TRIUMF Beam Physics Note
TRI-BN-18-12
Sept., 2018

AC Magnetic Field Tolerance for the HRS, and Shielding Possibilities

R. Baartman

TRIUMF

Abstract: Tolerances on AC magnetic fields are derived, found to be < 8 mG. Nearby AC current-carrying conductors cannot therefore have a net current larger than 4 Amps per metre of distance from the beamline in the HRS. Shielding of the net current by encasing the conductors inside a ferromagnetic conduit has no effect on this field. Balanced currents also cause AC fields, but these drop as distance squared, so larger currents are allowed. Further, the fields from such balanced lines do benefit from a ferromagnetic conduit, by about a factor 30. If AC fields larger than the tolerance are inevitable, the beamline itself can be shielded. Only a fraction of a mm of mu-metal is required.

4004 Wesbrook Mall, Vancouver, B.C. Canada V6T 2A3 Tel: 604 222-1047 Fax: 604 222-1074 www.triumf.ca

1 Allowed AC field

The HRS will have maximum resolution with a slit size of 100 microns. Small magnetic fields orthogonal to the beam path will deflect the beam by distances of up to 1 millimetre, but these can be corrected easily if they are static. But if they are fluctuating for example because of a nearby wire carrying a 60 Hz current, they will compromise the resolution unless the net peak-to-peak deflection is below about 10 microns.

There are 3 vulnerable areas: (1) From object slit to the first dipole (0.8 m), (2) between the dipoles in the region of the multipole (1.6 m), (3) from second dipole to the mass slit. The most stringent requirement comes from region 2.

1.1 region 2

The optics from the multipole to the mass slit is a 90 degree phase advance: all accumulated anglular deflections are converted to position deflection at the mass slit, and the conversion factor is 1.6 metre. Thus we find the allowable peak-to-peak deflection to be $\Delta\theta = 10\,\mu\mathrm{m}/(1.6\,\mathrm{m}) = 6.25\,\mu$radians.

The angle due to a field B is $\Delta\theta = BL/(B\rho)$, where L is the distance between the dipoles. It happens that $L = 1.6$ metres as well. Inverting, we get maximum allowable p-p field

$$B = B\rho\,\Delta\theta/L. \tag{1}$$

$B\rho$ is the magnetic rigidity of the beam $= mv/q$. The condition on B will be thus worst for the lightest beams, but on the other hand, the highest resolution is not needed for the very lightest beams. Referring to Marchetto's thesis, Fig. 1.13, we see that the lightest mass for which a resolution of 20,000 may be needed is about mass number 30. Assuming then this mass but with the highest energy of 60 keV, we find that $B\rho = 2000$ Gauss-metres.

Plugging in the number, we find

$$B_{\mathrm{p-p}} \leq 8 \text{ milliGauss} \tag{2}$$

1.2 regions 1&3

These regions are only half as long as region 2, and moreover the effect of an angular deflection declines linearly from dipole to slit. This results in another factor of two for an overall factor of 4. Thus, for these regions, the maximum p-p tolerance is 30 milliGauss.

2 Allowed current

Ampere's law, $\oint \vec{B} \cdot d\vec{l} = \mu_0 I$, results in a magnetic field

$$B(r) = \frac{\mu_0 I}{2\pi r} = 2\,\text{mG}\,\frac{I}{1\,\text{Amp}}\frac{1\,\text{metre}}{r} \tag{3}$$

a distance r from the wire. Thus, an unbalanced net current of 1 Ampere at 1 metre causes 2 mG field. At 2 metres, this would be 1 mG per Amp. And so on. This is for currents in the plane of the separator. Current components orthogonal to this plane have much smaller effects.

In terms of peak-to-peak currents in the plane, the above results can be summarized as follows.

Region	Field	Current at 1 m	2 metres
2	8mG	4 Amps	8 Amps
1&3	32mG	16 Amps	32 Amps

In the case of two currents exactly balanced, as is often the case with a power cord, the magnetic field is smaller by a factor δ/r where δ is the distance between wires. So for example, referring to the table above, if two wires are side-by-side with opposite currents 1 cm apart, the allowed current would be 400 Amps.

3 Shielding

We can think of two cases: Placing AC field sources inside shielding, or placing shielding around the RIB ion beam. In addition, there are two effects to consider: eddy currents and ferromagnetic material. The first depends upon the conductivity of the shielding material, and the second depends upon the magnetic permeability.

3.1 Eddy Current Effect

Any metal can attenuate AC magnetic fields, but this effect is small at low frequency. The time scale τ is given by[link]

$$\tau_{\rm e} = \frac{\mu_0 \sigma t b}{1 + 1/\mu_r}, \tag{4}$$

where b is the cylinder radius, t is the shield thickness, μ_r is the relative permeability, σ is the shield conductivity. As $\mu_r \gg 1$, we can drop the denominator. For steel, resistivity is $1/\sigma \sim 16\,\mu\Omega$cm, so $\mu_0\sigma \sim 8/\mathrm{m}^2$. A shield like 2-inch EMT conduit has $t = 1.65\,$mm, $R = 25\,$mm. Thus $\tau_{\rm e} \sim 0.3\,$milliseconds. Converted to a frequency $f_{\rm e} = 1/(2\pi\tau)$, this is $\sim 500\,$Hz. At $60\,$Hz, the effect will be minimal. At the fifth harmonic of 60 Hz, there might be a measurable effect.

