VARIOUS APPROACHES TO ELECTROMAGNETIC FIELD SIMULATIONS FOR RF CAVITIES

C. Liu, W.F.O. Müller, W. Ackermann, and T. Weiland
Technische Universität Darmstadt, Institut für Theorie Elektromagnetischer Felder (TEMF)
Schlossgartenstrasse 8, 64289 Darmstadt, Germany

Abstract

In the Superconducting Proton Linac (SPL) cavity, there is not only the fundamental mode for the particle acceleration but also many higher order modes (HOMs), which can lead to particle beam instabilities. This is very dangerous for the SPL cavity. Therefore it is necessary to simulate the electromagnetic field in the SPL cavity, so that the field distribution and the shunt impedance for the higher order modes can be precisely calculated. At TEMF this research work can be done in three different ways: field simulation with hexahedron mesh in frequency domain, field simulation with hexahedron mesh in time domain and field simulation with tetrahedral mesh and higher order curvilinear elements. Finally the HOM couplers will be considered for the effective damping of higher order modes in the SPL cavity.

INTRODUCTION

The Superconducting Proton Linac (SPL) [1] at CERN uses two families (β = 0.65 and β = 1) of elliptical five-cell superconducting cavities. Both families operate at 704.4 MHz. In this paper only the type β = 1 would be discussed. As shown in earlier studies [2], many higher order modes (HOMs) can cause particle beam instabilities. For this reason the properties of higher order modes should be exactly analyzed. For this propose the frequencies of HOMs must be calculated as accurately as possible. In addition, the detailed field distribution of HOMs is also essential to calculate the shunt impedance of the individual mode.

FIELD SIMULATION WITH HEXAHEDRON MESH IN FREQUENCY DOMAIN

The first way to calculate the field date of HOMs is the conventional eigenmode analysis with Eigenmode Solver from CST MICROWAVE STUDIO® [3]. The eigenmodes for the five-cell elliptical resonator could be analyzed with hexahedral discretization. The results from the Eigenmode Solver involve the frequencies and the field distribution of the eigenmodes. From that the shunt impedance of the individual eigenmode can be calculated. The frequencies as well as the shunt impedance of the modes in the fundamental pass band are listed in Table 1.

For the elliptical SPL cavities a large number of hexahedral grid points are required to achieve stable simulation results. This can result in a slow convergence of the Eigenmode Solver (see Figure 1), which lead to an extremely time consuming simulation and a huge hard drive space for saving the simulation results (see Table 2).

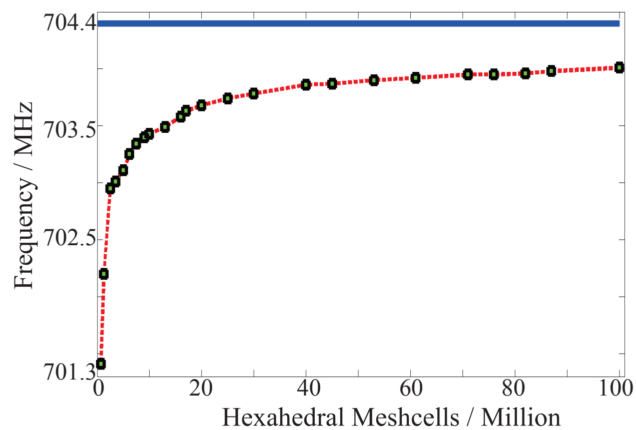

Figure 1: Convergence of the calculated frequency for $TM_{010,}$ π mode (Hexahedral mesh).

