OPEN LAB REPORT 2
Magnet design For Sputtering process of thin film deposition.

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1 Theory of Sputtering:

Sputtering[1] is the process of removing surface atoms from a target by particle (usually ion) bombardment. The liberated surface atoms can move to a surface(The substrate) to be coated and may condense there, thereby contributing to forming a solid (thin) film or (thick coating).

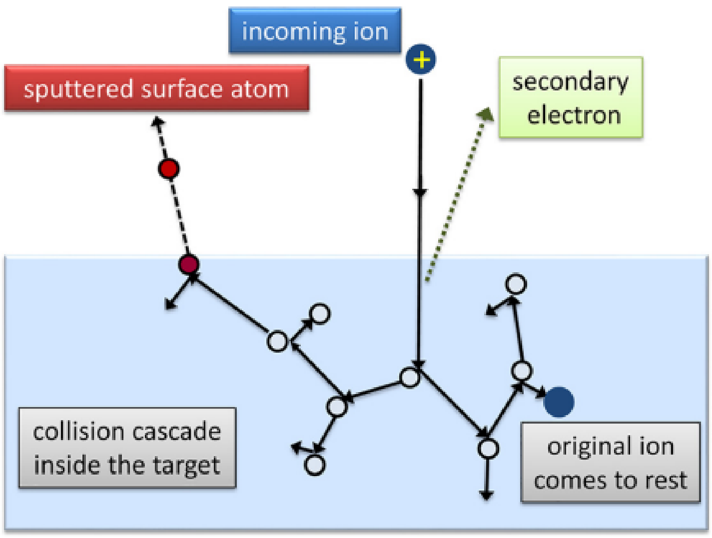


Figure 1: Collision cascade initiated by incoming energetic ions.

A collision cascade is triggered inside the target, caused by an energetic ion, knocking off one or more surface atoms. The fate of the original ion, which comes to rest in the target, depends on its chemical nature. Besides surface atoms, secondary electrons may also be emitted—they play an important role in sustaining the electric discharge.

In terms of film deposition by sputtering, an important parameter is the sputtering yield Y, defined as the ratio of the number of sputtered atoms, N_a, to the number of incident ions, N_i:

$$Y = \frac{N_a}{N_i} \tag{1}$$

In order to cause any sputtering, the incoming ion needs to have a minimum threshold energy,E_th. The threshold energy is directly related to the surface binding energy, E_{SB}, and also depends on the mass of the incident ion M_i and the target atoms, M_a, respectively.

$$E_{th} = E_{SB} \begin{cases} (1 + 5.7(\frac{M_i}{M_a}))/\Lambda & \text{for } M_i \leq M_a \\ 6.7/\Lambda & \text{for } M_i \geq M_a \end{cases} \tag{2}$$

[1]Tutorial: Reactive high power impulse magnetron sputtering (R-HiPIMS): J. Appl. Phys. 121,171101 (2017); https://doi.org/10.1063/1.4978350

Where,

$$\Lambda = \frac{4M_iM_a}{(M_i+M_a)^2} \tag{3}$$

is the energy transfer factor in an elastic equation.

The following is an example how the sputtering yield typically depends on energy of incident ion.

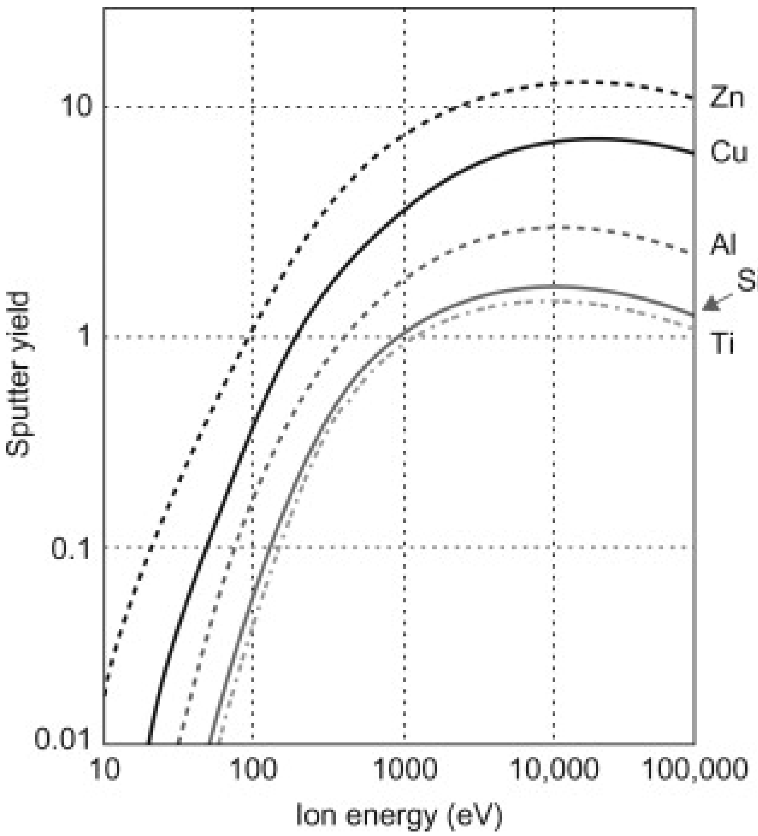


Figure 2: Caption

Discussion:

1. Low-energy (subthreshold) sputtering: at ion energies below the surface binding energy of the cathode material, typically <50 eV, sputter yields are orders of magnitude less than unity, in the range of 10^{-2} to 10^{-6}, since the bombarding ions can only eject the most loosely bound surface atoms or adsorbed molecular species.

2. Ion energies in the range of $\approx$ 10 eV to 1 keV are of prime interest for commercial and industrial applications of sputtering. Once the energy of the sputtering ions is greater than the surface binding energy of the cathode material, it is energetically possible to dislodge surface and near-surface atoms from their equilibrium sites. These dislodged atoms then in turn set in motion recoil collisions which eventually result in the ejection of atoms from the cathode surface. The key hallmark of this energy regime is the roughly linear dependence of the sputter yield on the ion bombardment energy and the ion current. Sputter yields in this regime are generally in the range of 0.1–3.0 for most materials of technological interest.

