ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-TUPO014

TRIUMF ISAC LINAC DEVELOPMENTS and UPGRADES

Z. T. Ang[†], T. Au, Y. Bylinski, K. Fong, J. Keir, D. Lang, R. Laxdal, R. Leewe,
B. Waraich, Z. Yao, Q. Zheng, V. Zvyagintsev
TRIUMF, 4004 Wesbrook Mall, Vancouver V6T 2A3, BC, Canada

Abstract

TRIUMF ISAC accelerator complex is in consists of ISAC-I room temperature linac and ISAC-II superconducting linac structure [1]. ISAC-I linac has seventeen RF systems in operation for about twenty years, and ISAC-II linac has forty superconducting QWR. The SRF cavities in operation for some about ten years. To match beam energy to RFQ, a small booster 3-gap structure at 11.78 MHz has been designed and installed in upstream of RFQ. A sliding mode extremum seeking control for LLRF control was developed and implemented in operation. Test results demonstrated very stable and reliable performs. Six of DTL systems have been working in the control mode. RFQ, two more DTL systems, HEBT and DSB bunchers, Rotator systems will be upgraded in the sliding mode control soon. The amplifiers for twenty ISAC-II QWR superconducting cavity SCB were developed and upgraded from YV-229 triode tube amplifier into a solid-state amplifier (SSA). The prototype and other four SSAs have been commissioned in 2017 and in operation over one year faithfully. The rest of 16 SSAs has been tested on bench at beginning of 2018. All twenty are in operation this year.

INTRODUCTION

The ISAC Linac of radioactive ions beams facility at TRIUMF have been in successfully operation for experiments many years. RFQ at 35.36 MHz to accelerate ions beam with $A/Q \leq 30$ from 2.03 keV/u to 153 keV/u and variable energy draft tube linac (DTL) at 106 MHz to accelerate the stripped ions beam of $A/Q \leq 7$ between 153 keV/u and 1.53 MeV/u. The designed capacity of beams energy for DTL to accelerate ions from 153 keV/u to 1.5 MeV/u with $A/Q \leq 6$. To meet the experiment requirements, some upgrades were done in DTL Tank number 3, number 4 and 5 in the RF power transmission line and final RF power amplifiers. The Tank 3 power amplifier outputs was increased to 20 kW from 16 kW after changing HCA 158-50 J coaxial semi-rigid transmission line to SPX communication technology 3-1/8'' copper rigid transmission line. Tank 5 amplifier's high voltage transformer has been upgraded to 51 KVA from 36.6 KVA, which output power increased from 20.5 kW to 28 kW. Tank 4 amplifier's specified power level increased to 22 kW from 19 kW after retuning amplifiers setup limit trip points. The temperatures of the tuners and RF coupler windows are monitored, and the coarse tuners were setup to meet fine tuner working distances for all power levels. Table 1 shows the DTL amplifiers upgrading results:

Table 1: DTL Amplifiers Output Power

System	Before	After upgrading
Tank 3	16 (KW)	19 (KW)
Tank 4	19 (KW)	22 (KW)
Tank 5	20.5 (KW)	28 (KW)

After the above upgrading for DTL RF systems there are more variable ions beams and beam energies could be delivered for experiments at TRIUMF.

RF BOOSTER

The 35.36 MHz RFQ is designed to accelerate beams with $A/Q \leq 30$ in CW. A three harmonic pre-buncher, located 5m upstream of the RFQ, operates with a fundamental frequency of 11.78 MHz so that one of every three RFQ buckets is filled with beams. The RFQ requires a beam injection energy at 2.03 keV/u for about 60% beam transmission. The injection energy acceptance of the RFQ requires that the ions beam must be extracted from a source at an electric potential up to about 60 kV. The ISOL target modules operate in a grim environment that can limit the source bias. Presently the ISAC target modules cannot hold higher than 54 kV and this value can degrade with time so that to schedule experiments for ions with $A>25$ has a risk.

