

# Magnetic Devices for a Beam Energy Recovery THz Free Electron Laser

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**Abstract:** This paper presents a numerical analysis of magnetic devices, dipole, quadrupole and undulator and a THz Free Electron Laser (FEL) electron-beam recovery system. Free Electron Laser are an important source of coherent radiation being used in the study of chemical properties of substances, thus being an important tool for various fields of science such as condensed matter physics, chemistry, biology and medicine. The magnetic device of this simulation is to contribute to the proposed deployment of a national laboratory for multiuser application and development of a recovery system FEL to operate in the far infrared range between 0.3 to 1.2 THz.

**Keywords:** Free Electron Laser THz, magnetic device, simulation in COMSOL.

## 1. Introduction

Free electron laser can be used are in spectroscopy thus have applications in scientific fields such as medicine, chemistry, condensed matter and biology [1]. Thus the Brazilian Center for Physics Research (CBPF) proposed a construction project of a Free Electron Laser (FEL) using the components of a Free Electron Laser of the College of Optics & Photonics (CREOL). The free-electron laser operating in the far infrared range working with wavelengths in the range of 200-600 micrometers. The equipment consists of a linear accelerator that generates electrostatic energy up to 1.7 MeV, a magnetic undulator, which is designed with permanent magnets made from neodymium iron boron (NdFeB) with 185 periods with a wavelength of 8 mm  $\lambda_u$  length of 1486 mm and a distance between the undulator cassette (gap) of 6 mm. Has magnetic dipoles and quadrupoles working in optics from the electron beam. The vacuum system is formed by mechanical, ionic pumps and turbomolecular [2], control is being developed for the LabView platform.

This paper focuses on the numerical analysis using the COMSOL software of magnetic elements that are the dipole, quadrupole and undulator. These components work changing the trajectory and the size of the electron beam.

## 2. Theory

### 2.1 Dipole

The magnetic dipole is an element that has the function deflect the electron beam [3]. The dipole magnetic field is generated by the electric current passing through the coils. This current in solenoid generates a magnetic flux in the iron core creating a unidirectional magnetic field in between irons given by the right hand rule. The magnitude of the magnetic field can be extracted by Ampere's law gives us the relationship between the electric current and the magnetic field.



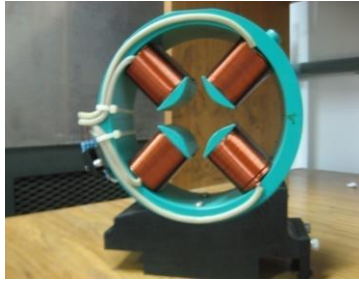
Figure 1: Magnetic dipole.

The dipole magnetic field is given by equation 1 where  $n$  is the number of turns, the electrical current  $I$ ,  $L_{gap}$  is the distance between the irons and  $\mu_0$  is the permeability of air.

$$B_{gap} = \frac{NI\mu_0}{L_{gap}} \quad (1)$$

## 2.2 Quadrupole

This component consists of four poles formed by rectangular hyperbolas with alternating magnetic fields, your objective is to change the diameter of the electron beam. The geometry of the quadrupole makes the magnetic field in the core is zero and the magnetic field is generated by modulo magnitude of the field in the x-axis and y-axis [3].



**Figure 2:** Magnetic quadrupole.

The quadrupole magnetic field can be calculated from the integration by Ampere's law.

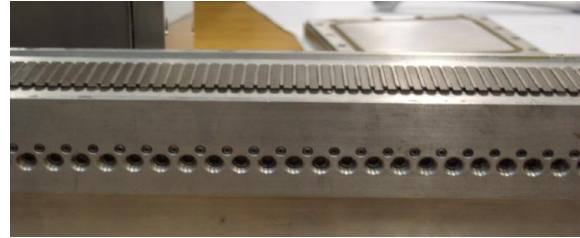
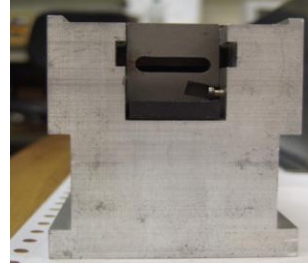
$$\int_B^A \vec{H}_1 \cdot d\vec{s} = NI \quad (2)$$

