Self-organization and Control in kinetic stimulated Raman backscattering

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Motivation

- Laser plasma interactions are a useful test-bed for exploring many nonlinear and complex plasma phenomena, such as resonant 3-wave parametric instabilities, a stimulated Raman scattering, in particular.

- In laser fusion concern is due to Backward SRS for energy and symmetry loss and target preheat. Large NIF target backscatter with bursts & broad spectra, hard to model in pF3D code for LPI.

- Toward **Exawatt** intensity regimes, relevant for nuclear and high-energy physics a new method based on Backward SRS (BRS) amplification was proposed. Experiments and PIC simulation show large BRS sensitivity and a narrow operation operational window.
Raman complexity - intermittent bursts & spectral broadening

(Hinkel, 2011)
Raman complexity - intermittent bursts & spectral broadening

(Hinkel, 2011)

(Yin, 2012 VPIC, LANL)

2013 US-Japan JIFT Workshop, Toki-shi
Outline

• Motivation

• Standard 3WI fluid model & absolute instability conditions

• EPW nonlinear frequency shift => Intermittency & broad spectra

• “Break-up” of Manley-Rowe invariants => Onset of nonstationarity

• Kinetic Raman saturation and Hybrid model (toy)

• FS coherent pulse generation by backward Raman in thin foils

• Future work
Important parametric 3WI in Laser Plasma Instabilities (LPI)

- Stimulated Raman scattering (SRS)
- Langmuir Decay Instability (LDI)
- Parametric Decay Instability (PDI)
- Stimulated Brillouin scattering (SBS)
- Two-plasmon Decay (TPD)

after D. Montgomery (LANL) PRL2002
Stimulated Raman Scattering (SRS)

The stimulated Raman scattering is a parametric decay of an incident EM wave into a scattered light and an electron plasma (EPW-Langmuir) wave. The matching condition for the frequencies and wave numbers are:

\[ \omega_0 = \omega_s + \omega_{EPW}, \quad k_0 = \pm k_s + k_{EPW}, \]

SRS matching condition

\[ k_0 = \frac{\omega_0}{c} \left( 1 - \frac{n}{n_{cr}} \right)^{1/2}, \]

\[ k_s = \frac{\omega_s}{c} \left( 1 - \frac{\omega_p^2}{\omega_0^2} \right)^{1/2}, \]

Analogous process to SRS, however, involving EMW scattering on an ion acoustic wave (IAW) : stimulated Brillouin scattering (SBS) instability
Laser fusion at NIF

Raman measurements and linear gain analyses agree in mid peak power, differ early and late

- “High Flux Model” (HFM) for rad-hydro:
  - DCA opacities, f=0.15 electron heat flux limiter
  - Cross-beam energy transfer: linear model w/ clamp
  - Measured backscatter removed

- Linear gain spectrum and measurements:
  - Early peak power: gain redshifted from measurement
  - Mid peak power: they agree well
  - Late peak power: gain redshifted again

- Overlapped laser (multi-quad) intensity:
  - Early peak power: gain spectrum blueshifted

- Gain and reflectivity time histories:
  - Early peak power: large reflectivity but small gain
  - Gain continuously increases in time
  - Reflectivity decreases late in peak power

Reflectivity vs linear gain=> anomalous!
C\(^3\) - Cascaded Conversion Compression

novel scheme for Exawatt to Zettawat, FS pulse generation

NIF & LMJ

Mourou, Fisch & Tajima, 2012

(Backward Raman Amplification)
Evolution of high-power laser systems

- 1960: Discovery of laser "a solution looking for a problem"
- 1960-1965: "Q-switched" & "mode-locked" lasers, intensity ~ $10^{12} \text{W/cm}^2$
- 1965-1985: Increase in laser intensity ~ $10^{15} \text{W/cm}^2$
- 1985: Discovery of CPA laser
- 1985+: quest toward (Ultra-) Relativistic intensities ~ $10^{18}$- $10^{24} \text{W/cm}^2$
C³ - Cascaded Conversion Compression

novel scheme for Exawatt to Zettawatt, FS pulse generation!

