Aether simulations of RF modes in an accelerator pumping port

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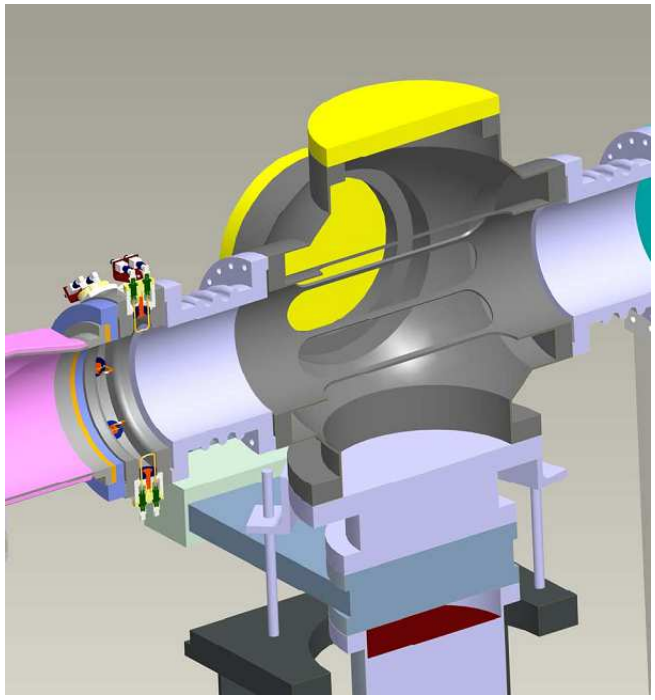

Figure 1: View of the pumping chamber

1 Introduction

Radio-frequency (RF) beam-position variations were observed during commissioning of the DARHT Axis-II accelerator. An excitation with frequency near 1.25 GHz reached a level sufficient to affect transport of the fourth beam pulse. A possibility cause identified by the DARHT staff was that electromagnetic energy from initial beam pulses accumulated in a resonant structure. Based on beam position measurements and analytic estimates of electromagnetic modes, a pumping port near the accelerator exit was identified as a potential candidate. The pump housing connected to the beam transport volume through large slots in the beam tube.

I carried out three-dimensional electromagnetic simulations of the pumping chamber with the following goals:

1. Calculate the excitation spectrum of the assembly for beam-deflection type modes.

2. Find the field properties of the mode near 1.25 GHz.

3. Determine how screens over the pumping ports and beam-pipe slots affect the excitation spectrum.

2 Aether capabilities

I used **Aether** for the calculations. The program has three operational modes:

Pulse
The program performs a straightforward time-domain solution to find pulsed electromagnetic fields. In a standard solution, the fields $|\mathbf{E}|$ and $|\mathbf{H}|$ have zero values at all positions at $t = 0.0$ s. Fields are generated by current distributions with prescribed spatial and temporal variations. An alternate pulse-initiation method is to start with $|\mathbf{H}| = 0.0$ and non-zero values of $|\mathbf{E}|$ calculated by the electrostatic program **HiPhi**. In this state (which could represent a charged transmission line), pulses are typically generated by changing the conductivity of a region (*i.e.*, a switch). Both methods may be combined in a solution. *Pulse* mode calculations may generate history files (temporal records of field quantities at specified positions) and spatial files (spatial records at specified times).

Res
The activity in this mode is to find the resonant modes of three-dimensional structures. **Aether** excites a time-domain solution with a uniform current density in one or more drive regions. The Fourier transform of the drive waveform is a rounded step function with a user-specified frequency width and central value. The program samples the field response at one or more probe points. The result of the calculation is a set of Fourier-transformed probe signals and a table of identified peaks in the listing file. The location of the drive region and the positions of the probes may be chosen for preferential detection of mode types.

RF
Aether determines a frequency-domain solution by running a time-domain solution to equilibrium and then converting the field values to phasor form. In contrast to the *Pulse* mode, the waveforms for drive currents are harmonic functions at a single frequency f_0. Drive regions may have prescribed spatial variations of current density and phase offsets. The output is a single space file listing field phasors and material properties.

For this work, I used the most recent **Aether** that emplys **OpenMP** routines for parallel processing. On a Core I7 machine, the run time reduction is close to a factor of four.

