Thomson Scattering from Nonlinear Electron Plasma Waves

A. DAVIES,[1] J. KATZ,[1] S. BUCHT,[1] D. HABERBERGER,[1] J. BROMAGE,[1] J. D. ZUEGEL,[1]
J. D. SADLER,[2] P. A. NORREYS,[3] R. BINGHAM,[4] R. TRINES,[5] L.O. SILVA,[6] and D. H. FROULA[1]

[1]University of Rochester, Laboratory for Laser Energetics,
[2]University of Oxford, Clarendon Laboratory; [3]Central Laser Facility Appleton Laboratory,
[4]University of Strathclyde; [5]Rutherford Appleton Laboratory; [6]Instituto Superior Tecnico

Summary

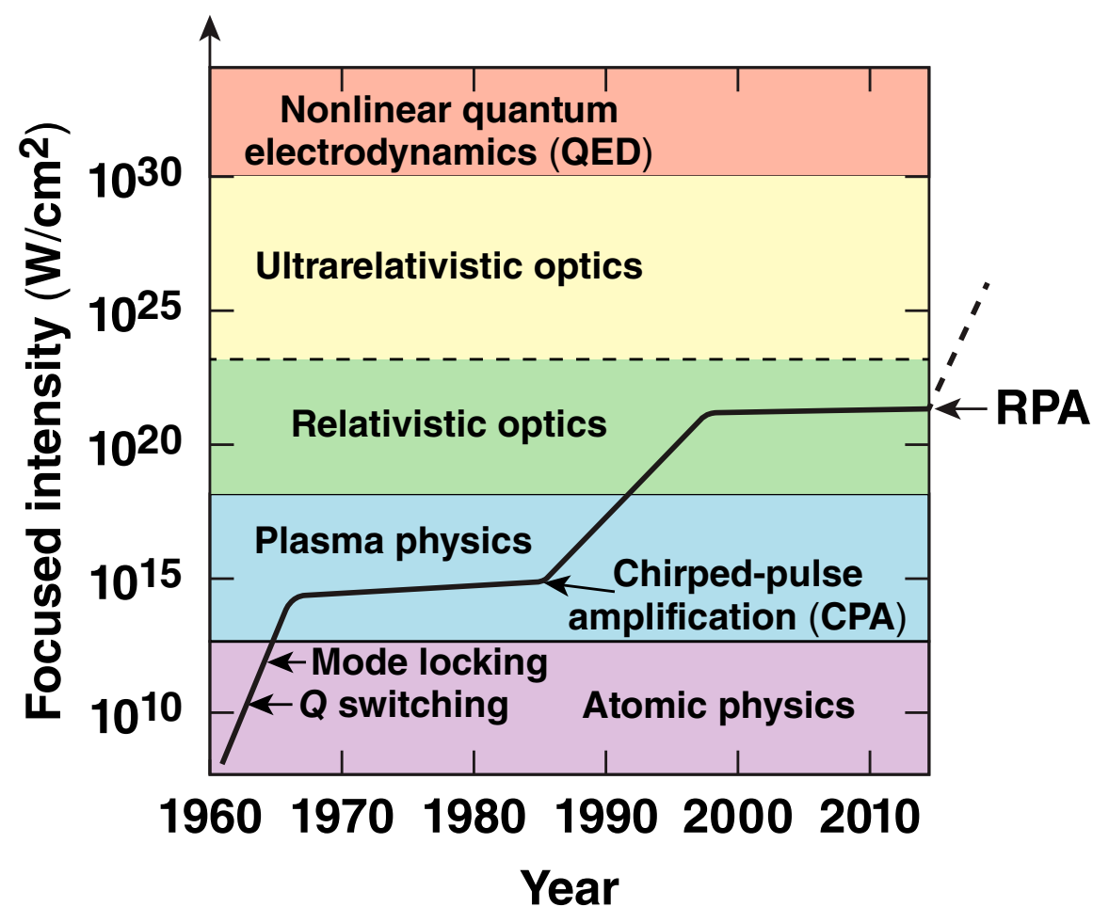
A time-resolved Thomson-scattering diagnostic is being built to measure the amplitude and frequency of nonlinear electron plasma waves in a Raman plasma amplifier

- Raman amplification has the potential to surpass current laser power limitations
- An experimental system is currently being constructed and characterized to conduct a pre-eminent Raman amplification experiment
- Efficient Raman amplification coincides with the presence of large-amplitude electron plasma waves (EPW's) that will be detected with a time-resolved Thomson-scattering diagnostic

Motivation

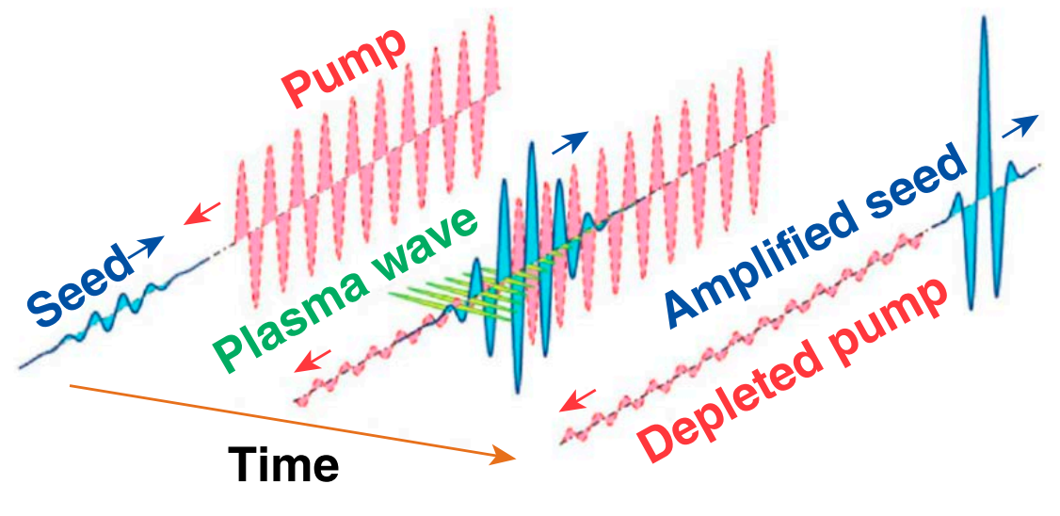
The next generation of high-intensity lasers requires a paradigm shift in technology

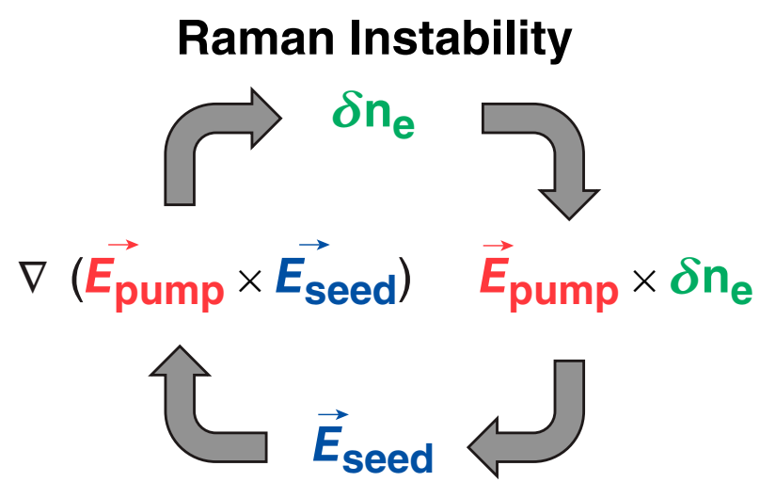
- Present-day petawatt-class lasers are limited by the grating-damage threshold
  - broadband gratings: fluence limit ~0.1 J/cm^2
- Plasma amplifiers have the potential to reach higher peak powers by avoiding the damage-threshold obstacle
  - plasma fluence limit: ~1000 J/cm^2 (assuming a 10-fs pulse)



RPA: Raman plasma amplifier

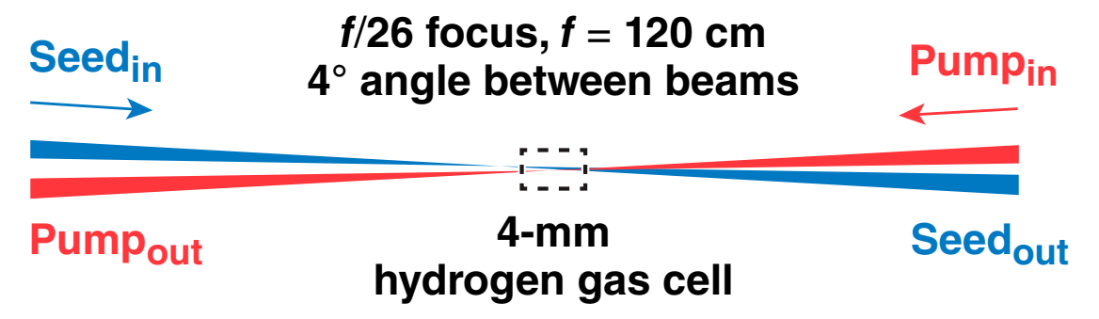
A plasma amplifier works by transferring energy from a long (tens of ps) energetic pump pulse into a short (tens of fs) counter-propagating seed pulse





$$\vec{k}_{pump} = \vec{k}_{seed} + \vec{k}_p \qquad \omega_{pump} = \omega_{seed} + \omega_p$$

Raman amplification at the Laboratory for Laser Energetics will utilize existing laser systems to provide the pump and seed



Pump

Multi-Terawatt (MTW) Laser System
Energy = 50 J
Δt = 25 ps
Radius = ~300 μm
Intensity = 10^{15} W/cm^2
λ_{pump} = 1053 nm

