# Dispersion Adjusting Knife Edge Scan for Optimization of Simultaneously Spatially and Temporally Focused Ultrafast Pulses

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**Abstract:** We present a pulse characterization technique based on dispersion scan which is capable of measuring the spatial focal quality and through-focus temporal evolution of simultaneously spatially and temporally focused ultrafast pulses. © 2022 The Author(s)

## 1. Simultaneous Spatial and Temporal Focusing

Simultaneous spatial and temporal focusing (SSTF) has been shown to be an enabling technology with many applications in laser material processing, ultrafast microscopy, and laser matter interactions [1]. In SSTF, a conventional two grating pulse compressor is modified so that a pulse exits the compressor with purely transverse spatial chirp. When an SSTF pulse is focused, the transverse chirp is converted to angular chirp and each spectral component (beamlet) individually focuses. The combination of the beamlet focusing and angular chirp give rise to an axially-dependent *geometric* dispersion, given by $\phi^{(2)}_{geo}(z) = -\frac{\gamma^2 \omega_0 z}{c}\left(1 + z^2/z_R^2\right)^{-1}$, which leads to temporal compression (focusing) of the pulse on the way to the focus. Here, $\gamma$ is the angular chirp rate, $\omega_0$ is the central frequency of the pulse, $z_R$ is the Rayleigh range of the beamlets, and $c$ is the speed of light in vacuum.

When an SSTF system is well aligned, the spectral crossing plane (where the beamlets are fully overlapped), the beamlet focal plane, and the temporal focal plane all coincide at the same axial position. However, misalignments in the SSTF system, beam aberrations, and residual intrinsic spectral phase can shift the three "focal planes" away from each other. This significantly reduces the peak intensity of the pulse in the focus and can even generate multiple intensity peaks along the optical axis.

## 2. Dispersion Adjusting Knife Edge Scan

Due to the complicated spatio-temporal evolution of SSTF pulses, and the difficulty of aligning SSTF systems, it has historically proved challenging to both generate and characterize high quality SSTF pulses. We have therefore developed a method, called dispersion adjusting knife edge scan (DRAKE-scan), to characterize the spatial focusing of SSTF pulses and their temporal evolution through-focus. DRAKE-scan combines a broadband knife edge (BBKE) measurement [2] with a novel version of the dispersion scan (d-scan) pulse measurement technique [3], called zero dispersion scan (zd-scan).

The BBKE spectrally resolves a standard knife edge beam size measurement to measure the trajectory and size of each beamlet at different axial positions within the focus. This allows for the beamlet focal plane, the spectral crossing plane, and the angular chirp of the pulse to be directly measured. The BBKE component of DRAKE-scan therefore measures all the relevant spatial properties of the pulse in order to optimize the alignment of the SSTF system.

To optimize the temporal focusing of the pulse, a zd-scan is employed which combines a through-focus dispersion scan (tfd-scan) with a conventional grating compressor d-scan. In a conventional grating d-scan, the dispersion of the pulse is iteratively varied by adjusting the separation of the diffraction gratings in the pulse compressor and a nonlinear signal (usually a second harmonic generation (SHG) spectrum) is measured at each dispersion setting to generate a 2D trace [3]. A phase retrieval algorithm is then employed to retrieve the spectral amplitude and phase of the underlying pulse from the trace using the applied dispersion. In a tfd-scan, a thin doubling crystal is instead iteratively moved through the focus of an SSTF pulse to sample the geometric dispersion at different axial positions. The maximal range to scan the crystal is the beamlet walk-off distance $\zeta_{bwo} = w_0/(\gamma\Delta\omega)$, where the spatial separation of the spectral components begins to significantly alter the local pulse structure. Here, $w_0$ is the focal spot size of the beamlets and $\Delta\omega$ is the full bandwidth of the pulse. The geometric dispersion (which can be calculated from information gained from the BBKE) can then be used to retrieve the spectral amplitude and phase of the pulse at the focal plane (which is measured by the BBKE). A zd-scan combines these two versions of d-scan in the following way. A thin doubling crystal is iteratively moved through the focus. At each crystal position, a conventional d-scan is measured by adjusting the grating separation in the SSTF compressor. This builds a 3D zd-scan trace with grating separation, crystal position, and SHG wavelength as the three axes of the trace. A phase retrieval algorithm can then be applied to each conventional d-scan in the 3D trace to retrieve the pulse at each crystal position. This allows the through-focus temporal evolution of the pulse to be measured and the temporal focal plane to be overlapped with the spectral crossing plane and beamlet focal plane by adjusting the compressor separation so that the pulse is shortest at the spatial focal plane.

