What’s special about the ARIEL HRS?

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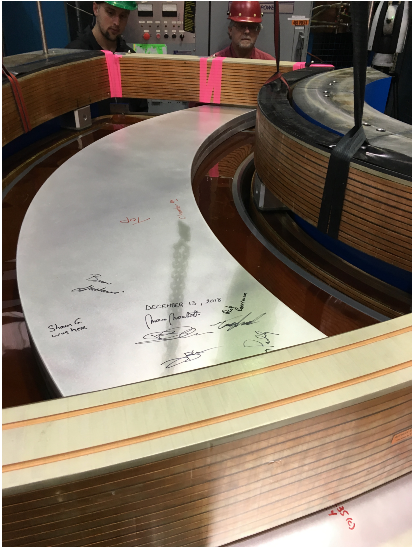
on behalf of Beam Physics Group

TRIUMF

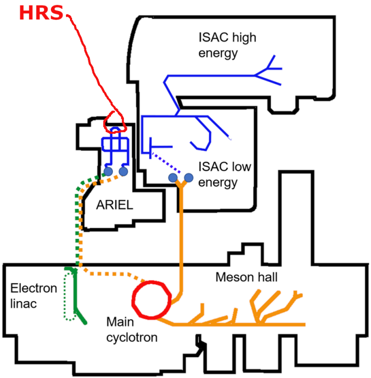
October 21, 2025



(from Carla Babcock's talk Monday)

TRIUMF-ISAC basics

- The TRIUMF cyclotron creates a beam of up to 100uA of protons at 480MeV to send to the ISAC target stations.
- ISAC (Isotope Separator and ACcelerator) delivers beams of radioactive ions to a variety of fundamental physics, life sciences, material sciences and astrophysics experiments.
  - 700 isotopes extracted
  - ~3000 h of high intensity RIB beam per year
  - State-of-the art experimental setups



TRIUMF schematic
(B.E. Schultz et. al. J. Phys : Conf. Ser. 2022)

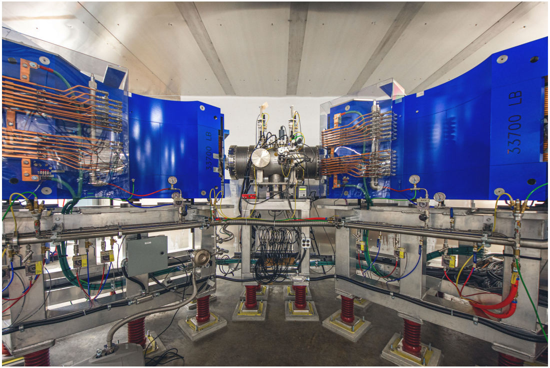
Outline

I. HRS should be designed to maximize $\mathcal{R}\epsilon_x$, not $\mathcal{R}$ alone.

II. Optics of TRIUMF's ARIEL HRS: The matching issue and the aberration correction.

III. Measured performance so far.

IV. COSY Simulations.



Resolution is not the figure of merit

Reminder: In a magnetic separator, mass resolution is meaningless without acceptance specification. Resolution $\mathcal{R} > 10^4$ by itself requires only a sufficiently large dipole and very stable power supplies.

It's getting high resolution **and** high transmission that is challenging.

Figure of merit ($\mathcal{F}$) should be the product of transmitted emittance and resolution: $\mathcal{F} = \epsilon_x \mathcal{R}$. Since resolution is dispersion divided by slit width $2s$, $\mathcal{R} = D_M/(2s)$, and emittance is product of slit width and divergence 2θ, $\epsilon_x = s\theta$, we have $\mathcal{F} = s\theta D_M/(2s)$:

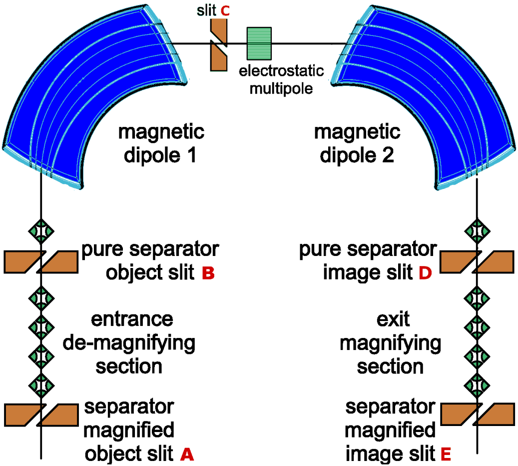
$$\mathcal{F} = D_M \theta / 2 \tag{1}$$

E.g.: ARIEL HRS: $D_M = 2.4$ m, $2\theta = 150$ mrad, so $\mathcal{F} = 90000\,\mu$m, or $\mathcal{R} = 20000$ when $\epsilon_x = 4.5\,\mu$m. This is borne out in simulations I'll show.

