Numerical Methods for Bio-electromagnetic Computation: A General Perspective

L.K. Ragha, *Member, IEEE,* and M.S.Bhatia.

***Abstract*—In electromagnetic (EM) , computational techniques are complementing the more traditional approaches of measurement and analysis of problems. An attempt is made to include common tools used in computational electromagnetic. This review paper mainly focuses on Finite Integration Technique (FIT), a method which has been successfully used since 1977 for the solution of electromagnetic field problems. Various methods for validating computational electromagnetic modeling techniques have been discussed.**

***Index Terms*—Bioelectromagnetic simulations; computational model validation; dosimetry; finite integration technique; geometry discretizations; numerical methods; specific absorption rate(SAR) calculations; three dimensional mesh; voxels.**

I. Introduction

COMPUTER techniques have revolutionized the way in which electromagnetic problems are analyzed. Today's design and analysis of problems needs reliable, accurate and flexible simulation tools for electromagnetic fields. Computer methods for analyzing problems in electromagnetic fall into one of three categories, analytical methods, numerical methods, and expert systems. Analytical methods are suitable for uniform and simple geometries. Numerical methods can be applied for complex and heterogeneous geometries. Expert systems do not actually calculate the field directly, but instead estimate values for the parameters of interest. Numerical methods require more computation than other two methods but they are very powerful simulation tools. A number of different numerical methods for solving electromagnetic problems are available. Each method is well suited for the analysis of a particular type of problem.

FIT is one of the most successful numerical methods for the simulation of electromagnetic fields and appeared in the year 1977. FIT belongs to the class of local approach in the sense, that the discrete equations are derived cell- by-cell by transforming the continuous Maxwell's equations on to the computational grid. Other representatives of local approaches are Finite Differences (FD), Finite Volumes (FV), Finite Elements (FE), And the Cell Method (CM). All these approaches are based on a volume discretization, defined by the three-dimensional mesh.

The FIT method has been used extensively for Bioelectromagnetic dosimetry. Values of interest in these assessments include induced current or current density and specific absorption rate (SAR), which is a measure of absorbed power in the body. The FIT algorithm is simple and efficient, which has made it one of the powerful numerical methods for Bioelectromagnetic simulations. It is well suited to these applications because it can efficiently model the heterogeneity of the human body with high resolution (1mm). It has been used to analyze whole-body or partial-body exposures to far field or near field sources. These sources may be sinusoidally varying (continuous wave) or time-varying such as those from an electromagnetic pulse (EMP). The FIT method has been used for applications over an extremely wide range of frequencies, from DC to THz.

II. COMPUTATIONAL METHODS

The early bioelectromagnetic computational methods represented the body by a variety of simple objects such as cylinders, conducting loops or spheres, and ellipsoids [1]. In most cases the conductivities of these models were assumed to be homogeneous. Solutions to these models were obtained by simple analytical methods for average and maximum E and J. The accuracy of these simple models to predict effects of environmental electric field exposures on internal electric fields and current densities has been extensively studied in animals and humans [2], [3]. More recently, the development of efficient computational algorithms and high-speed computers has led to the application of numerical methods to solve Maxwell's equations for the body in terms of individual cubes or voxels that are electrically distinct, with assigned conductivities. The advantages of these methods lie in the ability to model the complex shape and anatomy of the body, account for regional variations in conductivity, and estimate electric field or current densities in small cubes of tissue [4].A

L.K.Ragha is with the Department of Electronics & Telecommunication Engineering, SIES Graduate School of technology, Nerul, Navi-Mumbai-400706, India. (e-mail: laxman.ragha@rediffmail.com).

Dr.M.S.Bhatia is with the Laser & Plasma Technology Division, Bhabha Atomic Research Centre, Mumbai 400085 India (e-mail: msbhatia@barc.gov.in; monibhatia@rediffmail.com).

variety of numerical computation methods is used in bioelectromagnetics computing. The numerical methods most commonly used to compute induced E and J at ELF frequencies are as follows:

- the Finite-Difference-Time-Domain (FDTD) method,
- the Scalar-Potential-Finite-Difference (SPFD) method,
- the three-dimensional Impedance Method (IM),
- the Finite-Element Method (FEM) , and
- the Method of Moments (MoM).

