Homopolar Generator Design Exercises

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Abstract

This note illustrates the design of disk and drum style homopolar generators using the FEMM open source finite element solver of David Meeker. Along the way, we show the utility of the vector $\vec{A}$ potential for modelling and explaining homopolar generator characteristics.

Disk Style Homopolar Generators

Homopolar generators (HPGs), also known as Faraday disk, unipolar machines, or acyclic machines, generate a clean DC voltage with very low internal impedance. The Center for Electromechanics (CEM) at the University of Texas at Austin has designed, built and operated a variety of homopolar generators from the mid 1970s through the current day. The machine we are about to model is roughly based upon the "10 MegaJoule" machine from CEM, but this is not a dimensionally accurate model of that machine.

The 10MJ machine had a 14 cm diameter beryllium copper shaft and a 74 cm diameter by 28 cm long rotor. I've assigned a 4 cm by 28 cm space for the field coil. The stator outside envelope is 116 cm diameter by 68 cm. Internal air gaps are assigned at 1 cm. This machine is shown in schematic cross section in Figure 1.

Standard pencil and paper calculations for the disk style HPG assume a constant $\vec{B}$ field transverse to the disk. We calculate the flux cutting the disk and the induced voltage.

$$
\begin{aligned}
\Phi &= B * A = B * (2\pi(r_o^2 - r_i^2)) \\
V &= \frac{d\Phi}{dt} \approx f\Phi = \omega * B * (r_o^2 - r_i^2)
\end{aligned}
$$

Figure 1: Disk Style HPG with Cu Shaft and Field Coil

For this exercise, we will limit the rotor tip speed to 100 m/s (225 mph). We will also assume $B = 1.5$ T. We then have (given $r = 37$ cm.)

$$
\begin{aligned}
v &= r\omega \\
\omega &= v/r = \frac{100m/s}{0.37m} = 270 \ \text{ rad/s} = 43 \text{ Hz} = 2580 \text{ rpm} \\
V &= \omega * B * (r_o^2 - r_i^2) = 270 * 1.5 * (0.37^2 - 0.07^2) = 53V.
\end{aligned}
$$

To estimate the field coil requirements, we calculate the magnetic reluctance of the HPG from the point of view of the field coil. We have an air gap of 2 cm, which I assume will dominate the magnetic circuit.

$$
\begin{aligned}
R_{\text{air}} &= \frac{g}{\mu_0 A} \\
\Phi &= NI/R_{\text{air}} \\
NI &= \Phi R_{\text{air}} = (B * A) * \frac{g}{\mu_0 A} \\
&= Bg/\mu_0 = \frac{1.5T * 0.02m}{1.26\mu H/m} = 24 \text{ kA turns}
\end{aligned}
$$

FEMM Model for Disk HPG

The source file for this model can be downloaded from `http://www.kurtnalty.com/10MJ.fem`. Step by step instructions for creating the simulation file are included at the end of this paper. After drawing, meshing and simulating, we have an axisymmetric contour map of flux shown in Figure 2. Using the rainbow stripe widget, we can overlay a heat map of the magnitude of the B field, as shown in Figure 3.

So, what does this tell us, and how is the information derived?

For an axisymmetric configuration of currents and materials, the vector potential $\vec{A}$ has zero radial and axial components. The only non-zero component is A_θ, and this is the item solved by the finite element method. Knowing $\vec{A}$, we can easily get flux and flux density. In the following equations, S is a surface area element, while s is linear path length element.

$$
\begin{aligned}
\vec{B} &= \vec{\nabla} \times \vec{A} \\
\Phi &= \int \int \vec{B} \cdot d\vec{S} \\
&= \int \int (\vec{\nabla} \times \vec{A}) \cdot d\vec{S} \\
&= \int \vec{A} \cdot d\vec{s} \\
\Phi &= 2\pi r A_\theta
\end{aligned}
$$

Remembering that the generated voltage is $V = f\Phi$, we see that these contours are also the voltage gradient along the rotor.

$$
\begin{aligned}
V &= f\Phi \\
&= f2\pi r A_\theta \\
&= r\omega A_\theta \\
&= \vec{v} \cdot \vec{A}
\end{aligned}
$$

