How to Extract e- VDF using Raman Amplification of STUD Pulses in HEDP? Need a High Rep Rate Pump-Probe System, Interesting Plasmas, Ultrafast Optical Diagnostics, STUD Pulse Designs to Disentangle the Gain Encoded df/dv(t) Treasures

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BELLA Workshop
LBNL, Berkeley, CA
01-21-2016

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* **Work supported by DOE NNSA-FES Joint Program on HEDP and AFOSR**

What Does a Laser's Electric Field Look Like? What Are its Degrees of Freedom?

- Polarization
- Amplitude
- Wavelength
- Frequency
- Phase

$$\mathbf{E}_0(\mathbf{x},t)=\frac{1}{2}\sum_i \hat{\mathbf{e}}_i \; a_{0,slow,i}(\mathbf{x},t)\times\exp\left(\mathbf{k}_i\bullet\mathbf{x}-\omega_i(t)t+\phi_i\right)+c.c.$$

If you do not like too much coherence, what are you better off modulating?

What is most likely to disrupt resonant 3 wave instability growth?

Slight changes in frequency? Phase modulations? Polarization changes?

No. The only truly effective way is via turning the amplitude of the pump wave on and off on the instability growth time scale.

What do you mean off? Contrast of 100 or better should do the trick.

The Standard 4 Shock Temporal Pulse Shape of NIF with STUD Pulses Superposed: $f_{dc\%}$ = 20 in the Foot with T_{pulse} fixed and $f_{dc\%}$ = 50 in Main Drive with I_{max} Fixed.

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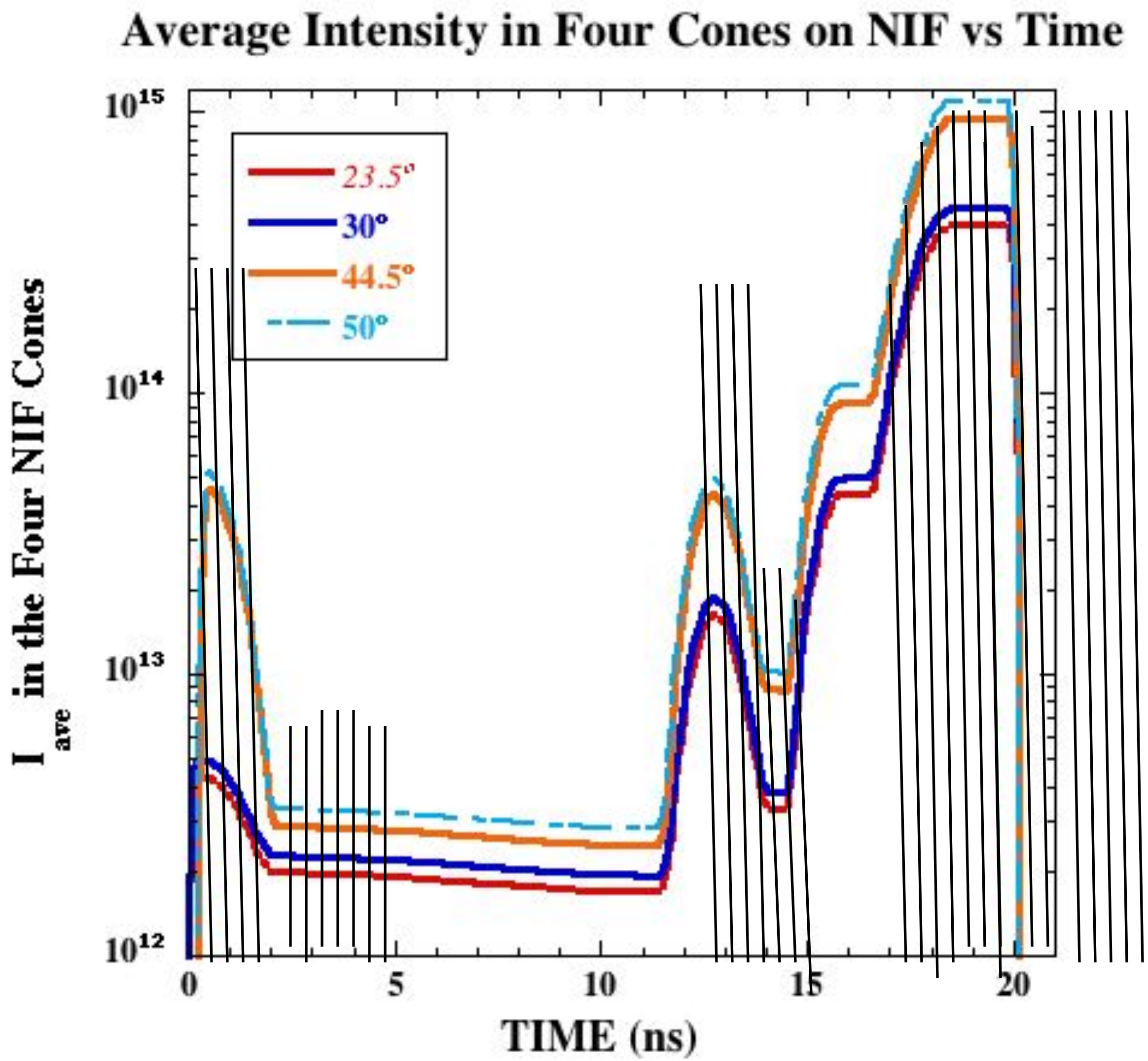
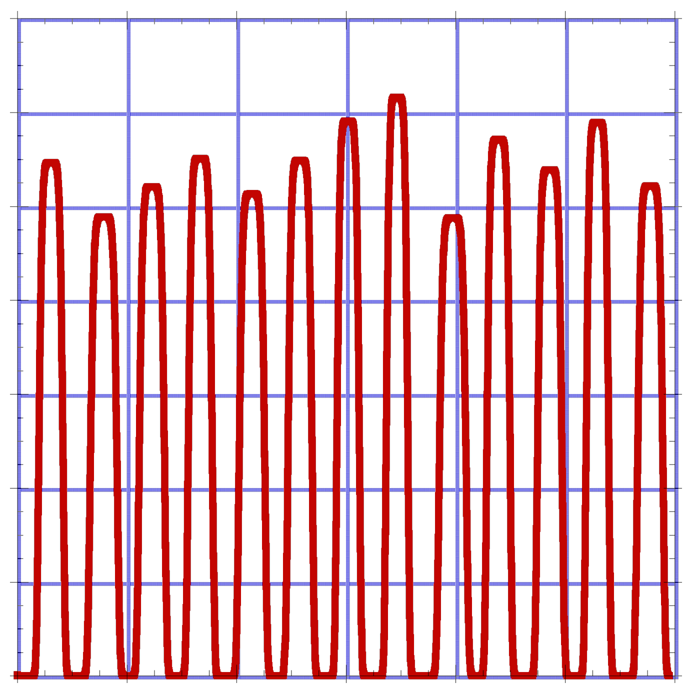


Large gaps in the foot (4 to 1) for interlacing cones and quads. T_{Max} fixed

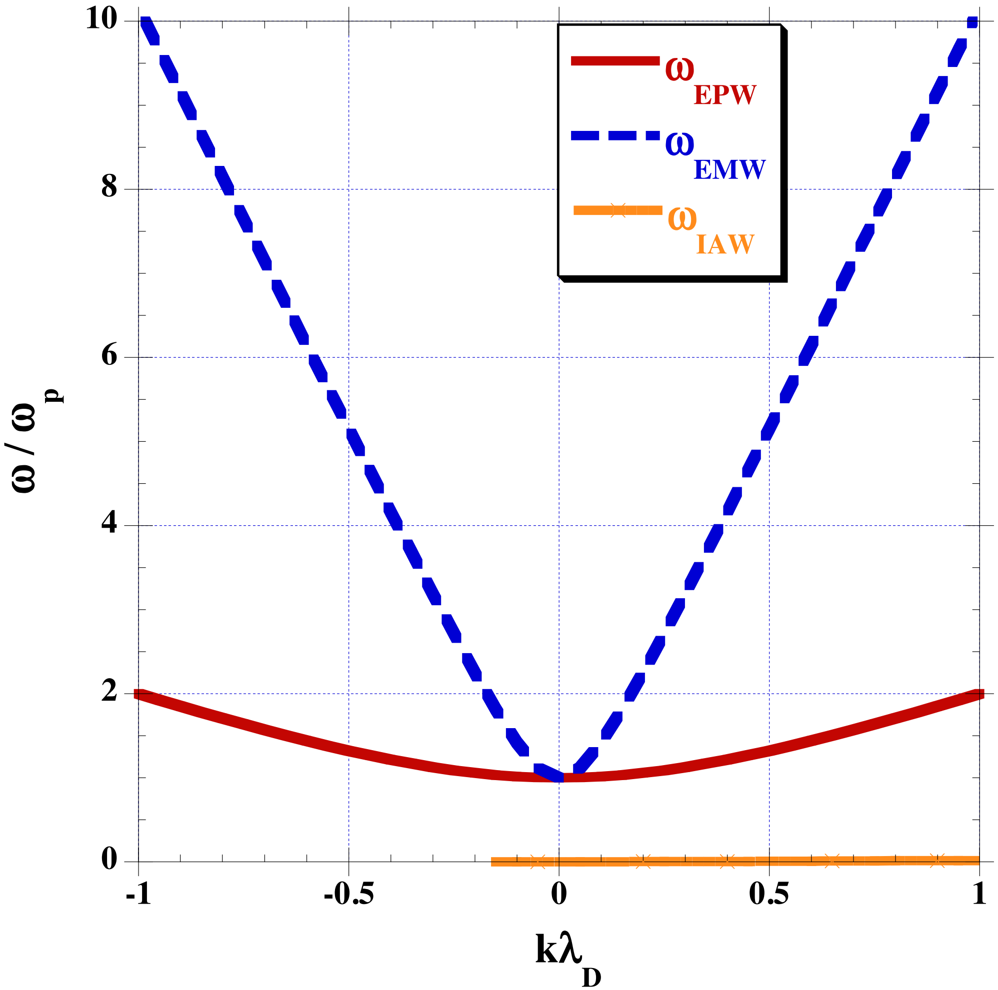
50% duty cycle during the main (twice as long) drive. I_{Max} Fixed.



