PHY4311
FREE ELECTRON LASERS

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1. Introduction

Free-Electron lasers are a class of modern lasers that open many avenues of scientific research and push the limits of current technology. This report will attempt to give an overview of the field of Free Electron lasers.

We first list basic properties and characteristics of free electron lasers. These properties and characteristics are what differentiate the free electron laser from other classes of laser. We will then describe the basic operating principles and physical theory behind the operation of the free electron laser, including basic cavity configurations, wigglers and undulators, the ponderomotive force, the formula for the emitted wavelength of the free electron laser, the mechanism of light amplification and the phenomenon of electron bunching in free electron lasers. After we have understood the basic principles that make a free electron laser possible we give an overview of the Xray free electron laser. Specifically we explain how Self Amplified Spontaneous Emission (or just SASE, pronounced sass-y) allows for laser like emission without a cavity, and we explain the limitations that arise from SASE free electron lasers. We then examine how these limitations are overcome by looking at the Linear Coherent Light Source (LCLS) as an example, as well as understanding the idea of bunch compressors. Finally we look at some applications of the free electron laser, like molecular imaging.

2. Properties and Characteristics

We first examine the properties and characteristics of free electron lasers that differentiate it from other traditional lasers. Free electron lasers have no medium, and do not rely on the discrete transition states of electrons bound to atoms. Instead, the source of radiation in free electron lasers (FELs) comes from the phenomenon of magnetic bremsstrahlung. That is, electrons (or any charges) that experience deceleration will emit photons, or radiation. In FELs, electrons pass through a spatially periodic, and constant magnetic field that is transverse to the direction of propagation of the electrons. The magnetic field is produced by an apparatus called the wiggler, also known as the undulator. The source of the electrons is a linear accelerator and the electrons are accelerated to relativistic speeds. Because the electrons are free, they are able to emit radiation in a continuum and are not limited to the difference in energy levels of two states like traditional lasers. Traditional lasers will rely on some transition in a molecule to produce radiation at a fixed frequency. This medium can be, for example CO_2 or ruby. If one wants a wavelength other than the transitions available in the atoms of the medium, a different medium must be used. However with FELs, the electrons are free to emit at any level because they are unbound particles, and so changing the emitted wavelength of the free electron laser can amount to simply changing the propagation velocity of the electrons. This allows the FEL to be tunable to a huge range of wavelengths.

This property of tunability has spurred a lot of interest in their development because of their potential to be used as general purpose lasers and sources of arbitrary wavelengths of radiation.

The figure below gives an example of the design of free electron laser.

