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# OPERATING EXPERIENCE ON CAVITY PERFORMANCE OF ISAC-II SUPERCONDUCTING HEAVY ION LINAC

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## *Abstract*

ISAC-II is a superconducting heavy ion linac with 40 quarter wave resonators (QWRs) as an extension of ISAC facility for ISOL based on radioactive ion beam production and acceleration. Phase-I with twenty 106 MHz cavities has been operating since 2006. The design spec was achieved with the completion of Phase-II with another twenty 141 MHz cavities in 2010. The cavity performance statistics and operating experience have been accumulated over years. This paper will summarize the operating experience on cavity performance of ISAC-II.

## INTRODUCTION

SRF at TRIUMF began in 2000 with cavity and infrastructure development in support of the ISAC-II heavy ion linac as an extension of ISAC facility for ISOL based on radioactive ion beam production and acceleration. The specification of ISAC-II is to accelerate heavy ions to and above the Coulomb barrier, specifically the goal is to reach an energy of E > 6.5 MeV/u for A/q = 6. This is equivalent to a minimum effective accelerating voltage of 30 MV [1]. In 2006 Phase-I with acceleration voltage of 20 MV was commissioned for operation [2]. Phase-II upgrade was completed in 2010 with achievement of additional 20 MV of acceleration voltage [3]. ISAC became a leading ISOL facility supporting a full physics program with both stable and radioactive beams being delivered.

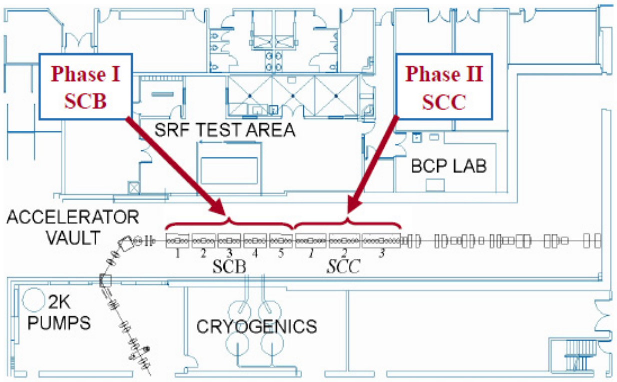

Figure 1: Layout of ISAC-II linac and SRF infrastructure.

The Phase-I (SCB) consists of twenty 106 MHz QWRs housed in five cryomodules with four cavities per cryomodule. The first eight cavities have a geometric beta of 0.057 and the remainder a geometric beta of 0.071. The Phase-II (SCC) also consists of twenty QWRs housed in three cryomodules, six cavities in each module for SCC1 and SCC2 and eight cavities in SCC3. These bulk niobium cavities have a geometric beta of 0.110 and are resonating at 141 MHz. Both Phase-I and Phase-II cryomodules have one 9 T superconducting solenoid symmetrically placed in the cryomodule. The layout of ISAC-II linac is shown in Fig. 1.

## ISAC-II CAVITIES

The ISAC-II cavities are QWRs, shown in Fig. 2, patterned after structures built for the low beta section of the INFN-Legnaro heavy ion linac. The cavities have a simple construction with a cylindrical shape, a rigid upper flange and an annular lower flange designed for mounting a removable tuning plate. The helium jacket is a cylinder of reactor grade niobium formed from two sheets and welded to the upper and lower flanges. A common outer conductor diameter of 180 mm is used for all cavities. The chief difference between the Phase-I and Phase-II cavities besides the frequency (and therefore the height) is that in Phase-II cavities the inner conductor beam port region is outfitted with a donut style drift tube to improve transient time factor. The cavities are specified to operate at an effective acceleration of 1.1 MV for a cavity power of 7 W at 4.2 K and corresponding peak surface fields of 30 MV/m and 60 mT [4]. The Phase-I cavities were produced by Zanon and the Phase-II cavities by PAVAC Industries.

