**Beam Physics Note**
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# Magnetic Hysteresis and TRIUMF's Fancy Set Function

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**Abstract:** The effects of magnetic hysteresis have introduced significant field errors to some of the magents in ISAC. To combat these uncertainties and make the fields more reproducible and stable, a technique new to TRIUMF has been implemented, called Fancy set. This technique ramps the current cyclically about the desired set-point to reach a reproducible field that is independent of its history. This function resides in the Jaya module of Accpy. Results of magnetic measurements at TRIUMF using this technique are shown, as well as how to use the function.

# Contents

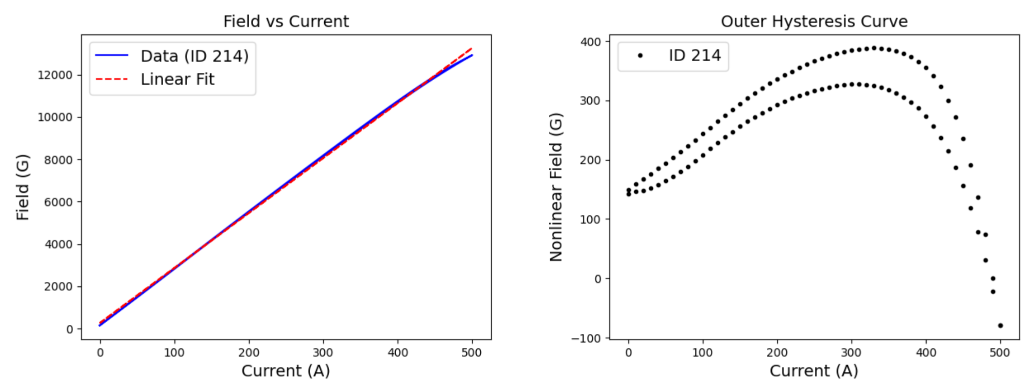
# 1 Introduction

At TRIUMF, particularly in ISAC, there are magnets in which the hysteresis is poorly understood. This makes it difficult to calculate the magnetic field for a given current. Magnets with bipolar power supplies can be demagnetized before each use and brought to a reproducible point, but the magnets we are investigating use unipolar power supplies which makes this impossible. In Decker's *A Physical Way to Standardize Magnets*, a technique is shown where cycling about a given current will bring it to a point independent of hysteresis. A similar technique is adapted for the magnets with unipolar power supplies in ISAC.

# 2 Initial Testing

Most of the testing was done on the dipole HEBT2:MB1 which has a unipolar power supply with a maximum current of 500 A. For the initial data collection, the current was increased from 0 A to 500 A, and back down to 0 A, in steps of 10 A. The field was recorded with a hall probe at each step, presented in Figure 1a. To see the hysteresis effects, the non-linear field, $B^*(I)$, depicted in 1b was calculated by subtracting the slope from 1a as:

$$B^*(I) = B(I) - k^* I \ , \tag{1}$$




(a) Field vs Current (b) Outer Hysteresis Curve

Figure 1: Initial data collection with HEBT2:MB1

The hysteresis curve shows that there are differences in the magnetic field depending on its history. The bottom branch of the hysteresis curve shows the fields that were recorded as the current was increasing from 0 A, and the top branch shows the fields as the current was decreasing from 500 A. We will refer to this hysteresis curve as the outer curve because we use the entire range of the power supply, whereas a smaller range could be used which would result in a different curve.

A technique described by Decker in 1991 shows that cycling the current around the point of interest can bring the field to the centre of the hysteresis curve, regardless of which branch it was originally on. To achieve this for the field at a given current, $I_*$, Decker suggests using the following decreasing sinusoidal function as a model for the current set-points:

$$I(t) = I_* + \Delta I e^{-t/\tau} \cdot \sin(wt) \tag{2}$$

To test this, the degaussing web application found at https://vpn.beta.hla.triumf.ca/degaussing/ generates set-points using the same form. Figure 2 shows the hysteresis as this technique is being applied for the field at 300 A, starting on the top branch, with change in time shown as a colour change from blue to red. As the current is looped around 300 A, the field approaches the centre of the hysteresis curve. This was tested starting on the bottom branch of the hysteresis curve as well, and the field similarly spirals inwards.

