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Observation of amplification of a 1ps pulse by SRS of a 1 ns pulse in a plasma with conditions relevant to pulse compression

R. K. Kirkwood, E. Dewald, S. C. Wilks, N. Meezan, C. Niemann, R. L. Berger, O. L. Landen, J. Wurtele, A. E. Charman, R. Lindberg, N. J. Fisch, V. M. Malkin

June 2, 2006

36th Anomalous Absorption Conference
Jackson Hole, WY, United States
June 4, 2006 through June 9, 2006

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Updated October 14, 2003

Observation of amplification of a 1ps pulse by SRS of a 1 ns pulse in a plasma with conditions relevant to pulse compression

NIF

The National Ignition Facility

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This work is performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

Introduction

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The compression of a laser pulse by amplification of an ultra short pulse beam Which seeds the stimulated Raman scatter of the first beam has been long been discussed in the context of solid and gas media.

We investigate the possibility of using intersecting beams in a *plasma* to compress nanosecond pulses to picosecond duration by scattering from driven electron waves.

Recent theoretical studies have shown the possibility of efficient compression With large amplitude, non-linear Langmuir waves driven either by SRS [1] or non-resonantly [2].

We describe experiments in which a plasma suitable for pulse compression is created , and amplification of an ultra short pulse beam is demonstrated.

[1] V. M. Malkin G. Shvets, and N. J. Fisch, PRL 82, 4448 (1999).
[2] G. Shvets, N. J. Fisch, A. Pukhov, and J. Meyer-ter-Vehn, PRL 81, 4879 (1998).

Two Beams in a Plasma Will Stimulate Plasma Waves That Scatter Energy Between the Beams

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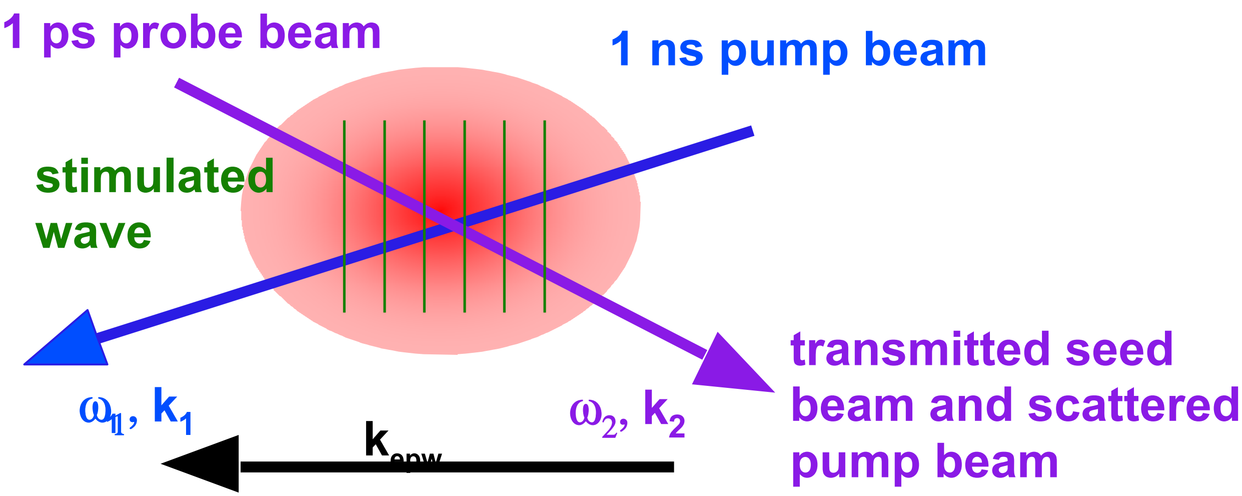

A beat intensity profile is produced by two beams that have spatial and temporal frequency component determined by the difference in the two beams.

$$k_{plasma} = k_1 - k_2$$
$$\omega_{plasma} = \omega_1 - \omega_2$$

With the right plasma conditions the wave is resonant and grows to large amplitude

The plasma wave forms a 3D Bragg cell grating that scatters power from one beam to the other.

If k λ_D is Small A Counter-Propagating Probe Pulse, Amplified by SRS, Can Deplete the Pump in a 15 cm plasma

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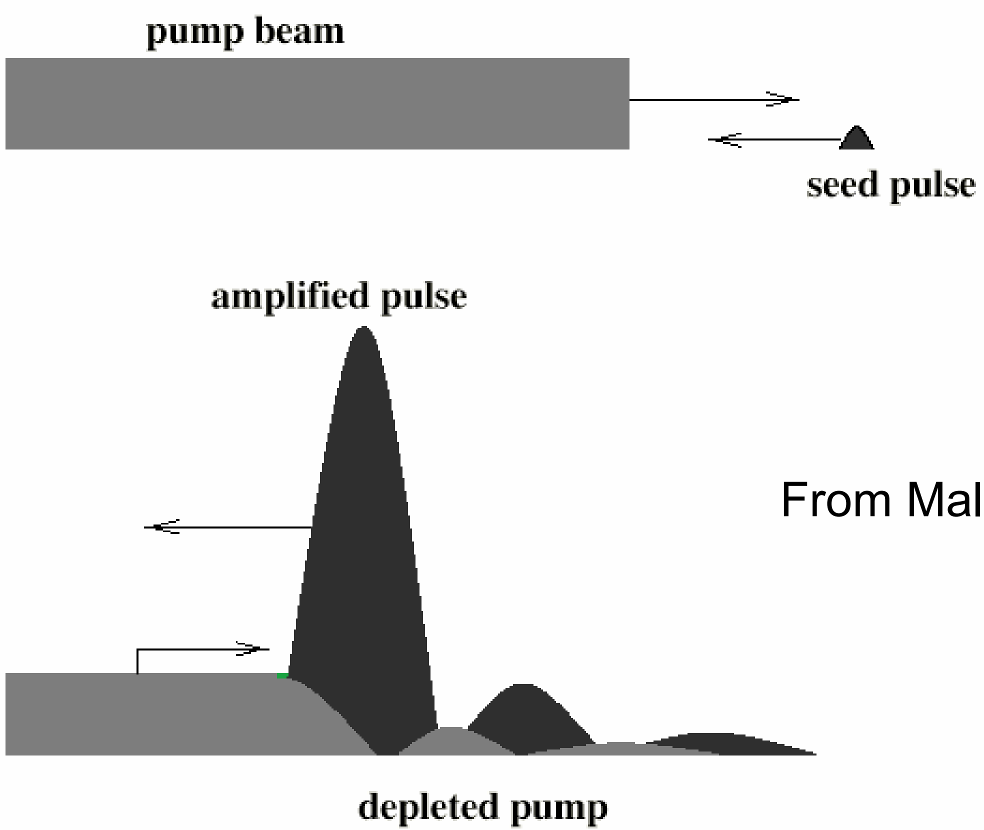
Counter propagating beams allow an ultra short pulse to extract all the energy Of a long pulse beam, causing pulse compression when SRS gain is high.

The interaction distance and plasma size are given by x = (1/2) c $\tau_{\text{long pulse}}$ or ~ 15 cm of plasma per ns of compressed pulse.



From Malkin et. al.

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Critical Issues for Pulse Compression by SRS in a Plasma

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1) The ponderomotive force of the two beams must be able to drive a large enough wave amplitude to scatter nearly 100% of the pump power.

a) The strongly non-linear wave response must be verified by by simulations and proof of principle experiments.
b) The necessary coherence of the scattered light must also be verified by experiments.

2) Desirable plasma properties include:

a) hot enough to *minimize inverse bremsstrahlung* absorption of the beams and the collisional damping of the Langmuir waves.
b) cold and dense enough to *allow weak Landau damping*.

Our Experiment tests 1) under conditions determined by 2)

Optimization of Plasma Conditions for Compressing 1 ns Pulses into 1 ps Pulses with 1 micron Wave Lengths

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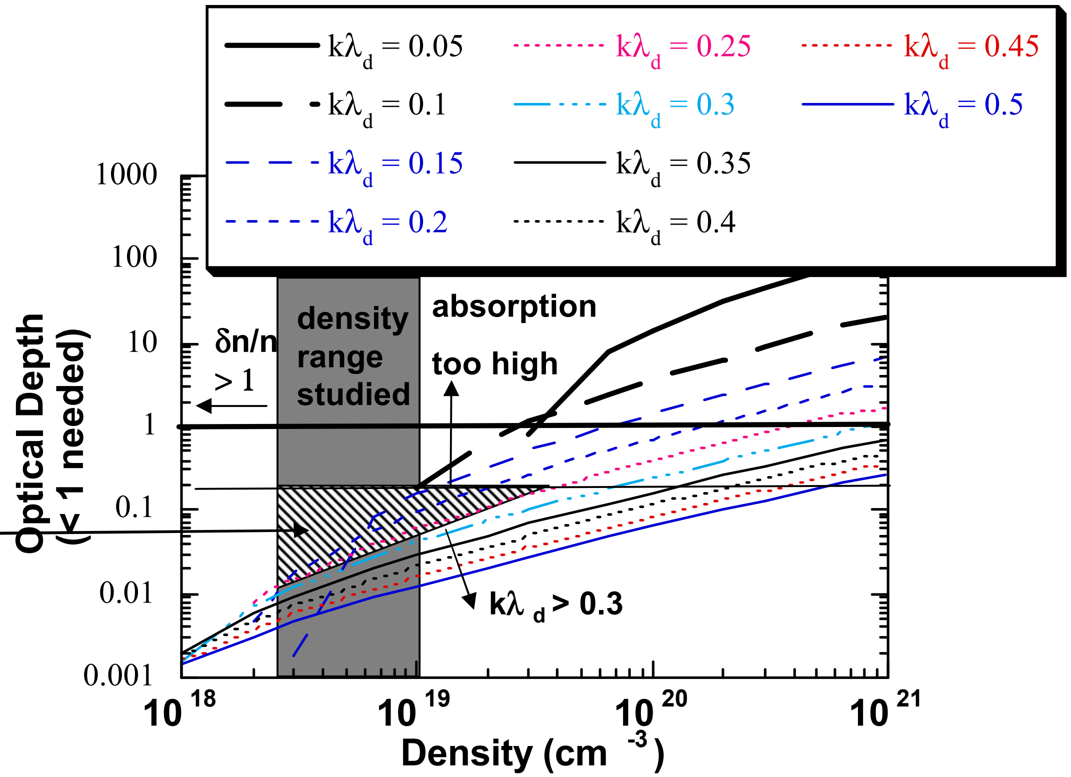
The minimum plasma density fluctuation to scatter 100% of the pump power Into the probe indicates average plasma densities of ≥ ~ 2-3 x 10^{18} are needed.

