

Ultrafast X-ray Source and Detector

Z. Chang

J. R. Macdonald Laboratory, Department of Physics,
Kansas State University, Manhattan, KS 66506, chang@phys.ksu.edu

The goals of this aspect of the JRML program are (1) to develop a high repetition rate, high intensity laser for laser-atom interaction studies at KSU, (2) to study the x-ray source based on high order harmonic generation from laser/OPA-atom/molecule interactions, and (3) to develop an ultrafast x-ray streak camera for time-resolved x-ray studies at synchrotron facilities.

Recent progress and future plans:

1) Development of the *Kansas Light Source*, a high repetition rate and high intensity laser system, *Bing Shan, Chun Wang, Shambhu, Ghimier and Zenghu Chang*

The new inhouse-built femtosecond laser laid the foundation for the initiative to study high intensity laser-atom interactions at KSU. It is a high repetition rate laser to reduce data acquisition time and to avoid space charge effects. It can operate at a 1 to 2 kHz repetition rate to accommodate the data acquisition electronics of the COLTRIMS and other time-of-flight spectrometers. A strong optical field (about 1 atomic unit) can be achieved with a moderate focusing lens. The laser oscillator and amplifier are pumped with diode pumped solid-state lasers to assure shot-to-shot and long time stabilities. The laser has been used by six users from the JRML and from outside, which include:

1. Zenghu Chang: high harmonic generation (one paper submitted).
2. C. Lew Cocke: laser-molecule interactions in a COLTRIMS.
3. Brett DePaola: laser-atom interactions in a MOTRIMS.
4. Patrick Richard and Zenghu Chang: laser-atom interactions using imaging detector.
5. Jin Wang (Argonne National Laboratory): streak camera testing (one paper submitted).
6. Itzik Ben-Itzhak: Laser-molecular ion beam interactions.

We are building a high intensity optical parametric amplifier that will produce 10^{15} W/cm² intensity in the 1-1.6 μm wavelength range. We also plan to build a hollow-core fiber compressor that will produce high intensity pulses with less than a 10 fs duration.

2) High harmonic cutoff extension with molecules, *Bing Shan, Mahendra Shakya and Zenghu Chang*

Since the early discovery of HHG at the end of the 1980s, most of the studies have been concentrated on rare gas atoms. There have been a number of experimental studies of HHG from molecules. In an earlier experiment, it was found that “the harmonic spectra from molecular gases are very similar to those obtained in the atomic gases, with a plateau and a cutoff whose location is strongly correlated to the value of the ionization potential”. As an example, the HHG spectra of O₂ are close to that of Xe. Their ionization potentials are comparable (~12 eV). Compared to the preliminary studies of HHG from molecules, the ionization of molecules has been studied more extensively. Recently, it

was found that the ionization of O_2 is suppressed by about one order of magnitude when comparing with Xe. However, there is no ionization suppression for N_2 when comparing with Ar, which has nearly the same ionization potential as N_2 . As is known, the HHG is closely related to the ionization in the intense laser. The suppressed ionization of O_2 should lead to a significant extension of harmonic spectra, which was not observed in the previous HHG measurements. Stimulated by such a controversy and the desire to further explore the relationship between the HHG and ionization, we studied the HHG cutoff behavior for molecules and their companion atoms, for cases with a strong ionization suppression (O_2 , Xe), and for cases with no ionization suppression (N_2 , Ar).

The experiment was carried out with the newly established high intensity laser facility at the J. R. Macdonald laboratory. We compared Ar and N_2 which have nearly the same ionization potentials, at 15.76 eV and 15.58 eV, respectively, and we found they have nearly the identical harmonic cutoff (The cutoff positions for Ar and N_2 are $q_c = 63$ and $q_c = 57$, respectively). On the other hand, while Xe and O_2 have nearly the same ionization potentials, at 12.13 eV and 12.06 eV, respectively, the harmonic cutoff for O_2 ($q_c=53$) is much higher than for Xe ($q_c=29$). The spectra are shown in figure 1. We attributed this to the O_2 molecule being much harder to ionize than the Xe although they have the same ionization potential. Therefore, the harmonic cutoff extension and the ionization suppression are strongly correlated. The cutoff extension caused by the ionization suppression provides another avenue for obtaining energetic x-ray photons.

In the future, we will generate high harmonic radiation from molecules with two laser pulses. The first pulse is to align the molecules and the second pulse generates high harmonic radiation from them.

