Field Precision LLC

MagWinder Design Techniques

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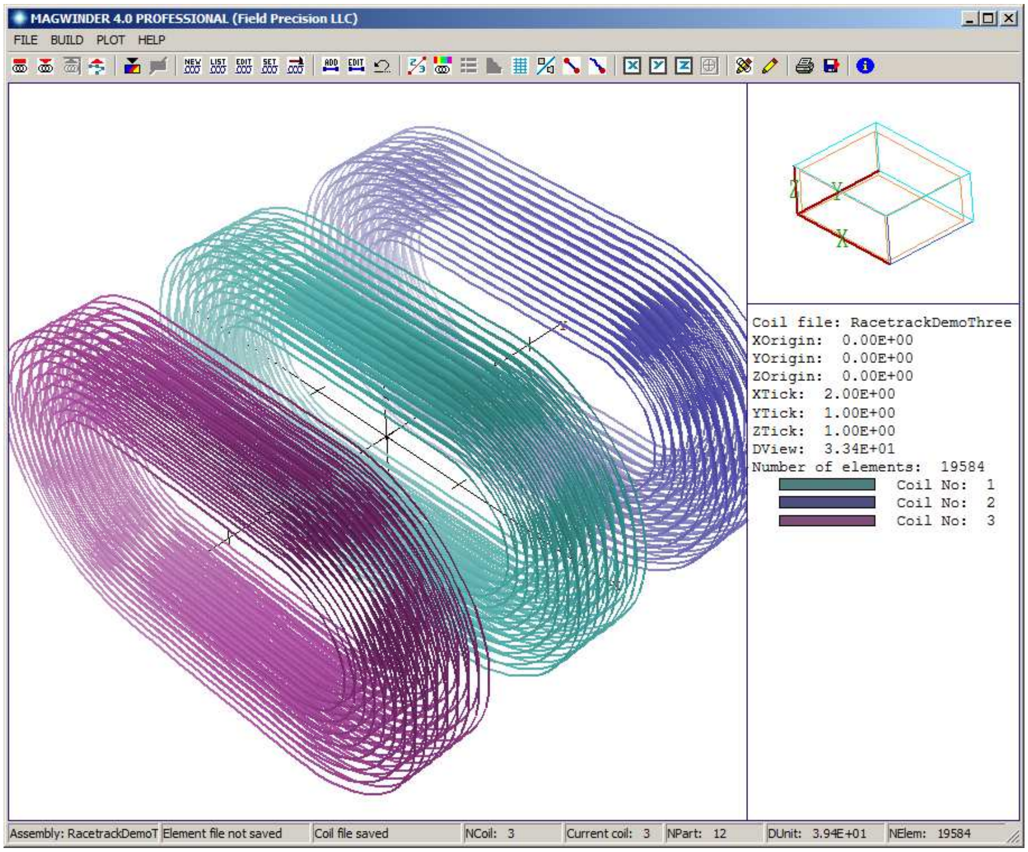


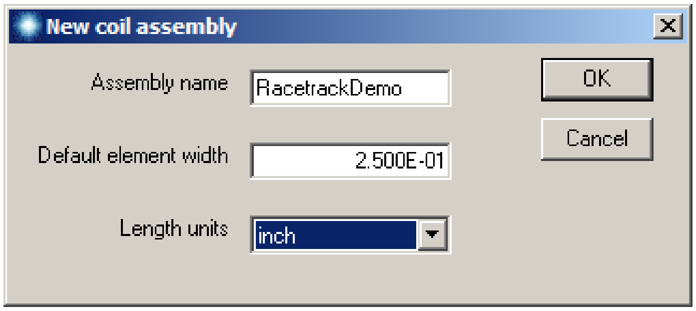
```
Coil file: RacetrackDemoThree
XOrigin:  0.00E+00
YOrigin:  0.00E+00
ZOrigin:  0.00E+00
XTick:  2.00E+00
YTick:  1.00E+00
ZTick:  1.00E+00
DView:  3.34E+01
Number of elements:  19584
        Coil No:  1
        Coil No:  2
        Coil No:  3
```

```
Assembly: RacetrackDemoT | Element file not saved | Coil file saved | NCoil: 3 | Current coil: 3 | NPart: 12 | DUnit: 3.94E+01 | NElem: 19584
```

Figure 1: Demonstration example, an array of three racetrack coils.