The magnetic field consists of two quadrupole components in the x and y axis, there is a resulting gradient  $g$  [T/ m]. Thus, the magnetic field in the x and y axes can be given by the equations  $B_x = gy$  e  $B_y = gx$ , where  $g = \frac{2\mu_0 NI}{r_0^2}$ , and the equation of the resulting magnetic field is equal to:

$$\mathbf{B} = \frac{2\mu_0 NI}{r_0} \quad (3)$$

## 2.3 Undulator

The undulator is a mechanical structure consisting of periodic magnets with alternating poles, separated by a distance called (gap). These magnets are made of magnetic material pure permanent magnetic (PPM). This structure causes synchronous radiation be concentrated in a beam, thus reducing the radiation loss.



**Figure 3:** Description of the undulator magnetic.

The magnetic undulator field is perpendicular to the x axis, and the direction of the z-axis. Because the poles are alternating magnetic field in the undulator has a sinusoidal behavior as can be seen in equation 4. [4]. Where  $\lambda$  is the wavelength of the undulator and  $B$  is the initial magnetic field. In equation 5 we have the initial magnetic field which is a ratio between the gap and the wavelength.

$$\mathbf{B} = -B_0 \text{sen} \left( \frac{2\pi}{\lambda_u} x \right) \quad (4)$$

$$B_0 [T] = 3.30 \exp \left\{ -\frac{g}{\lambda_u} \left( 4.94 - 1.45 \frac{g}{\lambda_u} \right) \right\} \quad (5)$$

## 3. Use of COMSOL Multiphysics

The numerical analysis of the dipole, quadrupole and undulator were built using the module AC/DC COMSOL multiphysics. To calculate the magnetic field in the dipole and quadrupole magnetic field the tool was used with the equation 6. In the undulator, the calculation of the initial magnetic field was carried out with the magnetic field in the current tool with the equation 7.

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}_e \quad \text{with} \quad \mathbf{B} = \nabla \times \mathbf{A} \quad (6)$$

$$\vec{\nabla} \cdot (\mu_0 \vec{\nabla} V_m - \mu_0 \mathbf{M}) = 0 \quad (7)$$

### 3.1 Dipole

The geometry of the dipole was constructed in 3D and has two types of materials are iron, which comprises all the dipole and charge air by the cylindrical shell. Infinite element domain was used for the cylindrical shell for emulating an infinite open space causing all numerical analysis considers the limited space as being infinite.

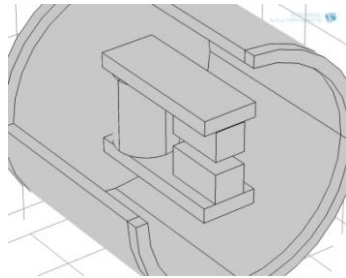


Figure 4. 3D geometry of the magnetic dipole.

The interface was used for the dipole Magnetic Field <Ampere Law for the iron structure and for calculating coil was used in Magnetic Field <muti-turn coil <Coil Current Calculation which calculate the magnetic field in the coil according to the current electrical and number of turns. The dipole has 877 turns and the maximum current is 2.5 A.

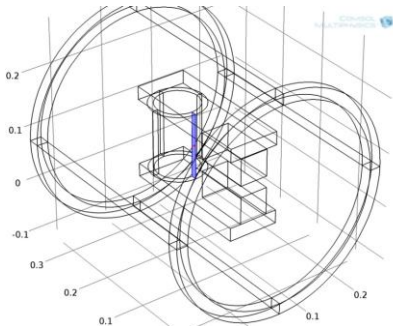


Figure 5. Coil Current Calculation in dipole magnetic.

Dipole in the fine mesh, which corresponds to 61114 domain element, boundary element 9728, 1039 edge element was used. The study used for the calculation of the dipole was the Stationary Parametric Sweep and the electric

current was applied in order to have values of -2.5 A to +2.5 A.

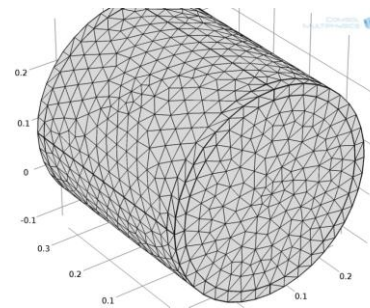


Figure 6: mesh magnetic Dipole.

