

Orinigal Article

Simulation Study on the Variation of Electric Field and Potential within Electrostatic Wiggler

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Abstract: Radiation is a naturally occurring component of our surroundings and can be produced intentionally or naturally. The free electron laser (FEL) is a novel form of coherent radiation based on three waves: the incident wave, the pump wave, and the space charge wave. This study examined the reduction of electron shift in electrostatic wiggler systems by analyzing variations in electric fields and potentials. It found that a narrow electrode at the entrance region can overcome electron beam shift defects by reducing the strength of the electric potential. Electrostatic wigglers that are meant to generate electromagnetic radiation are available in a variety of voltages. The oscillation of a beam of electrons that has gone through an electric field with an alternating electric field is caused by the electric field. Subsequently, electrons travel via a wiggler and then proceed straight ahead. The strong magnetic influence exerted by the first electrode of the wiggler causes the trajectory of the electron beam to wander from its optical axis during the experiment. Both the route of the electron beam and the oscillatory motion that occurs within a wiggler system are affected by the modification of electric potential and field strength. These aspects have been thoroughly researched for the electrostatic wigglers. Due to the fact that they are unable to escape from the wiggler, the electron beam that is moving away from its optical axis is unable to generate electromagnetic radiation. This departure of the beam from the optical axis causes the electron beam to collide with one of the electrodes that are held in place by the wiggler. The electron beam shift from its optical axis can be minimized through the employment of a few different approaches. These methods include either reducing the voltage of the first pair of electrodes in comparison to the other electrodes or limiting the width of the first pair of electrodes in comparison to the other electrodes.

Keywords: radiation, COMSOL, electrostatic wigglers, electro-magnetic wave

1. INTRODUCTION

Radiation is a naturally occurring component of our surroundings and can be produced intentionally or naturally. Over the past century, people have been exposed to radiation from various sources, including medical advancements that require higher amounts of radiation [1]. The free electron laser (FEL) is a novel form of coherent radiation based on three waves: the incident wave, the pump wave, and the space charge wave. FELs have high frequencies, powerful output, and tunable frequencies ranging from microwave to x-ray. The wiggler structure in free electron radiation generates radiation when electrons are moving at a faster speed. To provide superior quality radiation, the electron beam must be

