IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

COMPUTER MODELLING OF TWO- AND THREE-DIMENSIONAL CAVITIES

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

Abstract

The rf accelerating system is the heart of many low, medium and high energy particle accelerators and in many cases, it is also a major drain of investement money and operational costs. In order to increase efficiency, many computer codes have been developed in the last few decades. Recently, it has been realized that parasitic collective effects can also present serious problems in the most expensive front line high energy physics accelerators. Nowadays, cavity design is no longer only a question of optimizing the shunt impedance but also of optimizing the overall effect of the system. Also, all other non-rf cavities in an accelerator are found to cause many problems. For cylindrically symmetric structures well tested computer codes are in widespread routine use as design tools. Fully three dimensional codes are just coming into common operation. At the present time, we are able to solve almost every two or three dimensional cavity problem either by mode computation or by transient wake field computation.

Introduction

For many years, cavity modelling consisted of optimizing the shunt impedance of a specific structure in order to obtain the highest accelerating gradient for a given rf power. Since most rf structures have cylindrical symmetry, the lowest accelerating modes are cylindrically symmetric too and can be described by one scalar variable in a two dimensional grid (in the r-z plane). Codes for this kind of problem have existed for many years: MESSYMESH [1] (1961), LALA [2] (1966), SUPERFISH [3] (1976) and many others with improvements in speed or other details [4,5,6,7,8].

From practical experience it has been found that in a real cavity together with a real charged particle beam the fields are no longer fully cylindrically symmetric and as a consequence, problems arise with transverse modes. In general, a cylindrically symmetric structure has subsets of modes varying as $\cos m\varphi$ and only the m = 0 (TM0) family is used for acceleration. Any asymmetry in the beam or the structure leads to excitation of modes of family m = 1 (dipole) and higher.

In order to analyze these modes, new codes had to be developed that could calculate such transverse modes too. e.g. ULTRAFISH [8], PRUDE [9] and PISCES [10]. These codes suffered from some intrinsic problems caused by the ansatz used. However, a different method (URMEL [11]) which is free of these problems has been developed and has now been available for three years. Recently, an extension of URMEL to a triangular mesh was coded that also allows arbitrarily shaped permeable and/or permittive insertions (URMEL-T [12]).

The analysis of arbitrarily shaped and filled cavities of cylindrical symmetry can now be considered to be a solved problem.

In parallel to the development of frequency domain codes the use of transient wake field computations has become common practice as a complementary tool for analyzing cylindrical structures. For example the code TBCI [13,14] is widely used to investigate the contributions of many objects - not only the accelerating cavities - to the parasitic impedance of an accelerator. The code is well tested and proven [15,27]. Thus, we can consider the entire impedance problem of cylindrical structures to be solved.

In many accelerator devices, however, cavities with non-rotational symmetry are used, e.g. kickers, vacuum chamber joints, separator plates, rf-quadrupoles etc. For such structures, only a fully three dimensional code could give meaningful results. Such codes have long been available (1974 [16], 1982 [17] and 1983 [18]) but they are either not general in their application and/or because of a theoretical problem hidden in the ansatz, they do not give unique results, so causing severe problems and preventing widespread use. Recently [19], a three dimensional version of URMEL has been published. This code uses a different ansatz [20,21] and is free of numerical problems. This is now available and is part of a family of codes called MAFIA [22] that will provide a universal 3D-electromagnetic CAD-system to the accelerator community.

The transient wake field calculation in three dimensions has also been programmed recently. The first program [23] was described in 1984 but was applicable only to a specific geometrical shape. This three dimensional BCI [24] can treat arbitrarily shaped 3D problems and is also available as a part of MAFIA.

The situation today is that we are just beginning to use 3D-codes for the routine design of accelerators. It seems that the only limitation is the availability of cpu time, large core memory and colour graphics and that otherwise the problems of finding numerical solutions for Maxwell's equations have been solved. However, the next few years will show the limitations of 3D-computation and it will probably take more than a few years until 3D-codes can be used routinely by non-experts.

Since this new 3D-system is not yet well-known, we will describe it here with some preliminary examples.

2D-Codes

In this section we will describe the properties of the two codes URMEL and URMEL-T which we take as representative of all the others. The theory is described in sufficient detail elsewhere, so here it is sufficient just to state that both codes use electric (or magnetic) field components in the (r,z) plane as unknowns, that this is the major difference compared to the other codes and that this is why they have no problems.

