Efficient high-order harmonic generation boosted by below-threshold harmonics

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High-order harmonic generation (HHG) in gases has been established as an important technique for the generation of coherent extreme ultraviolet (XUV) pulses at ultrashort time scales. Its main drawback, however, is the low conversion efficiency, setting limits for many applications, such as ultrafast coherent imaging, nonlinear processes in the XUV range, or seeded free electron lasers. Here we introduce a novel scheme based on using below-threshold harmonics, generated in a "seeding cell", to boost the HHG process in a "generation cell", placed further downstream in the focused laser beam. By modifying the fundamental driving field, these low-order harmonics alter the ionization step of the nonlinear HHG process. Our dual-cell scheme enhances the conversion efficiency of HHG, opening the path for the realization of robust intense attosecond XUV sources.

The interaction of intense laser pulses with atomic or molecular gas media leads to the generation of harmonics of the laser light, up to very high orders¹. These harmonics are locked in phase, giving rise to attosecond bursts of XUV light. The simplicity of the experimental technique, together with the progress in ultrafast laser technology, has promoted HHG sources as essential tools in many laboratories; opening, in particular, the field of attosecond science². However, HHG suffers from low conversion efficiency, owing partly to phase mismatches in the nonlinear medium that prevent efficient build up of the macroscopic field³–⁶, but mostly to the weak response of the individual atoms to the field.

The atomic response to an external driving field can be described by a three-step model [Fig. 1(a)]: First, a bound electron tunnel-ionizes into the continuum; second, it is accelerated by the laser field; and finally, it recombines with the parent ion upon field reversal, emitting an XUV photon⁷–⁸. The electron trajectories can be grouped in two families, named the long and the short, depending on the excursion time of the electron and generated in intervals II and III of Fig. 1(a), respectively. The most interesting from a practical point-of-view are the short trajectories, which lead to collimated and spectrally narrow emission. Unfortunately, these trajectories start at times close to the zero-crossings of the driving electric field, suffering from very low quantum-tunneling probability.

Altering the driving electric field at the subcycle level⁹ provides a way of modifying the single atom response. This has been investigated mainly by adding the second harmonic field¹⁰–¹³, thus breaking the symmetry between consecutive half cycles. In contrast, odd-order harmonics modify the HHG process while maintaining the half-cycle symmetry. In a pioneering work, Watanabe and coworkers¹⁴ investigated the influence of the third harmonic (TH) on single ionization and HHG in Ar, obtaining an enhancement of up to a factor of ten for the 27–31 harmonics. Also, a few theoretical works discuss the influence of the TH on the enhancement of the yield¹⁵,¹⁶ and/or the extension of the cutoff energy¹⁷–¹⁹. Another approach to enhance the signal by modify the single atom response is to control the time of ionization by using attosecond pulse trains to initialize the three-step process via single photon absorption²⁰–²³.

In this letter, we demonstrate a simple and robust, yet powerful enhancement scheme based on a dual gas-cell setup [Fig. 1(b)]. We study HHG in neon using a high-energy (~20 mJ), near-infrared fundamental field, loosely focused in a long gas cell, resulting in high-order harmonics in the 40–100 eV range, with a typical energy of 10 nJ per harmonic order. The addition of a high-pressure Ar gas cell before the generation cell produces a large enhancement in the Ne signal, as seen in Fig. 1(c). We experimentally and theoretically show that the observed enhancement is due to below-threshold, low-order harmonics which modify the fundamental field in such a way that the contribution of the short trajectories is increased.
Results

In our experiment, the generation cell is placed approximately at the laser focus while the seeding cell is located a few centimeters before (see Methods). The gas pressures in the cells can be independently adjusted and are typically a few mbar in the generation cell (Ne) and up to tens of mbar in the seeding cell (Ar). In Fig. 2(a–c), HHG spectra from neon are plotted as a function of the seeding pressure for three different driving intensities. When no gas is present in the seeding cell, standard Ne spectra are obtained. As the seeding pressure increases, the signal from the neon cell decreases until it is almost completely suppressed. At higher pressures, the neon spectra reappear and are significantly enhanced in the 50 – 80 eV region while the maximum photon energy slightly shifts to lower harmonic orders.