TRIUMF ARIEL HRS Main features

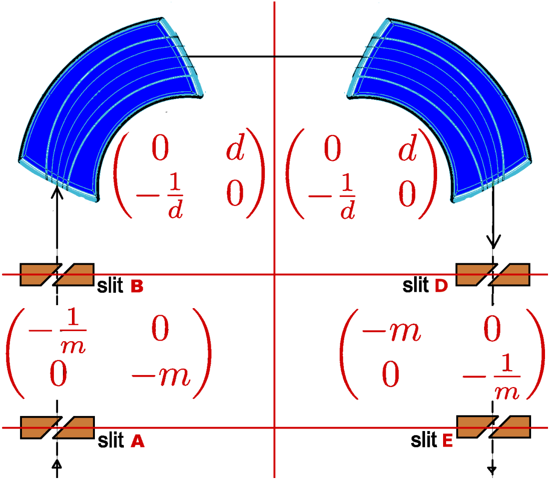
- Two dipoles, each 90°, arranged to have a $-I$ horizontal transport slit to slit.
- Dipoles have radius $\rho = 1.2$ m, resulting in mass dispersion of 2.4 m.
- Thus, a 0.100 mm slit results in a mass resolution of 24000.
- Slit to midpoint is 90° phase advance, $\beta_x = 1.6$ m, so dipoles' good field region of 320 mm results in acceptance of ± 100 mrad at slit. So phase space acceptance is $5\,\pi$mm-mrad for 24000 mass resolution, or $3\,\pi$mm-mrad and a $60\,\mu$m slit for 40000 mass resolution, but as will be shown, the optics cannot support this. We use at most 240 mm of the good field region.

TRIUMF ARIEL HRS Hardware Layout



Two features:

1. The matching quadrupoles can demagnify up to factor of $m = 10$, allowing object and mass slits to be 1 mm rather than 0.1 mm. Effective dispersion is up to 24 metres.
2. The high order correction device is a rectangular box of electrodes.



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$m = 3$ to 10, $d = 1.6$ m.

2 Modes of Operation

1. In ‘Pure Separator’ mode, the 4-quad sections are simply matching sections. Slit ‘B’ is used as object and Slit ‘D’ is image or mass selection. Mass dispersion is 2.4 m, so a slit width of 0.100 mm needed for a resolution of 24000.
2. In the second mode, slits ‘B’ and ‘D’ are ‘out’. The matching section can be tuned to a magnification of up to $m = 10$. Slit ‘A’ is the object and Slit ‘E’ the mass selection point. At $m = 10$, mass dispersion is also magnified and becomes 24 m, so slit sizes are 1.00 mm. In this mode, the mass selection is far less dependent upon the slit condition. The aberrations include those from the quadrupoles, but they also can be corrected by the multipole.

Match/Magnifier optimization

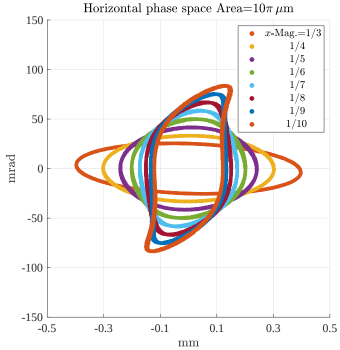
Match/Magnifier: The LEBT backbone is a periodic section of doublet cells. The doublet naturally creates waists and the 4-quad matching section to the HRS starts at such a waist in the horizontal plane. Slit 'A' is placed at this waist. The 4-quad matching section has tunable magnification in the horizontal plane. The demagnification required to focus an emittance of $3\,\mu$m down from its size 1.33 mm to the 0.100 mm needed to achieve a mass resolution of 24000 is $m = 13.3$, but beyond 10, aberrations are too large. So maximum resolution is 20000.

