TriComp 5.0

WaveSim
Frequency-domain electromagnetics

Field Precision
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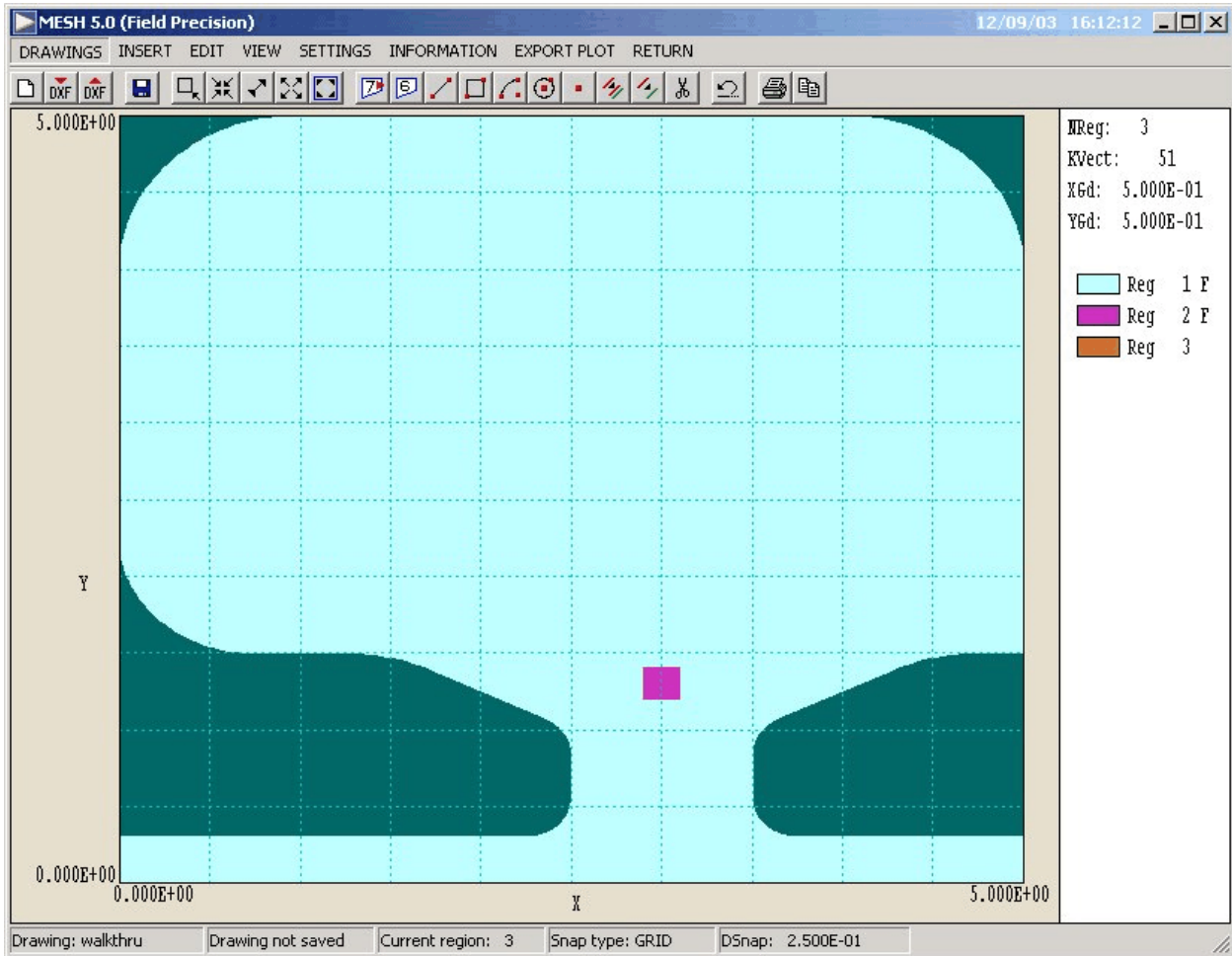Albuquerque, New Mexico 87192 U.S.A.
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Figure 1. Definition of the cavity geometry for the WALKTHRU example. The cavity has cylindrical symmetry about the lower axis. Dimensions are in cm.

2. Walkthrough example

To test the installation and to get acquainted with **WaveSim** procedures, we shall follow through an example in detail. We want to calculate the resonant frequency and quality factor (Q) for the klystron cavity shown in Figure 1. Note that the cavity is a figure of revolution about the abscissa. In the **WaveSim** calculation, the horizontal axis will be associated with z and the vertical axis with r. To begin, move the files WALKTHRU.DXF, WALKTHRU.WIN and WALKTHRU.SCR to a working directory such as \TRICOMP\BUFFER. Run **TC** (the **TriComp** program launcher) and check that the program and data directories are set correctly. The standard values are \TRICOMP and \TRICOMP\BUFFER.
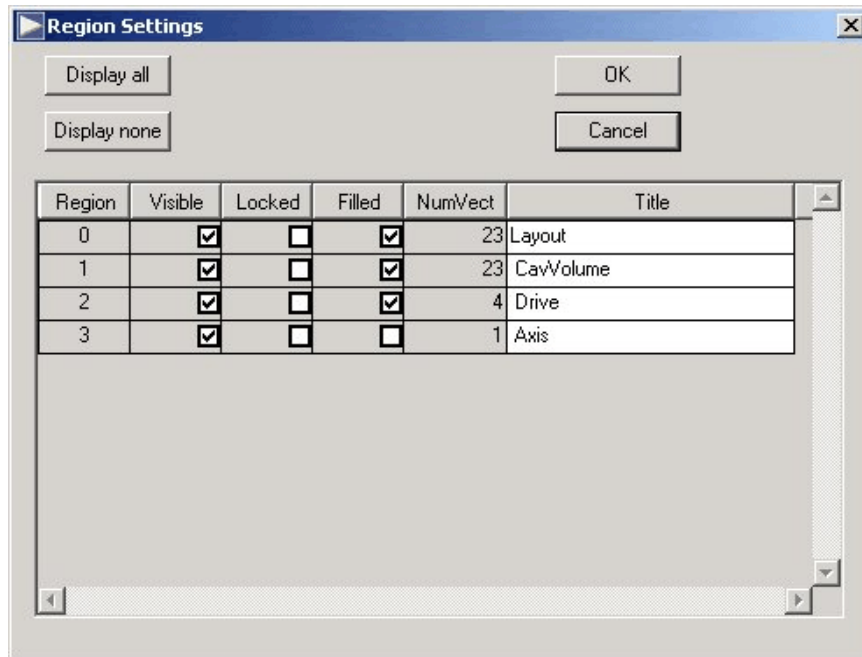
Figure 2. Region properties dialog.

