STATUS OF SUPERCONDUCTING ISAC-II AND ELINAC ACCELERATORS, AND SRF ACTIVITIES AT TRIUMF

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Abstract

The development for superconducting accelerators has been started at TRIUMF in 2000. The main milestones and material implementations are: 2006 - commissioning of Phase-I of the heavy ion superconducting accelerator ISAC-II, 2010 - Phase-II, 2014 - commissioning of Phase-I of the superconducting electron linear accelerator eLinac. We are using the accumulated experience and resources for farther SRF development at TRIUMF and external projects VECC, RISP, FRIB and SLAC. TRIUMF is also running fundamental studies for SRF and educational program for universities. Status of Superconducting ISAC-II and eLinac accelerators and SRF development aspects, results and plans are discussed.

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 on radioactive ion beam production and acceleration. In 2006 Phase-I of ISAC-II with 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: stable beams of 16O5+, 15N4+, 20Ne5+ and radioactive beams (and their stable pilot beams) of 26Na, 26Al6+, (26Mg6+), 6He1+, (12C2+), 24Na5+, (24Mg5+), 11Li2+, (22Ne4+) including 74Br14+ from the charge state booster.

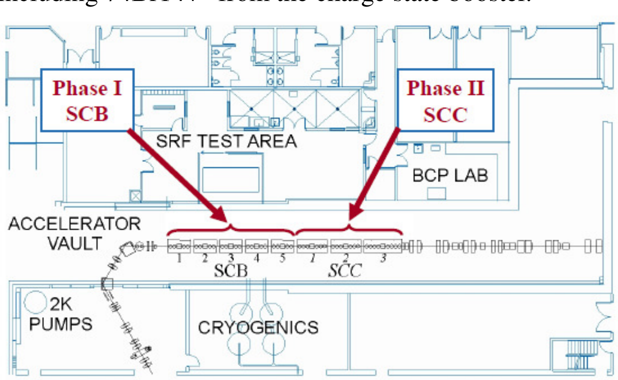

Figure 1: Layout of ISAC-II linac and SRF infrastructure.

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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.

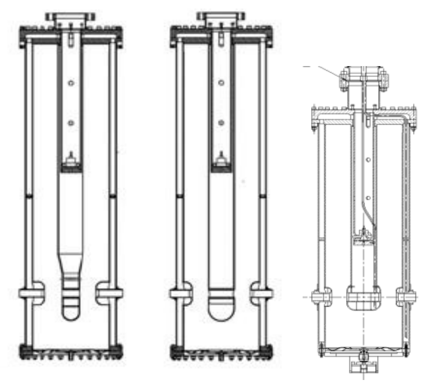

Figure 2: ISAC-II β=0.057, 0.071 and 0.11 cavities.

The Phase-II 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.

Cavities

The first eight of Phase-I cavities have a geometric β of 0.057 and the remainder a geometric β 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 with vacuum volume open to 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 and 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.

The Phase-II 141 MHz superconducting cavity with β 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 beamport 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

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and chemical laboratory (Fig. 1) was created at TRIUMF.

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 in helium system at 200W forward power.

Operating 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 corresponding to a peak surface field of 32 MV/m for Phase-I and 28.5 MV/m – 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 2 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. 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

- Replacement of coupler loop mechanical joints
- We experienced with several failures of internal cables due to RF glow discharge in vacuum. Hermetic cable assemblies were unavailable at that time due to a long delivery time. Since 2015 we started replacing 3/8" for ½" ANDREW HELIAX cables. It works fine so far.
- We replace Phase-I couplers that use a rack and pinion mechanical arrangement and Teflon guide bearing for Phase-II couplers with design with non-magnetic cross-roller bearings and symmetric loading – this has improved the mechanical motion which is important because of 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 cause cavity recoverable degradation.

- 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 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, sometimes it takes a significant time. We implemented 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. We started replacement for solid state amplifiers.

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.

ELINAC

The ARIEL project [6] will allow an increase in the radioactive ion beam (RIB) hours with the addition of a new electron linac 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 elinac is being installed in a phased way with stages shown schematically in Fig. 3.

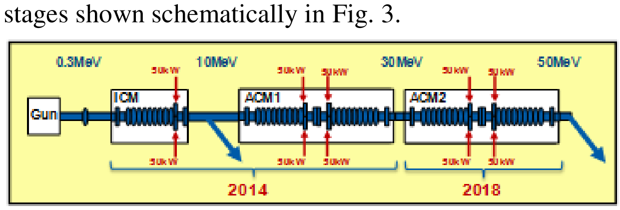

Figure 3: The stages of the eLinac project.

