Magnetic mapping aims and requirements – Draft 1 (Status: Brain Dump)

V. Blackmore

1 Why map the MICE magnets?

There are two main reasons for mapping our magnets,

1. Align the focus coil with the MICE magnetic axis.
2. Understand the magnetic field for simulations and analysis.
   (a) Check the operating fields for hysteresis effects.
   (b) Verify OPERA calculations.
   (c) Determine best coil geometry that reproduces the measured fields
   (d) Determine the effect of iron on the magnetic field and any measurable error fields.
   (e) Check linearity of field with current.
   (f) ?...Also useful to check force calculations...?

and the better we do (1), the easier it is to do (2) well.

2 Finding the magnetic axis

We want a continuous magnetic axis through MICE, which means aligning our magnets to the best of our ability. The magnetic axis is not necessarily the same as the geometrical axis along the magnet's bore. The cold mass of the focus coil was surveyed when installed, so in principle, determining the magnetic axis of the focus coil also verifies the original installation survey.

1. According to Tom Bradshaw's talk at CM30, the cold mass was aligned to the OVC (outer vacuum chamber) using CMM ("co-ordinate measuring machine") and alignment blocks.

Tab. 1: Hall probe positions on the face of the magnetic mapping disc, when the disc is aligned at $\phi = 0°$. Probe 6 has two radial positions, one for the Focus Coil (FC) and one for the Spectrometer Solenoid (SS) discs. *Note that probe 7 must be removed when measuring between $\phi = 125$ and $215°$ so that the disc can bypass the mapper 'carriage' (the part-cylinder it runs along).

Hall probe	r (mm)	ϕ (°)
1	0	0
2	30	0
3	60	270
4	90	0
5	120	90
6 FC (SS)	140 (150)	270
7*	180	0

2.1 Method 1

Assume that we have a coupled grid of co-ordinate points and field measurements, $\vec{x} = (x, y, z)_i$ and $\vec{B} = (B_x, B_y, B_z)_i$, so that at each point $\vec{x_i}$ we know all of the field components. There will be some systematic error on the measured positions, σ_x, some systematic error on the field, σ_B, and a minimum measurable field value $t \approx 2$mT.

The magnetic axis is defined as the line along which $B_x, B_y = 0$. Since we have a minimum measurable field, this becomes $|B_x|, |B_y| \leq t$. With this requirement we can make a selection on $\vec{x_i}$, picking out only those points that meet the on-axis field requirement, $\vec{x_{0i}}$.

Take the first and last points in this set as the start and end of our magnetic axis. The z-coordinates of these points are known and fixed throughout the rest of this process, essentially saying *'here is the start and end of our field map, now find the co-ordinates of the end points of the magnetic axis derived from these measurements.'* We know z_{start} and z_{end}, we must find $(x_{\text{start}}, y_{\text{start}})$ and $(x_{\text{end}}, y_{\text{end}})$. To do this, we use a minimizer such as Minuit and calculate a χ^2 straight line (three dimensional) fit.

Figure 1 illustrates the technique. Guess a start and end point $\vec{x_1}, \vec{x_2}$, where the z-component in each case is known and fixed. Then we step through each point in our set of $\vec{x_{0i}}$ and calculate the following,

$$\vec{A_i} = \vec{x_{0i}} - \vec{x_1}$$

$$\vec{B_i} = \vec{x_{0i}} - \vec{x_2}$$

$$\vec{d_i} = \frac{(\vec{A_i} \times \vec{B_i}) \cdot (\vec{A_i} \times \vec{B_i})}{(\vec{x_2} - \vec{x_1}) \cdot (\vec{x_2} - \vec{x_1})} \tag{1}$$

$$\chi^2 = \sum_i \frac{\vec{d_i} \cdot \vec{d_i}}{\sigma_x^2} \tag{2}$$

and let Minuit find the minimum value of χ^2, returning the best $\vec{x_1}$ and $\vec{x_2}$ that fit our measurements.