STUD Pulses for df/dv
Jan-212016

Dispersion Relations of Waves Whose Three Wave Couplings Give Rise to Laser Plasma instabilities

Dispersion Relations of EPWs, EMWs and IAWs in Uniform Plasmas



$$\omega_{\mathrm{EMW}}^2 = \omega_p^2 + c^2 k_{\mathrm{EMW}}^2$$

$$\omega_{\mathrm{EPW}}^2 = \omega_p^2 + 3\,\mathrm{v}_{th}^2\, k_{\mathrm{EPW}}^2$$

$$\omega_{\mathrm{IAW}} = \mathbf{u} \bullet \mathbf{k}_{\mathrm{IAW}} + c_s k_{\mathrm{IAW}}$$

$$\omega_0 = \omega_1 + \omega_2$$

$$\mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2$$

$$\omega_{\mathrm{EMW}} = \sqrt{1 + \left(511 / T_{e,keV}\right) k_{\mathrm{EMW}}^2}$$

$$\omega_{\mathrm{EPW}} = \sqrt{1 + 3\, k_{\mathrm{EPW}}^2}$$

$$\omega_{\mathrm{IAW}} = \sqrt{\frac{Z\, m_e}{M_I}}\; k_{\mathrm{IAW}}$$

Most Prominent LPI Processes Are: SRS, SBS, $2\omega_p$ & Filamentation

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SRS EMW --> EMW + EPW

Very dangerous Instability for indirect drive ICF. Did in the Shiva Laser at 1 μm back in the 70's. Almost equal amounts of hot e- generation and Backscattering

$$\omega_0 = \omega_1 + \omega_2$$
$$\mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2$$

SBS EMW --> EMW + IAW

Very dangerous Instability for indirect drive. Almost all the energy goes to the scattered light wave. Velocity gradients can potentially tame it.

2Wp EMW --> EPW + EPW

Very dangerous instability for direct drive. It has the lowest intensity threshold, all the energy goes to coherent high frequency oscillations of the plasma and then perhaps to IAWs but with preheat getting you first.

FIL Breakup of the laser light into dancing filaments. Really a 4 wave process including both Stokes and Anti-Stokes components interacting with a degenerate zero frequency IAW. Related to Self-Focusing in classical NLO.

We Can Make Rough Estimates for the Thresholds for Self-Organization in Continuously Driven LPI:

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EMW --> EPW + EPW

$$I_{14}^{2\omega_p} \geq 1.62 \frac{T_{e,keV}}{L_{n,100\,\mu m}\,\lambda_{0,0.35\,\mu m}}$$

$2\omega_p$ (Absolute modes)

EMW --> EMW + IAW

$$I_{14}^{SBS} \geq 17 \frac{T_{e,keV}}{L_{v,100\,\mu m}\,\lambda_{0,0.35\,\mu m}} \left[\frac{0.1}{(n/n_c)}\right]$$

SBS (Convective modes)

$$I_{14}^{SRS} \geq 120 \frac{T_{e,keV}}{L_{n,100\,\mu m}\,\lambda_{0,0.35\,\mu m}}$$

SRS (Convective modes)

EMW --> EMW + EPW

Typical hot spot gain lengths are $\sim 4 f^2 \lambda_0 = 90\ \mu m$ for $f/8$
$= 560\ \mu m$ for $f/20$

At intensities approaching 10^{15} W/cm^2, as in the peak of NIF pulses, you are well above threshold for all three. SRS mostly in hot spots or blame it on a multitude of beams making common cause.

Generic Model (Quadratic Coupling) Describing the Space-Time Evolution of 3WPI: LPI in Action

$$L_s\, a_s = i\gamma_0\, M_{op}\, a_0\, a_p^* + S_s$$ **Scattered Light Wave**

$$L_p\, a_p^* = -i\gamma_0^*\, M_{os}\, a_0^*\, a_s + S_p^*$$ **Plasma Mode (EPW, IAW, KEEN)**

$$L_0\, a_0 = i\gamma_0\, M_{op}\, a_s\, a_p + S_0$$ **Pump EM wave, laser(s)**

Propagators

Coupling Constant

Kinematic (Geometric) Factors

External Source terms

Wave Envelopes
(Slowly Varying Compared to k^{-1} and ω^{-1})

Simplest Generic Form of (Space-Time & Dissipative) Propagators + Kinematic Factors

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$$L_s\, a_s = i\gamma_0\, M_{op}\, a_0\, a_p^* + S_s$$

$$L_p\, a_p^* = -i\gamma_0^*\, M_{os}\, a_0^*\, a_s + S_p^*$$

$$L_0\, a_0 = i\gamma_0\, M_{op}\, a_s\, a_p + S_0$$

$$L_s = \left(\frac{\partial}{\partial t} - \mathbf{V}_s \bullet \nabla + v_s \right)$$

$$L_p = \left(\frac{\partial}{\partial t} + \mathbf{V}_p \bullet \nabla + v_p \right)$$

$$L_0 = \left(\frac{\partial}{\partial t} + \mathbf{V}_0 \bullet \nabla + v_0 \right)$$

$$M_{op} \sim \exp\left[i\int \left(\mathbf{k}_0 - \mathbf{k}_s - \mathbf{k}_p \right) \bullet d\mathbf{x} \right] \\ - \exp\left[-i\int \left(\omega_0 - \omega_s - \omega_p \right) dt \right]$$

Space-time varying carriers have been isolated and ordered ala WKB. Frequencies & wavenumbers of uncoupled waves are (nearly) matched.

There Exist Different Morphologies of Solutions to Generic 3WPI Coupled Mode Equations

- **Convective vs Absolute Instabilities:**
- **It is not enough to establish exponential growth (that's too crude)**

- **Establish whether growth is in space only (an amplifier, convective gain saturates by "walk-off" finite interaction length)**
- **Or whether it is growth in time localized in space (an oscillator) No saturation within linear theory despite finite interaction length.**

- **Saturation mechanism may be fluid (further secondary wave-wave interactions (decay, chaos, turbulent cascades).**
- **Or kinetic in origin, nonlinear kinetic plasma response: NL frequency shifts, modified distribution functions, particle trapping effects, bursting, intermittent violent swings in response, memory effects, correlations that die slowly (fat tails), unpredictable, unsteady evolution.**

SRS and SBS in the Strong Damping Limit Driven by STUD Pulses

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$$\bar{L}_1 a_1 = \left(\frac{\partial}{\partial t} + V_1 \frac{\partial}{\partial z} + i\,\beta_1\,\nabla_\perp^2 + \nu_1 - \frac{|\gamma_0|^2 |a_0|^2}{\bar{\nu}_2} \right) a_1 = \frac{\gamma_0 a_0 e^{i\varphi}}{\bar{\nu}_2} S_2^* + S_1$$

$$\bar{L}_0 a_0 = \left(\frac{\partial}{\partial t} - V_0 \frac{\partial}{\partial z} - i\,\beta_2\,\nabla_\perp^2 + \nu_0 - \frac{|\gamma_0|^2 |a_1|^2}{\bar{\nu}_2} \right) a_0 = \frac{\gamma_0^* a_1 e^{-i\varphi}}{\bar{\nu}_2} S_2 + S_0$$

$$\bar{\nu}_2 = \nu_2 - i\,V_2\,\left[k_0(z) - k_1(z) - k_2(z) \right]$$

$$S_0(z,t;x_\perp) = \sum_{i=1}^{N_{HS}} f_z\left(\frac{z - z_{C,i}}{z_{W,i}} \right) \sum_{j=1}^{N_{spikes}} S_{0,j}^{(i)} \left(\frac{t - t_{C,j}}{t_{W,j}} \right)$$

Transform into a frame moving with the STUD pulse SPIKES and do integration over pulses as integrals over space (z).

Then average over transverse distributions which reflect the hot spot exponential intensity statistics.

Action flux conservation:

$$\left(\frac{\partial}{\partial t} + V_1 \frac{\partial}{\partial z} + \nu_1 \right) |a_1|^2 = \left(\frac{\partial}{\partial t} - V_0 \frac{\partial}{\partial z} + \nu_0 \right) |a_0|^2 = \frac{2|\gamma_0|^2 |a_0|^2 |a_1|^2}{\left[\nu_2^2 + V_2^2 (k_2')^2 \right]} + 4\,\mathrm{Re}\left[\frac{\gamma_0\, a_0\, a_1^*\, S_2^*\, e^{i\varphi} \left(\nu_2 - i V_2 k_2' \right)}{\left[\nu_2^2 + V_2^2 (k_2')^2 \right]^2} \right]$$

The Gain Exponent of SRS or SBS in the Strong Damping Limit is Made Up of Individual Elements of this Form:

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$$\mathbf{L}_{HS}\left(4 f^2 \lambda_0\right) : \mathbf{L}_{INT}\left(\frac{\nu_2}{V_2 \kappa'}\right) : \mathbf{L}_{Spike(i)}\left(V_1 \tau_{Spike(i)}\right)$$

The smallest of these three lengths will dictate the individual HS's contribution to the overall gain during each spike of a STUD pulse train.

$$\tilde{G}^{(i)}(z) = \left[\frac{2\left|\gamma_0\right|^2_{Ave}\left|a_0^{(i)}\right|^2}{V_1 V_2 \kappa'}\left(1 - \frac{\nu_1 \nu_2}{\left|\gamma_0\right|^2_{MAX}}\right)\right] \times \left[\mathrm{Tan}^{-1}\left[\frac{\left(z - z_{PPMP}\right)}{L_{INT}}\right] - \mathrm{Tan}^{-1}\left[\frac{\left(z_R - z_{PPMP}\right)}{L_{INT}}\right]\right]$$

$$\tilde{G}^{(i)}(z)\Big|_{\text{Largest Possible Gain}} = 2\pi\left[\frac{\left|\gamma_0\right|^2_{Ave}\left|a_0^{(i)}\right|^2}{V_1 V_2 \kappa'}\left(1 - \frac{\nu_1 \nu_2}{\left|\gamma_0\right|^2_{MAX}}\right)\right]$$

$$\tilde{G}^{(i)}(z)\Big|_{\text{small Gain}} = \left[\frac{2\left|\gamma_0\right|^2_{Ave}\left|a_0^{(i)}\right|^2}{\left(V_1 \nu_2 + V_2 \nu_1\right)}\left(1 - \frac{\nu_1 \nu_2}{\left|\gamma_0\right|^2_{MAX}}\right)\right] \times \left|\left(z - z_R\right)\right|$$

$$S_0\left(z,t;x_\perp\right) = \sum_{i=1}^{N_{HS}} f_z\left(\frac{z - z_{C,i}}{z_{W,i}}\right) \sum_{j=1}^{N_{spikes}} S_{0,j}^{(i)}\left(\frac{t - t_{C,j}}{t_{W,j}}\right)$$

$$L_{INT}^{(SDL)} = \frac{2\left(\dfrac{\nu_1}{V_1} + \dfrac{\nu_2}{V_2}\right)}{\dfrac{d}{dz}\left(k_0 - k_1 - k_2\right)\Big|_{z = z_{PPMP}}}$$

