



Elias Haanpää

Magnetic Field Analysis with OpenEMS

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Abstract

Author: Elias Haanpää
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The aim of this thesis was to create user instructions for the OpenEMS simulation software and to simulate magnetic field emissions in a Buck converter circuit, to study these on a theoretical level, and to review methods of Electromagnetic Compatibility (EMC). OpenEMS calculates electromagnetic fields using the FDTD method based on Maxwell's equations. Thesis combined theoretical analysis with practical techniques to improve electromagnetic compatibility.

The report begins with a review of the theory of electromagnetism, forming the basis for a simulation process that integrates KiCad, FreeCAD, Octave, and ParaView software to work together with the OpenEMS simulation tool. The simulation demonstrated how the layout of PCB components affects electromagnetic compatibility and the reduction of magnetic fields. The report also offered both theoretical and practical approaches to addressing these issues.

The resulting OpenEMS setup manual developed during the thesis will assist designers in improving and simulating magnetic field emissions in the future.

Keywords: EMI, EMC, OpenEMS, FDTD, Magnetism,
PCB Design, Power Electronics

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Tämän insinööriyö tavoitteena on luoda käyttöohjeet OpenEMS-laskentaohjelmalle ja simuloida magneettikenttäpäästöjä Buck-säädinpiirissä, tutkia niiden muodostumista teorian tasolla sekä käydä läpi sähkömagneettisen yhteensopivuuden metodeita. OpenEMS laskee sähkömagneettisia kenttiä hyödyntäen Maxwellin yhtälöihin perustuvaa FDTD- menetelmää. Työssä yhdistetään teoreettista pohdintaa ja käytännön keinoja, joilla on mahdollista parantaa sähkömagneettista yhteensopivuutta.

Insinööriyö alkaa sähkömagnetismin teorian läpikäynnillä, jonka pohjalta on mahdollista luoda simulointiprosessi, joka integroi KiCad-, FreeCAD-, Octave- ja ParaView-ohjelmistot toimimaan yhdessä OpenEMS-laskentaohjelmiston kanssa. Simulointi havainnollistaa kuinka piirilevyn komponenttien asettelu vaikuttaa sähkömagneettiseen yhteensopivuuteen sekä magneettikenttien vähentämiseen. Työ tarjoaa myös teoreettisia ja käytännön tapoja näiden näiden ongelmien kanssa työskentelyyn.

Työssä muodostuneet OpenEMS ohjelmiston käyttöohjeet avustavat suunnittelijoita parantamaan ja simuloimaan magneettikenttäpäästöjä tulevaisuudessa.

Avainsanat: EMI, EMC, OpenEMS, FDTD, magnetismi, PCB, tehoelektoniikka

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List of Abbreviations

AC:	Alternating Current.
APPCSXCAD:	Graphical front-end application for CSXCAD.
ATE:	Laboratory for General and Theoretical Electrical Engineering (University of Duisburg-Essen).
BUCK REGULATOR:	A DC-to-DC converter that steps down the voltage.
C/C++:	General-purpose programming language.
CEM:	Computational Electromagnetics.
CISPR:	International Special Committee on Radio Interference.
CSXCAD:	Computational geometry framework.
DC:	Direct current.
EC-FDTD:	Equivalent-Circuit Finite-Difference Time-Domain method.
ELECTRIC FIELD:	Field representing the force exerted by electric charges.
EMC:	Electromagnetic compatibility.
EMI:	Electromagnetic Interference.
FDTD:	Finite-Difference Time-Domain, a numerical method for solving Maxwell's equations in the time domain.
FREECAD:	3D modelling software.
GNU OCTAVE:	Open-source numerical computation software.
GPL:	GNU General Public License.

GUI:	Graphical User Interface.
HDF5OCT:	Octave library for reading HDF5 files.
H5PY:	Python interface to the HDF5 data format.
HDF5:	File format and set of tools used for storing and managing large amounts of data.
HOME BREW:	Package manager for macOS and Linux.
IO:	Octave package for inputs and outputs.
KICAD:	Electronics design software.
LGPL:	GNU Lesser General Public License, a more permissive version of the GPL.
MACRO:	Predefined sequence of instructions or commands that can be executed as a single operation.
MOSFET:	A type of transistor commonly used for switching and amplification in electronic circuits.
MAGNETIC FIELD:	A physical field produced by moving electric charges or magnetic materials.
MATLAB:	Proprietary platform for numerical computing and algorithm development.
MATLIB:	tool library for python.
MOSFET:	A type of transistor commonly used for switching and amplification in electronic circuits.
OPENEMS:	Open Electromagnetic Simulator, a numerical field solver based on the Finite-Difference Time-Domain (FDTD) method.
OPEN SOURCE:	A software license allowing users to view, modify, and distribute the code freely, encouraging community collaboration and transparency.

PARAVIEW:	Data analysis and visualization software.
PCB:	Printed circuit board.
PEC:	Perfect Electric Conductor, an idealized material used in simulations.
PYTHON:	High-level programming language.
SYMBOLIC:	Octave package for symbolic computation.
TRACE:	A conductive copper path or line on a printed circuit board (PCB) that connects different electronic components.
VTK:	Visualization Toolkit; a powerful open-source software library for processing and visualizing 3D data sets.
YEE GRID:	A structured grid used in FDTD simulations based on Kane Yee's algorithm, which places electric and magnetic field components in a staggered spatial arrangement for numerical stability

1 Introduction

As the electronics industry continues to evolve, the importance of electromagnetic compatibility (EMC) has grown, significantly impacting circuit performance. This work explores and simulates magnetic field emissions in buck converters, providing a structured approach to analyze and mitigate electromagnetic emissions while also offering guidance for effectively using the open-source electromagnetic field solver OpenEMS software, which employs the Finite-Difference Time-Domain (FDTD) method.

The work models and evaluates electromagnetic field behavior within these circuits. It focuses on grasping the key principles behind electromagnetic interference (EMI) generation, applying computational methods to predict and reduce EMI, and utilizing OpenEMS simulations to demonstrate magnetic field distributions and assess the effects of design changes on performance. By melding numerical simulations with critical design considerations, this work seeks to deliver insights into improving circuit layouts and minimizing EMI in switching power supplies.

2 Electromagnetic Theory and Computational Methods

Magnetic fields are formed by movement of charged particles. Which can be presented by as vector field that influences moving charges and impacts various components.

Magnetic fields can be expressed as two primary quantities, magnetic flux density, B, and magnetic field intensity, H, to define the characteristics of a magnetic field's strength and direction (1). [1,715.]

$$B = \mu_0 H \quad (1)$$

Here, μ represents the medium's permeability, which determines how a material responds to a magnetic field. Permeability varies depending on whether the medium is free space (vacuum permeability, μ_0) or a specific material (relative permeability, μ_r). [1,717.]

These elements can generate or be subject to electromagnetic interference (EMI) in printed circuit boards (PCB), resulting in performance issues. Materials respond to these fields based on their magnetic properties. Ferromagnetic materials, like iron and nickel, exhibit noticeable magnetic characteristics due to the alignment of their internal magnetic domains. Paramagnetic materials, like aluminum, slightly enhance external magnetic fields but do not preserve magnetization once the external influence discontinues. Diamagnetic materials create an opposing magnetic field that diminishes the total effect of an applied magnetic field. These include copper and graphite. [1,718.]

2.1 Electromagnetic Compatibility

Electromagnetic Compatibility (EMC) is the capacity of electronic devices and systems, operating effectively in their intended environment while neither generating or being susceptible to unwanted electromagnetic interference. EMC

revolves around achieving a balance, minimizing emitted noise while maintaining operational integrity in environments with electromagnetic interference. [2.]

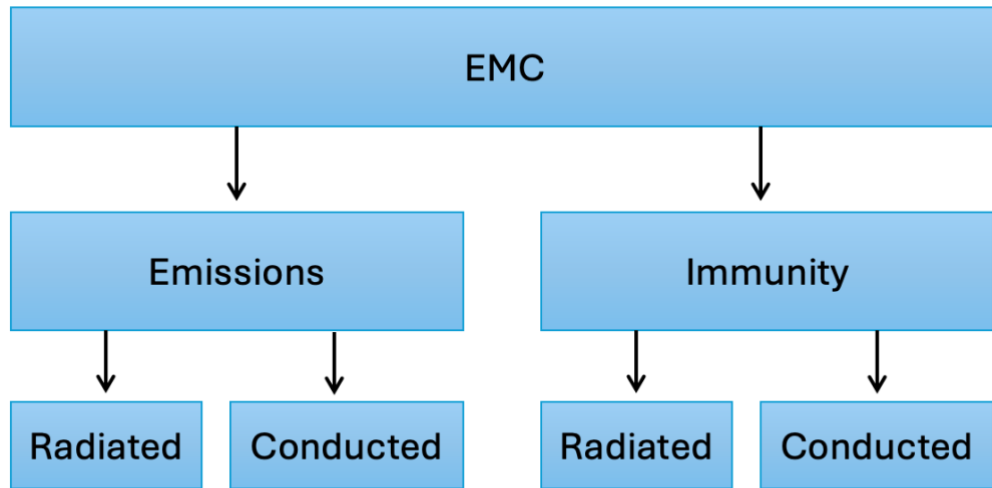


Figure 1 EMC Structure [2.]

EMC can be broken down into immunity and emissions (Figure 1). Radiated immunity is ability to resist electromagnetic fields of a device that come from external sources, while radiated emissions are unwanted electromagnetic waves emitted by a device into its environment. Conducted immunity is resistance to electromagnetic disturbances transmitted through conductor, and conducted emissions are the electromagnetic interference a device sends out through conductor. [2.]

When it comes to PCB design, the goal is to design a system where EMI is minimized, and the device can withstand external noise without malfunctioning. A well-designed ground plane helps minimize conductive coupling. Proper trace routing keeping high-speed signals away from sensitive analog or low-voltage circuits to prevent capacitive and inductive coupling. Power and signal traces should be isolated to reduce the risk of magnetic interference. Placing filters on power lines and signal inputs/outputs is an effective way to block unwanted high-

frequency noise. Finally, shielding sensitive components on the PCB and ensuring the layout minimizes loop areas. [2.]

2.2 Maxwell's Equations

These equations, developed by James Clerk Maxwell, unify electricity and magnetism into a single framework by describing how electric and magnetic fields propagate, interact with matter and travel. They form a fundamental part of computational magnetism. [3.]