While the computational strategies of the methods differ, the results, as will be discussed below are similar. The choice of the method depends upon the simulated field exposure, the size and shape of the object to be modeled, the resolution as reflected by the size of modeling element (voxel), computational efficiency, and memory requirements. Recently, a hybrid of the finite difference methods (FDTD/SPFD) has been employed for computing solutions to E-field exposures. This method first uses the FDTD method to develop a low-resolution solution to the computation of interior and surface potentials; then, the SPFD method is used to compute a more refined solution for interior potentials, using smaller-sized voxels [5]. As employed in the modeling of the body, the resolution of these methods is between 1 mm and1.31 cm. At the cellular level, the Finite-Element-Method has also been used for computations of E at a higher 1-µm resolution.

III. THE FINITE INTEGRATION TECHNIQUE (FIT)

CST MICROWAVE STUDIO[8] is a general purpose electromagnetic simulator based on the Finite Integration Technique (FIT), first proposed by Weiland in 1977 [6]. This numerical method provides a universal spatial discretization scheme, applicable to various electromagnetic problems, ranging from static field calculations to high frequency applications in time or frequency domain. The main aspects of this procedure are explained below.

Unlike most numerical methods, FIT discretizes the following integral form of Maxwell's equations, rather than the differential one:

$$\oint_{\partial A} \vec{E}.\mathrm{d}\vec{s} = -\int_A \frac{\partial \vec{B}}{\partial t}.\mathrm{d}\vec{A},$$

$$\oint_{\partial A} \vec{H}.\mathrm{d}\vec{s} = \int_A \left[\frac{\partial \vec{D}}{\partial t} + \vec{J}\right].d\vec{A}, \qquad (1a)$$

$$\oint_{\partial V} \vec{D}.d\vec{A} = \int_V \rho dV,$$

$$\oint_{\partial V} \vec{B}.d\vec{A} = 0. \qquad (1b)$$

In order to solve these equations numerically a finite calculation domain is defined, enclosing the considered application problem. By creating a suitable mesh system, this domain is split up into several small cuboids, so called grid cells. This first or primary mesh can be visualized in CST MICROWAVE STUDIO[8] in the mesh view , however, internally a second or dual mesh is set up orthogonally to the first one. The spatial discretization of Maxwell's equations is finally performed on these two orthogonal grid systems. In Figure 1 the electric grid voltages **e** and magnetic facet fluxes **b** are allocated on the primary grid **G** and the dielectric facet fluxes **d** as well as the magnetic grid voltages **h** on the dual grid $\tilde{G}$ **:**

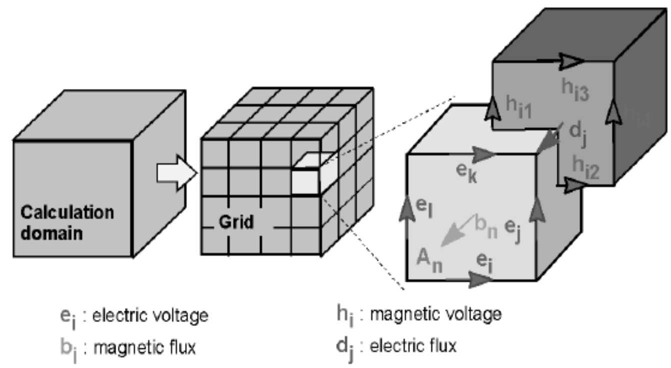


Figure 1.Dual discretization grids: the grids are interlaced by one-half spatial step. On the primary grid, electric voltages and magnetic fluxes are located.

Now Maxwell's equations are formulated for each of the cell facets separately as will be demonstrated in the following. Considering Faraday's law, the closed integral on the equation's left side can be rewritten as a sum of four grid voltages without introducing any supplement errors. Consequently, the time derivative of the magnetic flux defined on the enclosed primary cell facet represents the right side of the equation(Figure 2).By repeating this procedure for all available cell facets, the calculation rule can be summarized in an elegant matrix formulation, introducing the topological matrix **C** as the discrete equivalent of the analytical curl operator:

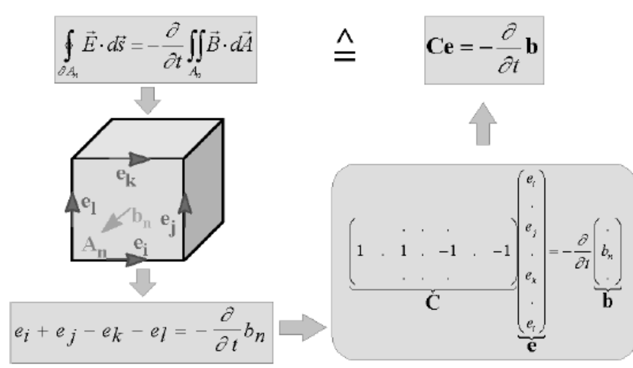


Figure 2. Calculation Summary.

