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Propagation of Ultrashort, Intense Laser Pulses Through the Atmosphere

Joe Peñano

Plasma Physics Division, Naval Research Laboratory

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Collaborators

Michael Helle, Gregory DiComo, Aliaksandr Mamonau[1], Scott Melis[2], Richard Fischer, John Palastro[3], Dmitri Kaganovich, Benjamin Rock, Bahman Hafizi, Luke Johnson, Antonio Ting[1,4]

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Andreas Schmitt-Sody, Jennifer Elle, and Adrian Lucero

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What is an ultrashort laser pulse?

laser parameters

peak power	GW to PW
intensity	10^{12} to 10^{23} W/cm^2
pulse duration	10^{-14} to 10^{-12} seconds
average power	1 W- 1 kW

comparison of electric field strengths

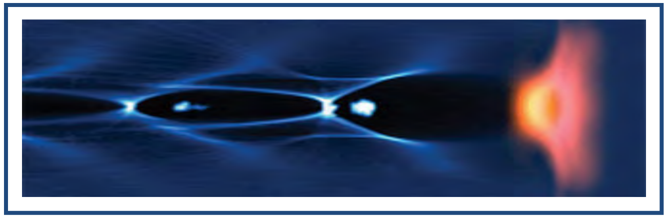
- laser electric field: E_{laser}[V/cm] = 27.5 $I^{1/2}$ [W/cm^2] $E_{laser} \sim 10^8$ to 10^{13} V/cm
- atomic electric field (over the barrier ionization): $E_{atom} \sim q/4\pi\varepsilon_0 a^2 \sim 5\text{x}10^9$ V/cm
- Schwinger field (potential difference of a rest mass across a Compton wavelength):

$$E_{sch} = m_e^2 c^3 / q\hbar \approx 10^{16} \text{ V/cm}$$

Fundamentally different interactions than long pulses

- laser wakefield acceleration of electrons

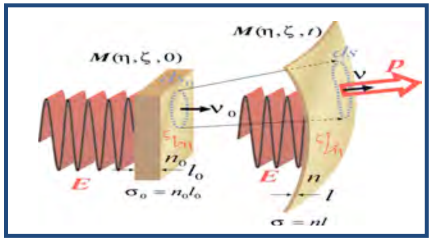
  a laser pulse propagating through plasma ponderomotively drives an electrostatic wave that can accelerate electrons to MeV-GeV energies



W. Lu et al., PRSTAB, 10 (2007).

- radiation pressure acceleration of ions

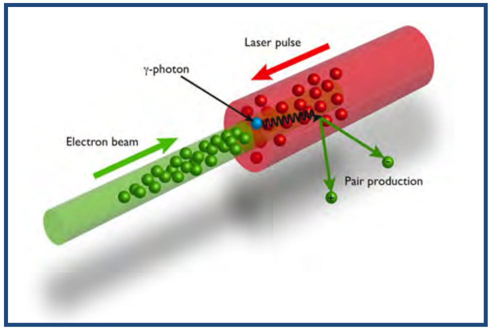
  a laser pulse incident on an overdense target acts as a light sail/piston, ponderomotively accelerating ions



S. V. Bulanov et al., Phys. Plasmas, 17 (2010).

- positron and gamma ray sources

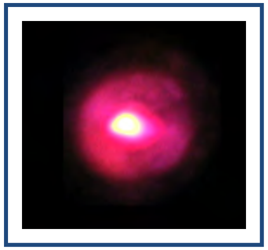
  a laser pulse incident on a counterpropagating multi-GeV electron beam yields gamma rays that pair-produce



extreme light Infrastructure website

- generation of ultrabroadband radiation

  a laser pulse propagating through a nonlinear medium undergoes octave-spanning spectral broadening and generation of far out-of-band radiation



S. Varma, thesis defense (2011).

Motivation for this talk

- Much of our understanding of optical propagation through atmospheric turbulence is based on the medium's **linear response** to the optical field.
- Relatively few studies of turbulence and nonlinear filamentation and nonlinear self-focusing*. The majority of these studies investigated cases where the peak laser power is larger than the self-focusing power of air (filamentation regime).
  - **Kandidov** et al.: modeling of nonlinear self-focusing (NLSF) in turbulence using phase screens. [Quantum Electron. 29, 911 (1999)]
  - **Chin** et al.: characterized filament wander in turbulence [Appl. Phys. B 74, 67–76 (2002)]
  - **Salame** et al.: laboratory experiments over regions of extended turbulence [Appl. Phys. Lett. 91, 171106 (2007)]
  - **Houard** et al.: characterized the competition between self-focusing and modulational instability, investigate filament stability in turbulence [Phys. Rev. A 78, 033804 (2008)]
  - **Penano** et al.: calculation of filamentation onset/suppression in turbulence [JOSA B 31, 963 (2014)]
- In this study, we present a way to propagate long ranges through strong atmospheric turbulence that avoids the "filamentation" regime.

Characterization of Atmospheric Turbulence

- turbulence: random fluctuations of air currents in the form of eddies driven by large scale thermal gradients

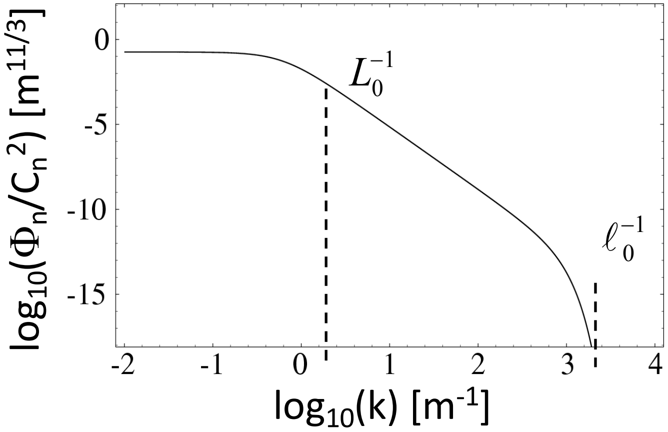
- Eddy scale distribution is described by the modified von Karman spectrum:

$$\Phi_n(k) = .033 C_n^2 \frac{e^{-\ell_0^2 k^2}}{(k^2 + L_0^{-2})^{11/6}}$$

L_0 : outer scale (1 – 100 m)

ℓ_0 : inner scale (~1-10 mm)

C_n^2 : refractive index structure constant (meteorological strength)



- Rytov variance parameterizes the optical effect: $\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$

$\sigma_R^2 << 1$ (optically weak) ; $\sigma_R^2 > 1$ (optically strong)

- Transverse coherence length of a plane wave: $\rho_0 = (1.46 k^2 C_n^2 L)^{-3/5}$

Andrews and Phillips, Laser Beam Propagation through Random Media

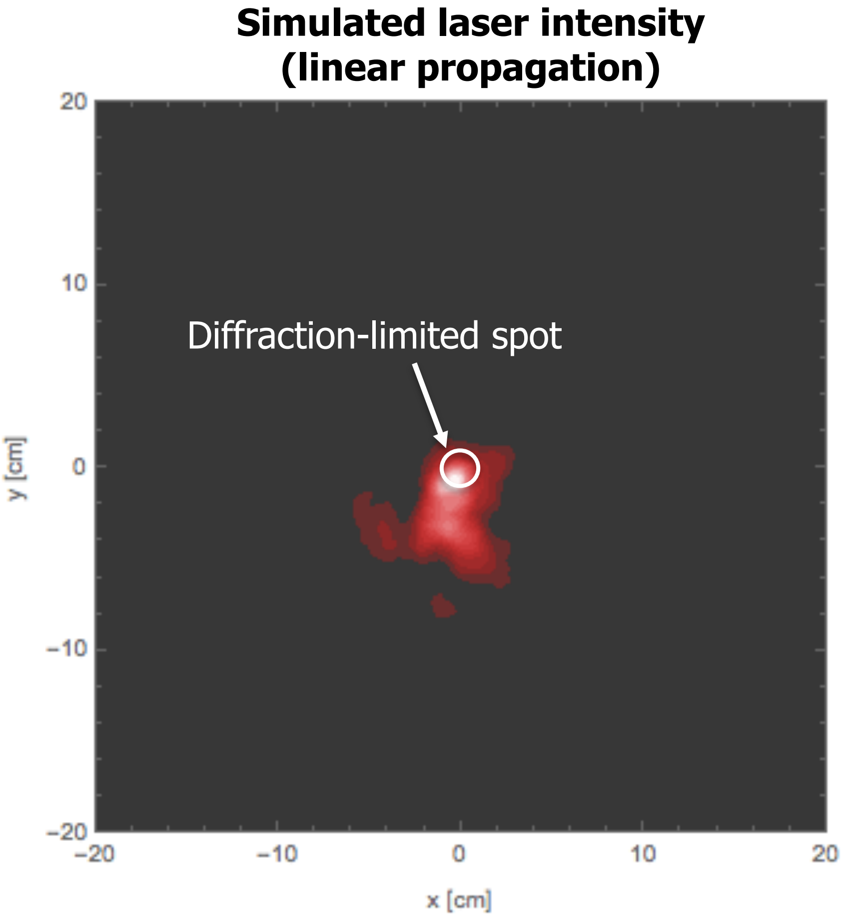
Turbulence and its effect on laser propagation

- Median turbulence over near-surface, horizontal path*: $C_n^2 = 3 \times 10^{-15} \mathrm{m}^{-2/3}$

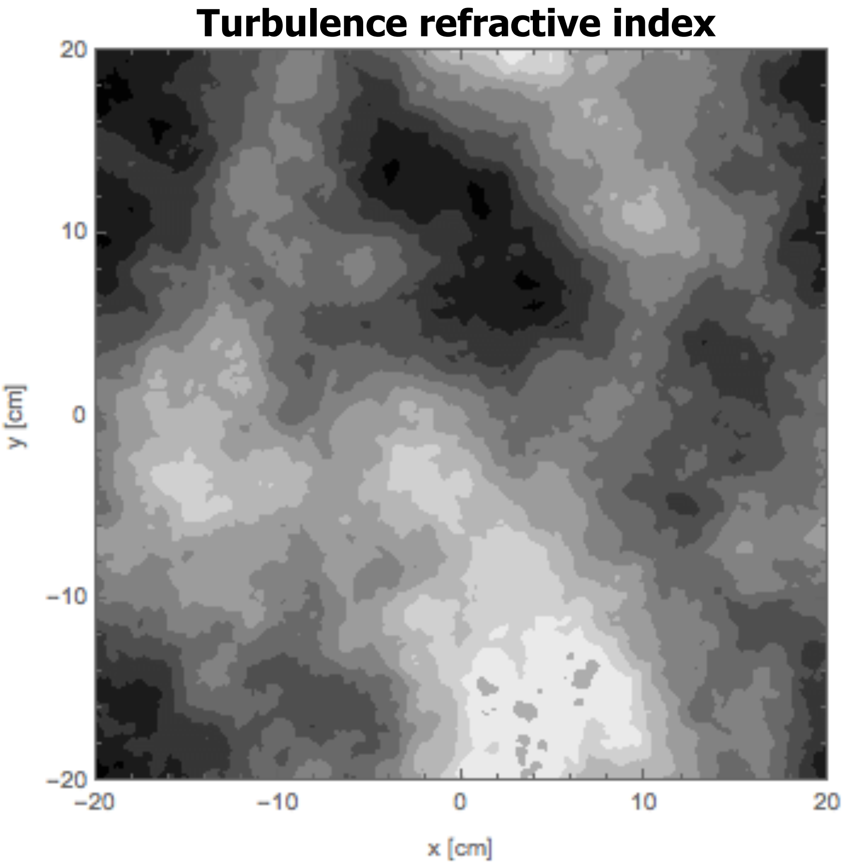
  *C.I. Moore, et al., Proc. of SPIE Vol. 5892(SPIE, Bellingham, WA, 2005):

