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Study on Reverberation Chamber for High-Frequency

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Preface

The thesis work was done in fulfilment of the course in Master's programme in Electronics Design at Halmstad University, Sweden. Ericsson AB, Lund was interested in the study on reverberation chambers that work for frequencies above 40 GHz and hence was actively involved in every stage of this thesis. The goal of the course is to train the student in independent technical development work and research work in electronics design. The student should during the course develop the prerequisites to work in a research or development environment.

One of the difficulties we faced during the thesis was that, so far there has been only a very few papers published on study of reverberation chambers at frequencies above the 40 GHz range. Another problem was that, large computational power was required for simulate in 3-D for high frequencies in large chambers.

It was an adventure to learn everything from the basics as there was no clear ground rules set. Throughout the thesis our Examiner Pererik Andersson had been supportive and helped us whenever we were stuck. In Ericsson AB our line manger Arya Khan-Amidy was motivative. Stefan Nilsson and Christian Heyl guided us throughout the work. They guided us in giving an understanding about the standards to keep for commercial use of reverberation chambers. We are grateful to Maria Gerling-Gerdin for giving us an detailed introduction to FEKO®. Alireza Kazemzadeh from FEKO® support Europe was kind enough to meet us and explain the technical difficulties of such a large simulation and helped us in approaching the problems in a different angle. The support given by our academic supervisor Ebrahim Chalengar to guide us in finding the right papers for literature study and during the writing made the work easier. We are grateful to all the people who helped us complete the thesis on time.

Abstract

The objective of this thesis work is about simulation of reverberation chambers for frequencies above 5 GHz. The frequencies of 40 GHz, 60 GHz and higher were also desired to be simulated but we realised that the simulation of this range was more complicated to achieve with our limited time and computational resources. The complexity issue become evident when higher frequency and large volume of reverberation chambers are implemented. Later when we had access to a high-performance cluster computer, the higher frequencies were also simulated. The variation of the electric field inside the chamber for change in frequency and by stirring the field inside the chamber was investigated. This was verified with the numerical values. At the beginning our aim was to simulate in an RC of the dimension $1200\ mm \times 800mm \times 1500mm$. Because of the long time required for simulation, we scaled down it by the factor of four for avoiding computational problem and minimizing our time. All the simulation were done for a cavity of the same dimensions. We also investigated reverberation chambers without stirrer, antenna, door etc. Later on stirrer to stir the field inside the chamber was used. Different material like Cooper (Cu), Silver (Ag), Iron(Fe) and perfect electric conductor (PEC) were used in simulation to find which one would give better quality factor and less losses. During simulation work for larger dimensions in FEKO® we faced lot of problems like core dumping, requirement of large computational and memory space in computer.

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List of acronyms and abbreviations

AC……...Anechoic Chamber

Ag……...Silver

Al……. Aluminium

Cu……Copper

DUT ……..…Device Under Test

EFIE ……. Electric Field Integral Equations

EHF…….……...Extremely High Frequency

EMC……...Electro Magnetic Compatibility

EMI ……Electromagnetic Interference

EM wave ……. Electromagnetic wave

EUT…… ……..Equipment Under Test

Fe……...Iron

MLFMM……...Multilevel Fast Multipole Method

mm ……millimetre

MoM …….....……. Method of Moments

OATS……Open Area Test Sites

PEC ……Perfect Electric Conductor

RAM…… Rando Access Memory

RC ……Reverberation chamber

RF…….Radio Frequency

RX……..…Receiving

TEM……..Transverse Electromagnetic

TX…….…..Transmitting

UHF……..…Ultra High Frequency

VIRC……...Vibrating Intrinsic Reverberation Chamber

1. Introduction

1.1 Technology Area and Applications

Frequency spectrum is a very valuable resource in cellular networks where the availability of spectrum and the frequency of use determine both the coverage and capacity achievable. Traditionally cellular networks use spectrum in the ultra-high frequency (UHF) band, which allows good radio propagation and meets most of the current demand for capacity. However, the demand for capacity is increasing significantly, driven in part by the popularity of smart phones but also by the increase in wireless video content [1] [2] and the likely increase in interaction between different devices. To meet the future demand for capacity, a change in how spectrum is utilised needs to be considered. One possible solution is the use of millimetre (mm) wavelengths for cellular networks.

Millimetre wavelengths are defined as electromagnetic spectrum with wavelengths from 1 to 10 mm or 30 to 300 GHz – this is also known as the EHF (extremely high frequency) band. Current cellular networks use frequencies in the UHF (ultra-high frequency) band (300 MHz to 3 GHz). Fifth-generation wireless (5G) systems mm wave is getting ready to be used. As a consequence, there is a lot of cellular and electronics devices used in electronic vehicles and other equipment that are being tested.

The testing of devices for the keeping up with the regulations can be done in RCs. RCs are becoming popular as an alternative to Transverse Electromagnetic (TEM) cells, Anechoic Chamber, Open Area Test sites to test for both electromagnetic and electromagnetic compatibility measurements such as, radiated emissions and immunity, shielding characterization of connectors, antenna measurements, characterization of material properties, etc. [3] [4] [5]

In this modern age, there is concern about the biological impact on human beings and the deleterious effects Electromagnetic Interferences (EMI) poses for electronic equipment. As a result, international and governmental bodies have established standards regarding electromagnetic emissions, immunity, and testing procedures [6] [7]. Testing for devices/systems' compliance with these international standards has led to the development of various test facilities as mentioned earlier, specifically designed to carry out the various tests for EMC (electromagnetic compatibility). [8, 9] Recently, a new testing technique for RFI/EMI immunity has drawn increasing attention—*i.e.*, testing using RCs. [8]

RC's have more repeatability and reproducibility than TEM cells and Open Area Test Sites (OATS) [5]. The replication of real world EM field makes RC better than other tests. Construction of it is also easy and cheap. [5]

In fact, use of a reverberation chamber has become far more common, especially in the aerospace, automotive, and defence industries in the U.S. and Europe.

1.2 What is RC

The chamber is essentially a metallic room with an arbitrarily shaped metallic rotating reflector, called stirrer or tuner [7]. This rotating reflector (stirrer) creates continuously changing boundary conditions of the EM fields inside the chamber. This creates a statistically uniform field distribution with random polarization making them efficient EM radiators. This create a real EM field environment similar to the field electronic devices experience when in operation. In this environment the electronic devices radiate a lot of spurious frequencies which interfere with other electronic devices. Hence it becomes necessary to reduce the radiation from these components themselves. This can be accomplished during the design phase by using 3D EM numerical tools. However, a more reliable, repeatable, quick and cost-effective test procedure is required to validate these designs. This can be accomplished using an RC. The study of RCs is growing in popularity for EMC research and development as well as in the testing community [10].

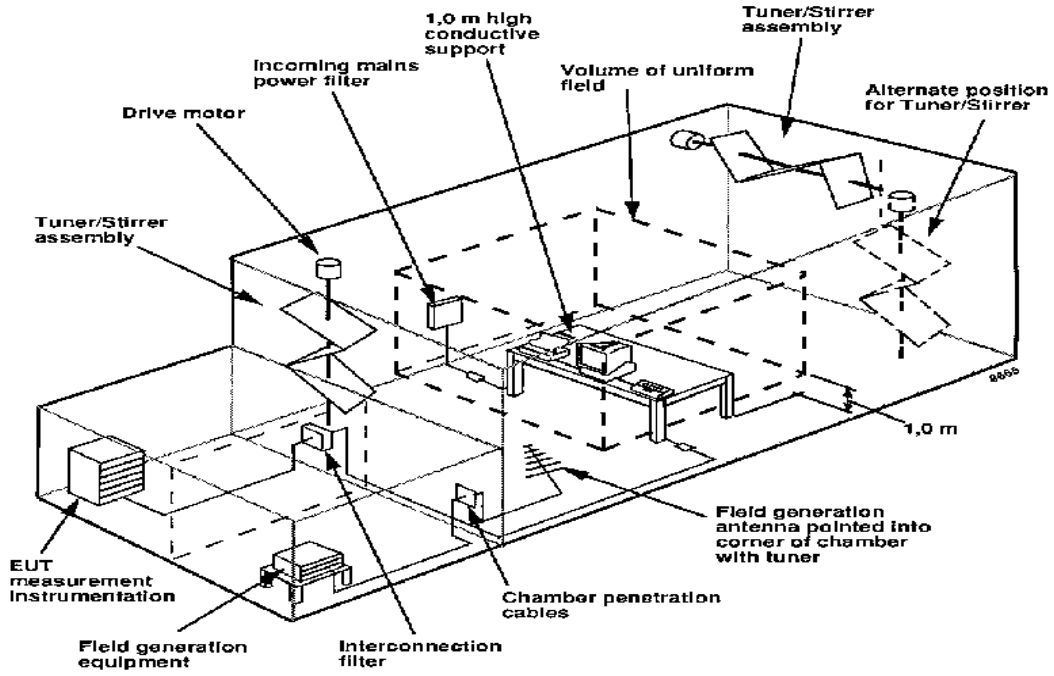


Figure 1.1 A typical reverberation chamber facility [7]

1.3 Thesis Goals and Outlines

This thesis work is a result of the mutual interest of Halmstad University and Ericsson AB in the development of RC suited for EM applications especially for testing of wireless devices in the frequency range up to about 40 GHz and beyond. The International Electrotechnical commission (IEC) specification 61000-4-21 Electromagnetic Compatibility (EMC) - part 4-21:

Testing and measurement techniques - RC test method is applicable. This standard clearly specifies the procedures to follow in RC construction and during its working [7].

The advancement in the field of mobile networks have forced, the usage of millimeter range wavelengths. At these frequencies, the electromagnetic (EM) wave propagation mechanism must be considered. So far, there has been only few studies, done on the effects, millimetre range of frequencies have on Electronic devices and the 5G networks. The primary aim of this study was to evaluate Reverberation Chambers (RCs) suited for frequencies above 40 GHz. Along with studying the effect of 40 GHz, the frequencies for 5G and its harmonic frequencies will also be tested like 60 GHz (covering 2x RF for 28 GHz) and then up to 80 GHz (2x RF for 39 GHz). But we managed to simulate 5 GHz to 15 GHz frequency range by decreasing the volume of RC. Frequencies above 20 GHz were done in cluster computer.

The outline of the thesis is as follows: at the beginning the theoretical background and foundation of RCs are introduced. Important parameters that should be considered for the design, construction, and operation of an RC are discussed. Starting with an abstraction of an RC having ideal rectangular cavity, the concept of modes, the field distribution, the number of modes, and the mode density are explained. As the focus is moved from an ideal cavity towards a realistic RC, the lowest usable frequency, the quality factor, and statistical field distributions like the spatial uniformity, polarization, isotropic behaviour are addressed.