Applying this scheme to Ampere's law on the dual grid involves the definition of a corresponding discrete curl operator $\tilde{C}$. Similarly the discretization of the remaining divergence equations (1b) introduces discrete divergence operators **S** and $\tilde{S}$, belonging to the primary and dual grid , respectively. These discrete matrix operators just consists of elements '0', '1', and '-1', representing merely topological information. Finally we obtain the complete discretized set of the so called Maxwell's Grid equations (MGE'S):

$$C_e = -\frac{\partial}{\partial t} b \quad , \quad \tilde{C}_h = \frac{\partial}{\partial t} d + j, \tag{2a}$$

$$\tilde{S} d = q, \qquad Sb = 0. \tag{2b}$$

Compared to the continuous form of Maxwell's equation's the similarity between both descriptions is obvious. Once again it should be mentioned that no additional error has been introduced yet. This essential point of FIT discretization is reflected in the fact that important properties of the continuous gradient, curl and divergence operators are still maintained in grid space:

(Algebraic Properties of the Matrix Operators)

$$SC = \tilde{S}\tilde{C} = 0 \Leftrightarrow div \quad rot \quad \equiv 0 \tag{3a}$$

$$C\tilde{S}^T = \tilde{C}S^T = 0 \Leftrightarrow rot \;\; grad \equiv 0 \tag{3b}$$

At this point it should be mentioned that even the spatial discretization of a numerical algorithm could cause long term instability. However, based on the presented fundamental relations (3a and 3b), it can be shown that the FIT formulation is not affected by such problems, since the set of MGE'S (2a) and(2b) maintain energy and charge conservation [7].

Finally, the missing material equations introduce the inevitable numerical inaccuracy due to the spatial discretization. By defining the necessary relations between voltages and fluxes their integral values have to be approximated over the grid edges and cell areas, respectively. Consequently, the resulting coefficients depend on the averaged material parameters as well as on the spatial resolution of the grid and are summarized again in correspondent matrices:

$$\vec{D} = \varepsilon \vec{E} \qquad\qquad d = M_{\varepsilon} e \tag{4a}$$

$$\vec{B} = \mu \vec{H} \qquad \Rightarrow \qquad b = M_{\mu} h \tag{4b}$$

$$\vec{J} = \sigma \vec{E} + \vec{J}_s \qquad\qquad j = M_{\sigma} e + j_s \tag{4c}$$

Now all matrix equations are available to solve electromagnetic field problems on the discrete grid space. The fact that the topological and the metric information is separated in different equations has important theoretical, numerical and algorithmic consequences [7].

As demonstrated, the FIT formulation is a very general method and therefore can be applied to all frequency ranges, from DC to high frequencies (figure 3). Electromagnetic field regimes are already covered by CST's software package MAFIA, whose development started more than 20 years ago. Based on this long experience, the "STUDIO"-family development started in 1997. Here, several improvements concerning user interface, visualization and solver performance were integrated. However, the most fundamental change is the new mesh strategy, the Perfect Boundary Approximation (PBA) technique [9], particularly extended by the Thin Sheet Technique™ (TST).

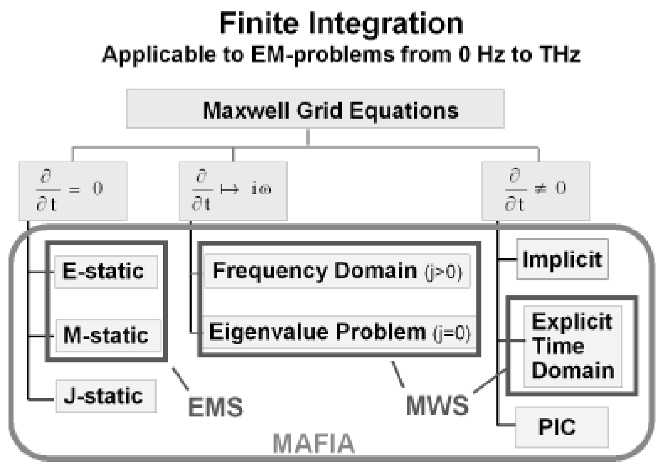


Figure 3. FIT applicable to EM problems.

