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PERFORMANCE OF CONTAMINATED SUPERCONDUCTING LINAC AFTER VACUUM EXCURSION*

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Abstract

ISAC-II superconducting heavy ion linac is the high energy section of TRIUMF ISAC facility to accelerate rare isotopes with A/q ≤ 6 from 1.5 MeV/u to above the Coulomb barrier for experiments. There was a vacuum excursion caused by an operational error and the failure of the fast protection system in summer 2022. The beamline downstream to the SC linac was vented with atmosphere air from the experimental hall resulting in pollution of the linac. This paper reports the RF performance of the contaminated linac. The typical cavity performance changes, the average magnitude of degradation, the impact range in the SC linac, the observations in the recovery processes and the analyses on the most distinct cavity are discussed. The cavity refurbishment in the recent winter shutdown with the observations and outcomes is also reported. The ISAC-II event provided a unique data set for the SRF community.

INTRODUCTION

The Isotope Separator and ACcelerator (ISAC) at TRIUMF (see Fig. 1) uses the Isotope Separation On-Line (ISOL) technique to produce rare-isotope beams (RIB) for studies in astrophysics, nuclear structure and reactions, electroweak interactions and material science [1]. RIB production consists of a 500 MeV cyclotron producing a proton driver beam of up to 100 μA onto one of two thick production targets, an on-line ion source and a mass-separator. The radioactive ions are accelerated in a chain of linear accelerators (linac) consisting of a room temperature RFQ and DTL to an energy of 1.5 MeV/u and a superconducting (SC) linac that adds a further 40 MV to the beam for nuclear physics investigations near the Coulomb barrier.

ISAC-II is the SC section downstream of the normal conducting linac and a S-bend beamline. It accepts RIBs at an energy of 1.5 MeV/u and further accelerates to > 6.5 MeV/u for A/q = 6 isotopes or > 16MeV/u for A/q = 2 ions. The SC linac was built in two stages. Phase-I (SCB) consists of five cryomodules. Each cryomodule has four SC quarter-wave resonators (QWR). SCB cavities operate at 106.08 MHz with two optimized beam velocities (β) at 5.7% and 7.1% of the speed of light. Phase-II (SCC) consists of three cryomodules. The first two modules have six QWRs, while the last one has eight QWRs. SCC cavities operate at 141.44 MHz with geometry β at 11%. The operating temperature is 4 K. Cryomodules use a single vacuum design where the RF spaces and the thermal isolation space share the same vacuum. There are no beam pipe connections between cavities or between the cavity and the vacuum tank.

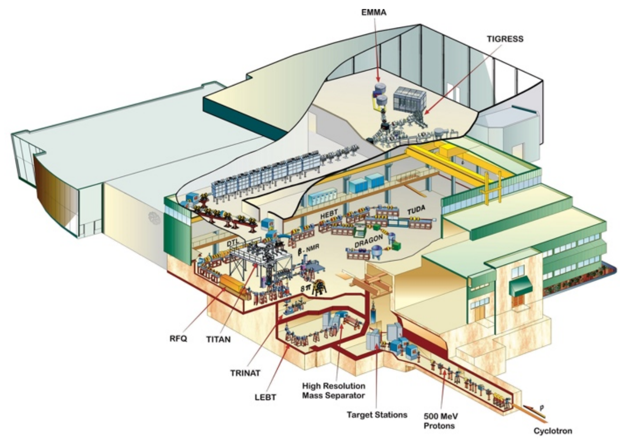

Figure 1: ISAC facility at TRIUMF. The top left corner is ISAC-II accelerator vault with the beam accelerating from left to right. The 8 grey boxes represent the 8 cryomodules. The upstream 5 boxes are SCBs while the downstream 3 boxes are SCCs. The top right corner is the ISAC-II experimental hall.

ISAC-II has been in operation since 2006 [2]. Cavities are specified to provide 1 MV effective voltage each. In the past 5 years, around 37 cavities were available for beam deliveries. The unavailable ones are due to the internal ancillaries' failures with either mechanical or RF reason. The total effective voltage had been improved to 39 MV gradually. The downtime of the beam delivery caused by the RF system and cryomodule failures has been reduced and maintained below 10 hours/year [3].

VACUUM EXCURSION

In June 2022, there was an accidental vacuum excursion caused by an inadvertent opening of a wrong valve such that atmospheric air was sucked into the beamline that was operating at vacuum. The valve location is 19.6 metres downstream of the ISAC-II linac. [4, 5].

