RECENT PROGRESS IN THE SUPERCONDUCTING RF PROGRAM AT TRIUMF/ISAC

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Abstract

The first phase of the ISAC-II superconducting accelerator has recently been commissioned. The heavy ion linac adds 20MV to the 1.5MeV/u beam injected from the ISAC post accelerator. The linac is composed of five cryomodules; each cryomodule housing four 106 MHz quarter wave resonators (β_0=0.057, 0.071) and one 9 T superconducting solenoid all operating at 4K. On-line performance has confirmed cw cavity operation at a peak surface field in excess of 35 MV/m. Performance after 18 months of operation and a full thermal cycle during the annual shutdown shows very little degradation in performance. The second phase of the program will see the installation of a further 20 MV of 141 MHz quarter wave cavities with (β_0=0.11. Two prototypes of the cavities are now in production. The mechanical drive for the coupling loop of the Phase I cavities is now being modified to improve the motion as part of the Phase II hardware development. TRIUMF is proposing to build a 50MeV electron driver as part of the next five year plan. Consequently plans are now underway to upgrade the SRF lab to support developments at 1.3 GHz. The report will summarize all aspects of the program.

INTRODUCTION

The ISAC facility [1] is now the leading facility for ISOL based radioactive ion beam production and acceleration. Beam production consists of a 500 MeV cyclotron producing a proton driver beam of up to 100µA 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 linacs consisting of a room temperature RFQ and DTL to an energy 1.5 MeV/u and a new superconducting linac that adds a further 20 MV to the beam for nuclear physics investigations near the Coulomb barrier. The experimental facilities are divided into low-energy areas (source potential), medium energies, variable from 150 keV/u to 1.8 MeV/u and the high energy hall after the superconducting linac. Presently we are limited by licensing restrictions to energies less than 5 MeV/u for experiment although commissioning studies restricted to the accelerator vault have produced beams up to 10.8 MeV/u.

Recent trends have shown a heightened interest in low beta (5-15%) cw superconducting light and heavy ion linacs including RIA, EURISOL, SPIRAL-II, SOREQ and REX-ISOLDE. All these facilities take advantage of the early developments, production and operation of QWR niobium cavities at ATLAS and later at INFN-LNL and JAERI. In the proposals the linacs are grouped into driver accelerator applications or RIB post-accelerator applications. Driver accelerators tend to be longer and cover a wider velocity range than post-accelerators with a larger number of cavity geometries. Consequently the operating gradients have to be chosen somewhat conservatively so that the beam can follow a prescribed velocity profile. In addition the driver beams are of higher intensity so halo control is important and gradient management particularly in the low velocity region overrides the actual capabilities of such cavities. In contrast when configured as a RIB post-accelerator the intensity of the beam is never an issue. The linac tends to be shorter, made up of only a few cavity types so gradients can be kept near the maximum possible with the number of cavities chosen as required by the experiment. Nonetheless maximum achievable gradient at a given cavity power is an important criteria since this will ultimately determine how much linac one requires to fit a prescribed set of experimental requirements. The technology has advanced, spurred by these pioneering labs to the point that high quality cavities are now available in industry and offer the small and medium size labs the ability to choose the technology without the added burden of developing an in-house cavity production expertise.

A particular well-suited application for SC linacs is in the post-acceleration of ions in ISOL based radioactive beam facilities. The short independently phased cavities provide a flexible, large acceptance machine to support a varied nuclear physics program. Present cw operation is limited to peak surface fields of 20-25 MV/m. The new projects are attempting to take advantage of the lessons learned over the past twenty years and push the cw gradients to minimize project costs. The TRIUMF ISAC-II superconducting linac is the first realization of this new generation facility with a design goal to operate at a peak surface field of 30 MV/m.

ISAC-II SUPERCONDUCTING LINAC

The linac is grouped into low, medium and high beta sections. The initial five medium beta cryomodules represent a first stage (Stage 0) with a further 20 MV of high beta superconducting linac to be installed over the next three years (Stage 1). The ISAC-II accelerator final low beta Stage 2 is foreseen after 2010. A schematic representation of the expansion is given in Fig. 1. The present installation is composed of twenty 106 MHz bulk niobium, quarter wave, rf cavities housed four per cryomodule in five cryomodules. Each cryomodule contains one 9 T superconducting solenoid for periodic transverse focussing.