Currently, there are two packages available: CST EM STUDIO™ (EMS), the lowfrequencypackage, which includes at the moment the electro- and magnetostatics solvers, and CST MICROWAVE STUDIO (MWS), covering the high frequency range, both in transient and in harmonic state. In the care of Cartesian grids, the FIT formulation can be rewritten in time domain to yield standard Finite Difference Time Domain methods (FDTD). However, whereas classical FDTD methods are limited to staircase approximations of complex boundaries, the mentioned PBA technique applied to the FIT algorithm maintains all the advantages of structured Cartesian grids, while allowing an accurate modeling of curved structures. In figure 4, the two "classical" geometry discretizations are shown: the Finite Element Method model on the left and the FDTD/Time Domain Transmission Line Matrix (TLM) model on the right. The FIT model together with the PBA theory in the middle combines the advantages of the other two-models. It offers either an excellent geometry approximation, without the segmentation of FE models, or staircase approximation of FDTD codes, and high simulation speed, as in the FDTD and TLM methods:

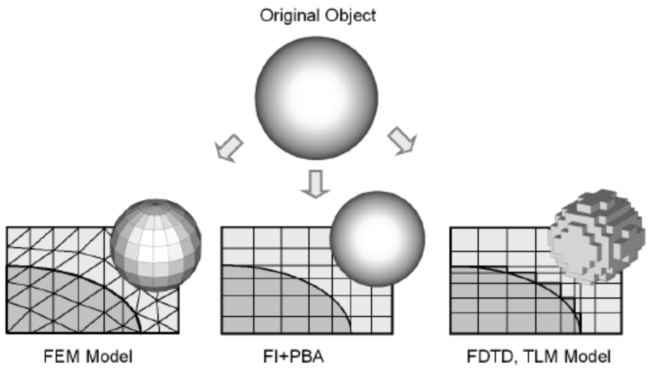


Figure 4. Classical geometry discretizations

IV. RANGE OF APLICATIONS

The FIT is applicable to a variety of electromagnetic problems: in bounded or unbounded domains, for electrically small or very large structures, in inhomogeneous, lossy, dispersive, or anisotropic materials [12]. A typical example is the SAR calculation inside a human head (figure 5),(figure 6)[14].

For a SAR calculation involve human head easily consume more than 4G memory

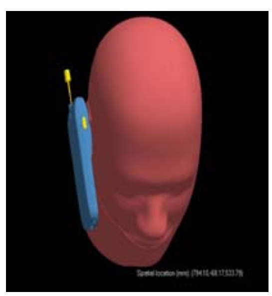


Figure 5. Real size Head and Cell phone used for SAR calculation

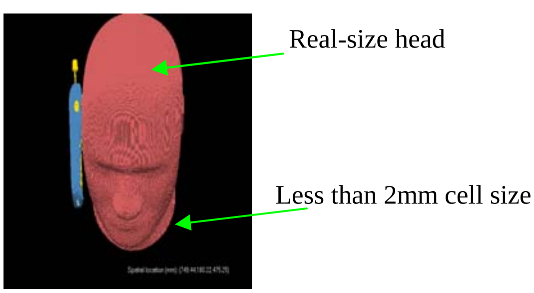


Figure 6. Meshed Real size Head and Cell phone

Ultra-Wide-Band(UWB) Printed Circular Dipole Antenna

The UWB dipole antenna with circular arms shown in figure 7 has been modeled and simulated with CST MICROWAVE STUDIO® (CST MWS)[8], [13].

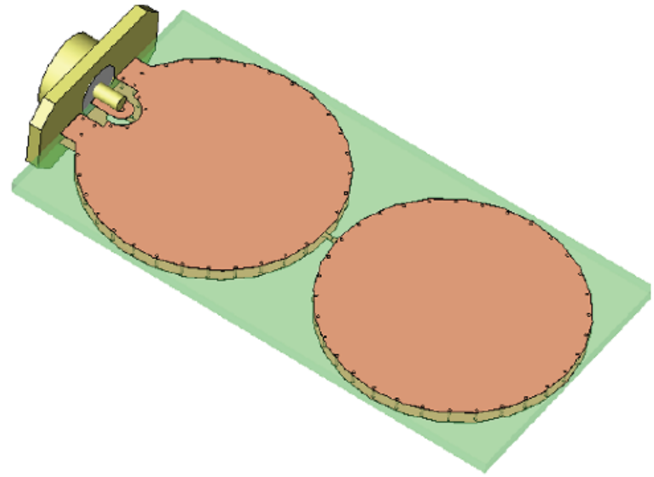


Figure 7: UWB Dipole Antenna

Figure 8 shows an electronic toll collection (ETC) system including the full model of the car.

