A new accelerator is being installed at TRIUMF and it is cool, even cold — well, very cold. To explain: An accelerator accelerates charged particles such as electrons, protons, or heavier ions, by a combination of electric and magnetic fields. Usually radio-frequency electric fields are used to accelerate the charged particles, and magnetic fields are used to direct and focus the particles as they are accelerated. In a linear accelerator (LINAC), the accelerating structure consists of a straight series of spaced hollow metallic tubes through which the beam passes. An alternating electric voltage at high frequency (RF) is applied across the gaps between the tubes. For each type (mass and charge) of particle to be accelerated, there is a definite relationship among the length of the tubes, the gaps between them, and the frequency of the applied electric field. When the beam, which consists of a series of short bursts or bunches, travels through one of the metallic tubes, it feels no electric forces, but when it emerges from the end of a tube, it is exposed to the voltage difference between adjacent tubes. If the length of the tube and the RF frequency are properly related, then the beam bunch will experience an accelerating electric force. During the time that it would feel a decelerating electric field, the burst is “hidden” inside the tube. As the velocity of the ions increase down the LINAC, the length of the tubes is increased, so their arrival at each gap between tubes is timed to coincide with the maximum RF voltage.

Accelerators are complex and expensive to build and operate. To reduce the capital costs, physicists and engineers seek to optimize the acceleration process in ways that shorten the overall LINAC length without compromising reliability and operating costs. For example, a higher peak electric voltage between tubes would mean a fewer number of tubes and a shorter LINAC. Higher voltages also mean higher resistive power losses and an increase in engineering difficulties. An analysis shows that long multi-gap RF structures are best for power efficiency. Because gap spacing and RF frequency are determined by a particle’s velocity, these structures are only optimized for the acceleration of one family of ions. Instead, lighter ions, which could be accelerated to a higher velocity for a given field, must follow a fixed velocity profile and a lower energy. Shorter two- or three-gap structures, although power hungry, can be independently phased to match the velocity of a wider variety of ions and constitute an accelerator for wide application. An effective but technically challenging way around this problem is to make the RF cavities electrically superconducting to reduce wall losses to almost nothing and allow the LINAC designer to use shorter structures capable of efficiently accelerating a wider range of ions.

The ISAC-I linear accelerators presently deliver beams of radioactive and stable ions to experiments with final energies variable between 150 thousand and 1.5 million electron volts per atomic mass unit (150 keV/u to 1.5 MeV/u), corresponding to velocities from 1.8% to 5.6% the speed of light. TRIUMF
is now constructing an extension to the ISAC facility, ISAC-II, to further accelerate the ions from 1.5 MeV/u to energies of at least 6.5 MeV/u (11.7% the speed of light). At the heart of the installation is a new superconducting linear accelerator. It is composed of resonant RF structures called cavities and superconducting solenoids that provide periodic focusing for the accelerating beams. The cavities and solenoids are housed in box-like structures called cryomodules, providing good thermal isolation for the cold elements of the LINAC. The LINAC is grouped into medium and high beta (velocity) sections. An initial installation of twenty medium beta cavities, corresponding to an accelerating voltage of 20MV, is due for commissioning by the end of 2005. The first major milestone, achieved in November 2004 and reported here, is the demonstration of the acceleration of ions with a single cryomodule.

The cavities are simple cylindrical structures with two accelerating gaps formed between the outer conducting wall and a baseball bat shaped inner conductor (see figure below).

The inner conductor has a hole near the tip through which the beam passes. RF energy is coupled into the cavity via a port in the side of the cavity near the top. The dimensions of the cavity are chosen so that the induced fields resonate at a particular RF frequency with maximum RF voltage built up at the tip of the inner conductor near the beam ports. A demountable flange on the cavity bottom supports a tuning plate, which is used to adjust the resonant frequency over a limited range. The cavity transverse dimensions are chosen to match a certain particle velocity, so the time a particle takes to cross from one gap to the next corresponds approximately to half an RF cycle and acceleration occurs at both gaps.

The cavities are fabricated from sheets of highly refined niobium, a Type I superconductor with a critical temperature of 9 K. Each cavity has its own jacket outside the outer conducting wall and, together with the hollow inner conductor, forms a volume to contain a bath of liquid helium. The liquid helium maintains the RF surface at a stable temperature of 4.2 K. When properly constructed, the cavity surface resistance is only a few billionths of an ohm. This means that RF voltages of 500kV can be induced on the inner conductor with as little as a few watts of power loss. In a room temperature cavity, it would take over 100,000 watts to sustain the same voltage. Furthermore, at room temperature, the voltages would have to be kept significantly lower because of the resultant surface heating.

While superconducting technology can produce high accelerating gradients at low power, there are significant technical challenges. The highly refined niobium must be treated very carefully during fabrication. All welding must be done with an electron beam welder in an evacuated chamber to avoid inclusions of other materials in the surface. Even very small inclusions of non-superconducting material can increase the local resistance on the RF surface, promoting heating of the niobium surrounding the inclusion and limiting the cavity performance. After fabrication, the cavities are chemically polished, then rinsed with high-pressure deionized water, and then dried in a clean room before mounting in the accelerator module. The resonating frequency of each cavity, 106 million cycles per second, must be set with high accuracy. To do so, TRIUMF has developed a mechanical tuner capable of both coarse (a few kilocycles) and fine (a few cycles) frequency adjustments. The demonstrated mechanical
resolution of the tuner is better than 0.001 of a millimetre. All cables and mechanical connections to the cavity must be thermally isolated or stage cooled with liquid nitrogen to avoid thermal losses on the liquid helium.

