Installing field coils, shields, and degaussing

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Abstract

Adam and I have assembled the magnetic field coils, magnetic shielding, and degaussing circuitry for the second generation of the ACME experiment. Details of the setup and our assembly process are described. Other ACME members (especially Jonathan) helped at various points in this process, and much of the preparation and design work was done by Brendon. This document gives an overview of systems involved (or references thereto) and the assembly process.

1 Degaussing coils

Although degaussing can only occur when the magnetic field coils and magnetic shields have been fully installed as described later in this document, most of the electronics can be set up in parallel with that work.

1.1 Coil winding

Each hemispherical μ-metal shield has a pair of connected ribbon cables to supply a degaussing field. There is a total of 100 windings per hemisphere. Each hemisphere has two Molex Mini Fit Jr. connectors, corresponding to IN and OUT signals. These are gendered so that the IN and OUT deterministically map onto the source connectors. IN connects to one wire of a ribbon cable, which then wraps around the shield, initially on the inner part of the hemisphere. (Here, "inner" and "outer" are toward and away from the axis of cylindrical symmetry, respectively.) The ribbon wraps around two full times, and is then connected back to itself such that the IN wire makes electrical contact with the wire adjacent to it. This repeats so that each wire connects to its succeeding wire after two loops around the shield. Every ribbon cable has 25 wires, so each ribbon accounts for 50 windings.

The last wire in this ribbon then connects to a second ribbon wrapped around the shield hemisphere in the same configuration, but offset in the x-direction. There are thus 100 windings around each shield hemisphere. The last wire from the second ribbon on a given shield is used as the OUT lead for that hemisphere via a Mini Fit Jr. connector. The OUT connector from the first hemisphere of a given shield attaches to the IN connector on the second

Coil #	R (Ω)	L (mH)
1 (inner)	103.2	62.7
2	112.3	77.3
3	125.7	81.0
4	134.2	91.5
5 (outer)	142.7	90.5

Table 1: Measured resistances and inductances of the degaussing coils.

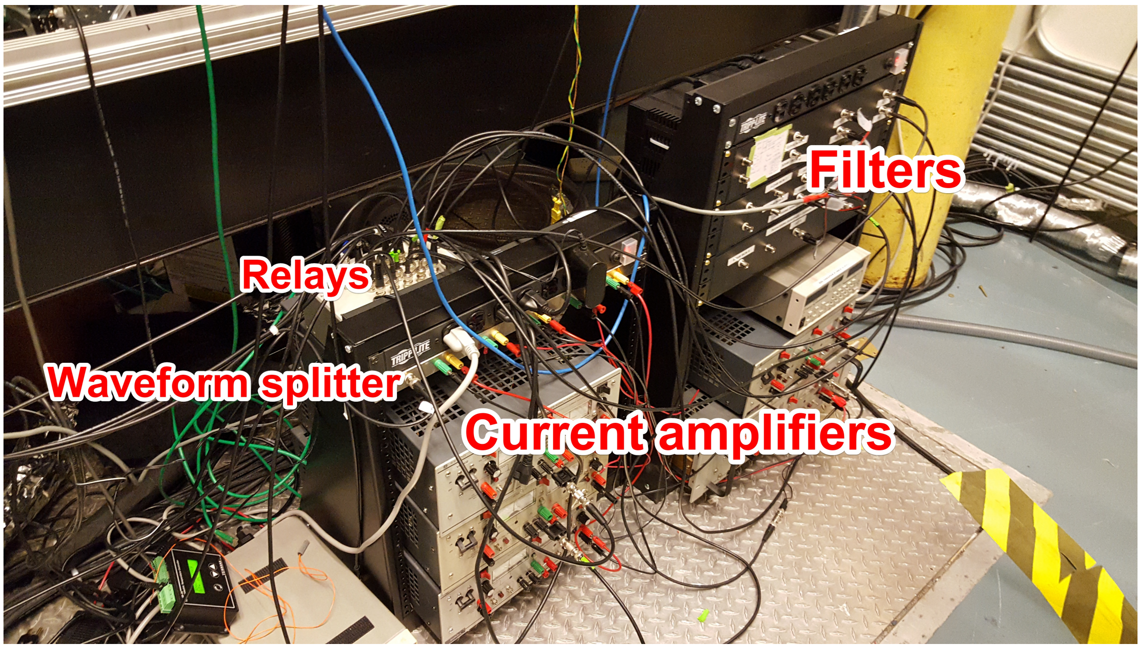

Figure 1: Electronics used in degaussing. Important components are labelled.

hemisphere. The configuration of the second hemisphere is identical, again with 100 total windings. The OUT from the second hemisphere mates to the return conductor for the degaussing signal.