The cavities consist of only two accelerating gaps giving

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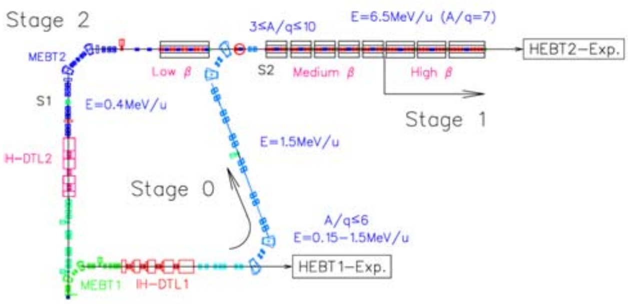
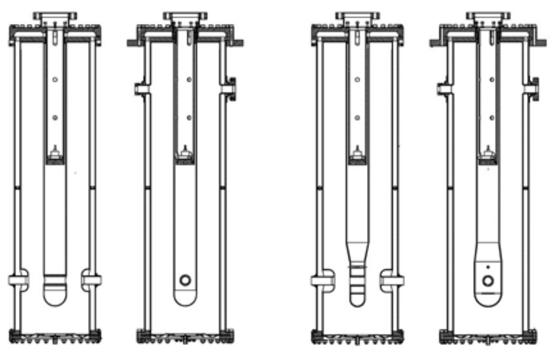


Figure 1: Stages 0, 1 and 2 for the ISAC-II upgrade.

a broad velocity acceptance. The first eight have a design velocity of $\beta_0 = 5.7$ % while the remaining twelve have a design velocity of $\beta_0 = 7.1$ %(Fig. 2). A demountable flange on the high field end supports the tuning plate. Rf coupling is done inductively through a side port near the upper end of the cavity.



(a) Nominal (β=7.1%) (b) Flat (β=5.7%)

Figure 2: The two medium beta quarter wave cavities for the ISAC-II linac.

The ISAC-II medium beta cavity design goal is to operate up to 6 MV/m across an 18 cm effective length with $P_{cav} \leq 7$ W. Note that there is no agreed upon definition of cavity length within the heavy ion community so accelerating gradient is not the best indication of performance. The ISAC-II design gradient corresponds to an acceleration voltage of 1.1 MV, a peak surface field of $E_p = 30$ MV/m and a stored energy of $U_o = 3.2$ J. This is a significant increase over other operating heavy ion facilities. The gradient may seem low compared to the present state of R+D in elliptical cavities where single cavity tests are pushing peak surface fields of 100 MV/m and gradients of 50 MV/m. There are two important points to keep in mind. Firstly ILC cavities will operate pulsed at or near the highest attainable peak surface field whereas cw cavities are restricted by the cryogenic system to a given cavity power. In this case the cavity Q at the operating point is the critical parameter. The second point is that because of the difference in the ion mass and velocity regimes, the cavity frequency is lower to give a reasonable cell length thus impacting the cavity geometry. This means that the E_p/E_a ratio differs markedly between a $\beta = 1$ cavity (E_p/E_a =2) and a heavy ion cavity ($E_p/E_a \sim 4-5$)). Future cw projects for relativistic electrons such as the Cornell ERL are specifying cavities with a $E_a = 15 - 20$ MV/m corresponding to peak surface fields from $30 - 40$ MV/m in line with the ISAC-II aims.

LINAC PREPARATION

Cryomodules

Each module has two main assemblies, the top assembly and the tank assembly. The top assembly shown in Fig. 3 includes the vacuum tank lid, the lid mu-metal and LN2 shield, the cold mass and the cold mass support. The tank consists of the vacuum tank, the mu-metal liner and the LN2 box insert. Both the top and bottom sub-components were assembled separately in a 'dirty assembly' area as a pre-assembly step. The sub-components were then disassembled, cleaned and delivered to the ISAC-II clean room for final assembly, alignment and testing.