MagWinder, a component of the **Magnum** suite for three-dimensional magnetic fields, is used to define the drive currents of electromagnets. The program employs parametric models for creating complex coil geometries in space. As in all 3D design programs, visualizing structures and part orientations can be challenging. For this reason, **MagWinder** features an interactive enviromental where users can build and modify coil structures step by step with a graphical display of the process. This tutorial follows a walkthrough example to demonstrate some **MagWinder** techniques. If you follow the example, don't worry about making mistakes. The *Undo* tool (*Build/Undo* in the menu) will reverse the previous operation.

Figure 1 shows the example, an array of racetrack windings to create a solenoid field over a rectangular region. Each coil has a straight sections of length 5.0" connected by circular sections with an outer radius of $R_o = 3.5$". The coils have radial thickness 2.0" and length 2.0". Therefore, the bends have an inner radius of 1.5". The displacement between coil centers is 4.0". Each coil carries 5000 A-turns.



Assembly name: RacetrackDemo

Default element width: 2.500E-01

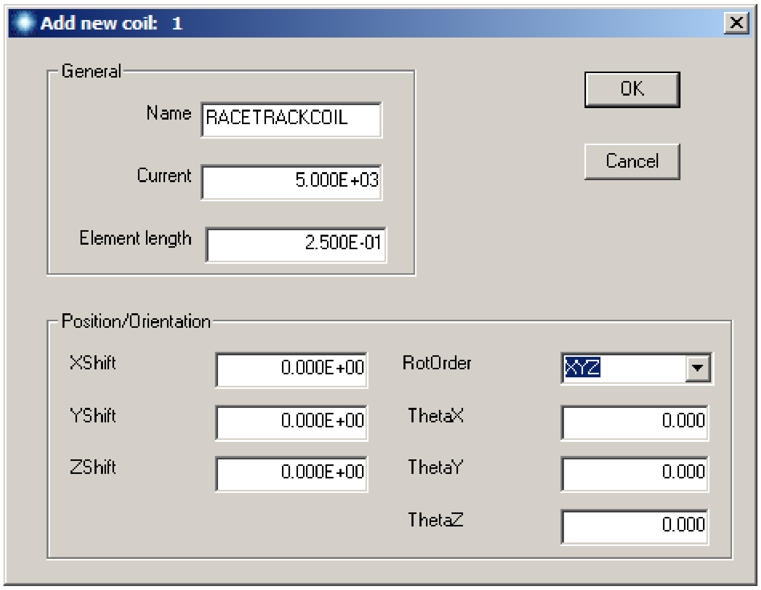
Length units: inch

Figure 2: Dialog to start a new coil assembly.

Run **Magwinder** and choose the *File/Set working directory* command. Pick a directory where you want to save your work. Then pick the command *File/New coil assembly* to open the dialog of Fig. 2. An assembly may contain multiple *coils*, each of which may include multiple *parts*. Fill in the information shown. The significant parameter is the element width, *Ds*. As described in Sect. 2.2 of the **Magnum** manual, an applied coil current is represented as a set of cylindrical elements with length and diameter equal to *Ds*. The choice of the element width determines the density of elements created by the **Magwinder** parametric models. Small values lead to a large number of elements and longer computational times in **Magnum**. If the elements are shorter than the spacing between windings or the distance to critical field regions, the increase in accuracy is marginal. To start, we pick a width of 0.25". This number can be changed later during the session. Click *OK* to return to the main program.

The strategy is to concentrate on building the central coil. Once it is set up correctly, it can be duplicated and shifted to create the other two. A physically-correct coil is a series of connected elements that carry a specified current. The elements are created by adding one or more part models. Click the *New coil* tool (*Build/New coil*) to open the dialog of Fig. 3 and fill in the values. We will use models that create sets of parallel elements. In this case, the program divides the current between them to give a total current of 5000 A-turn. If the quantity *Element length* equals 0.0, **MagWinder** uses the global default of $Ds = 0.25$".