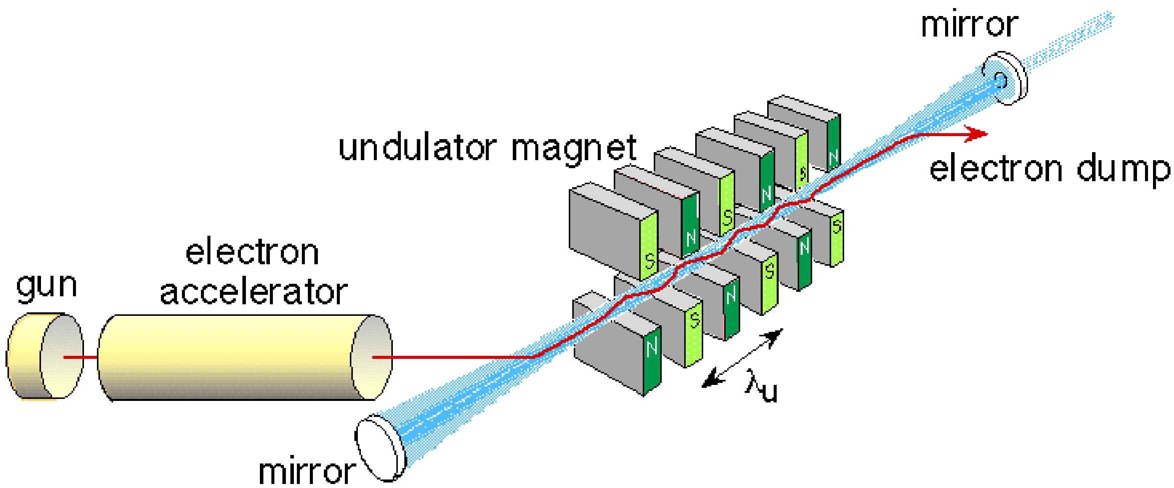

FIGURE 2.1. An example design of a Free Electron Laser

Observe in the figure that the FEL depicted consists of an electron gun, an accelerator, the undulator, and mirrors. The electron gun is the source of the electrons and can be, for example, a copper plate that is struck by pulses or beams of UV radiation. When the copper plate is struck by the UV radiation, electrons are ejected from the copper plate and enter the accelerator. The accelerator is a series of magnets and/or electrically charged plates that accelerate the electron. To reach relativistic speeds close to the speed of light, the length of the accelerator can reach kilometers long. Through a series of bending magnets, the beam of electrons can be guided to the wiggler. The wiggler depicted in the figure consists of alternating permanent magnets arranged periodically through space. The period of these magnets, the distance before the field repeats itself λ_u is an important parameter of free electron lasers and is a factor in the emitted wavelength of radiation. Electrons entering the wiggler start to wiggle back and forth, and radiation is emitted. Each time an electron decelerates, the energy lost by the electron is released in the form of photons, or electromagnetic radiation, which propagate in parallel to the propagation direction of the electrons. In the figure, when electrons leave the wiggler, bending magnets can be used once more to direct the electron beam away from the cavity. The light radiation is unaffected by the magnets. Mirrors can be placed to contain the light and to redirect it back towards the electrons in the wiggler, further amplifying the radiation. By using a mirror with a small transmission coefficient we have an output coupling and in this way we can obtain output laser radiation.

We will see that there are other ways to amplify radiation without cavity mirrors and we will also see that alternating magnets are not the only possible configuration for a wiggler.

3. Operating Principles and Physical Theory

We will now look more closely at the components of a free electron laser and understand the physics behind them.

The successful operation of the first free electron laser was reported in 1976 by Deacon, Elias, Madey, Ramian, Schwettman, and Smith at the High Energy Physics Laboratory in Stanford University. The figure below shows the setup they used.

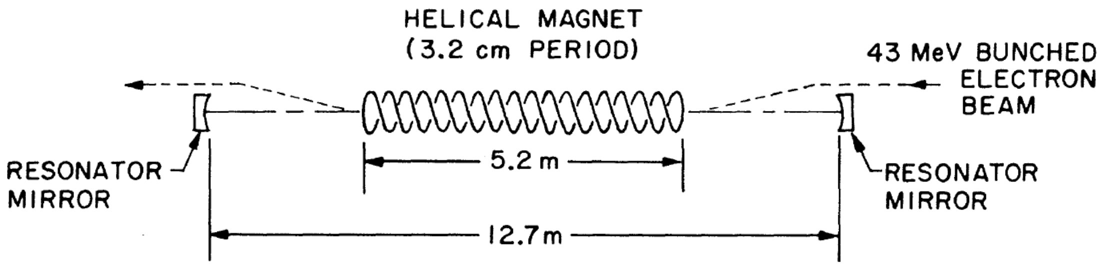

FIGURE 3.1. Diagram of the first operational free-electron laser.

Notice that the wiggler is a helical magnet, and not a series of alternating permanent magnets.

Wigglers

The purpose of a wiggler is to create a spatially periodic magnetic field. We have already seen two different configurations of wigglers. The first wiggler used in an operational FEL consists of a helical wire wrapped around an evacuated tube that is occupied by electrons and radiation. Current is passed through the helical wire and a magnetic arises due to the Biot-Savart law. From the Biot-Savart law we know the direction the magnetic field points is in the direction of

$$\mathbf{B} \propto I d\mathbf{l} \times \mathbf{r}$$

Alterntively we curl the fingers of our right hands around a section of wire and point our thumbs along the direction of the current. Imagining doing this with the helical wire pictured above, we see that the components of the magnetic field pointing along the direction of propagation of the electrons cancel out and only the tranverse components, that is, the components pointing perpendicular to the direction of propagation, are left. Moreover, we see that in between windings, the magnetic field oscillates between pointing into the page and out of the page. If we do this more carefully, we see that the magnetic field rotates around the axis of propagation in a circular motion. The spatial period of this rotation is λ_u.

