LATEST DEVELOPMENT IN CODES FOR ELECTROMAGNETIC FIELDS

T. Weiland
Deutsches Elektronen-Synchrotron DESY
Notkestrasse 85, 2000 Hamburg 52, Germany

Abstract

The latest development in codes for calculating electromagnetic fields has concentrated on fully three-dimensional programs. Two-dimensional codes are well established and in routine use for designing accelerator equipment. However, some 2D problems are not yet solved and are still being worked on, such as determining the impedance of cylindrical objects above the cut-off frequency of the adjacent beam pipe. Three-dimensional codes are still being developed but only a few are being used. The most advanced package, the MAFIA system, has been extended recently to allow solution of electrostatic and magnetostatic fields with quasi-open boundary conditions. The modules solving for resonant frequencies and modes have been improved in their accuracy and speed. A new major revision of the whole family of codes will provide a consistent and more comfortable user interface, which is fully menu-driven with built in on-line help for all commands. This new release will also include new modules for 3D particle-in-cell simulation. Many new modules are under development and will make this system a universal tool in the design of electromagnetic devices. A user guide to the MAFIA codes with easy-to-follow instructions and examples is now available to noncommercial institutions, as is also the source code. Concurrent codes, which are not generally available, such as ARGUS or SOS, have also been improved. One can observe that the different codes become more and more alike with time.

Introduction

In the last two years, since the last Linac conference at SLAC, only a few new codes have appeared. Most of the work has gone into further development of existing codes. In order to make this review useful we will list those codes that are in use in the field of accelerator physics. However, this list cannot be complete facing the limited length of this paper and I apologize (beforehand) for any programs I have missed. For the same reason I will show only few pictures of typical output from the codes.

The total number of codes is so large that we will concentrate on those which are either of wide use or of major interest. For a rather complete compilation of computer codes for electromagnetic fields and beam dynamics codes I recommend a Los Alamos report [1].

One important aspect of computer codes is certainly their power for solving difficult problems, but even more important seems to be the technical quality of the codes and their availability. Codes that are written in a poor programming style cannot be of use to the community because installation of these codes on different computers takes an enormous amount of time and produces many errors. Even the most clever algorithm has no value if it is not well coded. It should be mentioned here that the effort which goes into writing a stable code may far outweigh the effort which goes into the mathematical algorithm.

Another intrinsic problem is the language in use, which is mostly FORTRAN77. The use of pure FORTRAN77 is the only way that codes can nowadays be transferred from one computer to another without major recoding. Unfortunately, one often finds dialects being used such as VAX-FORTRAN77 etc.

The most important aspect, however, is the availability of codes to the community. A code being used and being useable by only one person at one laboratory can never have a significant impact on accelerator physics. Only codes that are made available to all scientific users should in fact be considered worth mentioning. Unfortunately, especially in the US, many codes are proprietary codes made by commercial companies or written in government laboratories "behind the fence". To make this review useful for the reader I will thus comment also on the availability of the various codes and where to obtain the sources. I take this opportunity to make some personal remarks about distributed codes: In order to make a wide distribution of codes possible the user community has not only to accept the codes and to run them but also uphold some discipline in maintaining the codes. A sad example for this is SUPERFISH [2] , of which there are at least 100 different versions around. Users finding errors in the code should in general not start to change the code and to implement their own ideas but talk to the authors and have them to repair the errors. To stay with the example of SUPERFISH, LANL now maintains a standard version of POISSON and is willing to help users with their problems, but can do this only if the same standard version is used.

Two Dimensional Codes

Two dimensional codes I call those which either assume cylindrical symmetry of the structures (accelerating cavities) or translational symmetry (e.g. waveguides). The symmetry concerns in general only the geometry but not the fields. Most codes mentioned are in routine use in many laboratories and most of the recent work concerns upgrades and minor improvements.

POISSON/SUPERFISH (LANL Version)

The code center group in Los Alamos AT Division has prepared a detailed userguide [3] and a reference manual [4]. Both may be obtained from the code group AT6 at LANL. The code itself has been in parts modified to FORTRAN77 standards at LANL and DESY. The codes are well enough known that a list of its capabilities may be omitted here.

Availability: The code is available in source form from LANL and is free of license charges. The code is also accessible on the NMFE computer center.

