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MASTER

Abstract

The calculation of three-dimensional rf structures is rapidly approaching adolescence, after having been in its infancy for the last four years. This paper will show the kinds of calculations that are currently being performed in the frequency domain and is a companion paper to one in which time-domain calculations are described.

Three-Dimensional RF Structure Calculations*

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Physics**

1 Introduction

As supercomputers become more available and computing costs continue to decrease, it becomes reasonable to consider performing truly three-dimensional calculations. These calculations clearly need large computer memories and fast computational speeds if they are to be performed in times short enough to allow for iteration of a design. These conditions having been met in recent years, the development of a number of three-dimensional codes for the analysis of the electromagnetic environment acting on the charged particle beams employed in accelerators has proceeded apace. These codes have been principally developed by workers coming from the two different communities of plasma physics and accelerator physics. The plasma physicists have extended their particle-in-cell codes to three dimensions and are now capable of performing analyses on three-dimensional structures in both the time domain and the frequency domain. The codes ARGUS[1] and SOS[2] are those codes from the plasma community best known to us. Mankofsky[3] has written a brief review of this type of code and cites other codes by different authors.

Those of us in the accelerator community have arrived at a similar

computational capability from a different route, having the heritage of SUPERFISH[4], URMEL[5], and TBCI[6] as the tools that have served us so well for so long. The MAFFA[7] codes, which we have developed in a five-year long collaboration between the Los Alamos National Laboratory, the DESY laboratory, and the Kernforschungs Anlage Jülich (KFA-Jülich), are a set of codes that will solve Maxwell's equation in the time and frequency domains, including sources and static solutions. Their development was specifically aimed at the solution of problems in the accelerator field, including such diverse applications as rf cavity design, vacuum chamber design for the minimization of wake-field effects, magnet design, and electrostatic device design. Pride of authorship compels us to believe that our codes are the best for applications in our field, but we acknowledge that there are clever people everywhere who are capable of solving extremely complex problems and we cannot claim a unique capability. The calculations presented in this paper are all frequency-domain calculations performed by that collection of the MAFFA codes (M3, R3, E3, and P3) sometimes referred to as 3-D URMEL.

The theory of the MAFFA code is well documented[8] and will not be repeated here; the intent of this paper is to show how we are

applying the MAFIA codes in the calculation of rf structures. In the presentation that follows, we will give the analysis of devices roughly in the order in which a particle beam would encounter them, 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.

2 RFQ calculations

The radio-frequency quadrupole provides both focusing and acceleration of low-energy (~ 100 keV for protons) ion beams. The two types of RFQ in use at the present time are the four-vane and the four-rod RFQs. Fig. 1 shows one quadrant of the end region of a four-vane RFQ as approximated by the MAFIA mesh generator M3. Shown in the figure is the feature being studied by the MAFIA codes, namely the undercutting of the vane for tuning the end region so that it matches properly the extended portion of the RFQ structure. The boundary condition used to match the resonant mode solution of the end region to the rest of the RFQ requires that the magnetic field be

perpendicular to the boundary that represents the joining of the end region with the rest of the structure.

Fig. 2 shows the rf magnetic field of the resonant mode employed to provide the focusing and acceleration of the ion beams. Complete details of the calculation are available[9]; these include conclusions on tuning and thermal dissipation in the end region.

Fig. 3 shows a four-rod RFQ as approximated by the M3 mesh generator. Opposing rods are connected to one vertical plate, with the other pair of rods being connected to the next vertical plate; the whole structure consists of a number of repetitions of this scheme.

Fig. 4 shows the magnetic field in a vertical plane slightly behind the first vertical plate shown in the previous figure. The circulation of the magnetic field evident in the figure indicates that there is a net longitudinal current being carried on the rods. Details of this current variation and other aspects of the numerical solution of the resonant modes of this structure are available[10].

3 DTL calculations

One application of three-dimensional frequency-domain codes is the determination of microwave circuit parameters of a given structure. Transmission lines and waveguides are frequently represented by lumped and distributed circuit elements, and in many cases it is possible to use the MAFIA codes to determine the values of these elements. A recent study by Shmoys and Li[11], using the MAFIA codes, has characterized the gap of a drift-tube linac in terms of circuit elements. In this study the structure was analyzed in terms of the two modes that would propagate in a coaxial structure that would exist if the drift tubes were replaced by one continuous conductor. These modes are the TEM mode and one polarization of the TE_{11} mode. The gaps between the drift tubes are then treated as microwave circuits loading the equivalent transmission lines representing the mode propagation. These gap circuits can be represented as symmetrical "tees" connecting the sections of coaxial line that are constituted by the drift tubes and the DTL tank wall. The results of modeling the drift tube structure using the MAFIA codes indicate that for the (azimuthally symmetric) TEM mode both the series and shunt arms of

the equivalent tee are capacitive in the range of frequencies near the operating frequency. For the TE_{11} mode the series arm is inductive with a strong frequency dependence, and the shunt arm is well represented as a parallel resonant circuit. The post coupler represents a series resonant circuit shunted across the line(s) and coupling both the TM_{01} and TE_{11} modes. Details of this calculation can be found in the work cited above.