To get an idea of the trajectory of the electron as it passes through the wiggler we simply note that the magnetic force on the electron is given by

$$\mathbf{F}_M = e(\mathbf{v}\times\mathbf{B})$$

We know that the magnetic field of the helical wiggler oscillates between pointing into the page and out of the page. Suppose the electrons in the beam are travelling to the left. Then when the electron is in a region of the wiggler where the magnetic field is pointing into the page, we compute the cross product and see that the the force on the electron is pointing down. So in this region the electron will tend downwards. When the electron is in a region of the wiggler where the magnetic field is pointing out of the page, we compute the cross product again and see that the magnetic force on the electron is now pointing upwards, the opposite of before. Thus the electron experiences a 'wiggling' force and so its trajectory is correspondingly wiggly. Doing this more carefully, we see that that the trajectory of the electron in the helical magnet is in fact helical, as shown in the following figure:

In the image of the helical trajectory, the solid line denotes the trajectory and the outline of the arrow on the sheet denotes the direction of the magnetic field.

Also depicted is a linear wiggler. This wiggler is the more common wiggler in use today and is a periodic arrangement of alternating permanent magnets. The field inside the linear wiggler is much simpler; instead of a magnetic field vector that rotates in a circle about the propagation axis like in the helical wiggler, the magnetic field spatiall oscillates sinusoidally in a plane, pointing towards one side of the wiggler to the other, still transverse to the direction of the propagation. Thus the electron trajectory is much simpler, it also oscillates in a plane perpendicular to the plane of the wiggler magnetic field.

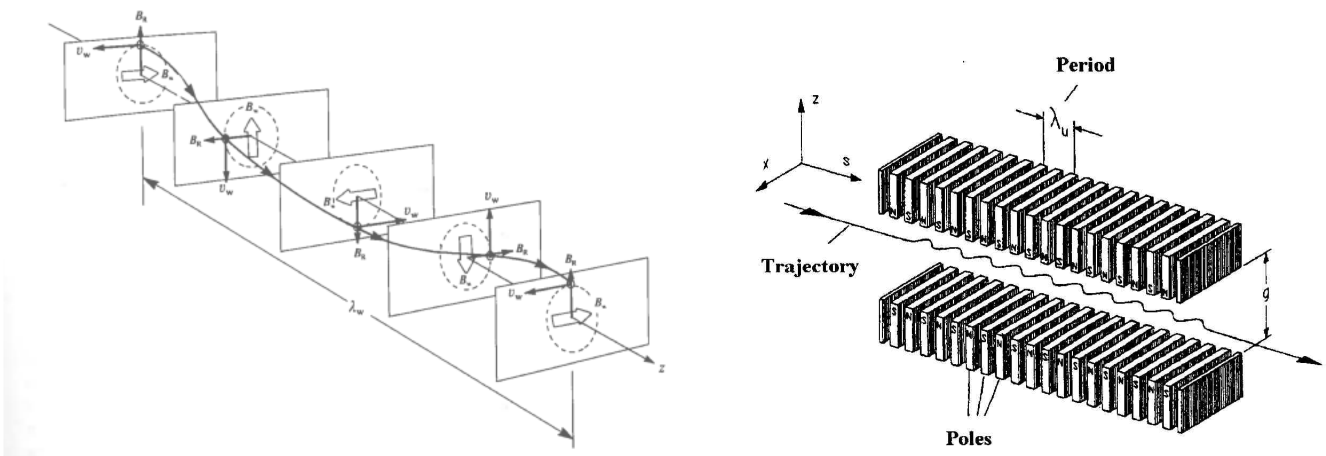

FIGURE 3.2. Trajectory in a Helical Wiggler and a Linear Wiggler, respectively.

As the electron passes through the wiggler it interacts with the magnetic field of the wiggler (as we have seen) and the field of the radiation already present in the cavity. It is this interaction that gives rise to light amplification.

Ponderomotive Wave

The ponderomotive force is the force an electron feels inside an oscillating electric field, like an electromagnetic wave. It can be thought of as the force the electron feels due to the intensity of light. As a reference, its form is given here for reference:

$$\mathbf{F}_p = -\frac{e^2}{4m\omega}\nabla E^2$$

where m is the mass of the electron, ω is the angular frequency of oscillation of the electric field and E is the amplitude of the electric field. Note that the intensity I is proportional to E^2.