### 3.2 Quadrupole

The quadrupole was developed in 3D for its construction it was done primarily in 2D and using the Work Plane tool, after it was extruded to 3D format.

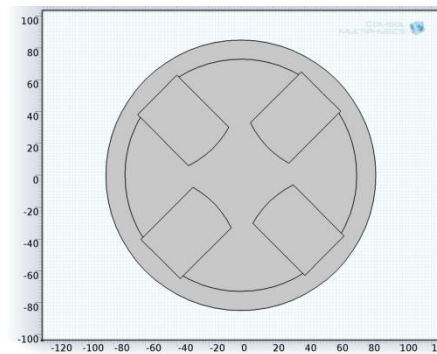


Figure7. Quadrupole magnetic geometric in 2D.

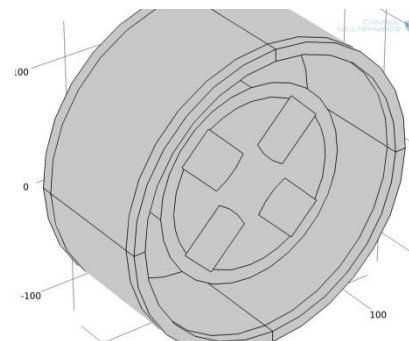
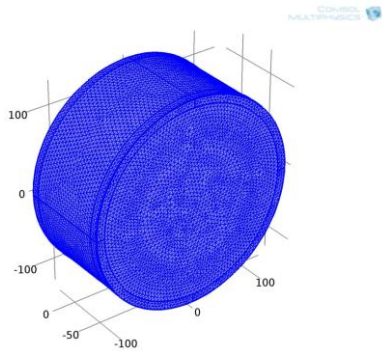


Figure 8. 3D geometry of the magnetic quadrupole.

The materials used in the quadrupole are air and iron and infinite element domain was applied to the cylindrical shell. To calculate the magnetic

field of the quadrupole physical Magnetic Field <Ampere Law, which calculates the magnetic field from the magnetization and uses equation was used  $M = \frac{NiA}{V}$ , where N is the number of turns, I is the electric current, A is the area and V is the volume of the coil. In the case of quadrupole have 344 turns and the electrical current worth 2.5 A. The magnetization in the quadrupole is oriented in the x and z axes have that each pole has a different orientation.

Quadrupole in the mesh extremely fine, which corresponds to 749885 domain element, boundary element 58352, 2772 edge element was used. The study used for the calculation of the quadrupole was the Stationary Parametric Sweep and the electric current was applied in order to have values of -2.5 A to +2.5 A.

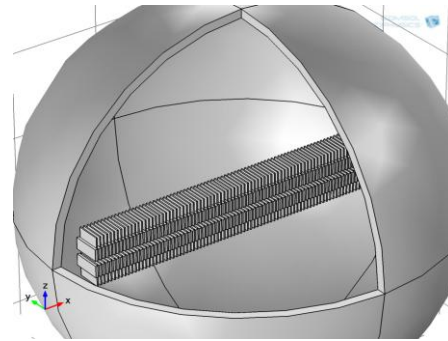


**Figure 9:** mesh magnetic quadrupole.

### 3.3 Undulator

For this work was a session of 3D undulator built with 400 mm in length and can change the wavelength and the distance of the gap. Undulator possessed these variations to resemble the original equipment. The initial magnetic field generated in the undulator does not depend on the distance of the gap but wavelength (equation 5) and thus it is possible to make a comparison between the simulation and the experiment.

The materials used were a NdFeB magnetic material is (33SH) and those manufactured with the air gaps 1010 steel, their averages are: x = 10.5 mm, y = 1.3 mm and z = 25 mm and x = 30mm, y = 2.7 mm and z = 13 mm, respectively [5]. On the external surface that is a spherical vacuum volume 220 mm radius of 5mm layer was used.



**Figure 10.** 3D geometry of the magnetic Undulator.

The magnetic field of the undulator was obtained using the Magnetic Field, No current Physical<Magnetic Flux. When applying a magnetic field in a material, the resulting field B is the sum of the applied field H and the field of the magnetized material, as in Equation 8.

