The ISAC Project at TRIUMF

H.R. Schneider

TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. Canada V6T 2A3

Development of a facility combining an isotope-separator-on-line (ISOL) with a post-accelerator, to produce energetic ion beams far from the valley of nuclear stability, was originally proposed for installation on one of the beam lines of the TRIUMF cyclotron about ten years ago. A test facility (TISOL) consisting of a target, ion source, and mass separator, but without a post accelerator, was subsequently installed and has been in use to support an experimental program and to aid in development of target/ion source systems. The facility is currently being augmented with the addition of a laser neutral atom trap for a proposed series of β decay and atomic parity non-conservation experiments, using selected radioactive alkali isotopes, to test some symmetry properties of the Standard Model. In addition, work has begun on a new upgraded facility consisting of remotely handleable target/ion source assemblies, a new mass separator with resolution m/Δm = 10,000, and post-acceleration to 1.5 MeV/u, for ions with A $\leq$ 30.

1 Introduction:

Installation of a radioactive beam facility on one of the TRIUMF cyclotron beam lines was first proposed in 1985, following two workshops [1,2] where requirements for such a facility were reviewed and defined. The primary motivation at the time was to determine cross sections of reactions involving short-lived nuclei in various stellar nucleosynthesis processes. For these measurements high quality beams of various unstable particles with masses $\leq$ 60u, energies variable from about 100 keV/u to about 1.5 MeV/u, and with intensities of the order 10^{10} particles/sec were specified as desirable. The proposed facility would have consisted of an isotope separator on line (ISOL) in which a 500 MeV proton beam, incident on a thick target, produces a wide range of unstable nuclei by spallation reactions . The nuclei then diffuse out of the target as neutral atoms and into an ionizer, from which ions would be extracted by high voltage and then analyzed in a magnetic mass separator. Mono-isotopic beams from the separator then could be directed to a low energy experimental area or injected into a two-stage linac consisting of an RFQ and drift-tube linac for acceleration to the required higher energies.

This project was not funded but some related work was nevertheless continued. With respect to the accelerator, studies were initiated to investigate the feasibility of using newly developed superconducting technology to either reduce the cost, or economically achieve higher energies [3]. At the same time, to address the many key and technically most challenging design and development problems, on the target/ion source end, a test-isotope-separator-on-line (TISOL) was installed at the end of the TRIUMF beam line 4A [4,5]. In addition to being a test bed for target and ion source development, the TISOL facility has also provided beams for a modest experimental program with radioactive beams at relatively low energies [12,13]. This facility is currently being augmented with the installation of an optical neutral atom trap on the end of one of the TISOL beam lines.

After a period of uncertainty following the decision to not fund the KAON project, a five-year funding plan for TRIUMF was announced in June 1995. Included in this is the provision for a modest accelerated radioactive beam project, called ISAC, which will be constructed on a new primary beam line from the TRIUMF cyclotron and will provide radioactive beams with ion mass $\leq$ 30u and energies up to 1.5 MeV/u. This facility could be the basis of a larger radioactive beam facility in the future.

2 TISOL - Test-Isotope-Separator-On-Line

Fig. 1 is an elevation view of the TISOL installation at the end of the 10 μA proton beam line 4A at TRIUMF. Although the beam line is rated at 10 μA, currents have been limited to less than 1.5 μA for the TISOL runs because of shielding and handling considerations. The major components of the facility consist of; a thick target mounted in a vacuum chamber that is physically and electrically separated from the beam vacuum line; an ion source coupled to the target and from which singly charged ions are extracted through a potential that is typically 18 kV; a mass analyzer consisting of two magnetic quadrupoles and a vertically mounted 90° dipole magnet, giving a mass resolution m/Δm of up to 3000; a vertical beam transport system consisting of five electrostatic quadrupoles followed by a 90° electrostatic bend and a further three electrostatic quadrupoles; ending finally with a switching magnet that delivers the beam via one of three beam lines to the experiment end stations.