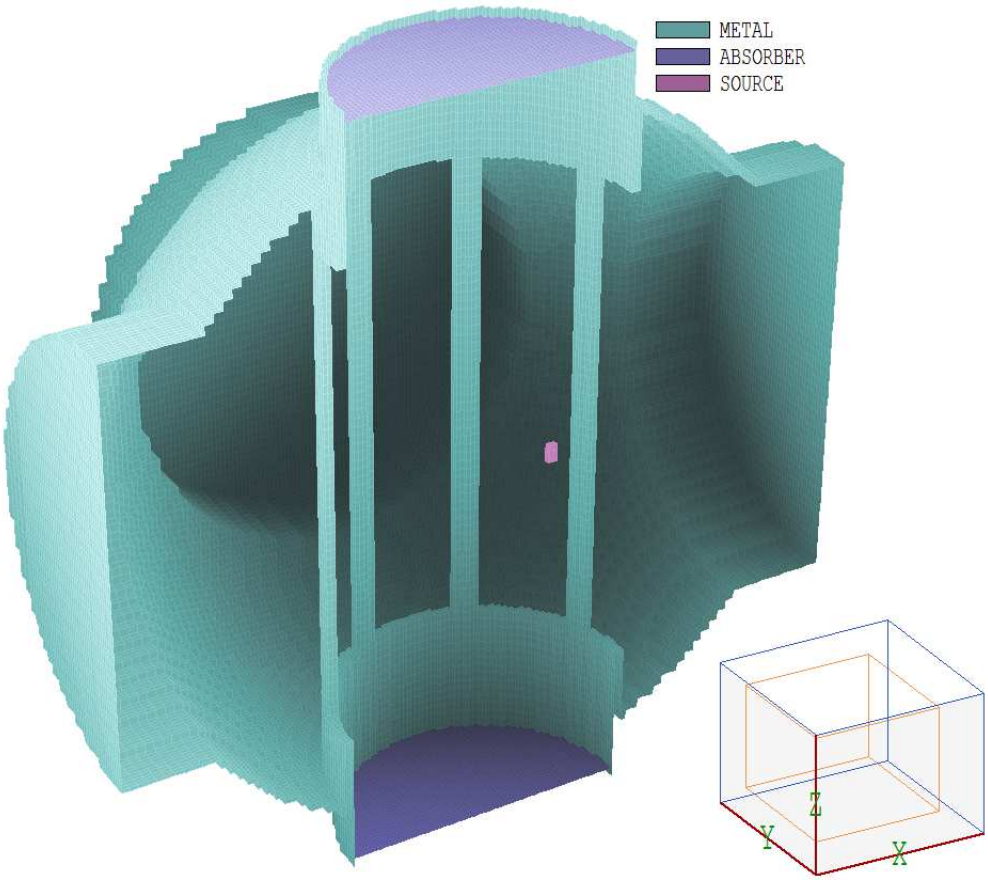

Figure 2: Three-dimensional view of the computational mesh showing boundaries of the metal, absorbing and source regions. The direction of beam propagation is from bottom to top.

3 Mesh generation

I worked from drawings of the pump station to create the mesh shown in Fig. 3. It contained 1,365,336 active elements. It was relatively easy to construct a good representation of the assembly through the following sequence of operations:

1. Fill a cubic solution volume (side length 17.2") with elements of a *Metal* region.

2. Cut out a sphere of radius 7.9" with *Vacuum* elements to represent the central volume of the pump port.

3. Cut out the side ports pointing in x and y with *Vacuum* elements. The ports are cylinders of radius 4.8". The length of 16.0" leaves a layer of *Metal* elements at the ends.

4. Add the *Metal* beam pipe, a cylinder of radius 3.4" and length 17.2" pointing in z.

5. Hollow out the beam pipe with a *Vacuum* cylinder of radius 3.2".

6. Add thin layers of *Absorber* elements at the upstream and downsteam ends of the beam pipe interior.

7. Use inclined boxes of *Vacuum* elements to cut eight slots in the beam pipe (width 2.0", length in z 7.00".

8. Add two small regions that carry current to drive modes. The sources are located at $x = \pm 1.5'''$, $y = z = 0.0'''$. They carry oppositely-directed axial current for preferential excitation of modes that create a field component H_y on the beam axis.

