



External Magnetic Field Reduction Techniques for the Advanced Stirling Radioisotope Generator

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Abstract

Linear alternators coupled to high-efficiency Stirling engines are strong candidates for thermal-to-electric power conversion in space. However, the AC and DC magnetic field emissions of these permanent magnet excited alternators can interfere with sensitive instrumentation onboard a spacecraft. Effective methods to mitigate both the AC and DC electromagnetic interference (EMI) from solenoidal-type linear alternators (like that used in the Advanced Stirling Convertor) have been developed and demonstrated for potential use in the Advanced Stirling Radioisotope Generator. The methods developed avoid the complexity and extra mass inherent in data extraction from multiple sensors or the use of shielding. This paper discusses these methods and also provides analytical results for both the AC and DC techniques. Data obtained during breadboard testing of the AC external magnetic field technique are presented. Preliminary testing of the DC technique is also discussed.

Nomenclature

ϕ	polar angle ($^{\circ}$)
μ_0	permeability of free space ($4\pi \cdot 10^{-7}$ Henries/m)
AC	alternating current
ASC	Advanced Stirling Convertor
ASRG	Advanced Stirling Radioisotope Generator
EMI	electromagnetic interference
FEA	finite element analysis
B	magnetic flux density (T)
B_{rem}	remanent magnetic flux density (T)
DC	direct current
H	magnetic field strength (kA/m)
I_{Ac}	Amperian current (A)
M	magnetization (T)
M_{bc}	magnetization of DC bucking magnet (T)
M_{mc}	magnetization of alternator magnet (T)
MM	magnetic moment of Amperian current hoop ($A\text{-m}^2$)
N	number of turns, linear alternator
N_b	number of turns, AC bucking coil
r_b	radius of AC bucking coil (mm)
r_{bc}	radius of DC bucking magnet (mm)
r_{mc}	radius of alternator magnet can (mm)

r_o	radius of hoop equivalent to alternator coil (mm)
t_{bc}	thickness of DC bucking magnet (mm)
t_{mc}	thickness of alternator magnet (mm)

Background

Stirling engine-driven linear alternators are considered to be promising candidates for providing electrical power for deep space missions, such as to the outer planets, where the insolation is inadequate for practical use of solar energy. Typically these engines take heat from a radioisotope source and in turn convert their linear motion to electricity by means of a coupled linear alternator. The engines themselves are basically thermodynamic oscillators, having a free piston and operating in a Stirling cycle-type mode.

Of particular interest to power instrumented planetary probes are Advanced Stirling Radioisotope Generators (ASRGs) in the 100-W class (Dudzinski (2011)). These spacecraft typically carry extremely sensitive instrumentation, such as magnetometers for field mapping, which can be adversely affected by the electromagnetic interference (EMI) fields emanating from nearby alternators. The magnetic field limit has been considered a potential roadblock to application of Stirling convertors to power certain instrumented missions. AC components are considered the most troublesome (Pope et al. (2009)) due to their amplitude, whereas the smaller DC components can presumably be cancelled locally at the sensor by a judicious placement of permanent magnets.

This paper discusses methods of reducing both the AC and DC components of the B-field emissions over an extended region from the alternator. The methods basically amount to field cancellation by superposition close to their source. However, their implementation differs sufficiently to require separate discussions.

Method of Suppression of AC Field Emissions

B-Fields and Alternator Geometry

An external B-field reduction technique was developed for use on an 80-W Advanced Stirling Convertor (ASC) intended for space power applications. The ASC is equipped with a permanent magnet excited linear alternator. The magnets (high-energy NdFeB-type) form a hollow can-like structure that is polarized radially outward and oscillates back and forth within a solenoidal pickup coil. This coil is surrounded by a shell of Hiperco-50 laminations and forms the stator of the alternator; the inner part of the stator is within the can and closes the magnetic circuit.

