



Pulse

**Time-dependent Magnetic Fields
with Eddy Currents**

Field Precision

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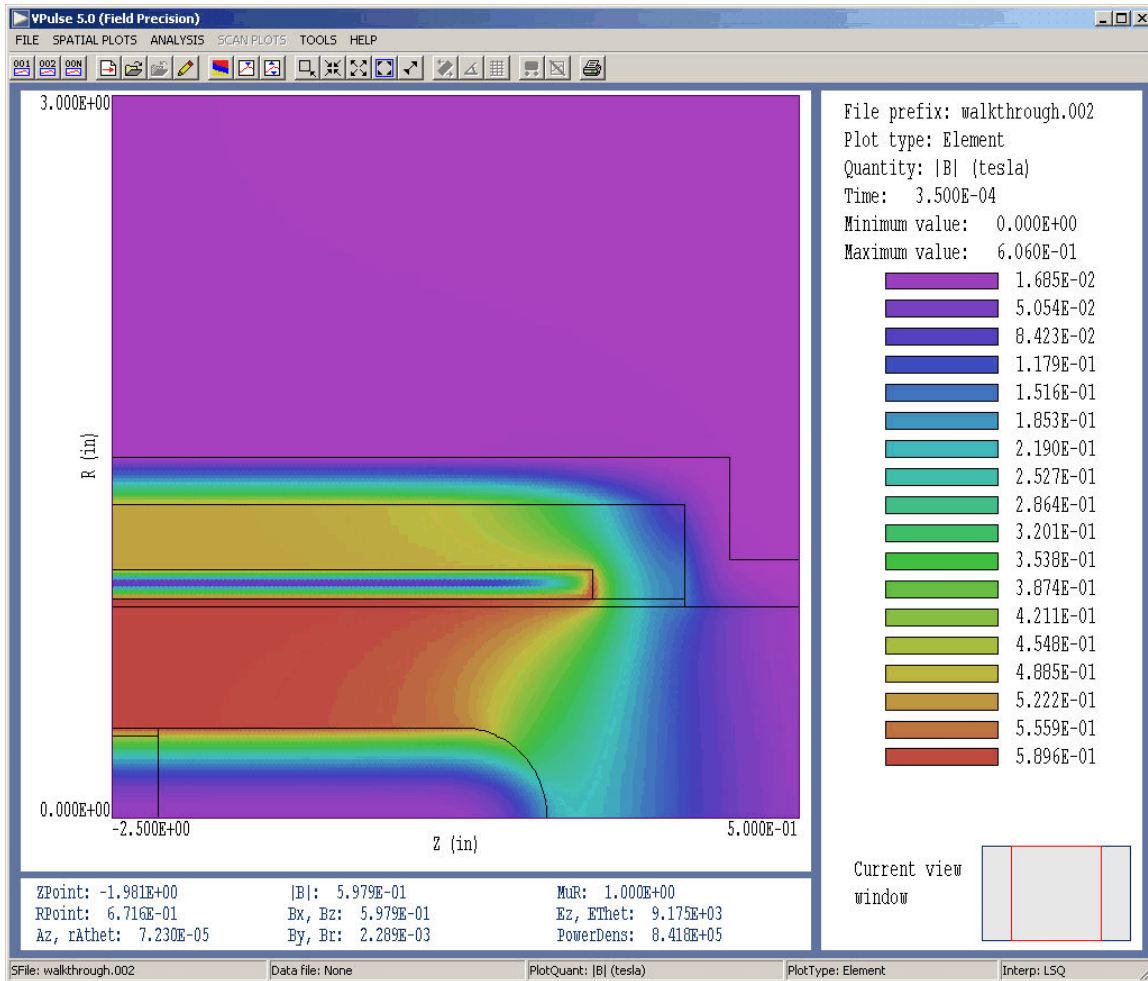


Figure 1. Screen shot – working environment of **VPulse**.

