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ELECTROMAGNETIC MODELING IN ACCELERATOR DESIGNS*

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INTRODUCTION

Through the years, electromagnetic modeling using computers has proved to be a cost-effective tool for accelerator designs. Traditionally, electromagnetic modeling of accelerators has been limited to resonator and magnet designs in two dimensions. In recent years, with the availability of powerful computers, electromagnetic modeling of accelerators has advanced significantly.

In the last few years, two conferences were organized to review the state-of-the-art of electromagnetic modeling of accelerators. These conferences were the first in a series which has as its goal an exchange of information about codes between those writing and those using these codes for the design and analysis of accelerators and their components. The first conference[1] was held in San Diego in January 1988, and concentrated on beam-dynamics codes and Maxwell's-equation solvers. The second conference[2] was held in Los Alamos in January 1990, and concentrated on three-dimensional codes and techniques to handle the large amounts of data required for three-dimensional problems.

Through the above conferences, it is apparent that breakthroughs have been made during the last decade in two important areas: three-dimensional modeling and time-domain simulation. Success in both these areas have been made possible by the increasing size and speed of computers. In this paper, the advances in these two areas will be described.

Three-dimensional modeling has been making steady progress in the last five years. The codes are now capable of producing credible results and three-dimensional calculations are routinely performed by accelerator designers. Available codes have been developed principally by workers in the plasma and accelerator physics communities. Among them, most notably, are the ARGUS[3] and SOS[4] codes from the plasma community and the

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MAFIA[5] codes from the accelerator community. Their capabilities are similar and will be illustrated in this paper using modeling experiences of actual devices in Los Alamos.

Time-domain simulations have grown in popularity in the last ten years. They, beside complementing the traditional frequency-domain computations, allow accelerator designers to achieve a better understanding of the physics by letting them visualize the development of electromagnetic fields in accelerator components. In this paper, we will show, in particular, time-domain simulations for computing beam-induced effects. These simulations are essential for designing high-brightness accelerators.

THREE-DIMENSIONAL (3-D) MODELING

Various groups of people have been involved in writing computer codes for modeling accelerator components in three dimensions since 1985. Their efforts have been successful because of the advances in computer hardwares both in the memory sizes and computing speed. At this time, the accelerator-physics designers are reaping the benefits of the foresight of these pioneers.

The capabilities of the 3-D codes will be illustrated in this section using analyses of accelerator devices in Los Alamos. These analyses will be presented roughly in the order in which a particle beam would encounter the devices, i.e. from the low-energy radio-frequency quadrupole (RFQ) focusing and accelerating device, to the drift-tube linear accelerator (DTL), to the coupled-cavity linear accelerator (CCL), to the traveling wave "jungle gym" structure. All of these devices involve asymmetric geometries, so that the use of 3-D codes for their analyses becomes necessary. The analyses were performed using the MAFIA codes. The theory of these codes is well documented in ref. 6 and will not be repeated here.

RFQ. The radio-frequency quadrupole provides both focusing and acceleration of low-energy ion beams (~ 100 keV for protons). Figure. 1 shows one quadrant of the end region of a four-vane

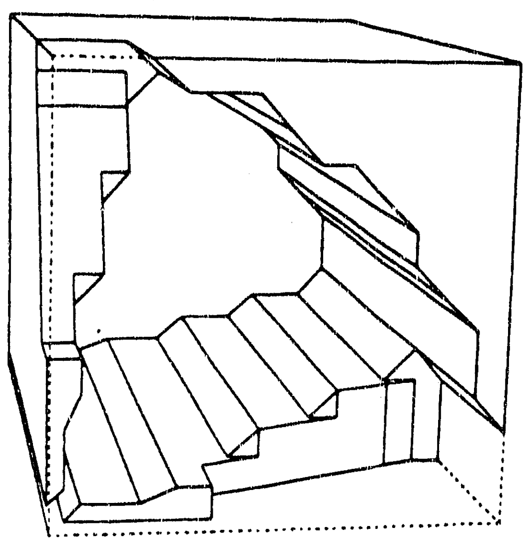

Fig. 1. One quadrant of a four-vane RFQ.

