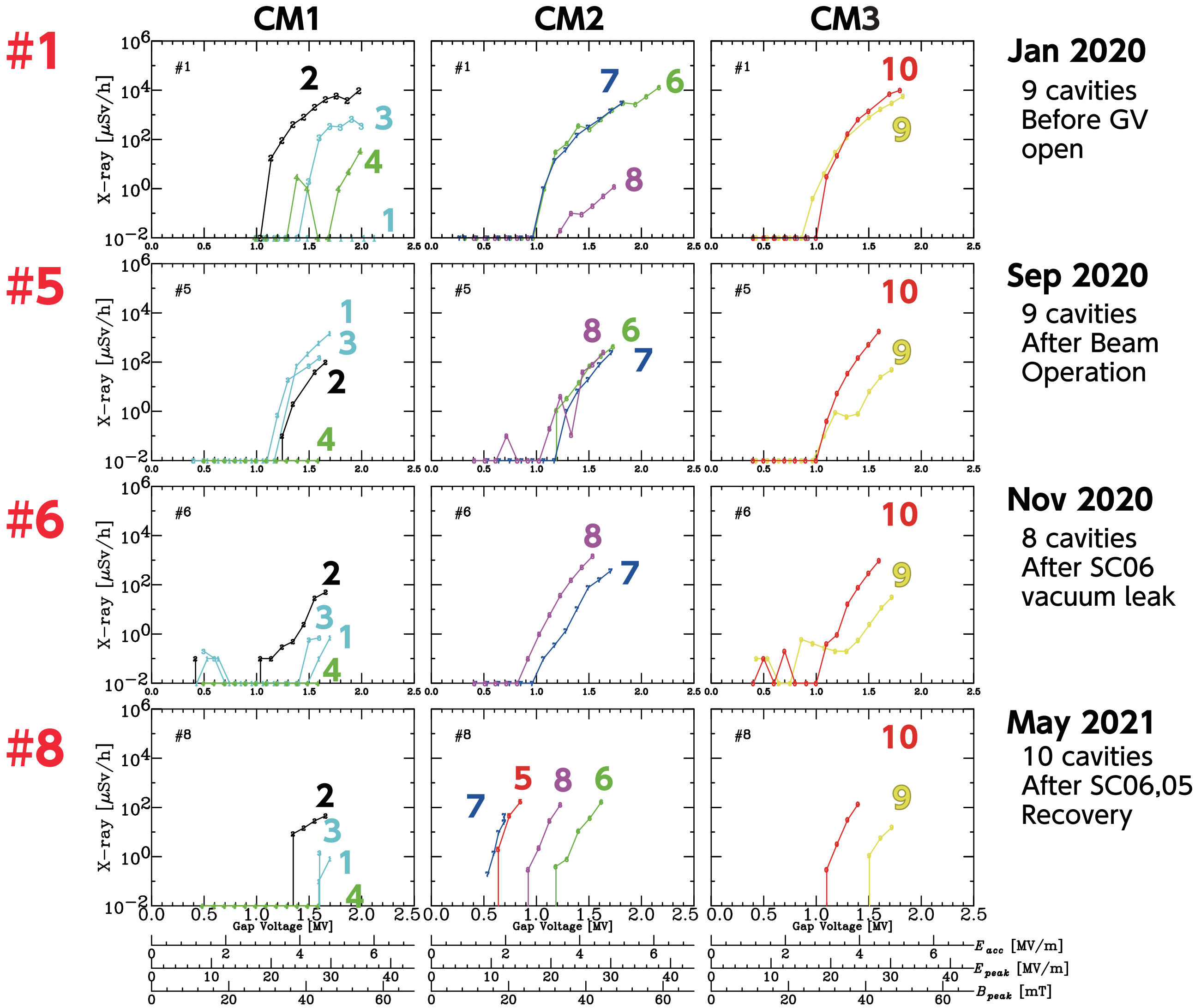

Figure 5: Radiation measurements #1, #5, #6, #8. Radiation levels is plotted as a function of gap voltage. The numbers in the plots denote the cavity number.

FIELD EMISSION MONITORING

Radiation monitoring is one of the most important techniques to know the cavity performance degradation. As indicated in Fig. 4 measurement was performed every time after cool-down. High-power RF test for radiation measurement was made every time after cooling-down to observe the situation of cavity degradation (#1–#8 in Fig. 4). Radiation levels are plotted as a function of the gap voltage are shown in Fig. 5. During a long term operation particulates might flow into the cavity and absorbed on the cold surface. In the worst case they turn to be new sources of FE. Three radiation monitors (MAR-784, Hitachi [8]) are permanently located at the middle position of cryomodules shown in Fig. 6.