Original proposal of BRA compression of ultra relativistic laser (2 stage) failed in 2D PIC, due to “competitive instabilities”, (Fisch & Malkin, 2000-)

Mourou, Fisch & Tajima, 2012
The one-dimensional model of SRS, assumes a uniform plasma layer of thickness $L$, irradiated by a laser beam from $x < 0$, which enters the plasma at $x \geq 0$, boundary. The EPW and the scattered light are allowed to grow from their thermal noise levels ($\varepsilon_1$ and $\varepsilon_2$, respectively). Moreover, the EPW is subjected to a weak dissipation characterized by the linear damping rate $\nu_e$. The nonlinear 3WI model derived here for the case of SRS describes the spatiotemporal evolution of complex amplitudes of the pump ($a_0$), scattered ($a_1$) and EPW ($a_2$) in a weakly coupling approximation. These equations are obtained from Maxwell's and fluid vlasma equaions in WKB approximation, assuming the resonant matching between frequencies and wave numbers of three waves ($\omega_0 = \omega_1 + \omega_2, k_0 = k_1 + k_2$) closely satisfying the corresponding linear dispersion relations

$$\omega_{0,1}^2 = \omega_{pe}^2 + k_{0,1}^2 c^2, \quad \omega_2^2 = \omega_{pe}^2 + 3k_2^2 v_{te}^2,$$

(3.34)

where indices 0, 1, and 2 stand for the pump, scattered, and EPW, respectively; $\omega_{pe}$ for electron plasma frequency; and $v_{te}$ for electron thermal velocity. For the case of backscattering, which is of most practical importance, the corresponding set of 3WI equations reads [102]

$$\frac{\partial a_0}{\partial \tau} + V_0 \frac{\partial a_0}{\partial \xi} = -a_1 a_2,$$

$$\frac{\partial a_1}{\partial \tau} - V_1 \frac{\partial a_1}{\partial \xi} = a_0 a_2^*,$$

$$\frac{\partial a_2}{\partial \tau} + V_2 \frac{\partial a_2}{\partial \xi} = \beta_0^2 a_0 a_1^*,$$

(3.35)

with time and space variables $\tau = \omega_0 t, \xi = x/L$, where the dimensionless amplitudes of the coupled waves are related to the physical quantities, electric fields $E_0$ and $E_1$ of the two electromagnetic waves, and EPW-driven electron density fluctuation $\delta n_e$,

$$\beta_0 \equiv \frac{V_{osc}}{c} = \frac{e E_0}{m_e \omega_0 c}, \quad \delta = \frac{3\omega_0^2 \omega_1}{c^2 \omega_{pe} k_2^2}$$

Skoric, et al. PRE1996

Laser pump strength

Relativistic NL freq. shift
Nonlinear Stimulated Raman Backscattering

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\frac{\partial a_2}{\partial \tau} + V_2 \frac{\partial a_2}{\partial \xi} &= \beta_0^2 a_0 a_1^* - \Gamma a_2 + i\delta |a_2|^2 a_2^*,
\end{align*}
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with time and space variables $\tau = \omega_0 t, \xi = x/L$, where the dimensionless amplitudes of the coupled waves are related to the physical quantities, electric fields $E_0$ and $E_1$ of the two electromagnetic waves, and EPW-driven electron density fluctuation $\delta n_e$,

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e.g. Rosenbluth et al., 1971