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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 [7]. This first phase is designed to accelerate CW up to 10 mA of electrons at 30 MeV. The initial beam dumps 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.

eLinac Design

An RF frequency for accelerating cavities of 1.3 GHz is chosen to take advantage of the considerable global design effort at this frequency both for pulsed machines (ILC) but also for CW ERL applications (KEK, Cornell, BerlinPro). The linac architecture was determined by the final CW beam power of 500 kW (10 mA/50 MeV electron beam) and the available commercial CPI VWP3032 couplers for 75 CW RF at 1.3 GHz. The cavity design allows two couplers per cavity arranged symmetrically around one end delivering a total of 100 kW of beam loaded power. This sets the number of cavities at 5 with a maximum gradient per cavity of 10 MV/m. It is our intention to install a future ERL ring with injection and extraction between 5-10 MeV and so a single cavity off-line injector cryomodule was chosen plus two 2-cavity accelerating modules. The electron hall is shown in Fig. 4 as it would appear at the end of Phase-I stage of the project.

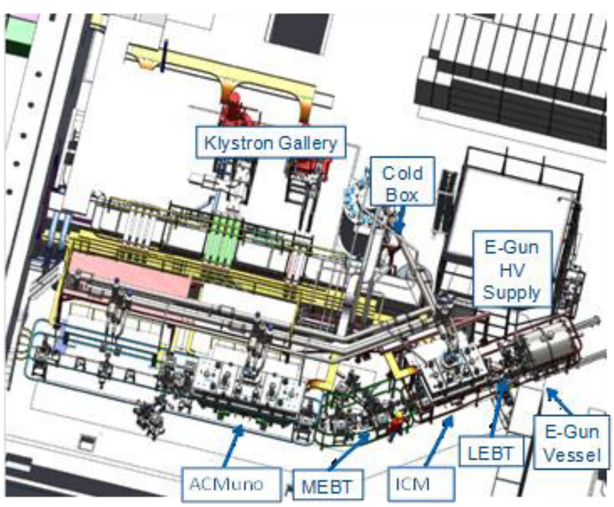

Figure 4: The Phase-I configuration of the eLinac.

The electron source provides electron bunches with charge up to 15.4 pC at a repetition frequency of 650 MHz. The main components of the source are a gridded dispenser cathode in a SF6 filled vessel, and an in-air high voltage power supply. The beam is bunched by superimposing a RF modulation to overcome a DC suppression voltage on the grid. The source is installed and conditioned to 320 kV with beam extracted at 300 kV up to the full CW intensity of 10mA.

The LEBT straight section contains three solenoids to provide transverse matching and transportation. The LEBT is now installed and commissioned [7].

Cavities

The cavity design parameters include f_o=1.3 GHz, L=1.038 m, R/Q=1000, E_a=10 MV/m. For $Q_o=1\bullet10^{10}$ the cavity power is P_{cav}=10 W at 2 K that sets the active load requirement for the cryogenics system. A rendering of the jacketed cavity is shown in Fig. 5.

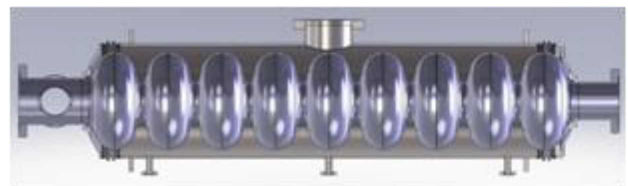

Figure 5: The e-Linac nine cell cavity with jacket.

The inner cells take their shape from the Tesla nine cell cavities but the end groups are modified to accept the two power couplers and to help push HOMs to dampers located on each end. On the power coupler end there is a stainless steel damping tube coaxial with the beam tube and extending into the beam pipe. On the opposite end of the cavity a coaxial CESIC tube is used. Each tube is thermally anchored at 77 K and thermally isolated from the cavity by a thin walled stainless steel bellows. The dampers are sufficient to reduce the HOMs to meet the BBU criterion of $Rd/Q\bullet QL<10^7$. The beam tube diameters on the coupler end and opposite end are 96 mm and 78 mm respectively. The vacuum jacket is made from Ti with a machined two convolution flexure on either end. A single 90 mm diameter chimney allows for large CW RF load of up to 60 W per cavity assuming a conservative heat transfer of 1 W/cm^2.