Finite element computations using the Maxwell software showed that most of the alternating B-field at 1 m distance was due to the load current in the coil. The contribution due to the stator laminations, even though being a magnetic material, was considerably less. According to the plots in Figure 1, the field geometry is essentially close to dipolar, having maximum amplitude on the axis. In short, with a steady 10 A in the coil, its far field essentially coincides with that of a point-like magnetic moment of strength of 1.30 A m^2 and aligned with the axis of symmetry. These computations show that the stator laminations, under the influence of the field of the coil, contribute a B-field that roughly mimics the geometry of the dipole-like field of the coil, resulting in a total field of about 1.2 times the field of the coil alone.

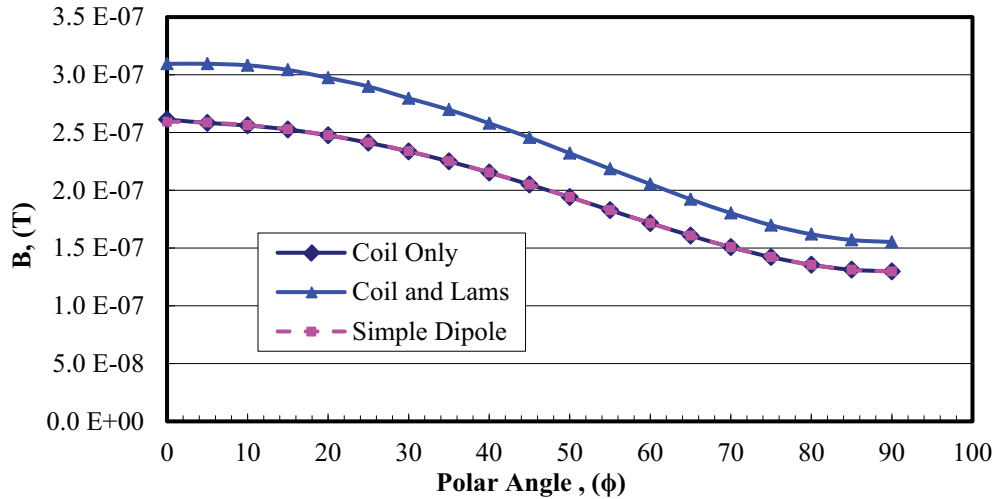


Figure 1.—B-field magnitude as a function of angle ϕ from the z axis. The dipole computation is according to classical formula. The magnet can is absent and coil current is 10 A. Note that the “coil only” and “simple dipole” curves coincide.

Estimate of Bucking Coil From Classical Dipole Field and Experiment

The external field due to the load current in the coil of the alternator can be reduced by winding a field bucking coil on the outside of the containment vessel and connecting it in series to carry the load current.

The parameters of the alternator coil being known, it is quite simple to calculate its magnetic moment, or even to replace it by a single current loop of equivalent moment and computed radius r_o . An order-of-magnitude estimate of the bucking turns required can be based on equating to the moment of the alternator’s coil. This calculation gives a quick starting point for experiment, even though it might be expected to overestimate the required turns. For example, consider a single-layer bucking coil of radius r_b , located just outside of the containment vessel of the alternator. Since the same current flows through both the alternator and bucking coils, the formula for the bucking turns is

$$N_b = N \left(\frac{r_o}{r_b} \right)^2 \quad (1)$$

However, this overestimates the turns required in the present case by nearly a factor of two. The reason is that the bucking coil sees the whole stator as a highly permeable cylindrical stub through its center. A better, although more laborious, estimate can be obtained through finite element analysis (FEA). A two-dimensional FEA model of the ASC linear alternator was created. The magnitude of the B-field at a distance of 1 m from the geometric center of the alternator was calculated for various bucking coil configurations and at various polar angles as shown in Figure 2. Comparing the coil and lams curves in Figure 1 with Figure 2, it is evident that about 18 turns should be an acceptable estimate.

