Design of a focusing magnet for a hollow-beam klystron

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Table 1: Parameters: focusing solenoid for the hollow-beam klystron

Property	**Value**
Field magnitude in uniform region	0.1 tesla
Inner radius of coils	22”
Outer radius of coils	26”
Length of magnet assembly	150”
Length of uniform-field region	120”

1 Introduction

This tutorial discusses the design of a solenoid magnet for a hollow-beam klystron using **PerMag**[1]. Table 1 lists the design constraints. The calculations described in this tutorial had two purposes: 1) find if the parameter goals are feasible and 2) determine an axial variation of coil current to achieve the maximum uniform field region.

To begin, we need a criterion for field uniformity. Injector studies with **Trak** showed that the annular beam in the klystron would cover a range of radius 5.271” $\leq r \leq$ 5.497”. The beam moves through a drift tube of radius 6.000”. The change of the beam outer radius should be much smaller than 0.500”. The beam electrons are closely tied to magnetic field lines; therefore, changes of radius are related to changes of magnetic field by

$$\frac{r}{r_0} = \sqrt{\frac{B_0}{B}}. \tag{1}$$

For a $\pm 1\%$ change in magnetic field, Eq. 1 implies that the change in radius of a beam with $r_0 = 5.4$” would be ± 0.027”. The distance is small compared to radial beam width and spacing to drift tube. Therefore, I will use the $\pm 1\%$ level as a criterion of field uniformity.

2 Unshielded magnet calculation

I inherited a preliminary design that did not include an external magnetic shield. Figure 1 shows the geometry. The assembly contained 22 coils of length 6.25” with the inner and outer radii listed in Table1. There was no shielding except for two iron plates of thickness 1.00”on the ends (inner radius

[1]The electron gun for the klystron case study is described in the tutorial **Electron Gun Design for a Hollow-beam Klystron using Trak**. The biased collector design is reviewed in the tutorial **Trak Design of a Single-stage Collector for a Hollow-beam Klystron**.

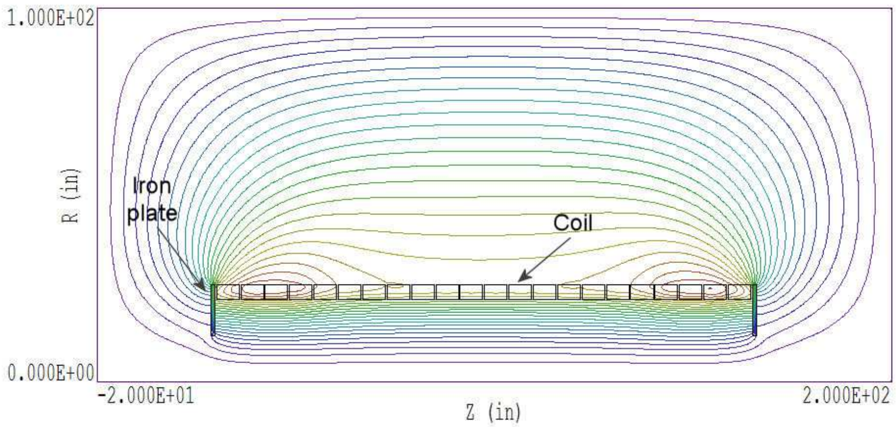

Figure 1: Unshielded magnet design: geometry and magnetic field lines.

12.5”, outer radius 26”). The assembly length (including the end plates) was 151.0”. The drive current of the four coils on the ends was 27.0 kA-turn. Coils 3, 4, 19 and 20 carried current 22.5 kA-turns and the remaining 14 coils had drive current 15.5 kA-turn. The total current was 415.0 kA-turn.

