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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 lightsources) 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 (0.00000000000001 seconds, or 10^(-14)s). 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.

Alba Synchrotron at Barcelona, Catalonia

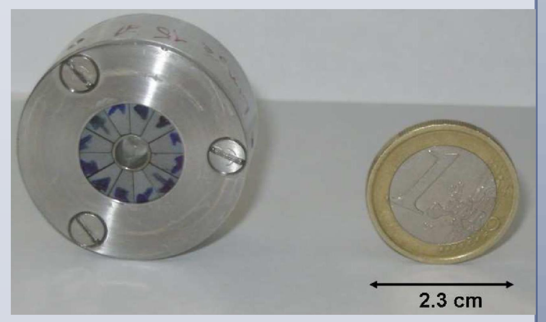
Laser Wakefield Acceleration

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 99.99999% the speed of light over centimeters.

courtesy of Shalom Jacobovitz

Permanent Magnetic Quadrupole Lenses (PMQ's)

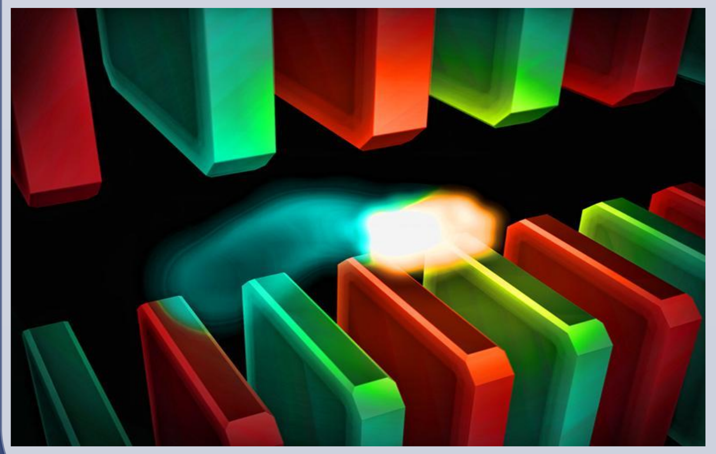
PMQ lenses manipulate the trajectory of the electron beam in such a way that two or more lenses, in a precise configuration, will focus the electrons onto a round focal point. To the right is an example of a PMQ lens compared to a one euro coin.



