Soft X-ray spectroscopy of optical field-ionized plasmas

T. Mocek, Y. H. Cha, K. H. Hong, C. M. Kim, H. J. Shin, D. G. Lee, and C. H. Nam
Department of Physics, KAIST
tomas@cais.kaist.ac.kr

Since the first demonstration of a lasing action by T. Maiman in 1960 there has been tremendous technological progress in decreasing the laser pulse duration and thus increasing the peak power. The latest breakthrough was caused by implementation of the chirped pulse amplification technique (CPA) which has become a popular method to achieve ultra-high optical intensity ($>10^{16}$ W/cm^2) from a compact laser system. The basic idea of CPA is to stretch the time duration of an initial short pulse, and thus to lower the peak intensity. The stretched pulse can be efficiently amplified to a high energy and then be recompressed, using a grating arrangement, back to near its initial pulse duration. A typical small-scale, high repetition rate (> 10 Hz) CPA laser system is able to generate pulse energies in excess of 100 mJ in a pulse of less than 50 fs, thus delivering peak power of several terawatts.

By focusing the femtosecond laser beam into a gaseous medium, multiply ionized, strongly non-equilibrium plasma can be produced by the mechanism of optical-field ionization (OFI). This process can be described using the barrier suppression ionization (BSI) or Ammosov-Delone-Krainov (ADK) models [1], both providing similar prediction. According to these models, OFI allows precise control of the stage of ionization by adjusting the intensity of the driving laser and even preparation of a desired electron energy distribution by varying laser polarization. In particular, a linearly polarized laser generates cold electrons, while circularly polarized one produces electrons with high kinetic energy. Gas phase targets are attractive for use in X-ray generation for many reasons. Particularly, coherent X-ray radiation can be produced through high harmonic generation, or through creation of a plasma channel with favourable conditions for X-ray lasing [2]. In this presentation, we give an overview of our experiments in which soft X-ray emission from OFI plasmas is investigated with special emphasis on the development of a table-top X-ray laser based on tunneling ionization and subsequent electron excitation.

The experiments have been carried out at KAIST using a 20 fs, 3 TW Ti:Sapphire laser system. The laser is based on CPA technique and will be described in detail elsewhere [3]. Linearly or circularly polarized laser pulses were focused into a gas jet, or a low pressure gas cell by means of spherical mirror. Circularly polarized light was generated by inserting a mica quarter-wave plate into the path of the laser beam after pulse compression. The measured spot size diameter was less than 50 μm, so the estimated maximum laser intensity in the focal spot was around 5 x 10^{16} W/cm^2. The gases under investigation were N_2, Ar, Kr, and Xe. In the case of gas jet, the peak gas density in the interaction region could reach up to 10^{19} cm^{-3} depending on backing pressure (1 to 15 bar) and height of the laser focus above the nozzle tip (typically 250 μm). On the other hand, the use of a differentially pumped static gas cell has made it possible to study interaction at low densities around 10^{17} cm^{-3}. The principal diagnostic was a space-resolving, flat-field extreme-ultraviolet (XUV) spectrograph [4] equipped with a backside-illuminated X-ray charge coupled device (CCD) detector. Time integrated soft X-ray spectra were taken transversely or longitudinally with respect to the direction of the laser beam. The covered spectral range was from 40 to 500 Å, and spectral resolution was ~0.2 Å at 200 Å.

We have observed strong resonance lines of eight-times ionized species in the transverse spectra from laser irradiated gas jets of Ar, Kr and Xe (Fig. 1). This result is in good agreement with the predictions of BSI and ADK models and demonstrates that the plasma was adequately ionized to produce Ne-like Ar IX, Ni-like Kr IX and Pd-like Xe IX stages by the mechanism of OFI. Particularly, the spectrum of Kr obtained with circularly polarized laser pulse is significantly stronger than that with linearly polarized pulse, indicating higher electron temperature and thus more efficient collisional excitation. In the spectra from gas cell, resonance lines belonging to Li-like N V and Pd-like Xe IX ions have been observed at pressures around 20 Torr.

A preliminary experiment on collisionaly excited OFI X-ray laser was performed in longitudinal irradiation geometry. Using high-pressure gas jet, lines at 326 Å in Kr IX and 418 Å in Xe IX, on which lasing was predicted, appeared in the spectra as a weak and rather not sensitive to the change of plasma length. The lasing line candidate at 418 Å in Xe IX was also observed in the spectrum from gas cell as a distinct, albeit not dominant feature. While increasing the length of plasma no amplification was observed on this line, however, the line could be always clearly resolved. These first results indicate that the plasma is properly ionized, but the average electron temperature is still low to provide a significant collisional pumping. The investigation on OFI X-ray laser is currently being pursued by employing an upgraded experimental setup and another pumping schemes.

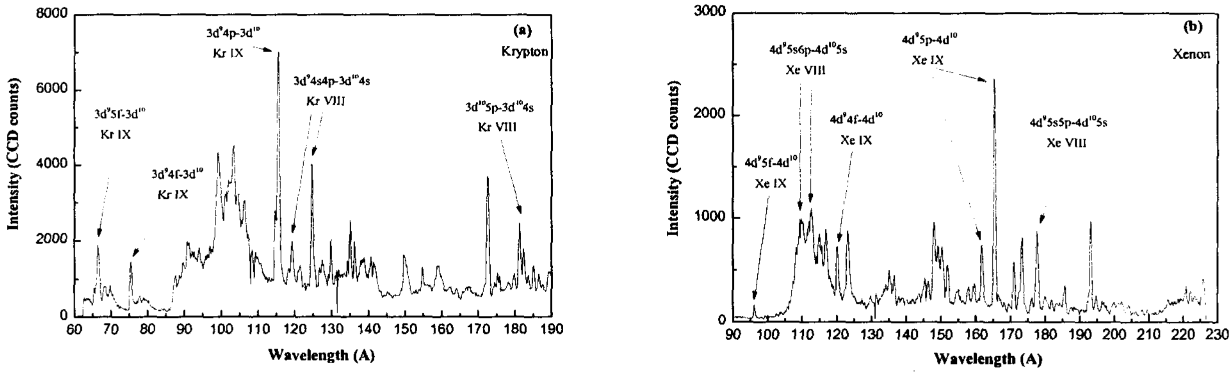

Fig. 1. Typical transverse spectra produced by circularly polarized laser pulse in a gas jet of (a) Kr (7 bar, 27 mJ, 100 shots), and (b) Xe (1 bar, 32 mJ, 50 shots).

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