In the next section the reasons that lead to the study of this RC is discussed. the requirements and specifications are outlined in detail. Basic information about the simulation tool and the computational requirements are addressed.

The simulation of a model of RC with a basic cavity, which is box of the specified size of $1200\,mm \times 800mm \times 1500mm$ that is almost impossible to simulate 5 GHz and above because of the volume. Then we minimize the volume one fourth of aimed RC that is $300\,mm \times 200mm \times 375mm$. The cavity is simulated to find the ideal effect of EM field inside the box to verify it with the change in the fields inside when components and materials are changed. In the initial stages Perfect Electric Conductor (PEC) is used as the material. PEC is a theoretical material with infinite conductivity used in the simulation tool. Different cavity materials were tried out, the shape, size, frequency, positions of stirrer are varied.

At the end of the thesis, aspects which were not addressed are outlined. The problems faced and suggestions on how to proceed further with these issues in the future are proposed.

2. Theory of Reverberation Chamber

2.1 Electromagnetic fields in a reverberation chamber

The RC in fully functional mode is a metallic shield room of finite conductivity with a device to stir the EM field inside. To understand the working principle better, RC is abstracted to an empty, rectangular cavity resonator with perfect electric conducting walls (PEC) at the beginning.

2.1.1 Modes inside an ideal cavity

A cavity resonator can be formed by short circuiting a rectangular waveguide at two sufficiently separated length [11] [12]. When the geometrical dimensions reach a certain length, at a given frequency an EM field within this resonator forms a standing wave pattern. This standing wave pattern can be mathematically described by solving the Maxwell's equations. [13]

The angular frequency ω can be calculated from

$$\frac{\omega}{c} = \frac{2\pi f}{C} = k_{mnp} = \sqrt{(\frac{m\pi}{w})^2 + (\frac{n\pi}{h})^2 + (\frac{p\pi}{l})^2} \quad (2.1)$$

where the dimensions of the cavity are w (width), h (height) and l (length) in *x*-, *y*-, *z*-directions. The indices m, n and p denote the number of half wavelengths in *x*-, *y*-, and *z*-directions. *m*, *n*= 1,2, 3… and p = 0,1, 2... and c is the speed of the wave given by:

$$c = \frac{c_0}{\sqrt{\varepsilon_r \mu_r}} \quad (2.2)$$

where,

c_0 = speed of light.

ε_r = relative permittivity

μ_r = relative permeability

In an ideal cavity (PEC walls) fig.2.1 the cut – off frequencies for the individual modes are described by

$$f_{mnp} = \frac{c}{2\pi} = \sqrt{(\frac{m\pi}{w})^2 + (\frac{n\pi}{h})^2 + (\frac{p\pi}{l})^2} \quad (2.3)$$

Depending on the actual dimensions of a cavity resonator the modes with the lowest cut off-frequencies are therefore either the TM_{110}, the TE_{011}, or TE_{101}. The total number of modes above cut off at a certain frequency f_{mnp} can be calculated by counting all (m, n, p)-tuples until $f = f_{mnp}$ is reached, whereby always at least two of the three indices are not equal to zero [13]. It is important to note that there can be several modes having the same cut off frequency– this is true for e.g. all $TE_{mnp}$and TM_{mnp}cavity modes with m≥1, n≥1,p≥1. If several modes exhibit the same cutoff frequency they are called "degenerate modes". [13]

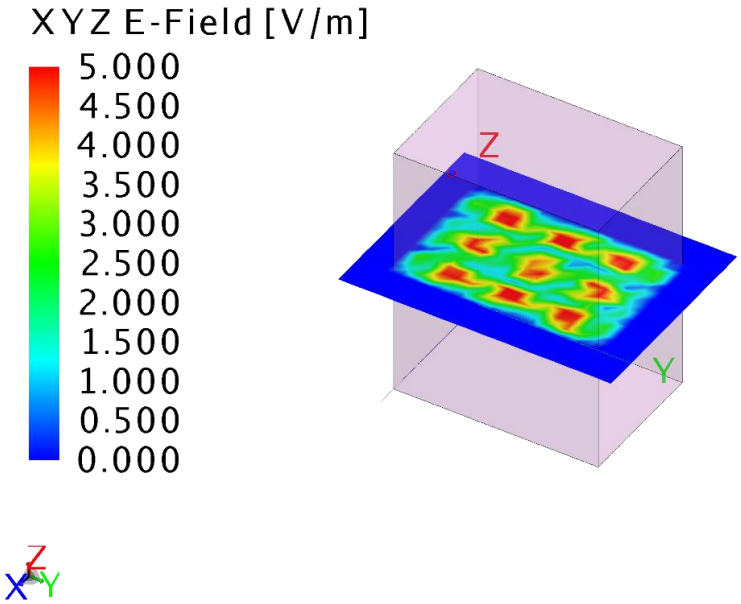


Figure 2.1: Standing waves pattern inside RC cavity

The total number of modes inside a cavity can be calculated by using equation 2.4.

$$N = a_x a_y a_z \frac{8 * \pi * f^3}{3 * c^3} - (a_x + a_y + a_z)\frac{f}{c} + \frac{1}{2} \qquad (2.4)$$

Where *ax*, *ay* and *az* are physical dimensions, f is the lowest usable frequency, and *N* is the number of modes above the cut-off frequency.

As in fig 2.1 the modes inside the cavity can be clearly seen at a plane. The EM waves form standing waves pattern depending on the dimensions and the frequency of wave.

2.1.2 Modes Inside a Lossy Cavity

For an ideal, lossless cavity resonator the mode spectrum is discrete – i.e. a resonance only occurs at a certain frequency f_o [12]. From a certain frequency onwards, several modes can be excited at a particular frequency, since their respective modal bandwidths start to overlap [12] [13]. Depending on the Q factor (section 2.2.2), more or less modes are excited at the same time at a given frequency, making the mono – mode regime to multi - mode regime.

2.1.3 Field Distribution Inside a Reverberation Chamber

The metal walls with a high Q factor allows large fields to be build up inside the chamber. This is the most significant quality of an RC, to create high EM field strength. To make a real EM environment the EM field should be

- Spatially uniform: the energy density in the chamber is the same everywhere

- Randomly polarized: the phase and thus polarization, between all the waves, is randomly distributed.
- Isotropic: the energy flow in all directions is the same. [7] [14] [15] [16]

2.2 Lowest Usable Frequency

The Lowest Usable frequency (LUF) is generally defined as the frequency at which the chamber meets operational requirements [7]. There are several definitions for LUF:

- The LUF equals three times the cut off frequency (fc) of the fundamental mode of a cavity with the same dimensions as the RC under investigation, i.e. $f_{LUF} = 3fc$ [7]
- f_{LUF} is defined as the frequency at which 60 ...100 modes within an ideal cavity of the same size as the RC are above cut off. [7]
- The LUF is also described as the lowest frequency at which a specified field uniformity can be achieved over a volume which is defined by an eight-location calibration data. [7]

2.2.1 Quality Factor

Quality factor is the ability of the system to store energy. A high Q factor indicates that an RC has low losses and is therefore very efficient in storing energy. [7] . It also limits the highest frequency that can be used. The Q factor can be calculated from the equation [17] :

$$Q \approx \frac{3}{2}\frac{V}{A\delta}, \tag{2.5}$$

In the eq.2.5 V is the volume of the chamber, A is the area and δ is the skin depth. (section 2.2.2). The chamber Q can be calculated by using and Transmitting (TX) and Receiving (RX) antenna inside the chamber and record the received and transmitted power P_{RX} and P_{TX} [18]

$$Q = \frac{16\,\pi V\, P_{Rx}}{\lambda_3 P_{Tx}} \tag{2.6}$$

The full derivation of Q Factor is explained in appendix B.

2.2.2 Skin depth

Skin depth of the material is an important parameter for the RC chamber, because it determines the quality factor and determines the leakage through the walls. Materials with

minimum skin depth are most ideal for the chamber. In simulation, all the variables are compared to PEC where skin depth is zero.

If the skin depth is larger than the thickness of the wall, EM waves will be leaked out through it. As a result, there will be a loss of strength of the EM field inside the chamber.

$$\text{Skin depth } (\delta) = \sqrt{\frac{\rho}{\pi f_o \mu_0 \mu_r}} \; ; \; \mu_0 = 4\pi * 10^{-7} \tag{2.7}$$

Where μ_o is the permeability of the inner walls, f_o is the frequency and ρ is the density.

2.3 Computation of Electromagnetic Fields

The simulation of a RC requires the calculation of the EM fields and currents which are excited by a source (usually a TX antenna) on and around a scattering structure which include the walls, the stirrers, the TX antenna itself, the RX antenna, and the Device under test (DUT) The resulting fields are defined by Maxwell's equations. These equations are further simplified by assuming that there are no free charges inside the computational volume V [7] [13]. Thus, the space inside is free space.

2.3.1 Computational Requirements

The computational requirements, like the main memory and solution time needed for the simulation of RCs are significant at higher frequencies and at large volume of cavity. It is therefore useful to estimate the up-front memory (RAM) and CPU-time it takes to complete one simulation run, which usually corresponds to one rotational stirrer position.

