# Spectral and Spatial Self-Transformations of Terawatt Laser Beams in Low-Pressure Gases

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**Abstract:** Spectral broadening of 25-fs multi-terawatt laser pulses has been achieved in low-pressure atmospheric gases without significant loss of spatial coherence in the laser beam by femtosecond laser filamentation. 

Studies on the propagation of high peak-power (> 1TW) femtosecond lasers have led to numerous applications including laser diagnostic of flows [1], remote sensing [2], filamentation-assisted pulse compression [3], air lasing [4], and strong THz generation [5-7]. These applications often rely on the spectral broadening aspect of the interaction and are sensitive to many different experimental conditions due to the extremely nonlinear process. Particularly, the peak power and choice of medium significantly impact the forward propagating beam. Above the threshold for self-focusing in a medium, often called the critical power, the beam can experience intense spatial modulation and breakup into many individual beams which are no longer mutually coherent [8]. In this context, the phenomenon is referred to as multiple filamentation, and it can limit the practical applicability of laser-induced filamentation. To avoid the negative consequences of multiple filamentation, the power of the laser must be on the order of the critical power for self-focusing or the critical power must increase. According to the Marburger formula, the critical power is proportional to $1/\rho$ where $\rho$ is the number density such that a decrease in pressure for a constant temperature and volume leads to a corresponding increase in critical power [9]. In our experiments we show that substantial spectral broadening of multi-TW laser beams can be achieved in a single-filament regime by reducing gas pressures to increase the critical power of self-focusing and reduce plasma defocusing.

In our experiments, multi-TW 25-fs-pulsed laser beams at 10 Hz repetition rate delivered by a Ti:sapphire system (Amplitude Technologies) were focused by a 1-m focal length optic (we used a spherical mirror or plano-convex lens in our setups) in a chamber filled with air, nitrogen, or helium at varying pressures from 1000 mbar to about $10^{-3}$ mbar. The spectra, as well as near-field and far-field beam profiles were observed after filamentation. The scheme of one of these experimental setups is shown in Figure 1.

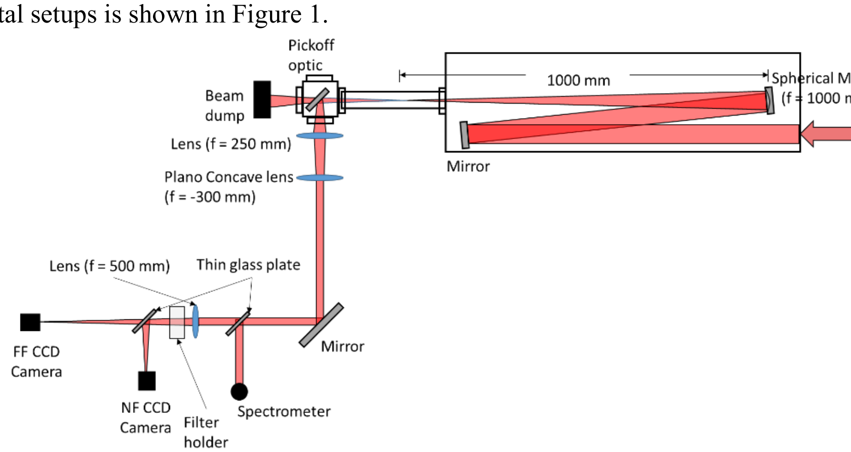


**Fig. 1**: Schematic of the experimental setup. The pickoff optic is a 1-mm thick glass slide or a $45^o$ dove prism to avoid spectrally broadened back-reflections propagating toward beam diagnostics.

After the interaction, the beam was collimated and sent to a spectrometer and beam profile diagnostics. The energy within the full-width at half maximum of the central spot of the focused beam was used as a metric to determine focus quality of the beam after filamentation. The width of a spectrum curve measured at 1/30th of the maximum spectral intensity was used to characterize the spectral broadening as the pressure and pulse energy were varied.

As the pressure increases, the spectral width increases, while the beam quality is reduced. In Figure 2a and 2b, the spectral width and energy fraction within the FWHM focal spot are plotted as a function of incident energy for 2-20 mbar $N_2$ (each data point is an average over a burst of 40 shots). The focal spot quality decreases quickly as a function of energy for pressures greater than 4 mbar, indicating that the beam is in the multiple filamentation regime.