We will first learn how the **Mesh** drawing editor can be used to create an input script that describes the geometry. Don't worry if you make a mistake in the following sequence. You can always use the prepared script `WALKTHRU.MIN` included with the examples. The file `WALKTHRU.DXF` is a drawing file that was prepared with QCAD, a freeware 2D CAD program included with **WaveSim**. Advanced features of the program were employed to generate the fillets (arcs) on the cavity boundaries. We added some features such as region names in the **Mesh** drawing editor. Launch **Mesh** and choose the menu command *DRAWING*. The program enters the drawing editor, one of the options for preparing **Mesh** input. Click on *DRAWING/IMPORT DXF* and choose the file `WALKTHRU.DXF`. Click *OK* again when the program displays a dialog listing information on the drawing. Next, click on *SETTINGS/DISPLAY REGION FILL*. You should see a display like Fig. 1 (we have changed some of the colors for clarity). As loaded, the drawing contains a layout layer and three active regions. Click on *SETTINGS/REGION PROPERTIES* to display the dialog of Fig. 2. The vectors of Region 1 comprise the closed outline of the cavity. The region has the *FILLED* property so the region number is assigned to all enclosed nodes and elements (light blue area in Fig. 1). This region will have the properties of vacuum in the **WaveSim** calculation. Region 2 (a small rectangle) is a drive region required for resonant-cavity calculations. This filled vacuum region will have a RF current density of arbitrary

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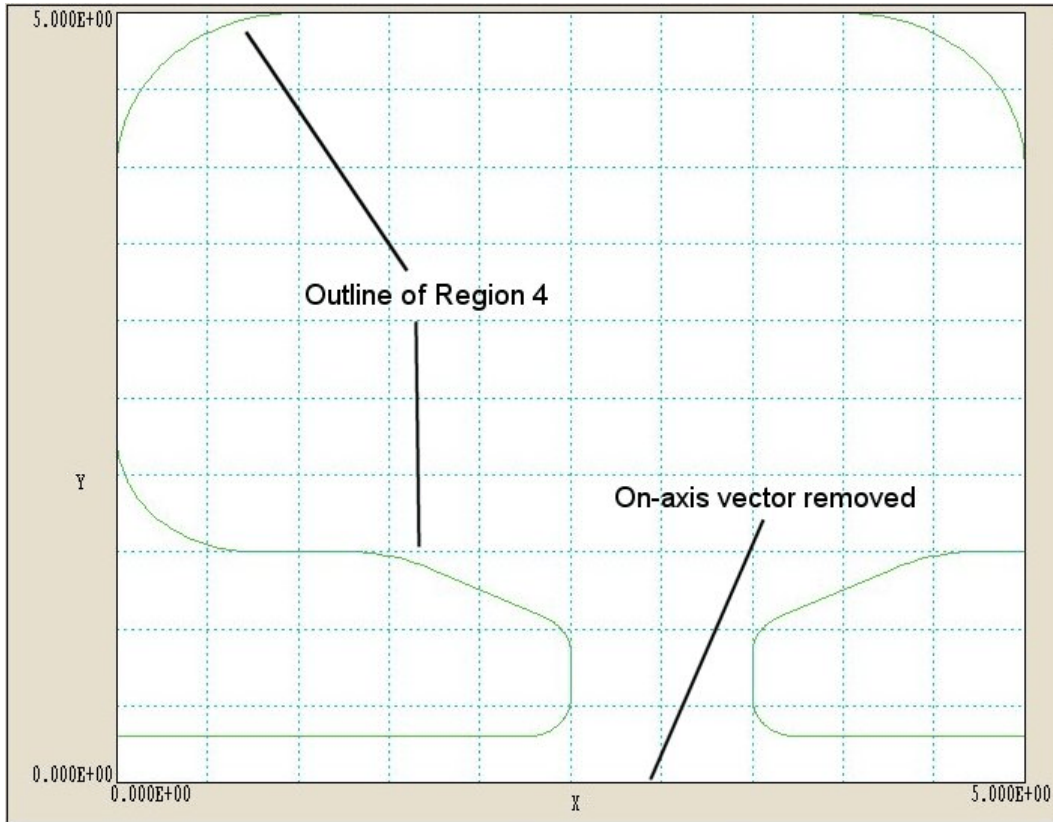
Figure 3. Line region for Q calculation.

amplitude to initiate the mode. Region 3 consists of a single vector that extends along the axis. This region will be used to set nodes to the fixed condition $rH_\theta = 0.0$.