meticulously controlled, oscillated at regular intervals, and maintained in a symmetrical configuration. Electrostatic wigglers and electro-magnetic wave wigglers were developed to perform similar roles to magneto-static wigglers [2]. The planar electrostatic wiggler is capable of modulating the motion of relativistic electrons effectively, just like the magneto-static wiggler in free-electron lasers. The X-ray free electron laser (XFEL) is considered the next generation of light sources due to its wide range of applications in various fields, including human health, agriculture, mining and minerals, research, industries, archaeology, energy generation, precise measurement, diagnosis, and semiconductor device creation. Scientists are encouraged to participate in the field of X-ray free electron laser due to significant discoveries and breakthroughs in the field of radiations [3]. The FEL is recognized as a one-of-a-kind instrument for scientific applications that require controllable coherent light in the far-infrared wavelengths. Many industrial companies are conducting extensive research into FEL technology to create strong UV FELs for use in industrial applications such as material processing, lithography, isotope separation, and chemical applications. FELs have proven output throughout a range of frequencies that extend far beyond the microwave spectrum and well into the visible and ultraviolet range, distinguishing them from other high power microwave sources. Radiation is a crucial component of our environment and has been used in various fields for over a century [4]. The development of FELs and wigglers has led to advancements in various fields, including medicine, energy generation, and semiconductor devices. This study focuses on the oscillation of electrons within an electrostatic wiggler due to variations in electric field and electric potential. Two types of wigglers are electrostatic and magneto-static wigglers [5]. Magneto-static wigglers use alternate magnet positioning to create a sinusoidal magnetic field, which controls relativistic electrons and pumps kinetic energy to the wave. They are responsible for linking electron motion with the electromagnetic wave model and pumping kinetic energy to the wave. Electro-static wigglers stack metallic plates in pairs or rings in parallel arrangements, generating an electromagnetic field within the wiggler. This field facilitates the oscillation of the electron beam created by the electron source, leading to the generation of electromagnetic radiation. However, the magnetic wiggler has a limited period, typically three centimeters, while the electrostatic wiggler can be extended to millimeters [6]. Two distinct varieties of electrostatic wigglers are available: ring-type electrostatic wiggler and planar type electrostatic wiggler. Ring-type wigglers consist of a sequence of co-axial conducting rings, with alternating rings biased with opposite potentials. They have a coaxial arrangement of each ring-shaped electrode along one axial line, with the inner radius (R) and width (W) organized coaxially. Planar type electrostatic wigglers form when metallic plates are aligned parallel in pair. Different voltages applied to the plates generate an electromagnetic field and potential, causing the oscillation of the electron stream. Electromagnetic radiation is produced by the oscillation of the electron beam inside the wiggler. This study investigates the electric field and electric potential within the planar type electrostatic wiggler and the radiation generated by the wiggler as a result of electron oscillation. Planar type wigglers are divided into two types: symmetric and asymmetric types [7]. Symmetric type wigglers have alternating electrode pairs biased in the opposite direction, while asymmetric type wigglers have both alternating electrode pairs biased in the same direction. Asymmetric type wiggler refers to the operation where electrodes are supplied with voltages at opposite potentials to parallel electrodes facing each other. This process generates an oscillating electric field and potential for charged particles, causing electrons to oscillate in a transverse direction, resulting in the generation of electromagnetic waves with a certain wavelength. Controlling the design parameter of the wiggler allows for the length of the electromagnetic wave's wavelength to be altered [8]. When operating in symmetric mode, there is no shift in the trajectory of the electron beam. However, when operating in asymmetric mode, the shift of the electron beam trajectory from the optical axis becomes more significant as it moves through the wiggler due to the fluctuating electric field and potential generated by the electrostatic wiggler. A typical electron beam going through a planar type wiggler tends to shift in a particular direction when operating in asymmetric mode. In symmetric mode, electron beam paths do not vary as much as they do in other modes of operation [9]. However, electrons within a specific range can oscillate with a significant amplitude, while electrons close to the optical axis are subjected to a transverse electric field