Figure 2(d) shows harmonics generated in the seeding cell. Harmonics with energies above the ionization threshold are not present at pressures where the enhancement in the generation cell occurs, and therefore are not responsible for the signal boost through single-photon ionization. At these pressures, only low-order harmonics are efficiently generated in the seeding cell, indicating that they are responsible for the seeding process.

In order to validate our interpretation, we performed numerical simulations for both cells. In the generation cell, we simulated the seeded HHG process using the strong-field approximation.
The total field can be written as

\[ E(t) = E_0 \left[ \sin(\omega t) + \sum_{q=0}^{n} r_q \sin \left( q \omega t + \Delta \phi_q \right) \right], \]  

(1)

where \( E_0 \) is the amplitude of the fundamental field, \( \omega \) its frequency, \( I_p \) the ionization energy, \( r_q \) the ratio between the fundamental and \( q \)th harmonic field, and \( \Delta \phi_q \) their relative phase. Although all harmonics below the ionization threshold of Ar may influence the enhancement phenomenon, we considered only the TH, which is the most intense one (we omit the subscript 3 below). A simulated HHG spectrum in neon with \( |r|^2 = 0.01 \), is shown in Fig. 3(a) as a function of \( \Delta \phi \). A relative phase of \( \sim 1 \) rad leads to an enhanced ionization probability, since the electrical field is increased at the time where the short electron trajectories are born [interval III in Fig. 1(a)]. Furthermore, the electric field amplitude is reduced around the peak of the fundamental field leading to suppressed probability for non-contributing trajectories (intervals I, II) and to an improved macroscopic situation since plasma dispersion and depletion effects are minimized. When \( \Delta \phi \approx 1 \pm \pi \), the situation is reversed and HHG is suppressed compared to the unseeded case.

We experimentally confirmed the dependence of the HHG signal on \( \Delta \phi \) by studying HHG using a combination of the fundamental and the TH generated in a crystal. To control the delay between the two fields, we used a Michelson interferometer with the TH produced in one arm. Our results, plotted in Fig. 3(b), show a strong delay dependence of the harmonic yield. However, we could not increase the overall HHG efficiency compared to the dual-cell scheme, since a large fraction of the fundamental field was needed for the TH generation and consequently lost for HHG.

In the seeding cell, we examined the pressure dependence of both low-order and high-order harmonic generation. Our calculations confirm the experimental observation that HHG in Ar peaks at a certain pressure (~10 mbar) which corresponds to optimized phase matching, while below-threshold harmonics continue to increase up to pressures as high as 100 mbar. We also investigated the propagation of the fundamental and TH fields in a high pressure cell (see Methods). This allowed us to examine their phase relation after the seeding cell and to eliminate the relatively weak reshaping of the fundamental field in our experimental conditions as possible cause for the enhancement. As Fig. 3(c) shows, for high enough seeding pressures, \( \Delta \phi \) will be between 0 and 2 radians during part of the laser pulse, leading to a gated enhancement mechanism.

**Discussion**

As in any enhancement scheme, a key question is whether our method is advantageous over “usual” HHG optimization, which can be achieved for example by using looser focusing, optimizing the position of the focus in the cell, or adjusting the pressure in the gas cell. Ideally, one would like to compare optimized HHG and optimized seeded HHG for a given fundamental pulse energy. This is not easy to realize experimentally, so we choose to benchmark seeded HHG against optimized unseeded HHG, with ~10 nJ at 63 eV (41st harmonic).

![Figure 3](https://example.com/fig3.png)

**Figure 3**: Influence of the relative \((\omega t, 3n\omega)\) phase in HHG. (a) SFA spectra as a function of \( \Delta \phi \) in the generation cell, normalized to the unseeded spectrum. Only the contribution of the short trajectory is considered. An effective grating response is included to mimic the experimental conditions. (b) Experimental results with the TH generated in a crystal, normalized to the highest signal. (c) Propagation simulations in the seeding cell: \( \Delta \phi \) at the exit of the cell as a function of time for different pressures.