2.2.1 Gauss's Law for Magnetism

Gauss's law for magnetism states that there are no magnetic monopoles in nature, indicating that magnetic field lines always form closed loops.

Mathematically, this is expressed by (2):

$$\nabla \cdot \mathbf{B} = 0 \quad (2)$$

Where B is the magnetic flux density (measured in teslas, T), this law shows that magnetic fields do not have divergence, reinforcing that magnetic field lines must always form closed paths. [3.]

2.2.2 Faraday's Law of Induction

Faraday's law describes how a changing magnetic field induces an electric field.

This principle is given by (3):

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (3)$$

Where E is the electric field (volts per meter, V/m) and $\partial B/\partial t$ represents the time rate of change of the magnetic flux density. This equation explains

electromagnetic induction, which is the basis for transformers, inductors, and wireless energy transfer. [4,374.]

2.2.3 Ampère's Law with Maxwell's Correction

Ampère's law describes how electric currents generate magnetic fields. This is illustrated by (4).

$$\nabla \times \mathbf{B} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (4)$$

Where \mathbf{B} is the magnetic field intensity (amperes per meter, A/m), \mathbf{J} is the current density (amperes per square meter, A/m^2), and $\partial \mathbf{D} / \partial t$ accounts for the displacement current. [4,354.]

Maxwell's correction predicted the existence of electromagnetic waves, which propagate through space according to the wave equations (5) and (6).

$$\nabla^2 \mathbf{E} - \mu \varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0 \quad (5)$$

$$\nabla^2 \mathbf{H} - \mu \varepsilon \frac{\partial^2 \mathbf{H}}{\partial t^2} = 0 \quad (6)$$

Where μ is the permeability and ε , the permittivity of the medium. [6.]

2.3 Computational Electromagnetism

Maxwell's equations, while providing excellent solutions for simple systems, which can be expanded for more complex calculations, using computational electromagnetics (CEM). CEM provides numerical techniques to solve electromagnetic problems derived from Maxwell's equations, providing ways to simulate electromagnetic phenomena. [7;6.]

2.3.1 Finite Difference Time Domain (FDTD) Method

One of the most used techniques in CEM is the Finite-Difference Time-Domain (FDTD) method. This provides a powerful tool for solving Maxwell's equations in the time domain by discretizing both space and time. The fundamental idea is to model how electromagnetic fields propagate in discrete steps, breaking down the continuous space and time into small intervals. Showcased by Electric and magnetic field equations (8) and (9), which are derived from Ampère's law.

$$H^{(n+1)} = H^n + \frac{\Delta t}{\mu} (\nabla \times E^n) \quad (8)$$

$$E^{(n+1)} = E^n + \frac{\Delta t}{\varepsilon} (\nabla \times H^n) \quad (9)$$

Where μ is the magnetic permeability of the medium, ε is the electrical permittivity, Δt is the time step, and $\nabla \times$ represents the curl operator.

To ensure numerical stability, the Courant-Friedrichs-Lewy (CFL) condition is imposed, given by (10).

$$C\Delta t < \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2} \quad (10)$$

Where c is the speed of light, and Δx , Δy , Δz are the spatial grid resolutions. The CFL condition ensures that the simulation time step is small enough to prevent errors and instability. [7.]

3 OpenEMS

OpenEMS is a free, open-source electromagnetic simulation tool based on the FDTD method, extending it with the Equivalent Circuit FDTD (EC-FDTD) method, which improves precision for simulating complex materials and components. Developed in C++ and launched by Thorsten Liebig in 2010, released under the GNU GPL v3, with its geometry handler, CSXCAD, under LGPL v3, allowing customization and redistribution. OpenEMS uses a time-domain approach, which makes it ideal for broadband simulations, with a key feature being its use of the Yee grid, which accurately models electric and magnetic fields by staggering them in space and time.

OpenEMS provides scripting support via MATLAB and Python, and includes a graphical interface (AppCSXCAD) for building and checking 3D models. The software also integrates with tools like KiCad and FreeCAD for a streamlined design-to-simulation workflow. Its main uses are EMC analysis of antennas, RF circuits, and radar systems. [8; 9; 12.]

3.1 Setup

OpenEMS requires specific configurations based on the operating system in use. To ensure compatibility and optimal performance, it is recommended to use the following tools: KiCad 6.0, FreeCAD 0.19, and ParaView 5.13. Both octave and python interfaces work for all operating systems(OS). For macOS users, octave is preferred for python version not supporting all architectures yet. Version 3.10 is ideal for Python, and Octave 9.2.0 for Octave users. All of these tools are open-source and actively maintained. [9.]

3.1.1 Installation

The setup process begins by installing OpenEMS from their official website, then either python or octave as interface. For macOS users this step includes downloading OpenEMS via package manager (HOMEBREW). Python version

requires tool library (MATLIB) and interface to the HDF5 data format (H5PY), while octave version similarly package for symbolic computation (SYMBOLIC), library for reading hdf5 files (HDF5OCT) and additionally package for inputs and outputs (IO). These dependencies can be downloaded via command prompt (Windows) and terminal with homebrew (MacOS). For both interfaces, corresponding files need to be assigned to interface path. The files can be found in OpenEMS folder. After this step, functionality of the system can be tested by running tutorial simulations, found on OpenEMS file (Figure 2). If the simulation files execute correctly, the software is functioning properly. [9.]

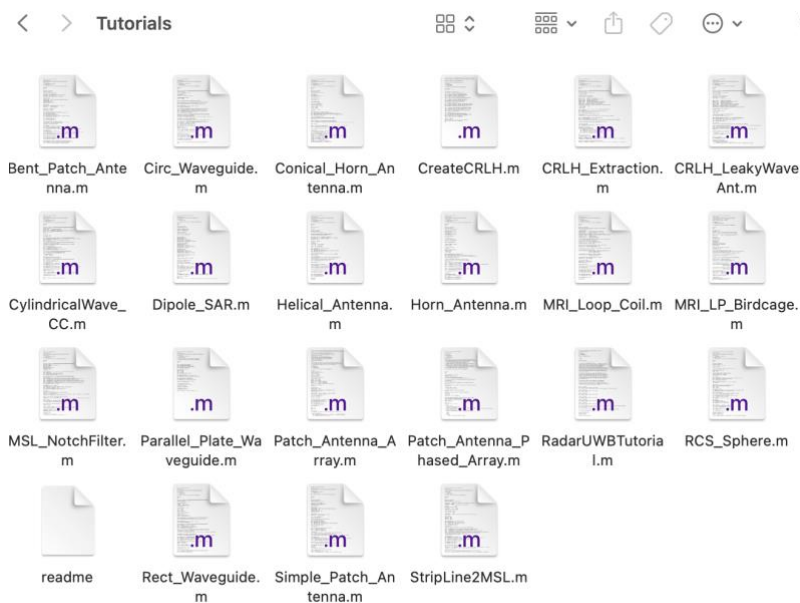


Figure 2 OpenEMS tutorials (MAC)

Next step is to download Electronics design software (KICAD), 3D modelling software (FREECAD), Data analysis and visualization software (PARAVIEW) and finally, OpenEMS macro. [10.] OpenEMS page offers tutorials on installation and version control including links to both software itself and the Freecad macro.

3.2 Simulation Workflow

For this workflow example, simple trace is created step by step to represent simulation workflow from start to finish, including visual presentation of magnetic- and electric fields and impedance calculations from data gathered.

The workflow of the simulation begins with importing the PCB design from Kicad into FreeCAD, where the design is converted into a 3D model and simulation parameters, such as material properties and boundary conditions, are defined. Next, the simulation data is exported to Octave or Python file, then run through either the Octave or Python interface, which launches the CSXCAD interface for managing material properties and simulation grids. Once the simulation is complete, the results can be visualized using Paraview (Figure 3)

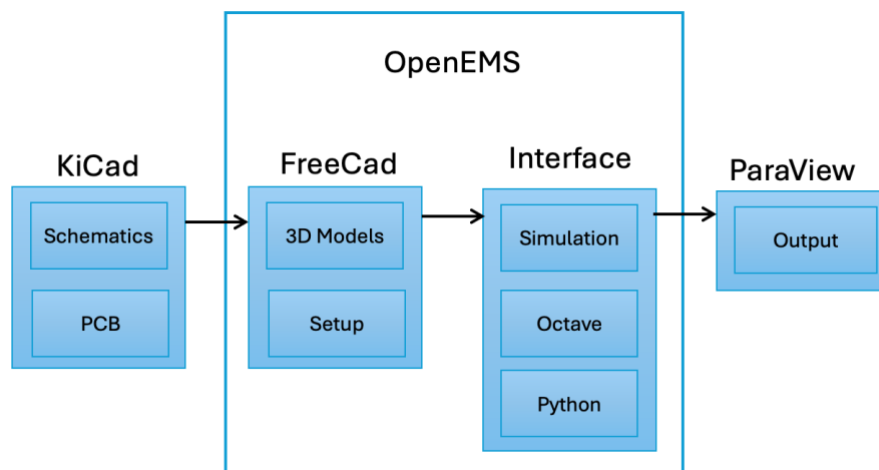


Figure 3 Workflow

3.2.1 Creating FreeCAD Models

The simulation process in OpenEMS is initiated by uploading a completed PCB design from KiCad into FreeCAD via OpenEMS macro (Figure 4 and Figure 5), using KiCad import tool.