---

Nonlinear EPW shift due to e.g. electron trapping/LDI/ relativistic
The most useful information on the SRS is contained in the reflectivity $R$, which designates a fraction of incident laser intensity reflected backward

$$ R = \frac{V_0 |a_1(0)|^2}{V_1 |a_0(0)|^2} $$

(3.41)

with its maximum value normalized to unity in the stationary case. To solve (3.35), appropriate initial and boundary conditions are required. We choose physically realistic boundary conditions, while the choice of the plasma slab length satisfies the criterion for the occurrence of the absolute instability. The wave amplitudes obey the corresponding initial and nonzero source fixed boundary conditions,

$$ a_0(x, 0) = 0 \quad \text{(for} \ x > 0) , a_0(0, t) = A_0 $$

$$ a_1(x, 0) = a_1(L, t) = \varepsilon_1 A_0 \quad a_2(x, 0) = a_2(x, t) = 0 $$

(3.42)

where $A_0$ follows from (3.36) for $E_0(0) = \varepsilon_0$.

Analysis has shown that $V_1V_2 > 0$, gives the convective instability, while for $V_1V_2 < 0$, absolute instability appears, if the additional condition is satisfied, namely

$$ \frac{\gamma_0^2 l^2}{|V_1V_2|} > \frac{\pi^2}{4} . $$

where $\gamma_0$ is the uniform linear parametric instability growth rate and $l$ is the length of the system.

$$ \gamma_0 \approx 0.5 \beta_0 \sqrt{\alpha / (1 - \alpha)} \omega_0 , \quad \alpha = \omega_{pe} / \omega_0 = \sqrt{n/n_{cr}} $$
Bifurcations to low-dimensional Chaos in B-SRS

By varying the control (laser & plasma) parameters, Route to chaos in space-time in 3WI relativistic B-SRS is found: via steady-state, periodic, quasi-periodic and intermittent transition to chaos. Complexities in non-stationary bwd-Raman regimes include, strong spiky-burst like temporal Reflectivity & broadened blue-shifted incoherent spectra.

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\frac{\partial a_0}{\partial \tau} + V_0 \frac{\partial a_0}{\partial \xi} &= -a_1 a_2, \\
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with time and space variables \( \tau = \omega_0 t, \xi = x/L \), where the dimensionless amplitudes of the coupled waves are related to the physical quantities, electric fields \( E_0 \) and \( E_1 \) of the two electromagnetic waves, and EPW-driven electron density fluctuation \( \delta n_e \),

\[
\beta_0 \equiv \frac{v_{osc}}{c} = \frac{eE_0}{m_e\omega_0 c}
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**Fixed point steady state**
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Reflectivity, power spectrum & phase diagram

As the relative pump strength $\beta_0$ increases, starting from the value 0.01, the attractor changes according to the symbolic sequence

$$FP \rightarrow P \rightarrow QP \rightarrow I \rightarrow C$$

where $FP$ stands for unimodal fixed point, $P$ for periodic, $QP$ for quasiperiodic, $I$ for intermittent, and $C$ for chaos. The quantitative boundaries in $\beta_0$ between successive attractors are depicted in Fig. 3.1.

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see, Skoric et al. LIRPP1993; PRE1996
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Intermittency

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![Attractor sequence diagram](image)

Figure 1: Time evolution of the reflectivity of stimulated Raman backscattering for the parameters: $\gamma_{n0} = 0.005 \times 10^{-3} \times \omega_p$, $\nu_e = 10^{-3} \times \omega_p$, $n_0 = 0.1 n_{cr}$, $L = 100 \times \omega_p$, $T_e = 1$ keV.

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\[
\beta_0 \equiv \frac{v_{osc}}{c} = \frac{e\mathcal{E}_0}{m_e \omega_0 c}
\]

\( L \) -Under-dense Plasma layer
Manly-Rowe “breaks” => Nonstationary relativistic SRS

Introducing the linear and nonlinear phase shift terms in the system of equations in the steady state \( \frac{\partial}{\partial t} \to 0 \), conserved quantities (invariants) are calculated as

\[
\alpha_i(x, t) = A_i(x, t) e^{i\phi_i(x, t)} \quad \text{total phase shift is } \phi = \phi_0 - \phi_1 - \phi_2
\]

where \( A_i \) and \( \phi_i \) is the amplitude and phase of the wave \((i = 0, 1, 2)\), respectively.

