Beam Physics Note
TRI-BN-24-27
October, 2024

Magnetic Measurement During the Cyclotron Main Magnet Ramp-up of April 2024

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Abstract: This is a report on the series of measurements that took place in April 2024, during the ramp up of the TRIUMF 500 MeV cyclotron main magnet after shutdown. The purpose of this measurement was to address shortcomings of the previous year's measurements and to try to round-out our understanding of the magnet's behaviour. The purpose of this note is to present a summary of the experimental data that we have collected, and to discuss the results of using the ramping procedure during the previous operating year.

1 Introduction

The outcome of the previous year's measurements, recorded in Ref. [1], was the development of the fancyset procedure, Ref. [2], which was put into operation as the primary method for turning on the main magnet power supply. Furthermore, a 2D simulation of the main magnet was produced.

Some questions were left unanswered after the previous year's measurements. Specifically, we wanted to find a way to accurately measure the time delay between the different radii. Additionally, informed by the 2D simulation, we wanted to measure the magnetic field on the top of the magnet yoke. Finally, we also wanted to round out the ramping data collected previously.

This note will summarize the data collected and analysed and report on the operational results over the past year.

2 Experimental setup

Similarly to the previous measurements, three Hall probes are temporarily installed on top on the cyclotron vacuum chamber as shown in Fig. 1. For more information about the configuration Ref. [3] is a good place to start. The "X" and "Y" probes are inserted into the small space between the magnet pole and the vacuum chamber under the leading edge of the cyclotron magnet. The probes are positioned along the leading edge at a specific radius from the cyclotron centre: the "X" probes was placed at 3.4 m radius and the "Y" probe at 7.3 m. The previous year had placed the "Z" probe along a vacuum chamber tie rod, which did not yield useful data. This time to try to compare to the simulations done previously, the "Z" probe was positioned on top of the magnet yoke, close to the leading edge at a 4.5 m radius.

The probes are once again connected to the same LakeShore 460 Gauss meter. The Gauss meter is read through a serial port connection to a Raspberry Pi. The setup is pictured here Fig. 2. Originally, the plan was to connect the Pi to the network using a long Ethernet cable, as was done last year. However, this time the port we had used previously was occupied by a wireless access points, so instead we used Wi-Fi, which surprisingly worked without issue.

The Raspberry Pi was configured with a new data collection system. The reworked code is available here: gitlab.triumf.ca/pjung/hall_monitor. Is is configured to automatically connect to the probe, configure the proper settings and then collects the probe data about 4 times per second, as soon as the Pi is connected to power. The controls system values for the main magnet power supply are simultaneously read by the program. All of the data are saved into a TinyFlux CSV file on the Pi's storage. The program automatically backs up the collected data every 5 min to the Beam Physics shared folder where it is still available here:

trcomp.triumf.ca:/data/beamphys/pjung/mm_measurement_2024/data

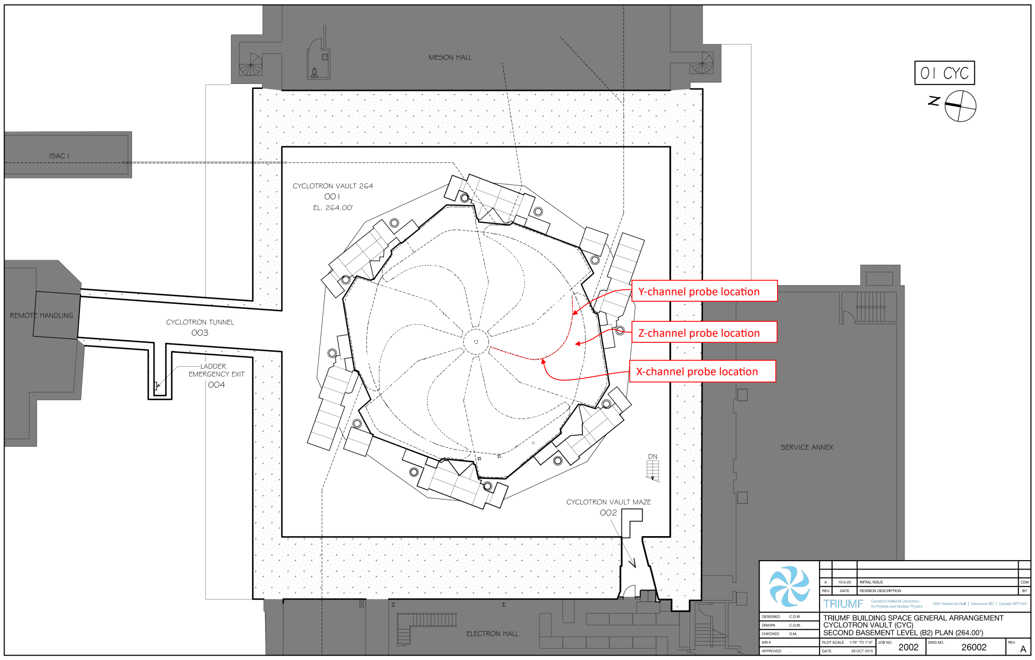

Figure 1: A sketch of the rough location of the 3 Hall probes installed on the top of the cyclotron, two on top of the vacuum chamber below the pole, and the third on top of the yoke.

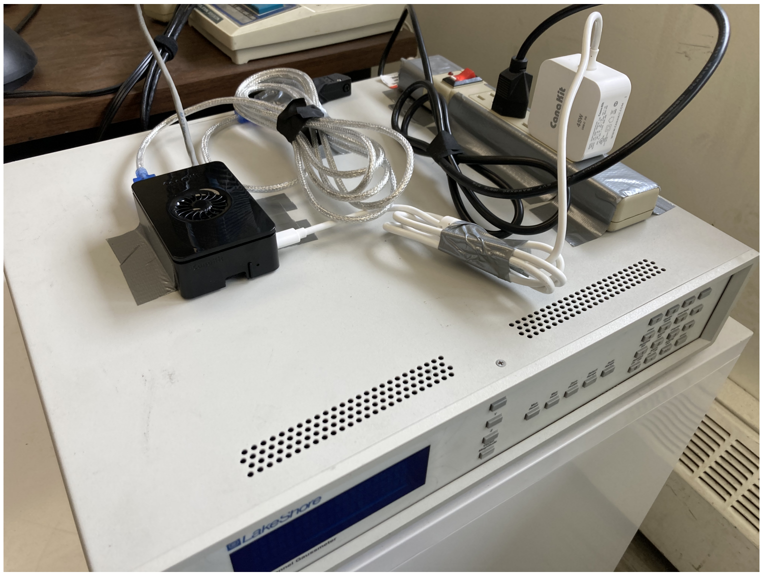

Figure 2: The Raspberry Pi and power bar duct-taped to the top of the Gaussmeter.

3 Ramp Rates

To try to understand the effects of the ramp rate on the field uniformity, many different ramps were performed. For each of the following ramps, the current was driven from 2.0 kA up to 15.0 kA, they are shown in Figs. 3 and 4. The shortest ramp exhibited extremely noticeable field overshoot, especially in the Z-probe on top of the magnet yoke. The other interesting feature to note, is that the curvature of the Z-probe dramatically changes with the ramp-speed: for slower ramps it is below the linear-current ramp and for the fast ramp it is consistent with the other probes.