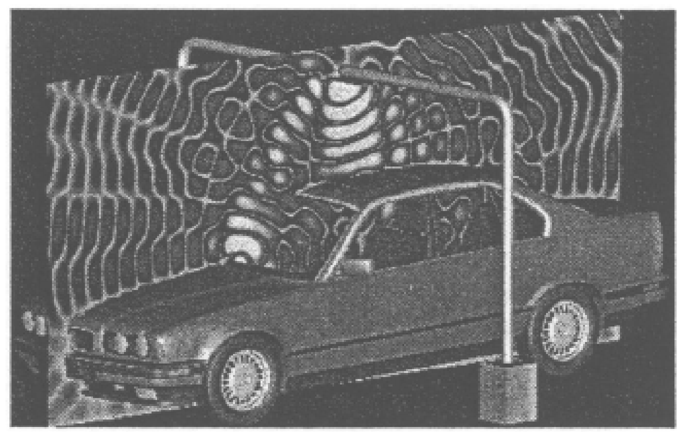


Figure 8. Electric fields around a car, produced by an ETC system Antenna

The 3D geometrical model of the Radio Frequency Identification Systems (RF-ID) [13]:

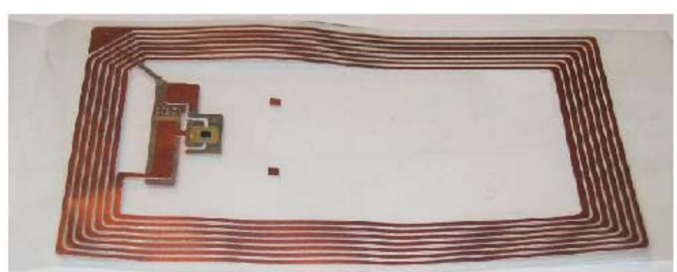


Figure 9: Photo of the transponder

Figure9. shows a typical example of an RFID. The 2D-layout was modeled in CST MWS. Applying appropriate extrusion operations to create metal thicknesses and by adding the substrate, the model was converted into a 3D model shown in Figure 10.

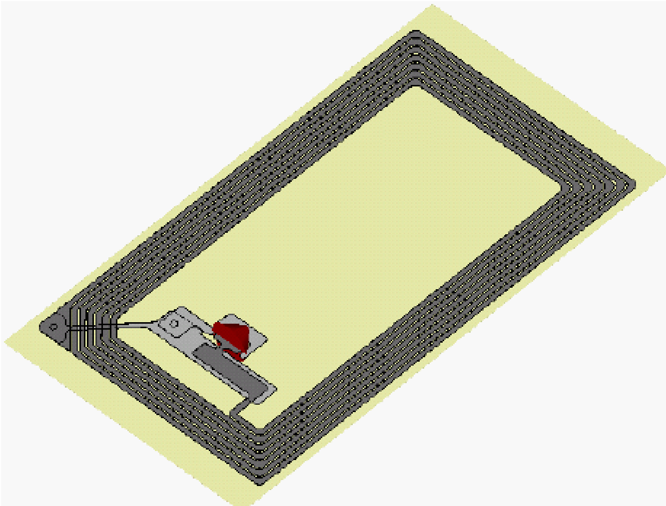


Figure 10: 3D- Model of the RF-ID tag used for simulation

The application example of an RF-ID demonstrates the ability of CST MWS to simulate antenna structures in a low frequency band (figure 11)