- Strong turbulence regime can be realized within several kilometers: $\left\{ \begin{array}{l} \text{5 km path} \\ \sigma_R^2 = 3.2 \end{array} \right.$

(~1 um wavelength)



Simulated laser intensity (linear propagation)



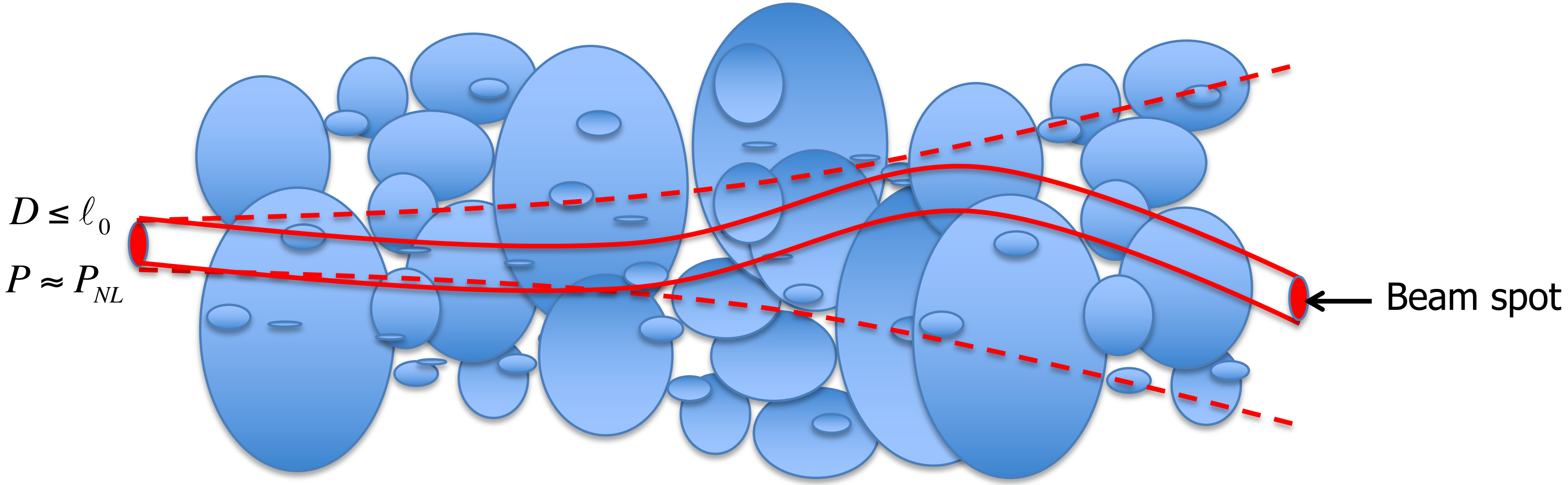
Turbulence refractive index

Self-channeling through turbulence

- Turbulence effects:
  - spreading is due to small scale turbulence $k_{eddy} R > 1$
  - wander is due to large scale turbulence $k_{eddy} R < 1$

R is the beam spot size

- Self-channeling concept
  - Use small spot size (smaller than the coherence length or inner scale) to *avoid spreading by turbulence*
  - Propagate near the critical power to cancel diffractive spreading



Channeling can persist for many Rayleigh lengths

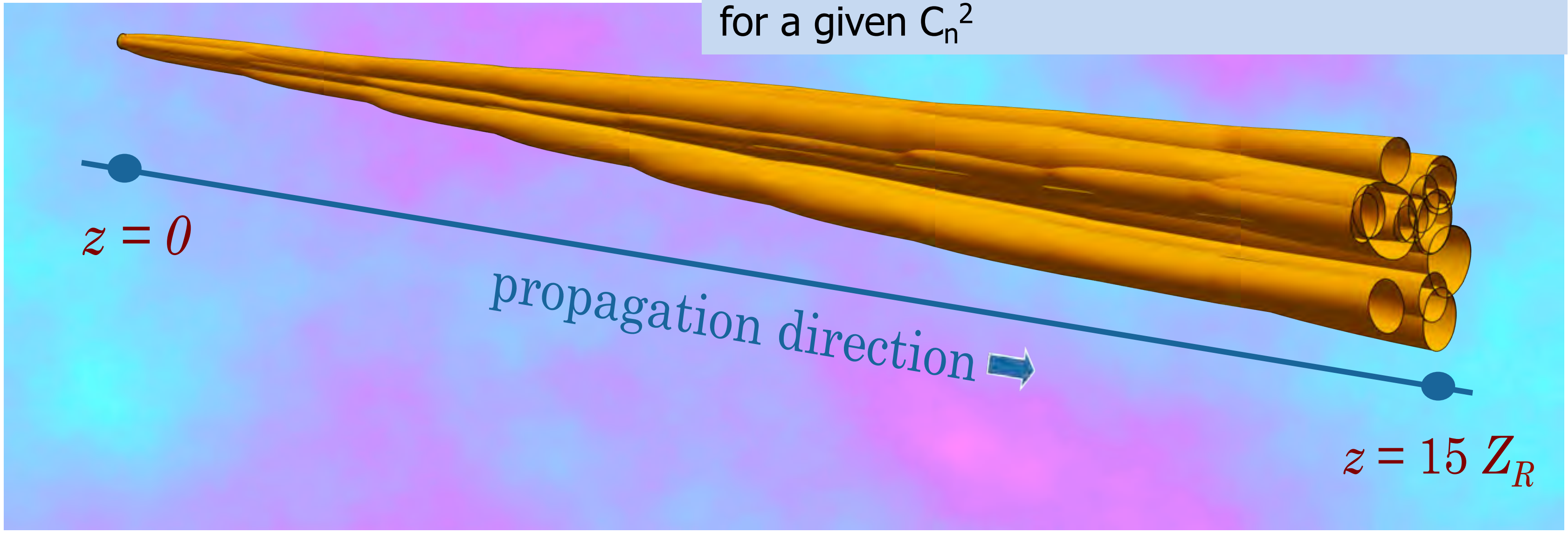
J. Peñano, J.P. Palastro, B. Hazi, M.H. Helle, and G.P. DiComo, *Phys. Rev. A*, 96(1):013829, 2017.

Simulations Indicate Effectiveness at Long Range (z >> Z_R)

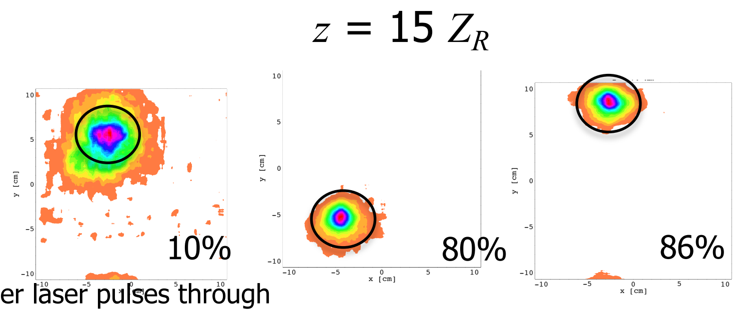
- Simulations solve NLSE in (x,y,z,t) including GVD, extinction, and turbulence

$$\left[2ik\left(\frac{\partial}{\partial z}+\alpha\right)-k\beta_2\frac{\partial^2}{\partial\tau^2}+\nabla_\perp^2\right]A=-2k_0^2\left(\delta n_T+n_2 I\right)A$$

100+ independent realizations of turbulence for a given C_n^2



- Characterize channeling by how much energy remains within the initial beam radius, W_0.

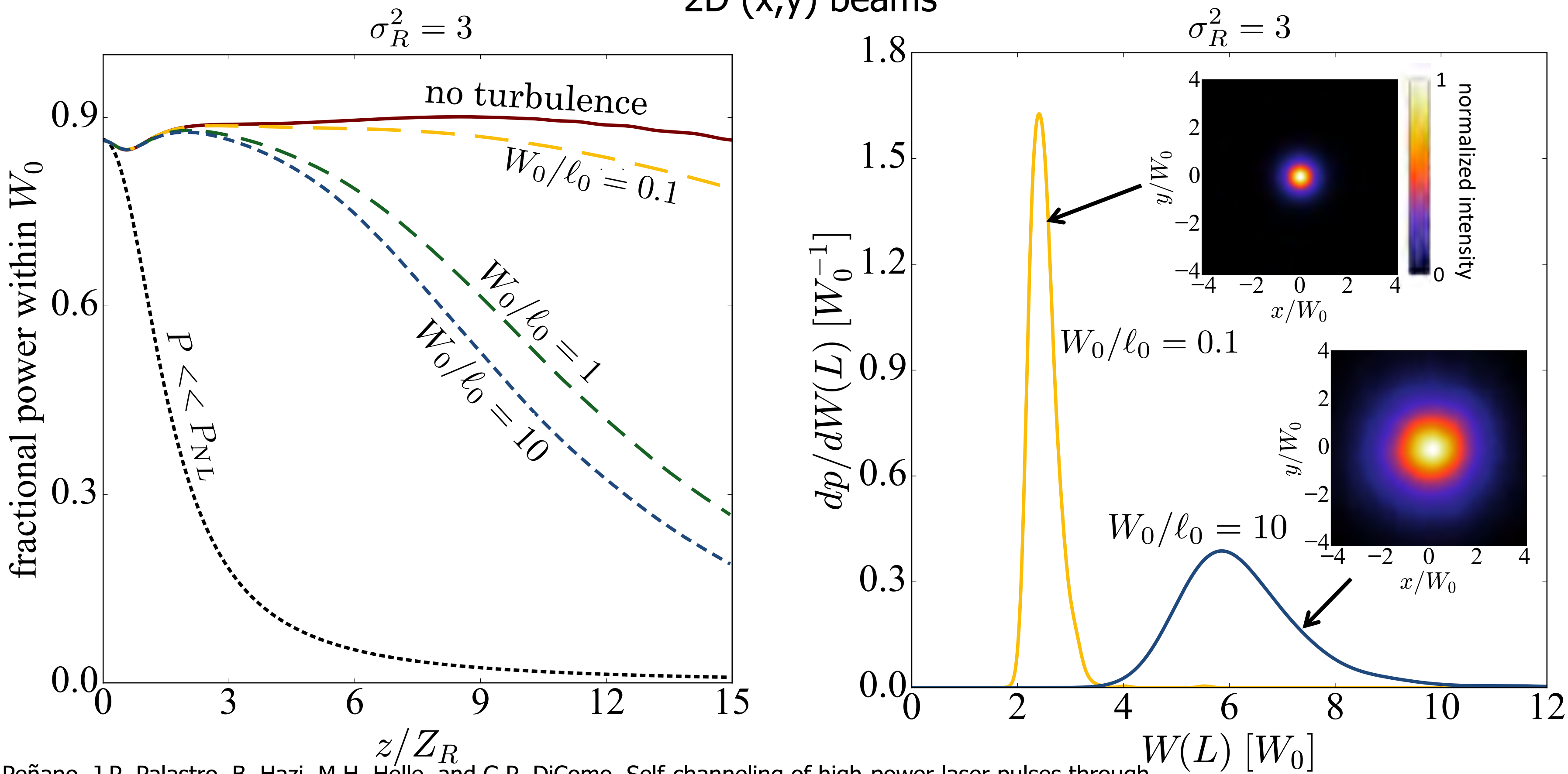


J. Peñano, J.P. Palastro, B. Hazi, M.H. Helle, and G.P. DiComo. Self-channeling of high-power laser pulses through strong atmospheric turbulence. *Phys. Rev. A*, 96(1):013829, 2017.