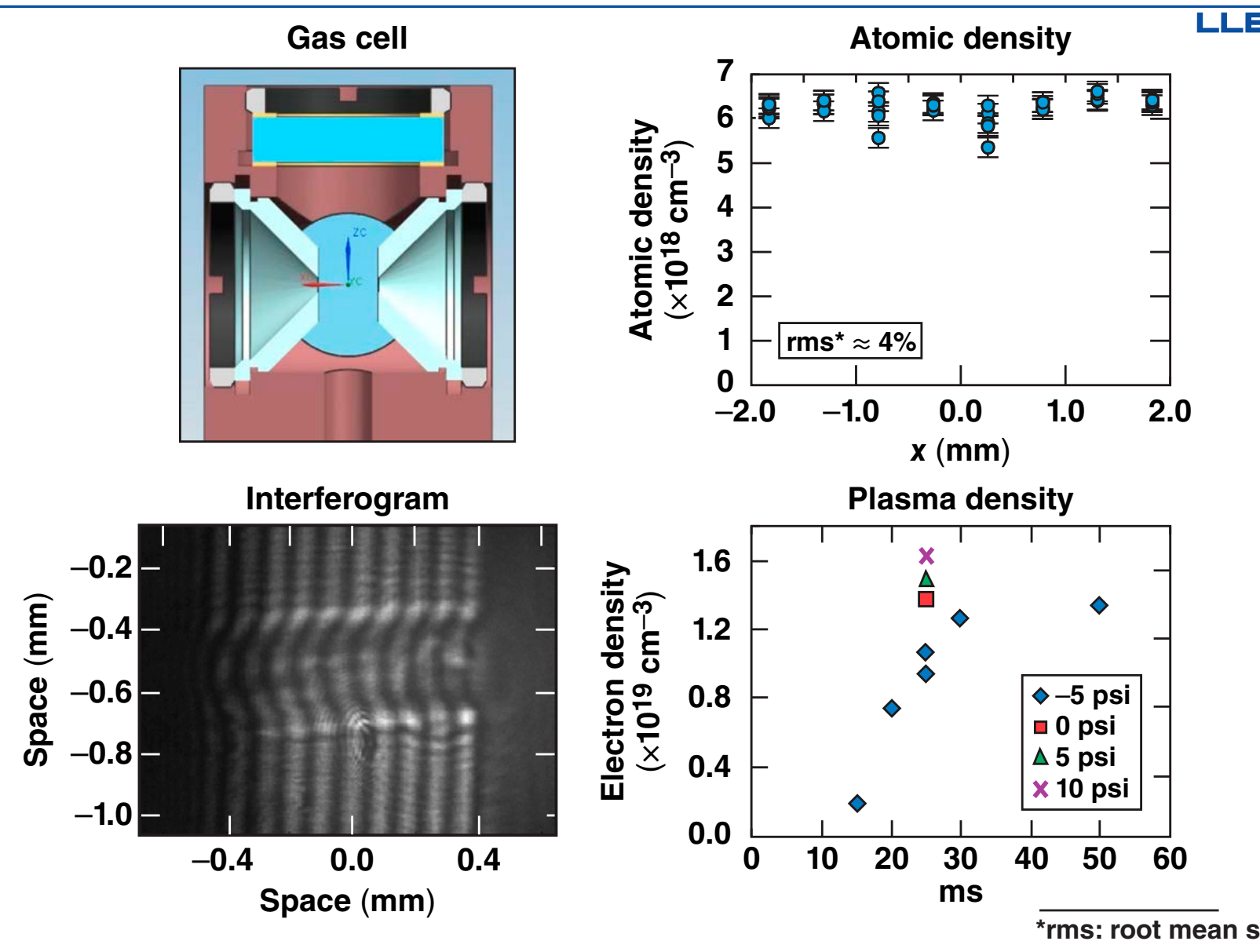
Seed

Optical parametric amplifier line (OPAL)
Energy = 50 mJ
Δt = 50 fs
Radius = ~300 μm
Intensity = 10^{14} W/cm^2
λ_{seed} = 1100 to 1300 nm

Unique conditions

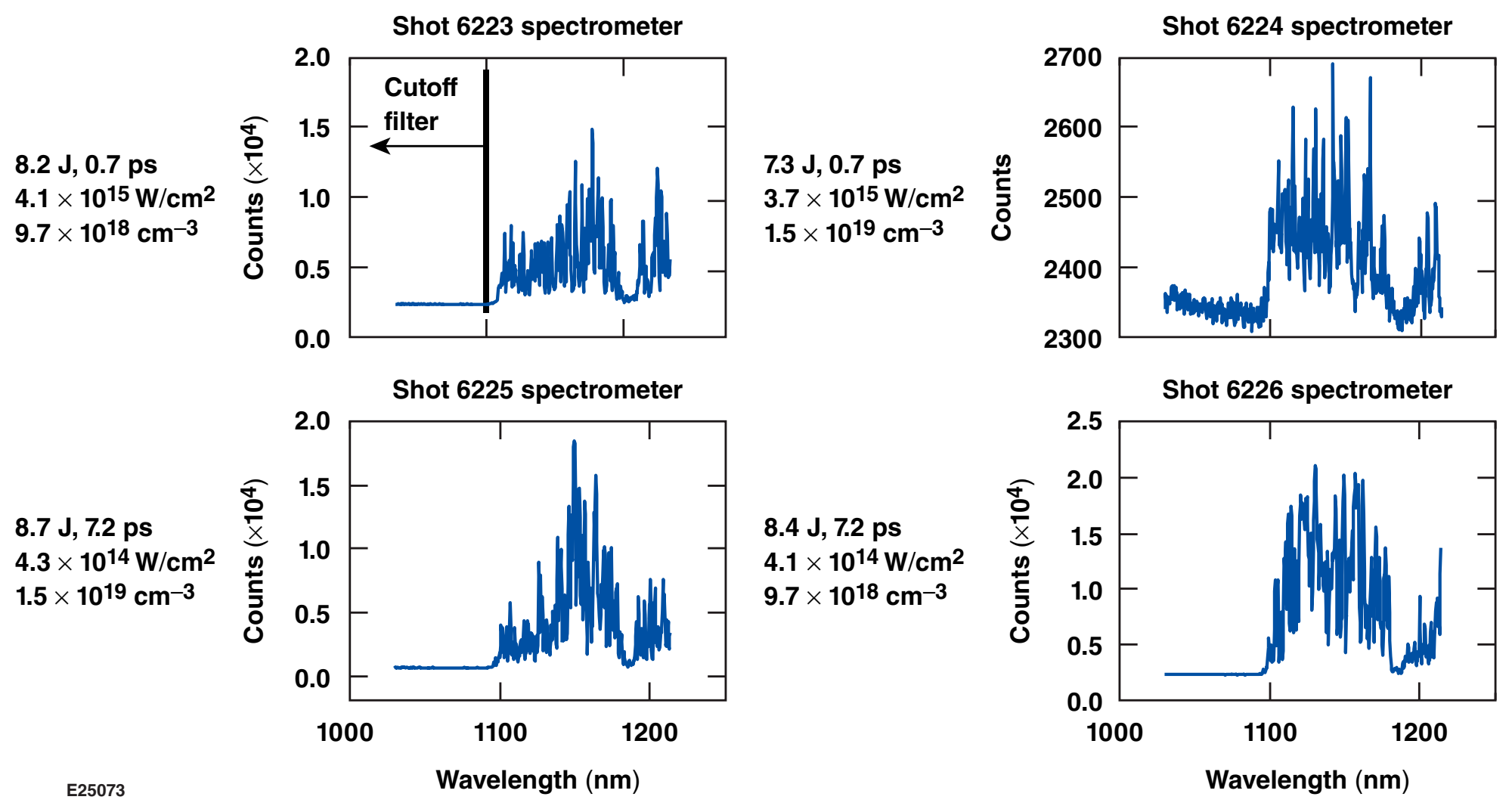
- Gas cell
  - long homogeneous plasma density
- High energy
  - practical energies for PW laser system
- High-intensity seed
  - quickly enter pump-depletion stage

To create a long homogenous plasma target, a gas cell target has been constructed and characterized using interferometry



*rms: root mean square

During diagnostics activation, four backscatter spectra were measured at focus (80-μm spot), which showed broad-bandwidth Raman backscatter



