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ALGORITHM TO MITIGATE HYSTERESIS IN MAGNETS WITH UNIPOLAR POWER SUPPLIES*

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Abstract

The effects of hysteresis on the fields produced by magnetic lenses are not accounted for in TRIUMF's models of the accelerators. Under certain conditions, such as quadrupoles with unipolar power supplies operating at low currents, these effects have introduced significant field errors with consequences upon transverse tunes. To combat these uncertainties and make the fields more reproducible and stable, a technique new to TRIUMF has been implemented. This technique ramps the current cyclically about the desired setpoint to reach a reproducible field that is independent of its history. Results of magnetic measurements at TRIUMF using this technique are presented, as well as the expected improvements to the accuracy of the beam optics model, particularly for unipolar quadrupoles.

INTRODUCTION

The beam optics models for quadrupoles in TRIUMF's ISAC (Isotope Separator and Accelerator) facility were calibrated using the initial magnetization curves of the magnets during machine commissioning, circa 2000. However, many of the quadrupoles have been installed with unipolar power supplies due to cost considerations and cannot be degaussed during beam delivery. Without degaussing, the fields of a quadrupole are constrained to be within the hysteresis loop bounded by the lower and upper branches shown in Fig. 1. The lower and upper branches are defined as the curves followed by either increasing from 0 to 60 Amps or decreasing from 60 to 0 Amps respectively.

There is a significant offset from the calibrated B-I relationship and the measured quadrupole fields due to hysteresis, as shown in Fig. 1. We can call this offset the *systematic error*, which will be calculated as the error between the calibration curve and the centre of the hysteresis loop in Fig. 1.

Furthermore, all points within the bounded area are possible depending on the magnet's history and the rate at which the power supply is ramped, both of which are not accounted for during machine tuning. Therefore, this error will be referred to as the *random error* and will be calculated as half the width of the hysteresis loop.

In this proceeding we will discuss a ramping technique that can mitigate these errors, and present the expected improvements to the beam optics models at TRIUMF.

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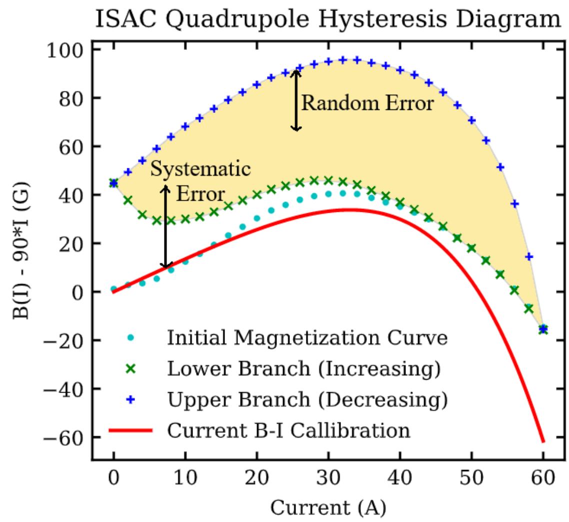

Figure 1: Diagram showing the hysteresis curve of a magnetic quadrupole with the systematic and random errors labeled. Y-axis is the tip-field with the linear portion subtracted.

RAMPING TECHNIQUE

The ramping technique originally described by Decker [1] involves cycling the current about the desired setpoint. TRIUMF's adaptation of this technique is programmed within a python package called Accpy [2] and called with a subroutine developed for this work, dubbed fancy_set. By using this technique, the field of the magnet is brought near the centre of the hysteresis curve regardless of the initial state. fancy_set also allows user control of the ramp rate, the number of periods, and the amplitudes of the cycles.

Figure 2 shows an example of the fancy_set ramping technique applied for a desired current setting of 30 A, starting from the lower branch of the hysteresis curve. As shown in Fig. 2 Top, the ramp rate is held constant throughout the process, and this constant can be maximized for each magnet to optimize the runtime and reproducibility of the technique. The field during this ramp is shown in Fig. 2 Bottom as the green dashed line which starts on the bottom branch and spirals toward the centre.

