Experience with operation of heavy ion superconducting accelerator ISAC-II and SRF activities at TRIUMF

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Abstract. The history of superconducting heavy ion accelerator ISAC-II started in 2000 with the development of niobium quarter wave cavities and cryomodules. The first stage of ISAC-II is in operation since 2006. In 2010 it was completed and made TRIUMF ISAC a leading ISOL facility supporting a full physics program with both stable and radioactive beams. TRIUMF is using its accumulated experience and resources for farther SRF development for ELINAC and external projects for VECC, RISP, FRIB and SLAC. Status of Superconducting ISAC-II accelerator and SRF development aspects, results and plans are discussed.

1. ISAC-II
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 radioactive ion beam production and acceleration. In 2006 Phase-I of ISAC-II with an acceleration voltage of 20 MV was commissioned for operation [1]. In 2010 the design goal of ISAC-II for 40 MV of acceleration voltage was achieved with completion of Phase-II [2]. ISAC became a leading ISOL facility supporting a full physics program with both stable and radioactive beams being delivered including stable beams of 16O5+, 15N4+, 20Ne5+ and radioactive beams (and their stable pilot beams) of 26Na, 26Al6+, (26Mg6+), 6He1+, (12C2+), 24Na5+, (24Mg5+), 11Li2+, (22Ne4+) with 74Br14+ and other high mass beams from the charge state booster.

The Phase-I segment (SCB section of Fig. 1) consists of twenty 106 MHz quarter wave cavities housed in five cryomodules with four cavities per cryomodule. The Phase-II (SCC section) consists of twenty 141 MHz QWR cavities at β=0.11 in three cryomodules with six cavities in each of the first two modules and eight cavities in the third (SCC section in Fig. 1). Both Phase-I and Phase-II cryomodules have one 9T superconducting solenoid symmetrically placed in the cryomodule.

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

The first eight Phase-I cavities have a geometric $\beta$ of 0.057 and the remainder a geometric $\beta$ of 0.071 (Fig. 2). The cavity design was conducted in collaboration with INFN-LNL (Italy) with adoption of ALPI INFN-LNL coaxial bulk Nb cavities concept. The cryomodule design developed at TRIUMF is based on the rf vacuum volume open to the cryomodule isolation vacuum. The cavities are specified to operate at 106MHz and to provide an effective acceleration of 1.1MV for a cavity power of 7W at 4.2K with corresponding peak surface fields of 30MV/m and 60mT [3]. 20 Phase-I cavities were fabricated at Zanon (Italy) and assembled in 5 cryomodules designed and fabricated at TRIUMF.

Table 1. Parameters of ISAC-II cavities

| $\beta$ | $f_0$ (MHz) | $R_sQ$ (Ohm) | $U/E_a^2$ (J/(MV/m)$^2$) | $E_a/E_p$ | $B_p/E_a$ (mT/(MV/m)) |
|--------|-------|--------|----------------|--------|------------------|
| 0.057  | 106.08 | 20.1   | 0.100           | 5.2    | 10.3             |
| 0.071  | 106.08 | 19.1   | 0.094           | 4.7    | 10.1             |
| 0.110  | 141.44 | 26.0   | 0.067           | 4.9    | 10.0             |

The Phase-II 141 MHz superconducting cavity with $\beta$ of 0.11 is shown in Fig. 2. It was developed at TRIUMF and has a similar structure to the ISAC-II Phase-I linac cavity. The chief difference here besides the frequency is the inner conductor beam port region is outfitted with a donut style drift tube to improve the transit time factor. The Phase-II cavity has the same specification as the Phase-I cavities [4]. Twenty Phase-II cavities were produced by PAVAC Industries in Canada. Three cryomodules with high beta cavities were successfully commissioned in April 2010 [2]. An SRF infrastructure for SC development including SRF test area, clean room and chemical laboratory (Fig. 1) was created at TRIUMF. The parameters of Phase-I and II cavities are presented in the Table 1.

Tuning of the cavities is provided with deformation of Nb plates bolted to the bottom flange. A mechanical damper installed inside of the inner conductor provides $>10$ dB attenuation of microphonics noise. The cavities operate in strong overcoupled regime (coupling ~50-100) to provide enough bandwidth to maintain stable operation from microphonics. The LN2 cooled coupling loop produces <0.25 W power dissipation to the helium system at 200W forward power.

1.2. Operation experience.
The performance of the cavities is monitored periodically during start-up after shutdown. The linac is warmed up once per year for three months as part of the site maintenance shutdown. The linac cavities operate with an average gradient $E_a$ corresponding to a peak surface field $E_p$ of 32 MV/m for Phase-I and 28.5 MV/m for Phase-II without any discernible reduction in performance. The reasons why Phase-II cavities performance is lower could be:

- **Q-disease.** Tests show that Phase-II cavities start degrading performance after 1h in the range of temperatures 200-100K, for Phase-I cavities it occurs after 10h. It could be due to higher hydrogen content in the Nb.

- **During production of Phase-II cavities two of them were rejected due to vacuum leaks that opened in the donut weld after a final BCP of 100µm. Due to the tight schedule we limited BCP (in the beam tube region) to 60µm on subsequent cavities. All leaking cavities were successfully repaired and tested. Another four cavities were installed in cryomodules without single cavity cryostat tests due to time constraints.**

We experience some cavity failures for different reasons but it doesn’t stop operation. Figure 3 shows the change of cavity performance and failures as a function of the time of operation; it could be restored after conditioning or MRO, dropped and even failed. Since every cavity has an independent RF system, we can compensate the performance of the unavailable cavities by increasing the gradient in other cavities (at power dissipation >7W).

