Magnet Measurement Specifications

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1 Scope

There are two objectives:

- To calibrate the magnetic field versus excitation current sufficiently well that magnets can be repeatedly and reliably driven to known set points.
- To automate the degaussing of magnets using uni-polar power supplies and polarity switching contactors.

This specification sheet outlines measurements that will characterize the E-Linac electromagnets listed below. The measurements complement, verify and extend beyond the data provided by the magnet manufacturers. There are two basic measurements:

- Determine the so-called B-I curves, magnetization versus excitation current. Due to hysteresis, these curves have two branches comprising a loop. Both branches shall be measured. The measured quantities are magnetic field at a particular location, and current at the power supply.
- Exercise the magnet through progressively smaller and smaller hysteresis loops, so as to achieve "de-gaussing" i.e. remnant field below a specified value. It is essential that a procedure be found that does not rely on a bi-polar power supply. The measured quantities are magnetic field at a particular location, current at the power supply, and the status of the polarity switch.

There is no requirement to perform automated mapping of magnetic field versus location on a 2D or 3D grid.

1.1 Magnet Types and Quantities

Magnet Type:	**Number of Magnets to be Measured**
Weak quadrupole	36
Medium quadrupole	35
Strong quadrupole	9
ELBD dipole	1
EMBD dipole	1
EMBT dipole	2
Strong dipole (S34)	7
Strong EHAT dipole (Y30)	3
Dogleg vertical dipole (DLVD)	2
Solenoids	5
Correctors	2 (one of each type)
Total number of magnets:	**103**

Table 1: Number of magnets to be measured.

The B-I curve will be measured for every: quadrupole, dipole and solenoid and only for one corrector of each type. This is because the VECC tests have shown us that is invaluable to fully understand the B-I characteristics for each magnet to decrease commissioning time.

2 Setup

2.1 Magnetic Field Measurements

To measure the magnetic field we will use a multi-channel gaussmeter (Lakeshore 460 3-Channel) with two different types of probes. The probes will be held inside specially designed jigs in order to do spot measurements. Overall, we want a combined relative error to be at most $5 \cdot 10^{-3}$. This value was chosen because the amplitude for the hysteresis (given by the vendor) for the quads is $\approx 1\%$ of the nominal field gradient. We want to measure the magnets accurately, so we want to be able to measure up to a small fraction of the 1%. This requires the relative error to be at most $5 \cdot 10^{-3}$. In fact, the relative error will be constrained to the same value for each type of magnet. To be able to correlate vendor's data, we will gather field data at a set current and link them with the measurements to the field integral measured by the vendor for the same excitation current (process is different for each magnet type, see Sec. 3)

We do not plan to do any field mapping, except possibly for the solenoids and correctors; such mapping would involve manual repositioning of the field probe.

It is expected that controls group will automate the acquisition and storage of the field measurement data in a mutually agreed format and file structure. The measurements and data processing will be performed by beam dynamics group.

2.2 Excitation Current Measurements

We want to measure the current provided by the power supply with a relative precision better than $5 \cdot 10^{-3}$ for the same reason discussed in the previous sub-section. Note that for when we do the demagnetization, the minimum final step current should be equal to the minimum non-zero current of the corresponding power supply.

It is expected that controls group will automate the acquisition and storage of the current measurement data in a mutually agreed format and file structure. The measurements and data processing will be performed by beam dynamics group.

2.3 Additional Considerations

For each measurement we will make sure to record the conditions. The conditions that will be considered are:

- positioning of the probes and the location of the measurement with respect to a set reference point (to be determined);
- magnet serial number;
- power supply serial number;
- temperature of the pole (at the beginning and at the end of each measurement);
- water flow (if the magnet is water-cooled);
- water temperature.

2.4 Temperature Measurements

We are going to do temperature measurements before and after doing the B-I characterization. The temperature of the pole of the magnets will be measured. On top of this measurement, we will do a controlled temperature change (by turning off water cooling, etc) to isolate the effects of temperature. These measurements are to show that the change in physical dimensions due to the change in temperature will have minimal effect on the magnetic properties. Note, we also need to set up an interlock/thermal switch in the current set-up.