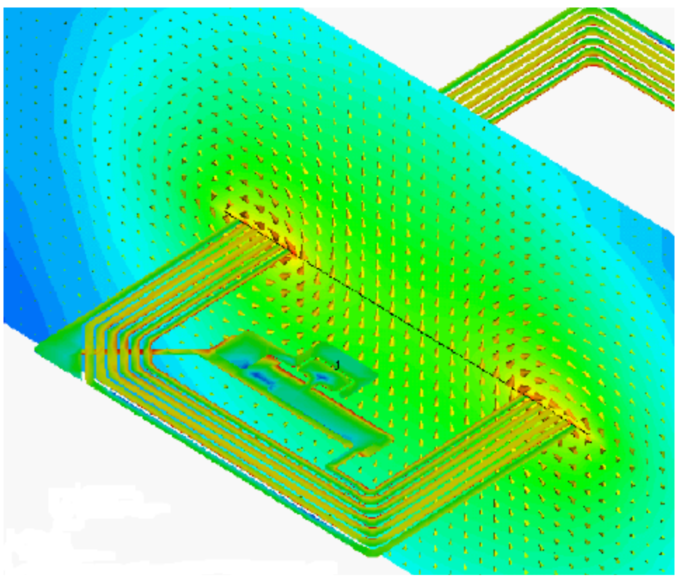


Figure 11: Depicted here is the surface current distribution of the coil and the magnetic field strength along a vertical cut plane at 13.56 MHz

V. VALIDATION METHODS

Various methods exist for effectively comparing multiple sets of electromagnetic observable data on a given problem for validation and verification (V&V) purposes. Oftentimes, the goal is to cross validate measurements with computer simulations or compare the results of multiple simulation runs in order to gain insight about error mechanisms and their control so as to ensure consistency, accuracy as well as repeatability. These methods are used to determine the degree of convergence (joint agreement) of such data and to investigate where and why disagreements may arise.

There are a number of different levels of model validation. When deciding how to validate a model, it is important to consider which level of validation is appropriate [11]. The levels are:

- Computational technique validation
- Individual software code implementation validation
- Specific model validation.

The first level of model validation is the computational technique validation. A new technique must undergo extensive validation to determine its limitations, strengths, and accuracy. But, for well known techniques, one need not repeat the basic technique validation.

The second level of validation is to insure the software implementation of the modeling technique is correct, and generates correct results for the defined model.

The third level of validation called specific model validation is the most common concern for engineers.

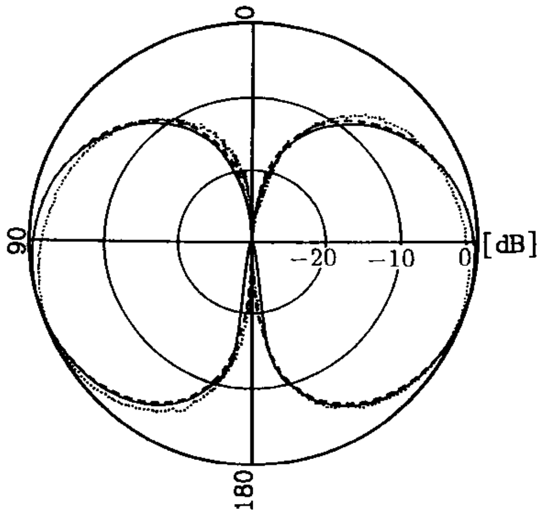
There are further subdivisions of this validation process, namely

- Validation using closed form equations
- Validation using measurements
- Validation using other modeling techniques
- Validation using intermediate results
- Validation using convergence.

A popular approach to validating simulation results is to model the same problem using two or more different modeling techniques. If the physics of the problem is correctly modeled with multiple simulation techniques, then the results should agree. As stated earlier, achieving agreement from more than one simulation technique for the same problem can add confidence to the validity of the results. There are a variety of full wave simulation techniques. Each has strengths and weaknesses. Care must be taken to use the appropriate simulation techniques and to make sure they are different enough from one another to guarantee a valid comparison.

A validation example:

The experienced professional can look at the data shown in Figure 7 and decide that the three plots have ‘good’ agreement, or ‘fair’ agreement etc., mostly depending upon what their individual criteria are.



__ FDTD, --- MoM, … Expt .

Figure 7. Example of three data sets for comparison.

VI. FUTURE DEVELOPMENTS

The flexibility and generality of the FIT allow imagining a variety of development lines in the future. With the wide range of already available modules, probably the most interesting would be the internal selection of the best approach for any given problem. The software could thus automatically select the solution algorithm, e.g. time- or frequency-domain, or the most appropriate mesh: classical Cartesian, PBA-type or non orthogonal mesh. Whereas the first two types of meshing are already available, the first research results on non orthogonal meshes [10] give encouraging signals that such kind of meshes could be efficiently implemented and used for a larger class of application types.