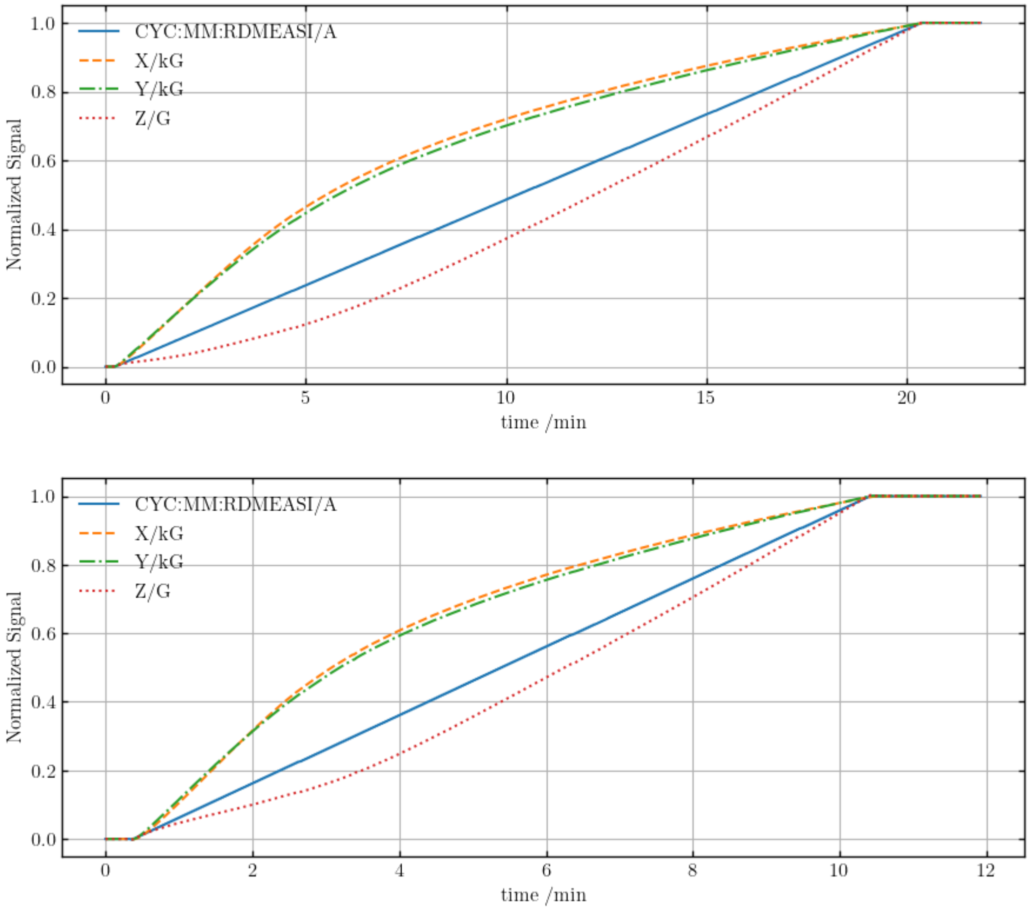

Figure 3: The ramp with a 20 min duration is shown on the upper plot and 15 min on the lower plot. The signals are normalized by the beginning and final values over the window to highlight the difference in curvature.