that is relatively weak due to the bias configuration of symmetric mode. The efficiency of an asymmetric planar type wiggler decreases due to electron deviation from their optical axis. The beam shift is determined by the physical features of the device, including the number of electrodes, width of the electrodes, insulating gap between the electrodes, distance between the upper and lower electrodes, and voltage settings applied. The equation for beam shift by the first electrode of a planar type wiggler can be expressed as $\Delta x = \frac{1}{2} a_x t^2$ equals $\frac{1}{2} (2\text{eV/ms}) \left(\frac{w}{v} \right) \phi^2$. The beam shift is proportional to the square of the electrode width, denoted by w , and the second parameter, S . Maintaining a consistent spacing is essential for obtaining an electromagnetic wave with favorable spectral properties [10]. An increase in FEL efficiency is made possible by using electron beam prebunching, which also decreases the time required to build up power, offers stable radiation at a single Eigen frequency, and prevents the accumulation of other modes. A high-energy electron beam passing through a wiggler generates waves, with the wiggler's period determining the wavelength of the spectrum. The electron beam oscillates periodically, generating electromagnetic waves and emitting radiation. The wiggler's parameters can influence beam shift, increasing efficiency and potentiality. To minimize beam shifting, the wiggler's parameters can be changed [11]. The electron beam in a wiggler is a non-linear medium, producing shorter wave lengths like conventional lasers. The optimization of a free electron radiation (FEL) design usually involves minimizing the FEL power gain length. The beam shift in a wiggler system is directly proportional to the square of width of an electrode. To reduce the overall electron beam shift, the first electrode of the electrostatic wiggler should be narrower than other electrodes. This reduces the electric field strength and potentiality at the entrance of the wiggler, reducing electron beam deviation due to the electric field at the first electrode. The length of the first pair of electrodes in an asymmetric type wiggler can be varied or reduced to study different types of electric fields and their potential distribution in the XZ-plane [12]. Reducing the length of the first pair of electrode also reduces the electric field and potential, resulting in trajectories of the electron beam remaining almost parallel with the optical axis. Simulation results for bias voltage ± 50 V and ± 100 V show similar characteristics, with smaller widths resulting in lesser beam shift due to smaller electric field and potential [13]. This study explored the phenomenon of electron shift reduction in electrostatic wiggler systems by analyzing variations in electric fields and potentials within the system. Data was collected along the z-axis at a distance of $5\mu\text{m}$ from the optical axis [13]. when bias voltage is ± 50 V, changes in the electric field inside the wiggler system are observed. The main difference is seen at the position and voltage of the entrance electrode. The field strength of narrow electrode ($w = 1\mu\text{m}$) is much weaker than wider electrode ($w = 10\mu\text{m}$), resulting in a smaller shift in $w = 1\mu\text{m}$. When voltages are applied at the electrodes of electrostatic wigglers, electric potential is generated inside the wiggler. Strong electric potential makes the electron beam shift from its optical axis, while weak electric potential cannot shift the electron beam from its optical axis, resulting in electromagnetic radiations [14]. The length of the first pair of electrode can be reduced to avoid beam deviation from its optical axis. Simulation work was performed by selecting a different value of w for a specific value of W , which can be generalized to an arbitrary value of W if the relation between w and W is maintained [15]. The simulation work suggests that the electron beam shift in electrostatic wiggler can be overcome by taking a narrow electrode at the entrance region of the wiggler, as it reduces the strength of the electric potential at the entrance. This study also found that reducing the voltage of the first pair of electrodes can reduce the electron beam shift, as weak electric potential is generated at the entrance of the wiggler due to applied low voltage. This weak electric field cannot shift the electron beam from the optical axis, resulting in a reduced beam shift. In conclusion, this study highlights the importance of understanding the variation of electric field and potential generated inside the electrostatic wiggler system to understand the phenomenon of electron shift reduction [16]. This study investigated the oscillation of electrons within an electrostatic wiggler due to variations in electric field and electric potential.

2. MATERIALS AND METHODS

This study required an atmosphere in which the effect of the outside world, which comes from a variety of radiation sources, should not interfere. Additionally, in this work, different voltages are employed in

the electrode, and these voltages need to be changed continuously. For the purpose of conducting experiments, it is challenging to establish such a setting in the laboratory. Because of this, the work for the dissertation is being studied and carried out on the computer. The wiggler is the subject of a simulation research that is carried out with the assistance of several computer programs. In the event that it is necessary, COMSOL Multiphysics provides an excellent platform for performing finite element analysis, problem solving, and model designing. In addition to chemical and mechanical applications, it also offers a single workflow for electrical and mechanical applications. It is a simulation platform that assists in all of the stages of the modelling workflow, beginning with the definition of geometrical material qualities and the physics that explains specific phenomena for the purpose of solving and post-processing models in order to produce results that are correct and trustworthy. This software for simulation study aids in geometric modelling and interface activities in sequences and selection, and it delivers reliable results. Additionally, it follows a consistent modelling methodology. Following the selection of a specific physics interface, the software will make recommendations for the types of studies that are available, such as time-dependent or stationary solvers. It is entirely preset, and the qualities that it possesses are based on physics modelling. Additionally, it is capable of doing both automated and manual meshing in accordance with the requirements. It bridges the gap between analysis, designing, and established conditions by use of simulation applications, covering and closing all of the gaps simultaneously. In the event that we choose a physics interface and the difficulties, COMSOL Multiphysics will recommend a variety of possible studies. In order to mesh our model, the COMSOL Multiphysics software employs a variety of numerical techniques. These techniques vary according to the type of physics or the combination of physics that we are investigating. We are also able to use our own equations to establish new physics interfaces with COMSOL, which allows for easy access and manipulation of these interfaces in the event that we decide to incorporate them into future models. Origin is a mathematical and graphical application that allows users to edit data and observe variations by charting and fitting it with a variety of standard equations. Origin is a data analysis software that is both strong and packed with useful features. We are able to perform multidimensional analysis, linear and non-linear curve fitting, model variation, and dataset comparison tools with the assistance of Origin. Origin facilitates improved collaboration across various research groups by allowing them to exchange research tools and content that they have generated with one another through the utilization of a centralized software platform. For the purpose of plotting the graph for electric potential and intensity utilized in this dissertation study, the Origin software was utilized. A variety of materials each possess their own unique set of characteristics. The use of a certain material for a particular set of functions is stated, and there are times when alternative materials cannot be utilized in place of those materials. When it comes to the construction of the electrodes for the planar type wiggler, a variety of materials can be utilized. On the other hand, semiconductor silicon is utilized in this dissertation as the material for designing the electrodes of the wiggler. The conductivity of this material falls somewhere between that of a conductor and an insulator. Doping silicon of the P type causes a change in its behavior, transforming it into a conductor by this process. By doping silicon with substitutional impurities, it is possible to exert control over the electrical conductivity of silicon throughout a wide range of orders of magnitude. A material's resistivity can also be determined via the doping process. Doping with N type results in a lower resistivity than doping with P type because N type doping has a better carrier mobility. Boron or gallium is the element that is used to accomplish the doping of silicon.