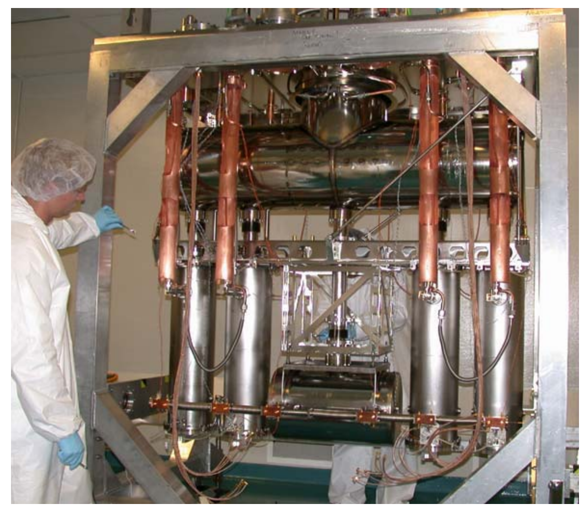


Figure 3: Cryomodule top assembly in the assembly frame prior to the cold test.

A view of the final vault installation is shown in Fig. 4.

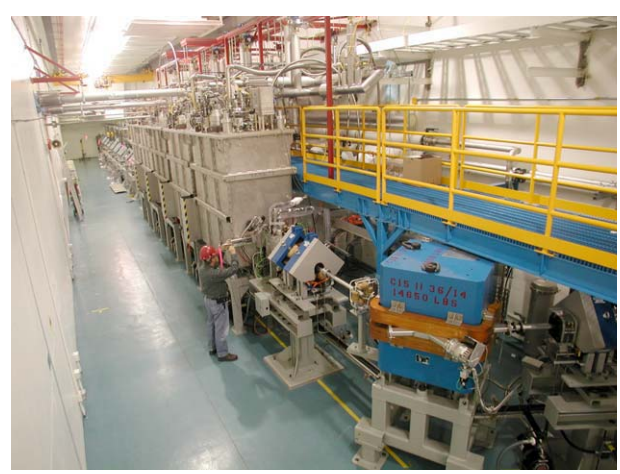


Figure 4: The ISAC-II accelerator vault.

Cooldown

The cavities are first baked at ~90°C for 48 hours. LN2 is then fed through the side-shields and the cold mass is cooled by radiation for at least 48 hours to bring the average temperature to about 200K before helium transfer. Linac cooldown is done sequentially, one cryomodule at a time, to achieve a cavity cooling rate of ~100K/hour to mitigate the effects of Q-disease[2]. This requires a LHe flow of ~100-150 ltr/hr. It takes about five hours to establish a 120 ltr inventory in the cryomodule and roughly 24 hours to complete the bulk of the thermalization. A full cooldown takes a minimum of seven days with two days for the cold box, dewar and trunk line and one day each for the cryomodules.

LINAC OPERATION AND COMMISSIONING

First beam from the linac came in April 2006 followed by a full set of commissioning studies. The first radioactive beam was accelerated in January 2007 followed by a shutdown with a full warm-up and maintenance activities. Beam production was resumed in May 2007.

Linac Tuning

The superconducting linac is tuned using stable beams from the ISAC off-line ion source. The beams are accelerated to 1.5 MeV/u and transported to the ISAC-II linac via a 25 m S-bend transport line complete with a 35 MHz two gap spiral buncher for longitudinal matching to the new linac. To accelerate each cavity is turned on and phased sequentially starting at the upstream end until the desired energy is reached. The last operating cavity is then fine tuned in voltage or phase to achieve the requested energy. The cavities are phased by measuring the beam energy (see below) for five different phases then fitting the data to a cosine profile to find 0°. All cavities are set to a synchronous phase of −25° for acceleration. The focusing solenoids and beamline optics are set to their theoretical settings as the acceleration progresses. The short independently phased cavities provide a useful flexibility. For example we have demonstrated that if a cavity becomes inoperable the linac can be retuned starting from the downstream cavity without a reduction in performance. The full linac can be tuned in about four hours. In most cases we have kept the gradients at the maximum cavity power level of 7 W and tuned the phases for each new beam; however we have also demonstrated that a 20% change in ion mass can be quickly tuned by rescaling of the rf voltages while keeping the rf phases fixed.

