Generation and Applications of High-Power Ultrashort Pulses

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ABSTRACT

Advances in femtosecond laser technology now make it possible to reliably generate laser pulses in the terawatt energy range with 20 fs pulse duration, using a laser system which fits on a single optical table. We have demonstrated two such systems: a 10 Hz, 3 TW system, and a 1kHz, 0.05 TW system. These lasers make possible new studies of strong-field laser-matter interactions, and the generation of reliable femtosecond pulsed soft x-rays.

Keywords: Femtosecond lasers, Terawatt Lasers, Chirped-Pulse Amplification, High Harmonic Generation

2. INTRODUCTION

Applications of high intensity light sources including ultrafast x-ray generation, extreme-ultraviolet harmonic generation, short-wavelength lasers, and multiphoton ionization require not only very high peak power excitation, but also often can benefit from shorter excitation pulses. Considerable progress has been made in the past decade in small-scale, high-power lasers, as a result of the development of the chirped pulse amplification technique.[1] More recently, it has now become routine to generate optical pulses as short as 10 fs[2,3] using self-modelocked Ti:sapphire lasers.[4] By combining these new ultrashort pulse lasers with the broad gain-bandwidth and high storage capacity of Ti:sapphire[5] as an amplifier medium, we can now generate pulses with high peak-powers and much shorter pulse durations that has been possible in the past. We have used these high-power pulses in the study of high-harmonic generation for short-pulse XUV radiation generation. The substantial advantages of using 20-30 fs laser pulses in this technique are likely to make this technique a practical source of short-pulse XUV radiation for use in time-resolved studies of materials dynamics.

3. DESIGN CONSIDERATIONS

In the development of high-power pulses with duration <<100 fs, there are two major effects which may limit the obtainable pulse duration. The first is gain-narrowing, which results in spectral narrowing of the pulse as it is amplified in an optical amplifier chain. Ti: sapphire is one of the broadest-bandwidth laser materials yet known, with a full-width at half-maximum gain bandwidth of 230 nm. However, since amplification of pulses to the millijoule energy level requires a total gain of $>10^7$, gain narrowing is still a fundamental limitation to the performance of ultrashort-pulse amplifiers. From simulations, assuming the gain profile of Ti:sapphire and a gain of 10^7, and assuming infinitely broadband input pulses, the amplified output spectrum is expected to be 46 nm FWHM. This bandwidth is capable of supporting pulses as short as 18 fs, at millijoule pulse energies. Thus, gain narrowing in ti:sapphire, although it limits the pulse duration in a laser amplifier system, still allows for substantial improvement in pulse duration over previously-existing laser systems. Although techniques for ameliorating the effects of gain narrowing are possible[6], these techniques increase the complexity of the laser system.

The second limiting effect on pulse duration is higher-order dispersion. The chirped-pulse amplification technique requires very accurate chirping and compressing of a laser pulse, since the pulse stretching factors are in the range of 10^3-10^4. Also related to this dispersion is the fact that any non-linear phase modulation will affect the recompression of the pulse, and must be minimized. Higher-

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order dispersion is known to limit the pulse durations obtained from ultrashort laser oscillators,[3,7] and the same considerations used in designing ultrashort pulse oscillators also apply to amplifiers. For pulse durations ≤ 30 fs, both second and third order dispersion must be compensated.

Several features are introduced into our amplifier design to reduce higher order dispersion.[8,9] In an ideal CPA system, the negative dispersion of the grating compressor exactly compensates for positive dispersion in the pulse stretcher. However in practice, because of the need to compensate for the linear dispersion introduced by the amplifier materials and optics, the stretcher-compressor pair must be mismatched. Thus, the net residual higher order dispersion is the sum of the material higher order dispersion and that introduced by the stretcher-compressor mismatch. In our design, we reduce the amount of material in the amplifier beam path so that linear dispersion, higher order dispersion, and non-linear self-phase modulation are as low as possible. We use short, highly-doped crystals (0.23%) as our amplifier media, and all-reflective optics whenever possible, including in the stretcher and compressor. By using relatively low groove-density gratings (600 per mm), we can reduce higher-order dispersion introduced by the mismatch, and make the stretcher-compressor alignment easy and reproducible. Finally, we use a multipass amplifier configuration, thereby avoiding the need for multiple passes through an electro-optic pulse switcher in a regenerative amplifier, which would increase nonlinear effects, unwanted uncompensatable dispersion and spectral clipping.