3. RESULTS AND DISCUSSION

A defect of electron beam shift was observed in the asymmetric type electrostatic wiggler throughout the course of this research. This defect was caused by the development of an electric potential and an electric field within the wiggler. By making adjustments to the parameters of the wiggler, an attempt is made to find a solution to the problem of the electron beam shift. as a result, the electric field and potential that are contained within the wiggler undergo alterations. Inside of the electrostatic wiggler, where there is an electric field present, the path of oscillating electrons is monitored with great

attention to detail. Electrons are able to emit electromagnetic radiations when they are oscillated through the use of various arrangements or tools [17]. Electrostatic wigglers are a versatile tool that can be utilized to oscillate electrons. Electrostatic wigglers can be classified into two distinct categories, namely symmetric type wigglers and asymmetric type wigglers, based on their structure and the process by which they function. In a symmetric type wiggler, the pair of electrodes are maintained with charged voltages that are identical to one another. On the other hand, in an asymmetric type wiggler, the pair of electrodes are maintained with different charged voltages, which results in a distinct electric field and electric potential within the respective electrodes. Variations in the voltages that are delivered to the electrode also result in variations in the potential and electric field there. Some models with the same separation (S) between parallel electrodes are taken into consideration in order to investigate the variations in electric potential and field that occur within symmetric and asymmetric planar type wigglers. It is presumed that the wiggler, which has a total of 18 parallel electrodes and two electrodes at both ends, is grounded. The width of every electrode, as well as the insulating gap (g) that exists between them, is precisely 10 micrometers. There is a distance of 20 micrometers (S) between the upper electrode and the lower electrode. Following the completion of the wiggler system with the design, the simulation analysis was carried out by adjusting the bias voltage that was applied to the electrodes. The calculation of the electric potential and field variation is performed at a distance of 4 micrometers from the axial line, for both symmetric and asymmetric modes along the z -axis. An examination of the electric potentials and fields that have been computed may be found in figures 01 and 02.