Besides the Gain Exponent, A Crucial Quantity Is the Gain Length Which Varies between SDL, WDL, SCL, WCL, SRS, SBS

$$L_{INT}^{(WDL)} = \left[\frac{2}{\left(\frac{V_2}{\omega_2}\right)\left(\frac{dk_2}{dz}\right)} \right] \left[\frac{\left(\frac{\gamma_0}{\omega_0}\right)\left(\sqrt{\frac{V_2}{V_1}}\right)}{\left(\frac{\omega_2}{\omega_0}\right)} \right]$$

$$L_{INT}^{(SDL)} = \left[\frac{2}{\left(\frac{V_2}{\omega_2}\right)\left(\frac{dk_2}{dz}\right)} \right] \left[\left(\frac{\nu_2}{\omega_2}\right) \right]$$

Design STUD pulses so that:

$L_{SPIKE} < L_{INT} < L_{HS}$

$L_{HS} \sim 4 f^2 \lambda_0$

$L_{SPIKE} = t_{spike} \times V_{g,\,scatt}$

For Raman Backscattering, in particular:

$$\left[\frac{2}{\left(\frac{V_2}{\omega_2}\right)\left(\frac{dk_2}{dz}\right)} \right]_{SRBS} = 4L_n$$

$$\left(\frac{\gamma_0}{\omega_0}\right)_{SRBS} = \frac{1}{2}\frac{v_{osc}}{c} = 4.267\times10^{-3}\sqrt{I_{14}}\,\lambda_{0,\mu m}$$

$$\left.\frac{\left(\sqrt{\frac{V_2}{V_1}}\right)}{\left(\frac{\omega_2}{\omega_0}\right)}\right|_{SRBS} = 7.66\times10^{-2}\sqrt{T_{e,keV}}\,\frac{\sqrt{\left(\sqrt{1-n/n_c}+\sqrt{1-2\sqrt{n/n_c}}\right)}}{\left(n/n_c\right)^{3/4}}$$

$$\left(k_{EPW}^{SRBS}\lambda_D\right) = 4.42\times10^{-2}\sqrt{T_{e,keV}}\,\frac{\left(\sqrt{1-n/n_c}+\sqrt{1-2\sqrt{n/n_c}}\right)}{\sqrt{n/n_c}}$$

$$\left(\frac{\nu_2\left(k_{EPW}^{SRBS}\lambda_D > 0.25\right)}{\omega_2}\right)_{SRBS} = -0.23+2.2\left(k_{EPW}^{SRBS}\lambda_D\right)-6.6\left(k_{EPW}^{SRBS}\lambda_D\right)^2+6.8\left(k_{EPW}^{SRBS}\lambda_D\right)^3-3.9\left(k_{EPW}^{SRBS}\lambda_D\right)^4+0.96\left(k_{EPW}^{SRBS}\lambda_D\right)^5$$

$$G_{MNR,MAX}^{SRBS(LIN)} = \frac{4\pi\left(\frac{\gamma_0}{\omega_0}\right)_{SRBS}^2\left(\frac{2\pi L_n}{\lambda_0}\right)}{\left[\left(\frac{\sqrt{1-2\sqrt{\frac{n}{n_c}}}}{1-\sqrt{\frac{n}{n_c}}}\right)\sqrt{\frac{n}{n_c}}\right]}$$

Further Details on SRBS & a Generalized Interaction Length that Goes from WDL to SDL (1 of 2)

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$$G_{MAX}^{(LIN)} = \frac{2\pi|\gamma_0|^2}{|\kappa' V_1 V_2|}\left(1 - \frac{\nu_1\nu_2}{|\gamma_0|^2}\right) = 2\langle K^{LIN}\rangle L_{INT}^{(LIN)}$$

$$\frac{|\gamma_0|^2}{\omega_0^2} = [4.267\times10^{-3}]^2 I_{14}\lambda_{0,\mu m}^2$$

$$L_{INT} = \sqrt{\left[\left(L_{INT}^{(WDL)}\right)^2 + \left(L_{INT}^{(SDL)}\right)^2\right]}$$

$$G_{MAX}^{(LIN)} = \frac{1.4188\times I_{14}\,\lambda_{0,\mu m}L_{n,100\,\mu m}}{\left[\left(\frac{\sqrt{1-2\sqrt{\frac{n}{n_c}}}}{1-\sqrt{\frac{n}{n_c}}}\right)\sqrt{\frac{n}{n_c}}\right]}$$

$$L_{INT}^{(WDL)} = 2\sqrt{\frac{2G_{MAX}^{(LIN)}}{\pi|\kappa'|}}$$

$$L_{INT}^{(SDL)} = 2\frac{|\nu_2|}{|V_2\kappa'|}$$

$$\left(\frac{\nu_2\left(k_{EPW}^{SRBS}\lambda_D > 0.25\right)}{\omega_2}\right)_{SRBS} = -0.23 + 2.2\left(k_{EPW}^{SRBS}\lambda_D\right) - 6.6\left(k_{EPW}^{SRBS}\lambda_D\right)^2 + 6.8\left(k_{EPW}^{SRBS}\lambda_D\right)^3 - 3.9\left(k_{EPW}^{SRBS}\lambda_D\right)^4 + 0.96\left(k_{EPW}^{SRBS}\lambda_D\right)^5$$

$$\frac{V_1}{c} = \frac{\sqrt{1-2\sqrt{\frac{n}{n_c}}}}{1-\sqrt{\frac{n}{n_c}}}$$

$$L_{INT} = 4L_n\left[\alpha^2 I_{14} + \left(\nu_2\left(T_{e,keV}\right)/\omega_2\right)^2\right]^{1/2}$$

So as the intensity increases, L_n must be decreased to keep L_{INT} fixed and ≈ 4 f^2 λ_0.

$$\frac{V_2}{c} = \left[\frac{3v_{th}^2}{c^2}\right]\left[\frac{\sqrt{\varepsilon} + \sqrt{1-2\sqrt{\frac{n}{n_c}}}}{\sqrt{\frac{n}{n_c}}}\right]$$

For fixed density and temperature, this represents a rule between L_n and I_{14}:

$$\frac{L_n}{\lambda_0} = \frac{(f/\#)^2}{\left[\alpha^2 I_{14} + \left(\nu_2\left(T_{e,keV}\right)/\omega_2\right)^2\right]^{1/2}}$$

This is the criterion with which to keep $L_{INT} = L_{HS}$, as the intensity of the laser is varied for fixed Landau damping rate, ν_2.

$$\left|\frac{c^2\kappa'}{\omega_0^2}\right| = \frac{\sqrt{\frac{n}{n_c}}}{2\left(\frac{V_2}{c}\right)\left(\frac{\omega_0 L_n}{c}\right)}$$

$$\alpha^2 = \frac{1.4188\,\lambda_{0,\mu m}\,L_{n,100\,\mu m}}{(n/n_c)}\left(\frac{V_2}{V_1}\right)$$

Further Details on SRBS & a Generalized Interaction Length that Goes from WDL to SDL (2 of 2)

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$$\frac{|\gamma_0|^2}{\omega_0^2} = [4.267\times 10^{-3}]^2 I_{14}\lambda_{0,\mu m}^2$$

$$G_{MAX}^{(LIN)} = \frac{1.4188\times I_{14}\,\lambda_{0,\mu m} L_{n,100\,\mu m}}{\left[\left(\frac{\sqrt{1-2\sqrt{\frac{n}{n_c}}}}{1-\sqrt{\frac{n}{n_c}}}\right)\sqrt{\frac{n}{n_c}}\right]}$$

$$\left(\frac{\nu_2\left(k_{EPW}^{SRBS}\lambda_D > 0.25\right)}{\omega_2}\right)_{SRBS} = -0.23 + 2.2\left(k_{EPW}^{SRBS}\lambda_D\right) - 6.6\left(k_{EPW}^{SRBS}\lambda_D\right)^2 + 6.8\left(k_{EPW}^{SRBS}\lambda_D\right)^3 - 3.9\left(k_{EPW}^{SRBS}\lambda_D\right)^4 + 0.96\left(k_{EPW}^{SRBS}\lambda_D\right)^5$$

$$L_{INT} = 4L_n\left[\alpha^2 I_{14} + \left(\nu_2\left(T_{e,keV}\right)/\omega_2\right)^2\right]^{1/2}$$

$$\frac{L_n}{\lambda_0} = \frac{\left(f/\#\right)^2}{\left[\alpha^2 I_{14} + \left(\nu_2\left(T_{e,keV}\right)/\omega_2\right)^2\right]^{1/2}}$$

$$\alpha^2 = \frac{1.4188\,\lambda_{0,\mu m}\,L_{n,100\,\mu m}}{\left(n/n_c\right)}\left(\frac{V_2}{V_1}\right)$$

Besides the Gain Exponent, A Crucial Quantity Is the Gain Length Which Varies between SDL, WDL, SCL, WCL, SRS, SBS

$$L_{INT}^{(WDL)} = \left[\frac{2}{\left(\frac{V_2}{\omega_2}\right)\left(\frac{dk_2}{dz}\right)} \right] \left[\frac{\left(\frac{\gamma_0}{\omega_0}\right)\left(\sqrt{\frac{V_2}{V_1}}\right)}{\left(\frac{\omega_2}{\omega_0}\right)} \right]$$

$$L_{INT}^{(SDL)} = \left[\frac{2}{\left(\frac{V_2}{\omega_2}\right)\left(\frac{dk_2}{dz}\right)} \right] \left[\left(\frac{\nu_2}{\omega_2}\right) \right]$$

Design STUD pulses so that:

$L_{spike} < L_{HS} < L_{INT}$

$L_{HS} \sim 4 f^2 \lambda_0$

$L_{spike} = t_{spike} \times V_{g,\,scatt}$

For Brillouin Backscattering, in the weak coupling and strong damping limit in particular:

$$\left[\frac{2}{\left(\frac{V_2}{\omega_2}\right)\left(\frac{dk_2}{dz}\right)} \right] = 2\left[\frac{1+M(0)}{M(0)}\right] L_V$$

$$L_{INT,SBBS,100}^{SDL} = 0.2\left[\frac{1+M(0)}{M(0)}\right] L_{V,100}\left(\frac{\nu_{IAW}}{0.1\,\omega_{IAW}}\right)$$

$$\left(\frac{\gamma_0}{\omega_0}\right)_{SBBS} = \frac{1}{2}\left(\frac{Z\,m_e}{M_I}\right)^{1/2}\left(\frac{n_e}{n_c}\right)^{1/2}\left(\frac{k_{IAW}}{\omega_0/c}\right)\frac{(\mathrm{v}_0/c)}{\sqrt{(\omega_{IAW}\omega_s)/\omega_0^2}}$$

$$\left(\frac{\gamma_0}{\omega_0}\right)_{SBBS} = 2.19\times10^{-3}\,\varepsilon^{1/4}\left(\frac{Z}{A}\right)^{1/2}\left(\frac{n_e}{n_c}\right)^{1/2}\frac{\sqrt{I_{14}}\,\lambda_{0,\mu m}}{T_{e,keV}^{1/4}}$$

$$G_{MNR}^{SBBS} = \frac{1.46\left(\frac{n_e}{n_c}\right) I_{14}\,\lambda_{0,\mu m}^2\left(\frac{2\pi L_{V,100}}{|M(0)|\,\lambda_{0.\mu m}}\right)}{T_{e,keV}}$$