1.2 Degaussing electronics

Since the hemispheres are of unequal diameter, the resulting resistance and inductance of the degaussing coils increase from inside to outside. These were measured with a handheld multimeter and inductometer and are shown in Table 1. Brendon has directly confirmed that the handheld inductometer is accurate [1].

See Fig. 1 for a picture of electronics used in degaussing. The degaussing waveform is generated by a DAQ analog output and split into five banana plug

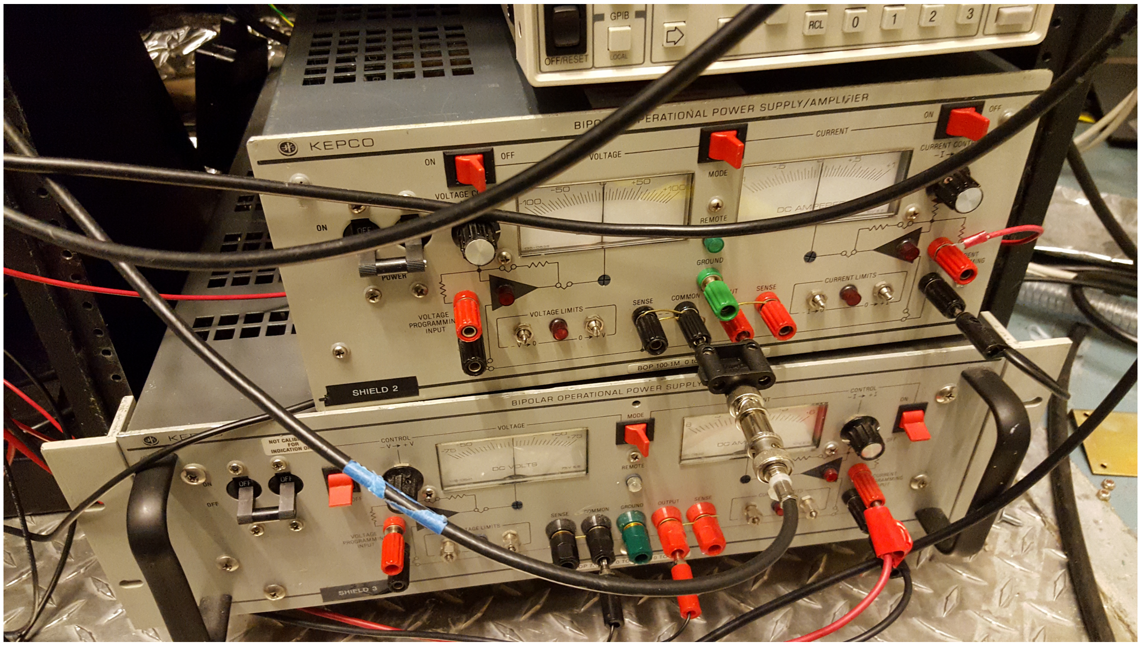

Figure 2: KEPCO BOP 100-1M (top) and 72-6M (bottom) used in degaussing.

outputs on a rack-mounted bar. These degaussing waveforms are of order 5 V and feed into separate current amplifiers. Four of these amplifiers are Kepco BOP 100-1M, and the last is Kepco BOP 72-6M. The first number indicates the voltage rating and the second indicates a current rating. With either current amplifier and any shield, the voltage limit is hit before the current limit. The 72-6M is therefore the most severely limited. Since the outer-most shield is the least important for the experiment, we use the 72-6M to degauss it. These current amplifiers generate 100 mA/V input. The current output is therefore of order 500 mA. See Fig. 2 for the power supplies.

These currents are fed into a relay array designed by Brendon. Each relay is addressed by a separate TTL, although we anticipate opening and closing all relays simultaneously during an experimental run.

The relay outputs are filtered by a circuit passing $\sim 10 - 1300$ Hz, shown schematically in Fig. 3. The details of the frequency response (especially at higher frequencies) depend on the values of resistance and inductance particular to a given coil. It has been confirmed that the filters function as expected.