Higher pulse energies can be supported at pressures < 4 mbar due to decreased plasma defocusing and increased critical power of self-focusing. After filamentation in 2 mbar $N_2$, the spectral width for 70 mJ (>2 TW) laser beams increases by a factor of 2 from its initial width, while the quality, 'Q', is maintained at roughly the same focal quality. In 4 mbar $N_2$, the spectral width is doubled at about 25 mJ (~1 TW) for similar focusability.

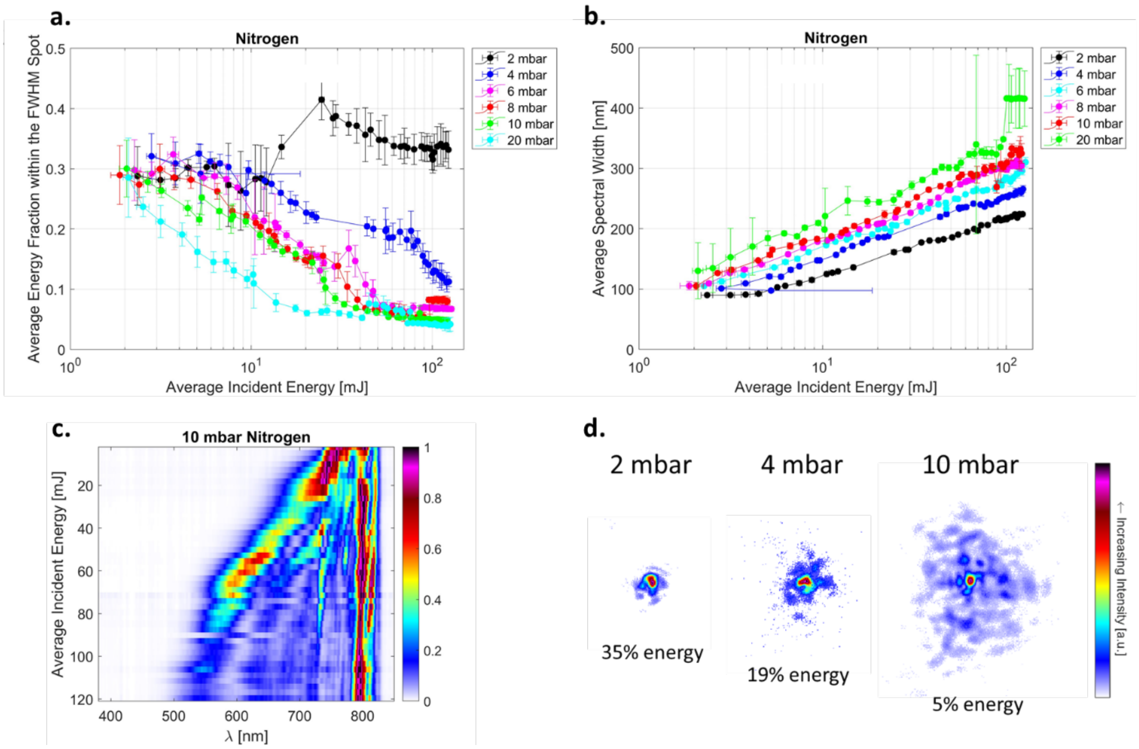


**Fig. 2**: (a.) Several pressures of nitrogen are plotted with spectral width (at 1/30th of maximum intensity level) as a function of incident energy and (b.) quality, 'Q', or the energy fraction within the FWHM focal spot as a function of incident laser energy. Both plots have error bars equal to the standard deviation. (c.) Is a figure plotting the spectra for 10 mbar nitrogen as a function of average incident energy with the color representing the normalized spectral intensity for each spectrum. (d.) Shows several select focal spot images for nitrogen for 2, 4, and 10 mbar for 70 mJ pulse energy. Under each focal spot is the energy fraction within the FWHM spot.

Figure 2c shows that propagation through 10 mbar nitrogen leads to an extended blue edge in the spectrum largely attributable to ionization blue shifting in addition to significant spectral modulation. Examples of the focal spot images for a 70 mJ beam in nitrogen are shown in Figure 2d and display the reduction in beam quality as pressure increases. This analysis was also performed for low pressure air and helium. Helium has a higher ionization threshold and lower nonlinear Kerr refractive index than $N_2$, thus supporting higher incident laser energies and allowing for finer control of the output spectra and focal quality.

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