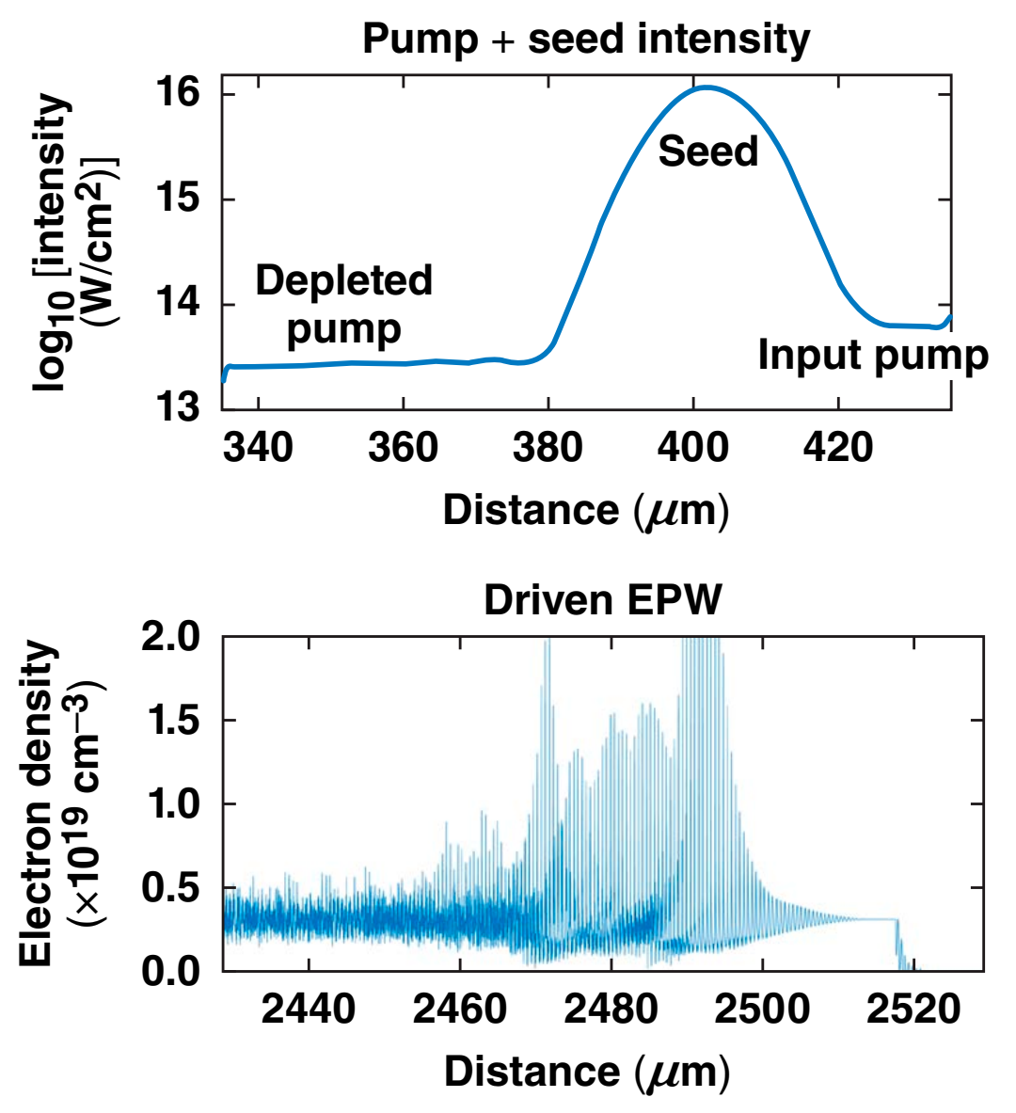
Shot 6223: 8.2 J, 0.7 ps; 4.1×10^{15} W/cm^2; 9.7×10^{18} cm^{-3}

Shot 6224: 7.3 J, 0.7 ps; 3.7×10^{15} W/cm^2; 1.5×10^{19} cm^{-3}

Shot 6225: 8.7 J, 7.2 ps; 4.3×10^{14} W/cm^2; 1.5×10^{19} cm^{-3}

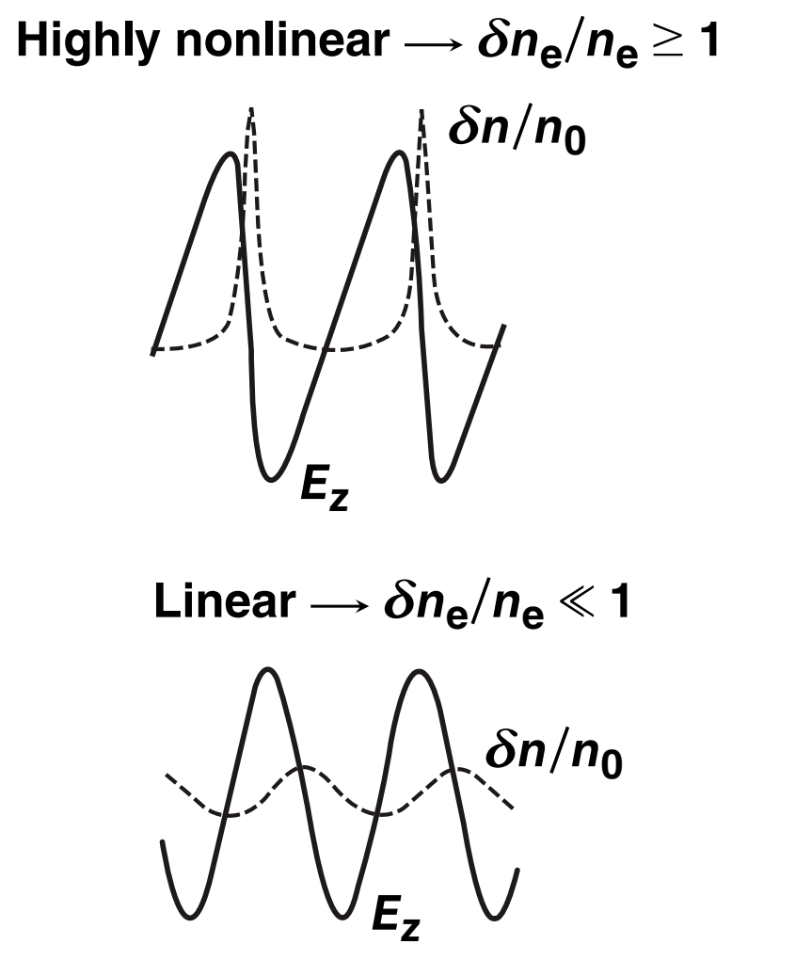
Shot 6226: 8.4 J, 7.2 ps; 4.1×10^{14} W/cm^2; 9.7×10^{18} cm^{-3}

Particle-in-cell simulations predict 40% pump depletion and a nonlinear EPW



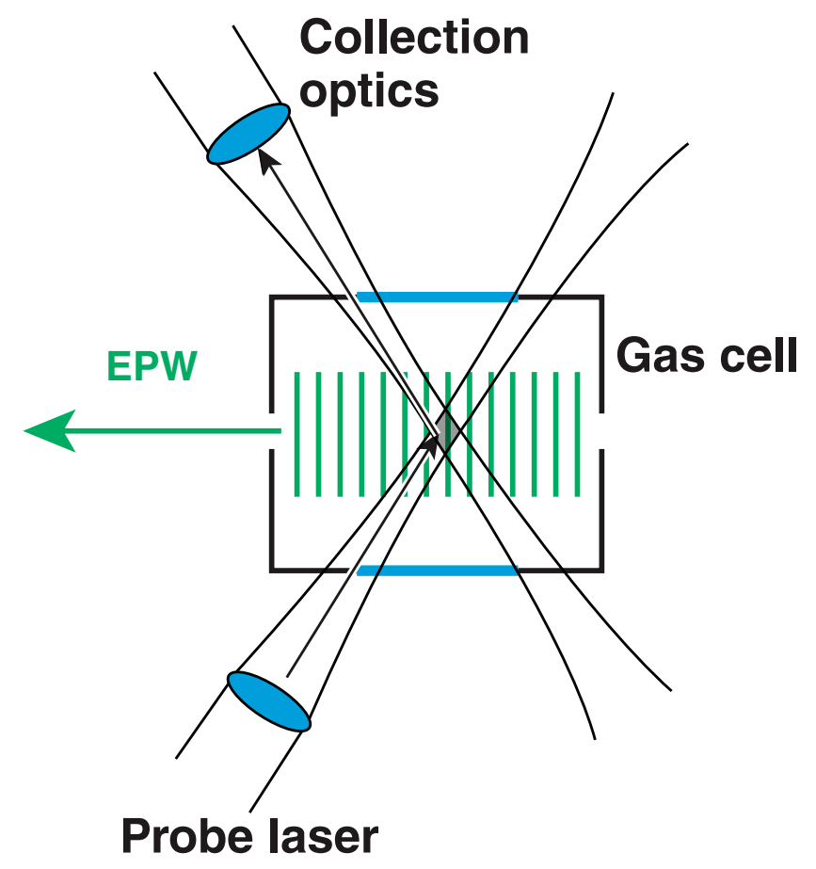
Large-amplitude EPW's are required for efficient Raman amplification; however, there is limited experimental knowledge of nonlinear EPW dynamics

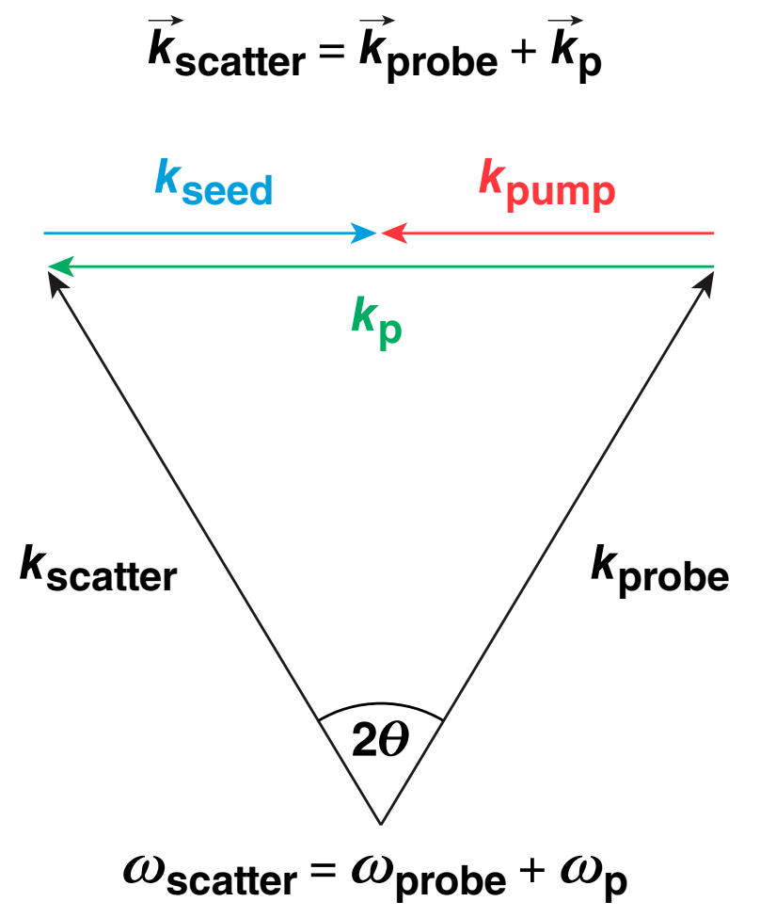
- Large-amplitude waves exhibit nonlinear behavior as δn_e approaches n_e
- Nonlinearity causes impulsive plasma densities, triangular electric fields, and enhanced wave amplitudes
- Nonlinear Landau damping causes amplitude oscillations and frequency shifts
- Highly nonlinear plasma waves break
- All of these nonlinear effects alter the Raman amplification scattering efficiency