3. Above an ion threshold energy of 1 keV, collision-cascade (nonlinear cascade) sputtering behavior is observed, in which the incident ions have enough energy to dislodge multiple cathode atoms. Sputter yields in this regime will be in the range of 5 to 50 and higher. Due to the high energies required and the high ejected energies of the sputtered atoms, this regime is usually not of industrial interest. Incident ion energies above 50 keV result in deep-ion implantation into the cathode and a reduction in net sputter yield.

2 Magnetron Sputtering:

The magnetron uses a magnet most often, but not always, a permanent magnet to effectively trap and utilize energetic electrons for ionization processes at low pressure. The magnetron discharge is a magnetically enhanced glow discharge. The magnetic field is used to "magnetize" electrons, which means that electrons can complete many gyrations, effectively allowing an electron to travel a much longer path in the same general space in front of the target than without the magnet. This allows us to operate the magnetron discharge at a much lower pressure (typically 1 Pa or even lower) than conventional glow discharges (typically 10 Pa or higher). Magnetization of electrons requires that the magnetic field is sufficiently strong so that the gyration radius

$$r_{g,e} = \frac{m_e u_{e\perp}}{eB} \tag{4}$$

is much smaller than a characteristic device dimension.$u_{e\perp}$ is the electron's velocity component perpendicular to the magnetic field vector $\vec{B}$.e is the electron's charge.m_e is the mass of electron.

A good characteristic dimension is the curvature radius of magnetic field vector over the target.The ions produced are accelerated by electric field toward the target causing the desired target sputtering process.

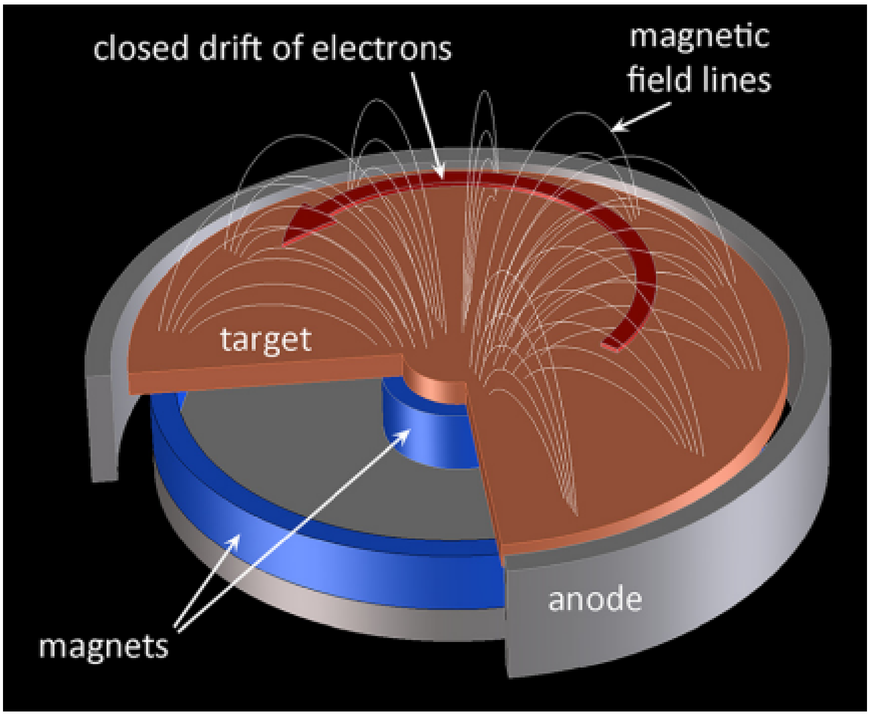


Figure 3: planar magnetron with a disk target

Magnetic field lines are approximate equipotential lines due to the high mobility of electrons along the field lines. As a result, the electric field is essentially perpendicular to the magnetic field.If we average over the periodic motion of gyration and the oscillatory motion of electrons along the field lines, we arrive at an average electron drift motion in the $\vec{E}X\vec{B}$ direction. The clever design of a magnetron makes use of the drift by closing the drift path: electrons, on average, drift back to the point where they came from, as indicated by the large curved arrow in Fig. 3[2]. The velocity of this drift is:

$$\vec{V}_{ExB} = \frac{\vec{E}X\vec{B}}{B^2} \tag{5}$$

[2]Image Source:Tutorial: Reactive high power impulse magnetron sputtering (R-HiPIMS): J. Appl. Phys. 121,171101 (2017); https://doi.org/10.1063/1.4978350

3 Magnetostatic problem and Finite element Analysis Software:

Magnetostatics Problem

$$\Delta . \vec{B} = 0 \implies \vec{B} = \Delta \times \vec{A}, \Delta \times \vec{B} = \mu_o \vec{J}$$

Coulomb Gauge $\Delta . \vec{A} = 0$

$$\boxed{-\Delta^2 \vec{A} = \mu_0 \vec{J}}$$

Magnetic materials

$$\vec{B} = \mu_o \vec{H} + \vec{M} = \mu_0 (1 + \chi_m) \vec{H} = \mu \vec{H}$$

magnetisation vector field equivalent to volume current density J_m

$$\vec{J}_m = \Delta \times \vec{M}$$

$$\frac{1}{\mu_0} \Delta \times \vec{B} = \vec{J}_{free} + \vec{J}_m = \vec{J}_{free} + \Delta \times \vec{M}$$

$$\Delta \times (\frac{1}{\mu_0} \vec{B} - \vec{M}) = \Delta \times \vec{H} = \vec{J}_{free}$$