1. Program function

Pulse calculates the time-evolution of magnetic fields in the presence of eddy currents. The program solves the two-dimensional magnetic diffusion problem in cylindrical and rectangular geometries. **Pulse** utilizes finite-element methods on variable-resolution conformal triangular meshes. The mesh size is limited only by the installed memory of the computer. Using a simple command language, you can define up to 127 regions to represent materials or coils with different current densities. **Pulse** can be applied to time-dependent problems or as a relaxation program to derive steady-state boundary value solutions. You can define multiple coils with arbitrary current waveforms using a flexible system of tabular function input. The program also handles non-linear magnetic materials with user-defined $\mu(|\mathbf{B}|)$ tables. In time-dependent runs, **Pulse** produces multiple data files at specified times and history files of

magnetic and electric field at given locations. Data files can be analyzed with **VPulse** an interactive graphical post-processor. The program provides full information on the fields and magnetic permeability. Other features include automatic calculation of stored energy, peak field values, magnetic forces and torques. **VPulse** makes a wide variety of screen and hardcopy plots. History files can be analyzed and plotted with the utility program **Probe**. **Pulse** has applications to transformers, magnetic recording devices, high-field pulsed magnets, linear induction accelerators, high-frequency inductors and magnetic coupling in microelectronic devices.

2. Walkthrough example

It is useful to review a complete solution to understand **Pulse** procedures. We shall consider a problem where the magnetic field generated by a pulsed coil penetrates surrounding metal structures. In preparation, move the files `WALKTHROUGH.MIN`, `WALKTHROUGH.PIN` and `CRITDAMP.DRV` from the example library to a convenient working directory like `\TRICOMP\BUFFER`. The file `WALKTHROUGH.MIN` (**M**esh **I**Nput) contains geometry information for the mesh generator, while the file `WALKTHROUGH.PIN` (**P**ulse **I**Nput) contains control parameters for **Pulse**. The file `CRITDAMP.DRV` contains a table that defines a curve for a normalized, critically-damped pulse. Start the **TriComp** program launcher (`TC.EXE`) and make sure that the program points to the working directory using the *SET DATA DIRECTORY* button. Note that you will need to scroll down the list of programs in `TC.EXE` to find buttons for **Pulse**, **VPulse**, **Probe**.

Figure 2 shows the geometry of the cylindrical system. Note that the figure is an r - z plot as opposed to the a longitudinal section. The physical system is a figure of revolution about the z axis and only values $r \geq 0.0$ are defined. The device is a miniature magnetically-insulated transmission line to carry pulsed voltages in the MV range to a high-current electron beam diode. The assembly is contained inside an aluminum vacuum chamber (indigo). The aluminum wall also confines the pulsed magnetic field, reducing inductance and minimizing external fringe fields. The pulse coil (cyan) has a uniform winding density that we approximate by a current density distributed uniformly over the cross-section. A thin layer of stainless steel (dark blue) acts as the outer conductor of the coaxial transmission line. The inner conductor is divided into three parts so we can study the effect of changing its material composition. In one configuration, *CCOND1* is vacuum, *CCONC02* is a thin stainless steel tube and *CCOND03* is a stainless steel cap. In the second configuration, all regions are assigned the properties of aluminum to represent a solid