P. Sprangle *et al*., Phys. Rev. Lett. 41, 4463 (1990).

A Thomson-scattering diagnostic will be used to study the plasma temperature, nonlinear plasma waves, and the driven wave in a Raman plasma amplifier



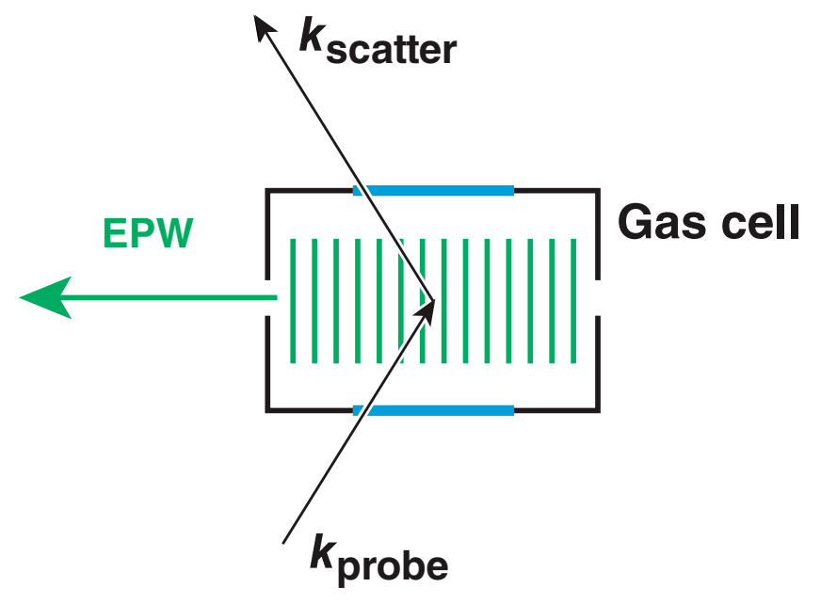


$$\vec{k}_{scatter} = \vec{k}_{probe} + \vec{k}_p$$

$$\omega_{scatter} = \omega_{probe} + \omega_p$$

Thomson scattering will spatially and temporally resolve the driven EPW's frequency and amplitude

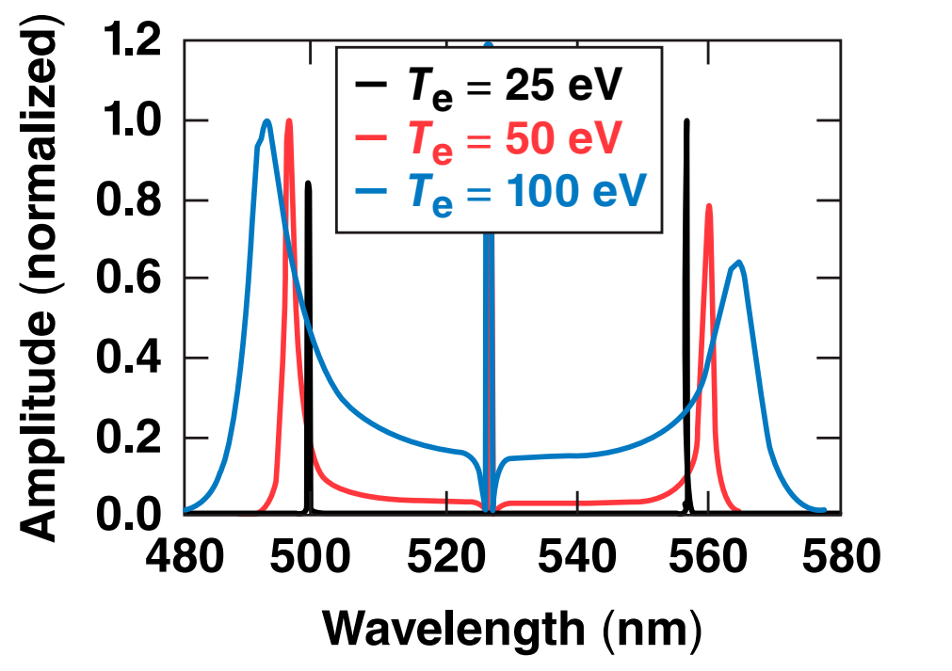
Dynamic Thomson scattering



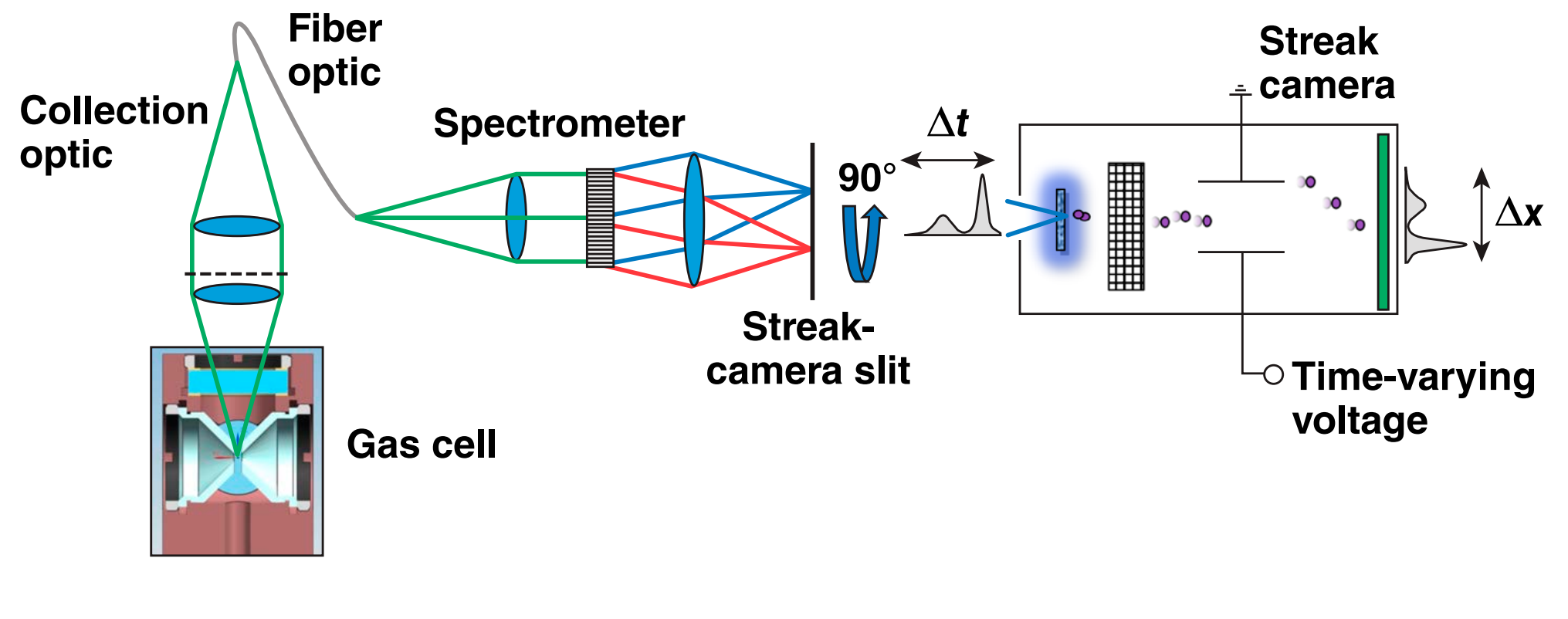
$$\eta = \sin \frac{\pi L_p \frac{\Delta n_e}{2n_c}}{\sqrt{\lambda_{probe}\lambda_{scatter}} \cos\theta}$$

Thermal Thomson scattering

$n_e = 1 \times 10^{19}$ cm^{-3}, θ_s = 123.34°, z = 1



The Thomson-scattering diagnostic utilizes a novel streaked optical spectrometer that achieves 1-ps time resolution by correcting the pulse-front tilt

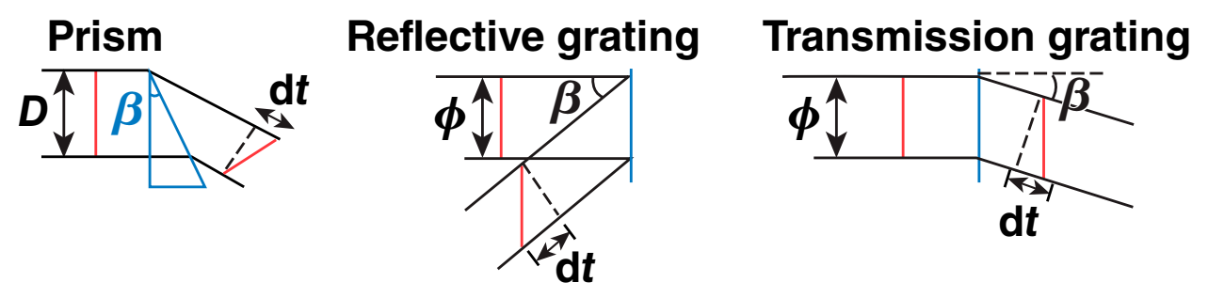


The pulse-front tilt is corrected with an echelon optic that archives the streak camera's maximum 1-ps time resolution