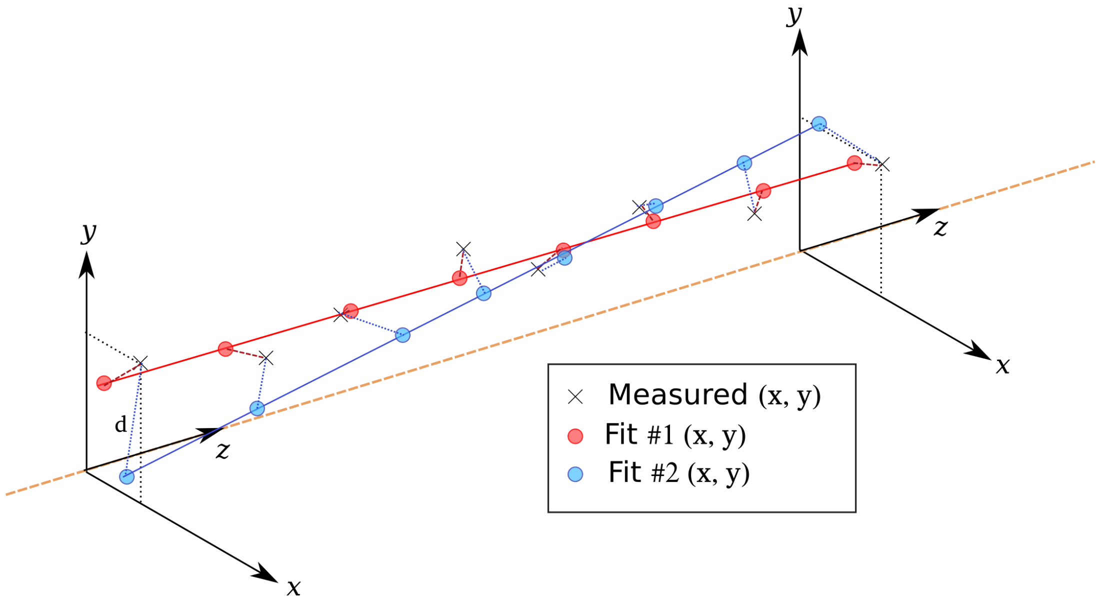

Fig. 1: Fitting a line through the measured values of (x, y) where $B_x \leq t$ and $B_y \leq t$, where t is a minimum measurable field value. The distance, d, between the fitted line and the measured co-ordinates is minimised to provide the best fit line.

Potential Problems:

1. We don't measure $|B_x|, |B_y| \leq t$ at any point. This could happen if the mapping device is not measuring near the magnetic axis.. and instead "steps over" it.
   (a) To avoid this, we would need to increase our tolerance, t and the number of longitudinal and rotational steps we measure.
   (b) Alternatively, use the method in Section 2.2 to get the $\vec{x_{0i}}$ points.
2. Mis-aligned hall probes, or hall cubes.
   (a) The facing of the hall probe is not going to be exactly known, nor is its position. The values of B_x, B_y, B_z are given in the hall probes local co-ordinate system and not in the surveyed co-ordinate system. The probes are all aligned along the $\pm x$ and y-axes, but there will still be small misalignment effects.

2.2 Method 2

This requires thought, but is probably a useful addition to Section 2.1. We build up points along a line, and then fit a line to the measured field components whose intercept should be at the magnetic axis. This could then be fed back into the three-dimensional line fitting described above to find the best start and end points describing the axis.

Need to consider error sources...