Rather than presenting the generator terms as $dV = (\vec{v} \times \vec{B}) \cdot d\vec{s}$, I prefer to use the $\vec{v} \cdot \vec{A}$.
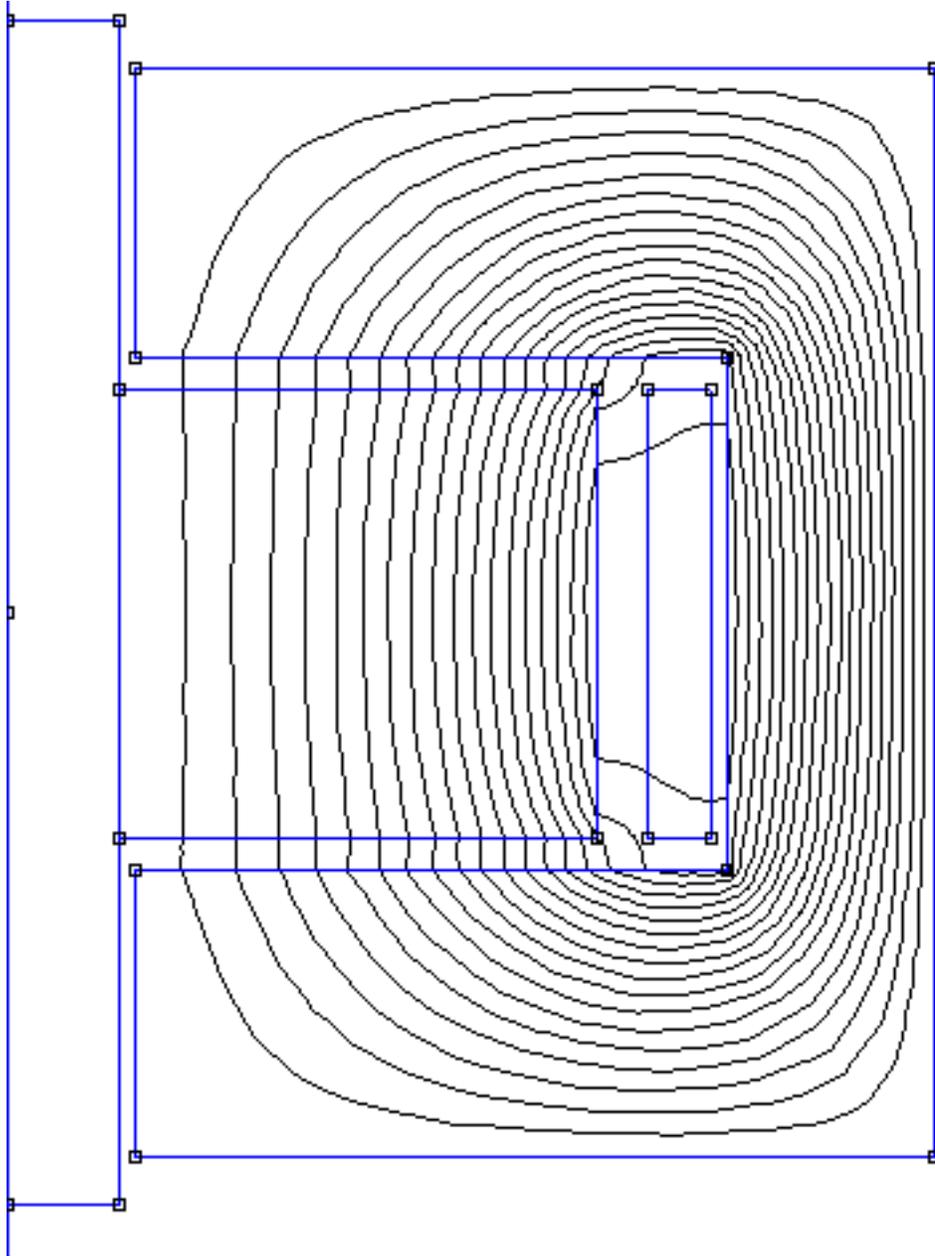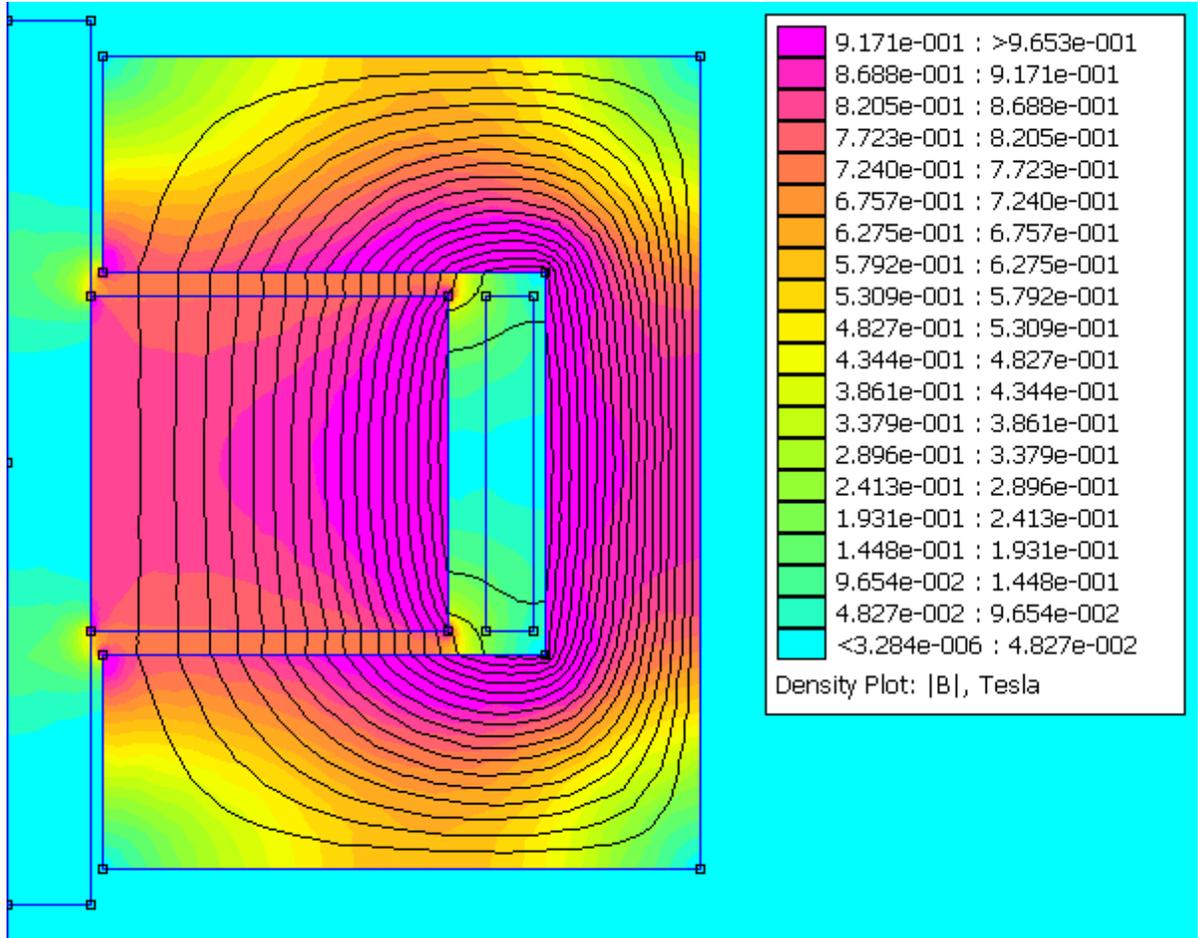
Figure 2: Contours of Constant Flux

