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ISAC-1: RADIOACTIVE ION BEAMS FACILITY AT TRIUMF

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This paper describes the ISAC-1 radioactive ion beam facility proposed at TRIUMF. A novel approach for the target/ion source station will allow an incident proton beam intensity of at least 10 μA at 500 MeV. This should give high luminosity for the production of nuclei far from stability with a very large isotopic range. After mass separation the beams can be sent to two different experimental areas. One uses the 60 keV energy beam for experiments such as the neutral atoms trap, parity violation, etc. The second one, mainly dedicated to nuclear astrophysics, will use the 0.2 to 1.5 MeV/u post-accelerated beam. Singly charged ion beams, with $A \leq 30$ delivered from the on line mass separator, with an energy of 2 keV/u, will be accelerated in a two stage linac consisting of an RFQ and a post-stripper drift-tube linac up to 1.5 MeV/u. CW operation mode is required to preserve beam intensity. As a consequence of the low charge to mass ratio of the ions a low operating frequency for the RFQ is required to achieve adequate transverse focusing. The main features of this accelerator are: 35 MHz RFQ, stripping at 150 keV/u, and beam energy continuously variable from 0.2 keV/u to 1.5 MeV/u.

I. INTRODUCTION

During the last decade there has been a growing worldwide interest in the use of radioactive ion beams (RIB) for both fundamental and applied sciences. The possibility of producing intense radioactive nuclear beams with N/Z ratios largely different from those of natural isotopes opens a new field of research. Some examples where the use of RIB can be of great interest are:

- In nuclear physics it will be possible for the first time to test the isospin dependence of a large variety of nuclear systems far from stability. Nuclear deformations predicted a long time ago with a variety of models can be tested. This will provide a strong constraint on nuclear models and will improve our understanding of the nuclear interaction.
- In astrophysics, it is believed that the lightest elements were synthesized immediately after the Big Bang. The process of synthesis of heavier elements includes nuclear capture and decay of, often very short-lived, unstable nuclei. Except for a few long-lived elements only a theoretical estimation of these processes can be applied in cosmology. With a RIB facility, empirical determination of crucial reaction rates will permit prediction of production probabilities of the heavier elements at various stages of stellar evolution.
- Atomic physics techniques are commonly used to measure many properties of the nucleus; such as the spin, electromagnetic moment and charge radius. On the other hand, nuclear physics techniques and nuclei far from stability can be used to address fundamental issues in atomic physics such as QED.
- Tests of the Standard Model of elementary particles can be complementary to and, in specific areas, competitive with those performed at high energy. For example, PNC experiments can be performed using unstable ions like Fr.
- In condensed matter RIB can be used for doping new generations of semiconductor material and as a probes to obtain information on their local surrounding on an atomic scale. RIB and muons techniques can be combined to study the dynamics of certain phenomena on a very short time scale. With low energy muons we can study the dynamics of magnetic processes off surface and thin layer. The later is complementary to the solid state physics program that is an active field of research at TRIUMF.

A proposal to install an ISOL (isotope-separator-on-line) and post-accelerator RIB facility at TRIUMF was first made in 1985[1]. Although the full project was not funded at that time, an on-line target/ion source and mass separator test facility was installed on one of the TRIUMF proton beam lines, and has been used since 1987 to provide low energy radioactive beams for experimenters and to develop the target-ion source system.

Radioisotope production by the ISOL method is achieved with an intense beam of energetic light particles, (eg. neutrons, protons, or light ions) incident on a thick target of high atomic mass material. The radionuclides thus formed are stopped within the target, which is heated to high temperature to promote diffusion to and desorption from the target surface. Once free of the target the radionuclides are ionized in an ion source and then mass analyzed with the selected species then delivered the low energy experimental area or to the post accelerator for further acceleration.

Particle fragmentation, employing a high energy heavy ion primary beam, is an alternative production method for radioactive beams. In this case however all ions emerge with velocities close to that of the incoming primary beam (e.g. with particle energies typically >30 MeV/u) with significantly larger emittances than the primary beam. In contrast the ISOL beams have properties similar to those of stable ion beams, such as low emittance, low energy spread, and if required, short pulse widths.

The high energy (500 MeV) and high intensity (>100 μA) of the TRIUMF H^- cyclotron make TRIUMF a time and cost effective choice for a RIB facility in North America. The high proton energy permits the use of a thick target providing a wide mass range of isotopes via a large number of reaction mechanisms. Lower energy machines can instead only produce intense RIB near the stability line, with constraints on the choice of target material set by the higher energy density deposition requirements.

