

Original Paper

Strategy for Locating and Eliminating Sources of Mains Frequency Stray Magnetic Fields

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Locating and Eliminating Sources of Mains-frequency Stray Magnetic Fields

It is generally recognized that stray magnetic fields can degrade the performance of electron optical instruments. Modern instruments are usually designed to be insensitive to fairly high levels of ambient field but some older instruments are not (Downing and Chiu 1980). Particularly sensitive are scanning microscopes in which the sample is located below the lens in a poorly shielded specimen chamber. The problem is even more serious when low accelerating voltages are used. This is both because the slower electrons are more easily deflected and because the upper lenses are often operated at lower demagnification to compensate for reduced source brightness and, as a result, the action of stray field on the beam in the upper part of the column becomes evident. This second point becomes even more important when electron guns that have smaller virtual source dimensions, such as field emission or sharply-pointed thermionic filaments are used. There is presently much interest in low voltage SEM operation (Pawley 1984) and we have found the analysis and procedures outlined below to be helpful in reducing the problems of mains-frequency AC stray magnetic field.

Sensors for Stray Field and Net Current

In order to locate the sources of stray magnetic fields it is necessary to be able to measure both the fields themselves and the presence of net AC current flow in a wire or cable. These sensors can easily be made or purchased.

Stray field sensor

Stray magnetic fields can be measured with a search coil and an oscilloscope. Choosing these components properly is, however, important to success. The signal from the coil in a given field is proportional to its area and to the number of turns. Large coils, however, are clumsy and difficult to insert into confined spaces in order to identify the actual source, so coils on the order of 2–3 cm on a side are desirable. The coil of a high impedance relay, sometimes referred to as a plate relay, is ideal. This coil can be calibrated in terms of Volts/Tesla or mV/mgauss at mains frequency by placing it and the probe of a calibrated AC magnetometer in the same location and orientation near a power transformer or some other source. Remember that the magnetometer will probably be calibrated for RMS reading while, on the oscilloscope peak-to-peak readings are more easily made (for a sine wave $V_{\text{rms}} = V_{\text{p-p}}/2.8$). Even an uncalibrated detector can be very

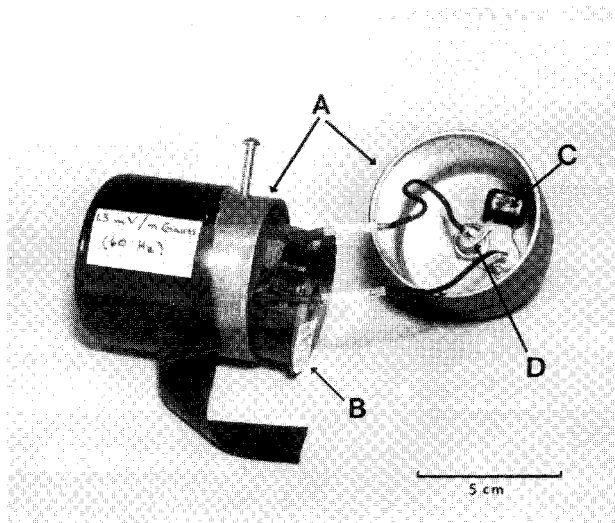


Fig. 1 Stray field sensor: The solenoid (B) is mounted inside a copper electrostatic shield (A) which is in turn wrapped in plastic tape. The two ends of the coil pass to a BNC output connector (D) and a small capacitor in parallel (C) to reduce radio frequency pickup.

useful for measuring how fields intensities vary with position or time of day or the relative effect of turning various electrical and electronic circuits on and off.

In many laboratories, it is surprising to discover that electrostatic fields at mains frequency are present at sufficiently high levels to be responsible for the majority of the signal from an unshielded coil such as that described above. As the electrical conductivity of the metal components of the column is very good at low frequency, it is unlikely that these electrostatic fields will interact with the beam and the sensing coil should therefore be shielded to exclude them if it is to give a meaningful output. Some relays come in hermetically-sealed metal containers and these will usually shield the coil sufficiently if they are grounded to the side of the coil which is connected to the shield of the coaxial hook-up cable. Otherwise, a tightly fitting thin foil copper shield should be used. The outside of the shield should be wrapped with plastic tape to prevent the formation of a ground loop should the shield inadvertently touch some grounded piece of equipment. A sense coil (40k turns; #40 copper wire; 14.7 k Ω) mounted in such a shield is shown in Fig. 1. Two small capacitors have been added in parallel to further reduce radio frequency pick-up. The sensitivity of this coil is about 1V/10⁻⁴T (1 mV/mgauss).