Table 2: Time needed for simulation and the hard drive space for saving the simulation results.
(Simulation: Calculation of TM_{010} modes with Eigenmode Solver from CST MWS 2010. CPU: Intel(R) Xeon X5472 @ 3.00GHz. DRAM: 64GB)

Meshcells [Million]	Time for simulation [h]	Hard drive space [GB]
61	111	31
71	238	36
88	256	40
100	275	51

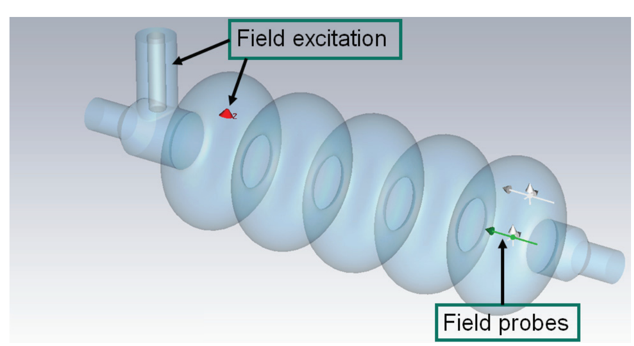

Figure 2: Main coupler and discrete port in cell 1, Field detection in cell 5.

Table 1: Electromagnetic Field Simulation Results (Hexahedral Mesh and Tetrahedral Mesh)

	Hexahedral Mesh (CST MWS 2010)			Tetrahedral Mesh		
Mode	Meshcells [Million]	Frequency [MHz]	Shunt Impedance [Ω]	Meshcells [Million]	Frequency [MHz]	Shunt Impedance [Ω]
$TM_{010, 1/5}\ \pi$	100	692.011	0.0023	6.2	692.446	0.0016
$TM_{010, 2/5}\ \pi$	100	695.247	0.0411	6.2	695.676	0.0366
$TM_{010, 3/5}\ \pi$	100	699.325	0.0300	6.2	699.744	0.0105
$TM_{010, 4/5}\ \pi$	100	702.689	0.1162	6.2	703.101	0.0669
$TM_{010, 5/5}\ \pi$	100	704.006	565.378	6.2	704.398	565.366

FIELD SIMULATION WITH HEXAHEDRON MESH IN TIME DOMAIN

Compared to the first method the simulation with hexahedral grid in time domain is considerably more efficient. The simulation should be carried out with Transient Solver from CST MICROWAVE STUDIO® [3]. In order to excite the electromagnetic field in the cavity a broadband high-frequency pulse was coupled into the cavity through a coaxial-type main coupler, furthermore a discrete port was put in the first cell of the SPL cavity. Some probes in x-, y- and z-direction were placed in the fifth cell of the cavity, so that the electromagnetic field in time domain can be detected and recorded (see figure 2). After that a Fourier transformation of the recorded field date yields the eigenmode spectrum. It is obvious by comparing between the results from frequency and time domain, that many eigenmode frequencies are located at the maximums from the eigenmode spectrum. For example the fundamental passband TM_{010} and dipolpassband TE_{111} are shown in figure 3 and figure 4 respectively. Therefore the frequencies of the eigenmodes can be measured from the eigenmode spectrum. Before the second simulation in Transient Solver the electric field monitors for the measured frequencies should be defined, so that the field distribution of the eigenmodes can be achieved after the second simulation and the corresponding shunt impedance can be determined.

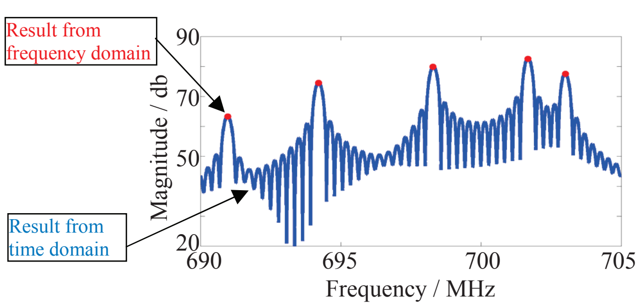

Figure 3: The eigenmodes in monopol-passband TM_{010}.

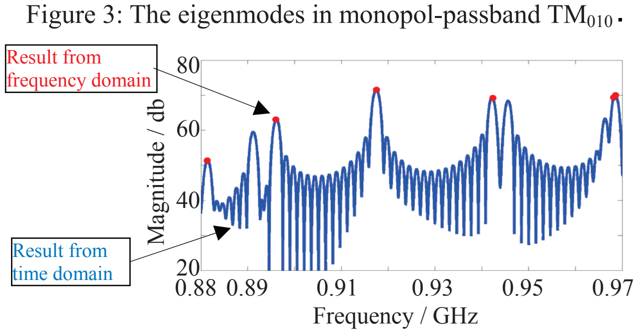

Figure 4: The eigenmodes in dipol-passband TE_{111}.