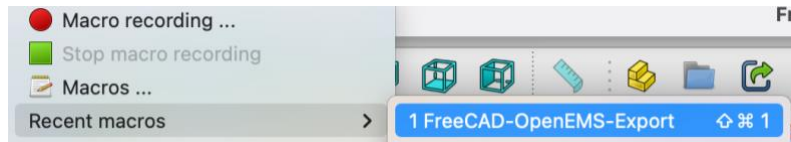


Figure 4 OpenEMS Macro

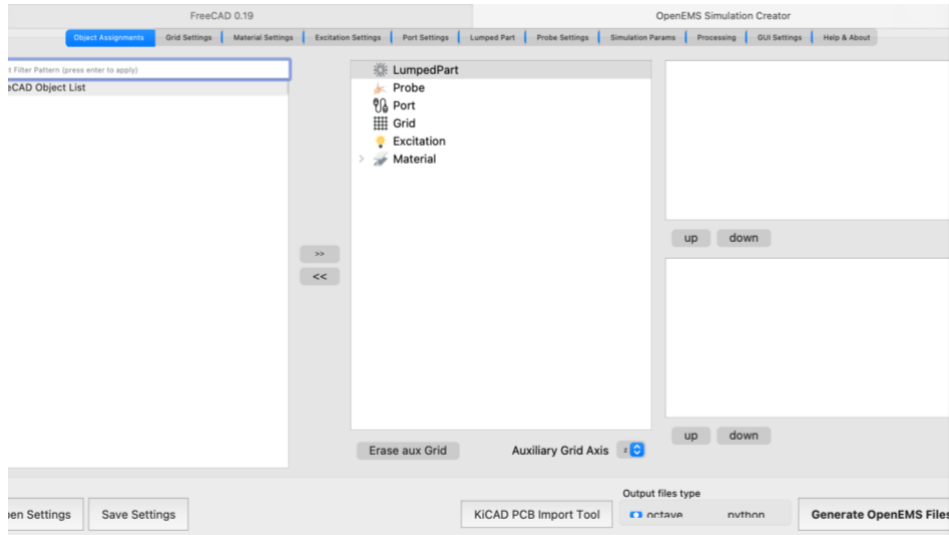


Figure 5 OpenEMS Simulation Creator

After the upload is completed, FreeCAD report window prompts, and all components are visible (Figure 6 and Figure 7).

```

18:28:57 freecadObjectChanged :Unnamed#coppers_drilled ('coppers_drilled#F.Cu') property
18:28:57 freecadObjectChanged :Unnamed#holes_solid001 ('holes_solid001#F.Cu#th') property
18:28:57 freecadObjectChanged :Unnamed#coppers_drilled ('coppers_drilled#F.Cu') property
18:28:57 freecadObjectChanged :Unnamed#coppers_drilled ('coppers_drilled#F.Cu') property
18:28:57 cut done
18:28:57 done making all copper layers
18:28:57 all done

```



Figure 6 Upload Completed

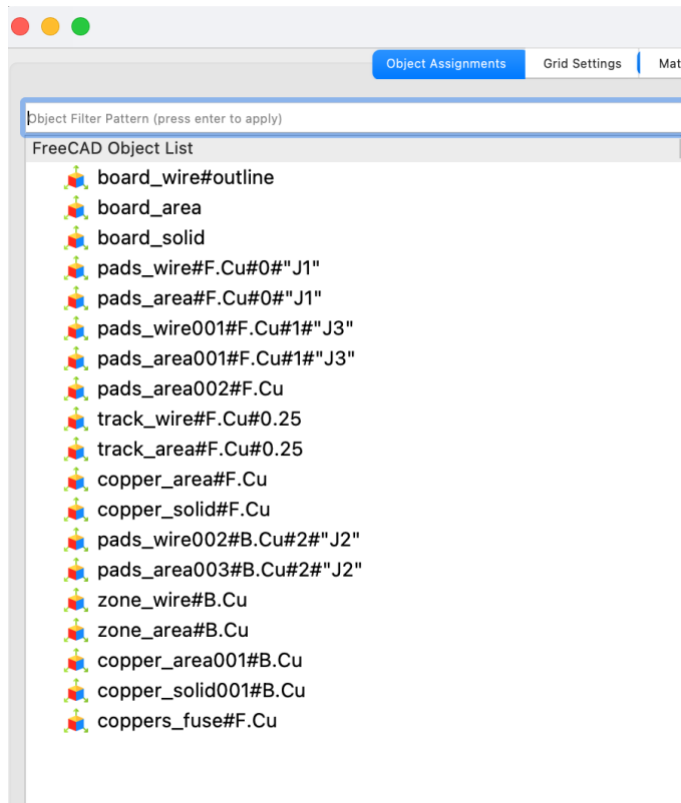


Figure 7 Uploaded Dimensions

3D- presentation of the imported board is visible on the FreeCAD project window (Figure 8).

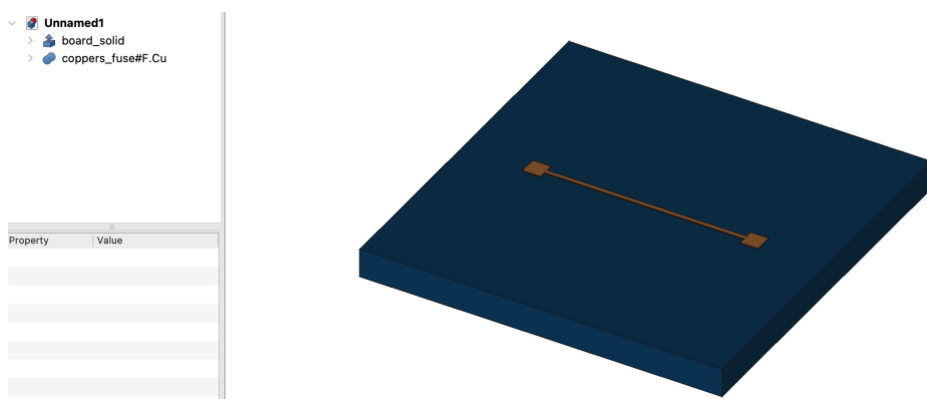


Figure 8 Demo Board

Next step is to copy and paste copper dimensions into project. This step reveals possible errors in the upload phase and ensures correct procedure (Figure 9).

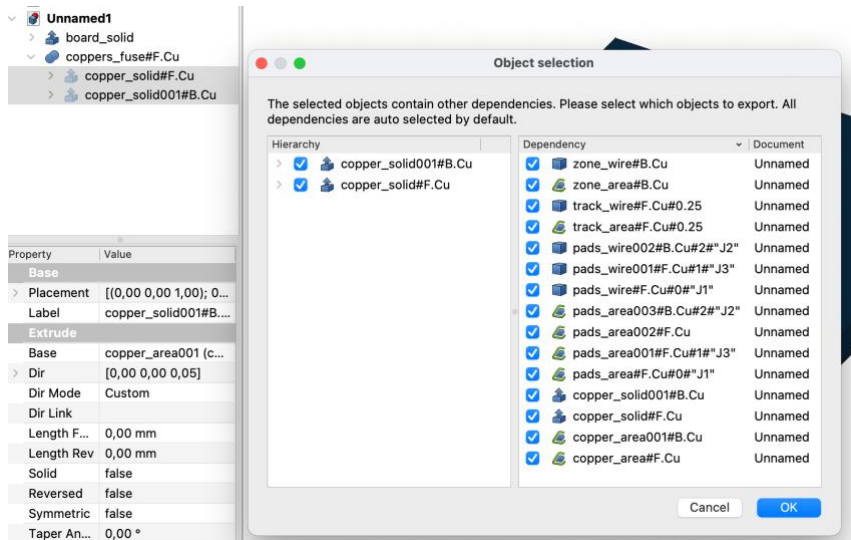


Figure 9 Copying Copper Dimensions

PCB layout will need to be converted into solid 3D objects, which is utilized for the simulation to perform calculations correctly. This is done by navigating into part workbench, located at the workbench panel, then selecting boolean union and creating a simple copy of it (Figure 10). Ground plane also will be converted similarly.

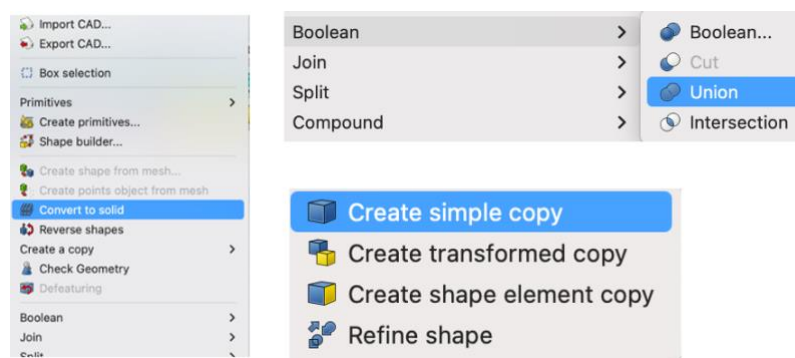


Figure 10 Creating Solid Objects

After board, trace and ground dimensions are converted to solid, all the original dimensions can be deleted, leaving only the copied and solid dimensions (Figure 11).

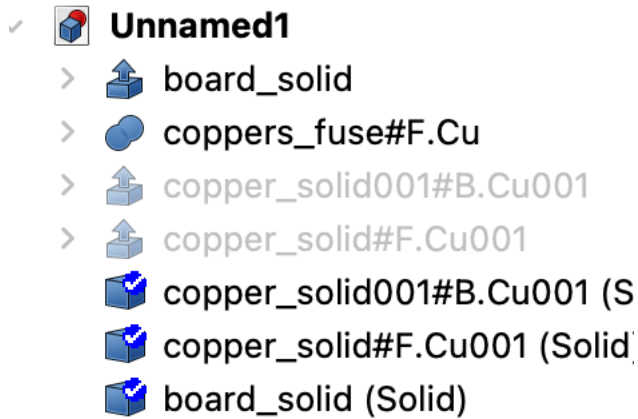


Figure 11 All Board Dimensions Solid

When all components are solid, next step is to add Air, Electric field, Magnetic field and power input into the 3D Design (Figure 12). Air dimension should be 5mm larger in y dimension and 1mm larger in x dimension than the PCB. Field dimensions are copies of air dimension, except their height is 0.05mm. Fields are placed between trace and ground plane, and magnetic field is placed 0.1mm below the electric field (Figure 12). Also, the portin box is input pad and board height sized for input signal used in this example.

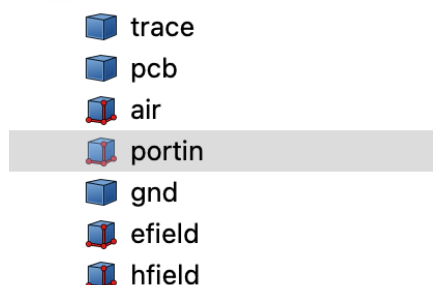


Figure 12 All Dimensions

Dimension topology is showcased in Figure 13. 3D- representation of the completed 3D- model can be seen in Figure 14.