Commissioning results

Initial commissioning beams were chosen to span the range of anticipated mass to charge ratios. The beams included 40Ca10+, 22Ne4+, 20Ne5+, 12C3+, 4He1+ and 4He2+ with A/q ratios of 5.5, 4 and 2. Prior to acceleration the cavity voltage for each is set to a cavity power of 7 W to benchmark the cavity performance.

Final achieved energies are shown in Fig. 5(c) compared to expected final energies assuming the design gradient of 6 MV/m. Final energies of 10.8, 6.8 and 5.5 MeV/u are reached for beams with A/q values of 2, 4 and 5.5 respectively. The average cavity gradients for the three cases as calculated from the acceleration rate are shown in Fig. 5(a). The average gradient in each case is 7.2 MV/m corresponding to an average peak surface field of 36 MV/m and an average voltage gain of 1.3 MV/cavity.

Initial rf test results from the single cavity cryostat are plotted for comparison. In this case the average peak surface field for the cavities is 38 MV/m at a cavity power of 7 W. This corresponds to a gradient of 7.6 MV/m and a voltage gain per cavity of 1.4 MV. The *in situ* gradients in general match well the gradients from initial single cavity tests. A few cavities have obviously been contaminated during assembly while others have improved perhaps during the final assembly rinse. A significant point is that the average operating gradient during the initial commissioning period is down by only 5% from the single cavity result.

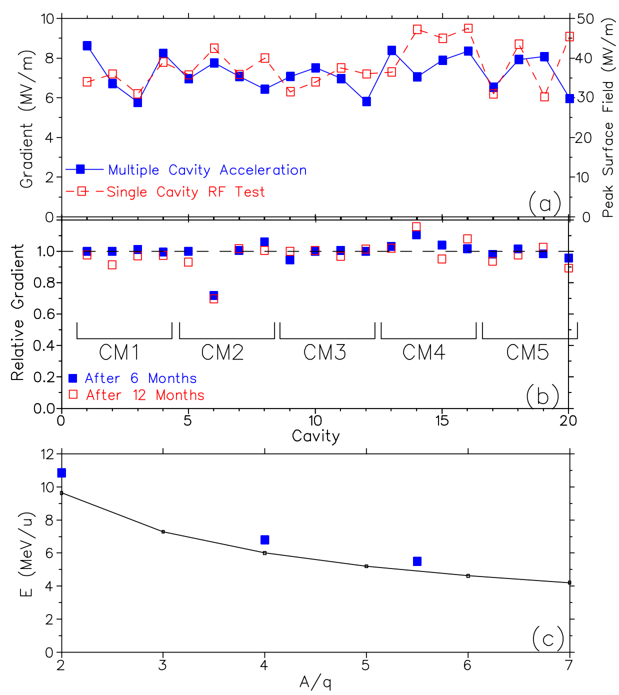


Figure 5: (a) Average cavity gradients for the three A/q values and for 7 W cavity power. Results are inferred from the step energy gain per cavity during acceleration. Also shown are gradients from initial single cavity characterizations. (b) Relative cavity gradients at 7 W comparing the initial *in situ* results to results at both six months and twelve months after the initial tests. (c) Final energies for the three cases compared to expected final energies assuming the design gradient of 6 MV/m.

Shutdown Activities and Start-up

RIB production at the ISAC facility is dependent on the availability of the TRIUMF cyclotron drive beam. The cyclotron typically is shut down for three months of the year and the ISAC-II linac is warmed during these shutdown periods. During the shutdown significant work was done. One cryomodule (CM1) was taken out of the line, removed to the cleanroom and the cold mass opened for repair of a coupling loop drive. The removal, repair and reinstallation of the cryomodule takes about two weeks. As well four turbo-pumps, two Leybold Maglevs and two Varian pumps with ceramic bearings had failed during the previous running period. (The reason for the high rate of failure (four out of ten) is still not clear.) One of the pumps was replaced in the clean room during the coupling loop drive repair. The other three were replaced *in situ*. Due to the single vacuum space for rf and thermal isolation the risk of particulate contamination is a serious concern. The replacements were done by venting slowly with filtered nitrogen and removing the pump while providing a slight overpressure of filtered nitrogen for control of particulate contamination. During repair it was discovered that one Varian pump on CM4 had completely failed with turbine blade shards scattered on the LN2 thermal liner. The shards were removed from the turbo-pump port, the LN2 shield vacuumed as access would allow and the pump was replaced. No attempt was made to remove the cryomodule for particulate decontamination in the clean room due to the lack of time.