RFQ as approximated by the MAFIA mesh generator. The codes were used to design the undercutting of the vane for tuning the end region so that it matches properly the extended portion of the RFQ structure.[7] Figure 2 shows the joining of two RFQs to form a compensated structure. The coupling between the RFQs has improved the separation between the quadrupole modes, and has improved the longitudinal rf stability. A long RFQ made by joining short RFQs can offer more robust operation than a single long RFQ.[8]

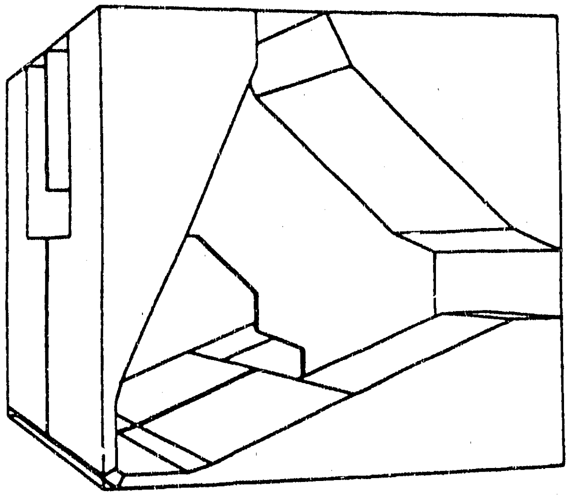

Fig. 2. The coupling of two RFQs.

DTL. A drift-tube linear accelerator is efficient for the acceleration of low-energy ions. Figure. 3 shows a four-gap DTL with a slug tuner, the drift-tube supports, and post couplers used for achieving a flat accelerating-field profile.

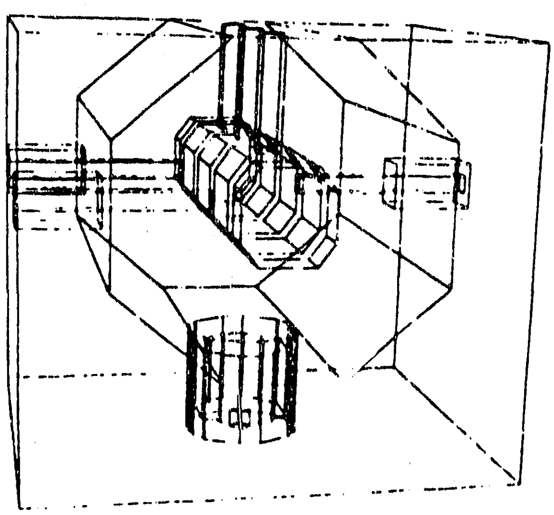

Fig. 3. A three-dimensional approximation to a four-gap DTL.

A study by Shmoys and Li[9] has represented a DTL as a coaxial line with microwave circuit loading representing the gaps and post couplers. One application of the MAFIA codes is the determination of microwave circuit parameters of such a structure. Details of such an analysis can be found in ref. 9.

The MAFIA codes have also allowed the designers to investigate the mode structures around the operating mode of a DTL. The analysis has shown that no harmful modes (Figs. 4 and 5) have been introduced by the supports of the drift tubes and post couplers in the vicinity of the operating mode. The analysis has also provided considerable insight without the need for expensive fabrication and rf testing.

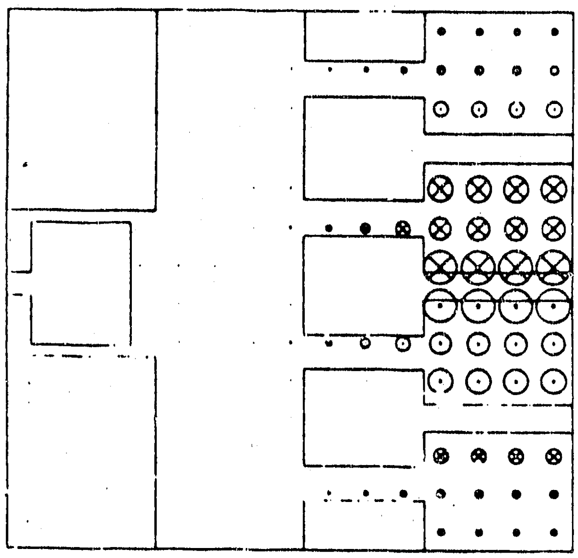

Fig. 4. The magnetic field of a stem mode.