Yields from a variety of target materials have been studied [6,7]. The targets consist of a cylindrical tantalum oven approximately 90 mm long and 20 mm in diameter, containing up to several g/cm^2 in thickness of target material. The oven is sealed except for a transfer line connecting it to the ionizer. To promote diffusion and desorption of the neutral radioactive products from the target, the oven can be electrically heated to tem-

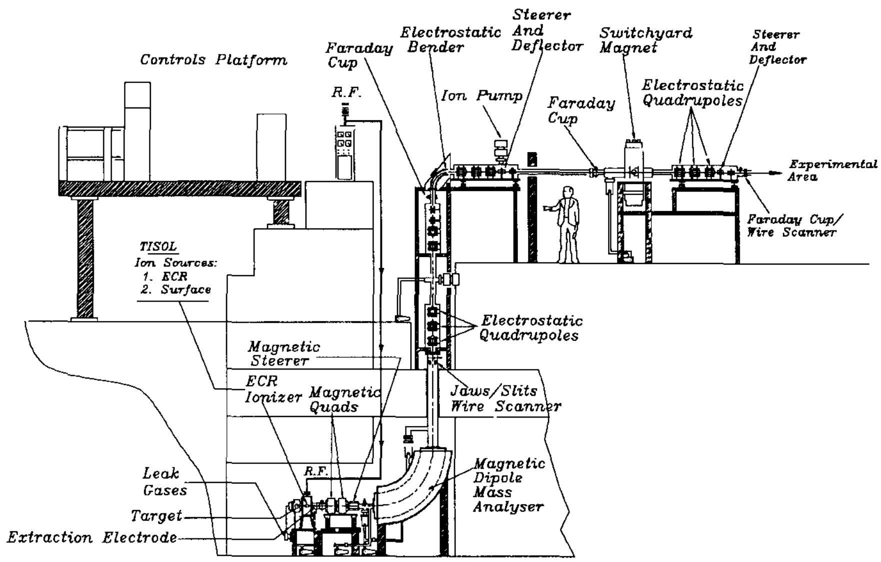

Figure 1: TISOL elevation view

peratures as high as 2000°C.The target materials used have, in most cases been refractory materials, either compounds such as AlN, ZrC, MgO, UO_2, or SiC, or metals such as Ti, Zr, or Nb in the form of foil or powder. Although not capable of being heated to the high temperatures of the other target materials, the zeolite NaAlSiO4 has produced the highest yields for some of the C, N, and Ne isotopes [7]. In general release rates for different radioactive species are target dependent. This can often be used to advantage as the first stage in separating the desired species from others produced in the target.

Depending on the radioactive ions required, one of two ion sources is used. For the alkali metals, as well as Ga, In, and Yb, a surface ionization source, consisting basically of an electrically heated graphite tube containing a Re foil, is employed. For other ions, because of its high ionization efficiency, an ECR source is used [7]. Observed yields of some of the radioactive species produced in the TISOL facility are given in Table 1.

2.1 Neutral Atom Trap - TRINAT

Development of magneto-optic neutral atom traps in recent years has provided a promising new tool with which radioactive atoms can be used to study symmetry properties of the Standard Model for elementary particles. For example, the ability to trap and cool radioactive atoms in a small volume, along with the possibility of achieving nearly 100% nuclear polarization, makes a new class of symmetry tests in β decay possible. Since the β particle and recoiling daughter nucleus are both observable in this case, free from scattering in the source, and

Table 1: Example of isotope yields observed with TISOL

Isotope	Yield (p/s/μA)	Target (gm/cm^2)	Ion Source
^{8}He(119 ms)	3.7 x 10^5	AlN (7.5)	ECR
^{10}C(19.3 s)	3.8 x 10^5	MgO (6.2)	ECR
^{15}C(2.4 s)	2.6 x 10^4	MgO (6.4)	ECR
^{16}N(7.1 s)	6.5 x 10^6	zeolite (13.1)	ECR
^{17}Ne(109 ms)	1.5 x 10^6	MgO (12)	ECR
^{20}Na(446 ms)	1.2 x 10^6	SiC (6.06)	surface
^{35}Ar(1.8 s)	1.1 x 10^6	zeolite (13.1)	ECR
^{38}K(7.6 m)	1.3 x 10^6	Zr	surface
^{21}Na(22.5s)	4.5 x 10^7	SiC (6.06)	surface
^{210}Fr(3 m)	1. x 10^8	ThO/C (8)	surface

are emitted from a well-localized volume, measurements of exceptional precision become possible. Another test of the Standard Model follows from the unification of electromagnetism and the weak force which then allows atomic transitions that would otherwise be parity forbidden. Measurement of parity non-conservation (PNC) in atomic transitions can therefore provide a mechanism for study of the Standard Model predictions. In this case one of the most sensitive measurements requires the heaviest alkali element Francium, for which no stable isotopes exist. A range of Francium isotopes has been produced with TISOL and with development of efficient trap injection scheme precision PNC measurements will be possible [8].