FIELD SIMULATION WITH TETRAHEDRAL MESH

The program, which is able to analyze the eigenmodes with tetrahedral mesh grids, is developed at Computational Electromagnetics Laboratory (TEMF), Technische Universität Darmstadt. For the discretization with tetrahedral grids higher order curvilinear elements are used, so that the contours of the elliptical resonator can be excellently represented. In comparison to the hexahedral mesh grids the convergence of eigenmode solver with tetrahedral grid is much better. With the higher resolution the operating frequency ($TM_{010,}\ \pi$) goes very quickly to the design operating frequency (see figure 5). Furthermore the required calculation time and the hard drive space are also economical. The calculated frequencies as well as the shunt impedance of the modes in the fundamental pass band are also listed in Table 1.

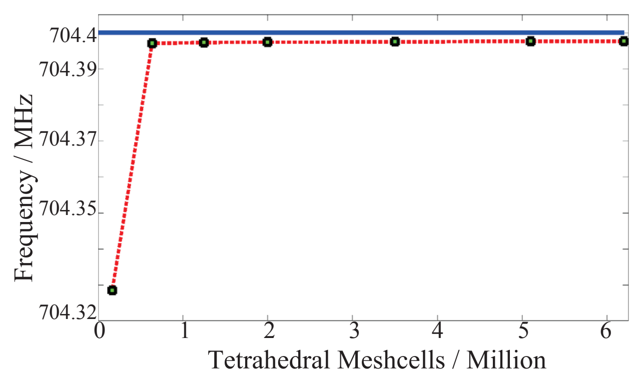

Figure 5: Convergence of the calculated frequency for $TM_{010,}\ \pi$ mode (tetrahedral mesh).

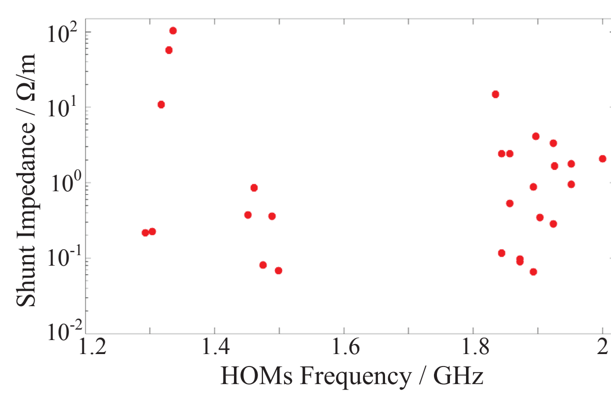

Figure 6: Longitudinal shunt impedance ($R/Q_{\|}$) of eigenmodes with high $R/Q_{\|}$ values.

The higher order modes with high shunt impedance are very dangerous to the particle beam. So the longitudinal and transversal shunt impedance of HOMs have been calculated and plotted in figure 6 and figure 7.

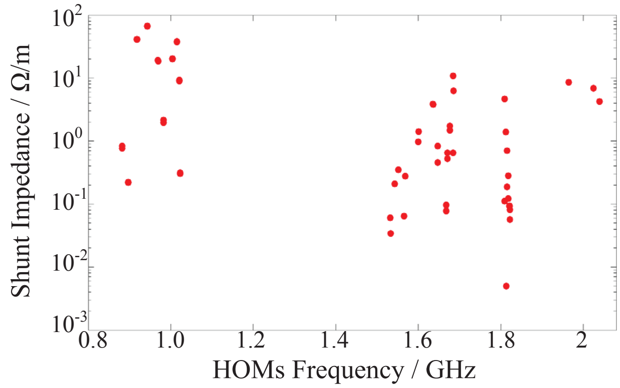

Figure 7: Transversal shunt impedance ($R/Q_{\perp}$) of eigenmodes with high $R/Q_{\perp}$ values.