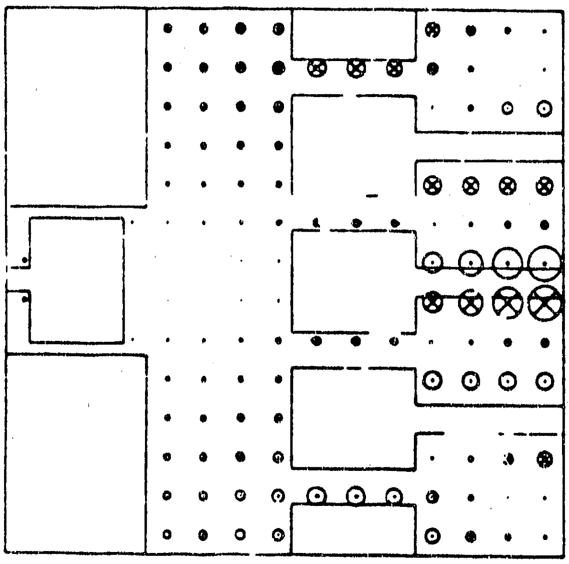

Fig. 5. The magnetic field of a higher-order mode.

CCL. Coupled-cavity linear accelerators are efficient for accelerating high-energy ion beams. The popular side-coupled and on-axis-coupled structures are shown in Fig. 6 and 7 respectively. Recently, there have been experimental reports of the asymmetry effects introduced by the coupling slots.[10] The asymmetry introduces quadrupole focusing fields near the axis. Figure 8 shows these additional quadrupole fields as calculated using the MAFIA codes.[11] These field patterns were obtained by taking the difference of two field solutions generated for structures with and without the coupling slots.

Jungle-gym Structure. The Jungle-gym structure is an advanced bar-loaded traveling-wave accelerating structure for high-energy ($v \approx c$) particles. The structure has been studied experimentally by Tigner at Cornell.[12] A unit cell of this structure consists of a pair of vertical bars followed by a pair of horizontal bars. An approximation of a three-cell structure

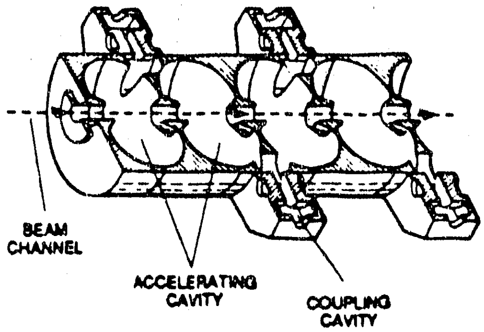

Fig. 6. A cutaway drawing of a side-coupled linac structure.

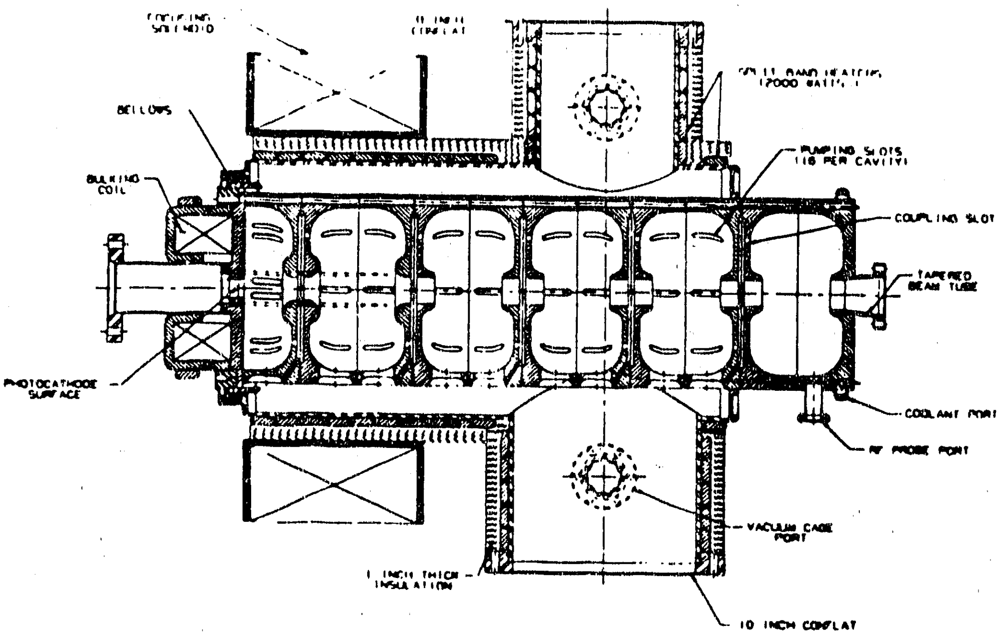

Fig. 7. A cutaway drawing of an on-axis-coupled linac structure.