For each magnet, fancy_set is applied for various current settings within the range of the power supply to construct a full model of the middle branch. This is shown in Fig. 3 for a 52 mm diameter aperture, 325 mm effective length quadrupole in use at TRIUMF. The reproducibility of the technique is shown as error bars at each point, which is obtained by applying it for various initial condi-

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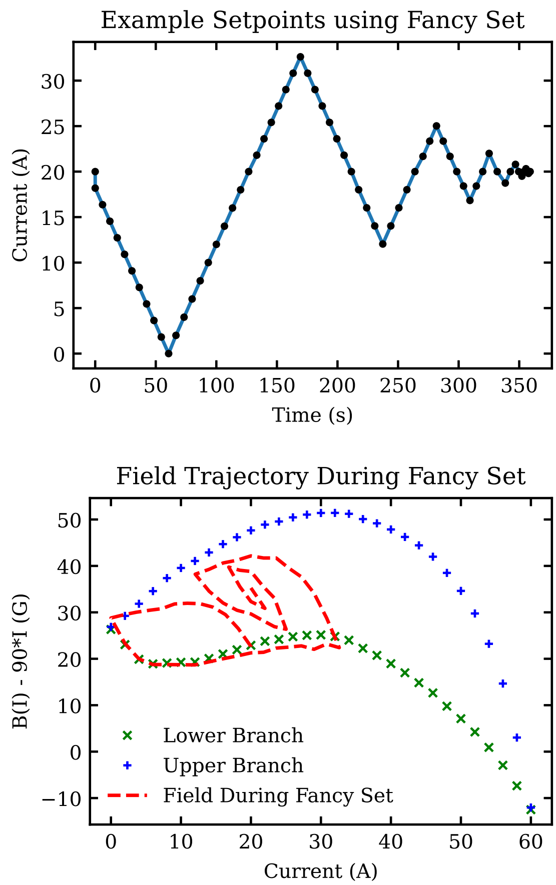

Figure 2: Example of FANCY_SET ramping technique used at 20 A. **Top:** Current setpoints versus time. **Bottom:** Field during FANCY_SET.

tions. For the particular settings chosen for this quadrupole, the FANCY_SET runtime is between 2 minutes and 8 minutes depending on the current chosen. The model shown in Fig. 3 is a 5th order polynomial, which fits the data very well for the current range used. However, due to the nature of polynomials with even orders, the model diverges from the measurements in negative currents. This does not pose an issue for TRIUMF's quadrupoles with unipolar power supplies, but magnets with bipolar power supplies may need to be modelled with more complex functions such as those of the Jiles-Atherton model [3].

RESULTS AND IMPROVEMENTS

With the previous quadrupole B-I characterization, the systematic error and random hysteresis error are plotted in Fig. 4, as well as the reproducibility error of the middle branch using FANCY_SET.

For the majority of the quadrupole settings, the random hysteresis error is over 1%, and for low currents, such as below 10 A, it causes 2-3% error. Furthermore, at these low currents, the systematic error is consistently above 5%, diverging as 0 A is approached.

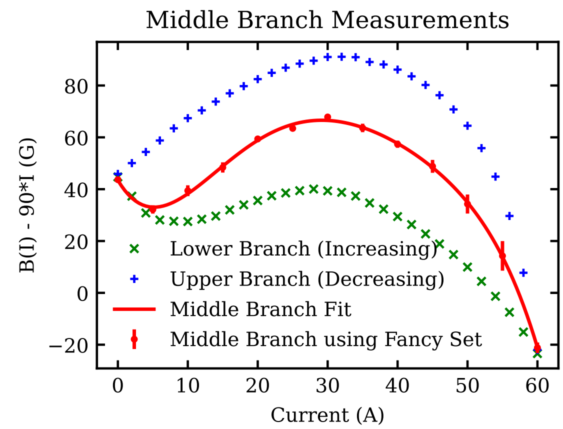

Figure 3: Using FANCY_SET to construct a middle branch, and fitting with a 5th order polynomial.