A general summary of the DRAKE-scan method is as follows. A BBKE measurement is performed. The information in the BBKE measurement is then used to spatially overlap the spectral crossing plane and beamlet focal plane of the SSTF pulse. This typically requires repeated BBKE measurements after adjustments are made to the SSTF system to achieve good overlap. The angular chirp of the pulse is additionally measured. A thin doubling crystal is then placed at the spatial focal plane and used to perform a zd-scan. A phase retrieval algorithm is then used to retrieve the pulse at each crystal position. Lastly, the compressor separation is adjusted so that the pulse is shortest at the spatial focal plane. Higher order intrinsic spectral phase can additionally be compensated for. This fully aligns and optimizes the SSTF system to be used for other experiments or applications.

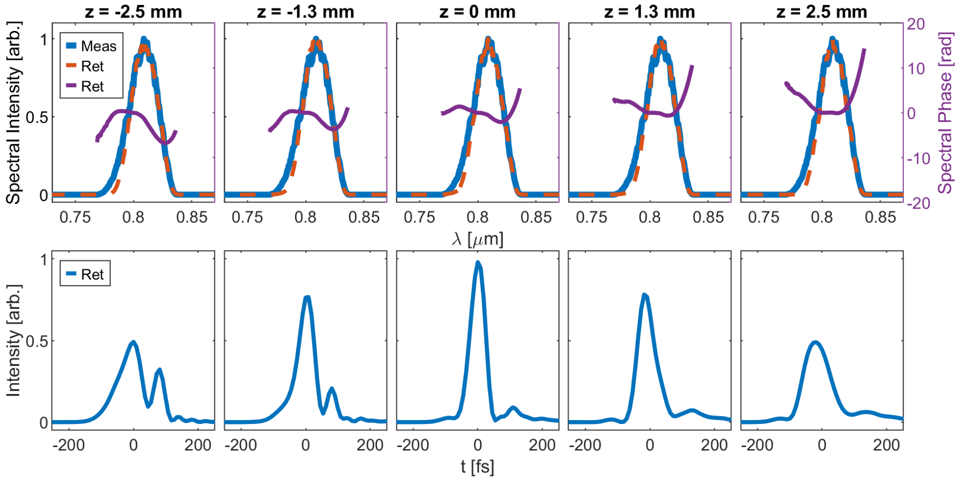

Fig. 1. Top row: Experimentally measured spectra (blue) and retrieved spectra (orange-dashed) at different axial positions of an SSTF pulse optimized with DRAKE-scan. The retrieved spectral phase at each axial position is shown in purple. Bottom row: Retrieved temporal profile for each axial position.

Figure 1 shows the retrieved temporal profiles of an experimentally measured SSTF pulse at different axial positions whose spatial and temporal focusing was optimized using the DRAKE-scan method. Accurate retrieval of the full pulse spectrum occurs at each axial position and the quadratic evolution of the pulse's spectral phase can be seen as it passes through-focus. The temporal focusing (compression) can be seen in the retrieved temporal intensity profiles of the pulse as the pulse duration is shortest at the spatial focus ($z = 0$) and increases on either side of focus. Due to the changing sign of the geometric dispersion on either side of focus and higher order residual spectral phase, the pulse shape is not the same for positive and negative $z$. For this demonstration the relevant pulse parameters were $\gamma = 0.302 rad/PHz$ and $w_0 = 51\mu m$ and a $100\mu m$ BBO doubling crystal was used in the zd-scan. The phase retrieval algorithm used was the root preserving ptychographic algorithm we have previously demonstrated [4]. This demonstration shows that the DRAKE-scan method is a relatively simple method for both characterizing and optimizing the alignment and evolution of SSTF pulses. We gratefully acknowledge funding through the NSF/DOE Partnership for Basic Plasma Science and Engineering under NSF grants PHY-1619518 and PHY-1903709 and the AFOSR grant FA9550-18-1-0089.

## References

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