Our development and engineering has led to very efficient and effective cavities, which can generate an acceleration voltage of 1.1 megaVolts across their effective length of 18 cm, a significant improvement over other heavy ion facilities in the world.

Two pairs of these cavities are grouped together with a superconducting solenoid placed between them. The solenoid, used to focus the beam, is designed to operate at fields up to 9 Tesla, 200,000 times the earth’s magnetic field. At each end of the main coil, an oppositely wound smaller coil serves to minimize the magnetic field that could interfere with the operation of neighbouring cavities.

The four cavities and solenoid are housed in a cryomodule that provides a vacuum to shield the cold mass from a molecular heating load. A liquid nitrogen cooled box enclosure inside the vacuum wall reduces the radiative thermal load. The stainless steel vacuum tank has dimensions 2m x 2m x 1m. Cavity performance is reduced if the cavities are cooled in the presence of a magnetic field; magnetic shielding in the form of sheets of high permeability alloy is placed between the warm wall and the cold shield. The shielding is designed to reduce the earth’s magnetic field by a factor of twenty.

The superconducting elements are supported on a beam that is suspended from the lid by struts. The struts are slung from three support points, two upstream and one downstream, that are laterally and vertically adjustable. There is an independently mounted liquid helium reservoir (120 litre capacity) suspended from the lid, which feeds liquid helium to the cold elements during operation (see figure below). Five of these cryomodules are required to achieve the desired final energy.

Correct acceleration requires precise alignment of the cavities and solenoid with respect to the beam axis: within ±0.4 mm for the cavities and ±0.2 mm for the solenoid. Aligning to this tolerance at temperatures slightly above absolute zero presents an interesting engineering challenge as assembly of the cryomodule has to take place at room temperature. The temperature drop of some 300°C causes all the internal assembly to shrink in length, in different amounts for different components. For example, the centre of the solenoid moves upward by about 5 mm while the accelerating gaps in the cavities move somewhat less, by 3.8 mm. In order to provide a pair of eyes inside the cryomodule, an electric positioning system has been devised to chart the position of the cold mass during cooldown cycles and determine the magnitude and repeatability of the contraction. Each cold mass element is outfitted with a position monitor.

A wire running parallel to the beam axis and through the monitors carries an RF signal that is measured by the monitors and is converted to an x-y position.

Each cryomodule has a single vacuum system for thermal isolation and beam acceleration. This demands extreme cleanliness of all internal components and precludes the use of volatile lubricants and flux, as well as any particulate generators, to avoid contaminating the superconducting surfaces. Assembly and commissioning tests are done in the new ISAC-II clean laboratory area. A mounting frame is used to assemble the tank internals to the lid and, initially to align the components.

The first stage of the ISAC-II accelerator, to be completed in December 2005, will see the installation of five of the medium beta cryomodules. Each cryomodule is first assembled in an open ‘dirty’ lab space, then disassembled, cleaned and reassembled in the ‘clean room’. After re-assembly, the modules are tested in the lab before being certified for installation on line.

The first cryomodule served as prototype. After assembly, a series of three cold tests were performed to characterize the module. In April, 2004, the first cold tests, without RF ancillaries installed, characterized cryogenic performance
and determined the warm offset required to achieve cold alignment. The cryogenic performance of the cryomodule is characterized by measuring the helium boiloff under static load (no RF power) conditions and by measuring the LN$_2$ consumption required to sufficiently cool the side shield. Temperature sensors are placed in the cryomodule to provide test information. Cryogenically, the cryomodule performed well, with a helium static load of 13W and liquid nitrogen consumption of 5 liquid-litres per hour, both near the expected values. The test also determined the repeatability of the alignment during cooldown and established offset values for each cavity and the solenoid to enable warm positioning compatible with alignment at cold temperatures. The positions of the cold masses were measured over three cooldown cycles and found to be repeatable to within ±0.05 mm vertically and ±0.1 mm horizontally. The results of the first test are then used to adjust the final warm alignment of the cavities and solenoid to be compatible with alignment at cold temperatures.

The second cold test confirmed the integrity of the RF systems and controls. During this test, the four cavities and solenoid were powered together, and locking of the four cavities to an external frequency was demonstrated. Operation of the high-field solenoid did not appreciably affect cavity performance. As expected, the surface resistance of the cavities proved the effectiveness of the magnetic shielding.

For the third cold test, the cavities were removed from the assembly and given a final high-pressure rinse. The goal was to duplicate the operating conditions of a functioning LINAC module. The test was a complete success. All cavities were operated simultaneously at the ISAC-II operating frequency and voltage. As a proof of principle, alpha particles from an external radioactive source were injected through a thin foil into the cryomodule, and a silicon detector to measure alpha particle energy was placed at the exit of the cryomodule. Starting from the upstream end, the cavities were turned on sequentially and phased to maximize the final energy. The energy spectra obtained when 0 through 4 cavities were powered is shown in the figure below. Because emission of the alpha particles is not synchronized to the RF, a large fraction of them are not optimally accelerated, adding a large low energy component to the spectra; it is the particles with maximum energy that demonstrate the accelerating voltage in the cavities. The exciting result is that the measured maximum energy of 9.4 MeV is within 6% of the expected final energy for cavity voltages at the ISAC-II specification. This is the first demonstration of acceleration using superconducting RF cavities at TRIUMF and marks the beginning of a new and exciting area of accelerator physics and technology.