2.3.1.1 Simulation Memory

The FEKO® implementation of the electric field integral equation (EFIE) and direct solution using the MoM leads to the following memory requirements [13]

- One basis function needs one variable of type "double complex" for storage, i.e,16 Byte
- The surface current distribution on a single metallic triangle is described with three basic functions, provided that all edges of the triangle are connected to other triangle.
- Dielectric structures need twice as many basis functions as metallic triangles
- One or two basic functions are used at the outer parts of a structure where there are triangles only connected on less than three edges to other triangles [19]

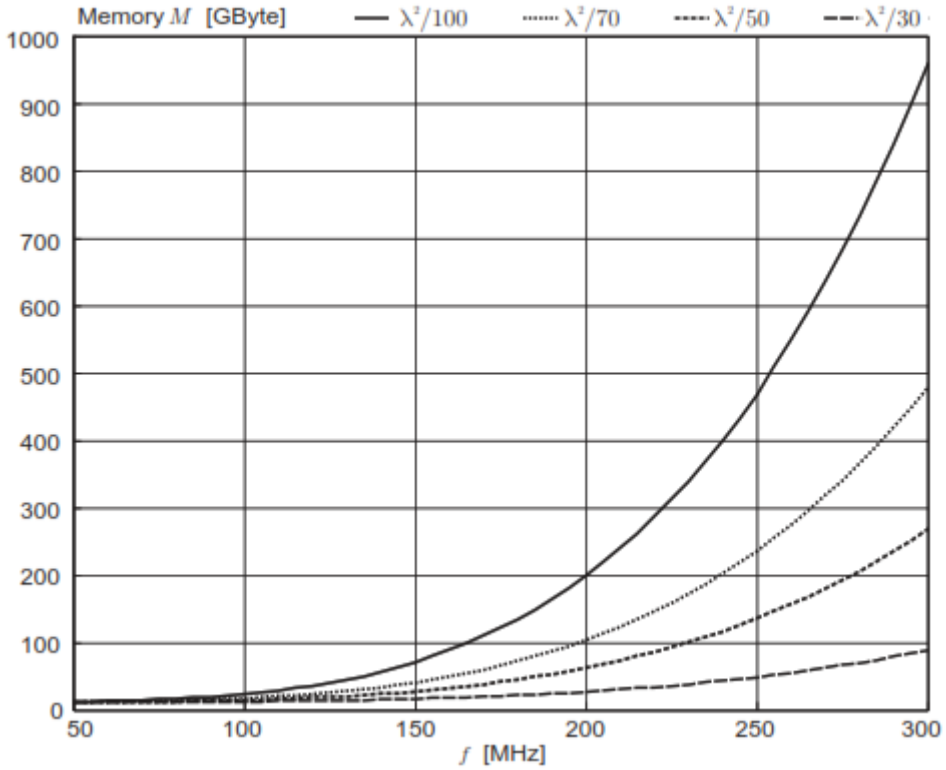


Figure 2.1: Theoretical memory requirements of an RC simulation with A = 50 m^2 of discretized surface and N_S = 870 segments for four different triangular mesh resolution AΔ in the f = 50 … 300 MHz frequency range (fig 3.1 in [13]) A is area, N_S is the number of segments of triangles

2.3.1.2 Simulation Time

For small EM problems, at low frequencies, and depending on the numerical solver, time to setup can take a significant part of the total simulation time t_{tot}. In a high-frequency RC simulation, with a fine discretization however, the time required for solving matrix equation clearly dominates over the setup period. Computation times obtained in actual RC simulations with FEKO are listed in Table 2.1:

Table 2.1 Comparison of runtime and memory requirements of RC simulation for a single frequency and one stirrer position. Simulation were run using the standard FEKO solver without symmetries or approximation methods. [13] pg 51, table 3.1

Frequency f [MHz]	Number of triangles N_T	Memory M [MByte]	CPU runtime t [s (hh:mm)]
100	2934 [a]	310	2299 (00:38)
300	5828 [a]	1195	7630 (02:07)
500	11276 [b]	4563	37161 (10:19) [c]
700	13486 [b]	6481	93679 (26:01) [c]
1000	19112 [b]	12980	655311 (182:02) [c]

[a] in addition to the triangles, for the discretization of the biconical TX/RX antenna 162 segments were used
[b] —— of the logper TX/RX antenna 435 segments were used
[c] for parallel computations the individual per-process run times were summed up

Due to the strong frequency dependence of t_{tot}, the rate at which the CPU runtime increases with growing frequencies is even more dramatic than the increase in required memory. The strong frequency dependence of both computational memory and solution time emphasizes the importance to use as few triangles N_T and segments N_S as possible within the numerical restrictions of the MoM for the discretization. Therefore, to minimize the number of triangles needed to mesh the large RC wall surface, a frequency-adaptive and geometry-dependent discretization was used. Table 2.1 also states the numbers of triangles required at different frequencies and at a fixed stirrer position using a standard MoM approach without symmetries. The drawback of reducing the number of triangles decreases the resolution that is also be noted.

2.3.2 Method of Moments

After contrasting the requirements against advantages and disadvantages of several methods, an EFIE based on MoM technique was chosen, as implemented in the commercial field solver FEKO®. [20]. A 2-D MoM based RC simulation and statistical analysis was described by Laermans and De Zutter in [21]. Computational requirements for simulation time and memory was estimated and was understood that it is expensive to use this method for very high frequencies, or when the ratio of wavelength to the cavity area was high. [13]e.g. 1 GHz require more than 12 GByte of main memory and a significant time.

2.4 Reverberation Chamber Standards

The IEC standard dealing with shielding efficiency measurements of components such as cable assemblies or connectors: IEC 61726 standard [22] gives a detailed description about the stirrer design. This was published in 1999.
IEC 61000-4-21, published in 2003 explains in detail the construction of RC, the simulation and other parameters that's included in its construction [7].

2.5 Stirring Methods

There are several techniques to stir the EM field inside an RC. Any type of stirring that allows the formation of statically uniform and statistically isotropic environment can be used [7]. A basic description about the stirring methods are explained below.
Symmetries in the design and placement of the stirrer should be avoided, to maximize the maximum number of independent positions that it can generate [7].

2.5.1 Mechanical Stirrer

The EM field distribution in an RC is usually accomplished using a mechanical stirrer. Even though the stirrer is unavoidable it is undesirable for two reasons [13] : First reason is that the presence of the stirrer reduces the active region available for testing of the EUT [7]. The second reason is that the stirrer (or tuner) represents a somehow disturbing mechanical element in this otherwise purely electrical testing environment. The feed-through bearing for the stirrer axle is difficult to shield properly, care must be taken not to move the stirrer manually since otherwise the precision gear may be damaged, and rotating the stirrer from one position to another is time-consuming (acceleration, deceleration, decay of stirrer oscillations) [13].

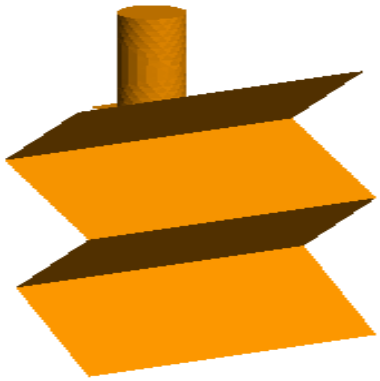


Figure a: Asymmetric Z-shaped stirrer

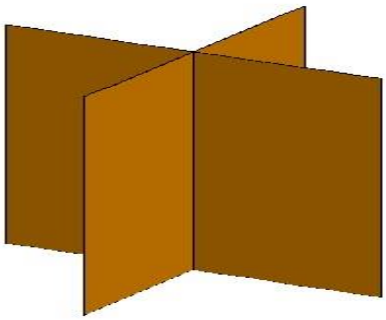


Figure b: Symmetric Stirrer

Figure 2.3: 3D view of a) Asymmetric Z-shaped Stirrer b) Symmetric Stirrer

2.5.2 Moving Walls

An efficient way to mechanically stir the EM field in an RC is to change the field distribution by moving the walls. A lot of study on this approach was done by F. Leferink [23] [24]. The "Vibrating Intrinsic Reverberation Chamber (VIRC)" is essentially a "tent" which is made of electromagnetically conducting cloth. Small motors with eccentric drive fixtures wobble the cloth sufficiently so that the field is changed and a certain field uniformity is achieved within the "tent". This approach does not get rid of mechanical problems completely, but it removes the stirrer from the RC's interior. It was successfully applied to build up "mobile" RCs in order to test equipment which is e.g. too large to be moved. There are however problems with achieving sufficient radio frequency (RF) SE through electromagnetically conducting cloth. [24]

2.5.3 Electronic Stirring

Methods of field stirring without any mechanical stirring devices within an RC are commonly referred to as "electronic stirring". One limiting factor of electronic stirring is that until now it is only applicable – if at all – to immunity testing of Equipment Under Test (EUT) in RCs [13]. The major problem arising for these methods in emission measurements is that one has no control over the emitted spectrum of a test object. This renders it very difficult to ensure proper interaction between the electronic stirring equipment and the EUT. Furthermore, since changes of the EM field distribution occur virtually instantly (compared to the very slow changes using mechanical stirrers), the response time of an EUT in immunity testing must be known [6]. In addition, the advantage of eliminating (rather cheap) mechanical stirrers by electronic means comes at a considerable price: expensive RF equipment, such as additional antennas, power combiners, mixers, frequency modulators, up/down converters, etc. needs to be used.

2.6 Materials Used for The Chamber

The main materials used for construction of RCs are usually galvanized steel, aluminium, and copper, see table 2.2. The material conductance is a very important factor in the RC chamber because the conductance determines the skin depth. If the skin depth is more than the material thickness, it leads to leakage and interfere with the calculation. (sec. 2.2.2)

Table 2.2: Typical electric conductivity values for material used in EMC application

Material	Conductivity κ $[10^6\,\mathrm{S/m}]$	Conductivity $\kappa/\kappa_{\mathrm{Ag}}$ (relative [c])
Silver (Ag) [a]	61	1
Copper (Cu) [a]	58	0.95
Aluminum (Al) [a]	37	0.61
Aluminum [b]	27	0.44
Zinc (Zn) [a]	16	0.26
Zinc [b]	12	0.20
Iron [b]	8	0.13
Galvanized steel (GS) [b]	3	0.049
Stainless steel [b]	1	0.016

[a] pure material at T = 300 K [25]
[b] commercially available material at T = *300* K [25]
[c] normalised to the conductivity of pure silver

2.7 A Basic Comparison Between RC and AC

Table 2.3: Basic difference between the AC and RC EMC test environment (partly extracted from [26]).

	Anechoic Chamber (AC)	Reverberation Chamber (RC)
Mechanical Setup	-Shielded room -Absorbers -TX/RX Antenna	-Shielded Room -Stirrers -TX/RX Antennas
Type of field	Plane wave/Single path	Multi-mode/ Multi path
Polarization	Linear, fixed	Arbitrary, not known
E, H phase relation	Fixed	Not Fixed
Direction of incidence	Known, fixed	All directions, “isotropic”
Field impedance	377Ω	Unknown
EUT radiation pattern	Assumptions: -” well- behaved” -” dipole-like”	No assumptions made
Emission testing	-extensive scanning needed to get peak -one direction at a time	- “isotropic approach” -omnidirectional testing
Production line testing	Slow, impossible	Fast, automated

3. Experiment and Results

3.1 Modelling procedure

The basic model of the RC chamber was designed in CAD FEKO. It was basically a cavity resonator without the antenna or the doors. For convince Aluminium was chosen as the material for the walls. To avoid losses due to leakage the thickness of the walls was made thicker than the skin depth. (table 3.1)

The lowest usable frequency for the chamber calculated by the equation 2.4 with the number of modes of 60 and 100 was 2.04 GHz and 2.43 GHz, respectively.