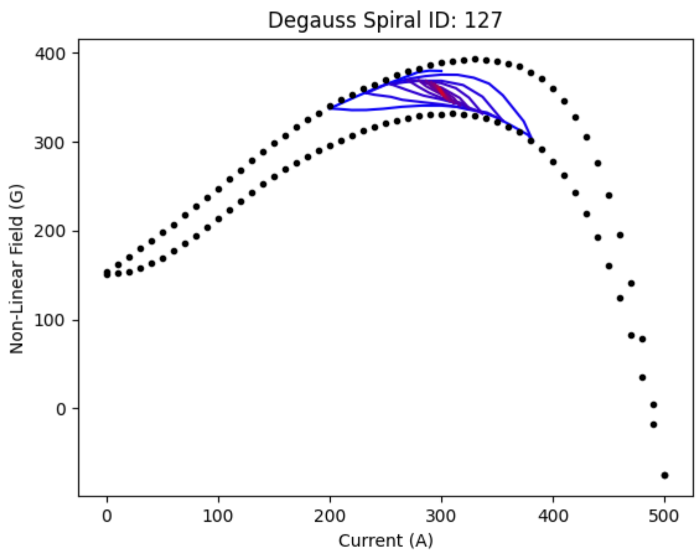



Figure 2: Initial testing of Decker's technique

## 3 TRIUMF's fancy set Function

Shown in Figure 3 is the current set-points generated with the Jaya function *fancy_set* which serves the same purpose as Decker's technique with slight changes. The same process is used where the current is cycled up and down around the set-point. The number of periods can be specified for each magnet, and the magnitudes of these fluctuations are determined by defining the amplitudes of the first and last peaks, and exponentially decreasing between each peak as follows. In the following calculation, the initial amplitude is multiplied by an arbitrary factor, k, for each peak and trough in the process, and finishes at the final amplitude. We can use this to calculate k, and then use k to obtain the amplitude of each peak and trough.

$$A_{initial} \cdot k^{2 \cdot \text{Number of Periods}} = A_{final} \tag{3}$$

$$A_{i+1} = A_i \cdot k \tag{4}$$

Then, instead of a sinusoidal shape, the current is simply increased and decreased to each peak for the number of periods at the same rate for the entire process. The following sections describe each of the decisions that were made when creating the function, and how to use it using accpy.

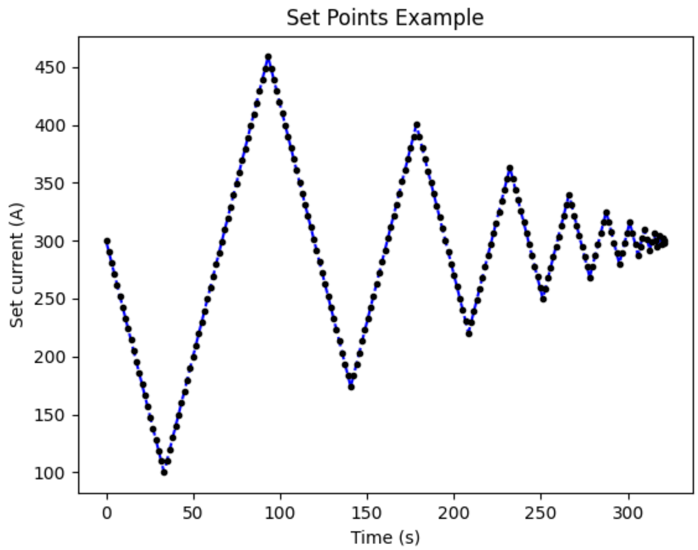



Figure 3: Fancy_set Example

### 3.1 How to use fancy_set

The fancy_set function will be stored in Jaya module of accpy (https://gitlab.triumf.ca/hla/acc-utilities/accpy). The two arguments it takes are a dictionary of PVs and setpoints, and the path which is being set. An example of the PV-setpoint dictionary is shown below, for which the corresponding path would be 'ios-mws-hebt2-dragon'

