Publishable Executive Summary

TUIXS
Table-top
Ultra Intense
Xuv Sources

www.tuixs.org

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Summary description

The TUIXS (*Tabletop Ultra-Intense XUV Sources for Femto-Biology and Related Applications*) project goal is to deliver to the scientific community a new kind of soft x-ray source, needed for progress, for example, towards future x-ray flash imaging biological experiments.

The approach is based on the extension of the concept of a laser chain into the XUV domain. A laser chain is conceptually separated in an oscillator, one or several amplifier(s) and several optics for relaying the output of the oscillator to the entrance of the first amplifier and then from one amplifier to the one after. Very recently visible laser chains started to include active sensing and optics to keep all along the amplification a high optical quality required for tight focusing and then production of very high intensity. The TUIXS idea is to use high-optical quality, High Harmonic Generation (HHG) soft x-ray source as a seed (oscillator-like), and subsequently amplify harmonics by six orders of magnitude beyond the state-of-the-art that existed at project initiation. HHG having femtosecond duration, the soft x-ray laser amplifier chain has to be designed such a way to preserve the brevity of the pulse. Apart from the high-energy output and short pulse duration, the TUIXS source should have a regular wave front to achieve focusing to a small spot size (~0.1 µm) with expected intensity in the 10^{19} Wcm^{-2} range. Such ultra-high intensity will be a major breakthrough opening many never explored fields from plasma physics, atomic physics to Biology.

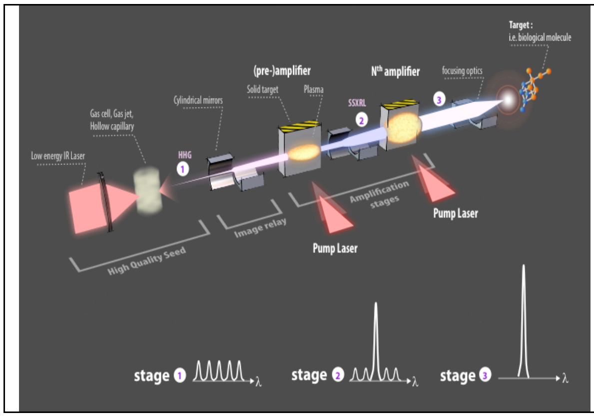


Figure 1:
Artist view of a three stage amplification chain working in the soft x-ray range. At the end of the chain, the seeded soft x-ray laser is tight focus on a biological sample for flash imaging experiment

The final goal is to produce femtosecond-range pulses with energy up to the mJ range, near 13 nm with sufficient control on the full process to achieve routine production and also to ensure the spreading of this invention to many laboratories in Europe and also world wide.

This work will be done on several aspects in parallel : optimization of tunable HHG generation, achievement of plasma amplifiers having high gain and good homogeneity to preserve the HHG wave front, and soft x-ray optics development. After the first year integration of the different components will start to concentrate on one major experiment by the end of the project with clear demonstration of interest of such a ultra-intense soft x-ray source for femto-biology. At the final stage of the chain, the beam will be focused, and this will enable exciting new experiments in biology. The goal of these experiments is to demonstrate that structural information on biological samples can be obtained by the scattering of XUV pulses from the sample *before* the sample structure is destroyed as the heated sample turns into plasma.

The high harmonic development will focus on few topics. For ensuring a successful seeding, the wavelength of the HHG must coincide with the wavelength of the soft x-ray laser. HHG tenability, although being demonstrated years ago, has still to be improved and better controlled for our experiment. Intensity at the entrance of the amplifier has to be strong to reach the saturation over few millimeters of plasma and to keep a short pulse duration. At 30 nm, our starting wavelength, this is not an issue while at shorter wavelengths, 13 nm for TUIXS project and 4 nm beyond our project, HHG intensity is known to be weak. We will work on its enhancement. Finally, the seed beam quality (coherence, polarization, wave front) has to be very good since it will give the final properties of the soft x-ray laser.