Langmuir wave growth requires low $k\lambda_D$ while good beam transmission requires low inverse bremstrahlung, which leads to greatest effects at lowest densities.

Our experiments begin with 2.5 x 10^{18} and 1 x 10^{19} cm^{-3} As the resonant density

And produce temperatures In the triangular region of Interest.



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An Single Beam Produces a Uniform Density Plasma, Simulations Confirm Little Time Variation During 1 ns

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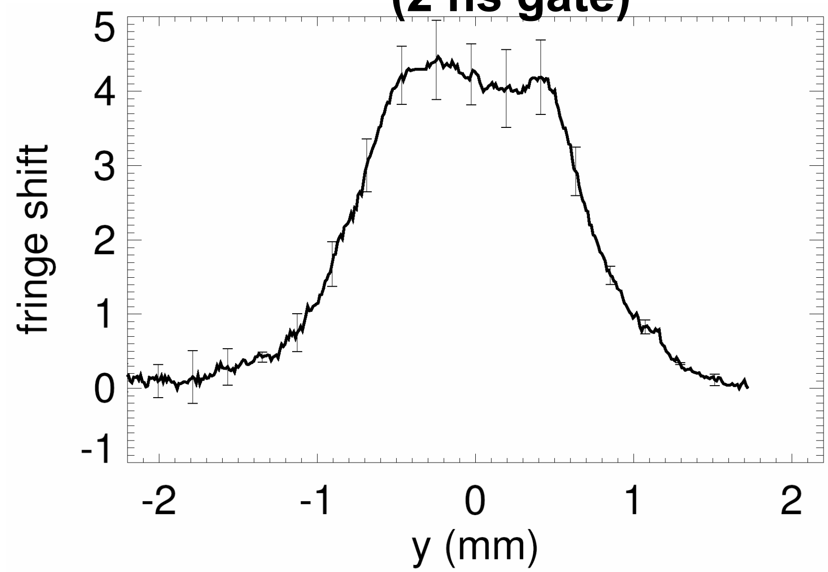
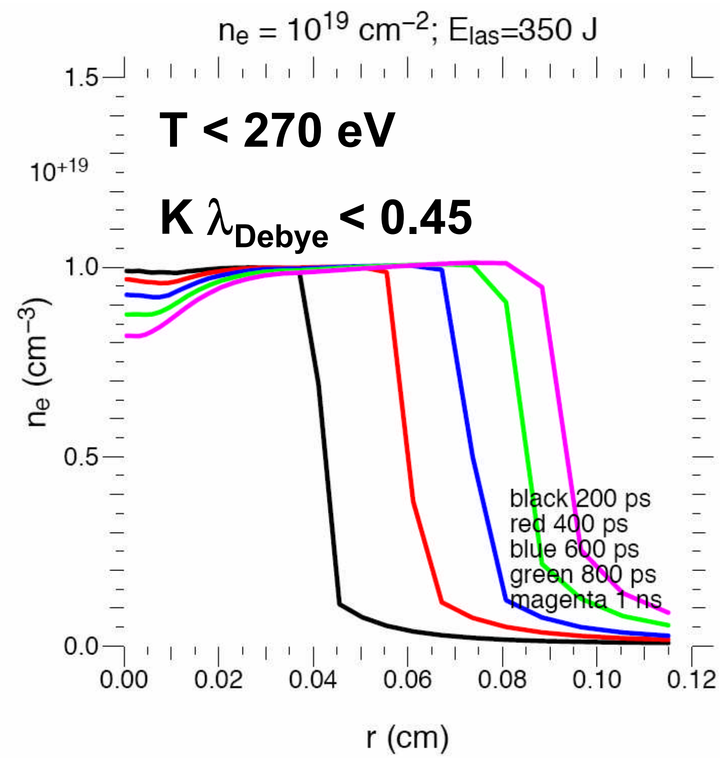
527 nm Interferometer
(2 ns gate)





Interferometric measurements with a single (unsmoothed) beams Have confirmed uniform initial gas and plasma density over the range of parameters.

Hydra simulations of RPP smoothed beam confirm little variation of density plateau during the 1 ns pulse, and low temperatures at 2.5 x $10^{18}/cm^3$ density. (Experiments have shown the simulated temperature may be an overestimate due to a local transport model, Gregori PRL 2004).

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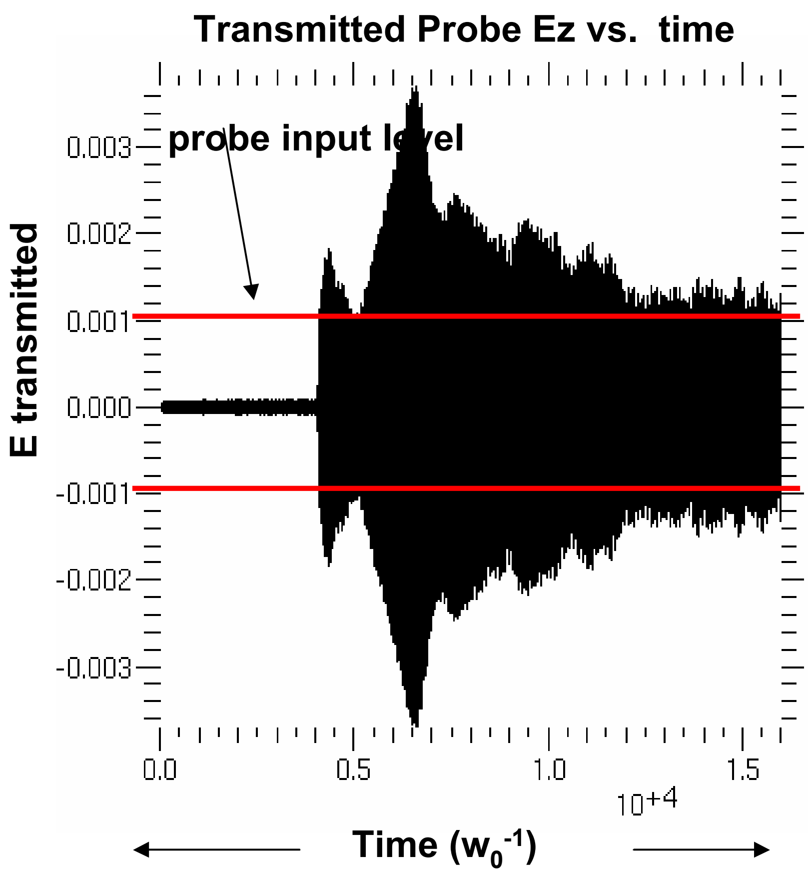
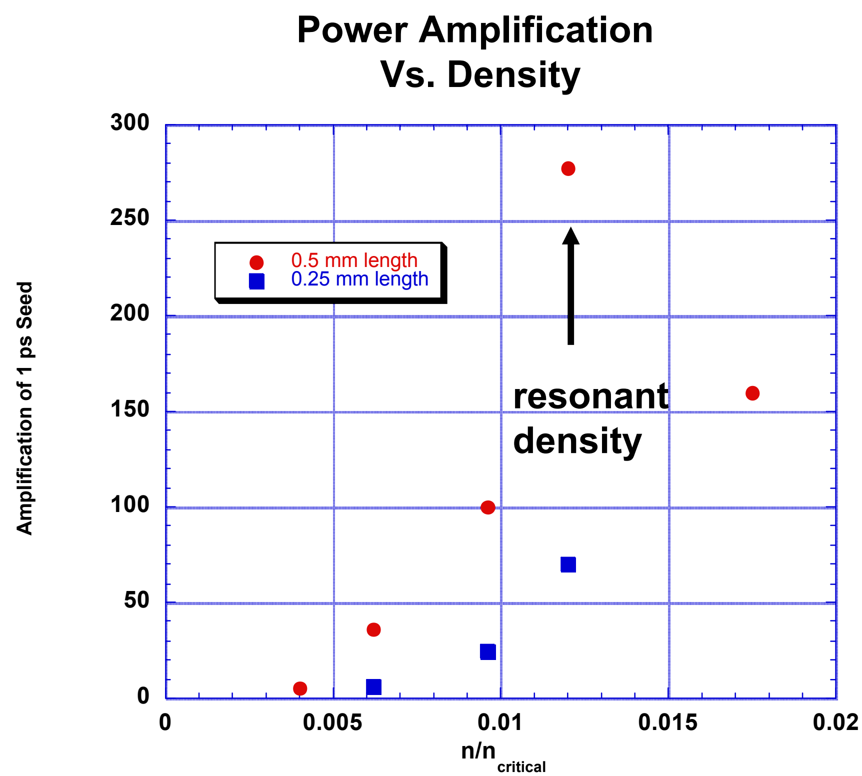
PIC Simulations of Experimental Conditions Show Substantial Amplification Under These Conditions





PIC simulations confirm *significant amplification* of a 1ps pulse under these Conditions, and show the *amplified pulse length ~ 1ps*, and the maximum Amplification is near the *resonant value of density.*

