# Magnetic Separator for light RIB production

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A magnetic separator- momentum achromat is being set up, to extract projectile-like secondary ion beams following the reactions of heavy-ion beams from superconducting LINAC booster at Mumbai. Forward focussed RIB with relatively small energy spread will be generated using production reactions in inverse kinematics. Reactions with these low intensity secondary beams can then be used to probe their properties through a variety of physical processes.

## Introduction

Understanding of nucleon-nucleon interaction in a nucleus is not only fundamental for nuclear physics but is also important to other areas of physics. Recently there has been an increased interest in experiments with beams of short-lived radioactive nuclei addressing the questions in areas of nuclear structure, nuclear astrophysics and fundamental interactions. Our understanding of nuclei is still largely empirical and is based on the knowledge of stable and near stable nuclei. The astrophysical processes like rp process, r process (responsible for energy generation) or stellar nucleosynthesis critically depend on properties of nuclei close to drip lines (at the limit of binding). Radioactive ion beams allow us to probe and help provide insights into the structure and dynamics of such nuclei [1].

Due to the strong interest in the physics with accelerated short-lived nuclei, a proposal for RIB facility in India is being actively pursued. The collaborative research programmes at various RIB facilities worldwide like GANIL (France), GSI (Germany) to address specific physics questions have also been initiated recently. Alternatively, low intensity (and low energy) radioactive beams can be produced following fusion, transfer, break-up reactions or fission in-flight (for heavy beams) and can be separated with a suitable spectrometer. have The CRIB, magnetic spectrometer followed by a velocity filter, at Riken [2] has been specifically developed for nuclear astrophysics study. In India, the recoil mass separator at IUAC was used for producing $^{7}$Be beam to measure $S_{17}$ [3]. At Argonne National Laboratory, several experiments have been carried out with secondary ion beams using a Enge split pole spectrograph as a separator. Similar facilities are also set up at University of Louvain (Belgium), Florida State University (REsolut), University of Notre Dame (TWINSOL). Reactions with these low intensity secondary beams can then be used to probe their properties through a variety of physical processes. It has been demonstrated that high precision experiments can yield good results even with low intensity beams [5-8]. Therefore, a proposal to set up a magnetic separator for production of low energy (~few MeV/nucleon) Radioactive Ion Beam (RIB) was initiated at TIFR-BARC accelerator facility.

## Development of a Momentum Achromatic Separator

A momentum achromatic separator to extract projectile-like secondary ion beams following the reactions of heavy-ion beams from LINAC. For light nuclei reactions like (p,n), (d,n), (p,d), can be used to produce unstable nuclei. Assuming the cross section of 100 mb, with a primary beam intensity of 10 pnA on a 1 mg/cm$^2$ target, the intensity of secondary beam particles at primary target location is ~ $10^6$ pps. Reactions in inverse kinematics result in forward focused products with relatively smaller angular and momentum widths, which is useful for efficient collection of the reaction products. At present, with Pelletron + LINAC, ions upto mass A ~ 80 can be accelerated to E/A ~ 5−12 MeV. The available beam intensity ~0.1− 10 pnA is limited by the SNICS ion source. With the proposed ECR based positive ion injector system [9], the primary beam intensity and variety will be enhanced. In (p,n) reaction, the angular spread $\Delta\theta$ is $\leq$ 1/A. For light ion beams the change in q is quite significant and that alone can suffice to separate the products. Thus, a magnetic separator with large solid angle ($d\Omega_{geom}$ ~25 msr) and momentum acceptance ($\Delta P/P$ ~ 5 %) is designed for this purpose.

## Design details

We have chosen a symmetric configuration, namely, Q1-Q2-D-Q3-Q3-D-Q2-Q1.