4. LOW REPETITION-RATE GENERATION OF TW LASER PULSES

We have developed two laser systems based on this design philosophy. The first is a 10 Hz amplifier shown in figure 1.The input to the amplifier is from an 11 fs self mode-locked Ti:sapphire oscillator.[2] From this oscillator, the beam passes through a pulse stretcher which uses all-reflective optics. The stretcher uses a single grating, a single parabolic mirror of focal length 30 inches, and two flat mirrors. We use a gold-coated, 600 groove/mm grating, with a reflectivity of 90% in the stretcher. Reflections from the grating are at Littrow and disperse the beam in the horizontal plane, with slight beam deviations vertically to extract the beam. The single-grating Littrow stretcher design maintains alignment while the separation and/or angle of the grating are adjusted. When combined with the relatively modest stretching factor (~4500), optimization of the pulse duration is straightforward and repeatable. An identical set of gratings is used in a standard, double-pass compressor design.

After the stretcher, single pulses are selected from the modelocked pulsetrain at 10 Hz by a KD*P Pockels cell and crossed polarizers and then sent to the first stage amplifier. An amplifier rod is at the focus of four 1-meter radius-of-curvature dielectric mirrors, which form an eight-pass figure "8" amplifier. A Pockels cell is placed after the first stage amplifier to reject ASE, and to isolate the first stage amplifier from the second stage. A spatial filter after the Pockels' cell cleans the beam profile before it enters second amplifier stage.

The second stage amplifier is similar to the first one, except that the beam is not focused through this stage. We use flat mirrors instead of curved ones to multi-pass the beam 4 times through the crystal. To obtain a more uniform amplifier beam, we split the pump beam into two beams, one of them is flipped horizontally then both beams are sent into the crystal. The signal beam is flipped both horizontally and vertically after each pass through this amplifier as well. A beam expander is placed after the second stage amplifier to lower the fluence before it is sent to the pulse compressor. The multipass amplifier configuration transmits the input modelocked beam, making it possible to adjust for dispersion compensation through the system, before turning on the amplifier.

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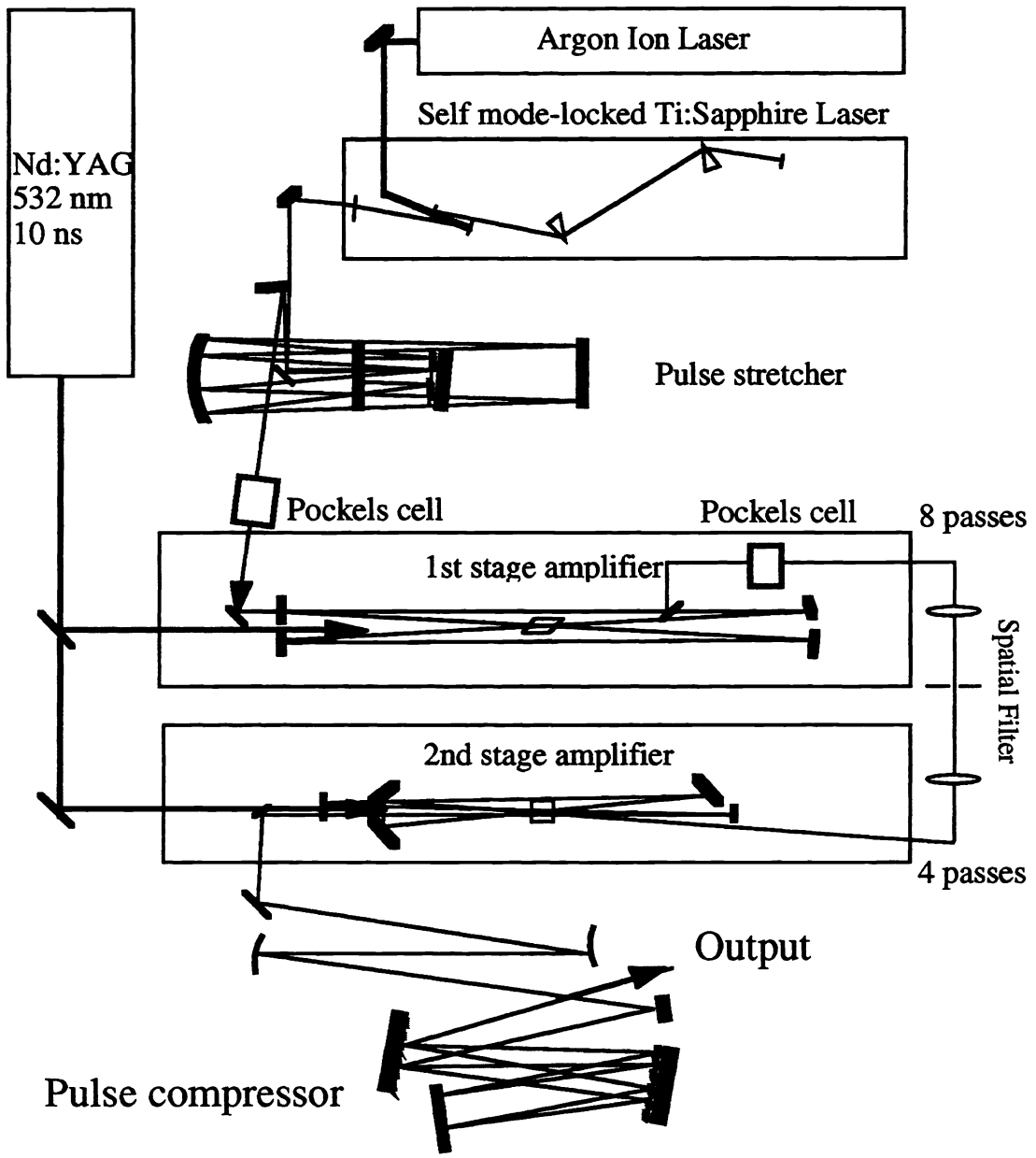