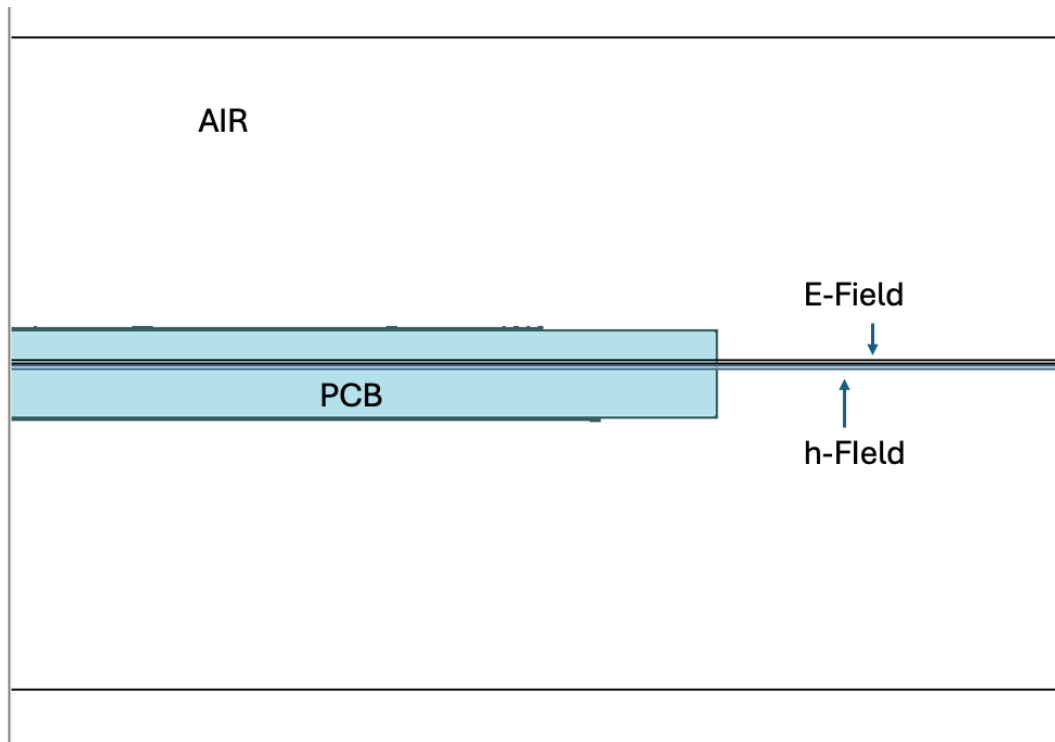


Figure 13 Fields

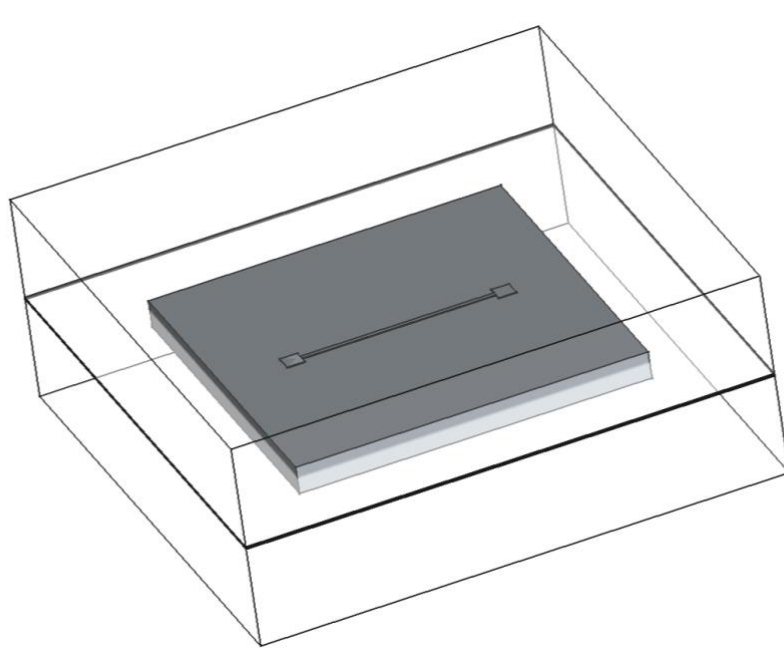


Figure 14 Complete 3D-Model

After defining the dimensions, simulation parameters will need to be set up in the OpenEMS macro. This includes material properties, methods probes, and grid settings (Figure 15).

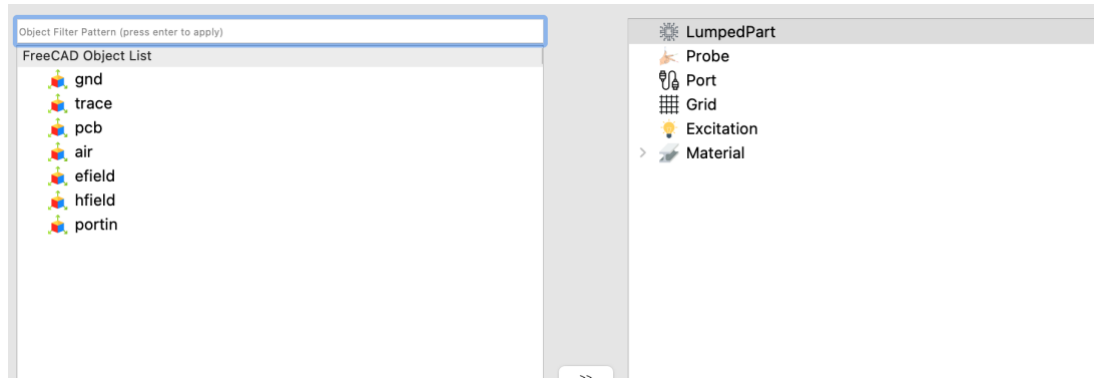


Figure 15 Simulation Setup

The grid is the first to be defined for the simulation setup (Figure 16). At least one grid xyz dimension with trace width is needed. For complex boards, extra grids are recommended for trace and field dimensions. This enhances simulation times and accuracy.

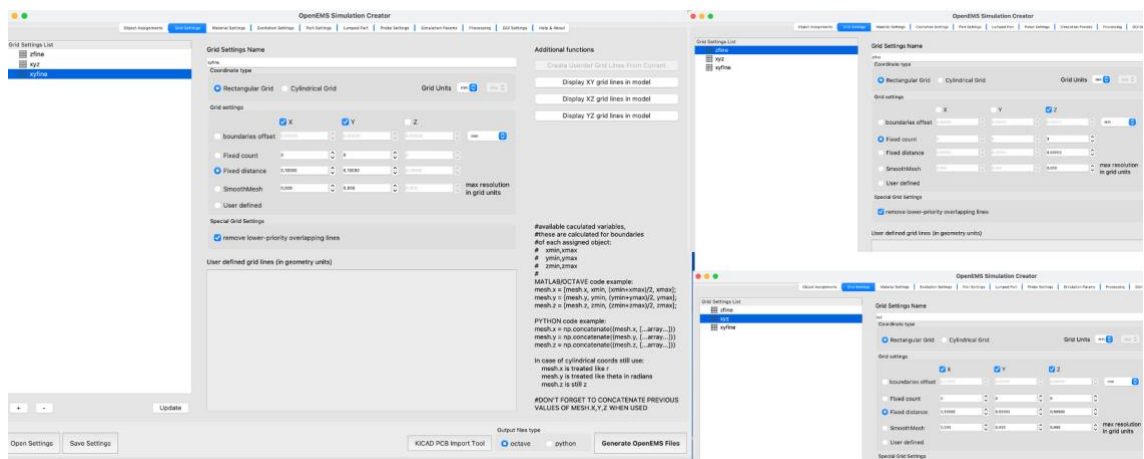


Figure 16 Grids

For materials, defining board material and air is sufficient. Copper can be included, but for most simulations, a Perfect Electrical Conductor (PEC) is added

automatically to the parameters. Boards with a ground plane should have their own material for trace and ground (Figure 17).

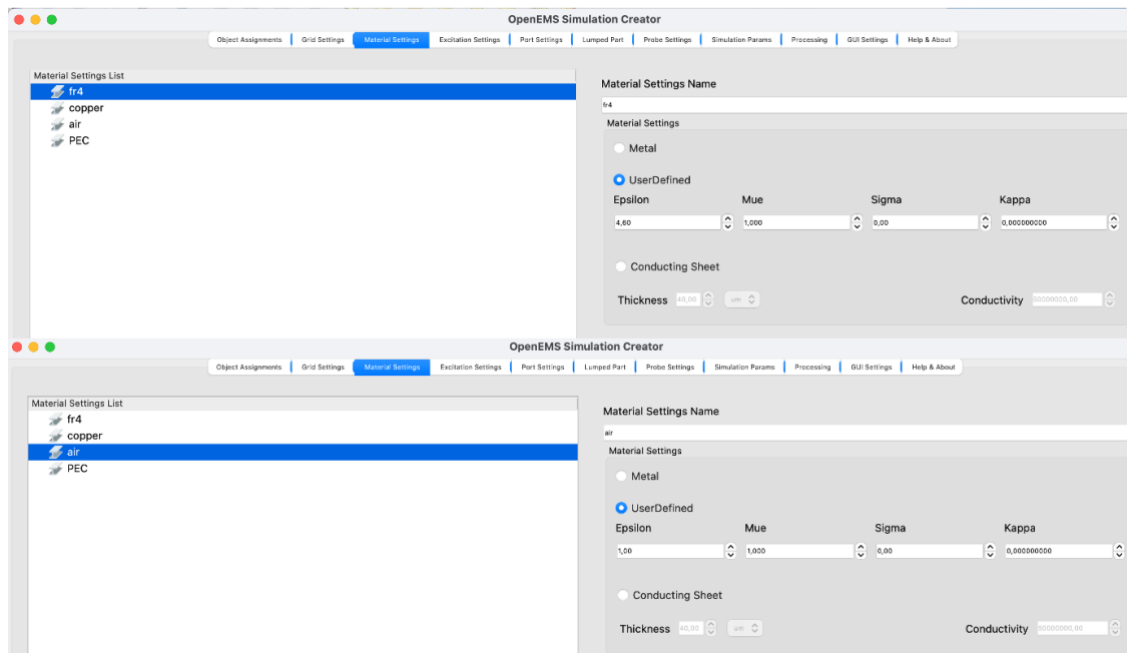


Figure 17 Board Materials

Utilizing excitation methods, a Gaussian signal is ideal for this straightforward board, while a step function is recommended for more complex boards (Figure 18).