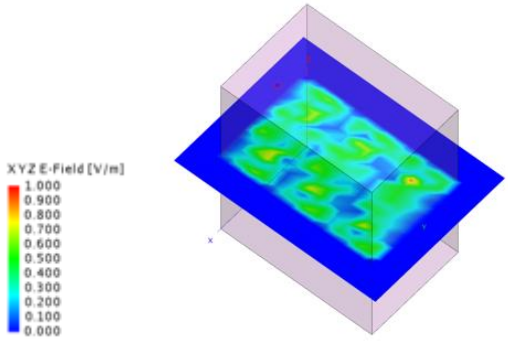
3.2 Design of the cavity

The initial aim was to design an RC with the dimension 800 X 1200 X 1500 mm and working at frequency above 40 GHz, but because of the time and computational constrain (section 2.3.1), the chamber was scaled down in size by 4 to get a chamber of size 200 X 300 X 375 mm.

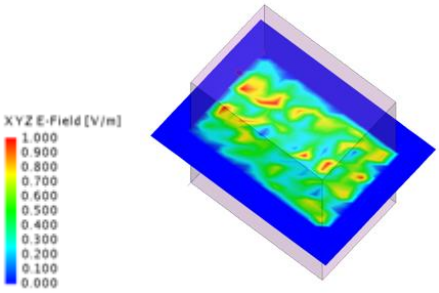
The chamber was modelled in CAD FEKO with aluminium as the material used for the walls. Thickness of the wall was taken to be 20 mm. The thickness was considered precisely since the penetration skin depth varied from 7.117 μm at 5 GHz to 4.11 μm at 15 GHz. The values for skin depth and conductivity are shown in the file of FEKO simulation software. The cavity considered a free space in order to make the computation simple. Since the simulation for 40 GHz was not feasible with the available computational power, it was simulated by the FEKO Europe Support Centre.

The effect of change in frequency on the EM field inside the chamber was studied by considering a simple RC model without the stirrer, doors and other geometrical details – i.e. a cavity. The cavity was studied so that the simulation results can be used as a comparison for the change in EM fields inside the cavity when different components are added.

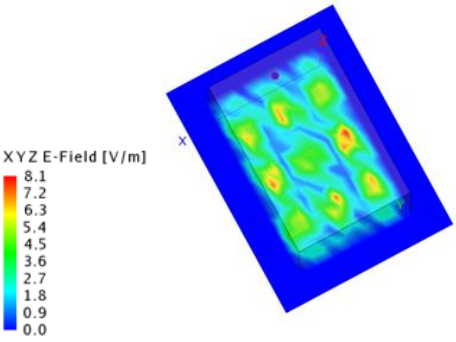
In figure 3.1, by changing the frequency, the EM field distribution inside the chamber also changes. The number of modes increase with increasing frequency. For that, different scales are chosen to show clearly the number of modes inside the cavity. It's difficult to understand if kept the scale constant. From equation 2.4 it can be seen that as the frequency increase the distribution of the EM field inside the cavity is more spread and becomes closer to an RC environment even without the use of a stirrer. From having a look at figure 3.1 (d) for frequency 40 GHz it can be seen from that the field is distributed equally even without using a stirrer and a large number of modes are also created.



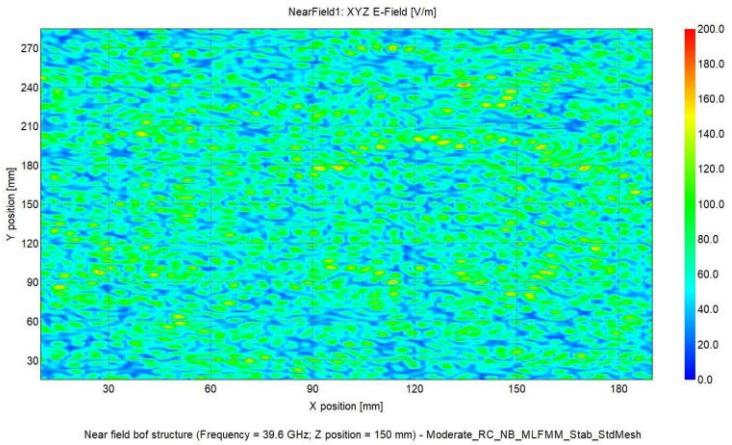
a) 5 GHz



b) 10 GHz



c) 15 GHz



d) 40 GHz

Figure 3.1: Change in the EM field with different frequencies a) 5GHz b) 10 GHz c) 15 GHz d) 40 GHz [27] in an Al cavity chamber.

3.3 Symmetric Stirrer positions

To study the effect of symmetric stirrer in the reverberation chamber a simple stirrer (figure 2.5, b) was modelled in CAD FEKO (figure 3.2). It was placed at an arbitrary position along the plane of incidents of the EM field from the dipole antenna [7]. According to IEC 61000-4-21 measurements must be taken for at least 12 different angles of rotation. [7] .

In this study 5 GHz frequency was considered because of the computational limitations. Aluminium was chosen as the material for the walls of the cavity. The rotation of the stirrer disturbs the field and for every angle of rotation a different RC field is created. When the stirrer is symmetric the field inside the chamber is also symmetric. In figure 3.2, the E field for different positions in X and Z axis is plotted. It can be seen that E field is symmetric for X axis at 100 mm for different Z positions. The E field shows clear symmetry when measured away from the walls. Towards the walls the field reduces to 0 according to the properties of the material.

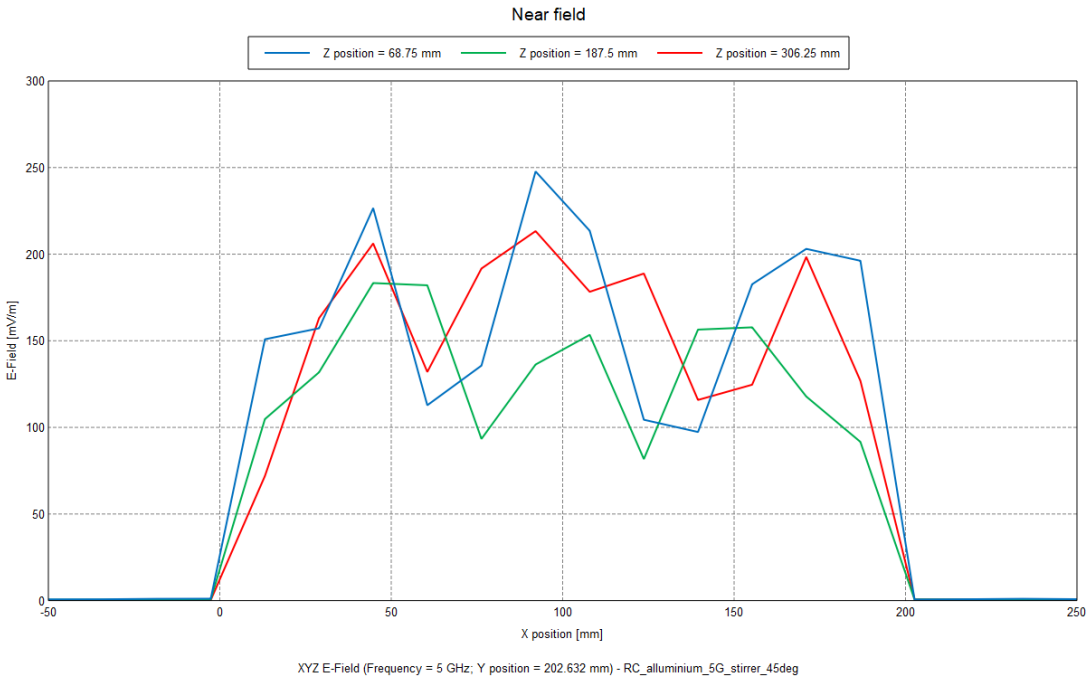


Figure 3.2: Graph showing the E field for different x and z positions. Here the field is symmetric in the x axis at x= 100 mm

In figure 3.3, the positions of stirrer are changed at 0-degree, 25-degree, 45-degree, 65-degree and 90-degree. And simulate E-fields in each specified degree. As a result, generated E-field is same for 0-degree and 90-degree because of the symmetric effect. That's why, asymmetric stirrer is preferable in RC [7].

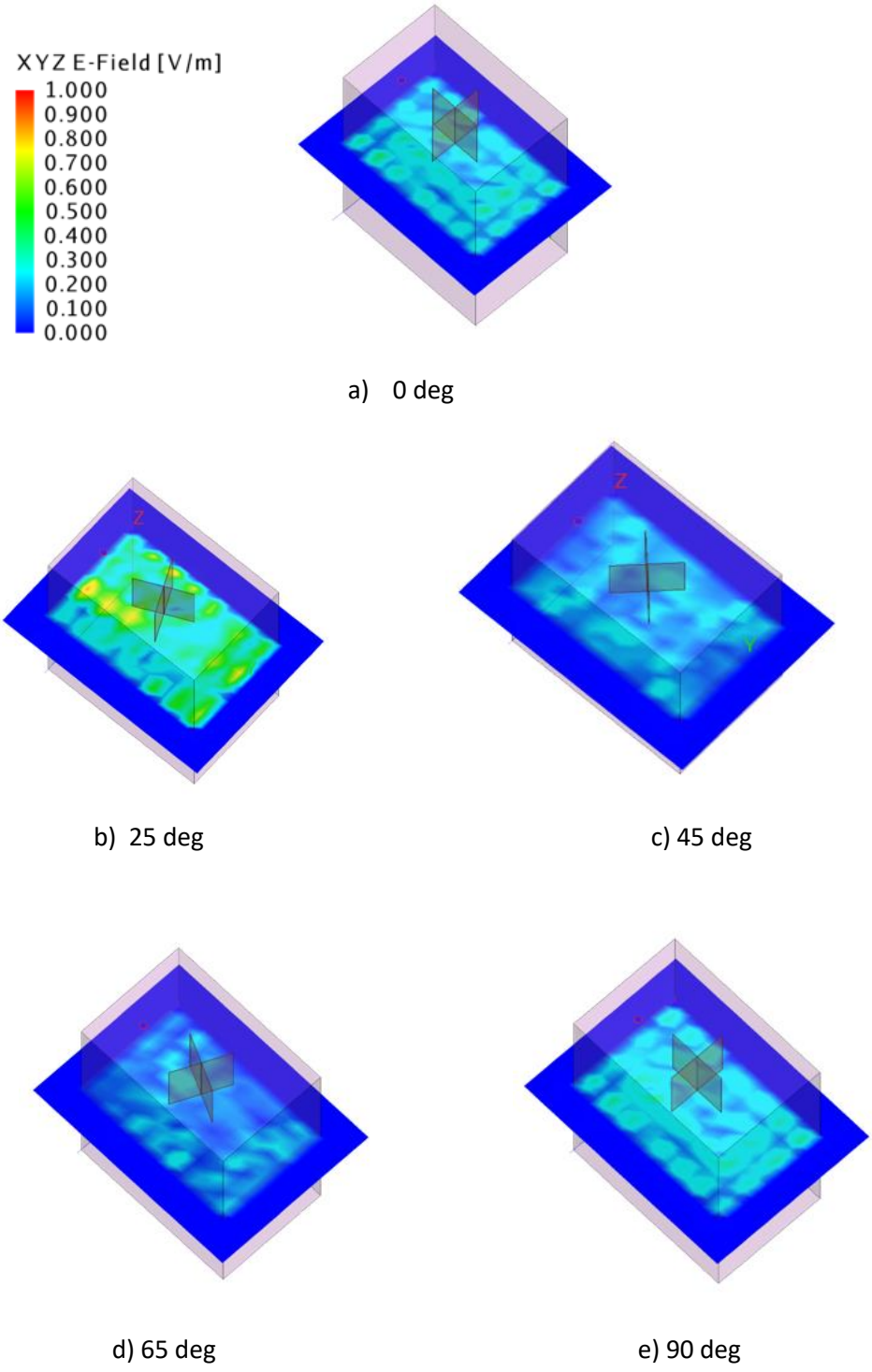


Figure 3.3: The EM field distribution in the XY plane for Z = 187 mm for stirrer at a) 0-degree b) 25-degree c) 45-degree d) 75-degree e) 90-degree