The first measurement (#1) taken before opening the gate-valves provides a reference data. As shown in Fig. 5 some radiation was already observed while no radiation was observed in the bare cavity performance test. It was found that degradation of SC06, SC07, SC08 was not severe even with

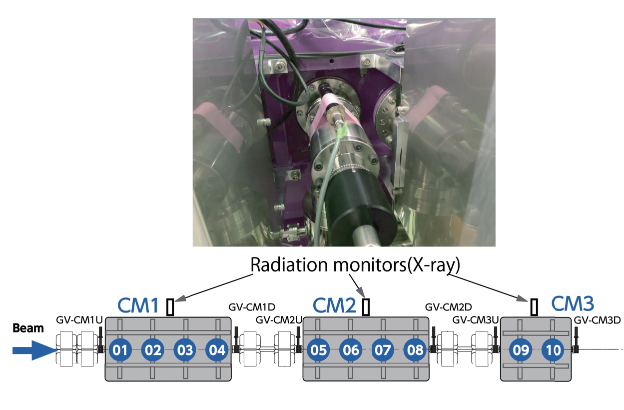

Figure 6: Radiation measurement setup.

an vacuum leak from the RF window of SC05. No significant increase of radiation levels existed after beam operation

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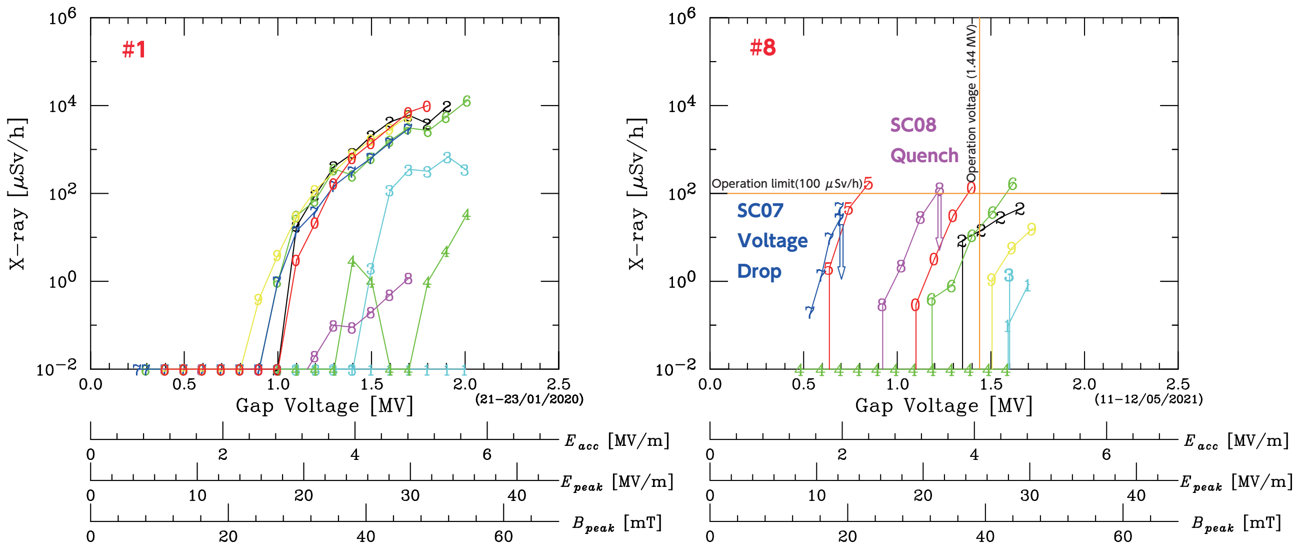

Figure 7: Comparison between radiation measured for the first time and radiation measured after 1.5 yr beam operation.

(#5). After vacuum leakage of the SC06 PC radiation levels of CM2 apparently increased (#6). SC05, SC06 cavities were successfully excited after recovery (#8) but radiation levels became worse. SC08 quenches at 1.2 MV gap voltage and SC07 had sudden drop of gap voltage at 700 kV. These cavities are operating below the critical gap voltage and below radiation level of 100 µSV/h. Radiation levels before operation and after 1.5 year operation are compared in Fig. 7. From the radiation levels of SC01 and SC10 located at both ends of the SRILAC section there are no significant increase of radiation owing to DPS. Reassembling of CM2 and cleaning of cavity surfaces is needed for recovery of their original performance.

SUMMARY

RIKEN Superconducting Linac (SRILAC) got into the user beam-service phase. Beam loss was being minimized so as not to get serious degradation of SC-QWRs and no degradation of cavity performances were recognized so far. Vacuum leakage of SC06 PC brought significant degradation to CM2 in #8 measurement. User beam-service will be cautiously continued by observing radiation levels of SC-QWRs.

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