When a coil is defined, you can add parts from the available models. If an assembly has multiple coils, operations to add or to edit parts are performed on the *current* coil. In the present case, the single coil is automatically the current one, as shown in the status bar at the bottom of the window. Click the *Add part* tool (*Build/Add part*) to open the dialog of Fig. 4*a*. Click the *Pick type* pulldown menu to reveal the set of parametric models available in **MagWinder**. We will start with the 180° bend on the $+x$ side of the coil (Fig. 1). Pick the model *ELBOWR*, a circular bend with a rectangular cross



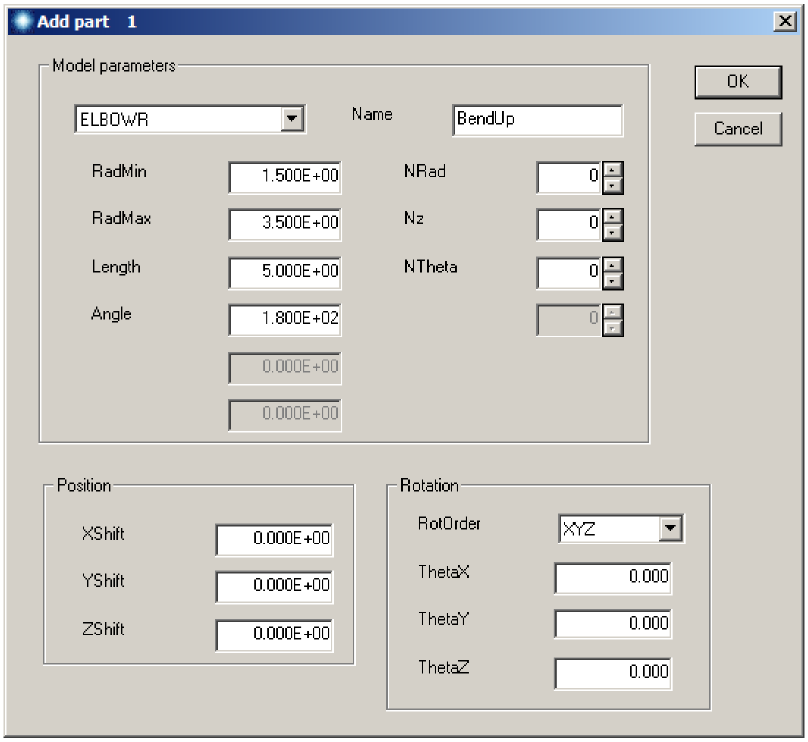
Name RACETRACKCOIL
Current 5.000E+03
Element length 2.500E-01
XShift 0.000E+00
YShift 0.000E+00
ZShift 0.000E+00
RotOrder XYZ
ThetaX 0.000
ThetaY 0.000
ThetaZ 0.000

Figure 3: Dialog add a coil to the assembly.

section. Fill in the values $RadMin = 2.0$”, $RadMax = 3.5$”, $Length = 2.0$” and $Angle = 180^{\mathrm{o}}$ and then exit the dialog. **Magwinder** creates the elements shown in Fig. 5. The program has picked a number of parallel filaments in the radial and axial directions based on the specified element length/width *Ds*. You can change the element size with the *Build/Set Ds* command. Changes are reflected in the plots and the number of elements.

Figure 5*a* shows the *ELBOWR* model in its default position. Current flows parallel to the x-y plane in the direction of positive rotation, starting on the plane of the x axis. We need to make two changes for the correct position and orientation: 1) rotate the part -90° about the z-axis so it will form the upper end of the structure in Fig. 1 and 2) shift it 2.5” in the $+x$ direction so it will connect to the 5.0” straight sections. Click the *Edit part* tool (*Build/Edit part*) and select *BendUp* to return to the part definition dialog. Set $ThetaZ = -90^{\mathrm{o}}$ and $XShift = 2.5$”, then exit the dialog.

We can improve the display before proceeding to the next part. In the default mode, the origin for the axes in 3D plots in set at the center of mass of the current set of elements. As we add multiple parts and coils, it is preferable to fix the origin at the center of the coordinate system. Click the *Grid control* tool (*Plot/Grid control*) to open the *Set Axes/Ticks* dialog. Make sure the boxes *Include axes* and *Fix origin* are checked. Then enter values of 0.0 in the origin text boxes. When you exit the dialog, the display looks like Fig. 5*b*.



Model parameters

ELBOWR

Name: BendUp

RadMin: 1.500E+00

RadMax: 3.500E+00

Length: 5.000E+00

Angle: 1.800E+02

0.000E+00

0.000E+00

NRad: 0

Nz: 0

NTheta: 0

0

Position

XShift: 0.000E+00

YShift: 0.000E+00

ZShift: 0.000E+00

Rotation

RotOrder: XYZ

ThetaX: 0.000

ThetaY: 0.000

ThetaZ: 0.000

Figure 4: Dialog add a part to the current coil.

