MEASURING ELECTROMAGNET POLARITY USING MAGNETIC REMANENCE*

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Abstract

Large accelerator systems typically include many individually powered electromagnets. An important activity prior to commissioning with beam is verifying that the polarity of the installed magnets matches the design lattice. In the present work, we motivate the measurement of magnet polarity in a manner that is electrically safe, by measuring the magnetic remanence of iron yokes of normal conducting electromagnets. This has been used to confirm the polarities of iron-dominated dipole and quadrupole electromagnets at the Linac Extension Area at the Advanced Photon Source.

INTRODUCTION

During installation and commissioning of accelerator systems, a common quality assurance task associated with the installation is ensuring that magnets are connected to power supplies with the correct polarity [1–4]. Magnetic polarity checkout has typically been performed in under administrative controls with magnets energised [5]. We consider that procedures which require workers to approach energised magnets potentially presents an unacceptable electrical safety hazard.

In the present work, we summarise a technique for performing magnet polarity checks using the remnant magnetic field from prior excitation using the connected power supply. Measuring the remnant field with the power supply off obviates the principal safety concern of needing to work adjacent to energised electrical conductors.

BACKGROUND

In many accelerators, the main magnets are powered by unipolar power supplies. Hence, a quality assurance task associated with the installation of a magnet and power supply system is to confirm that the installed magnet polarities match the design polarities of the lattice [6–9]. When powered, electromagnets have the opportunity to present both electrical and magnetic hazards to personnel approaching them [10]. There are different ways of mitigating these hazards, for instance by implementing electrically insulating shielding or shielding that restricts personnel from approaching the magnetic field that the magnet generates. Another way is to switch off the magnet power supply, and Lock-Out-Tag-Out (LOTO) the source of hazardous energy.

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METHOD

We tested this procedure using the bending magnets of the booster bypass vertical ramp and the Linac Extension Area (LEA). The steps in the procedure are outlined below.

1. Accelerator enclosure secured.
2. Accelerator magnets energised at its nominal current setpoint for 10 minutes using its connected power supply. This puts the magnet on its hysteresis curve.
3. Accelerator magnets de-energised, leaving only the remnant field in the magnet.
4. Lock-Out-Tag-Out (LOTO) accelerator magnets, and verify zero energy state by Zero Voltage Verification (ZVV). At this point, all LOTO requirements should be complete to enable authorised access to the accelerator enclosure.
5. Lower the accelerator access control system level to authorised access.
6. Enter the accelerator enclosure and approach the unpowered electromagnet.
7. Measure the polarity of the remnant field (without any electrical hazard) using a permanent magnet probe.

RESULTS

Initial Measurement

On the 22nd of August, 2022, Kent Wootton performed magnet polarity checks on booster bypass and LEA magnets. A magnet polarity checker Magnaprobe MKII was used. The north pole of the bar magnet on the magnet probe is coloured red, and the south pole of the magnet is coloured blue. The polarity checker is illustrated in Fig. 1.

The polarity of quadrupoles and vertical bending magnets (skew dipoles) along the booster bypass transport line was measured. We measured the ‘top-left’ most pole of quadrupoles, and the ‘left’ pole of skew dipoles. This pole convention is illustrated in Fig. 2.

The probe was held near the poles of the magnets. Photographs illustrating polarity measurements are given in Fig. 3 and Fig. 4. One can see that the experimenter’s hand is quite close to the magnet while performing the measurement.

Results of polarity measurements are summarised in Table 1. Magnet polarity measured from remnant field on the 22nd of August, 2022. Magnet types Q_1 correspond to upright quadrupole, and B_2 to skew dipole (vertically deflecting). We deliberately included a couple of quadrupoles from

Figure 1: Polarity checker.

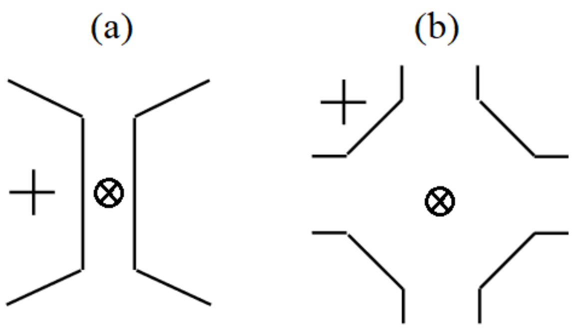

Figure 2: Pole used for measurements, and convention used to express measurement results. (a) Skew dipole, beam direction into the page. The colour of the polarity checker directed towards the left pole is indicated. (b) Normal (upright) quadrupole, beam direction into the page. The colour of the polarity checker directed towards the top-left pole is indicated.