pv_dict = { 'HEBT2:MB1:CUR' : 300.0, 'HEBT2:Q1:CUR' : 60.0 }

The output of the function will be a list of JSON objects that can be interpreted by Jaya and sent to the power supplies of the magnets simultaneously. When multiple magnets are being set, at each step, the program will wait the *longest* amount of time required at that step for all the magnets to settle. This way the process does not exceed the maximum speed each magnet takes to perform this process. There are default values for all the parameters of fancy_set, such as the number of periods, however, these can be specified in the ACC database as shown on line 107 of the example in Figure 4.

```
104  <notes> Sunrise Engineering and MFG. INC. May 2000 - S/N 4118-2 </notes>
105  <element id="HEBT2:MB1" type="mb" s="2349.5635*mm" l="392.7094*mm">
106    <layout x="22877.541*mm" y="86691.612*mm" z="7907.6309*mm"/>
107    <fancy_set_parameters didt_max="6.0" final_step="1.0" number_periods="8"/>
108    <epics>
109      <setpoint pv="HEBT2:MB1:CUR" type="current" unit="A" min="0.0" max="500.0"/>
110      <setpoint pv="HEBT2:MB1:FLD:SETP" type="Bfield" unit="G" min="0.0" max="12000.0"/>
111      <readback pv="HEBT2:MB1:RDCUR" unit="A"/>
112      <readback pv="HEBT2:HALLMB1:RDFIELD" unit="G"/>
```

Figure 4: ACC Database Fancy_set Parameters

Not all the values need to be specified in the ACC database. For example, number of periods can be specified for a magnet, and the rest of the parameters will be retrieved from the defaults. The defaults are found in the file "defaults.yaml", and the current values are specified below:

| Default Fancy Set Parameters | |
|---|---|
| didt_max | 3.0 |
| final_step | 1.0 |
| number_periods_fine | 10 |
| number_periods_coarse | 5 |
| max_step_frac | 0.02 |

### 3.2 Maximum di/dt

The first thing we sought to improve was the time that it takes to perform the full technique. However, there are limitations to how quickly a magnet will respond to a change in current, caused by physical effects such as Eddy currents, and other limitations such as lag from power supplies. To account for all these limiting effects, we define the parameter didt_max which should be unique to each type of magnet. The ideal value of didt_max will effectively eliminate the hysteresis to the needed precision in the shortest time possible. A value for didt_max can be estimated by doing the following:

1. Change the current on the magnet by a typical step size used by fancy_set, such as 1/50th of the range of the power supply
2. Record the field continuously until it completely settles at this point
3. Inspect how long it takes to reach 95 % of the settled value.
4. $di/dt_{max} \approx \frac{Step\ Size}{Time}\ A/s$
5. Repeat for the whole range of the power supply and average the results

There is a python script in the repository that will automatically do this, given a measurement ID of a measurement that is increasing in step sizes with sufficient measurement times until the field settles, at:
gitlab.triumf.ca/hla/student-projects/magnetic-hysteresis-testing/-/tree/master/2nd%20Term%20-%20Measuring%20Magnets/Python%20Measurement%20Scripts

Now with an estimate for how fast the current can be changed, we can use this value to define the rate for the entire process. This is the largest change made from Decker's technique, as his sinusoidal process does not have a constant rate of change. The fancy_set's constant slope makes the process much quicker, and has been shown to still be effective and precise.