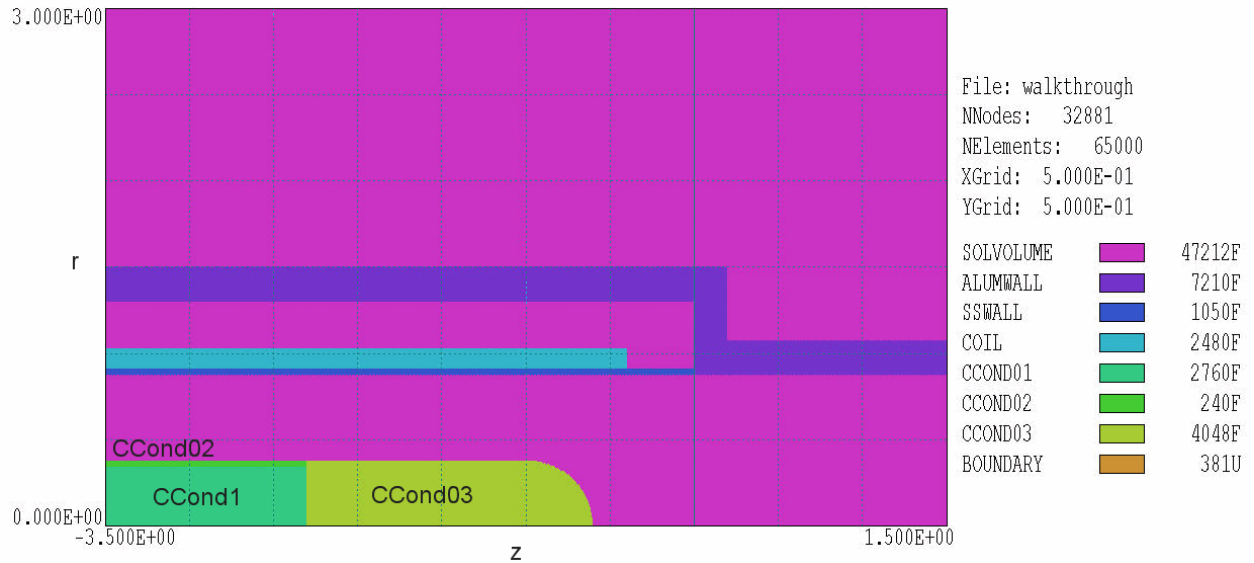


Figure 2. Region definitions for the WALKTHROUGH example.

assembly. The remaining elements of the solution volume (light violet) represent air or vacuum ($\mu_r = 1.0$). There is an additional region (*BOUNDARY*) that is not displayed in Fig. 2. The region consists of the nodes on the bottom, right and top sides of the solution volume to which we shall apply a special condition (discussed below). To review, the term *nodes* applies to the vertices of triangles that constitute the mesh. The function of **Pulse** is to calculate time dependent values of the vector potential A_z (for planar solutions) or stream function rA_θ (for cylindrical solutions) at the node points. The **VPulse** program takes numerical derivatives of these quantities to find magnetic field components. Finally, the term *element* refers to the triangles. Physical properties like magnetic permeability and electrical resistivity apply to the triangle areas (which represent physical volumes).

To begin, launch **Mesh** from **TC**. (If the program does not start, check that the program is available in the *Program Directory* specified in **TC . EXE**). Click on *LOAD SCRIPT (MIN)* in the *FILE* menu. If the data directory is correctly set, you should see the file **WALKTHROUGH . MIN** in the dialog. Choose it and click *OPENFILE*. Before creating a mesh, we will take a look at the contents of the file. In the *FILE* menu, click on *EDIT CURRENT SCRIPT (MIN)* to open an edit window. The script is divided into several sections. The *GLOBAL* section defines control parameters and the initial size of triangular elements. Each *REGION* section corresponds

to one of the regions in Fig. 2. The outlines of the regions are defined by sets of line (*L*) or arc (*A*) vectors. Most of the *REGION* statements contain the *FILL* keyword, which means that the current region number is assigned to all elements and nodes inside the boundary. When the *FILL* statement is absent, **Mesh** only sets nodes on the boundary.

Exit the editor by clicking on *FILE/EXIT* or the close button and then choose the *PROCESS* command. In response, **Mesh** analyzes the contents of the script to create a conformal mesh. The program displays screen information on the progress of the run. The program also records the information in a listing *WALKTHROUGH.MLS*. Press any keyboard button or click the mouse inside the text area to continue. Click on *FILE/SAVE MESH(MOU)* to save the mesh configuration. The program creates the file *WALKTHROUGH.MOU* which contains information on node coordinates and the region numbers of nodes and elements. This file is one of the required inputs for the **Pulse** calculation. Before proceeding, you can check some of the **Mesh** plot capabilities by clicking on *PLOT/REPAIR*. The **Mesh** manual gives detailed descriptions. Note how the program has flexed triangles to create accurate and smooth surfaces. The right-hand side of Figure 2 shows some of the information displayed in **Mesh** plots. The mesh contains 32,881 nodes and 65,000 elements. The region representing vacuum/air is of the filled type and contains 47,212 elements, while the boundary region is unfilled and contains 381 nodes.