VII. CONCLUSION

The FIT, 30 years young, is probably the numerical method for electromagnetic field simulation with the most dynamic development. Due to its capability to solve electromagnetic problems in both time- and frequency-domain, to the variety of material properties, and to its exceptional numerical efficiency and accuracy, FIT is used worldwide for the simulation of a wide range of devices, from DC to THz. Moreover, the FIT'S theoretical background contributed, in the last decade, to fundamental changes of viewpoint for other numerical methods, such as the Finite Element Method.

VIII. REFERENCES

[1] Hart, FX. Mathematical modeling of electromagnetic interactions with biological systems. *In*AA Marino (ed.). Modern Electricity. M. Dekker, Inc., New York. 1988.

[2] Kaune, WT, Phillips, RD. Comparison of the Coupling of Grounded Humans, Swine and Rats to Vertical, 60-Hz Electric Fields. Bioelectromagnetics. 1:117-129. 1980.

[3] Kaune, WT, Forsythe, WC. Current Densities Measured in Human Models Exposed to 60-HzElectric Fields. Bioelectromagnetics. 6:13-32. 1985.

[4] Paulson, KD. Computational bioelectromagnetics: modeling methods for macroscopic tissue interactions. *In* JC Lin (ed.). Advances in Electromagnetic Field in Living Systems: Vol 2. NewYork: Plenum Press. 1997.

[5] De Moerloose, J; Dawson, TW; Stuchly, MA. Application of the finite difference time domain algorithm to quasi-static field analysis. Radio Science. 32:329-341. 1997

[6] T. Weiland, "A discretization method for the solution of Maxwell's equations for six-component fields",Electronics and Communication (AEC), vol.31, p. 116,1977.

[7] T. Weiland, "Time Domain Electromagnetic Field Computation with Finite Difference Methods", Intemational Journal of Numerical Modelling, vol. 9, pp. 295-319, 1996.

[8] CST MICROWAVE STUDIO® 4 – Advanced Topics

[9] B. Krietenstein, R. Schuhmann, P. Thoma, and T.Weiland, "The Perfect Boundary Approximation technique facing the challenge of high precision field computation", in Proceedings of the XIX International Linear Accelerator Conference (LINAC'98), Chicago, USA, 1998, pp. 860-862.

[10] R. Schuhmann and T. Weiland, "Stability of the FDTD Algorithm on Non orthogonal Grids Related to the Spatial Interpolation Scheme," IEEE Transactions on Magnetics, vol. 34, no. 5, pp. 2751-2754, 1998.

[11] IEEE Project 1597.1: Standard for validation of computational electromagnetics (CEM) computer modeling and simulation (IEEE P1597.1 Draft™/D1.2), 20 January 2005.

[12] Marko Walter, Dariusz Korzec, Michael Htltten and JtlrgenEngemann, "Computer-Aided Design of MicrowavePlasma Sources: Potential and Applications", Jpn. J. Appl.Phys. Vol. 36 (1997) pp. 4777-4783 Part 1, No. 7B

[13] CST STUDIO SUITETm 2006 User s Manual;http://www.cst.com

[14] http://www.remcom.com

IX. BIOGRAPHIES

L.K.Ragha received the B.E. degree in Electronics & communication Engineering from University of Mysore, Mysore, India and M.E. degree in Digital Electronics from Karnatak University ,Dharwad ,India in 1985 and 1997, respectively. . He is currently pursuing the Ph.D. degree in Electronics Engineering at BARC, Mumbai, India. He is currently with the Department of Electronics and Telecommunication Engineering, SIES Graduate School of Technology, Navi-Mumbai, India as an Assistant Professor. His current research interests are dosimetric aspects of the interaction between electromagnetic fields and biological systems, medical applications of electromagnetic fields, and numerical techniques. He is member of many professional bodies including IEEE.

Dr. M.S. Bhatia was born at New Delhi, India on Dt.06-10-1954. He completed Bachelor of Electrical Engineering from Delhi College of Engineering in 1977. He earned his Doctorate degree in 1993 from IIT, Delhi. Currently, He is heading Beam Electronics and Application Section of Laser and plasma Technology division in Bhabha Atomic Research Centre, Mumbai. Simultaneously, he is also working as Professor in Homi Bhabha National Institute, Mumbai. His major fields of study are Electron beam technology, Lasers and Plasma devices. He has published several papers on diverse topics in refereed journals.