C1 blocks DC current, contributing to the high-pass filter. R1 provides a path for C1 to discharge when the relays are open. R2 is a resistor in series with the entire circuit, so the voltage drop across R2 provides a measure of the total current supplied to the circuit. The components R3, C2, R4, and L1 together form a damped resonator. The inductor and capacitor set the low-pass frequency. R3 damps the resonator and provides a path for C2 to discharge if the

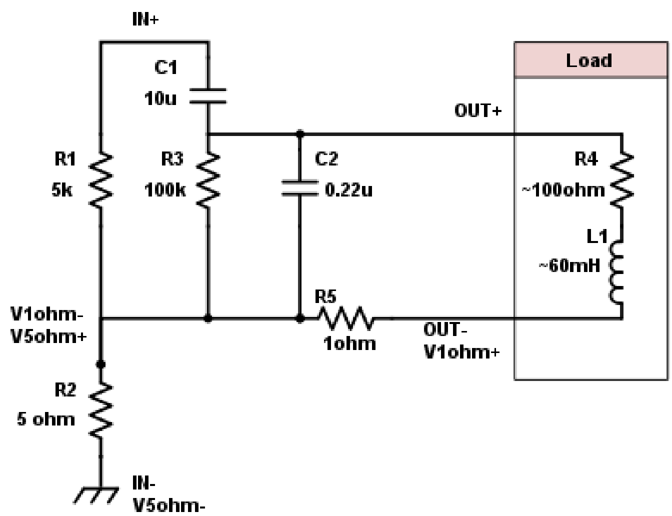

Figure 3: Schematic of degaussing filter

load becomes disconnected. During normal operation, C2 discharges primarily through the load. The voltage drop across R5 allows us to monitor the current flowing through the coils.

Brendon previously found high-frequency noise on the degaussing signal associated with relay switching. We choose to place the relays immediately after the current amplifiers so that this noise doesn't somehow complicate the amplifier operation. In any case, it is important that the relays precede the filters.

Since the voltage input to the current amplifiers ultimately comes from a DAQ, the input is referenced to earth ground. As a result, IN- is held at ground. If the 1 Ω monitor resistor is observed on a grounded oscilloscope, then a short is effectively introduced across R2. As a result, it is not possible to observe both monitors on an oscilloscope simultaneously. (We initially swapped the roles of + and - for the 5 Ω monitor, relative to the schematic shown here, thus allowing both monitors to have a common ground. However, since this put GND = IN- above R2, the supply monitor ceased to be useful.)

2 Magnetic field coils

Brendon has documented much of the hardware and software used in the magnetic field coil system in [2]. Pictures of the coils themselves can be found in [3], copied here in Fig. 4. Details of the installation and diagnosis of the coils