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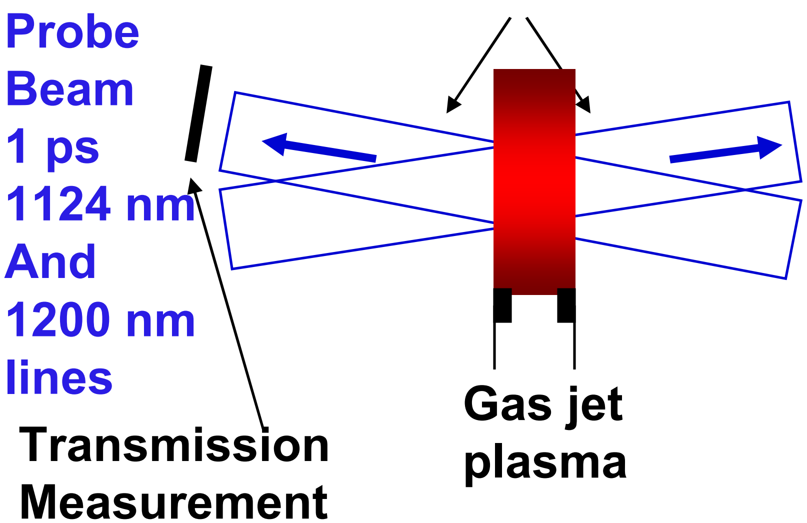
Experiments with Janus/Comet Laser Systems Test USP Pulse Amplification in a Plasma Suitable for 1ns Pulse Compression

- Experiments with Janus/Comet Beams show amplification of the 1ps Comet beam by the 1ns Janus beam.
- A gas jet produces a He plasma about 1-3 mm wide.
- High intensity interaction across the entire plasma could deplete 10-20 ps slice of pump beam and demonstrate pulse compression
- Available intensities (< 1.1 x 10^{15}/cm^{-2}) are well above what is needed if plasma response is linear, so the non-linear response has been studied.



The back scatter geometry has the beams nearly parallel. (beams perpendicular to jet)

The 1ps beam is converted to 1124 nm and 1200 nm by a *H_2 gas Raman Cell*

Maximum energy is Exchanged between beams <u>when density is adjusted to resonant value.</u>

Unseeded (single beam) SRS spectra from Low Density He Plasmas Shows Rapid Increase of Scattering, and the Expected Increase of Wavelength, with Plasma Density (or Gas Pressure)

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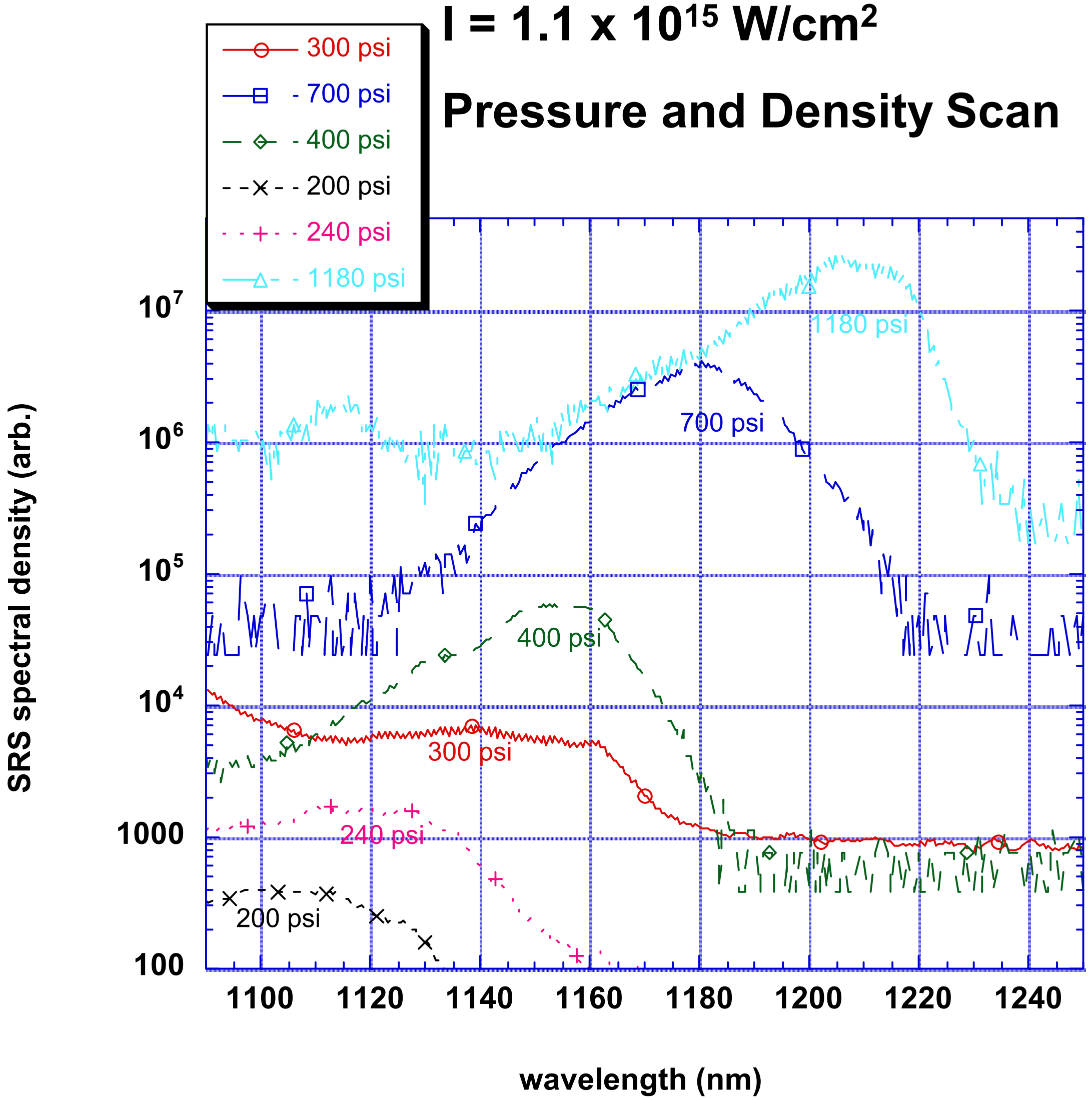
$I = 1.1 \times 10^{15}$ W/cm^2

Pressure and Density Scan



SRS is seen to be Much more intense and At longer wavelength As plasma density is Increased, as expected.

Interferometer measurements show plateau plasma density is consistent with the SRS Spectral peak.

Additional measurements At low beam intensity Show little change in SRS reflectivity, Consistent with strongly Saturated waves.

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Seeding the high density plasma with a 1ps probe pulse at the resonant wavelength of 1200 nm produced a large amplification showing high density is favorable as expected.

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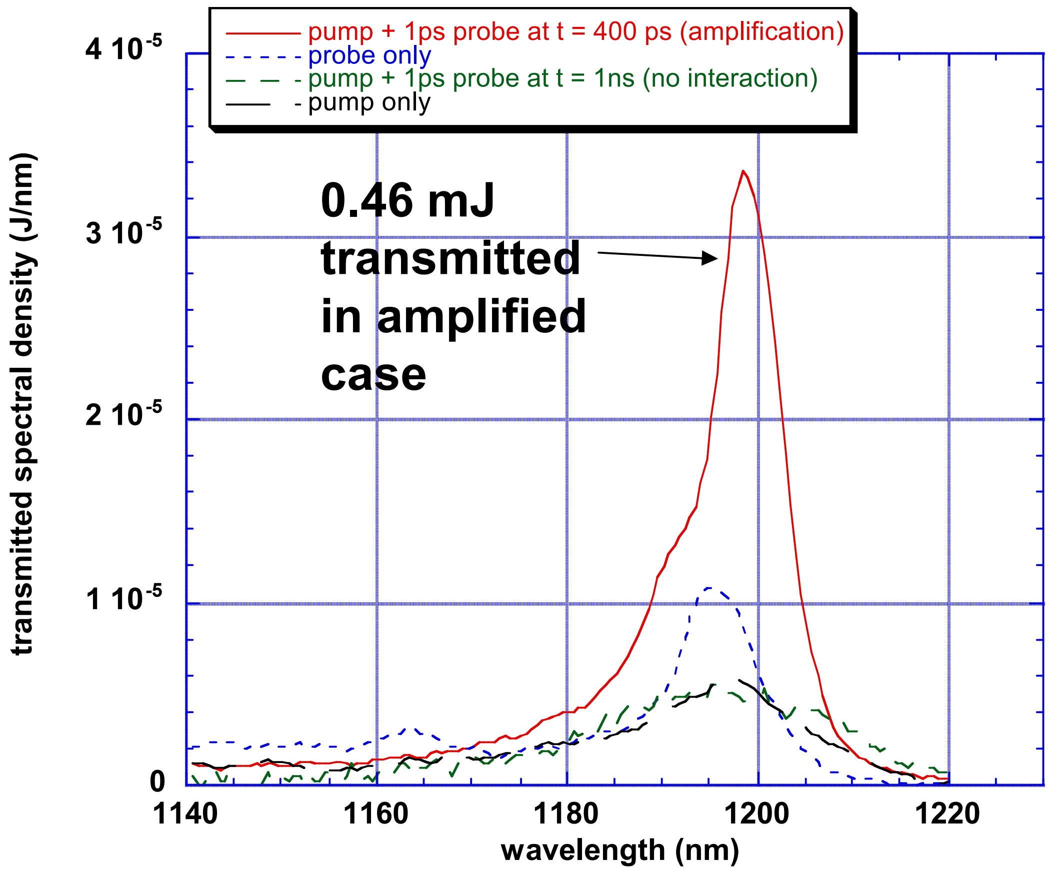
$I_{pump} = 3.5 \times 10^{14}$ W/cm^2 , 115 J
$n_e = 1.0 \times 10^{19}$ cm^{-3}



The observed amplification of the transmission of the seed pulse is consistent with weak damping and saturation of the scattering Langmuir waves at this density.