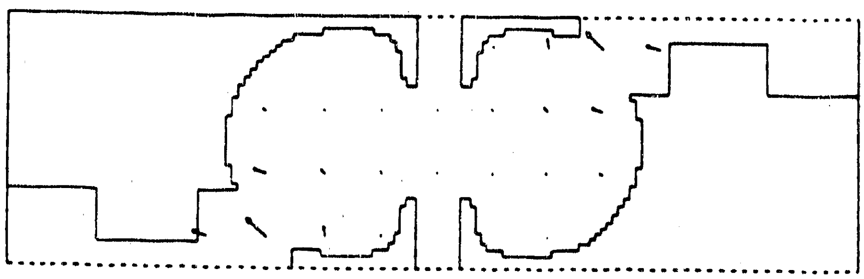

Fig. 8. Difference fields between a symmetrical cavity and a side-coupled cavity, showing the effect of the coupling slots and cells.

by the MAFIA codes is shown in Fig. 9. Only one-fourth of the structure is shown; the x and y planes are planes of mirror symmetry as far as the structure is concerned. Figure 10 shows plots of the accelerating field on the axis for several of the modes calculated. The dispersion curve calculated by the MAFIA codes was in good agreement with that measured by Tigner. Details of the analysis are given in ref. 13.

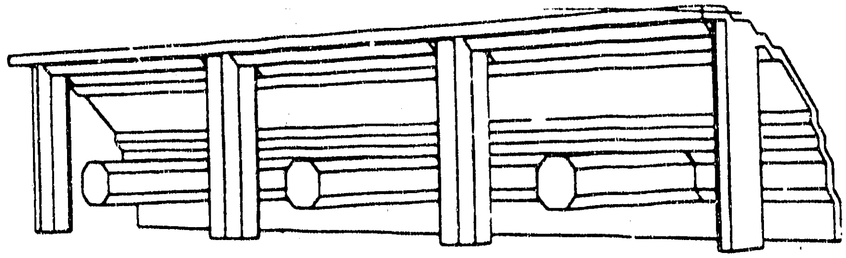

Fig. 9. One quarter of the jungle gym structure with three cells.