The major components of a magneto-optical trap as illustrated in Fig. 2 are; three orthogonal pairs of counter propagating left and right circularly polarized laser light

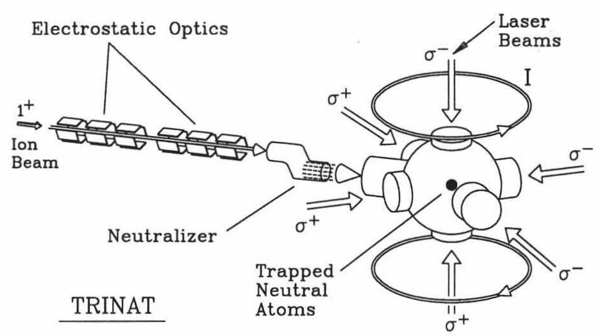

Figure 2: Schematic view of a magneto-optical trap

beams, red shifted with respect to the absorption line of the atom to be trapped; a high vacuum chamber enclosing the trapping volume defined by the beam intersection; and a pair of anti-Helmholtz coils, symmetrically placed with respect to the trap centre. The coils generate the magnetic field gradient required to produce a position dependent Zeeman splitting of atomic excited state. Since the magnetic field in this configuration reverses on passing through the trap centre, the Zeeman splitting also reverses, i.e. if the lowest energy transition from the ground state to the first hyperfine level of the exited state corresponds to Δm_j=+1 for an atom to the right of the trap centre, it will correspond to Δm_j=-1 for an atom to the left of centre. This means σ+ polarized light, propagating from right to left say, will be preferentially absorbed by atoms to the right of the trap centre, while σ- light propagating left to right will be preferentially absorbed by atoms to the left of centre. In either case the unidirectional absorption of the laser beam photons and the multidirectional emission of the atomic de-excitation photons results in a net restoring force directed to the trap centre.

At the same time the red-shifted laser light is Doppler shifted by the atomic thermal motion so that a net cooling or damping of the atomic motion results from preferential absorption of light propagating in the direction counter to the atomic motion. Temperatures of typically 600 μK or lower are achievable in these traps[9].

A neutral atom trap has been successfully operated off-line at TRIUMF with stable K atoms and is currently being installed in a specially constructed clean room at the end of one of the TISOL beam lines. The trap consists of a 100 mm diameter spherical Pyrex bulb as the ultra high vacuum enclosure with small anti-helmholz coils wound on the outside to provide a field gradient of 10 G/cm. The output of a 1.5 W Ti:sapphire laser is split and formed into three 40 mm diameter parallel beams that are then aligned to intersect orthogonally in the centre of the trap enclosure. On exiting the beams pass through $\lambda/4$ plates and are retro-reflected to produce the required counter propagating beams with reversed polarization. The injection scheme is one of the most challenging aspects of using this trap for the relatively energetic (in the trap context) radioactive beams from TISOL. A system using heated metal foils to stop the ions and then re-emit them as neutral atoms, is under development and will be used when the first on-line trapping tests with a beam of ^{38}K begin later this year.

3 The New ISAC Facility

3.1 Overall layout

One of the advantages of H^- cyclotrons is the ease with which multiple external beams can be provided. When the TRIUMF cyclotron was built, two external high energy proton beam lines were installed. The vacuum tank was however constructed with extraction probe and beam ports for additional beam lines, one of which will now be installed for the ISAC facility. The new beam line will transport the proton beam from the cyclotron vault via a tunnel to the target/ion source stations in a new building. A preliminary layout of this building showing two target/ion source stations is illustrated in Fig. 3. The building,of approximately 2100 m^2 is divided into two distinct parts, namely the heavily shielded and sealed target facility, and the post-accelerator/experimental hall.

