Reply to Comment on "Direct observation of laser filamentation in high-order harmonic generation"

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We concede the point raised by Tosa and Nam regarding the interpretation of our recent measurements of intense laser pulse dynamics. Although the measured fluence shows a double focus that is suggestive of filamentation, pulse-propagation simulations show no resurgence in intensity at the second beam waist. An interplay between the generation of plasma and natural diffraction of the apertured beam gives rise to this unusual behavior without requiring a sizable n_2. © 2007 Optical Society of America

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Prior to receiving the Comment from Tosa and Nam, we independently arrived at a similar interpretation of our experimental results. Because the geometry of our experiment is distinct from what Tosa and coworkers previously considered [1], we could not directly compare our experimental findings with theirs, which did not show a double focus. We have since performed beam-propagation simulations for our geometry that show good agreement with the simulation presented in the Comment [2]. Our simulations indicate that the fluence reconverges to a second focus without a corresponding resurgence in the intensity and without the need for a sizable n_2. These findings resolve many of the open questions and speculation contained in our Letter [3] and a related paper [4].

Following a standard approach [5], similar to that used by Tosa *et al.* [1], our pulse-propagation simulation employs scalar, paraxial, and slowly-varying-envelope approximations. The effects of free electrons are included using the ADK ionization model. The nonlinear refractive index n_2 is also included, although its effect is inconsequential using the previously accepted value. To account for the effect of the aperture on our beam, we used Fresnel–Kirchoff diffraction to produce a suitable initial pulse just prior to the focus, as did Tosa and Nam. In our simulations, we observed results similar to that in Fig. 1 of the Comment. It is interesting to note that the on-axis intensity continuously decreases after an initial peak, in spite of a second focus in fluence.

Figure 1 of our Reply shows a snapshot of a laser pulse simulated under our experimental conditions, as it propagates near the focus of a mirror ($f = 100$ cm). Plasma generated on axis during the early part of the pulse causes much of the energy in the latter part to move radially outward. This effect is apparent after the pulse has propagated several centimeters at an intensity sufficient to generate plasma (about 2% ionization). In our experiment, we measured fluence rather than intensity. Figure 2 shows the calculated fluence from our simulation as a function of radius and axial position, which shows good qualitative agreement with our measured results. Near 100 cm, the fluence takes on a flat-top profile. At the second focus (3 cm downstream), the on-axis fluence increases, even though the intensity decreases markedly, as previously mentioned. This implies that some off-axis energy returns to the axis. It also implies a significant increase in the pulse duration, which we have observed in our pulse simulations.

Our previously reported focused peak intensity in vacuum is inconsistent with the values for pulse energy (5 mJ after aperture), radius (105 μm FWHM best focus), and duration (30 fs) given in our paper. These values suggest a peak intensity of only 1.3×10^{15} W/cm^2, under a (somewhat crude) Gaussian assumption. A similar computing error appears to have occurred also in our related paper [4]. This re-

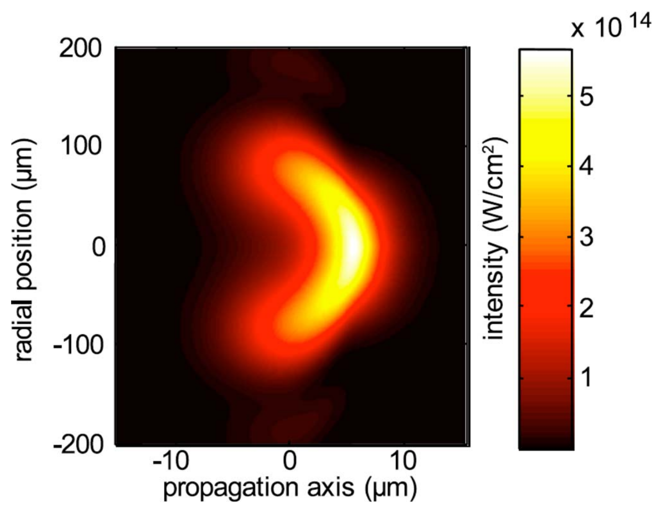

Fig. 1. (Color online) Snapshot of a 5 mJ, 30 fs laser pulse propagating in 80 Torr of He at the focus of a 1 m focal-length mirror. A partially closed aperture defines $f/125$ focusing.

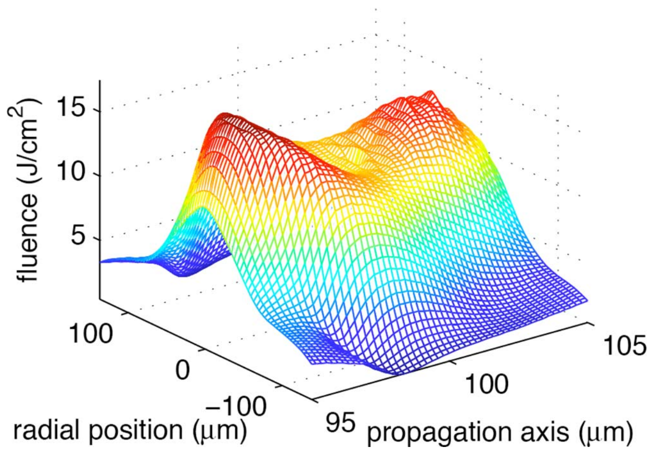

Fig. 2. (Color online) Beam fluence as a function of radial and propagation distance near the focus for the pulse seen in Fig. 1.

vised peak intensity is slightly greater than the value used in the above comment, and slightly less than the value used in our simulation.

In the near future, we will report on simulated phase matching of high-harmonic production in this focusing geometry. In particular, we will examine the role of the aperture, which has a large influence on phase matching.

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