Figure 3: B Field and Flux Contours

Unique Information from Finite Element Solution

So, what information do we get from the finite element model that we didn't already know from the pencil and paper calculations?

As we look at the heatmap, we see that the rotor has a real voltage gradient (about 11%) along the outer surface. Current collection brushes should be placed single file in the center plane of the rotor to reduce currents in adjacent brushes in the z direction. Likewise, the low B in the center plane of the rotor reduces $\vec{J} \times \vec{B}$ forces on the current carrying brushes as well.

We also notice at the inside radius of the stator near the rotor, that we have a significant field concentration, and flux leakage into the shaft. We should radius this corner, increasing the local air gap, to reduce these fields which may introduce currents into seals or bearing in this area. Otherwise, just make sure we don't place bearings or seals in this location.

The current collected on the outer rim needs to be evenly split, and transported down the interior of the stator (becoming a compensating turn) to avoid high axial forces on the thrust bearing due to asymmetrical loading, and to reduce self inductance and armature reaction. Each shaft will have set of brushes for the low voltage return, and a coaxial feed for the higher voltage from the rotor tip. External to the HPG will need to be a common bus bonding these two halves together.

Drum Style Homopolar Generators

The drum style HPG shown here is guided by the Balcones Power Supply set of six HPGs at the Center for Electromechanics. For this design, we have two series connected, but oppositely wound field coils which drive flux radially through the outer cylinder portion of the rotor.

Figure 4 illustrates the drum style machine. Our design equation is the standard physics formula $V = B*l*v$, where B is the magnetic field, typically around 1.5 T, l is the active length of the rotor, and v is the tip velocity of the rotor. We use the principle of equal areas for flux transport to size the radius, length and stator back iron dimensions.

FEMM Model for Drum HPG

The source file for this model can be downloaded from `http://www.kurtnalty.com/Drum003.fem`. The creation of the FEMM file for the drum HPGs fol-
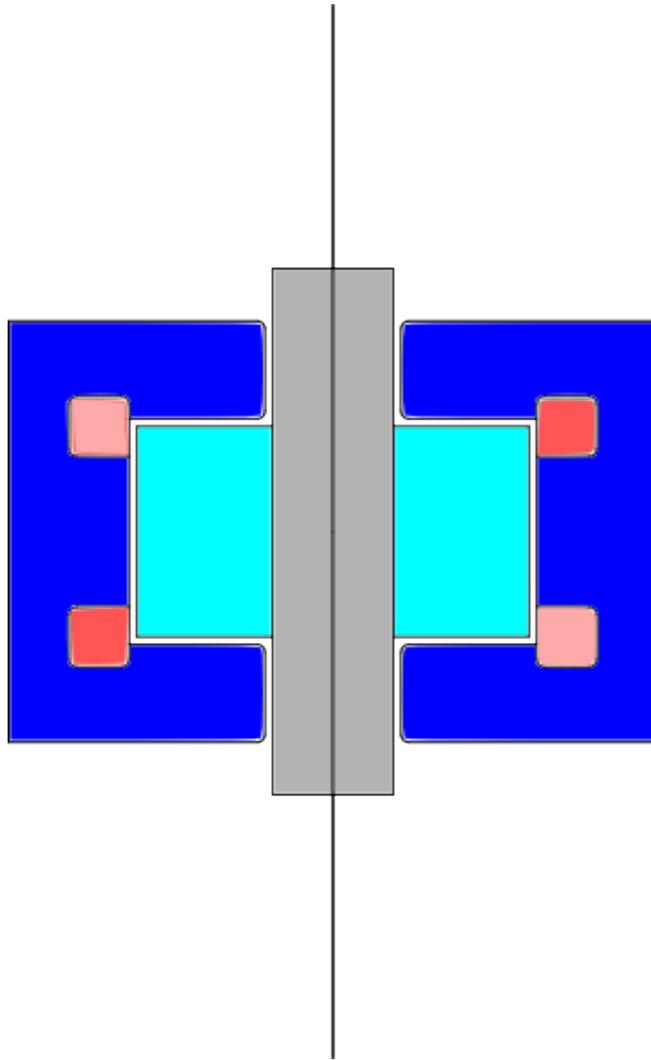
6

Figure 4: Drum HPG Geometry

lows much the same sequence as the 10MJ file. The new feature is the two field coils must be connected in series, but with the number of turns for the first coil a positive value (+1), while for the other coil, use a negative value (-1) for the number of turns.

Looking at the flux map only (Figure 5), we see that assuming the shaft is at zero potential, the two output brushes on the extreme ends of the rotor are going to be at opposite polarities. For example, the outputs could be +25V and -25V with respect to the shaft.

Now, let's look at the combined flux and B map (Figure 6). For this iteration, the position of the field coils has been adjusted to provide a low flux location for the brush rings about a cm from the rotor edges. The output of the collection brushes will come along the interior of the stator inside to the midplane of the stator, and be brought out radially along equator. Notice the use of radiusing to locally groom the airgap to reduce fringing fields in the shaft.