2.3 Requirements from data

1. N field measurements, (B_x, B_y, B_z), at positions (x_i, y_i, z_i)

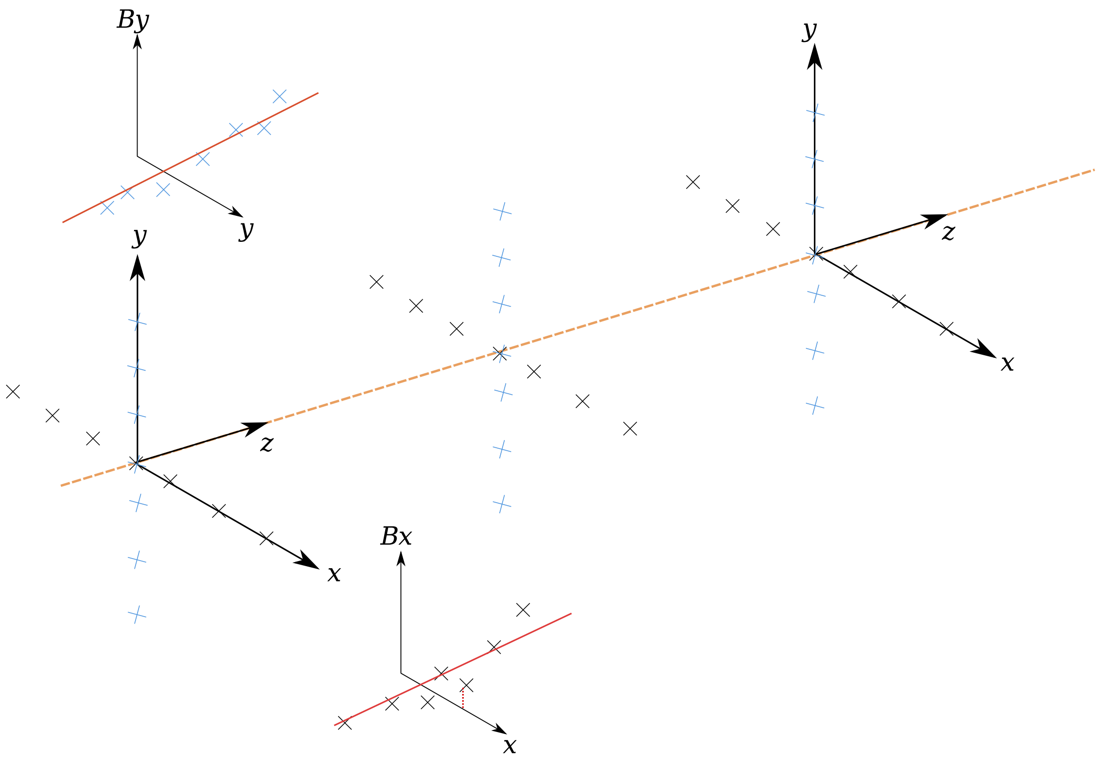

Fig. 2: An alternative method of finding the axis that needs more thought. Measurements are taken at rotations where we can build up lines to evaluate the field along and fit a line through.

(a) Minimum number of z-steps taken to be investigated with software before the mapping begins.

(b) Coarse gridded data taken to begin with to check that outputs are as expected, finer detail may be needed for the magnetic axis measurement.

2. Preferably at least two 'lines' of data, one horizontal and one vertical, passing through the origin of the mapper so that we can follow Section 2.2.

3. Measurements in flip mode and solenoid mode.

   (a) Want to make sure the magnetic axis does not change between these two modes.

4. Measurements at $0.33I_D$, $0.66I_D$, and I_D, where I_D is the full design current.

   (a) We want to make sure that the magnetic axis stays constant regardless of the magnet currents. The field on-axis should scale linearly with current, and the axis should not change.

   (b) Check that changing the current from $0.66I_D$ to I_D and back to $0.66I_D$ does not introduce any hysteresis effect that also changes the magnetic axis (unlikely, but easily checked, and we want to do this anyway for the generally understanding the magnetic field).

5. At least one current measured several times with the same mapping grid to check for statistical and systematic errors stemming from current drift or the mapping device not driving to the exact same place (believe it has mm-accuracy).

6. Need at least one measurement **with field** with fine ϕ measurements so we can track the field around a loop and work out any Hall probe offsets on their tiny cube a la ATLAS.

7. Measurements from the survey (below).

2.4 Requirements from survey

1. Verification of the longitudinal mapper co-ordinates.

2. Verification of the (x, y) co-ordinates of each hall probe on the mapper disc face.

3. Monitoring of the (x, y, z) co-ordinates as the mapping disc moves through the magnet bore.

   (a) Making sure that there's no 'sag' or twist in the support under the mappers weight.

   (b) Don't need a magnetic field to check this

4. Verification that the mapper disc rotating by $\phi = 5°$ really is 5°.

   (a) Check the position of one exterior hall probe at $5, 15, 90, 180, 200, 270°$, do the math and check that it all averages out correctly.

   (b) Checking some angles from the top and some from the 'bottom' of the disc in case there's a weighting issue (but I doubt there actually is)

   (c) Also monitor the z position of the probe as it goes around so see if there's any tilts on the disc.