Although the output of such a coil can be measured with a high impedance AC millivoltmeter, being able to see the waveform of the signal is often very helpful in determining its source and so an oscilloscope is preferable. It should have a sensitivity of at least

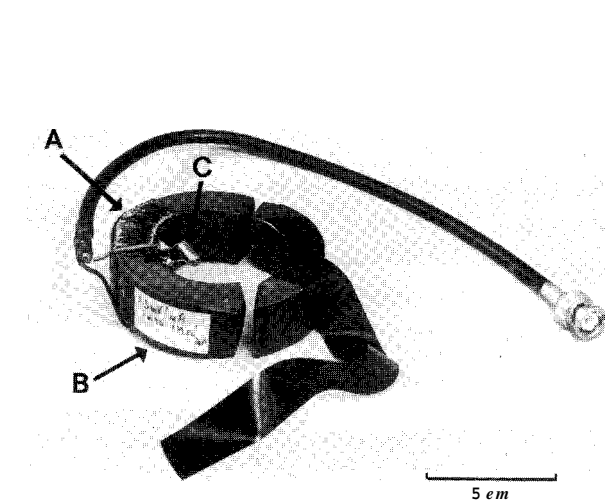


Fig. 2 Net current sensor: About 500 to 1000 turns of magnet wire (A) are wound on a large fractured ferrite core (B) and connect to a shielded cable in parallel with a small capacitor (C) to remove radio frequency pickup. The two parts of the core are then wrapped separately in plastic tape.

1mV/division and should be grounded only through its power cord. If an instrument with a differential input is found to be necessary, care should be taken to use a single shield for the two balanced input leads or, if two separate coaxial cables are used, to twist them together between the oscilloscope input and the sensor and to ground the shields only at the oscilloscope input. The finished sensor should show no output when surrounded by a high permeability shield such as a lens bore or a Mu-metal tube and it should show no change when wrapped in additional grounded copper foil or when touched to a piece of grounded equipment.

When searching for stray fields bear in mind that the sensor is only sensitive to fields passing along the coil axis and therefore it must be constantly rotated to detect the maximum field. It will probably be necessary to reduce fields to less than 0.2-1x10⁻⁷T, (1T = 1Vsm⁻² = 10⁴ gauss) near the column (with all equipment operating) in order to obtain optimal low voltage SEM results. The region of the electron gun and the sample chamber are particularly sensitive because here the electron beam is not shielded by high permeability lens structures.

Net AC current sensor

A net current sensor is really a step-up transformer in which the cable to be measured constitutes a single-turn primary and the output is taken from a multi-turn secondary. The magnetic core that connects the two windings is split so that it can be placed

around the wire to be measured. Such a sensor can be purchased from an oscilloscope manufacturer but these are often only large enough to go around small wires. A larger sensor capable of encompassing power conduits can be easily fabricated by fracturing a large (5–10 cm diam.) ferrite core into two approximately equal segments and wrapping about 1000 turns of magnet wire around one of these. Such a sensor is shown in Fig. 2. In use, the two halves are held together by hand around the cable to be tested and the output from the coil is fed to the oscilloscope. The exact sensitivity of the transformer will depend on the low-field permeability of the ferrite and the accuracy of the fit on reassembly; but it should be about $1\text{mV}/\text{mA}$ and can easily be checked by measuring the current through fixed resistors fed with a measured AC voltage. Such a sensor is also sensitive to stray magnetic field but this can be compensated for by making a second measurement with the sensor in the same position and orientation, but without the wire passing through it.

Finding the Source

Mains frequency fields are produced by an AC current flowing in a loop. The strength of the field is proportional to the current and inversely proportional to the area of the loop. The strength decays with at least the third power of the distance from the loop when this distance is measured in units proportional to the area. In other words large loops produce smaller fields but they diminish more slowly with distance. It is sometimes helpful to divide sources of stray field into those associated with the building and those produced by the instrumentation itself.

Obvious possible sources of the first type are the coils of large electric motors or transformers, but perhaps because flux leakage from the magnetic armatures of these devices represents inefficiency in performance, the actual stray field output from such sources is often much less than expected. An important exception is the saturable transformer used in some types of AC voltage regulator. Sometimes such regulators are used not only to condition the power supply for the microscope itself but also to provide a coarse regulation to the power supplies in test instruments used near the microscope. Main trunk power cables are another obvious source but here again, as long as both the “hot” and neutral of every circuit are enclosed in the same conduit, the loop between them is small and the field drops rapidly with distance. Of far greater practical importance are mistakes in the building wiring where, for instance, the neutral return is erroneously attached to the ground wire on a piece of equipment which is also

grounded independently, perhaps by a strap to the water line. As a result a current will flow through a large loop, up the “hot” line and down the water pipe. A similar loop can be caused by having two possible current paths between any two nodes in the house wiring and because the loop is large the field it produces can extend for tens of meters. Location and eradication of these faults usually requires the two sensors described above, a patient electrician and a thorough process-of-elimination search at a time when the power circuits can be separately disabled and the net current flow in various branches of the house wiring measured. A more complete discussion is found in *Alderson* (1975, pp 46–66).