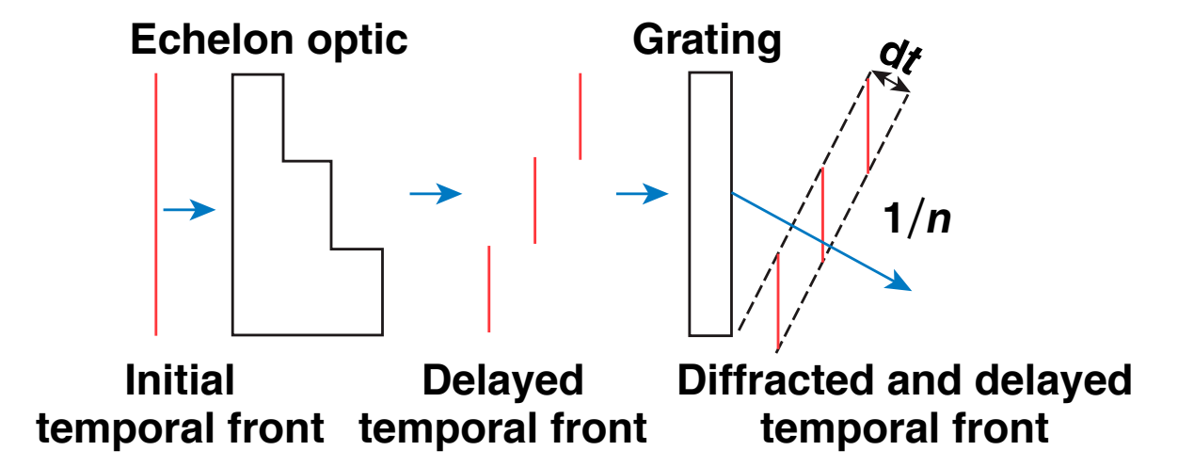
$$dt = \frac{Nm\lambda}{c} = \frac{\phi\lambda\cos\beta}{c}\frac{d\beta}{d\lambda}$$

$$dt_{corrected} = \frac{dt}{n}$$

Pulse-front tilt from a dispersive optic



Pulse-front-tilt correction



dt = pulse-front tilt
N = number of grooves illuminated
m = diffraction order
$\frac{dB}{d\lambda}$ = angular dispersion

J. Katz RSI (2016) to be published

Summary

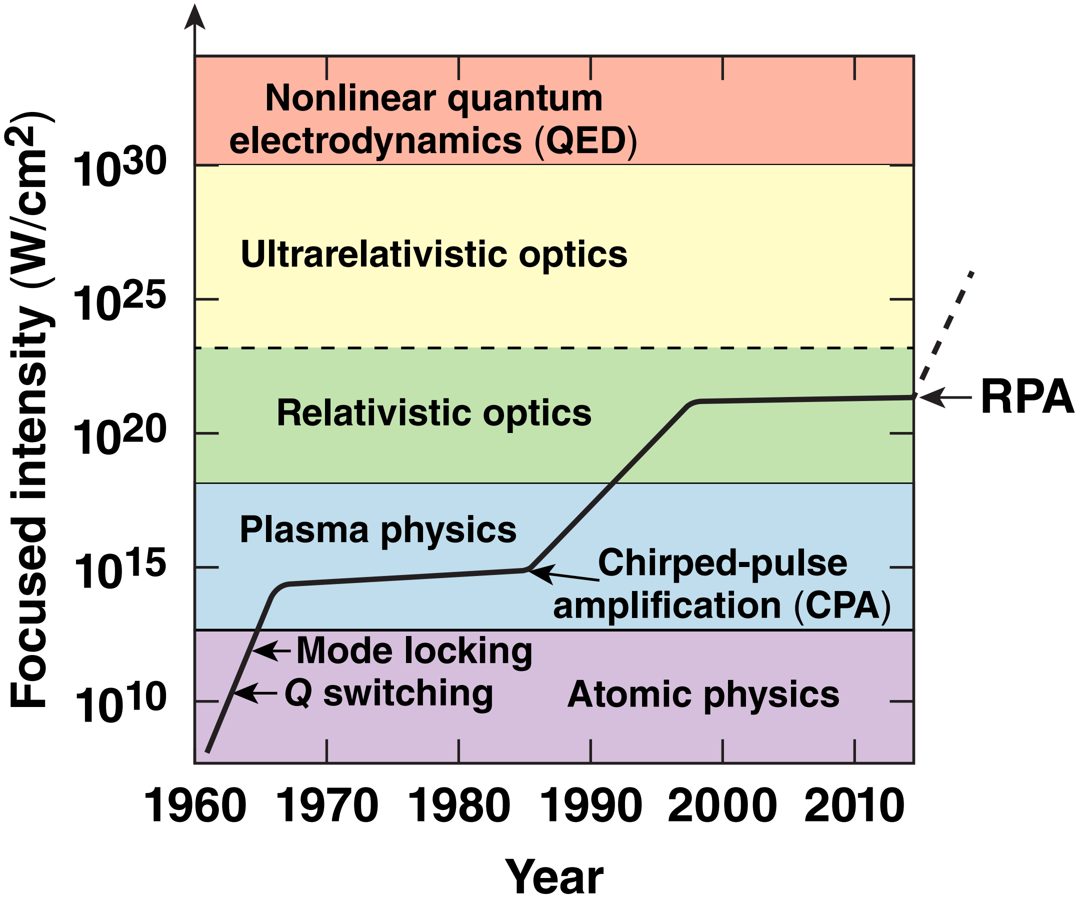
A time-resolved Thomson-scattering diagnostic is being built to measure the amplitude and frequency of nonlinear electron plasma waves in a Raman plasma amplifier

- Raman amplification has the potential to surpass current laser power limitations
- An experimental system is currently being constructed and characterized to conduct a pre-eminent Raman amplification experiment
- Efficient Raman amplification coincides with the presence of large-amplitude electron plasma waves (EPW's) that will be detected with a time-resolved Thomson-scattering diagnostic

Motivation

The next generation of high-intensity lasers requires a paradigm shift in technology

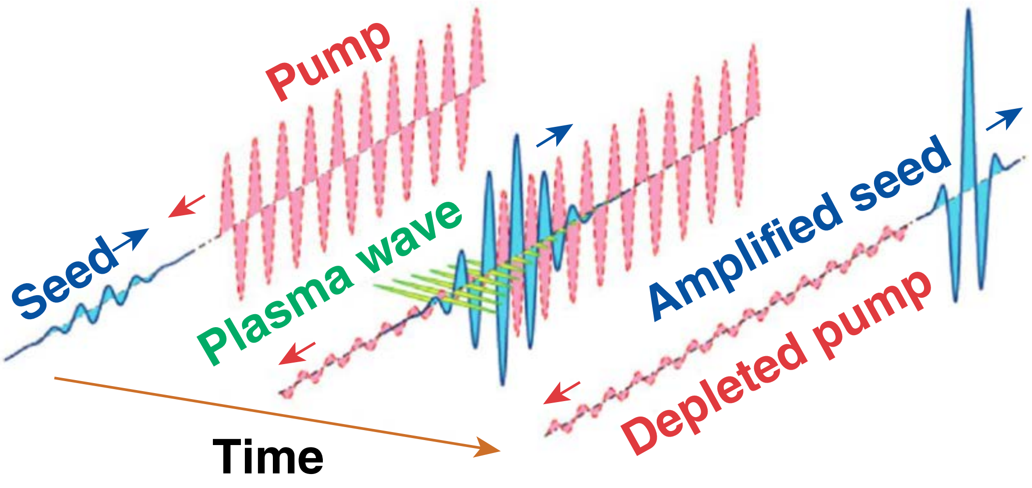
- Present-day petawatt-class lasers are limited by the grating-damage threshold
  - broadband gratings: fluence limit ~0.1 J/cm^2
- Plasma amplifiers have the potential to reach higher peak powers by avoiding the damage-threshold obstacle
  - plasma fluence limit: ~1000 J/cm^2 (assuming a 10-fs pulse)



RPA: Raman plasma amplifier

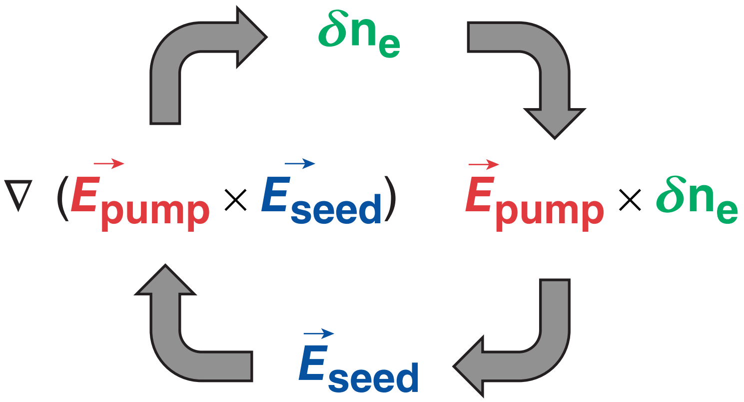
E24634a

A plasma amplifier works by transferring energy from a long (tens of ps) energetic pump pulse into a short (tens of fs) counter-propagating seed pulse



$$\vec{k}_{\text{pump}} = \vec{k}_{\text{seed}} + \vec{k}_{\text{p}}$$

Raman Instability



δn_e

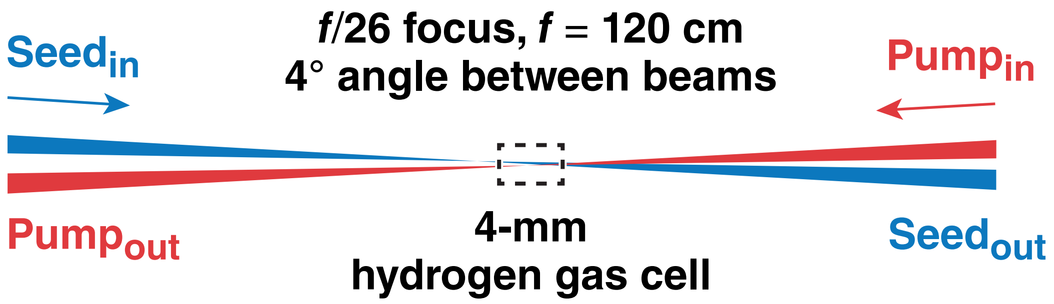
$\nabla\,(\vec{E}_{\text{pump}} \times \vec{E}_{\text{seed}})$