5. Must be able to relate the two halves of the focus coil maps (one taken from each side of the magnet at the same current)

6. Not strictly survey, but we need a record of any current drifts/variations whilst mapping the magnet.

2.5 Requirements from software

The above methods are completely independent of the fields and coil geometries. We need,

1. Ability to read N field measurements, (B_x, B_y, B_z), at positions (x_i, y_i, z_i) from the CERN mapping machine, *i.e.* interpreting data files and potentially re-writing in a more user-friendly format.

2. Basic plotting abilities for plotting field components versus spatial components for each Hall probe and/or combination of hall probes.

3. Contour plots of $(x,z),(y,z),(r,z)$ versus B_x, B_y, B_r, B_z or other combinations.
4. Ability to identify points lying along the same x or y and plot position versus B_x or B_y, fit with a line and find where it crosses the axis.
   (a) Need to do this all along the mapper so we can join the dots using Section 2.1.
   (b) Need a minimum of a horizontal and vertical string of lines passing through the origin.
5. Implementation of Equations 1 and 2.
   (a) Easiest option is with a language that naturally supports vector algebra, e.g. python, Matlab...
6. Transformation of mapper data from mapper disc co-ordinates to surveyed reference frame (as when the mapper disc rotates, the recorded positions of the sensors stays constant).
7. Overlaying data sets from field maps taken from both sides of the focus coil at the same current.
   (a) May need flexibility regarding overlaying different grid spacings.
   (b) Unlikely we'll manage to arrange it so that we have overlapping z positions in the two maps, but as long as we're measuring in the same survey co-ordinate system, I don't believe we'll need to do any interpolation...
8. Checks for sensible data.
   (a) Measured temperature variations are within the hall probe's calibrated region.
   (b) Check repetition of field measurements at a fixed current and mapper gridding, looking for statistical/systematic errors creeping in from current drifts, the mapping disc not returning to the exact same position.
   (c) Check that the field around a closed loop is zero (*i.e.* track one sensor making a complete loop – any deviations from the integral of measurements being zero should be small. If so, it's due to the probe not being perfectly aligned on its card.) Important: A non-zero result here is not indicative that the field map is faulty as long as it's a small effect. A large effect means something more sinister is happening. (Maxwell's equations aren't at fault.. we would be).
   (d) Check that the on-axis field is in *approximately* the right region for the current we're using. If we're a million miles away from expectation, something is wrong.
   (e) Check that the field taken at different ϕ but same radius (*i.e.* same Hall probe) is approximately constant.
   (f) Check that a contour plot of the field horizontally across the magnet is pretty similar to a one vertically across the magnet.

3 Understanding the magnet

If we've understood the magnetic axis well enough, we've made our lives simpler for understanding the magnet itself. In this case, we want to locate the position of the cold mass relative to the survey co-ordinates and the rest of the focus coil. We then want to determine the best-fitting coil geometry that reproduces our measurements (which is likely to be very similar to the design values, albeit with differences such as layer spacing as the coil stretches itself when powered). The "standard procedure" for doing this is,

1. Develop a magnetic field model
2. Compare with measurements
3. Include sources of systematic error

We want to be able to learn enough about these magnets that we can reliably reproduce their magnetic fields no matter what configuration we end up running them in. In other words, just taking the field map and doing a bit of interpolating and then using it with our data *is not good enough* – we have a lot of different field configurations we could potentially use, so it would be very time consuming for us to measure them all to the precision necessary for direct-use. Plus that isn't helpful if we decide later to lower/raise the currents by 10% for some unknown reason.

There's two approaches that are taken as standard for doing this. The first is the 'coil model', which fits the measured field with a coil geometry, and the second uses Maxwell's equations to quantify the residual field. These methods are usually used in combination, but MICE may be able to get away with the coil model only – the Maxwell/residual field approach is most commonly used to quantify the effect of a return yoke, but we won't have one of those for our measurements (even if we have one later).