Figure 3: BBBD1. The polarity of the left pole is denoted ‘red’. The beam direction in this photograph is from right to left.

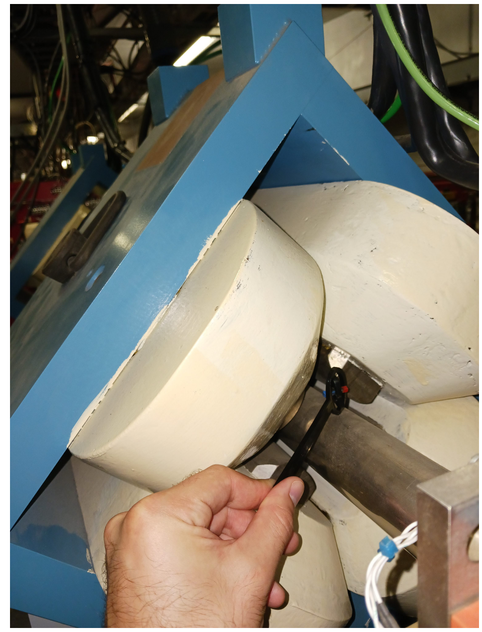

Figure 4: PTB:Q8. The polarity of the top-left pole is denoted ‘blue’. The beam direction in this photograph is from right to left.

the PTB line, so that we could associate a known focussing or defocussing polarity with the existing, operational lattice of the accelerator beamline.

We see from the results of polarity measurements in Table 1 that the magnets which had previously been operated in the booster bypass (designations BB and LA) had the correct polarity, while newly installed magnets in the LEA beamline (designation LEA) did not all have the correct polarity. We used this information to correct the polarity of magnets in the LEA beamline.

16th of March, 2023

After correcting the magnet power supply lead polarities of LEA quadrupole magnets, the magnets were re-energised to reverse the remnant field of the magnets. The polarity of a subset of the above magnets (LEA magnets) was re-measured on the 16th of March, 2023. The results are summarised in Table 2. This shows that the polarity of all the quadrupoles has been corrected to match the design lattice.

DISCUSSION

From the perspective of electrical safety, we think this might be the safest way to perform a magnet polarity test. The time required to perform each test was minimal: a few seconds at most per magnet. It took longer to record the result of the measurement than perform the test.

We had expected that remnant field of the magnet may be relatively short-lived. Instead, we found that the remnant magnetisation is comparatively long-lived.

We demonstrated this procedure using magnets as part of the Linac Extension Area beamline. The procedure was useful in identifying magnets with incorrect power supply polarity, which was corrected.

Alternative schemes such as connecting a small laboratory power supply that is capable of providing current and voltage output so low as to be considered electrically safe was also considered as a different technique. However we consider that such an approach has the potential to introduce new measurement errors, because the supply has to be connected with the correct polarity.

We have tested this method using magnets powered by single unipolar magnet power supplies. Future work could include testing this technique for magnets wound with multiple power supplies (for instance, a quadrupole with additional horizontal and vertical corrector trims). Whether corrector power supplies are able to generate sufficient field to cancel the remnant magnetisation of the main magnetic circuit is probably a detail that depends on the implementation of individual magnet designs.