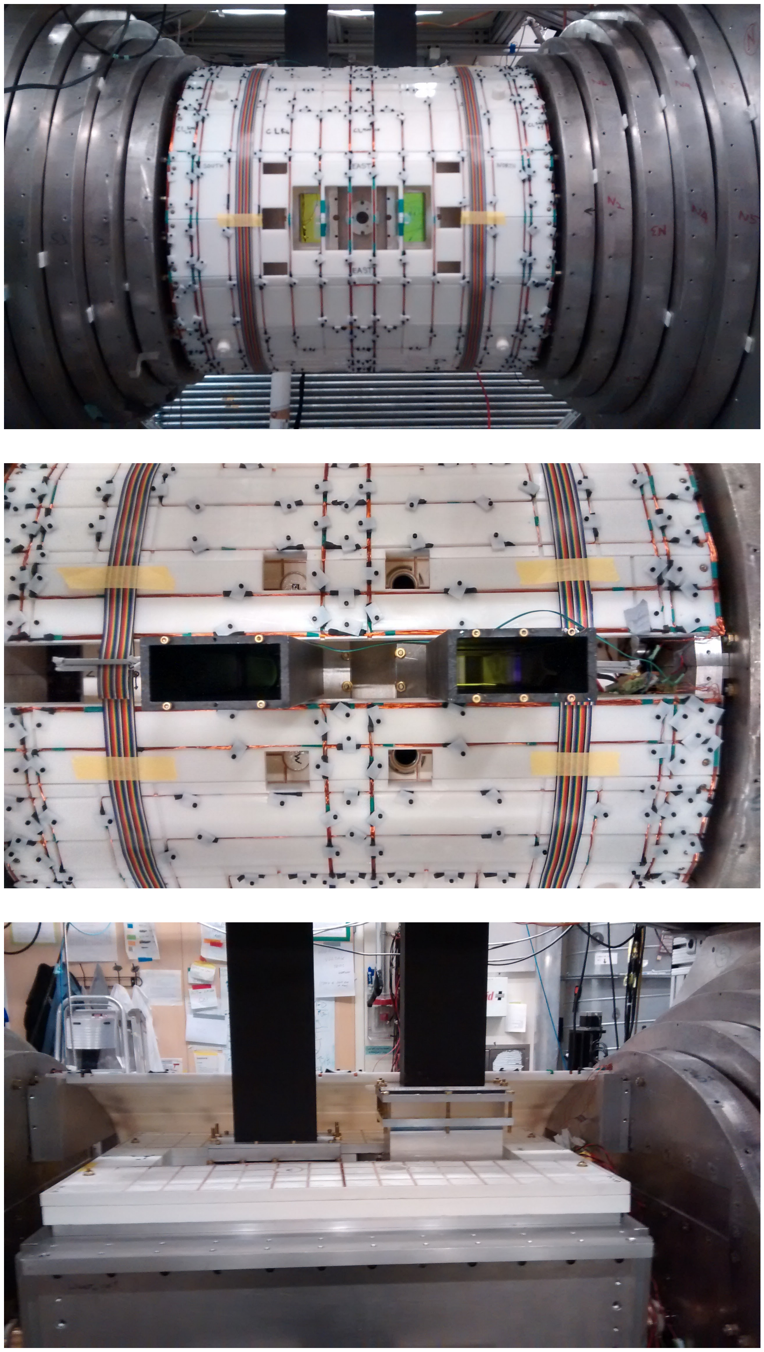

Figure 4: Pictures of the magnetic field coils: side and top views followed by a picture of the top Y-coils, which clamp directly on the interaction region.

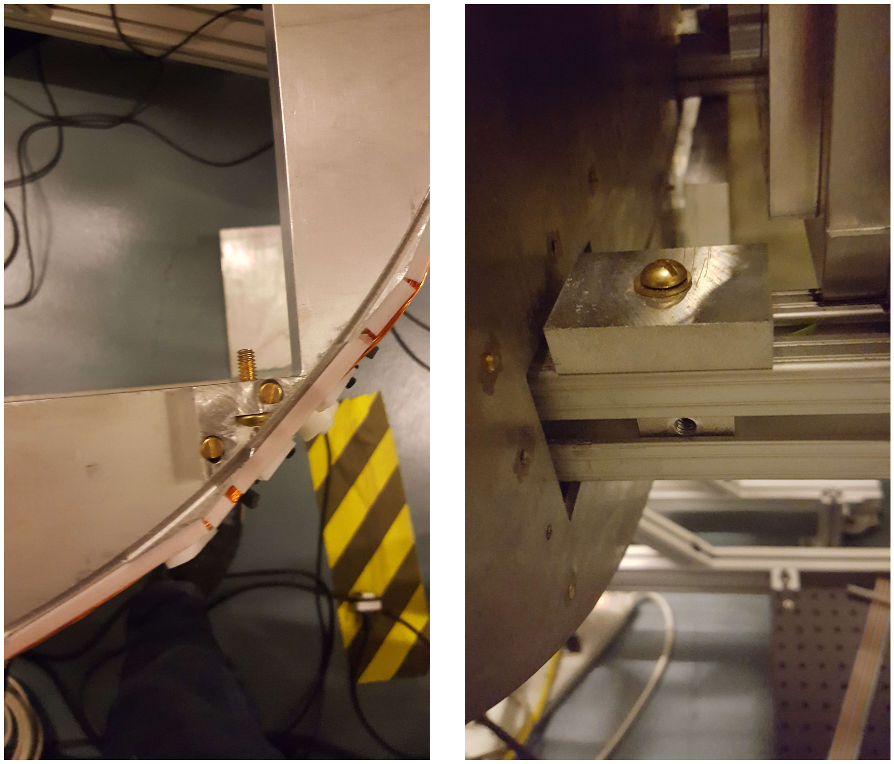

Figure 5: Components for mounting the magnetic field coil assembly (left) to the 80/20 structure under the interaction region (right).

is described in the following subsections.

2.1 Installation

Each hemisphere of the magnetic field coil assembly is attached to the 80/20 structure under the interaction region by two screws. See Fig. 5 for a closeup. The hemispheres attach to each other at the top by a screw, which acts as a rod preventing relative motion (the screw thread is non-functional here). See Fig. 6. Both the bottom and top mounting components are visible on the west coil hemisphere in Fig. 7. We found it useful to insert (or when disassembling, to remove) the screw in the top holes using long tweezers, as in Fig. 8. One should be careful not to drop the screw, since the light pipes exiting the interaction region are exposed below.