POISSON (LBL Special Version)

Special extensions of POISSON have been developed at LBL that include open boundary conditions [5] and toroidal boundary conditions [6]. Both are valuable additions to POISSON and I hope that they will eventually be available with the standard LANL version of the codes.

Availability: The codes are probably available. For more details please contact the authors.

POISSON (Multigrid Version)

A special multigrid solver has been developed [7] at the University of Giessen which speeds up the computation significantly. The code is pretty much compatible with the standard POISSON family.

Availability: The code is (to my knowledge) freely available in source form. For more details please contact the authors.

SUPERFISH (special versions)

Two special versions of SUPERFISH [2] are being worked on by R.Gluckstern and coworkers [8]. One version allows periodic boundary conditions and thus enables the evaluation of modes in infinitely repeating structures. This code calculates essentially the same problems as URMEL-P [9] but uses SUPERFISH as the basic code. The second version treats the impedance as a function of frequency, especially above cutoff.

and thus is comparable with URMEL-I [10]. The mathematical method of treating the boundary conditions at the infinite pipes is somewhat different from URMEL-I.

Availability: The impedance above cutoff code is (to my knowledge) not freely available. For more details please contact the authors. The periodic version can be obtained from AT-6 group in LANL.

EGUN

The electron trajectory program EGUN [12] which has been in use for many years has now been transformed into C-Language and can run on PC-type computers.

Availability: The PC version is commercially available, the original FORTRAN version is free of charge. For more details please contact the authors.

URMEL

Meanwhile URMEL [13] is well established and proven by comparison with many measurements and with other codes. It is still the only available code that can compute many modes at a time without searching algorithms and the only one (except URMEL-T) that can compute modes with azimuthal variation (dipole and higher azimuthal modes). It has been modified to follow pure FORTRAN77 standards, not using any dialect, and some minor things have been modified. It is now available in release 5.2. A new userguide has been prepared [14] and may be obtained from DESY and LANL, group AT-6.

Availability: The code is available in source form from DESY and is free of license charges for non-commercial users. The code is also accessible on the NMFE computer center.

URMEL-I

This special version [10] of the URMEL code computes the impedance of cylindrical objects as function of frequency. Its main use is the evaluation of impedances above cut-off frequency where resonator codes such as URMEL cannot be applied. This code is still under development. The matrix of the resulting system of linear equations that has to be solved at any desired frequency is intrinsically indefinite at resonant frequencies. This results in a rather bad condition number at all other frequencies and thus poses a very difficult numerical problem to be solved. Extensive tests are underway using the modern multigrid methods but so far it seems that these methods do not converge as well as they do for Poisson type equations. A typical result of this code is shown in Fig. 1.

Availability: The code will be made available in source form from DESY free of license charges for non-commercial users as soon as it reaches a final state.

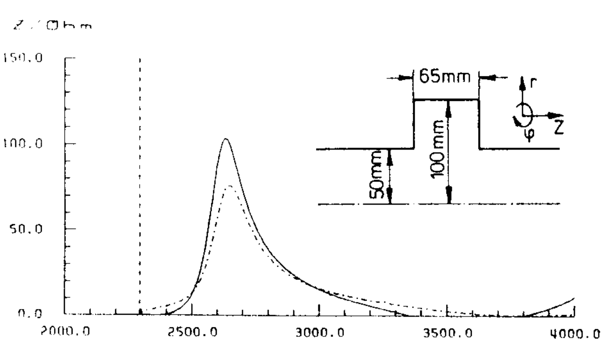

Figure 1: Real part of longitudinal impedance calculated by URMEL-I above and below the cut off frequency of the beam pipe for a pill box cavity and results from a pill-box code by Heino Henke [11]. URMEL-I can calculate arbitrarily shaped cavities but this example was chosen for comparison with a code that is restricted to pill-boxes.

URMEL-P

This special version of URMEL [9] enables the evaluation of eigenmodes in infinitely repeating structures and calculation with an arbitrary phase factor. The code has not been developed much further during the last two years, mainly due to lack of requests from the user community and to lack of manpower. It is still planned to make this periodic boundary condition part of the standard URMEL code in the future.

