IRSTI 29.31.26 https://doi.org/10.26577/phst2024v11i2b010

A new system to the spectroscopy analysis with multiple X-ray of free electron laser

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(Received August 22, 2024; received in revised form November 22, 2024; accepted December 2, 2024)

The primary goal of this paper is the possibility of improving spectroscopy analysis using a new mechanism that has the ability to detect small crystalline defects and the fast transitions that occur within electronic states, which contributes significantly to the development of various fields and applications of scientific knowledge. The working mechanism is summed up by obtaining two laser pulses with specific specifications within the x-ray range, by creating an executive program (SAMXFEL) using the MATLAB program for the purpose of simulation. This system allows the investigation of rapid changes in the structure of matter. By analyzing the simulation results, two pulses of electron lasers were obtained with wavelengths ranging from (0.316535, 0.114399) nm and powers (927686, 927683) watts, in addition to pulse durations within (1.05512, 0.38133) atto-seconds that ensures that the target material is protected from damage. The proposed system in this paper is mainly based on the spectral and spatial separation of the two pulses to interpret the scattered and diffracted X-rays. The spatial separation allows multiple X-ray pulses to be emitted from different angles of the sample. X-ray diffractography using multiple simultaneous pulses from different angles becomes possible without loss of photon energy generated by the spectrometer.

Key words: Spectral analysis, pulses laser, pulse durations, undulator, diffraction.
PACS number(s):

1. Introduction

In general, spectral techniques rely mainly on three types of interactions of electromagnetic radiation with matter, which are emission, absorption and scattering. Because X-rays are of high energy, which are used to eject electrons from the inner shells of atoms to be replaced by electrons from the outer shells. Thus, energy will be emitted as distinct photons for each element, which allows to identify elements and understand how the atoms within various materials interact [1-7].

In the seventeenth century, the optical microscope was discovered, which had a great impact on the scientific revolution, as we were able to see things that were not visible to the naked eye. In 1667, Robert Hooke was able to improve the microscope and used it to examine snow and plants. While others were able to see very small things like hair, bones and skin [8]. William Henry Bragg and his son were the first to use X-ray spectroscopy in the 20th century to study how X-ray radiation interacts with atoms inside crystals, and they won the Nobel Prize in physics in 1915 [9].

In this work, it has been used a new system to the spectroscopy analysis with multiple x-ray of free electron laser (SAMXFEL). This system is characterized by its high ability to diagnose an important case represented by the very rapid transitions of the electronic states and structures of the sample. This is achieved only by using two laser pulses with wavelengths within the X-ray range and using free electron laser technology, which will have a great impact on scientific progress in the fields of physics and chemistry.

2. The Technique and mechanism

Analysis of the components of a sample based on irradiating it with a laser pulse based on X-ray free electron lasers (XFELs) technology is currently a very advanced technology for obtaining spectral analysis of materials at the atomic and molecular levels with high-resolution imaging.

The most important feature of XFELs is that they provide us with very intense and coherent X-ray beams with very short pulse durations, which are essential conditions for studying and analyzing the structure and dynamics of the sample in unprecedented detail, which includes a number of steps such as X-ray Generation, X-ray-Matter Interaction, detection, data analysis, interpretation and visualization [10-15].

XFEL technology has made tremendous scientific progress in the field of materials science, allowing scientists and researchers to study and analyze the basic properties of a sample with exceptional accuracy, as well as explore dynamic processes at the atomic level, which has contributed to the advancement of many civil and military applications [8,9].

In this paper, a new system called SAMXFEL is proposed, based on the self-amplified spontaneous emission scheme (SASE) as shown in Figure (1). Where two laser pulses with different wavelengths within the X-ray range will be generated as a result of the technique of creating two undulators with different gaps instead of one undulator in the path of the accelerated electrons to obtain the best spectral analysis.