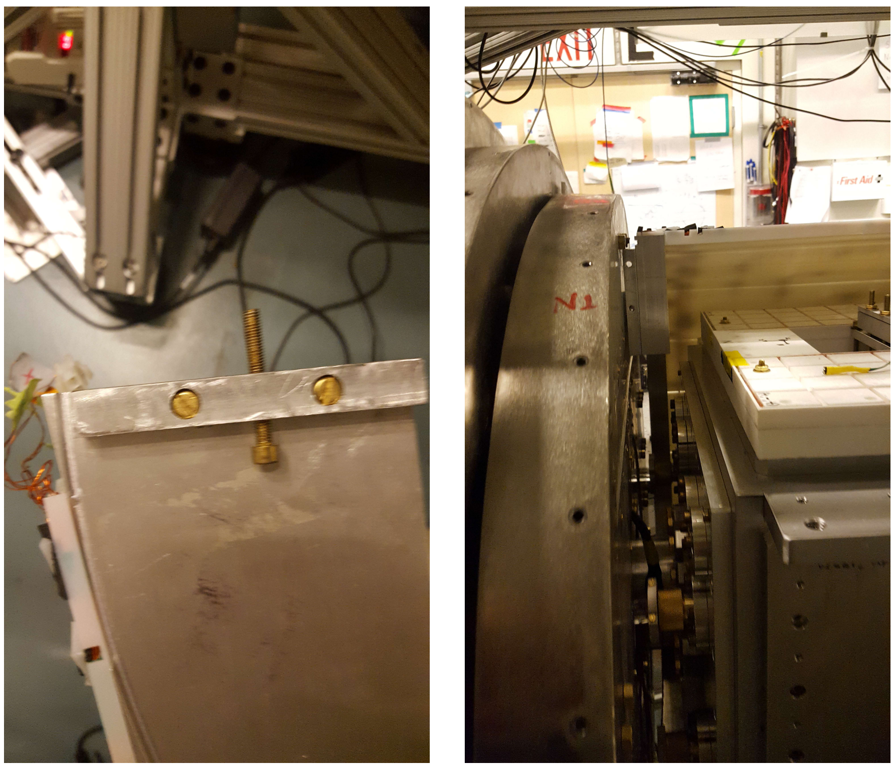

Figure 6: Components for connecting the magnetic field coil hemispheres to each other. A single screw acts as a rod preventing relative motion between the two halves on the top.

Figure 7: A coil hemisphere viewed from the side. The lower and upper mounting components are visible on the near face.

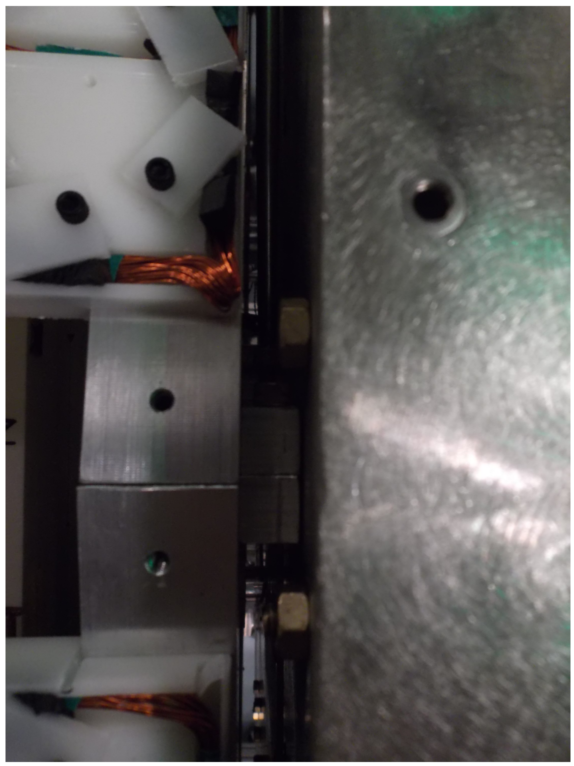

Figure 8: Tweezers are used to insert and remove the screw that fastens each coil hemisphere together at the top.

Figure 9: Mini Fit Jr. connectors used for the magnetic field coils. The larger connector on the left has a broken lead.

2.2 Coil connections

The field coils are connected via Molex Mini Fit Jr. connectors to leads that attach to a terminal block on the south side of the interaction region. The terminal block connections are given in Table 2. Even when the μ-metal shields are off, it is easiest to reconfigure most coils on the terminal block since the Mini Fit Jr. connectors are gendered. To re-connectorize a coil, one must cut the wire to the connector and crimp it into a new pin insert, which locks into a new connector. Male pins go with female connectors and vice versa. The coils that apply B_x and dB_x/dx are ribbon cables and are much easier to reconfigure than the others.

The leads attaching to the Mini Fit connectors are not strain relieved, and are therefore liable to snap if one is careless. See Fig. 9.