The design had several problems. The main one was that there was no uniform region. Figure 2 shows a plot of B_z as a function of z at radius 5.4”. The field was close to the target value at the center, but was 24% high near the ends. Furthermore, the distance between the peak field regions was only 84.7”. Even with careful adjustment of coil currents, it would be impossible to achieve a uniform-field region approaching 120”. The were several additional problems associated with the absence of an external iron shield:

Magnetic fields extended radially a long distance from the solenoid. For the calculation illustrated with a boundary at $r = 100.0$”, the average external field is 65 G.

With the strong external fields, the choice of boundary position affects fields inside the solenoid. The implication is that for a real system, nearby iron objects could affect beam transport.

The drive current must be relatively high to maintain the external fields.

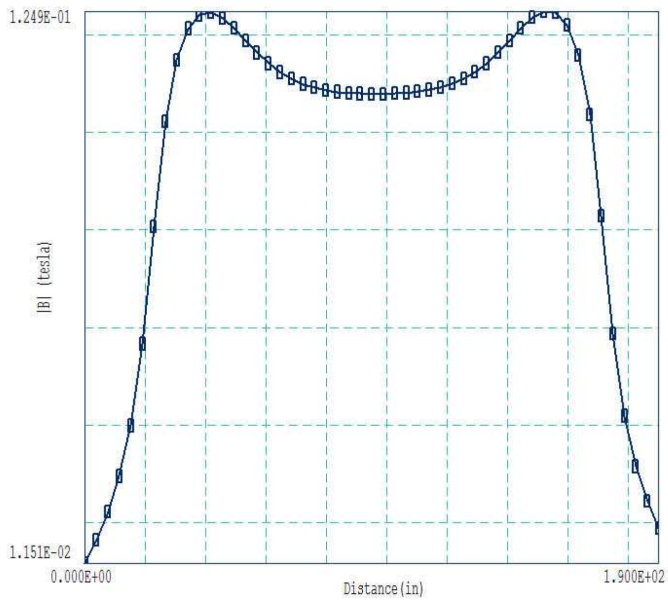

Figure 2: Scan of B_z as a function of z for the calculation of Fig. 1 at $r = 5.4$".

3 Shielded magnet design

I made calculations to investigate the advantages of a shielded magnet. Figure 3 shows the baseline geometry. For ease in analysis, I treated a magnet with axial symmetry about a midplane at z =0.0". The full assembly included 20 coils of length 7.50" with inner and outer radii of 22.0" and 26.0". With end plates of thickness 1.00", the total length of the assembly was 152.0". The plates had inner radius 12.50" and outer radius 26.75". The shield was a cylinder of length 152" with inner radius 26.00" and radial thickness 0.75". I used a soft iron table for the shield and end plate saturation properties.

The dashed line in Fig. 4 shows $B_z(z)$ at $r = 5.4$" with a uniform coil current of 15.30 kA-turn. The total drive current was 306 kA-turn. The uniform field region (distance to 98% of the peak) was 104" in length. To lengthen the uniform-field region, I calculated the field level at the center of the ten coils in the simulation and then raised the drive currents by a factor equal to 50% of the deviation from the uniform central value. This rule-of-thumb evolved from several experiments. I achieved a good solution after only two iterations. Table 2 lists the final coil currents and $B_z(z)$ at $r = 5.4$" is plotted in Fig. 4. The field rose about 1.0% from the central value and then fell to 99.0% at $z = 61.0$". The length of the uniform-field region was therefore about 122.0". The outer shield was not saturated. The minimum value of μ_r in the shield was about 1200. In consequence the field