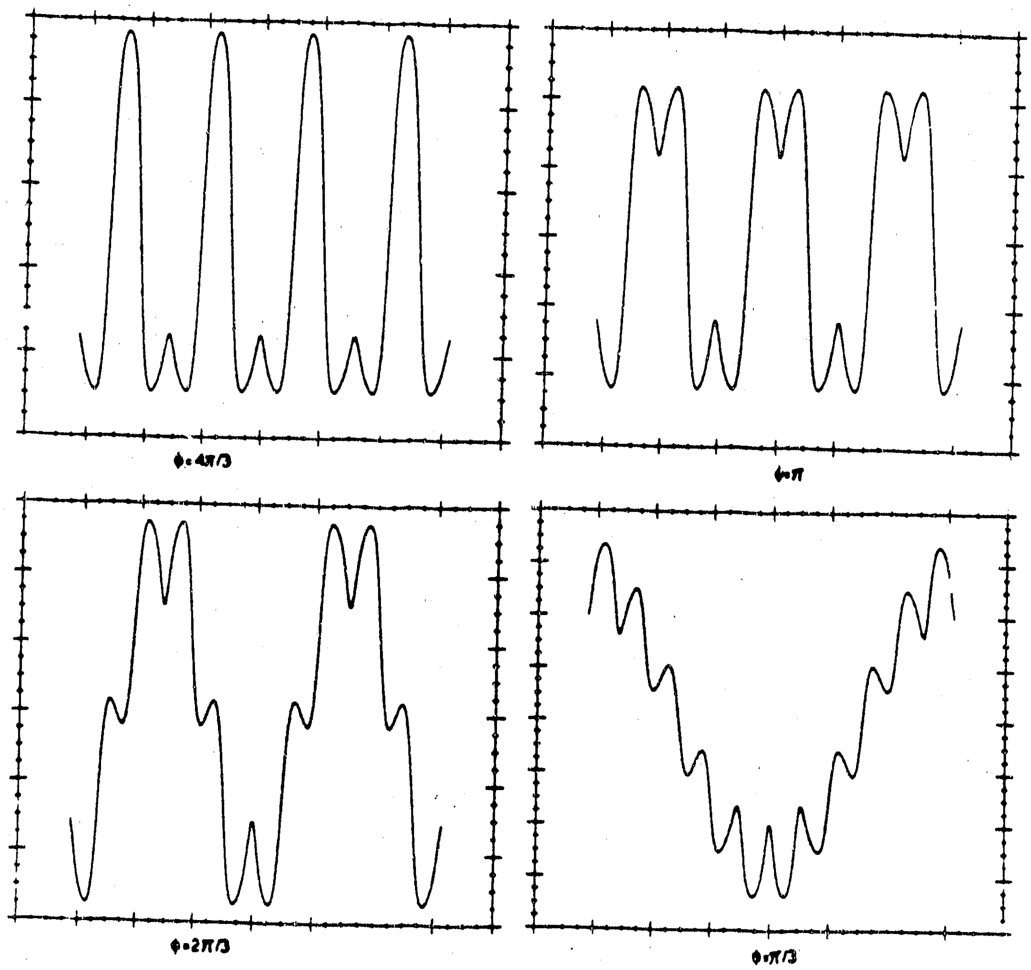

Fig. 10. Plots of the longitudinal field on axis for several modes of the jungle gym structure. The various values of φ denote the phase shifts per cells.

TIME-DOMAIN SIMULATION

In accelerator design, electromagnetic modeling can be performed in either the frequency domain or the time domain. In the past, accelerator modeling was mainly performed in the frequency-domain by calculating eigenfunctions, similar to analyses as described in the last section except they were for two dimensions. Time-domain modeling has become popular only in the last ten year. It has become popular because of the availability of computer codes and because of the needs for calculating beam-induced effects of short beam bunches with high charge densities in accelerators with high beam brightness. Frequently, the time-development of the electromagnetic fields as simulated in time-domain modeling is captured in a time-sequence of pictures or movies, giving a vivid representation of the physics interplay of the problem.

In this paper, we will show two analyses in the time domain: the radiations of a sub-nanosecond pulse of protons exiting a beam pipe; and the excitation of a relativistic klystron with a field-transformer accelerator structure. We will also comment briefly about the computer codes and results of direct comparisons of calculations using these computer codes to experiments.

<u>First Analysis</u>. Figure 11 is a time sequence of pictures showing the development of radiations when a sub-nanosecond proton bunch moves from a beam pipe into open space. This calculation models an experiment performed at the Los Alamos Meson Physics Facility. The comparison of the measured radiations to calculations has been described in detail in ref. 14 and will be mentioned briefly later in this section.