2.5 Beam Line Pipe Measurement

We plan to carry out a simple spot measurement with and without the beam pipe to verify that the pipe is as non-magnetic as it is thought.

3 Measurements of B-I Curves

3.1 Quadrupole Electromagnets

There are three distinct types of quadrupole magnets: weak, medium and strong. Each of the quads have their respective maximum currents, outlined in Table 2.

Quadrupole Electromagnet Details

Weak maximum current ($I_{W_{max}}$)	6 A
Medium maximum current ($I_{M_{max}}$)	40 A
Strong maximum current ($I_{S_{max}}$)	43 A

Table 2: This table shows the maximum current for each of the three main type of quads.

We would like to characterize each quad with its respective B-I relationship. The measurement will be done by using two radial probes that will be placed a fixed distance apart in a jig, which then will be fitted inside the quadrupole. A procedure will be developed so that the placement of the jig will be reproducible. From the two field measurements, we will then infer the average field gradient. This measurement will be repeated ≈ 80 times, for different values of excitation current, for currents ranging from $-I_{max}$ to $+I_{max}$ (see Table 2). Additionally, after a measurement is completed, the entire setup (probes and jig) will be rotated 180° and measured again as a redundancy to check accuracy.

The relationship between the data and integrated field gradient will be inferred from other measurement data provided by the vendor.

3.2 Dipole Electromagnets

The measurement for the dipole electromagnets will be similar to the one for the quads, but with only one radial probe placed in the direct center of the dipoles. We will measure only the local field strength and repeat this measurement ≈ 80 times, changing the current in the range of $-I_{max}$ to $+I_{max}$ as shown on Table 3. Note that these measurements will be done at the physical center of the magnet, not the magnetic center. To determine the physical center of the magnet we will work together with the beamline group, since they are aligning the magnet ie. they have a precise alignment machine. We are not going to measure with respect to the magnetic center of the magnet because we are not going to do any field mapping.

Dipole Electromagnet Details

ELBD maximum current ($I_{ELBD_{max}}$)	0.4 A
EMBD maximum current ($I_{EMBD_{max}}$)	33.8 A
EMBT maximum current ($I_{EMBT_{max}}$)	64.6 A
Bender strong maximum current ($I_{BS_{max}}$)	244.4 A
Bender strong EHAT maximum current ($I_{BSE_{max}}$)	320.0 A
Bender vertical maximum current (I_V)	??

Table 3: This table shows the maximum current for each of the main types of dipoles.

3.3 Solenoids

Our measurements for the solenoids will be only a spot measurement of the field strength using a three-axis probe. If time permits, we will do partial field mapping. This measurement will be taken place on the beam-axis. Using the data from the measurements, a B-I curve will be produced.

3.4 Correctors

We will only measure one corrector of each type. These measurements will only be a spot measurement of the field strength using an three-axis probe. If time permits, we will do partial field mapping. This measurement will be taken place on the beam-axis. Using the data from the measurements, a B-I curve will be produced.

4 Study of Magnetic Hysteresis

This study of magnetic hysteresis will be done on one magnet of each type. We want to investigate the behaviour of the magnetic properties. We have two goals:

- learn how to degauss a magnet using a unipolar power supply with polarity switch;
- learn how to ensure reproducibility of the field from the magnet.

Having a better understanding of this behaviour will help us understand how to degauss materials more effectively and efficiently. For this study, we want to try different current waveforms with varying periods. Therefore, we will need a power supply that can deliver user-inputted current functions (or a good approximation). In order to avoid extraneous magnetic behaviour, we need a ramping and step capability on the current output. We need to be able to control how fast the ramp will occur and how long the step delay will be. A polarity switch is required on the power supply in order to study the full hysteresis effect. An example of a typical wave form we will try is,

$$I(t) = A\mathrm{e}^{-\mathrm{t}/\tau}\sin(2\pi\mathrm{ft}).$$

Essentially, we will try different values for the time constant τ and the frequency f. Note that we want to determine an optimal general procedure first, and then we will see how near we can approximate/implement the waveform using the EPICS control system.

Additionally, we want to determine a procedure that will ensure have reproducible traversal of a B-I curve.