Lecture 6 6.5.13

Last time: HHG using atoms in a gas phase

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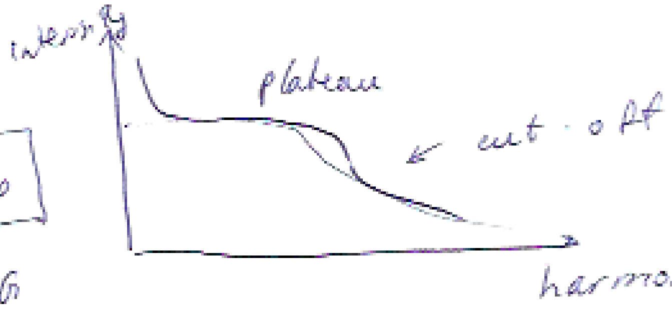

$\boxed{\hbar\omega \ll I_p < U_p}$

condition for HHG in gas

Helium: $I_p = 0.9$ au

U_p (for $F = 0.1$ au) $= 1.7$ au

$E_{max} = \hbar\omega_{max} \simeq I_p + 3.17 U_p$
$= 6.289$

@ 800 nm ($\omega = 0.057$) $\Rightarrow n = 110$

⇒ make up an attosecond pulse ⇒ can get harmonics in the XUV range 40 - 120 nm

ionizing radiation of Ti: sapphire ~ 800 nm

⇒ cut-off wavelength ≈ (for $n = 110$): $\lambda_{cut\text{-}off} \approx 7$ nm (x-ray)

Today ⇒ HHG & attosecond pulse generation on plasma mirrors

⇒ higher frequency (in the x-ray range):

$\lambda = 0.01 - 10$ nm ⇒ x-ray range

⇒ inner shell dynamics of atoms (characteristic of transition freq. from ~~outer~~ inner shells).

⇒ higher energy flux

⇒ as pump - as probe experiments

(current experiments use as as a probe & infrared as a pump or vice-versa.

Example: tunnel ionize an atom with an ultra-short Ti-sapphire laser pulse: FWHM ~ 5 fs, $\lambda \approx 800$ nm; then probe the evolution of a hole left behind by a transient absorption of an as pulse Goulielmakis, Nature 466, 739, 2010

Plasmas ⇒ can go to much higher laser intensity ⇒ instead of $10^{15} \frac{W}{cm^2} \Rightarrow 10^{22} \frac{W}{cm^2}$!

(ultra-relativistic regime)

⇒ solid surface, but turns to plasma due to high laser intensity

⇒ First experimental demonstration of using plasma mirrors to generate as pulses ⇒

Nomura, et al, Nature Phys. 5, 124, 2009

First, why can't go above $10^{15} \frac{W}{cm^2}$ in ~~gases~~ gases?

⇒ depletion due to high intensities
⇒ poor phase matching
⇒ magnetic fields become important ⇒ introduce drifts
(no recollision step because of B fields!)

HHG in plasmas ⇒ focus intense, ultrashort pulse on a solid target

⇒ due to time-scales (fs), very little plasma expansion

⇒ laser pulse reflects on <u>dense</u> plasma

⇒ this is called <u>plasma mirror</u>

Two mechanisms behind HHG on plasma mirrors:

1) Coherent Wake emission (CWE)
2) Relativistic Oscillating mirror (ROM)

} very different harmonic spectra

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3 steps of HHG using CWE

(i) Electrons @ the plasma surface are pulled into a vacuum & then slammed back into the plasma by the laser field

(ii) Electrons propagate in the dense part of the plasma, forming ultra-short bunches, exciting local plasma oscillations

$\Rightarrow$ frequency of plasma osc. depend on depth

deeper $\Rightarrow$ higher frequency

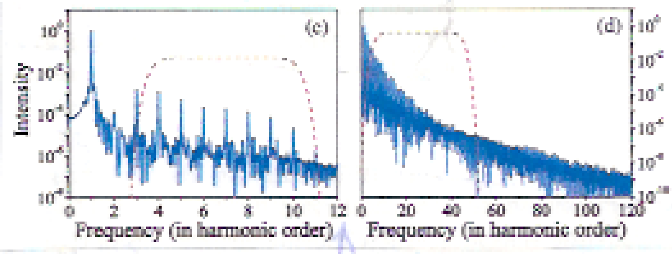
(iii) high harmonics are generated with frequency given by the local plasma freq.

