論文の要旨

題目　Spectroscopic Study on Enhancement of Water-Window X-ray Radiation Emitted from Laser-Produced Gold Plasmas
(レーザー生成金プラズマからの水の窓域Ｘ線放射増大に関する分光研究)

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X-ray microscopy has attracted great attentions, since it allows for observation of the inner structure of materials and of biological cells. In particular, water-window (WW) soft X-ray (wavelength: 2.3-4.4 nm) having drastic change of transmission between carbon and water – the main constituents of living organisms –achieves a high imaging contrast. In order to observe an intact and vivid specimen with a high spatial resolution, a bright X-ray is required, whereas the blurring effects occurred in the specimen has to be suppressed by using a sub-nanosecond X-ray pulse. One of the candidates for intense and short X-ray pulse is laser-produced plasmas. However, the conversion efficiency from laser energy to X-ray is even weak (for WW X-ray wavelengths: ~1%), which hinders the realization of practical X-ray microscope.

Recently, it was found that the enhancement of WW soft X-rays from laser-produced gold plasmas was observed under N_2 atmospheres. However, the laser used was 100-J class high-power laser, and the repetition rate was 3 hours/shot. In order to provide an affordable, tabletop X-ray microscope suitable to laboratory base experiments, a commercial joule-class, 10 Hz laser system would be preferable. The new finding on the X-ray enhancement and requirements for compact X-ray microscopes motivated to conduct more sophisticated experiment and simulation. The objectives of the present thesis research are as follows:

(1) Confirmation that this phenomenon occurs by a compact laser system,
(2) Enhancement of X-ray yields and identification of the mechanism,
(3) Installation of the various X-ray diagnostic apparatus and development of reliable radiation hydrodynamics simulation code for Au plasma.

The enhancement of WW soft X-rays emitted from Au laser plasmas under various gaseous surroundings (N_2, O_2, Ne, He, Ar) was investigated. A gold slab target was irradiated with a Nd:YAG laser pulse (wavelength: 1064 nm, duration: 7 ns, energy: <1 J). Emission spectroscopy was carried out to measure the X-rays from Au plasmas. The results showed that with increasing N_2 gas pressure the WW X-ray yields were also increased. Thus, the result observed by the high-power laser was reproduced by the low energy laser system. At 400-Pa N_2 atmosphere, the yield became higher by 13 times than that in vacuum. Considering that this trend was obtained only in N_2 atmospheres, thus the reason for this enhancement should be found in atomic structure attributed to the nitrogen atom/molecule.

In order to clarify the enhancement mechanism, the radiation hydrodynamics simulation was conducted to investigate plasma parameters. In addition, the flexible atomic code was employed to align the spectra from various charged Au ions. By considering the results obtained by the experiments and simulation data comprehensively, the underlying physical mechanism responsible for the increase was revealed. First, the photoionization of N 1s innershell electron by broadband X-rays created many Auger electrons, because it's cross section is very high (~1 Mbarn). The Auger electrons with quasi monochromatic energy of 360 eV caused state selective collisional excitations of $4d$-$4f$ and $4f$-$5g$ in Au^{21+} and Au^{22+} ions, and subsequent intense radiative decay resulted in the X-ray enhancement of 345-375 eV photons. Consequently, the energy down-conversion of hard X-ray could be main reason for the enhancement in WW soft X-ray.

For more comprehensive understanding for the enhancement mechanism and further intense X-ray emission, a sophisticated radiation hydrodynamics simulation code incorporated with reliable opacity data and N_2 gas effects is necessary. Therefore, X-ray diagnostic tools were installed in a vacuum chamber to measure the spatiotemporal emission profile and X-ray spectra with a high dispersion, by which reliability of the simulation code was validated. A grazing incident spectrometer equipped with a toroidal mirror and flat field grating measured the spectral profile and provided 2D image of a given wavelength. A pinhole camera with thin foil filters observed direct X-ray images. In addition, the temporal evolution and emission energy of the laser plasma X-ray were determined by two Si detectors. On the other hand, 2D radiation hydrodynamics simulation (Star2D) for laser plasma was significantly improved and became applicable to Au laser plasmas. The experimental data were in excellent agreement with the simulation results. Thus, the development of the reliable laser plasma simulation code was successfully achieved.

The results obtained throughout this thesis absolutely contributes to development of a more intense, short pulse laser plasma X-ray radiation source, by which a compact, low cost X-ray microscope will be realized and provides a powerful tool for various scientific fields in near future.