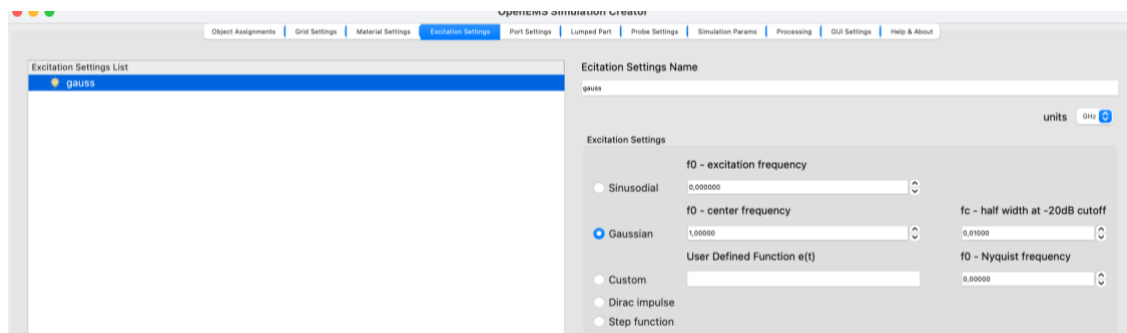


Figure 18 Calculation Method

Port setup is shown in Figure 19. Lumped ports can also be simulated as resistors, capacitors, or inductors. This simulation covers material-based fields.

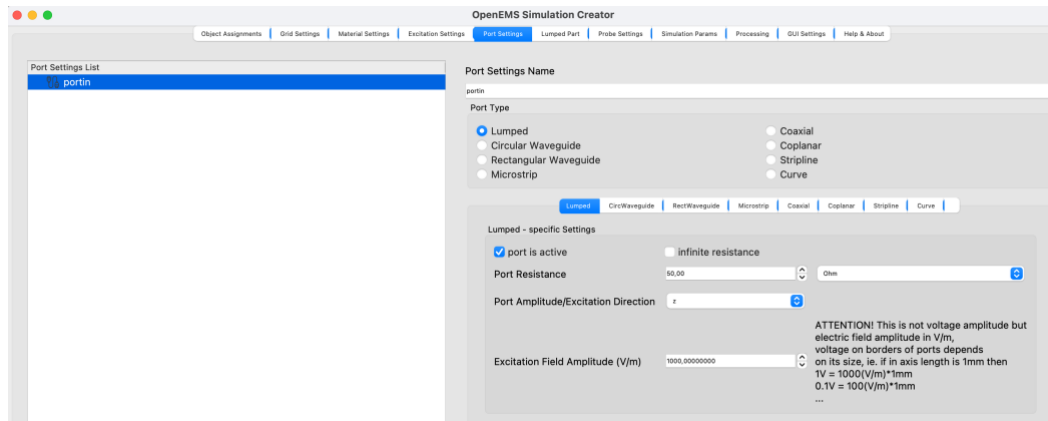


Figure 19 Ports

Probes are used to acquire simulation data in various methods. For this example, both electric and magnetic fields are used (Figure 20).

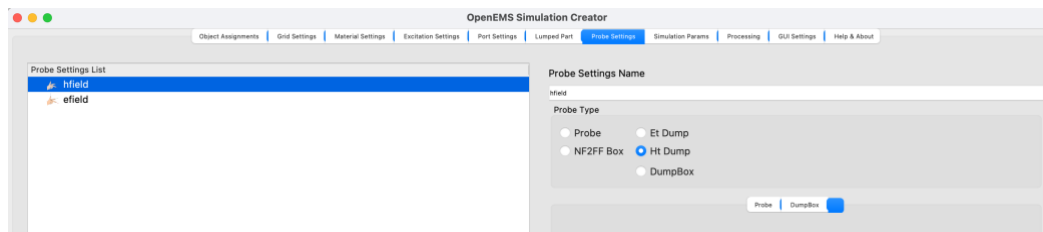


Figure 20 Field Probes

Timestep and simulation parameter setup, shown in Figure 21. In this simulation, the Perfectly Matched Layer (PML) is selected. PML allows the signal to travel out of its layer without interruptions.

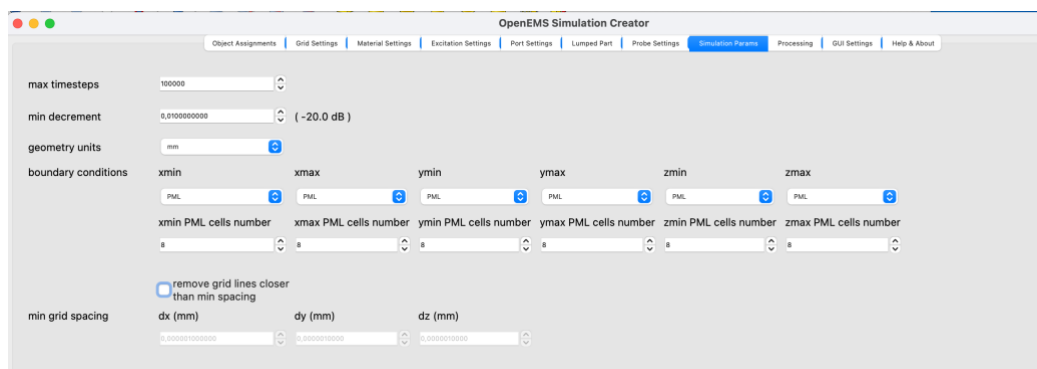


Figure 21 Timesteps

Once all components of the simulation are defined, each 3D object will need to be assigned. Below, Figure 22 shows an example setup for this board.

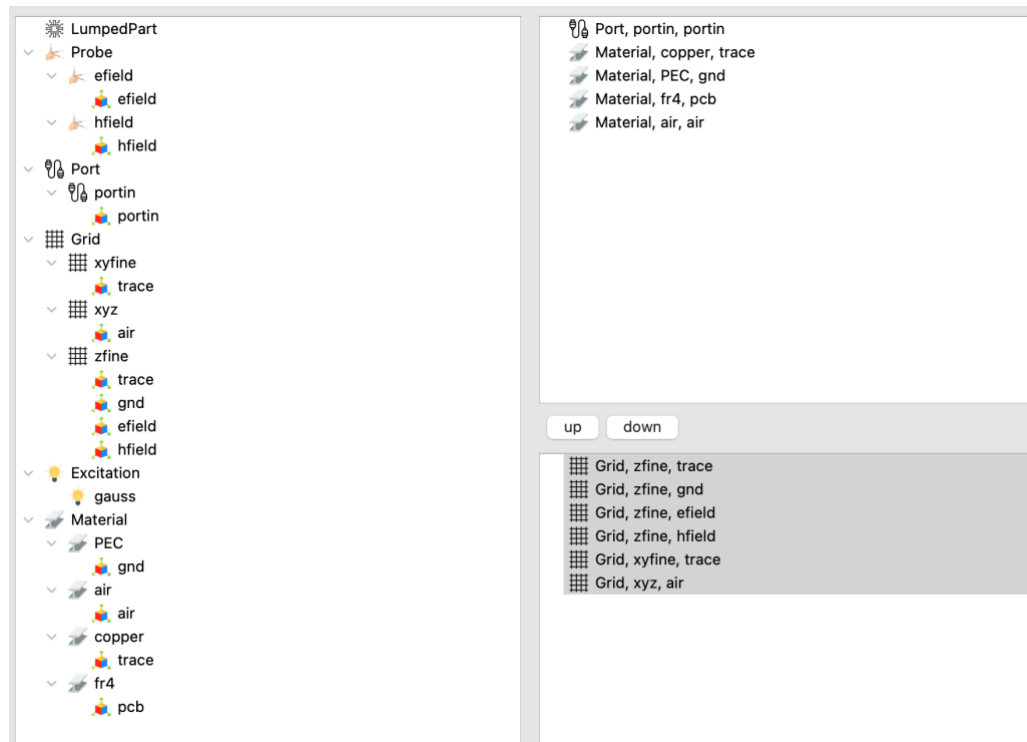


Figure 22 Demo Setup

Once the setup within FreeCAD is complete, the simulation data is exported to either Octave or Python (Figure 23). Both Octave and Python provide user interfaces to observe, modify, and fine-tune the simulation settings for adjusting simulation parameters. The macro also generates a 3D model of the created dimensions, which is saved in a designated folder along with other simulation setup files (Figure 24). Before continuing, simulation setting should be saved. Dimensions in FreeCAD also can be saved.



Figure 23 Generate Simulation Files



Figure 24 Simulation Files

3.2.2 Running Simulation

Once the simulation setup has been finalized and the simulation files have been generated, it can be executed using either the Octave or Python interface. This is done by using the run command and the path to the created simulation file (Figure 25). Upon initiating the simulation, the CSXCAD interface will automatically open (Figure 26).

```
Octave was configured for "aarch64-apple-darwin23.6.0".  
  
Home page:           https://octave.org  
Support resources:  https://octave.org/support  
Improve Octave:     https://octave.org/get-involved  
  
For changes from previous versions, type 'news'.  
octave:1> run('/path to/simulation.m');
```

Figure 25 Initiating Simulation

The CSXCAD interface allows for a final preview of the simulation (Figure 26). In this window, the Grid should be checked to ensure it matches the setup.