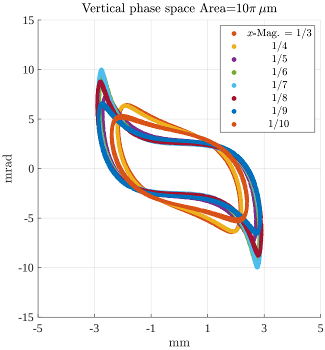
Aberrations: In a linear code it is straightforward to estimate the major quadrupole aberration: $\frac{\Delta\epsilon}{\epsilon} = \frac{\Delta x'}{\epsilon/\hat{x}} \sim \frac{\hat{x}^4}{\epsilon f^2 L} = \frac{\beta_x^2 \epsilon}{f^2 L}$ (f, L are focal length and length of quad). If we add this to the contribution due to mismatch, we can let the optimizer minimize this sum as it shuffles around the quadrupole lengths, strengths and separations, ~ 11 parameters. I used simulated annealing for this. Once design is finalized, only the 4 quad strengths are fitted to find match for any m.

Match/Magnifier Aberrations

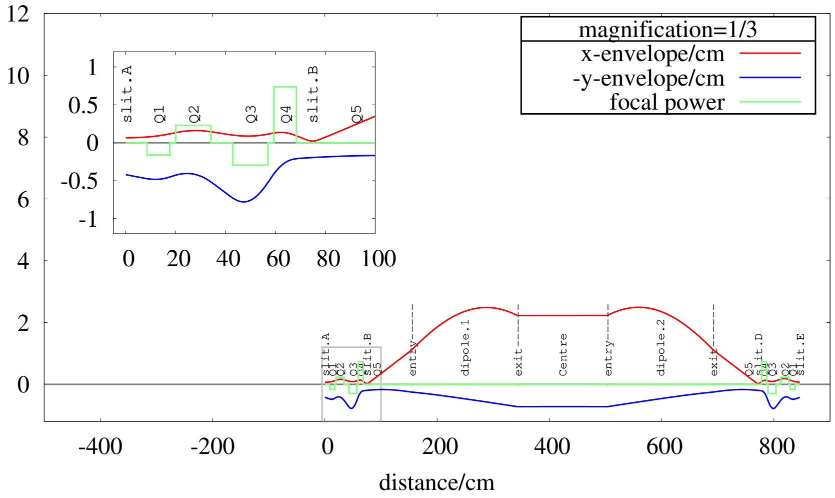
The matching section operates as a ‘zoom’ lens in the horizontal plane. Using requirements: (1) (De)Magnification ($M_{22} =$) from 3 to 10, (2) Entry (Slit ‘A’) should image to exit (Slit ‘B’), i.e. $M_{12} = M_{21} = 0$.

Below is shown the 8 different magnifications calculated to 5$^{\text{th}}$ order in `COSY` at slit B. Only the emittance perimeter shown.

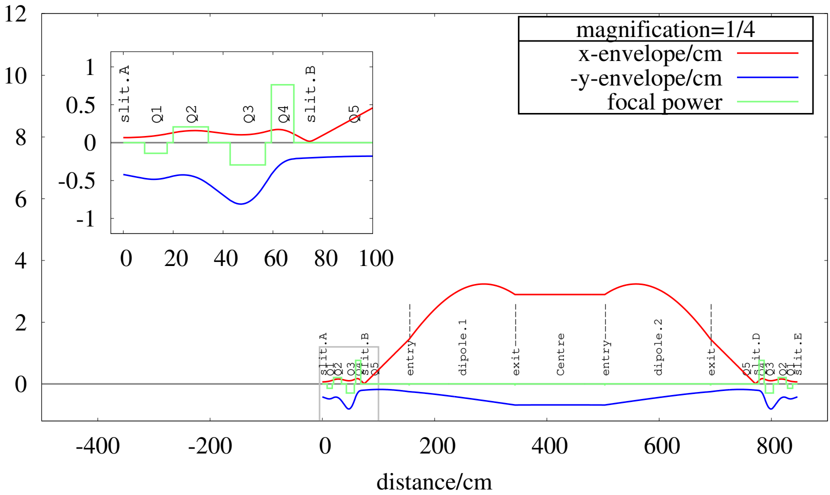




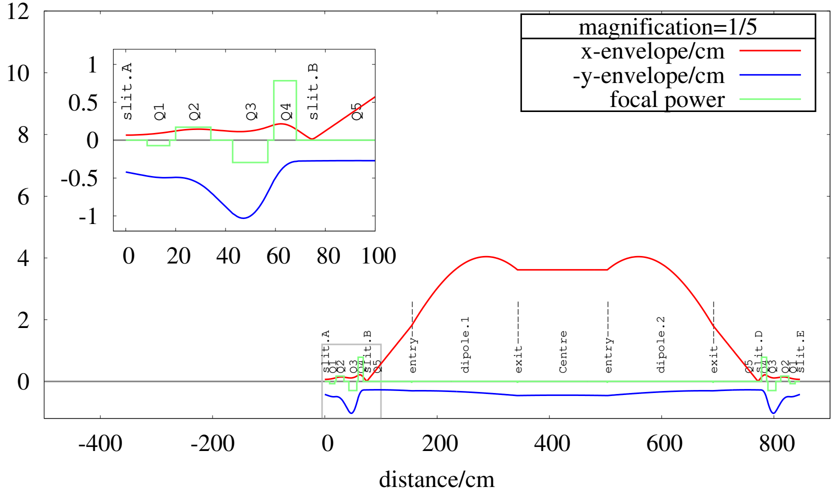
Beam envelopes vs. magnification (zoom)