Availability: The code will be part of URMEL and available in source form from DESY free of license charges for non-commercial users.

URMEL-T

The triangular mesh version [15] of URMEL did have some bugs in the mesh generator that were found and reported by friendly users. Most of these bugs have been removed. URMEL-T is still the only available and widely used code that permits dielectric and/or permeable material insertions of arbitrary shape for both cylindrical and rotational symmetry. It thus enables the evaluation of all modes in cavities and complicated waveguides. A new userguide has been prepared [14] and may be obtained from DESY and LANL, group AT-6. The code is currently available in release 2.03. Some more minor bugs are known and currently being removed. This code has been, as all other DESY codes, modified to entirely follow ANSI FORTRAN77 standards.

Availability: The code is available in source form from DESY and is free of license charges for non-commercial users. The code is also accessible on the NMFE computer center.

TBCI

TBCI [16] has been for years the standard code for wake field computation and in routine use in many accelerator laboratories. No bugs have been found in the last two years and thus no major changes were necessary. The code has been, as all other DESY codes, modified to follow entirely ANSI FORTRAN77 standards. It is now availabe in release 5.01. A short user's manual is also available from DESY and LANL.

Availability: The code is available in source form from DESY and is free of license charges for non-commercial users. The code is also acessible on the NMFE computer center.

TBCI-SF

TBCI-SF [17] is a Particle-In-Cell (PIC) version of TBCI. It uses the self-consistent current algorithm of ISIS [18]. The code computes the particle motion and electromagnetic fields self-consistently for cylindrical geometries. Its capabilities can be compared with the widely-used MASK [19] code. However, TBCI-SF is more general and allows presetting of parts of the mesh with precalculated resonant fields from URMEL [13] and static fields from PROFI [20]. This allows a correct computation of the interaction of the particle beam with rf cavities and avoids the modelling of cavities with port approximations [21]. The code has been applied to various cases, such as the wake field transformer hollow beam gun [22] [23], a superconducting photo emitter [24], the wake field transformer itself [25], an electron source at CERN for testing a CLIC injector [26], electron sources for small storage rings etc. Its use outside DESY is increasing. A typical result is shown in Fig. 2

Availability: The code in the current version may require in some cases output data from PROFI [20] (e.g. for iron shielding of coils). This limits the transportability because PROFI is a commercial code. The code therefore is being modified to adopt the MAFIA [27] standards, which will make it both easier to use and independent of other codes. This next version will be available soon in source form from DESY and will be free of license charges for non-commercial users.

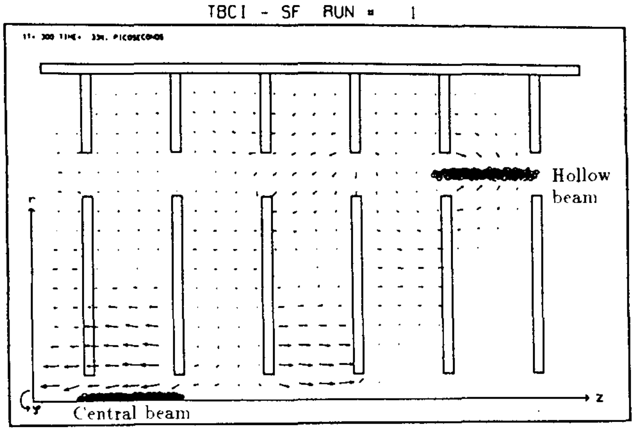

Figure 2: Typical result from TBCI-SF, a fully consistent particle-in-cell simulation code that solves the particle motion and Maxwell's equation simultaneously as function of time. The plot shows two particle bunches in a wake field transformer. The upper hollow cylindrical beam excites wake fields that accelerate the on-axis witness beam. This structure has been used in the first experimental proof of the wake field transformer principle [23].

Three Dimensional Codes

Fully three dimensional codes are much fewer in number than 2D codes because the coding requires much more work. Furthermore 3D codes do need much more computing power. However, in recent years a few codes have been developed and enable modelling of truly 3D cavities and other structures.
We will concentrate here on rf codes rather than on static codes, many of which have been around for years and are well tested. The reason why rf codes lag behind static codes is due to the fact that the matrices are three times as big and that 3D rf problems suffer very much from unphysical solutions.