The four pump ports were capped with metal flanges, while the two beam ports had absorbing boundaries to represent an infinite extension of the pipe. To save time, I did not attempt to represent every weld and bevel in the pumping port. The slots in the assembly drawing had radii on the ends. I used slots with a rectangular cross section with about the same area.

4 Excitation spectrum and primary resonant mode

The first activity was to set up a resonance search in the full assembly. Table 1 shows the **Aether** control script. Commands in the *Control* section set the *Res* mode, specify the mesh described in the previous section with dimensions in inches, and set a central frequency for the excitation pulse of 1.5 GHz with a full width of about 3.0 GHz. The *Source* commands specify the direction of current-density in the source regions ($\pm j_z$). The region commands set elements to the conditions of metal, vacuum and an absorbing layer of thickness 0.2". Finally, diagnostic probes are located on the axis and at position $x = 4.0$" (outside the beam pipe).

The run time was 49 minutes on a dual-core machine. Figure 3 shows relative Fourier transforms of $H_y(t)$ for the two probes. (Note that the height of the peaks should not be given too much significance because they depend on the locations of the probes and excitation sources.) As observed in experiments, there is a prominent resonance near 1.25 GHz. There is also considerable high-frequency activity, probably the result of coupling of the TM_{110} mode of the beam pipe to complex excitations in the surrounding space of the pumping port. I made several checks to confirm that the mode spectrum was independent of the source properties. I rotated the sources

Table 1: Example of an **Aether** control script in the *Res* mode.

```
* File PumpStation03.AIN
* Displace source +-1.50" in x

*----CONTROL----
Mode = RES
Mesh = PumpStation03
DUnit = 39.37
Freq 1.5E9 3.0E9
Courant 0.75

* --- SOURCES ---
Source(4) 0.0 0.0 1.0
Source(5) 0.0 0.0 -1.0

*----REGION PROPERTIES----
Metal(1)
Vacuum(2)
AbsLayer(3) 0.2
Vacuum(4)
Vacuum(5)

*----DIAGNOSTICS----
History = 0.000 0.000 0.000
History = 4.000 0.000 0.000
Probe = 0.000 0.000 0.000 Hy
Probe = 4.000 0.000 0.000 Hy

EndFile
```

22.5° about z to position them opposite a current-return bar rather than a slot. I also removed on of the sources for asymmetric excitation. The changes had no detectable effect on the mode spectrum.

Next, I set up an **Aether** calculation in the *RF* mode to find the field distribution of the excitation at $f_0 = 1.23$ GHz. The source regions carried harmonic currents at f_0 with a phase difference of 180°. The excitation envelope had a smooth rise (raised-cosine function) over three RF cycles and dropped to zero over cycles 10 through 13. Phasors were computed on cycle 14. Figure 4 shows the calculated fields. The top plot is a snapshot of E_z at reference phase 0.0° in the plane $z = 0.0$". Electric fields have high amplitude in the regions outside the beam pipe with opposite phases at $\pm x$. The bottom plot shows H_y at a reference phase of 90.0° in the plane $z = 0.0$ with added vector lines. The plots demonstrate that the mode is the equivalent of the $\mathtt{TM}_{110}$ for the complete pumping port structure. The return-current bars play a significant role in shaping the magnetic field.

5 Effect of screens

I investigated two methods to remediate the growth of the low-frequency resonant mode:

Add screens over the side pumping ports.

Add a screen around the beam pipe.

In both cases, it was easy to change the mesh to represent the modified geometries. For the first case, I replaced the vacuum volumes to cut the side port with cylindrical metal plates that defined flat screen surfaces at displacements of $x = \pm 6.2$"and $y = \pm 6.2$". For the second case, I eliminated all external structures, leaving a beam pipe with inner radius 3.2". Again, I performed calculations in the **Aether** *Res* mode.