For this geometry, the formula $V = Blv$ is certainly valid. However, the formula $V = \vec{v} \cdot \vec{A}$ also provides the correct voltage at each contour, as long as you keep in mind that A_θ has opposite polarities in the upper versus lower machine halves.
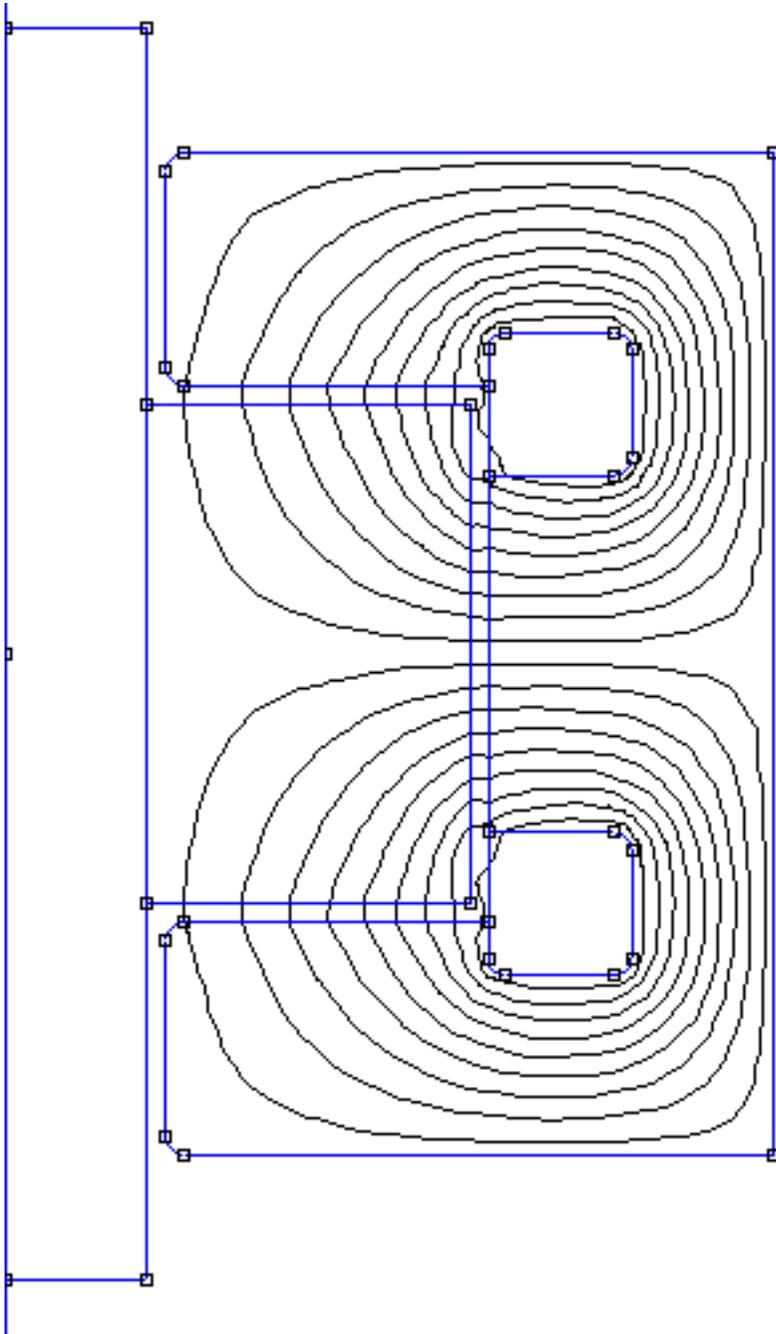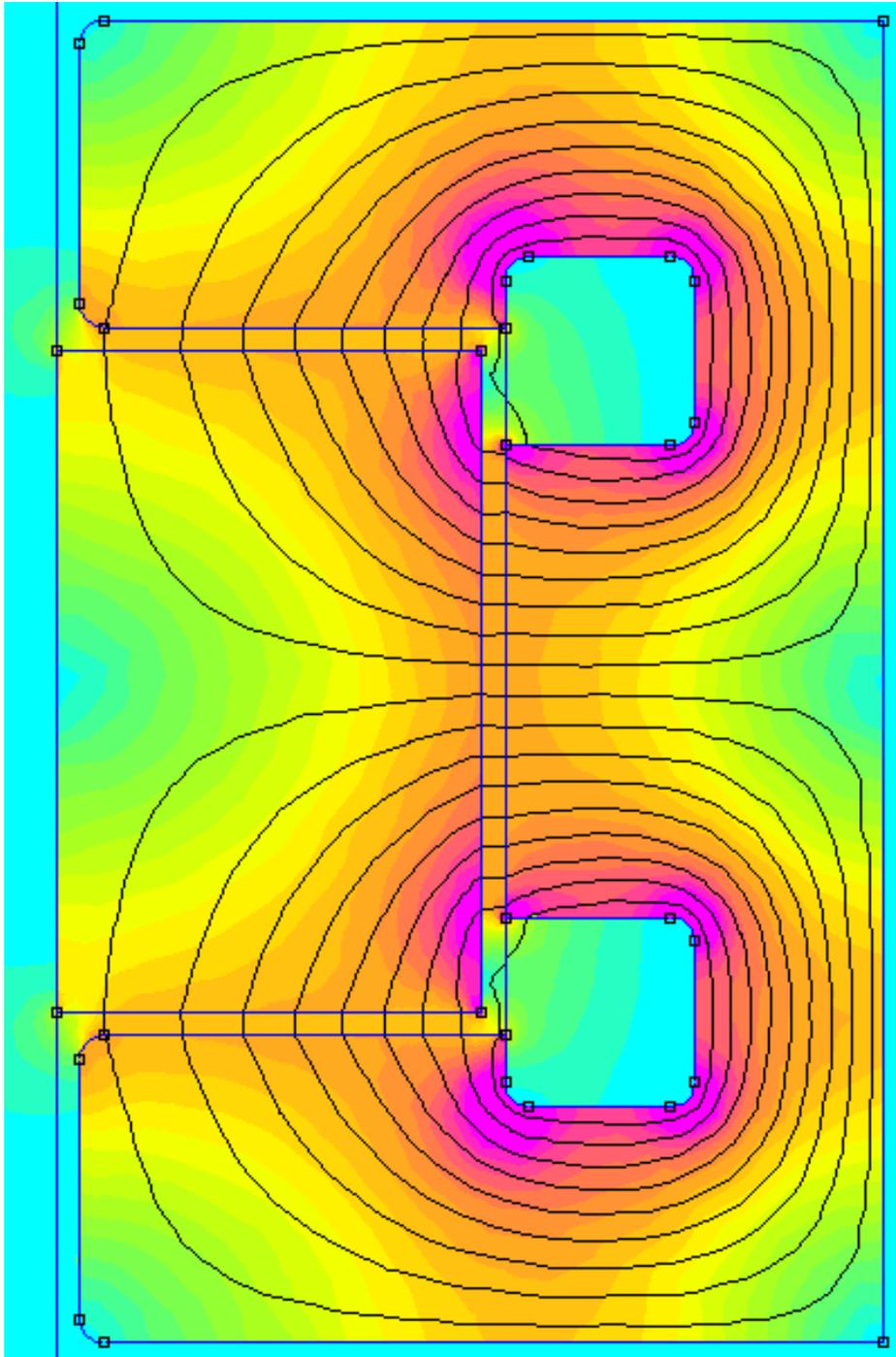
Figure 5: Drum Contours of Constant Flux