PROFI, MAGNUS, TOSCA

PROFI [20] is being improved continually and the latest release is much more user friendly and handy than previous versions. The capabilties are also extended to include eddy current problems. In order to shorten the list of 3D static codes we will only mention here the very flexible MAGNUS code [28] and TOSCA [29] since these codes are widely used in accelerator laboratories.

Availability: These codes are available commercially. For more information and prices please contact the authors.

KOBRA

The KOBRA[30] beam trajectory code includes space charge and allows plasma boundary conditions. It is a valuable tool for the design of guns and used in some laboratories. Recent changes concern minor improvements.

Availability: The code is available free of charge from GSI, Darmstadt.

ARGUS

The ARGUS [31] code is a product of SAIC corporation that allows time and frequency domain solution. In the time domain it can be run as a PIC code or particle trajectory code. Recently, the frequency solver has been improved and now uses the algorithm of the MAFIA solver [27] [32] [33]. Thus the number of modes that can be found and the cpu time consumption are comparable. The code allows dielectric insertions. Permeable insertions are still undergoing tests at SAIC. Boundary contours are approximated by stair steps, i.e. the code allows only empty or entirely filled mesh cells. (Contrary to MAFIA which allows subdivision of mesh cells and thus better approximation of curved boundaries.) The authors have developed a domain decomposition scheme which allows treatment of subdomains sequentially and thus economizes the use of main memory. Various comparisons have been made with MAFIA of which we show one result in Table 1. The size of the problems that can be solved is also comparable with MAFIA. In fact, ARGUS is the main competitor to MAFIA as the capabilities of the codes are very similar.

Availability: The code is commercially available through contracts with SAIC corporation and so far only inside the US.

SOS

SOS [34] is a fully 3D PIC code that also can do some mode computation. The eigenvalue solver is not far developed and can calculate only very few modes. The code has been written at Mission Research Corporation. The PIC capabilities can be compared with ARGUS.

Availability: The code is probably commercially available, but (to my knowlegde) not outside the US.

Hara's Code

In 1981 at RIKEN in Japan, Hara [35] had already developed a 3D rf resonator code using the finite element technique. The first code was limited to only 1000 mesh points and suffered significantly from unphysical solutions. Meanwhile they have changed their elements so that they are very similar to the standard finite difference method in order to get rid of the unphysical solutions [36]. The code is still rather limited due to the algorithm for eigenvalue searching which it uses. It can only handle (so far) small meshes of the order of 1000 nodes.

Availability: Please contact the authors for more information.

Oak Ridge Code

This code developed at Oak Ridge laboratory [37] solves frequency domain eigenmode problems. It apparently allows only homogeneously filled cavities, i.e. no dielectric nor permeable insertions are permitted. The publications unfortunately do not give much information on maximum number of mesh points, cpu time and memory requirements. From results I have seen this code is not developed as highly ARGUS or MAFIA.

Availability: Please contact the authors for more information.

MAFIA (release 2)

Being the chairman of the MAFIA collaboration [38] I cannot resist the chance to describe this code and its latest developments in more detail. MAFIA is a group of modular codes for solving Maxwell's equations. An easy-to-follow user guide is available [39]. The codes are entirely written in pure FORTRAN77.

The following modules are either available (release 2.x) or under testing(*) (release 3.x):

M3	mesh generator
R3	matrix generator
R3C*	matrix generator for lossy materials
E31	eigenmode solver, sub-space method
E32	eigenmode solver, multigrid method
S3*	electro- and magnetostatic field solver
T3	wake fields of rigid bunches
TS3*	Particle-In-Cell version of T3
P3	graphics and physics post processor

These modules communicate via a standardized data base. As one can see from the list of modules, MAFIA covers a wide range from static problems via rf problems to selfconsistent PIC applications. The codes have been distributed to many laboratories around the world [1] in recent years and are being applied to a countless number of problems. Among use in accelerator physics the codes have also been applied to a number of other

[1] Austria(1), Belgium(1), Brazil(1), Canada(1), China(5), France(4), Germany(21), India(1), Italy(5), Japan(8), Mexico(1), Netherlands(1), Sweden(1), Switzerland(2), Taiwan(1), United Kingdom(4), USA(29), USSR(1)

problems such as medical applications (nmr spectroscopy), to rf filter design in communication electronics and resonator design in physical chemistry [40]. Many comparisons with measurements have shown that the codes are very valuable and able to predict field patterns very accurately.