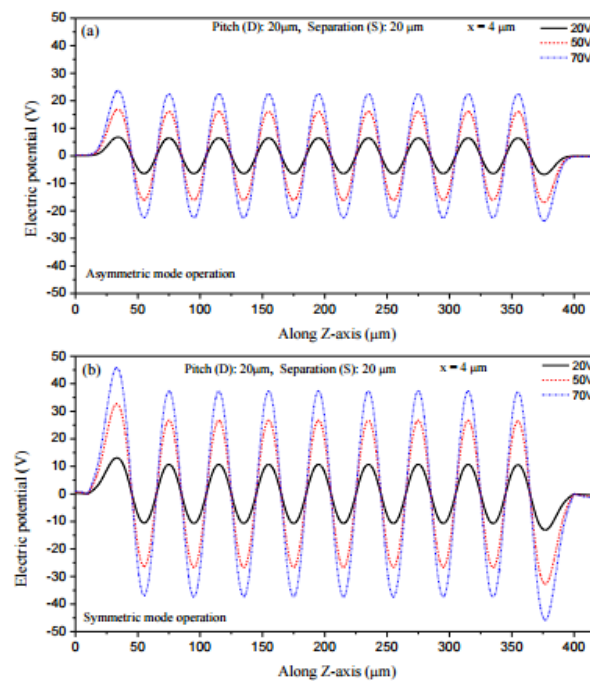


Figure 01: Variation in electric potential inside (a) asymmetric (b) symmetric mode of operation

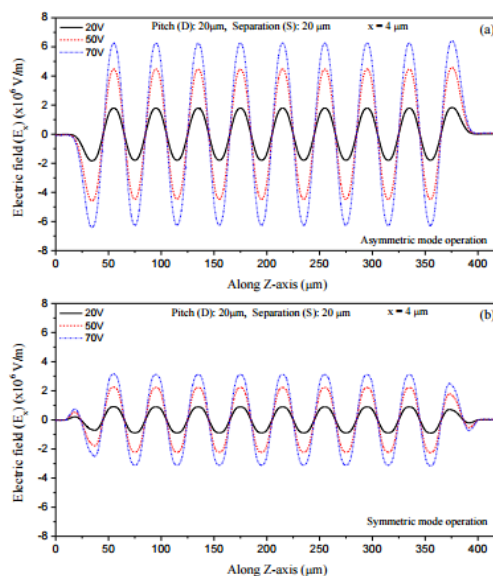


Figure 02: Variation of electric field inside (a) asymmetric (b) symmetric mode of operation

In the symmetric wiggler, the electric potential that is obtained is greater than that of the asymmetric wiggler. On the other hand, the strength of the electric field that is obtained in the asymmetric mode is about twice as strong as the strength that is obtained in the symmetric mode. In spite of the fact that an asymmetric mode operation results in a significant shift of the electron beam, it has one significant advantage over symmetric mode operation, and that is the fact that electrons in an asymmetric mode wiggler encounter a proportionally larger electric field [18]. Two volts is the actual potential difference that exists between parallel plates that are face to face when the bias voltage configuration is asymmetric mode. Since they are biased in the opposite direction, the overall potential difference is equal to $+V$ minus $(-V) = 2V$, which is a magnitude that is bigger than what it would be in symmetric mode [19]. As a consequence of this, the electric field intensity in a wiggler of the asymmetric planar type is significantly higher than that of the symmetric mode. As a result, the majority of electrons that move through the wiggler are subject to the impact of a powerful electric field, and they oscillate with a frequency that is relatively high in amplitude. Because of this, the asymmetric mode wiggler is favorably regarded over the symmetric mode. Because of this disparity in potential voltages, the electric field that is contained within the wiggler is produced [20]. One of the benefits of operating in asymmetric mode is that, due to the bias arrangement, it is possible to obtain a substantially stronger electric field than when operating in symmetric mode [21]. As soon as a beam of electrons from the source of electrons is introduced into the wiggler through the first pair of electrodes, the electrons begin to oscillate as a result of the electric field that is present within the wiggler. While the beam is oscillating, it moves away from the optical axis, which causes the beam to exhibit a deviation. A deviation from the optical axis occurs in the path of the beam after it has oscillated, and it is orientated in the direction of one of the electrodes of the wiggler [22]. Because of this, the beam connects with one of the electrodes of the wiggler, and it does not escape from the appropriate location outside of the wiggler. If the electrostatic wiggler is unable to produce powerful electromagnetic radiation, then the use of the wiggler as a source of electromagnetic radiation will be completely pointless. The most significant disadvantage of the asymmetric type electrostatic wiggler is the beam shift that it provides. It is necessary to either control or limit the beam shift away from the optical axis in order to obtain radiation with a high potential power. This issue can be remedied by making certain adjustments to the settings of the wiggler. This will allow for the generation of an acceptable electric field and potential within the wiggler [23]. Considering that the symmetric type of wiggler is responsible for the development of both a high potential and a weak electric field, it is also one of the remedies for beam shift in the asymmetric type of wiggler. The symmetric type of wiggler is characterized by the presence of identically charged voltages in the electrodes, which results in the generation of a homogeneous