Notice that the effect depends on the cross-sectional area of the conduit, so how much material would be needed to create effective shielding? The 2-inch conduit has a mass of 2 kg per metre of length. To use the eddy current shielding effect, we would need $f_{\rm e}$ to be 100 times smaller, requiring conduit of 200 kg/m. This is unrealistic.

These considerations apply whether the shield is around the source or the beam.

3.2 Permeable material

3.2.1 shield around one unbalanced current

This **does not work**.

Recalling the boundary condition that the tangential component of the magnetic field is continuous across a boundary, the fact that **all** of the field is tangential implies that a circular cylindrical shell or conduit of ferromagnetic material, carrying inside of it a current wire concentric with the shell, will have no effect on the magnetic field from that wire external to the shell. This is independent of the permeability of the shell. If the symmetry is broken, for example if the wire is off-centre, the shield will re-distribute the fields somewhat, but the overall size will remain as it is for the symmetric case. There is a very nice demonstration of this (non)effect by an electrical engineer on youtu.be.

3.2.2 shield around two balanced currents

In the case of two opposite currents $\pm I$, separated in the x-direction by a distance δ, the magnetic field is

$$\vec{B} = \frac{\mu_0 I}{2\pi}\frac{\delta}{r^2}\left(\sin 2\theta, \cos 2\theta\right), \tag{5}$$

where θ is the azimuthal coordinate. In this case the field is not azimuthal, and shielding is effective.

To calculate it, we use the scalar potential in polar coordinates. (Since we are only interested in the shield factor, we scale current and constants out of the potential to simplify the notation.)

$$\Phi(r,\theta) = \frac{\sin\theta}{r}. \tag{6}$$

In each of the 3 regions: air for $r < a$, ferromagnet for $a < r < b$, air for $b < r$, the potential must be of the form $Cr\sin\theta + D\sin\theta/r$, because of the $\sin\theta$ azimuthal dependence. For the 3 regions:

$$\Phi = \sin\theta \begin{cases} C_1 r + 1/r & : r < a \\ C_2 r + D_2/r & : a < r < b \\ D_3/r & : b < r \end{cases} \tag{7}$$

The 4 unknowns are found from the 4 boundary conditions:

$$\begin{gathered} \partial_r\Phi_1(a,\theta) = \partial_r\Phi_2(a,\theta), \\ \partial_r\Phi_2(b,\theta) = \partial_r\Phi_3(b,\theta), \\ \partial_\theta\Phi_1(a,\theta) = \mu_r\partial_\theta\Phi_2(a,\theta), \\ \mu_r\partial_\theta\Phi_2(b,\theta) = \partial_\theta\Phi_3(b,\theta), \end{gathered} \tag{8}$$

where μ_r is the relative permeability of the shield. I will spare you the details. The only parameter of interest is D_3 since it is the reciprocal of the shielding factor η. It is found to be

$$\eta = \frac{1}{D_3} = \frac{(\mu_r+1)^2 - (\mu_r-1)^2(a/b)^2}{4\mu_r} \tag{9}$$

In most situations of interest, the shield thickness $t \equiv b - a$ is much less than its outer radius b, and μ_r is much larger than their ratio: $\mu_r \gg b/t \gg 1$. Under these conditions, we have the simple form:

$$\text{Shield Factor} \equiv \eta = \frac{\mu_r t}{2b} \tag{10}$$

A commercially-available 2-inch conduit has wall thickness $t = 1.65\,\text{mm}$, and expected to have $\mu_r \sim 10^3$. This gives a factor $\eta \sim 30$.

3.2.3 shield around the beam

An infinite cylindrical shield, radius b placed in and perpendicular to an ambient field will reduce this field by roughly the same factor as above. The factor $1/2$ would be $2/3$ for a spherical geometry, and so is expected to vary for less regular geometries but remain of order 1.

Ordinary mild steel has permeability of only 1,000 or so and a remanent field of a few Gauss. Fields this large are undesirable even if DC. So mild steel is not considered in this application.

Mu-metal, or permalloy is better, having a permeability of up to 10^5 and remanent fields of a few mG. Commercially, this is available in many thicknesses. Let us assume result in fields of 80 mG and we wish a factor 10 reduction. Then for 1 metre size, we need no more than a foil as thin as $50\,\mu$m. Since all the flux that would have been in the shielded region is now inside the foil, the field there is b/t times as strong; 80 mG times 1 metre / 0.05 mm = 1600 Gauss. This is still below saturation. The material is rather cheap though so we might use 10 times thicker sheet. It is still rather easy to bend and apply to cover the beam pipe, as we have done in the past for the ISIS optics box.

4 Conclusion

- Conductors carrying AC should be kept as far away from the particle beam is practical.
- Conductors carrying AC should be tightly paired to minimize unbalanced current. Twisting also helps.
- Wrapping conductors in ferromagnetic conduit is of no value for reducing unbalanced currents, but can reduce the fields of balanced currents by a factor of 30. But the balanced current fields fall off more sharply than those from the unbalanced, so are likely not a concern even if not shielded.
- If resulting AC fields are still larger than 8mG, mu-metal shielding should be applied to the HRS vacuum vessels (but not inside the dipoles). The thickness needed is less than 1 mm.