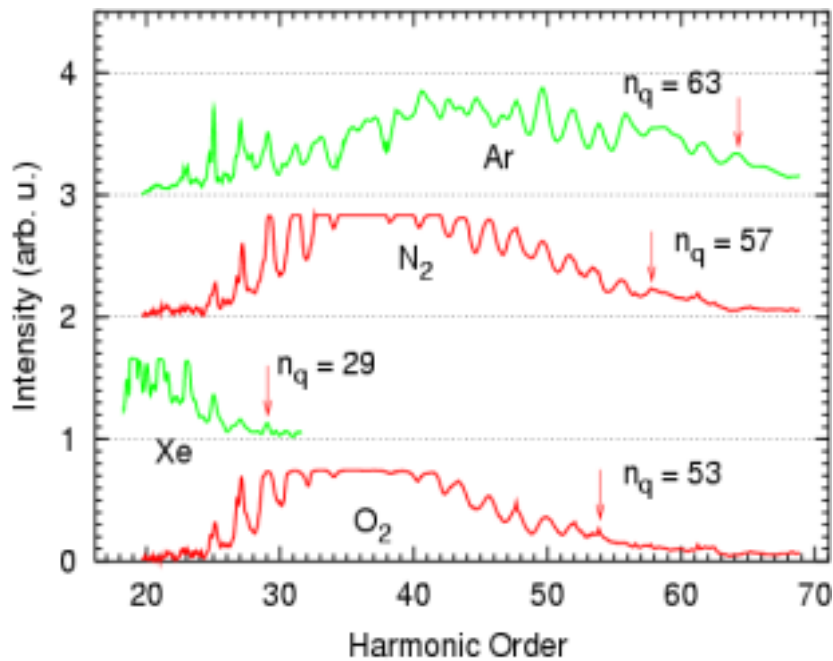


Fig. 1 The comparison of harmonic cutoff between atoms and their companion molecules. O_2 's cutoff photon energy is two times higher than Xe's though their ionization potentials are almost identical.

3) High harmonic generation by using a long wavelength field from an optical parametric amplifier. Bing Shan, A. Cavalieri(U. M.), and Zenghu Chang

We demonstrated that by using a long wavelength ($\sim 1.5 \mu\text{m}$) infrared pump pulse with 10^{14} W/cm^2 from an optical parametric amplifier, the cut-off photon energies of Ar and Xe atoms were increased by a factor of two or more compared to that by a conventional 800nm pump laser. For Xe gas, the cutoff is $\sim 40 \text{ eV}$ with an 800nm pump and is $\sim 80 \text{ eV}$ with a $1.5 \mu\text{m}$ pump (Fig.2). It also shows that a harmonic wavelength can be easily tuned to cover any wavelength from the 5th order to the cutoff by changing the OPA wavelength.

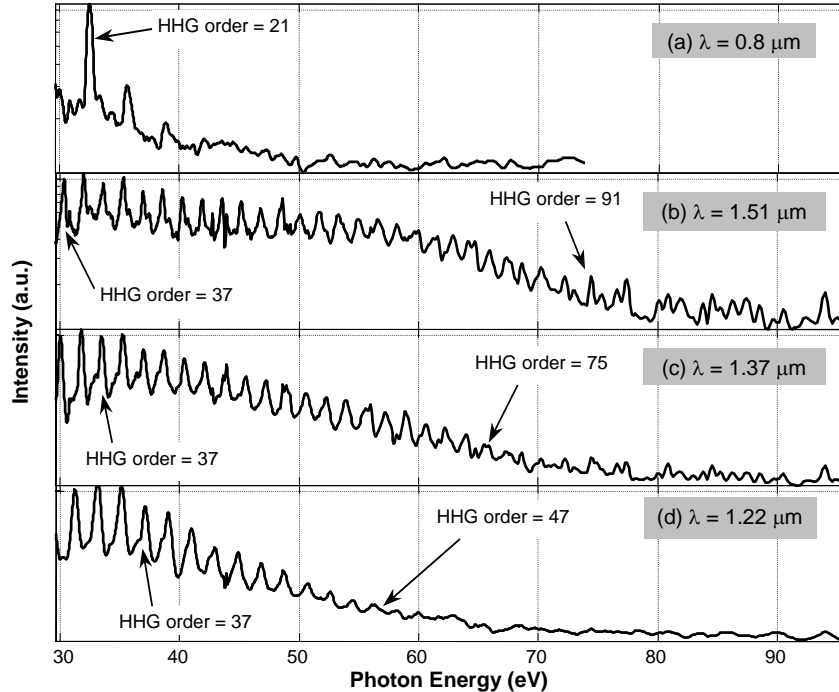


Fig. 2: Harmonic spectrum using different pump wavelengths, constant pulse energy and focal point size.

