Chapter 6

Other Systematic Effects

6.1 Synchronous Magnetic Fields from Electric Field Discharge and Leakage Currents

6.1.1 Discharge Currents

A microscopic examination of the surface of an electric field plate will show it to have numerous irregularities, pits, and protrusions. Protrusions on the cathodes are sites of local high electric field where electrons are more likely be pulled off. The electrons accelerate across the gap striking the anode where they release adsorbed gas and possibly bits of molten anode material, both of which may be ionized.

The positive ions then accelerate back across the gap where, striking the cathode, additional electrons or negative ions are released. This may initiate a complete breakdown or produce a continuous but irregular discharge current. The discharge current will produce a magnetic field that along with the discharge current will change sign and magnitude with the electric field reversal, mimicking an EDM.

Because the discharge current rises very rapidly as the breakdown voltage is approached, it is generally a matter of backing off the voltage—typically a few hundred volts—to reduce the discharge current to a safe level. It is even possible to set the discharge current below the sensitivity of the measuring apparatus by extrapolating a curve of voltage vs. discharge current. High discharge currents are generally erratic and unstable. They suddenly change magnitude and may disappear as the current polishes out the imperfections, or may grow into a full breakdown within minutes or hours. For this reason discharge currents, even if they are large and unrecognized, are more likely to cause erratic data than a subtle systematic effect.

6.1.2 Insulator Leakage Currents

If the insulating spacers, that separate the electric field plates and separate each electric field plate from conducting parts held at ground (Fig. 4.6), do not have infinite resistance, leakage currents and associated magnetic fields will be present when the plates are charged. Insulators are typically fabricated from alumina (high purity Al_2O_3) or fused silica (pure Si_2O_4). While fused silica has a room temperature D.C. volume resistivity of about $10^{19}\,\Omega\,\mathrm{cm}$, that of high-purity alumina is only $5 \times 10^{15}\,\Omega\,\mathrm{cm}$. In the proposed experiment all spacers will be fused silica spacers

With the very high volume-resistivity of the quartz spacers, bulk current flow is insignificant. Surface resistivity will need to be controlled by keeping the insulators clean and free of contamination. Techniques for doing this were well developed in the vacuum tube industry. Unlike glass, fused silica has no added oxides and so does not form surface hydrates.

6.1.3 Calculation of Magnetic Fields and Measurement of Currents

Currents flowing along the surface of or through the insulated spacers between the electric field plates, or between ground and an electric field plate (Fig. 9.1), will reverse with the electric field polarity. So will discharge currents, which typically initiate from a microscopic surface protrusion on the cathode and will change location and size with electric field reversal and may be more prevalent in one polarity than the other. If these currents create magnetic fields along the electric field direction that change with polarity, they can create a systematic effect that mimics an EDM signal.

A current flowing across the gap between the high-voltage electrodes, either from a discharge or insulator leakage, travels through the electrode, along the backing plates, and completes a circuit through the high-voltage feedthroughs and the power supplies. If the electric field is along the z axis, y is the vertical direction of travel of the atoms, and x is parallel to the electrodes (Fig. 3.1a), then currents in the z direction across the gap or an insulator, and currents through the electrodes (front-to-back resistance $\approx 8\,\mathrm{M}\Omega$), produce magnetic fields in the x-y plane.

If a discharge originates at a point on one electrode and travels only in the z direction to the corresponding point on the opposite electrode, there is little opportunity to generate a magnetic field in the z direction. Equal currents traveling along the opposing backing plates, in $+y$ and $-y$, create a magnetic field in the x direction; and equal currents traveling across the width of the opposing backing plates, in $+x$ and $-x$, create a magnetic field in the y direction. If the positive and negative high voltage attach at same location in x and y for each plate, then little or no field is expected in the z direction. The electric field plate design (Fig. 9.1) has the high voltage attachment points in this configuration.

There is however no physics reason why the discharges can not have a small x or y component. The electric field over the longer path length is reduced, and discharge currents drop rapidly with decreasing fields, so the x and y components will be modest, but looking at photographs of electric discharges reminds one that they do not often occur only between the closest points. In the case of leakage currents across insulators, the current might, due to some surface contamination, start on one side of a cylindrical insulator and end on the opposite side.

The experiment is designed to have a sensitivity to a shift of $3.4 \times 10^{-7}\,\mathrm{Hz}$ for an EDM limit a factor of 100 below the present bound. The magnetic moment of an unpaired electron (and hence of an alkali atom) is $(9.27 \times 10^{-24}\,\mathrm{J/T})/6.626 \times 10^{-34}\,\mathrm{J\,s} = 1.40 \times 10^{10}\,\mathrm{Hz/T}$. Hence a shift of $3.4 \times 10^{-7}\,\mathrm{Hz}$ can be caused by the reversal of a magnetic field of $2.4 \times 10^{-17}\,\mathrm{T}$.

If we know the relationship between discharge and leakage currents and the magnetic fields they generate (and the extent to which these magnetic fields are then experienced by the atoms in the fountain), and if we are able to measure the discharge and leakage currents, then we can insure that the discharge and leakage currents do not add to the systematic error budget.

