SPECIAL MAFIA POSTPROCESSORS FOR THE ANALYSIS OF RF STRUCTURES*

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Abstract

This paper describes three stand-alone programs that use the electromagnetic fields generated by the MAFIA 2.04 codes to analyze radio-frequency (RF) cavities. Illustrations are provided that show how these codes are used to (1) analyze the effect of the coupling slots on the electric and magnetic fields of the linacs for the APLE Prototype Experiment (APEX) and the Advanced Free-Electron Laser (AFEL), (2) verify the Panofsky-Wenzel theorem for a high-energy deflecting cavity proposed for the Accelerator Transmutation of Waste (ATW) project, and (3) study the effectiveness of that deflecting cavity.

Introduction

Major breakthroughs in the three-dimensional modeling of RF structures have been made during the last decade. In particular, the electromagnetic field solvers called MAFIA have proved to be important tools for modeling such structures [1]. This paper describes the following three stand-alone programs that extend the usefulness of the MAFIA 2.04 codes in the analysis of radio-frequency cavities: DIFF, FIELDS, and POWER [2].

Program DIFF

Program DIFF allows the user to see the effect of perturbations, such as coupling slots or tuning slugs, on the electric and magnetic fields of a MAFIA-generated cavity. More specifically, DIFF subtracts a specified factor times the electric and magnetic fields of a mode of a MAFIA model without a perturbation from the fields of that mode of the cavity with the perturbation. The mesh for the two models must be identical; only the mesh fillings may differ.

The use of this code was the first step toward understanding the effect of the coupling slots on the beam in the APEX and AFEL photoinjector linacs [3]. The beam dynamics code PARMELA predicted that the beam produced by the APEX linac would be symmetrical, but when the structure was built, the beam was elliptical. A quadrupolar component to the field produced the asymmetry. This quadrupole effect was possibly caused by the arrangement of the coupling slots in the photoinjector.

The APEX photoinjector accelerator is a 1300-MHz, on-axis-coupled linac with two slots 180° apart on each end wall of the coupling and accelerating cells. The slots are rotated 90° across each coupling and accelerating cell. Figure 1 shows a cross section of one section of such a linac. The two half coupling cells are at the left- and right-hand sides of the structure; the accelerating cell is in the middle. A dashed line shows the outline of the structure being modeled, and the hatched area represents the metal of the MAFIA model. The two horizontal slots can be seen at the entrance, that is, at the left side of the accelerating cell. The two vertical slots at the exit (at the right side of the accelerating cell) do not appear in this cross section.

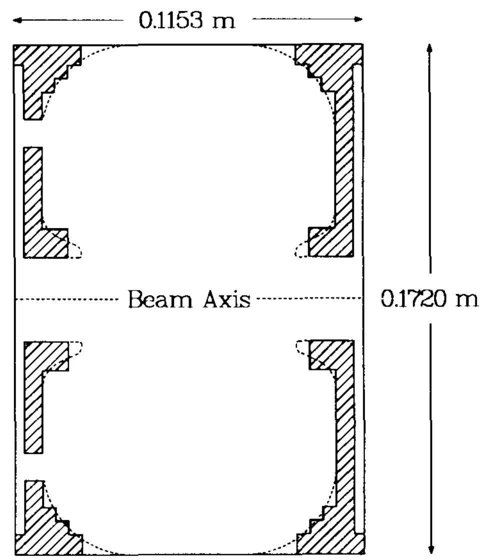

Fig. 1. Cross section of an on-axis coupled linac section.

This section was modeled with and without slots, and the respective fields were normalized so that $\int E_z dz = 1$ MV along the length of the model. A MAFIA arrow plot, the difference between the electric fields for the two cases, is shown in Fig. 2. This plot was taken at the center of the accelerating cell.

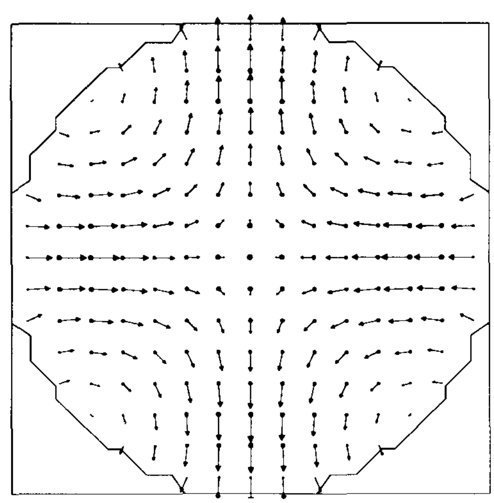

Fig. 2. Difference between the electric fields at the center of the cavity.