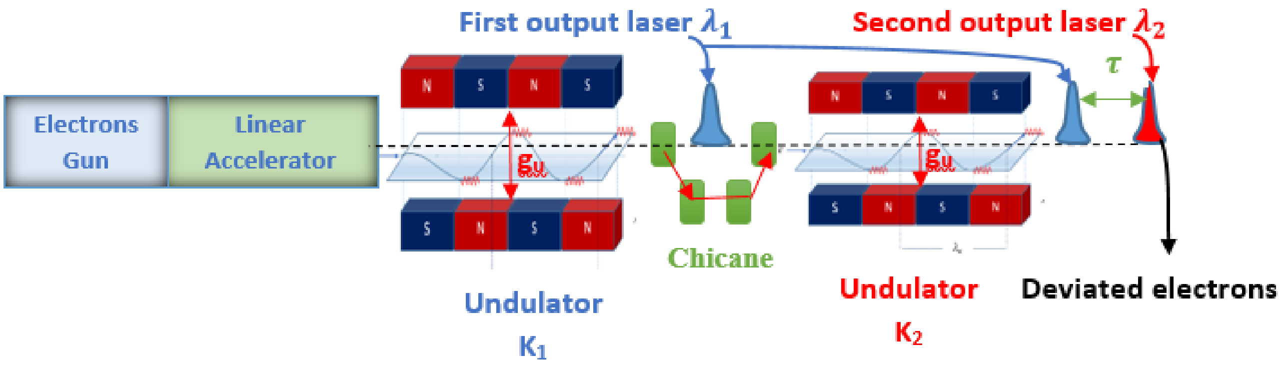

Figure 1 – The SAMXFEL system with two undulators.

The two pulses are separated for a certain period of time (About a few femto-seconds) by magnets that separate the undulators to delay the electrons. In addition, these pulses have pulse duration in atto-seconds and powers in megawatt. Thus, the SAMXFEL system can explain the mechanism and dynamics of the ultrafast X ray transformations of structures and electronic states, which support greatly to progress of quantum x-ray optics, plasmas, astronomy, ultrafast chemistry [16,17].

The SAMXFEL system allows the investigation of rapid changes in the structure of matter, the two pulses are separated spectrally and spatially to interpret diffracted or scattered X-rays. Spatial separation allows multiple X-ray pulses to be irradiated from different angles of the sample. X-ray diffraction imaging with multiple simultaneous pulses from different angles becomes possible without loss of photon power generated by the spectrometer.

In a free electron laser FEL, any wavelength λ of the output laser can be obtained according to equation (1) [18-21].

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{k^2}{2}\right) \quad (1)$$

Where λ_u is the wavelength of electron in undulator, k is the undulator parameter, and γ is relativistic Lorentz-factor [21-23].

$$\gamma = \frac{E_e}{m_e c^2} \quad (2)$$

$$k = \frac{e\, \beta\, \lambda_u}{2\pi\, m_e c} \quad (3)$$

Where E_e is the electrons beam energy, m_e is the electron mass. β is the magnetic field [18,20,23].

$$\beta = 4.22 \exp\left[-\frac{g_u}{\lambda_u}\left(5.08 + 1.54\, \frac{g_u}{\lambda_u}\right)\right] \quad (4)$$

Where g_u is the distance between the two rows magnets of undulaor.

The power P_u of output laser for two pulses is given by the equation(5): [18-20].

$$P_u = \left(\frac{\chi^2\, c\, E_e\, N_{PH}}{9\,\lambda}\right) e^{(21.57\,\rho\;L_u/\lambda_u)} \qquad (5)$$

Where χ is Pierce parameter, L_u is the length of the undulator and N_{PH} is the coherent photons [23-26]:

$$N_{PH} = 2\,\chi\;E_e\,\lambda/h\,c \qquad (6)$$

3. Results and discussion of simulation

In order to obtain the two laser pulses proposed in this paper, an executive SAMXFEL program was created using MATLAB R2023b (see Figure 2). SAMXFEL contains many parameters to perform simulations and obtain the dimensions and specifications of the free-electron laser system suitable for producing the two proposed laser pulses as shown in Figure (1).