A Hierarchy of Scales and Models Dictate the Additional Physics Needed to Properly Model SBS or SRS in Different Regimes of Operation

- **WDL:** $\nu_{IAW} / \gamma_0 << 1$ ➔ $G \sim \gamma_0^2/\kappa' V_1 V_2$ **but also, the possibility of an absolute instability**

- **SDL:** $\nu_{IAW} / \gamma_0 >> 1$ ➔ $G \sim \gamma_0^2 / \kappa' V_1 V_2$ **without absolute instabilities.**

- **WCL:** $\gamma_0/\omega_{IAW} << 1$ ➔ $G \sim \gamma_0^2/\kappa' V_1 V_2$ **easy to violate this limit in hot spots.**

- **SCL:** $\gamma_0/\omega_{IAW} >> 1$ ➔ $G \sim \gamma_0^{2/3}$ **+ laser intensity dependent IAW frequency shifts. Most alarmingly, allows multiple resonances in an inhomogeneous flow profile.**

- **<u>Pump Depletion</u> or w/o PD: Clamp Gain to Reflectivity < 1 values or allow arbitrarily large growth or need to model IAW nonlinearity.**

- **<u>Self Focusing</u> or w/o SF: SCL & FIL in nonuniform flow lead to nonstationarity: No longer GRF. Prominent tails develop. New regimes of statistical behavior.**

- **<u>Single Beam vs Overlapped Beams</u>: Also possible to get off the GRF reservation. Without Gaussian Random Fields, the theoretical arsenal schrinks considerably.**

Relative SRS reflectivity onsets quickly and saturates slowly for continuous pulses

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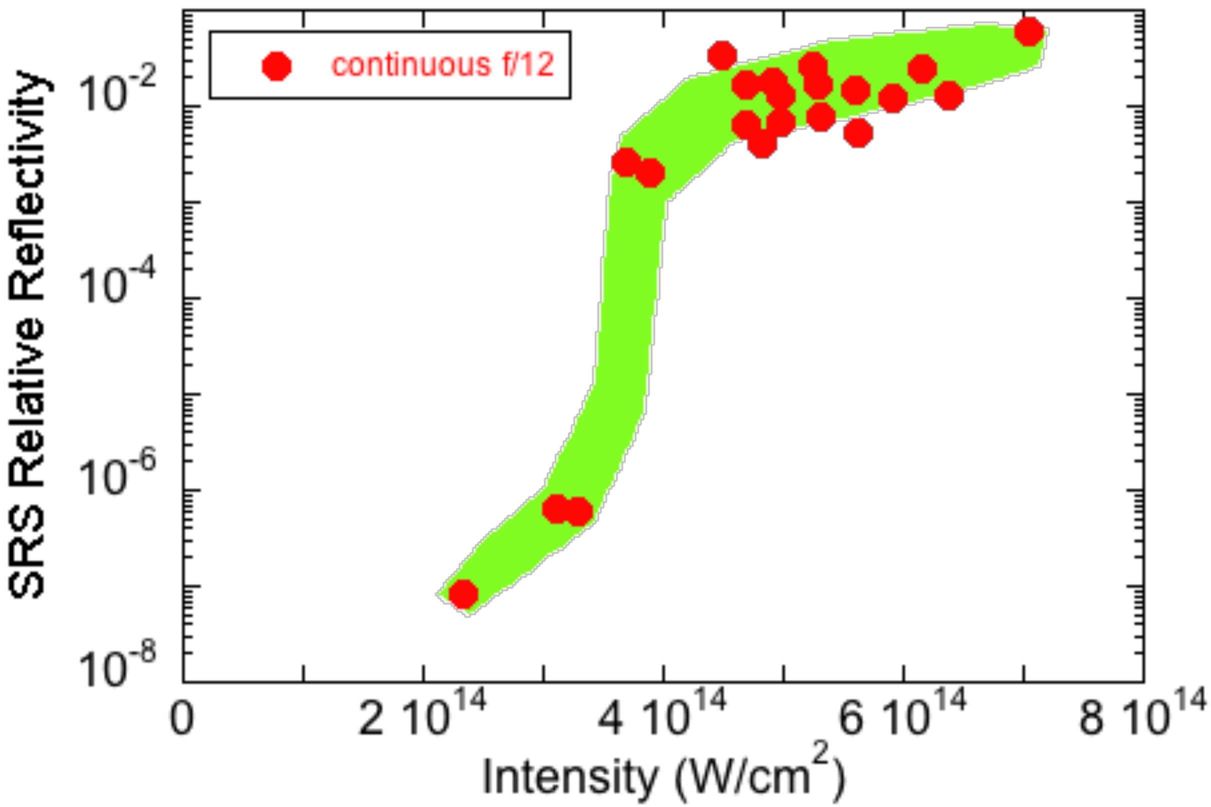
SRS Relative Reflectivity, continuous pulses



- Trends qualitatively consistent with:

  - critical onset intensity from hot spots[1,2]

  - inflation and saturation effects due to trapping[3]

1. H.A. Rose, D.F. DuBois PRL (1994),
2. J. Garnier, Phys. Plasmas (1999)
3. L. Yin et al., Phys. Plasmas (2012)

f/12 focusing
N_2H_2

$T_e = 500$ eV
$n_e/n_{cr} = 0.04 - 0.05$

Los Alamos NATIONAL LABORATORY EST. 1943

What Do STUD Pulses Look Like?

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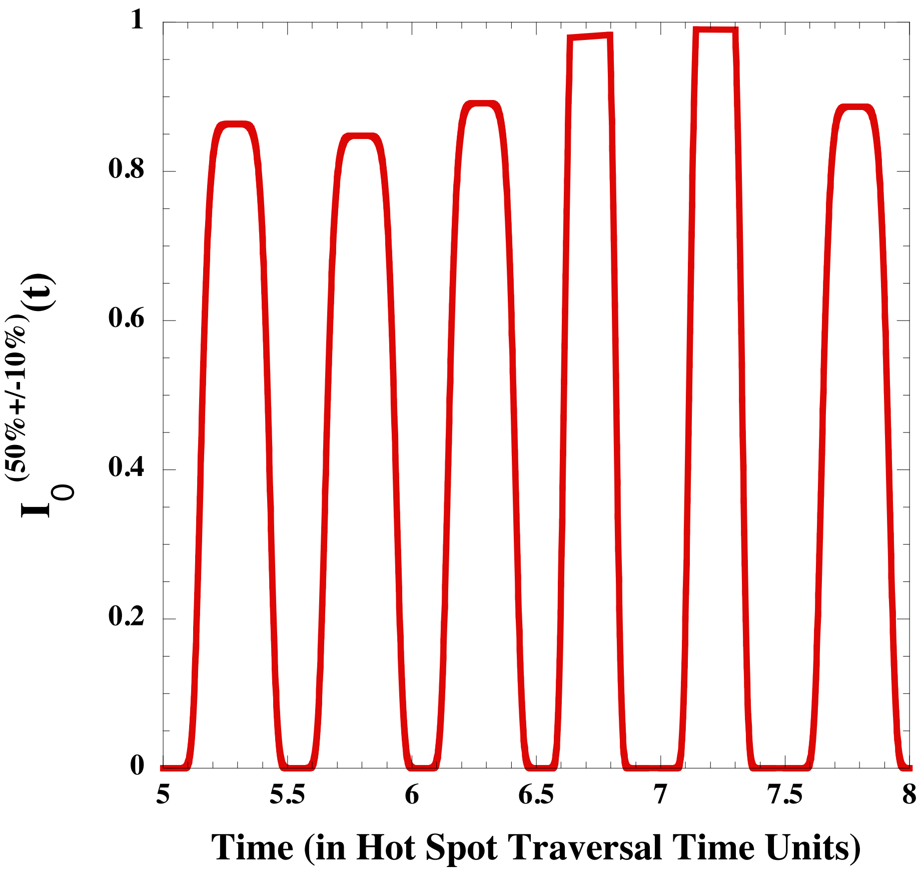
$$I_0(t) = \sum_{n=1}^{N_{SPIKES}} I_0^{(n)} \exp - \left[\frac{\left(t - t_c^n\right)}{\left(t_W^n/2\right)}\right]^{2\sigma_n}$$

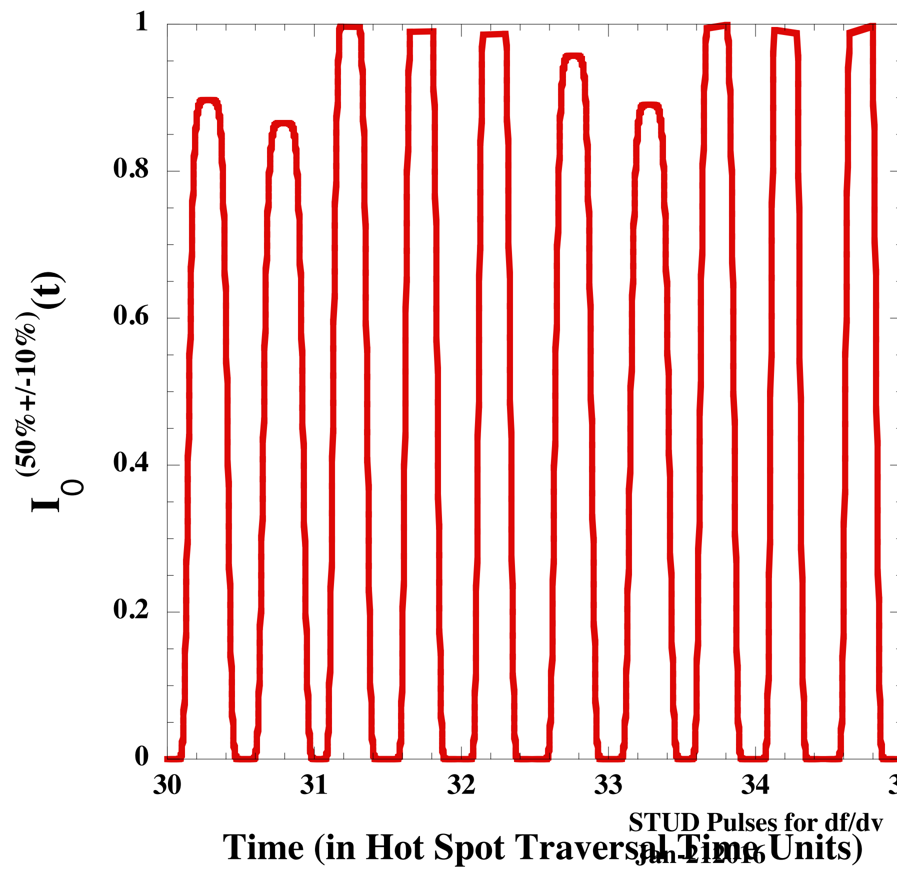
$$I_o^{(n)} \times t_{width}^{on(n)} = I_o^{(n+1)} \times t_{width}^{on(n+1)}; \quad \forall n$$

$$t_{width}^{on(n)} + t_{width}^{off(n)} = t_{width}^{on(n+1)} + t_{width}^{off(n+1)}; \quad \forall n$$

STUD Pulse Shape 10% Random Modulation of a 50% Duty Cycle



STUD Pulse Shape 10% Random Modulation of a 50% Duty Cycle



What Do STUD Pulses Look Like in Time and Frequency?