M3: The mesh generator has been improved in some minor details and the graphics routines have been speeded up significantly by use of more advanced hidden line algorithms. Typical output is shown in figures 3, 4, 5 and 6.

R3: No changes were necessary except minor internal changes to accomplish the needs of the upgraded E31.

R3C: We are currently testing a fully complex version of R3/E31,32 which will allow lossy dielectrics and metals of finite conductivity. The losses are not incorporated by pertubation methods but put directly into the field equations, resulting in complex eigensolutions. This code will be part of the next release.

E31 The eigenvalue solver based on the well known subspace method [33] was first coded at CERN [32] for use in URMEL. Meanwhile it has been upgraded and speeded up by a factor of up to four by one of the MAFIA group (B.S.). When solving the eigenvalue problem in the iterated subspace we now use the curl-curl equivalent operator in the mesh to group all unphysical solutions to one end of the spectrum. This is much more convenient and faster as well. It still is the most solid solver in the MAFIA system. In comparison with ARGUS's domain decomposition it should be mentioned that E31 has also two internal paging systems to reduce the memory requirements when necessary, at the cost of increased elapsed computer time. At DESY the code has been extensively used running on a CRAY at the HRLZ at KfA Jülich to optimize and design many HERA beam kickers [41] and other vacuum elements such as unavoidable small cavities at beam tube transitions. A typical result is shown in Fig. 5. A large number of application by other users may be found in accelerator conference proceedings.

E32 The multigrid solver turned out to be not as stable as expected, due to intrinsic problems of multigrid method with the type of differential equation to be solved. It is running after major changes, as fast as E31 up to 50,000 nodes and its main advantage, that the cpu time increases only linearly with the number of meshpoints, will pay off only in the future. E31 can solve in minutes on a CRAY XMP problems with matrices as large as 700,000 by 700,000, and thus there is no urgent need for a second algorithm. However, looking into the future, multigrid methods still seem the only way to go, although it is a hard way.

S3 The static solver solves electrostatic and magnetostatic field problems [42]. Compared to existing static codes such as PROFI it has the advantage that it allows open boundary conditions. This circumstance allows rather small meshes. Note that in static fields the artificial boundary at the end of the mesh introduces significant errors [42]. Apart from the open boundary condition S3 does not differ significantly from existing static codes. The main purpose of S3 is to provide static fields for input into TS3 and to make the MAFIA system complete. Ideally, the user would use only one single program environment instead of using many different codes, each with its own input and output data structure. Typical output from S3 is shown in Fig. 3, and Fig. 4 shows the end region of a radio frequency quadrupole. This module is almost complete and will be part of the forthcoming new release of the MAFIA code group.

T3 T3 [43] is mostly used to evaluate wake fields and wake potentials in accelerator structures. Using analytical properties of the beam-environment impedance, it can significantly reduce numerical noise and thus run very large problems. At DESY the code has been used to design the entire vacuum system of HERA [43] (all pumps, bellows, position monitors etc.), see e.g. Fig. 6. In order to do so we had to run problems with more than one million meshpoints. The code turned out to be an invaluable tool for designing vacuum systems as the human intuition does not seem to work quantitatively where transverse impedances are concerned. A number of bugs have been removed after they were found and reported by very friendly users. The quality the code has today reached results largely from the cooperation with the external users.

TS3 We are currently testing a PIC version of T3 which will use the same particle pushing procedures as TBCI-SF. Via the MAFIA data base the code can communicate with other MAFIA modules and thus use precalculated static and resonant fields. This code will be used in only a few applications because of the vast amount of cpu time required for a true 3D PIC simulation. However, some problems such as the hollow beam gun under development at DESY [22] do need this simulation.

P3 The postprocessor has mainly been debugged and is now quite stable. It is used to display fields in arrow plots, contour line plots or isoline plots. It can perform one, two and three dimensional integrals in order to obtain secondary quantities such as stored energy, impedances etc.

Availability: The codes are available free of charge to non commercial users from DESY. They are also accessible on the NMFE network. All MAFIA codes are written in pure FORTRAN77 language.