### 3.3 Initial Amplitude

With the technique now working more quickly, each of the characteristics were then tested to optimize the effectiveness of the procedure, starting with the initial amplitude of the first loop. For this test, Fancy Set was applied to HEBT2:MB1 at 300A from both the top and bottom branches of the hysteresis curve. Figure 5 shows the difference between these points, representing field error we can expect after the Fancy Set procedure. This shows that the larger the initial amplitude, the better the agreement between points with different initial hysteresis. This helps increase reproducibility because the large ramp downwards brings any point to the upper branch of the hysteresis curve (if it is on the upper branch already, it will simply follow that branch, and if it is on the lower branch, it will have room

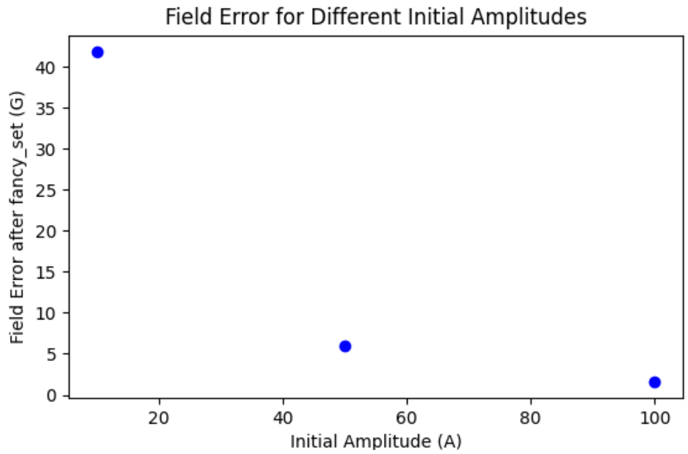



Figure 5: Testing with different amplitudes

to transition to the upper branch). Therefore, it was decided that fancy_set will obtain the minimum and maximum limits on the power supply for each magnet, and use the largest possible initial amplitude for that given set-point.

### 3.4 Final Step

Testing with the final step parameter showed that this parameter must be sufficiently small, which may vary between magnets, so it is left as a customizable parameter. For HEBT2:MB1, the results for different final amplitudes are shown in Figure 6. 10A is shown to be too large because on the final increase in current, the points move to the bottom branch. 1A and 2A both work well since they are both driven to the centre of the loop.

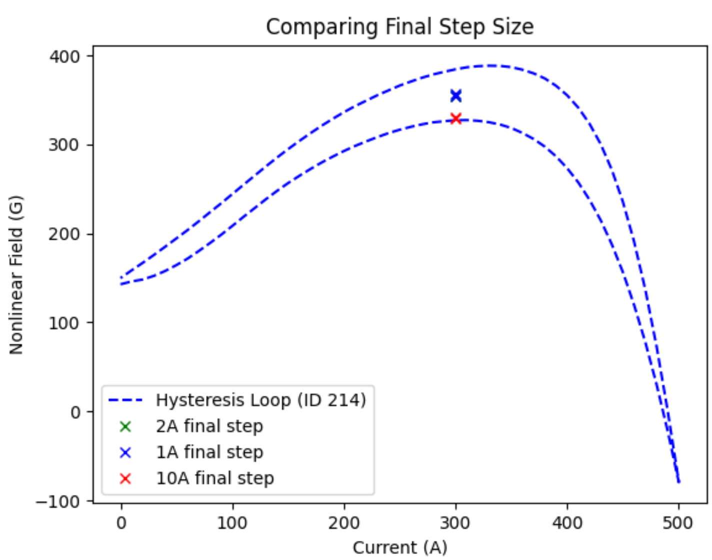
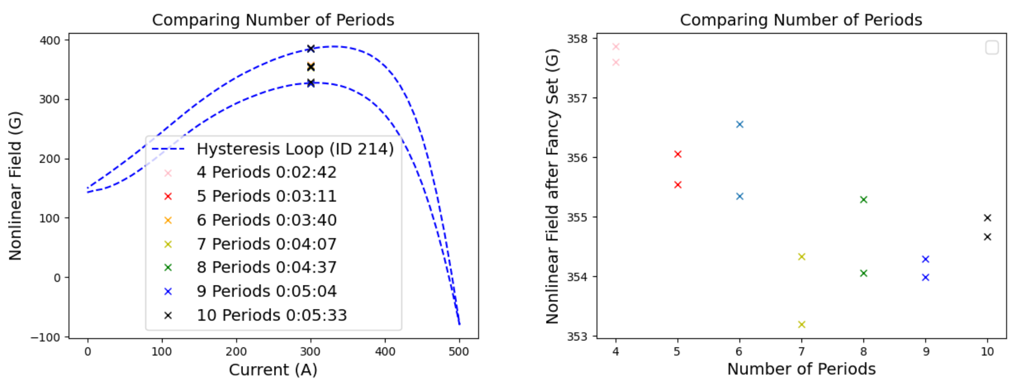