In order to accelerate high mass beams and to mitigate against further source bias degradation a small 3-gap RF structure cavity has been installed at upstream of RFQ. The effective voltage for the booster was specified 16 KV. A 7 KV effective voltage has been achieved for beam experiments. 2 KV, 4 KV and 6 KV effective voltage for ions beams of Carbon and Nitrogen have been tuned through RFQ at the designed transmissions respectively. Table 2 shows the effective voltages with RF power feeding to the primary coil in the RF circuit box. A stable operation could not be approached while effective voltages applied to beams higher than 8 KV.

Before we installed the RF structure and RF circuitry box in beam line, we powered the system to 150 W RF power through primary coils in RF Lab driven from a 300 watts CW amplifier. The forward and reflected RF powers were monitored. A stable RF performs off line tests gave us a confident to install it for beam test. Instead of real RF structure and feedthrough, we used two capacitors with equal capacitances to the feedthrough and draft tubes for the test and tuning resonance frequency. However, when we installed the structure in beam line to test with beams in vacuum, the effective voltage to beam is much lower from simulations and bench tests.

[†] Email address: zang@triumf.ca

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-TUPO014

Table 2: Beams Test with RF Power

Ions	Effective V	RF Power
C/N	2 (KV)	4 (W)
C/N	4 (KV)	7.5 (W)
C/N	6 (KV)	26.5 (W)
C/N	7 (KV)	60 (W)

At 8 KV effective voltage, RF amplifier was driven from 150 W to 200 W in closed loop control. The system could not be in stable operation due to thermal RF dissipation in the system. Further tests and diagnostic tell the strong thermal existing in RF structure and RF circuitry box. The VSWR and the quality factor vary significantly comparison to the higher and lower RF power applied in the system. In Table 2, we could see that the 7 KV effective voltage to beams, much higher RF power dissipated in system.

To reduce the heat impacts in the system, the RF circuitry in box has been modified shown in Fig. 1 (left). The primary coils, tuning capacitors and matching capacitors in Fig. 1 (right) are eliminated; instead, a coupler loop is adopted. Water cooling are applied to coils and through RF feedthrough. It is much simpler for tuning system of the matching and the frequency:

- The matching capacitors in box (in primary circuitry) warm up at high power level, which affects the operation stability.
- The secondary coil and feedthrough capacitors values are fixed. Therefore, the VSWR less than 2 could not be achieved in the previous circuitry.
- The RF structure support and isolation Marco was replaced by a Teflon bar as the Marco RF character is poor than later one. There is a discoloured spot in the Marco bar which shown strong RF power dissipations during RF power tests.
- The new coils supported via two Teflon bars. They are amounted on both side of aluminium box connect with screw nut, which could squeeze or stretch the coils to tune frequency easily. The two bars also tighten the coils from any vibrations.
- The new coils have water cooling. The 1/8” copper tube is inserted inside of the half-inch copper tube. The cooling water through feedthrough and the 1/4” copper leads which joint with the bolted sleeves [2].

After the modification, the system was tested with water-cooling. Two resonant frequencies were measured. The Push-pull mode frequency is 11.78 MHz, and Push-push mode 19.5 MHz. About 10 kV effective voltage achieved for the structure in RF Lab. Beyond the voltage, the system could not be stable operation. Tracing the problem, we realized that a lower rating voltage capability of the feedthrough were being employed, which could not hand higher than 10 kV. A larger diameter feedthrough likes ISAC-I chopper 11 [3] will be procured later. A transition between RF structure and circuitry box will be amended when the new feedthrough arriving.

A new LLRF control board has been developed for ISAC booster based on existing LLRF control configurations. In addition, a new digital LLRF control system is being developed at TRIUMF. It will carry out in this booster system next year. EPICS control panel for the beam operation is under way.