MODE	MAFIA f/MHz	ARGUS f/Mhz	Difference/%
1	662.413	658.492	0.6
2	667.105	666.397	0.1
3	776.228	755.625	1.4
4	992.353	983.726	0.9
5	995.116	986.267	0.9
6	1011.270	1011.270	0.0

Table 1: comparison of computed frequencies for a deflecting cavity (CEBAF Accelerator cavity) showing excellent agreement (taken from [31]) between ARGUS and MAFIA.

3.8 MAFIA (release 3)

The wide acceptance of the MAFIA codes in the scientific community has prompted us to upgrade the entire system to a new release. The next version will have much more flexible and understandable file and memory management system. The user interface has been completely renewed and is now coherent between all modules [27]. The codes may be run in batch or interactively. There is online help for all commands. The logical structure of the code as far as seen by the user is very simple and all currently possible commands are displayed in optional menus. The new system is similar to a small computer operating system with its own file handling capabilities.

However, the internal physics routines were not changed, and there is no risk of new bugs in the new release on this account. The major advantage for us is that it becomes very easy to modify the code and to introduce new modules because of the new memory and file manager.

Availability: The codes will be available free of charge to non commercial users from DESY as soon as release 3 is ready for distribution. This will certainly be the case before this paper is printed.

Acknowledgement

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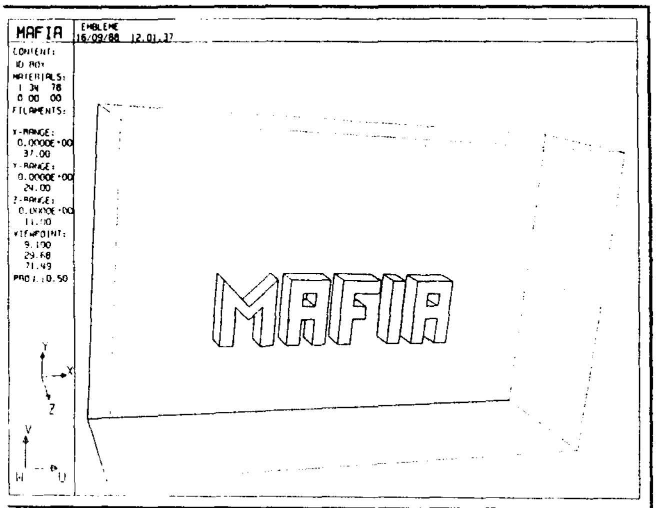

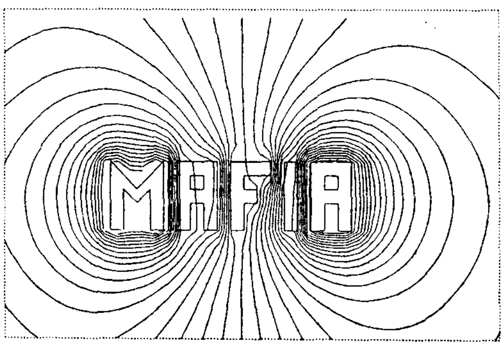

Figure 3: Result from S3 showing a metallic **M** and **A** and dielectric **AFI** and equipotential lines in a cut plane. Note the behaviour of the potential lines near the boundary showing an excellent approximation of open boundary conditions

