Title: New Design Studies for TRIUMF's ARIEL High Resolution Separator

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New Design Studies for TRIUMF's ARIEL High Resolution Separator*

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Abstract
As part of its new Advanced Rare IsotopE Laboratory (ARIEL), TRIUMF is designing a novel High Resolution Separator (HRS) [1] to separate rare isotopes. The HRS has a 180 degree bend, separated into two 90 degree magnetic dipoles, bend radius 1.2 m, with an electrostatic multipole corrector between them. Second order correction comes mainly from the dipole edge curvatures, but is intended to be fine-tuned with a sextupole component and a small octupole component in the multipole. This combination is designed to achieve 1:20000 resolution for a 3 μm (horizontal) and 6 μm (vertical) emittance. A design for the HRS dipole magnets achieves both radial and integral flatness goals of < 10⁻⁵. A review of the optical design for the HRS is presented, including the study of limiting factors affecting separation, matching and aberration correction. Field simulations from the OPERA-3D (OPERA) [2] models of the dipole magnets are used in COSY Infinity (COSY) [3] to find and optimize the transfer maps to 3rd order and study residual nonlinearities to 8th order.

INTRODUCTION
The ARIEL HRS is designed with the goal of separating rare isotope species with a fractional mass difference of 1:20000 for an input beam with 3 μm (horizontal) and 6 μm (vertical) emittance. Mass separation is achieved by creating dispersion using bending magnets. Dispersion is a function of the bending radius and angle of the magnets. Isotopes of differing masses are transported to a shifted final horizontal position relative to the target isotope as they travel through the separator. Slit apertures can then be used to collimate the beam, allowing only the desired isotope to be transmitted through the HRS. The separation criterion can be expressed as a function of mass dispersion \(D\), resolving power of the separator \(R = \text{mass/Δmass}\), and the full width of the horizontal slit aperture \(2\alpha\):

\[2\alpha = D/R\]

For example, in the case of the ARIEL HRS, dispersion \(D\) is created using two 90 degree magnetic dipoles, bend radius 1.2 m. This creates dispersion at the exit to the separator of approximately 2.4 m. To achieve separation of 20000, the full width of the horizontal slit aperture is limited to 120 μm. For a 3 μm horizontal emittance, this horizontal beam size limit means the angular deviation in the beam would be up to +/- 50 mrad.

Energy spread within the beam and aberrations in the beam optics also directly affect resolution. These limitations are discussed later in this paper.

HRS DIPOLE MAGNETS
The dipole magnets for the HRS, like the one shown in Figure 1, were designed using OPERA. The design requirements for the ARIEL HRS dipoles include both radial and integral flatness goals of < 2.5·10⁻⁵. This goal is set for the 'good field' region of the magnet, where the beam is intended to travel and field quality must be the highest. This requirement is directly derived from the desired resolving power of 20000. The specification requirements for integral field flatness, as well the radial field flatness at the center of the magnet, are met in the design model. The effective field edge is optimized in order to coincide with the curved field edge of an equivalent (same \(B_0\) at the center of the dipole) hard edge magnet. The curvature was chosen from beam dynamics simulations to minimize second order aberrations in the beam optics. The saturation level in the iron is kept below 1.5T in order to have reproducible fields at low excitation.

HRS LAYOUT AND PARAMETERS
The ARIEL HRS design [1] is based on the study of a "pure separator." In this case, the magnetic dipoles are placed symmetrically between the entrance (object) and exit (image) aperture slits. The spacing between the dipoles was set to match the spacing of planned periodic beam line sections, and the drifts between the slits and the dipoles is set to achieve horizontal imaging from slit to slit. The entrance and exit edges of the magnetic dipoles are angled to add vertical focusing, and the system is designed to achieve imaging of unit magnification in the horizontal plane. These elements define the linear beam

Figure 1. Example of preliminary OPERA model of the ARIEL HRS magnetic dipole.
motion. Electrostatic quadrupoles are added to provide correction for manufacturing and positioning tolerances in machining the dipole edge angles or potential alignment issues. The parameters for the HRS are outlined in Table 1, and a schematic detailing the general layout is presented in Figure 2.

Table 1. Summary of ARIEL HRS parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift length to E. quad</td>
<td>0.200 m</td>
</tr>
<tr>
<td>E. quad length</td>
<td>0.050 m</td>
</tr>
<tr>
<td>Drift length from E quad to Dipole</td>
<td>0.546 m</td>
</tr>
<tr>
<td>Dipole Edge Angle</td>
<td>26.5 degrees</td>
</tr>
<tr>
<td>Dipole Edge Radius of Curvature</td>
<td>2.23 m</td>
</tr>
<tr>
<td>Dipole Vertical half aperture</td>
<td>0.070 m</td>
</tr>
<tr>
<td>Drift length between Dipole and Multipole</td>
<td>0.650 m</td>
</tr>
<tr>
<td>Multipole length</td>
<td>0.300 m</td>
</tr>
<tr>
<td>Multipole half aperture</td>
<td>0.200 m</td>
</tr>
</tbody>
</table>

The dipole entrance and exit edges are also curved to provide a second order correction to nonlinearities in the HRS optics. An electrostatic multipole located in the center of the HRS allows for fine-tuning the second order correction. It also allows for additional corrections of higher order aberrations by providing an octupole, decapole and duodecapole component. Figures 3(a)-(b) demonstrate the horizontal and vertical beam motion within the HRS.

