Tower section magnetometry system

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Contents

1 Introduction

This is a documentation of the magnetometry system that we developed to measure the magnetic field inside our two long tower sections. The magnetic field profile along the center line of the main tube informs us the performance of the mumetal shield, as well as any magnetic anomaly in the stainless steel vacuum system. Such information is useful to estimate the deflection of the atoms and the transfer efficiency of π-pulses during an interferometry sequence.

The main challenge of this measurement is to make the magnetometry system UHV compatible. Any shuttle system that sends a magnetometer down the length of the vacuum tube needs to be sufficiently cleaned, at least on the surfaces that may contact the inner wall. For the prototype tower, additional complexity arises due to the smaller tube aperture at the charge neutrality chamber (see Fig.1).

Since the electrodes require a polished surface to suppress high voltage discharge, to avoid any scratch, it is preferred that the magnetometer shuttle does not touch the electrodes during operation. Our design features a ski-lift-like system on a cable loop, which is tensioned

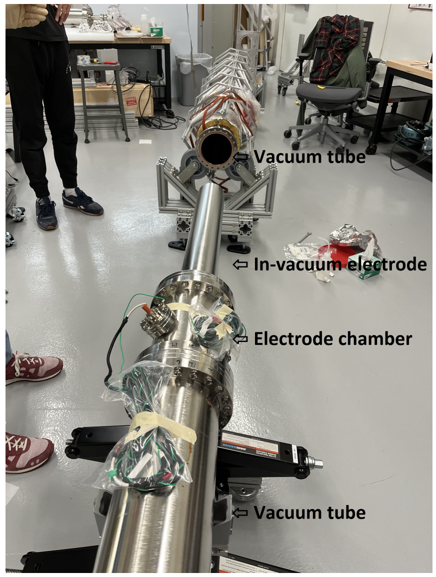

Figure 1: The prototype tower section has two cylindrical electrodes inside vacuum tubes. This image is taken before one of the vacuum tubes is installed, hence an electrode is visible. These electrodes reduce the tube aperture from 6″ to 4.5″.

over pulleys that interface with the vacuum system on both ends. Two opposite sides of the loop move anti-parallelly inside the vacuum tube when a hand-wheel is turned. The magnetometer is mounted in an aluminum box, which is secured to one side of the loop but slides freely on the other side. Turning the hand-wheel thus moves the magnetometer from one end of the vacuum system to the other.

The magnetometry system consists of the following five parts:

- The cable loop and the tools that help thread the cable through the vacuum system.
- The cart holding the magnetometer and electronics, which moves on the cable loop and takes data;
- The active-pulley side with a hand-wheel-turned pulley, also serves as the access port of the magnetometer cart;
- The passive-pulley side with a pulley on a ratchet strap, used for tensioning the cable loop;
- The laser distance sensor on the passive-pulley side, which measures the position of the cart and communicates with it.

In the next few sections, we discuss each of these parts in detail. We will also discuss our magnetometer calibration and data analysis procedures.

2 The cable loop

Historically we have been using PVC coated 316 stainless steel wire ropes (like the 1/16″ option in this website [1]). Later we found that the magnetization of these wire rope could add fake signals to our magnetic field measurements. This is especially problematic when we degauss the vacuum system, as the wire segments at the end of the shield are simultaneously exposed to an AC degaussing field and a large edge-effect DC field, leading to a $H = 0, B \neq 0$ state after degaussing. As a result, we used nylon mono line fish tape (like this Amazon product [2] that is about 1.5 mm thick and rated to 400 lbs) for the final measurements. The cable is connected end to end by aluminum crimps to form a loop. Note that nylon will lose tension over the course of a few hours, so periodic further tensioning is helpful in between measurements. In practice, we maintain the tension below 50 lbs (a spring scale monitors the force but reads twice the value, see Fig.4). When we need to leave the setup overnight, we release tension on the cable to prevent overstretching.