Prior to the event, the ISAC-II linac was under vacuum with all isolation valves opened up to the first valve (SEBT1:IV0) on one beamline in ISAC-II experimental hall. IV0 was closed and interlocked. The beamline downstream of IV0 was open to atmosphere for an experimental chamber alignment. When experimenter requested for the line of sight, the interlock of IV0 was bypassed and the valve was opened in error. The beamlines upstream of IV0 was exposed to atmosphere air from the experimental hall.

There is a fast valve on the beamline at about 5 m downstream of the last SCC cryomodule (SCC3) in the accelerator vault, whose purpose is to quickly close to protect cry-

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omodules in events like this. But the fast valve did not respond, and then was found in a faulty mode. Ion gauges tripped along the beamline, which caused the corresponding isolation valves to close. But the valves are not fast enough to prevent the pressure wave from reaching the cryomodules and air and particulates reached the cryomodules. The archiver data shows the convectron gauge at about 0.5 m downstream of SCC3 reached 200 Torr pressure in the event with a very low sample rate at every 5 minutes. It would be a good assumption that SCC3 saw air at around atmosphere pressure in the excursion.

The ion gauge of SCC3 tripped, which caused RF and helium supply valve to trip in this cryomodule. Pressure on SCC2 ion gauge increased by an order of magnitude to 1×10^{-8} Torr at 5 minutes sample rate. There were no visible pressure changes in the rest of the upstream cryomodules. But SCC2 and SCC1 also experienced RF trips, while SCC3 and SCC2 lost significant amounts of liquid helium in their LHe reservoirs. Some of the boil-off was due to automatic rf start-up routines which would be trying to start cavities at their operating setpoints. The contaminated cavities would dissipate much more RF power at the previous operating setpoints.

RF PERFORMANCE

After vacuum and cryogenic systems were restored, cavity performance was measured.

ISAC-II cavities are equipped with variable fundamental power couplers. The external quality factor can be adjusted on-line from 10^4 to $> 10^9$ to accommodate various coupling requirements for operation, Q measurement, and RF conditionings. On ISAC-II, we do routine Q-curve measurement on all cavities once a year before the first beam delivery. Data is used to track cavity performance over years and to set the operating gradient below the knee of the deep Q-slope in the higher field regime, which is typically caused by field emission in ISAC-II, for stability consideration.

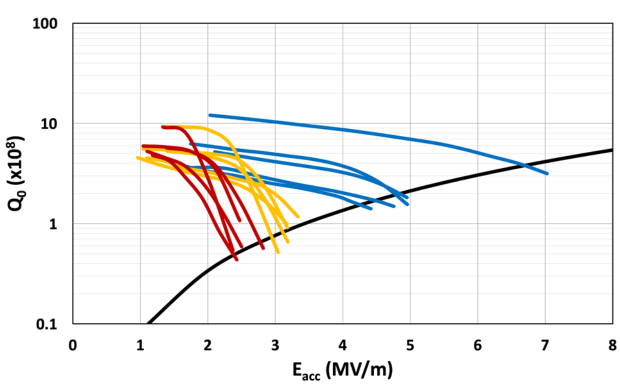

Figure 2: Q-curves of SCC3 cavities. Blue: before vacuum excursion; Red: after vacuum excursion; Yellow: post-conditioning.

The Q-curve comparisons of SCC3 cavities are shown in Fig. 2 as an example. Blue curves were measured prior to beam deliveries in 2022, Red ones were measured right after the vacuum excursion. Then pulse conditioning was applied to push the usable operating gradient as much as possible. The post-conditioning curves are shown in Yellow colour. There was significant gradient degradation in SCC3, but not obvious Q change in the low field regime. The knees of Q-curves were reduced from above 4 MV/m to ~ 1.5 MV/m and the changes are independent from their original performances. The corresponding E_{peak} is ~ 7.5 MV/m. We did not have X-ray data to verify the field emission onset. It was assumed the onset field equals to the gradient at the knee. Pulse conditioning pushed the onset field to above 2 MV/m, corresponding to 10 MV/m E_{peak}. The improvement of pulse conditioning is measurable, but not enough to restore performance. Due to the beam schedule, other potential in-situ process, such as helium conditioning, was not applied to date.

Cavity performance was checked from downstream cryomodule to upstream one, up to SCB4, which is the fifth in the path. Degradation was observed in 3 SCC cryomodules, but not clear in SCB ones. The average usable gradients of each SCC cryomodule are shown in Fig. 3. Colours represent the same stages as those in Fig. 2. There is a clear trend of the average performance of the contaminated cavities versus the distance from the contamination source.