In addition to the target stations the target facility includes hot cells and warm cells for target maintenance, decontamination facilities, and storage for radioactive materials and target modules. Much of the target facility is below grade to take advantage of shielding by the surrounding earth. The accelerator/experimental hall on the other hand is at grade level except for the mass separator, which will be located at the cyclotron beam level, adjacent to, but shielded from, the target/ion-sources. After separation the beam is bent vertically to bring it up to grade level where it is either delivered to the low energy experimental area or injected into the post-accelerator. The arrangement of the accelerators and experimental facilities is still under review. An in-line accelerator configuration is shown in Fig. 3, but an arrangement with a 90° bend between the RFQ and DTL is a possibility. Although this would require a more complex beam transport and matching section between the RFQ and DTL, it would have the advantage of providing easy charge state selection after the stripper, as well as making more efficient use of the floor space in the building which is constrained in shape by existing laboratory property boundries.

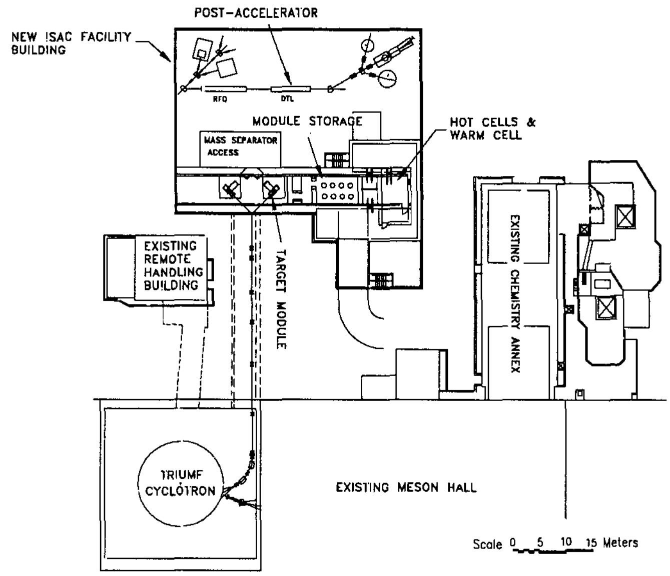

Figure 3: Buidling layout for the new ISAC facility

3.2 Low energy stage

As in TISOL, the unstable isotopes will be produced by bombardment of a thick target with a 500 MeV proton beam. In this case however, proton beam intensities up to 10 μA, and targets up to 125 gm/cm^2 thickness will be used. High operating and residual radiation fields around the target require that it be heavily shielded. Following the approach used for shielding of the meson production targets at TRIUMF, the target will be located at the bottom of a steel and concrete shield canyon that is closed by steel plugs and concrete shield blocks during operation. Access and entry of all services is from the top. In the current design, the target, ion source, and extraction system are mounted on a central, 2 m high, steel shield plug. To minimize the probability of the contamination of the surroundings by loose radioactive material originating from the often rather friable targets, the entire assembly is enclosed in a virtually completely sealed vacuum container, to form a single remotely handleable module as illustrated in Fig.4. Vacuum pump and all service connections are made at the top of the shield plug. The shield plug is electrically insulated from the grounded vacuum enclosure and is biased to give extraction voltages in the range 10 kV to 60 kV. When servicing is required, the target module can be removed from the beam line by a crane and transported to a hot cell or placed in one of the shielded storage silos that also form part of the target building complex

Ions extracted from the ion source are transported a short distance to the mass separator which is at present

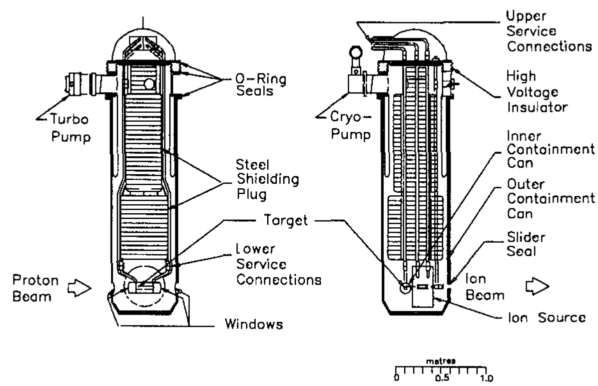

Figure 4: Cross sections of target/ion source module

in the preliminary design stage. The design objective is a mass resolution of m/Δm=10,000 for beam emittances (un-normalized) less than 2π mm-mrad. An electrostatic beam transport line including two 90^o bends then takes the separated beam up to the experimental hall and post accelerator.