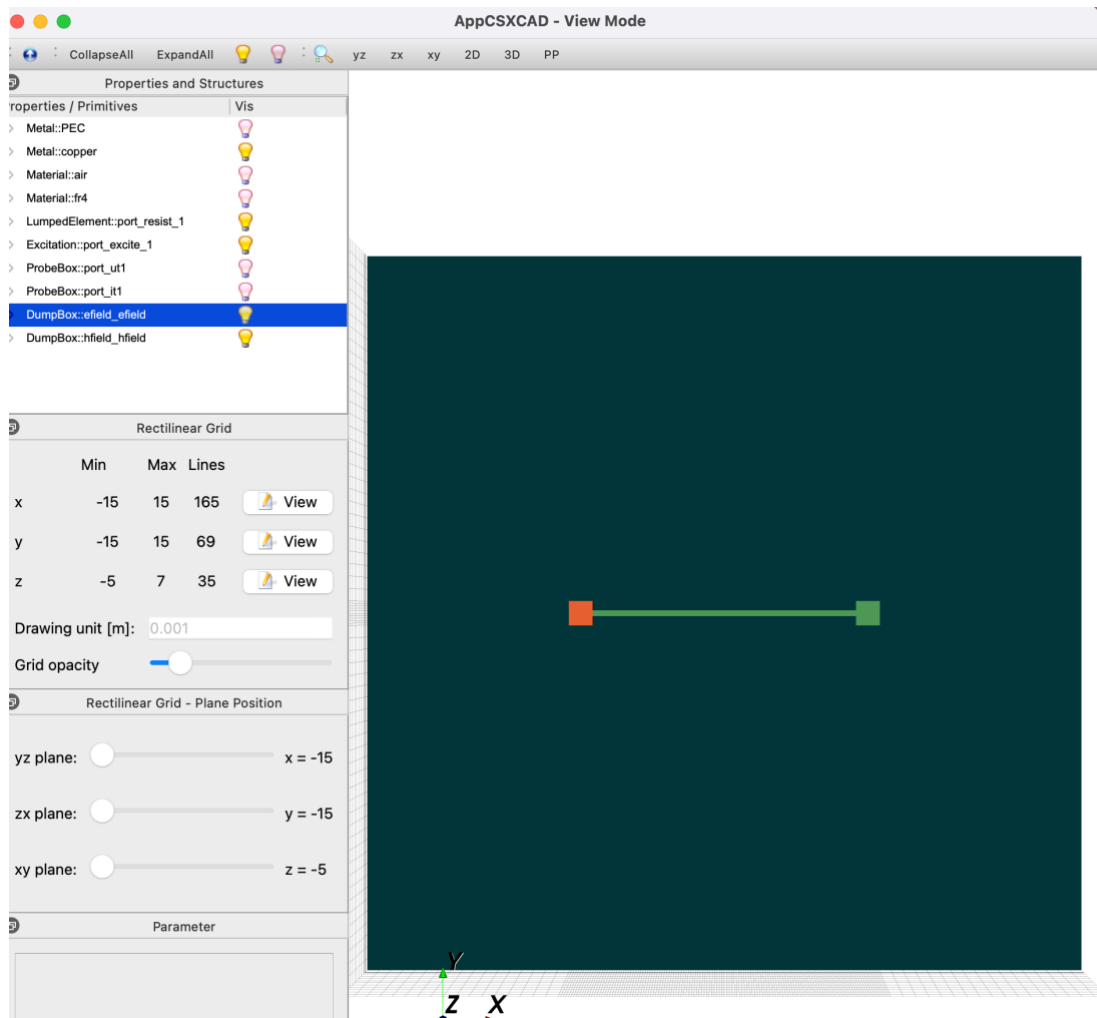


Figure 26 App CSXCAD

After the CSXCAD window is closed, the simulation starts automatically. Upon completing the simulation, the interface asks for further input. Simulation times vary from seconds to hours, usually under 10 minutes if everything is set up properly.

3.2.3 Visualizing Results

Output files are automatically generated and placed in the simulation folder when the simulation is running (Figure 27). The simulation file is named after the setting name.



Figure 27 Generated Output Files

The simulation file (Figure 28) contains different timesteps of the fields, port information, field information, and the simulation result. The field timesteps are used to visualize magnetic and electric field activity with Paraview. The port files contain voltage and current over time numerical data.



Figure 28 Output Folder

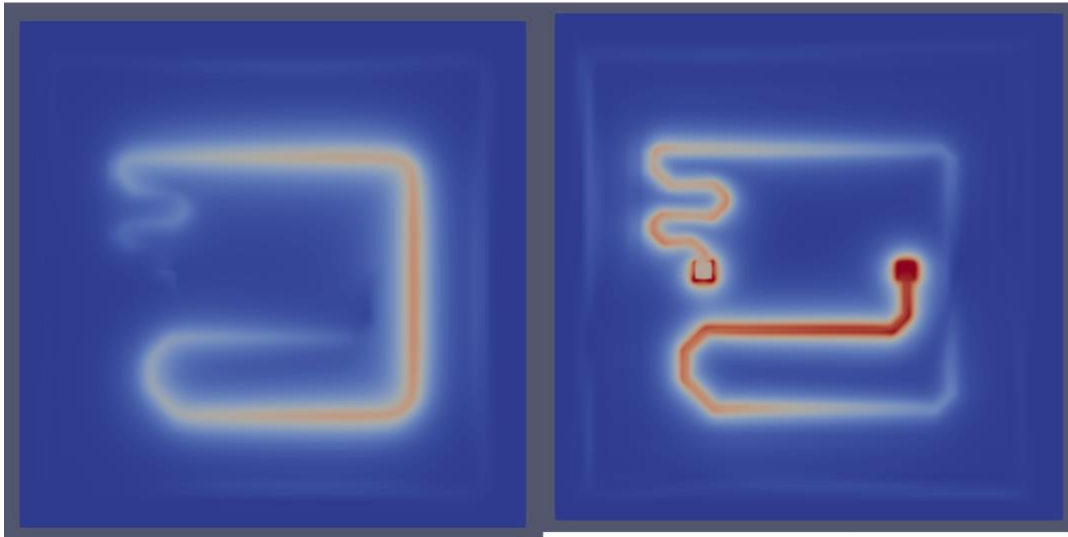


Figure 31 Magnetic and Electric Fields

3.3 Impedance

For numerical data and impedance calculations, excitation is set to a sinusoidal wave, and the ground plane and trace are to be combined into one solid object. Measuring is done from input voltage and current files (Figure 28). From there, chart can be created representing the relation between current and voltage on the trace over one period (Figure 32).

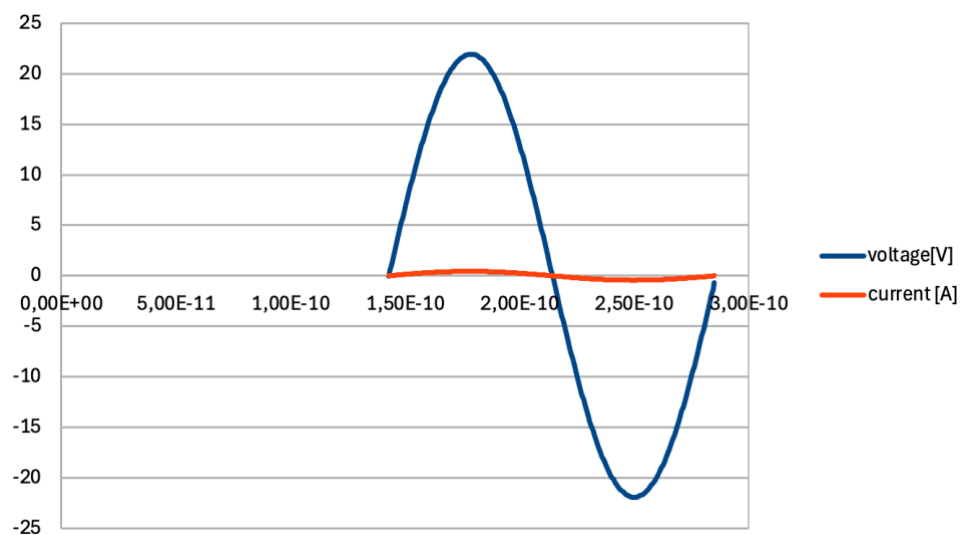


Figure 32 Current and Voltage over period

With these values, impedance can be calculated as (11).

$$Z = \frac{V_{rms}}{I_{rms}} \quad (11)$$

Where: V_{rms} the effective value of alternating voltage and I_{rms} the practical value of alternating current in AC signal. The RMS values can be calculated from gathered signal data (12).

$$V_{rms} = \sqrt{\frac{1}{T} \sum_{n=1}^T v_n^2} \quad (12)$$

Where: v_n is the voltage at n:th point, and N is number of samples [13;14.]

4 Electromagnetic Interference in Buck Regulators

4.1 Introduction to Buck Regulators

Buck regulator, or step-down DC-DC converter, efficiently reduces a higher input voltage to a lower output level by switching a transistor (typically a MOSFET) on and off at high frequencies. This switching action controls energy transfer from input to output via an inductor and output capacitor.

Buck regulators operate by rapidly switching a transistor on and off to produce a pulse-width modulated (PWM) waveform. This waveform is then smoothed by a low-pass filter composed of an inductor and a capacitor, resulting in a stable DC output

Adjusting the switching signal's duty cycle can precisely control the average output voltage. A feedback loop continuously monitors the output and adjusts the duty cycle as needed to maintain regulation, even with varying input voltages and loads. This approach leads to far greater efficiency. [16, 10-20.]

4.2 Sources of EMI in Switching Power Converters

In buck regulators, EMI mainly arises from the fast switching actions of the components within the converter. When the switching transistor rapidly turns on and off, it creates differential-mode noise due to the abrupt changes in current. This noise travels along the power lines and can spread through both the inputs and outputs, amplified by the inductors and capacitors. Common-mode noise emerges from significant voltage alternations at the switch node, which induces parasitic capacitance. This results in current flow through both the power and ground lines, making it challenging to filter out using standard EMI filters. Additionally, magnetic coupling happens when the inductor and current loop generate magnetic fields that bypass EMI filters, further complicating noise measurements. [17.]

4.2.1 Impact of PCB Layout

One of the simplest ways to reduce EMI in PCB design is to change the board itself. One effective way is to use decoupling capacitors, which will lower the impedance of power buses and thus lower transient currents. It is also important to evaluate and limit inductance and capacitance in the circuit layout, as they can significantly impact the suppression of both conducted and radiated emissions.

Other methods, such as shielding, filtering, grounding, and component planning, can be effective when done correctly. Also, careful routing on the PCB can lower stray inductances and is one of the most used methods. [18.]

4.3 EMI Estimation Methods

Central to predicting EMI is comprehending how magnetic fields are generated in high-frequency systems. Ampère's Law establishes a connection, indicating that the magnetic field surrounding a conductor carrying current is directly proportional to the current it encloses. In a simplified manner, the strength of the magnetic field at a certain distance from a current loop can be expressed as (13).

$$B = \frac{\mu_0 I}{2\pi r} \quad (13)$$

Where μ_0 is the permeability of free space, this equation illustrates the direct influence of loop area and current magnitude on field strength. [18, 300-320.]

4.3.1 Fourier Series of a Switching Waveform

The voltage at the switching node of a buck converter closely resembles a square wave. This waveform can be decomposed into its harmonic components using Fourier series. The general form of the decomposition is (14):

$$v(t) = \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_{sw}}{n\pi} \cos(n\omega_t t + \phi_n) \quad (14)$$

where:

$V_n = \frac{4V_{sw}}{n\pi}$ represents the amplitude of n:th harmonic.