In the free electron laser, the radiation field of the light in the wiggler combines with the magnetic field of the wiggler by superposition. This combination is called the **ponderomotive wave**. The ponderomotive wave travels slower than the speed of light c. This is because the magnetic field of the wiggler is constant in time and has no time evolution ($\omega_u = 0$), while the light field has both a spatial evolution and a time evolution. Thus in the superposition of these waves, the resulting wave has a wavenumber that is equal to the sum of the wavenumbers of the two waves ($k + k_u$) and the frequency is just the frequency of the light field (ω). Thus the phase velocity of the ponderomotive wave is less than c, since:

$$v_p = \frac{\omega}{k + k_u} < \frac{\omega}{k} = c \qquad \text{where } k_u = \frac{2\pi}{\lambda_u}$$

Since the ponderomotive wave is slower than c, and since the electrons are relativistic, it is more than the plausible that the electrons can travel at the same speed and near the same speed as the ponderomotive wave. In addition to electrons travelling slower than the ponderomotive wave, there can be electrons that travel faster than it.

Light Amplification

Suppose we match the speed of the electrons to close to the speed of the ponderomotive wave. We can do this because we know can know ω and k_u independently of the electrons and calculate what electron speed v_e we want so that $v_e \approx v_p$. The electrons feel the ponderomotive force due to the field of the ponderomotive wave. This force pushes electrons away from the antinodes of the ponderomotive wave towards the nodes of the wave where the electrons can form bunches and travel with the wave in resonance. Electrons that are moving slightly faster than the ponderomotive wave are slowed down and lose kinetic energy. This kinetic energy goes to the wave and the wave is amplified. Electrons that are moving slightly slower than the ponderomotive wave are sped up and gain kinetic energy at the expense of the wave. Thus if the beam is mostly composed of electrons that are faster than the ponderomotive wave, then the wave will be steal energy from the electron beam and be amplified.

Emitted Wavelength

To understand the wavelength that gets emitted we note that there are two phenomena at play in addition to the process of bremsstrahlung that the electron undergoes. The first is that the electrons are travelling close to the speed of light and so as they pass through the wiggler they experience a spatial magnetic period of λ_u/γ instead of λ_u because of length contraction. Here γ is the relativistic factor and is given by

$$\gamma = \left(1 + \frac{v^2}{c^2}\right)^{-1/2}$$

In addition to the length contraction that the electrons experience, the light is emitted by a relativistic source and then measured in the lab frame. This means there will be a relativistic doppler shift, and we get a second factor of γ.

The equation that gives the value of the emitted wavelength, derived starting from Maxwell's equations and keeping in mind the relativistic phenomena, is given by

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

The parameter K^2 is called the strength parameter and characterizes the strength of the magnetic field of the wiggler. It is given by

$$K^2 = \frac{1}{4\pi^2}\left(\frac{\lambda_u^2 r_0 B^2}{mc^2}\right)$$

Where r_0 is the classical radius of the electron, B is the strength of the magnetic field of the wiggler, and mc^2 is the rest energy of the electron.

From the equation for λ we see explicitly how free electron lasers are tuned. Normally λ_u and B are chosen during the design and construction of the free electron laser. Thus it is the γmc^2 term that we control to tune the laser during normal operation. One can easily pick a desired wavelength λ and then calculate for the γ required to emit the desired wavelength.

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

From this one know the necessary speed of the electrons and the energy of the electrons.

4. Xray Free Electron Lasers

Free electron lasers can be tuned to many wavelengths but the hard Xray wavelengths (0.01 to 0.2nm) pose a special challenge. Mirrors for these wavelengths do not exist and so a cavity cannot be constructed. Without a cavity the light cannot be fed back into the wiggler for further amplification.

To get around this, Xray free electron lasers are designed with extremely long wigglers that can reach the length of over a hundred meters (compare this to the 5.2m wiggler used in the first free electron laser). The question still remains, how does the light become coherent without a cavity?

SASE Free Electron Lasers

The mechanism of self-amplified spontaneous emission is what allows the xray radiation to be amplified and coherent. As an example we look at the operation of the free electron laser at the LCLS.

The process begins with an ultraviolet pulse that bombards a copper plate. After each pulse hits the copper plate, a burst of electrons packed together into a bunch leave the copper plate and enter the accelerator. The electron bunches are accelerated and then enter the especially long wiggler. In the wiggler the electrons begin to emit xray radiation. The electrons travel with the radiation and amplify it by the mechanism described above. Moreover, the ponderomotive force pushes the electrons away from the antinodes of the radiation and the electrons in the bunches form thin sheets of electrons separated by the wavelength of the radiation. These are called microbunches. When the electrons are in microbunches they continue to emit radiation and because the electrons are equally spaced by the wavelength of radiation from each other the radiation they emit is in phase and coherent, and very intense.