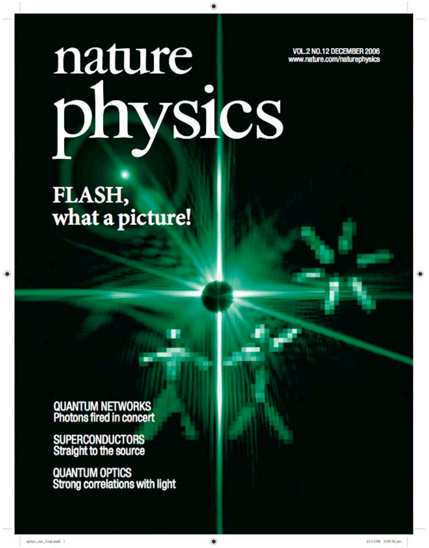
Achievement of strong amplification with output energy near 1mJ per pulse required creation of a plasma in which it is possible to store a large amount of energy. Solid targets are known to have large storage energy (about $1 J/cm^2$). However, solid targets are often poorly homogeneous leading to beam degradation during amplification. Intensive numerical studies will be performed to guide the experimentalists in the design and achievement of a high-gain, homogenous solid amplifier. Since such modeling is far beyond the actual state of the art, both experiment and numerical developments will be done in close-loop, by doing benchmarking experiments for example. Targeted experiments on the improvement of plasma homogeneity are planned. Wave front being a key property of the seeded soft x-ray laser, we will adapt a soft x-ray wave front sensor to be able to measure the beam quality of an ultra-intense soft x-ray beam in a single shot.

In advance to ultra-high intensity flash imaging of bio-samples, we will progress on coherent imaging with femtosecond sources as well as flash imaging with picosecond soft x-ray sources. We are mainly planning to work on digital in-line holographic microscopy, Mie scattering and diffraction.

Results achieved so far and expected.

As explained above, the project might be artificially view as a three-step timing. First, we set all the scientific and technologic components of TUIXS, second we will progressively merge these components to construct the first soft x-ray amplification chain working with solid targets, and then we will finish by demonstrating flash imaging experiment using this novel source.

At the moment, the planning is somehow progressing much faster than initially expected. Indeed, thanks to the opening of beamtime at FLASH free-electron laser, the Prof. J. Hajdu's group and collaborators were able to test for the first time the flash diffraction of a sample irradiated by a 25 fs, ultra-intense (4×10^{13} Wcm^{-2}) soft x-ray source (H. Chapman et al, Nat. Phys., 2, 839, 2006). Despite the pure beauty of the diffraction image achieved, this experiment demonstrated that very short pulse enables to acquire structural information of a sample with nanometer resolution before being destroyed by the soft x-ray beam itself. Although the wavelength is still too high for achieving 3D images of large bio-molecules, this result paves the way to future experiments on X-ray FELs (LCLS or European X-FEL).



nature physics

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FLASH, what a picture!

QUANTUM NETWORKS
Photons fired in concert

SUPERCONDUCTORS
Straight to the source

QUANTUM OPTICS
Strong correlations with light

Figure 2:
Cover page of the December 2006 issue of the review Nature Physics showing in an artist view the diffraction pattern as well as the sample used (two figures and the sun)

Important developments have also been made concerning the realization of small-scale ultra-intense soft x-ray sources pumped by laser. In a way, TUIXS started thanks to the demonstration at the LOA of a strong amplification of a high harmonic source (seed). At the beginning of TUIXS this source was not fully characterized in particular the optical quality was inferred from previous experiments but not directly measured. Since our objectives is to focus the beam on a spot size as small as possible (final goal around 100 nm in diameter), spatial coherence as well as the wave front must be checked carefully. We then measured this parameters using a gas amplifier and surprisingly we observed that the amplifier acts very efficiently as a spatial filter. The beam was much more coherent after amplification than before and the wave front was much better going from λ to λ/10 (λ=32 nm). This results relax strongly the need on HHG beam quality.