3.4 Material change

The ca $300\,mm \times 200mm \times 375mm$) was constructed with different materials like Al, Cu, Ag, and PEC with conductivity, skin depth and impedance collected from the FEKO out file. It can be seen that when the conductance increases the skin depth decreases (2.2.1 Quality Factor, 2.2.2 Skin depth). This is the reason that the materials with high conductivity are selected to construct a RC.

Reasonable conductivity values for the RC walls and stirrers (listed in Table 3.1) were obtained from initial simulations considering a simple RC model without stirrers, doors or other geometrical details – i.e. a cavity.

From Eq. 2.5 we can calculate the Q factor of the cavity and is displayed in figure 3.4. It's clear that the Q factor increases with higher conductivity of the material.

Table 3.1: Relation between Electrical conductivity and skin depth for different frequencies

Material	**Freq (GHz)**	**Conductivity (S/m)**	**Skin Depth (μm)**	**Surface Impedance (ohm)**
PEC	5	PERFECT CONDUCTOR		
Copper	5	5.813E+07	0.93354	1.843E-02 +j 1.843E-02
Aluminium	5	1.000E+06	7.11763	1.405E-01 +j 1.405E-01
Silver	5	6.173E+07	0.905914	1.788E-02 +j 1.788E-02

CM : Custom material

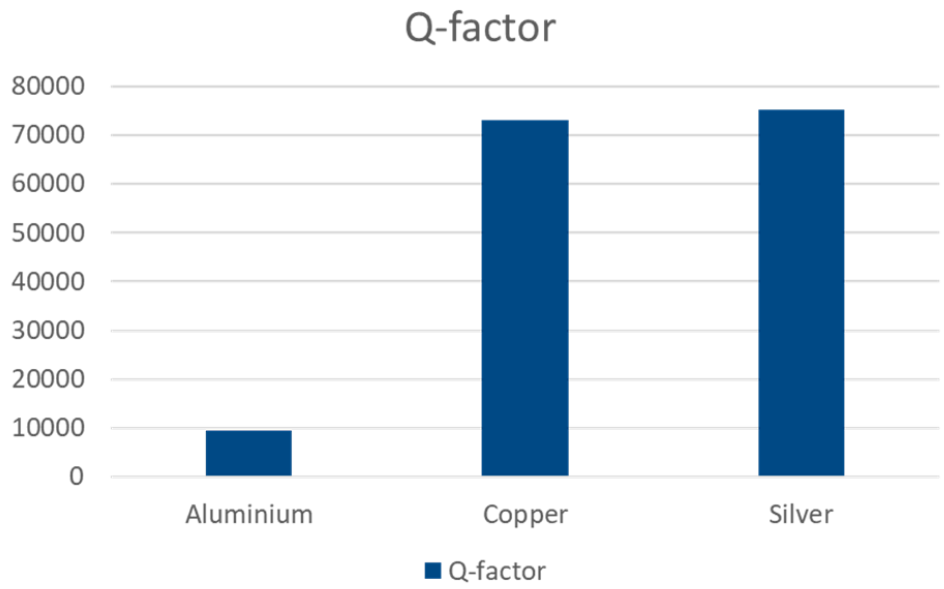


Figure 3.4: Graph showing the Q factor for different material at 5 GHz

3.5 Change in Frequency

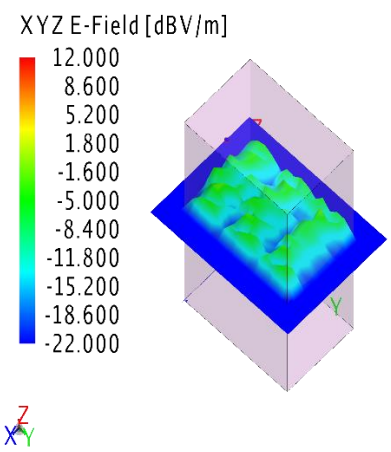
The EM field simulated into two different frequency band. These were SHF (Super High Frequency) band and EHF (Extreme High Frequency) band. Usually 3 GHz to 30 GHz for SHF band and 30 GHz to 300 GHz to EHF band have been considered.

The EM fields have simulated at 5 GHz, 10 GHz and 15 GHz from SHF and 40 GHz, 60 GHz and 80 GHz from EHF band. Those simulation have done in FEKO by using MLFMM (Multilevel Fast Multipole Method).

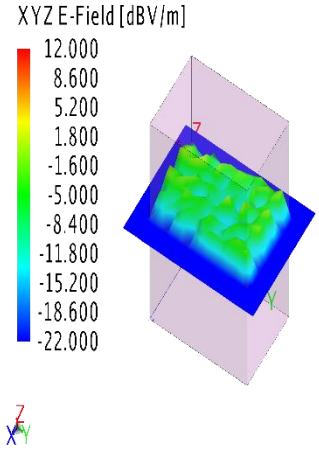
From the figure 3.5, 3.6 and 3.7 the EM field distribution can be seen. In figure 3.5 have extrusion of 20 % to see the fields inside the chamber in 3D. As the frequency increase the average value of EM field intensity will also increase, this trend can be seen for frequencies of 5 GHz, 10 GHz and 15 GHz [13] [18].

But at frequency range from 40 GHz, 60 GHz, and 80 GHz the value EM decreases. This is may be due to the higher path loss for high frequencies [18] [11] along with the constructive and destructive harmonics formed inside the box, but this is an area that's needs a better study.

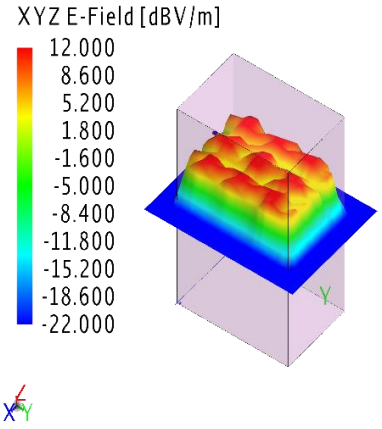
3-D EM simulation inside the chamber at SHF band:



(a) 5 GHz

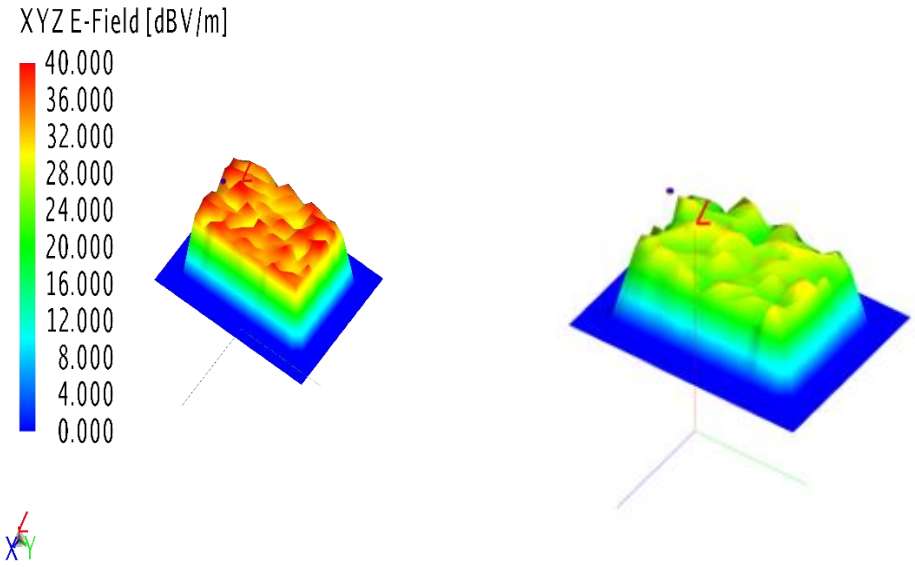


(b) 10 GHz



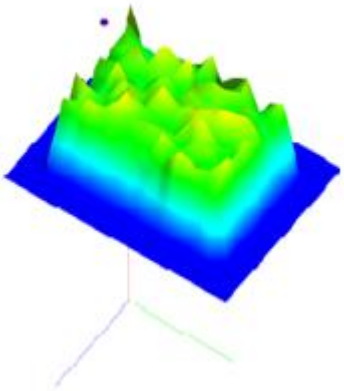
(c) 15 GHz

3-D EM simulation inside the chamber at EHF band:



(d) 40 GHz

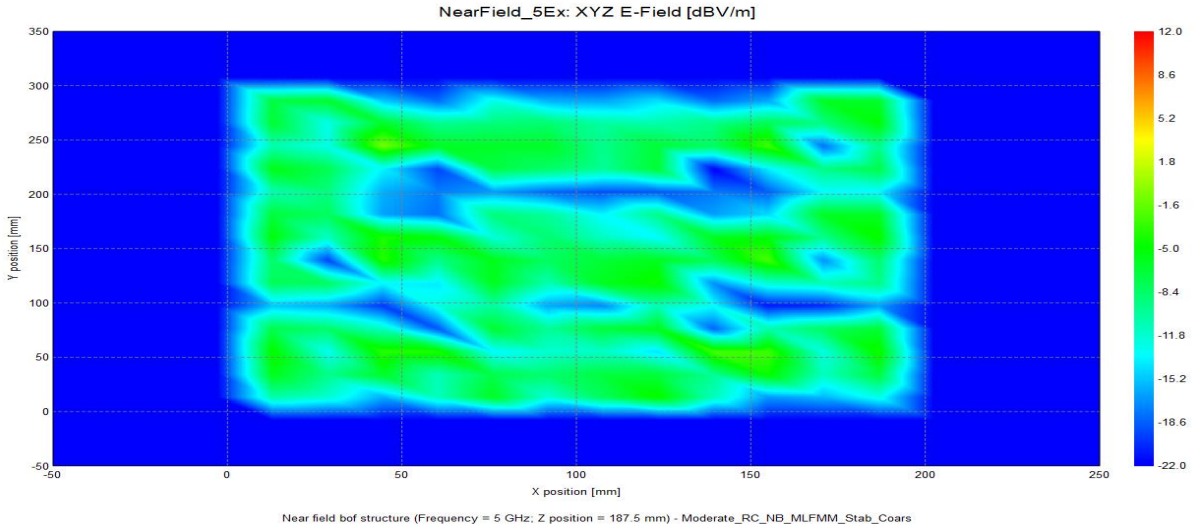
(e) 60 GHz



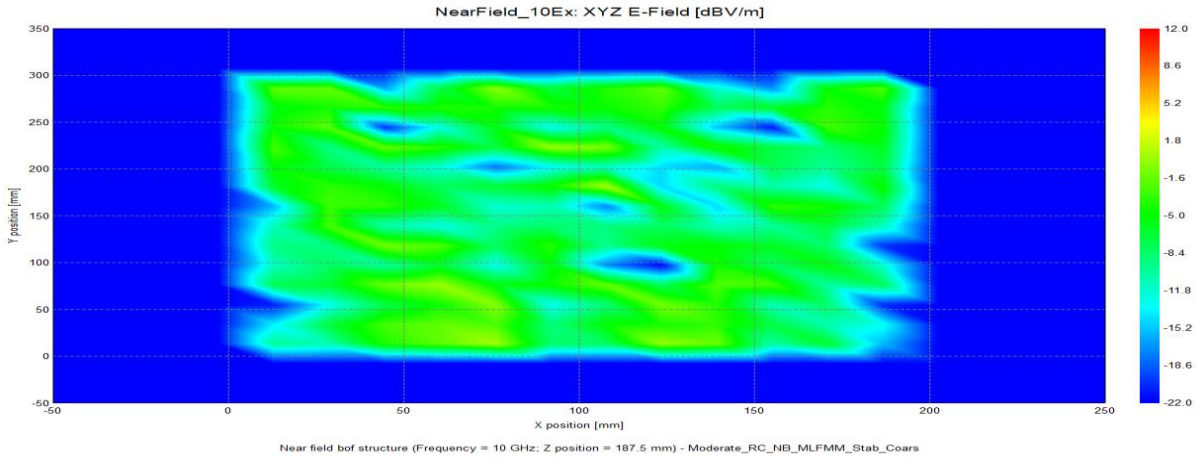
(f) 80 GHz

Figure 3.5: The 3D view of EM field distribution in the XY plane for Z = 187.5 mm for frequency (a) 5 GHz (b) 10 GHz (c) 15 GHz (d) 40 GHz (e) 60 GHz (f) 80 GHz

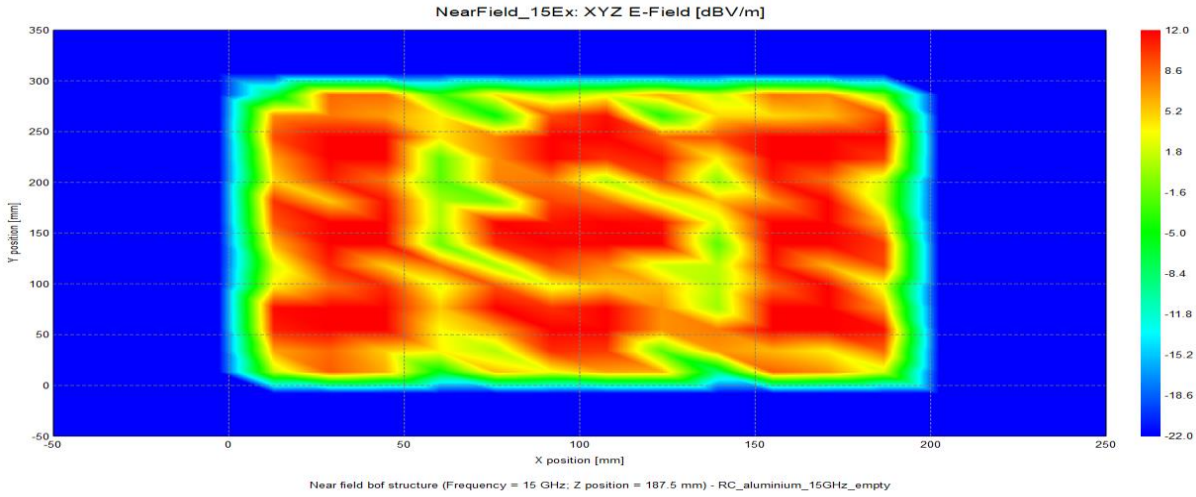
EM simulation on cartesian surface where x and y positions are variable and Z is constant at SHF band:



(a) 5 GHz

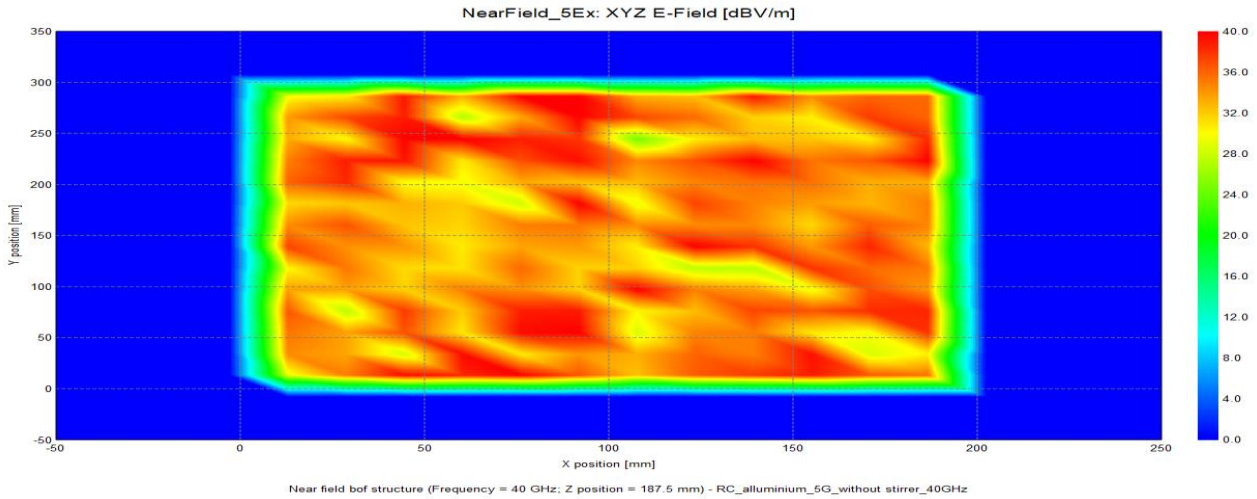


(b) 10 GHz

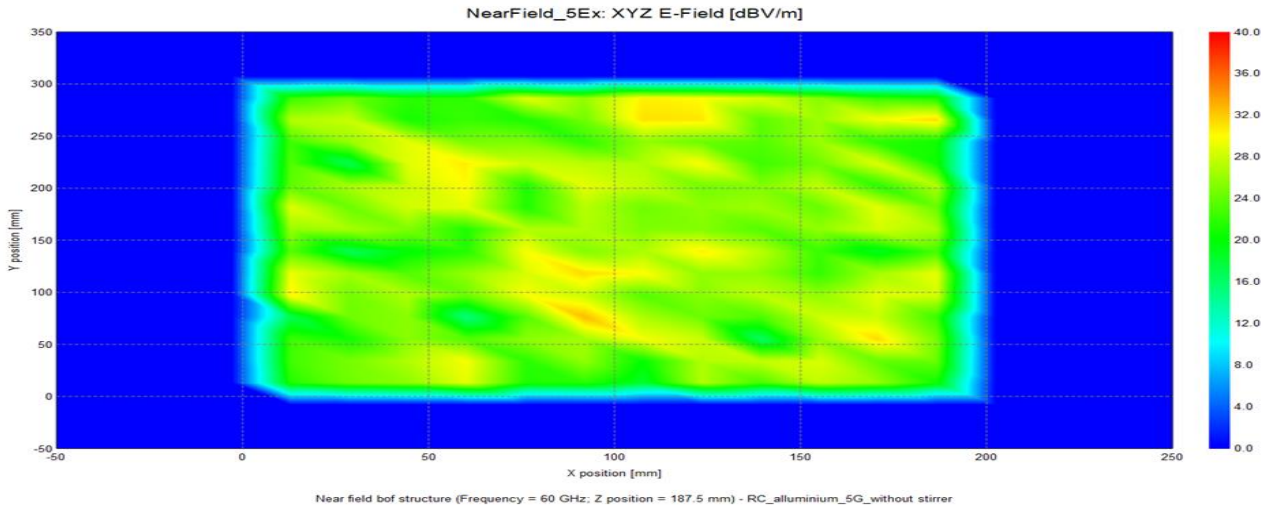


(c) 15 GHz

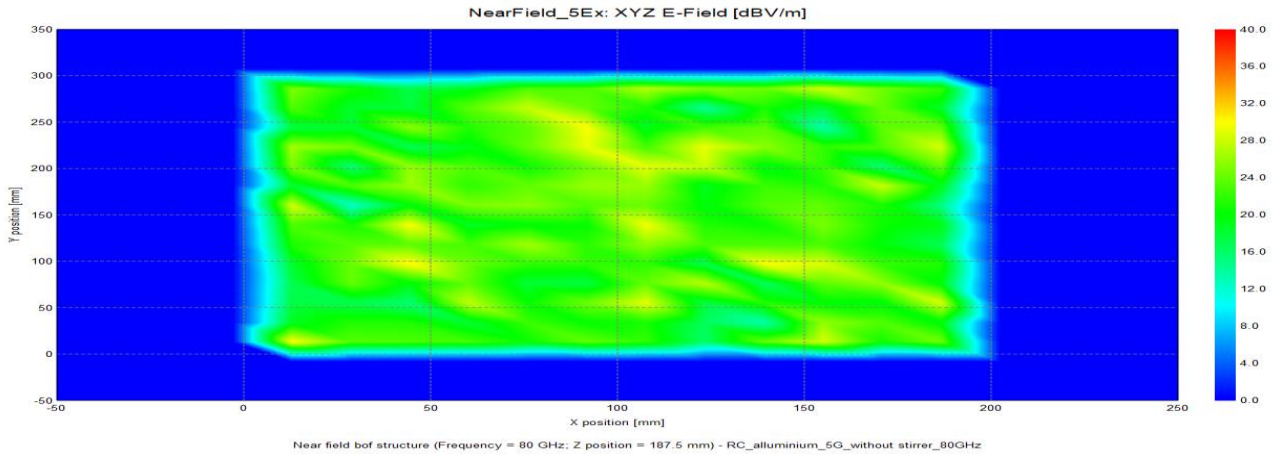
EM simulation on cartesian surface where x and y positions are variable, and Z is constant at EHF band:



(d) 40 GHz



(e) 60 GHz

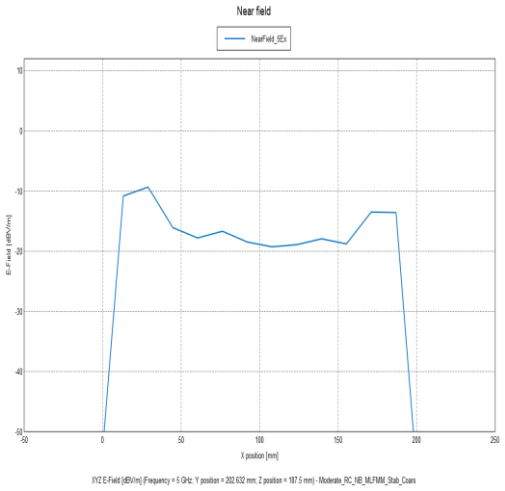


(f) 80 GHz

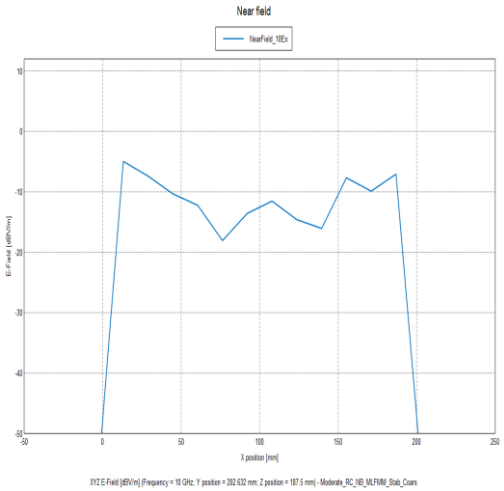
Figure 3.6: Surface EM field distribution for (a) 5 GHz (b) 10 GHz (c) 15 GHz (d) 40 GHz (e) 60 GHz (f) 80 GHz at Z-position=187.5 mm

According to IEC 61000-4-21 [7] the goal of an RC is to create a statically uniform environment for all locations with the defined working volume. In a working RC there should uniformity of the field at an expected magnitude for different stirrer positions and field at different stirrer positions are averaged. But due to time constrain the change in uniformity and magnitude for different frequencies were studied. Field uniformity is about $\pm$10 dB at 100 MHz and decreases as the frequency increases [7]. For frequencies 5 GHz and 10GHz the field changes from -18 dB to -9 dB for 15 GHz it varies from -2 dB to 12 dB. While for frequencies 40 GHz and 60 GHz it varies from 25 dB to 40 dB while for 80 GHz the field varies from 15 dB to 30 dB. From these results we also clearly observed the E field energy is increasing from 5 GHz to 15 GHz. But E field energy significantly decreasing from 40 to 80 GHz due to free space path loss (FSPL).

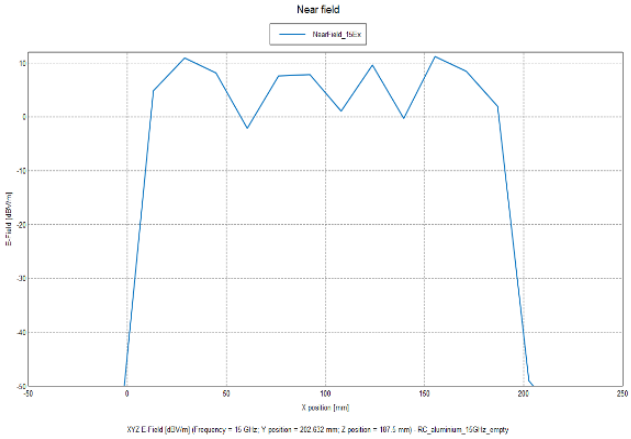
In figure 3.7, cartesian graphs where Z and X positions are constant and Y position is variable at X-axis in SHF band:



(a) 5 GHz

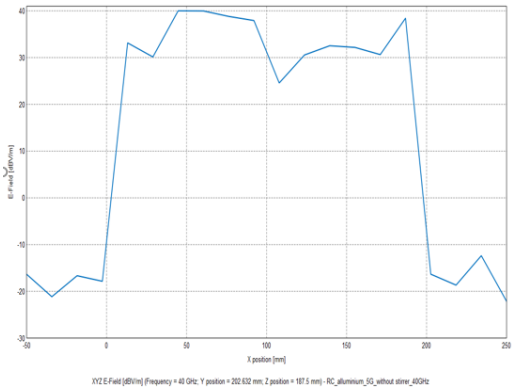


(b) 10 GHz

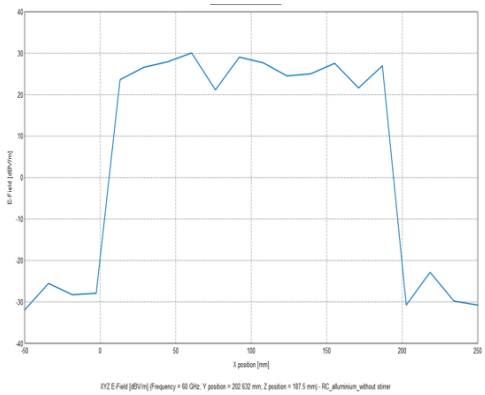


(c) 15 GHz

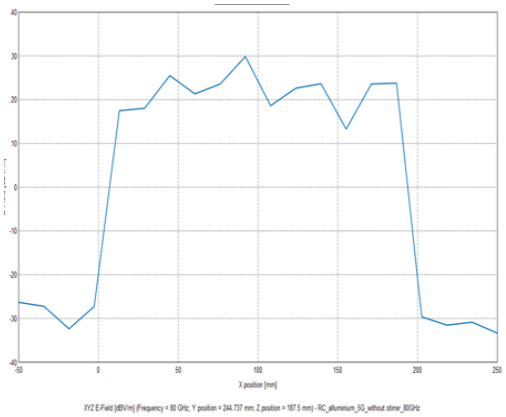
In figure 3.7, cartesian graphs where Z and X positions are constant and Y position is variable at X-axis in EHF band:



(d) 40 GHz



(e) 60 GHz



(g) 80GHz

Figure 3.7: Cartesian graph for frequencies (a) 5 GHz, (b) 10 GHz, (c) 15 GHz (d) 40 GHz (e) 60 GHz, (f) 80 GHz

4.Conclusions

The three-dimensional simulation of a reverberation chamber (RC) was presented in the thesis. In the beginning key parameters of a RC for instance the modes, its effects with increase in frequency, the lowest usable frequency and the quality factor were studied. Furthermore, there is a possibility to study and understand the effects of finite metal conductivity as well as that of high resonant structures. Even though the chamber is large, to form far field approximation the computation is done using the near field at an arbitrary number of chamber locations. To do that, a free chamber was simulated using frequency-domain EFIE-based MoM technique. It was difficult to find previous studies of RC for millimetre range waves. Another striking result of the literature survey was that a thorough simulation validation tends to be neglected in majority of the published materials.

RC was simulated for different frequencies, different stirrer angles, and for different chamber material. The presence of a stirring device shifts the modes in frequency depending on their respective field. Knowing the electromagnetic field at any arbitrary position within the RC and being able to visualize the field distribution is essential for the designers. But the knowledge of the electromagnetic field at a lot of spatial positions within the chamber, computed for many different angular stirrer positions over a broad range of frequencies with a fine frequency resolution is most needed. Taking these into consideration the time required to compute at the high frequencies is longer and is not computationally feasible. At frequencies above the lowest usable frequency, where a high number of modes is above cut off, almost any RC works well regardless of the chamber shape. With increasing frequency, the field within an RC becomes more and more sensitive to even small geometric details, which makes proper modelling numerically not feasible. The simulation at 40 GHz at the early stages of our work was done by the representatives of FEKO at Lund, Sweden on their processors, later we were able to do them on the cluster computer at the Halmstad university. The ratio of chamber volume to EM wavelength is the main factor that affects the computation power.

The EM field intensity distribution is an important factor in a RC chamber. the change in field distribution and its uniformity was studied for different frequencies and stirrer positions.

The subject provides for a detailed study in each stages of development of a RC. Effect of doors, protection from leakage, antenna efficiency, cable interference etc. To increase Q factor a better shape with larger volume to area ration should be studied. In respect of software, developers may focus on designing better solver to simulate EM at ultra-high frequency and greater volume within efficient time.

Appendix A

EM simulation software FEKO

Main components

There are three main components for FEKO®

1. CAD FEKO® :It is used for modelling of the object in 3-D.
2. POST FEKO® : The post processing is done and plots are created using this software.
3. EDIT FEKO® : Advanced commands like FOR Loops, Statements etc are added in this stage.

A flow chart on the steps to be done in FEKO® is shown n figure A3.

Introduction to basics of FEKO® simulation:

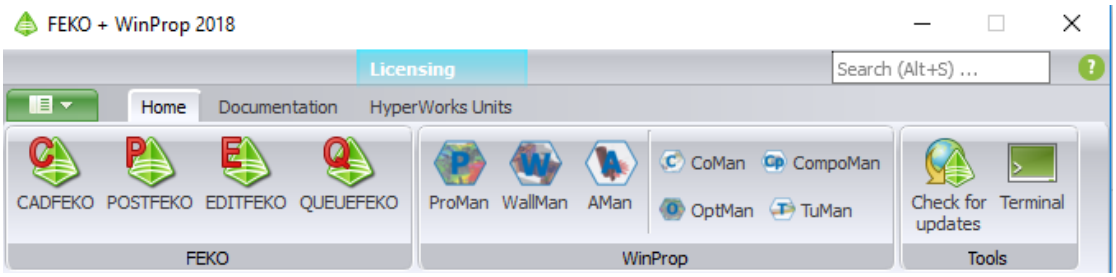


Figure A1: start up window for FEKO

1. Select “create a new model” in the CAD FEKO window.
2. In the window that opens, construct the respective geometry using the tools.

