Novel Compact Particle Accelerators and X-ray Sources

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Figure 2 Rutherford Laboratory

Energetic beams of charged particles and the radiation they produce are important tools for modern science and progress in technology. High quality bunches of electrons travelling at almost the speed of light with narrow energy spread, can be used to produce visible light and x-ray radiation and are thus essential to synchrotron light sources and free-electron lasers. Figure 1 shows a state-of-the art 3rd generation synchrotron facility, the Diamond Light Source. Electrons are accelerated into a storage ring from which they can be fed into an undulator. Figure 2 shows an undulator, a periodic assembly of permanent magnets, which forces traversing electrons to wiggle and give of high quality x-ray light flashes. Medical and life sciences, engineering and industry crucially depend on the unique properties of these light sources for research and development.

Energetic bunches of electrons are equally important for high energy particle physics and to help mankind understand the fundamental laws of physics and the beginning of the universe. Conventional accelerators are limited to relatively low accelerating fields, requiring hundreds of metres to reach the gigaelectron volt (GeV) beam energies needed by synchrotrons, and kilometers to achieve energies needed for particle physics.

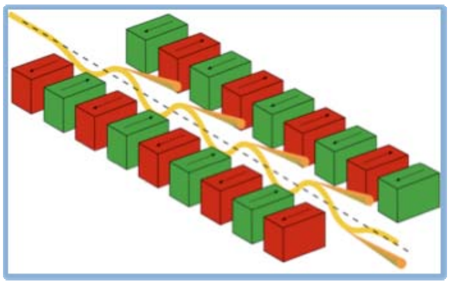

Figure 1 Schematic of an undulator

A short laser pulse can create a plasma wave when focused at high intensity into a gaseous medium. By using the enormous electric fields of the plasma wave, one can mimick the mechanisms of electron acceleration and radiation generation that occur in a large conventional accelerator. But rather than doing this on the hundreds of meter scale, in a plasma wave it can happen in only millimetres, because the fields of the plasma wave that accelerates the electrons can be 100-1000 times stronger than in a conventional accelerator. This has the potential to greatly reduces the size and cost of the accelerator device. A schematic of the experimental setup is shown in figure 3.

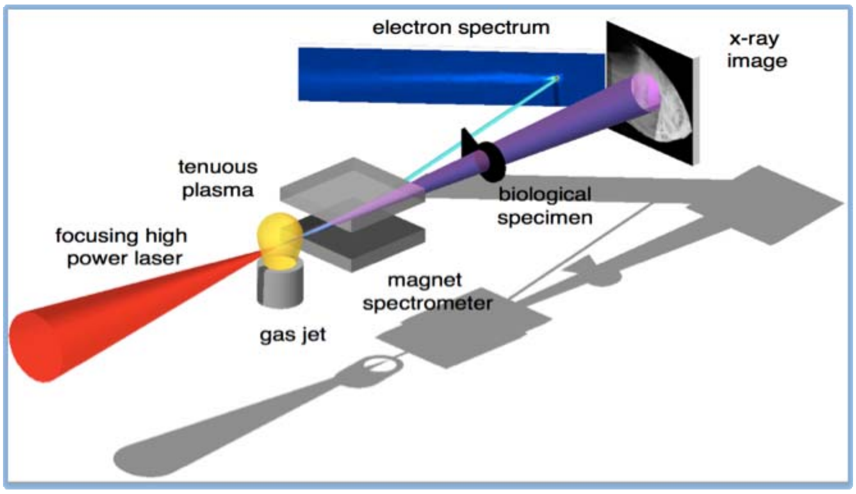

Figure 3 Experimental Setup

For this experiment, the Astra Gemini laser at the Central Laser Facility, located in the background on the areal photograph in figure 1 is ideally suited. The interaction produces electron beams that are then deflected with a magnet, dispersing them according to their energy. The dispersed electrons strike a phosphor screen, producing a visible signature of their spectrum. The spectrum is recorded with a digital camera. The analysed data is shown in figure 5. The electrons were accelerated to 250 MeV with a very narrow energy spread, small (5 in 1000) divergence and ultrashort (femtosecond = 10^{-15}s) pulse duration.

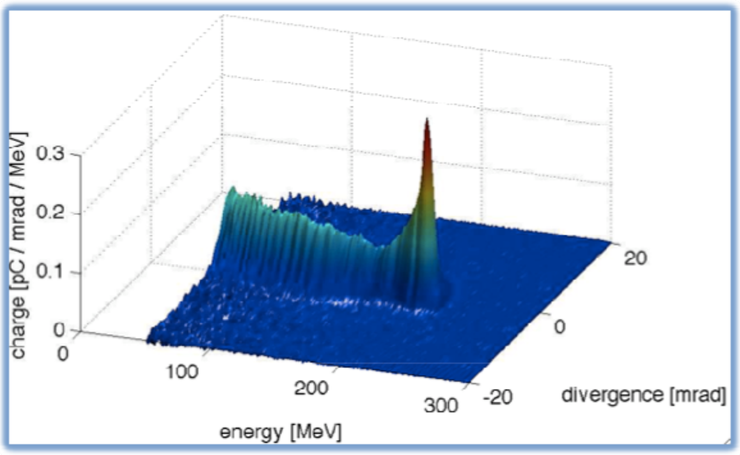

Figure 4 Sample electron spectrum

The plasma wave not only accelerates the electrons in the direction of the propagating laser. Transverse electrostatic fields wiggle the beam around, and make it give off x-rays analogous to the mechanism in the permanent magnet undulator in figure 2. The x-ray beam is found to be highly directional and ultrashort, just like the electron beam itself. The x-rays stem from a tiny, micrometer-sized source and have a peak brightness that parallels conventional synchrotrons like the Diamond Light Source shown in figure 1.

This table-top plasma undulator has the potential to open up a plethora of applications, ranging from optical-pump x-ray probe experiments to taking snapshots of ultrafast dynamics on the micrometer scale and beyond. Figure 3 shows how such an experiment could look like. After the electrons have been deflected from the beam axis, only x-rays are left, that can be used to imaging a biological specimen. In this case, an orange tetra fish was chosen. A single flash of x-rays from the plasma undulator is preferentially absorbed in the densest parts of the specimen (skeleton), producing a finely detailed medical x-ray. More recently, it was found that the x-rays from the plasma undulator possess a quality called spatial coherence, which makes them ideally suited for advanced imaging techniques. In phase contrast imaging, the spatial coherence properties of the x-rays enhance image contrast from specimens such as an insect or single cell, that give rise to little or no x-ray absorption.

Figure 5 X-ray Image of a fish

Abundant sources of high brightness, spatially coherent ultrafast x-rays may fundamentally change the way we conduct science, repeating the impact that the advent of the first x-ray tubes had a hundred years ago.

For more information, read:

SPD Mangles, et al., *Nature*, **431**, 535 (2004)
S Kneip et al., *Physical Review Letters*, **100**, 105006 (2008).
S Kneip et al., *Nature* Physics, **5**, 1789 (2010)