Before we create an input script for **Mesh** from the drawing, we need to create an additional region. We shall assign region number 4 to nodes on the cavity boundary with the exception of the axis. This identification will be used for a diagnostic in the **WSV** postprocessor. Click on *EDIT/COPY REGION*. To select Region 1, move the mouse inside the blue area close to the wall. Click the left button. The boundary of region 1 should be highlighted. The program next asks for two points that define a displacement for the copied region. We want no displacement, so click the left button twice with the mouse in the same position. The list on the right-hand side of the screen shows that the new region has been added. To view the region, return to *SETTINGS/REGION PROPERTIES*. Uncheck the *VISIBLE* attribute and check the *LOCKED* attribute for Regions 1, 2 and 3, then click *OK*. The display shows the green outline of Region 4 (Fig. 3). We need to delete the on axis vector. Choose

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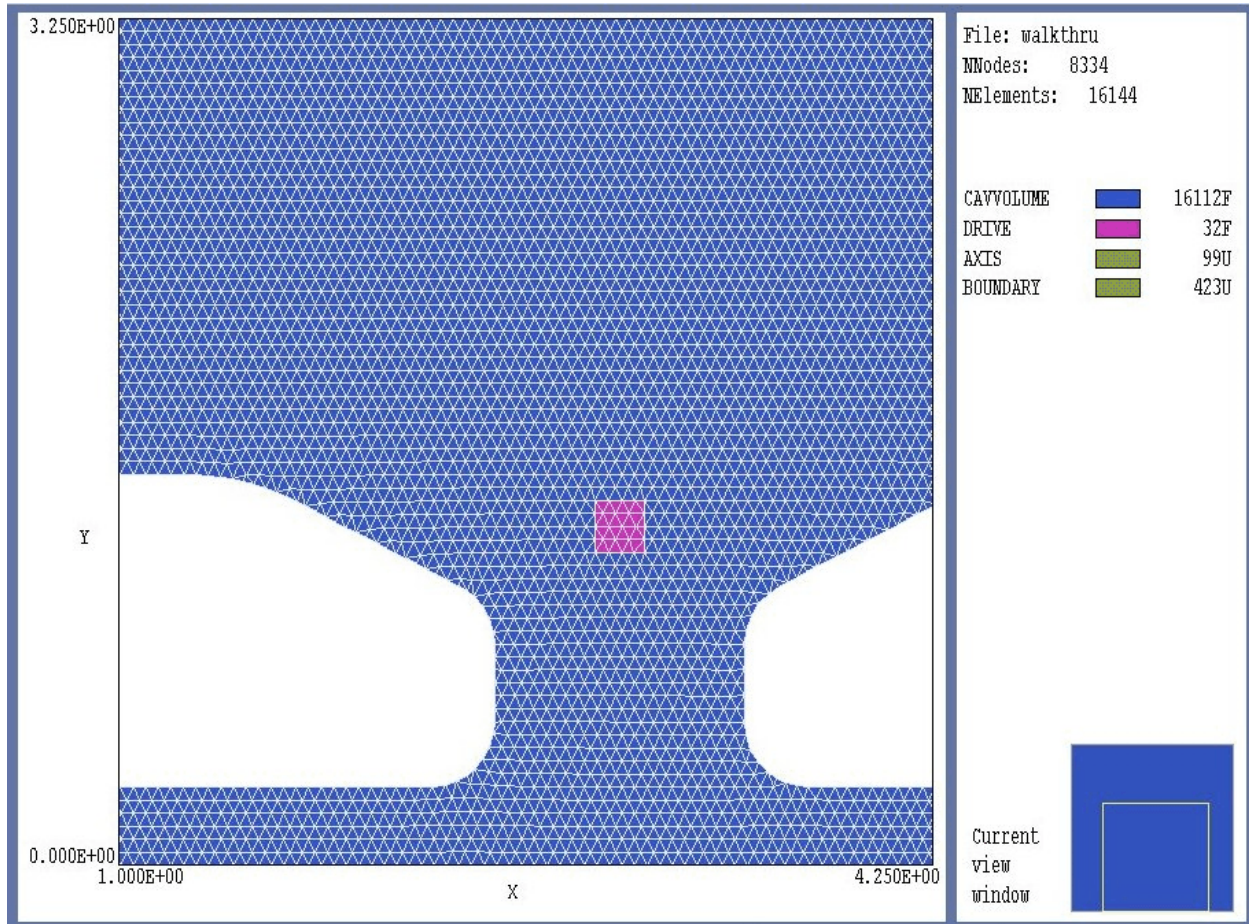
Figure 4. Mesh for the WALKTHRU example (detail near the axis)

EDIT/DELETE/VECTOR, move the mouse close to the axis and click the left button. You can check that the operation was successful by comparing the number of vectors in Regions 1 and 4 in *SETTINGS/REGION PROPERTIES*. While in the dialog, assign the name *BOUNDARY* to region 4. To save your work, choose *DRAWINGS/EXPORT DXF*.

The next step is to create a script in the **Mesh** input format. Click on *DRAWINGS/CREATE MIN FILE*. The program automatically translates the DXF vector information into a **Mesh** script and shows the result in the internal text editor. We shall make no changes, so simply close the text editor and exit the drawing editor by clicking on *RETURN*.