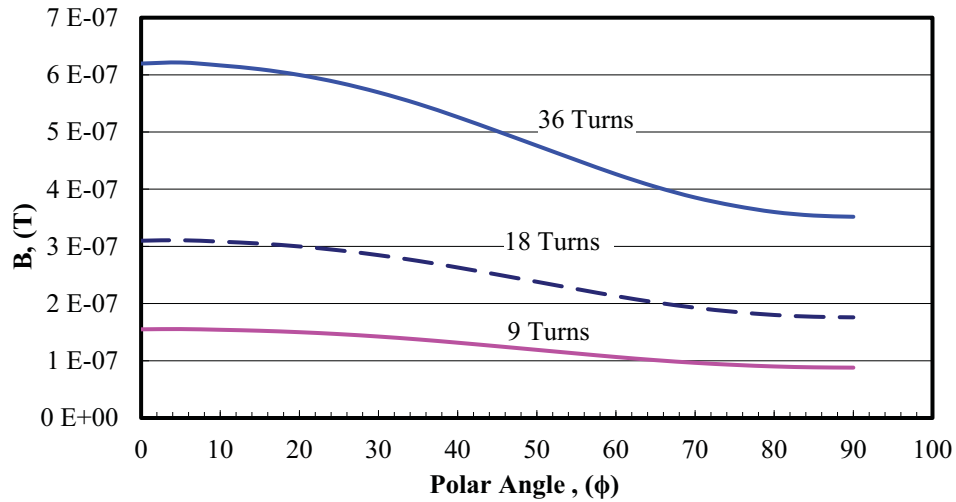


Figure 2.—Magnitude of the B-field at 1 m distance produced by the bucking coil with the stator as a core. Plots are for the indicated number of turns carrying 10 A and $r_b = 3.4$ cm.

Experimental Verification of AC B-Field Reduction

Two Stirling engine-driven linear alternators of above type were mounted in an opposed piston configuration and positioned as they would be in the ASRG application. Each alternator was equipped with a bucking coil wired in series with alternator output such that the turns count could be varied. Operation was electrically phase locked to minimize vibrations, which is the purpose of the configuration. Data taken are shown in Figure 3. As per custom, B-field values are shown in dBpT, which in the case of picoTesla is defined by

$$\text{dBpT} = 20 \log \left[\frac{B \text{ (in pT)}}{1 \text{ pT}} \right] \quad (2)$$

Evidently, the use of 19-turn bucking coils reduced the axial B-field from 87.1 dBpT to 62.1 dBpT at the particular position of measurement, which amounts to a fractional reduction of 94 percent on a linear scale. At off-axis positions, a 20-turn bucking coil seemed to be preferable. This is a very significant reduction of the external B-field of an alternator, at least at a distance that is large compared to the size of the alternator, thus demonstrating the concept. Details of the mounting of a bucking coil are shown in Figure 4.

Method of Suppression of DC Field Emissions

In this case, partial cancellation of the external DC magnetic field of a solenoidal linear alternator can be achieved by superposition of a bucking field generated by a can-like configuration of external magnets, which mirrors as close as possible the moving magnet configuration doing the excitation. To be most effective, the bucking magnets clearly need to be placed as close as possible to the pressure vessel containing the alternator. Moreover, in the DC case, the use of permanent magnets to buck has two advantages. The use of equivalent external coils, or hoops, would require inconveniently large and steady currents and external DC field suppression by permanent magnets is always active, even if the alternator is inactive. Next follows the derivation of the heuristic approximations to define the details of the scheme.