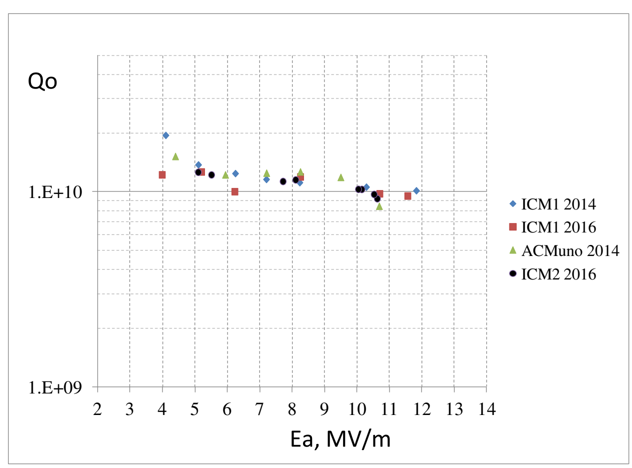

Figure 6: Q-curves of the cavities in eLinac cryomodules.

The ARIEL cavities have been fabricated by PAVAC [7]. To date four cavities have been received. The cavities are tuned, degreased then given a 120 µm BCP before

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final tuning. After the initial cold test all ARIEL cavities were each degassed at FNAL at 800 C for four hours. All the cavities exhibit similar test results. The cavities reach, during 'vertical' tests, the specified gradient of 10 MV/m but at a Q_0 of $6{\bullet}10^9$. So far 3 ARIEL cavities after jacketing were installed in cryomodules: ICM, ACMuno and ICM2 (for VECC). All of them in, 'horizontal' mode, shown $Q_0 > 1{\bullet}10^{10}$ at E_a=10 MV/m (Fig. 6). Cavity jacketing was done at PAVAC. Due to problems with Ti-bellows from the sub-contractor PAVAC proposed to machine Ti flexures into the jacket. These work well with no significant increase to the cavity stiffness of 1800 N/mm.

Cryomodules

In brief the module is a top-loading box-like structure with a stainless steel vacuum chamber (Fig. 7). The cold mass is suspended from the lid and includes a stainless steel strongback, a 2 K phase separator pipe, cavity support posts and the cavity hermetic unit. The hermetic unit consists of the niobium cavities, the end assemblies, an inter-cavity transition (ICT) with a stainless steel HOM damper, the power couplers (FPC) and an RF pick-up. The end assemblies include the warm-cold transition (WCT), CESIC HOM damping tubes and beam-line isolation valves. Other features include a scissor jack tuner and warm motor, LN2 cooled thermal isolation box and two layers of mu metal and alignment monitoring via a WPM diagnostic system.

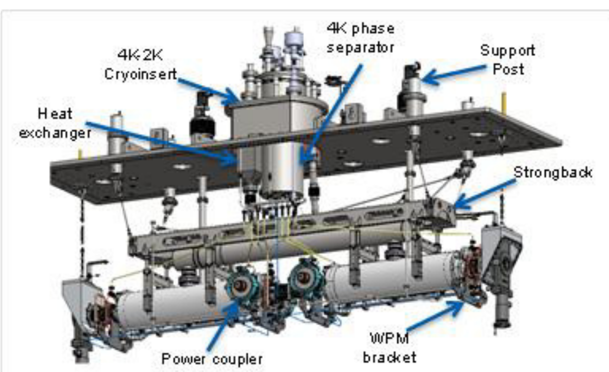

Figure 7: Accelerating cryomodule for ARIEL eLinac.

Each cryomodule is outfitted with an on-board 4 K to 2 K cryogenics insert. The insert consists of a 4 K phase separator, a 2.5 gm/sec heat exchanger and a JT expansion valve, a 4 K cooldown valve and a 4 K thermal intercept syphon supply and return. During cooldown the 4K valve is used to direct LHe to the bottom of the cold mass until 4 K level is reached. The level in the 4 K reservoir is regulated by the LHe supply valve, the level in the 2 K phase separator is regulated by the JT valve and the 2 K pressure is regulated by the sub-atmospheric line valve. Piping within the module delivers the syphon supply to a number of 4 K thermal intercept points (WCT, ICT and FPC) and then returns the two phase LHe back to the top of the 4 K phase separator.

In 2014 the second cavity for ACM1 was not ready and it was decided for installation along with a `dummy' cavity that occupies the second cavity space in the cryomodule and the RF System was adapted accordingly. The 'dummy' cavity contains all the interfaces to the helium system so that all helium piping surrounding the dummy will be final. In addition the 'dummy' cavity is installed with a DC heater to replicate cavity active loads and WPM brackets to permit alignment studies. The one cavity ACM variant we term 'ACMuno'. This configuration allows a full cryo-engineering characterization of the cryomodule. Both cryomodules are equipped with protection systems developed and fabricated at TRIUMF for fast trip of RF drive in case of cavity quench and threshold signals for RF power, vacuum and temperature.