The resulting excitation spectra are plotted in Fig. 5. A screen over the beam-pipe slots (bottom) eliminates low-frequency modes and reduces the complexity of high-frequency excitations. The strong peak corresponds to the $\mathtt{TM}_{110}$ mode. The theoretical frequency for a pipe with inner radius R_w is:

$$f_{110} = \frac{3.832\ c}{2\pi R_w}.$$

For $R_w = 0.08128$ m, the value is 2.250 GHz. Screens over the pumping ports (top plot) raise the frequency of the global resonance to 1.58 GHz. The amplitude and complexity of high-frequency modes is also reduced. The

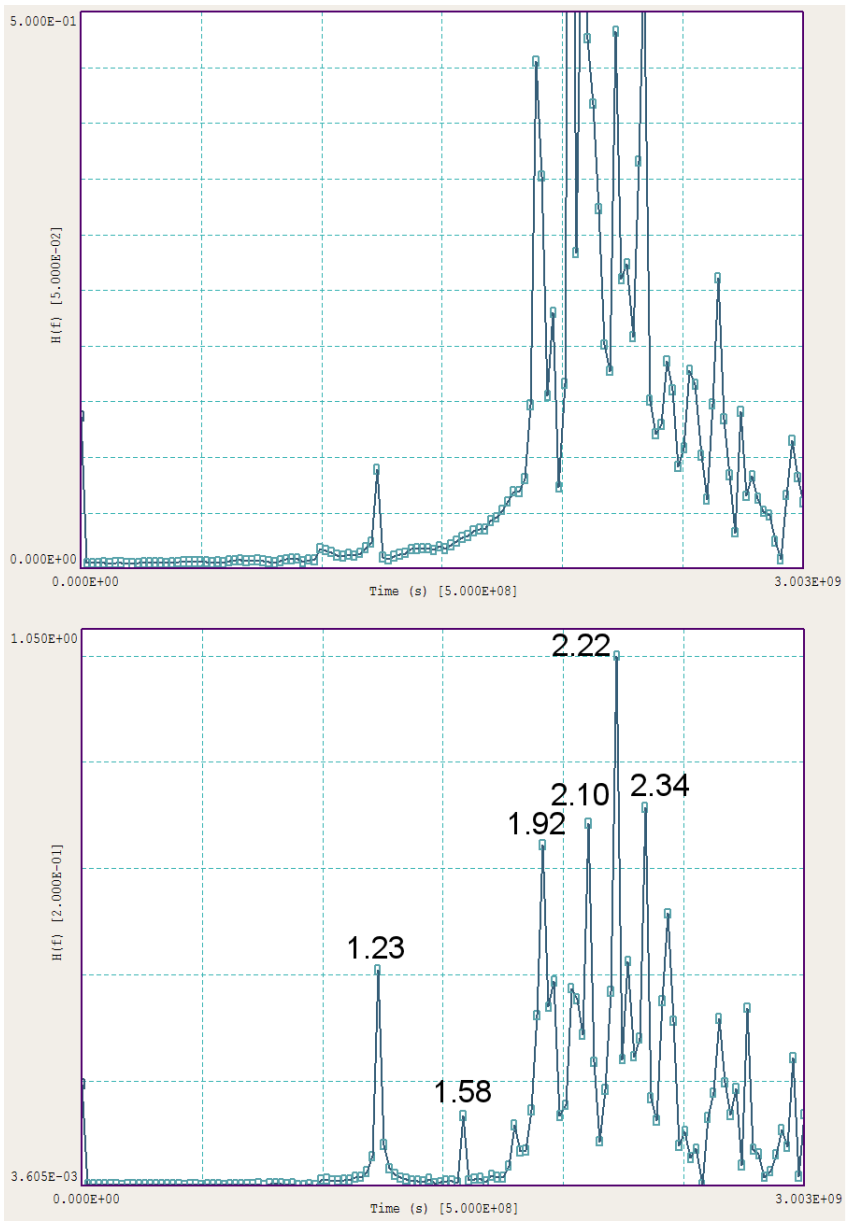

Figure 3: Relative probe response for the full assembly over the frequency range 0.0 to 3.0 GHz. The detected quantity is H_y. Top: probe on axis (0.0", 0.0", 0.0 inch). Bottom: probe outside the beam pipe (4.0", 0.0", 0.0 inch). Frequencies in GHz are listed for some of the peaks.