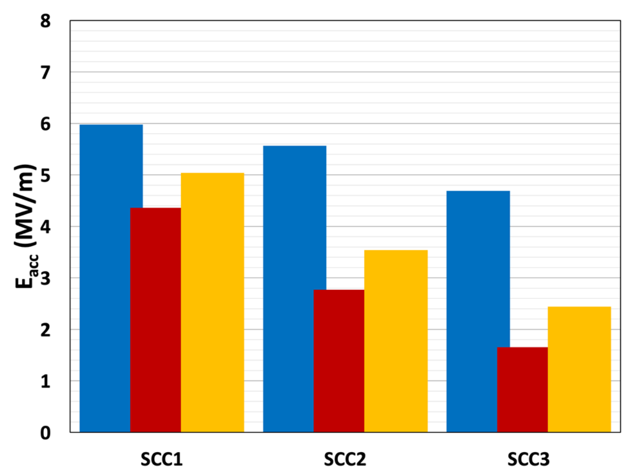

Figure 3: The average usable operating gradient of SCC cryomodules. Blue: before vacuum excursion; Red: after vacuum excursion; Yellow: post-conditioning.

To have insight of the correlation, the post-contamination data was plotted moving from SCC3 in the upstream direction as shown in Fig. 4. The position of the downstream isolation valve of SCC3 is defined as the origin and assumed it is the contamination source. The midpoint of each cryomodule on the beam axis is used as the average cavity position. Then a simple exponential relation can be found between the degraded performance and the distance for both pre-conditioning and post-conditioning data sets. Cavities at farther positions have less degradation but also gain less from pulse conditioning. An interesting point to note is that the extended fitting curves to the SCB5 position (centre at ~ 10 m) are above the SCB5 performance prior to the event and the ISAC-II specification at 6 MV/m. This is an indication that SCB cryomodules were not affected by the vacuum excursion, which is consistent with SCB4

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and SCB5's Q-curves. In other words, the particulate migration range for this event is around 9 m in the ISAC-II cryomodules.

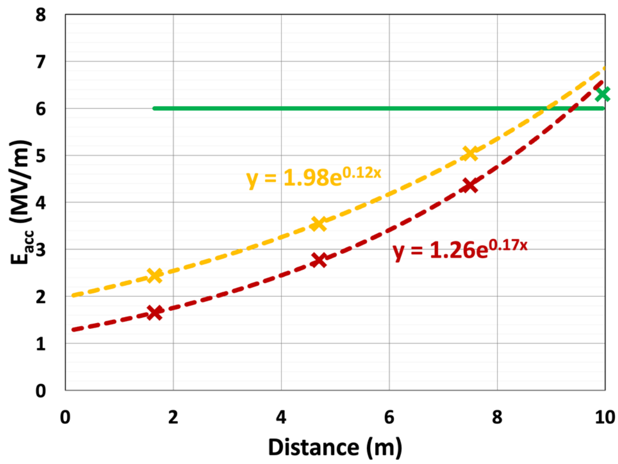

Figure 4: The correlation between average cryomodule performance and the distance to the contamination source. Red: after vacuum excursion; Yellow: post-conditioning; Green line: gradient specification; Green cross: average gradient of SCB5 before the vacuum excursion.

In the above discussion, the average gradient was used to represent the performance degradation. Looking at the individual cavity performance, 2 SCC1 cavities (#1 and #3) were barely affected in the event. These 2 cavities plus 2 more SCC1 cavities (#2 and #6) and 1 SCC2 cavity (#5) were almost restored after pulse conditioning. Individual cavities gave more random performance changes in SCC1 and SCC2. But SCC3 displayed consistent degradation as shown in Fig. 2.

In the RF measurements, the last 3 available cavities (SCC3#5, #6, #8) required considerable conditioning to overcome multipacting barriers, which was not required on all other upstream cavities. (Note that SCC3#7 was unavailable due to RF coupler issues.) We conclude that the secondary electron yields enhancement due to frozen layers is demonstrated to have an effective range of around 1.5 m in this event.

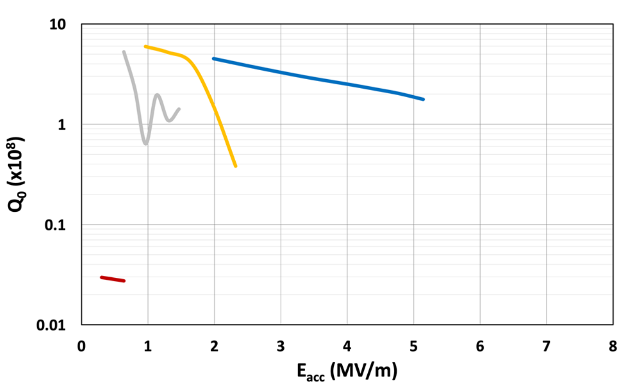

Figure 5: Q-curves of SCC3#8. Blue: before vacuum excursion; Red: after vacuum excursion; Gray: after 300 K thermal cycle; Yellow: post-conditioning after thermal cycle.