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Seeding the high density plasma with a 1ps probe pulse at the resonant wavelength of 1200 nm at Increased Intensity produced Higher Amplification showing Scaling with Intensity.

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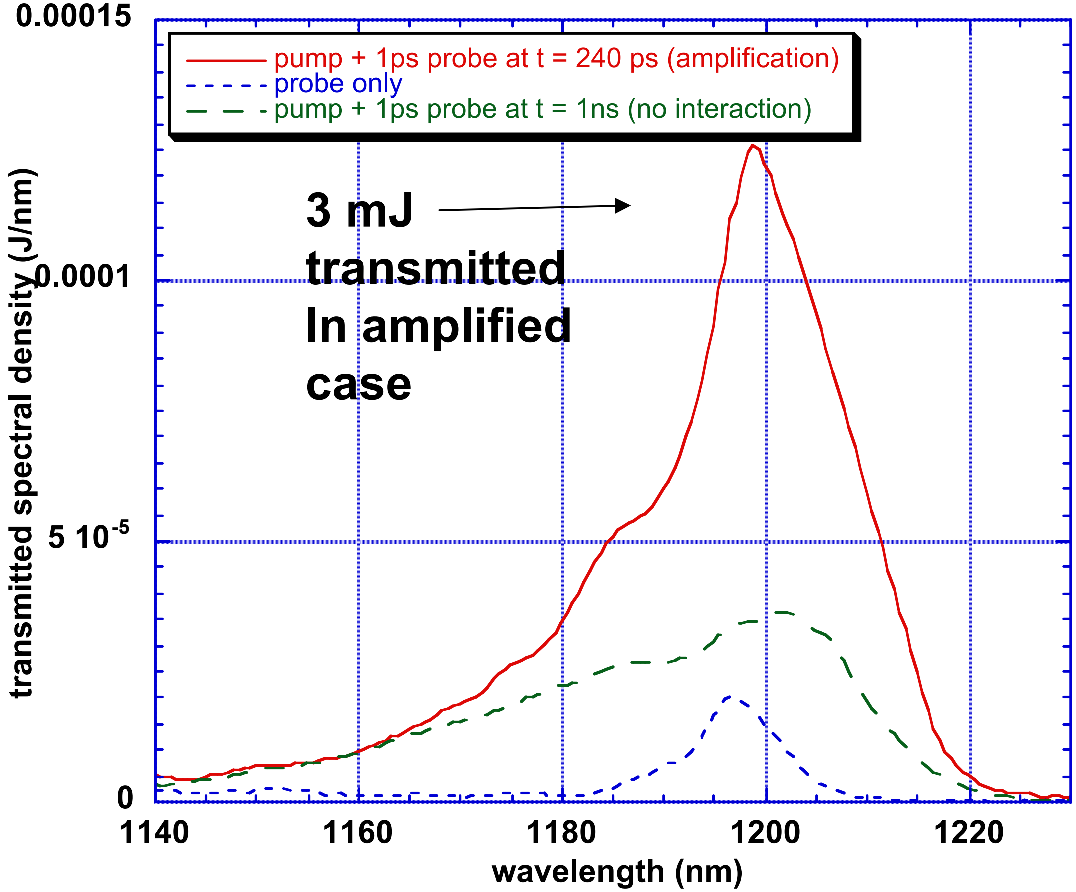
$I_{pump} = 1.1 \times 10^{15}$ W/cm^2
$n_e = 1.0 \times 10^{19}$ cm^{-3}



The observed scaling of the amplification of the transmission of the probe pulse with intensity is will allow a pulse compression experiment to be designed.

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Attenuation of Non-Resonant Light (1124 nm) Shows 4x Attenuation Due to Plasma Absorption and Beam Spreading, Indicating The Real Amplification at 1200 nm is Even Greater

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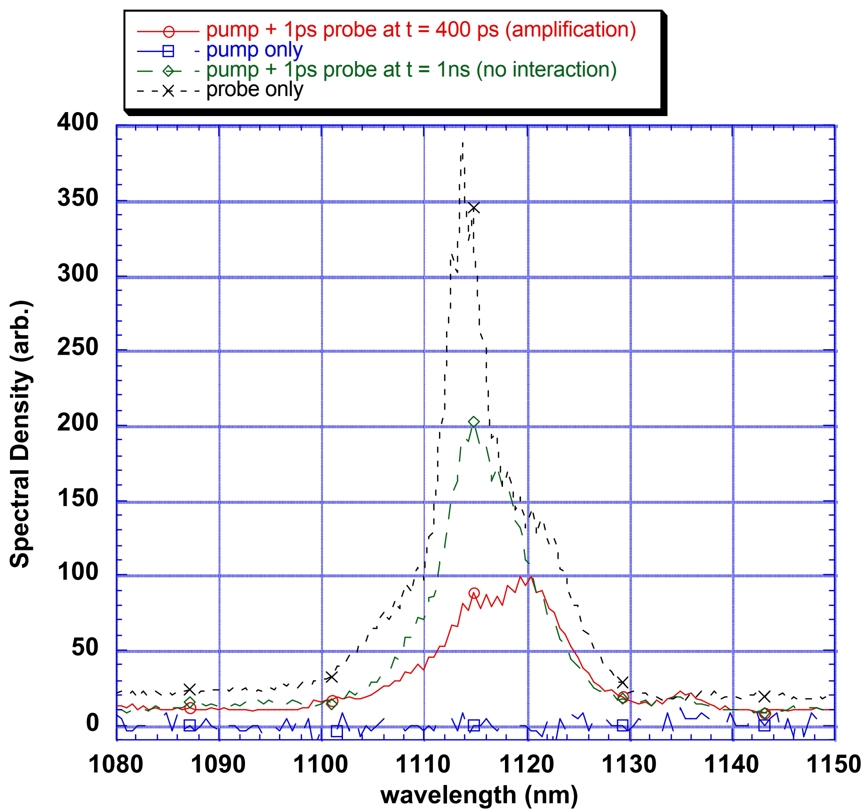

The 1124 nm transmission is Measured on the same shots, With the same timing and plasma conditions and indicate 4x attenuation of 'Non-resonant' light at the time of the Interaction

Attenuation is due to both inverse bremsstrahlung absorption and spreading of the beam outside the collection optics.

This increases measured gain following

Amp. = ('Pump+seed' -'Pump only') / (attenuated 'seed only')

= 4.4x at low I
= 16x at high I

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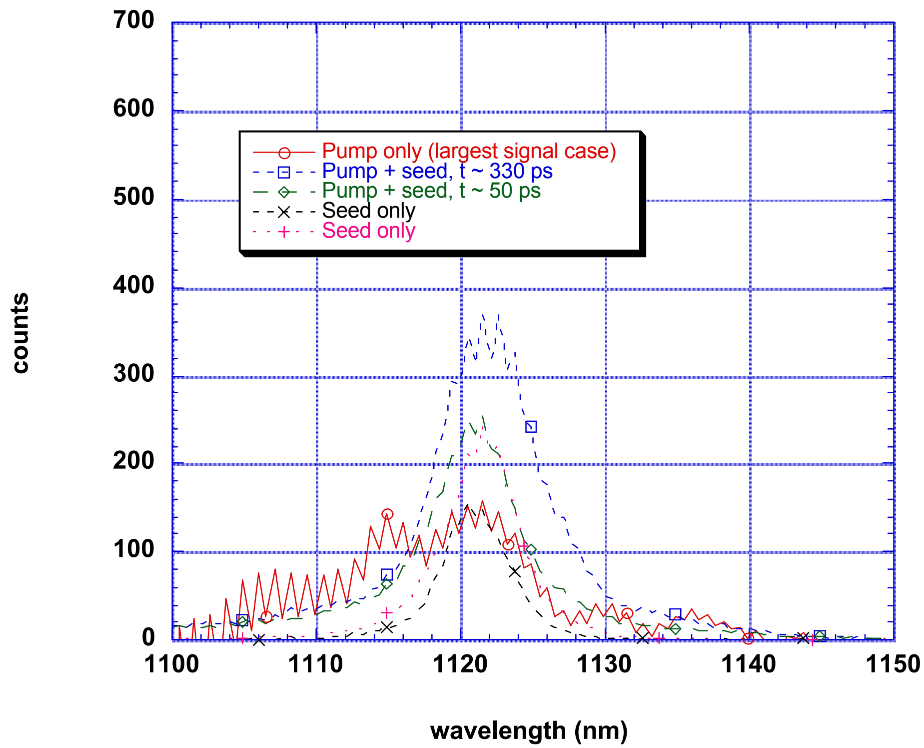
Seeding the low density plasma with a 1ps pulse at the resonant wavelength of 1124 nm produced less amplification than at high density



The 'pump+seed' waveform is Only slightly larger than the sum of the 'pump only' and 'seed only' cases at early time

Pump only SRS is weak and varying adding to un-certainty of amplification.