electric field throughout the entirety of the wiggler [24]. It is impossible for electrons to wander from their optical axis when they are subjected to this homogenous electric field. One additional alteration that can be made to the wiggler is to shorten the length of the first pair of electrodes it contains. The electric field at the entry of the wiggler becomes powerful and sharp as the length of the first pair of electrodes is decreased. This causes the beam to fluctuate strongly, but it does so in close proximity to the optical axis. Despite the fact that the amplitude of this oscillation at the entrance is very low, it is still able to prevent the beam from moving away from the optical axis. When an asymmetric type of electrostatic wiggler is used, this helps to lessen the beam shift that occurs away from the optical axis. By lowering the voltage of the first pair of electrodes, it is also possible to make modifications to the asymmetric form of electrostatic wiggler. The low voltage that is supplied causes the potential of the electrodes that are located at the entry to be low. Low voltage is applied at the entrance of the wiggler, which results in the generation of a low electric field at the place where the wiggler is introduced. This low electric field causes the electron beam to oscillate with a modest amplitude, and it prevents the beam from deviating from its route in a direction that is far from the optical axis. The beam shift from its optical axis is reduced thanks to this insignificant oscillation of the electron, which aids in the process. Therefore, we are able to alter the intensity of the electric field and the range of potential within the wiggler by decreasing the length of the first pair of electrodes and by decreasing the voltage of the first pair of electrodes [25]. Moreover, the symmetric form of electrostatic wiggler contributes to the reduction of the beam shift away from its optical axis. This adjustment in the asymmetric type wiggler serves to boost the performance of the wiggler, and it is possible to obtain the high-power electromagnetic radiation that is necessary. The electrostatic wiggler's power can be utilized for a variety of purposes, depending on the situation. In light of this, the electrostatic wiggler has the potential to serve as a generator of electromagnetic radiation.

4. CONCLUSION

This study focussed on the generation of electromagnetic radiation. Through the utilization of an appropriate electrostatic wiggler system, this study has been carried out in order to enhance the overall power radiation. Each and every instance of radiation is the product of electron oscillation. When electrons are subjected to an electric field, it is possible to cause them to oscillate. This location provides access to an oscillatory gadget that was designed to oscillate the electrostatic wiggler of electrons. Electrostatic wigglers that are meant to generate electromagnetic radiation are available in a variety of voltages. The numerous potentials that are produced by this voltage in the electrodes of an electrostatic wiggler are responsible for the formation of an electric field within the wiggler at the same time that they facilitate the generation of an electromagnetic field. The oscillation of a beam of electrons that has gone through an electric field with an alternating electric field is caused by the electric field. Subsequently, electrons travel via a wiggler and then proceed straight ahead. The strong magnetic influence exerted by the first electrode of the wiggler causes the trajectory of the electron beam to wander from its optical axis during the experiment. Both the route of the electron beam and the oscillatory motion that occurs within a wiggler system are affected by the modification of electric potential and field strength. These aspects have been thoroughly researched for the electrostatic wigglers. Due to the fact that they are unable to escape from the wiggler, the electron beam that is moving away from its optical axis is unable to generate electromagnetic radiation. This departure of the beam from the optical axis causes the electron beam to collide with one of the electrodes that are held in place by the wiggler. The electron beam shift from its optical axis can be minimized through the employment of a few different approaches. These methods include either reducing the voltage of the first pair of electrodes in comparison to the other electrodes or limiting the width of the first pair of electrodes in comparison to the other electrodes. It is possible to alter the magnitude of the electric field and the potential at the entry of the electrostatic wiggler by adjusting the length of the first pair of electrodes, either by increasing or decreasing it. This also causes a change in the route that the electron beam of oscillation takes. Because of the strength of the second electrode, it is possible to push back the significant beam shift that is caused by a weak electric field at the entry. As a result, the path of the electron beam remains relatively near to the optical axis. The electron is oscillated by a