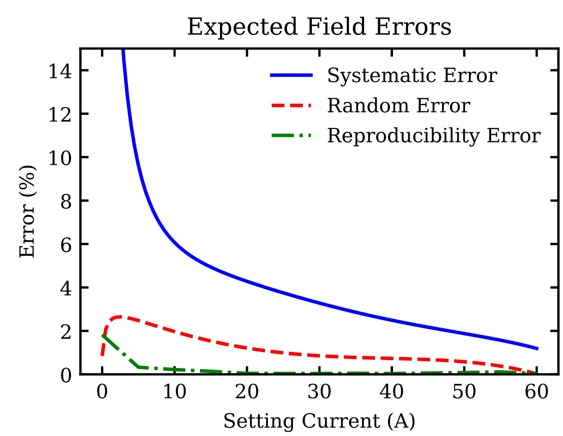

Figure 4: Types of field errors versus current for a 52 mm diameter aperture, 325 mm effective length quadrupole.

For a tune requiring low quadrupole gradients, as is frequently the case for ISAC delivery, we expect the transverse beam optics to possess field errors of at least 2.5%. An example of the consequences of such errors is shown in Fig. 5, showing the spread in 2rms beam containment envelopes computed with TRANSOPTR [4], obtained using a Monte-Carlo technique to simulate hysteresis errors corresponding to those shown in Fig. 4 on the ISAC-MEBT optics. The cumulative mismatch in the tune becomes considerable after 300 cm in the longitudinal position. This showcases the great sensitivity of the tune upon small errors in the quadrupole fields, highlighting the importance of FANCY_SET improving control of the optics at ISAC. Instead, using a 0.5% reproducibility error from the FANCY_SET technique, we see that this effect is successfully mitigated in beam simulations.

FURTHER USE WITH TRIUMF'S 520 MEV CYCLOTRON MAIN MAGNET

While this research was primarily focused on magnetic quadrupoles, the technique can be applied to any type of