If you did not complete the above procedure, copy the file WALKTHRU.MIN (**M**esh **IN**put) from the example directory to continue the demonstration. In the main **Mesh** menu, click on *FILE/LOAD SCRIPT*

(MIN) and choose the file WALKTHRU.MIN. Next click on *PROCESS*.
Mesh reads the boundary specifications, shapes elements to conform to
the material divisions and assigns region numbers to nodes and elements.
Click on FILES/SAVE MESH (MOU) to create an output file (**M**esh
OUtput). This file will supply the geometric information for the **WaveSim**
solution. At this point, you can experiment with some of the plot
capabilities of Mesh. Figure 4 shows a detail of the conformal elements
near the axis. The box to the right shows region names along the with
number of elements (for filled regions) or the number of nodes (for open
regions).

Table 1. File WALKTHRU.WIN

```
* File WALKTHRU.WIN

SET Geometry Cylin
SET DUnit 100.0
SET Solution H
SET Probe 2.5 4.8

* Commands to perform the initial scan
* SET FStep 30
SET Mode Scan
SET Range 1.2E9  2.0E9

* Commands to find the fundamental resonant mode
* SET Mode Search
* SET Range 1.45E9  1.55E9

REGION(1) Mu 1.0
REGION(1) Epsi 1.0
REGION(2) Drive 1.0 0.0 0.0
REGION(3) Reflect
REGION(4) Mu 1.0
REGION(4) Epsi 1.0

ENDFILE
```

A **WaveSim** calculation requires a **Mesh** output file to define the
geometry and a script to control field solution. Table 1 shows the contents
of the file WALKTHRU.WIN (**W**avesim **IN**put). Commands that begin
with the keyword *SET* define values that control the program. Command
that begin with *REGION* set physical properties for the regions. The *SET*

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GEOMETRY command states that the system has cylindrical symmetry and the *SET DUNIT* command specifies that dimensions (including those in the **Mesh** file) are given in centimeters. The command *SET SOLUTION H* indicates that the primary quantity of the desired TM_{010} mode is rH_θ while the derived quantities are E_r and E_z. Section 5 discusses electromagnetic mode types. The command *SET PROBE* defines the position of a probe to sense the response of the cavity to the drive near the axis (Region 2). The probe is located near the anticpated position of maximum rH_θ.

Two next two groups of commands determine the type of solution that **WaveSim** will perform. The first group calls for a calculation in the *SCAN* mode, while the second group (deactivated by comment symbols) defines a high-accuracy resonance search. In a *SCAN* calculation, **WaveSim** carries out a series of solutions in a frequency interval and records field values at the probe location. Zero-crossings of the probe signal indicate resonances in the interval. Using the results of the scan, a high-accuracy search is performed over an interval that contains the desired resonance. In the example the cavity has an outer radius of $R_o = 0.05$ m. The maximum possible frequency for the TM_{010} mode is

$$ f = \frac{2.405 \ c}{2\pi \ Ro} = 2.3 \quad (GHz). $$

The re-entrant beam tube structure adds extra capacitance near the axis and lowers the frequency. As an initial guess we picked the scan range 1.2 to 2.0 GHz.

The remaining commands assign physical properties to the regions:

- Region 1. Vacuum with $\epsilon_r = 1$ and $\mu_r = 1$. The commands are included as reminders -- in the absence of any specification the default is vacuum.

- Region 2. A vacuum region with a drive current density. The parameters of the *REGION DRIVE* command specify that the current density has zero phase points and points along the z axis with amplitude $rj_z = 1.0$ A/m. The drive amplitude is arbitrary in resonant-cavity calculations with no losses.

- Region 3. The boundary condition $rH_\theta = 0$ on the axis.

- Region 4. The line of nodes along the cavity wall for **WSV** diagnostics.
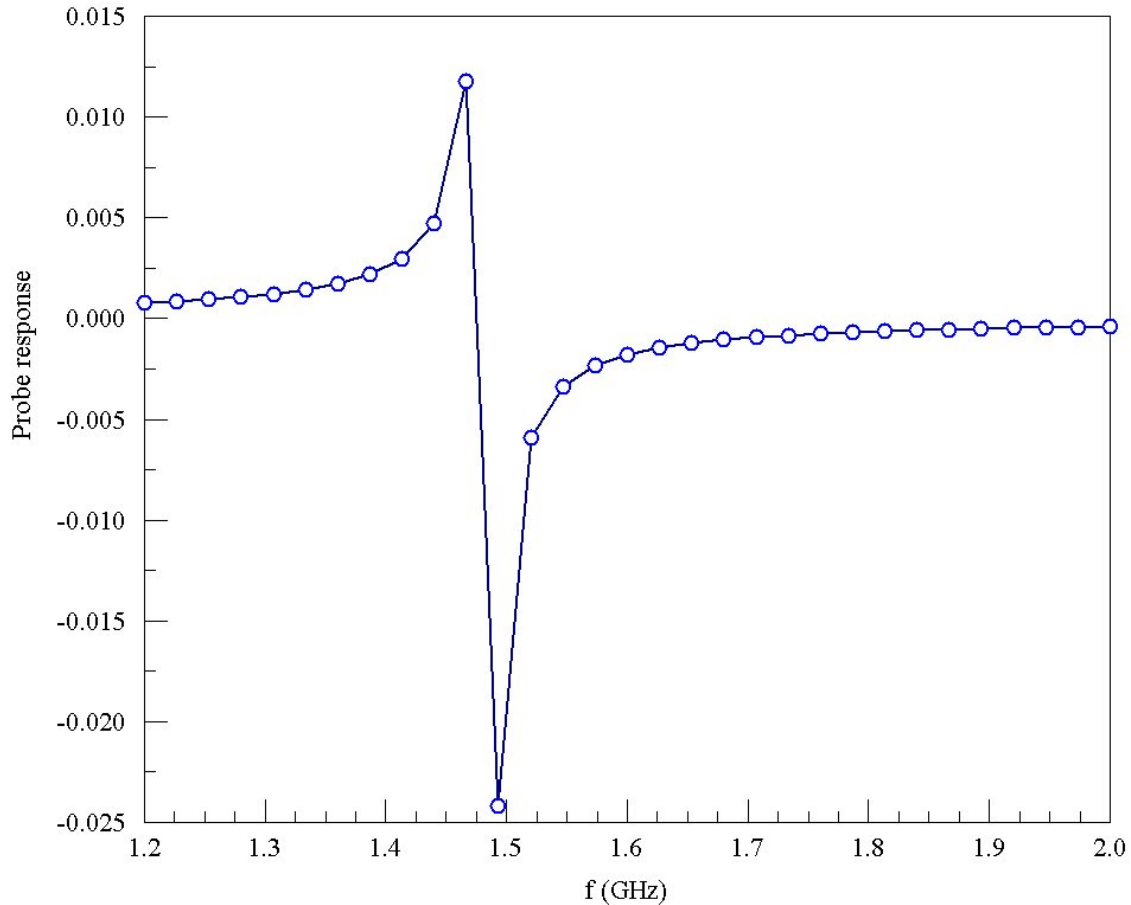
Figure 5. Probe response as a function of frequency for the `WALKTHRU` example.