weak and small electric field, and the beam of electrons is ejected from the wiggler. The amplitude of the oscillation is minimal. It is also possible to lessen the beam shift of the electron beam away from its optical axis by lowering the voltage of the first pair of electrodes in comparison to the voltages that are applied in the other electrode locations. The beam oscillates with a modest amplitude because of the weak electric field that is produced by the voltage that is present at the entry of the wiggler. The beam cannot be turned away from its optical axis for this reason. Through the use of the second electrode, it is possible to easily push back modest shifts. Because of this, the path of the electron beam remains relatively near to the optical axis. Consequently, the wiggler is capable of oscillating and producing electromagnetic radiation with relative ease. By implementing this modification to the electrostatic wiggler, the instruments that are designed to generate electromagnetic radiation are able to function more effectively.

REFERENCES

- [1] Jha, V. K., Shah, N. K., Sah, B. K., & Ray, R. B. STUDY ABOUT THE VARIATION OF ELECTRIC FIELD AND ELECTRIC POTENTIAL BETWEEN PARALLEL PLATE ELECTRODES AND PLANAR TYPE ELECTROSTATIC WIGGLER.
- [2] Singh, J., Rajput, J., Kant, N., & Kumar, S. (2022). Comparative study of inverse free-electron laser interaction based on helical and planar wiggler. *Optik*, 260, 169017.
- [3] Abdollahi, F. S., Abdoli-Arani, A., & Mohsenpour, T. (2022). Study of gain and trajectories in elliptical electron beam considering a planar wiggler and self-fields and ion-channel in free electron laser. *Chinese Journal of Physics*, 77, 1946-1962.
- [4] Abkenar, S. B., Jafari, S., & Dezhpour, A. (2022). Effects of Helical and Planar Wiggler Fields on the Dust Characteristics in a Plasma Sheath. *Brazilian Journal of Physics*, 52(2), 32.
- [5] Pourali, M., Hasanbeigi, A., & Mehdian, H. (2021). Nonlinear simulation of TM mode free electron laser in rectangular waveguide with ion-channel. *Laser Physics*, 31(3), 035002.
- [6] Lee, Y. B., Ahn, S., Kim, D. W., Song, Y. H., & Kim, Y. C. (2023). Ultra-Compact Free-Electron Laser Advanced Model for Carbon Nano-Tube Tip. *Applied Science and Convergence Technology*, 32(3), 58-62
- [7] Albà, A., Seok, J., Adelman, A., Doran, S., Ha, G., Lee, S., ... & Zholents, A. (2022). Benchmarking collective effects of electron interactions in a wiggler with OPAL-FEL. *Computer Physics Communications*, 280, 108475.
- [8] Divya, S., Gopal, K., Kumar, R., & Singh, S. (2024). Far IR field generation by mixing of cosh-Gaussian and dark hollow Gaussian laser in encapsulated plasma. *Physica Scripta*, 99(6), 065609.
- [9] Prabesh Adhikari, Suresh Khadka, Laxmi Prasad Odari, Yamnath Poudel, Sandhya Gautam & Hari Prasad Lamichhane (2024). Computational Study on Vibrational Properties of Chlorophyll-B Model Molecules in Gases Phases. *Dinkum Journal of Natural & Scientific Innovations*, 3(01):101-108.
- [10] Abdollahi, F. S., A. Abdoli-Arani, and T. Mohsenpour. "Study of gain and trajectories in elliptical electron beam considering a planar wiggler and self-fields and ion-channel in free electron laser." *Chinese Journal of Physics* 77 (2022): 1946-1962.
- [11] Rubin, T., Rax, J. M., & Fisch, N. J. (2023). Magnetostatic ponderomotive potential in rotating plasma. *Physics of Plasmas*, 30(5).
- [12] Sahai, A. A., Golkowski, M., Gedney, S., Katsouleas, T., Andonian, G., White, G., ... & nano²WA collaboration. (2023). PetaVolts per meter Plasmonics: introducing extreme nanoscience as a route towards scientific frontiers. *Journal of Instrumentation*, 18(07), P07019.
- [13] Singha, A., Sekretareva, A., Tao, L., Lim, H., Ha, Y., Braun, A., ... & Solomon, E. I. (2023). Tuning the type 1 reduction potential of multicopper oxidases: Uncoupling the effects of electrostatics and H-bonding to histidine ligands. *Journal of the American Chemical Society*, 145(24), 13284-13301.