These codes run on an arbitrarily shaped cylindrically symmetric structure that may contain some material bodies (ε,μ). An automatic mesh generator that needs only the total number of mesh points as input generates a suitable mesh, see figures 1, 2 and 3. Both codes calculate for a given cylindrical mode number m (m = 0: monopole, m = 1: dipole, ...) a set of N modes (N typically ≤ 50) and all related quantities such as shunt impedance and quality factor.

Many measurements have been undertaken to verify the correctness of the computation, see e.g. [25,26,27].

Figure 1 shows the shape of the half cell of the PETRA seven cell cavity. Figures 2 to 5 show generated meshes and results of the computation.

In addition to cylindrically symmetric structures both codes can also solve for cavities with translational symmetry, i.e. cavities with arbitrary cross section but no longitudinal variation.

The cpu time consumption of all 2D-codes is moderate: on an IBM 3081 a typical run takes a few minutes with 20 modes and 5000 mesh points. For simple problems, such as a half cell calculation, 1000 mesh points are sufficient in many cases and it takes only 20 seconds to determine the lowest 20 modes.

The only commonly used code for two dimensional wake field calculations is TBCI [13,14]. This program can calculate transient fields excited by bunches of charged particles. The particles may have relativistic or non-relativistic velocity and an arbitrary distribution. A typical result of this code is shown in figure 7.

The cpu time consumption of TBCI is also moderate in spite of the fact that one may use many mesh points (up to 60000 for 2 Mbyte on an IBM 3081).

By using URMEL and TBCI in combination, it is possible to treat many cavity problems in accelerator design.

3D-Codes

Fully three dimensional codes for mode calculation and transient fields has been described in several publications [16,17,18,23]. However, due to a problem in the ansatz the resonator codes do not produce reliable results, i.e. eigensolutions which should be purely oscillatory sometimes contain admixtures of static fields. Then a certain parameter has to be varied and the sensitivity of the result to that parameter has to be observed in order to identify bad solutions. A different method for the discretization published recently [21] does not suffer from this problem: the 3D-URMEL produces unique solutions that are purely resonant.

For time domain calculations, there is also a new version (3D-BCI [24]) now available that can deal with arbitrarily shaped structures.

Since input and output of 3D-codes is quite a complicated job, a 3D-code system called MAFIA [22] is now being prepared by an internatinal collaboration which has been set up between DESY, KfA Jülich and LANL in order to provide the accelerator community with a universal 3D-CAD system for all electromagnetic problems in accelerator design. This system has a common input processor (M3) generating the meshes so that one can run 3D-URMEL and 3D-BCI (or other 3D-codes for magnets etc.). Results are subsequently displayed by a post processor code (P3). Here we present only that part dealing with cavities.

M3: This part of MAFIA is a general mesh generator (so far only in cartesian coordinates). The user specifies a 3D-grid and fills it with bodies that can be described in different ways. The following types are available in Release 1:

- 3D match box,
- cylinder of arbitrary cross section,
- general figure of rotation,
- ellipsoides,
- spheres
- toroides,
- circular cylinders,
- truncated cones.

Typical output of M3 is shown in figures 9, 10 and 11. Results from M3 are written on a common file base that is subsequently used by the field calculator programs. In order to allow multi-grid methods to be used, M3 can produce n subgrids for a given problem. These are used by a multi-grid solver in the eigenvalue calculation and in the static field problems (not yet installed).

BCI-3D: This three dimensional version of BCI calculates the transient electromagnetic field excited by a bunch of charged particles passing through the structure. Such wake fields are quite important in the design of all kind of accelerator parts such as vacuum chamber transitions, bellows, kickers etc. and of course also for the accelerating system.

The code can deal with very large meshes making use of a window option [28] where only a small fraction of the total mesh is inside memory at the same time. As an option, open boundary conditions can be used and a compensation algorithm for fields travelling with the beam along the downstream beam pipe is being prepared.

A typical result for the sliding vacuum chamber joint in PETRA is shown in figure 9.

This code is now being used at DESY to design all vacuum parts for HERA.