Launch **WaveSim** from **TC.** Click on *RUN/START RUN* and choose the file `WALKTHRU.WIN`. The program loads the input data files, sets up node equations and carries out a series of sparse matrix inversions to find complex values of rH_θ at all nodes. The scan takes about 3-4 minutes. When the run is complete, click on *FILE/EDIT LISTING FILES* and choose `WALKTHRU.WLS`. The file (shown in Table 2) contains a listing of the probe response at 31 frequencies (30 uniform intervals). Figure 5 shows a plot of the real part of the probe response. The zero crossing near 1.5 GHz indicates the presence of a resonance. Based on this information, we choose the bracketing frequency interval of 1.45 to 1.55 GHz for the resonance search.

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Table 2. Results of the frequency scan in the WALKTHRU example

```
--- Frequency Scan ---
    NStep:    30
  FreqLow:    1.200000E+09
 FreqHigh:    2.000000E+09
   ProbeX:    2.510869E+00
   ProbeY:    4.800000E+00

  NStep    Frequency     Probe(Real)    Probe(IMag)    Probe(Mag)
  ==============================================================
     0  1.200000E+09   7.729098E-04   0.000000E+00   7.729098E-04
     1  1.226667E+09   8.485153E-04   0.000000E+00   8.485153E-04
     2  1.253333E+09   9.417076E-04   0.000000E+00   9.417076E-04
     3  1.280000E+09   1.059745E-03   0.000000E+00   1.059745E-03
     4  1.306667E+09   1.213002E-03   0.000000E+00   1.213002E-03
     5  1.333333E+09   1.421275E-03   0.000000E+00   1.421275E-03
     6  1.360000E+09   1.718083E-03   0.000000E+00   1.718083E-03
     7  1.386667E+09   2.178917E-03   0.000000E+00   2.178917E-03
     8  1.413333E+09   2.982848E-03   0.000000E+00   2.982848E-03
     9  1.440000E+09   4.748147E-03   0.000000E+00   4.748147E-03
    10  1.466667E+09   1.175621E-02   0.000000E+00   1.175621E-02
    11  1.493333E+09  -2.420435E-02   0.000000E+00   2.420435E-02
    12  1.520000E+09  -5.935348E-03   0.000000E+00   5.935348E-03
    13  1.546667E+09  -3.374799E-03   0.000000E+00   3.374799E-03
    14  1.573333E+09  -2.355437E-03   0.000000E+00   2.355437E-03
    15  1.600000E+09  -1.807685E-03   0.000000E+00   1.807685E-03
    16  1.626667E+09  -1.465374E-03   0.000000E+00   1.465374E-03
    17  1.653333E+09  -1.231654E-03   0.000000E+00   1.231654E-03
    18  1.680000E+09  -1.062099E-03   0.000000E+00   1.062099E-03
    19  1.706667E+09  -9.332518E-04   0.000000E+00   9.332518E-04
    20  1.733333E+09  -8.323748E-04   0.000000E+00   8.323748E-04
    21  1.760000E+09  -7.510412E-04   0.000000E+00   7.510412E-04
    22  1.786667E+09  -6.843203E-04   0.000000E+00   6.843203E-04
    23  1.813333E+09  -6.284751E-04   0.000000E+00   6.284751E-04
    24  1.840000E+09  -5.811739E-04   0.000000E+00   5.811739E-04
    25  1.866667E+09  -5.405628E-04   0.000000E+00   5.405628E-04
    26  1.893333E+09  -5.053715E-04   0.000000E+00   5.053715E-04
    27  1.920000E+09  -4.745641E-04   0.000000E+00   4.745641E-04
    28  1.946667E+09  -4.474191E-04   0.000000E+00   4.474191E-04
    29  1.973333E+09  -4.233323E-04   0.000000E+00   4.233323E-04
    30  2.000000E+09  -4.017980E-04   0.000000E+00   4.017980E-04
```

Exit the editor and click on *FILE/EDIT INPUT FILE*. Choose
WALKTHRU.WIN . The editor displays the contents of Table 1. Modify
the comment status of control lines to change the program mode for the
next calculation. The file should look like this:

```
* Commands to perform the initial scan
* SET FStep 30
* SET Mode Scan
* SET Range 1.2E9  2.0E9

* Commands to find the fundamental resonant mode
SET Mode Search
SET Range 1.45E9  1.55E9
```

Save the file and exit the editor. Start the second solution using the
RUN/START RUN command. The resonance search takes about 30-40
seconds and produces the following entry in the listing file:

```
Iteration:   1   Frequency:   1.484390E+09   Response:   1.246726E+00
Iteration:   2   Frequency:   1.484653E+09   Response:  -1.332502E-01
Iteration:   3   Frequency:   1.484578E+09   Response:   3.498476E-01
Resonance search successful.
     Final frequency:   1.484653E+09
     Writing data to file WALKTHRU.WOU
```

In this run **WaveSim** identified the fundamental mode frequency as
1.4847 GHz and created an output file of field values at that frequency.
We can now proceed to an analysis of the solution.