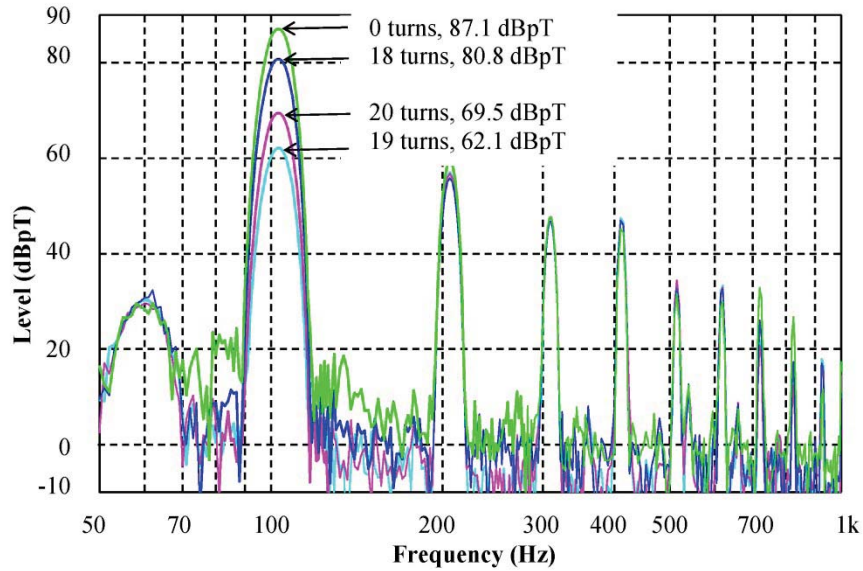


Figure 3.—B-field measured on the z-axis at 1 m from the center of the nearest alternator for selected number of bucking coil turns. Both alternators used the same number of bucking coil turns. The alternators are operating at 103 Hz, with a current of about 7-A root mean square (RMS), or 10 A peak. B-field values are RMS.

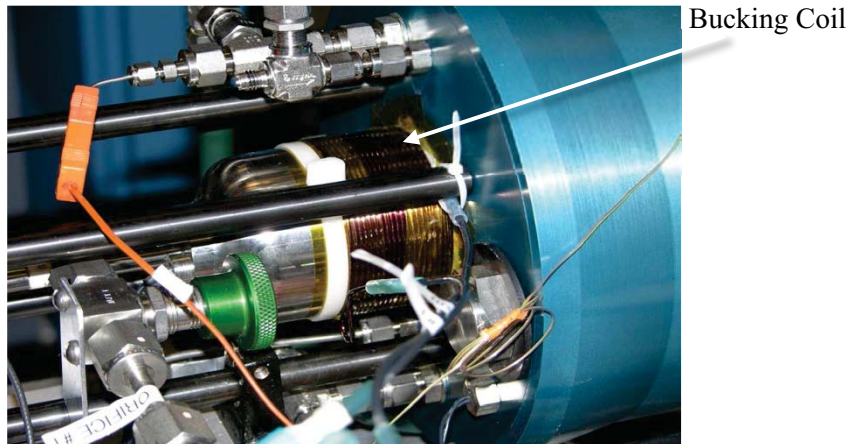


Figure 4.—Bucking coil wound on the pressure vessel containing the linear alternator.

Solenoidal alternators, such as the type used in the ASRG, have slat-like exciting magnets arranged in the shape of a hollow cylinder and are polarized radially relative to the longitudinal axis. Although the stator laminations efficiently direct the flux from the cylinder through the surrounding solenoidal coil, these laminations unfortunately cannot prevent a small part of the exciting field from escaping to the external space as a DC field, which wobbles a slight bit axially with the motion of the exciting magnet cylinder. Fortunately, a straight-forward magnetic moment analysis gives a useful estimate of field strength.