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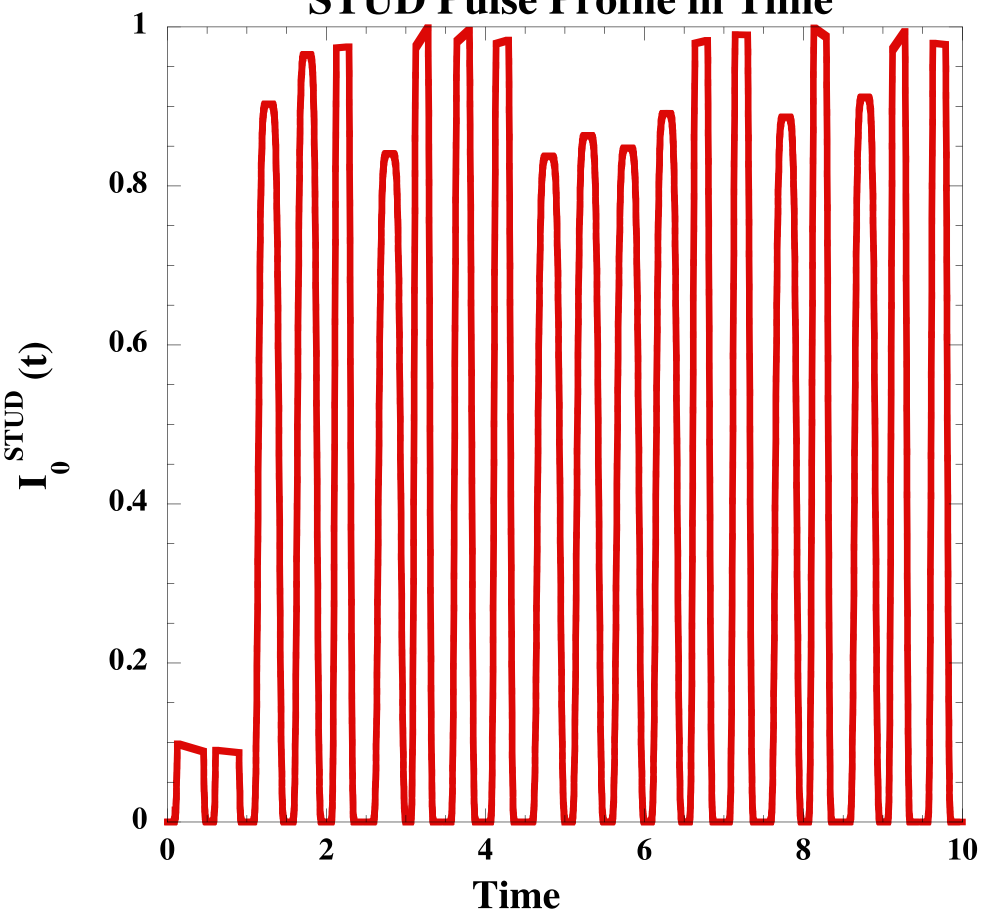
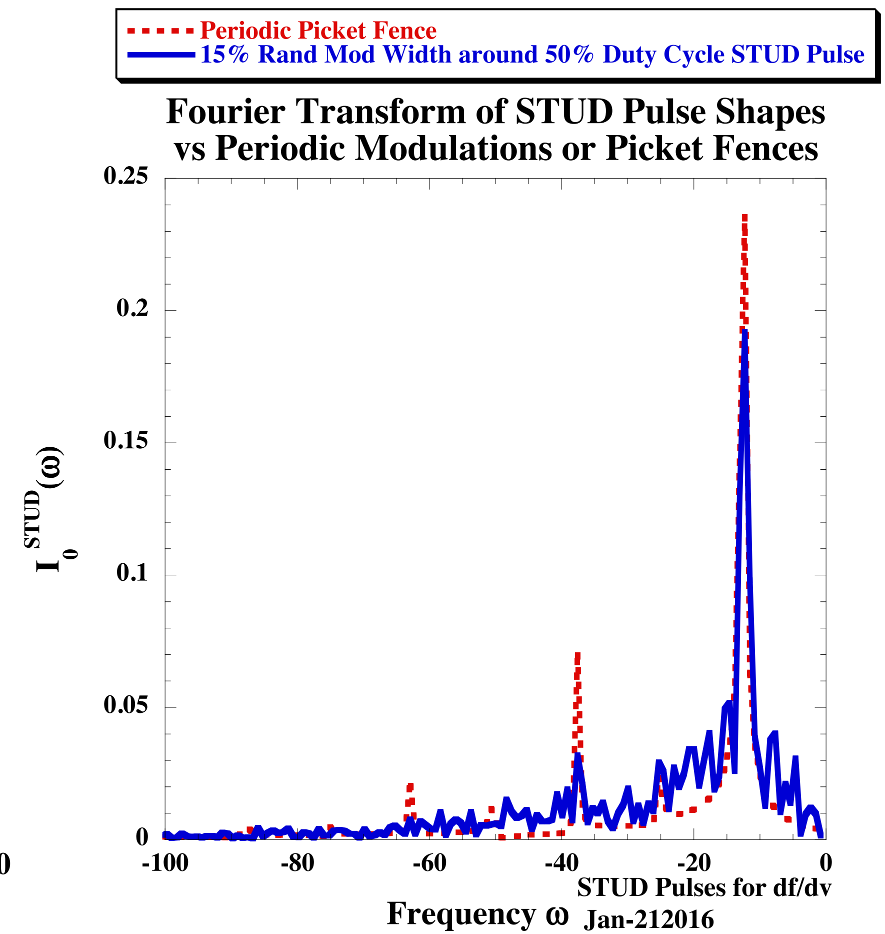
$$I_0(t) = \sum_{n=1}^{N_{SPIKES}} I_0^{(n)} \exp - \left[\frac{\left(t - t_c^n\right)}{\left(t_W^n/2\right)}\right]^{2\sigma_n}$$

$$I_o^{(n)} \times t_{width}^{on(n)} = I_o^{(n+1)} \times t_{width}^{on(n+1)}; \quad \forall n$$

$$t_{width}^{on(n)} + t_{width}^{off(n)} = t_{width}^{on(n+1)} + t_{width}^{off(n+1)}; \quad \forall n$$

10% Randomly Modulated Spike Width
STUD Pulse Profile in Time





How Can We Measure the e^- VDF of a Fast Nonlinearly and Kinetically Evolving Plasma?

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- Use Pump-probe near backscatter geometry with a burst of spikes as the pump.
- Measure the transmission or gain of the probe.
- Back out plasma conditions and isolate the e- or ion VDF information via the kinetic Landau damping rate.
- Compare neighboring regions at the same or nearby densities. Back out the extend of large beam nonlinear phenomena by a control burst of weakly nonlinear interactions under our control with small signal gain.
- Design sequences of spikes in successive STUD pulses so as to have unambiguous evidence of what is taking place in a quiet or highly agitated plasma.
- Designing the right STUD pulse sequences based on previous shots and optimizing and automating the procedure is the key.

Extract the ps Time Scale Evolution of the e⁻ VDF $\nu\{df(t)/dv\}$ Using STUD Pulses and SRS