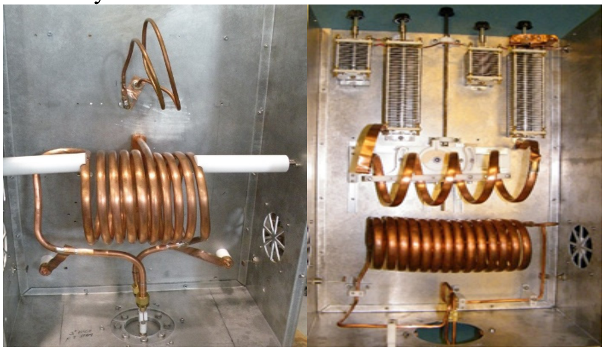

Figure 1: New RF circuitry box replacing the previous one.

SLIDING MODE RF CONTROL

A sliding mode extremum seeking control have been developed at TRIUMF [4]. The idea of the sliding mode control induced into LLRF control for the room temperature resonant is to minimize reflected power and minimize the driven RF power as well. The original LLRF control for ISAC-I DTL system, are based on frequency and phase control, which need to have a stable loop phases within certain range for system control stability. The operational RF cavities are frequency tuned through a phase comparison technique, which is sensitive to temperature variations if the facility or longer signal transportation cables are not temperature controlled. Temperature induced phase errors render this technique labour and time intensive. The temperature variations in ISAC-I linac building can be as high as over twenty degrees between summer and winter. This big temperature divergence could cause burden of the system stability. Figure 2 shows the measuring results of the forward, reflected powers and tuner positions vary with environment temperature during 12 hours without prosecuting the sliding mode control. The Fig. 3 shows the same measurements in another RF system that the sliding mode control has been implemented. It is distinctly shown that much smaller of the forward power and reflected power variations achieved in the new control mode.

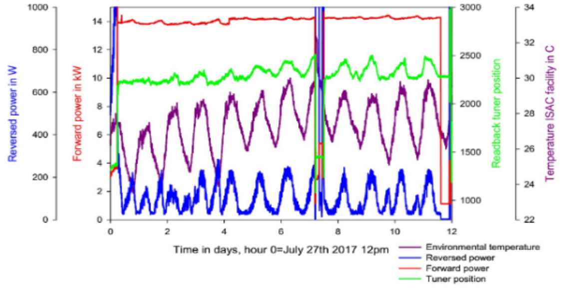

Figure 2: The forward, reflected powers vs. temperature.

The different RF characters among ISAC-I linac room temperature cavities, the control parameters for each system have to be carefully setup to achieve a reliable operation. A stability analysis provides conditions on how to

ISBN: 978-3-95450-194-6
ISSN: 2226-0366
doi:10.18429/JACoW-LINAC2018-TUPO014

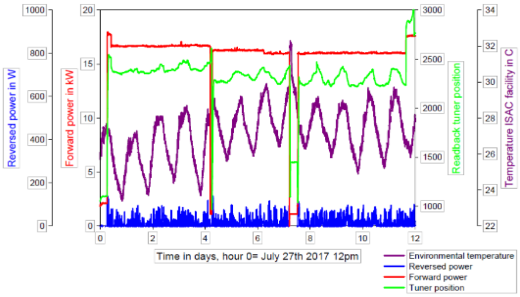

Figure 3: The forward, reflected powers vs. temperature while the sliding mode control implemented.

choose the controller parameters to guarantee stable system operation up to twice the cavity bandwidth, which is a controllable bandwidth improvement of a factor of two. The system first was carried on two of ISAC-I DTL Tank4 and 5 room temperature cavities and long-term measurements show that the system effectively counteracts the RF heating effect as well as diurnal temperature variations. Figure 4 shows how stable of Tank 5 at higher power level while sliding mode control applied.

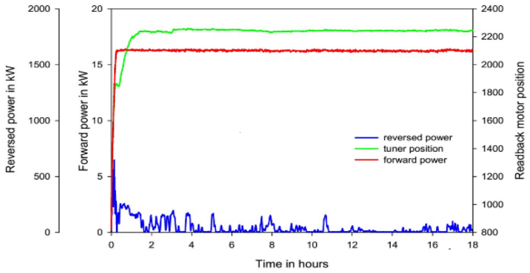

Figure 4: Forward, reflected power Vs. Temperature.