Figure 6: Drum Flux and B Field

Step by Step Instructions for Creating the 10MJ.fem File

I am using FEMM 4.2 for this project. Here is a step by step sequence to create the simulation file.

```
Step by step for 10MJ

Start FEMM
New Problem
Select "Magnetics Problem" OK
Problem Menu
    Axisymetric
    Units Centimeters
    Comment - Practice HPG
    OK
View->Keyboard (Set viewing area)
    Bottom -120
    Left 0
    Top 120
    Right 120
    OK
Press NODE widget (Define centerline)
tab r-coord 0  z-coord -120  OK
tab r-coord 0  z-coord    0  OK
tab r-coord 0  z-coord  120  OK
Press LINE widget (Draw centerline)
Single Click on bottom left (0,-120) node
      Single Click on top right (0,120) node
Properties -> Boundary (quasi-open space)
Add Property
Name <- ABC
BC Type <- Mixed
c_0 = 1.0/(uo*4.0*cm)
c_1 = 0
OK
OK
Press ARC widget (Draw outside boundary)
```

Single Click on bottom left (0,-120) node
Single Click on top left (0,120) node
Arc Angle 180
Max. segment 2.5 Degrees
Boundary Condition <- ABC

// Define Material Properties

Properties -> Material Libraries (very bottom choice)
Drag Air to right hand panel
Expand Solid Non-Magnetic Conductors
Drag Copper to right hand panel
Shrink Solid Non-Magnetic Conductors
Expand Soft Magnetic Materials
Expand Low Carbon Steel
Drag 1020 Steel to right hand panel
OK

// Define shaft

Click on NODE widget
tab r-coord 0 z-coord 37 OK
tab r-coord 7 z-coord 37 OK
tab r-coord 7 z-coord -37 OK
tab r-coord 0 z-coord -37 OK

Click on LINE widget
click on (0, 37) then click on (7, 37)
click on (7, 37) then click on (7,-37)
click on (7,-37) then click on (0,-37)
click on (0,-37) then click on (0,37)

Click on green BLOCK LABELS widget
tab r-coord 3 z-coord 0 OK
right click on (3,0). (Square will highlight red.)
spacebar
Block type <- Copper
OK

```
// Define rotor

Click on NODE widget
tab r-coord  7 z-coord -14  OK
tab r-coord 37 z-coord -14  OK
tab r-coord 37 z-coord  14  OK
tab r-coord 7  z-coord  14  OK

Click on LINE widget
click on ( 7,-14) then click on (37,-14)
click on (37,-14) then click on (37, 14)
click on (37, 14) then click on ( 7, 14)
click on ( 7, 14) then click on ( 7 -14)

Click on green BLOCK LABELS widget
tab r-coord 10  z-coord  -10  OK
right click on (10, -10). (Square will highlight red.)
spacebar
Block type <- 1020 Steel
OK

// Define Field Coil

Properties -> Circuits
Add Property
Name <- Field Coil
Amps <- 25000
Series Radio Button selected
OK
OK

Click on NODE widget
tab r-coord 40  z-coord -14  OK
tab r-coord 44  z-coord -14  OK
tab r-coord 44  z-coord  14  OK
tab r-coord 40  z-coord  14  OK
```

```
Click on LINE widget
click on (40,-14) then click on (44,-14)
click on (44,-14) then click on (44, 14)
click on (44, 14) then click on (40, 14)
click on (40, 14) then click on (40,-14)

Click on green BLOCK LABELS widget
tab r-coord 42  z-coord  0  OK
right click on (42,0). (Square will highlight red.)
spacebar
Block type <- Copper
In Circuit <- Field Coil
Number of Turns <- 1
OK

// Define Stator

Click on NODE widget
tab r-coord   8 z-coord -34  OK
tab r-coord  58 z-coord -34  OK
tab r-coord  58 z-coord  34  OK
tab r-coord   8 z-coord  34  OK
tab r-coord   8 z-coord  16  OK
tab r-coord  45 z-coord  16  OK
tab r-coord  45 z-coord -16  OK
tab r-coord   8 z-coord -16  OK

Click on LINE widget
click on ( 8,-34) then click on (58,-34)
click on (58,-34) then click on (58, 34)
click on (58, 34) then click on ( 8, 34)
click on ( 8, 34) then click on ( 8, 16)
click on ( 8, 16) then click on (45, 16)
click on (45, 16) then click on (45,-16)
click on (45,-16) then click on ( 8,-16)
click on ( 8,-16) then click on ( 8,-34)

Click on green BLOCK LABELS widget
```

```
tab r-coord 32  z-coord  -24  OK
right click on (32, -24). (Square will highlight red.)
spacebar
Block type <- 1020 Steel
OK


// Define Air

Click on green BLOCK LABELS widget
tab r-coord 90  z-coord  0  OK
right click on (90, 0). (Square will highlight red.)
spacebar
Block type <- Air
OK


// Save file

Hit yellow MESH widget

Hit CRANK widget

Hit EYEGLASS widget

Hit RAINBOW widget
Plotted Value <- Flux Density
Show Density Plot
Show Legend
OK


Zoom in and pan to see solution.

Edit -> Copy as bitmap
Paste into GIMP or other image software.
```