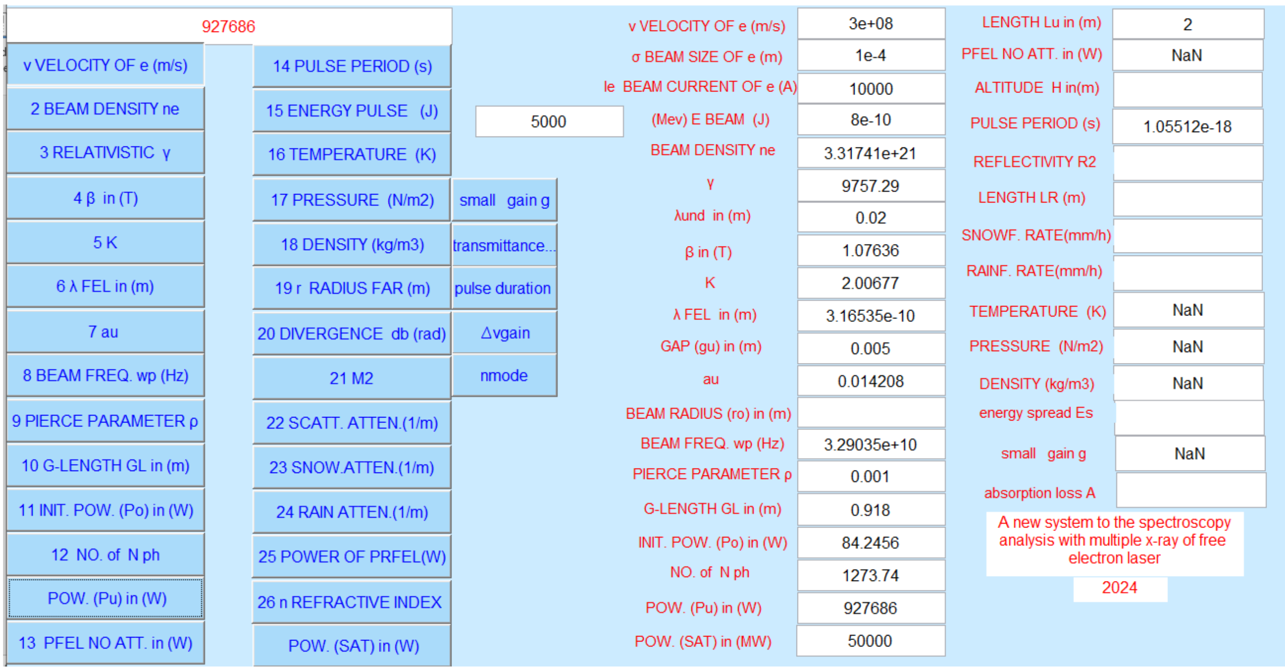

Figure 2 – An executive SAMXFEL program interface.

Table 1 represents the results obtained, dimensions and specifications of the free electron laser system proposed for spectroscopy. Two laser pulses with wavelengths of 0.114399 nm and 0.114399 nm were obtained within the X-ray range by using Equation 1.

Table 1 – The data of simulation for the dimensions and specifications of SAMXFEL system.

E_e (Mev)	λ_u (m)	γ	ρ	L_u (m)		
5000	0.02	9757.29	0.001	2		
g_u(m)	β(T)	K(Tm)	λ(nm)	N_{PH}	PP(as)	P_u (w)
0.005	1.07636	2.00677	0.316535	1273.74	1.05512	927686
0.01	0.226465	0.422221	0.114399	460.342	0.38133	927683

The basic idea for obtaining the two pulses is to fix the majority of the parameters in the system while changing one parameter, which is shown in Figure 2. Two undulaors were placed inside the free electron laser system, differing in the distance g_u between the magnetic poles of the undulaors, which is shown in Figure 1.