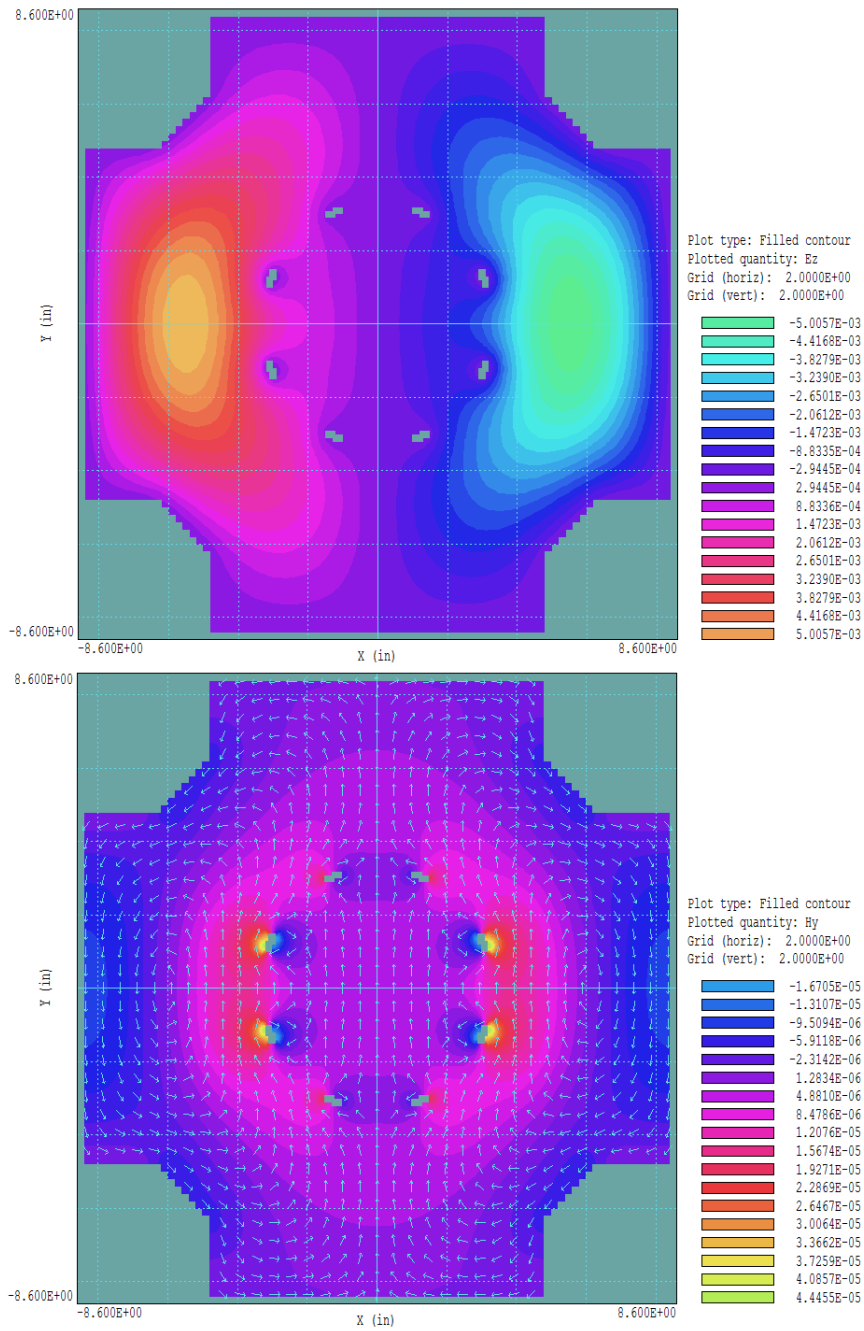

Figure 4: Field distributions of the 1.23 GHz mode. Top: E_z in the plane $z = 0.0$" at a reference phase of 0.0°. Bottom: H_y in the plane $z = 0.0$" at a reference phase of 90.0° with added vector arrows.