Slat Magnets Viewed as Amperian Current Loops

A representative magnet slat that comprises the cylindrical arrangement has a lateral area, A , and a thickness, t , which is small compared to its lateral dimensions. From dimensional considerations of the form of a magnet constitutive equation

$$B = \mu_0 H + M \tag{3}$$

it becomes clear that M/μ_0 represents a magnetic moment per unit volume. Hence, the total moment of the uniformly magnetized slat is $A t M/\mu_0$. This moment is also just $I A$, when the slat is replaced by its Amperian current (Furlani (2001)) flowing around its periphery. Thus, this cursory argument has shown that the peripheral Amperian current of a magnet slat is simply $I_{Ac} = t M/\mu_0$, from which follows the above remark that to simulate a magnet slat used here ($t \sim 1$ mm, $M \sim 1$ T) requires an inconveniently large current ($I \sim 1000$ A). Considering the assembly of all the magnet slats forming the cylinder, it is further evident that the longitudinal Amperian currents of neighboring slats cancel, leaving oppositely polarized current hoops at the ends of the cylinder. The magnetic moment of each hoop is simply

$$MM = \pi I_{Ac} r_{mc}^2 \tag{4}$$

directed oppositely. The subscript “mc” simply refers to the moving magnet cylinder. These magnetic moments are considered as the source of the DC field that appears external to the alternator.

A cylindrical arrangement of thin magnets external to the alternator will be effective to cancel the external DC field, if its end hoop moments are the same as those of the moving cylinder. Figure 5 is an illustration of the arrangement of the external bucking magnets, showing also the hypothetical Amperian currents in two adjacent magnets. Here it is assumed that the magnetization M is uniform, that is, $\nabla \cdot M = 0$. The Amperian currents in the volume of the magnets vanish and only the currents at the edges remain, which are proportional to $n \times M$, where n denotes the unit normal vector to the magnet’s surface (Furlani (2001)). These are illustrated by the red loops in Figure 5.

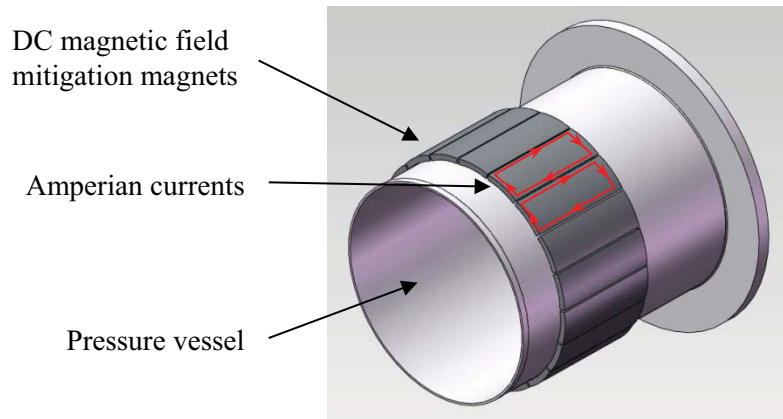


Figure 5.—Bucking magnets arranged on the containment vessel of the alternator. Amperian currents on adjacent edges of the magnets cancel, leaving current hoops on ends.

This should work well, except very close to the alternator, provided the external bucking magnet cylinder, denoted by the subscript “bc,” is as close as possible to, or even inside, the pressure vessel enclosing the alternator. Equivalency of magnetic moments gives a simple formula relating the design parameters of this bucking arrangement:

$$\left(\frac{r_{mc}}{r_{bc}}\right)^2 \left(\frac{t_{mc}}{t_{bc}}\right) \left(\frac{M_{mc}}{M_{bc}}\right) = 1 \quad (5)$$

Numerical Simulation

The concept was first verified by finite element computation, obtaining very promising results based on the geometry of an 80-W ASC. Without any field mitigation, computation shows the expected magnitudes of the external DC B-fields, plotted in Figure 6.

Although small by local planetary standards, the fields displayed above are big enough to interfere with field mapping in interplanetary space. With the addition of a shell of carefully picked mitigating magnets, arranged as in Figure 5, the external DC B-fields can be reduced to extremely low values, as shown in Figure 7.