Figure 1: Schematic of a 10 Hz, 25 fs amplifier system.

After two stages of amplification, the pulse energy is 120-140 millijoules. The compressor loses about 50% of the pulse energy, resulting in a new pulse energy of 60-70 millijoules. The corresponding pulse spectrum is shown in Figure 2(a). The Fourier transformation of this spectrum corresponds to a pulse duration of about 24 fs, while we measure a 25.5 ± 2 fs (assuming a sech^2 pulse shape) pulse duration, as shown in figure 2(b). This corresponds to nearly 3 TW peak power. The laser pulses focus to less than 2 times the diffraction limit.

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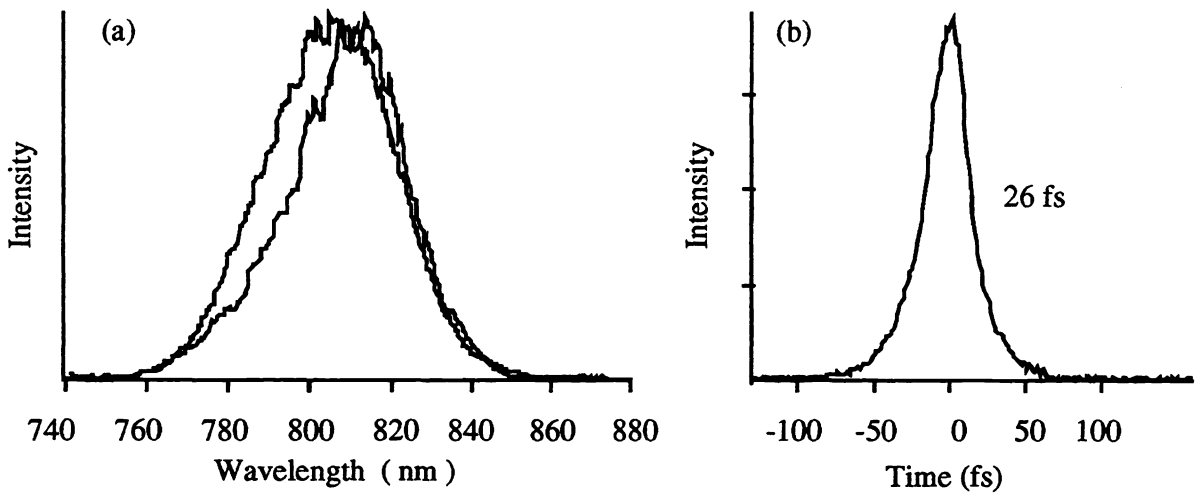


Figure 2: (a) Spectrum of the output pulses at full energy: after the second amplifier, the spectrum is 39 nm FWHM with a pulse energy of 120 mJ; after passing through the compressor, the spectrum narrows to 32 nm, and the pulse energy is reduced to 60 mJ. (b) Single shot autocorrelation trace, showing a 26 fs laser pulse at 60 mJ pulse energy.