$\vec{E}_{\text{pump}} \times \delta n_e$

$\vec{E}_{\text{seed}}$

$$\omega_{\text{pump}} = \omega_{\text{seed}} + \omega_{\text{p}}$$

Raman amplification at the Laboratory for Laser Energetics will utilize existing laser systems to provide the pump and seed



Pump

Multi-Terawatt (MTW)
Laser System
Energy = 50 J
Δt = 25 ps
Radius = ~300 μm
Intensity = 10^{15} W/cm^2
λ_{pump} = 1053 nm

Seed

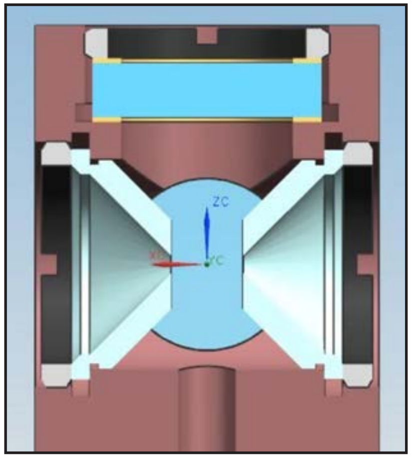
Optical parametric
amplifier line (OPAL)
Energy = 50 mJ
Δt = 50 fs
Radius = ~300 μm
Intensity = 10^{14} W/cm^2
λ_{seed} = 1100 to 1300 nm

Unique conditions

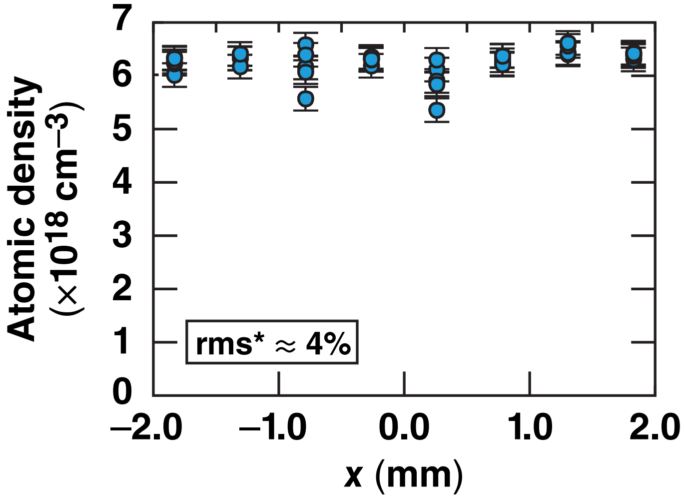
- Gas cell
  - long homogeneous plasma density
- High energy
  - practical energies for PW laser system
- High-intensity seed
  - quickly enter pump-depletion stage

To create a long homogenous plasma target, a gas cell target has been constructed and characterized using interferometry

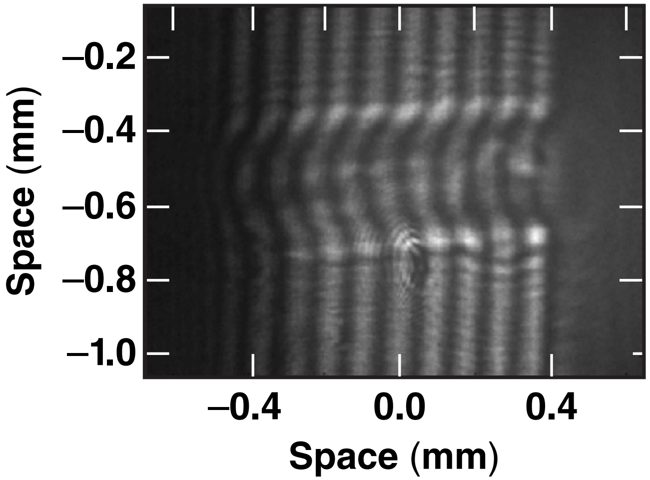
Gas cell



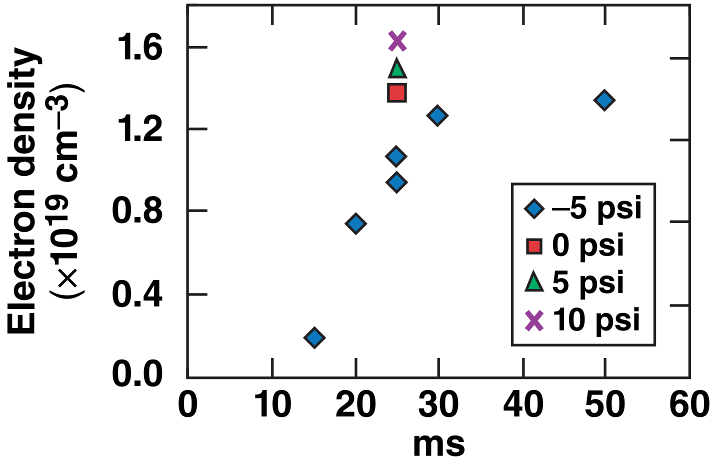
Atomic density



Interferogram



Plasma density

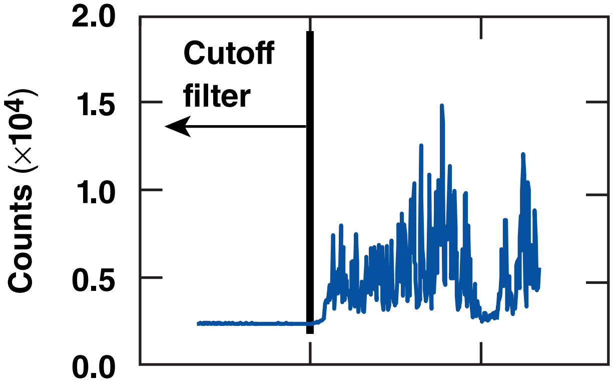


---

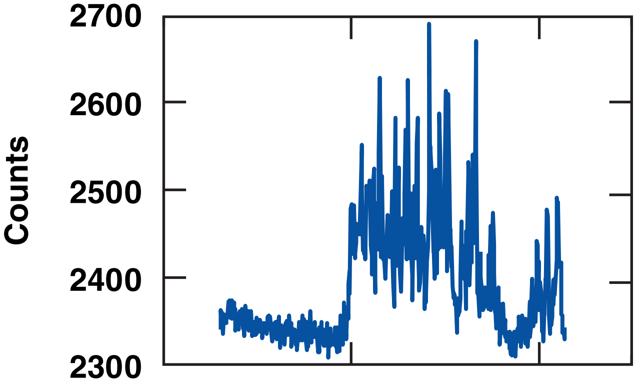
*rms: root mean square

During diagnostics activation, four backscatter spectra were measured at focus (80-μm spot), which showed broad-bandwidth Raman backscatter

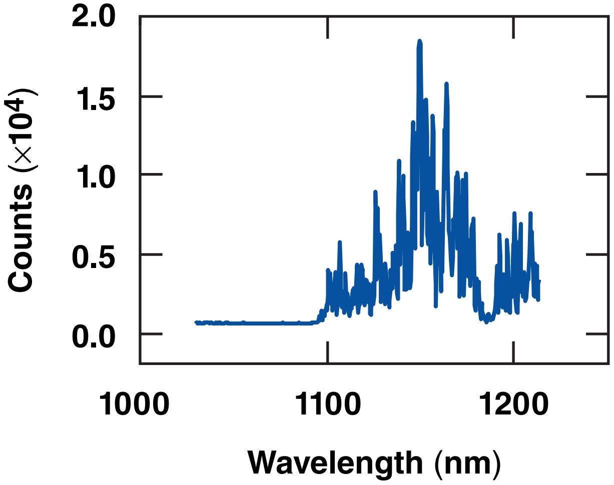
8.2 J, 0.7 ps
4.1×10^{15} W/cm^2
9.7×10^{18} cm^{-3}


Shot 6223 spectrometer

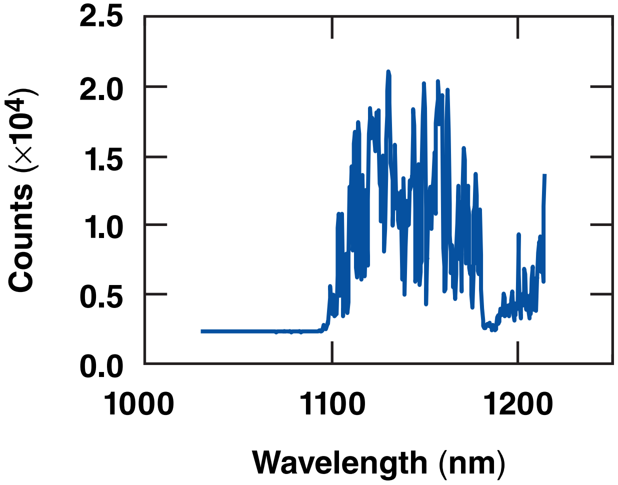
7.3 J, 0.7 ps
3.7×10^{15} W/cm^2
1.5×10^{19} cm^{-3}