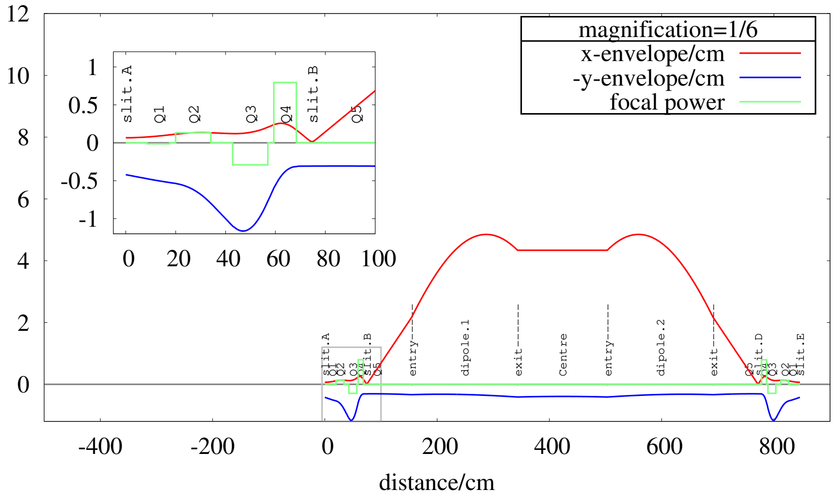
Beam envelopes vs. magnification (zoom)



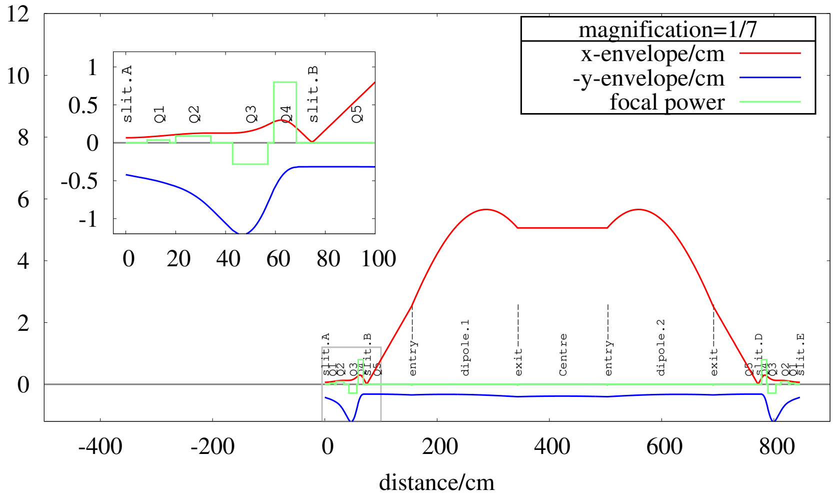
Beam envelopes vs. magnification (zoom)



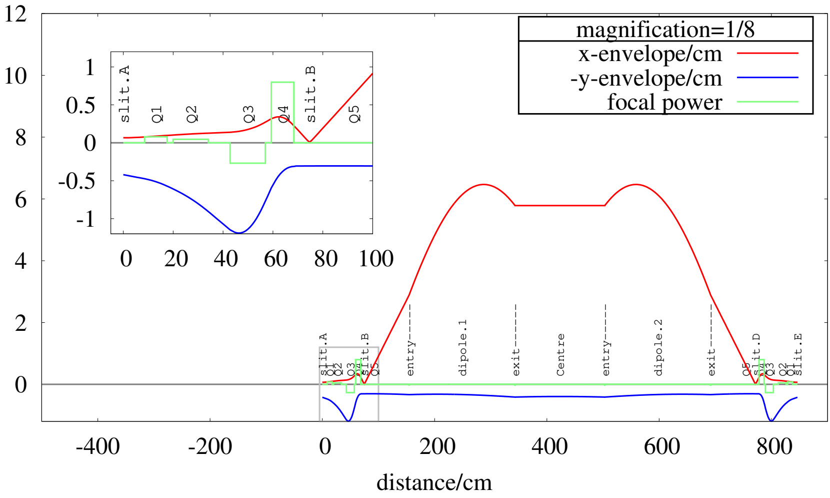
Beam envelopes vs. magnification (zoom)