Fig. 5 shows the M3 approximation to a four-gap DTL with a slug tuner and three coupling posts of an unique design, called a "coaxial post coupler." This post coupler has a section of coaxial line extending into the wall of the tank. In order to test this structure for the existence of spurious resonances in the vicinity of the accelerating frequency, a MAFIA calculation was performed. Fig. 6 shows the magnetic field of the accelerating mode, and figs. 7 and 8 show the fields of other modes calculated. No troublesome modes were found; this kind of calculation can clearly provide considerable insight without the need for expensive fabrication and cold testing.

4 CCL calculations

The popular side-coupled cavity linear accelerator structure is shown in fig. 9. Fig. 10 shows an M3 approximation in which the structure is modeled from the midplane of one coupling cell to the midplane of the next coupling cell. Fig. 11 shows the electric field pattern of the accelerating mode as calculated by MAFIA. Some penetration of field into the nominally unexcited coupling cells can be seen. To study the effect of the slots on the field distribution near the axis, a difference was taken between two different solutions. One solution was generated for the structure without any coupling slots and then this solution was subtracted from the solution that includes the coupling cells. This difference is shown in fig. 12. Taking a difference this way emphasizes the effect of the coupling geometry.

5 The jungle gym

The bar loaded traveling-wave accelerating structure (the jungle gym) was studied experimentally by Tigner[12] at Cornell. The unit cell of the structure consists of a pair of vertical bars followed by a pair of horizontal bars. Fig. 13 shows the M3 approximation to a three-

cell structure. 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. Fig. 14 shows plots of the accelerating field on the axis for several of the modes calculated. The dispersion curve calculated by the MAFIA codes for this structure was in good agreement with that measured by Tigner. Details are given in ref. 13.

6 Conclusion

The variety of rf structures encountered in accelerator practice can be effectively analysed by the MAFIA three-dimensional codes. In progress are extensions of the codes to include particle-in-cell calculations and the inclusion of losses in the eigenvalue calculations. These extensions will extend the range of applicability of these codes.

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FIGURE CAPTIONS

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

Fig. 2 The rf magnetic field of the operating mode.

Fig. 3 The four-rod RFQ as modeled by M3.

Fig. 4 The magnetic field halfway between the two vertical plates.

Fig. 5 A three-dimensional approximation to a four-gap DTL.

Fig. 6 The magnetic fields of the accelerating mode.

Fig. 7 The magnetic field of a stem mode.

Fig. 8 The magnetic field of a high-order mode.

Fig. 9 A cutaway drawing of a side coupled cavity linac structure.

Fig. 10 The M3 approximation to the side-coupled cavity.

Fig. 11 The electric field of the accelerating mode of the side coupled cavity.

Fig. 12 Difference fields between a symmetrical cavity and the side coupled cavity, showing the effect of the coupling slots and cells.

Fig. 13 One quarter of the jungle gym structure with three cells.

Fig. 14 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 cell.

mafio

gla n/a end, 1.3 cm overhang, 2.0cm sloped cut, .7 cm gap

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contents

Series

waterbus:

1

2

Parameters

zrange:

0.0000

0.8445e-01

zrange:

0.0000

0.8445e-01

zrange:

-0.4500e-02

0.0000

zrange:

-0.2400e-01

0.0000

0.4000

zrange: 0.00

4

X

4

Z

4

4

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plotting
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area: 0.00

surface
mode: 0.0
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425.84

mesh: 0.00
x: 0.00

max area: 7.5e-04

z
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mafia

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plotting range z:1 0.00 0.22) x:1 -0.13 0.13)

picture
content
drift plot

z field
mode 10.0
frequency
855.15
mesh plane:
y=10
x=0.00
max speed 1
0.1e-04

mafia

drift tube (nac (4 cells)
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plotting range y:1 -0.15 0.08) z:1 0.00 0.22)

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momentum
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test particle
x=14
x= 0.00

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$$\phi = \pi$$

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$$\phi = \pi/3$$