4) Ultrafast X-ray streak camera development, Bing Shan, Jinyuan Liu(ANL), Andrew MacPhee(LBL), Jin Wang (ANL) and Zenghu Chang

When a streak camera operates in the accumulation mode, the dominating factor that limits the time resolution is the timing jitter. While the response time of the photoconductive switch to the triggering laser may be instantaneous, the timing jitter is not zero unless the laser pulse is absolutely stable. At the present time, the lasers used in synchrotron facilities for time-resolved x-ray studies are Ti:Sapphire lasers operating at kilohertz repetition rates. The same laser is used to pump the sample under investigation and to trigger the photoconductive switch. The pulse energy fluctuation is on the order of 1 % RMS. This energy fluctuation causes the output amplitude of a photoconductive switch to change from shot to shot, which in turn produces timing jitter. When the switch responds to the laser energy linearly, the timing jitter is inversely proportional to the rise time of the ramp voltage for given ramp slope. Therefore, the jitter can be reduced by decreasing the rise time.

In our previous camera, the rise time is limited to 300 ps by the bandwidth of the deflection plates. The jitter-limited resolution is 2ps. The photoconductive switch and deflection plates are redesigned so that the response time is improved to 150 ps. The measured response time of the switch and the deflection system are shown in Figure 3a. We expected the two-fold reduction of the response time to result in a two-fold timing jitter, which was confirmed by the measurement shown in Figure 3b. This confirmation is important because it points us in the right direction for future work. Compared to other approaches such as improving laser pulse energy fluctuation in order to reduce timing jitter, our method is much easier to implement.

We plan to further reduce the time jitter. This will be accomplished by improving the response time of the photoconductive switch and the deflection plates by a factor of three (from 150 ps to 50 ps).

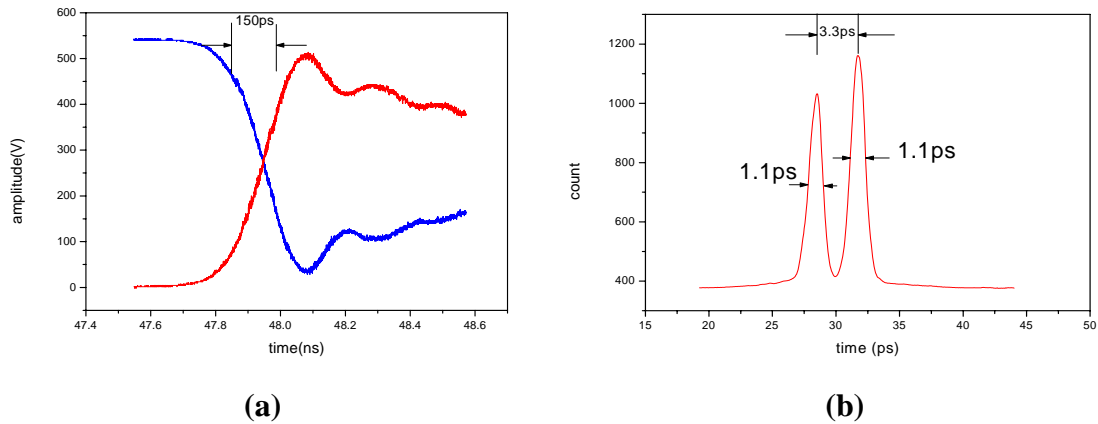


Fig 3. (a). The combined response time of the photoconductive switch and the deflection plates. (b). The temporal resolution measured with the switch and the deflection plates.

PUBLICATIONS

- 1).B. Shan, Z. Chang, "Dramatic extension of the high-order harmonic cutoff by using a long-wavelength pump", *PHYS. REV. A*, Vol.65, 011804(R) (2002).
- 2).A. M. Lindenberg, I. Kang, S. L. Johnson, R. W. Falcone, P. A. Heimann, Z. Chang, R. W. Lee, J. S. Wark, "Coherent control of phonons probed by time-resolved x-ray diffraction", *OPTICS LETTERS*, Vol.27, 869 (2002).
- 3).PA Heimann, AM Lindenberg, I Kang, S Johnson, T Missalla, Z Chang, RW Falcone, RW Schoenlein, TE Glover, HA Padmore, "Ultrafast X-ray diffraction of laser-irradiated crystals", *NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT* , Vol. 467, Part 2, 986-989 (2001).
- 4).Wark-JS; Allen-AM; Ansbro-PC; Bucksbaum-PH; Chang-Z; DeCamp-M; Falcone-RW; Heimann-PA; Johnson-SL; Kang-I; Kapteyn-HC; Larsson-J; Lee-RW; Lindenberg-AM; Merlin-R; Missalla-T; Naylor-G; Padmore-HA; Reis-DA; Scheidt-K; Sjoegren-A; Sondhauss-PC; Wulff-M, "Femtosecond X-ray diffraction: experiments and limits", *PROCEEDINGS OF THE-SPIE—THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING*. Vol.4143; p.26-37 (2001).
- 5).B. Shan, A. Cavalieri, and Z. Chang, "Tunable High Harmonic Generation With an OPA", *APPL. PHYS. B*, accepted for publication.