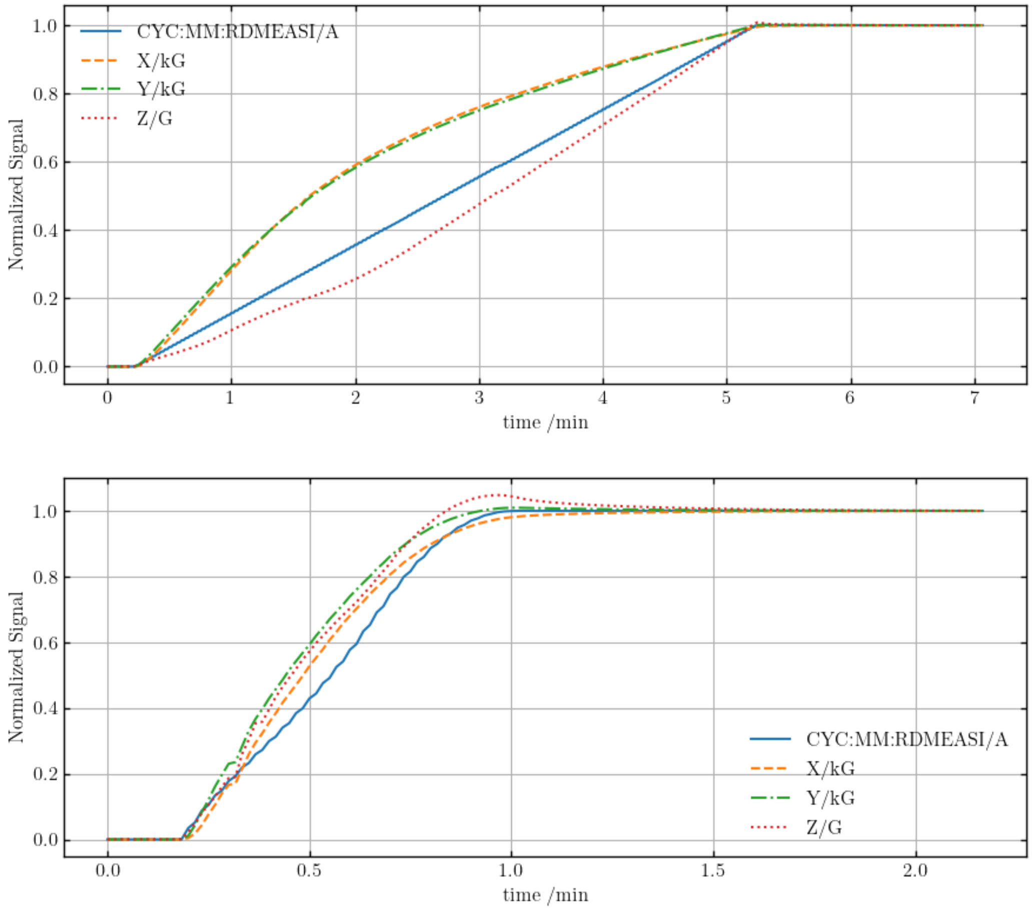

Figure 4: The ramp over 5 min is shown on the upper plot, and the ramp from just setting the current setpoint to 15.0 kA which is then driven at the maximum 80V, takes about 1.25 min shown on the lower plot. The signals are normalized by the beginning and final values over the window to highlight the difference in curvature.

4 Time Constant

To measure the response time of the magnet to current inputs, the current was modulated sinusoidally to try to detect a phase offset. The data is shown in Figs. 5 and 6, and the signals are fit to sine functions, the fit data and the calculated phase differences between the signals are tabulated in the following subsection. The fitted curves agree very well and reliably reproduce the time period of of the driven oscillations.

4.1 Fit Curve Parameters

wiggle 2	Signal	Unit	Amplitude	Period/s	Phase/rad	Mean
	I	A	250.167	120.651	6.17295	2124.2
	X	kG	0.137847	120.596	5.80179	1.57474
	Y	kG	0.157127	120.611	5.97121	1.56801
	Z	G	2.15767	120.632	0.403306	3.41068
wiggle 3	Signal	Unit	Amplitude	Period/s	Phase/rad	Mean
	I	A	49.9098	60.1972	3.13412	2025.07
	X	kG	0.0204836	60.1419	2.57849	1.51174
	Y	kG	0.0262346	60.166	2.84044	1.49117
	Z	G	0.68666	60.2375	3.42366	3.14248
wiggle 4	Signal	Unit	Amplitude	Period/s	Phase/rad	Mean
	I	A	99.922	60.2632	0.615993	14999.9
	X	kG	0.0102556	60.245	0.416297	5.35383
	Y	kG	0.0152893	60.1898	0.495739	5.59663
	Z	G	1.43103	60.2368	0.659218	134.254
wiggle 5	Signal	Unit	Amplitude	Period/s	Phase/rad	Mean
	I	A	49.302	30.1371	0.172455	14999.8
	X	kG	0.00474956	30.0862	6.10479	5.35968
	Y	kG	0.00738566	30.0899	6.26803	5.57421
	Z	G	0.753603	30.0857	0.22555	133.152