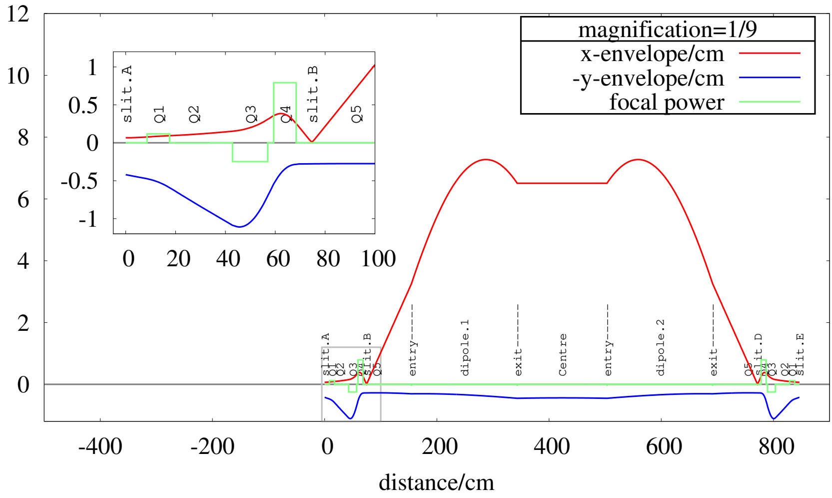
Beam envelopes vs. magnification (zoom)



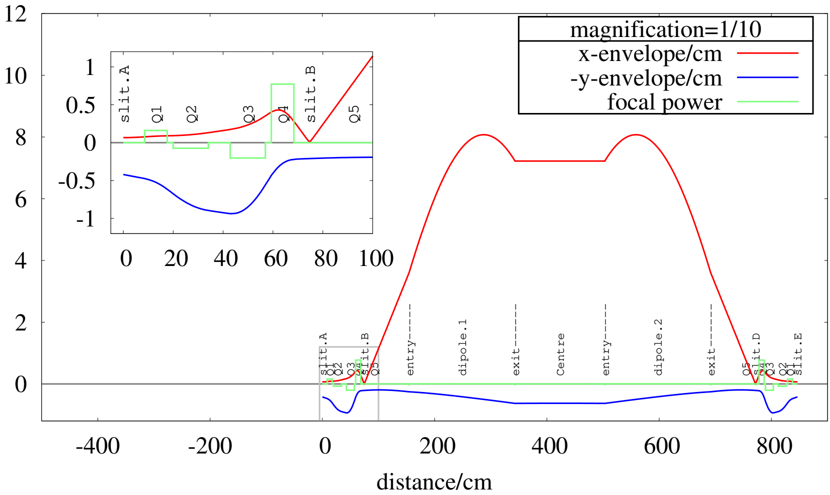
Beam envelopes vs. magnification (zoom)



Beam envelopes vs. magnification (zoom)

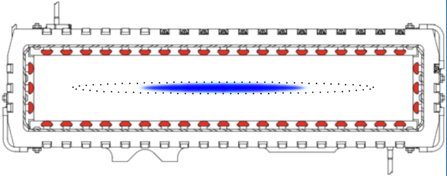


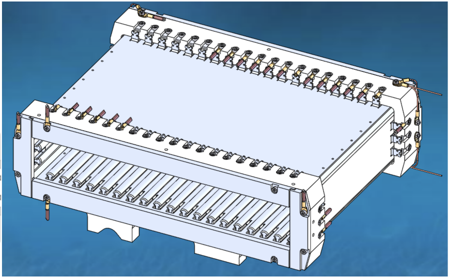
Beam envelopes vs. magnification (zoom)



“Multipole”

HRS multipole corrector, viewed in the direction of the reference trajectory (left), and 3D (right). Inside size is 29 cm W by 5 cm H. Each electrode (Red) is 20 cm in length. Typical beam used so far is coloured Blue. Eventually it will be twice this width (dotted outline).