II. TARGET/ION SOURCE SYSTEM

Flexible target handling and containment of the radioactivity are the major considerations in the present design[2]. The target will be placed at the end of a steel shield plug. The target station is to be housed in a new heavily

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shielded building which is attached to and extends into the existing proton hall. Figure 1 shows the target/ion source handling concept. All highly activated and potentially contaminated components such as production targets, beam dump, ion sources and initial focusing devices will be located in this building along with the primary radiation shield. Services required to operate the target area components will also be housed in this building. Hot cell, warm cell and a decontamination and storage facility will be included.

III MASS SEPARATOR

There is no universal ion source for the production of all the elements required for the physics program. Beam properties will depend on the type of ion source used. The extraction system will be optimized for each individual ion source to give the highest source brightness and small angular divergence. Space has been allowed in the target module design to incorporate additional optical elements such as steering devices or other optical elements.

The design of a radioactive ion beam mass separator system requires that a number of fundamental issues be addressed and resolved. These issues are the following: extraction from the ion source, matching of the beam to the mass separator, beam emittance and high beam current aspects, multiple beam requirements from the mass separator, high mass resolution (for $6 \leq A \leq 240$) and transport to the user.

In our present design the mass separator consists of two anti-symmetric QQQDDQQQ systems each with a total bend angle of 112°. It will have a source-defining entrance aperture. Aberrations are corrected by four sextupole and four octupole elements placed near each dipole. This separator will have a dispersion at the focal plane of 6 cm/% in DM/M and a mass resolving power of 10,000. A movable slit system will be placed on the focal plane to select the mass to be transmitted. The second bend section can be maintained at an elevated potential to provide additional beam purification if this is required.

IV. ACCELERATOR

Most of the astrophysics and applied program can be achieved within an energy range of 0.2 and 1.5 MeV/nucleon, while higher energies (≤ 10 MeV/u) would be desirable for nuclear structure studies, fusion reactions, etc. This could be viewed as a possible upgrade in the future. At present, for ISAC-1, we are limiting ourselves to the following specifications, (Table 1).

The block diagram in fig. 2 illustrates the two-stage linac that would satisfy the ISAC-1 specifications. Further improvements to this design are being contemplated. For example, the addition of a charge state selector will improve the tuning capability by eliminating other charge states and will prevent radioactive contamination of the drift-tube linac.

A radio-frequency quadrupole operating at 35 MHz provides the initial acceleration of the singly charged ion beam delivered by the ISOL system. Taking singly charged mass 30 as the reference particle we are led to an operating frequency of 35 MHz, with an inter electrode voltage of 85 kV, and r_0 = 0.86 cm. This gives a design value of B = 3.

Table 1 - Basic specifications for ISAC-1.

Input beam	
Energy	60 keV
Ion mass	$A \leq 30$
Ion charge	1
Beam current	< 1 μA DC
Beam emittance	≤ 0.25 π mm mrad (Normalized)
Accelerated beam	
Output energy range	$0.15 \leq E \leq 1.5$ MeV/u
Resolution ΔE/E	≤ 0.1 %
Duty factor	100 %

In the RFQ design the conventional shaper is replaced by a buncher of a few modulated cells, followed by cells with no vane modulation. Then, after one quarter synchrotron oscillation, the synchronous phase is jumped from -90 to -85 degrees. Then the beam is accelerated while the vane modulation parameter and synchronous phase vary smoothly, according to the Yamada prescription, toward final values of m=2.5 and $\Phi_S = -20°$, respectively. The output longitudinal emittance is ≤ 1 π keV.ns/u, the transverse normalized acceptance is 0.55 π.mm.mrad, and the transmission is 92 %3[3].

From a structural point of view, the low frequency of the RFQ dictates that a semi-lumped resonant structure be used to generate the required RF voltage between the RFQ's electrodes. Various RFQ models have been built and the structure proposed for the ISAC-1 accelerator is a variant of the 4-rod structure developed a the University of Frankfurt[4]. A 4-rod RFQ split-ring structure has been chosen because of its relatively high specific shunt impedance, its mechanical stability, and the absence of voltage asymmetries in the end regions [5].

Calculations using MAFIA combined with model measurements have been used to optimize dimensions. For our present design, the rings have a rectangular section (15 cm axially by 8 radially), a mean diameter of 43.5 cm, and are spaced at 40 cm intervals along the RFQ electrodes. The theoretical specific shunt impedance Z_S for this structure when enclosed in a 1 m diameter tank, is 500 kΩ m.