Next, launch **Pulse** from **TC**. Click on *FILE/EDIT INPUT FILES* and choose *WALKTHROUGH.PIN*. Table 1 shows a condensed version of the file content. There are three types of commands: *SET*, *REGION* and *DIAG*. *SET* commands define values for program control parameters. The first four commands in Table 1 control the automatic time-step calculation for the solution of the diffusion equation. The fifth and sixth commands specify that the geometry has cylindrical symmetry and that the coordinates from **Mesh** are in inches (39.37 inches/m). The *REGION* commands set the physical properties of regions. The vacuum/air region (number 1) has $\mu_r = 1.0$ and $\rho = 100.0 \Omega\text{-m}$. Note that the volume resistivity is much larger than the metal regions but not infinite. In a diffusion solution, information must propagate at a finite velocity. The speed of light is not inherent in the magnetic diffusion equations discussed in Sect. 4. Therefore, the choice $\rho = \infty$ would give an infinite mesh velocity leading to numerical instability. The choice $\rho = 100.0$ ensures that changes of magnetic field move rapidly through the air/vacuum regions compared to the rise-time of the drive current pulse.

Table 1. Condensed content of the file WALKTHROUGH.PIN

```
SET Safety = 5.0
SET DTMin = 1.0E-7
SET DTMax = 1.00E-6
SET TMax = 400.0E-6
SET Geometry = Cylin
SET DUnit = 39.37
REGION(1) Mu = 1.0
REGION(1) Rho = 1.0E2
REGION(2) Rho = 2.7E-8
REGION(3) Rho = 81.0E-8
REGION(4) Rho = 1.0E2
REGION(4) Current(Table) = CRitDamp.DRV (350.0E-6, 6.967E4)
REGION(5) Rho = 2.7E-8
REGION(6) Rho = 2.7E-8
REGION(7) Rho = 2.7E-8
REGION(8) Fixed = 0.0
DIAG DTime = 175.0E-6
DIAG History = (-2.00, 1.55)
ENDFILE
```

Commands of the type *REGION(RegNo) MU* have been omitted from the other regions because the code default value is $\mu_r = 1.0$. The *RHO* commands set the volume resistivity for the stainless steel outer conductor and set all sections of the inner conductor to the volume resistivity of aluminum. The command

```
REGION(4) Current(Table) = CritDamp.DRV (350.0E-6, 6.967E4)
```

defines the total current in the coil region (number 4). The keyword *TABLE* and string *CRITDAMP.DRV* designate that the current waveform is defined by the table in the file. The file consists of 150 data lines – each line contains a value of time t and a functional value $f(t)$. In this case, the function is a normalized critically-damped waveform $f(t) = 2.7183 t \exp(-t)$. The table was created from a spreadsheet. The two real-number parameters adjust the normalized function so that: 1) the peak current occurs at 350.0 μs and 2) the magnetic field in the transmission line gap has a magnitude of 0.6 tesla for an aluminum center-conductor.

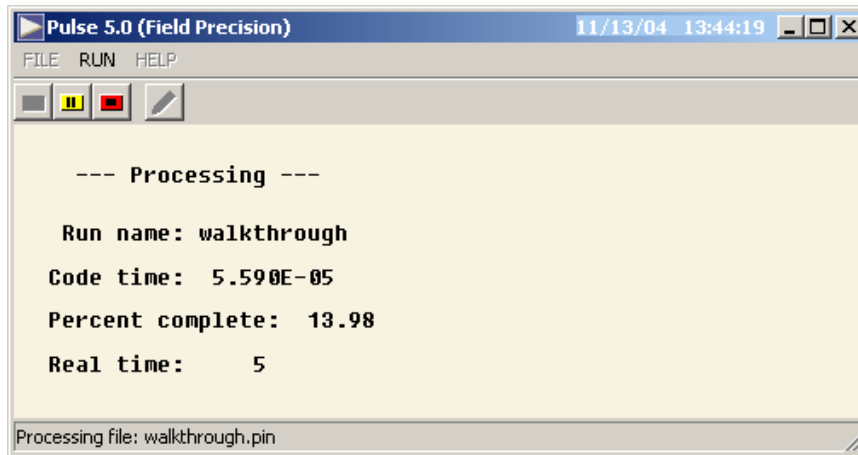


Figure 3. Pulse screen display during a calculation.