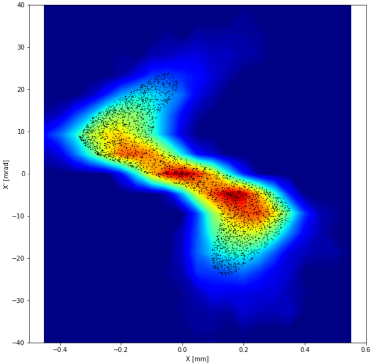


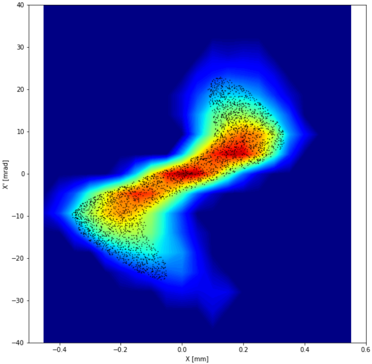


The electrodes are set according to an algorithm that uses the emittance scan at the mass slit (rotated 90° in phase space). No decomposition into multipole components is used or needed. This has been tested with success. [TRIUMF internal note TRI-BN-21-15]

“Multipole” tests

Measured emittance scans at the mass slit using a ^{39}K source. In this test, the central multipole electrode was powered to 5 volts (left) and -5 volts (right). The coloured contours are from emittance scan, the Black dots are a `ZGOUBI` simulation using initial uniform beam.

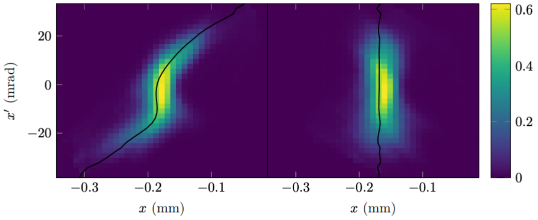




[O. Lailey, M. Marchetto, S. Saminathan, TRIUMF internal note TRI-BN-21-15]

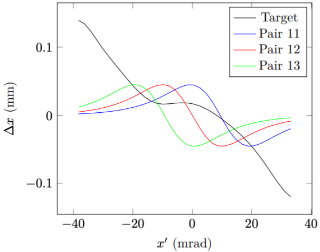
“Multipole” algorithm development

Emittance scan → Locus of centring error (black curve) → Set of electrode voltages



(a) Original (b) Corrected

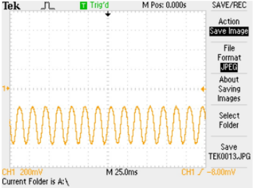
There are 19 electrode pairs; each forms a “basis function”. (Only 3 shown here.)



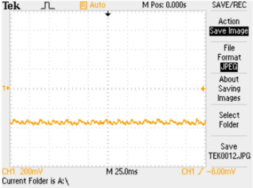
[J. Kraan, S. Saminathan, T. Planche, TRIUMF internal note TRI-BN-22-26]

(an exercise in computer application of linear algebra theory named “Singular Value Decomposition”)

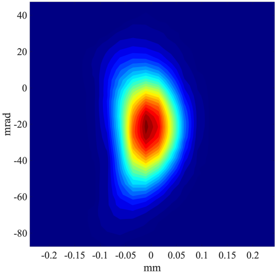
Anomalous emittance growth: found and cured



Modulation signal (function generator)

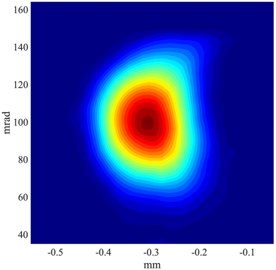


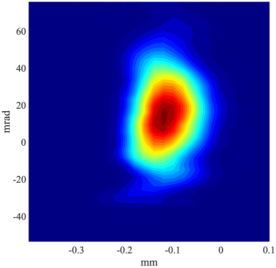
Faraday cup current downstream of HRS dipoles (w/ modulation)



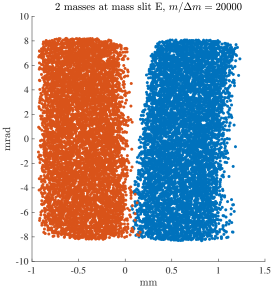
Above is emittance at object slit. On the right-top is resulting image at mass slit. FWHM=0.165mm.On the right-bottom is after correcting an offending 60Hz ripple in extraction power supply. FWHM=0.120mm.

The beam energy, $30\,$keV, times extra beam width of $0.045\,$mm, divided by dispersion of $2.4\,$m implies a peak-to-peak ripple of 0.56 Volt.