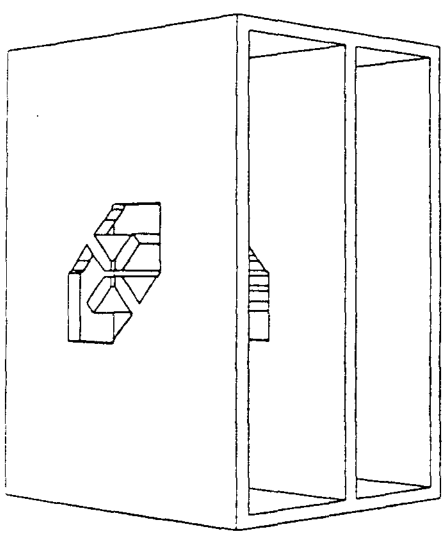

Figure 4: A four rod rfq analyzed bei MAFIA

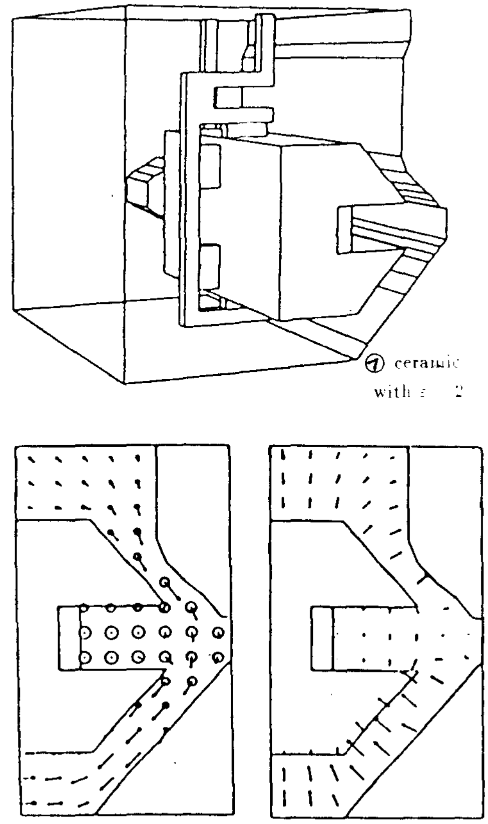

Figure 5: A complicated removable kicker that was intended to operate in PETRA for ejection of protons into HERA. From results of R3/E31 for the parasitic shunt impedance it was found that such a kicker would cause strong multi bunch instabilities. Thus the design had to be changed [41]

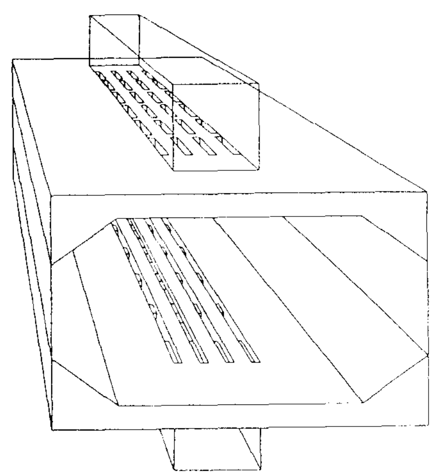

Figure 6: Geometry of the HERA quadrupole vacuum chamber with getter pumps and connecting slots on top and bottom. This is a typical example of the countless chamber sections that have been designed using T3. The goal was to minimize the total deflecting broad band impedance such that it is small compared to the unavoidable impedance of the accelerating cavities. T3 runs a bunch of particles along the center and computes the transient fields as function of time. From these fields one obtains the deflecting wake potentials.

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[38] MAFIA is an international collaboration between **DESY** (F.Ebeling, P.Hahne, R.Klatt, F.Krawzcyk, D.Rusthoi, P.Schütt, T.Weiland, S.G.Wipf), **LANL** (T.Barts, M.J.Browman, R.Cooper, G.Rodenz) and **KfA Jülich** (B.Steffen). The goal of this long lasting effort is to provide the accelerator community with freely accessible 3D codes for accelerator physics problems.

[39] The MAFIA user guide is available from the: Los Alamos Accelerator Code Group, MS H829, Los Alamos National Laboratory, Los Alamos, New Mexico 87545.

[40] S. Pfenninger, J. Forrer, A. Schweiger, T. Weiland, Review of Scientific Instruments, Vol.59(5), May 1988, p.752-760

[41] E. Lawinsky, T. Weiland, S.G. Wipf, "RF Impedance Calculations for Three Dimensional Devices for HERA", contribution to the 1st EPAC Conference, Rome, Italy July 1988, see forthcoming proceedings

[42] F. Krawczyk, T. Weiland "3D Magneto- and Electrostatic Calculations using MAFIA-S3", contribution to the 1st EPAC Conference, Rome, Italy July 1988, see forthcoming proceedings

[43] R. Klatt, T. Weiland, "Electromagnetic Design of the HERA e- Vacuum System", 1986 Linear Accelerator Conference, SLAC report 303, p.282 and contribution to the 1st EPAC Conference, Rome, Italy July 1988, see forthcoming proceedings