These activities proved a good test of procedures and give some indication of the sensitivity of cavity performance to contamination and to warming cycles. A comparison of the relative cavity gradients after the initial operating period (six months) and after the shutdown (twelve months) compared to the gradients recorded in initial measurements are shown in Fig. 5(b). The cavity performance shows only minimal deterioration with an average of 99% of performance after six months and 98% after twelve months. In particular despite the work done in the shutdown the cavity performance in CM1 and CM4 are unaffected. The one significant change is to CM2:Cavity2 that suffered a modest performance reduction that we think is related to Q disease based on the past history with this cavity. In the last running period an rf drive connection in the cryomodule has opened up on one of the cavities. Except for this cavity the remainder of the cavities are still operating at an average of 100

During the beam delivery period the SC-linac ran well with an integrated downtime of only 32 hours out of 1100 split roughly 50/50 between the cryogenic system and the cavities. The cavity downtime was due to aging of the tubes in five of the rf amplifiers.[4] Records showed that the amplifier tubes had more than 9000 operating hours. The tubes have since been replaced in all the twenty amplifiers.

On two occasion cryogenic procedures forced a warm-up of the cavities above transition. Since the solenoids have a larger thermal mass they stayed below transition and even though driven to zero still retained frozen flux that upon subsequent cooldown contaminated the adjacent cavities and reduced the Q. This is a well documented phenomenon [5] observed during cryomodule testing. The solution is to warm both the solenoid and cavities above transition to quench the frozen flux before recooling. After this procedure cavity performance returned to previous levels.

The performance represents the highest accelerating gradient for any operating cw heavy ion linac. The experience from the first full year of operation including full thermal cycling and significant maintenance and repair involving venting of the primary vacuum of sixteen of the cavities indicates stable cavity performance with little or no cavity degradation. This is extremely encouraging and suggests that for cw applications a single vacuum system does not preclude high performance operation.

PRESENT INITIATIVES

Present activities involve prototyping studies in support of the next stage of the ISAC-II linac installation as well as infrastructure growth to support future initiatives at high frequency. The development and design program for the Stage I expansion is now well underway. These include cryomodule modifications that reflect the increase in the cavity number per module from four in the medium beta section to six and eight cavities in the high beta section as well as the installation of a new cold box and cryogenic distribution. The SRF group is presently responsible for two separate developments; an improved mechanical drive for the coupling loop and the design and prototyping of the high beta cavity.

The medium beta coupling loop is driven by an offset rack and pinion arrangement adopted from an INFN-Legnaro design. The large stored energy requires an rf system capable of achieving stable performance. The chosen tuning bandwidth of ± 20 Hz demands a cw forward power of ~ 200 W and peak power capability of ~ 400 W to be delivered to the coupling loop. An LN2 cooled coupling loop [6] was developed to handle the higher forward power while releasing less than 0.5 W to the LHe. We have found that the LN2 cooling circuit and heat exchange block added to the loop to allow operation at higher forward power adds a significant side-load to the loop drive mechanism and has stiffened the motion in some units after cooldown. The aim of the present development is to find a more robust drive mechanism for the loop and at the same time reduce the side loads. The proposed upgrade utilizes cross-roller bearings in a symmetric arrangement to add side stability. The LN2 feed is symmetric with the loop vertical axis to reduce side-loads and the VCR LN2 couplings have been reduced from 3/4 inch (19 mm) to 3/8 inch (10 mm) to reduce the bulk. The prototype loop was recently cold tested to quantize the thermal perfomance. The goal is to have a loop that duplicates the rf and thermal performance of the existing production loop but is more reliable mechanically. In the cryogenic test the static load of the crystat is measured based on boil off rate with a gas flow-meter. The rf is then turned on at a cavity power of 4 W and the loop is adjusted for a coupling β of 200 (P_f=200 W) and the system is allowed to thermalize for several hours. The rf power is then turned off and the static load is monitored over time to estimate the thermal load from the 'hot' coupling loop. The extra heat from the loop is measured at ∼ 0.3 W at 4K in line with design requirments. The remaining design question with the loop is the material choice since the first cross-roller bearings were found to be of magnetic material. We are presently sourcing non-magnetic bearings.