N.B.: These show total divergence $2\theta \sim 80\,$mrad, so (eq. 1)
$\mathcal{F} = 2.4\,$m $\times\, 40\,$mrad$/2 = 48000\,\mu$m; about half the HRS's ulitmate capability.



At left is the result at the mass slit: well separated beam at $\mathcal{R} = 20000$. The transmission of the $10\,\pi\mu$m beam is 26%. For reference, the case on the right was calculated for multipole OFF.

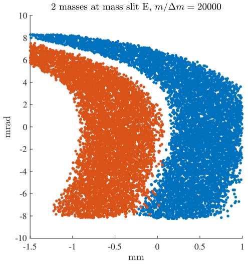


Table: Transmission and resolution at base (100% separation) versus input emittance (uniform ellipse). Slit 'A' is 0.8 mm by 12 mm; slit 'C' is 240 mm by 8.6 mm. Note $\mathcal{F} > 90000\,\mu$m.

Input $\epsilon_x \times \epsilon_y$	Final $\epsilon_x \times \epsilon_y$	Tx	$\mathcal{R}$
$1\,\mu$m $\times$ $1\,\mu$m	$1.0\,\mu$m $\times$ $1.0\,\mu$m	100%	26300
$2\,\mu$m $\times$ $2\,\mu$m	$1.7\,\mu$m $\times$ $2.0\,\mu$m	85%	23800
$3\,\mu$m $\times$ $3\,\mu$m	$2.2\,\mu$m $\times$ $3.1\,\mu$m	72%	23000
$3\,\mu$m $\times$ $6\,\mu$m	$2.3\,\mu$m $\times$ $5.2\,\mu$m	72%	22700
$10\,\mu$m $\times$ $10\,\mu$m	$4.5\,\mu$m $\times$ $6.7\,\mu$m	26%	21600
$20\,\mu$m $\times$ $20\,\mu$m	$4.7\,\mu$m $\times$ $8.8\,\mu$m	8%	21000

Conclusion

Caveat: The simulations show the design to be good, but they do not include misalignment or slit errors.

Status: Functioning of all optics has been successfully demonstrated. There are still diagnostic and controls issues to resolve; see Riley Schick-Martin poster. It has performed very well in part because the stable source has a too-small emittance of $3\,\mu$m; we have not yet explored the limits.

Acknowledgements

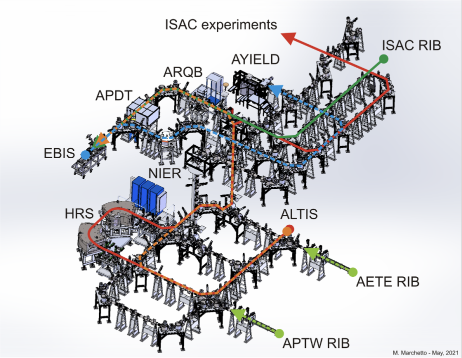
Marco Marchetto for magnet design, Jim Maloney for pure HRS parameters, Thomas Planche for clarifying physics of magnets and for ZGOUBI, Suresh Saminathan for commissioning, the co-op programs and the many students (Owen Lailey, Dan Sehayek, Joshua Kraan, ...) that were made available.

TRIUMF

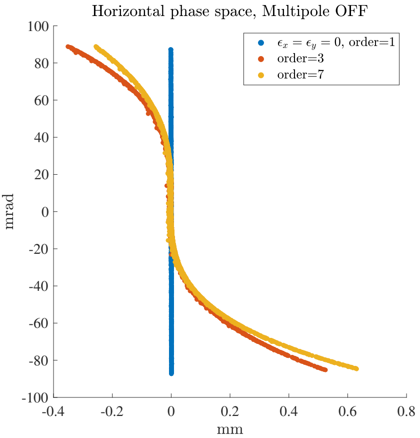
Thank you
Merci

TRIUMF expanded RIB program

- Three RIBs production target stations
  - 2 x 50 kW protons and 1 x 100 kW electrons
- Multi-user operation
  - Up to three simultaneous radioisotope beams
  - Up to 9000 RIB hours
- More efficient post acceleration
  - Charge state breeder + Nier-spectrometer
  - Unique Δm/m 1/20,000 high resolution separation
- Medical Isotopes
  - Production of ^{225}Ac in ARIEL proton target station

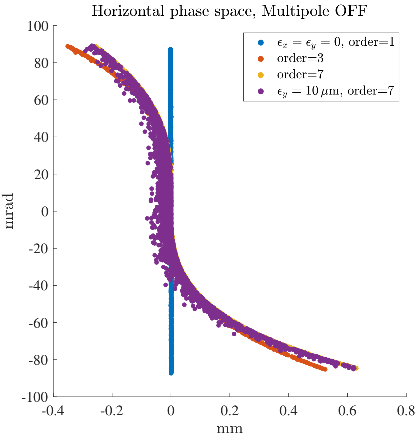


COSY-∞ Simulations



Simulating “pure” separator, i.e. from slit ‘B’ (with zero width to clearly see x-aberration) to slit D, and multipole OFF.