Cryogenics characterization. The static heat loads are measured by observing the rate of falling LHe level after the supply valves are closed to the volume and noting the volume change of LHe per unit time and the heat of vaporization. The rate of 2 K production is measured by closing the 4 K supply valve while regulating the JT valve to keep the level constant in the 2 K space. In this case the falling level in the 4 K space is a combination of the static loads of the 4 K and 2 K space plus the vapour lost due to expansion from atmosphere to 31.5 mbar. The 77 K static load is measured by noting the warmed GN2 flow required at the exhaust side in order to keep the LN2 thermal shield cold. In this case the measurement is an overestimate since it was difficult to regulate the LN2 at a lower level but the thermal shield was always cold. Measured values for the ICM are pretty close to design: static load for 4K, 2K are 6.5, 5.5 W correspondingly. The 2 K production efficiency improves as a function of mass flow as the temperature of the heat exchanger and JT valve decreases: 70% at 0.5 g/s, 80% at 1g/s and 86% at 1.5 g/s. The ACMuno cryogenics test with one cavity and one 'dummy' show 6.4 W of static load for 4 K and 6.5 W of static load for 2 K.

RF characterization. The test includes cavity turn on and phase/amplitude lock, tuner frequency range and tuner lock, microphonics measurements and beam acceleration. The tuner range was measured at +400 kHz – the tuner motion was very stable. Due to the excellent frequency stability and broad bandwidth phase lock could be obtained with stable forward power even without the tuner but the tuner lock was easily achieved in any case. Cavity quality factors were estimated based on calorimetric measurements. The Q-curves of ARIEL1, ARIEL2 and ARIEL3 cavities installed in ICM, ACMuno and ICM2 cryomodules are presented in Fig. 6. The Q_0 values in the cryomodules are higher than the values measured in the vertical test. This can be due to an additional BCP of 20 μm that each cavity received after vertical test or an improved magnetic environment or both. The cavities meet ARIEL specifications of Q_0=10^{10} corresponding to power dissipation of 10 W at 2 K for E_a=10 MV/m. The results indicate that the magnetic shielding is sufficient and that the HOM dampers do not

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load the fundamental mode. The goal RF coupling for ARIEL cavities for 10mA/10MV performance at $Q_0=10^{10}$ is $Q_{ext}=10^6$. The coupling adjustment is in the range of $Q_{ext}=7•10^5…3•10^6$. For the initial beam test we set the minimum coupling of $Q_{ext}=3•10^6$.

Cryogenics System

The design of the cryomodules allows a simplified cryogenics system. A standard commercial 4 K ALAT LL Cold Box is employed delivering 4 K liquid to a supply dewar near atmosphere. The LHe in the dewar is pushed through the cold distribution with slight overpressure (1.3 Bar) and delivered to the cryomodule 4 K reservoir with parallel feed from a common distribution trunk and cold return back from each cryomodule to the exhaust side of the trunk. Specification for a pure refrigeration performance of 600 W and a pure liquefaction performance of 280 l/h was defined. The final commissioning produced a pure refrigeration performance of 837 W and a pure liquefaction performance of 367 l/h comfortably above the criteria. Four sub-atmospheric pumping units rated at 1.4 g/s each are installed. More can be added as the 2 K production increases in Phase-II.

RF System

The RF system includes one high power RF source for each cryomodule. In Phase-I each cryomodule is driven by a dedicated klystron. For Phase-II one of these klystrons will drive ACM2 while the ICM will be driven by a 150 kW power source to be determined. The ACM RF power feed is split to feed each of the cavities equally. A further splitting is required to feed each of the power couplers while phase shifters in each leg are used to achieve the proper phase conditions. One LLRF system is used for each cryomodule with a vector sum compensation of voltage and phase drifts in the ACM.

Two CPI VKL7967A 290 kW CW 1.3 GHz klystrons and two 600 kW 65 kV klystron power supplies from AMPEGON are now installed. Waveguide elements have been installed and tested. The power couplers have been conditioned by two couplers at once at room temperature in a Power Coupler Test Station (PCTS) using a 30 kW IOT.

Beam Acceleration Test

A ‘23 MeV Beam Test’ of the front end unit is a project milestone to validate cryogenics, HLRF, LLRF, e-Gun operation, LEBT, ICM, ACMuno engineering and overall synchronization [7].

The beam energy was estimated based on the dipole setting at the maximum current intensity into the dump Faraday cup. Beam simulations were done to calculate the final energy assuming a certain cavity gradient. For the beam tests a gradient of 12 MV/m is achieved for the ICM and 11 MV/m for the ACM cavity. The required forward powers are 18 kW and 14 kW CW respectively.

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 novel Spoke cavity for RISP.

We developed and fabricated variable test couplers for SRF tests of FRIB SC QWR and HWR cavities.

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.

SUMMARY

Next year 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. The TRIUMF SRF team was honoured to host the SRF 2015 Conference.

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