V_{sw} is peak voltage of switch waveform.

$\omega_s = 2\pi f_s$ is the angular switching frequency.

ϕ_n is n:th harmonic.

This representation demonstrates that significant energy exists in the harmonic frequencies, especially in the lower MHz range, which often fall within the frequencies of concern for electromagnetic compatibility (EMC) testing. These harmonics are key contributors to both conducted and radiated emissions. [19.]

For conducted emissions, the expected noise voltage on power lines can be estimated as (15). [19.]

$$V_{\text{emi}} = Z_s \cdot I_{\text{switch}} \quad (15)$$

where

Z_s is the source impedance and

I_{switch} is the high-frequency switching current.

Comparing these theoretical estimates with measured or simulated EMI spectra provides valuable insight into noise sources and mitigation techniques. [19.]

5 Simulation With Buck Regulator

For this simulation, a circuit with two regulators and a microcontroller was designed to analyse how different layouts behave when a power source is applied (Figure 33). The aim of this simulation is to showcase how OpenEMS visualises magnetic fields on a practical circuit. Simulation is only material-based at this level, so it gives an estimate of how magnetic fields flow on this circuit. Complete schematics and bill of materials (BOM) can be found in appendices.

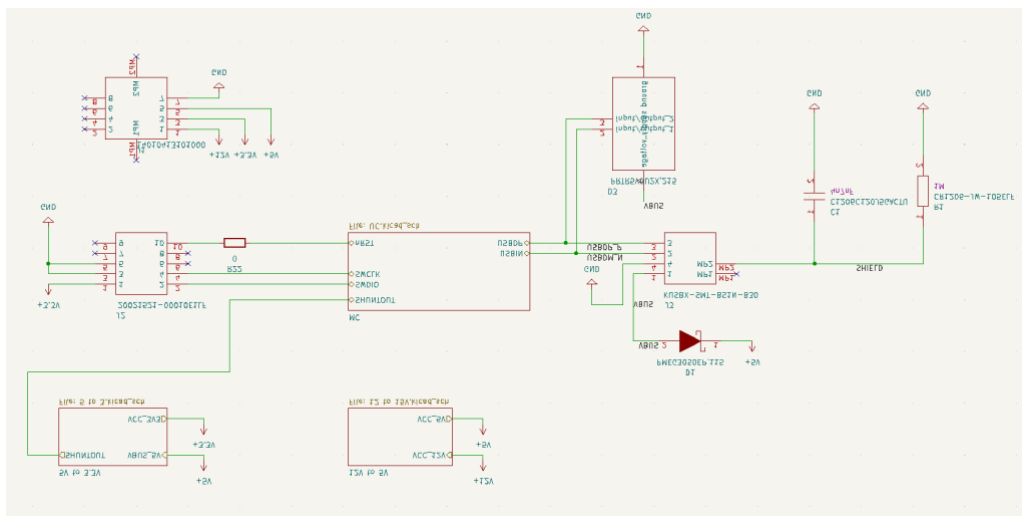


Figure 33 Schematic

5.1 PCB Design

To implement magnetic field simulation, the PCB needed to be designed to allow enough space for a clear view of the fields, while ensuring that the circuits were positioned close to each other. All traces were drawn on the top layer of the board, which made the whole process a bit more time-consuming (Figure 35). This design serves as the foundation of the project. For comparison, a second board was created, incorporating a ground plane and vias, as well as two additional signal layers to mitigate magnetic field emissions (Figure 36). Complete schematics for the project can be found in the appendices, along with the bill of materials.

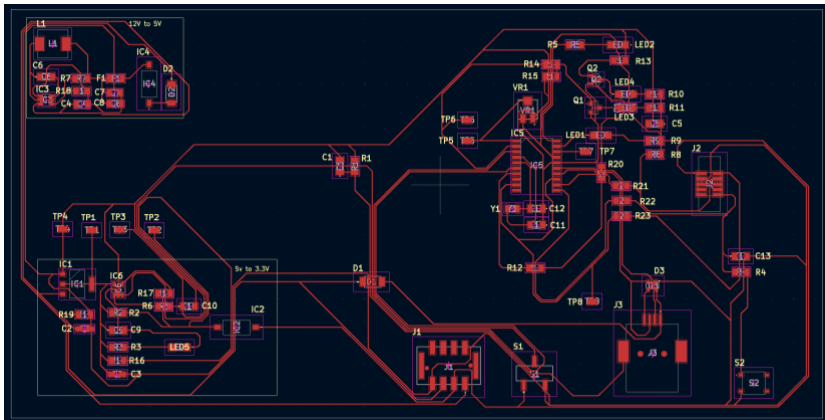


Figure 34 PCB Ground on Top

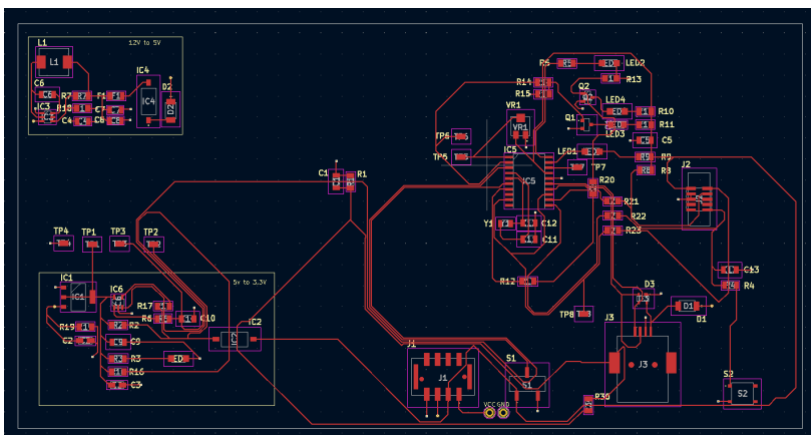


Figure 35 PCB 4-Layer

5.2 Modelling

First, Kicad models were uploaded to FreeCAD, and modelling was carried out according to the dimensions and methods discussed previously. Both completed boards are shown in Figure 36. The input port was integrated into the regulator circuit power input on both boards (Figure 37).

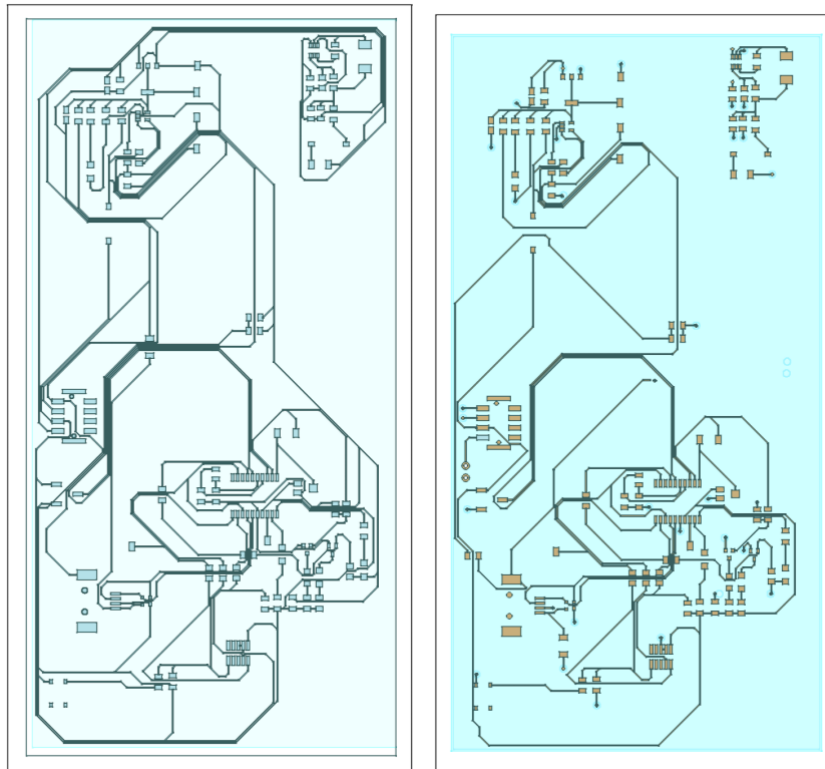


Figure 36 3D-Layout of Both Boards

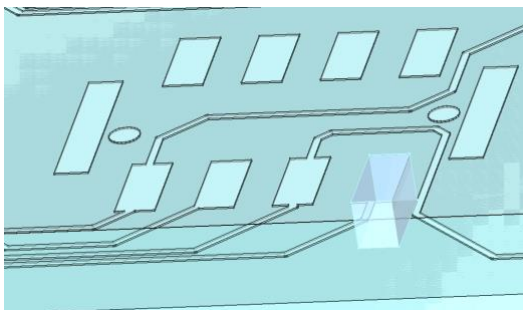


Figure 37 Input Placement

The simulation setup is completed according to the demo board with a Gaussian signal (Figure 38). Finer grids were established to optimize calculations on the trace and ground plane. For the board without a ground plane, the copper was replaced with PEC.

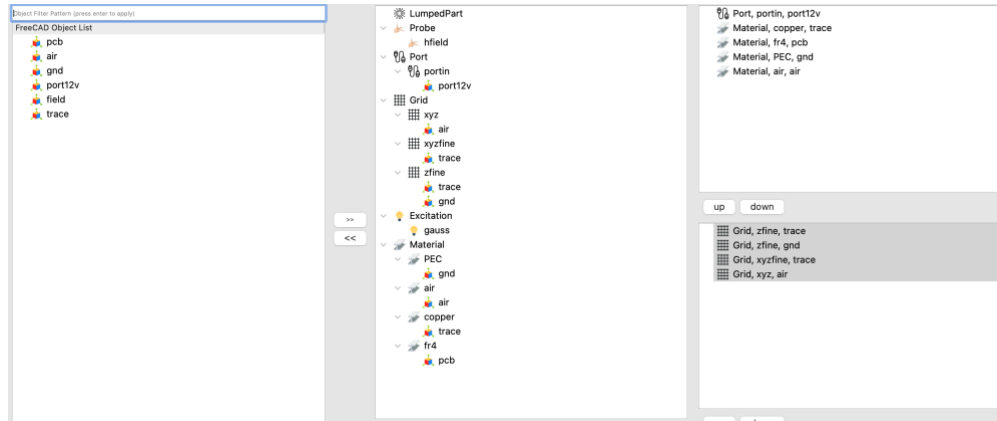


Figure 38 Simulation Setup

5.3 Visualising Results

After the simulation finished, results were visualized in Paraview.