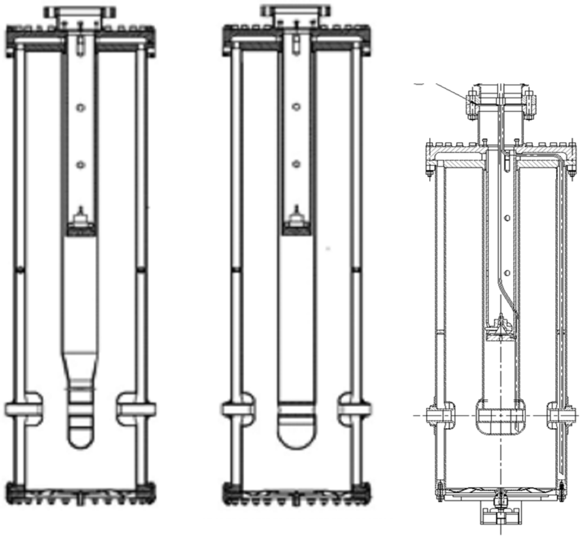

Figure 2: ISAC-II cavities for the geometry betas of 0.057, 0.071 and 0.11.

The RF parameters of Phase-I and Phase-II cavities are listed in the Table 1.

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Table 1: Parameters of ISAC-II Cavities

| | **Flat** | **Round** | **Donut** |
|---|---|---|---|
| $f_0$ (MHz) | 106.08 | 106.08 | 141.44 |
| Geometry beta | 0.057 | 0.071 | 0.110 |
| G (Ω) | 20.1 | 19.1 | 26.0 |
| $U/E_a^2$ (J/(MV/m)$^2$) | 0.100 | 0.094 | 0.067 |
| $E_p/E_a$ | 5.2 | 4.7 | 4.9 |
| $B_p/E_a$ (mT/(MV/m)) | 10.3 | 10.1 | 10.0 |

## OPERATING EXPERIENCE

ISAC-II linac has been in service for a decade. Excluding a major shutdown in winter and a minor one in autumn, the linac normally provides about 8 months' availability for beam acceleration. 24 hours RF support is provided by RF/SRF department at TRIUMF during experiments. Experience to maintain stable operation is accumulating over years, including cavity performance and accessories, RF amplifiers, LLRF, cryogenics, and vacuum. The discussion in this paper will focus on the SRF cavity.

### *Cavity Performance*

Cavity performance is monitored periodically typically during start-up following a shutdown. The accelerating gradient at 7 W power dissipation is measured at critical coupling. Figure 3 summarized the performance history of SCB cavities since April 2015. There is some fluctuation in an individual cavity over time. The major performance change is caused by glow discharge in RF power cable, such as SCB1#2 and SCB4#2. Some particular cavities, for example SCB3#1, had rigid multipacting barriers time to time. The dramatical Q-switch could also be observed during operation, like the first two cavities of SCB2 in 2015. Some details will be discussed in the following sections.

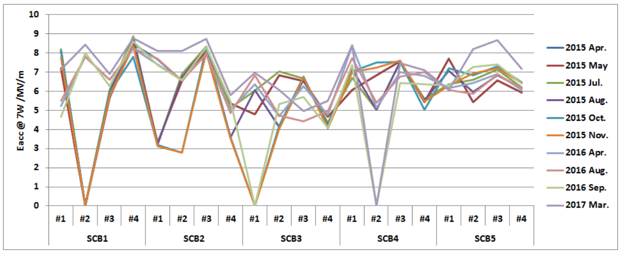

Figure 3: The operational accelerating gradient of each individual SCB cavity in the past three years.

The average cavity performance is consistent, shown in Fig. 4 with total accelerating voltage. Comparing to the initial results after installation in 2006 for SCB and 2010 for SCC, there is about 14 % degradation for the whole linac. Proper maintenances gradually improve the performance year by year. But the limited resources and the priority on site restrict the progress. Nevertheless, the linac was keeping the capable of meeting the original ISAC-II specification.

The recently measured Q-curves of SCB and SCC cavities are shown in Fig. 5. In general, SCB cavities perform better than SCC. The initial $Q_0$ below 2 MV/m is higher for SCB, and Q-slope in medium field level is moderate. In addition, field emission is a common phenomenal in both SCB and SCC cavities, while Q-disease appears more frequently in SCC.