Little attenuation of seed is seen, Or expected at this density, so Amplification is compared to Vacuum seed transmission to Give: Amp. <~ 1.75x at high I and low n_e

The small amplification of the transmitted seed pulse relative to its vacuum value is consistent with strongly damped or saturated Langmuir waves at this density

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Amplification was Optimized vs. Time in Pulse and Resonant value of Plasma Density

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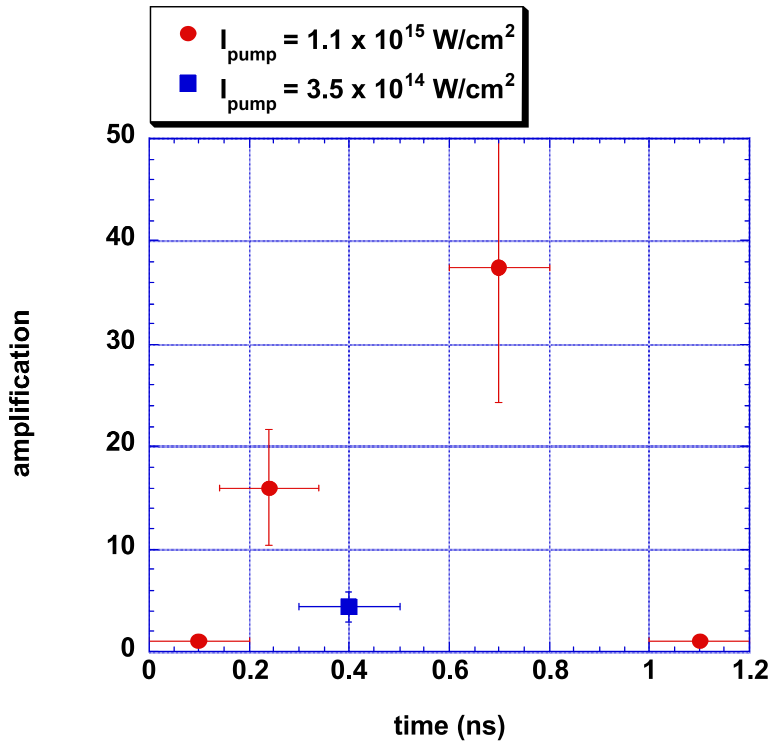
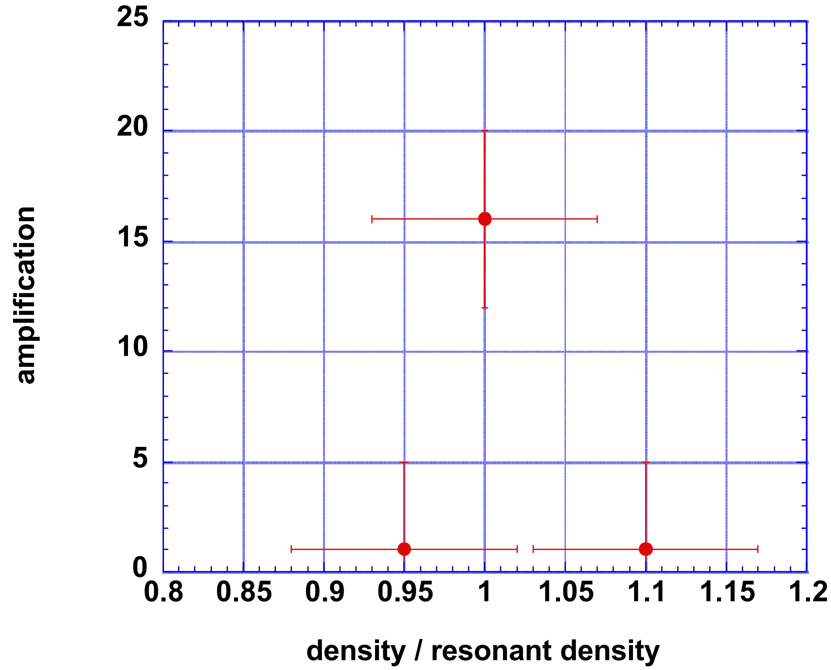
Amplification of 1200 nm seed vs. time in 1 ns pulse



Amplification of 1200 nm seed vs. density



Scans of beam timing and plasma density show amplification is resonant with density and time varying during pump pulse. (Amplification factors are relative to measured transmission of the non-resonant wavelength line).

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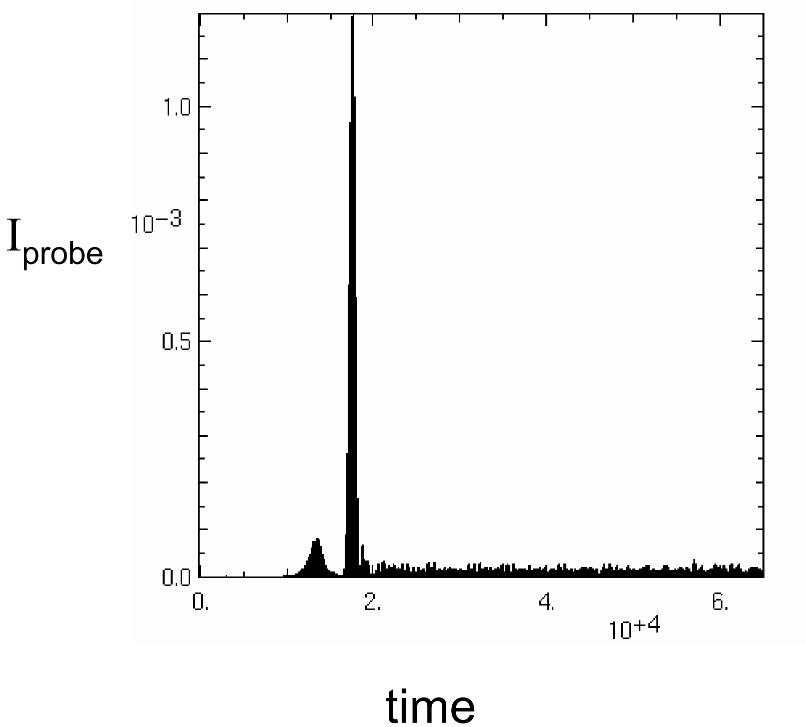
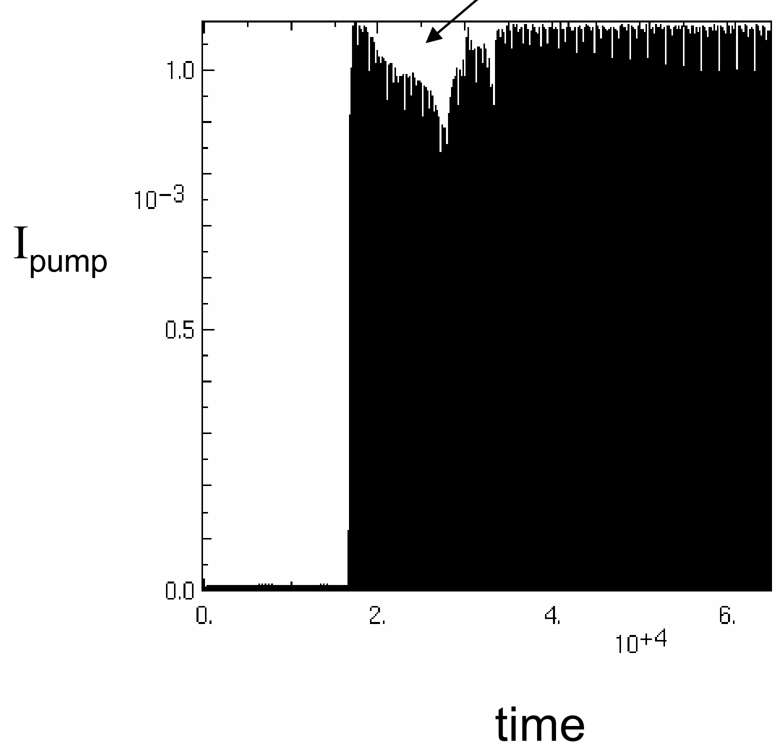
PIC Simulations Predict as Little as 35 mJ of Seed Energy Begins to Deplete the Pump Under These Conditions

Output Seed Pulse



Output Pump Pulse

This "missing" energy went into the probe.



ZOHAR Simulations of the present experimental configuration with the seed energy increased ~300 x (to 35 mJ) already deplete the pump

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Summary

Low density and low temperature plasmas have been recognized as desirable for efficient compression of a 1 ns pulse by Stimulated Raman Scattering in a Plasma.

Experiments are *the first demonstration, and study of the scaling of, the amplification of a 1 ps pulse in a plasma produced by a 1ns pulse, and have demonstrated as much as 37x amplification of a short pulse* with $1.0 \times 10^{19}/cm^3$ electron density and 1.1×10^{15} W/cm^2 pump intensity.

Further experiments showed a large reduction in amplification at low density (< 1.75 x at $2.5 \times 10^{18}/cm^3$) and a smaller reduction at low intensity (4.4 x at 3.5×10^{14} W/cm^2), suggesting favorable scaling with density and intensity.

Simulations also show that pump depletion is possible with increased seed energy

Single beam near backscatter measurements under these conditions show scattering increasing rapidly with plasma density in the density range studied, with weaker dependence on beam intensity.

Both Comet Only and Janus Only Data Showed Good Reproducibility, Supporting the Amplification Result

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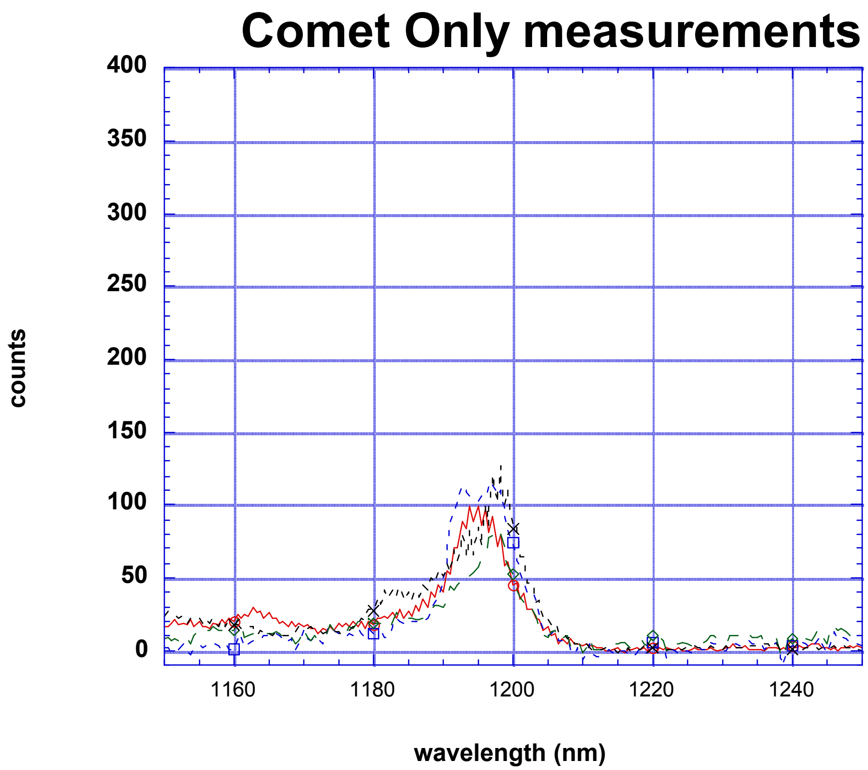

Five 'Comet Only' shots (shown) Before and after the amplification Experiment show little variability.