URMEL-3D: The three dimensional URMEL has so far only been used for calculating modes in some test cavities [19]. In order to increase the calculation speed, the code has been separated into two pieces, the generation of the matrix and the calculation of the eigenvalues. Two eigenvalue solvers may be used, one which is the same as in the 2D-URMEL and a new one by one of us (B.S, [22]) using a modern multi-grid method.

The code can determine the n lowest eigenfrequencies and fields in arbitrarily shaped 3D-cavities with or without insertions of permittive or permeable material.

Results (Table I) for the pill box cavity indicate the accuracy as well as the comparison with measurements (Table II).

More realistic examples are now being worked on but results were not available in time for this conference.

Table I: Modes calculated in a cylindrical pill box using 2D and 3D grids (for geometry see figure 10).

	f/MHz		
Mode Type (notation see /7/)	URMEL $N_2 = 5000$	3D-calculation $N_3 = 21^3 = 9261$	error
TMØ-EE-1	116.53	116.76	$1.7\cdot10^{-3}$
1-ME-1	168.23	168.30	$4.2\cdot10^{-4}$
1-EE-1	179.14	179.24	$5.6\cdot10^{-4}$
TMØ-ME-1	190.76	190.71	$2.6\cdot10^{-4}$
2-ME-1	208.67	208.87	$9.6\cdot10^{-4}$
1-ME-2	225.97	226.30	$1.5\cdot10^{-3}$
2-EE-1	244.02	243.97	$2.0\cdot10^{-4}$

Table II: Lowest mode frequency as calculated and measured for the dielectric loaded rectangular cavity shown in figure

	f/MHz		
	measured	calculated $N_3 = 690$	calculated $N_3 = 3185$
with dielectric tube	1258	1255	1256
without dielectric tube	1319	1310	1319

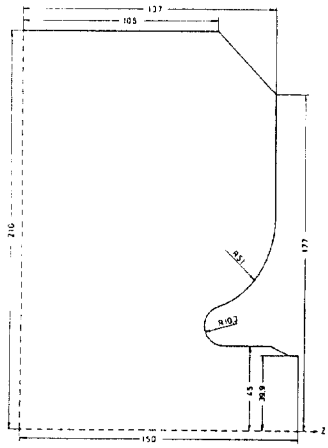

Fig. 1: Geometry of half a cell of the PETRA seven cell cavity.

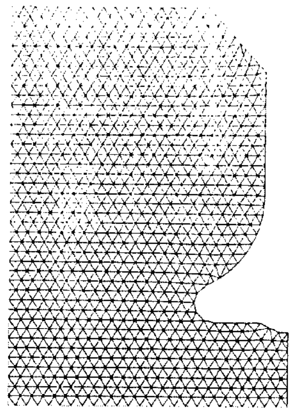

Fig. 2: Triangular mesh generated by URMEL-T.

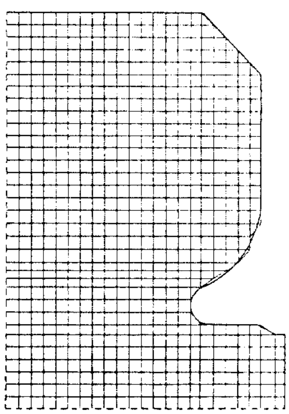

Fig. 3: Rectangular mesh with subtriangles generated by URMEL.

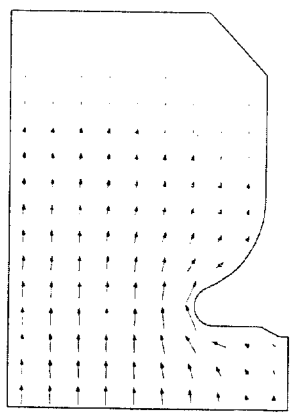

Fig. 4: Lowest dipole mode in the PETRA 7-cell cavity, f = 874 MHz. The arrows represent the electric field.