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The arrangement of the slots clearly produces a quadrupolar component to the electrical field.

Program FIELDS

This quadrupole effect and the resulting beam asymmetry was of great concern in the design of the high-brightness AFEL linac. A slot arrangement that minimized emittance growth needed to be found for that machine. In other words, the effect of the slots needed to be included in the beam dynamics calculations. PARMELA, which previously used the azimuthally symmetric electromagnetic fields calculated by SUPERFISH, was now modified to include the effect of the non-azimuthally symmetric components [4]. These three-dimensional effects were added as a perturbation to the SUPERFISH fields, because a much finer mesh can be used for a two-dimensional code than for a three-dimensional code. The new version of PARMELA needs these three-dimensional perturbation fields as a function of position, but MAFIA does not calculate the components of the electric and magnetic fields at the same point. Thus the difference fields generated by DIFF can not be used directly.

MAFIA calculates the components of the electric fields at the center of the edges of each mesh cell and the components of the magnetic fields at the center of the faces of each mesh cell. Program FIELDS was written to interpolate the MAFIA-generated electric or magnetic fields to a common point [5]. In other words, these values are generated as a function of position.

When the effect of different slot arrangements on beam emittance was studied, we found that two slots on each end wall, with the slots parallel across the accelerating cell and rotated 90° across the coupling cell, were sufficient once the beam was relativistic. Four slots placed symmetrically around each end wall, with the slots parallel from end wall to end wall, were necessary in the first few cells to produce a high-quality beam.

Using FIELDS to Verify the Panofsky-Wenzel Theorem

Program FIELDS was written to be general purpose, so it has been used to analyze other structures. The main body of the code is a set of subroutines that enable users to call the electric and/or magnetic field components as a function of position. Users write their own calling program depending upon what they wish to calculate.

For instance, FIELDS was used to verify the Panofsky-Wenzel theorem for the deflecting cavity shown in Fig. 3 [6]. (The material around the cavity has been left transparent for clarity.) This 350-MHz, $\beta\lambda/2$ structure is of the type proposed by Leeman and Yao [7], modified for a 1-GeV, high-current proton beam. The cavity is 33.8 cm long and 26 cm in diameter. The rods are 15.57 cm long and 5 cm in diameter; the vertical distance between the rods is 5 cm, and the gap between the ends of the rods is 2.67 cm. The beam pipe is 5 cm in diameter. The beam is moving from left to right (in the $+z$ direction) through the center of the cavity.

The deflecting mode is a TEM-like mode, with the magnetic fields curving around the rods, adding in the beam region. Figure 4 shows plots of the MAFIA-generated electric and magnetic fields for the deflecting mode.

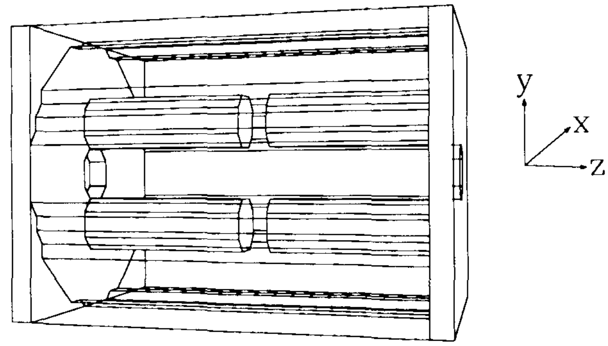
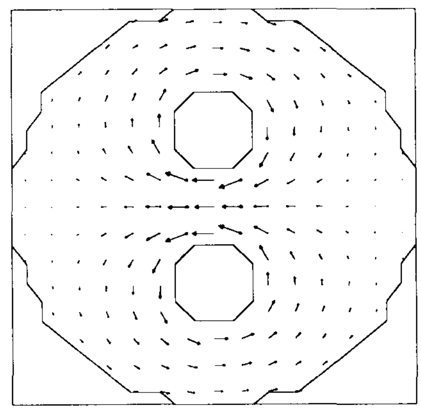
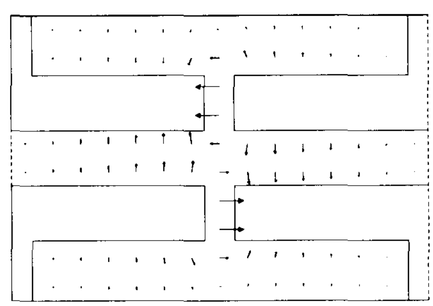