Shot 6224 spectrometer

8.7 J, 7.2 ps
4.3×10^{14} W/cm^2
1.5×10^{19} cm^{-3}

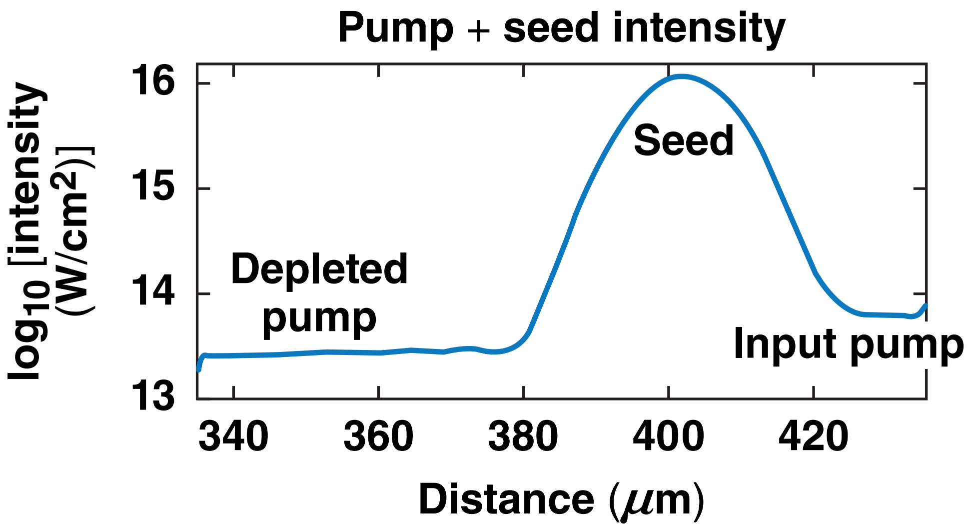

Shot 6225 spectrometer

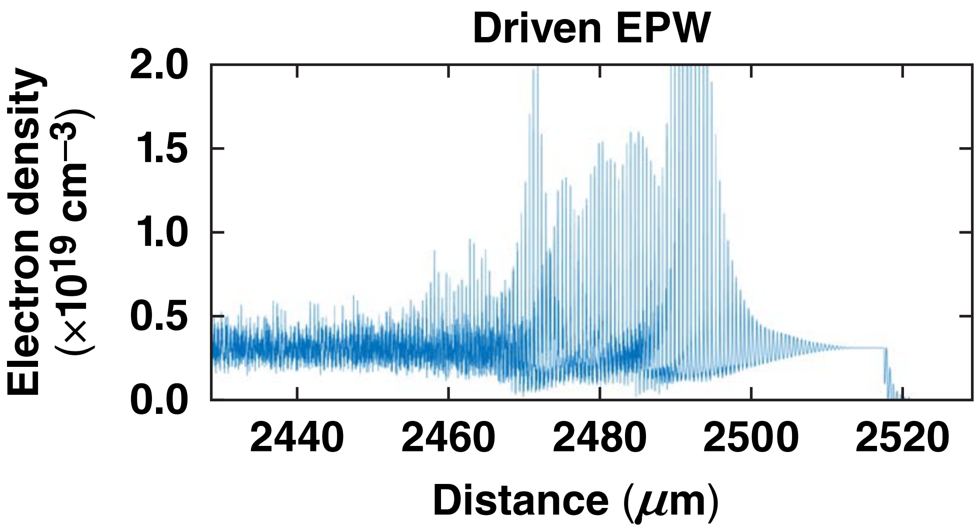
8.4 J, 7.2 ps
4.1×10^{14} W/cm^2
9.7×10^{18} cm^{-3}


Shot 6226 spectrometer

E25073

Particle-in-cell simulations predict 40% pump depletion and a nonlinear EPW

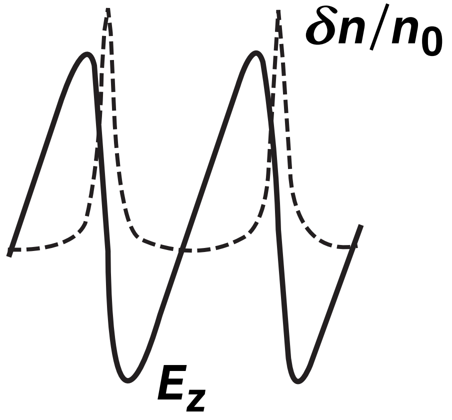




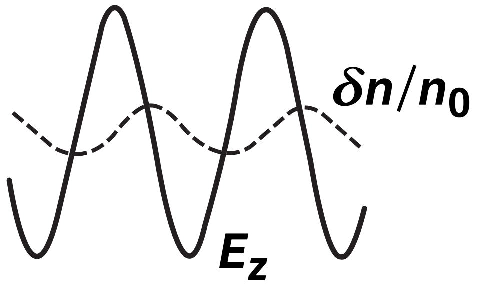
Large-amplitude EPW's are required for efficient Raman amplification; however, there is limited experimental knowledge of nonlinear EPW dynamics

- **Large-amplitude waves exhibit nonlinear behavior as δn_e approaches n_e**
- **Nonlinearity causes impulsive plasma densities, triangular electric fields, and enhanced wave amplitudes**
- **Nonlinear Landau damping causes amplitude oscillations and frequency shifts**
- **Highly nonlinear plasma waves break**
- **All of these nonlinear effects alter the Raman amplification scattering efficiency**

Highly nonlinear $\longrightarrow \delta n_e/n_e \geq 1$

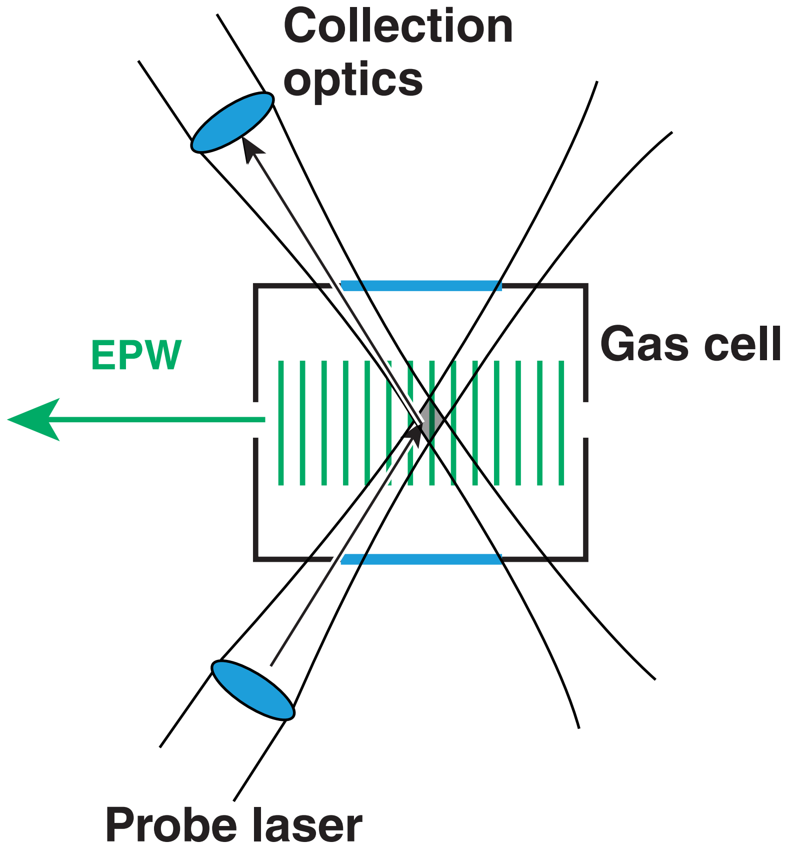


Linear $\longrightarrow \delta n_e/n_e \ll 1$

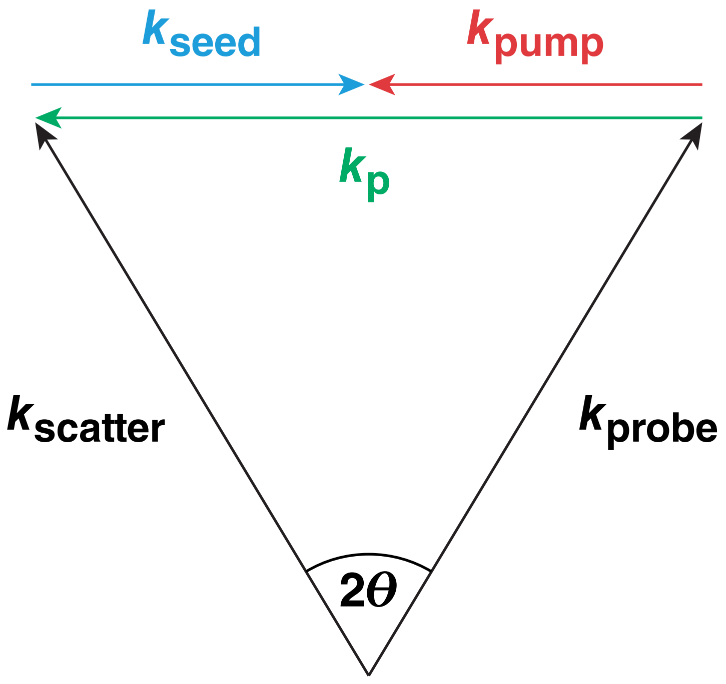


P. Sprangle *et al*., Phys. Rev. Lett. <u>41</u>, 4463 (1990).

A Thomson-scattering diagnostic will be used to study the plasma temperature, nonlinear plasma waves, and the driven wave in a Raman plasma amplifier



