

Shining Light on the Light - Investigating a Theoretical Model that Predicts Free-Electron Laser Properties

Do you remember your first look through a microscope, probably in a biology class? That moment you discovered that an onion is made of neatly ordered cells? However, perhaps the most important learning of that biology class was not about onions at all, but rather about how microscopes allow us to see what was previously invisible and to better understand the world we live in.

But there is a limit. Optical microscopes resolve structures only down to a certain size, and at some point the instrument must be exchanged with another device, such as an electron microscope. What all of these have in common is that they capture static images. But what if we don't only want to see an onion's DNA, but to learn about its dynamic processes in real time? How does it change or react when hit by ultraviolet light or X-rays? To answer these and other dynamic questions, an instrument is needed that does more than zooming in: the Free-Electron Laser, or FEL. Basically, if earlier tools give us a photograph, an FEL gives us the first frames of a movie!

Unlike conventional lasers, where electrons are bound to atoms, FELs use unbound - *free* - electrons accelerated close to the speed of light by an accelerator facility. Special magnetic structures bend the path of the electrons, causing them to emit radiation down to extremely short wavelengths - precisely what we need to image tiny structures. But how do FELs resolve time-structure? The processes of interest occur on extremely short time scales, down to femtoseconds, which conventional measurement techniques cannot resolve. This time unit is so small that it goes beyond human imagination, as it is shorter than the time it takes a hummingbird to flap its wings once by a factor of 10 trillion! To access ultrafast processes, FELs probe a sample by subsequent ultrashort, extremely bright pulses of light, separated by a precisely controlled delay. Repeating an experiment upon varying this delay enables a reconstruction of the time evolution of a process, similar to adding the frames of a movie.

Like any microscope, the FEL must be calibrated to properly image the sample. In the specific FEL setup that this study focused on, tuning involves manipulating two key components: the electron beam and a seed laser, which is used to initiate the radiation process. However, this task is complex and requires careful adjustments of magnetic and optical elements.

To tackle this challenge, a novel theoretical model has been developed that predicts the spectral properties and pulse energy of the FEL using a set of mathematical equations. By implementing these in a computer program, the FEL output for a given electron beam and seed laser configuration can be computed rapidly, an approach that enables more efficient optimization of the FEL settings. Beyond predictions of the FEL output, the theoretical model has additional capabilities. One particularly powerful application is a "reversed" use of the model, after the spectrum and pulse energy of the FEL have been measured in an experiment. By fitting the model to the experimental data it can recover the beam and seed laser parameters that produced these results, which is invaluable for parameters that are hard to measure or inaccessible otherwise.

However, this model is expected to give reliable results only under certain electron beam and seed laser conditions, as approximations and assumptions were included in its derivation. Therefore, this study investigated certain boundaries of the reliable parameter space and aimed to quantify the accuracy of the model's predictions within these boundaries. Identifying why the model breaks down outside the defined region provided a foundation for future extensions of the model, such as correcting oversimplified or neglected physical processes.

Such extensions of the model bear the possibility to not only contribute to optimize the FEL for further experiments, possibly investigating the most fundamental properties and processes in matter, but also to give us a better understanding of the underlying FEL mechanisms themselves.