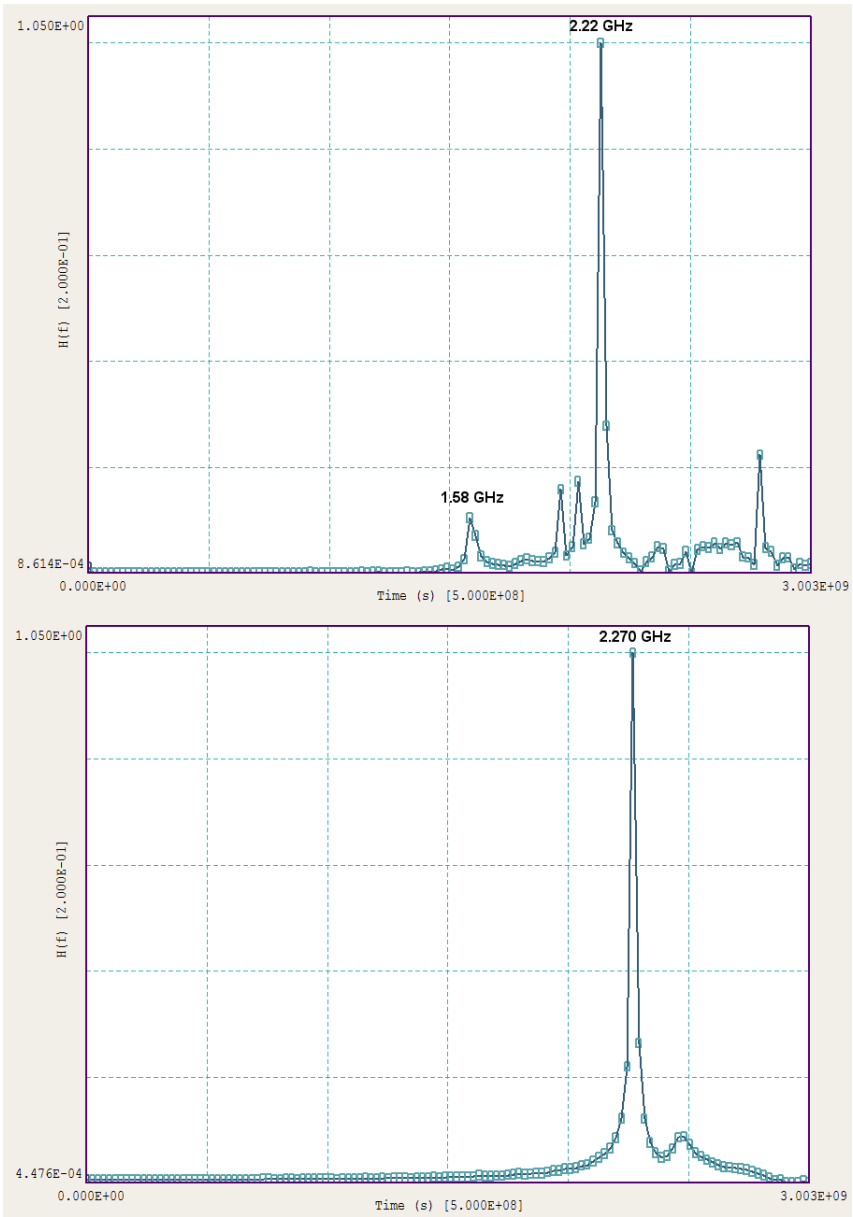

Figure 5: Relative probe response for modified systems over the frequency range 0.0 to 3.0 GHz. The detected quantity is H_y at position (0.0",0.0",0.0"). Top: screens over pumping ports. Bottom: screen over the beam-pipe slots.

primary peak in the plot corresponds to the TM_{110} mode of the beam pipe. The frequency is reduced because of increased inductance associated with axial current flow along the current-return bars.

The calculations lead to the following conclusions:

> With no shielding, the pump port supports a beam-deflection-type resonant mode at the 1.25 GHz frequency observed in measurements with beam-position monitors.
>
> Inclusion of screens over the pump ports raises the frequency of the fundamental deflection mode 26% (to 1.58 GHz).
>
> With screens on the beam-pipe slots, coupling to the pump-port volume is eliminated. In this case, the code calculation of the TM_{110} mode frequency in the uniform beam pipe is in good agreement with theory.