We next add a part to represent the bend on the $-x$ end of the coil. To save time, we will make a copy the first part and then change a few parameters. Click *Build/Copy part* and select *Part 1*. Then use the command *Build/Paste part*. You will not see an immediate change in the plot because the parts are exactly on top of each other. Click the *Edit part* tool and select *Part 2*. Change the name to *ElbowDn*, set the rotation to $+90^{\text{o}}$ and set $XShift = -2.5$".

To complete the coil, we will add the straight sections. For this, we will use the *BAR* model. To start, we will create the part in the $+y$ position. Click on the *Add part* tool to open the dialog. Name the part *StraightUp*. In the default position, the *BAR* is a rectangular length of current elements pointing in $+z$ with a specified length *Lz* and dimensions *Lx* and *Ly*. In this case, $Lz = 5.0$" along the direction of current flow. If we enter $Lx = 2.0$" and $Ly = 2.0$" and exit the dialog, the updated plot is shown in Fig. 6*a*. We need to rotate the part -90$^{\text{o}}$ about the y axis so that the current flows in the correct direction and shift it by a distance 3.5"-1.0" $= 2.5$" in y so that it connect with the end sections. Click *Edit part* and pick *StraightUp*. Set $ThetaY = -90^{\text{o}}$ and $YShift = 2.5$". Figure 6*b* shows the state of the assembly after closing the dialog. To complete the ring, copy and paste part *StraightUp*, click on *Edit part* and choose the new entry. Change its name to