Connector	Coil		Connector	Coil
1	XNR		19	[NC]
2	XNB		20	Y- - -R
3	XSR		21	Y- - -B
4	XSB		22	NsEB
5	Y+ + +R		23	NsWB
6	Y+ + +B		24	SsWB
7	Y+ + -B		25	SsEB
8	Y+ + -R		26	MER
9	Y+ - +R		27	MEB
10	Y+ - +B		28	MWB
11	Y+ - -B		29	MWR
12	Y+ - -R		30	NsER, NsWR
13	Y- + +B		31	SsWR, SsER
14	Y- + +R		32	CER
15	Y- + -B		33	CEB
16	Y- + -R		34	CWR
17	Y- - +R		35	CWB
18	Y- - +B		36	[NC]

Table 2: Connections on the magnetic field coil terminal block. Letters N, E, S, W correspond to north, east, south, and west, respectively. Lowercase "s" indicates a side coil. The E and W side coils are connected together (via the terminal block) for both the N and S ends of the interaction region, so we cannot control them independently. M indicates main coils, while X indicates the ribbon cables used to apply B_x and dB_x/dx. C indicates "center" coils, which are not normally used. R and B indicate red and black wires, respectively. [NC] stands for Not Connected. There are 8 "Y" coils, positioned on the 8 corners of a cube. The position is indicated by [X][Y][Z], with the sign giving the direction from the center of the interaction region along the corresponding axis.

2.3 Checking the coil orientation

Many of the coils were not initially configured consistently with the assignments in some of our software. This can be solved by either changing the software assignments (e.g., which sign of current corresponds to a positive field) or by physically changing the wire connections. Although the software fix ought to be straightforward, it seems possible that fixing the assignment in one place would not fix it for all software. Therefore, we chose to reconfigure the orientations directly until they all agreed with our expectations based on software control.

To diagnose the magnetic field orientations, we used four Bartington Mag-03 magnetometers. Two are attached to rotation stages and a shared vertical translation stage (≈ 15 cm range) on the laser lounge. One of the magnetomers, the "probulator," is on a rotation stage and translation stage allowing motion along the molecular beam line. A fourth is dedicated to go on a rotation stage on the east magnetometer port (without translation), but we found it useful to move it around by hand for diagnostics. Our user-friendly magnetometer VI relies on assignments between magnetometer channels and lab axes. We initially found it useful to rely on the magnetometer channel readings directly so as not to be fooled by incorrect channel assignments. We first calibrated the orientation of the z coils (ME, MW, NsE, NsW, SsE, SsW) using the handheld magnetometer. We then rotationally oriented the remaining magnetometers by maximizing the increase in the field along the z-direction when applying a nominal B_z with respect to the magnetometer rotation angle. At this point, we were able to characterize the orientation of all fields and gradients. Detailed analysis of these fields will be covered in a separate document.

2.4 Probulation

The probulator is shown in Fig. 10. The fluxgate magnetometer is mounted on a thin rod, which is inserted into a large plastic tube. A smaller plastic tube is epoxied inside the larger tube toward the upstream end. The fluxgate fits snugly into this smaller tube, which passes between the electric field plates, allowing the fluxgate to be scanned along the molecular beam line. The fluxgate rod is mounted on a rotation stage, which is in turn mounted on vertical and horizontal translation stages. The vertical stage is used only for alignment; the horizontal stage is used to scan magnetic fields over the length of the beam line. The horizontal stage has a range of about 25 cm.

The large tube that the fluxgate is inserted into is strapped by bungee cord to "cars" that smoothly translate along rails. These rails are finely aligned using translation stages at both ends. Initial alignment is performed using an endoscope on a rod, which is mounted to the probulator rotation stage (and therefore the translation stage) and inserted down the probulator tube. This allows us to see how well aligned the probulator axis is to the guard rings, as well as how close the plastic probulator tube is from the collimating aperture when we carefully advance it along the rails. When the plastic tube is nearly too close for comfort, we install a hard stop with optics posts. It is also necessary