The first look (Figure 39) provides a brief visual difference in how the ground plane affects the behaviour of magnetic fields. The board without a ground plane (Left) is less contained, and the peaks are greater than those of the board with a ground plane (Right), which, on the other hand, is briefly weaker and pulsates less freely.

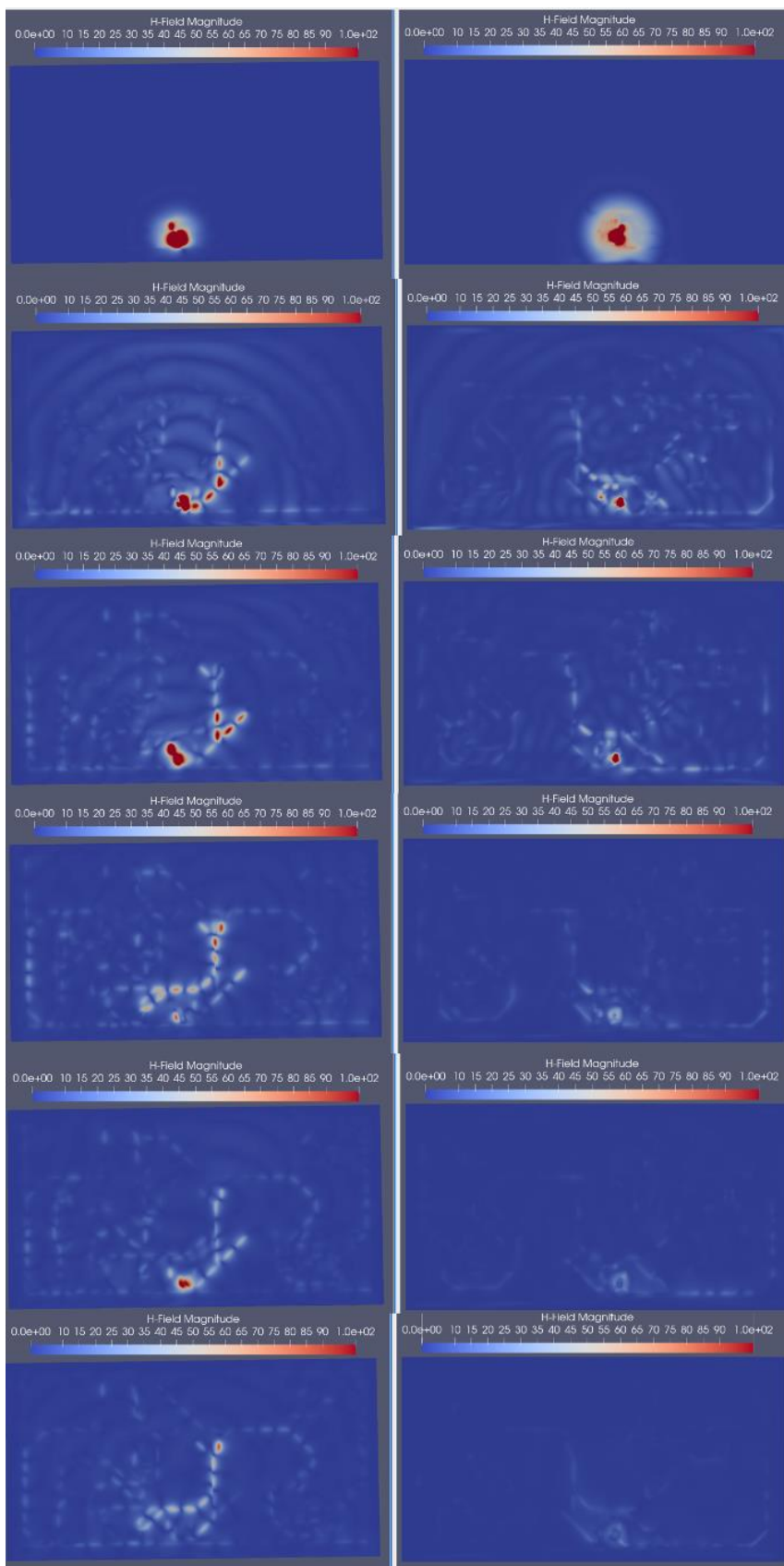


Figure 39 Buck Regulator fields at $t=10-100$

5.4 Analysis

The simulation results reveal how PCB design choices influence magnetic field behavior around buck regulators. The first board, lacking a ground plane and using a single top-layer layout, displayed significantly more intense magnetic field emissions. The field lines were erratic and extended further from the regulator circuit, indicating insufficient confinement and a higher likelihood of EMI, as seen in the visual outcome (Figure 39). Input signal was also visualised to check if the board works in the desired manner (Figure 40), measured in volts per meter (V/m), and calculated with input pad dimensions, and current (A)

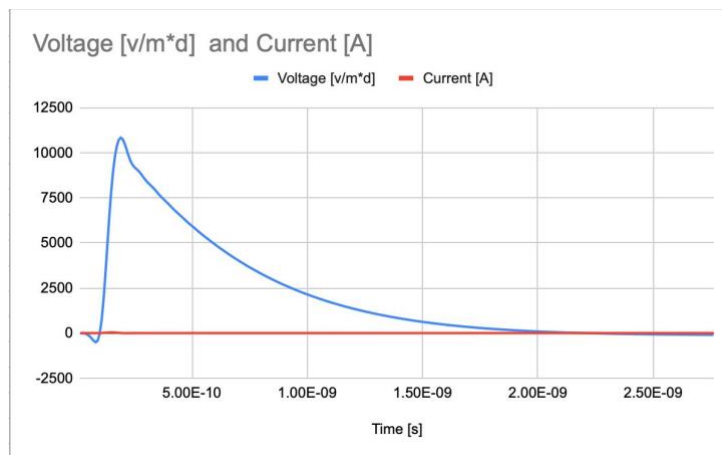


Figure 40 Graph of Gaussian Signal

In contrast, the second board, equipped with a ground plane, additional signal layers, and a small shield near the regulators, showed improved field control. The magnetic fields became more localized, with lower peak values. Despite the small shield, it helped dampen high-frequency field spikes, particularly near the switching node, aligning with established shielding effects where partial coverage can redirect or absorb radiated energy.

While exact field values were not measured, a visual comparison indicates notable differences in field intensity. The unshielded, single-layer version exhibited stronger and more dispersed magnetic field peaks, while the shielded version showed more contained fields near the power input and switching components.

6 Discussion and Future Work

OpenEMS is a solid simulation method for analysing the behavior of magnetic and electric fields in simple circuits. This work covers material based simulating with the software. For more complex analysis with more components included, the software needs more development due to lumped port elements not functioning correctly, as well as software optimizations for simulation speeds and interface bugs, making OpenEMS more practical for educational purposes. Perhaps even importing a complete design with component values and dimensions included would make simulating these elements more effective. This could also be affected by the usage of a not yet fully supported OS, which made the setup progress challenging. Overall, the software is a good addition to EMC studies and provides a visual side to the ever-growing topic.

6.1 Summary of Key Findings

OpenEMS handles simulation data and results using the HDF5 file format. This format enables efficient storage and structured access to large simulation outputs, a key point in high-resolution or broadband simulations. The platform supports post-processing and visualization through dedicated modules, allowing for field plotting and frequency domain transformations directly within the scripting interface.

In terms of extensibility, OpenEMS accommodates additional packages and modules and various material models, which can be invoked within the scripting layer. This supports the inclusion of anisotropic, dispersive, or lossy materials, thereby expanding the range of physical phenomena that can be modeled.

From an academic and research standpoint, OpenEMS provides a transparent and modifiable simulation environment. Its open-source nature allows full access to the underlying algorithms and solver mechanisms, which are beneficial to method development, verification, and reproducibility in research contexts.

Overall, OpenEMS presents a structured and adaptable platform for electromagnetic field simulation, with capabilities that support careful modeling, flexible scripting, and detailed data analysis across a broad range of applications in computational electromagnetics.

6.2 Challenges and Limitations in Simulation

A key limitation of OpenEMS is its lengthy simulation times, which can take hours even on advanced computing systems. At present, OpenEMS performs best in situations with standard material properties, potentially limiting its effectiveness for more complex analysis.

During setup, a problem was discovered in the OpenEMS macro, at least for MacOS. Python Function intended to detect duplicate entries caused errors during initialization. This issue was fixed by commenting out the problematic lines during preprocessing (Listing 1).

```

1425 # CHECK FOR DUPLICATES OF object in category where object is added

1426 isObjAlreadyInCategory = False
1427 itemWithSameName =
self.form.objectAssignmentRightTreeWidget.findItems(leftItem.text(0),
QtCore.Qt.MatchFixedString | QtCore.Qt.MatchFlag.MatchRecursive)
1428 for item in itemWithSameName:
1429 #there must be check if item has parent, if parent is None it means
it's category name and categories ALWAYS HAVE SUBCATEGORIES
1430     #case scenario::
1431         #         - item freecad obj is named excitation
1432         #         - there is excitation category
1433 #         - in itemWithSameName Excitation category is included so next
condition filter it away
1434     #
1435     if (item.parent() != None and item.parent() == rightItem):
1436         print(f"Found parent {item.parent().text(0)} item
1437         {item.text(0)}")
1438     isObjAlreadyInCategory = True
1439
1440     if (isObjAlreadyInCategory):
1441         self.guiHelpers.displayMessage(f"Object {leftItem.text(0)} already
exists in category {rightItem.text(0)}")

```

1442 `continue`

Listing 1 Duplicate Check in OpenEMS Macro

This change enabled stable simulation exports while maintaining the overall functionality of the FreeCAD OpenEMS interface. Such challenges are typical in open-source software, however, in this instance, the bug was minor and easily resolved.

6.3 Conclusion

Despite facing challenges during setup and simulation, OpenEMS has shown itself to be a flexible and informative tool for analyzing electromagnetic fields. Its open-source design, along with a wide range of customization options, positions it as a significant asset for both educational purposes and research in computational electromagnetics. Although there are areas for enhancement, especially regarding simulation efficiency and software stability, OpenEMS continues to serve as a robust platform for investigating both fundamental and advanced concepts in electromagnetism.

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Appendices

Appendix 1: Buck regulator schematics