Channeling is dependent on relationship between spot size (W0), inner scale (l0), and coherence length (r0)

(i)	$W_0 < (\ell_0, \rho_0)$	long-range channeling (> 10 Z_{R0})
(ii)	$\ell_0 < W_0 < \rho_0$	rms spot increases, central hot-spot remains intact
(iii)	$W_0 >> (\ell_0, \rho_0)$	nonlinear self-focusing is not effective

2D (x,y) beams



J. Peñano, J.P. Palastro, B. Hazi, M.H. Helle, and G.P. DiComo. Self-channeling of high-power laser pulses through strong atmospheric turbulence. *Phys. Rev. A*, 96(1):013829, 2017.

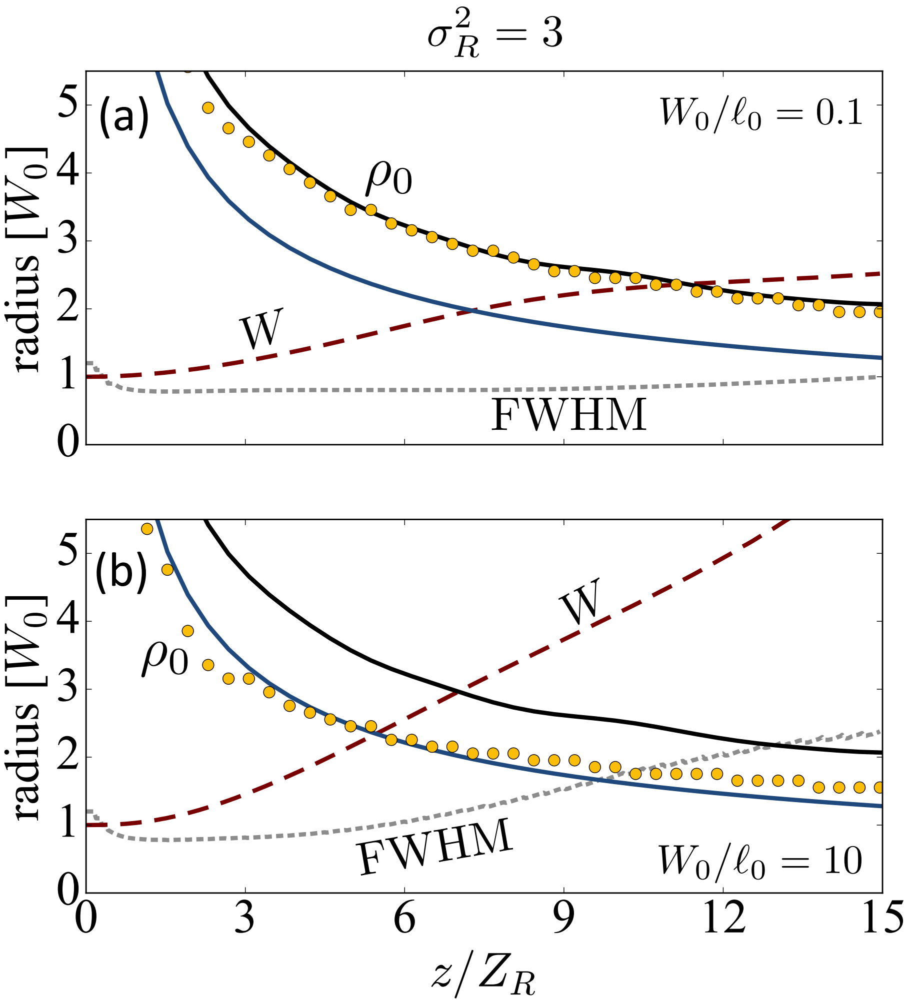
Channeling is degraded by field incoherence

- Channeling of the central hot spot is lost when the coherence length of the field becomes smaller than the beam rms radius. (beam and “reservoir” become incoherent)

- Coherence length of the channeling Gaussian beam is characteristic of that of a plane wave.

Solid curves: theoretical plane wave coherence radius for ▬ $W_0/\ell_0 = 0.1$

▬ $W_0/\ell_0 = 10$



J. Peñano, J.P. Palastro, B. Hazi, M.H. Helle, and G.P. DiComo. Self-channeling of high-power laser pulses through strong atmospheric turbulence. *Phys. Rev. A*, 96(1):013829, 2017.

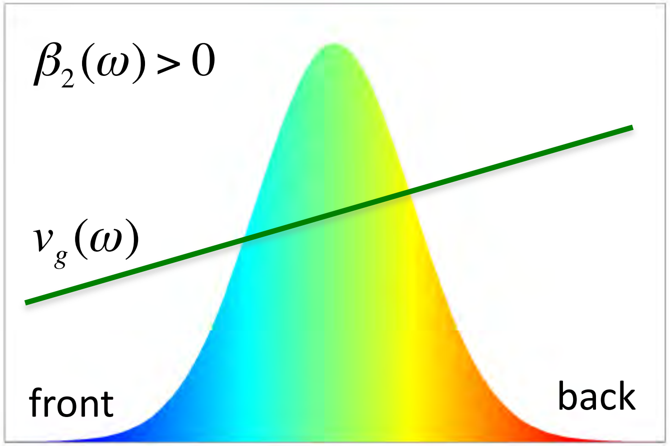
Longitudinal Compression of Laser Pulses in Air

- Air is a dispersive medium at optical frequencies, i.e., frequencies have different group velocities
- Ultrashort pulses have sufficient bandwidth such that atmospheric dispersion can compress or stretch the pulse significantly over hundreds of meters of propagation
- Pulse duration after distance z:

$$T(z) = T_o\left(\left(1 + \beta_o \frac{z}{Z_T}\right)^2 + \left(\frac{z}{Z_T}\right)^2\right)^{1/2}$$

$$Z_T = T_o^2 / 2|\beta_2| \qquad \beta_0 = \frac{T_0}{2\beta_2}\frac{\partial T}{\partial z}\bigg|_{z=0}$$

Compression of a chirped pulse

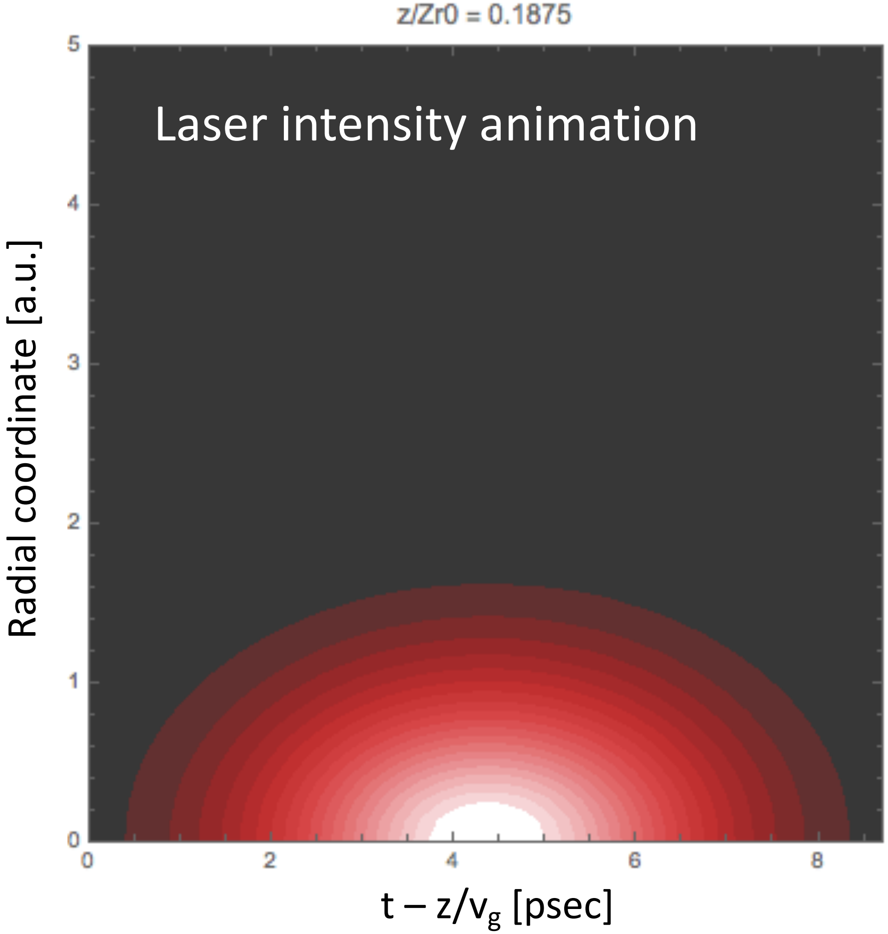


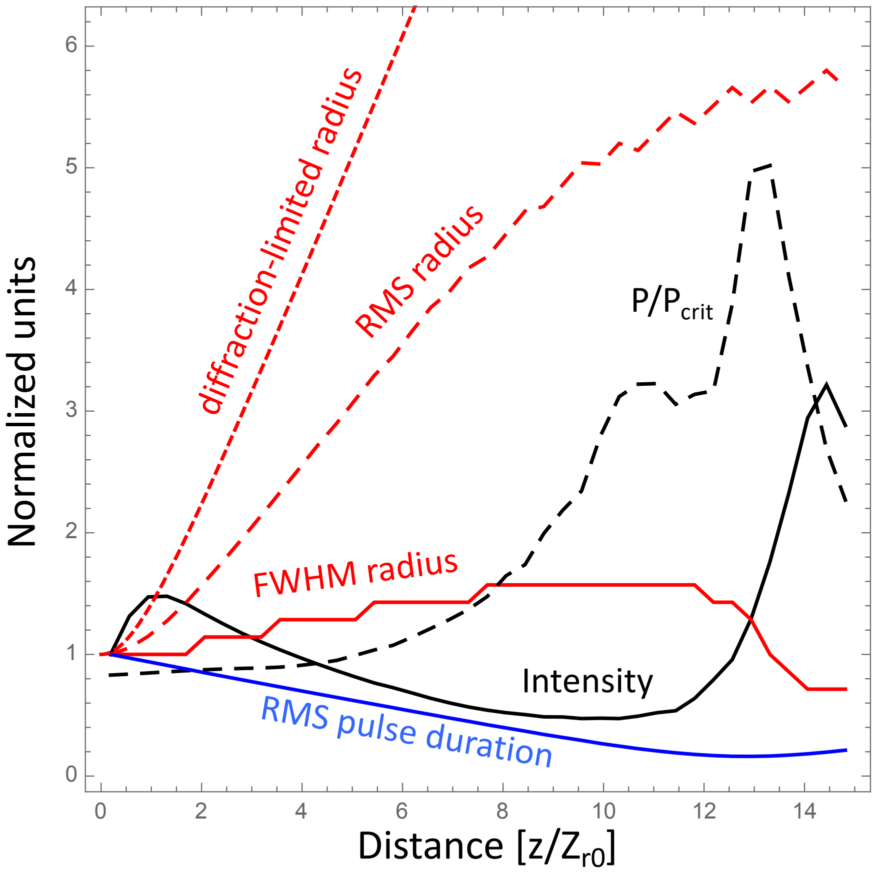
- Arranging spectral content of the pulse so frequency decreases from front to back (negative chirp) results in longitudinal compression (for wavelengths ~ 1μm where $\beta_2(\omega)$>0)