Table 1: Initial Magnet Polarity Measurement August 2022

Magnet	**Magnet type**	**Polarity**	
		Measured	**Correct?**
PTB:Q8	Q_1	Blue	Yes
PTB:Q9	Q_1	Red	Yes
BB:QE1	Q_1	Blue	Yes
BB:QE2	Q_1	Red	Yes
BB:Q1	Q_1	Blue	Yes
BB:BM:1-1	B_2	Blue	Yes
BB:BM:1-2	B_2	Blue	Yes
BB:BM:1-3	B_2	Blue	Yes
BB:BD:1	B_2	Red	Yes
BD:Q1	Q_1	Red	Yes
BB:Q2	Q_1	Red	Yes
BB:Q3	Q_1	Blue	Yes
BB:Q4	Q_1	Red	Yes
BB:BM:2-1	B_2	Red	Yes
BB:BM:2-2	B_2	Red	Yes
BB:BM:2-3	B_2	Red	Yes
BB:Q5	Q_1	Blue	Yes
BB:Q6	Q_1	Red	Yes
LA:Q1	Q_1	Blue	Yes
LA:Q2	Q_1	Red	Yes
LEA:Q1	Q_1	Blue	Yes
LEA:Q2	Q_1	Red	Yes
LEA:Q3	Q_1	Red	No
LEA:Q4	Q_1	Red	No
LEA:Q5	Q_1	Blue	No
LEA:Q6	Q_1	Red	No
LEA:Q7	Q_1	Red	Yes
LEA:BD	B_2	Red	Yes

Table 2: Subsequent Magnet Polarity Measurement March 2023

Magnet	**Magnet type**	**Polarity**	
		Measured	**Correct?**
LEA:Q1	Q_1	Blue	Yes
LEA:Q2	Q_1	Red	Yes
LEA:Q3	Q_1	Blue	Yes
LEA:Q4	Q_1	Blue	Yes
LEA:Q5	Q_1	Red	Yes
LEA:Q6	Q_1	Blue	Yes
LEA:Q7	Q_1	Red	Yes
LEA:BD	B_2	Red	Yes

SUMMARY

We present a step-by-step procedure to test the polarity of magnets installed with their associated power supply off. By exciting the magnet briefly, we propose putting the magnet on its hysteresis curve, and observing the polarity of the excitation using the remnant magnetic field. This procedure allows someone to approach and measure a magnet without electrical hazards.

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REFERENCES

[1] A. Nadji, "Commissioning of an Accelerator: Tools and Management", in *Proc. 11th European Particle Accelerator Conf. (EPAC'08)*, Genoa, Italy, Jun. 2008, paper WEZG02, pp. 1926–1930.

[2] J. Galambos, "Commissioning strategies and methods", CERN, Geneva, Switzerland, Rep. CERN-2013-001, Mar. 2013. `doi:10.5170/CERN-2013-001.465`

[3] S. M. Liuzzo, N. Carmignani, A. Franchi, T. Perron, K. B. Scheidt, E. Taurel, L. Torino, and S. M. White, "Preparation of the EBS beam commissioning", *J. Phys.: Conf. Ser.*, vol. 1350, pp. 012022, 2019. `doi:10.1088/1742-6596/1350/1/012022`

[4] S. Tepikian *et al.*, "SNS Ring and Transport System Magnet Acceptance and Installation Preparation", in *Proc. 2003 Particle Accelerator Conf.*, Portland, OR, USA, May 2003, paper WPPE033, pp. 2390–2392. doi:10.1109/PAC.2003.1289130

[5] A. Hillman, private communication, Oct. 2016.

[6] M. Buzio et al., "Checking the Polarity of Superconducting Multipole LHC Magnets", *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 1391–1394, June 2006. doi:10.1109/TASC.2005.864490.

[7] L. Bottura, M. Buzio, P. Galbraith, A. Masi, F. Thierry and A. Tikhov, "Design and Implementation of an Automated Polarity Checker for Superconducting Magnets", in *Proc. 2006 IEEE Instrum. Meas. Technol. Conf.*, Sorrento, Italy, 2006, pp. 55–60. doi:10.1109/IMTC.2006.328173

[8] P. F. Tavares *et al.*, "Commissioning of the Max IV Light Source", in *Proc. NAPAC'16*, Chicago, IL, USA, Oct. 2016, paper TUB3IO01, pp. 439–444. doi:10.18429/JACoW-NAPAC2016-TUB3IO01

[9] M. Eriksson *et al.*, "Commissioning of the MAX IV Light Source", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 11–15. doi:10.18429/JACoW-IPAC2016-MOYAA01

[10] T. Otto, "Risks and Hazards of Particle Accelerator Technologies", in *Safety for Particle Accelerators*, Springer, Cham, Switzerland, 2021, pp. 5–54. doi:10.1007/978-3-030-57031-6_2