\[
m_0 = V_0 n_0(x) - V_1 n_1(x) = \text{const.}, \tag{3.27}
\]

\[
m_1 = V_0 n_0(x) + V_2 n_2(x) = \text{const.},
\]

\[
K(x) = A_0 A_1 A_2 \sin \phi - \frac{\sigma}{4} A_2^4 - \frac{\delta}{2} A_2^2 = \text{const.}
\]

with \( n_i(x) = A_i(x)^2 \). For boundary conditions

\[
n_0(0) = 1, n_1(L) = 0, n_2(0) = 0 \tag{3.28}
\]

the third invariant becomes \( K(0) = 0 \). However, at the other boundary \( x = L \), from (3.20), one calculates \( K(L) \neq 0 \); which breaks the invariance condition, i.e., \( K(x) \neq \text{const.} \), hence, contradicts our basic assumption of the steady state. This simple argument, due to Škorić (1997) based on a nonlinear phase mismatch, explains a generic cause of nonstationarity in 3WI processes, such as, e.g., nonlinear stimulated Raman (also Brilloiun) instability saturation in laser plasma interactions.

Skoric AIP, 1997, 2009
Manly-Rowe “breaks” => Nonstationary BRS saturation

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m_0 = V_0n_0(x) - V_1n_1(x) = \text{const.},
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Generic cause for intermittent bursts and spectral broadening in BRS saturation, and poor scaling in Raman amplification!?

e.g., Malkin & Fisch, PoP 2000-2006; see R. Trines et al. PRL & Nature Phys. 2011

\[\text{Manly-Rowe relations} \quad \text{e.g., Forslund, PF 1975}
\]

\[\text{Skoric, 1996, details in Book, Ch12}
\]

\[\text{Kono & Skoric, Springer (2010)}\]
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By varying the control (laser & plasma) parameters, Route to chaos in space-time in 3WI relativistic B-SRS is found: via steady-state, periodic, quasi-periodic and intermittent transition to chaos. Complexities in non-stationary bwd-Raman regimes include, strong spiky-burst like temporal Reflectivity & broadened blue-shifted incoherent spectra.

As the relative pump strength $\beta_0$ increases, starting from the value 0.01, the attractor changes according to the symbolic sequence -> absolute BRS

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where FP stands for unimodal fixed point, P for periodic, QP for quasiperiodic, I for intermittent, and C for chaos. The quantitative boundaries in $\beta_0$ between successive attractors are depicted in Fig. 3.1.

<table>
<thead>
<tr>
<th>FP</th>
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<th>QP (mode locking)</th>
<th>I</th>
<th>C</th>
</tr>
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<tbody>
<tr>
<td>0.01</td>
<td>0.020</td>
<td>0.026</td>
<td>0.3</td>
<td>0.6</td>
</tr>
</tbody>
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Figure 1: Time evolution of the reflectivity of stimulated Raman backscattering for the parameters: $\gamma_{BS} = 0.005 \times 10^3$, $\nu_0 = 10^{-3} \omega_p$, $n_0 = 0.1 n_{cr}$, $L = 100 \, \text{cm}$, $T_e = 1 \, \text{keV}$.