Multipole can accept and correct up to ± 75 mrad ($2\theta = 150$ mrad as in slide -14.)



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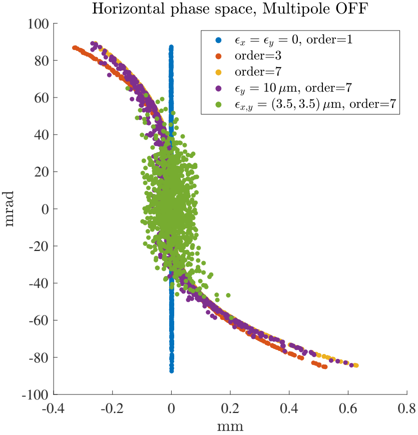
Purple: Smear caused by nonlinear coupling when y beam size in dipoles allowed to reach 16 mm full vertical size.



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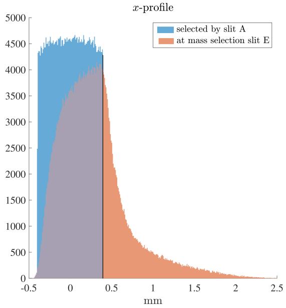
Multipole can accept and correct up to ± 75 mrad ($2\theta = 150$ mrad as in slide -14.)

Green dots are a Gaussian to represent the stable source used up till now. Clearly this is consistent with hardly having to use the multipole up to this point.

COSY-∞ Simulations of Ultimate Performance



Starting with a typical surface source emittance area of $10\,\pi$mm-mrad, but uniformly filled, we apply slits A, not using B. Even though x aberrations are cancelled by the multipole, the performance is poor. This can be traced to nonlinear coupling, namely, the $(x|yy)$, meaning the shift in x due to y^2.

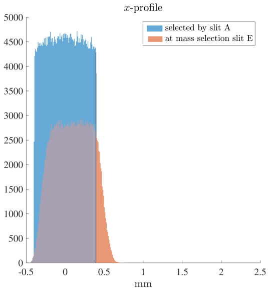
This is from the $P_x y^2$ term in the Hamiltonian for a sector magnet when it's expanded to third order:

$$H(x, P_x, y, P_y) = \frac{1}{2}\left(h^2\, x^2 + P_x^2 + P_y^2 + hx(P_x^2 + P_y^2) + h'\, y^2 P_x\right)$$

Here, $h = h(s) = 1/\rho$ so h' is only non-zero at the dipole edges. From that term, we find $x' = \frac{\partial H}{\partial P_x} = h' y^2/2$. Since y is very close to constant over the short distance of the magnet edge, we easily integrate to find a shift in x:

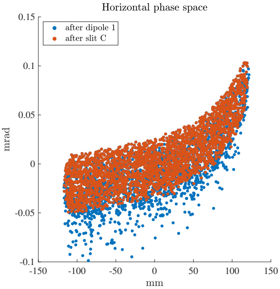
$$\Delta x = \frac{y^2}{2\rho}.$$

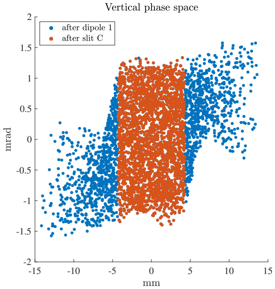
COSY-∞ Simulations with slit C



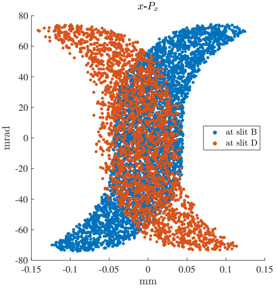
With slit 'C' set to 9 mm full height, the final focus is restored to 1.0 mm FW.

At right we can see the effect of the slit C; it collimates the vertical beam and eliminates the downward smear of the horizontal beam.





COSY-∞ Simulations: Aberrations in the 4-Quad magnifier



At left we can see large third order aberration of the 4-quad match/magnifier. These are cancelled by the multipole and by the fact that the pure separator is an exact $-I$.

In spite of the "S"-shaped distortion, the beam arrives at the mass slit upright, as seen on the right.