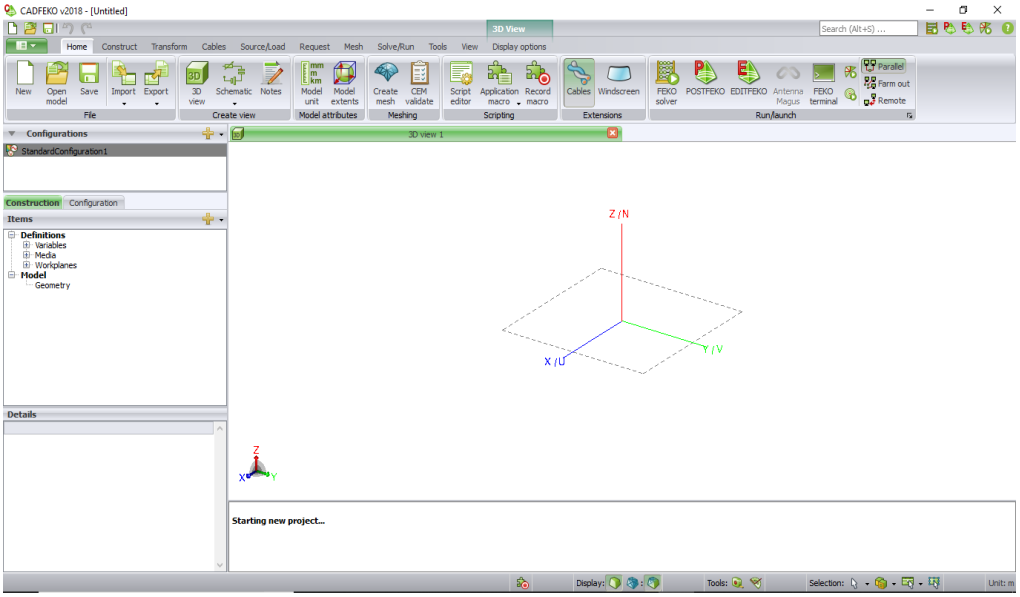


Figure A2: Start up window of CAD FEKO

3. Specify the source and load from the source/load option in tool bar.
4. From the request tool bar choose whether near field or far field solution is needed

5. Mesh the geometry
6. Run Feko solver in the solve/run tool bar
7. Run Post Feko in solve/run tool bar, a new Post Feko window will open up

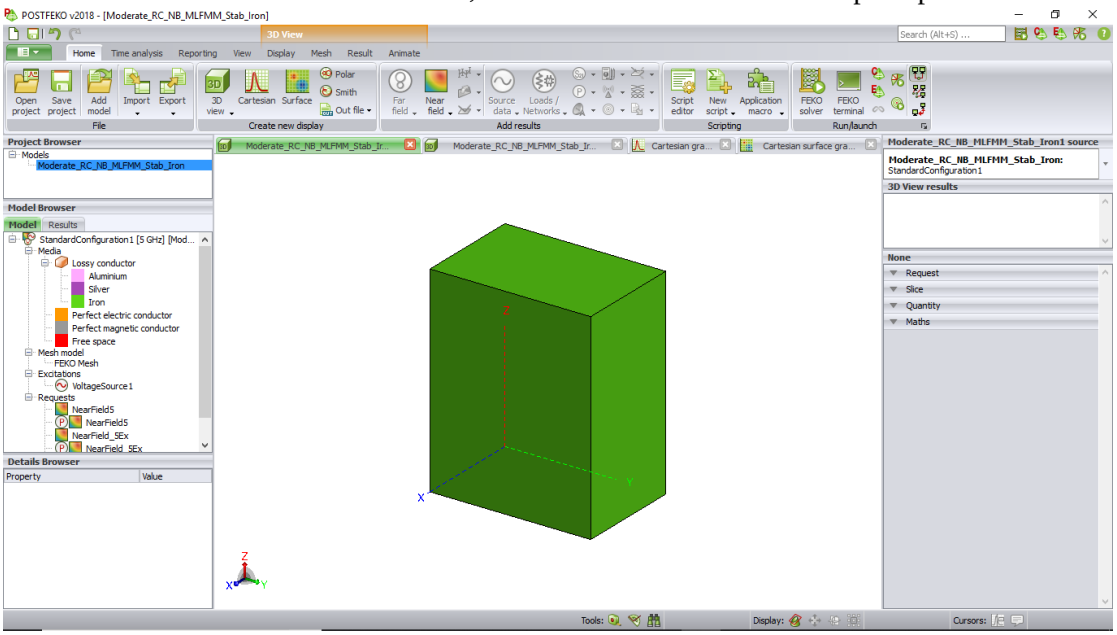


Figure A.3 Post Feko window

8. Choose the respective field (near field/ far field) same as the one selected in Cad Feko
9. Depending upon the interest select the graph and the coordinates.

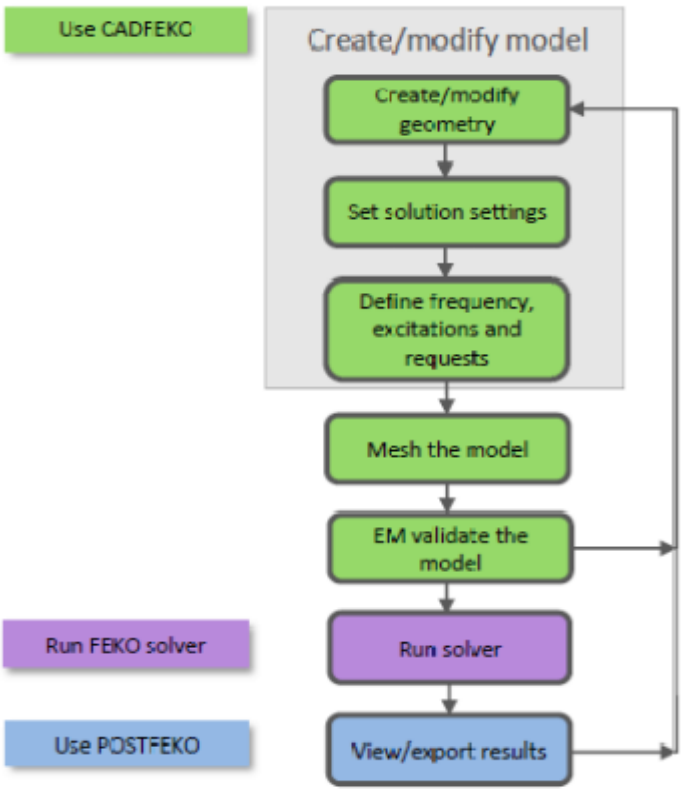


Figure A.4: A basic work flow of FEKO

Parallel solver execution mode

The command runfeko filename -np x --machines file machname calls the pre-processor PreFEKO to generate the simulation model from the file filename and launches 'x' parallel FEKO processes on the machines listed in the file machname. Load distribution and communication between these machines is managed by FEKO

Model geometry validation

To quickly check the geometry for errors such as inhomogeneous discretization, duplicate or degenerated elements, and label cross-referencing, FEKO can be invoked with runfeko...--feko-options --check-only. FEKO. It will check simply the geometry and try to allocate and de-allocate the required memory. However, it will not start to set up and solve the system matrix.

Appendix B

Q factor calculation

When the RC has many mode Q factor can be calculated based on resonant bandwidth:

$$Q = \frac{f_0}{\Delta f_Q} \tag{C.1}$$

f_0 is the resonant frequency and Δf_Q is the modal bandwidth. But this method is difficult and meaningless in practical situations [28].

A better approach is to use the basic definition of Q factor based on the time-averaged stored energy W_S and the energy dissipated during one period W_d within a resonator

$$Q = 2\pi \frac{W_s}{W_d} = \frac{\omega W_s}{P_d} \tag{C.2}$$

With P_d being the dissipated power.

$$W_s = \frac{1}{2}\iiint_v \vec{D}.\vec{E}\, dv = \frac{1}{2}\varepsilon \iiint_V \left|\vec{E}\right|^2 dv \tag{C.3}$$

Using (C.3) in (C.2) and considering that the dissipated power is equal to the net input power P_{in} leads to the equation

$$Q = \frac{\omega\varepsilon}{2P_{in}} \iiint_V \left|\vec{E}\right|^2 dv \tag{C.4}$$

Evaluation of (C.4) in practice requires the knowledge of all individual loss mechanism within RC: wall losses, absorption due to e.g. an EUT, aperture leakage (doors, interconnections between sheet metal panels etc) and losses introduced by the finitely conducting RX and TX antennas [13]. But (C.4) by definition includes all these losses, the simpler formula is

$$Q = \frac{3V}{2\mu_r \delta_S A} \frac{1}{\left[1+\frac{3\lambda}{16}\left(\frac{1}{l}+\frac{1}{w}+\frac{1}{h}\right)\right]} \tag{C.5}$$

Accounting only for ohmic losses in the walls is often used for RC's where V is the chamber volume and A the inner RC surface [13]. δ_s in (C.5) denotes the skin depth of metal (section 2.2.2). The Q – factor estimate of (C.5) can be used as long as the walls are highly conducting and the losses in the RC walls are the dominant absorption mechanism. Expression (C.5) can be further reduced by considering the values of l, w, h and λ (where l w and h are close to 1 while $\lambda < 1$) to

$$Q = \frac{3V}{2\mu_r \delta_S A} \tag{C.6}$$

This is also the Q- factor estimate proposed by the IEC 61000-4-12 standard [7]. But the Q factor calculation by (C.5) and (C.6) is of little practical use, as the Q values are higher than the practical values by a factor of 10 to 500 [13] [18] [28].

In a RC the chamber Q can be calculated by TX and RX antenna inside the chamber by recording the received and transmitted power P_{RX} and P_{TX} [18] by

$$Q = \frac{16\pi^2 V P_{RX}}{\lambda^3 p_{tx}} \quad \text{(C.7)}$$

This Eq (C.7) can be calculated over one full stirrer rotaton to get the mean chamber quality factor.

Appendix C

Processor Requirements to run FEKO

In the beginning the simulation was done in personal computer for geometries like simple cavity with frequency of 5 GHz. For frequencies above 10 GHz the cluster computer was used (table C.1)

Table C.1: Computational features required for simulation of FEKO

Frequency (GHz)	**Number of triangles for simulation**	**Processor**	**Operating @(GHz)**	**Numb er of CPU**	**Number of Processors**	**Memory(GBytes)**	**Time per processor**	**Total Time (adding the parallel times)**
5	284	Intel(R) Core(TM) i5-7200U	2.50	1	4	7.919	0.493 sec	0.986 sec
40	1298406	Intel(R) Xeon(R) CPU E7-8867 v4	2.40	4	144	503.796	2.856	205.643hr
80	5207042	Intel(R) Xeon(R) CPU E7-8867 v4	2.40	4	144	503.796	12.931 hr	930.229 hr

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