The nylon cable will touch the floor of the vacuum system before it is tensioned. Therefore, it needs to be properly cleaned and handled with clean-room gloves before feeding into the vacuum tube. Note that isopropanol should be used instead of acetone to avoid damaging the nylon. To prevent the cable from coiling up inside, we first pass through the vacuum tube a stiffer guiding "cable". We choose a spool of 1/4″ PVC pipe with clean foil wrapped around it. The wrapped pipe undergoes the same cleaning and handling procedure as the cable to ensure vacuum cleanness. Once the wrapped pipe passes through the entire vacuum system, we doubly fold the clean nylon cable and connect it to the end of the pipe, then pull the nylon across the vacuum tube. The ends of cable are then threaded through the pulleys and the cart, and finally crimp connected to form a loop. From our experience, both PVC feeding and nylon wiping require three people.

	Person 1	**Person 2**	**Person 3**
PVC feeding	Hold spool	Wrap sections of PVC pipe in foil and wipe	Feed wrapped pipe section into vacuum tube
Nylon wiping	Hold one end	Hold the other end and stand far away from Person 1, keeping nylon stretched	Wipe between Person 1 and 2

Table 1: Labor split between a team of three people.

The cable loop is out of contact with the vacuum system once it is tensioned. Before releasing its tension, the cable should be wiped again with isopropanol for vacuum cleanness. Cable sections inside the tube can be accessed and cleaned by turning the hand-wheel on the active-pulley side.

3 The cart

To avoid vacuum contamination, the magnetometer needs to work autonomously inside the tube and no power or data wire should come out of the cart. Therefore, we designed a battery-powered system, where an Arduino Nano reads the magnetometer data and stores them into a mini-SD card. There is also an accelerometer that reads the tip/tilt of the cart for potential angle correction in data analysis, but this feature is rarely used. All of these components are either plugged in or soldered to a PCB inside the cart. The Arduino also receives data from the laser distance sensor, which measures the position of the cart by sending a red laser at it and measuring the light travel time. Since the laser distance sensor is outside the vacuum system, this communication is done through infrared transceivers.

Table 2 contains the part numbers of the electronics, including those used on the laser distance sensor PCB. The schematics and Gerber files of the cart are in my Github [4].

Name	**Part number**	**Notes**
Magnetometer	Applied Physics 534D 150-7117	Digital flux-gate, range 1G
Arduino	Nano	
SD card board	Adafruit 254	$\leqslant$16G card only
Battery		Lithium ion polymer 3.7V
Battery board	Adafruit 2465	
Accelerometer	Adafruit 163	Not necessary
IR transceiver	Vishay TFBS4652-TR1	Need lens on transmitting side
IR encoder/decoder	Microchip MCP2120-I/P	
Laser distance sensor	DFRobot SEN0366	

Table 2: Part numbers of the electronics.

The cart itself is made of sheet metal aluminum, and has a lid that can be opened to access the components inside. Two wheels are mounted on the sliding side to guide the cable. The cart measures $5.5''$(L)$\times 1.875''$(W)$\times 1.625''$(H) and weighs around 300(?) grams. The CAD model of the cart and some components can be found here [5].

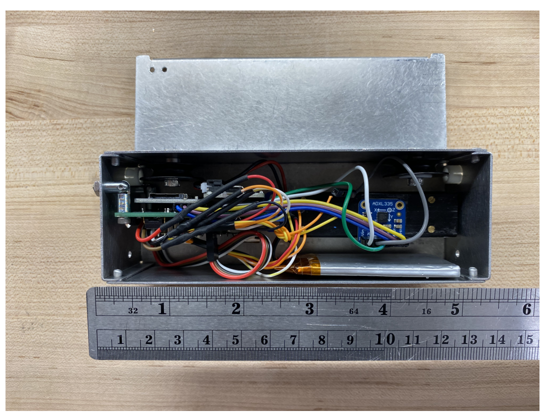

Figure 2: The cart. The lid is the actually same size as the cart. It looks smaller because it is farther away from the camera.

4 Active-pulley side

Both active- and passive-pulley sides refer to the 80/20 structure that attach to the ends of the vacuum system, as well as the pulley setups that mount to the 80/20 and support the cable loop. Each side connects to the 8″ ConFlat flange via a custom aluminum mounting plate. This is a $8'' \times 8'' \times 0.25''$ square with two/four mounting holes for $5/16''$ fasteners that go into the flange, a rectangular cut in the center for the cart to travel through, and some fastener holes to attach to the 80/20. A copper gasket should be used between the plate and the flange to protect the knife edge.