Permanent magnet $\vec{J}_{free} = 0$

$$\Delta \times \vec{H} = 0 \implies \vec{H} = \Delta V$$

$$\implies \boxed{\Delta . (\mu_0 (\Delta V + \vec{M})) = 0}$$

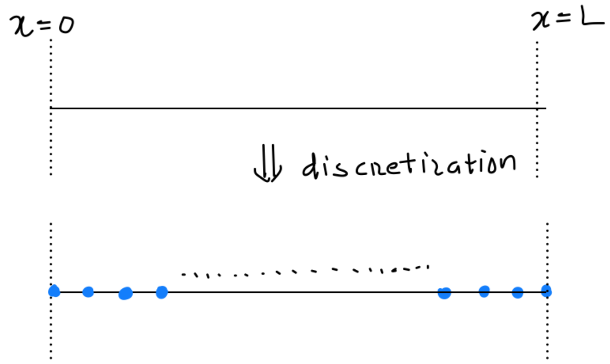
Figure 4: Differential equation to be solved in Magnetostatics

Finite Element Analysis

- **FEA is a computational technique used to obtain approximate solutions of boundary value problem.**
- **Governing differential equations and Boundary conditions.**
- **Governing equations are written in Integral equations equivalent to the original form.**
- **The Domain is broken into many smaller finite elements like triangles ,tetrahedrons ,squares.**
- **Finite element approximations:**

$$u(x) \approx \sum_{i=1}^{n} N_i(x) . u_i \qquad u(x) \approx [N]\{U\}$$

$N_i(x)$ **are very simple functions like** $1 - x, x^2$ **etc.**



These approximations plugged in to the Integral form to obtain an algebraic system of equations to solve for {U}.

Software used:FEMM ,COMSOL

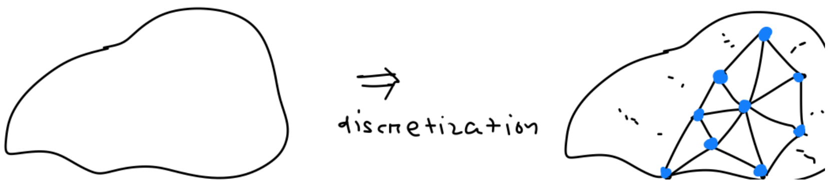


Figure 5: Finite Element Software

4 Magnet Design:

On an Iron Yoke There are two semicircular discs having radius 10 cm.They are separated by a distance of 1 cm.