Bunch Compressors

As part of the acceleration stage of the electrons, the electrons go through a series of bunch compressors. Bunch compressors decrease the spacing between the bunches of electrons and in so doing can control the the duration of time between pulses. The bunch compressor (also called a chicane) works by introducing a slight s-curve in the path of the electrons. Much as an s-curve in a road, the electron bunch that reache the s-curve first must slow down to make the turn. This allows the electron bunches behind the first bunch to close the distance between the two. With careful tweaking the bunches after leaving the bunch compressor can be made to be closer together. The following figure shows an example of a bunch compressor:

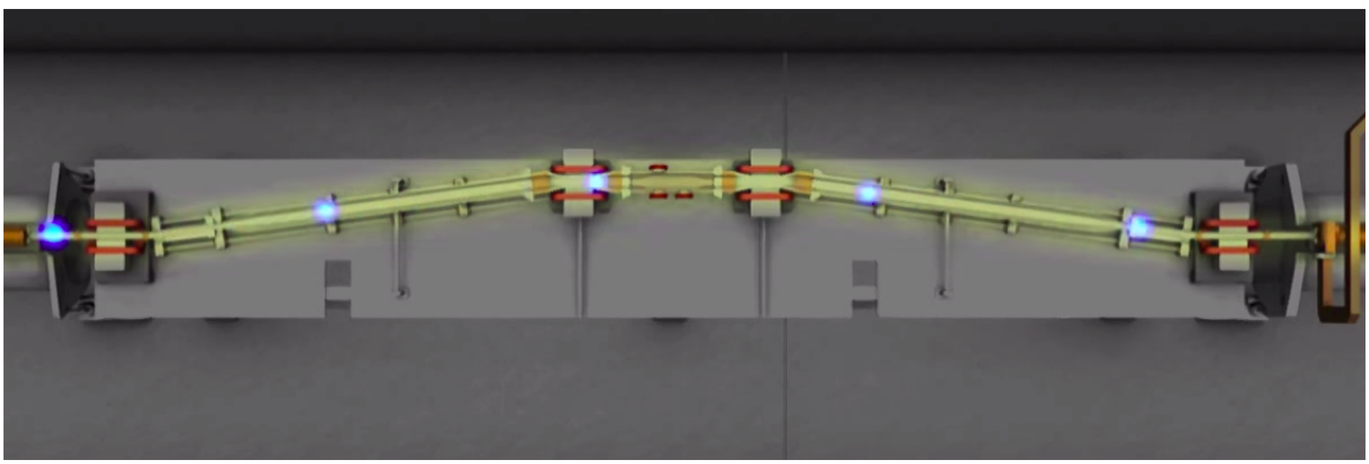

Figure 4.1. Bunch Compressor

Temporal Coherence Limitation and Self-Seeding

The mechanism of SASE leads to noise in the output pulse because the electrons initiall start off in large bunches and are emitting incoherent radiation that travels along with the electrons along the whole length of the undulator. This causes the temporal coherence of the beam to be limited and noise.

A possible solution to this is to filter out the noisy frequencies to decrease the bandwith. The main disadvantage to this is that by filtering out these noise frequencies the beam loses a lot of its intensity. Another solution is to inject a temporally coherent pulse that is tuned to the resonance of the free electron laser (to the speed of the electrons and period of ther wiggler) and then the electrons in the laser amplify this pulse. This is called **seeding**.

Though seeding is an effective solution that preserves the intensity of the beam as well as the temporal coherence, finding a seed pulse in the Xray range is difficult because conventional xray lasers don't exist.

In 2012, researchers at LCLS developped a mechanism by which the xray free electron laser could seed itself. This process of self-seeding works in the following way. Use the first half of the undulator to generate xray pulses. Then, pass the xray pulses through a diamond monochromator. The monochromator selects a very narrow bandwith of frequencies and so what comes out of the monochromator is a highly temporally coherent xray pulse. Then, use this pulse as a seed for the second half of the undulator. As the pulse passes through the undulator, it gets amplified, and because the pulse is composed of a very pure color of xray, the output pulse has a very sharp bandwidth and increased intensity. The figure below compares LCLS's measurements of the spectral intensity using SASE operation and LCLS's measurements of the spectral intensity using self-seeding.