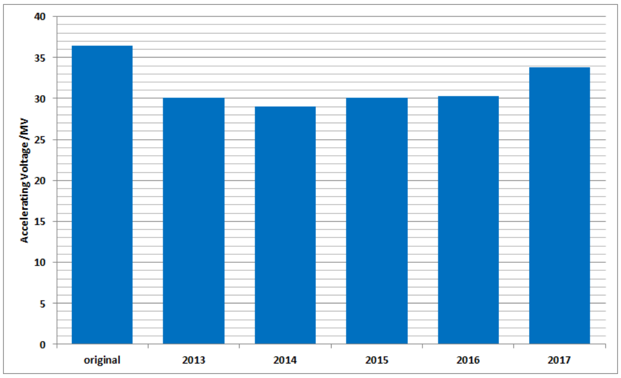

Figure 4: The comparison of the total accelerating voltage of ISAC-II linac over years.

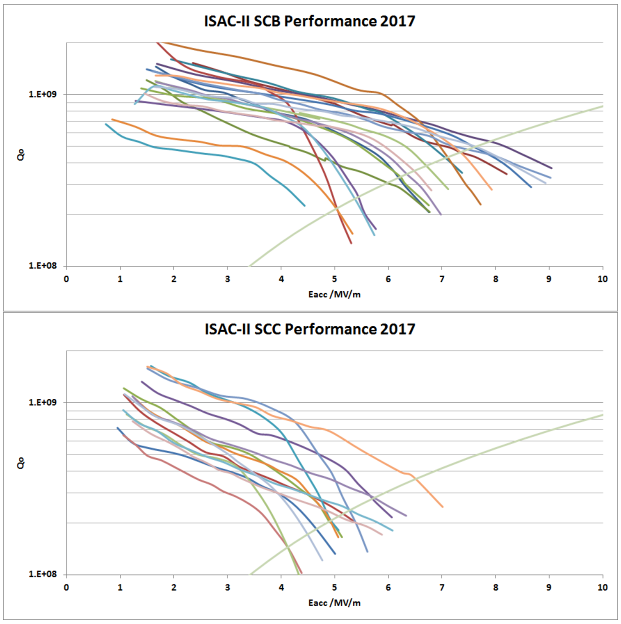

Figure 5: The Q-curves of ISAC-II cavities in cyromodules in 2017. Top: SCB cavities; Bottom: SCC cavities.

### *Multipacting*

The multipacting barriers of ISAC-II cavities are in the accelerating gradient range from10kV/m to 100kV/m [5]. It is two or three orders of magnitude less than the operational field level, and does not impact the operational performance. This low level multipacting in some cavities is responsible for delay of start-up and tuning. In the worst case, the cavity could not be practicable for operation, like SCB3#1 in Fig. 3. Pulse RF conditioning in self-excited loop with strong over-coupling is required to turn on RF in these cavities. But sometimes it takes a significant amount of time. A technique is developed and in place where all the twenty cavities in each phase are conditioned simultaneously using a single driving signal from an external signal generator bypassing LLRF system. The

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driven signal sweeps a bandwidth of frequencies that covers all the resonant frequencies of the cavities, and modulates in magnitude loop. This is apparently demonstrated to be more efficient for breaking through the low level barriers. The time consumption is generally decreased from days to hours for post-shutdown conditioning. Multipacting could disappear during operation and reappear after warmup. It could also be brought back by electron load activities in cavity, such as field emission caused quench.

### *Q-disease*

A series of cold tests demonstrated an obvious Q degradation due to Q-disease can be obtained after one hour of soaking in temperature range of 50 K and 200 K for SCC cavities, comparing to ten hours for SCB [6, 7]. The higher hydrogen content in SCC cavities could be introduced during fabrication, such as bad vacuum for EB welding. And the cavities were not heat treated for hydrogen degassing. In addition, due to the vacuum leak opening up in the saddle weld joining the drift tube assembly to the inner conductor in four cavities after bulk BCP, the etching specification was reduced from 100 um to 60 um to mitigate this risk. The residual damage layer on RF surface is another potential source of the hydrogen contamination.

On the cryogenic side, a typical cool down duration in the sensitive temperature range is about 45 minutes. The rate is to prevent vacuum leak due to thermal shock, and also limited by the capability of cryogenic plants. The bigger cold mass of SCC cryomodule makes it even slower. Liquid nitrogen precooling at 24 hours in advance also contributes to the low temperature soaking influence.