magnetic Problem Definition

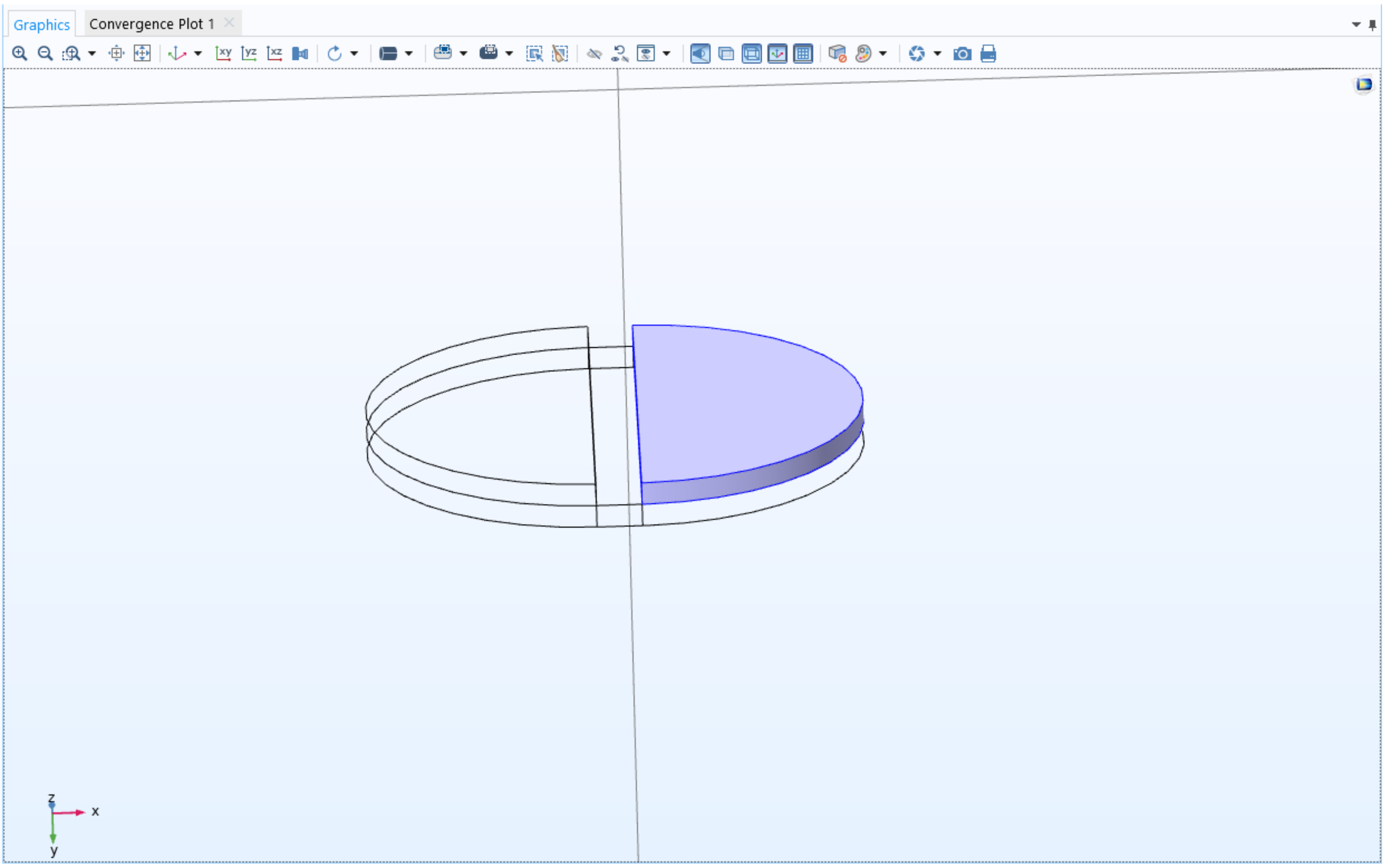


Figure 6: Magnet geometry

Field Lines

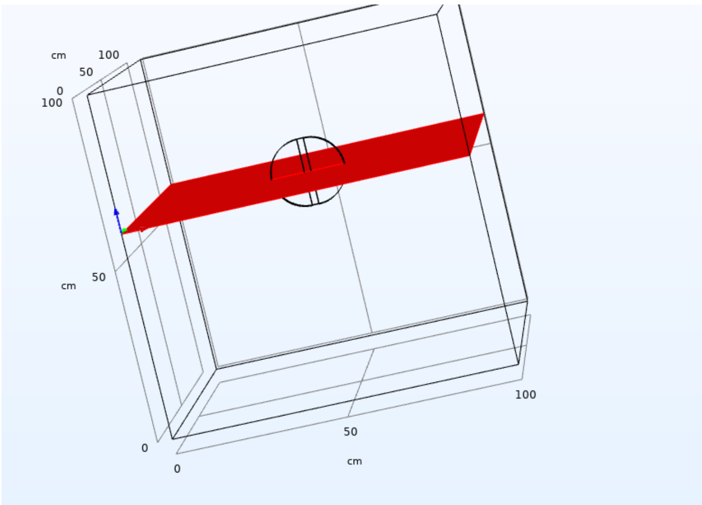


Figure 7: Plane cutting through the Magnet perpendicular to plane of Semicircular Disc.

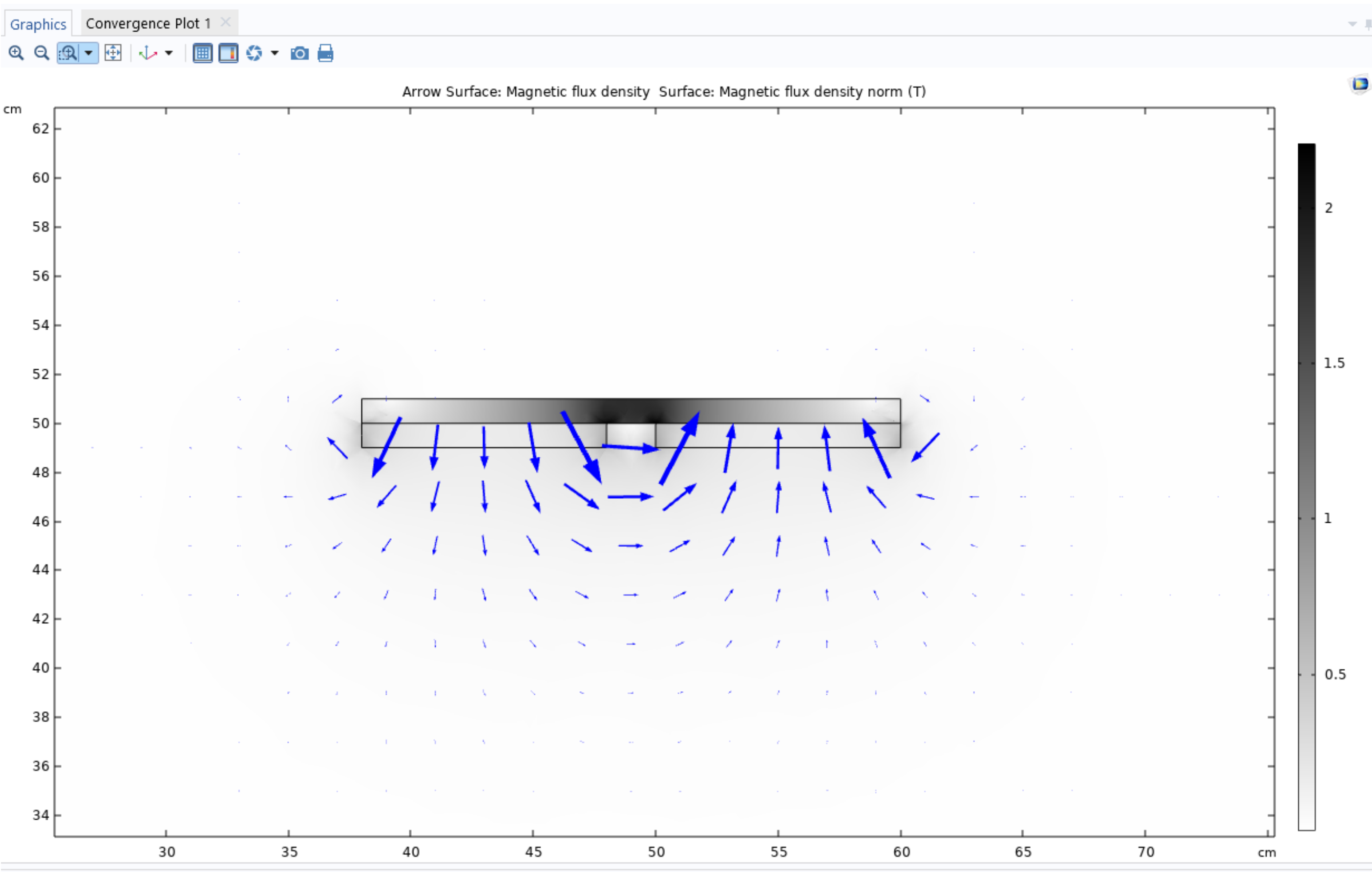


Figure 8: Plot of component of Magnetic Field Lines On the Plane Defined in fig.7

