Manipulation of Beams of Ultra-relativistic Electrons to Create Femtosecond X-ray Pulses

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Manipulation of Beams of Ultra-relativistic Electrons to Create Femtosecond X-ray Pulses

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Objective

Typical conventional high-brightness X-ray sources (so-called synchrotron light sources) are up to 30 football fields in size (an example is shown below). Our group uses a novel technique based on ultrahigh-power lasers to develop a similar source that can readily fit into a single, university-scale laboratory. The X-ray pulses produced by this new method are as short as 10fs (0.000000000001 seconds, or 10^-14s). This is a time resolution fine enough to resolve molecular structure during chemical changes. However, in our study we focused on a particular stage of the overall process, that is, manipulating ultra-relativistic electron beams under certain given constraints. We used particle tracking codes to examine the focusing characteristics of Permanent Magnetic Quadrupole lenses. These results were then used to model the action of an undulator. The results will guide future experimental design and inform avenues of study on ultra-relativistic electron beams.

Laser Wakefield Acceleration

The Diocles petawatt-scale laser shoots a 10fs pulse into a gas jet, exciting the gas into a plasma. The laser pulse manifests an electric field that carries electrons from the plasma along like an ocean wave carries a surfer along. The electrons are accelerated to approximately 99.999999% the speed of light over centimeters.

Permanent Magnetic Quadrupole Lenses (PMQ’s)

PMQ lenses manipulate the trajectory of the electron beam in such a way that two or more lenses, in a precise configuration, will focus the electrons onto a round focal point. To the right is an example of a PMQ lens compared to a one euro coin.

Undulator

Undulators consist of series of alternating dipole magnets, placed side-by-side, in order to create a unique magnetic field. Imagine the north end of a bar magnet positioned parallel, and beside, the south end of another similar magnet, such that the pattern is repeated. Then, to insure the alternating magnetic field directions, another series of dipole magnets, with the opposite pattern, are placed facing each other as depicted in the figure to the left. When electrons travel through the magnetic field, produced by the undulator, they experience a force that “shakes” them. Subsequently, the shaking electrons produce energetic light that propagates in the direction of the electrons.

Simulation Software

- Two computer codes, General Particle Tracer (GPT) and Synchrotron Radiation Workshop (SRW), were used for most of the analysis of the PMQ lenses and undulator radiation.
- GPT is a versatile program that generates an electron beam modeled on the beams from the plasma accelerator.
- GPT then tracks each particle as they travel down the beamline, modeling electron-electron repulsion, electron energy spread, and PMQ lenses.
- This allows for accurate predictions about the trajectory of the electron beam from the exit of the electron accelerator through the lenses, undulator, and magnetic spectrometer.
- The image to the right is a visualization of a focused electron beam generated with GPT. Each dot corresponds to one simulated particle.
- SRW can accurately and efficiently compute synchrotron radiation in the near field region.
- By inputting the initial values for the various structures outlined in the simulation code, the program can track the changes as the experiment evolves.
- With the additional modification of Synchrotron Radiation Workshop, Igor Pro has the ability to model undulator radiation.
- This allows for accurate predictions about the high brightness x-ray energies, spatial dimensions, and irradiance.

Conclusions

Through the use of General Particle Tracer and SRW, we examined the manipulation of femtosecond ultra-relativistic electrons and x-ray generation. We produced the theoretical data necessary to design laboratory experiments and have demonstrated the feasibility of this technique.

References


Note: The graph to the left is 45 times larger than the one on the right. The small white box on the left graph is 200 x 200 μm, the same window size as the right graph.

PMO results

One example of a focused 1GeV electron beam is shown below. The first graph shows electron’s paths projected onto the xz plane, while the second is a projection onto the yz-plane. These two projections highlight an important property of PMQ lenses. A single lens will flatten the beam in one transverse direction and elongate the beam in the other transverse direction. By exploring PMQs using General Particle Tracer, we developed techniques to focus ultrarelativistic electron beams.