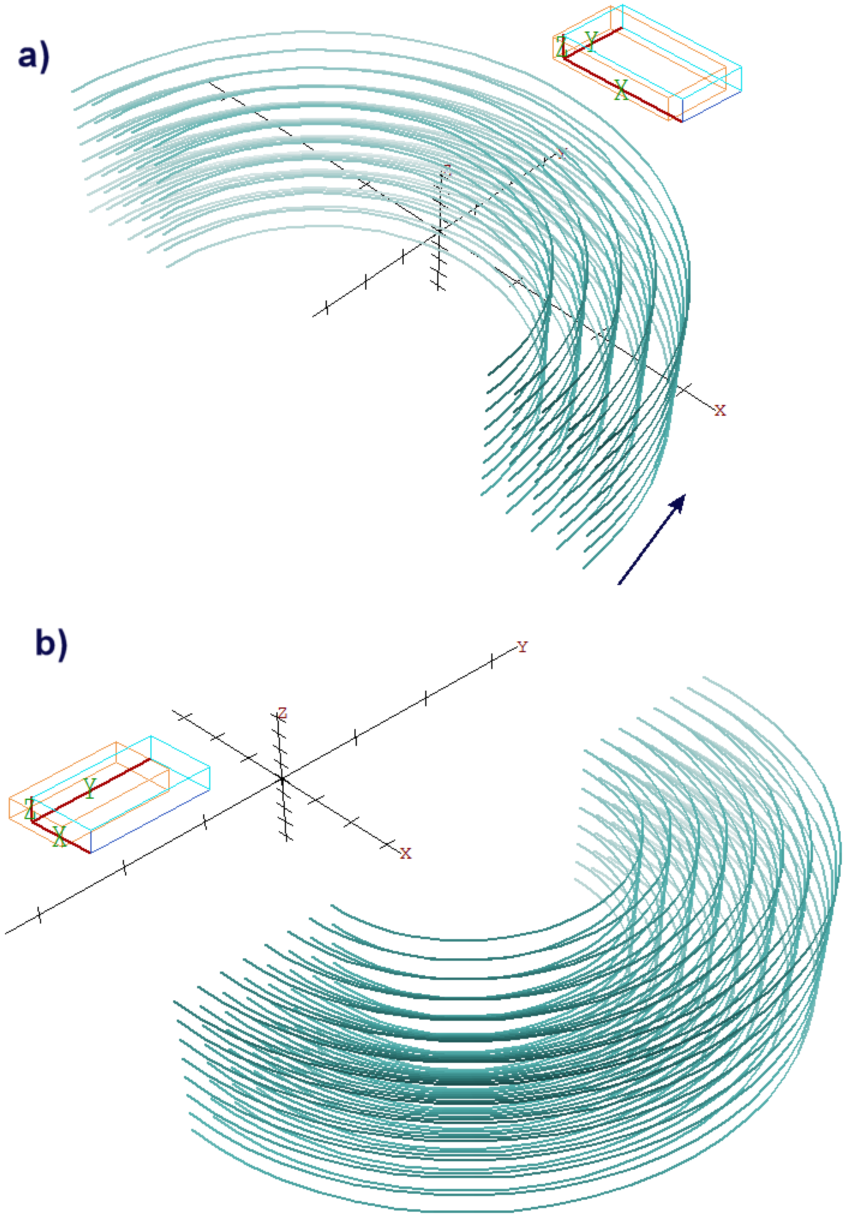


Figure 5: Working on the bend on the $+x$ side. *a*) Elements using the default Ds with no displacement and rotation. The arrow shows the direction of current flow. *b*) With corrected orientation and position.

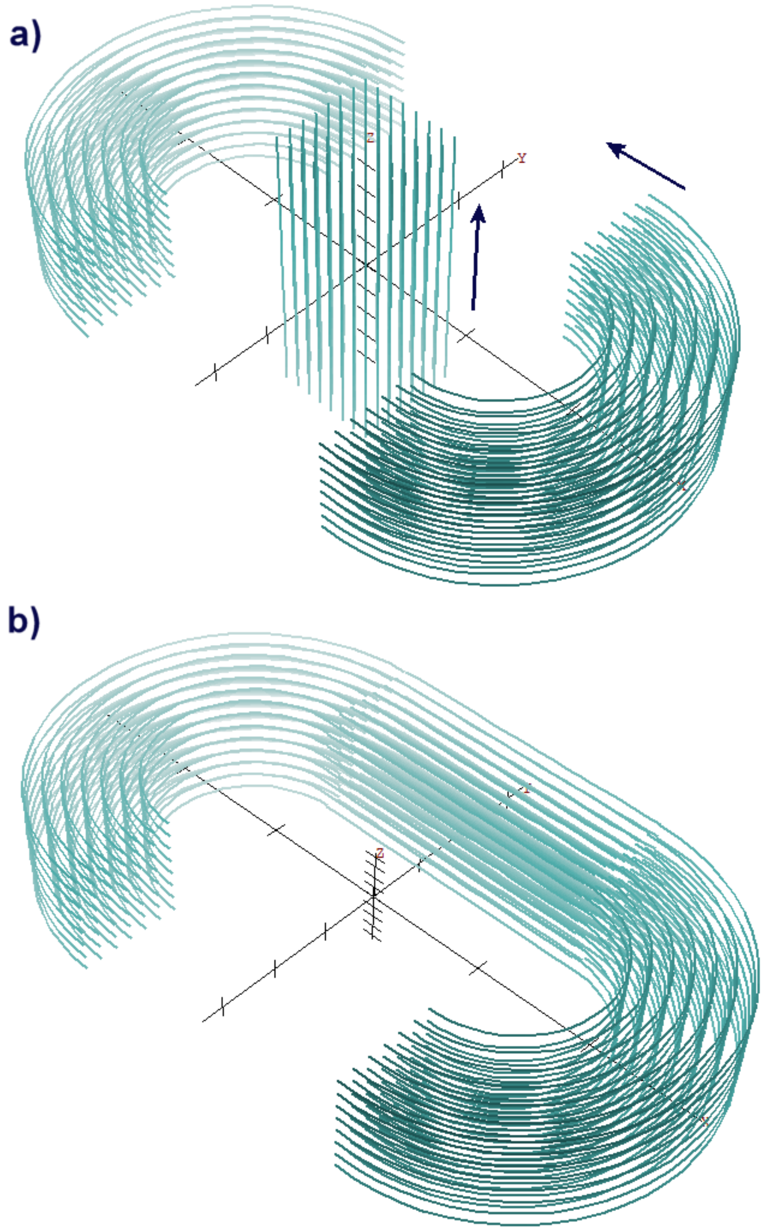


Figure 6: Adding the top straight section *a*) The *BAR* model in the default position. The arrow shows the direction of current flow. *b*) With corrected orientation and position.