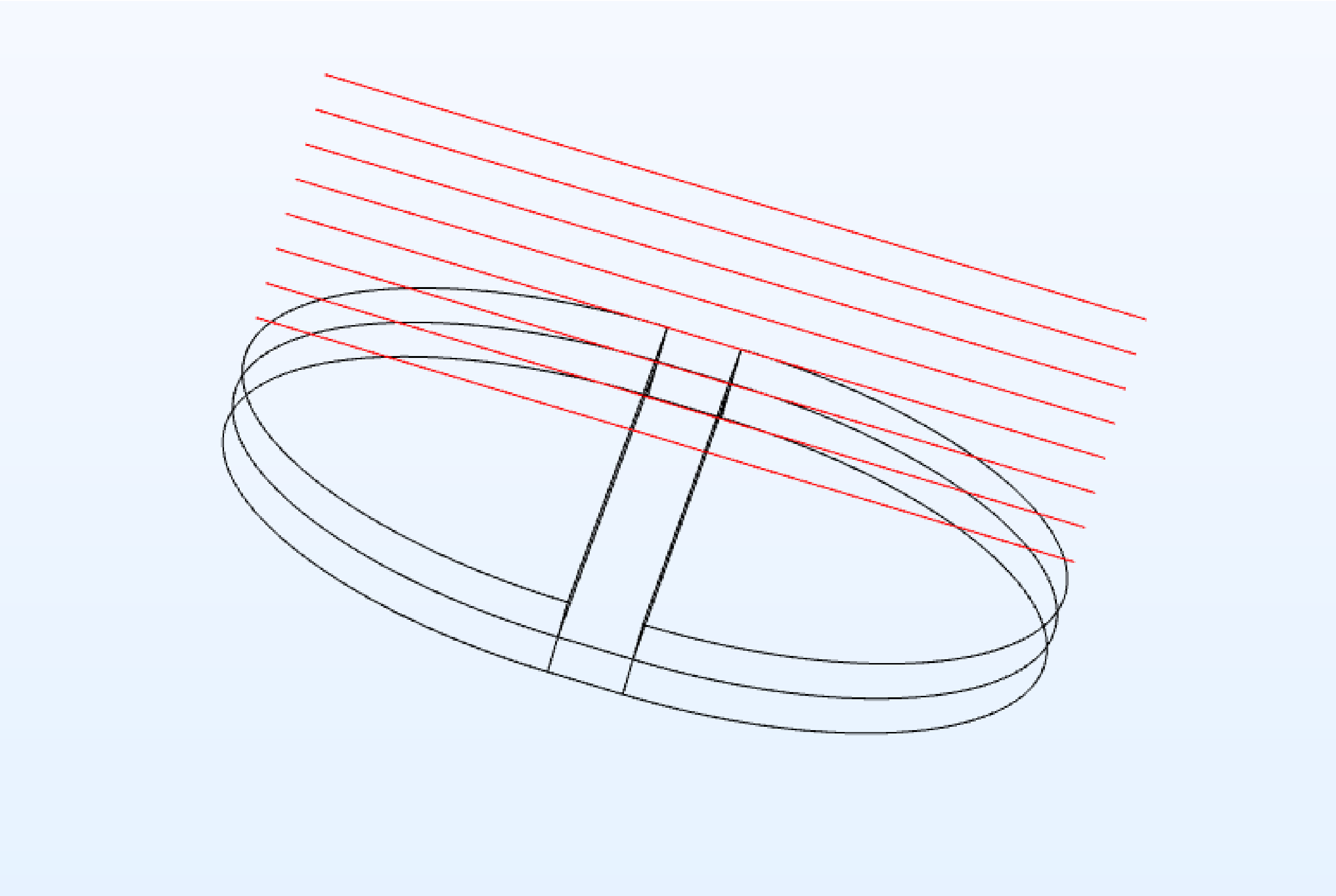


Figure 9: Series Of straight lines starting with a distance of 2 cm from magnet.Distance Increases by 1cm.