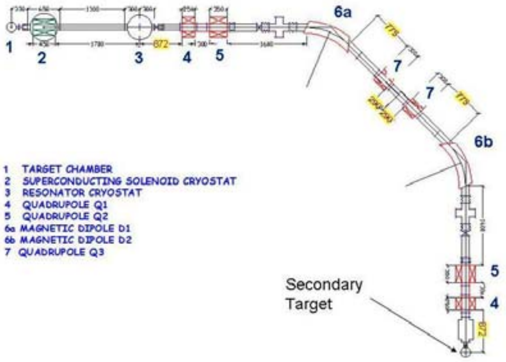

**Figure 1:** Schematic layout of magnetic separator

The design was optimized using a ray tracing program developed by us and verified with TRANSPORT code [10]. A superconducting solenoid (150 mm bore, 450 mm long, 5.5 T), to be fabricated in-house, at the entrance of the magnetic separator will ensure a good collection of reaction products. A provision is also made for a superconducting resonator (debuncher) to reduce the energy spread and thereby improve both collection efficiency and the secondary beam quality. A schematic layout the magnet system is shown in Fig. 1. The major components have been fabricated by Danfysik, Denmark. The installation work of the achromat in the new user beam hall, is in progress.

Table 1 shows the specifications of quadrupole magnets. The vacuum chambers for quadrupoles have been fabricated at the central workshop, TIFR. The magnetic field in the quadrupole was measured at different radial positions using a high precision Hall probe as a function of excitation current. The higher harmonic content (n = 3 to 14) was also measured at factory using rotating coil and was found to be less than 0.3−0.4%.

**Table 1:** Quadrupole Specifications

| Quadrupole | Length (mm) | Bore dia. (mm) | $B_{max}$ (T) |
|---|---|---|---|
| Q1 | 250 | 128 | 0.6 |
| Q2 | 350 | 128 | 0.4 |
| Q3 | 300 | 154 | 0.3 |

The dipole specifications are listed in Table 2. Figure 2 shows the linear variation of magnetic field as a function of current. The uniformity of the magnetic field was verified in the central region (see Figure 3). The field was also measured in the median plane at both ends to extract effective field boundaries. However, due to the large pole gap, higher order aberrations have to be taken into account. We are planning to do a 3D field mapping to extract higher order multipole components. A special, high precision measurement setup is being fabricated in TIFR workshop for this purpose.

**Table 2:** Dipole Specifications

| | |
|---|---|
| Maximum Field | 0.9T |
| Bending Radius | 1.2 m |
| Bending angle | $45^0$ |
| Mass Energy Product | $55^*Q^2$ MeV-amu |
| Entrance angle (α) | $27^0$ |
| Exit angle (β) | $40^0$ |
| Pole gap | 80 mm |
| Uniform Field zone ($\leq 10^{-3}$) | ± 40 mm in X<br>± 35 mm in Y |

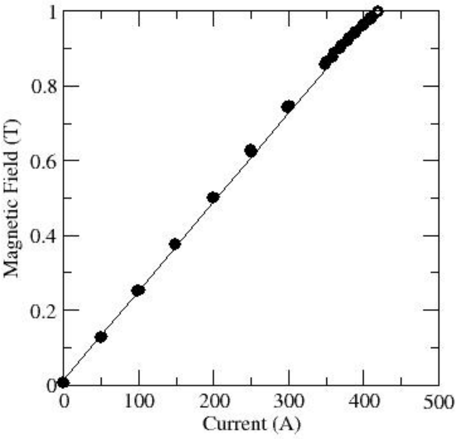

**Figure 2:** Variation of magnetic field as a function of current as measured during the factory test at Danfysik- Denamark. The open (closed) symbols represent field measured during ramping up (down) of current while linear fit is indicated by straight line.

Figure 4 shows the calculated beam profile through this achromat till mid-point using ray tracing program. The total angular acceptance is 30 mrad (x') x 110 msr (y'). The expected momentum dispersion is 10 mm/%.