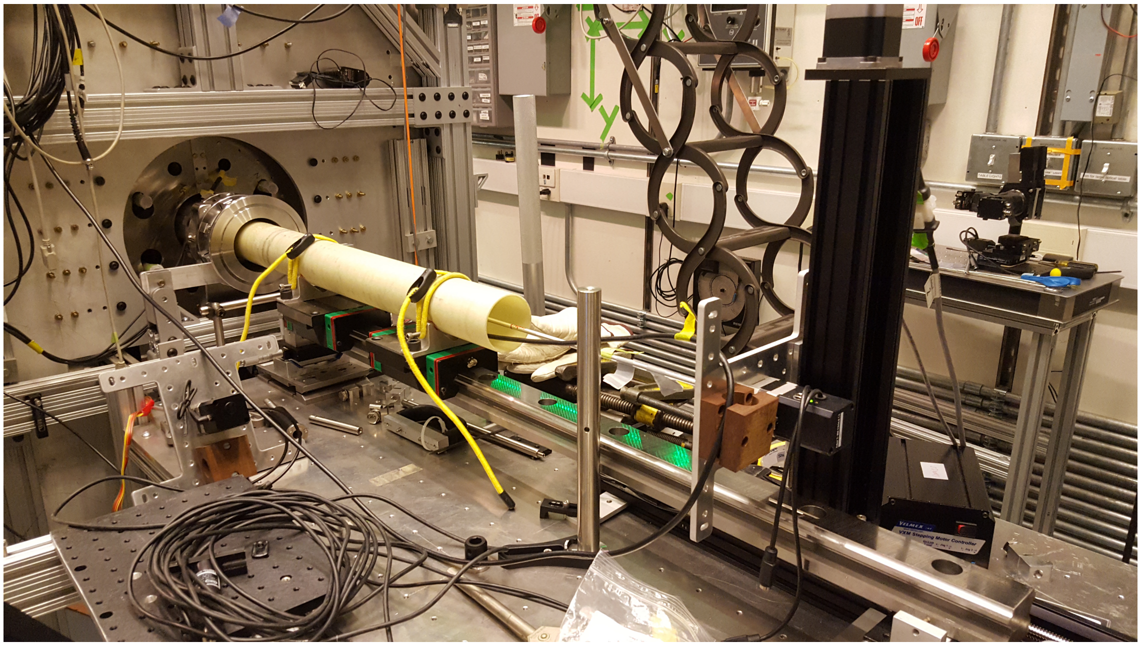

Figure 10: The probulator; see main text for detailed description.

to install a stop with optics posts for the downstream translation stage, which otherwise relies only on a spring to prevent motion in one direction.

We then remove the endoscope and install the fluxgate. We slowly advance the translation stage and mark the rod where the fluxgate is centered in both the pump and probe windows. We also mark the center of the interaction region at the position directly between these two points. We install a stop when the fluxgate reaches the end of the plastic tube, based on visual inspection. It can be useful to slide the cars back at this step.

Magnetic field scans can be performed "by hand" on the translation controller or in Labview. Our Labview program (1) sends both the probulator and vertical magnetometers to a given position, (2) applies a field, (3) rotates the magnetometers to eliminate electronic offsets along the non-axial directions, (4) flips the field, (5) repeats magnetometer rotations, and (6) repeats all steps at another position. This procedure allows us to map out reversing and non-reversing components of the magnetic field. Of course, before the magnetic shields are installed, non-reversing components can be many hundreds of mG.

It is important to realize before installing the probulator that the dump region gate valve is pneumatically actuated and will close if power is lost. Obviously, this would mean clamping down on the probulator and probably wrenching it into the field plates. To remove this possibility, we bled the pneumatic line to the gate valve and removed its power while the probulator was outside the apparatus.

3 Assembling the magnetic shields

Once we were confident that the magnetic field coils were correctly configured, we assembled the magnetic shields on the interaction region.

Before putting on a shield, it is important to make sure that all of the ribbon cable connectors are made and the ribbons are securely fastened to the shields with tape. One can then lift the shield into place while another person clamps down with a few screws. The shield hemispheres have joggles along their edges, allowing them to connect to each other. For a given shield (pair of hemispheres), the joggles are designed so that whichever hemisphere sits above the other on the top of the interaction region also does so on the bottom; this prevents either compression or expansion of the hemisphere radii. We prefer installing the "bottom" hemisphere second so that we can more easily align it below by overshooting and then lifting up, while we can easily see what we are doing on the top. The larger shields especially sag under their own weight, so it can be useful to have a person below the interaction region to apply some restoring force during installation. Otherwise, one hemisphere might stretch enough to wrap completely around the other.