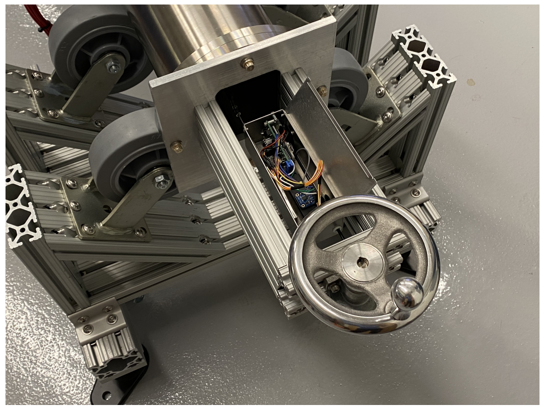

Figure 3: Active-pulley side with the cart in place.

The 80/20 frame on the active-pulley side has an opening to access the magnetometer cart (see Fig.3). This is handy since multiple lid openings are performed during measurement. The hand-wheel is connected to a fixed pulley through a shaft, which is supported by bearings mounted on the end of the 80/20 structure.

Preparation for a measurement is done on this side. This includes plugging in the SD card, switching on the electronics, closing the lid an wiping the cart with acetone/isopropanol. The cart is then sent into the vacuum tube via the hand-wheel. Once it hits a stop on the other end, the hand-wheel is turned backwards to retrieve the cart. Thus the magnetometer measures along the length of the tube twice. The measurement finishes when the cart returns to the active-pulley side. The SD card is collected and the system is ready for the next measurement.

5 Passive-pulley side

The pulley on the passive side is mounted on a T-slot slider, which can move on a pair of long 80/20 rails and modify the tension of the cable loop. The slider is pulled by a spring scale and then a ratchet strap. The stretchiness of nylon wire requires a $2.5' \sim 3'$ overhead space on the 80/20 rail.

Cable tensioning is done with the ratchet strap. We usually go for $80 \sim 100$ lbs on the gauge, which translates to $40 \sim 50$ lbs tension on the cable.

6 Laser distance sensor

The laser distance sensor is controlled by an Arduino and periodically measures the cart location by a laser beam. The Arduino then encodes this information and sends it towards

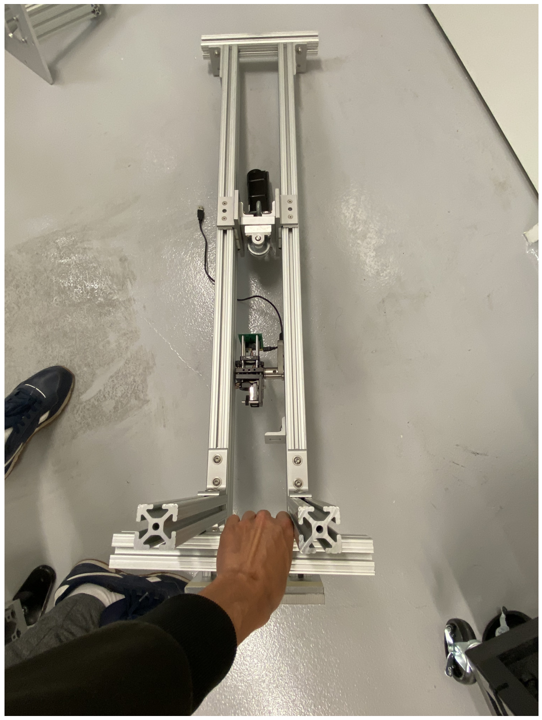

Figure 4: Passive-pulley side. The ratchet strap is not shown. It hooks onto where I'm holding, goes over the horizontal 80/20 on the end, then hooks to the black spring scale (McMaster 1756T5). Between my hand and the pulley is the laser distance sensor. There is also an L-bracket that serves as a stop for the cart.

the cart via an IR transceiver (part numbers in Table 2). All electronics, except for the laser distance sensor itself, are mounted to a custom PCB. The schematics and Gerber files can be found in my Github [4]. The laser distance sensor has a larger profile and connects to the PCB via ribbon wires.