4.2 Fit Curve Phase Offsets

	Signal Diff.	Δ Phase/deg	Δ Phase/s
wiggle 2	(I-X)	21.266	7.12548
	(I-Y)	11.5591	3.8733
	(I-Z)	29.4237	9.86033
	(X-Y)	9.70682	3.25187
	(X-Z)	50.6896	16.983
	(Y-Z)	40.9828	13.7317
	Signal Diff.	Δ Phase/deg	Δ Phase/s
wiggle 3	(I-X)	31.8357	5.32094
	(I-Y)	16.8271	2.813
	(I-Z)	16.5889	2.77484
	(X-Y)	15.0086	2.50785
	(X-Z)	48.4246	8.09628
	(Y-Z)	33.416	5.58806
	Signal Diff.	Δ Phase/deg	Δ Phase/s
wiggle 4	(I-X)	11.4418	1.91504
	(I-Y)	6.89008	1.15268
	(I-Z)	2.47658	0.414484
	(X-Y)	4.55168	0.761362
	(X-Z)	13.9183	2.32904
	(Y-Z)	9.36666	1.56666
	Signal Diff.	Δ Phase/deg	Δ Phase/s
wiggle 5	(I-X)	20.1025	1.68144
	(I-Y)	10.7495	0.899184
	(I-Z)	3.04214	0.254453
	(X-Y)	9.35299	0.781703
	(X-Z)	23.1447	1.93425
	(Y-Z)	13.7917	1.15267