3.3 Post-accelerator

General description

One of the principle purposes of the ISAC facility is to provide the short-lived radioactive beams required for nuclear cross section and related measurements of importance to the nucleosynthesis studies in astrophysics.

Table 2: Basic Specifications for the ISAC Accelerator

Input Beam		
	Energy	2 keV/u
	Ion Mass	A≤30
	Ion charge	±1
	Beam current	$\ll 1\mu$A
	Transverse emittance (normalized)	$\leq 0.2\pi$ mm-mrad
Output Beam		
	Energy range	0.15 - 1.5MeV/u
	ΔE/E	< 0.1%
	Macro duty factor	100%

Beam energies up to 1.5 MeV/u are required for these measurements. Even higher energies would be desirable for nuclear structure studies and could be provided in a future upgrade. For the present ISAC project however the post-accelerator specifications are as summarized in Table 2.

To make most efficient use of the continuously produced radioactive ion beam, CW rather than pulsed operation of the accelerator is specified. Also since the ions extracted from the ion source are most abundant in the singly charged state, it is for these relatively low charge to mass ratio particles that the accelerator must be designed, at least in the initial stage. To limit accelerator size however,the beam will be passed through a stripper to increase the charge to mass ratio at some intermediate point in the acceleration process. For the ISAC specifications the total effective accelerating voltage required is minimized when the stripper foil is located at the point corresponding to a beam energy of about 150 keV/u. Fig. 5 is a block diagram of the proposed two stage accelerator consisting of an RFQ to capture, bunch and accelerate the singly charged beam to 150 keV/u, and, after a beam matching and stripper section, a drift- tube (DTL) stage to provide the major part of the acceleration to 1.5 MeV/u. The overall length of the accelerator is 18.7 m.

The RFQ

The low charge to mass ratio and low energy of the beam delivered from the mass separator lead to the requirement for a low operating frequency for the RFQ, both to achieve adequate transverse focusing and to have initial cell lengths in the RFQ that are at least comparable in size to the aperture so amplitudes of deleterious higher order field harmonics are kept small. Contrarily, the physical size of the RFQ, both length and diameter, increases with wavelength, so that in general, the highest possible operating frequency is preferred. For the ISAC

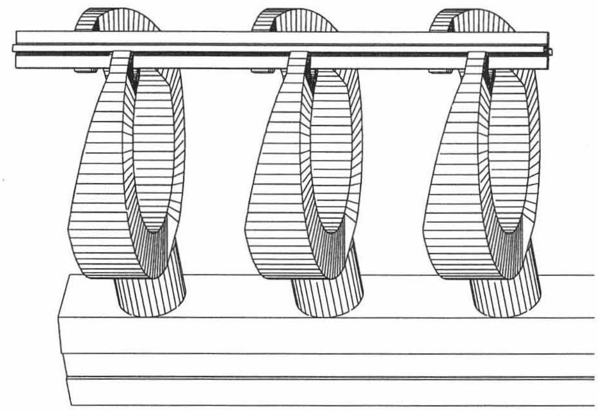

Figure 6: Three modules of a split-ring RFQ

specifications, an RFQ operating frequency of 35 MHz best satisfies the requirements. With a maximum vane voltage amplitude of 85 kV, a beam with q/A < 1/30 is bunched and accelerated to 150 keV/u in an 8 metre long RFQ with 347 cells. From a mechanical point of view, the low operating frequency dictates some form of resonant, semi-lumped parameter structure be used to generate the high RF voltages on the vanes, rather than a resonant cavity, as used at higher frequencies. The structure chosen for the ISAC accelerator is a variant of the 4-rod structure [10]. In this case the distributed capacitance of the vanes in combination with the inductance of the split ring supports as illustrated in Fig. 6, forms the resonant circuit. For the 35 MHz design, the rings have a rectangular cross section (150 mm axially by 80 mm radially), a mean diameter of 435 mm, and are spaced at 400 mm intervals along the vanes. RF currents flowing along the vanes have nodes midway between rings. This makes it possible to break the structure into modules with each module consisting of one support ring centrally connected to a 400 mm long set of vanes. The RFQ is then assembled by attaching the modules end to end on a strong back rail inside a 1 metre diameter vacuum tank. Each ring is supported on a mounting fixture with six degrees of freedom to permit precision alignment of the modules. From model measurements as well as 3-dimensional field calculations, using the code MAFIA, the expected power dissipation per module will be less than 4.5 kW. Cooling for the vanes and ring will be supplied through the ring mount.