Reflectivity, power spectrum & phase diagram
The Great Wave off Kanazawa
神奈川沖浪裏
by K. Hokusai (1832, Edo)
Quantitative Signature of Spatio-Temporal of Raman Complexity

Open convective spatially-extended weakly-confined dissipative model => Quasi-periodic route to Intermittency

The Topological dimension calculated by the Singular Value Decomposition-SVD

ST- Intermittency in plasma waves

FIG. 13. Topological dimension of the electron plasma wave attractor for various values of the relative pump strength $\beta_0$. 
Control of stimulated Raman backscattering by EPW damping ($L_a$)

Fig. 1. Temporal development of SRS reflectivity in a homogeneous plasma layer for: $\beta_0 = 0.03$, $n_0 = 0.1n_{cr}$, $L = 100c/\omega_0$, $\kappa T_e = 1$ keV, $\varepsilon = 10^{-3}$ and for EPW damping rates $\Gamma/\omega_{pe}$: (a) $2 \times 10^{-2}$, (b) $10^{-3}$, (c) $10^{-4}$, (d) $10^{-5}$. 
Control of stimulated Raman backscatter
-Bifurcation diagram for onset of Complexity-

Figure 1. Raman complexity in time ($10^3/\omega_0$) versus EPW damping rate $\Gamma/\omega_{pe}$: (a) 0.06, (c) 0.018, (d) 0.012, for $\beta_0 = 0.1$, $n_0 = 0.1n_{cr}$, $L = 100c/\omega_0$, $T_e = 1keV$ and Bifurcation diagrams for onset of complexity (c) ($\Gamma - \beta_0$) and ($\Gamma - n_0$) for (f) $\beta_0 = 0.03$, (g) $\beta_0 = 0.1$

Useful for parametric survey of plasma conditions for BRS
Pulsations and bursts in kinetic stimulated Raman Backscattering (PIC)

Miyamoto, Skoric, Mima, 1998

Fig. 4. PIC simulations results for reflectivity versus time and frequency spectra for different pump intensities $\beta_0$: (a) 0.02, (b) 0.05, (c) 0.05; show a general agreement with 3WI scenario (Figs. 1 and 2) displaying threshold for absolute SRS and increasing backscatting complexity through quasi-periodic and intermittent bursting evolution. The spectra are calculated for times before suppression (full line) and for the entire time of evolution (dotted line), to show relativistic blue-shift, quasi-periodic modulations and increase broadening due to intermittent incoherence.
Simulations of Anomalous Stimulated Raman Backscattering

(a) \( \beta_0 = 0.02 \quad \omega_0 t = 6300 \)

(b) \( \beta_0 = 0.03 \quad \omega_0 t = 4200 \)

(c) \( \beta_0 = 0.03 \quad \omega_0 t = 8400 \)

(d) \( \beta_0 = 0.02 \quad \omega_0 t = 6300 \)

(e) \( \beta_0 = 0.03 \quad \omega_0 t = 4200 \)

(f) \( \beta_0 = 0.03 \quad \omega_0 t = 8400 \)
Control of stimulated Raman Backscattering Complexity

• Absolute instability condition is satisfied in uniform plasma, driving a large BRS signal from a background noise. e.g., for moderate pump, $I \sim 10^{14} \text{ W/cm}^2$, over ~10 microns in 10% $N_{cr}$; absolute Raman dominates

• It sets for interaction length- $L_0$ shorter than, both, plasma-$L$ and absorption length-$L_a$: $L_0 = (V_e V_s)^{1/2}/\gamma_0$; $L_a = V_e / \nu_e$; $\gamma_0$ -growth rate, $V_e$ and $V_s$, group velocity

• $L_0$ and $L_a$ very in time with plasma parameters; hot electrons, bulk temperature-growth suppress Raman!
Kinetic-hybrid dissipative (toy) model of stimulated Raman Backscattering

\[ \frac{\partial a_0}{\partial \tau} + V_0 \frac{\partial a_0}{\partial \xi} = -a_1 a_2, \]

\[ \frac{\partial a_1}{\partial \tau} - V_1 \frac{\partial a_1}{\partial \xi} = a_0 a_2^*, \]

\[ \frac{\partial a_2}{\partial \tau} + V_2 \frac{\partial a_2}{\partial \xi} + \gamma a_2 + i\sigma |a_2|^2 a_2 = \beta_0^2 a_0 a_1^*, \]