5. KILOHERTZ AMPLIFICATION OF 20-FS PULSES

The same design principles used for low-repetition rate amplification of ultrashort laser pulses can also be extended to kilohertz repetition-rate high-power pulse generation.[10] We have recently developed such a system, shown in figure 3. In this system, the 10 Hz extracavity-doubled Nd: YAG laser is replaced by an intracavity-doubled Quantronix Model 527 DP-H multi-mode Nd:YLF laser (Excel/Quantronix), which produces up to 20 W of 527 nm light at 1 kHz. Gain-narrowing considerations are identical to the case of the 10 Hz system, and the stretcher/compressor configuration is nearly identical. However, thermal lensing in the amplifier becomes significant at kHz repetition rates, and is the limiting factor on average power in this system. Nevertheless, this laser can produce pulses of nearly 1 millijoule energy in 21 femtoseconds (Figure 4)-- a peak power of 50 GW. The entire system including pump lasers can easily fit on one optical table, and the short-pulse oscillator and amplifier occupy a 1.5' x 9' section of table. This system offers substantially-improved peak-power over previously-demonstrated systems high repetition CPA systems reported by Rudd et al. (350 μJ, @ 55 fs), Wynne et al. (60 μJ, @ 30 fs),[11,12] and several commercial vendors.

Other innovations in this system include a novel, 3 mirror multipass amplifier geometry in which the number of passes can easily be varied, along with a multiple-hole aperture which limits the effect of thermal defocusing on the output. Since the beam size through the pulse compressor is smaller than in the low repetition-rate system, and since grating aberrations are the main limitation on focusability, the focusability of the pulses is near the diffraction limit.

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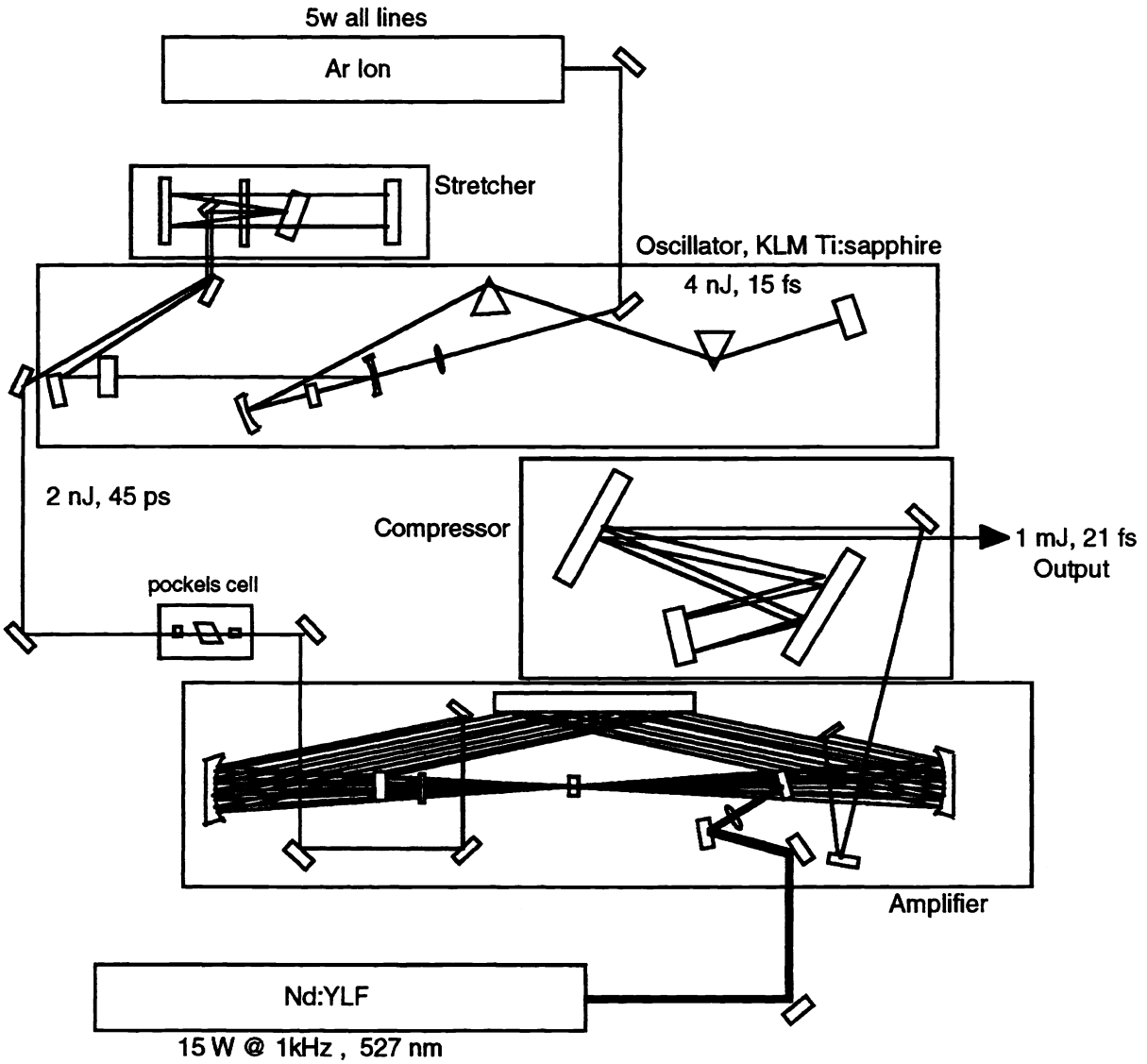