Except for above six DTL RF systems have been working in the sliding mode control, there are another six RF systems in ISAC-I linac will be upgraded in the sliding mode control soon.

ISAC-II SCB AMPLIFIERS

ISAC-II linac are consisting of 40 QWR superconducting cavities, 20 SCB cavities working at 106 MHz and 20 SCC at 141 MHz. SCC system is employing 20 solid-state amplifiers to power cavities. Twenty 600 W tube amplifiers power the SCB. The cavities operate in over coupled regimes with RF forward power up to 250 W CW; seven W is dissipating in the superconducting cavity and the rest of RF power reflected back to the amplifier. The amplifier output is connected with cavity via a 1000 W circulator, and all the reflected RF power is dissipated in a dummy load of the circulator.

The 600 W amplifier have two stage amplifiers. The 50 W pre-amplifier amounted on a heat sink with fan separated from the main amplifier in a chassis. It used a Motorola MRF-141G FET capable 150 watts output maximum. Main amplifier adopted YC-229 ceramic triode tube and employed a grounded grid circuit for the final amplifier. The performance of the amplifiers are not identical. Some of the amplifiers degraded fast, could not last one year, which affects routing operational efficiency a lot.

After last 10-year operation of the tube amplifiers in ISAC-II SCB, the disadvantages of the tube amplifiers are obviously comparison with SCC amplifiers. There are about 100 tubes being used since the SCB commissioned. Each tube costs more than 2000 US dollars. The major handicaps of the amplifier are as following:

- The degradation of the tube amplifiers is very fast.
- Tunings for matching and phases are often to make system operation ineffective.
- Costs to replace the failure/aged tubes are big for long term operations.
- Investigate failures of system is intricate.
- Time of replacing failed amplifier, pre-amplifier or DC power supply is not negligible for operation efficiency.

A 550 W solid-state amplifier for the replacement of the SCB tube amplifiers was developed in TRIUMF. The new amplifier performs met the operational requirements. So complete replacement of the tube amplifiers had been brought forward.

Based on the experience of homemade solid-state amplifier, BBEF produced a prototype amplifier for test and operation for experiments at TRIUMF, which was met our specifications and operation requirements. Then four amplifiers arrived TRIUMF for operation and commissioned in year 2016. The last seventeen amplifiers from BBEF shipped to TRIUMF at the end of 2017. All 20 SCB tube amplifiers were moved out from operations. The new SSAs have all been installed and commissioned for routine operation this year. Instead of individual DC power supply, pre-amplifier and final power amplifier, the new SSA is integrated power supply, pre-amplifier, final amplifier and control board all in one chassis. To replace a fail SSA is only a few minutes. Spare modules for SSA are swappable and easy to access.

CONCLUSIONS

ISAC-I linac RF system upgrading allow experiments having more choices of ions beams and beam energies. The developments and upgrades in ISAC linac RF system have increased the machine operational reliability and reduced beam down times.

REFERENCES

[1] R.E. Laxdal, “ISAC-I and ISAC-II at TRIUMF: Achieved Performance and New Construction,” in *Proc.* LINAC2002, Gyeongju, Korea, August 2002, paper TU302, pp. 294.

[2] V. Zvyagintsev, “Novel RF structure for energy matching into an RFQ,” in *Proc. 8th Int. Particle Accelerator Conf. (IPAC2017)*, Copenhagen, Denmark, May 2017, pp. 4111, doi:10 https://doi.org/10.18429/JACoW-IPAC2017-THPIK003

[3] A.K. Mitra, “RF Test and Commissioning of Low and High Beta Bunchers for the TRIUMF ISAC Facility” *in Proc.* EPAC, 2002, Paris, France, June 2002, pp. 2178.

[4] R. Leewe, “Novel Scheme to Tune RF Cavities using Reflected Power,” in *Proc.* LINAC2016, East Lansing, MI, USA, September 2016, paper THOP06, pp. 757, doi: https://doi.org/10.1829/JACoW-LINAC2016-THOP06