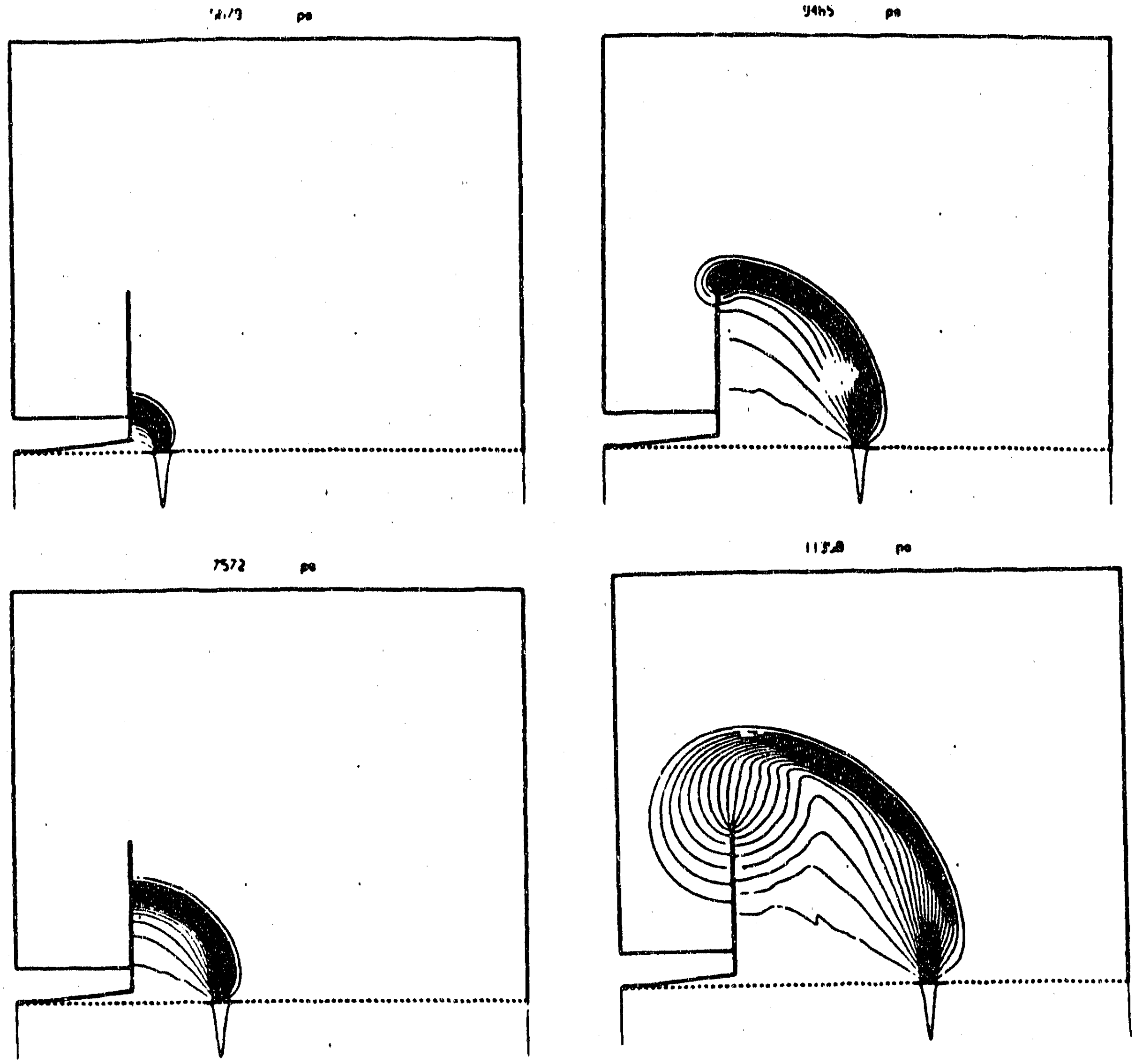

Fig. 11. Time sequence showing the electric fields induced by a proton beam.

Second Analysis. Figure 12 shows a sequence of pictures which simulates an experiment being conducted at the Naval Research Laboratory.[15] A high-intensity bunch of relativistic electrons was used to excite a coaxial cavity via an accelerating gap. The electromagnetic energy in the cavity built up and was coupled to an accelerating structure for the acceleration of a high-energy low-intensity beam. The excitation of the coaxial cavity and then the structure has been clearly depicted in Fig. 12.