Figure 3: Schematic of laser system based on high repetition-rate multipass amplification.

6. XUV HARMONIC GENERATION USING ULTRASHORT LASER PULSES

High peak-power laser pulses can be used to generate VUV and soft x-ray radiation using a number of processes, such as high-density laser-produced plasma emission[13], Thomson scattering,[14] and high-harmonic generation[15-17]. In recent work, we extended studies of high-harmonic generation to shorter pulse-duration using our 10 Hz, 25 fs laser system.[18] Figure 5 shows a series of spectra of XUV harmonic emission using argon gas, as a function of the chirp of the pulses, and thus the pulse duration. This data demonstrates that shorter-duration excitation pulses can extend the "plateau" of harmonic orders to higher photon energies than has previously been observed. The shortest-wavelength peak, the 61st harmonic at 96 eV, is 50% higher than would be expected using the barrier suppression model of

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multiphoton ionization. High-harmonic generation occurs due to recombination of an ionized atom with the just-ionized electron. The barrier suppression ionization model sets the maximum intensity for a just-ionized atom at the point where the electric field of the laser suppresses the coulomb potential of the atom enough to make the electron unbound.[19] The ponderomotive energy of the electron at this intensity limits the maximum high-harmonic energy at $I_p + 3.2\ U_p$,[20] where I_p is the ionization potential and U_p is the ponderomotive energy of the electron as it ionizes. For the conditions that this data was taken at, the BSI limit is expected to be 64 eV. Thus, our data demonstrates that an atom does not instantaneously ionize when the coulomb barrier is suppressed, but can take several optical cycles. For a 25 fs pulse, the intensity of the laser can increase significantly during this time, resulting in higher-energy harmonics.

As the chirp of the laser is varied, the center wavelengths of the harmonics shift substantially, making it possible to tune the harmonics. However, the wavelength shift is asymmetric with the sign of the chirp, possibly a result of an atomic phase-matching effect which we are investigating further. These data were taken at constant peak intensity; i.e. for a 200 fs pulse the driving pulse energy was ~8 times that of the 25 fs pulse. Since the harmonic emission intensities are all comparable, this demonstrates that shorter optical pulses are more efficient at generating XUV harmonic radiation. The combination of higher harmonic energy and higher efficiency should make kilohertz, 20-fs laser systems such as described in section 5 practical sources of XUV radiation with energies up to 100 eV.

7. CONCLUSION

In conclusion, we have demonstrated that by using a simple multipass amplifier design, together with a very short seed pulse and careful dispersion control, we can obtain amplified pulse durations close to the theoretical limit imposed by gain narrowing in Ti:sapphire. The multipass amplifier design is simple, inexpensive, and straightforward to align and operate. We can routinely generate amplified pulses with peak powers of more than 2 TW. These high-energy, ultrashort pulses are ideal for many applications in high intensity physics such as plasma x-ray generation, high harmonic generation, or as the pump energy sources for XUV or x-ray lasers.

8. ACKNOWLEDGMENTS

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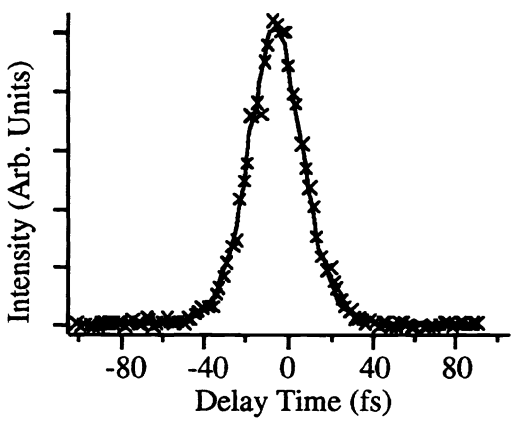


Figure 4: Autocorrelation trace, and best fit to a $Sech^2$ pulse shape, of a 0.8 mJ pulse at 1 kHz repetition rate. The pulse width is 21 fs.