The relationship between the discharge current and the magnetic field produced has been determined by calculation and by measurement at low voltage (simply by shorting out a set of plates), and the relationship between the magnetic field produced by the discharge and the magnetic fields actually seen by the atoms in the fountain trajectory has been determined by further calculation. The measurements were performed on a set of titanium and aluminum plates that were shorted with a metal shim (Fig. C.1). The calculations and measurements are described in Appendix C.

Briefly, the model assumes a (realistic) worst case of a discharge at 30° to the normal between the plates and separately calculates the magnetic field for the discharge tilted in the x and y directions. Magnetic fields in the z direction are produced from the component of discharge current in the x and y directions, and from the difference in resulting path lengths of the currents flowing in the electric field plates and the backing plates. The path length difference occurs in the electric field plates, but because the electric field plates have higher resistivity than the backing plates, the longest current path flows are through the backing plates.

Because the z component of the magnetic field decreases rapidly with distance from the discharge, the location of the discharge is important. The atoms in the fountain spend the most time near the turnaround point so a discharge here will subject the atoms to the strongest average field. In our model (See Appendix C.5) this is 7×10^{-7} T/A, implying a maximum allowed current of 34 pA.

Discharges will however be randomly distributed and the resulting upper limit for the average z-direction magnetic field due to random discharge currents is, from a Monte Carlo calculation (Appendix C.6), 5×10^{-9} T/A, implying a maximum allowed current of 5 nA.

Because the insulators are always at least several cm from the fountain, z-direction magnetic fields from leakage currents across insulators will, for the same current, be smaller than magnetic fields from discharges across the main electric field plates. Discharge currents and leakage currents between the backing plates and ground will likewise produce smaller z-direction magnetic fields at the fountain.

We can monitor the discharge and leakage currents by measuring the currents flowing through the high voltage cables going to the electric field plates. To do this we measure the voltage across a resistor in series with the electric field plates as shown in Fig. 6.1, as was done in the experiment[1] in Ref. [ACC+90]. In the proposed experiment, a relay will disconnect the resistor during charging or if not in use.

In our worse case scenario of discharges only at the apogee, a 100 MΩ series resistor will produce a voltage of $\pm 3.5 \times 10^{-3}$ V for our allowed discharge current limit of 34 pA. (For discharges averaged over the entire electric field plate system, the allowed discharge current limit produces a voltage of 0.5 V.)

[1]The resistor and a battery-operated voltmeter floated at the electric field plate voltage, typically ±10 kV, with the voltmeter viewed through a plastic window. Reversing the polarity subjected the voltmeters to an over-voltage and a full breakdown occasionally destroyed meters. The design in Fig. 6.1 alleviates that problem.

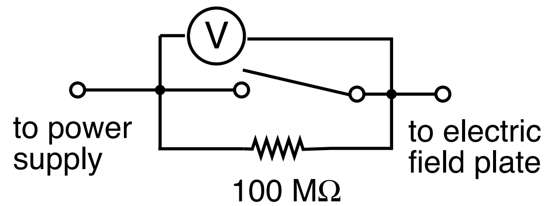

Figure 6.1: Discharge and leakage current measuring apparatus. The closing of the relay when a measurement is not needed protects the meter during charging and discharging and in the event of breakdown (See Section 9.3).

The 0.5 V is easy to measure and the 3.5 mA is just within the limit of an inexpensive battery-powered voltmeter. Far smaller currents can be measured with more sensitive meters.

At some point the discharge current is below the current caused by leakage current through the polyethylene insulation in the coaxial cable carrying the high voltage between the current-measuring meter and the electric field plates. This leakage takes place far from the fountain atoms but registers on the meter. It can be suppressed by manufacturing cable with a higher resistivity dielectric insulation and/or by using a triaxial cable [Fah11] with a slightly lower voltage intermediate between the high voltage and ground (guard voltage) to reduce the current flow across the inner dielectric.

6.2 Magnetic Fields from Electric Field Plate Charging Currents

The charging and discharging of the electric field plates requires a current to pass through the magnetic shielding layers and along the inside of the inner shield layer. Because the electrodes charge to ±50 kV, the current flows into one electrode and out from the other. If the currents are large and their path is close to the magnetic shielding, the resulting magnetic fields can magnetize the shields, producing magnetic fields that persist after the charging is complete and which change synchronously with the electric field reversal, mimicking an EDM signal. There are a number of defenses against this problem and a number of simple tests to set limits on the possible size of an effect.

Because a reorientation of magnetic domains is needed to magnetize the shields, very small magnetic fields do not permanently magnetize the material. This has been confirmed in the proof-of-principle fountain EDM experiment [AMG07, Ami06], where magnetic fields of about 0.02 A/m (30 nT) were applied by coils just inside the inner magnetic shield and then reversed. This was done to measure the size and direction of remnant magnetic fields in the apparatus using the cesium fountain beam as the magnetometer and using a three-axis set of coils inside the inner shield as magnetic the field source (the field at the beam, 7 cm from the shields, was about 50 nT). No hysteresis effects were observed with successive reversals of this applied magnetic field. In the cesium magnetic prototype apparatus (Section 7.1) there will be opportunities for more sensitive tests.