We are conducting continuous development to upgrade the cavities systems and mitigate failures. These developments include:

- **Replacement of coupler loop mechanical joints.**
- **Due to several failures of internal cables due to RF glow discharge in vacuum since 2015 we started replacing 3/8” for ½” ANDREW HELIAX cables with positive results.**
- **Replacing Phase-I couplers that use a rack and pinion mechanical arrangement and Teflon guide bearing with Phase-II couplers with a more robust design that includes non-magnetic cross-roller bearings and symmetric loading. This has improved the mechanical motion which is important because the ½” cable is more rigid and provides more side load for the coupler mechanism.**
- **During maintenance we are doing high pressure rinsing and sometimes light etch to recover the cavities performance.**

During operation cryogenics failures can cause cavity degradation after recovery including the effects of: 

![Figure 3. ISAC-II cavities performance as acceleration gradient $E_a$ measured at power dissipation of 7W on cavities walls during recent in situ cavity tests.](image-url)
• Trapped magnetic flux from short interruption of LHe supply. Full recovery (~two hours activity) involves degaussing the solenoid and environs, then warming cavities and solenoid to 30K to quench all solenoid trapped flux, then recooling the cold mass [5].

• Q-disease due to long interruption of LHe supply. Full recovery requires cavity warmup to room temperature.

Low level multipacting in some cavities is responsible for the delay of start-up and tuning. It is three orders of magnitude less than the operational field level and doesn’t affect performance. Pulse RF conditioning in self-excited loop is required to start these cavities and sometimes it takes a significant time delaying beam delivery. We implemented a driven option for multipacting conditioning from a signal generator and apparently we see that it is more efficient. Multipacting disappears during cavity operation and reappears after warmup.

The Phase-I system uses tube amplifiers and they have been a source of downtime due to tube aging issues causing phase drift and non-linear output affecting LLRF operation. Replacement solid state amplifiers have been developed and successfully tested in operation. All tube amplifiers will be replaced with new solid state amplifiers in the summer of 2018.

For the future we intend to make a development for degassing of Phase-II cavities to eliminate Q-disease issue and increase the cavities operational gradient.

2. Other SRF activities at TRIUMF
The accumulated experience and resources from ISAC-II linac development were used for farther SRF development at TRIUMF including ELINAC and external VECC, RISP, FRIB and SLAC projects.

2.1. ELINAC
The ARIEL project [6] will allow an increase in the radioactive ion beam (RIB) hours with the addition of a new electron linac (ELINAC) driver of 50 MeV (0.5 MW), a new proton line from the 500MeV cyclotron and new production target stations. Accelerated electrons can be used to generate RIBs via the photo-fission process. The electrons are stopped in a converter to generate bremsstrahlung photons for fission in actinide target material. An electron beam intensity and energy of 10 mA and 50 MeV is required for a fission rate of $10^{13}$ fissions/sec.

The electron linac is housed in a pre-existing shielded experimental hall adjacent to the TRIUMF 500 MeV cyclotron that has been re-purposed as an accelerator vault. The e-Linac is being installed in a phased way with stages shown schematically in Fig. 4.

A first phase consisting of a 300 kV 16 mA electron gun, an injector cryomodule, ICM, containing one 1.3 GHz nine-cell cavity and an accelerating cryomodule, ACM1, that now contains one 1.3 GHz nine-cell cavity (and eventually two cavities) plus associated beamlines is now installed and is being commissioned with one cavity in ACM1 at energy of 23 MeV[7]. This first phase is designed to accelerate CW up to 10 mA of electrons at 30 MeV. The second cavity for ACM1 finally was fabricated and installed for commissioning in 2017. The initial beam dump and production targets will only be compatible with 100 kW operation. A second phase, dependent on funding, will see the
addition of a second accelerating module, ACM2, and a ramp up in beam intensity to the full capability of 50 MeV 0.5 MW.

2.2. External projects
In frame of collaboration agreement with VECC (India) TRIUMF developed and successfully commissioned a copy of the ELINAC injector cryomodule ICM2 and 30 kW CW IOT Transmitter which was used for ELINAC power coupler conditioning. The IOT Transmitter was used also for 4kW 1.3GHz couplers conditioning for the SLAC LCLS-II project.

TRIUMF SRF infrastructure is extensively involved in testing of SC QWR and HWR cavities for RISP. We are conducting development of a novel Spoke cavity for RISP. We developed and fabricated variable test couplers for SRF tests of FRIB SC QWR and HWR cavities.

2.3. SRF development
TRIUMF is developing design and ‘in house’ fabrication of SC Deflecting cavity for ELINAC ERL separator. We are conducting a series of developments for SRF technology: µSR material samples study, vertical electro polishing, induction oven for cavities degassing and doping, T-map for SRF cavities tests.

3. Summary
In 2017 we are going to complete Phase-I of ELINAC with installation and commissioning of second cavity in ACM cryomodule and completion of the RF System.

We are going to proceed with development for ISAC-II cavities performance and reliability. External projects and collaborations help to raise expertise and extend competency of TRIUMF SRF team.

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