SCC3#8, the first cavity seeing air in the cryomodule, demonstrated a unique degradation, shown in Fig. 5. Unlike other cavities, the base Q dropped by more than 2 orders of magnitude, from 5×10^8 to 3×10^6. Due to the extremely high heat load, the cavity at this low Q is not usable for operation. To restore cavity Q, a full thermal cycle up to the room temperature was attempted on SCC3. After the thermal cycle, the base Q was recovered to the mid of 10^8. The Q curve of the initial ramping up showed multiple field emitters in the gradient range from 0.5 MV/m to 1.5 MV/m, the Grey curve in Fig. 5. The onset level is also lower than other cavities in the same cryomodule at around 1.5 MV/m. Pulse conditioning cleaned the very low field emitters and pushed the onset field to around 1.5 MV/m as shown in the Yellow curve in Fig. 5.

There was a pronounced outgassing in the warmup as expected. Fig. 6 shows the pressure versus time data measured with the cryomodule ion gauge. An RGA is not available on ISAC-II cryomodules, the outgassing was analysed based on the correlation with temperatures of the cryomodule cold mass. There are 3 major pressure peaks at ~ 6 hours, ~ 30 hours and ~ 60 hours respectively. The first peak started when the helium stack was warmed up a bit. The spikes on the shoulder of this peak, at ~ 10 hours, were when the helium reservoir crossed the temperature range between 25 K and 35 K, which is the sublimation temperature of solid nitrogen and solid oxygen in this pressure regime [6]. The second peak is the largest one and tripped the ion gauge. It is combined of several major sub-assemblies crossing the characteristic temperatures. The vacuum excursion corresponded to the cavities and thermal shield going from 150 K to 180 K, that is the transition temperature of solid H_2O [6]. The major contribution is expected from the solenoid, which is the coldest part in the warmup and should act as a 'cryo-pump' absorbing gases released from other warmer parts. In this second peak, the solenoid temperature ramped up through 30 K and the majority portion of the sucked air was outgassed. The third peak is 'noisy', as a feature of the humidity outgassing [7]. It was consistent with the solenoid temperature crossing the sublimation temperature ranges mentioned above.

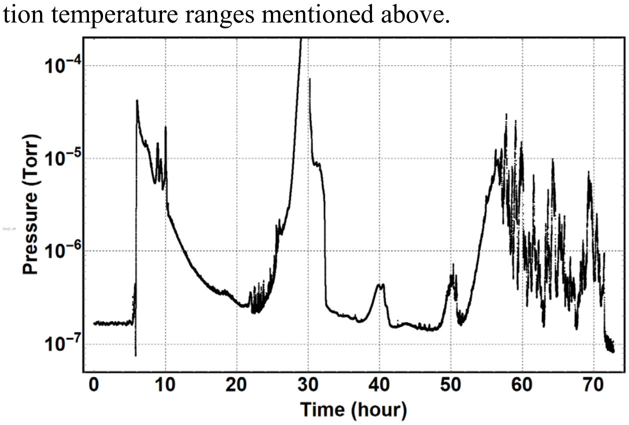

Figure 6: SCC3 cryomodule vacuum in the warmup from 4 K to room temperature.

In addition, a few hypotheses were proposed to explain the severe Q drop on SCC3#8.

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1. The cavity experienced a high heat load when it met the warm air. The niobium cavity with its niobium helium jacket quenched. As the superconducting solenoid was operating at 5 T from the previous beam delivery, there was strong magnetic field from the solenoid as the background in the cryomodule. This background field is designed to be shielded by the helium jacket as a Meissner shield in operation. But due to the cavity and the jacket quenching simultaneously, the cavity was exposed to the strong magnetic field, and would trap considerable amount of flux during cooling through the superconducting transition. We had previously studied a 4-cavity cryomodule on the impact of the active solenoid on the cavity when it is accidentally thermal cycled cross the superconducting transition [5]. The inference predicted the surface resistance of SCC3#8 would be increased by about 400 nΩ in the worst-case scenario. The base Q could reduce by no more than an order of magnitude in this case. But the cavity Q dropped more than 10 times of the prediction. The hypothesis #1 is not the major contribution to the Q degradation.