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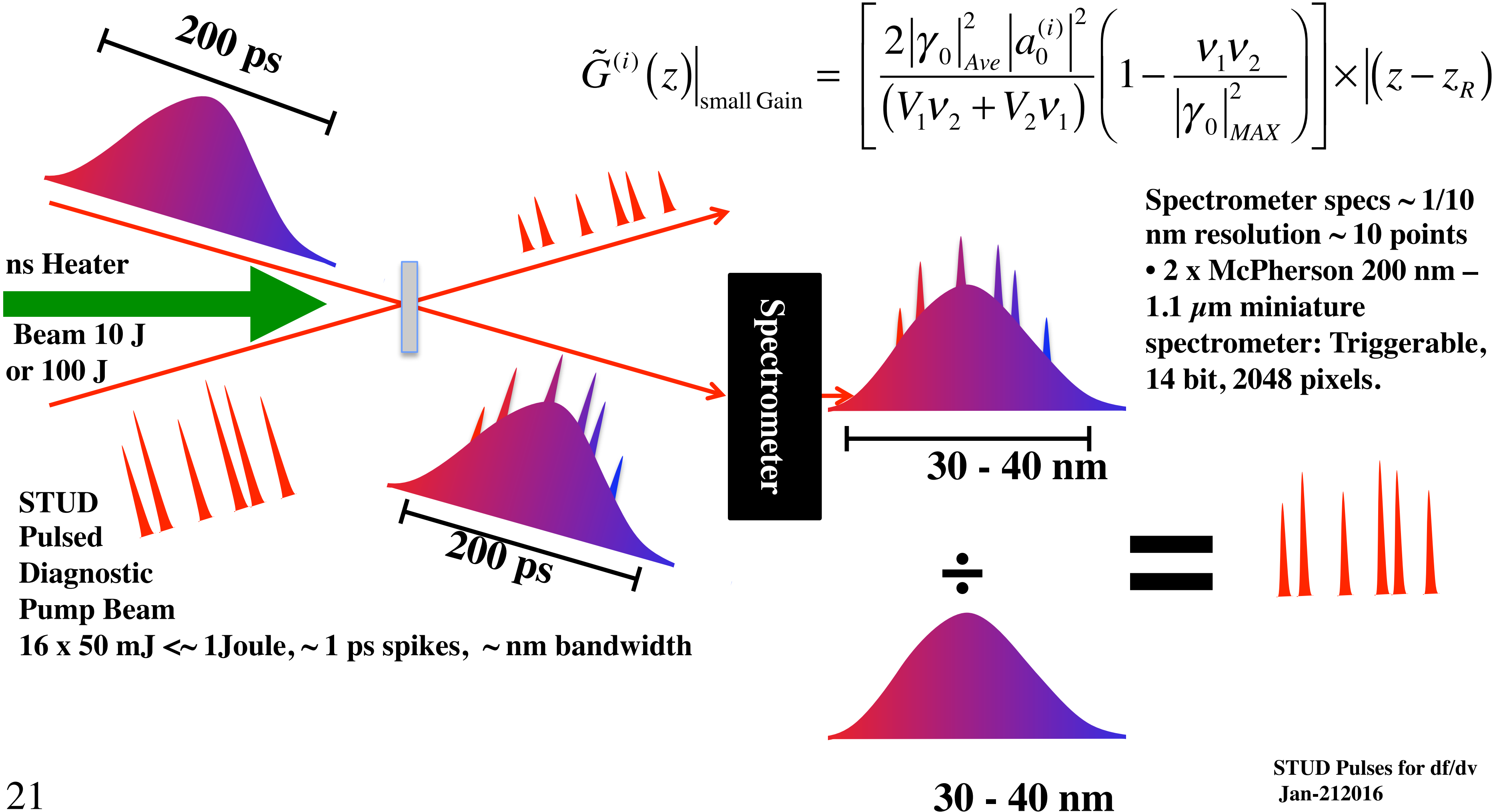
Probe Diag. Beam either a spectrally broadened and then stretched fiber laser, 1 μm wavelength, ~ 200 psec, ~ μJ, ~ 30 nm FWHM bandwidth. Amplitude Technologies, Imra.
Or a Ti:Sapphire pumped OPA tunable from 1 μm to 2 μm and doubled to cover 500 nm to 1 μm, ~100μJ, ~ 30 nm FWHM bandwidth. Coherent or Spectra Physics off the shelf.
The probe diag. beam is chirped so as to encode time to frequency at spectrometer: 5 ps / nm

$$\tilde{G}^{(i)}(z)\Big|_{\text{small Gain}} = \left[\frac{2|\gamma_0|^2_{Ave}\left|a_0^{(i)}\right|^2}{(V_1\nu_2+V_2\nu_1)}\left(1-\frac{\nu_1\nu_2}{|\gamma_0|^2_{MAX}}\right)\right]\times\left|(z-z_R)\right|$$



Spectrometer specs ~ 1/10 nm resolution ~ 10 points
- **2 x McPherson 200 nm – 1.1 μm miniature spectrometer: Triggerable, 14 bit, 2048 pixels.**

How Does SRS Amplification Evolce in Time with and w/o STUD Pulses?

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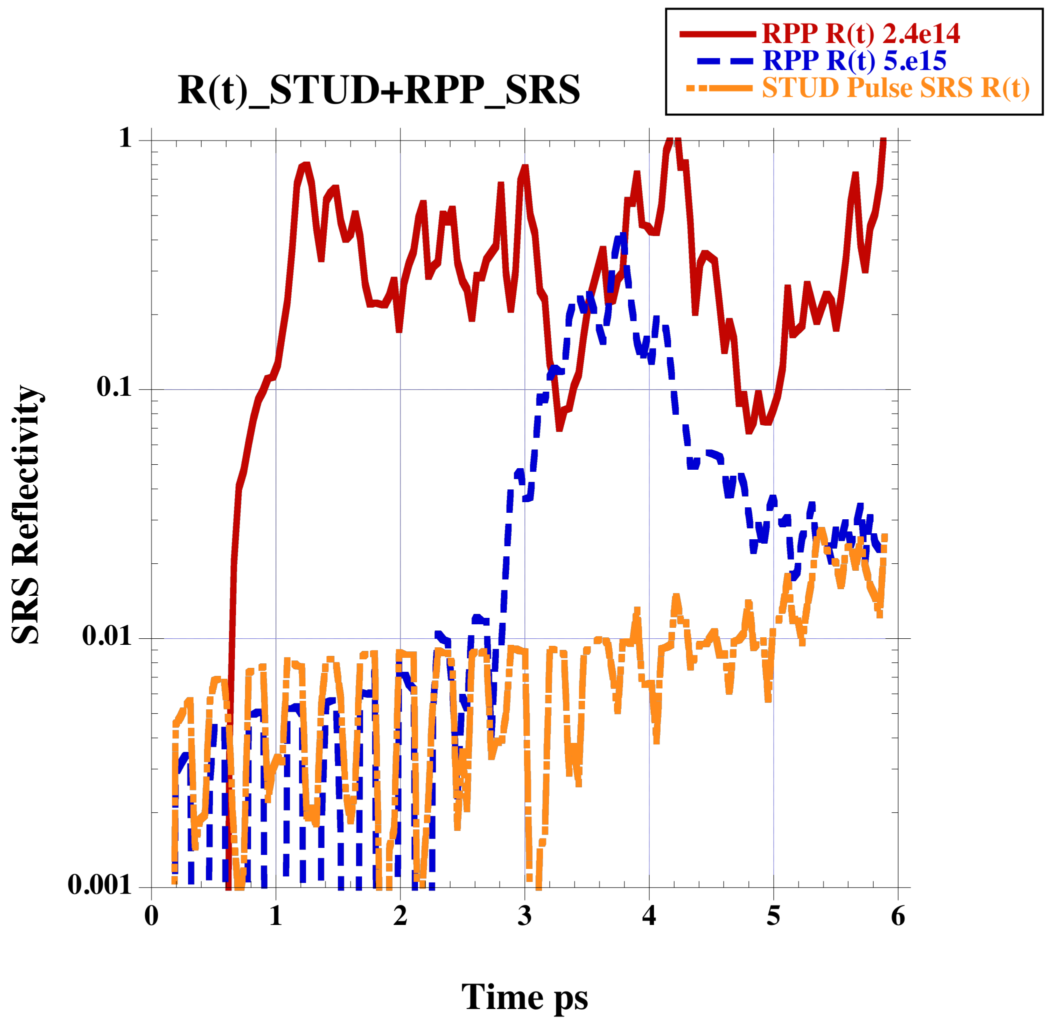
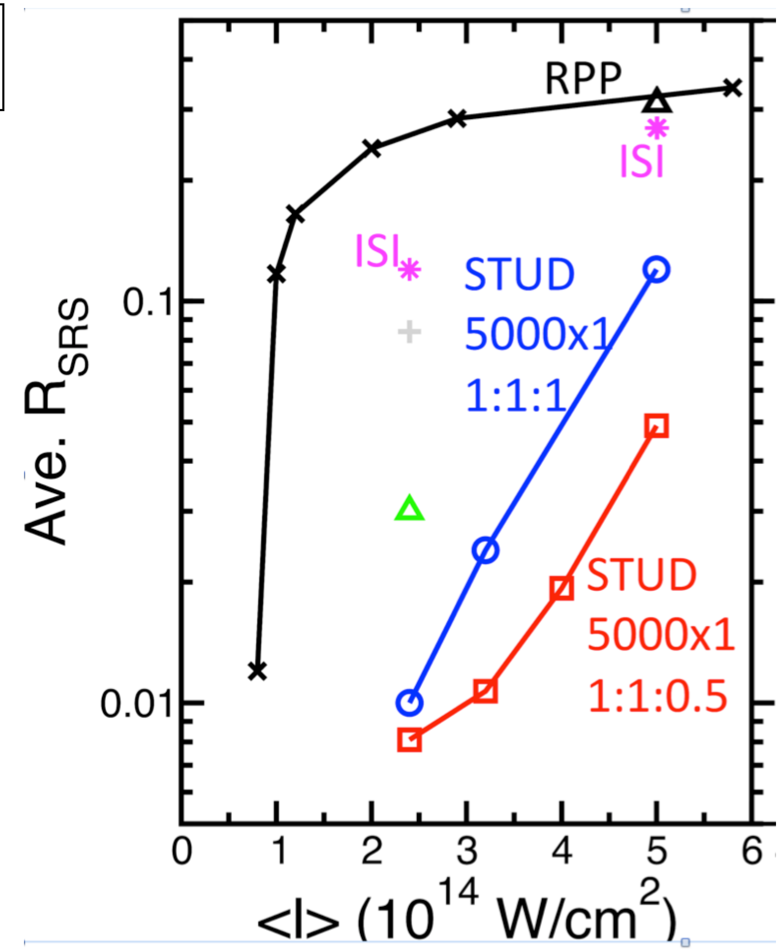
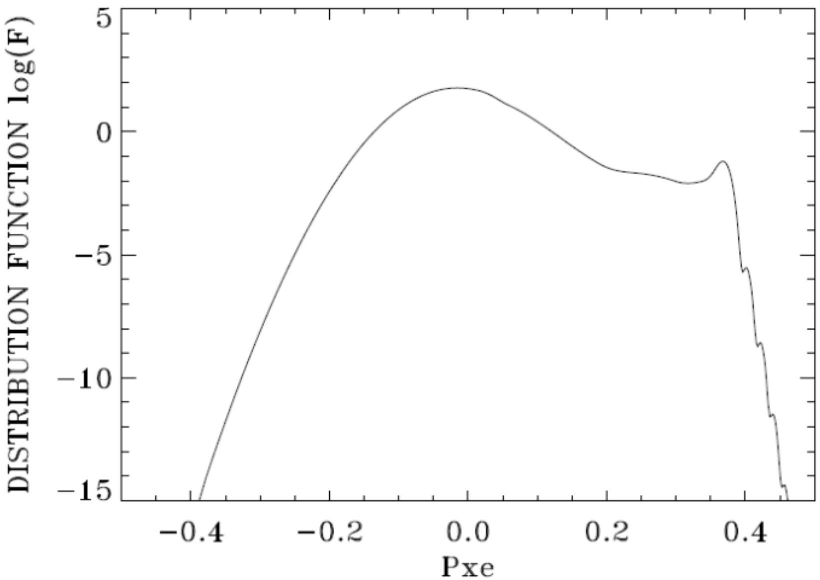
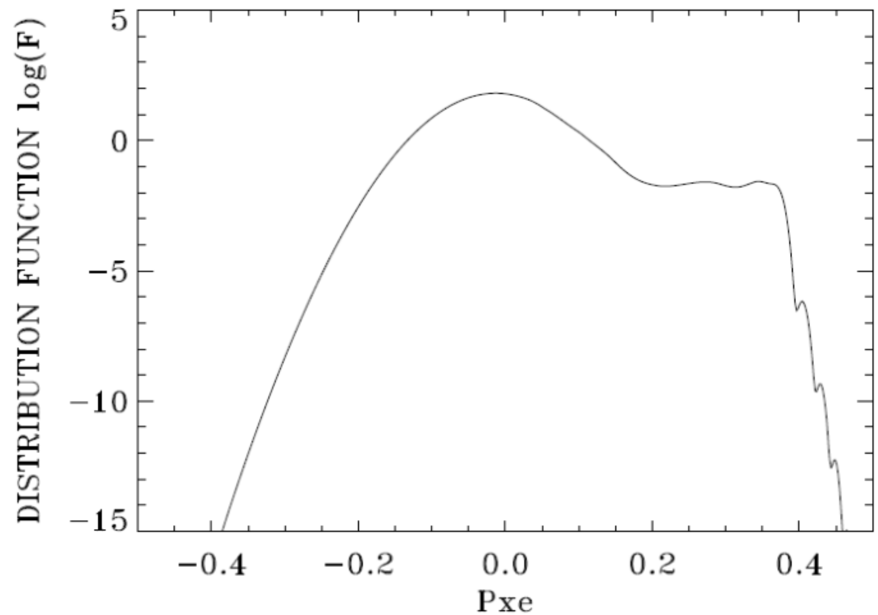
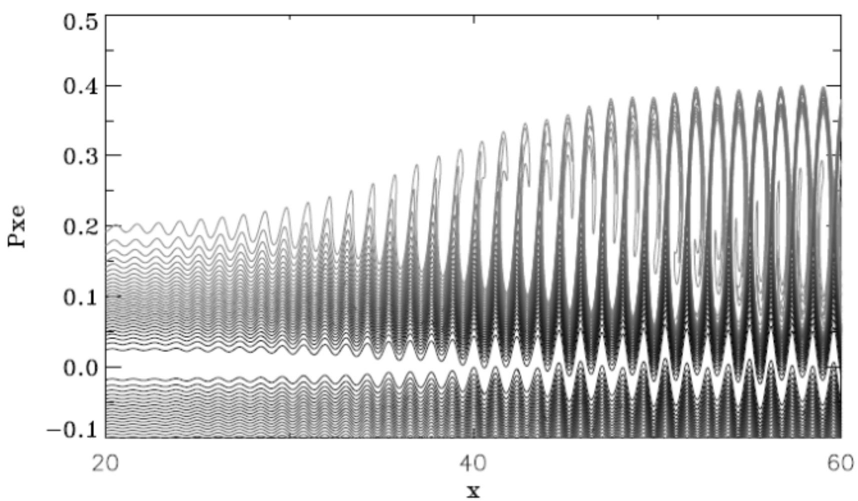