The Q-disease-like curves having lower $Q_0$ combined with stronger Q-slope in medium field level range are showing reduced accelerating gradient at nominal RF power dissipation. To mitigate the influence, the investigation of an optimized cool down procedure after winter shutdown is in progress. The larger cryomodule is preferred to be cooled first to benefit the full power of cryogenic plant for reducing cool down duration. The aheading time of liquid nitrogen cooling is also reduced to five hours. To improve operational performance against Q-disease, 800 ºC degassing is the choice as the future plan of ISAC-II upgrade.

### *Field Emission*

Field emission is a common feature of ISAC-II cavities at higher peak surface electric field than 20 MV/m after a decade of service. This is attributed mainly to the common vacuum configuration for RF and isolation spaces. Since the linac is thermally cycled once a year during winter shutdown, the fine particulate introduced during clean assembling or generated during the pump explosion eventually can migrate and contaminate the cavity RF surface. Field emission can reduce cavity operational gradient, bring in possibility of instability due to unstable phase shift of uncontrolled electron loading, and increase the risk of Q-switch during operation.

RF pulse conditioning is generally the way to remove field emitter or push the barrier to higher field level. The recent experience in 2017 winter shutdown demonstrated that it improved the total accelerating voltage at 7 W per cavity by 2.03 MV, which is equivalent to the effective voltage of two more cavities. Due to a limited time window for RF start-up after shutdown, the optimization of pulse conditioning procedure is under going. As an example of the benefit, SCB2#1 performance before and after conditioning is shown in Fig. 6. The 7 W gradient is stretched out to 7.0 MV/m from 6.5 MV/m. However, after months of RF operation at 7 W, cavity performance was back to similar as initial curve. It was caused by immigration of field emitters during strong field emission or cavity quench. More pulse conditioning is required to lift cavity performance back. But this recovery procedure could introduce half to one hour downtime during experiments.

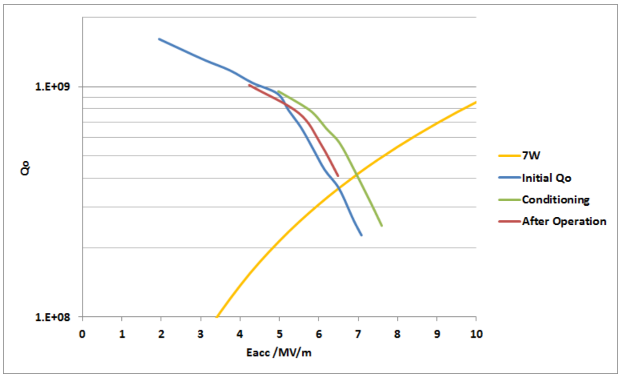

Figure 6: Q-switches in SCB2#1 after RF conditioning and after months of RF operation at 7W.

To avoid field emission caused Q-switch or to enhance the stability and reliability of linac operation, a practical method is setting the operational gradient setpoint at lower field level without the high field Q-slope in Q-curve regardless of cavity power consumption. It compensates operational stability by consuming total voltage if the final beam energy meets experiment requirements.

### *Q-switches*

Q-switches could happen either switching up or down during operation. The positive example shown in Fig. 3 is SCB1#1. With a switching up quality factor resulted by the mitigation of field emission in 2016, the operational gradient increased from 5 MV/m to 7 MV/m. However, in most cases, Q-switches affect the cavity performance, such as SCB2#1 shown in Fig. 6, and SCB2#1 and SCB2#2 shown in Fig. 3. The immigration of field emitters generated Q-switch has already been discussed in the previous section. Another factor was demonstrated to have correlation with trapped magnetic flux, especially for the cavities with strong Q degradations. The operational gradient of SCB2#1 was decreased from 7.7 MV/m to 3.2 MV/m after degradation in 2015, while that of SCB2#2 was also reduced from 6.7 MV/m to 2.8 MV/m. All cryomodules were warmed up to room temperature

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during winter shutdown 2016. It was noticed $Q_0$s of both cavities were restored after cooldown to 4 K in April.