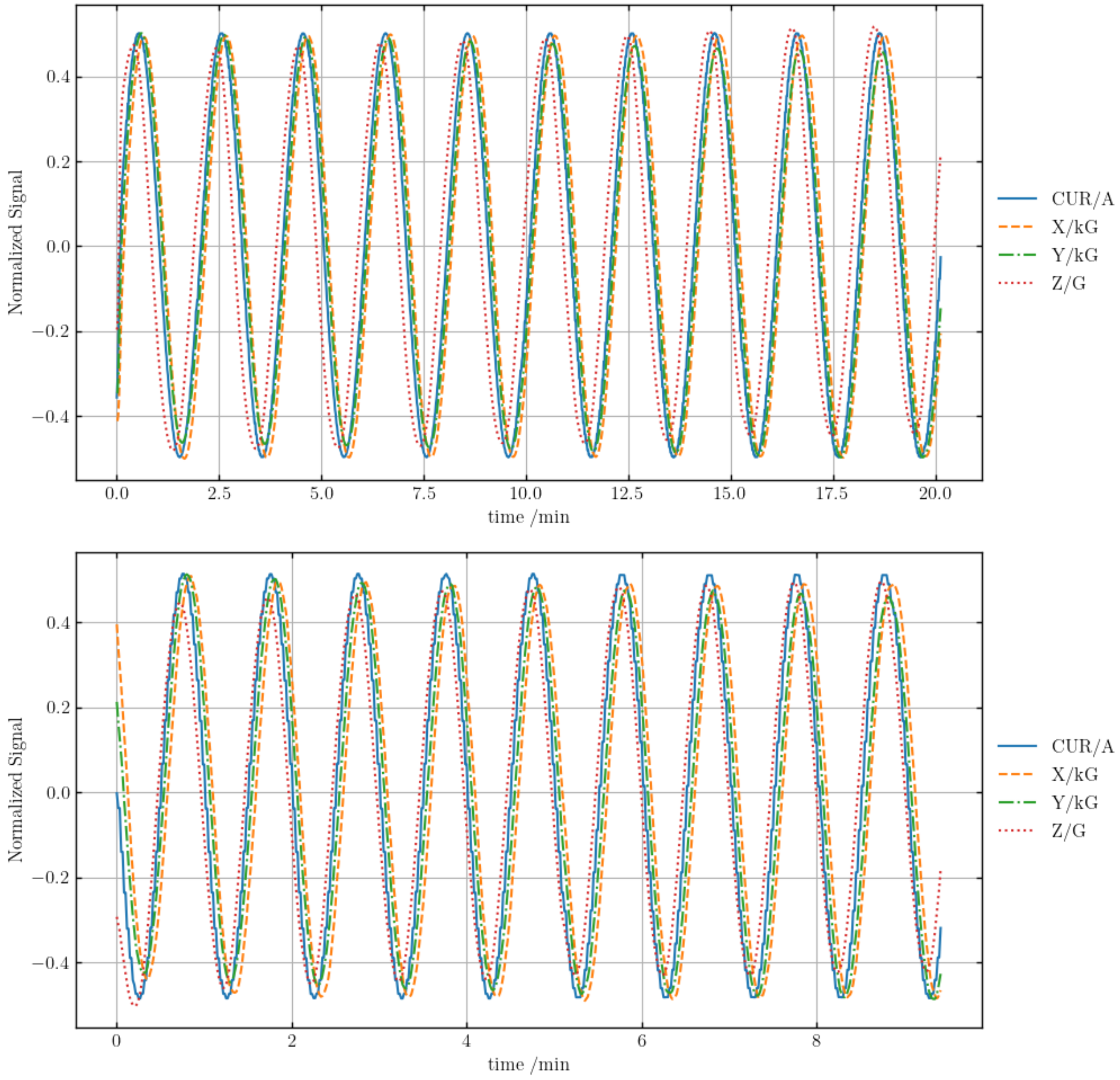

Figure 5: The first two current oscillations measured, the normalized signals are plotted for each probe and the power supply current readback. The current was driven about a mean current of around 2100 A. The top plot used an oscillation period of 2 min and an amplitude of 250 A, whereas the bottom used a 1 min. period and an amplitude of 50 A.