The shields and (probably moreso) endcaps have become deformed over many iterations of being installed and uninstalled, so we use several tricks to get good alignment of the hemispheres to the endcaps and to each other. See Fig. 11 for an example of severely misaligned joggles. In no particular order, any of the following might be helpful:

- Tighten large straps around the circumference of the shields to squeeze them together (reducing their effective radius). This does not help with north-south alignment.
- "Walk" the shields: sequentially insert one screw at a time along an edge, thus slowly twisting that edge into place. If the top part of a hemisphere is aligned, for example, then inserting screws sequentially downward can be more effective than alternating higher and lower screws.
- Insert a slightly undersized Allen key through a clearance and tapped screw hole, then torque the holes into better alignment. This can make it much easier to insert a screw into an adjacent hole.
- Clamp the plate that supports the endcaps against the 80/20 structure, effectively pulling the endcaps farther away from each other. See Fig. 12.
- Insert a wedge between endcaps to reduce the distance between the endcaps of the shield being installed. This is only minimally effective for the inner shield since the wedge must be inserted between the first and second endcaps, and the second endcap will flex at least as much as the first. However, on the outermost shield, a wedge can be driven between the endcap and a large plate that is rigidly fixed in place. See Fig. 13 for one variant of this technique. This process is liable to disrupt the positions of the small white plastic shims used to prevent the endcaps from

Figure 11: The shield hemispheres can be severely misaligned to each other and to the endcaps on initial installation, even when they are fastened to the endcaps in some positions. Here the joggles are so far out of alignment that the threaded hole is not visible at all through the clearance hole.

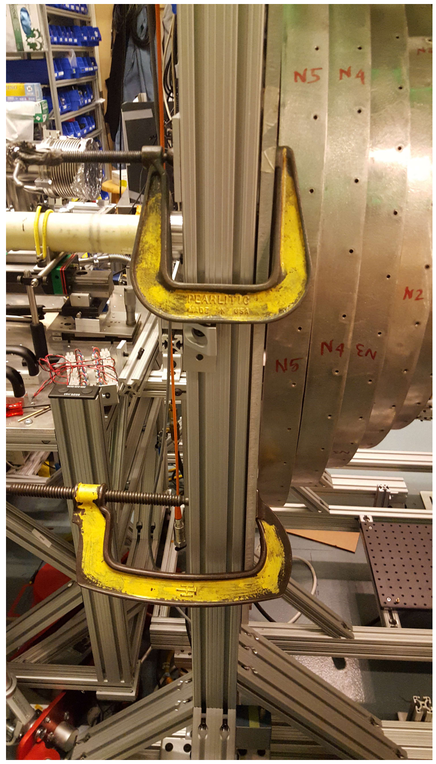

Figure 12: C-clamps used on the endcap mounting plate and 80/20 structure to increase the separation between endcaps.

making contact with each other, so make sure they are returned to their appropriate positions if they become loose.

- When the seams between hemispheres are misaligned north-south, one can pass a rope along the inside of the joggle region between window holes, tie each end around a rigid rod, orient the rod in the horizontal plane, and twist it (rotate it about the vertical axis) to apply a force pulling the shields together. This should allow one to insert a screw into other holes along the joggle, after which the rope can be slackened and removed.

There seems to be no particular pattern to the deformations; e.g., they do not get successively worse in either direction (inward or outward), and there is no cardinal direction or top/bottom distinction that seems to be consistently problematic. It is advisable to use most of the screw holes when possible since this probably minimizes asymmetric deformation that will make future installations even more difficult. It might be advisable to punch larger clearance holes in the shields so that alignment need not be as exact. Further, we might consider using titanium instead of brass for the screws, since we have found that

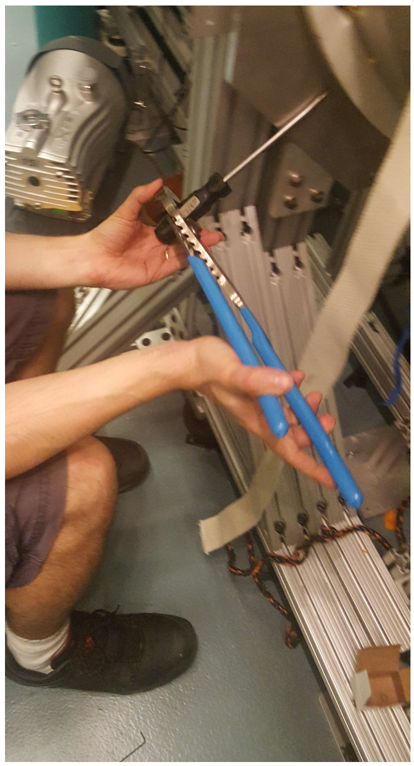

Figure 13: A variant of inserting a wedge between an endcap and the the endcap mounting plate. Here, a screwdriver is inserted and then torqued, pushing the endcap inward.

the brass screws strip easily. On the other hand, the μ-metal threads also strip easily, and titanium might exacerbate this more serious problem. We always mark bad μ-metal taps with Sharpie.

References

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