In the presence of extinction, the pulse must be chirped to preserve peak power and maintain channeling

- Pulse duration vs. z: $T(z) = T_0\left[(1+\beta_0 z/Z_T)^2 + (z/Z_T)^2\right]^{1/2}$; $Z_T = T_0^2/(2|\beta_2|)$
- Optimal chirp: $\beta_0 \approx \alpha T_0 E_0/(\beta_2 P_{NL}) \longrightarrow T'(z) = E'(z)/P_{NL}^{-1}$

(compression rate equal to energy loss rate)



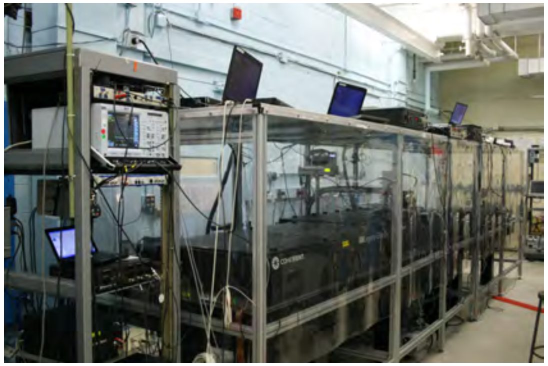


~50% energy lost

J. Peñano, J.P. Palastro, B. Hazi, M.H. Helle, and G.P. DiComo. Self-channeling of high-power laser pulses through strong atmospheric turbulence. *Phys. Rev. A*, 96(1):013829, 2017.

Validation Experiments at Increasing Distances

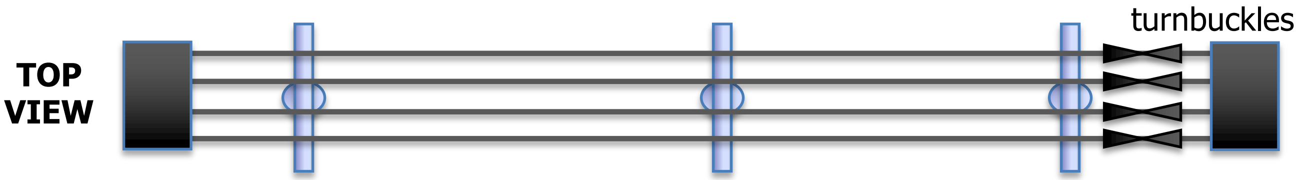
2015-16 **Lab environment at NRL**
kTFL laser (5 mJ, 35 fsec, 1 kHz, 800 nm)
Nonlinear channeling in turbulence



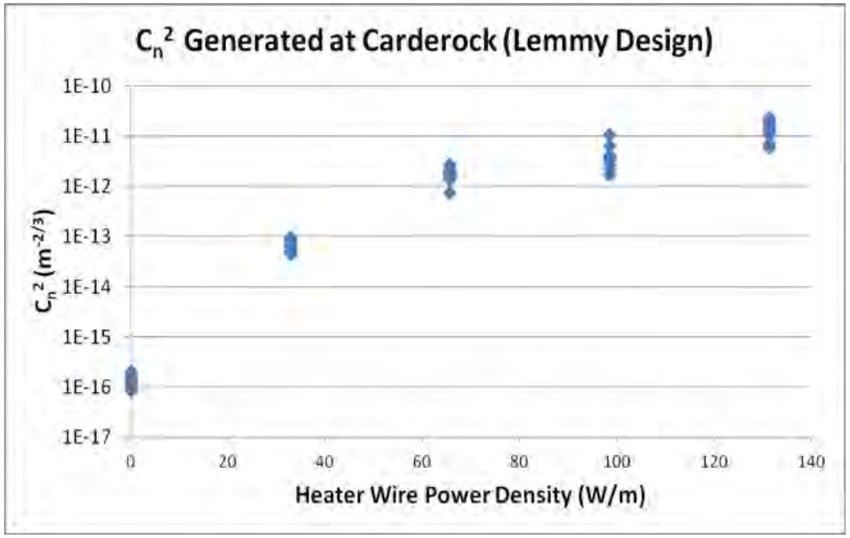
2016 **AFRL Facility**
Pheenix laser (40 TW, 35 fsec, 10 Hz, 800nm)
Nonlinear channeling in deep turbulence (Rytov > 5)

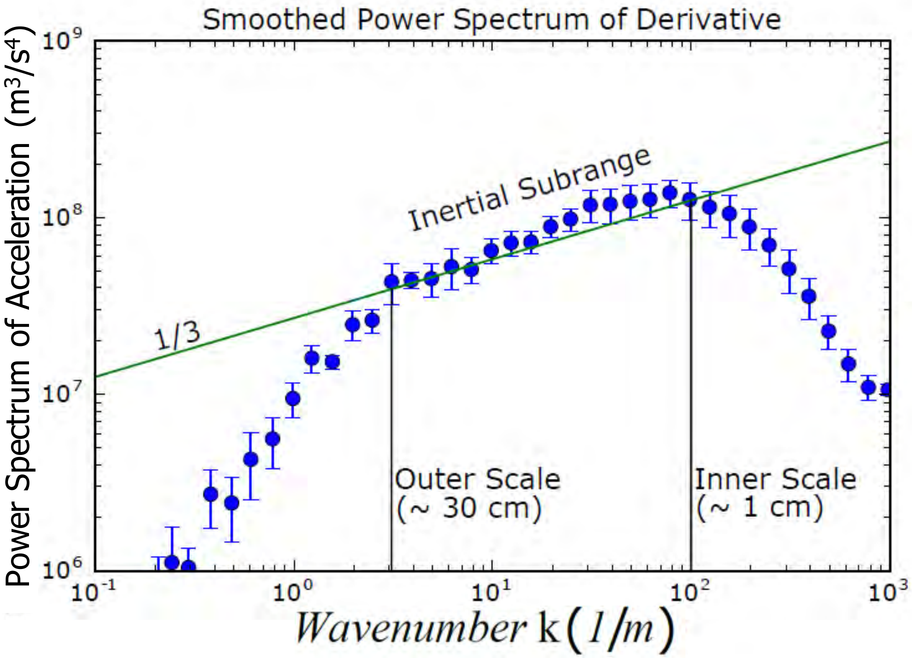
2017 **Carderock Facility**
Astrella laser (7 mJ, 35 fsec, 1 kHz, 800 nm)
Nonlinear propagation through turbulence
Pulse compression
Control of nonlinear focal range

Laboratory Turbulence Generator for high-power laser propagation experiments*



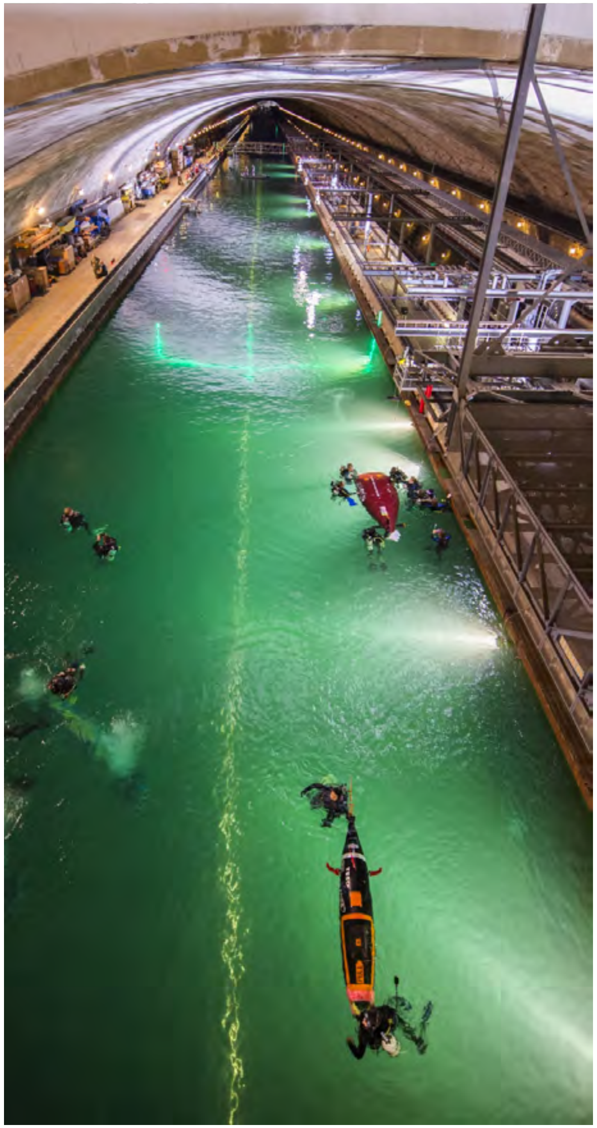
- 5 orders of magnitude range of turbulence
- Kolmogorov spectrum over the inertial sub-range
- Ideal for high-power experiments (no phase plates to damage)





*G. DiComo et al. "Implementation of a long range, distributed-volume, continuously variable turbulence generator," Applied Optics 55, 5192 (2016).
S. Pond, R. W. Stewart, and R. W. Burling, Journal of Atmospheric Sciences, vol. 20, pp. 319-324 (1963).