Drift-tube linac

After exiting the RFQ the beam is transported through the matching and stripper section where, after passage through a thin carbon foil stripper, the ion charge to

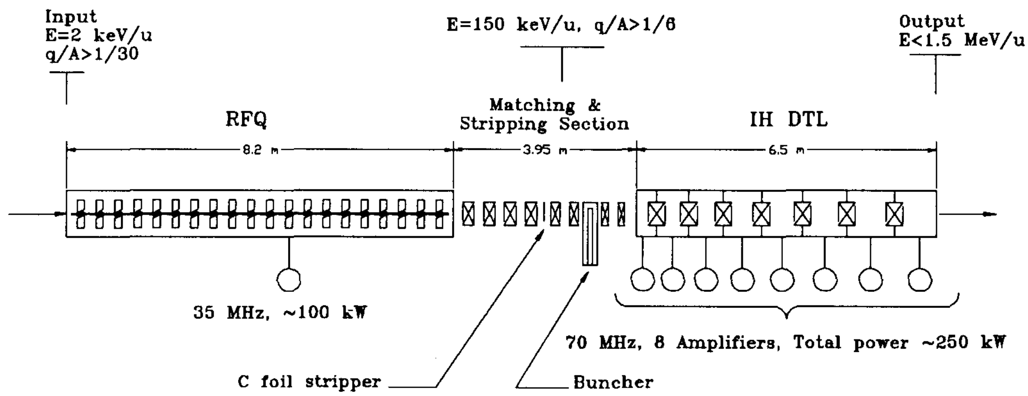

Figure 5: Block diagram of the ISAC post-accelerator

mass ratio is increased to q/A $\geq 1/6$, for the most probable charge state. A buncher after the stripper compenstates for debunching in this relatively long section and matches the beam to the phase acceptance of a DTL operating at 70 Mhz, (double the RFQ frequency). An IH structure [11] is chosen for the DTL because of its very high shunt impedance for the ion velocities of interest here, and because of its small transverse dimensions relative to its operating wavelength.

The high shunt impedance is due, in part, to the use of thin cylindrical shells as drift-tubes which, as a consequence, results in low capacitive loading of the structure. This however, means that quadrupole magnets, often included in linac drift-tubes to compensate for the RF defocusing in the accelerating gaps and to transport the finite emittance beam, cannot be used. In this case, we find that quadrupole doublets at six cell intervals are sufficient to compensate for the RF defocusing corresponding to a 3.0 MV/m accelerating gradient, and to transport the beam with a normalized transverse emittance of $\leq 0.5\pi$ mm-mrad through the channel defined by the 20 mm diameter drift-tube aperture. Eight groups of six cells are required for the 1.5 MeV/u output energy. Energy variability is accomplished by selectively turning on the RF drives of the separately driven, six cell units, starting with the lowest energy one, and partially powering the last powered unit. Inter-unit spaces, accommodating the quadrupoles are kept as small as possible to minimize debunching. In the current conceptual design of the DTL, it would consist of one tank, 6.5 m long and 1.6 m in diameter, internally divided into the eight accelerating units, with the quadrupoles doublets in field free spaces between units. From particle tracking calculations through the entire linac, an output beam with transverse and longitudinal emittances less than 0.94π mm-mrad and 11π (keV/u)$\cdot$ns respectively are expected. Overall transmission through the linac, exclusive of losses at the stripper is 86%.

4 Current Status and Schedule

Since the funding was announced in June 1995 work has been proceeding on defining the facility building so detail design can begin before the end of the year. At the same time a short prototype RFQ, consisting of three split-ring modules is being designed with some construction already underway. A cusp ion source designed for the special requirements of the ISOL application has been built and preliminary tests done at Lawrence Berkeley Lab. This source will be incorporated into a model of the ISAC target module and installed on a new target/ion source test stand now under construction. Beam tests on this stand should begin before the end of the year.

Construction of the building will begin in 1996 and be completed at the beginning of 1998. By that time the new 500 MeV proton beam line from the cyclotron will be ready, and installation of the target facility and mass separator will begin. Concurrently construction and installation of the post-accelerator will proceed so that by the end of 1999 the target, mass separator, and the RFQ accelerator stage should all be operational. Completion of the entire project is expected by the end of the year 2000.

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