The two Janus shots with no Comet Interaction showed similar Scattering results

Further, calorimeter measurements showed 456 mJ on the amplification shot and <~ 200 mJ (trig.level) on all other shots.

These results indicate that the large signal on the Janus +Comet shot was due to plasma Amplification (not laser fluctuation).

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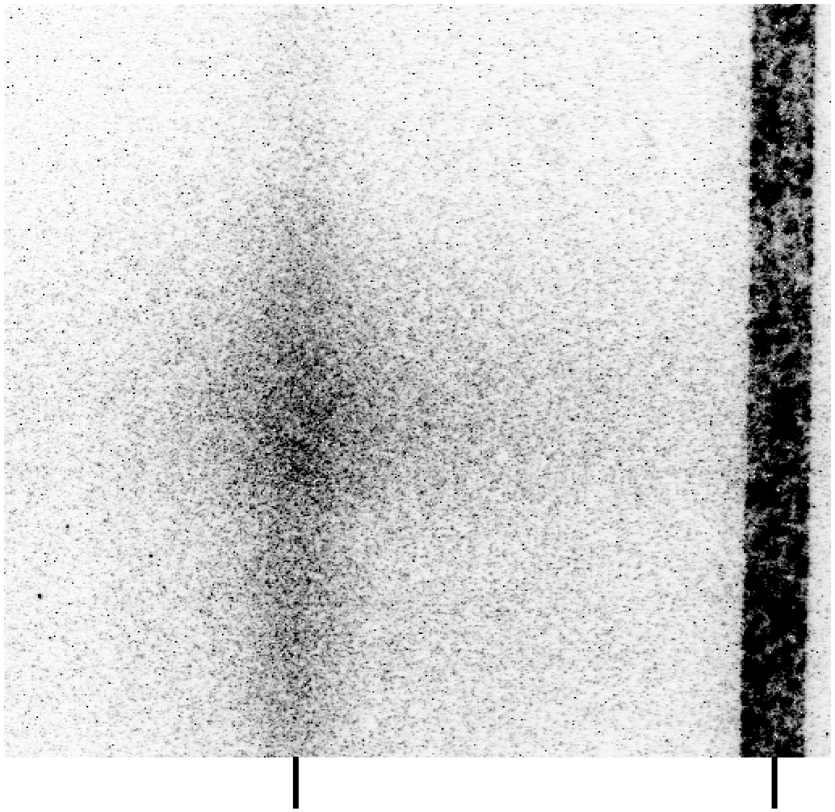
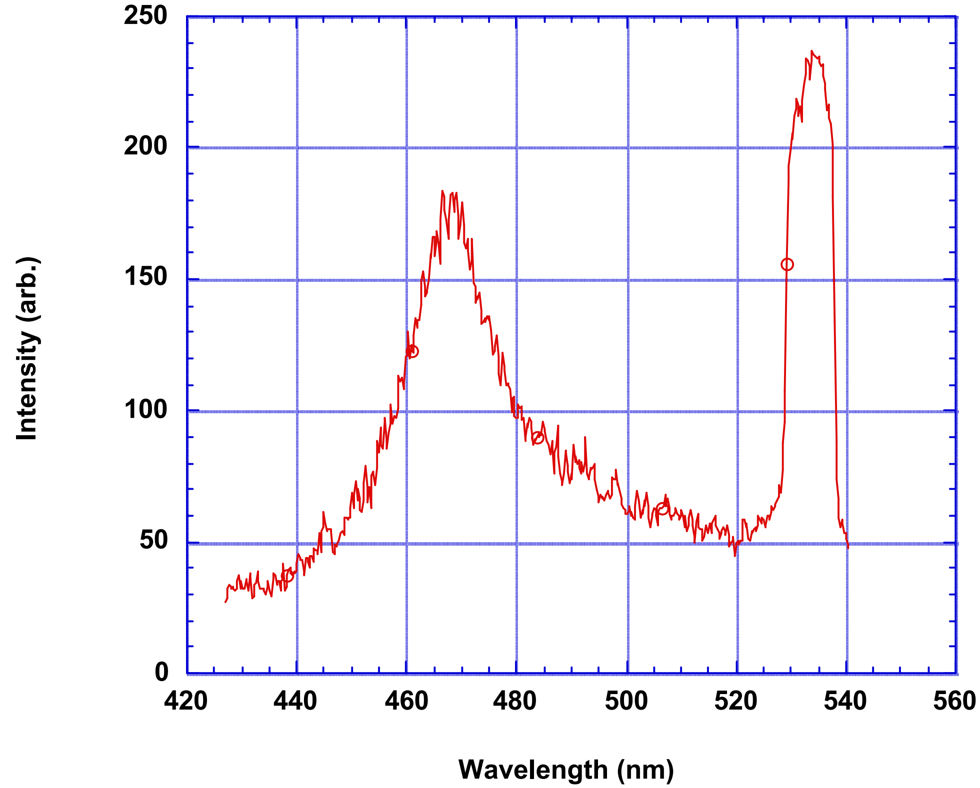
469 nm HeII Line Indicates T - ~25 eV Near Resonant Density



469 nm
(HeII)

532 nm
(probe
laser)



Line to continuum ratio at 85psi jet pressure consistent with ~ 25eV electron temperature (un inverted). Spatial imaging indicates localization to beam.

He Line to Continuum Ratio Gives T_e vs. Position

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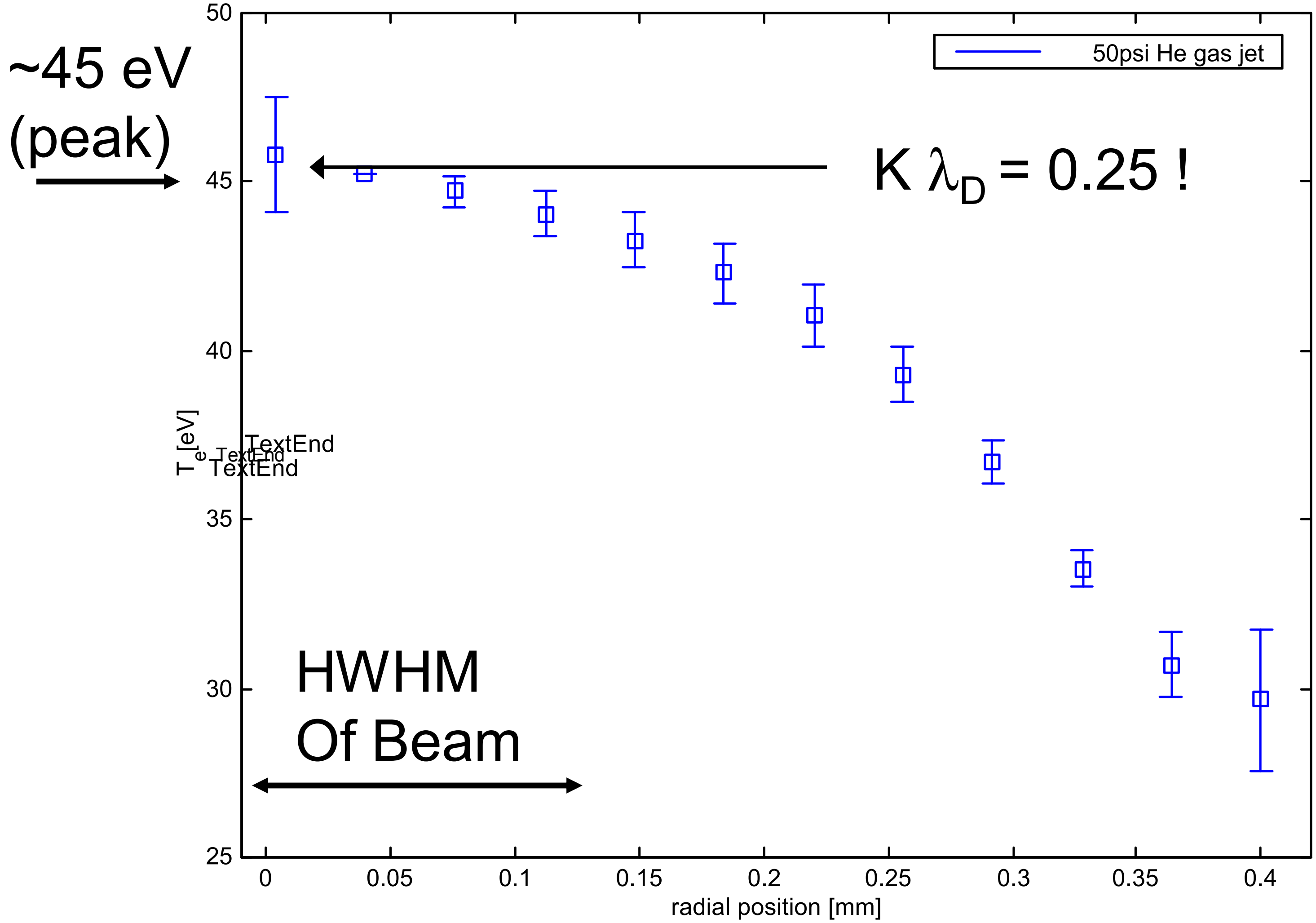

85psi jet pressure

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Interferometer Measurements Show Peak Density Approximately Tracks Gas Jet Pressure, as Expected