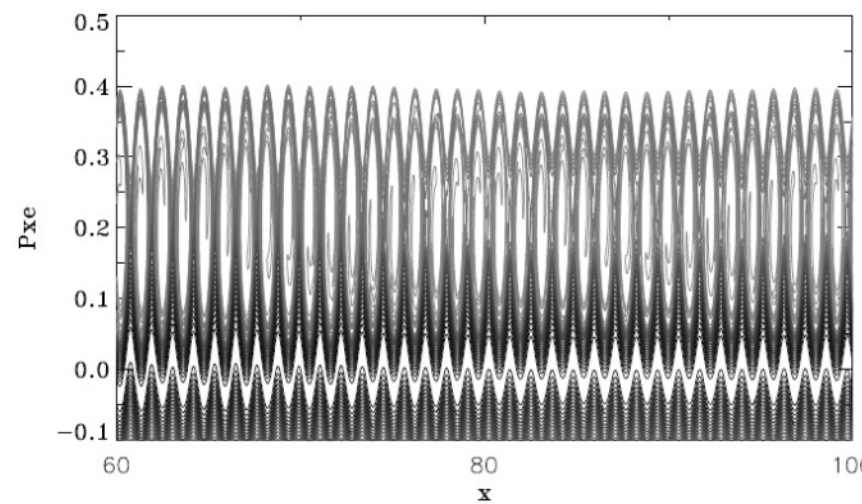


How Are e- VDF’s Modified In the Presence of Highly Nonlinear Kinetic SRS?

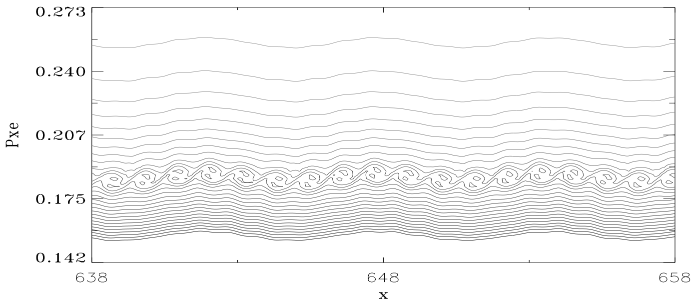


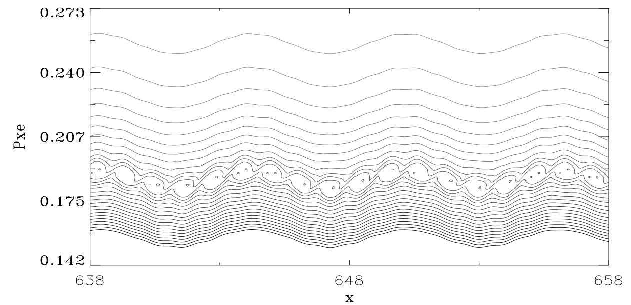


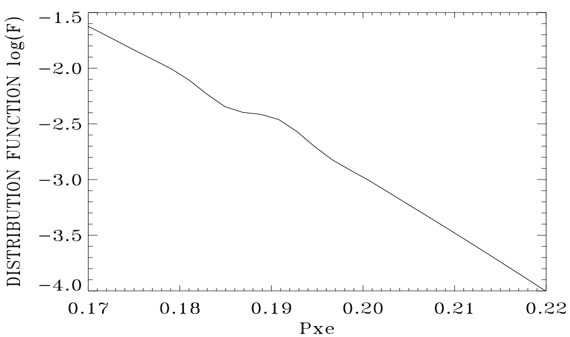


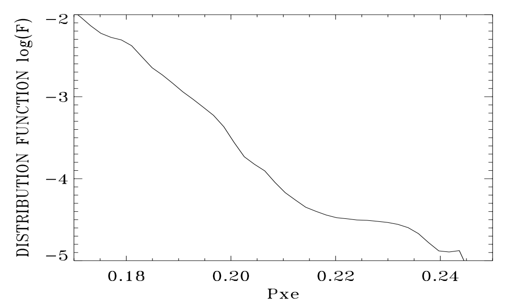


How About More Esoteric States? SRS + SKEENS





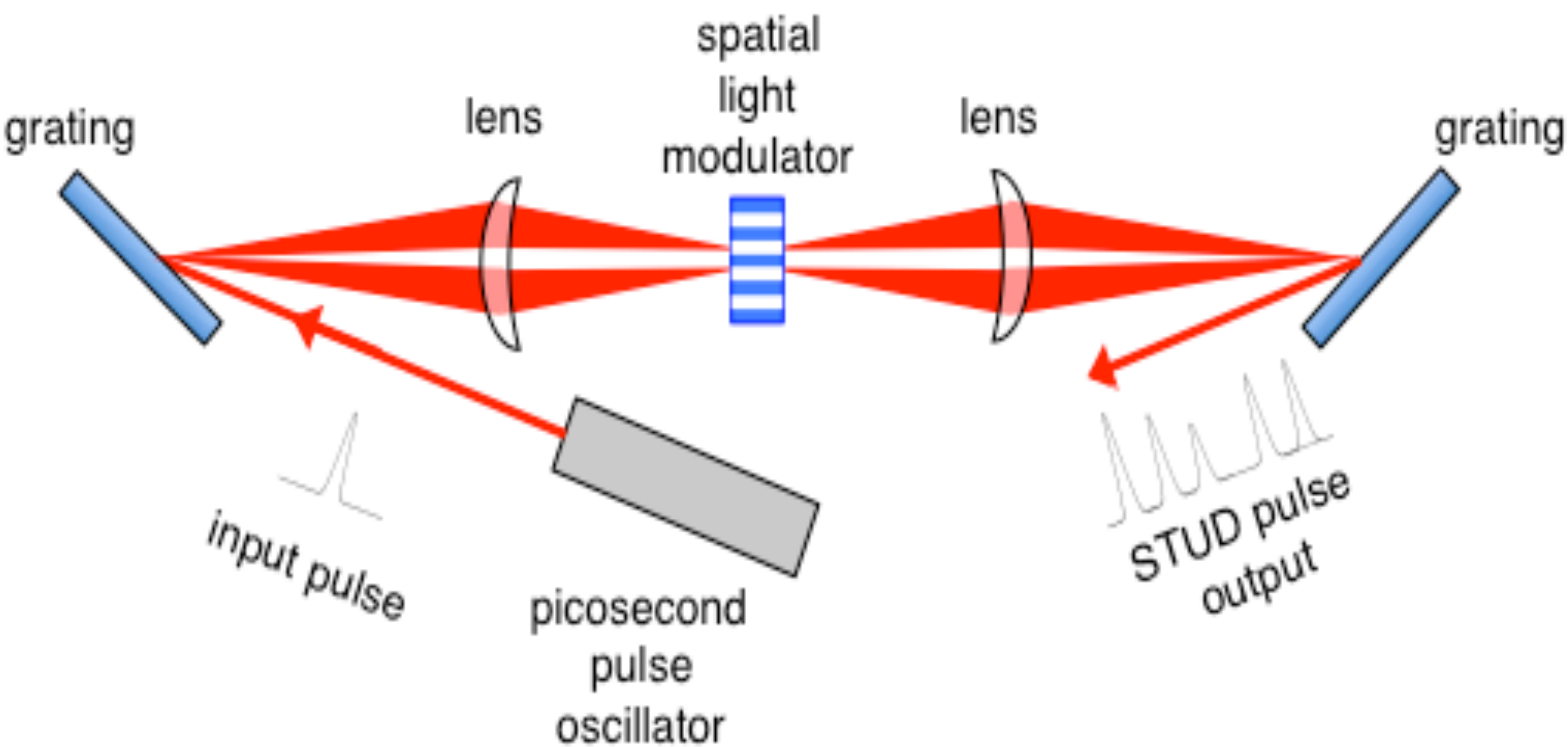




http://www.intechopen.com/books/references/computational-and-numerical-simulations/stimulated-raman-scattering-with-a-relativistic-vlasov-maxwell-code-cascades-of-nonstationary-nonlinear-interactions

Is a Conventional 4*f* System (Frequency Domain Pulse Sculpting) Good Enough to Generate STUD Pulses?