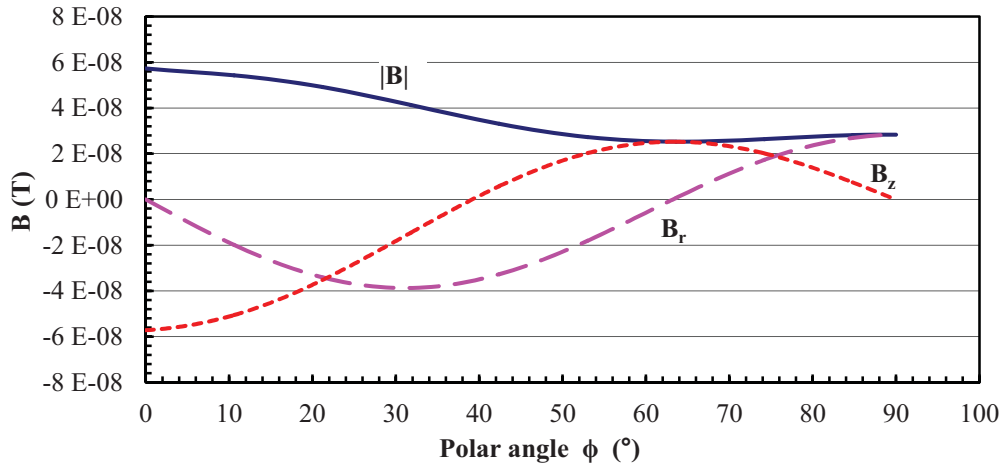


Figure 6.—Unmitigated external B-fields computed for an 80-W solenoidal alternator.

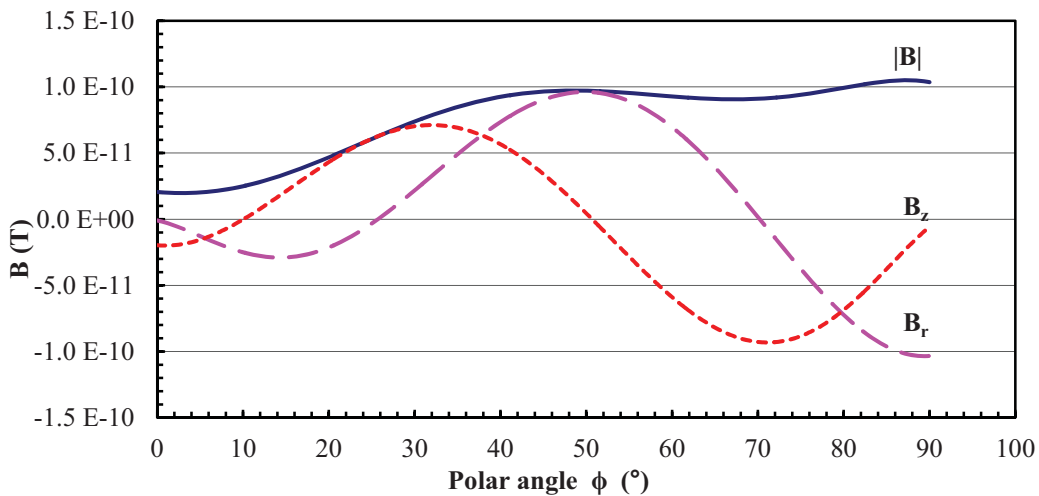


Figure 7.—External B-fields for the alternator of Figure 6 when equipped with a shell of bucking magnets having a $B_{rem} = 0.35$ T.

These finite element computations for a single alternator show that the DC external magnetic field at a distance of 1 m can be reduced to about 1×10^{-10} T or less, everywhere, by choosing the remanence (B_{rem}) of the bucking magnets to be 0.35 T. A physical machine including the alternator has ancillary elements that modify the fields, but these computations give limits to what might be expected. To actually test DC B-field mitigation at such extremely low levels will require special facilities.