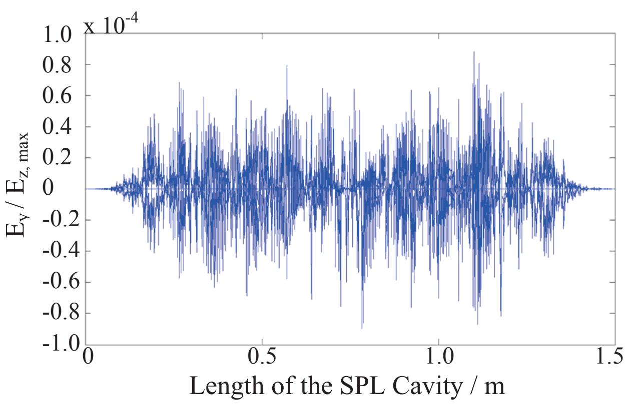

Figure 8: Electric field of TM_{010}, π mode: Transversal electric field E_y along the particle beam axis.

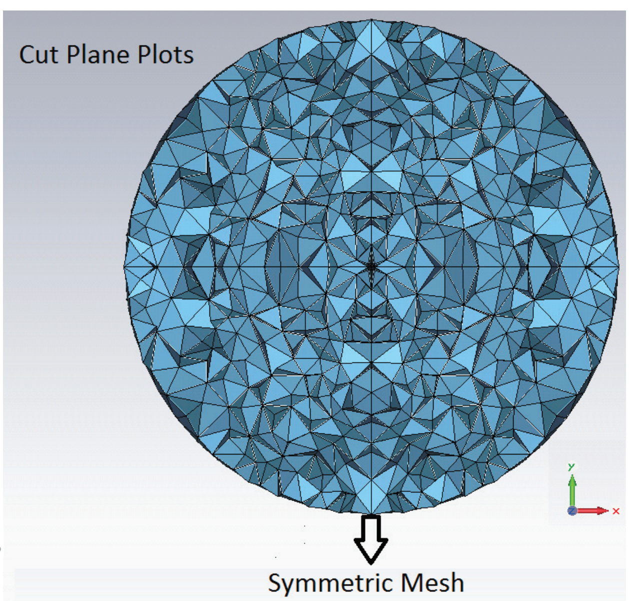

Figure 9: Symmetric tetrahedral mesh grids.

In order to calculate the longitudinal shunt impedance, the electric field distribution along the particle beam axis is essential. But in this paper the calculated field yielded an inaccurate field distribution along the beam axis. For TM_{010}, π mode transversal electric field along the beam axis appeared (figure 8). Such transversal field, which can cause inaccurate values of shunt impedance, should be suppressed. To overcome such difficulties, symmetric grids must be applied for the discretization with tetrahedral grids. The tetrahedral grids should be symmetric to the particle beam axis (see figure 9). So far the generation of symmetric tetrahedral grids can be only realized for the calculation of TM_{010} modes. The Algorithm to generate symmetric tetrahedral grids, which allow the calculation for all eigenmodes, is still being developed at TEMF.

CONCLUSION AND OUTLOOK

Because of the slow convergence, the extremely long simulation and the huge hard drive space for saving the simulation results, the conventional eigenmode analysis with hexahedral mesh grids in frequency domain is not an ideal approach to electromagnetic field simulations for elliptical SPL cavities. By comparison, the eigenmode analysis with tetrahedral mesh grids is highly efficient. The frequencies of eigenmodes can be quickly and precisely calculated. But if the simulation is carried out without symmetric tetrahedral grids, the inaccurate field data will lead to imprecise values of the shunt impedance.

In the future the electromagnetic field for SPL cavities will be simulated with symmetric tetrahedral mesh grids. In addition, the field simulation in time domain will be performed also with the transient solver from CST MICROWAVE STUDIO®. Finally the HOM coupler will be considered for the damping of higher order modes in the SPL cavity.

REFERENCES

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[2] H. Padamsee, J. Knobloch and T. Hays, “RF Superconductivity for Accelerators”, Second Edition, Wiley-VCH, Weinheim, 2008.

[3] CST MICROWAVE STUDIO®, CST AG, Darmstadt, Germany, www.cst.com