Figure 6: Final Step Testing

### 3.5 Number of Periods

This parameter can also be customized for each magnet, and is important for saving time or increasing precision. Shown in Figure 7 the same test was repeated for 4 to 10 periods, along with the time it takes to perform each test in hr:min:sec. While all the tests are effective, there is a span of results as seen in 7b, and the higher periods are in the centre of the span. Therefore, increasing the number of periods can increase the effectiveness of this process, but at the cost of much longer times. For most magnets, 5 to 6 periods should be sufficient, but for magnets that are being run at low currents where hysteresis can cause significant errors, more periods should be allocated. Furthermore, magnets being run at low currents will have smaller amplitudes, so the fancy_set process should be quicker regardless.

UPDATED IN APRIL 2022: Near the bounds of the power supply, there is less room to cycle, so fancy_set is less effective. Therefore, since hysteresis poses a bigger issue at low currents, fancy_set will inspect if the current being set is in the lowest 1/6th of the range of the power supply (this choice is arbitrary), and will make a choice to use "number_periods_fine" instead of "number_periods_coarse" to increase the effectiveness.



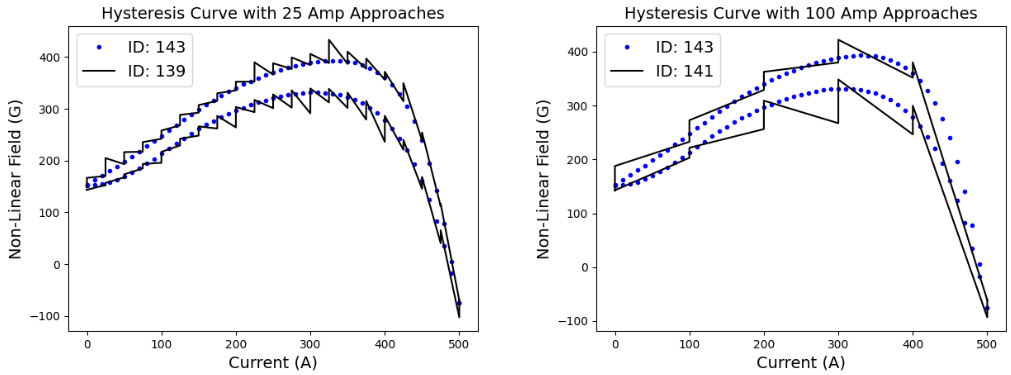

(a) Results shown with outer loop

(b) Points after fancy_set is applied

Figure 7: Testing the number of periods

### 3.6 Maximum Step Size

The number of set-points in each peak is dictated by a maximum current step size, which the default set to 1/50th (0.02) of the range of the power supply. The reason this parameter was added was because of effects that were seen in early testing, where the field would move off of the hysteresis curve if the steps were too large. Shown in Figure 8, at each step, the current field should move onto the hysteresis curve, but for large steps it slightly overshoots. We would like to avoid this because it may be causing the magnetic field to be less uniform, and thus make the results less reproducible.




(a) Steps of 25A (b) Steps of 100A

Figure 8: Maximum Step Size

# 4 References

Decker, F.-J. (1991, May). The Physical Way of Standardizing Magnets. Confrence Record of the 1991 IEEE Particle Accelerator Conference.
https://doi.org/10.1109/pac.1991.164893