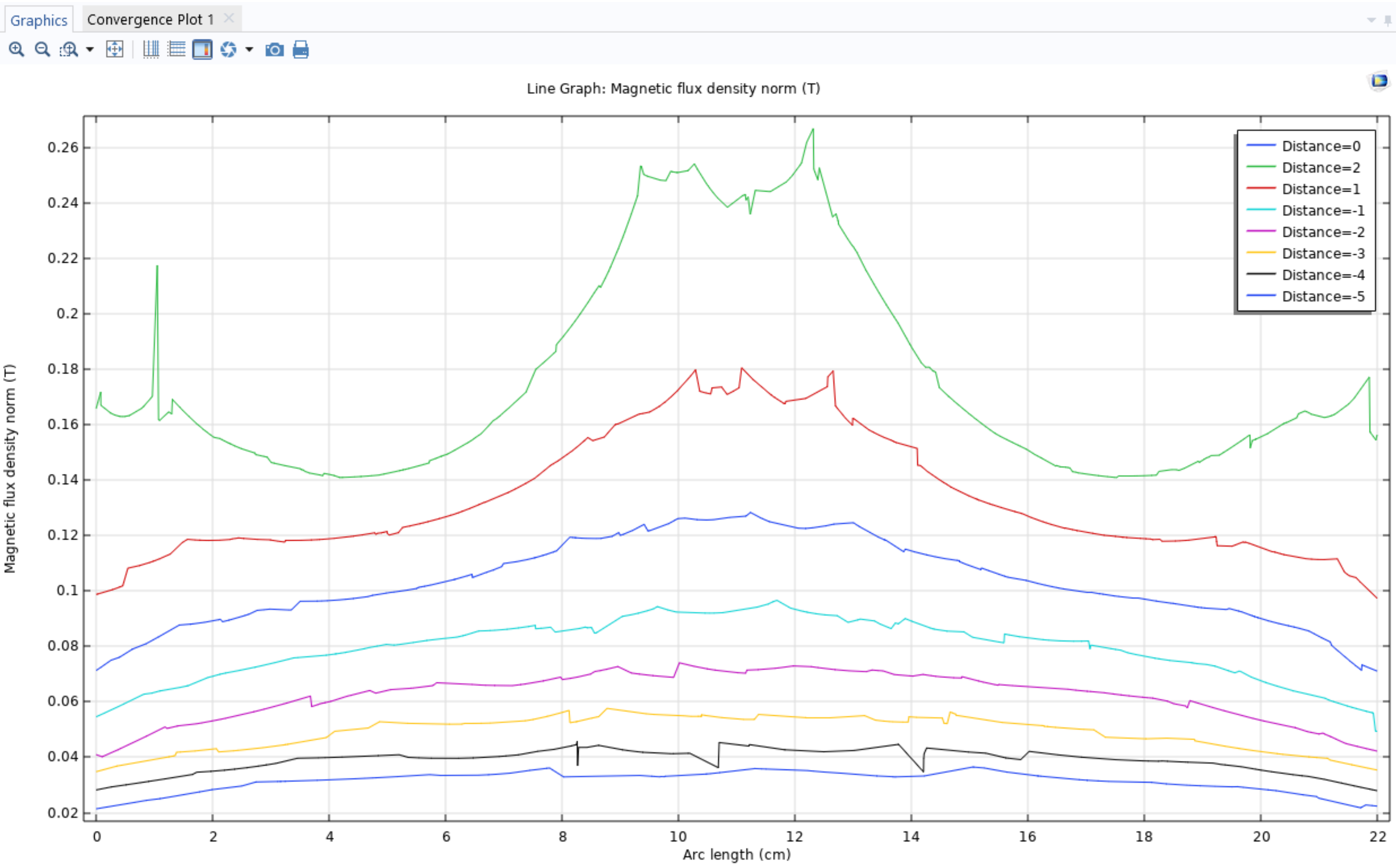


Figure 10: Plots of Magnetic Flux Density Norm on the straight lines defined in Fig.9

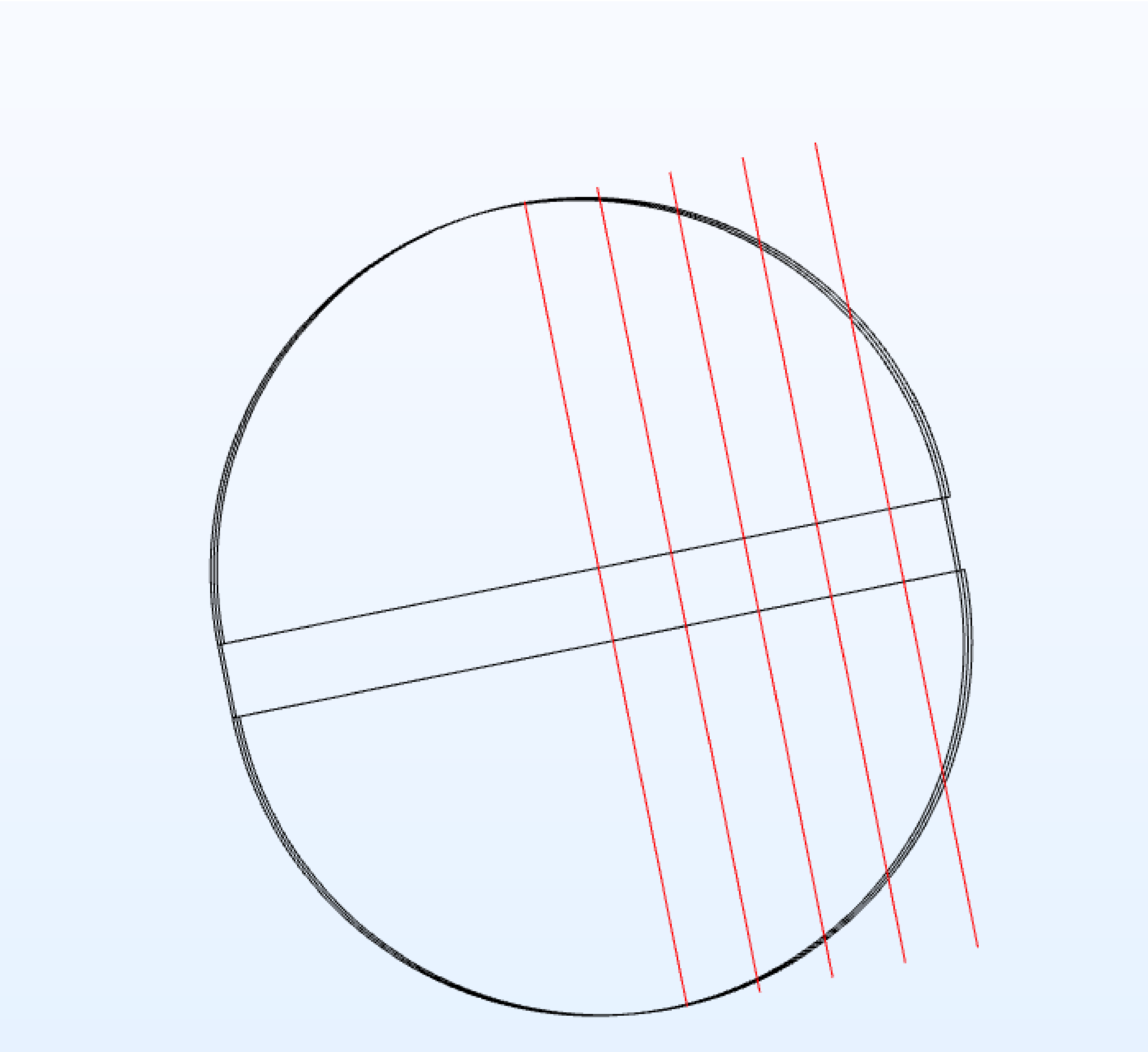


Figure 11: Series Of Straight lines at a height of 4 cm from magnet.Distance Increases by 2 cm.