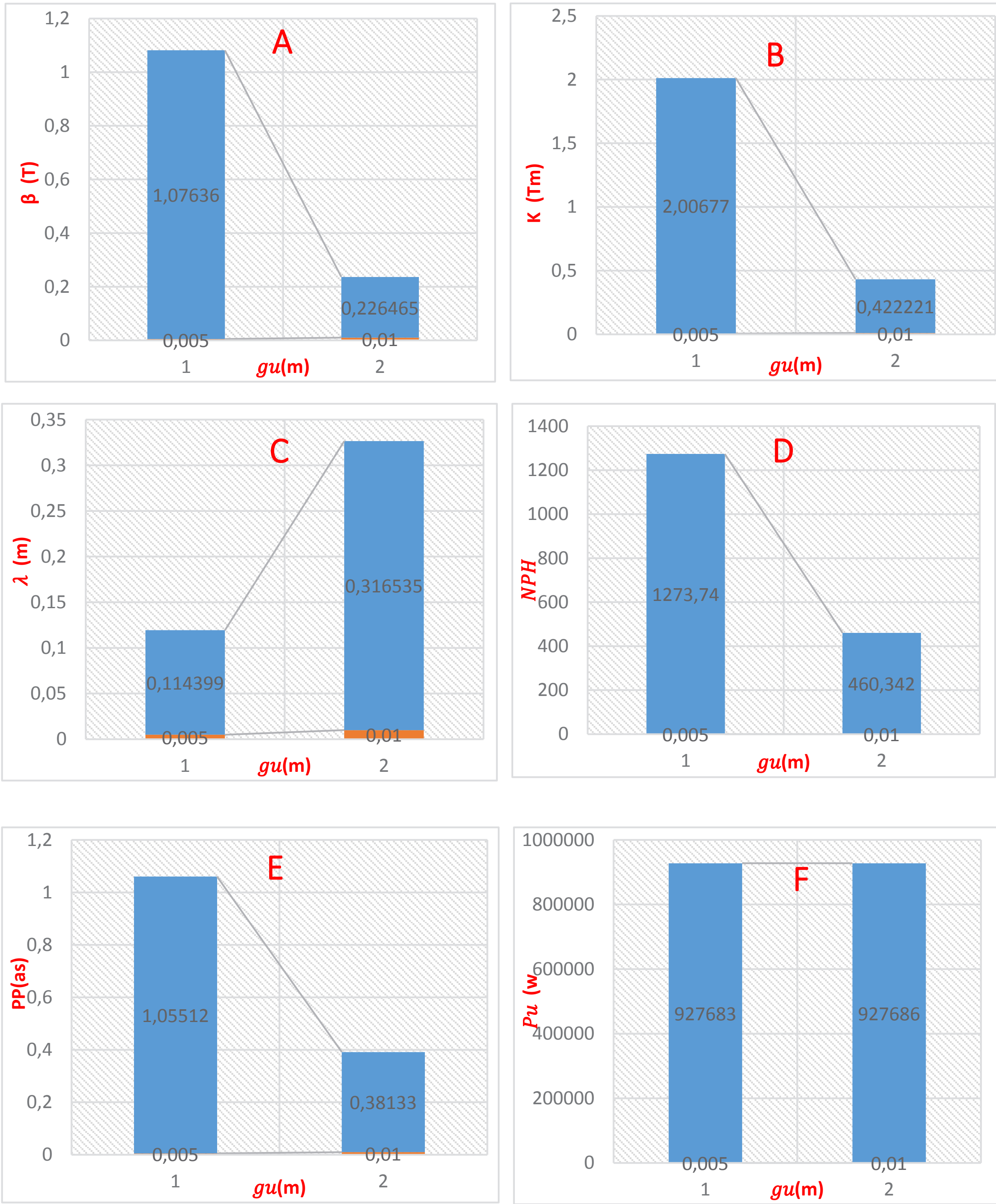

Figure 3 – The relations between g_u versus (β, K, λ, N_{PH}, PP , P_u)

According to Equation 4, changing the distance g_u necessarily leads to a change in the value of the magnetic field β arising between the magnets in an inverse relation as shown in Figure 3-A , this leads to a change in the value of the parameter k according to Equation 3 in a direct relation. Figure 3-B, is clearly shows that reducing the distance g_u between the rows of magnets necessarily leads to an increase in the parameter K as a result of a decrease in the strength of the magnetic field β responsible for the oscillatory movement of electrons inside the undulator. Thus, the wavelength λ of the two resulting laser pulses was controlled and tuned according to Equation 1 as shown in Figure 3-C. By changing the chicane parameters, the time interval between the two pulses laser can be tuned with femtosecond precision. This is considered a very important feature of the SAMXFEL system to achieve better spectral analysis and reach the goal of the paper described in the previous paragraph.

Figure 3-D, indicates an important fact in the free-electron laser system, represented by the increased influence of the magnetic field on the movement of the electrons passing through it. Photons are produced from the oscillation of the electrons, which increase significantly when the wavelength of the two resulting laser pulses is increased according to Equation 6.

Figures 3-E and 3-F, show the features and properties of the resulting laser pulses in terms of pulse duration, which changes significantly as a result of changing the wavelength of the laser pulses, while we note that the power of the two laser pulses is very close, on the order of a megawatt, due to the power depending on several variable parameters according to Equation 5.

4. Conclusion

This is a very important feature of the SAMXFEL system, as the two laser pulses, with close powers and a relatively large difference in wavelength, have a very large effect during interaction with the target material during spectroscopic analysis. Because two different bands of the X-ray band are absorbed with the same effective power. This leads to the generation of different peaks, which means obtaining the best possible spectroscopic analysis and detecting minor crystalline defects and rapid phase transitions. In addition, it can explain the mechanism and dynamics of electronic states and structures, which will greatly contribute to the progress of physical and chemical scientific fields.

From analyzing the simulation results obtained using the SAMXFEL system, it can be concluded that it is possible to obtain two laser pulses within the X-ray range with characteristics suitable for the spectroscopy process. So that the two pulses can be separated spatially and temporally to irradiate the target material at different angles to obtain a diffraction pattern without losing the power of the simultaneous photons resulting from the spectrometer, and to achieve a spectral analysis characterized by high accuracy. Obtaining ultra-short pulse durations for both laser pulses within a atto-seconds ensures that the target material is protected from damage.

Acknowledgments

I would like to extend my sincere thanks and appreciation to the Department of Physics at the College of Education for Pure Sciences Ibn Al-Haitham / University of Baghdad for providing support and assistance in completing this research by providing scientific facilities in all areas of work to help overcome obstacles.

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