Experimental Facility for Validation at ~850m



- Continuous indoor path with low ambient turbulence
- Distributed turbulence with tunable Rytov from 10^{-3} to >10
- Two weeks to build

- Laser operation during graveyard shift over 2 months
- Laser intensity profile and pulse length fully characterized

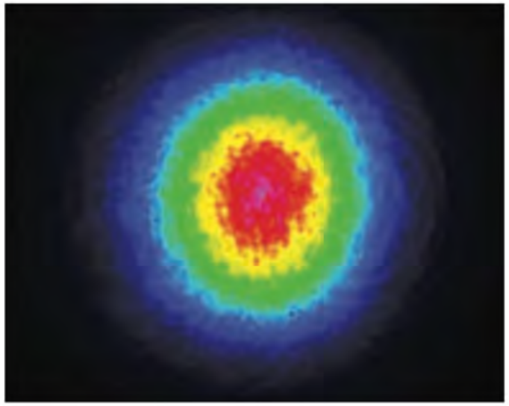
Portable USPL for propagation experiments

Coherent ASTRELLA

- Wavelength: 800nm
- Rep Rate: 1 kHz
- Energy: 7 mJ
- Pulse length: 35fs
- Beam Quality: $M^2 < 1.25$

Laser housing open for setup

- Integrated Vitara seed laser, revolution pump laser, STAR regenerative amplifier and sealed, compact stretcher/compressor
- HASS* verified (ruggedized for portability)
- All major sub-systems thermally-stabilized for reliable long-term performance
- Water-only cooled Ti:Sapphire rod assembly for improved beam quality and thermal management ($M^2 < 1.25$, stability <0.5% rms)
- Sealed stretcher/compressor (pulse width <35 fs to 3ps)



Typical Near Field Mode Quality

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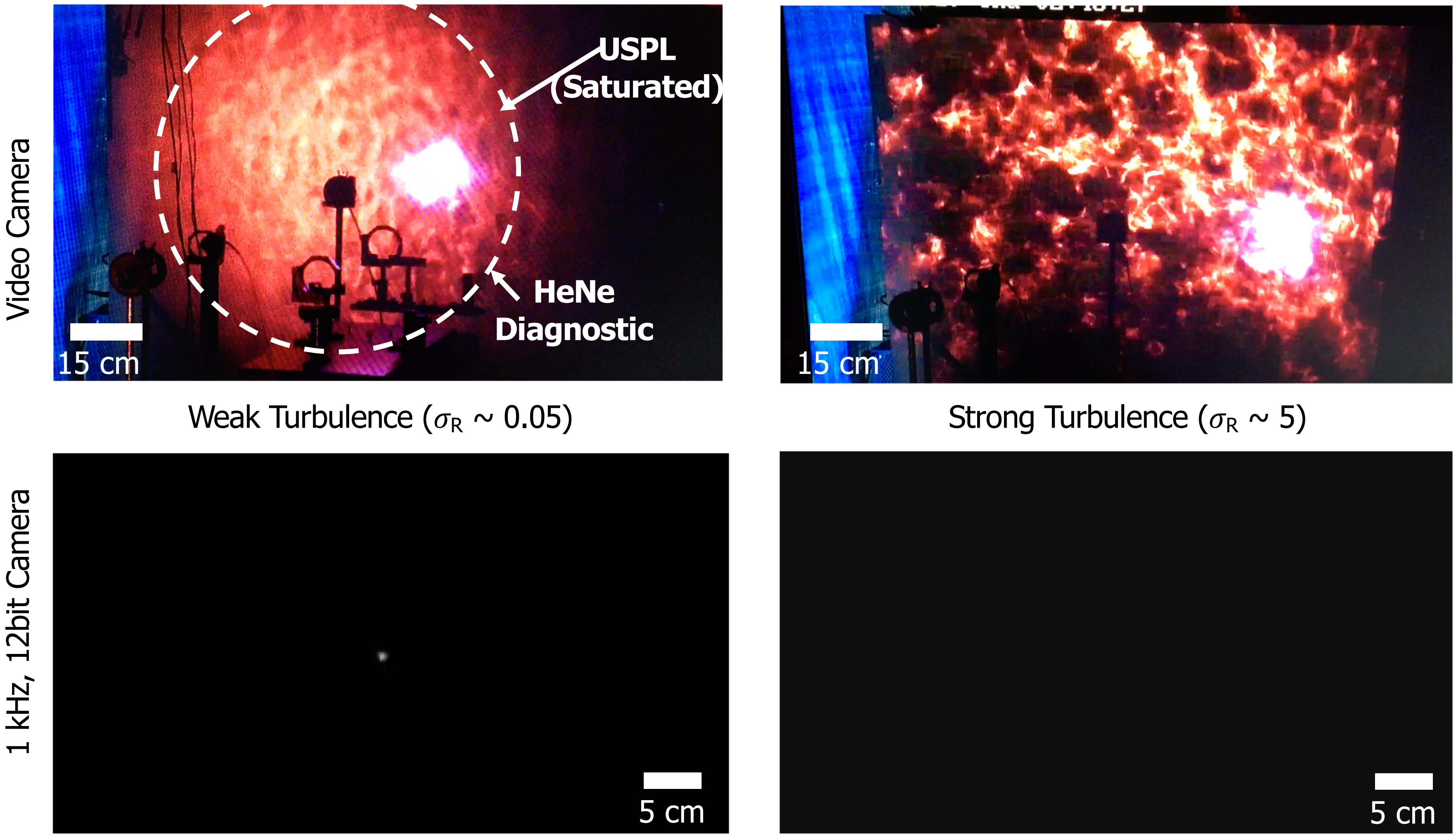
*Highly Accelerated Stress Screening

Self-Channeling Observed in Strong Turbulence



Weak Turbulence ($\sigma_R \sim 0.05$)

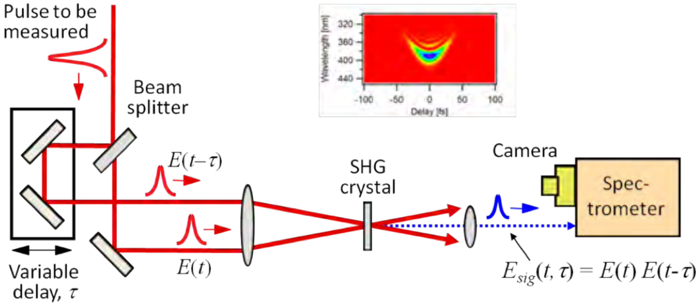
Strong Turbulence ($\sigma_R \sim 5$)

High-power beam **remains small (<< diffraction limit)** in strong turbulence

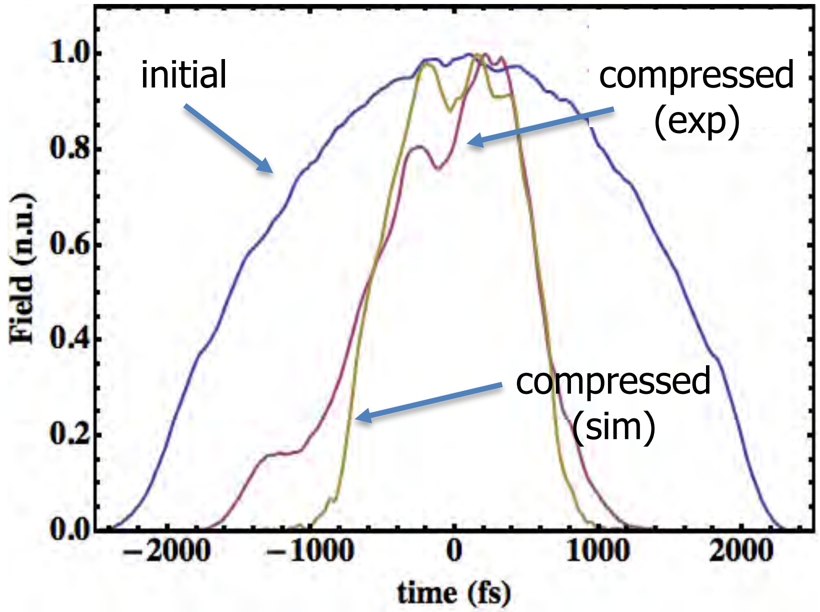
Experimental measurement of temporal profile

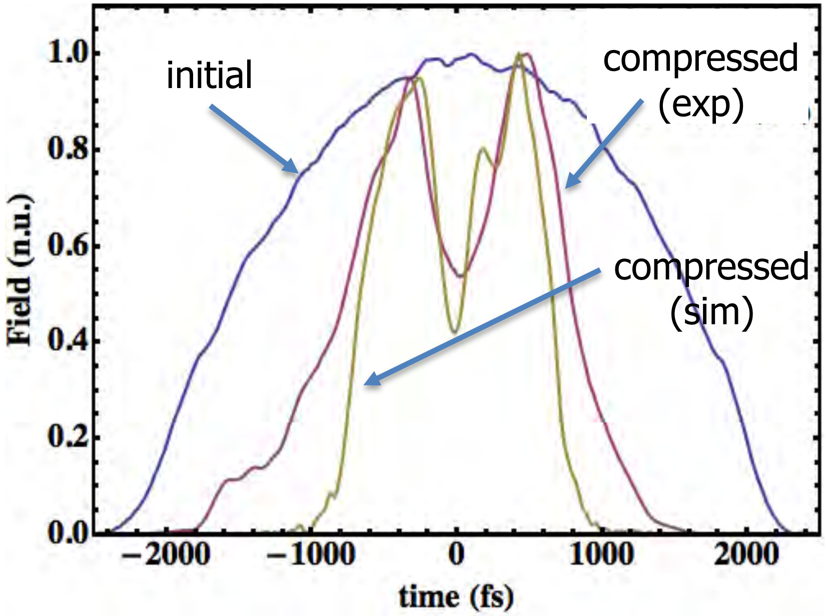
- Built SHG FROG to measure complex field (Can measure low intensities)
- Pulse was characterized at laser and received end of range
- Nonlinear effects such as self-phase modulation and self-steepening can be observed for the high power pulse

Frequency-Resolved Optical Gating (**FROG**)

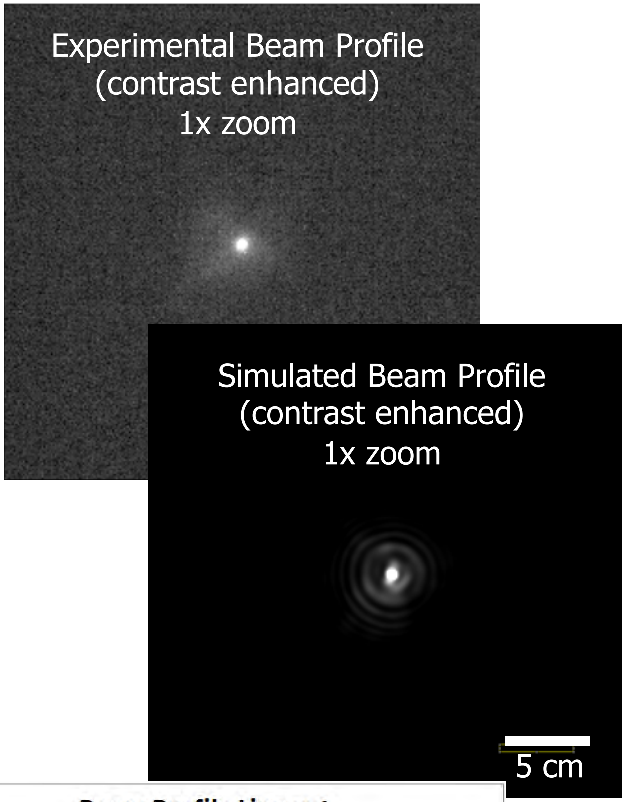


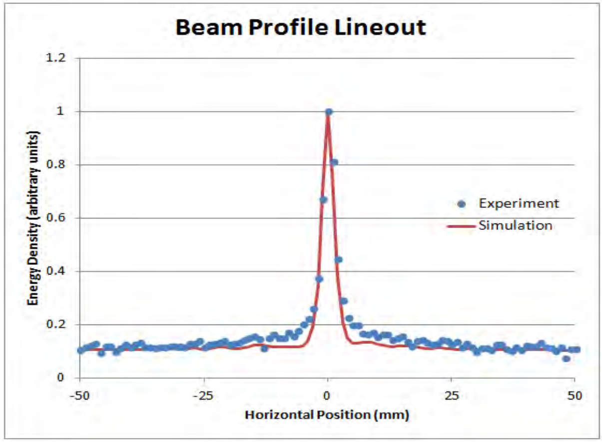
SHG FROG is the most sensitive version of FROG.