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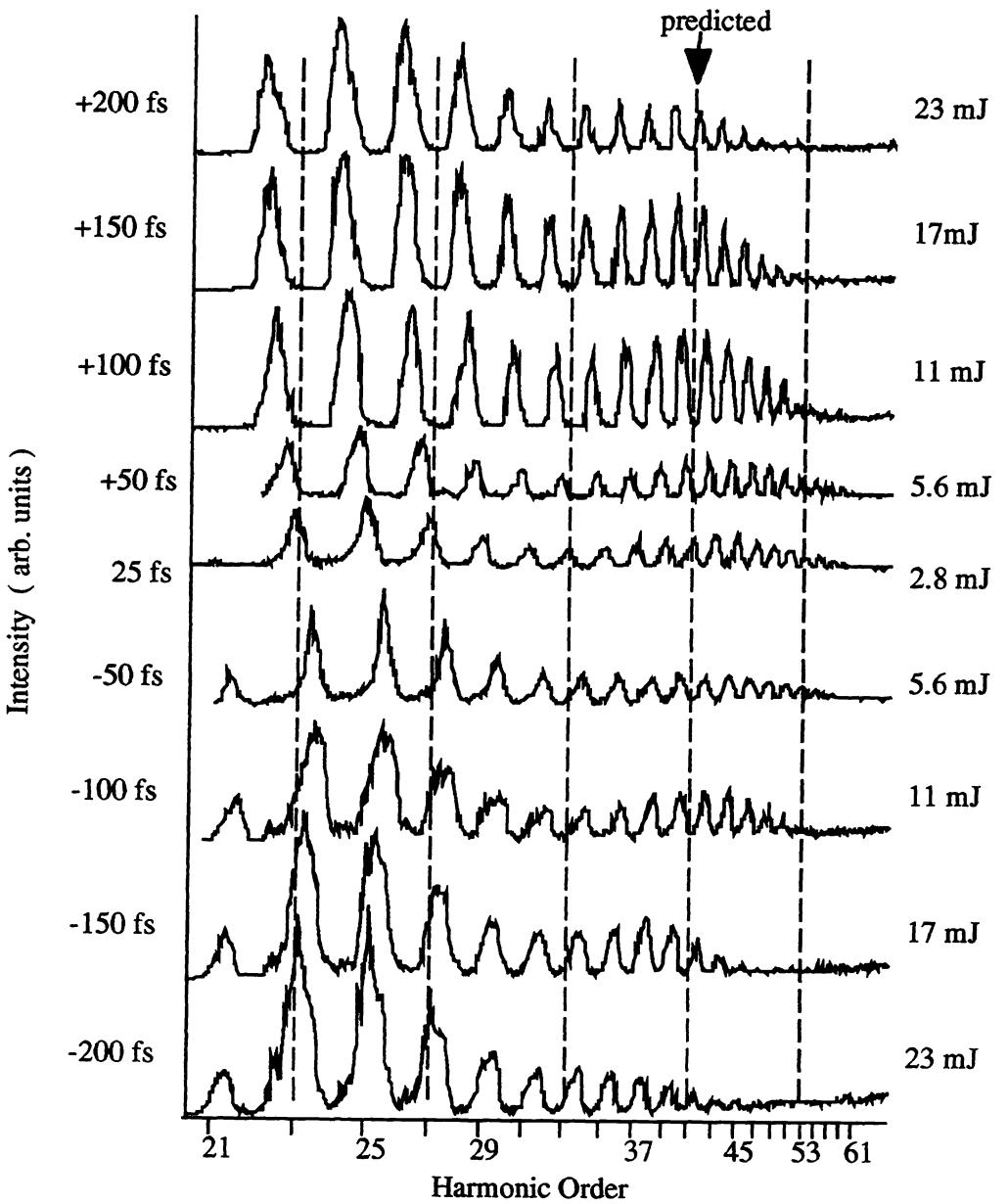


Figure 5: Harmonic spectra generated in 5 torr of argon, for fixed peak laser intensity of 5×10^{14} W/cm^2, and for various laser pulse chirps.

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