After acceleration to 150 keV/u in the RFQ, the beam passes through a matching and stripper section, where its charge to mass ratio is increased to ≥1/6. Thereafter it is injected into a 70 MHz drift-tube linac and accelerated up to 1.5 MeV/u. To permit variation of the output beam energy, the 48 accelerating gaps of the drift-tube stage are divided into eight independently driven sections of six gaps each. Quadrupole doublets between sections provide the transverse focusing necessary to maintain the beam well focused along the drift-tube linac. Self consistent particle tracking computations through the RFQ, stripper and matching section, and drift tube linac have been carried out using computer codes. We start with a 2 keV/u, single charged mass 30 ion beam. A random distribution of 5000 particles in the 4 dimensional transverse phase space, with normalized emittance of 0.25 π mm mrad, is used as input. Angular and energy straggling in the stripper carbon foil is assumed having a Gaussian distribution with σ of 8 mrad and 26 keV, respectively. The beam at the output of the linac shows final transverse and longitudinal emittances of 0.94 π mm mrad and 11 π (keV/u) ns. The overall transmission through the linac, excluding losses at the stripper, is 86%.

IV. CONCLUSION

Recent developments in the field of isotopic separation on line can now be combined with the remote handling expertise of meson factories to produce a very attractive RIB facility providing beams with intensity large enough to allow many new experiments. Applications can be performed on a relatively small scale and require modest investment if based on existing facilities. This will provide the opportunity to perform front-line multidiciplinary research. In nuclear astrophysics this opens the possibility to measure reaction cross sections of processes occurring in stellar sites. Ion beams with relatively low energy and submicron dimensions would have important applications in the semi-conductor and computer industries. In material sciences, techniques such as Mößbauer spectroscopy and perturbed angular correlation will become possible with radioactive tracers implanted within bulk material.

The accelerator solution presented satisfies the specifications for the presently envisaged experimental program. It serves as a reference design which will be developed and modified to match physics requirements

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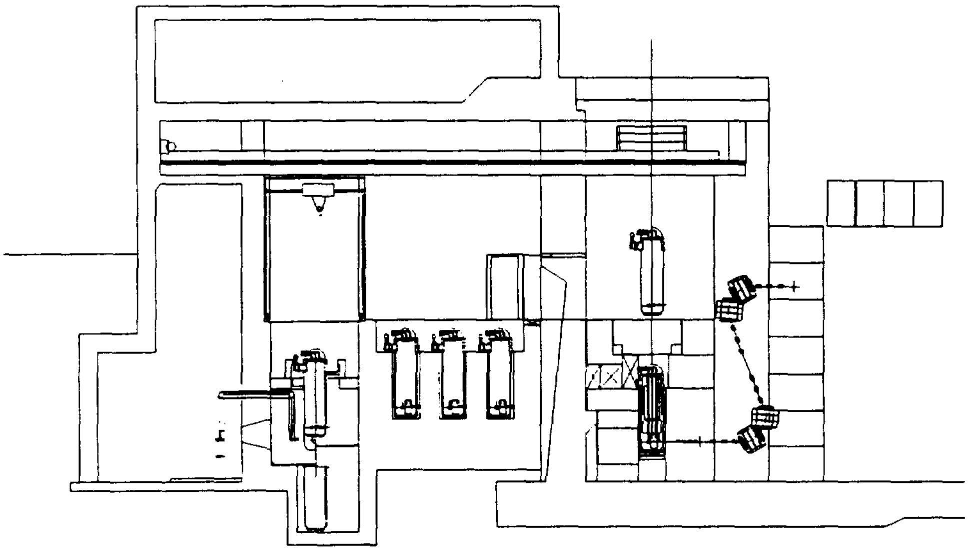

Fig. 1 - Vertical view of the target and remote handling annex.

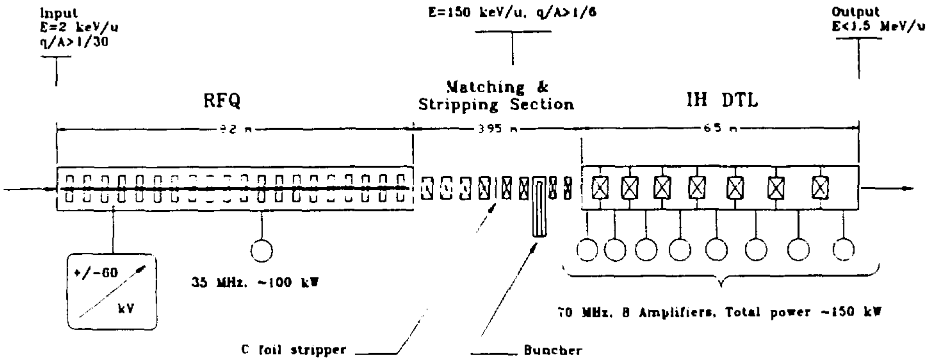

Fig. 2 - Block diagram of ISAC-1 post-accelerator.