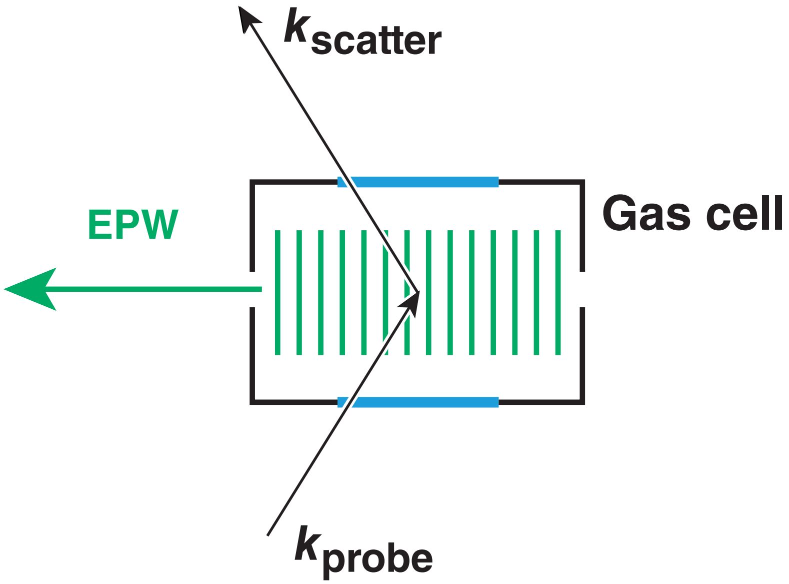
$$\vec{k}_{\text{scatter}} = \vec{k}_{\text{probe}} + \vec{k}_{\text{p}}$$



$$\omega_{\text{scatter}} = \omega_{\text{probe}} + \omega_{\text{p}}$$

Thomson scattering will spatially and temporally resolve the driven EPW's frequency and amplitude

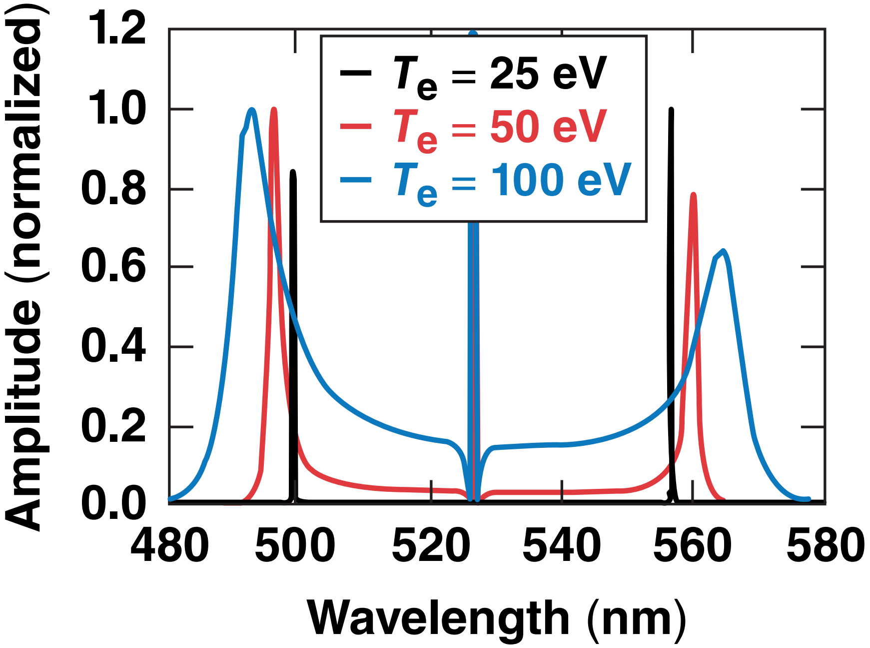
Dynamic Thomson scattering



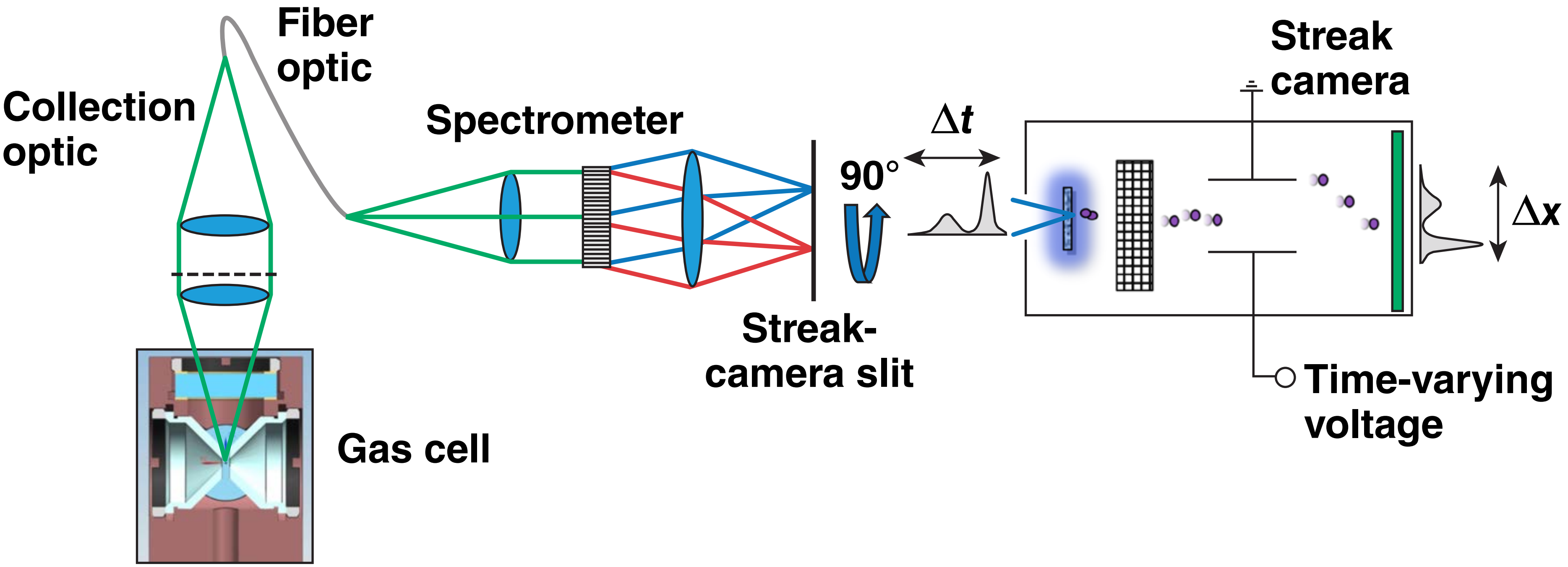
$$\eta = \sin \frac{\pi L_p \dfrac{\Delta n_e}{2n_c}}{\sqrt{\lambda_{probe}\lambda_{scatter}}\cos\theta}$$

Thermal Thomson scattering

$n_e = 1 \times 10^{19}$ cm^{-3}, $\theta_s = 123.34°$, z = 1



The Thomson-scattering diagnostic utilizes a novel streaked optical spectrometer that achieves 1-ps time resolution by correcting the pulse-front tilt



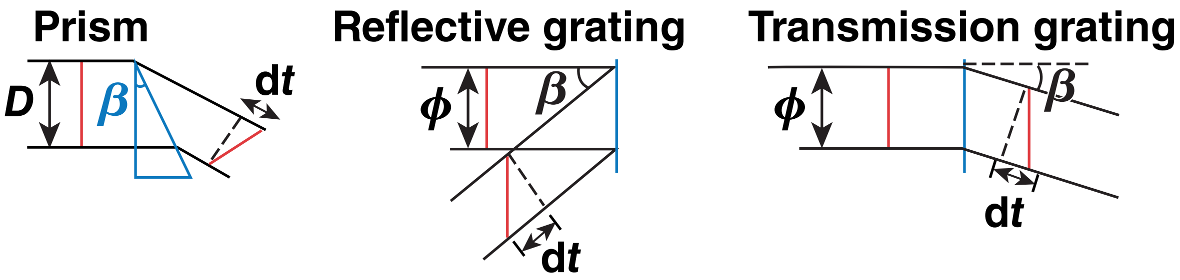
The pulse-front tilt is corrected with an echelon optic that archives the streak camera's maximum 1-ps time resolution

$$dt = \frac{Nm\lambda}{c} = \frac{\phi\lambda\cos\beta}{c}\frac{d\beta}{d\lambda}$$

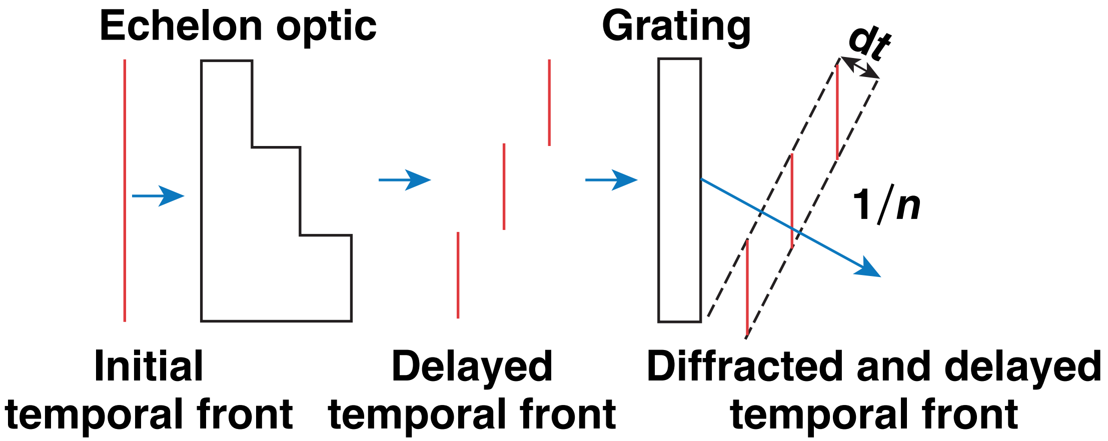
$$dt_{corrected} = \frac{dt}{n}$$

dt = pulse-front tilt
N = number of grooves illuminated
m = diffraction order
$\frac{dB}{d\lambda}$ = angular dispersion

Pulse-front tilt from a dispersive optic



Pulse-front-tilt correction



J. Katz RSI (2016) to be published