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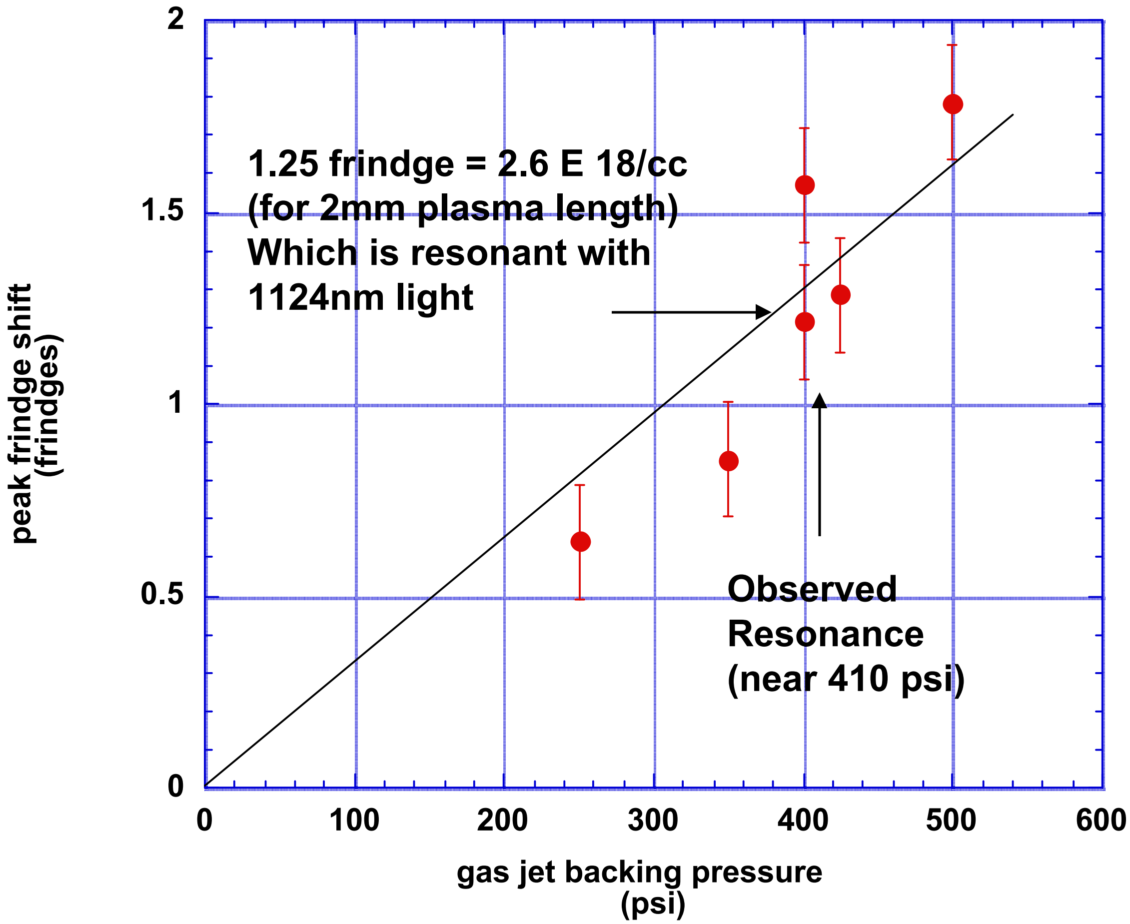

Error bars indicate Frindge reading uncertianty

4mm dia. nozzle

Even with varying profiles, peak frindge shift on interferometer approximately follows the gas jet pressure.
(pressure may be best indication of average density)

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Thermal SRS Observed at Higher Plasma Densities Have Appropriate Wavelengths for Measured Density Profiles

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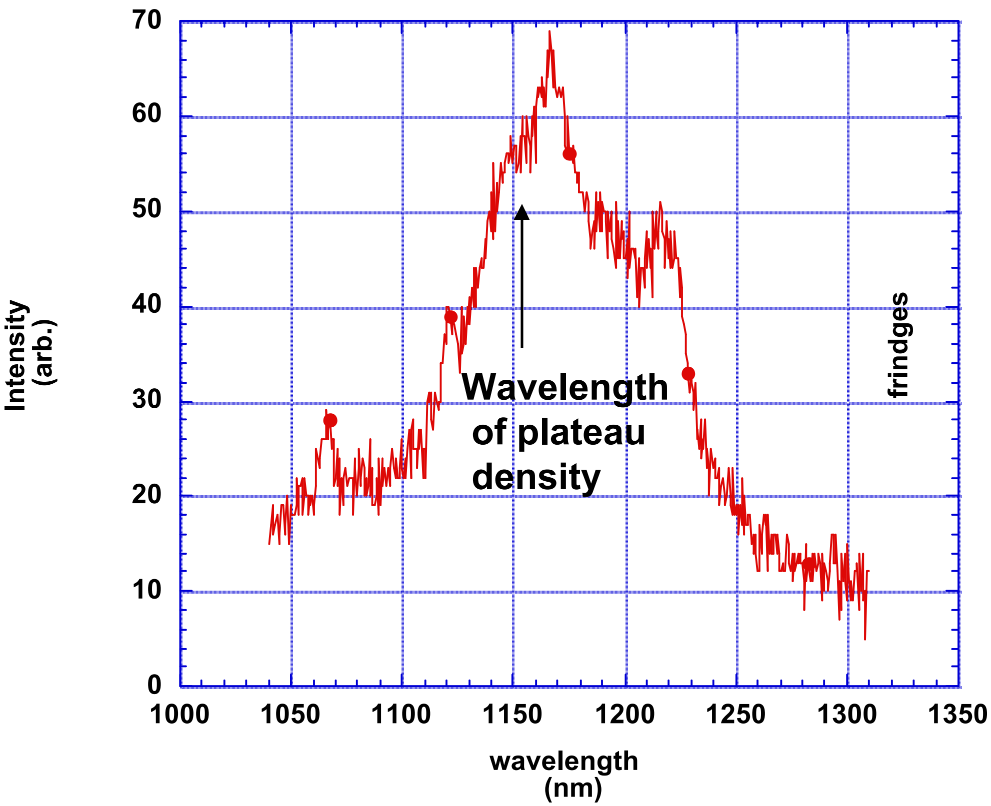
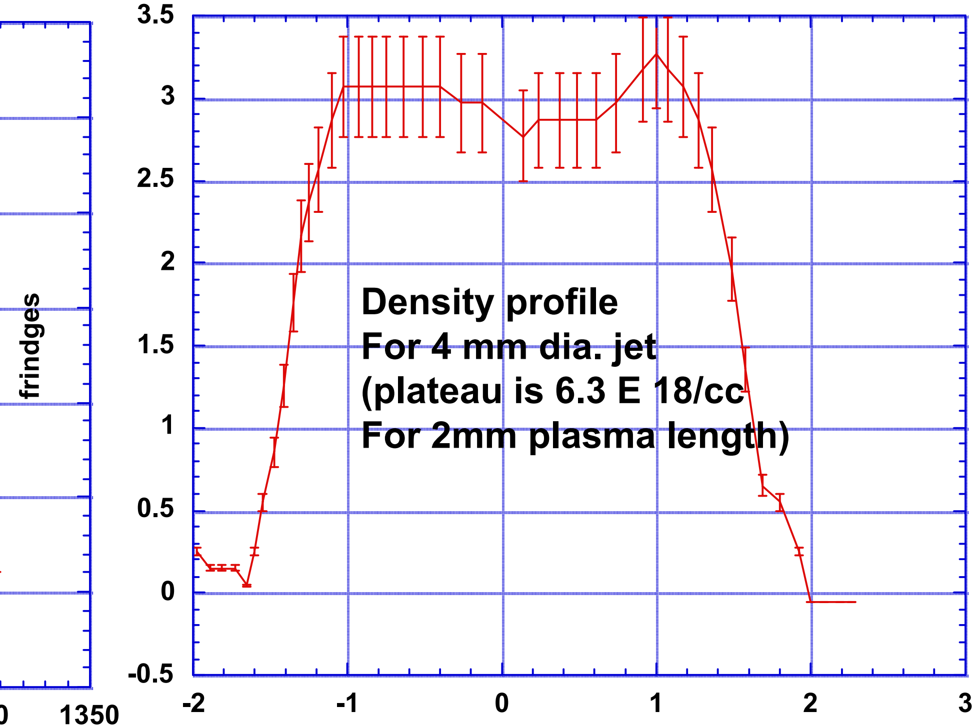
SRS Spectrum