2. Two fingers of a nitrile rubber glove were sucked into the beamline during the vacuum excursion. It was used to cover the opened beam line in atmosphere temporally. The bits of the glove were found in the diagnostic box downstream of cryomodules [4, 5]. We assumed that a few bits were sucked into cryomodule and even into the last cavity. The dielectric loss of the nitrile rubber was estimated with various sizes and at various positions on the RF surface. A 10 mm diameter piece sticking to the high electric field area could reduce the cavity Q to the 10^6 level. But this hypothesis was not supported by the Q recovery after the 300 K thermal cycle. The observation in the following winter shutdown, described in the next section, eliminated it from the list.

3. The pronounced outgassing was observed in the thermal cycle discussed above. The major compositions of air, nitrogen and oxygen, are in the ice form at 4 K and under 10^{-7} Torr vacuum. This hypothesis assumes a layer of ice mixture of solid nitrogen and oxygen was formed on the RF surface. This insulation layer adds extra RF loss via dielectric mechanism. Authors do not have available dielectric and loss data of solid nitrogen and oxygen at the specified temperature and frequency to date. This hypothesis is pending to be verified. Advice would be welcomed and appreciated.

REFURBISHMENT

ISAC typically has a shutdown from mid-December to mid-April each year for standard maintenance. In the 2023 winter shutdown, the SCC3 cryomodule was moved from the beamline to the cleanroom and refurbished, as its performance was most impacted in the vacuum excursion. Also 2 cavities previously unavailable could be restored by fixing RF issues on internal transmission lines. Cavity assemblies were removed from the strongback, inspected and high pressure rinsed. The cryomodule interior surfaces were also cleaned with alcohol wiping, such as the 80 K thermal shield and the strong back. Dusts were observed but it could not be concluded as a result of the vacuum excursion. Small pieces of the blue nitrile glove were found on the top flange of cavity #6 and the nearby area on the strongback, but not on the internal surface of any cavities. The rubber bits entered the cryomodule on the beamline level was forced up by around 0.5 m before attaching to a surface. A study on the supersonic leak-induced jet in vacuum for aerospace applications [8] predicts the position of the bits is covered by the expanded jet velocity map in an open space. But the complex geometry and the cryogenic temperature in the cryomodule make it more complicated to obtain a straightforward explanation.

The post-refurbishment RF performance was measured when the ISAC-II linac was cold. It demonstrated the field emitters brought in by the vacuum excursion have been removed by HPR. The total effective voltage of this module was improved by 4.9 MV, half of which was due to cleaning the RF surface while the other half was from 2 additional cavities now available for operation. The average operating gradient was improved by about 10% comparing to the pre-contamination performance in the previous year. In addition, we did not find obvious improvements nor further degradations on all other cryomodules after a full thermal cycle to room temperature. The total effective voltage of the linac is 37.5 MV this year. It is planned to refurbish SCC2 in the next shutdown.

SUMMARY

ISAC-II linac was contaminated in the vacuum excursion in summer 2022. 20 cavities in the 3 SCC cryomodules were impacted with the reduced field emission onset levels. There is a statistical trend that the cavity closer to the vent spot has more serious degradation. Cavities in SCB cryomodules were not affected, consistent with the degradation trend and directly demonstrated from RF measurements. We did not find obvious Q drop on most contaminated cavities only field emission on-set. SCC3#8 is the last SRF cavity in ISAC-II accelerator chain, and the first cavity seeing the sucked air from the beamline. Its performance was anomalous at first. The base Q was reduced by more than 2 orders of magnitude but was restored by a 300 K thermal cycle. After pulse conditioning, its usable gradient achieved the similar level as other cavities in the same cryomodule. In addition, pronounced outgassing was recorded in the cryomodule warmup. The ISAC-II event provided a unique data set for the SRF community.

The recent winter shutdown refurbishment successfully recovered SCC3 performance. We did not find any visible debris on the RF surface of any cavity, such as bits of rubber glove. HPR is sufficient to clean contaminations, which is expected to be only particulates. Another shutdown is required to bring the total effective voltage of the linac back to the level prior to the vacuum excursion. One more shutdown will restore the performance of all contaminated cavities.

In addition to the RF performance, our RIB operation team identified lessons learned from this event. The logic of the protection system has been upgraded in the recent winter shutdown. The fast valve must be armed prior to

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opening to ensure it is actived. The isolation valves between the SRF linac and the vault wall are interlocked to the 'ready' signal of the fast valve. The procedures and documentations have also been reviewed and updated to establish a systematic approach to prevent the vacuum excursion in the future operation.

ACKNOWLEDGEMENTS

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