Experimental Verification of DC B-Field Reduction

A brassboard demonstration of the DC B-field reduction technique was performed on an ASC. For this demonstration, a series of arc magnets were positioned on the outside of the convertor pressure vessel as shown in Figure 8. The arc magnets were magnetized radially inward, and the flux density was adjusted to balance the external DC magnetic field emanating from the alternator. The concept was tested in the Glenn Research Center EMI test facility in September of 2012. The test results indicated that the external magnetic field emanating from the ASC linear alternator can be significantly reduced in specific zones. An 80 percent reduction in the DC magnetic field was measured in the radial direction with respect to the axis of the linear alternator at a distance of 1 meter. It is important to note that the purpose of the test was to demonstrate proof of concept and not optimal DC field mitigation. Further reductions in the ASC external DC field can be achieved.

In the ASC alternator, the exciting magnets are slat-like and arranged in a can-like configuration. The magnets used in the external DC magnetic field bucking jacket are also slat-like and arranged in a similar can-like configuration. Ideally, all alternator magnets are alike and uniformly magnetized, and all DC magnetic field bucking magnets are alike and uniformly magnetized. Therefore, in the Amperian current loop model, currents along the adjacent edges of the magnets are equal and opposite, and cancel. This leaves only uniform Amperian loops on the ends of the cans. Unfortunately, the magnetizations of the DC magnetic field bucking magnets used in this test are known to vary from magnet to magnet, as shown by checking their remanence. This means that the Amperian currents along their adjacent edges will not cancel exactly, leaving spurious magnetic moments that have no bucking moments arising from the exciting magnet can. Such an effect might contribute to the less than optimal data observed in this experiment.

The Glenn EMI test facility was not designed to measure the ultra-low DC magnetic fields encountered during this test. The ideal test facility would use large Helmholtz coils to cancel the Earth's magnetic field, and would be remotely located. The Glenn EMI facility is located near other buildings and in a populated area. The movement of metal objects both inside (i.e., doors) and outside (i.e., automobiles) of the building affected the measurements. Therefore, none of the data recorded during the test are presented in this paper.

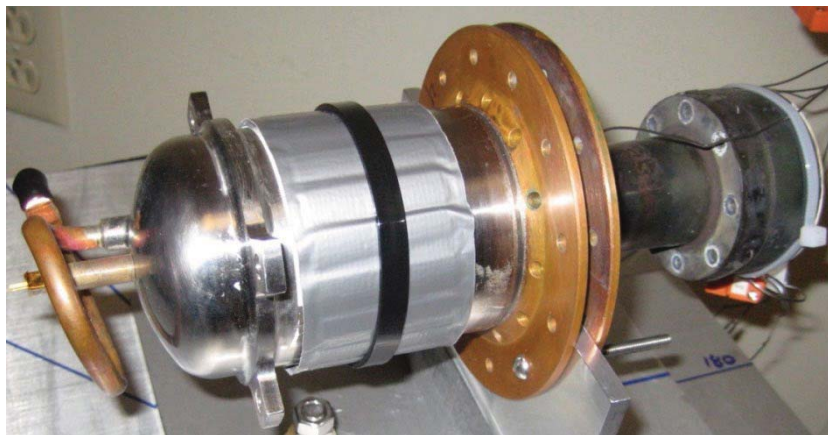


Figure 8.—DC magnetic field bucking magnet jacket installed on Advanced Stirling Convertor (ASC).

Conclusion

In conclusion, the magnetic field emissions generated by the linear alternator of the Stirling power convertor-type used in the ASRG can be significantly reduced. Techniques for reducing both the AC and DC emissions of the ASC linear alternator have been developed and tested. Significant reductions in both fields have been verified experimentally. We have shown that modeling of the external B-field emissions from solenoidal-type linear alternators by dipole-like sources leads to successful suppression of these emissions by field superposition from “counter-dipole” sources, which are easy to implement. These techniques can be used on the ASC convertor to expand the potential set of missions for ASRG. ASRG can now be considered for use on missions that might have sensitive equipment onboard (such as fluxgate magnetometers).

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