The largest magnetic field that can be tolerated can be estimated from the mu-metal coercivity, defined as the applied magnetic field needed to reduce magnetization of that material to zero after the magnetization of the sample has been driven to saturation. The coercivity of Carpenter Steel's HyMu 80, used for our half-scale test shields, is $\geq 0.64\,\mathrm{A/m}^2$. One centimeter (a likely clearance between a cable and the shield) from an infinitely long current carrying wire, we have from $B = \mu_0 i/2\pi d$ and $H = B/\mu_0$ that $H = 16i\,\mathrm{A/m}$, suggesting that the current should be kept below 40 mA and/or that the high voltage cable kept further than one centimeter from the shielding. The electric field plates plus 10 m of high voltage coaxial cable have a total capacitance of roughly 300 pF and at 100 kV they store 3×10^{-5} Coulombs of charge. To keep the inrush below 40 mA, the charging time needs to be greater than $7.5 \times 10^{-4}\,\mathrm{s}$. We plan a charging time of about four seconds, as explained below.

In the proposed EDM experiment, the atoms are collected for roughly nine seconds before launching and this time is available for electric field reversal[2]. To reverse the electric field the voltage will first be lowered to zero at a rate that maintains a near constant minimum current. Several seconds are thus available for charging or discharging with additional time left for the voltage to stabilize after reversal. The relay will be reversed at zero voltage and the voltage increased, again at a rate that maintains near constant current. Finally, should it ever be deemed necessary, the charging currents can be nulled by running a low-voltage current-carrying wire alongside the high voltage cables: the current in the wire preprogrammed to match the charging/discharging profile or programmed from the current metering of the high voltage power supplies.

6.3 External Synchronous Magnetic Field Effects

A magnetic field synchronous with the reversal of the electric field may be generated, for example, by the switching of relays, or by current flowing in ground loops that change with the logic state of a computer-driven circuit. The first line of defense is to avoid them by electrically isolating the magnetically sensitive part of the apparatus, pairing relays and high current drivers to cancel magnetic fields, placing potentially offending equipment far from the fountain, and by periodically reversing the relation between switch or logic state and electric field polarity.

Magnetic shielding also plays an important role and the increased shielding factor, needed to reduce magnetic noise with increasing EDM sensitivity, also shields synchronous magnetic fields by a similar factor. In the francium EDM experiment, the state preparation and analysis takes place inside the magnetic shielding but the detection is done after the atoms leave the shielded region. This keeps the currents from photodetectors outside the shielding and leaves no atoms in the interaction region

[2] Thermal atomic beam electron EDM experiments have reversed electric fields from as often as nearly every second to as infrequently as once every 30 seconds.

or even sensitive to magnetic fields while photocurrents are flowing.

To check for unforeseen synchronous external magnetic fields, one or more fluxgate magnetometers can be set up outside the magnetic shielding to detect synchronous changes in the ambient magnetic field. The experimental EDM sensitivity of a shift of 3.4×10^{-7} Hz could be caused by a reversing magnetic field of 1.2×10^{-17} T, or by about 1.2×10^{-10} T outside of the shields (a larger field would be required if the shielding factor was larger than 10^{7}). This is large enough to be readily picked up by our low-noise Magson fluxgate magnetometer. In addition, tests will be run using magnetic field coils to test the sensitivity of the experiment to synchronous fields.

6.4 Electric Field Incomplete Reversal

For an incomplete reversal of the electric field to lead to a systematic effect in our experiment at least three conditions must be met:

1. There must be a pollution of the state preparation and/or the state analysis. The tensor polarizability being the same for $\pm M$ ($M \neq 0$), a superposition of of $\left|F, M\right\rangle$ and $\left|F, -M'\right\rangle$ (where $M = M'$) is insensitive to the tensor polarizability and therefore insensitive to an incomplete reversal of the electric field. If the state preparation or analysis laser polarization contained an admixture of circular polarization then atoms that were not in a superposition of $\pm M$ (for example, $\psi = \left|5, 1\right\rangle$) could be present.
2. The phase advance must deviate from $k\pi$. There may be an incremental departure a of the Stark phase from an integer multiple k_ϵ of π, namely
$$\int_{-\infty}^{\infty} \epsilon_z^2(t)\, dt - k_\epsilon \pi = a \neq 0 \; . \tag{6.1}$$
This however is kept very small (Section 5.6).
3. There must be not just an incomplete reversal of the electric field but a systematic incomplete reversal of the electric field. For a reversing system that uses mechanical relays in a very high impedance circuit, possible differences in contact resistance are not of great concern and are averaged out by cable swapping at no cost to experimental progress[3].

The limit on any systematic effect from incomplete reversal as a function of laser polarization purity and electric field reversal will be experimentally bounded.

[3] We are unaware of any electron EDM experiment of the past 50 years in which incomplete reversal of the electric field has led to a systematic problem.