Run **WSV** from **TC** and click on *FILE/LOAD SOLUTION FILE*. Pick
WALKTHRU.WOU and click *OK*. The program loads the data and displays
the default plot of electric field lines shown in Fig. 6. Contours of rH_θ are
separated by equal intervals of magnetic-field flux; therefore, the spacing
is larger near the axis. **WSV** has extensive capabilities. We will perform
two specific tasks:

   ■ Plot the magnitude and direction of the electric field near the
   interaction gap for a given amplitude of deceleration field

   ■ Determine the Q value for an ideal copper cavity.

Remember that the magnitude of field values for a resonant solution is
arbitrary. First, we must renormalize the solution for a given peak
deceleration field. Click on *ANALYSIS/SCAN PLOT QUANTITY* and
choose $|E_z|$. Next click on *ANALYSIS/LINE SCAN* and move the mouse
pointer into the plot area. Note that the cursor changes to a cross-hair
pattern when the mouse is active inside the plot. Using the coordinates
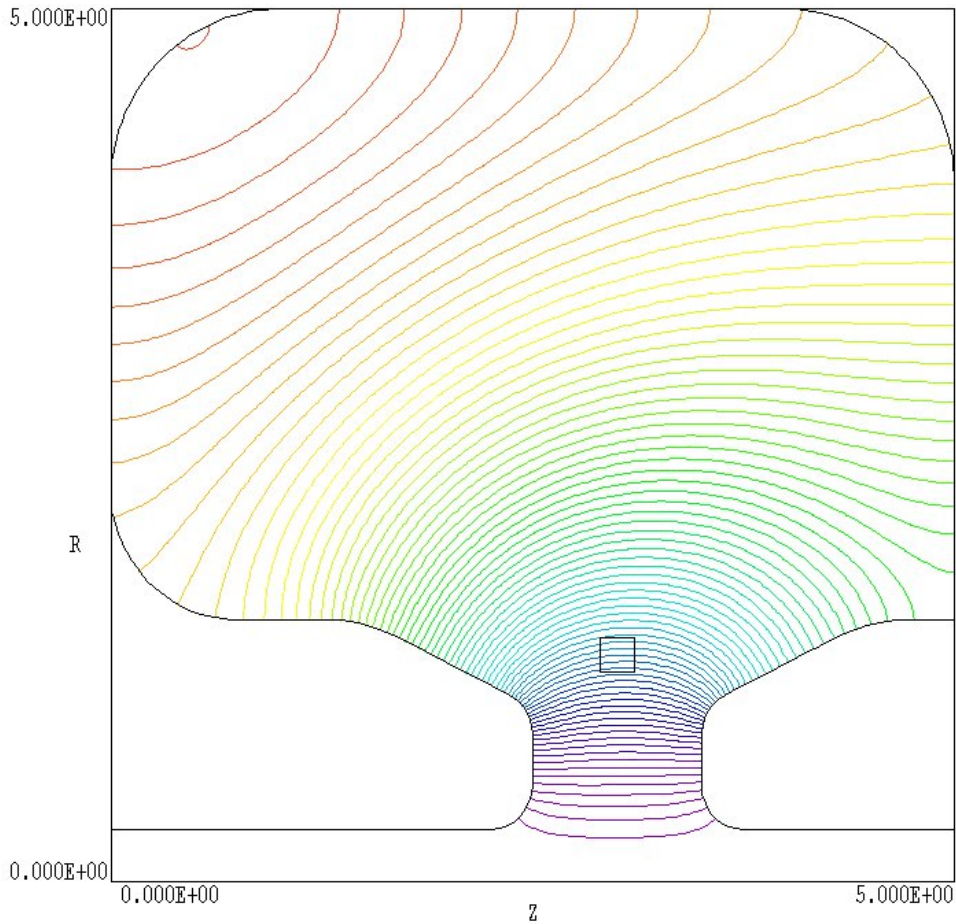
Figure 6. Electric field lines separated by equal intervals of magnetic field intensity flux, `WALKTHRU` example.

listed at the bottom of the screen, move the pointer to a psotion near the point [$x/z = 1.5$, $y/r = 0.0$] and click the left mouse button. Then move the mouse to the position [$x/z = -1.5$, $y/r = 0.0$] and click again. **WSV** calculates a sequence of $|E_z|$ values and displays the results (Fig. 7). Note that the peak field is 1.524×10^5 V/m, while the target peak field is 7.5×10^6 V/m. We shall increase the field values by a factor of 49.21. Exit the scan plot menu by clicking *SCAN PLOTS/CLOSE SCAN PLOT* and choose the command *ANALYSIS/RENORMALIZE FIELD*. Type '49.21' in the box and click *OK*. **WSV** multiplies all values of rH_θ by the normalization factor.