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) \quad (8)$$

Magnetic materials have hysteresis magnetization curves called reduce to zero the magnetic field applied, as can be seen in equation 9 [6].

$$\mathbf{B} = \mu_0\mathbf{M} \quad (9)$$

The magnetization is added in Magnetic flux Conservation, as the magnetization of the magnets are oriented alternately is necessary to indicate the direction of magnetization in this case, the direction is along the x axis. The mesh used was extra fine, possessing 5842814 domain boundary elements 681 250 and 80 793 edge and the study used was stationary.

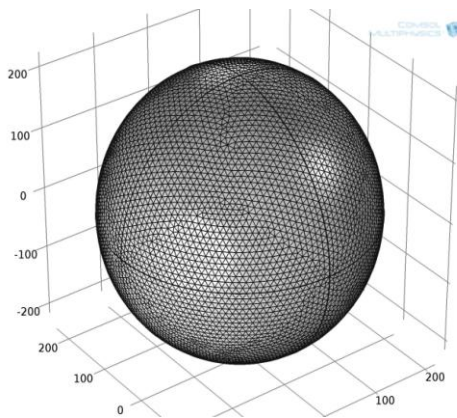


Figure 11. Mesh Undulator magnetic.

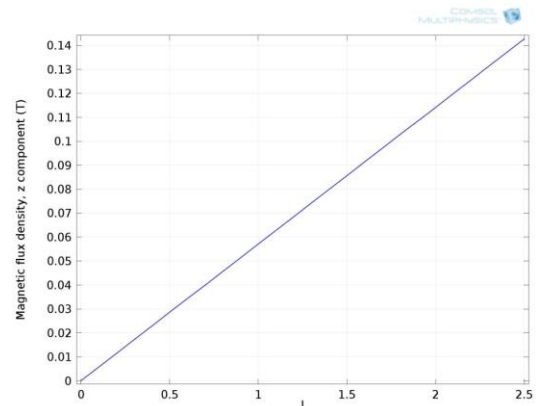


Figure 13. Graph magnetic field x current electric in dipole.

## 6.0 Results

### 6.1 Dipole

The simulation dipole was constructed to compare the value of the modulus of the magnetic field with the experimental value in Figures 12 and 13 have the simulation results.

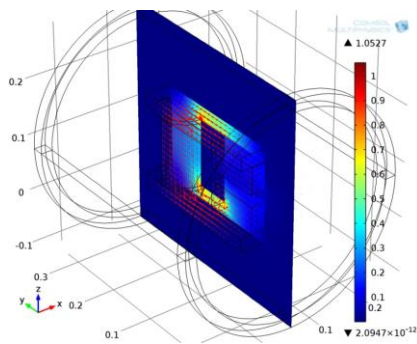


Figure 12. Magnetic Flux density in an dipole magnetic device.

**Table 1:** Comparison of the magnetic field obtained from the simulation and experimental analysis in the dipole magnetic device.

	Experimental	COMSOL
Magnetic Field (T)	0,11	0,14

The magnetic field values are obtained for the maximum value of electric current of 2.5 A. Thus the table 1 it can be seen that the three values are close to a percentage error of 3% between experiment and COMSOL.

### 6.2 Quadrupole

The simulation quadrupole was constructed to compare the value of the modulus of the magnetic field with the experimental value in Figures 14 and 15 have the simulation results.

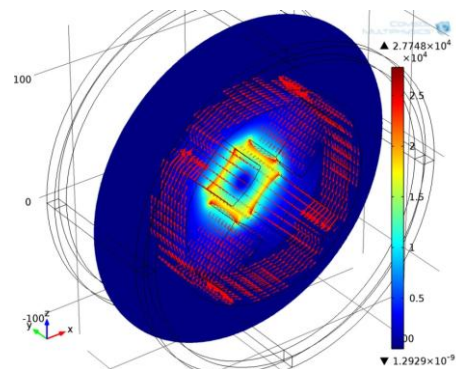
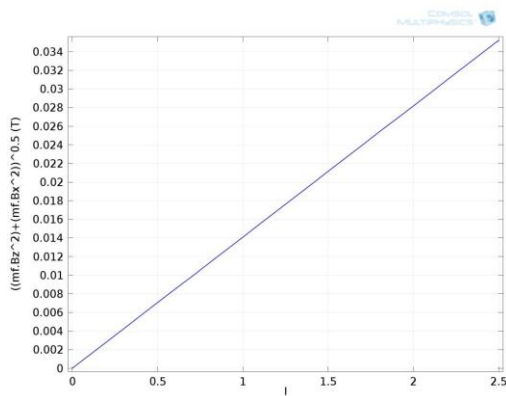


Figure 14. Magnetic Flux density in an quadrupole magnetic device.



