MULTIPOLE TUNING ALGORITHM FOR THE CANREB HRS AT TRIUMF

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Abstract

The TRIUMF CANadian Rare isotope facility with Electron Beam ion source (CANREB) High Resolution Separator (HRS) has been designed to separate rare isotopes with mass/charge differences of only one part in 20,000 for beams with transverse emittances of 3 μm. To reach this resolution, high-order aberrations must be corrected using a multipole corrector. From experience, tuning such a multipole is very challenging. The unique geometry of our multipole motivated a novel tuning method based on determining the desired pole voltages directly from measured emittance. This novel tuning algorithm is presented alongside a web application which has been developed in anticipation of the commissioning of the HRS.

INTRODUCTION

The High Resolution Separator (HRS) at TRIUMF consists of a pair of 90° magnetic dipoles [1] and upstream and downstream matching sections. An electrostatic multipole corrector is positioned at the center between the two dipoles. There is a 90° phase advance between the multipole corrector and the mass selection slit. Diagnostics at the mass selection slit will also measure the beam's horizontal emittance. A simplified schematic of the HRS layout is shown in Fig. 1.

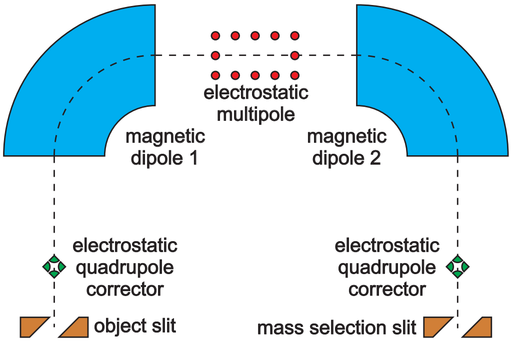

Figure 1: Simplified schematic of the HRS layout [1].

The purpose of the multipole is to correct non-linear aberration in order to achieve a resolving power of 20,000 for beams with transverse emittances of 3 μm. Its design consists of 44 individual electrodes arranged in a rectangular grid configuration as seen in Fig. 2. This novel design [2] mirrors the asymmetric physical beam's shape between the dipole magnets due to the large dispersion.

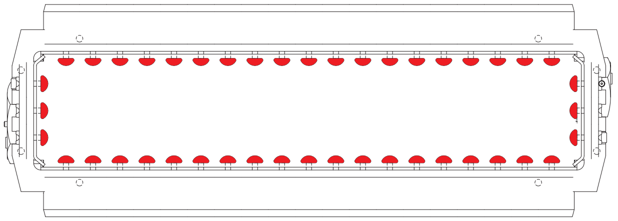

Figure 2: Multipole schematic as viewed with beam axis into the page. The 44 electrodes (in red) will initially be powered in a vertically-symmetric configuration leading to 23 independent knobs, each with a potential range of ±1 kV.

In addition to the advantage of lowering required electrode potentials, this asymmetric design challenges the operational model for determining the multipole's setting. This typically would involve decomposing an estimate for the correction in terms of different strengths for each pole order (dipole, quadrupole, sextupole, etc.). The unique shape of our multipole motivates a new tuning algorithm to determine the setting of each electrode directly from the shape of the emittance profile measured at the mass selection slit.

TUNING ALGORITHM

The maximum resolving power is achieved when the horizontal distribution of particles is upright in phase space at the location of the mass selection slit. The actual phase space distribution will be measured using an emittance scanner. For each x'_n, the measurement will give us the position $x_c(x'_n)$ of the "local" beam centroid:

$$x_c(x'_n) = \frac{\sum\limits_m x_m I(x_m, x'_n)}{\sum\limits_m I(x_m, x'_n)}, \tag{1}$$

where $I(x_m, x'_n)$ represents the measured beam density. An upright distribution would have $x_c = 0$ for all x'_n. A centroid calculation for an example phase-space distribution is shown in Fig. 3.