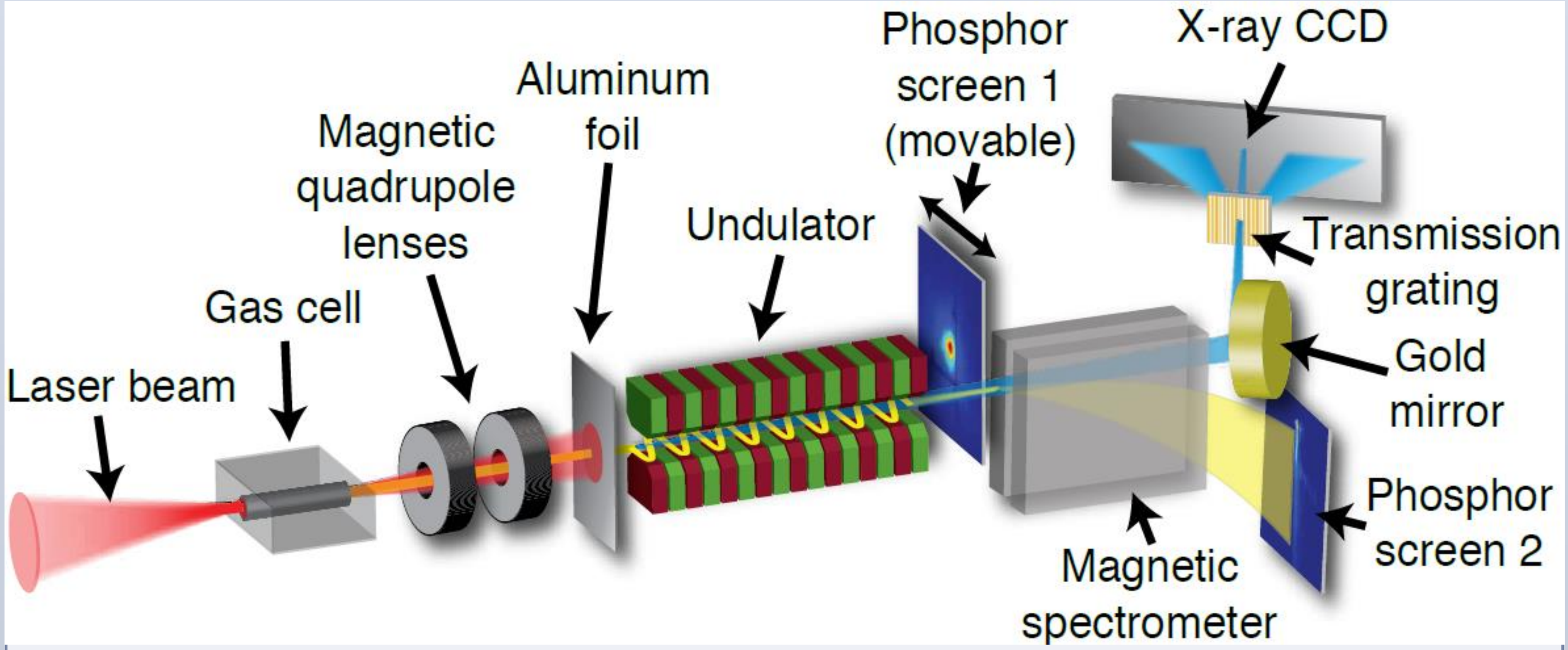
Courtesy of T. Eichner

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.