\( \gamma \) – effective “kinetic” dissipation (hot electrons/trapping)


2013 US-Japan JIFT Workshop, Toki-shi
We start by assuming the electron distribution function, for thermal (bulk) and hot component, to be approximated by bi-Maxwellian

\[ F(x,t,v) = n_h(x,t)f_h(v) + n_b(x,t)f_b(v), \] (9)

where \( n_h \) and \( n_b (\gg n_h) \) stand for slowly varying hot and bulk electron densities, respectively, with each \( f(v) \) normalized to unity. We assume that the total hot electron current includes a source term due to trapped resonant electrons (in the thermal Maxwellian tail). Therefore we write

\[ j_h(x,t) = \int_{v_{ho}}^{\infty} vF(v)dv = n_h(x,t) \int_{-\infty}^{\infty} vf_{h}(v)dv \]

\[ + n_b(x,t) \int_{v_{ph}^{+}v_{tr}}^{v_{ph}^{-}v_{tr}} vf_{b}(v)dv, \] (10)

where \( v_{ph} \) is the plasma wave phase velocity and \( v_{tr} \) stands for average velocity of resonant electrons (with \( v \sim v_{ph} \)) trapped in a trough of a large amplitude plasma wave \[4\].
Hot electron balance

\[ \frac{d}{dt} n_h(x,t) = \frac{\partial}{\partial t} n_h(x,t) + \text{div} j_h = 0 \]  

(11)

or, after performing the spatial average, defined as

\[ \langle \cdots \rangle_L \sim \frac{1}{L} \int_0^L (\cdots) dx, \]

(12)

where \( n_h(t) \) is hot density averaged over the plasma length \( L \), we obtain

\[ \frac{d}{dt} n_h(x,t) + \frac{1}{L} j_h(x,t)|_0^L = 0. \]  

(13)

Using the electron current one gets equation for the hot electron generation

\[ \frac{dn_h(t)}{dt} = \frac{n_h(L,t)}{L} \int_{v_{ph} - v_{tr}(L,t)}^{v_{ph} + v_{tr}(L,t)} v f_h d\nu - \kappa n_h(t). \]  

(14)

We note \( v_{tr}(0,t) = 0 \) due to the boundary condition for a plasma wave. The loss term is due to electrons which escape through open plasma boundaries, with \( \kappa = k v_h / L = k v_{ph} / L \), and \( k = 1 \) and 2 for a free streaming and a Maxwellian flow,
we introduce the spatially integrated plasma wave energy density, through

\[ W(t) = \frac{1}{L} \int_0^L \frac{1}{8\pi} |E(x,t)|^2 dx. \quad (15) \]

The rate of plasma wave energy dissipation through linear and nonlinear processes is

\[ 2 \gamma(t)W(t) = 2 \gamma_{Landau}(t)W(t) \]
\[ + \frac{mn_b(L,t)}{2L} \int_{v_{ph} - v_{tr}(L,t)}^{v_{ph} + v_{tr}(L,t)} v^2 f_b(v) dv, \]

(16)

where an integral term, gives a nonlinear term in a plasma wave damping, thus determining the value of \( \gamma_{nl} \).

**Thermal bulk energy balance**

\[ \frac{d}{dt} \left[ n_b(t)T_b(t) \right] = 2 \gamma W(t) - \frac{d}{dt} \left[ n_h(t)T_h(t) \right] \]
\[ - \frac{k}{L} \left[ \Phi_{th} + \Phi_h - \Phi_q \right]|_0^L, \quad (19) \]

where we have introduced \( \Phi_q \) as the return flux of fresh ambient electrons through an open plasma boundary (vide
Self-organization at Micro & Macro scales versus $k$-transport coefficient (inhibition)

Closed system (exploding foil)

$\beta_0 = 0.025$, $n = 0.1n_{cr}$, $L = 100\ c/\omega_0$, $T_e = 0.5\ KeV$
Self-organization at Micro & Macro scales
versus $k$- transport coefficient (inhibition)