**Figure 15.** Graph magnetic field x current electric in quadrupole.

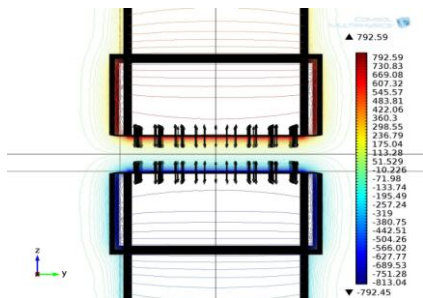
**Table 2:** Comparison of the magnetic field obtained from the simulation and experimental analysis in the quadrupole magnetic device.

	Experimental	COMSOL
magnetic Field (T)	0,054	0,035

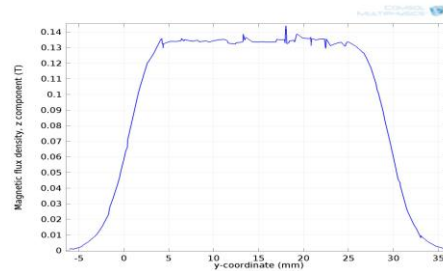
The magnetic field values are obtained for the maximum value of electric current of 2.5 A. Thus the table 2 it can be seen that the three values are close to a percentage error of 1,9 % between CREOL and experiment.

### 6.3 Undulator

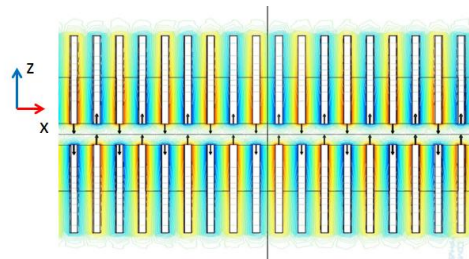
The simulation study of the undulator was developed for the x axis and y axis. In Figures 16, 17, 18 and 19 have a magnetic field initial described in the two axes respectively.



**Figure 16.** Magnetic Flux density in an undulator magnetic device (front view).

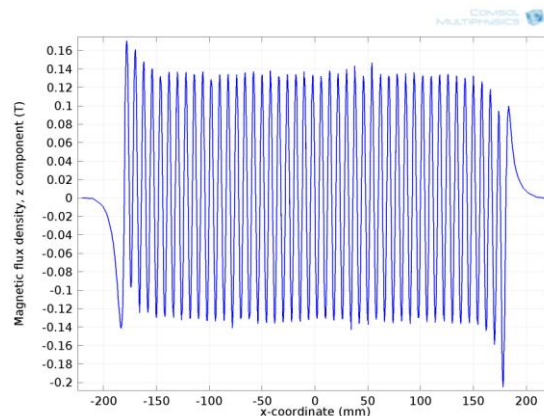


**Figure17.** Magnetic field of the undulator gap measured in the z axis direction with respect to distance in the y direction.



**Figure 18.** Magnetic Flux density in an undulator magnetic device (side view).

In Figure 19 we have the magnetic field in the undulator which is a sine function according to equation 10, so this simulation is in agreement with theory. In Table 3 it can be observed that the values stipulated by the project, experiment and COMSOL, so it is possible that there is an error 1% compared to COMSOL and experiment.



**Figure 19.** Undulator magnetic field measured at the gap in the z direction as a function of distance in the x direction.

**Table 3:** Comparison of the magnetic field obtained from the simulation and experimental analysis in the undulator magnetic device.

	Experimental	COMSOL
Average magnetic field initial (T)	0,13	0,12

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## 7.0 Conclusion

In this paper we present 3D simulations of the dipole, quadrupole and undulator magnetic elements that are owned by a Thz Free Electron Laser. The results have to numerical simulation results are in agreement with experiment validating the paper. To the next module using the practical tracing in COMSOL, an electron beam will be added with the aim of studying the behavior of the electron beam in magnetic elements.

## 8 Reference

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