A preliminary study was done on SCB5#2, which had similar phenomenal in late 2016. The Q-curves before and after Q-switch are shown in Fig. 7. Rhombus points are calibrated with beam energy measurements, and round points with error bars are calculated with RF measurements. The low field $Q_0$ estimated with the trend of the curves was degraded by a magnitude of one order, and operational gradient decreased from 7.0 MV/m to 3.1 MV/m. As the whole curve shifted down, trapped magnetic flux was highly suspected.

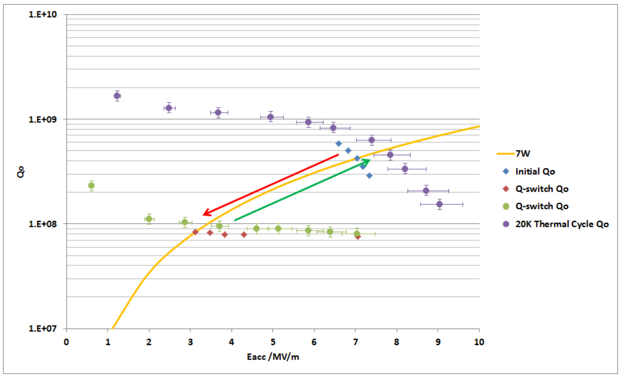

Figure 7: Q-switch in SCB5#2 and recovery after a 20 K thermal cycle. Blue rhombus: $Q_0$ without Q-switch. Red rhombus and green round: $Q_0$ after Q-switch. Purple round: $Q_0$ after recovery via a 20 K thermal cycle.

To release the trapped flux, the method of re-opening the normal zone by quenching cavity with the degaussed solenoid was the fastest procedure. But it showed little chance to change cavity performance in this case.

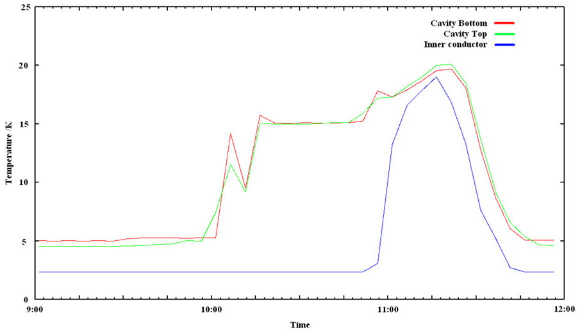

Figure 8: The 20K thermal cycle of SCB5#2. Red: cavity bottom (capacitive end). Green: cavity top (short end). Blue: cavity inner conductor.

The alternative recovery procedure is warming up cavities above the critical temperature of superconducting transition, 9.2 K for niobium, with zero magnetic field from solenoid. The temperature sensors' readings in the thermal cycle procedure are shown in Fig. 8. For SCB5#2, the whole cavity including niobium helium jacket was warmed up to around 20 K before cooling again. The cavity performance was measured afterwards, and shown in Fig. 7 with purple round points. The $Q_0$ was fully recovered after thermal cycle. The variance between purple and blue points is supposed to be introduced by different calibrations. It also demonstrated the recovery of cavities in SCB2.

The thermal cycle recovery procedure includes degaussing solenoid, warming up to above 15 K, cooling down back to 4 K, and RF characteristic. It typically introduces four hours' downtime in between an experiment, and requires cryogenic support on site. Comparing to rephasing the whole linac, which could take up to eight hours depending on the number of cavities following the failure one and operator´s experience on beam tuning, thermal cycle is a competitive approach to bring degraded cavity back to normal operation and save downtime for operation.

The further study is undergoing at TRIUMF to investigate the mechanism of trapping magnetic flux during operation. This degradation apparently occurred on the cavities operating with field emissions and after cavity trips. In addition, the niobium helium jacket was designed to be magnetic field shield during operation. But the Meissner state is turned out to be broken somewhere on the jacket during Q-switch. The jacket and liquid helium should involve the process. As a consequence, the dynamics of cavity quench and heat transfer in liquid helium, and the statics of magnetic field distribution of 9 T solenoid will be studied.

## SUMMARY

ISAC-II superconducting heavy ion linac has been in operation for more than 10 years. The cavity performance statistics and operational experience have been accumulated over time. The factors affecting cavity operational performance, including multipacting, Q-disease, field emission, and Q-switches, were discussed in this paper. The developments and future research were also reported.

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