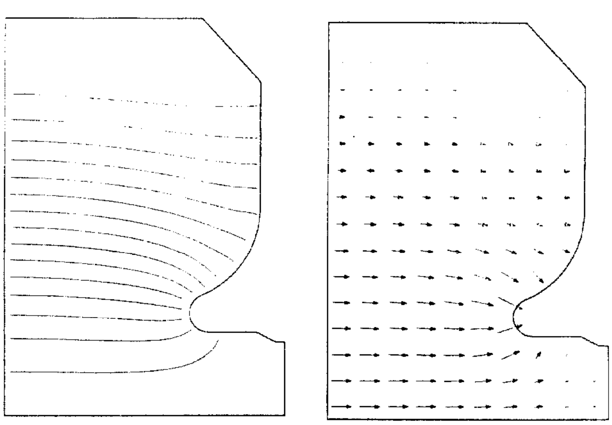

Fig. 5: Accelerating monopole mode in the PETRA 7-cell cavity at f = 509 MHz. Shown are a) arrows representing the electric field and b) lines of constant $\rho \cdot H_\varphi$.

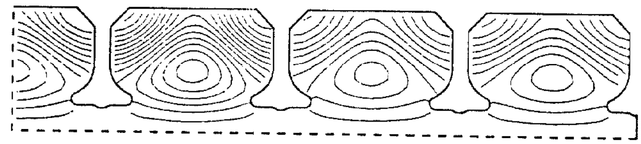

Fig. 6: Mesh and higher mode computed by URMEL-T in the multicell model of the PETRA 7-cell cavity (f = 1273 MHz).

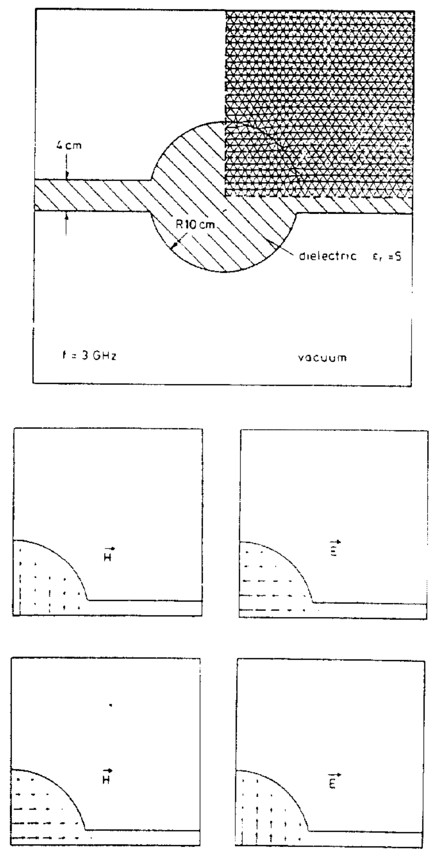

Fig. 7: Field patterns of the two lowest travelling waves on a dielectric guide calculated by URMEL-T.

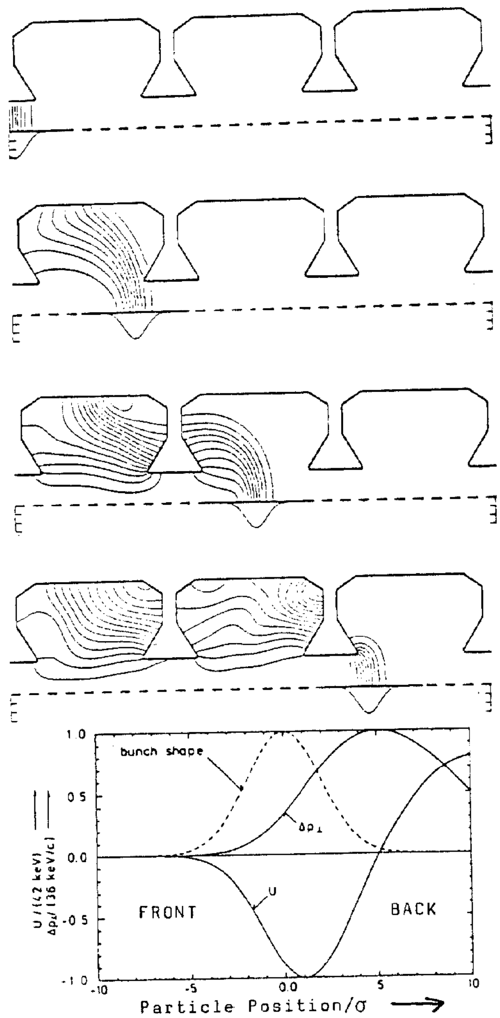

Fig. 8: Typical output of TBCI showing transient fields excited by a bunch of charged particles traversing three accelerating cavity cells, and the resulting distribution of change in energy and transverse momentum due to dipole fields (m=1) (Gaussian bunch, Q=1μC, σ=2cm, 0.5cm off axis, ß=1, U and Δp are given per cell).