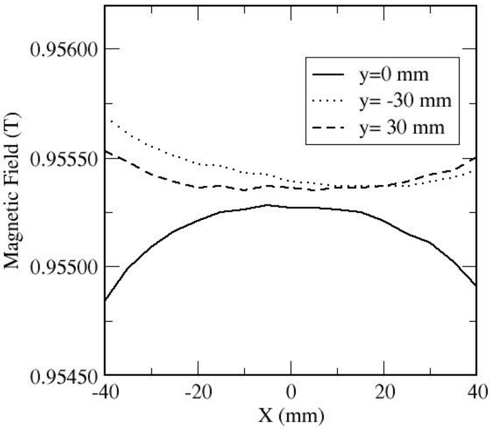

**Figure 3:** The field measurements at the center of the dipole, total variation is ~ ± $4x10^{-4}$.

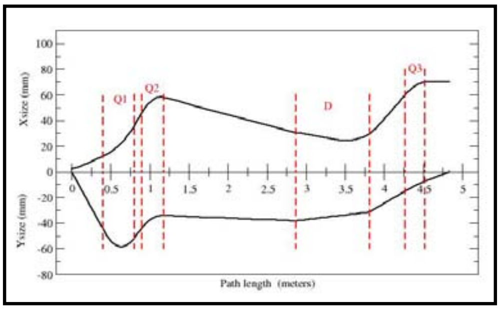

**Figure 4:** The calculated beam profile through the separator till half point.

## Identification and characterization of secondary beam

The identification of secondary ion beam requires combination of various parameters. The primary identification will be achieved with Bρ measurement. The magnetic field (B) in the dipole will be measured using a Hall probe at a fixed location, which is calibrated during the factory test. In addition, the time of flight between the primary target and the focal plane will be measured. Small beam spot and good timing at primary target spot essential. There is also a provision to mount a thin degrader foil at half-way point. The energy loss through the foil will be different for ions of same mass but different Z and will further help in separation (e.g. ref. [2]) of ions in second half. Gas filled mode will also be helpful for isobaric separation. Individual ray tracking using position sensitive, fast timing detectors at focal plane will be essential. We have developed a MCP based detector for this purpose. Two position sensitive MCPs separated by 25-30 cm will provide event by event x, y information at secondary target position.

## Primary Beam rejection

The secondary ion beam and main primary beam will be separated in the spectrometer due to their different A/Q. As the secondary ion beams will be of low intensity, reduction of scattered primary beam background is of paramount importance. We have provided for adjustable stoppers at half point, to stop the bulk of the primary beam. Further, dipole chambers have tantalum lining on inner sides to reduce the scattered primary beam.

This facility can be used for addressing a variety of research problems. For example, the elastic scattering of exotic mirror nuclei (e.g. $^{12}$N, $^{12}$B) in order to understand isospin dependence, fusion/transfer reactions close to the Coulomb barrier, (p,$\gamma$) reactions of astrophysical interest in inverse kinematics, etc. At the secondary target position, high efficiency, high resolution detectors both for charged particles and gamma rays are required. A combination of annular Si detectors ($\Delta$E-E) with both $\theta-\phi$ segmentation will be essential for identifying the charged particles and extracting the angular distribution information. Compton suppressed HPGe detectors will be used for measurement of characteristic gamma rays.

A primary target should be able to handle large beam current and introduce as little straggling as possible. We propose to develop a rotating target and cryogenic gas cell at primary target site.

Although the design emphasis has been on secondary ion beam production in inverse kinematics, residue tagging in normal kinematics is also possible for heavy ions. In this mode, it will be possible to separate CF/ICF/beam like events. This will facilitate study of rare processes like double GDR in compound nuclear reaction.

## Summary

A magnetic separator is under development to produce low energy RIB using light ion beams from LINAC in inverse kinematics. The work to install the magnets and vacuum components in new user hall at TIFR-BARC heavy ion accelerator facility is underway and will be completed shortly. Detailed 3D field mapping for dipole magnets will be carried out. The beam optics will be verified with a point source at primary target position. Direct reactions with light RIBS (e.g. study of (p,$\gamma$) reactions of astrophysical interest, elastic scattering) will be studied.

With the proposed positive ion injector system for LINAC, higher intensity and wider variety of primary beams will further enhance the scope of physics goals that can be addressed. This facility will give us a valuable experience for low beam intensity experiments which will be useful for experiments with national/international RIB facility.

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