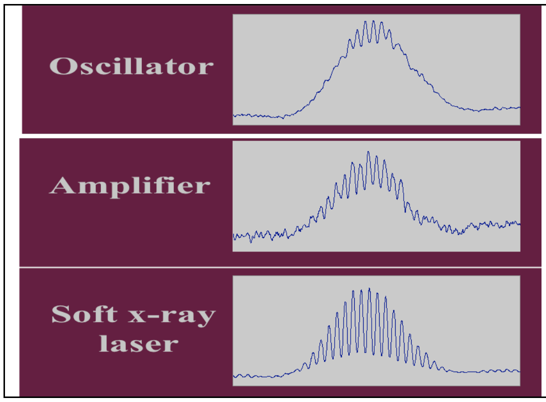

Figure 3:

Plots of three diffraction patterns achieved with a double Young's slit experiment and the high harmonic beam alone (top), the amplifier self-running (middle) and the seeded soft x-ray laser (bottom). The contrast enhancement is striking

Amplification with solid target is quite complicated since the time and region of gain creation are purely given by the plasma hydrodynamic. It is then complicated to know where and when the HHG beam has to be seeded in the plasma. Also, it is well known that plasmas may be inhomogeneous if high care is not taken when created. Since any inhomogeneity will strongly impact on the amplified beam quality, this issue is crucial. However, at the beginning of TUIXS there was no open hydrodynamic code having a sufficient accuracy for guiding our researches on plasma amplifiers. We adapted the ARWEN code from Universidad Politecnica de Madrid, Spain, and then generated important breakthroughs. For example, we demonstrated that the classical plasma shape produces a gain zone between a 1/3 to ½ of the laser focal spot size. This means that most of the driving laser energy was spoiled. On the contrary, using super-gaussian focal spot ensures to have between 70 to 90% of the focal spot that creates amplifying plasma. This allows for example to reduce by a factor 2 to 3 the laser energy (so the prize) to achieve the same output energy of the seeded soft x-ray laser.

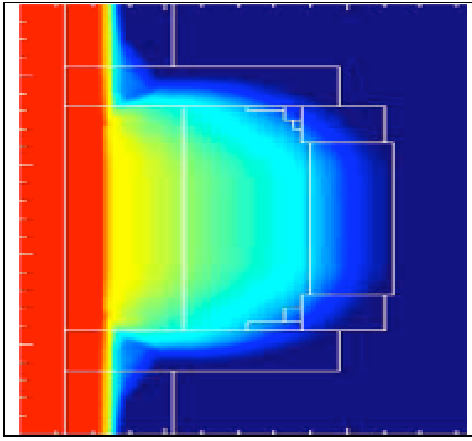

Figure 4:
False colour representation of the plasma plume created by a super-gaussian laser. The red is for the target, the blue for the vacuum. The driving laser comes from the right to hit the target. The white cells are numerical cells used for the so-called Adaptive Mesh Refinement, AMR, technique

We are now halfway through the project and we thus are starting to concentrate our efforts on 1) the experiment on FLASH free-electron laser, 2) on having a very accurate plasma and seeding modeling for guiding our experiments, and 3) the first integrated experiment with solid target amplifier and full metrology of the amplified beam.

Spin-offs and dissemination :

As soon as the intensity is increased by few orders of magnitude, plasmas may be created from soft x-ray lasers opening important spin-off for Astrophysics or civil thermonuclear fusion.

Finally, to increase the data generation capability of the XUV laser one would like to keep the repetition rate as high as possible. The repetition rate in the XUV systems is limited by the pulse repetition rate of the driving optical laser. Therefore, to insure a high degree of dissemination of the results achieved within the TUIXS project, we are studying several types of XUV chains, each of which depends on the laser facility where they are implemented.

In broad perspective, creating the tabletop x-ray laser will have a significant impact on a very wide area in science and industry. These new sources represent a technological leap for laser chains, extending the high intensity domain to the soft x-ray range on small-scale facilities. The final goal is to produce an amplified harmonic beam with a brightness level similar to the first-stage VUV-FEL enabling many European groups to start research linked to this cutting-edge development.

The TUIXS project also has an important societal impact by producing high profile scientific results, helping to attract promising researchers to the field, and helping to increase general public awareness of interdisciplinary studies where the biological and physical sciences become interdependent.