![Figure 4](https://example.com/fig4.png)

**Figure 4**: Optimization of HHG. (a) 41st harmonic energy as a function of the driving intensity for seeded (red) and unseeded (blue) HHG. Unseeded HHG is optimized at the maximum intensity. (b, c) Corresponding experimental spectra at 3.5 and \( 4.4 \times 10^{14} \) W/cm², respectively.
Figure 4(a) compares the 41st harmonic signal in the seeded and unseeded cases as a function of the driving intensity. The intensity required for saturating seeded HHG is only half that needed for unseeded HHG. This explains the reduction of the cutoff energy and the lower divergence for the harmonics. The enhancement factor depends on the driving intensity [Fig. 4(b,c)]. For the 41st harmonic, we observe an increased harmonic yield for a variety of gas combinations, and even when the same gas is used in both cells. Our experiments show that the enhancement can be scaled far above one order of magnitude by increasing the low-order harmonic intensity, for example by using longer cells, higher pressures or gases with higher nonlinearities. This also leads to a shorter temporal gate, of interest for single attosecond pulse generation.

### Methods

#### Experimental setup

The harmonics were generated using 45 fs pulses, centered at 800 nm. The gas cells used in this setup were 1 cm long with a diameter of 1 mm. The gas cells were placed at the focus of a tightly focused laser beam. The harmonics were observed using a monochromator and a CCD camera. The monochromator was used to select the short trajectory:

\[
S(t; f) = \frac{1}{2\pi}\int d\tau \left\{ \frac{P - \epsilon(t)}{2m} \right\}_{t} \exp[-iS_{\tau}(t)]
\]

(2)

is calculated for a combined vector potential of the fundamental field and a weak parallel auxiliary field consistent with the field definition in Eq. (1). \( t \) and \( \tau \) correspond to the tunneling and recombination times for an electron with canonical momentum \( p_\tau \), \( I_\tau \) is the ionization potential, and \( A \) the vector potential of the field. We approximate the HHG dipole as

\[
x(t) = \int_{-\infty}^{\infty} dt' \left( \frac{\tau}{\epsilon(t') + i\tau/2} \right)^{1/2} d_{2p}(t, t') - A_{2p}(t) x(t') + \exp[-iS_{\tau}(t)] F(t) + c.c.
\]

(3)

where \( S(t; f) \) is the stationary phase approximation performed over momentum, with \( p_{2p}(t, t') = \mathcal{E}(t) - \mathcal{E}(t') + i\tau \), where \( t - t' \) is the excitation time in the continuum.

We also insert a filter function \( F(t) \) to select the short trajectory:

\[
F(t) = 1 \text{ for } t < 0.657 \text{ and } F(t) = 0 \text{ for } t > 0.657, \text{ where } 0.657 \text{ corresponds to the position of the cutoff.}
\]

The integral in Eq. (3) is then evaluated numerically on a finite grid followed by a numerical Fourier transform for the dipole emission.

#### Seeding

We performed calculations which combine the solution of the time-dependent Schrödinger equation in a single-active electron approximation and the ionization in a partially ionized medium using a slowly-varying envelope approximation. Our main goal was to examine the influence of the pressure both for low-order and high-order harmonic generation in conditions mimicking the experiment. We found a maximum for HHG at around 10 mbar, while below-threshold, low-order harmonics which are not reabsorbed in the medium continue to increase up to very high pressures (100 mbar).

Conversely, the intensity of the third cell harmonic in the seeding cell was calculated using a (3 + 1)-dimensional, unidirectional, nonlinear envelope equation. The complete field-dependent dispersion relation is considered, enabling to propagate the fundamental and the third harmonic simultaneously. It is numerically integrated using a split-step technique, where the linear contributions, such as dispersion and diffraction are treated in k-space, while the nonlinear part, taking into account the Kerr effect, third-harmonic generation as well as plasma dispersion and plasma defocusing is treated in normal space. The method is described in detail in22. The calculated phase variation is mainly due to plasma dispersion effects. There are also small contributions from the geometrical phase acquired along the seeding cell as well pressure-dependent third harmonic phase matching.

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F.B., C.M.H. and P.R. contributed equally to this work. F.B., C.M.H., P.R. and L.R. performed the experiments. D.K. and C.L.A. performed the propagation calculations. C.M.H. and J.M.D. performed the SFA calculations. J.M, P.J., A.L. and all the other authors helped with the interpretation and the writing of the article.

Additional information
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