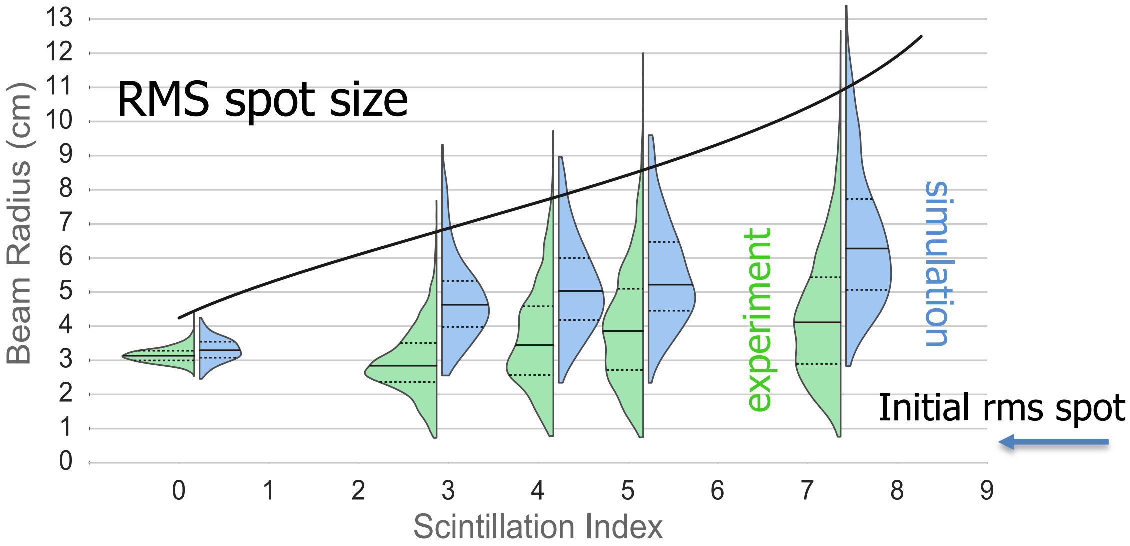


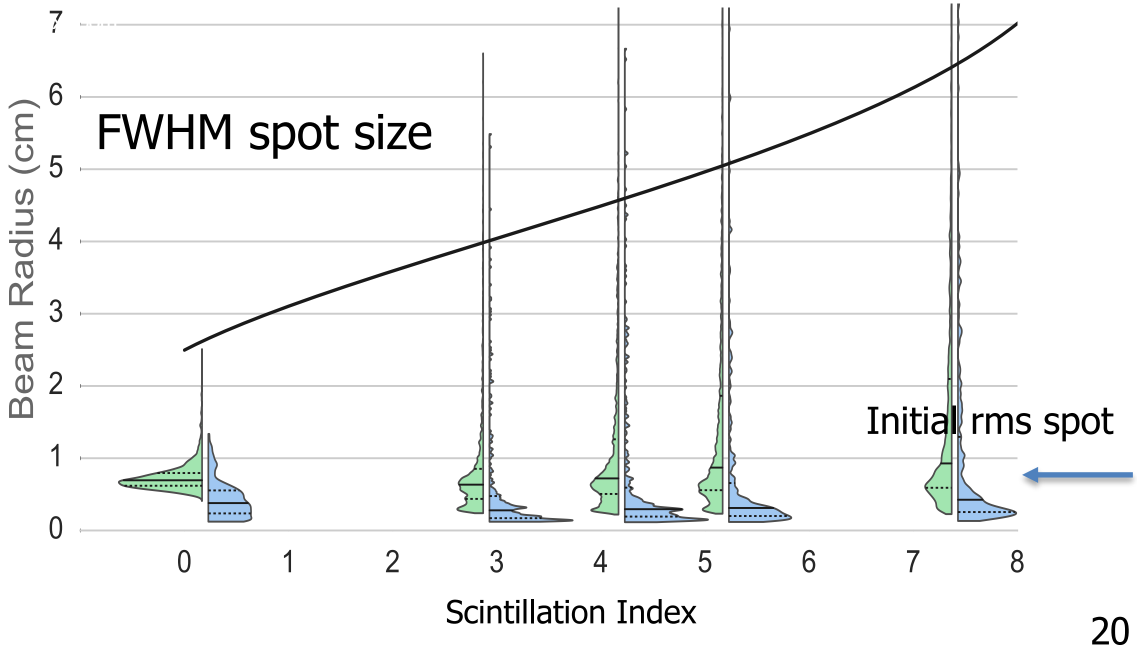


Experiments validate nonlinear self-focusing models in strong turbulence

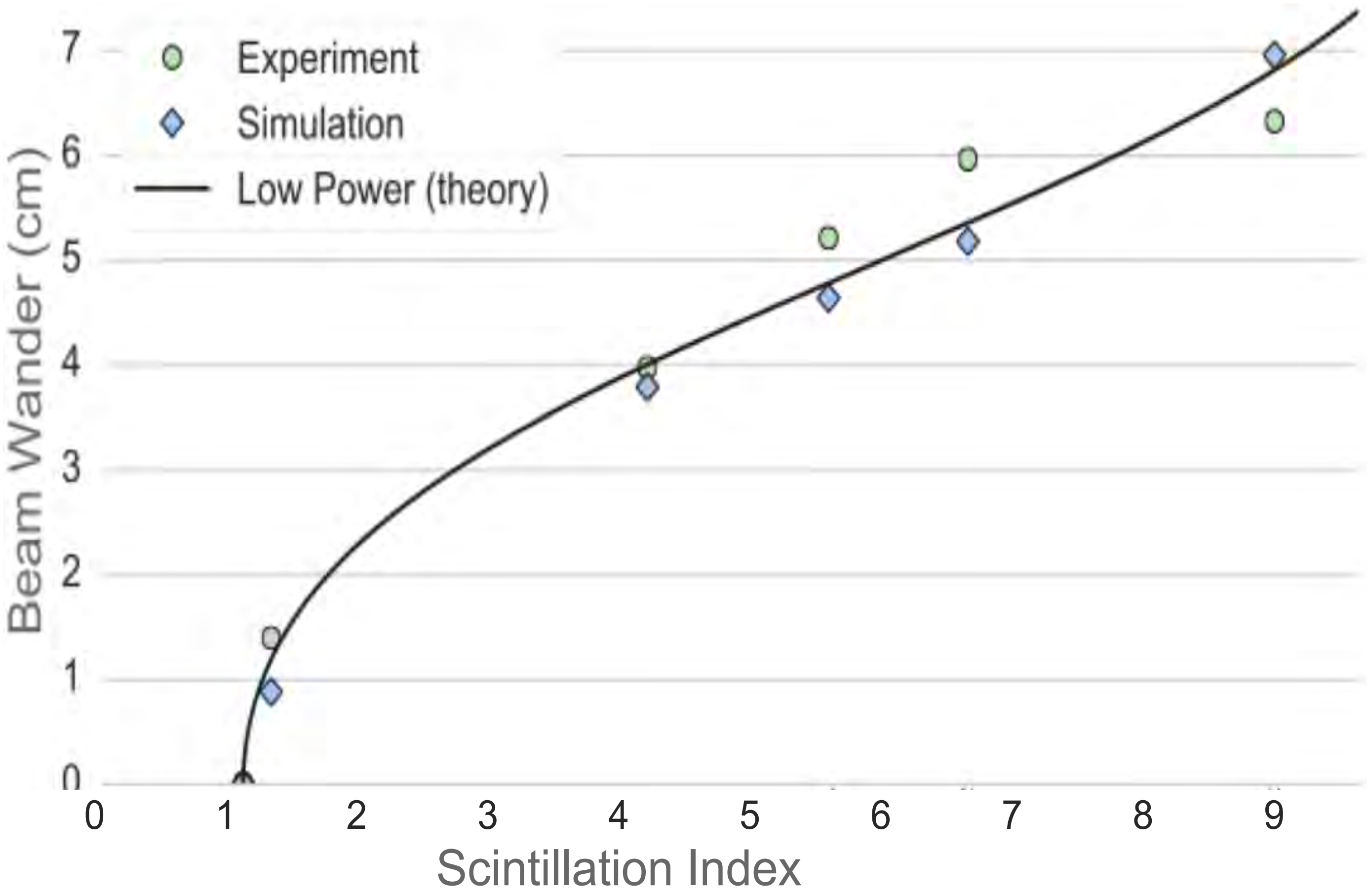








Beam wander is consistent with linear physics



Self-focusing of non-Gaussian beams

- For a given rms spot size, Gaussian beams have the longest diffraction length compared with any other beam shape

- Experimentally generated laser beams are never purely Gaussian, nor perfectly coherent

- What are the nonlinear self-focusing properties of non-Gaussian, partially coherent beams? Do they afford any propagation advantages?
  - Bessel beams
  - Partially coherent beams

The Critical Power of an Arbitrary Beam Shape

- The ensemble averaged beam spot size, *w(z)*, along the propagation axis *z* is

$$w^2(z) = \frac{2}{P}\int r^2\langle I(r,z)\rangle d^2r - 2\langle R_c^2(z)\rangle$$

- The spot size satisfies the following **mathematical** identity

$$\frac{\partial^2 w}{\partial z^2} = \frac{\lambda_0^2}{n_0^2\pi^2}\frac{M^4(z)}{w^3}$$

where the ensemble beam quality (spreading angle normalized to the the Gaussian spreading angle) is:

$$M^4(0) = \frac{n_0^2\pi^2}{\lambda_0}\left\{-\frac{1}{4}\left(\frac{\partial w^2}{\partial z}\bigg|_0\right)^2 + \frac{w(0)^2}{2}\,\frac{\partial^2 w^2}{\partial z^2}\bigg|_0\right\}$$

- In the absence of turbulence, it can be shown that M^4 is a conserved quantity. If M^4 can be evaluated at $z=0$ then we will know how the ensemble of beams will propagate.