The final region command,

```
REGION(8) Fixed = 0.0
```

sets $rA_0 = 0.0$ for all nodes on the bottom, right and top boundaries. The condition constrains the magnetic field to be parallel to surfaces. It is clear that the condition holds on the bottom boundary (axis of rotation), but some explanation is needed for the other two. The field will not be completely contained by the aluminum vacuum chamber. Some flux will leak out, and one of our goals is to find the magnetic field amplitude outside the tube. In a finite-element calculation of magnetic-field diffusion, it is not possible to define an ideal free-space boundary. In **Pulse**, there are two choices for the boundary condition: 1) parallel **B** and 2) normal **B**. To approximate the free-space condition, we include an isolating air region around the system and apply the parallel-**B** condition. With no specification, the left boundary automatically assume the natural boundary conditions for a finite-element magnetic-field solution (normal **B**). Because there is a long, uniform section of transmission line to the left of the solution volume, the condition that $B_r = 0.0$ is approximately correct. The two *DIAG* commands control data output. The first initiates generation of field snapshots at 175 and 350 seconds. The second places a probe just outside the aluminum vacuum chamber in the transmission line region to measure leakage field.

Exit the editor and click on *RUN/START RUN*. **Pulse** reads the files *WALKTHROUGH.MOU* and *WALKTHROUGH.PIN* and starts the calculation. After reading data from *CRITDAMP.DRV*, the program initiates the magnetic diffusion calculation. The screen display (Figure 3)