3.1 Coil method

Represent the coil as a series of closed current loops and evaluate the field as a superposition of them. The focus coil was surveyed as it was built, so we have a good idea of what it should look like. Exploiting cylindrical symmetry, the field from a current loop is

$$B_r = \frac{\mu_0 I}{\pi}\frac{z}{2\alpha^2\beta r}[(r^2+\rho^2)\mathcal{E}(k) - \alpha^2\mathcal{K}(k)], \tag{3}$$

$$B_z = \frac{\mu_0 I}{\pi}\frac{1}{2\alpha^2\beta}[(r^2-\rho^2)\mathcal{E}(k) + \alpha^2\mathcal{K}(k)], \tag{4}$$

$$B_\phi = 0, \tag{5}$$

where

$$\rho^2 = r^2 + z^2,$$
$$k = 1 - \frac{\alpha^2}{\beta^2}$$

$$\alpha^2 = r^2 + \rho^2 - 2rR_c,$$
$$\beta^2 = r^2 + \rho^2 + 2rR_c,$$

and (r, z) is the co-ordinate the field is evaluated at, I is the operating current, R_c is the radius of the current loop, and $\mathcal{K}, \mathcal{E}$ are complete elliptic integrals of the first and second kind respectively.

We can build up our coil from layers of multiple current loops, separated by a longitudinal distance dz which we find as $dz = W/(N_{\text{turns}} - 1)$, where W is the width of the coil pack and N_{turns} is the number of windings/turns per coil layer. Finally, the current layers as the coil are built up, starting with a layer at radius R_{inner}, the interior radius of the coil pack, and extending to R_{outer}, the outer radius. These layers are separated by a radial distance $dr = (R_{\text{outer}} - R_{\text{inner}})/(N_{\text{layers}} - 1)$, where N_{layers} is the number of layers of superconductor on the coil.

Equations 3 and 4 then become,

$$B_{r,\text{total}}(r, z) = \sum_{\text{m = 1}}^{N_{\text{layers}}} \sum_{\text{n = 1}}^{N_{\text{turns}}} B_{r,mn}(r, z, R_c, I, dr, dz) \tag{6}$$

$$B_{z,\text{total}}(r, z) = \sum_{\text{m = 1}}^{N_{\text{layers}}} \sum_{\text{n = 1}}^{N_{\text{turns}}} B_{z,mn}(r, z, R_c, I) \tag{7}$$

The complication with this method is the time taken to compute the field over a large (or fine, or both!) grid of points. The more coils you add, the worse this becomes. The focus coil calculation takes on the order of ≈ 15 minutes for one field map, which quickly adds up when fitting to measurements.

Finding the 'best-fit' coil geometry is done using Minuit and a simple χ^2 fit taking the coil geometry and its position as free parameters, so that we minimise

$$\chi^2 = \sum_{i,r,\phi,z} \left(\frac{B^{\text{data}}_{i,r,\phi,z} - B^{\text{model}}_{r,\phi,z}(\vec{x})}{\sigma_B} \right)^2, \tag{8}$$

where B^{model} is the predicted field of the model at the co-ordinates of $B^{\text{data}}_{i,r,\phi,z}$, where i runs over all measured points.

There are a corrections that may need to be made to the data:

1. Hall probe normalisation and calibration
2. Probe alignments and positions – the three field components measured by the hall probe are **not** measured at exactly the same point
3. Probe tilts and alignments on the cards
4. Measured carriage tilts and skews as it goes through the magnet bore (not expected to be large)
5. Survey corrections

Survey corrections play a large role in our understanding of the fitting procedure. It is both easiest and quickest to calculate the field with the magnetic axis aligned along the bore in the centre of the magnet, so that we can assume cylindrical symmetry and use Equations 3 and 4 to calculate the field from our current loops. However, it's unlikely that the mapping machine will be aligned along the magnetic axis, therefore,

1. We need to know where the magnetic mapper is with respect to the magnet throughout the entire measurement region. If it is tilted in any way, we need to know.
2. We need to identify the magnetic axis of the magnet so as to re-align our measurements to a cylindrical co-ordinate system based about this axis (see Section 2)
3. Check the realignment and set limits on parameters by doing an on-axis calculation and minimisation.
4. Do the χ^2 fit to the re-aligned measured data to reduce computation time.

3.2 Residual field/Fourier-Bessel method

The Fourier-Bessel model is a more general way of modelling the field using Maxwell's equations. It is typically used to quantify the 'residual' field, the difference between the field calculated from the best-fit coil model (Section 3.1) and the measured data points. Other reasons for using this include the fact that the coil model assumes a constant coil winding density and a cylindrical cross-section, and those differences between the assumed model and reality can then be described using this method.