To enhance the IR transmission range, an $F = 50$ mm lens is placed in front of the IR transceiver. The lens is supported by a Thorlabs 30 mm cage. The PCB design has incorporated mounting holes for the cage system.

A kinematic mount fixed to the 80/20 supports the laser distance sensor. It also supports the above-mentioned lens mount. The setup is arranged such that the laser and IR transceiver are facing the same direction, which can be adjusted via the kinematic mount knobs. We use these knobs to align the laser beam into the vacuum system, such that it does not hit the walls and always lands on the front surface of the cart.

7 Magnetometer calibration

Bias in the magnetometer reading comes from two sources: the internal offset of the sensor chip, and the magnetization from the electronics inside the cart. Each of them can contribute to a background of a few to tens of mG. Keep in mind that this bias is not a function of position and thus not relevant if we only care about field variation. It matters when we want to know the absolute field inside the shield.

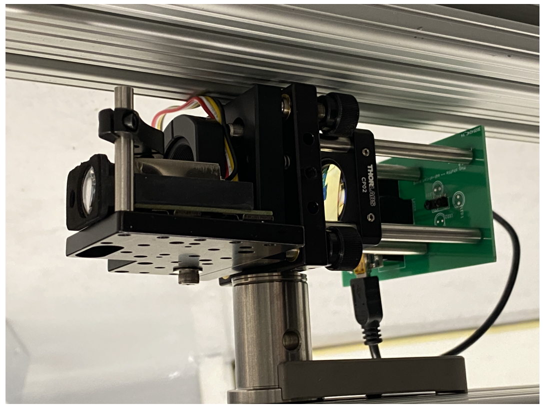

Figure 5: Laser distance sensor on a kinematic mount, and the PCB with other electronics.

To remove the first (i.e. internal) source of sensor bias, we fix the magnetometer inside a small mumetal container ($3.4'' \times 1.73''$ can from [3]), while leaving all the electronics out, sufficiently far away from the container. We then close the lid as much as we can, only leaving a small gap for wires to exit the container. We then flip/rotate the container 180°. For both orientations, magnetic field readings are recorded and compared. For the axes of the magnetometer that are flipped, the readings should nominally be equal and opposite, yet the bias will have the same sign. We thus deduced it by averaging the readings. We use this method to calibrate all 3 axes.

To remove the second (i.e. external) source of sensor bias, we secure the magnetometer to the cart and set the cart at a fixed position. We then move the electronics in and out of the cart and measure the differential field.

After calibration, the bias is subtracted from the measured field. We believe we can measure the bias up to mG level, which sets the error bar of our absolute field measurement.

8 Data collection and analysis

In an actual measurement, as we turn the hand-wheel and send the cart down the tube, the Arduino queries the IR receiver through serial about position data. Once the data comes in, the Arduino sends a serial command to the magnetometer asking the field components. It also reads the accelerometer's output voltages and converts them in unit of g. Once hearing back from the magnetometer, it writes position, acceleration and field values to the SD card.

To analyze the data, the file in the SD card is cleaned (the first data point is always corrupted) and read by a Mathematica script. The script extracts numbers from the file and plots them, with some hard-coded parameters and settings for the prototype tower, which needs to be modified for MAGIS. All codes mentioned in this documentation (Arduino/Mathematica) can be found in my Github [6].

References

[1] Stainless Steel Marine wire rope, https://stainlesssteelmarine.com/product/stainless-steel-wire-rope-7-x-7-black-pvc-coated-316-marine-grade

[2] Nylon fish tape, https://www.amazon.com/SEACHOICE-Black-Mono-Line-400/dp/B002IZ9G3M

[3] Mumetal container and lid for sensor calibration, https://www.magnetic-shield.com/mumetal-cans-lids-round-and-rectangular

[4] Yijun Jiang's Github - magnetometry PCB design, https://github.com/yijunj/Magnetometry/tree/main/PCB

[5] Yijun Jiang's Github - magnetometry cart CAD, https://github.com/yijunj/Magnetometry/tree/main/CAD

[6] Yijun Jiang's Github - code collection, https://github.com/yijunj/Magnetometry/tree/main/Code