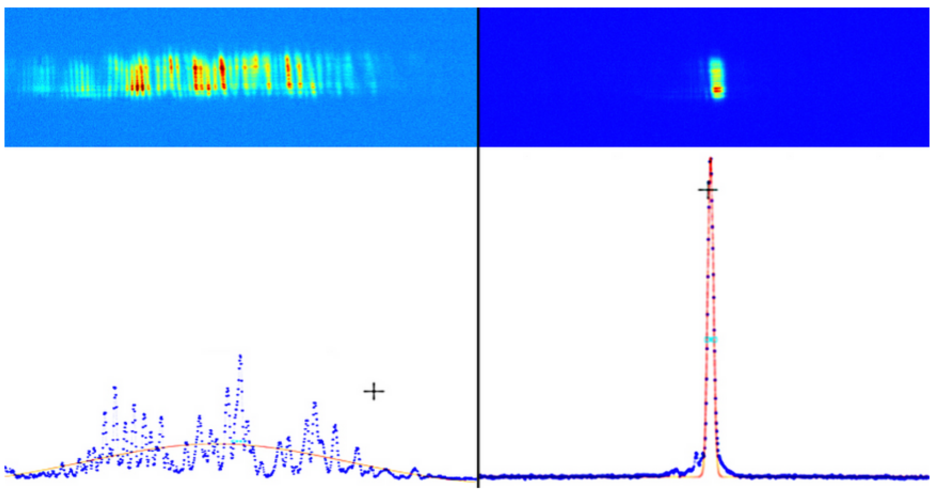

FIGURE 4.2. Spectral Profile in SASE mode and in Self-Seeding mode

The spectral profile in SASE mode is characterized by multiple noisy peaks of varying intensity, while the spectral profile in the self-seeding mode is an almost perfect and pure singular pulse. Moreover, The intensity is orders of magnitude more powerful. The improvement is almost astronomical, and many free electron lasers around the world are incorporating the self-seeding mode into their own apparatus.

5. Applications

Free electron lasers can have many applications in various sectors including, surgery, biology and military applications. In surgery, infrared FELs can be used to cut or ablate soft tissues like the skin, the cornea and brain tissue without causing collateral damage to surrounding tissue. Military applications include an active research and development program into the use of FELs as an antiaircraft anti-missile weapon, vaporizing materials with a 100kW beam.

The xray free electron laser has unique applications in biology due to its extremely short pulses and high intensity. Using xray diffraction, a biological sample (like a cell or virus) can be bombarded by a pulse of xray photons. The intensity of the pulse is more than enough to completely obliterate the biological sample, but because of the extreme shortness of the pulse, the photons are bunched together very closely in space, and all the photons in the pulse have a chance to scatter off the material ahead of the damage before the sample is destroyed. This is referred to as "diffract before destroy".

This is done multiple times on multiple samples and a collection of diffraction patterns are collected to form a 3d representation of the sample. From this one can infer electron densities and other structures in the material. Below is an example of data collected for the mimivirus using this method showing a single image of xray diffraction, a 3d combination of multiple diffraction patterns of the same sample from different angles, and the inferred electron density distribution in the mimivirus.

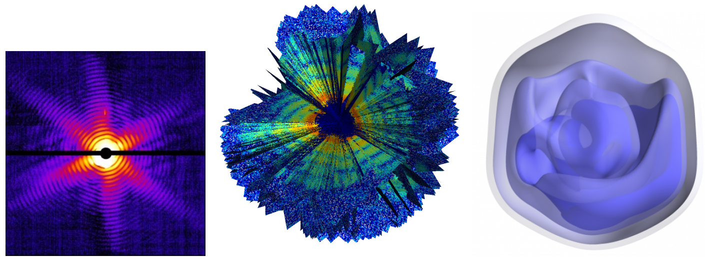

FIGURE 5.1. Xray Diffraction Data of Mimivirus

6. Conclusion

In this report we gave an overview of the free electron laser. We explained the basic operating principles and physical theory behind its functioning, including the mechanism of amplification and the interaction between the electrons and the radiation wave in the undulator. We also explained the operation of an xray free electron laser, highlighting the SASE mode and the self-seeding mode. We saw that self-seeding was a solution to the noise and temporal coherence problems that arose from self-amplified spontaneous emission. Finally we gave an overview of the different applications that free electron lasers can be used for with a focus on the application of xray free electron lasers to molecular imaging.

References

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