To create the field plot, click on the command *SPATIAL PLOTS/PLOT TYPE*, choose the option *VECTOR* and click *OK*. The program issues an error message because the present quantity (rH_θ) is not supported in a vector plot. Click on *SPATIAL PLOTS/PLOTTED QUANTITY* and choose

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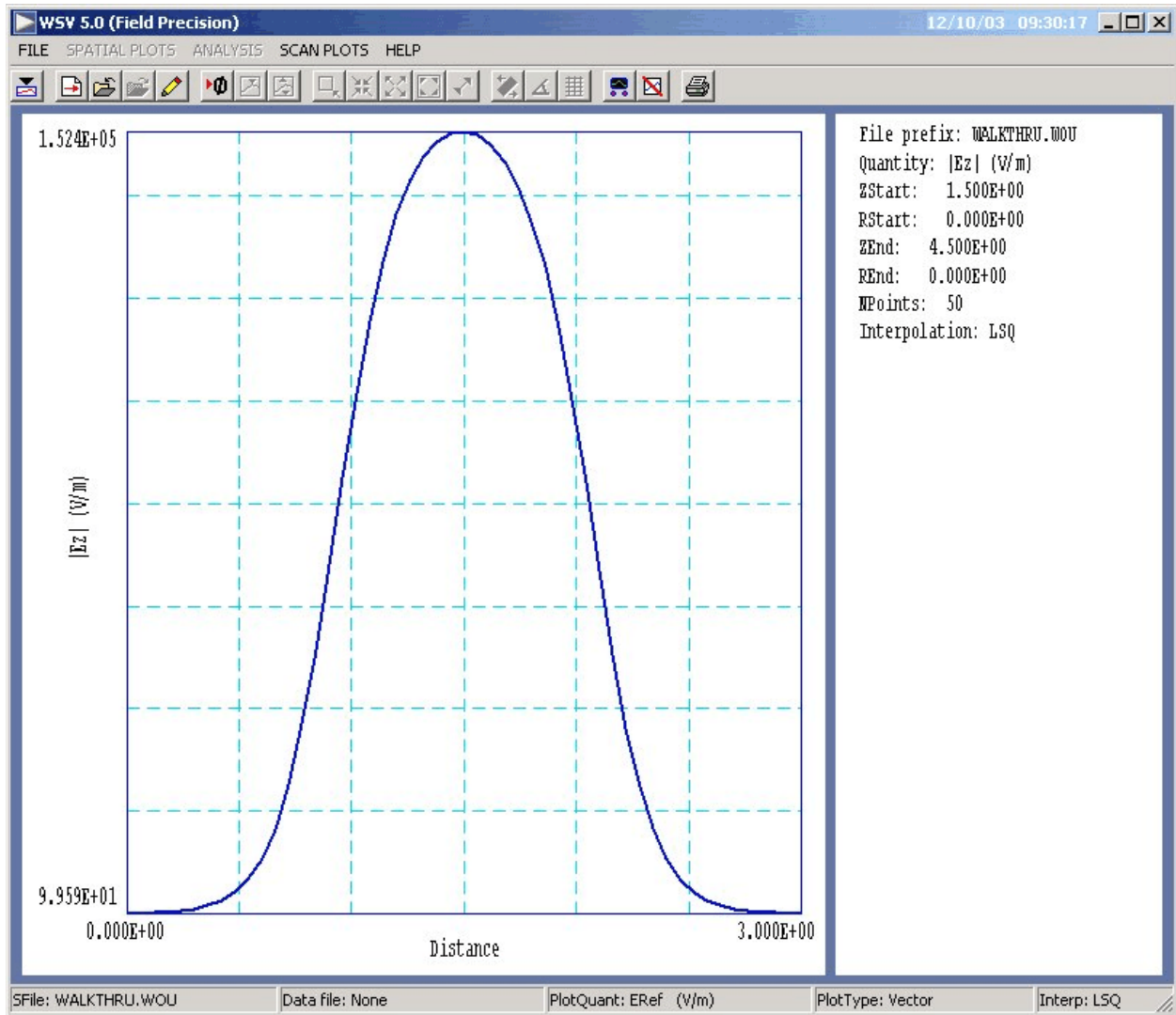
the single option |*ERef*|, the magnitude of the electric field at the reference phase. **WSV** creates a blank plot with no content. This is because the default value of reference phase is 0° and the electric field is 90° out of phase with the drive current (set to 0° in **WaveSim**). Click on *ANALYSIS/SET REFERENCE PHASE* and enter '90' in the box. Upon exiting the dialog, WSV creates a plot of electric field vectors with the background color-coded by the amplitude of the electric field. You can use the *ZOOM* tool to create the plot of Fig. 8.
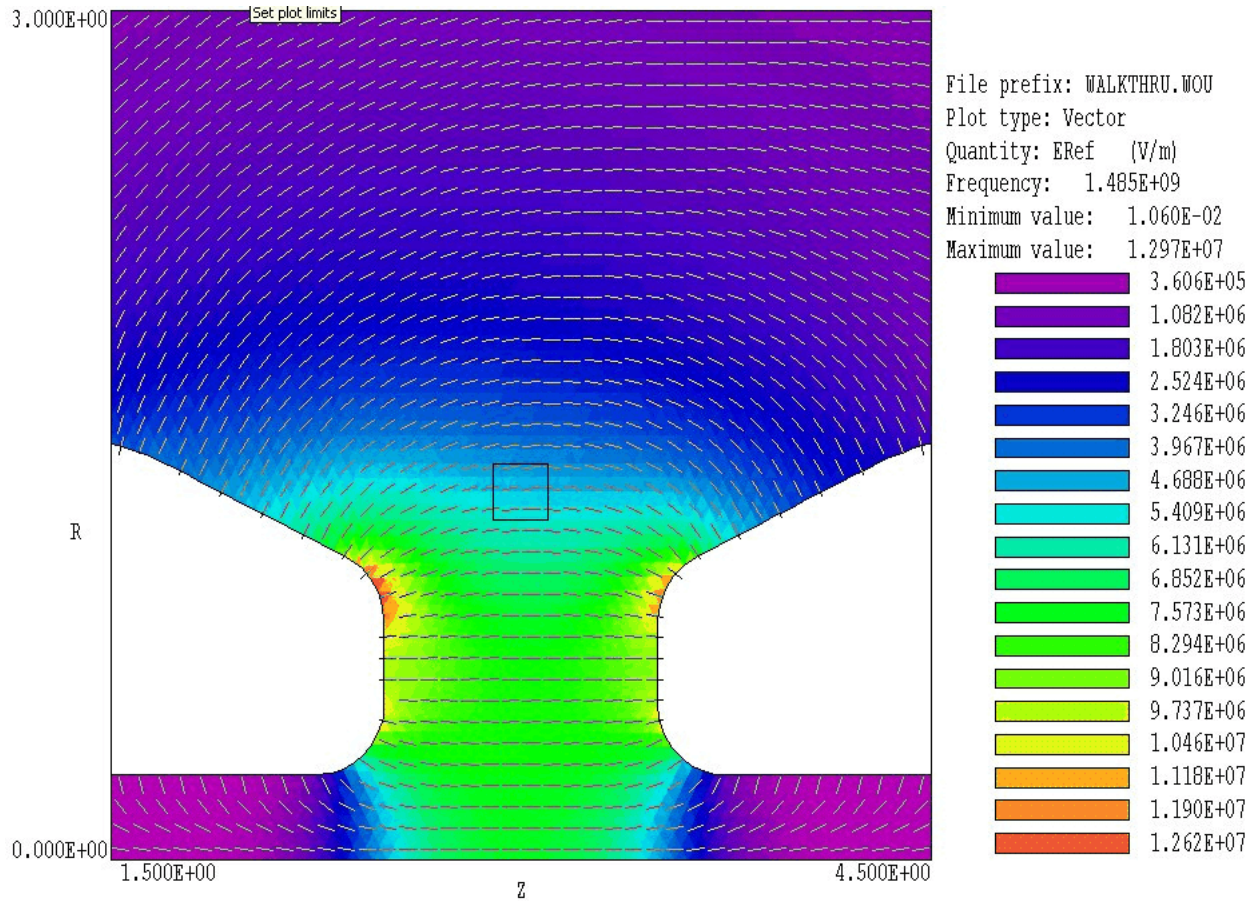
Figure 8. Electric field magnitude and direction near the deceleration gap, WALKTHRU example.