In the region where we measure the field, we have no currents flowing and no magnetic materials, so

$$\nabla \cdot \vec{B} = 0,$$
$$\nabla \times \vec{B} = 0,$$

and $\vec{B}$ can be expressed in terms of the magnetic scalar potential Φ, as $\vec{B} = -\nabla\Phi$. Φ must satisfy Laplace's equation, $\nabla^2\Phi = 0$, a solution to which is found by separation of variables (in cylindrical co-ordinates),

$$\Phi\left(r, \phi, z\right) = R\left(r\right) P\left(\phi\right) Z\left(z\right)$$

We attempt to find the field by considering its values on the surface of a closed cylinder (*i.e.* not all the points in the map, but only those at one specific radius).

What eventually follows here are some long series full of bessel functions...

3.3 Requirements from data

Everything mentioned in Section 2.3 still applies here. Additionally,

1. A minimum of 8 rotations about ϕ at 0, 45, 90, 135, 180, 225, and 270°

3.4 Requirements from survey

1. From Tesla survey:
   (a) We must know $N_{\text{turns}}, N_{\text{layers}}$ before beginning the fit. If we don't, an upper and lower bound should be placed on the possible values to restrict the minimisation routine and speed it up.
   (b) We must know the coil pack width and separation when it was assembled, then we can place appropriate upper and lower limits on these values.
   (c) Similarly, we want to know $R_{\text{inner}}, R_{\text{outer}}$ for each coil, and again place appropriate upper and lower limits on these values.
2. From R9/Hall survey:
   (a) Don't think there's anything beyond the list in Section 2.4

3.5 Requirements from software

4 Sources of systematic error

1. Hall probe normalisation and calibration
2. Probe alignments and positions – the three field components measured by the hall probe are **not** measured at exactly the same point
3. Probe tilts and alignments on the cards
4. Measured carriage tilts and skews as it goes through the magnet bore (not expected to be large)
5. Survey corrections

5 Misc questions

1. When we change from flip mode to solenoid mode (or *vice versa*), we switch the cables on one coil. Do we also need to switch anything on the quench protection? How long is this all going to take (guess: longer than we think)?

6 Table of Measurements

Need to do all the survey measurements and correction measurements before we take any data. We don't necessarily need to do anything with them on-the-spot, but we will need to do something with them eventually in which case we need that data. A full list of measurements is shown in Table 2, and notes on the different measurements are given below, organised by their ID tags:

Survey** Measure different properties of the mapping machine with respect to the magnet or surveyed co-ordinate system.

Survey03 The aim of this measurement is to track any deviations of the mapper from a straight line as it moves through the magnet.

Survey04 A repeat of Survey01 after the mapper has been moved. We want to check that we reliably return to specific points.

Survey05-07 We are checking that the assumed 5° rotation increments of the mapper disc are correct, and also checking for any tilts in the disc by examining the z-component. The Hall probe at 140mm (or 150mm if the Spectrometer Solenoid mapping disc is in use) is chosen since it can be measured at $\phi = 180°$, whereas the outermost one cannot. Combine these measurements with the output of Survey04 for the $\phi = 0°$ measurement.

Data01 The first field map is mostly for checking that we're seeing sensible results. We want to examine this fairly carefully:

1. Plot the field seen by each probe at each rotation and look for anomalies in the flat-field region.
2. For each probe, compare the measurements at $\phi = 0, 90$ and 180°. They should all be similar, in other words, we shouldn't see any evidence of a B_ϕ component to the field.
3. Make a contour plot of the total field, $|B|$ in the horizontal and vertical plane. They should look similar.
4. Make a first estimate of the magnetic axis and compare the residuals – might we need a finer mapping grid for later measurements?

Data02 A repeat of Data01, we want to see how repeatable our results are. Compare some plots from Data01 with similar ones from Data02. There shouldn't be any large differences.

Data03 The first fine-mesh field map. XYZ needs a bit of study to see what is acceptable when looking at smeared simulation, but is *probably* 1–2cm and 45° (depending on available time).

Data04 A quick field map at an intermediate current. The purpose of this is to compare it to the $\phi = 0°$ map from Data01-02 and check that the field scales linearly with current.

Data07 A full ϕ scan is necessary to later locate and correct for any offsets in the hall probe mountings on the cards. It also allows us to normalise the Hall probe outputs. Three z positions may be overkill – it depends on time – but a minimum of one must be done, preferably at full field so the Hall probes are in their element.

Data08 Checking for hysteresis effects. Compare with Data05, where we approached the current from below.