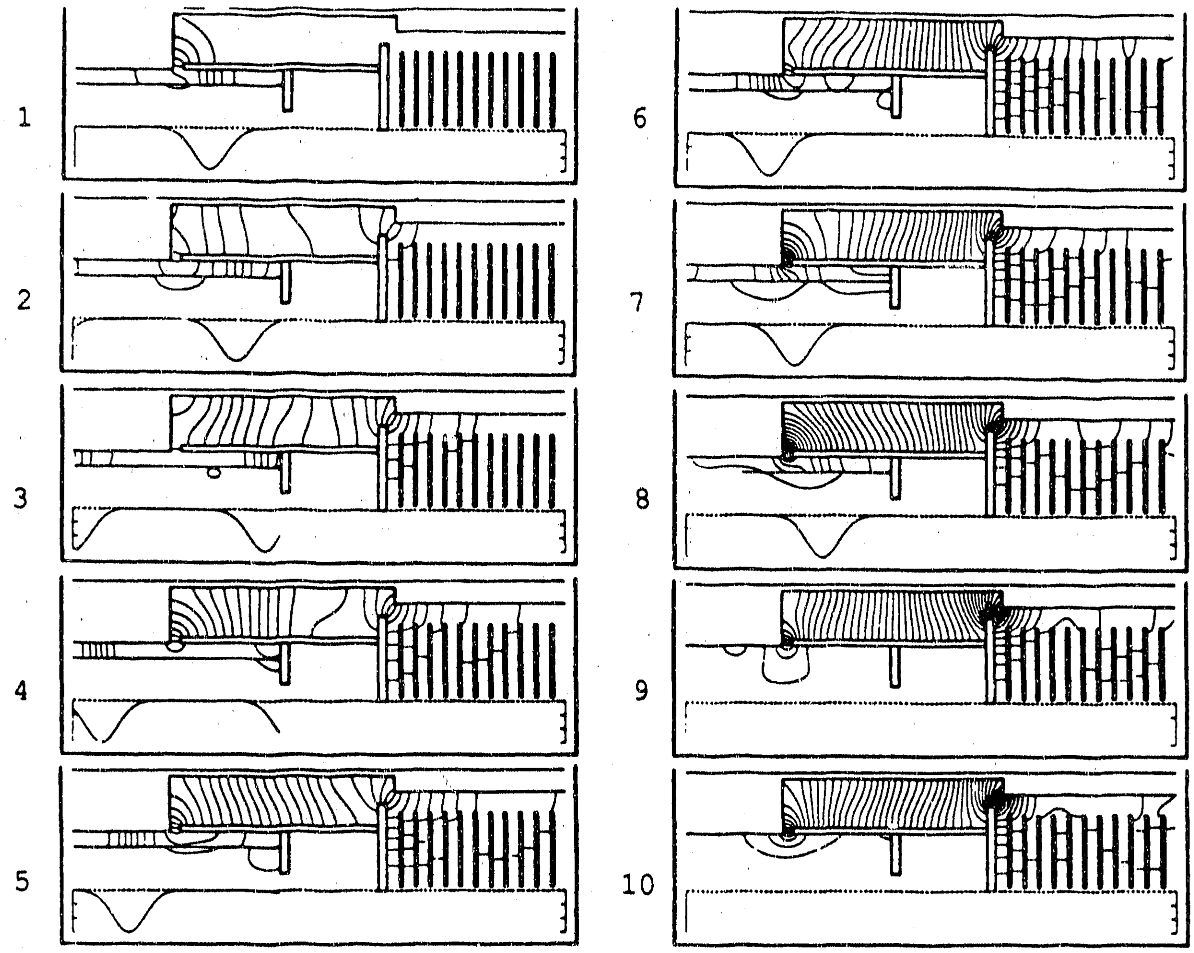

Fig. 12. Time sequence showing the excitation of a coaxial cavity and an accelerating structure.

Computer Codes. Although time-domain particle-in-cell (PIC) codes have been used by plasma physicists for a long time, the time-domain code most used in the accelerator physics community, TBCI[16], written by Thomas Weiland, appeared only in 1981. This code uses the finite-difference method and is designed for the analysis of axially symmetric structures. IBCI incorporates features for saving CPU time, such as the open-boundary condition for modeling infinite beam pipes, and the window option, exploiting causality of particles traveling at the speed of light. This code has been extended to three dimensions and is a part of the MAFIA codes.

A time-domain code usually uses the finite-difference forms of the Faraday's and Ampere's laws, and uses a leapfrog integration method to advance the electric field and magnetic field, alternatively, in time. Such an algorithm is a natural candidate for use in a massively parallel computer. Each node on the mesh corresponds to a single processor in such a machine. Recently, such programs have already been successfully implemented in the Connection Machine at the Argonne National Laboratory, with impressive performance.[17]

The results of TBCI have been compared directly to experiments. Figure 13 shows a typical comparison for radiations emitted from a sub-nanosecond proton bunch as in an experiment described earlier in this section. The comparison shows excellent agreement, considering the 15% error bars of the experimental data. Recently, experimenters of the Advanced Accelerator Test Facility at Argonne National Laboratory measured the longitudinal and transverse fields induced by a beam bunch in a dielectric-lined waveguide. The experimental data are compared to simulations using the MAFIA and ARCHON[17] codes in Fig. 14 showing good agreement.

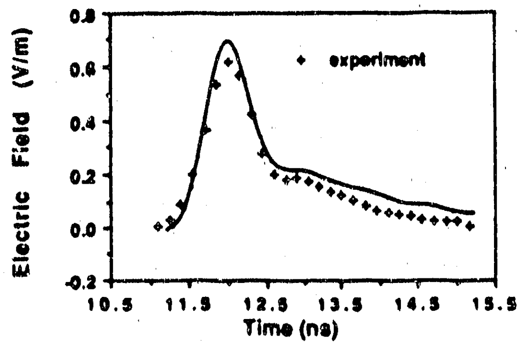

Fig. 13. Electric field induced by a 800 MeV proton beam exiting a beam pipe. The calculated results are shown as a solid curve.