- Define the critical power as the condition $M^2 = 0$

The Critical Power of an Arbitrary Beam Shape (cont.)

$$M^4(0) = \frac{n_0^2 \pi^2}{\lambda_0} \left\{ -\frac{1}{4} \left(\left. \frac{\partial w^2}{\partial z} \right|_0 \right)^2 + \frac{w(0)^2}{2} \left. \frac{\partial^2 w^2}{\partial z^2} \right|_0 \right\}$$

- Only the 2nd term is important in evaluating M^4 (the first term represents a “lens” contribution which does not affect M^4):

$$\frac{\partial^2 w^2}{\partial z^2} = \frac{2}{P} \int r^2 \left\langle \frac{\partial^2 I}{\partial z^2} \right\rangle d^2 r = \frac{2}{P} \frac{c n_0}{8\pi} \int r^2 \left\langle \left| \frac{\partial A}{\partial z} \right|^2 + A^\star \frac{\partial^2 A}{\partial z^2} + \text{c.c.} \right\rangle d^2 r$$

- The physics of the laser propagation is introduced through the nonlinear Schodinger equation (NLSE)

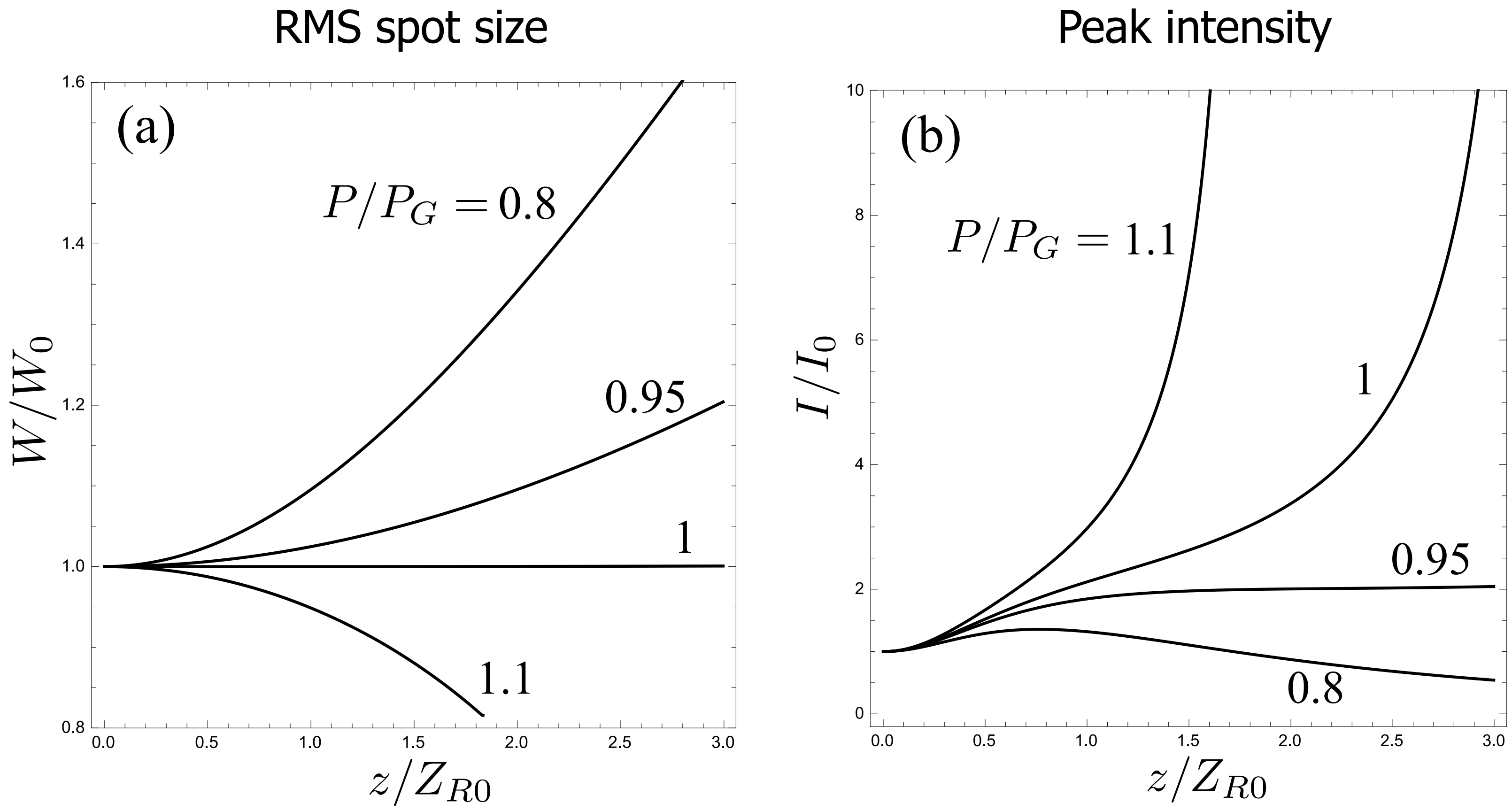
$$\frac{\partial A}{\partial z} = \frac{i}{2k_0} \left(\nabla_\perp^2 A + 2k_0^2 \frac{n_0^2 n_2 c}{8\pi} \left| A \right|^2 A \right)$$

diffraction self-focusing

- Using a Gaussian beam as the initial condition in this formalism recovers the usual expression for the self-focusing power:

$$P_G = \lambda^2 / (2\pi n_0 n_2)$$

Propagation of an initially Gaussian beam near the critical power



RMS spot size

Peak intensity

Partially-Coherent Beams

- The Gaussian-Schell model is a way to generate a partially-coherent field

$$A(\vec{r}) = \left(\frac{8\pi I_0}{c n_0}\right)\left(\int a(\vec{k}) e^{i\vec{k}r} d^3k\right) e^{-r^2/R_0^2}$$

where *a(k)*, the angular correlation function of the field, and the intensity are

$$\langle a^\star(\vec{k}) a(\vec{k}')\rangle = \frac{\rho_c^2}{\pi} e^{-k^2\rho_c^2}\delta(\vec{k}' - \vec{k}) \qquad I(\vec{r}) = \frac{c n_0}{8\pi}\langle A^\star(\vec{r}) A(\vec{r})\rangle$$

- By applying the formalism described in the previous slides, we obtain for the normalized spreading angle

$$M^4(0) = n_0^2\left(1 + \frac{R_0^2}{2\rho_c^2} - \frac{P}{P_{\text{crit}}}\right) \qquad P_{crit} = \frac{\lambda_0^2}{2\pi n_0 n_2}$$

focusing

defocusing

- The defocusing term due to incoherence is identical in form for propagation in turbulence with the coherence length replaced by the Fried parameter (the atmospheric coherence length)

Bessel beams with OAM in finite apertures

Field envelope: $A = \left(\frac{8\pi I_0}{n_0 c}\right)^{\frac{1}{2}} J_m(r j_{mn}/R_0)\exp(im\theta)(1-H(r-R_0))$;

j_{mn} is the n^{th} root of J_m

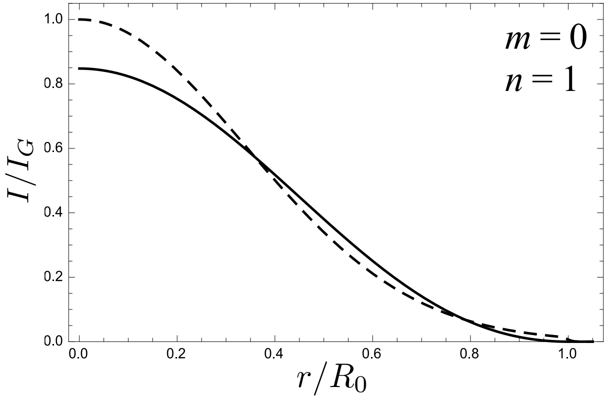
aperture radius: R_0

Power of a Bessel beam: $P_{mn} = \pi R_0^2 I_0 J_{m-1}^2(j_{mn})$

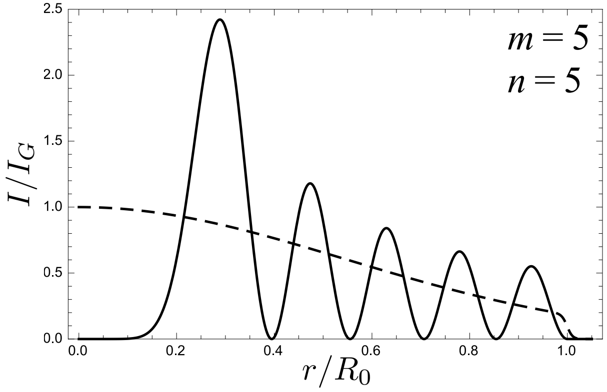
Comparison with apertured Gaussian beam:

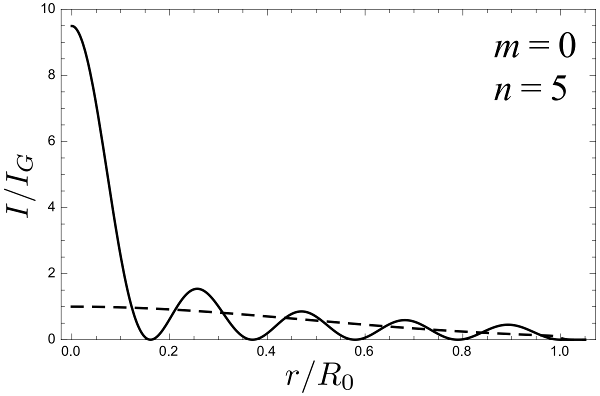
- For both beams to have equivalent RMS radius: $\frac{W_0^2}{2} - \frac{R_0^2\exp(-2R_0^2/W_0^2)}{1-\exp(-2R_0^2/W_0^2)} = \langle r^2\rangle_{mn}$
- For apertured Gaussian with intensity I_G to have equivalent power:

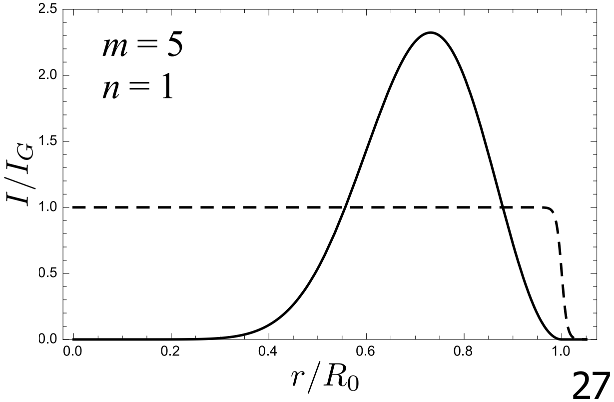
$$\frac{I_G}{I_B} = \frac{2R_0^2}{W_0^2}\frac{J_{m-1}^2(j_{mn})}{1-\exp(-2R_0^2/W_0^2)}$$



Figures show intensity profiles of Bessel beams (solid curves) and apertured Gaussian beams (dashed curves) with equivalent RMS spot size and power.





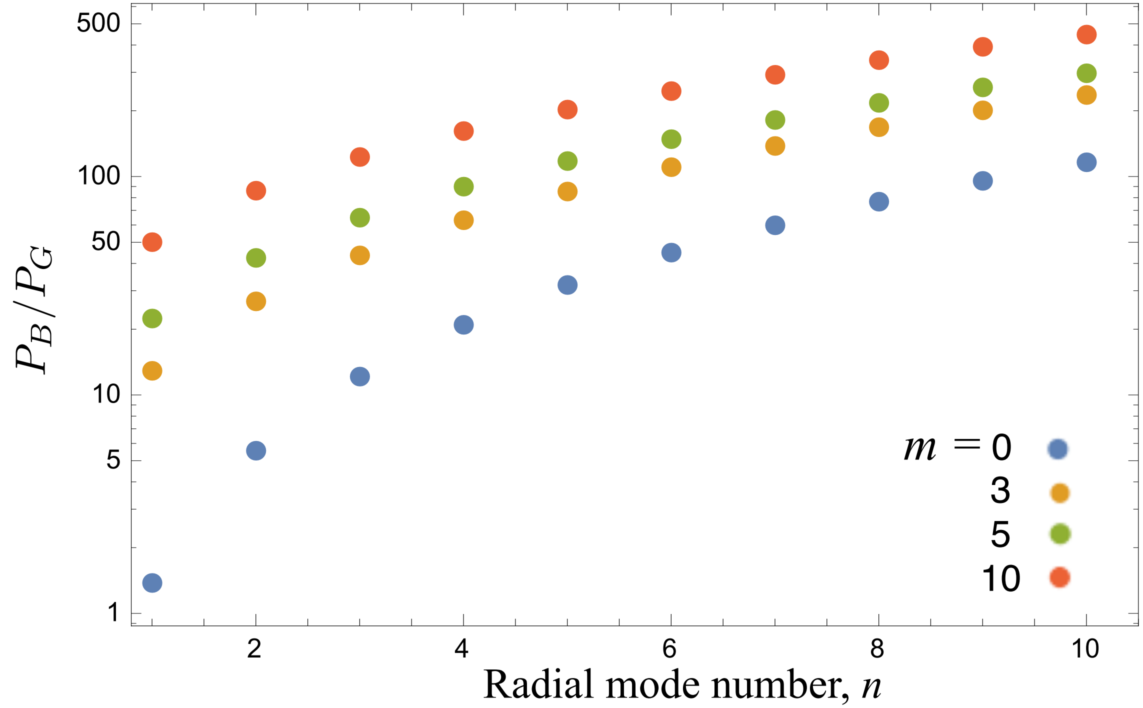


Self-focusing power of Bessel beams with OAM in finite apertures

Self-focusing power (P_B) of a Bessel beam transmitted through an aperture of radius R_0

$$P_B = \frac{P_G}{2} j_{mn}^2 J_{m-1}^2(j_{mn}) \frac{\int_0^{j_{mn}} dx \left[\frac{x}{4} \left(J_{m-1}(x) - J_{m+1}(x) \right)^2 + \frac{m^2}{x} J_m^2(x) \right]}{\int_0^{j_{mn}} dx x J_m^4(x)}$$