The high beta cavity moved from design stage to prototyping. A local company, Pavac Industries Inc., is working with TRIUMF to produce two prototype cavities. Initial studies involved the fabrication of two models out of copper. The fabrication includes all steps including frequencing tuning to work out a correct protocol before the niobium material was released. The high beta cavities are similar to the medium beta cavities with a cyclindrical inner conductor and a simple hole for the beam port. A second variant with an extended beam tube welded into the inner conductor has also been rf modeled and fabricated in copper (Fig. 6). The beam tube improves the cavity efficiency by increasing the transit time factor and reduces the asymmetry in the rf defocussing fields. Parameters relevent to the two cavity variants are shown in Table 1. The tube also increases the geometric beta. This feature provides an improved match to the beams from the medium beta section considering that the operating gradient of this section exceeds the original design. These improvements have led us to choose the donut variant for the two niobium prototypes scheduled for completion by the end of 2007. An order for the production of twenty cavities will be given in early 2008.

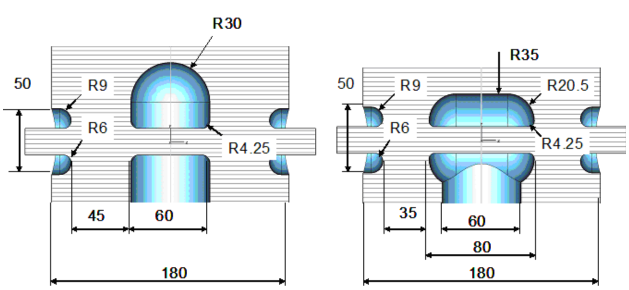


Figure 6: The two cavity gradients considered in the prototyping stage. The 'donut' variant was chosen for manufacture.

FUTURE INITIATIVES

Plans are underway to design and install a 50 MeV, 10 mA cw electron linac at TRIUMF as a driver for radioactive beam production through photo-fission. The new driver is intended to augment the present cyclotron driver and give ISAC the capability of delivering two or more simultaneous radioactive beams to experiment. The cyclotron driver presently delivers 500 MeV protons at up to 100 μA onto one of two production targets. The new initiative would include the addition of a new target area with two or more independent actinide production targets. The new production area would be supplied 500 MeV proton driver beams from the cyclotron from a new extraction line as well as the 50 MeV electron beams from the new e-linac.

Table 1: Comparison of round and 'donut' inner conductor.

Parameter	Round	Beam Tube (Donut)
f_o (MHz)	141.4	141.4
Q_{Cu}	7500	7650
$R_s\ Q_o$	25.1	25.6
TTF_0	0.88	0.938
β_0	0.104	0.112
R_{sh}/Q_o	490	545
E_p/E_a	5.1	4.9
B_p/E_a (mT/MV/m)	10.3	9.9

The photofission process is enhanced with increasing electron energy up to ∼50 MeV so this sets the energy specification. The number of fissions per second and hence RIB production is proportional to beam intensity. The maximum intensity is set by considerations of target heating and we have chosen a top end of 10 mA giving a total beam power of 500 kW. This is a factor of ten increase over the ISAC production targets and will represent a significant engineering challenge. An existing experimental hall adjacent to the cyclotron is of a convenient size (25mx25m) and with existing shielding to house the new linac. Present thinking is to configure the original single pass linac in a layout that would be compatible with an upgrade to an energy recovery linac for IR-FEL and accelerator studies similar to the prototype ERL's at Daresbury or Beijing. A layout of the new linac (in this case configured as an ERL) on the TRIUMF site is shown in Fig. 7. A common tunnel houses both the electron and the proton beamlines.