STUD Pulse Generator



Wiener, *Ultrafast Optics*, 2009

Ultrafast Waveform Generation Techniques Applicable to the Generation of STUD Pulses

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Technique	Temporal Resolution	Time-Bandwidth Product	Wavelength of operation
Time to frequency conversion and subsequent frequency-to-time conversion using time lens	100 fs (after aberration correction)	2000 (after aberration correction)	Visible, near-IR
4-*f* Pulse Shaper	100 fs	100	Visible, near-IR
Temporal compression using time lens (time telescope)	1 ps [1]	24 [1]	C and L bands

[1] M. A. Foster, R. Salem, Y. Okawachi, A. C. Turner-Foster, M. Lipson, and A. L. Gaeta, "Ultrafast waveform compression using a time-domain telescope,“ Nature Photonics 3, 581-585 (2009)

Preferred Time Lens Scheme Involves 4WM (using nonlinear waveguides with zero dispersion within the visible and uv bands, and femtosecond sources that operate at the zero dispersion wavelength of such waveguides)

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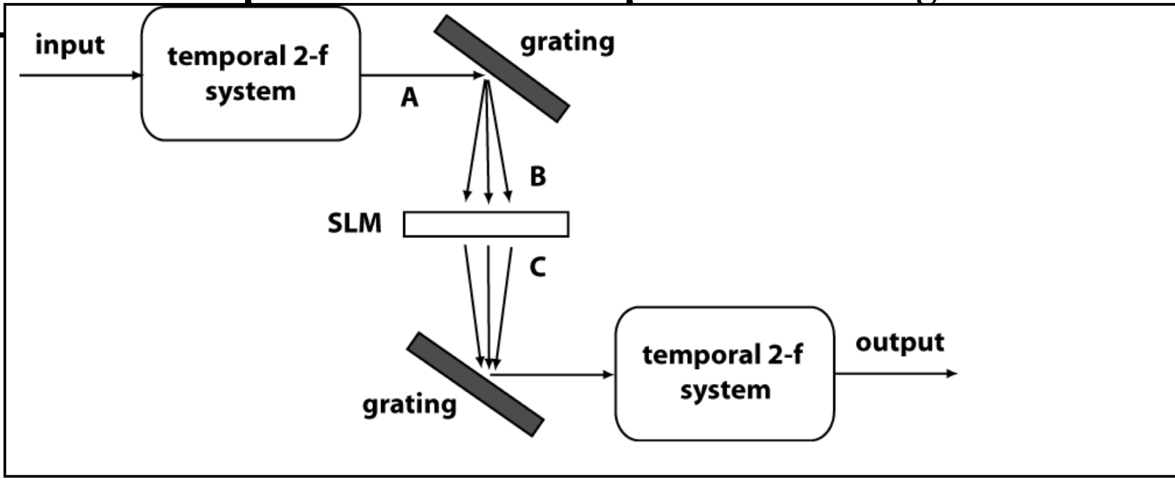
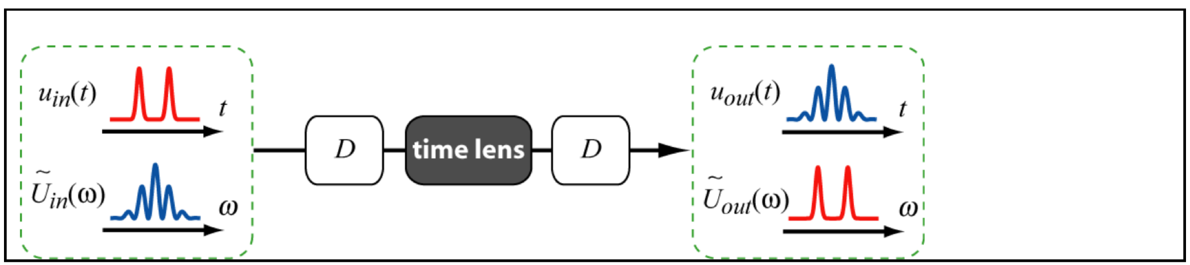


SLM: 1000 pixels, 10 μm pitch
4 nm bandwidth (100 fs) pump pulse

Gratings: 1800 lines/mm
Reciprocal linear dispersion P = 0.5 nm/mm
Effective focal length: 1 M.

L_{MAX}= 2 $\Delta\lambda$/ P = 16 mm

A time lens based system to generate STUD pulses encodes the time domain STUD pulse shape in the frequency domain directly. Need PCF with ZDW at 550nm or shorter.



GDD = FGD

Group Delay Dispersion in D =
Focal Delay Dispersion in time lens

$$\Delta\omega_{in} / \Delta t_{out} = D$$

$$\Delta\omega_{out} / \Delta t_{in} = -1/D$$

A Temporal 2*f* system is the basic building block of this time lens based systems.
It allows Fourier processing in the time domain.
To be used for both STUD pulse generation as well as for amplified Probe detection

M. A. Foster, R. Salem, D. F. Geraghty, A. C. Turner-Foster, M. Lipson, and A. L. Gaeta, "Silicon-chip-based ultrafast optical oscilloscope," Nature 456, 81-84 (2008)

R. Salem, M. A. Foster, A. C. Turner, D. F. Geraghty, M. Lipson, and A. L. Gaeta, “Optical time lens based on four-wave mixing on a silicon chip,” Opt. Lett. 33, 1047-1049 (2008)

Single-Shot Ultrafast Characterization Techniques

Technique	Temporal Resolution	Time-Bandwidth Product	Wavelength of operation	Measurement bandwidth
Time to frequency conversion using time lenses	100 fs (after aberration correction) 220 fs (demonstrated [1])	4000 (after aberration correction) 450 (demonstrated [1])	Visible, near-IR	4 THz
X-SPIDER	700 fs [2]	150 [2]	Visible, near-IR	0.5 THz
Time stretching using time lenses	100 fs (after aberration correction) 300 fs (demonstrated [3])	4000 (after aberration correction) 500 (demonstrated [3])	C and L bands	4 THz
Streak Camera	1 ps	100	Visible, near-IR	0.3 THz
FROG	10 fs	20	Visible, near-IR	40 THz
SPIDER	5 fs	10	Visible, near-IR	80 THz

[1] M. A. Foster, R. Salem, D. F. Geraghty, A. C. Turner-Foster, M. Lipson, and A. L. Gaeta, "Silicon-chip-based ultrafast optical oscilloscope," Nature 456, 81-84 (2008)

[2] Pasquazi, Alessia, Peccianti, Marco, Park, Yongwoo, Little, Brent E, Chu, Sai T, Morandotti, Roberto, Azana, Jose, Moss, David J "Sub-picosecond phase-sensitive optical pulse characterization on a chip" Nature Photonics Vol. 5, no. 10, pp. 618-623. Oct 2011

[3] www.picoluz.com (device specifications)

How Do Time Lenses Work in Time Dilation Mode?

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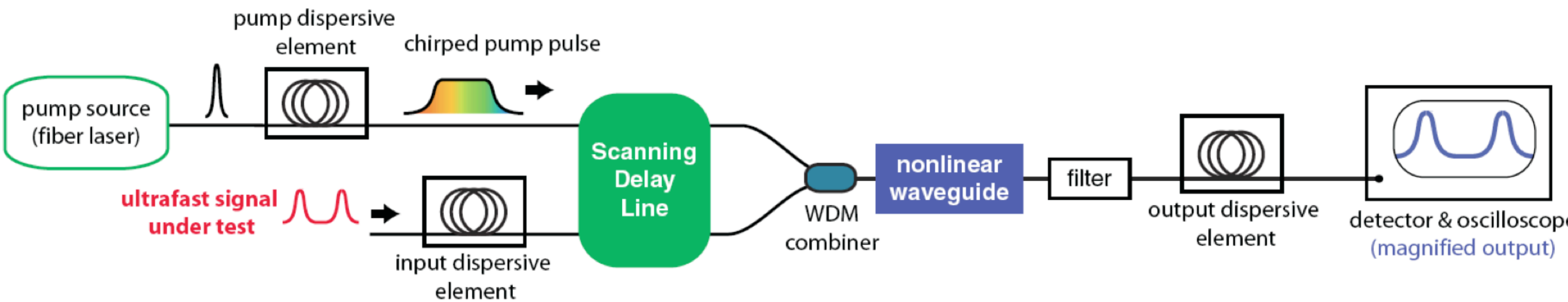

Schematic diagram showing the concept of temporal magnification, or "Time-Lens", using **nonlinear optical mixing in a waveguide**. The scanning delay line allows a delay between the measurement window and the input pulse. The measurement window is as large as 200-ps, with <1-ps resolution on a single shot. The nonlinear wave guide mixes the linearly chirped pulse with the input pulse, encoding the time-dependence of the input pulse on the chirped pulse. The input pulse is filtered out, and the **encoded chirped pulse stretches out in time via linear dispersion in a long fiber**. The stretched pulse is then measured using a conventional oscilloscope. Temporal magnification up to M=500 have been reported.

"**High-speed optical sampling using a silicon-chip temporal magnifier**," R. Salem, M.A. Foster, A.C. Turner-Foster, D.F. Geraghty, M. Lipson, A.L. Gaeta, *Optics Express* **17,** 4324 (2009)

5 Ingredients Are Needed to Execute the STUD Pulse Program on NIF:

- **Implement the SPA ACE Design of STUD Pulse Generation with 1-3 ps features lasting for 250 ps per box. Stack four boxes to get 1 ns. Repeat.**

- **Conduct experiments on Trident and Jupiter to test LPI control concepts via STUD pulses:**

  Use SPA ACE boxes. Develop and field fast diagnostics: OUFTS, etc. Measure df/dv (t).

- **Model CBET and SBS with deterministic to random STUD pulses in any Z plasma regime: from weak to strong damping limits and from weak to strong coupling regimes. Include any angle crossing beams: resolve laser wavelengths, 2^nd^ order in space.**

[a] Model laser propagation through NIF architecture with STUD pulses. Have parallel modeling capability of STUD pulse propagation in laser media as well as in plasmas of interest. 3ω and 2ω

- **Design targets with lower average power, lower radiation temperature but with higher capsule to case ratio and thinner ablators: more suitable for LPI control. Can this win?**

LLNL-PRES-677356
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory