Visualization of Wake Fields in 3-D

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Abstract

Rapid advancements in computing capability, such as supercomputers, are enabling scientists and engineers to use numerical modeling tools to analyze large scale problems of volumetric complexity never considered before, and which are impossible to solve analytically. The Finite Difference Time Domain method (FDTD) is widely used to model different electromagnetic interaction problems. The large amount of information obtained from 3-D simulations makes global data analysis difficult. Visualization allows this analysis to be done in a more efficient manner. This technique is implemented here, using the FDTD code. For this purpose, we have generated a short video to observe the 3-D time evolution of the wake fields, as a beam travelling in a cylindrical pipe encounters two structures: a cylindrically shaped pillbox cavity with and without parallel flat plates.

I. INTRODUCTION

In two previous PAC papers [1,2] we briefly described the algorithm used in the FDTD code. The reader should refer to those papers for further readings. The FDTD code is a full 3-D code written in cartesian coordinates. The wide variety of problems the FDTD code has been applied to (radar cross section analysis, electromagnetic wave penetration analysis, antennas, moving targets, biological effects, plasma physics, and high-speed integrated circuits analysis) makes this code a powerful tool when compared to other available codes. Recent work with the FDTD code include the ability to incorporate conformal modeling of curved surfaces in 3-D, contrary to the stepped edge surface modeling used in many other codes. This feature is implemented here for the first time to generate 3-D geometries. The task of modeling, exactly, curved surfaces in 3-D is not easy and a more detailed description of the conformal modeling can be found in [3]. One highlight of the FDTD code, of potential application in particle accelerators problems, is the ability to model thin wires, slots and cracks, of sub-cell dimensions, such as found in beam profile monitors and resistive wall monitors. The code also allows for an impedance condition to be imposed on the boundary of an impenetrable medium. We also expect to be able to include, in the near future, dispersive material characteristics. Such a capability will enable us to add microwave filters with given characteristics to our model, and investigate the possibilities of filtering out undesired frequencies in the spectrum of the wake fields.

II. VISUALIZATION SETUP

A simple schematic representation of the setup used in our visualization of wake fields is shown in Fig. 1. All CPU
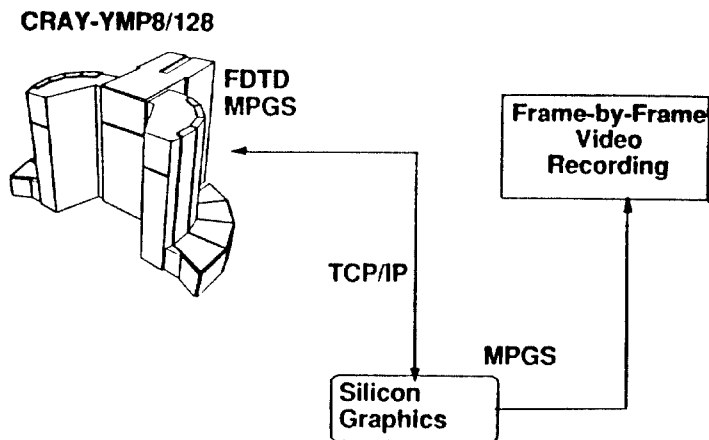