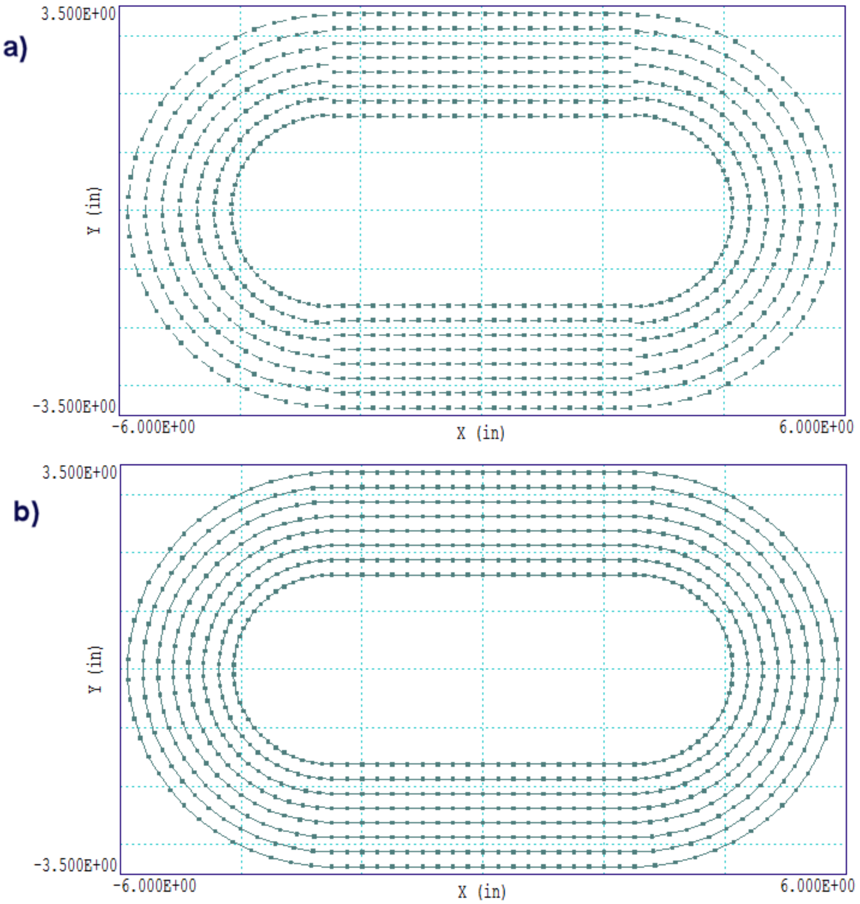
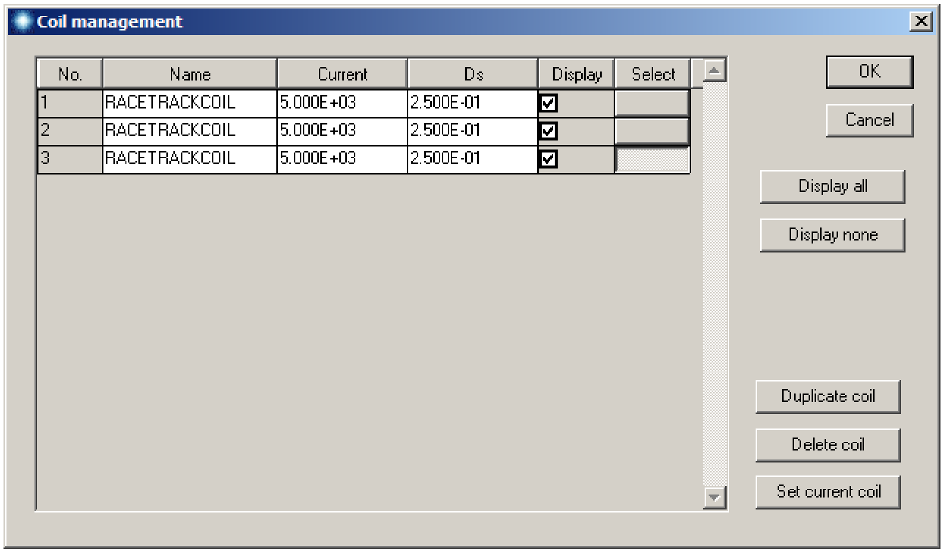


Figure 7: Viewing the assembly in the 2D view mode normal to the z axis. a) With default divisions into parallel elements set by the program. b) Manual settings of the division into filaments for the *ELBOWR* and *BAR* models.

StraightDn and adjust the parameters $ThetaY = +90^o$ and $YShift = -2.5$”. The full coil appears when you exit the dialog.