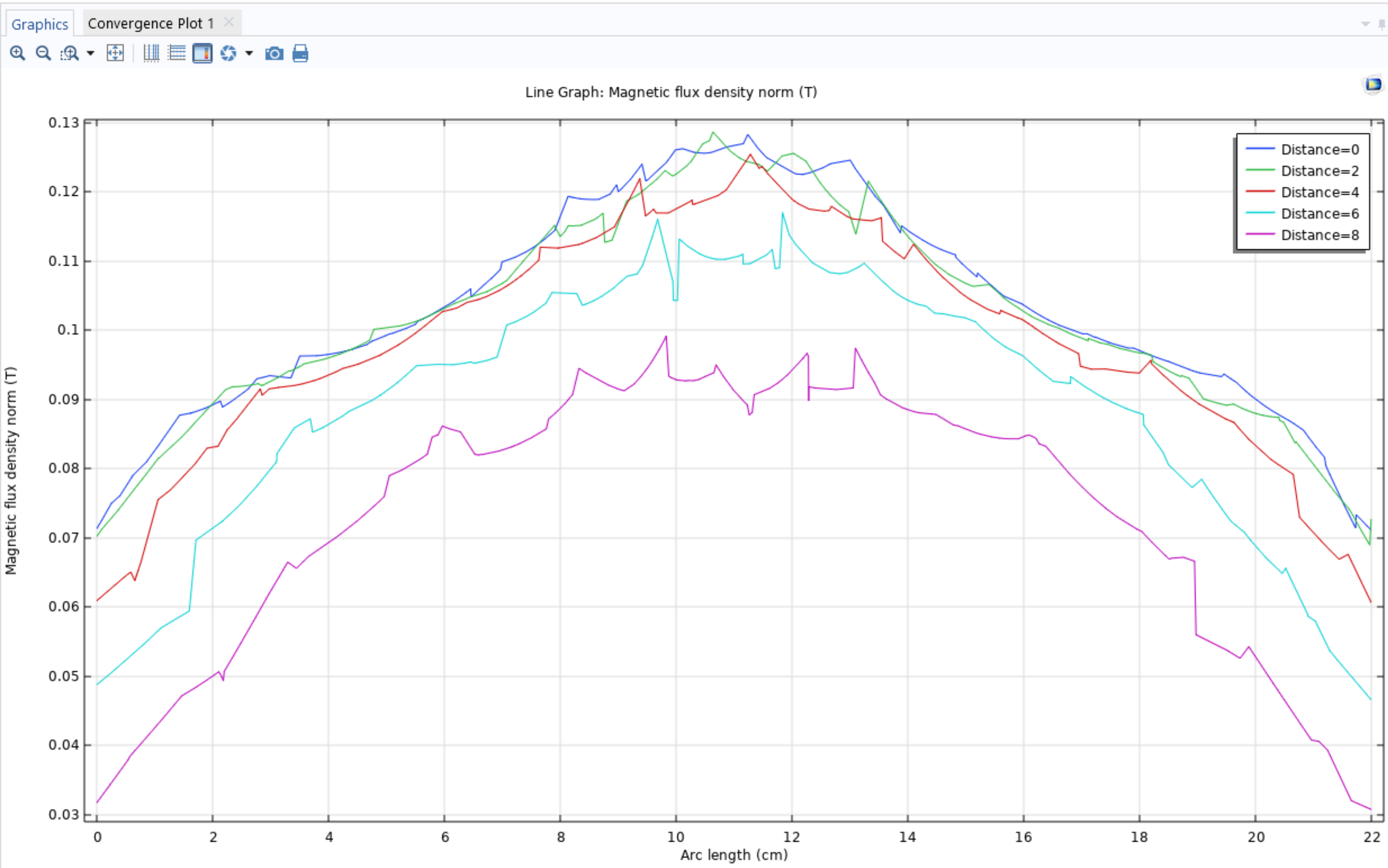


Figure 12: Plots of Magnetic Flux Density Norm on the straight lines defined in Fig.11