Stray fields produced by the instrument itself often become a problem only when *too* much equipment is compressed into a small area. Magnetic fields from point sources such as mechanical pump motors, television monitors, and ion-pump transformers drop off with at least the third power of distance and so strong fields from these sources can usually be reduced by moving or possibly just rotating the sources. On the other hand, occasionally the presence of the ferromagnetic material in the instrument will distort existing stray fields in the room in such a way that an area of low field becomes an area of high field and vice versa. Separate surveys should be carried out before and after installation and whenever a major accessory is added. Be particularly suspicious of electromechanical clocks and timers such as may be used to keep liquid N_2 reservoirs filled.

If it is found impossible to eliminate the sources of stray magnetic field, the only solution is either to shield the source or the instrument. The former sometimes can be accomplished by surrounding the source with a soft iron box while the latter entails the use of high permeability materials such as Permalloy (16.7% Fe, 79% Ni, 4% Mo, 0.3% Mn) or Mu metal (18% Fe, 75% Ni, 2% Cr, 5% Cu). To work efficiently, shields made of these special materials must be carefully heat-treated to about 1200°C in a controlled atmosphere after fabrication, a process usually best performed by a specialized company rather than an experimental electron microscopist. They are mentioned here so that we can point out that such materials saturate at relatively low magnetizations (0.6–0.8 Tesla vs 2 Tesla for pure Fe). If they are placed in a strong DC magnetic field such as that produced by an ion pump or lens, they may saturate and cease to be effective in shielding AC fields. Saturation by a DC field can often be detected using a small compass. This indicator should show no preferred orientation when placed just inside a magnetic shield.

Stray Currents

Even if there are no stray fields at the outer surface of the column, they can still exist on-axis if they are introduced by stray currents to the various electromagnetic components such as lenses, deflection coils, or by currents flowing through the column as a result of ground loops. Though it is not appropriate to give here a comprehensive treatment of the engineering considerations that must be observed to produce stable lens and deflection current supplies, it is possible to draw attention to some general principles that are sometimes overlooked during the initial installation.

With the exception of the electron beam, no currents should flow through the structure of the column. It should be electrically connected to the neutral of the electronic power supply and to building ground only by one heavy braided wire. If the braid is removed from the column, all of the wires carrying currents to or from the column should be totally isolated from it. All currents should be carried in shielded cables and the shields should be grounded only at the power supply ends. If this has been done correctly there should be no net current flow in any of the cables going to the column because the current in the hot wire to each component will exactly balance the return current in the neutral wire and the shield will carry no current.

Net AC current in a wire can be sensed with the clip-on current transformer described above. All cables between the column and the electronics or between either and any accessory equipment and also all connections to the mains should be checked and readings above a few mA should be investigated. It is sometimes possible to cancel the signal from one cable by including more than one cable in the ferrite core. This indicates that there probably exists a connection between at least some of the conductors at both ends of these cables, instead of only at one end. A common problem is that the microscope and some computer-based accessory are often grounded both through their power supply and through the shields of various co-axial cables between them. This can be avoided by removing the ground connection through the power cable and taking precautions that the ground path via the signal wiring cannot be accidentally removed under any conditions. Without this second precaution there could be a serious shock hazard to personnel in the event of a short in the equipment. In the event that the ground loop cannot be broken, the wires involved should be twisted together and inserted into a heavy sheath of copper braid to make the loop as small as possible.

Power supplies in the SEM are usually said to be current-referenced in that the voltage, V_s , across a resistor in series with the electron optical component is compared with the control voltage, V_c , by an operational amplifier which operates on the regulator circuit to keep $V_s - V_c = 0$. If, however, a stray field induces a current in the components and wires that make up the driving circuit or the feedback loop, the operational amplifier will put out an erroneous current of proportional size, though opposite phase, through the electron optical component. For this reason it is important to keep strong stray magnetic fields away from circuitry driving any electron optical component. In circuits handling currents that normally change only very slowly such as those supplying lenses (except dynamic-focus coils) and alignment coils, mains frequency ripple can be removed by passive filtering but this is not true of scanning currents. Mains frequency components in the output from the scan generator and scan amplifier are very difficult to detect because at high magnification the signal levels are very small. However, an indication can be obtained by measuring across the resistor in series with the scan coils when the input of the scan amplifier is shorted (spot mode) using an oscilloscope grounded to the instrument power supply neutral and having a sensitive (10–50 $\mu\text{V}/\text{div}$), AC-coupled, differential input. The main frequency signal should not be visible above the broad-band noise signal. To ensure that the measuring set-up is not inadvertently producing the measured signal one should check that the signal disappears when the scan amplifier is unplugged.

Acknowledgement

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