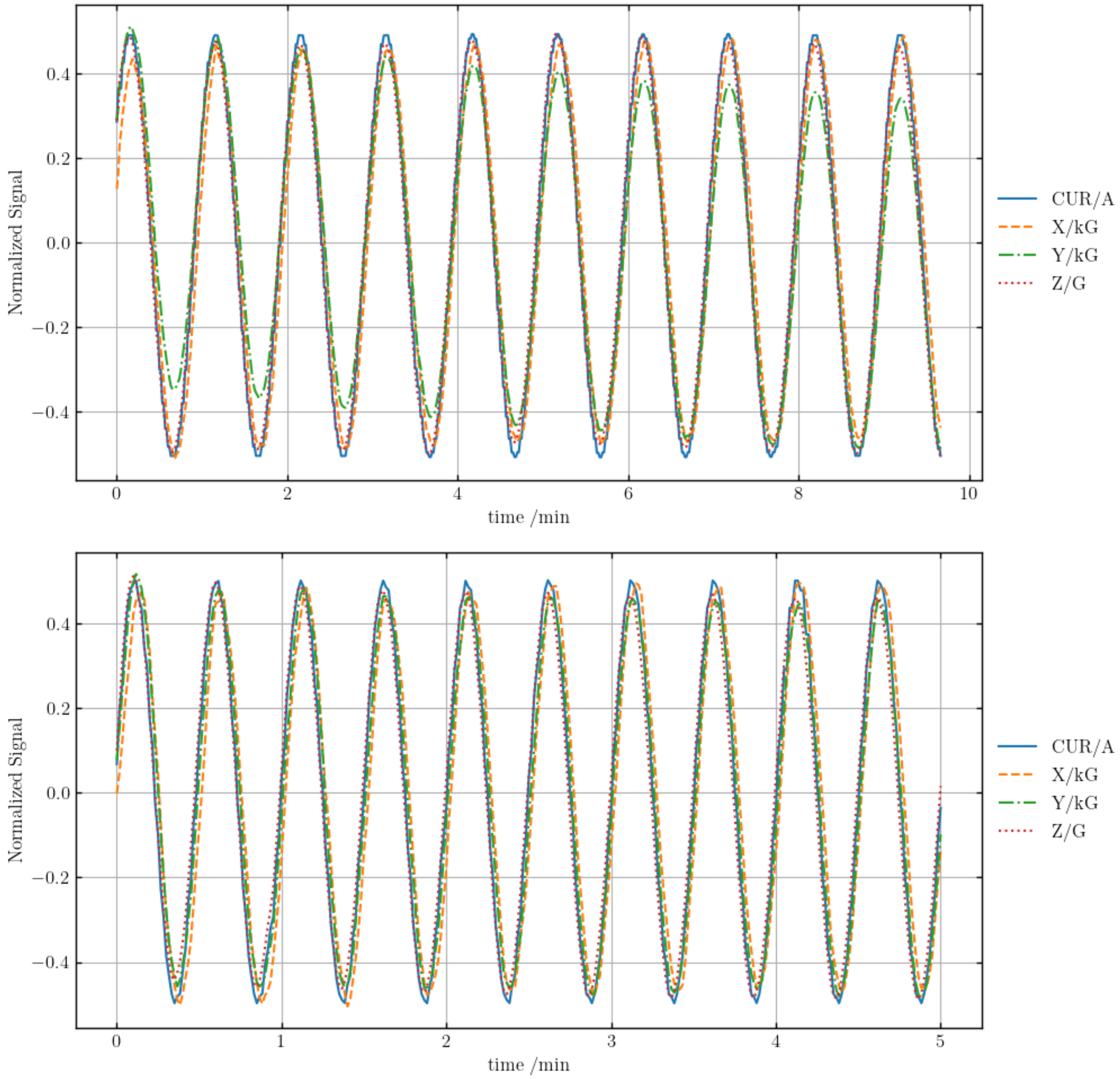

Figure 6: The second two current oscillations measured, the normalized signals are plotted for each probe and the power supply current readback. The current was driven about a mean current of around 15,000 A. The top plot used an oscillation period of 1 min and an amplitude of 100 A, whereas the bottom used a 0.5 min. period and an amplitude of 50 A.

5 Operational Results

The previous year's testing of the fancyset procedure showed that it resulted in a much more resilient magnetization state both over time and also when exposed to large perturbations.

The past year's operational results exceed expectations. The cyclotron tune was often able to be recovered almost entirely just using the fancyset procedure to start it back up after an unexpected trip. This was a very welcome change for operators compared to the previous years' experience: an unexpected trip would require a complete re-tuning of the trim coils and could take many hours to recover.

To show this result objectively, let's look at the main tuning knobs that operators use to adjust the magnetic field after recovery which are the trim coils 15BZ and 35BZ. The operating values of these coils are plotted over the last few years in Fig. 7 and Fig. 8 respectively. To illustrate the point more clearly, the pre-fancyset year 2022 is compared to 2023 the year using fancyset in Fig. 9. These plots clearly show that the magnitude of required manual tuning was significantly reduced.

Figure 7: Trim Coil 15 BZ plotted since August 2021 to the over the last few years. Note the relatively stable plateau for the year 2023, the year that fancyset was used.

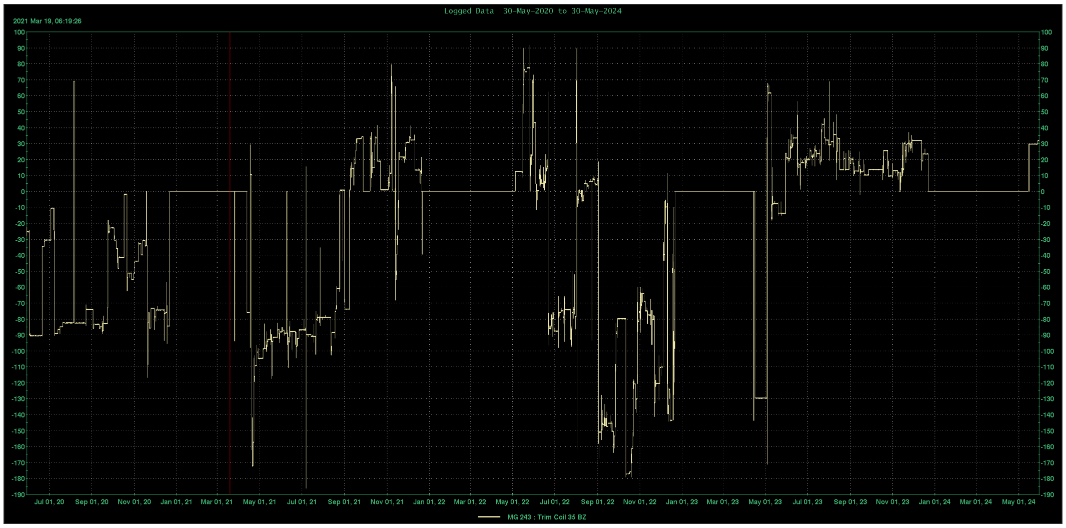

Figure 8: Trim Coil 35 BZ plotted since August 2021 to the over the last few years. Note the relatively stable plateau for the year 2023, the year that fancyset was used.