The problem is to determine the optimum set of voltages to apply to the electrodes of the multipole to straighten up the phase space distribution. Given that electrostatic fields linearly superimpose, the effect of the multipole on the centroids can be written:

$$\boldsymbol{X}_f = \boldsymbol{X}_i + \Delta\boldsymbol{X}\cdot\boldsymbol{\Phi}, \tag{2}$$

where $\boldsymbol{X}_f$ and $\boldsymbol{X}_i$ contain the final (after correction) and initial (before correction) positions of the "local" centroids,

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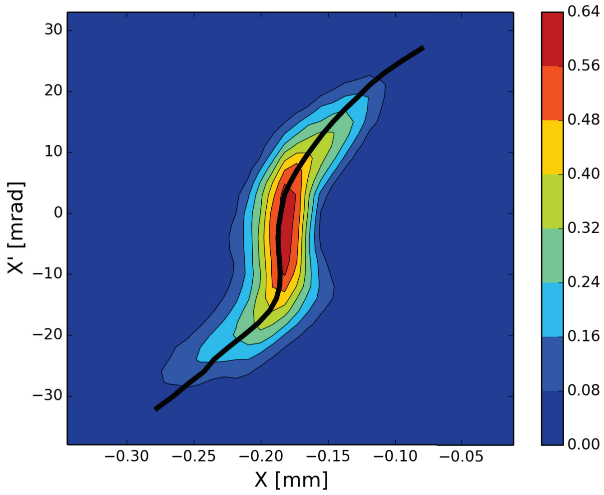


Figure 3: An example phase-space distribution is shown with its corresponding centroid calculation, $x_c(x'_n)$, given by the thick black line.

respectively; $\mathbf{\Phi}$ contains the potential applied to each electrode (or pair of electrodes) of the multipole. The coefficients of the matrix ΔX are obtained numerically using the ray-tracing code Zgoubi [3].

Using Equation 2, we apply the least squares method to minimize the norm of $\mathbf{X}_f$. In case the system is strongly overdetermined, we assign binary weights to each x': a script loops through several possible sets of equations and selects the set of weights resulting in the optimal correction. The method employed for selecting these sets involves varying an increment parameter, δ, and truncation parameter, τ. If w_n denotes these weights, then $w_n = 1$ if $n \in \{\tau + \eta\delta, \eta \in \mathbb{Z}^*\}$ and $\tau \leq n \leq N - (\tau + 1)$ where N is the number of measurement points in x'. A working range for the parameters δ and τ is determined empirically.

Simulation Results

The algorithm was initially tested on several cases in which x is a simple mathematical function of x'. Figure 4 shows the resulting multipole corrections for cases in which x is a quadratic and cubic function of x'.

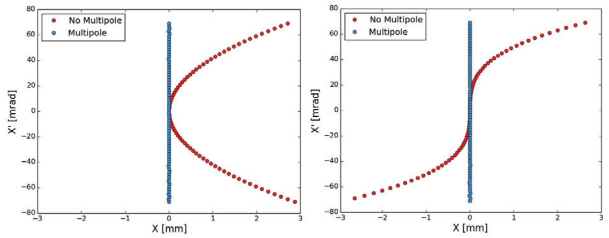


Figure 4: Multipole corrections for quadratic and cubic relations of x with respect to x' using the method of least squares.

The ranges in x were greatly exaggerated in order to evaluate how well the algorithm performs while keeping electrode potentials within limits. As can be seen in Fig. 4, the algorithm is capable of producing nearly perfect corrections for these test cases.

Following the tests on simple mathematical functions, the algorithm was evaluated for its performance on a simulated distribution of particles located at the HRS mass selection slit. As with the previous cases, the algorithm produced a solution which provided efficient correction. Both the original and corrected distributions are shown in Fig. 5.

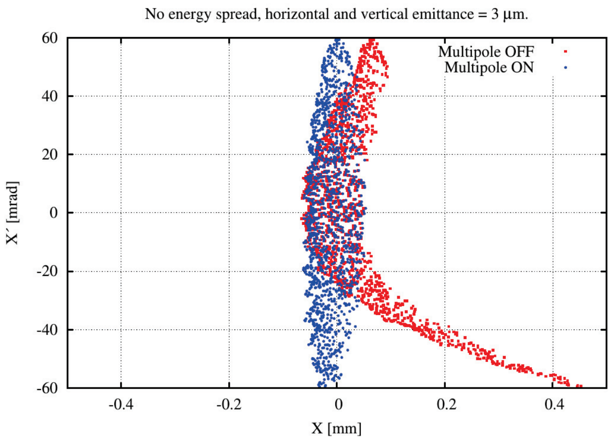


Figure 5: Zgoubi simulation results at the location of the HRS selection slit. An uncorrected (Multipole OFF) particle distribution is shown in red. From this uncorrected distribution the optimal multipole settings are calculated using the algorithm described in this paper, resulting in the corrected (Multipole ON) distribution, shown in blue.