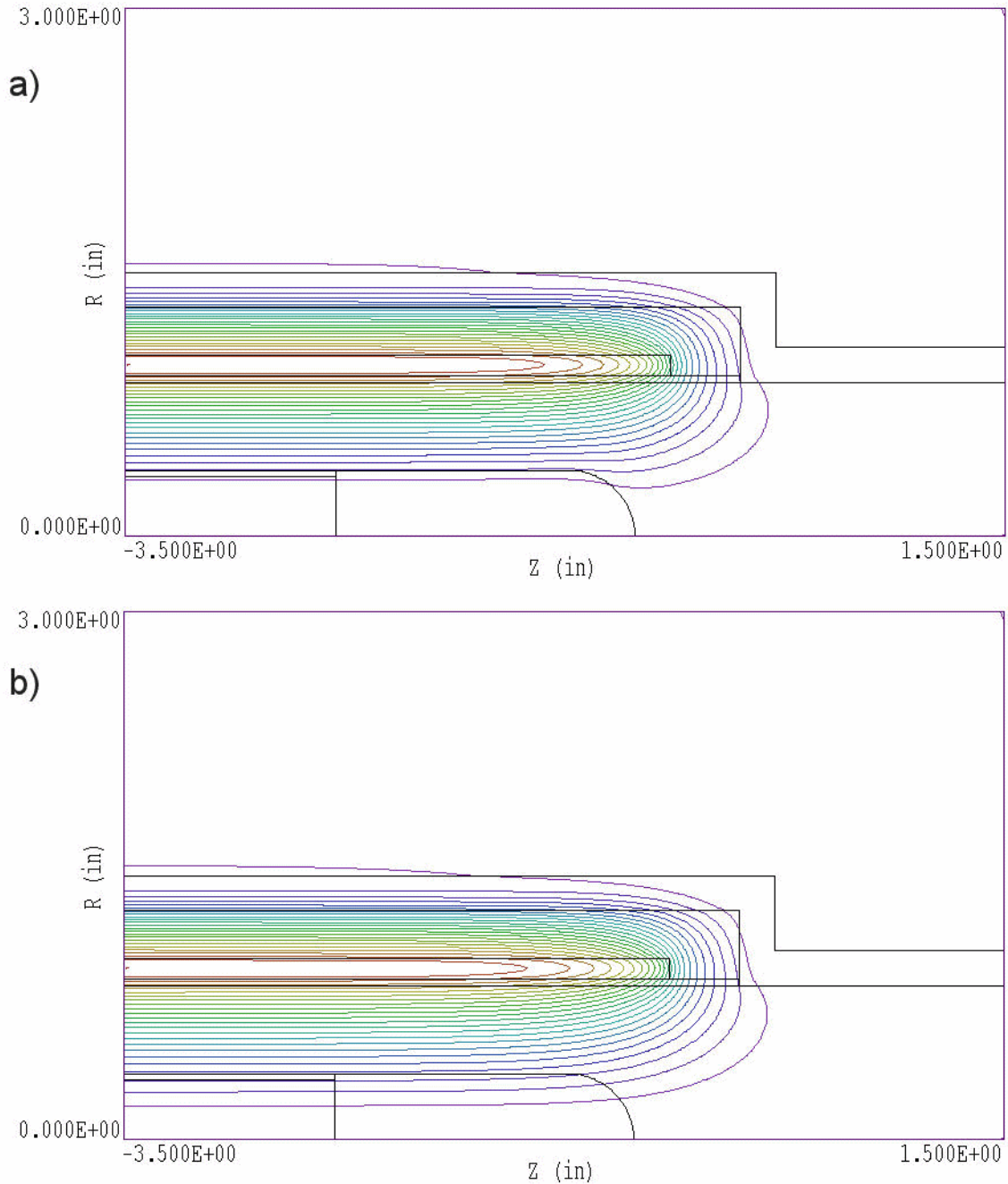


Figure 4. Magnetic field lines for the WALKTHROUGH example at $t = 350$ seconds. Note that lines are separated by equal intervals of flux so that the spacing appears larger near the axis. *a)* Solid aluminum center-conductor. *b)* Center-conductor comprised of stainless steel tube and cap.

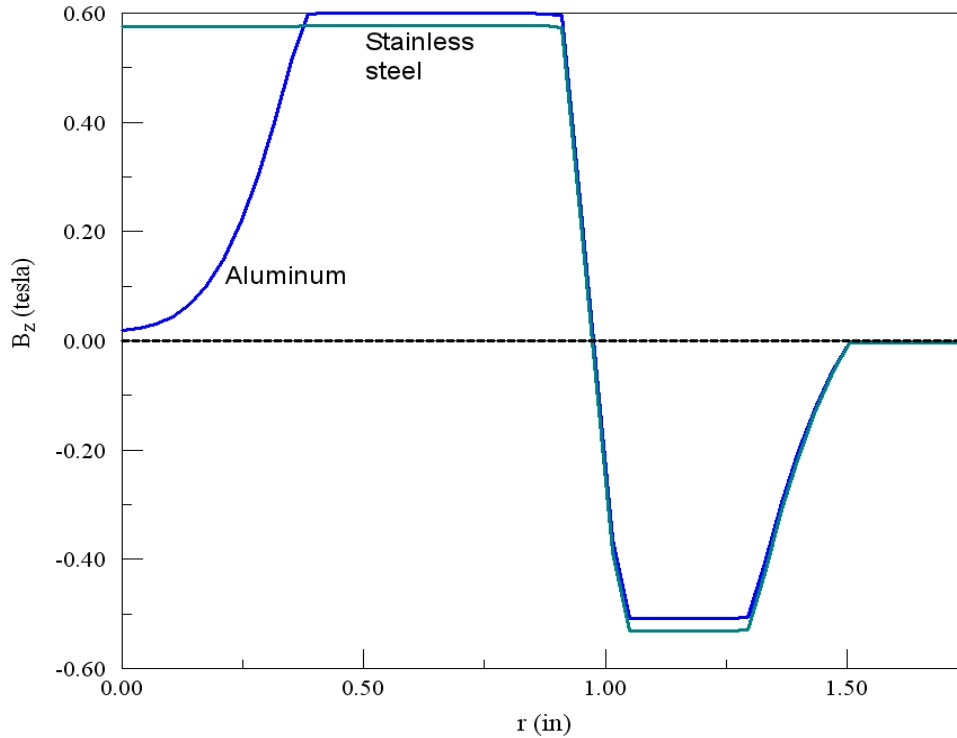


Figure 5. Variation of B_z along the left boundaries of Figs. 4a and 4b.

shows the progress of the run. The process takes about 40 seconds on a 3 GHz computer. Pulse adds the following files to the working directory: WALKTHROUGH.001, WALKTHROUGH.002 and WALKTHROUGH.P01. The first two files are the field snapshots at 175 and 350 seconds, while the third is the probe record.

Launch **VPulse**, click on *FILE/LOAD FIRST SOLUTION FILE* and choose *WALKTHROUGH*. The program loads WALKTHROUGH.001 and creates a default magnetic field-line plot (Figure 4). Click on *FILE/LOAD NEXT SOLUTION FILE* to advance to the solution at the peak of the drive current (350 seconds). At this point, you can experiment with the extensive plot and analysis functions of **VPulse**. Figure 4 shows field-line plots for two choices of center-conductor materials. Figure 5 plots the variations of B_z along the left boundary of Fig. 4. Values for the plot were calculated using the *LINE SCAN* command in **VPulse**. Figure 1 is an element-type plot of $|\mathbf{B}|$ for an aluminum center-conductor which clearly illustrates diffusive field penetration. Sections ## give detailed descriptions of **VPulse** capabilities.