$P_G = \lambda^2/(2\pi n_0 n_2)$ is the self-focusing power of a Gaussian beam



Bessel beams are very unstable to filamentation

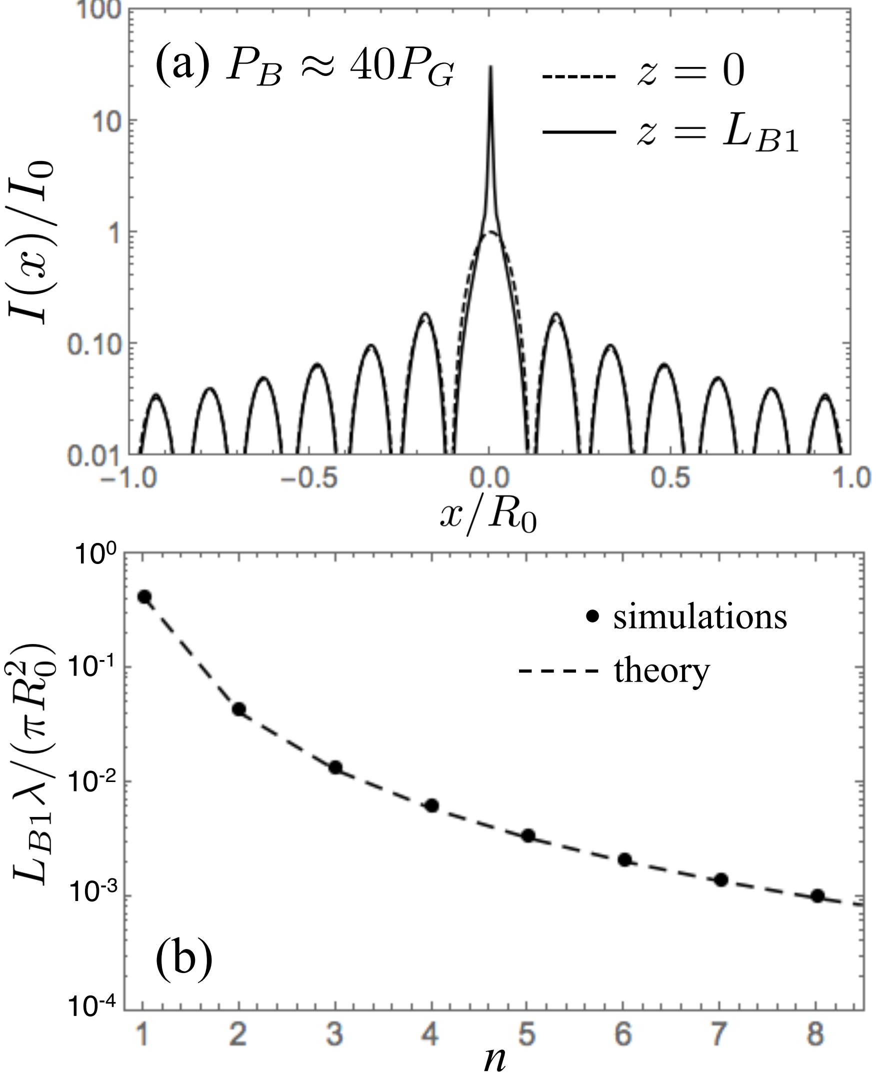
- For Bessel beams at the "critical power", filamentation is governed by smaller-scale filamentation.

- For example, the m=0 mode has a filamentation distance given by:

$$\L_{B1} \approx 0.257(\pi r_1^2/\lambda)/\sqrt{P_{B1}/P_G - 1}$$

which can be much shorter than the Rayleigh length of the whole beam.

Self-focusing of an apertured, high-order Bessel beam at the "critical power"

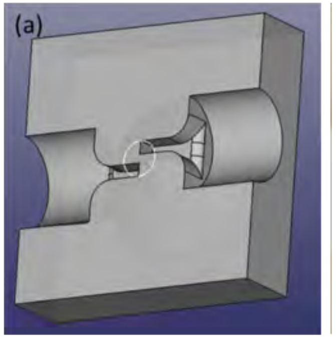


Using a gas lens to create a Bessel beam

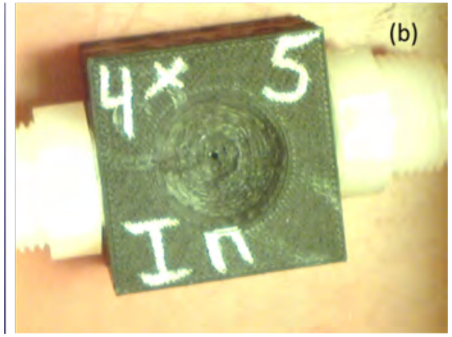
- A gas or plasma can be used to create a radial refractive index variation that can act as a lens with very high damage threshold for high-intensity laser pulses.

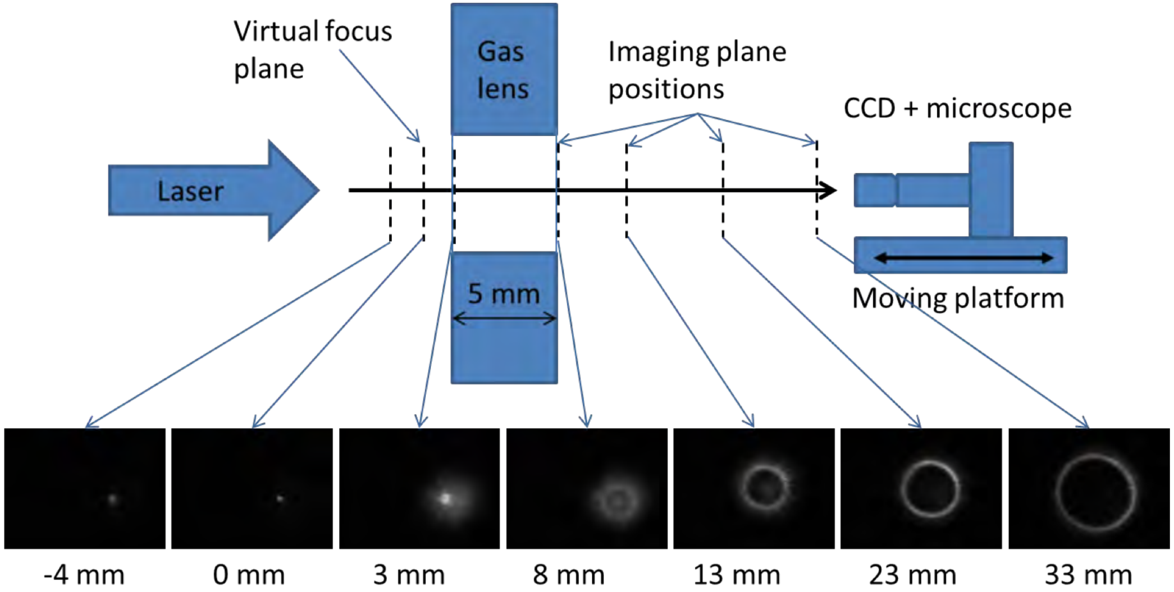
- NRL recently created a vortex flow gas lens that acts as a negative axicon, and can be used in conjunction with a focusing lens to create Bessel beams.

Lens schematic



3D printed lens





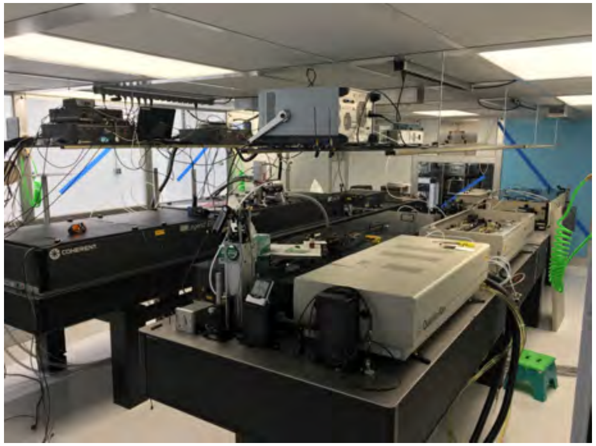
Formation of annular beam
(focuses to a Bessel beam)

NRL's newly-renovated ultrashort pulse laser facility

- 350 sq. ft. ISO 4 cleanroom
- 40TW 5Hz high energy laser
- 0.5TW 1kHz repetition rate laser
- Tunable OPA
  - Currently: 1.1-2.6um
  - 200nm-15um July 2018
- Laser-driven electron and ion accelerators

A unique facility that enables high-precision, pump-probe experiments involving any combination of photons at almost *arbitrary wavelengths* (THz thru X-ray) and high energy particles (electrons and ions)

- Ultrafast laser-matter interactions and propagation
- Novel radiation sources



Summary Remarks

- Nonlinear self-channeling is achieved when the laser pulse power is close to the self-focusing power and the transverse dimensions are smaller than the turbulence coherence scale.

- Experiments demonstrate
  - Self-channeling over many Rayleigh lengths achieved
  - Self-channeling in deep turbulence
  - Self-channeling maintained over distances where temporal spreading (GVD) becomes important
  - quantitative validation of simulations

- Future work to include propagation of partially coherent, intense beams in atmospheric turbulence

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Refereed Publications

J. Peñano et al. “Self-Channeling of High-Power Laser Pulses Through Strong Atmospheric Turbulence,” Phys. Rev. A **96**, 013829 (2017).

G. DiComo et al. "Implementation of a long range, distributed-volume, continuously variable turbulence generator," Applied Optics 55, 5192 (2016).

J. Palastro et al. "Reciprocity breaking during nonlinear propagation of adapted beams through random media," Optics Express 24, 18817 (2016).

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W. Nelson, J.P. Palastro et al. ”Using an incoherent target-return to adaptively focus through atmospheric turbuelnce," Optics Letters 41, 1301 (2016).

B. Hafizi, J. Peñano, J.P. Palastro, R.P. Fischer, and G. DiComo, “Laser beam self-focusing in turbulent dissipative media,” Optics Letters 42, 298 (2017).