- [14] Ehsani, H., & Mohsenpour, T. (2021). Electron trajectories and radiation growth rate in free electron laser with electromagnetic wiggler. arXiv preprint arXiv:2112.13313. Ehsani, H., & Mohsenpour, T. (2021). Electron trajectories and radiation growth rate in free electron laser with electromagnetic wiggler. arXiv preprint arXiv:2112.13313.
- [15] Rezaei-Pandari, M., Mirzaie, M., Hojbota, C. I., Niknam, A. R., Massudi, R., Kim, K. Y., & Nam, C. H. (2024). Investigation of terahertz radiation generation from laser-wakefield acceleration. *AIP Advances*, 14(2).
- [16] Nikrah, B., & Jafari, S. (2021). The effect of chirped Gaussian laser pulse on the acceleration of plasma electrons in a plasma wakefield accelerator in the presence of a planar undulator field. *Brazilian Journal of Physics*, 51(4), 1026-1034.
- [17] Méot, F. (2024). *Understanding the Physics of Particle Accelerators: A Guide to Beam Dynamics Simulations Using ZGOUBI*. Springer Nature.
- [18] Saeidpour, S., Khoshnevisan, B., Boroumand, Z., & Ahmady, N. (2023). Effect of electrode design and dust particle size on electrodynamics dust shield procedure. *Physics Open*, 14, 100131.
- [19] Qiang, L., Luo, W., Zhang, J., Teng, Y., Li, Y., Wang, Y., & Wang, H. (2022). Transverse magnetic electromagnetic mode analysis with electron beam effect in overmoded waveguide of coaxial magnetic wiggler. *AIP Advances*, 12(7).
- [20] Sharma, V., Midha, H. K., Kant, N., & Thakur, V. (2024). Enhancing electron acceleration with sinh-squared Gaussian pulse under external magnetic fields. *Journal of Optics*, 1-8.
- [21] Lyutikov, M. (2021). Coherent emission in pulsars, magnetars, and fast radio bursts: reconnection-driven free electron laser. *The Astrophysical Journal*, 922(2), 166
- [22] Mandal, D., Vashistha, A., & Das, A. (2021). Electromagnetic wave transparency of X mode in strongly magnetized plasma. *Scientific Reports*, 11(1), 14885.
- [23] Malik, H. K., & Dwivedi, M. (2022). Effect of transverse wiggler magnetic field on the growth rate of Raman backscattering of X-mode laser in rippled density plasma. *Journal of Theoretical and Applied Physics*, 16(2).
- [24] Sharma, V., Kumar, S., Kant, N., & Thakur, V. (2023). Effect of frequency chirp and pulse length on laser wakefield excitation in under-dense plasma. *Brazilian Journal of Physics*, 53(6), 157
- [25] Bashiri, A., Large, M. J., Griffith, M. J., Papale, L., Philippa, B., Hall, C., ... & Posar, J. A. (2025). Flexible Organic X-Ray Sensors: Solving the Key Constraints of PET Substrates. *Advanced Functional Materials*, 35(8), 2415723.