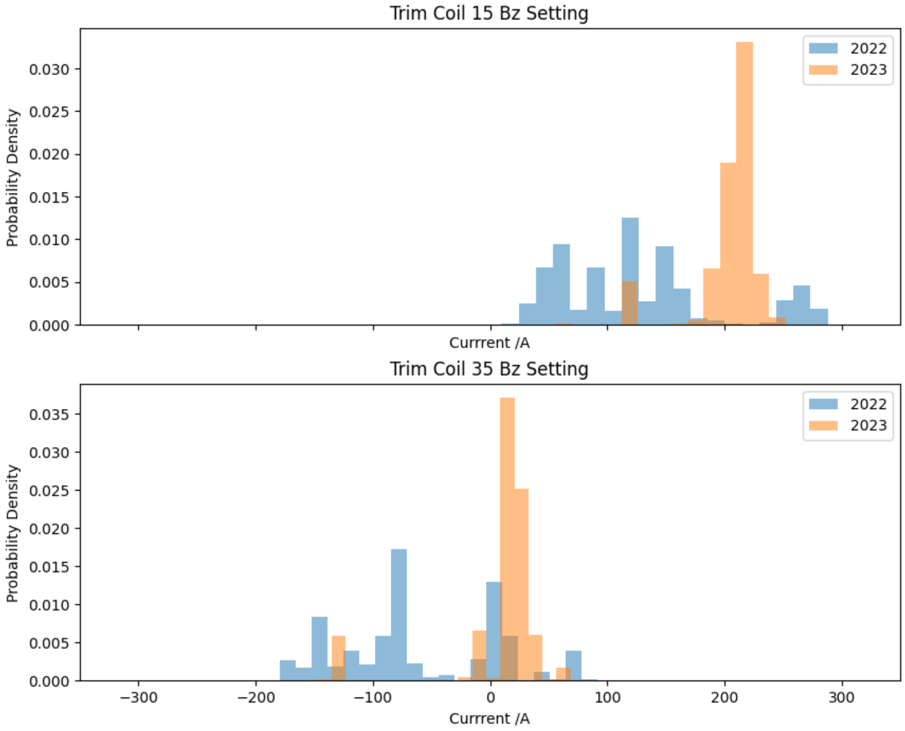

Figure 9: The trim coil settings over the operating years of 2022 (before fancyset) and 2023 (using fancyset) are binned and shown above. The year using fancyset exhibits much more consistent setting of the currents.

6 Conclusions

The new magnet ramping procedure was shown to be an operational success. The collected data was sufficient to motivate the choices for the fancyset parameters. The data collected this year helped to complete an empirical picture of the main magnet's time dependence.

If a more accurate measurement of the time constants is needed in the future, more probes would need to be installed at different radii and azimuth along the pole surface. This would require a different magnetic measurement device, with longer leads.

References

[1] T. Planche, P. Jung, H. Koay, L. Zhang, R. Baartman, Magnetic measurement during the cyclotron main magnet ramp-up of april 2023, Tech. rep., TRI-BN-23-12, TRIUMF (2023).

[2] J. Nasser, R. Baartman, O. Kester, S. Kiy, T. Planche, S. Rädel, O. Shelbaya, Algorithm to Mitigate Magnetic Hysteresis in Magnets with Unipolar Power Supplies, in: Proc. IPAC'22, no. 13 in International Particle Accelerator Conference, JACoW Publishing, Geneva, Switzerland, 2022, pp. 156–159. `doi:10.18429/JACoW-IPAC2022-MOPOST039`. URL `https://jacow.org/ipac2022/papers/mopost039.pdf`

[3] J. Burgerjon, O. Fredriksson, A. Otter, W. Grundman, B. Stonehill, Construction details of the TRIUMF H^- cyclotron, IEEE Transactions on Nuclear Science 20 (3) (1973) 243–247.