7 Summary and Conclusions

The laser-based generation of X-ray pulses is a field of scientific research which currently witnesses rapid progress in both, the development of new radiation sources as well as new applications in a number of different fields. On the source-side the development is going towards increased flux parameters and towards higher repetition rates. While the latter is coupled to the progress of pump laser technology (and therefore limited to about 50 kHz in foreseeable future[1]), the X-ray flux may be increased by a number of different parameters:

- Shorter laser pulses (advanced dispersion compensation in amplifiers will enable routine operation with output pulse lengths shorter than 20 fs),
- Higher pulse energies from stronger amplification (20 mJ at 1 kHz were already realized),
- Higher focused intensities by application of closed-loop beam profile control using modulator schemes.

Target technology will be adapted to these new laser systems. Continuous operation with a rapid exchange of the exposed target surface together with a sub-micron spatial stability will be required as a direct consequence of the laser development.

It was a major goal of the work presented here to develop a system for the laser-based generation of X-rays that included up-to-date laser technology as well as a target system that fulfills the above mentioned requirements. That was done with a laser system that is small, reliable and –in its major components- commercially available. It was found to be capable of producing focused laser intensities of 3×10^{16} W/cm² (2 mJ pulse energy, equivalent to the specified Spitfire output) and of 5×10^{16} W/cm² with 3 mJ pulse energy from the MBI-post amplifier. A new target system incorporating a microscopic jet of liquid metal or of water was exposed to the laser pulses and was found well suited to the particular requirements of laser-plasma experiments at high repetition rates. Time resolved photography of the jet with a resolution of <200 ns showed how the jet dynamics evolve after exposure to the focused laser

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[1] In pulse trains higher repetition rates can be created [WLM98]. For such a system a water jet with 10 µm diameter was used as target with good results in XUVgeneration at 250 kHz [VOG02].

pulse: a gap in the jet is formed and propagates with the velocity of the target. No instability or vibration of the jet was observed in that experiment and extrapolation of the time, the jet needs to move a new pristine target surface into the laser focus, sets the maximum laser pulse repetition rate for this target to more than 200 kHz.

With liquid gallium as target material a source for X-ray diffraction experiments was characterized. The photon budget from Ga $K_{\alpha 1}$ line radiation was determined to 5.5×10^8 photons per second. This is more than from other kHz-systems but, due to lower laser energy, less than from common 10 Hz terawatt devices. The key question, if that is enough for diffraction experiments, could be answered positively: In a Bragg-diffraction experiment the Ga $K_{\alpha 1}$ and $K_{\alpha 2}$ lines at about 9.2 keV with only 27 eV energy difference (or 0.004 Å in wavelengths) were measured well separated with high resolution and a signal-to-noise ratio as good as 1:80. This is fully sufficient for future diffraction experiments. Results from the terawatt systems give reason to expect from a further increase in focused laser intensity of one order of magnitude a larger increase of the photon numbers. That would make the gallium jet target a system competitive or superior to conventional wire and tape targets.

Beside the line radiation, the broadband bremsstrahlung emission of different target materials was investigated. It turned out, that water, although less efficient than the higher-Z materials, could be an interesting target material for the generation of tunable radiation in the range of tens of keV.

Additional experiments were conducted to understand basic plasma processes on this target and to develop further applications of this new laser-target combination. Among the various plasma processes, the acceleration of electrons is of particular interest, since this is the key process in the energy conversion from laser light to X-ray photons. Water has a low cross section for interaction with energetic electrons. This is deleterious for X-ray generation but desirable for the investigation of electron beams. Therefore, with a water target, collimated beams of electrons were detected directly. Additional analysis of the visible radiation emitted during these experiment gave evidence that electron-acoustic waves may be play an important role in the electron acceleration process. This happens typically in a pre-plasma and since acceleration is done over a longer distance can be more efficient than the acceleration processes on the critical surface which are more typical for high contrast laser pulses.

Since all ideas about the generation of beams of relativistic electrons from LPP rely directly on the presence of an ultrastrong laser-field it must be assumed, that these 'beams' are electron bunches with a temporal extension not larger than the original laser pulse width. Such sub-ps electron bunches offer entirely new possibilities for time resolved experiments of interaction between matter and energetic electrons.

Finally, the acceleration of ionized hydrogen, i.e. protons, from the water jet target was investigated. This is an effect, well-known from large scale facilities which can now (thanks to the advanced laser technology) be investigated in small laboratories as well. Protons with energies of up to 400 keV were found. The spatial distribution of the protons was almost isotropic, with occasional hot spots. The origin of the latter effect remains unclear and underlines that more experimental and theoretical research is necessary for a full understanding of the proton acceleration mechanisms. Since proton acceleration in LPP is a point of frequent discussion and active research the water jet experiments may be continued within the community and result in a device that offers (again: ultrashort) bunches of energetic protons for time-resolved interaction experiments.

Since the whole setup supports synchronization with laser pulses, pump-and-probe schemes using proton (or electron) bunches for the determination of reversible and non reversible structural changes become feasible. Furthermore, one can envisage combinations of these methods with time resolved X-ray studies facilitated by a high-repetition rate femtosecond X-ray source of the type described here.

This work is the outcome of the rapid progress in laser technology. This process is still very dynamical and will give physicists new tools for the time-resolved investigation of matter. Ultrashort pulses of hard X-rays, electrons and protons may play an important role in that and as shown in this work, such experiments may become possible for an increasing number of smaller or university laboratories.