Table 3. Contents of the file WALKTHRU.SCR

```
* File: WALKTHRU.SCR
* Script control demonstration
* Assume that the file WALKTHRU.WOU has been opened
* and that the field values have been normalized by
* a factor 49.21
INPUT WALKTHRU.WOU
OUTPUT WALKTHRU
VOLUMEINT
ENDFILE
```

To conclude, we shall calculate the quality factor for the cavity using the automatic-analysis feature of **WSV**. Click on *FILE/RUN SCRIPT* and choose WALKTHRU.SCR. This file has the contents shown in Table 3. The script opens an output file WALKTHRU.DAT and records the results of a volume analysis. To see the results, click on *FILE/EDIT DATA FILE* and choose WALKTHRU.DAT. Table 4 shows the results of the analysis. At the chosen field normalization, the electromagnetic energy inside the cavity is $U = 3.292 \times 10^{-3}$ joules. The other quantity of interest for the Q-factor calculation is the following integral taken over the surface of Region 4:

$$\iint_S dS \; H_p^2/2 \; .$$

In the equation H_p is the amplitude of the component of magnetic field intensity parallel to the wall. The calculated value is 2.444×10^5 A^2. Following S. Ramo, J. Whinnery and T. Van Duzer, **Field and Waves in Communication Electronics** (Wiley, New York, 1965), Sect. 5.15, the time-averaged power lost to walls is :

$$P = R_s \iint_S dS \; H_p^2/2 \; .$$

The quantity R_s is the surface resistivity. For copper, this quantity is given by:

$$Rs = 2.61 \times 10^{-7} \; \sqrt{f} \qquad \Omega \; ,$$

The surface resistivity is $R_s = 1.006 \times 10^{-2}$ at f = 1.485 GHz, so that average power loss is $P = 2.458 \times 10^3$ W. Using the formula

$$Q = \frac{2\pi f \; U}{P} \; ,$$

we find that the quality factor for ideal copper walls is $Q = 15,520$. In practice, the quality factor may be lower because of imperfect surface finish on the cavity walls.

Table 4. Volume integrals for the WALKTHRU example

```
 --- Volume Integrals ---
Volume:   3.558E-04 m3
Field energy:   3.292E-03 J
Volume power dissipation:   0.000E+00 W
EMax:   1.297E+07 V/m
    Z:   2.503E+00,  R:   9.629E-01
HMax:   8.232E+03 V/m
    Z:   5.881E-01,  R:   1.530E+00

    Integrals by region
 NReg    Volume       Energy       Power
          (m3)          (J)         (W)
 ====================================
     1  3.554E-04  3.273E-03  0.000E+00
     2  3.267E-07  1.930E-05  0.000E+00

 --- Line Integrals over Line Regions ---
 NReg     Int(Hp^2/2)
            (A^2)
 ====================
     3       0.000E+00
     4       2.444E+05
```