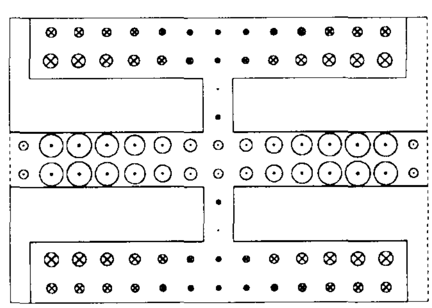
Fig. 3. MAFIA model of deflecting cavity.



Magnetic field in an x-y plane.



Electric field in the z-y midplane.



Magnetic field in the z-y midplane.

Fig. 4. Plots of the MAFIA-generated electric and magnetic fields.

The deflection will be in the downward ($-y$) direction for both the electric and magnetic fields if the particle is phased so that the magnetic field is at its peak in time when the particle is midway between the gaps. This phasing was assumed in the calculations below.

Panofsky and Wenzel show that the transverse momentum imparted to a charged particle moving in the z direction is proportional to the integral of the transverse gradient of E_z along the path of the particle [8]. In other words,

$$\mathbf{\Delta p}_{\perp} = -e\left(\frac{i}{\omega}\right)\int_0^l \nabla_{\perp} E_z(z,t)\, dz\,, \qquad (1)$$

where ω is the angular frequency, and l is the length of the cavity.

We can see from Fig. 4 that the electric field does have a transverse gradient of E_z in the region of the gaps. The deflection will be at a maximum if the particle is halfway between the gaps when the magnetic field is at its maximum or minimum in time.

The deflection impulse calculated using the line integrals from the MAFIA postprocessor P3 is

$$\mathbf{\Delta p}_{\perp} = (e/v)\int [\mathbf{E}_{\perp} + (\mathbf{v}\times\mathbf{B})_{\perp}]\, dz = -0.1227\mathrm{eV/c}\ \hat{\mathbf{y}}\ ; \quad (2)$$

the deflection impulse calculated using program FIELDS and the MAFIA fields is

$$\mathbf{\Delta p}_{\perp} = -e\left(\frac{i}{\omega}\right)\int \nabla_{\perp} E_z(z,t)\, dz = -0.1248\mathrm{eV/c}\ \hat{\mathbf{y}}\,, \quad (3)$$

where $\hat{\mathbf{y}}$ is the unit vector in the $+y$ direction. The two methods agree to better than 2%.

Program POWER

Program POWER computes the following data [9]:

- the stored energy in a resonant structure;
- the total power loss due to the finite conductivity of metal for all conductors in the structure (POWER uses the relative conductivities specified by the user in the input file to the MAFIA program R3);
- the individual power loss for each metal; and
- (if desired) the power-loss densities for the metals specified by the user.

The standard (release 2.04) MAFIA postprocessor P3 allows the user to compute the stored energy of the structure as well as the power loss for material 1. It assumes that material 1 is copper, with a conductivity of 5.8×10^7 mhos/m.

Program POWER is useful for calculating the power loss for metals other than copper, for finding the power loss in specific regions of interest, and for calculating power-loss densities. For instance, for the cavity of Fig. 3 we needed to know how much a particle could be deflected if the maximum power-loss density was 25 w/cm^2. MAFIA normalizes the electric field so that the maximum component of the electric field is 1 V/m; POWER was used to find the appropriate scaling factor for the electric and magnetic fields. Given the power-loss-density limit, a 1-GeV proton would be deflected 0.5 milliradians [10].

Acknowledgments

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Conclusions

The MAFIA release 2.04 codes are extremely useful in analyzing RF structures. For some problems they can be made even more useful by writing special postprocessors. The codes discussed above are available to friendly users.

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