Data12 We can't forget to repeat the other side of the hysteresis check measurement!

Tab. 2: A checklist of measurements that need to be made, in the order I believe they need to be taken in. 'Operating Mode' describes how the magnet is powered ('S' = Solenoid Mode, 'F' = Flip Mode) and at which end of it the mapper is placed. Currents A, B, C are in principle $0.3I_D, 0.6I_D, I_D$ respectively, where I_D is the design current, but these need checking to make sure the expected fields are within the range of the Hall probes.

	ID	Operating Mode	I(A)	Measurement Description
☐	Survey01	S, US	0	Measure Hall probe positions on mapper disc face at far upstream end of carriage.
☐	Survey02			Measure Hall probe positions on mapper disc face at far downstream end of carriage.
☐	Survey03			Measure centre Hall probe position on mapper disc face when travelling through the bore of the magnet.
☐	Survey04			Measure Hall probe positions on mapper disc face at far upstream end of carriage (checking repeatability of (x, y, z) positioning, particularly z).
☐	Survey05			Rotate mapper disc to $\phi = 5°$ and measure (x, y, z) position of $r = 140$(150 for SS)mm Hall probe.
☐	Survey06			Rotate mapper disc to $\phi = 45°$ and measure (x, y, z) position $r = 140$(150 for SS)mm Hall probe.
☐	Survey07			Rotate mapper disc to $\phi = 180°$ and measure (x, y, z) position $r = 140$(150 for SS)mm Hall probe.

Data13 Similar to Data01, except this time in Flip Mode. Of particular interest is how the Hall probes behave as they go through the zero-crossing of the field. Check this region and decide if we need to increase our map mesh from XYZ to something else. Do the same sanity checks as for Data01.

Data17 Make sure there's no hysteresis that strangely only affects Flip Mode.

Data21 Combines with Data17 for hysteresis check.

Tab. 3: Continues from Table 2

	ID	Operating Mode	I(A)	Measurement Description
☐	Data01	S, US	A	Field map the magnet in $z = 10$cm steps at $\phi = 0, 90, 180$ and $270°$.
☐	Data02			Repeat Data01
☐	Data03			Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data04		B	Field map the magnet in $z = 10$cm steps at $\phi = 0°$.
☐	Data05			Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data06		C	Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data07		C	Measure through one full ϕ rotation (*i.e. in* $5°$ *steps*) of the mapper disc at $z = -100, 0, +100$cm.
☐	Data08		B	Approach this from current C (hysteresis check). Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.

Tab. 4: Continues from Table 3

	ID	Operating Mode	I(A)	Measurement Description
☐	Survey08	S, DS	0	Measure Hall probe positions on mapper disc face at far upstream end of carriage.
☐	Survey09			Measure Hall probe positions on mapper disc face at far downstream end of carriage.

Tab. 5: Continues from Table 4

	ID	Operating Mode	I(A)	Measurement Description
☐	Data09	S, DS	A	Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data10		B	Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data11		C	Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data12		B	Approach this from current C (hysteresis check). Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.

Tab. 6: Continues from Table 5

	ID	Operating Mode	I(A)	Measurement Description
☐	Survey10	F, DS	0	Measure Hall probe positions on mapper disc face at far upstream end of carriage.
☐	Survey11			Measure Hall probe positions on mapper disc face at far downstream end of carriage.

Tab. 7: Continues from Table 6

	ID	Operating Mode	I(A)	Measurement Description
☐	Data13	F, DS	A	Field map the magnet in $z =$ 10cm steps at $\phi = 0, 90, 180$ and $270°$.
☐	Data14		A	Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data15		B	Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data16		C	Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data17		B	Approach this from current C (hysteresis check). Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.

Tab. 8: Continues from Table 7

	ID	Operating Mode	I(A)	Measurement Description
☐	Survey12	F, US	0	Measure Hall probe positions on mapper disc face at far upstream end of carriage.
☐	Survey13			Measure Hall probe positions on mapper disc face at far downstream end of carriage.

Tab. 9: Continues from Table 8

	ID	Operating Mode	I(A)	Measurement Description
☐	Data18	F, US	A	Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data19		B	Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data20		C	Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.
☐	Data21		B	Approach this from current C (hysteresis check). Field map the magnet in $z = XYZ$mm steps at $\phi = XYZ$ intervals.