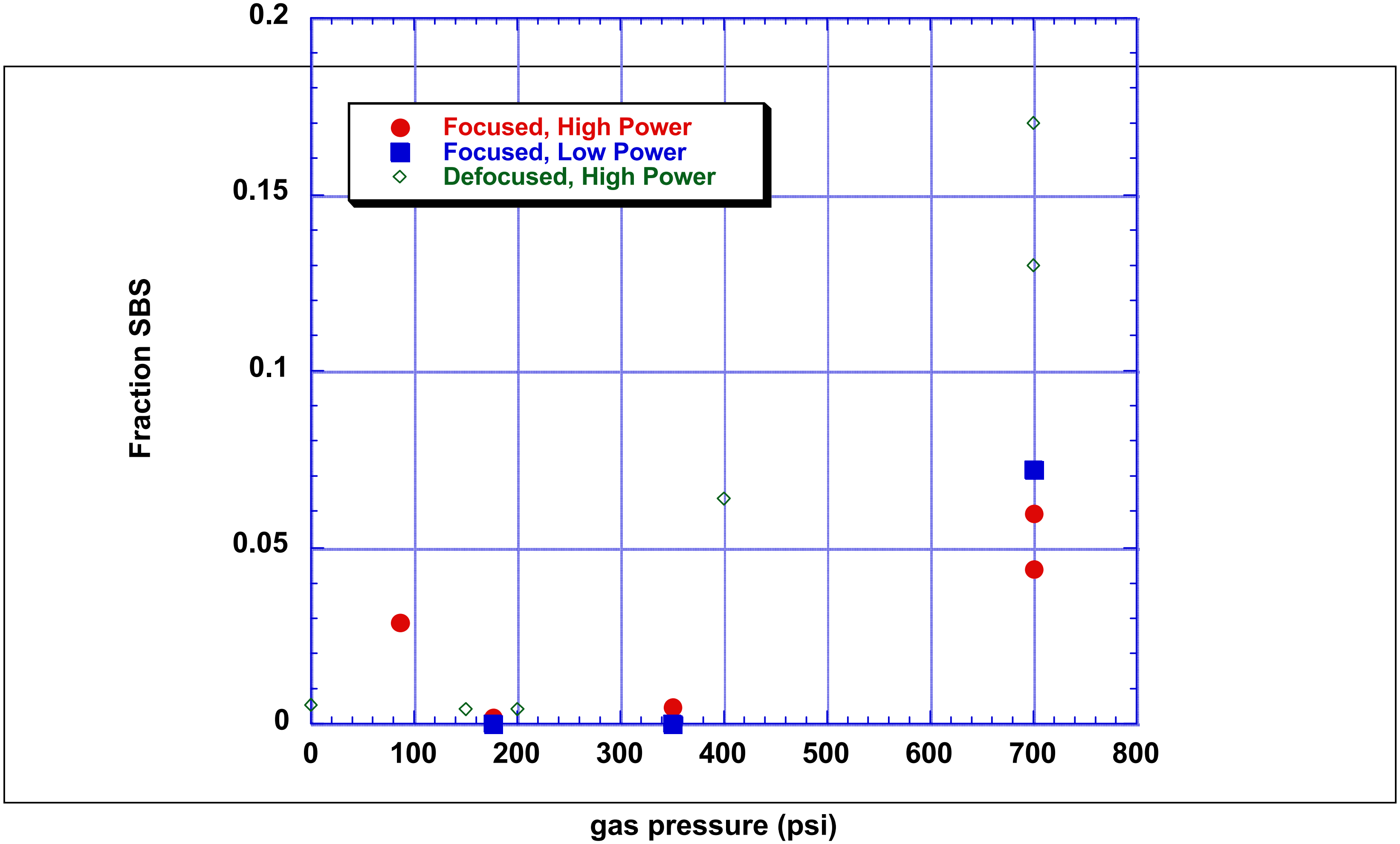


Measured Frindge Profile



Operation of jet at higher pressure allows high density plasma to be produced and thermal SRS spectrum (un seeded) is observed.

SBS Was Found to be Very Large Even with with Defocused (Low Intensity) Beams at High Density



Further SBS studies in this plasma in a later talk by D. Froula

Demonstration of Efficient Raman Conversion of a 1 ps Beam to 1124 nm Has Been an Essential Step

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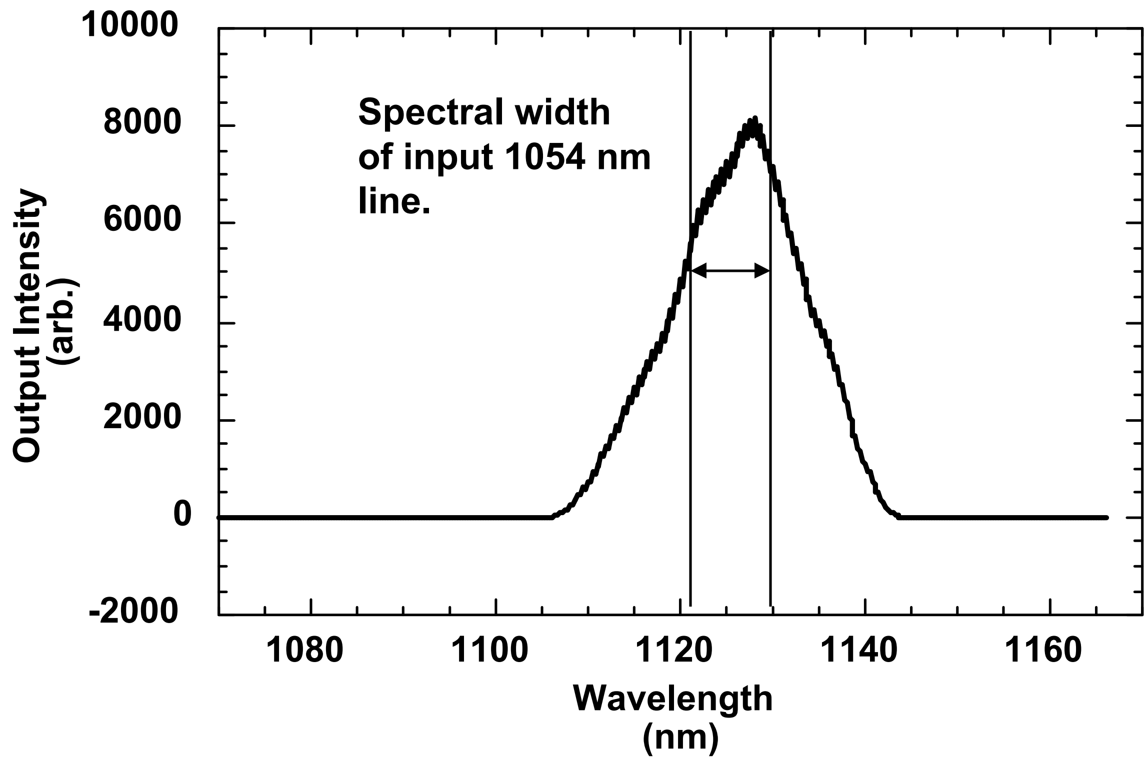

An H_2 gas Raman Cell (500 psi, 1 m length) allows the 1054 nm Comet line to be converted to 1124 nm with ~ <u>15% efficiency</u>.

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Short pulse Transmission Measurement in Small Scale Plasma Gave Some Evidence of Amplification Near the Resonant Density

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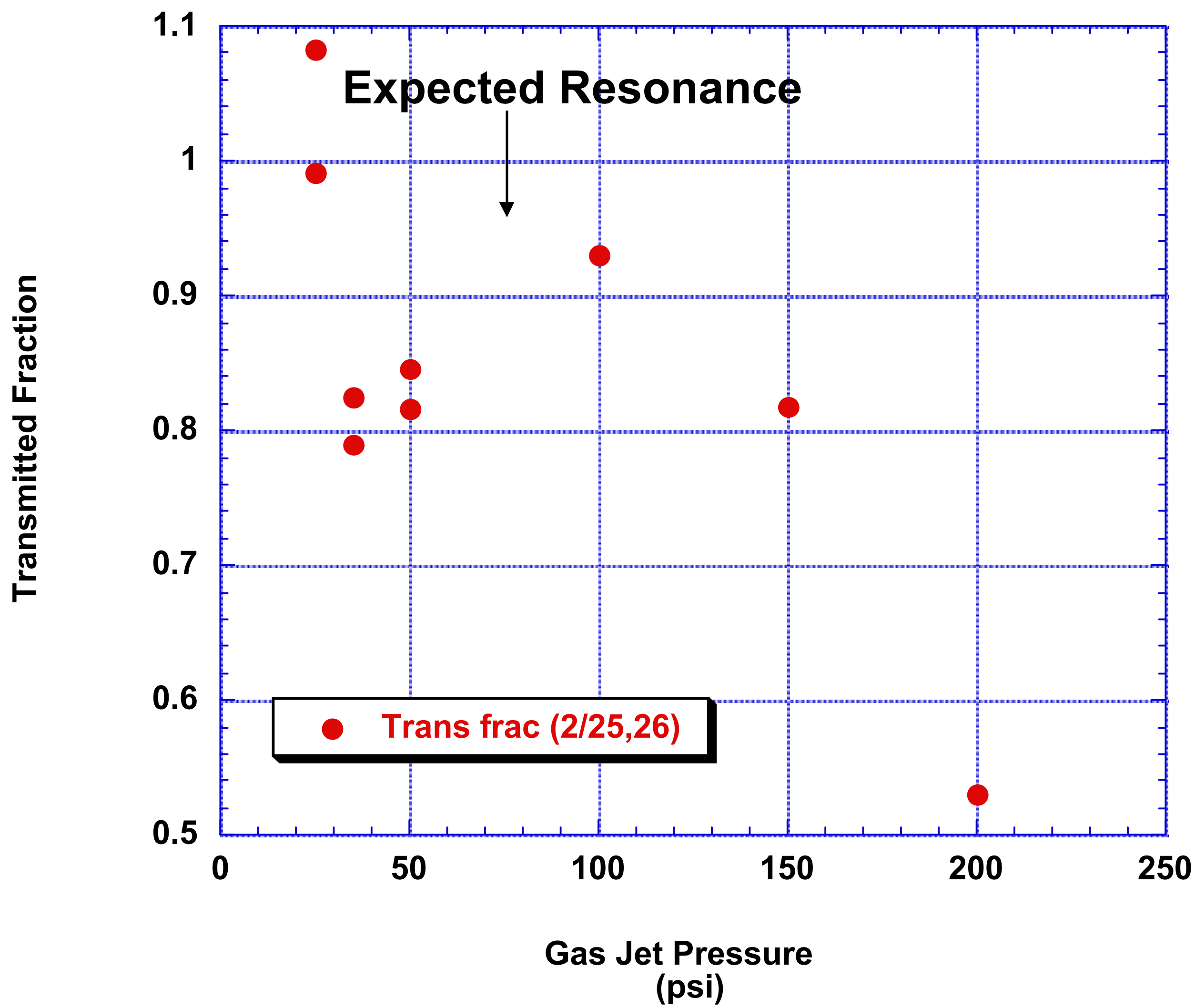

Plasma waves Amplitudes at 'trapping threshold' n/n <~ 10^{-3} would produce <~ 2x amplification

Maximum amplification observed with small scale plasma is <~ 1. 2x

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