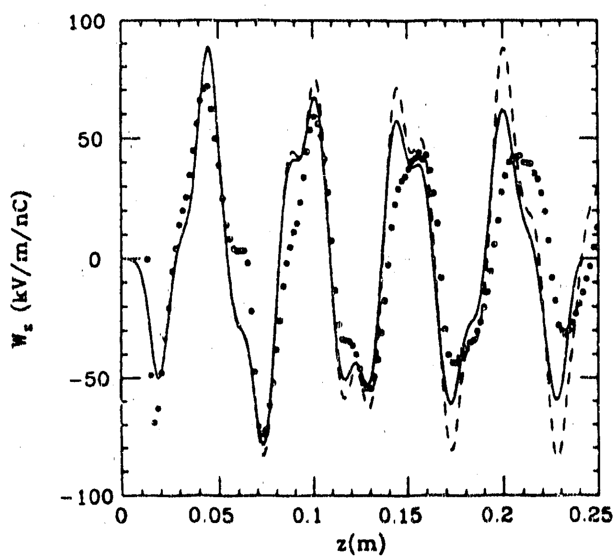

Fig. 14. Comparison of the longitudinal W_z and transverse field W_t induced by a beam bunch in a dielectric-lined waveguide. The open circles are the measurement. The solid and dashed curves are, respectively, calculations using MAFIA and ARCHON.

SUMMARY

Electromagnetic modeling in accelerators has been an expanding area of research in the last ten years with great progress in three-dimensional modeling and time domain simulation.

REFERENCES

1. C. R. Eminhizer, Ed., "AIP Conference Proceedings 177: Linear Accelerator and Beam Optics Codes, La Jolla Institute, 1988," American Institute of Physics, New York, (1988).
2. R. K. Cooper, Compiler, "Proceedings of the Conference on Computer Codes and the Linear Accelerator Community, Los Alamos National Laboratory, January 22-25, 1990," Los Alamos National Laboratory report LA-11857-C, (1990).
3. C. L. Chang, D. Chernin, A. Drobot, K. Ko, M. Kress, A. Mankofsky, A. Mondelli, and J. Petillo, "Three-Dimensional Modeling of Accelerators," pp 27-55 in ref. 2.
4. B. Goplen, K. Heaney, J. McDonald, and G. Warren, "SOS Reference Manual Version October 1988," Mission Research Corporation final report MRC/WDC-R-190 (March 1989).
5. T. Weiland, "Solving Maxwell's Equations in 3D and 2D by means of MAFIA," pp 3-25 in ref.2.
6. T. Weiland, "On the Numerical Solution of Maxwell's Equations and Applications in the Field of Accelerator Physics," Particle Accelerators **15**, (1984), pp 245-292 and references therein.
7. M. J. Browman, G. Spalek and T. C. Barts, "Studying the End Regions of RFQs Using the MAFIA Codes," Proceedings of the 1988 Linear Accelerator Conference, Continuous Electron Beam Accelerator Facility, Newport News, Virginia, Oct. 3-7, 1988, CEBAF-Report-89-001, p 64, (1989).
8. M. J. Browman and L. M. Young, "Coupled Radio-Frequency Quadrupoles as Compensated Structures," Presented at the 1990 Linear Accelerator Conference, Sept. 10-14, 1990, Albuquerque, NM.
9. J. Shmoys and R. Li, "Transmission Line Modeling of Drift Tube Linear Accelerators," Los Alamos National Laboratory internal report AT6:ATN-88-16.
10. H. Euteneuer, "Notiz zur Drehung der MAMI Beschleunigungssektionen um Ihre Langsachse," University Mainz Internal Note MAMI 1/89, 1989.
11. M. J. Browman, private communication.
12. M. Tigner, "Bar Loaded Waveguide for Accelerator Service," IEEE Trans. Nucl. Sci. NS-18, No. 3, p 249, (1971).
13. J. Loo, M. J. Browman, K. C. D. Chan and R. K. Cooper, "Numerical Studies of the Jungle Gym Slow-wave Accelerator Structure," Particle Accelerator **23**, p 279, (1988).
14. K. C. D. Chan and R. K. Cooper, "Time-Domain Calculation of Sub-nanosecond Pulse Launched by a Proton Beam", presented at the First Los Alamos Symposium on Ultra-Wideband Radar, Los Alamos, NM, March 5-8, 1990. Also in Los Alamos National Laboratory report LA-CP-89-263.
15. M. Friedman, V. Serlin, A. Drobot, and L. Seftor, "Self-Modulation of an Intense Relativistic Electron Beam," J. Appl. Phys. 56 (9), p 2459, (1984).
16. T. Weiland, "Transverse Beam Cavity Interaction, Part I: Short Range Forces," Nucl. Inst. Meth. 212, pp 13-24, (1983).
17. P. Schoessow, "Wakefield Calculations on Parallel Computer," pp 377-386, in ref. 2.

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