Figure 1: Basic Setup

intensive calculations are done on the Cray Y-MP8/128 at Cray Research Inc. in Minnesota. This is a parallel processor machine with eight processors, 128 Mwords, and running under UNICOS (Unix Cray Operating System). Main features of the operating system include autotasking and autovectorization. These utilities can significantly increase the running time of a code if certain simple guidelines are followed in writing the code. The FDTD code, written using simple do-loops, without any matrices, makes it more suitable for autovectorization. To handle large analysis runs, Cray Research Inc. has developed a Multi-Purpose Graphics System (MPGS) postprocessing engineering system. This is an interactive menu-driven visualization tool, very easy to use, that uses distributed processing between a UNIX-based workstation and any Cray system running the UNICOS operating system. Memory and CPU-intensive tasks are processed on a Cray, while the user interface and graphics manipulations are processed locally on a graphic workstation via TCP-IP. With a Silicon Graphics workstation and MPGS, our task to view and manipulate the 3-D FDTD data became relatively simple. Using the many features of MPGS one can select different ways of displaying the 3-D data. To keep things relatively simple, we chose to show the magnitude of the electric E field, $\sqrt{E_x^2 + E_y^2 + E_z^2}$, at each node in space in a 2-D plane cut containing the longitudinal axis of the beam pipe. Looking at Fig. 2, this represents the (x, z) plane at $y = 0$. Although we are using a 2-D cut in displaying our results,

the fields are computed in a 3-D grid. Cuts in other planes are taken to show the variation of the field magnitude in a plane perpendicular to the longitudinal axis. Finally, the frame-by-frame field data is recorded. Table 1 is a summary of some relevant numbers. To reduce the amount

Table 1: Parameters Relevant to Video Production

Beam pipe grid size	27x27x400 cells
Pillbox grid size	65x65x50 cells
Number of time steps per case	300-500
Estimate size of each frame	0.3 Mbytes
Estimate CPU time /9%processor	0.35s/time step
Number of frames /s	30
Number of new frames /s	10
Estimate record time / frame	30s

of memory required to run the FDTD code and therefore speed up the running time, the total FDTD grid is divided into two blocks. The first block represents the beam pipe while the second block represents the pillbox cavity. This way the grid size of the beam pipe in the transverse direction is no longer dictated by the bigger pillbox grid dimension since it is now modeled separately. This also enhances the parallelization of the FDTD code in future applications.

III. DESCRIPTION OF PROBLEM

A half-geometry view of the problem is shown in Fig. 2. Four different cases are considered starting with the
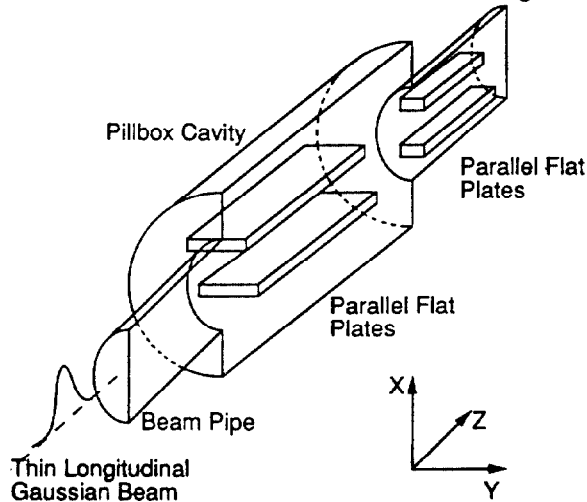

Figure 2: Half-geometry Cut

simplest case of a pillbox cavity in a cylindrical pipe with the beam moving on axis. In all cases the beam is traveling at the speed of light. The second case is similar to the first case except that the beam is now moving slightly off axis in the positive x-direction. The third and fourth cases contain parallel flat plates, perfectly conducting, in the pillbox cavity and the cylindrical pipe, with the beam

Table 2: Beam and Structure Parameters

Longitudinal σ of the gaussian beam	6 cm
Total charge	1 C
Number of cells/σ	10
Beam pipe/Pillbox radius	$1.1\sigma/3.3\sigma$
Beam pipe/Pillbox length	$40\sigma/3\sigma$
Flat plates $l \times w \times t$	$(2 \times 1.1 \times 0.1)\sigma$
Flat plates separation	1.1σ
Beam offset in the x-direction	$(0.3 \text{ and } 0.6)\sigma$