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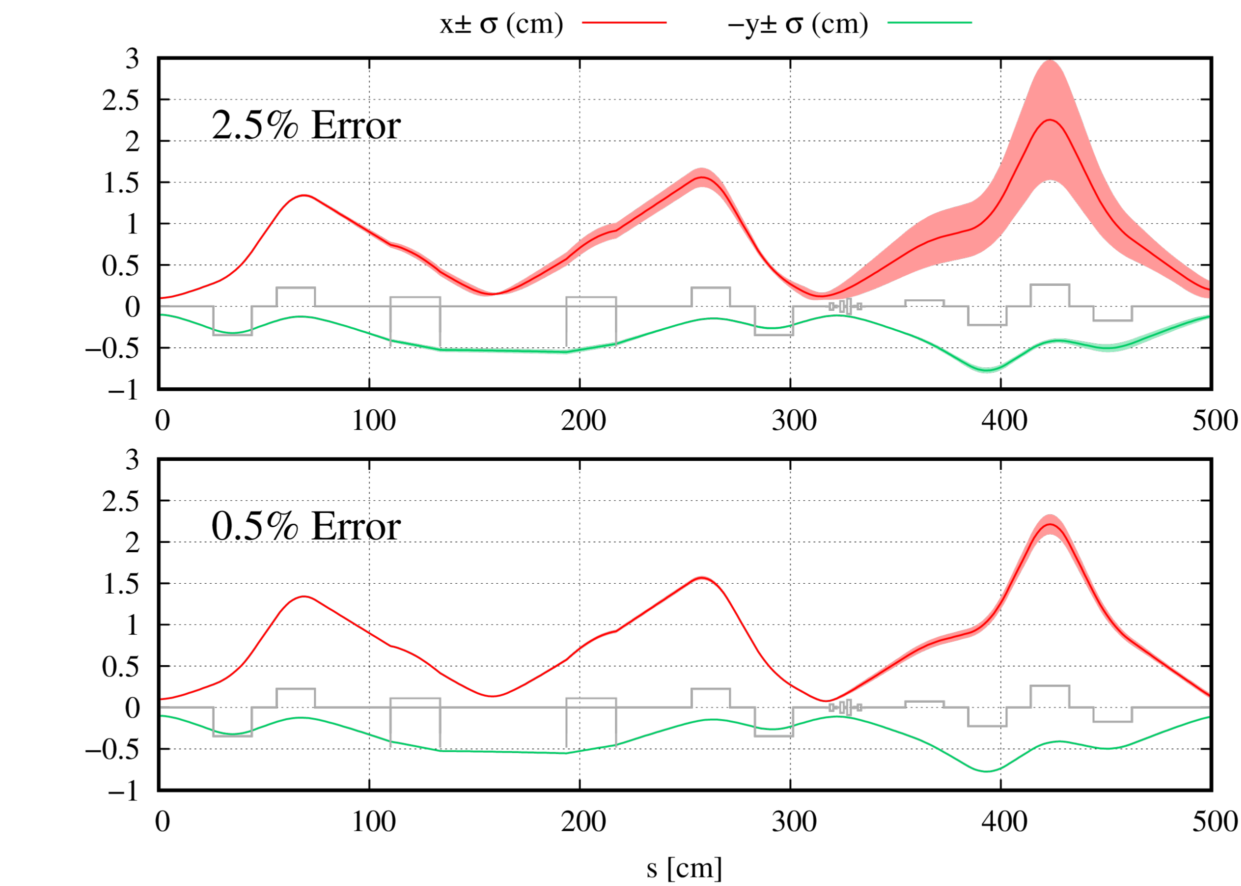

Figure 5: Spread in envelope sizes using the random hysteresis error (**top plot**), and the reproducibility error from FANCY_SET (**bottom plot**).

magnet. The cyclotron's main magnet also uses a unipolar power supply, and the previous ramping method was to set the field to the upper branch of its hysteresis curve. By applying FANCY_SET during the inital ramp of the magnet, as shown in Fig. 6, we effectively set the field to the centre of its hysteresis curve which has been shown to mitigate drifting and increase the field's stability.

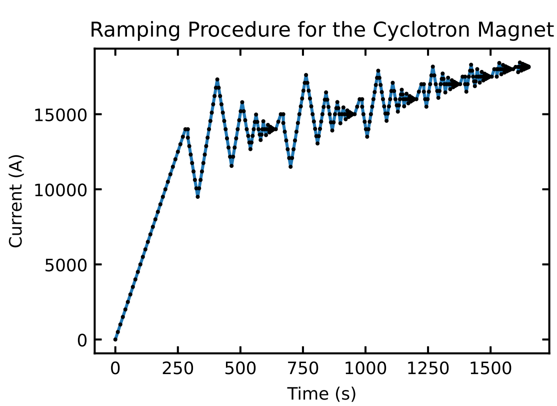

Figure 6: The new ramping procedure for the 520 MeV cyclotron main magnet using FANCY_SET.

CONCLUSION

TRIUMF's new ramping techinque, FANCY_SET, provides a way for magnets with unipolar power supplies to be set in a reproducible manner, regardless of the magnet's history. It is particularly useful for TRIUMF's ISAC facility where the errors in the magnetic quadrupoles accumulate significantly for tunes requiring low quadrupole gradients. By changing the B-I calibrations of these quadrupoles, the predicted tunes will be more accurate and stable, thus reducing tuning time for operators overall. Furthermore, this technique is adaptable for any magnet, with TRIUMF now using it for the ramping of the main cyclotron magnet.

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