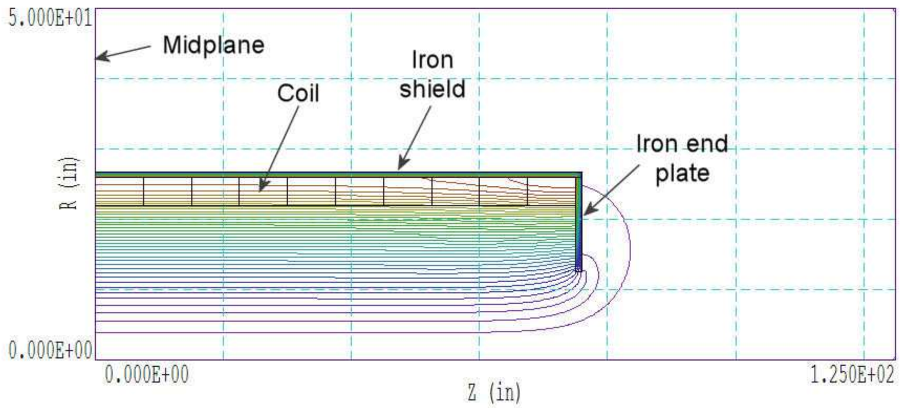

Figure 3: Shielded magnet design: geometry and magnetic field lines.

Table 2: Optimized coil currents, 0.75" shield.

Coil No	**Current (kA)**
11	15.30
12	15.30
13	15.30
14	15.30
15	15.30
16	15.35
17	15.42
18	15.61
19	16.10
20	18.00
Total	314.0

external to the solenoid with a flux conserving boundary at $r = 50.0$" was only 7.2 G. The total current was 314 kA-turns. In comparison to the coil of Sect. 2, the shielded magnet requireed only about 57% as much drive power.

The solution was less favorable when the outer shield thickness was reduced to 0.5". The iron was pushed into saturation, with values of relative magnetic permeability as low as $\mu_r = 130$. As a result, return flux was forced outside the solenoid assembly. The external field increased to 64 G, and it was necessary to raise the coil currents by about 5.4%. The length of the uniform-field region dropped to 118.0".

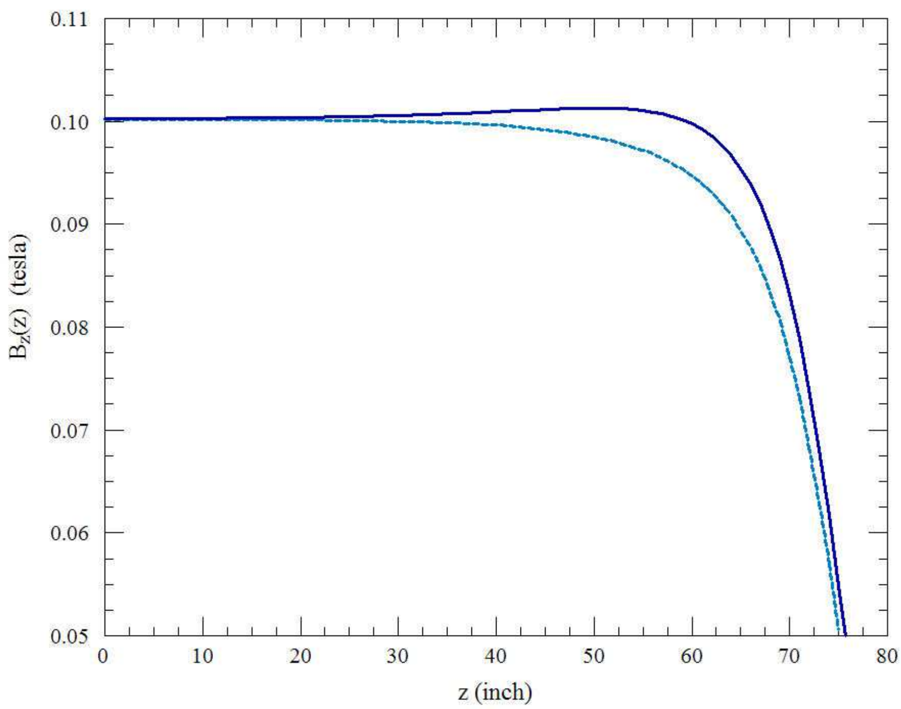

Figure 4: Scan of $B_z(z)$ at $r = 5.4$" for the solenoid of Fig. 1. Dashed line: uniform coil current. Solid line: optimized coil current.