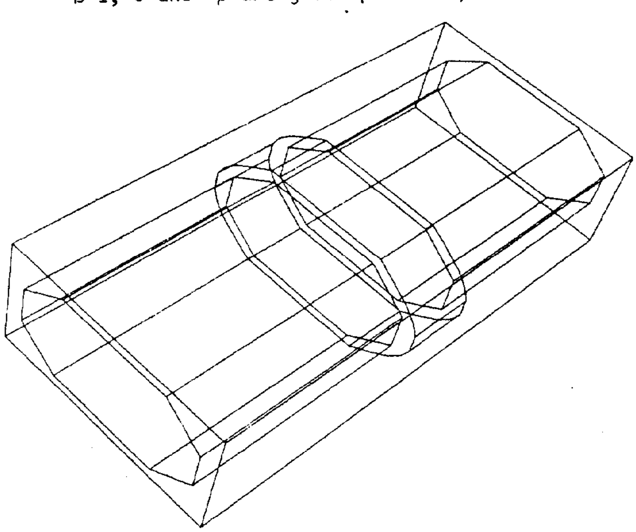

Fig. 9: The PETRA sliding contact vacuum chamber joint in mesh representation.

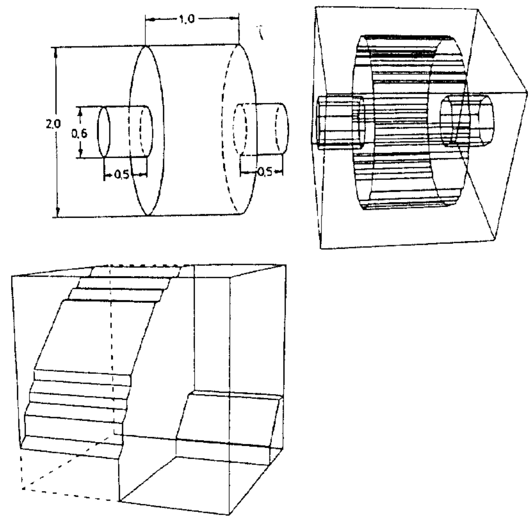

Fig. 10: Pill box with beam parts and approximated cavity (full size and one octant).

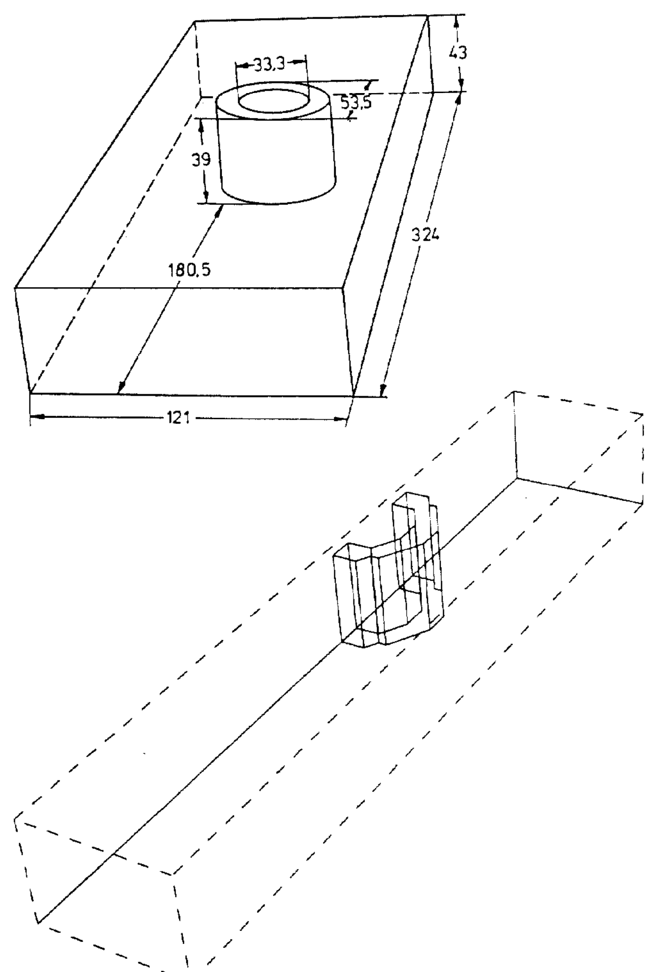

Fig. 11: Dielectric loaded rectangular wave guide and its mesh representation.