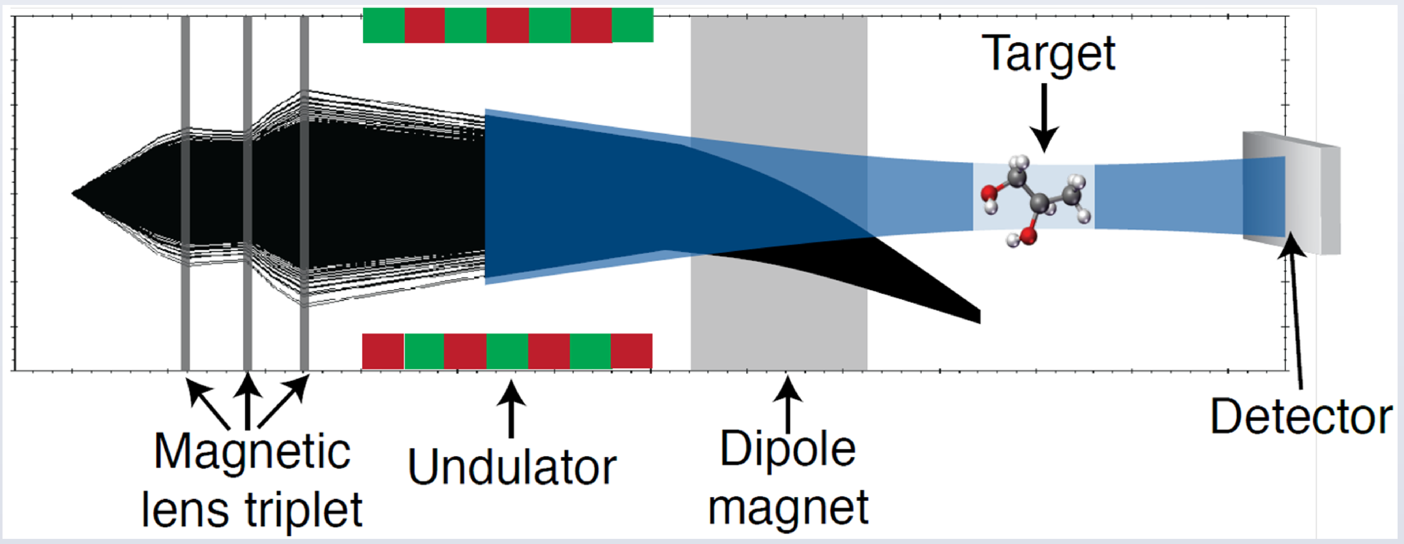


Courtesy of Greg Stuart/SLAC



Experimental Design

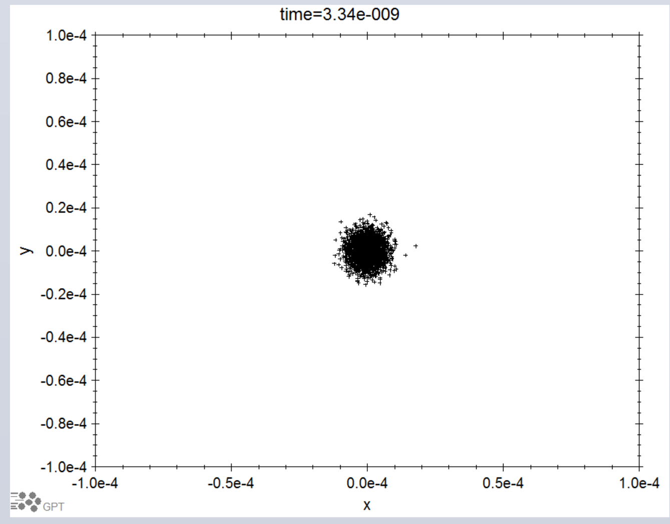
Above is an image of a tabletop ultrashort x-ray source. The laser beam enters the plasma accelerator, where it generates an electron beam 10fs in duration. The beam spreads out as it travels through space, so a precise configuration of magnetic quadrupole lenses focuses the beam. After the lenses, the electrons enter the undulator. The undulator causes the electrons to emit focused x-rays. The electrons are then pulled onto a phosphor screen by the magnetic spectrometer for characterization, and a 10fs x-ray beam is available for experiments such as ultrafast x-ray diffraction, as shown below.



Courtesy of M. Fuchs

Simulation Software

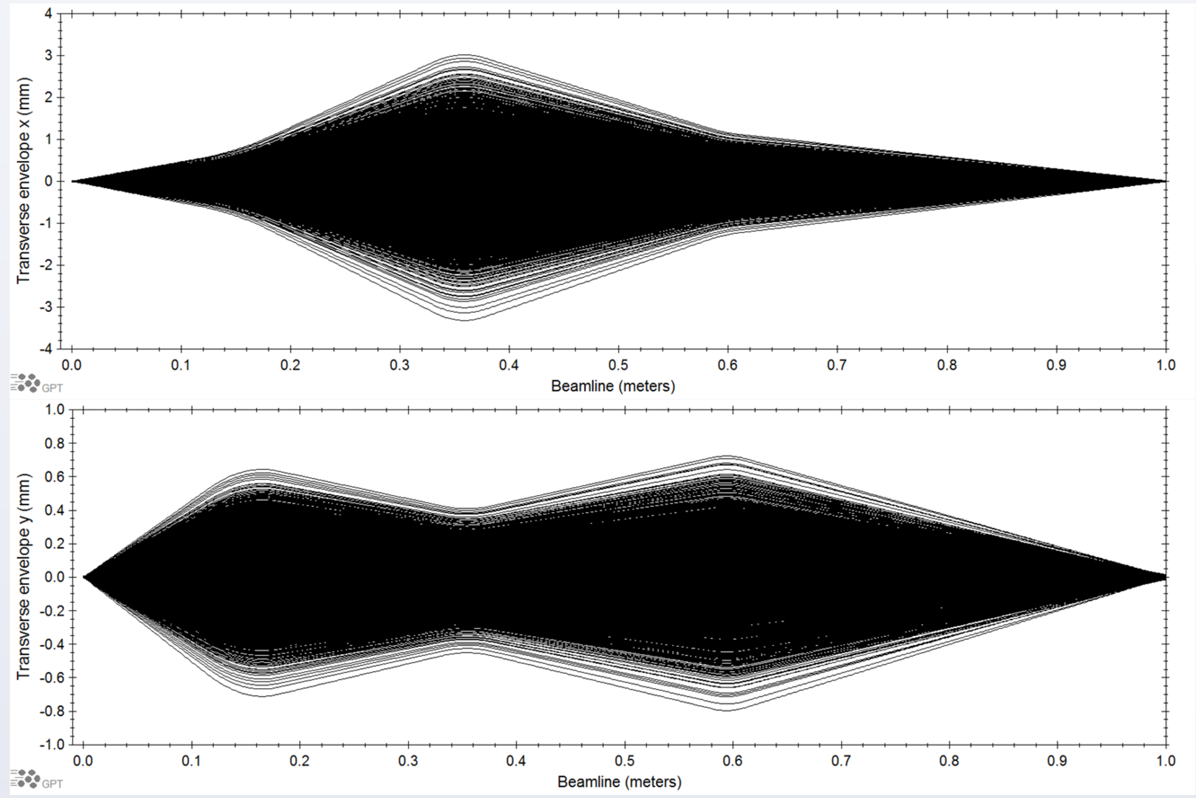
- Two computer codes, General Particle Tracer (GPT) and Synchrotron Radiation Workshop (SRW), were used for most of the analysis of the PMQ lenses and undulator radiation.
- GPT is a versatile program that generates an electron beam modeled on the beams from the plasma accelerator.
- GPT then tracks 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.