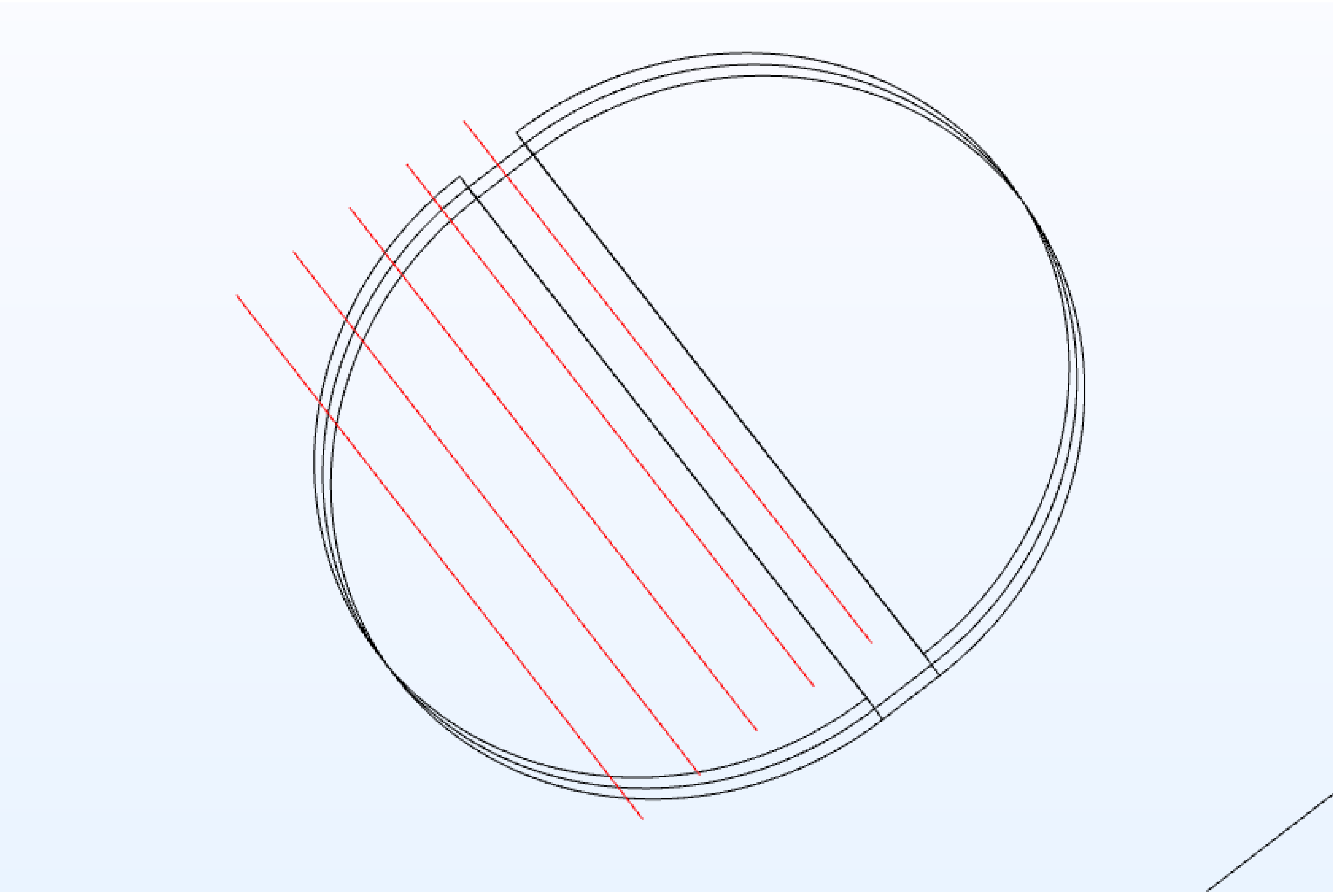


Figure 13: Series Of Straight lines at a height of 4 cm from magnet.Distance Increases by 2 cm.

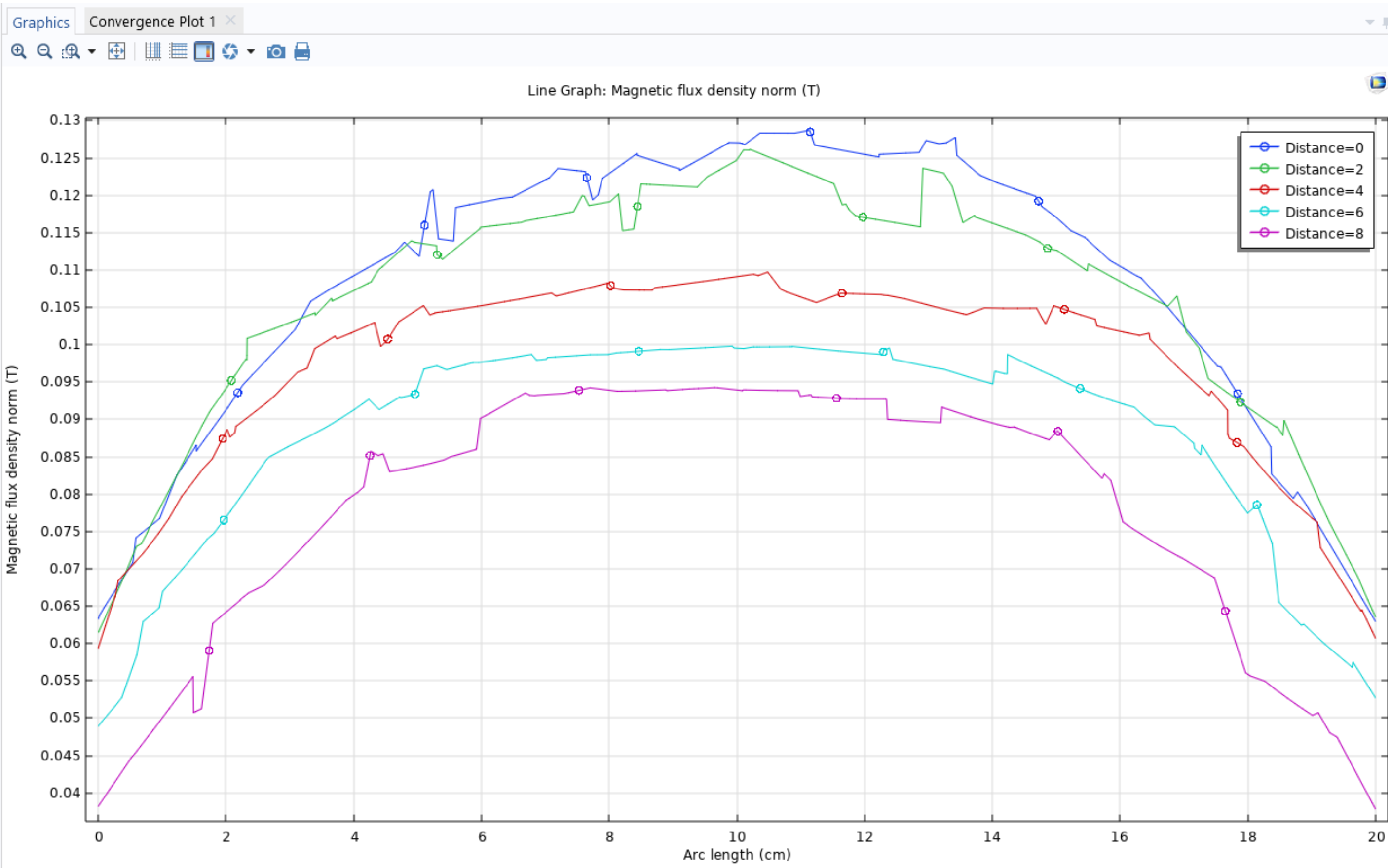


Figure 14: Plots of Magnetic Flux Density Norm on the straight lines defined in Fig.13

5 Conclusion

We started with simple Magnet Designs.They have been Submitted in the First report.The Magnet Design Shown in this Report is the best one designed So far in the semester.Initially we had been trying geometries with a presence of central cylindrical magnet was giving us a central dip in the flux density.Removal of that led to better uniformity.But How the plasma behaves in the field lines generated by the design presented in this report is yet to be simulated.

6 References:

1. Tutorial: Reactive high power impulse magnetron sputtering (R-HiPIMS): J. Appl. Phys. 121, 171101 (2017); https://doi.org/10.1063/1.4978350 Submitted: 17 November 2016 • Accepted: 18 February 2017 • Published Online: 21 March 2017

2. Physics and technology of magnetron sputtering discharges : J T Gudmundsson 2020 Plasma Sources Sci. Technol. 29 113001

3. COMSOL MANUAL:https://www.comsol.com/multiphysics/magnetostatics-theory

4. FEMM Manual:https://www.femm.info/Archives/doc/manual42.pdf