HRS MATCHING

The “pure” separator slit setability requirement would ideally be 10 μm or less. As well, over a period of weeks or days of heavy ion bombardment, the slit edges erode to a non-ideal shape. To mitigate this effect, demagnification/magnification sections are added, respectively, before and after the pure separator. The magnification factor is tunable from 3 to 13 while maintaining imaging in the horizontal plane, as in an optical “zoom” lens assembly. The maximum magnification is limited by third order quadrupole aberrations becoming larger than the intrinsic aberrations of the pure separator. The horizontal envelopes and quadrupole layout are shown in Figure 4.

Figure 2. Schematic of ARIEL HRS layout.

Figure 3(a)-(b). COSY simulations of the horizontal (above) and vertical (below) beam motion in the ARIEL HRS.

Figure 4. COSY simulation of horizontal beam motion through the ARIEL HRS with matching/magnification section.
HRS ACCEPTANCE STUDIES

To meet the difficult performance requirements of the HRS, several studies have been done to assess stability of the design and acceptance criteria for the beam. For example, it is well known that fringe fields encountered by the beam will result in nonlinear effects on the beam motion. Many simulation codes, however, assume that the transverse fields experienced by the beam extend to infinity. In reality, the magnetic poles will have some edges and the field drop off near these edges can induce nonlinearities into the field felt by particles in the beam. The wider the magnetic pole relative to beam size, the more appropriate it is to ignore this effect.

Using OPERA to model the ARIEL dipole, the transverse magnetic field variation in the midplane was examined. A function was fit to the OPERA data and the effects at third order and above were isolated. The linear and second order terms are ignored since they are induced through longitudinal edge shaping. Figure 5 shows the maximum variation due to these effects, as a function of pole width, within the chosen ‘good field region’ of +/- 0.2 m.

Figure 5. Nonlinear field variations in the ‘good field region’ due to variation in transverse pole width.

An additional study was made of the geometric acceptance of the dipoles. Higher order terms in the multipole expansion limit the acceptance of the dipole. To study this, the edge curvature and central multipole were used to minimize nonlinear effects to third order and the final horizontal phase space of a set of particles was examined. These particles enter the HRS on the reference trajectory but with horizontal angles deviating from the reference trajectory by +/- 80 mrad. As shown in Figure 6, the 50 μm half-width for the aperture slits need for mass separation of 1:20000 limit angular acceptance to approximately +/- 60 mrad.

Figure 6. Variation in final horizontal position due to initial angle entering the HRS corrected to 3rd order.

This result was particularly helpful in defining the ‘good field region’ for the magnets, since the beam envelope within the dipole is primarily determined by the motion of particles with large angular deviations.

Energy variation in the beam was also examined because of the crucial role it plays in separation. Dispersion induced in the magnetic dipoles will cause a shift in final horizontal position due not only to mass, but also energy variation within the beam. For example, for the ARIEL HRS, designed to achieve a target resolution of 20000 with a horizontal emittance ($\varepsilon_x$) of 3 μm, for a 60 keV beam with a total energy spread ($\Delta E$), the effective resolution can be approximated as:

$$ R_{\text{effective}} = \frac{20000}{\frac{\varepsilon_x}{3.75 \, \mu m} + \frac{\Delta E}{3 \, eV}} $$

Figure 7 illustrates the practical trade-offs in the operation of the HRS.

Figure 7. Compromises between energy spread and emittance for various separator resolutions.
Mechanical limits include the precision in setting the gap with the entrance and exit slits that collimate the beam, as well as erosion after extended operation. Electrical limitations arise from the need to maintain peak-to-peak high voltage and ground variations at a level of less than 0.5 V full width. Magnetic field flatness in the good field region is limited by the power supply ripple and machining tolerances of the magnetic poles.

ABERRATION CORRECTION

Nonlinear effects (i.e., optical aberrations) in the HRS can also substantially limit the resolution of the separator. These effects result from the geometry of the magnets as well as the fringe fields from both magnetic and electrostatic elements. COSY has been used to study the nonlinear optics of the HRS. Using differential algebra, COSY can provide an accurate Taylor expansion, to arbitrary order, of final beam coordinates based upon initial beam parameters. To achieve the desired separation, the variation in final horizontal position must be smaller than the full width of the horizontal slit aperture (2s). The higher order terms in this expansion are due to optical aberrations, and can be minimized to improve resolution. The largest second order aberrations in the HRS are minimized by introducing a symmetric curvature to the entrance and exit edges of the magnetic dipoles. Because machining tolerances will not precisely match simulation, a sextupole component of the electrostatic multipole located in the center of the HRS is available for fine-tuning the second order correction. The multipole also provides an octupole, decapole and duodecapole for further aberration correction as necessary. These corrections require small voltages at the poletip, even with multipole that has the 20 cm radial aperture needed to accommodate the large horizontal beam size. For example, the octupole correction voltage at the poletip is only ~15 V. The optimal poletip voltage based on simulation for a decapole is less than 5 V, and less than 1.5 V for a duodecapole.

Figure 8 shows the final horizontal phase space at the exit of the pure separator portion of the HRS for two masses separated by 1:20000. In this simulation, done with COSY, aberrations were corrected to 3rd order, but uncorrected aberrations through 8th order were included. Figure 8 is based on a COSY simulation using its internal model for a magnetic dipole. Additional simulations were done in COSY using a field map for the magnetic dipoles and their fringe field regions generated from the OPERA model of the magnets. Figure 9 shows a simulation corrected to 3rd order based on this OPERA field map.

Figure 8. Final horizontal phase space at HRS exit calculated from COSY 8th order simulation, for two masses differing by 1/20000, 3 µm (horizontal) x 6 µm (vertical) emittance, ΔE of 1 eV.

Figure 9. Final horizontal phase space at HRS exit calculated from COSY 2nd order simulation using OPERA field maps, for two masses differing by 1:20000, 3 µm (horizontal) x 6 µm (vertical) emittance, ΔE of 1 eV.

REFERENCES