To check the dimensions and current polarity of the assembly, click the tool *Toggle 2D/3D* (*Plot/Toggle 2D/3D*) to switch to a 2D view. If necessary, click the *Z normal* tool (*Plot/Z normal*). Finally, click the *Arrow plot* tool (*Plot/Arrow display*) to generate the view of Fig. 7*a*. The arrows (or more accurately the flagellated protozoa) show that the direction of current in all parts is correct. Note that the filaments of the bars and elbows do match exactly. Because the current consists of clouds of cylindrical elements, the mismatch has little effect on the solution accuracy. Even though the parts have different numbers of filaments, the current of elements is adjusted so that each part carries the same total current. On the other hand, to improve

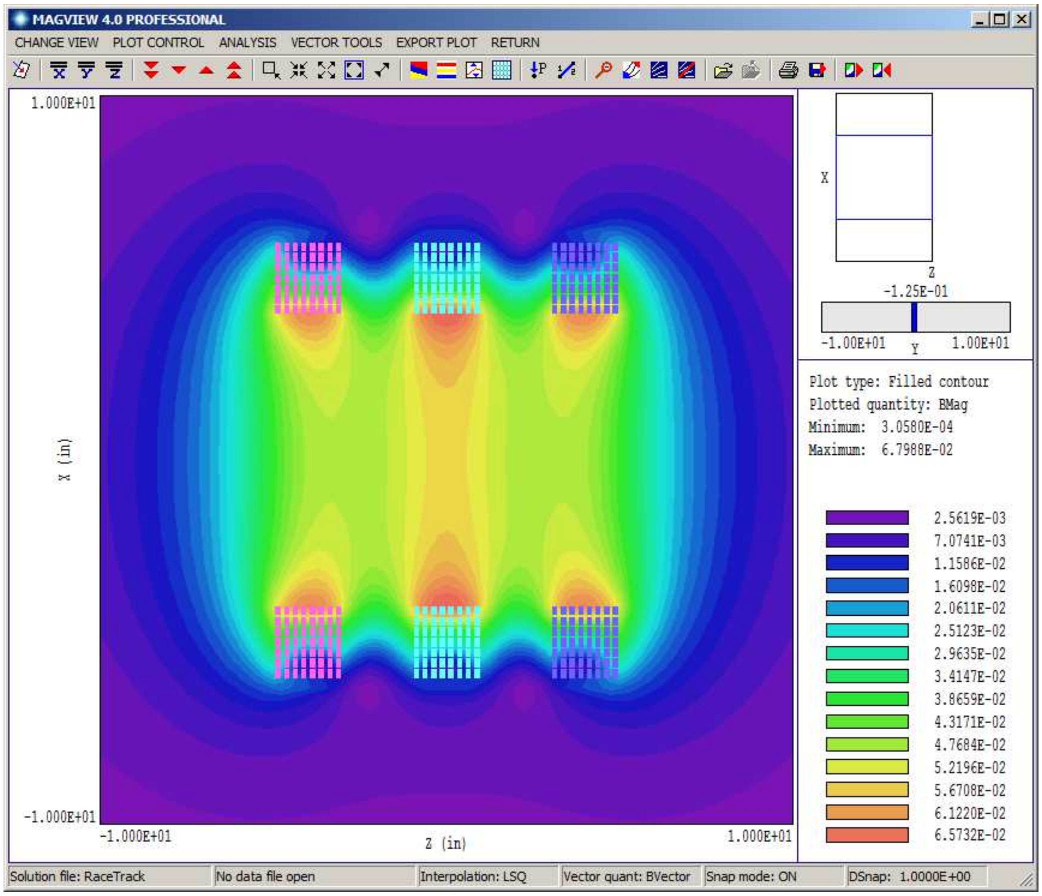


No.	Name	Current	Ds	Display	Select
1	RACETRACKCOIL	5.000E+03	2.500E-01	☑	
2	RACETRACKCOIL	5.000E+03	2.500E-01	☑	
3	RACETRACKCOIL	5.000E+03	2.500E-01	☑	

Figure 8: Dialog to manage coil properties. Options to change the coil name, current, element width and display. Other operations include duplicating or deleting coils and setting the current for part editing.

the appearance of the setup we can manually set the number of filaments rather than let the code made a default selection based on *Ds*. Open one of the *ELBOWR* parts in the *Edit part* dialog and supply values for all the integer parameters: $NRad = 8$, $Nz = 8$ and $NThet = 30$. Modify the other elbow and set $Nx = Ny = 8$ for the bars. Figure 7*b* shows the modified model in the *EndPoint* display mode.