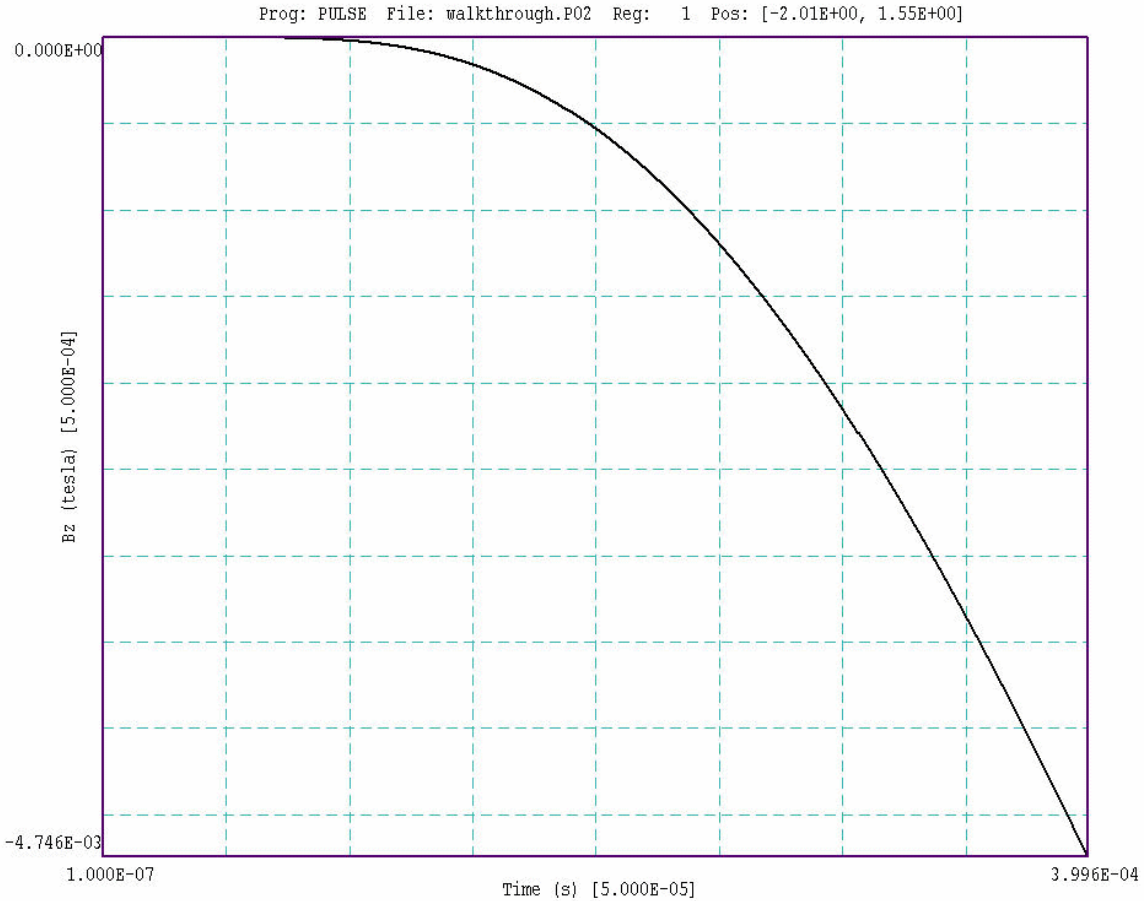


Figure 6. Probe plotting capabilities. *WALKTHROUGH* example – magnetic field $B_z(t)$ just outside the aluminum vacuum tube at $z = -2.00$ inches.

To conclude, launch **Probe** from **TC**. Click on *LOAD PROBE FILE* and choose *WALKTHROUGH.P01*. The program displays a summary of file information – click *OK* to proceed. **Probe** creates the default plot shown in Fig. 6. As expected, the external field rises exponentially with time, reaching a peak value of about 33 G at $t = 350$ seconds. Within the program you can change quantities, modify the plot limits or use the digital oscilloscope features to find specific values. The **Probe** manual describes program capabilities in detail. Note that probe files are in text format so it is easy to port information to your own analysis programs.