The design will borrow, where applicable, technology from the ILC to both take advantage of and contribute to the global design initiative. Although the design is still in the early stages an initial concept is taking shape[7]. Due to the high beam loading and limits on power couplers the gradient is limited to 10 MV/m for the five, 1300 MHz, nine-cell cavities to produce 50 MeV. This limits the maximum rf beam loaded power for any cavity to 100 kW. It is envisaged that two power couplers would be used per cavity. The heavy beam loading requires strong coupling ($Q_{opt} = \frac{V_{acc}}{\frac{R}{Q} I \cos\phi} = 1 \times 10^6$) so detuning from microphonics should not be an issue. Initially a thermionic dc gun will be installed with the option to go for a high brightness source when required for ERL mode. A capture cavity of up to two cells would match the beam from the DC gun to the first nine-cell cavity. We are also considering a variant with a set of room temperature capture cavities. Three cryomodules are envisaged; an injector module holding the capture cell and one nine-cell and two driver cryomodules

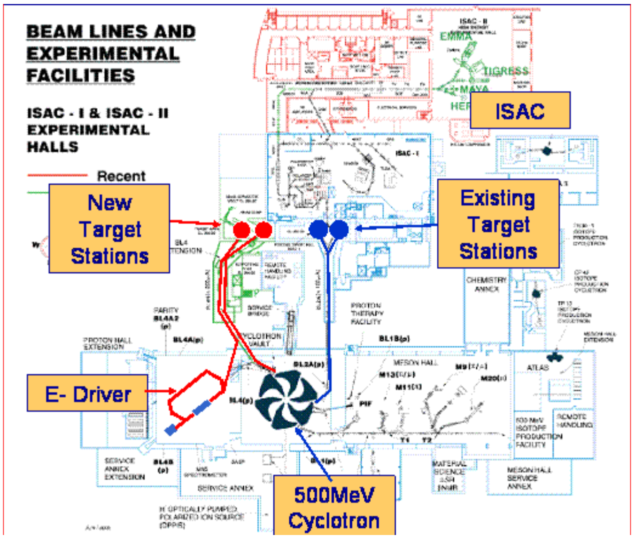


Figure 7: Schematic of the proposed electron linac and new production targets at TRIUMF.

each with two nine-cell cavities. A parameter list for the proposed machine and cavities is shown in Table 2. A schematic of the proposed machine is shown in Fig. 8.

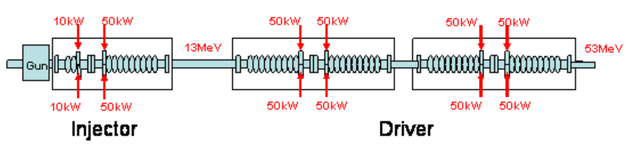


Figure 8: Schematic of the proposed electron linac at TRIUMF.

Table 2: Parameters of the E-linac

Parameter	Value
Final Energy	53 MeV
Max. Current (mA)	10
Max. Charge/bunch (pC)	7
Duty Factor	cw
No. of Cavities	5 Tesla 9-cell; 1 capture
Frequency (MHz)	1300
T(K)	2
Gradient (MV/m)	10
Cavity length (m)	1.04
R_{sh}/Q_o	~ 1000
Q_0 at 2K	1×10^{10}
Q_{ext}	1×10^{6}
P_{cav} (W)	11

Development at 1.3 GHz

TRIUMF to date is only equiped for srf testing at 4 K. Existing infrastructure includes a single cavity cryostat for testing the ISAC-II quarter wave cavities, a clean room for assembly, an rf test area with a shielded pit, and a HPWR area. We are presently installing a BCP facility adjacent to the HPWR area with ~50^2m of floor space. The facility will enable both pre-weld etching and full cavity etching of ISAC-II quarter wave cavities and Tesla style 9-cell cavities. Plans are underway to augment the infrastructure to allow an srf program at 1.3 GHz to support the new e-linac and allow ILC collaborations. The plans include the design and fabrication of a new cryostat compatible with both single cell and nine-cell testing and infrastructure to allow sub-atmospheric helium operation for testing at 2K. The new 500 W Linde cold box for the extension of the heavy ion linac will be commissioned in Feb. 2008 and will be available to support 1.3 GHz testing through to the end of 2009 until the high beta linac is operational. A new shielded high bay test area has been identified for 1.3 GHz testing. The infrastructure upgrade program will begin early next year.

TRIUMF has joined the TTC and is opening a collaboration with Fermilab on single cavity development. One of the aims of the collaboration is to qualify PAVAC as another North American supplier of ILC cavities. The development stage will see the production of several single cell cavities and at least one nine-cell cavity.

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