$\Rightarrow$ cut-off given by the maximum plasma frequency, $\omega_p^{max} \approx n \cdot \omega_{Laser}$ where $n \approx 15-30$

$\Rightarrow$ ROM is the dominant contribution beyond ω_p^{max}

ROM HHG spectra

CWE HHG spectra



cut-off given by ω_p^{max}

much higher cut-off in ROM compared to CWE

When do different regimes contribute?

CWE vs ROM?

Parameter a_0 ~~no~~ that depends on intensity & frequency of laser: $a_0 = \cancel{\frac{eE}{\omega_L}} \frac{eE}{m\omega_L \cdot c}$

↗ normalized vector potential

For Intensity $= 10^{15} \frac{W}{cm^2}$; 800 nm field

$a_0 \simeq 0.03$

CWE dominates the harmonic signal for $a_0 \lesssim 1$

⇒ need intensity ~ $10^{18} \frac{W}{cm^2}$ for ROM to become significant

⇒ therefore need to go to intensity > $10^{18} \frac{W}{cm^2}$ to get harmonics in the x-ray regime (since CWE can only go up to $n \approx 30$)

⇒ ROM produced by the Doppler shift created by the relativistically oscillating mirror surface

⇒ ROM extensively studied analytically

⇒ CWE only recently identified

⇒ however as pulse generation achieved predominantly using CWE in Nomura, Nat. Phys. 5, 124, 2009 $\sim 10^{19} \frac{W}{cm^2}$

⇒ HHG has been achieved with both ROM & CWE

⇒ Note HHG not enough to create an as pulse ⇒ need <u>phase coherence</u> (phase locking btwn different harmonics)

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Nomura et al, Nat. Phys. 5, 124, 2009

How did they know CWE was the main contributor to HHG? regime $a_0 \sim 1 \Rightarrow$ intensity (average) $\approx 4 \times 10^{18} \frac{W}{cm^2}$

1) Appearance of a distinct cut-off frequency (in the n = 15-30 range)

$a_0 \approx 1.5$ (both ROM & CWE can contribute)

2) Scaling of this cut-off with target density
→ higher cut-off with higher density

→ ROM theoretically well studied but as pulses have not been experimentally demonstrated

→ CWE only recently & discovered, but experimentally shown to produce as pulses

→ would like as pulses with ROM (much higher $w_{cut-off}$)

→ clearly still much to do for experimentalists!

→ For theory → better understanding of CWE is desirable

CWE → harmonic order given by local ~~pe~~ plasma freq. of osc. $n_e(x)$ → plasma density

plasma density is same as electron density, $n_e(x)$ (neutral plasma) → so can have different harmonics if there is a density gradient : $n_e(x)$, where x is the depth of the plasma

Plasma oscillations → "Langmuir waves" →
rapid osc. of electron density in conducting media

In cold neutral plasma, displacing the electrons with respect to ions, creates oscillations @ plasma frequency:

$\frac{1}{4\pi \epsilon_0} = 1$ (in a.u.)

$$w_{pe} = \sqrt{\frac{n_e(x) e^2}{m \epsilon_0}}$$

$\omega_{pe} \sim O(1)$ au , since

$\omega_{cut-off} = n \cdot \omega_L$ where $n = 15-30$

& $\omega_L \approx 0.057$

⇒ so plasma freq. is close to freq. of osc. inside the hydrogen atom.

How to create a plasma mirror? what is a plasma mirror?

- ⇒ start with a solid target
- ⇒ plasma created at the front of the pulse, intensities $10^{14}-10^{16}$ $\frac{W}{cm^2}$
  - ⇒ plasma hardly has enough time to expand for an ultrashort pulse (under 100 fs)
  - ⇒ sharp plasma-vacuum interface
  - ⇒ the surface of low Z target (such as aluminium, Z=13) is almost fully ionized
  - ⇒ high density $n(x) >> n_c$ ← critical density

where n_c corresponds to the density that would produce osc. @ frequency ω_L: $n_c = m\epsilon_0\omega_L^2/e^2$

material (plastic) : $n = 200 n_c$; aluminium silica $n = 400 n_c$

Therefore, laser field is not absorbed ⇒ incident light reflected ⇒ plasma mirror.

⇒ plasma-vacuum interface is flat (due to limited expansion)

⇒ pulse is not distorted on reflection