Practical Considerations

Although there is a 90° phase advance in the beam between the multipole and the mass selection slit, alignment error can cause a particle that crosses the multipole through its center to arrive at the mass selection slit with $x' \neq 0$. To identify which angle at the mass selection slit corresponds to the central position at the multipole, we will install a retractable vertical wire at the exit of the multipole. This wire will intercept the beam and create a shadow visible on the emittance measurement. This will allow us to determine the x' offset to apply.

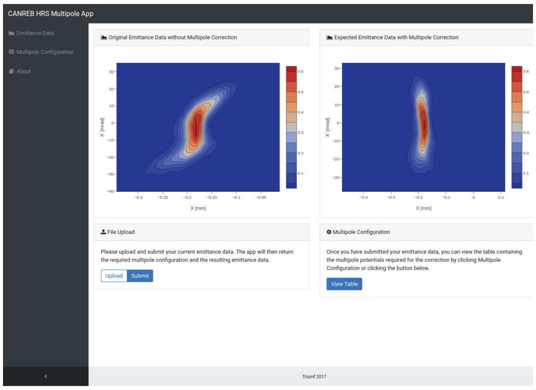
So far we have limited our discussion to horizontal errors; however, there may be vertical errors as well due to misalignment or field aberrations. These vertical errors may be corrected by asymmetrically powering the multipole electrodes and applying the same algorithm in the vertical direction. To this end, we anticipate that this algorithm may not produce the desired results immediately, but may require several iterations in order to converge to the best solution.

Web Application

A prototype web application has been deployed to the high level application server at TRIUMF [4]. This application allows the user to upload emittance measurement data taken at the mass selection slit and obtain the corresponding

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPML079

multipole configuration settings provided by the algorithm. It outputs the expected resulting phase space as shown in Fig. 6a, as well as a heat map of the potential settings as shown in Fig. 6b. The border of the electrode in the heatmap schematic turns red when the electrode has reached its maximum capacity–a key indicator to maximize performance during operation of the multipole.

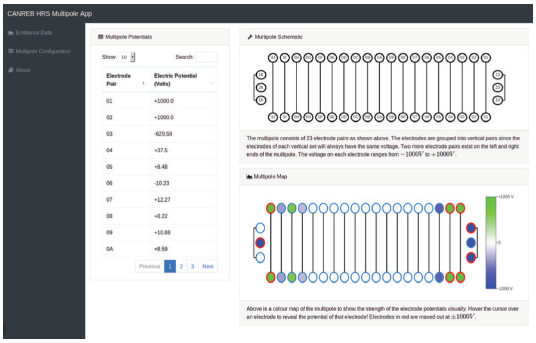


Please upload and submit your current emittance data. The app will then return the required multipole configuration and the resulting emittance data.

Multipole Configuration

Once you have submitted your emittance data, you can view the table containing the multipole potentials required for the correction by clicking Multipole Configuration or clicking the button below.

(a) User-uploaded phase space correction.



Electrode Pair	Electric Potential (Volts)
01	+1000.0
02	+1000.0
03	-629.58
04	+37.5
05	+8.48
06	-10.23
07	+12.27
08	+8.22
09	+10.88
0A	+8.59

The multipole consists of 23 electrode pairs as shown above. The electrodes are grouped into vertical pairs since the electrodes of each vertical set will always have the same voltage. Two more electrode pairs exist on the left and right ends of the multipole. The voltage on each electrode ranges from $-1000V$ to $+1000V$.

Above is a colour map of the multipole to show the strength of the electrode potentials visually. Hover the cursor over an electrode to reveal the potential of that electrode! Electrodes in red are maxed out at $\pm 1000V$.

(b) Heatmap schematic of calculated correction settings.

Figure 6: Screenshots from the multipole web application.

CONCLUSION

In order to systematically eliminate high-order aberrations, a tuning method for the HRS multipole corrector has been extensively studied in anticipation of the upcoming HRS commissioning at TRIUMF. The unique geometry of this multipole motivated the approach for this algorithm which has been designed to determine the desired pole voltages directly from measured emittance.

Overall, the algorithm has proven to be effective at correcting several different types of phase space distributions in simulation while obeying the voltage constraints on each of the electrodes. Thus, we anticipate this tuning method shall provide an effective and reliable procedure, and we plan on testing the results of the multipole settings through commissioning with a control room web application written for automatic tuning of the multipole.

REFERENCES

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