moving on axis and off axis respectively. The walls of the beam pipe and pillbox are selected, for this demonstration, to be also perfectly conducting. One can think of the flat plates as a simple representation of separators or a beam monitor. The flat plates are centered in the pillbox cavity and equally spaced from the center axis both in the pillbox and in the beam pipe. The beam is modeled as a thin longitudinal current with a gaussian distribution, although a transverse thickness can be easily added. Beam placement in the pipe is such that the initial conditions associated by artificially creating a charge at a particular point in space are eliminated. The FDTD code as it stands right now assumes a rigid beam. Some numbers defining the beam and structure parameters are shown in Table 2. The dimensions are selected for demonstration purposes and do not reflect any real physical problem dimensions.

IV. DISCUSSION OF RESULTS AND VALIDATION

As mentioned earlier, we chose to show the magnitude of the electric field at each node in the 2-D (x, z) plane at $y = 0$ (refer to Fig. 2). Results of the nature shown here are meant to be qualitative in nature and not quantitative. Still, a validation is necessary.

A. Qualitative Analysis

Qualitatively, the fields in the beam pipe do have the right behavior. No longitudinal **E** or **H** field is generated. This is to be expected for a beam travelling at the speed of light in a smooth perfectly conducting pipe [4]. Also, for the beam travelling on axis the magnitude of the **E** fields throughout the structure have the right symmetry. The ratio $\frac{\mathbf{E}}{\mathbf{H}}$ in the beam pipe is also equal to Z_o (the free space impedance).

B. Quantitative Analysis

Quantitatively, the fields in the beam pipe decay as $\frac{1}{r}$ with a very good agreement to the analytical results (refer to [3] for a comparative plot). The empty pillbox cavity dimensions are such that the dominant mode is the TM_{010} mode with a resonant frequency of 0.58 Ghz, assuming a closed cavity without the beam pipe. The effect of the side

2513

beam pipes is to increase the resonant TM_{010} frequency. Calculations made with SUPERFISH [5], given the same dimensions, show an increase in frequency from 0.58 Ghz to 0.59 Ghz. By watching the video we can count about 83 time steps between a minimum and maximum **E** fields in the cavity. This corresponds to a resonant frequency of about 0.6 Ghz. This strongly implies, as one might expect, a resonant dominant mode corresponding to the TM_{010} mode. The small discrepency with SUPERFISH results can be caused by our rough visual estimate of the occurences of minimum and maximum, and the presence of other less dominant modes in the resonating fields.

With the TM_{01} mode cut-off frequency in the beam pipe equal to 1.74 Ghz, most of the resonant **E** field will be trapped in the pillbox cavity as seen in the video. One can also observe the evanescent waves stretching beyond the pillbox cavity and into the beam pipe, but dying off before they are able to propagate.

The off-axis beam without the plates result in a quite different resonant patterns. The final two cases with the parallel flat plates clearly show most of the resonant **E** field being focused between the edge of the flat plates and the edge of the pillbox cavity connected to the beam pipe. This same effect was observed in an early study of a beam pipe with separators using the MAFIA T3, and TBCI codes [6]. On the contrary, very small resonant edge effects are observed in the second set of parallel flat plates located downward in the beam pipe.

V. CONCLUSIONS

In this paper we have used the FDTD code to visualize the wake fields in 3-D associated with a traveling beam. The magnitude of the **E** were shown in a 2-D plane cut, however the information is available to show other forms of results. For example, by adding a simple subroutine one can calculate the integrated longitudinal **E** field or wake potential. One can also look at the magnitude of the **H** fields and take other cuts. Different scenarios can be presented. Even for the relatively simple cases considered in this paper one can observe the complicated field patterns resonating in the cavity. Visualization, supercomputers, and numerical modeling are important tools for the analysis of wake fields in complicated 3-D structures. The FDTD code allows us to consider various structures of much more volumetric complexity and material characteristics than what was considered here. Visualization is also an excellent tool to educate future young accelerator scientists and engineers.

VI. REFERENCES

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