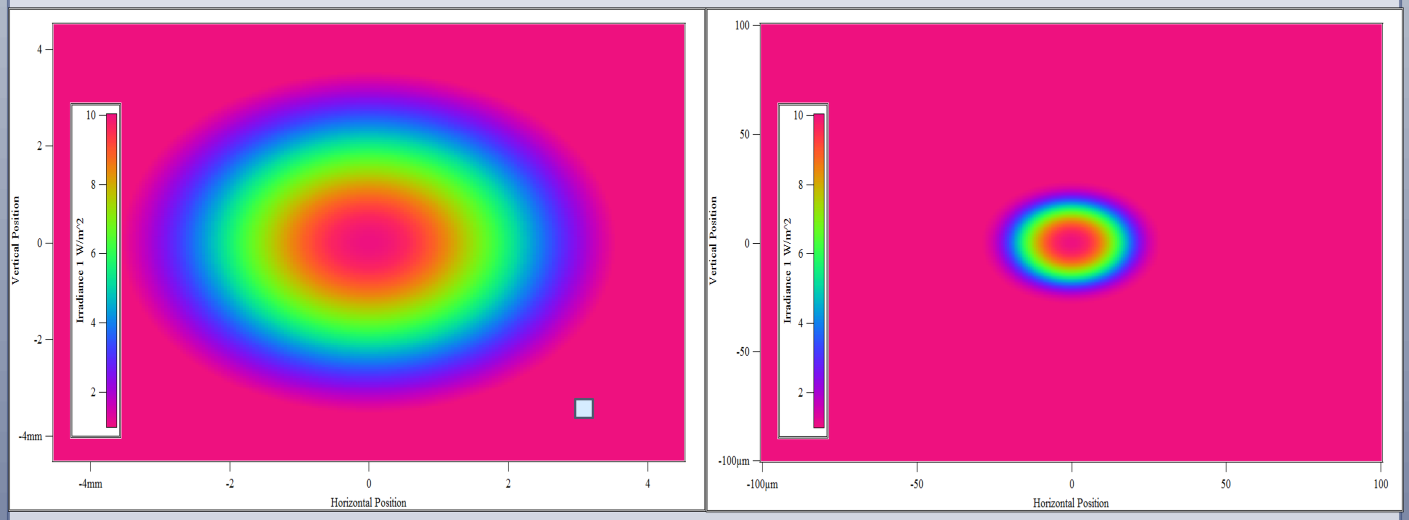
PMQ results

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.



Undulator Results

The two graphs below are the results from SRW simulations for radiation produced by 1GeV electrons passing through a 30 cm undulator. The graph on the left shows the intensity of light at the focus, without the aide of the PMQs, whereas the graph on the right shows the same yet this time with the PMQ setup above. Notice the axes change scales, from 4mm to 0.1mm. It's apparent that without the PMQs the spot size of the light at the focus is significantly larger than that of the light produced by electrons on a focused trajectory. For our purpose we need the light at the target to be focused and intense; therefore, it's imperative for us to use focusing elements, which in our case are PMQs.



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.

Conclusions

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

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