With a good model of the central coil, we can complete work to add the other coils. First, we will make a backup. Click the *Save coil file* tool (*File/Save coil file*) and save the work as `RacetrackDemo1Coil.CDF`. Now, click the *Coil management* tool (*File/Coil management*) to open the dialog of Fig. 8. Click the *Duplicate coil* button twice to create two additional coils with identical properties. Exit the dialog, switch to 3D view and activate *Endpoint* display. The plot shows the three coils occupying the same space. Click the *Set coil* tool (*Build/Set current coil*) and choose coil number 1. The current coil number is updated in the status bar. (Note that when there are multiple coils, part operations apply to the current coil.) Then click the *Edit coil* tool (*Build/Edit coil*) to display the properties of coil 1. Change its name to *CoilMid* and exit the dialog. Change the current coil to number 2 and open the *Edit coil* dialog. Change the name to *CoilUp*, set $ZShift = 4.0$” and exit the dialog. The coil shift operation moves parts of the coil globally, supplementing individual shifts of the parts. Next, set the current coil to 3 and edit the coil. Change the name to *CoilDn* and set $ZShift = -4.0$”. Exit the dialog to see the full assembly of Fig. 1 with $19,200$ elements. Save



Plot type: Filled contour
Plotted quantity: BMag
Minimum: 3.0580E-04
Maximum: 6.7988E-02

Solution file: RaceTrack
No data file open
Interpolation: LSQ
Vector quant: BVector
Snap mode: ON
DSnap: 1.0000E+00

Figure 9: Freespace **Magnum** calculation using the demonstration coil set. Plot of $|B|$ in the plane $y = 0.0$".

the coil file as `RacetrackDemo3Coil.CDF`. Save the element file (*File/Save element file*) as `RacetrackDemo3Coil.WND`. This file can be used as input for **Magnum** calculations.

Click the menu item *File/Edit coil file* to see the saved `CDF` file. You can also open the file with any text editor. Note the clear organization of coils and their parts. As an alternative to the interactive environment, you can change assembly properties directly in the file. For example, if we opened the file `RacetrackDemo1Coil.CDF` with a text editor, we could copy the single coil section and paste it twice. After changing the new coil names and the values of $ZShift$, we could save the file as `RacetrackDemo3Coil.CDF`, achieving the same result as that of the interactive environment. Direct script editing has advantages for extensive sets of runs. For example, suppose we want to measure the uniformity of $|\mathbf{B}|$ as a function of the spacing between coils. The coil positions could be changed quickly with an editor. Furthermore, values in the `CDF` file could be changed with a Python script and **MagWinder** and **Magnum** could run as command line programs to generate large sets of results automatically.

Finally, we consider how the density of drive-current elements affects the accuracy of the solution. There is no definitive answer – the criterion depends on how close the critical region of magnetic field is to the coils. The important point is that we can use the programs to get information on accuracy. To illustrate, Figure 9 shows the results of a **Magnum** freespace calculation using `RacetrackDemo3Coil.WND` as input. The plot shows $|\mathbf{B}|$ in the plane $y = 0.0$". This calculation uses specified numbers of model filaments with $Ds = 0.25$". With 19,200 current elements, the calculation takes 150 seconds and gives a field at the magnet center $B_z(0,0,0) = 554.421$ G. If we remove the manual specifications and let **MagWinder** pick the number of filaments base on Ds, then there are 18,096 elements. The run time is 141 seconds and $B_z(0,0,0) = 554.446$ G, a difference of only 0.001%. The result supports the earlier statement that model filaments need not connect perfectly to achieve a good solution. Finally, if we remove manual specifications on the number of filaments and take $Ds = 0.35$", then the number of elements drops to 5,400. The run time for the free space calculation (approximately proportional to the number of elements) is 44 seconds. The field value is $B_z(0,0,0) = 554.615$, a difference of 0.03% from the longer calculation.[1]

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[1] Freespace solutions in **Magnum** benefit significantly from parallel operation. For example, adding the statement `Parallel 4` to the **Magnum** script reduces the run time for the detailed model from 150 to 46 seconds.