Summary

The modelling of cylindrically symmetric structures is now very far advanced and takes into account parasitic wake field effects and also standard optimizations such as shunt impedance. These codes are routinely used for designing accelerator components and they are well tested and easy to use.

Three dimensional cavity analysis is still a job for experts and general codes are just coming into common distribution. The most advanced system, MAFIA, allows computation of 3D-cavity modes, 3D-transient wake fields and other field problems within one structured code system. The main parts of this system have just been finished and have survived the first tests. They will be distributed in the near future. Provided that computer size and speed continues to increase these 3D-codes will also be a common tool soon.

Acknowledgement

The author wishes to thank D. Barber for careful reading of the manuscript.

References

[1] T. Edwards, MURA rep. 622 (1961)

[2] H.C. Hoyt, D.D. Simmonds, W.F. Rich, Rev. Sci. Instru. 37 (1966), p. 755

[3] K. Halbach, R.F. Holsinger, Part. Accel. 7 (1976), p. 213

[4] R.L. Gluckstern, Proc. of the IV-th Compumag Conf., Geneva 1983, being published

[5] B.B. Fomel et al., Part. Accel. 11 (1981), p.173

[6] P. Fernandes, R. Parodi, Part. Accel. 12 (1982), p. 131

[7] A.I. Fedoseyev et al., NIM 277 (1984), p.411-419

[8] R.L. Glückstern et al., 1981 Linear Accel. Conf. Santa Fe, p. 102

[9] A.G. Daikovskii, In.I. Portugolov, A.D. Riabov, Part. Accel. 12 (1982), p. 59

[10] J. Iwashita, paper submitted to the COMPUMAG Conference, Colorado, June 1985

[11] T. Weiland, DESY 83-005, 1983 and DESY M-82-24 (1982) and NIM 216 (1983), pp. 329-348

[12] U. van Rienen and T. Weiland, paper to be published about the triangular version of URMEL

[13] T. Weiland, XI-th Internat. Conf. on High Energy Accel., Geneva 1980, p. 575

[14] T. Weiland, DESY 82-015 (1982) and NIM 212 (1983), pp. 13-21

[15] K. Bane, T. Weiland, SLAC-AP1 (1983) and 12th Conf. on High Energy, 1983

[16] M. Albani, M. Bernardi, IEEE MIT 22 (1974),p.446

[17] W. Wilhelm, Part. Accel. 12 (1982), p. 139

[18] M. Hara et al., IEEE-NS 30 (1983), p. 3639

[19] T. Weiland, DESY 84-111 (1984), and Particle Accelerators, accepted for publication

[20] T. Weiland, AEÜ 33 (1979), p. 170

[21] T. Weiland, Particle Accelerators 15 (1984), pp. 245-292

[22] MAFIA is the name of an electromagnetic CAD system (Maxwell's Equations by finite integration theory and their application) that can solve 3D resonant (3D-URMEL) and transient (3D-BCI) field problems and stationary fields as well. This system is the product of an international collaboration between DESY, Kernforschungsanlage Jülich and Los Alamos National Laboratory. General Publications will be available soon. Present list of authors: R. Klatt, C. Palm, W.R. Novender, U. van Rienen and T. Weiland from DESY, B. Steffen from KfA-Jülich, G. Broman, R.K. Cooper, T. Mottershead, G. Rodenz and S. Wipf from LANL

[23] Y. Chin, KEK 83-19, November 1983

[24] R. Klatt and T. Weiland, a paper to be published on three dimensional transient wake field calculations (3D-BCI)

[25] J. Peters and T. Weiland, DESY M-83-31, Oct.1983

[26] J. Peters and T. Weiland, DESY M-85-02, Feb.1985

[27] K. Bane and T. Weiland, 12th Internat. Conf. on High Energy Accelerators, Chicago 1983

[28] K. Bane and T. Weiland, 12-the Internat. Conf. Accel., pp. 314-316