Closed system (exploding foil)

Open system (large plasma)

$\beta_0 = 0.025$, $n = 0.1 n_{cr}$, $L = 100 c / \omega_0$, $T_e = 0.5$ KeV
Self-organization at Micro & Macro scales versus $k$-transport coefficient (inhibition)

Closed system (exploding foil)

Open system (large plasma)

Coherent pulsations

$\beta_0 = 0.025$, $n = 0.1n_{cr}$, $L = 100 \, c/\omega_0$, $T_e = 0.5 \, \text{KeV}$
FIG. 11. Three-dimensional view of the electron velocity distribution in time for different saturated Raman regimes, as indicated by values of parameter $k$. Microkinetic scale self-organization of varying complexity is revealed in both thermal and suprathermal
FIG. 13. Simulation data for the Raman reflectivity in time obtained by a 1 ¼ electromagnetic, relativistic, particle-in-cell code (after Miyamoto et al. [13]). Initial plasma parameters were the same as above, with a pump equal to 0.02.
FS Pulse Generation by Backward Raman Compression in a Thin Foil Plasma

Skoric, Mima et al. LIRPP (AIP), 1997

3WI coupled model

QP Pulsation regime!

FIGURE 1. Time series of Raman reflectivity slightly above bifurcation threshold for transition into quasiperiodic regime for plasma parameters \(n_0 = 0.1n_{cr}, L = 0.75\lambda_0\) and: a) \(T_e = 1\) keV, \(\beta_0 = 0.26\), b) \(T_e = 5\) keV, \(\beta_0 = 0.68\).
FIGURE 2. Pulse length $T/T_0$ (full line) and laser intensity $\beta_0$ (broken line) versus plasma foil thickness $L$ with corresponding peak reflectivity for plasma temperatures of 1 keV (triangles) and 5 keV (dots). Plasma is underdense ($n_0 = 0.1n_{cr}$); $\lambda_0$ and $T_0$ are the laser wavelength and period, respectively.
FIGURE 3. PIC simulation reflectivity versus time for two different pump intensities $\beta_0$: a) 0.02, b) 0.03. For the fundamental wavelength 1.06 $\mu$m, the pulse lengths are estimated to approximately 1 ps and 0.5 ps, respectively. Plasma is underdense: $n_0 = 0.1n_{cr}$, $T_e = 0.5$ keV and $L = 16\lambda_0$. 

Particle simulations
Single compressed pulse!

Pulsations suppressed by hot / bulk electron heating
Raman compression to FS pulses in a exploding foil plasma- PIC code

Single tailored pulse < 50 fs

$T = 500 \text{eV}$
$a_0 = 0.6$
$n = 0.25 n_{cr}$
$L = 8 \lambda_0$
Raman compression to FS pulses in thin exploding foil plasma- PIC code

Single pulse < 10 fs

Reflectivity

$T = 500 \text{eV}$
$a = 0.5$
$n = 0.25n_{cr}$
$L = 4\lambda_0$
Raman compression to FS pulses in a exploding foil plasma- 1D PIC

NO single pulse- Incoherent BRS

\[ T = 500 \text{eV} \]
\[ a_0 = 0.2 \]
\[ n = 0.25 n_{CR} \]
\[ L = 8 \lambda_0 \]
Future work on Control of Raman complexity

- By relativistic 1D PIC simulations test feasibility and scaling of FS pulse compression by BRS in thin foils (~ 1 micron), against 3WI model

- By relativistic 2D PIC test the robustness of BRS compression in competition with parametric inst.: forward & side SRS, self-focusing..

- Parametric study by hybrid BRS model, conditions for suppression of Raman complexity in fusion targets ("Raman map")
Thank you ...!
Plasma and Fusion Science - PhD course
National Institute for Fusion Science
Toki, Japan

http://soken.nifs.ac.jp/index.html