Parallel PIC simulations of high-energy density science involving laser and beam transport related to ICF

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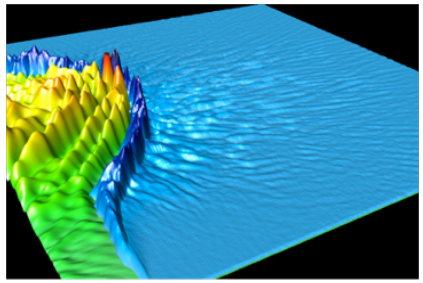
** *Now at IST*



Work supported by DOE-NNSA: DE-FG52-09NA29552

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Suite of Parallel PIC codes at UCLA: Unique!

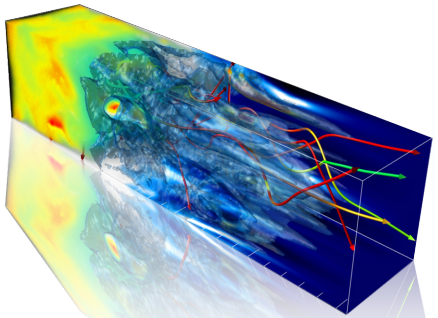
- **OSIRIS**
  - FDTD
  - Local field solver
  - Dynamic Load balancing
  - Two particle collision model
  - New Hybrid model for modeling dense collisional plasmas (Cohen et al.)
- **PARSEC**
  - Spectral field solver (Superior accuracy and noise properties)
  - Two particle collision model
- **UPIC**
  - Framework for parallel PIC
  - Supports Electrostatic, Darwin, and Electromagnetic Spectral field solvers
  - Gridless model
  - Algorithm for GPUs
  - Dynamic Load balancing
  - Optimized parallel particle manager
- Scale to **300,000+** processors, higher order particle shapes
- **Extended diagnostics and data analysis: VizXD**

OSIRIS 2.0

osiris v2.0

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST



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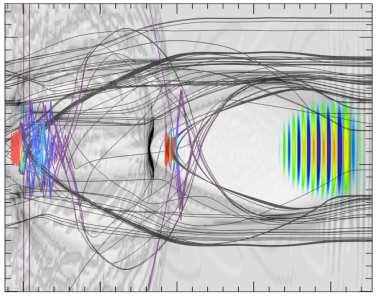
http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/



New Features

- High-order splines
- Binary Collision Module
- PML absorbing BC
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- Parallel I/O
- Scales to 300,000+ cores
- Runs on vector units

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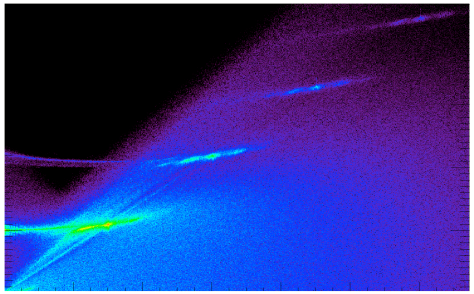
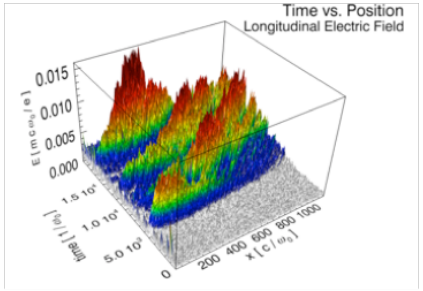
Anomalously Hot Electrons, Kinetic Inflation, and Plasma Wave Localization

Simulations of relevance to SRS on NIF and to IFE





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*Work supported by DOE grant DE-FG52-06NA26195

Simulations performed on the UCLA Hoffman 2 Cluster

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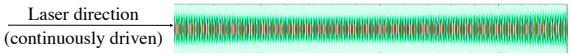
Simulation Parameters – Part I

- 1D/2D simulations with the electromagnetic particle-in-cell code OSIRIS
  - 512/256 ppc, dx~λ_D, t_{max} = 4-10ps



Runs with both constant density and linear gradient and fixed and mobile ions

1D

- Length = 180 μm ($8f^2\lambda_0$ for 3ω laser with *f*/# = 8)
- T_e = 2.5 – 3 keV
- H+ ions with ZT_e/T_i = 1 – 5
- n/n_{cr} = 0.09-0.11
- λ_{laser} = 0.351 μm, I_{laser} = 2-3 x 10^{15} W/cm^2
  - v_{osc}/c = 0.013, 0.016

2D

- 100μm x 14μm, laser spot width = 2.4μm, I_{focus} = 3.6x10^{15} W/cm^2
- n/n_{cr}=0.10, T_e=2.5keV, fixed ions

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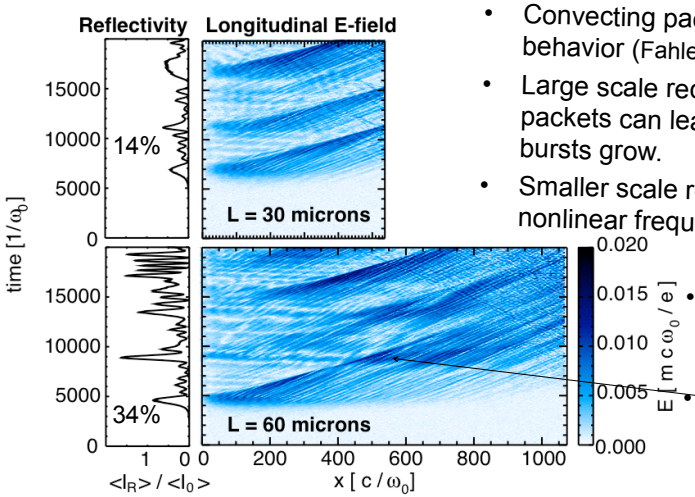
Convecting packets strongly influence physics

Phys. Rev. E 81, 045401(R) (2010)

Reflectivity levels are higher for longer interaction lengths
Observe kinetic inflation (Vu et al.)



- Convecting packets leads to recurrence behavior (Fahlen *et al*. PRL 2009)
- Large scale recurrence is regular when packets can leave the box before new bursts grow.
- Smaller scale recurrence is from nonlinear frequency shifts of packet
- The periodicity is disrupted for longer lengths
- New bursts can occur not just in the original region, but also after a packet has etched away

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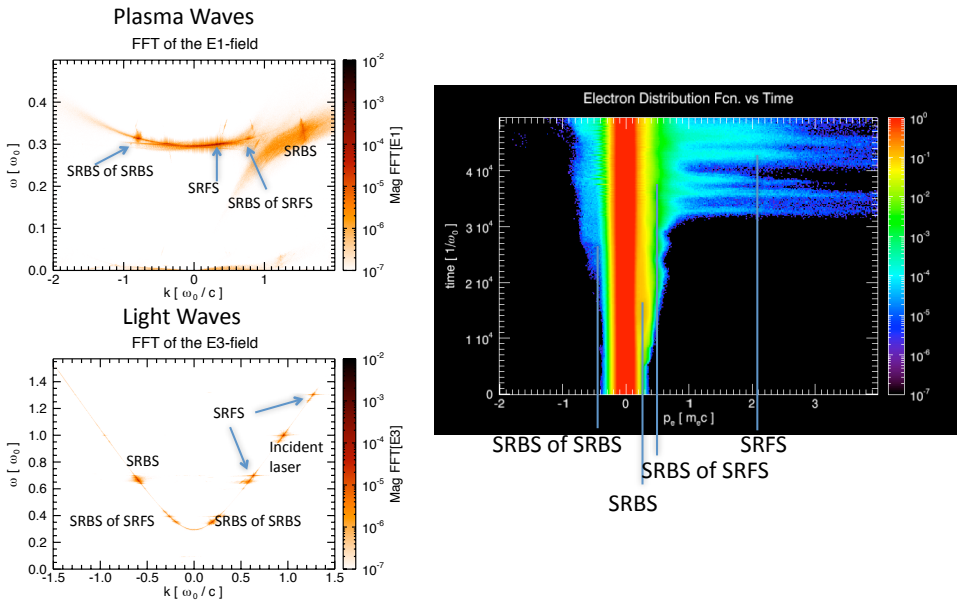
All types of SRS can be present simultaneously and trap electrons for longer interaction lengths or higher intensities

T_e=2.5keV, n/n_{cr}=0.09, fixed ions, L=180um, I_0=3e15 W/cm^2

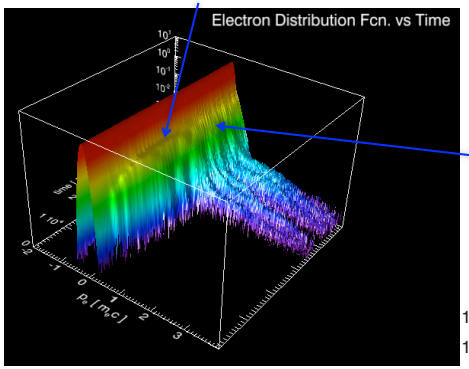


SRBS of SRBS
SRFS
SRBS of SRFS
SRBS

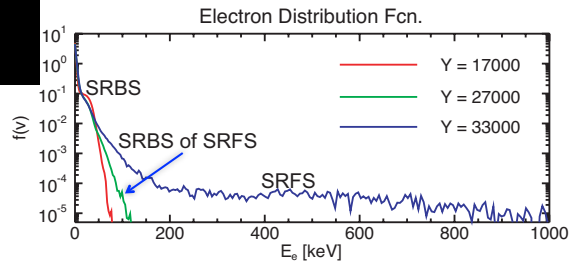
All types of SRS can be present simultaneously and trap electrons

T_e=2.5keV, n/n_{cr}=0.09, fixed ions, L=180um, I_0=3e15 W/cm^2

The electron distribution initially flattens due to SRBS.



Later in time, these hot electrons get bootstrapped into (1) rescatter of SRFS and (2) SRFS, resulting in the cascade of electrons from initial hot tail to hotter tails



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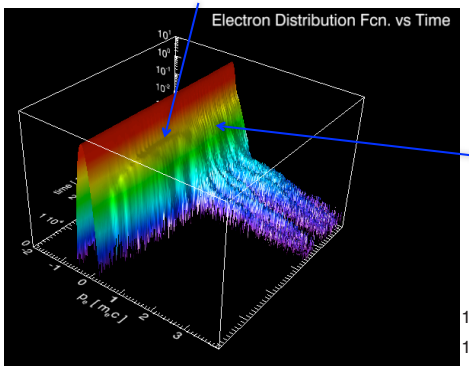

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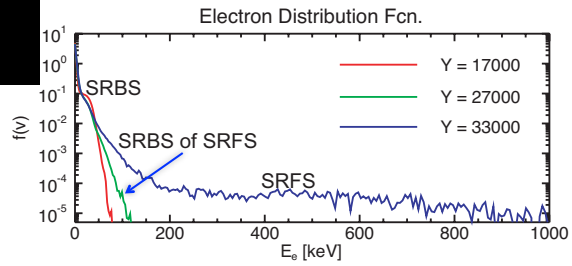
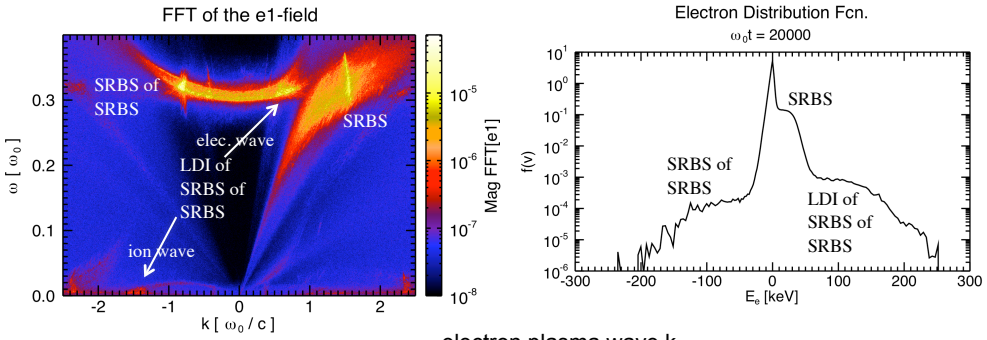


Ion waves (LDI) can saturate forward SRS, but they can also create more electron plasma waves

Linear density gradient n/n_{cr}=0.09-0.10 over L=180μm, I_0=4e15 W/cm2, T_e = 2.5 keV, ZT_e/T_i = 3



electron plasma wave $k_{\text{rescatter of backscattered light}}$

ion wave $k_{\text{LDI of rescatter}}$

electron plasma wave $k_{\text{LDI of rescatter}}$

- Heating electrons in both positive and negative directions:
  - LDI of the rescatter generates a plasma wave with approximately the same wavenumber as the rescatter but traveling in the opposite direction

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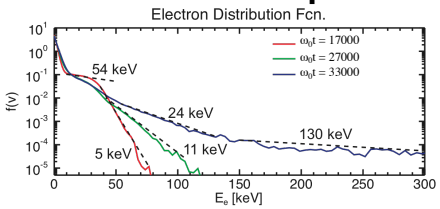
Electron Temperatures evolve in time

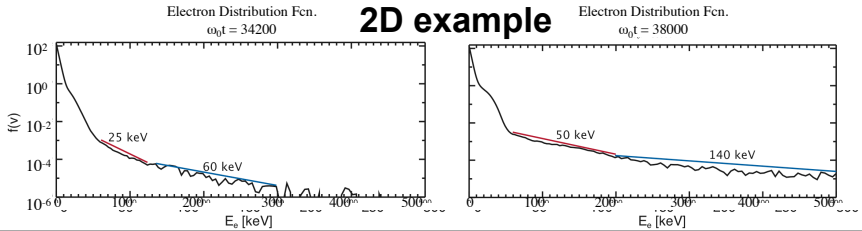
1D example



- The hot tails are constantly in flux
  - The distribution function begins to flatten at the phase velocity of the relevant plasma wave
  - A flat tail, from SRBS for example, will have a very hot temperature

- For rescatter and forward scatter:
  - Electrons can accelerated to energies ranging from 50keV – 1MeV
  - Distribution tails with temperatures ranging between 20-100 keV for rescatter and >100 keV for forward scatter

2D example



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PIC simulations of $2\omega_p$ and HFHI

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* Department of Physics & Astronomy, UCLA

†Polymath Research Inc.

Sponsored by DOE, NSF and NRL

Hi Everyone. This is a talk on the PIC simulations of the 2wp instability. My co-authors are Bedros Afeyan of Polymath Research, and Warren Mori of UCLA. Here is the funding information…

Simulation Setup

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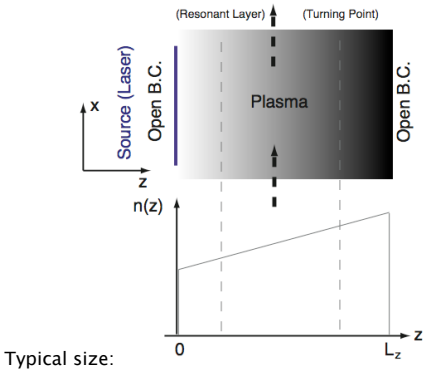
Simulations are done using the particle-in-cell (PIC) code OSIRIS. In the simulations presented here, the initial plasma has a linear density profile (in z), and the following boundary conditions:

- Plane wave laser, excited from left to right, periodic b.c. in the transverse direction (x).
- "Open" b.c. in the parallel direction (outgoing b.c. for the fields and a thermal bath for the outgoing particles).
- Width of the box is chosen to resolve all the perpendicular modes relevant to the 2ωp/HFHI Instability.
- Length of the box is chosen to cover all possible resonant layers, and the turning point physics (with a safety margin).
- Resolution:

$$\Delta x = \Delta z \approx \lambda_D$$



Typical size:

[3,040 x 5,136] cells

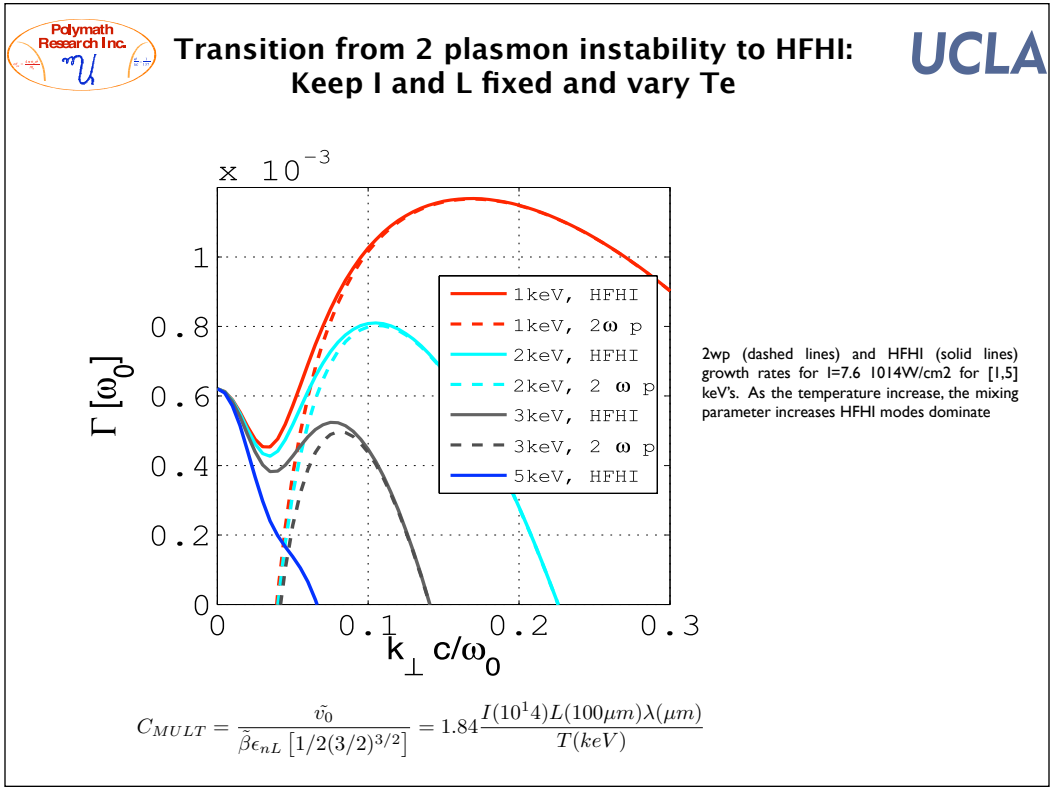
(30 x 50.88 microns)

density range = [.19, .265]n_c

~ $5x10^9$ particles (128 particles/cell per species)

~ 2 - 10 pico-seconds (3ω light)

Mention normalization here!!



The basis of our comparison is the theoretical work by Afeyan and Williams. This paper considers the 2wp instability under a large number of scenarios, such as….

The growth rate is a function of two normalized parameters, b and C. The definition of these parameters are on the next page, but physically Cmult measures the amount by which the system is above the instability threshold. And beta-wiggle is the "universal scaling" for the perpendicular mode number.

Two features about this plot. One is that 0 degree mode is not allowed, and as C_MULT increases, there are more unstable modes, and the growth rates approaches the growth rate in a uniform plasma, which is "one" in these units.

Physically, having 2 degrees of freedom suggest that all 3 are equivalent

As you go higher and higher above threshold, you will excite more modes, and the largest growth rate approaches the growth rate in a uniform plasma. Nonetheless, this equation has only 2 degrees of

Excellent agreement between simulations and 2wp and HFHI Theory*

*Afeyan and Williams 1997

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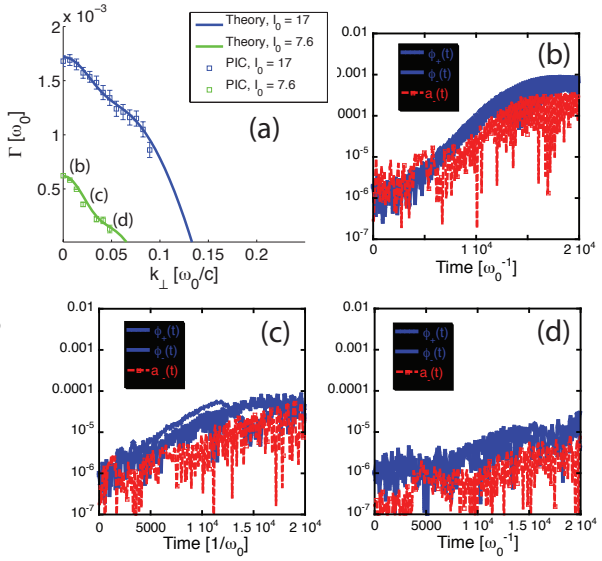
- The growth rate agreements between theory and simulation is excellent, and all 3 daughter waves grow together, as seen below
- The ratio A^-/phi^- decreases as k_{perp} increases as one expects.



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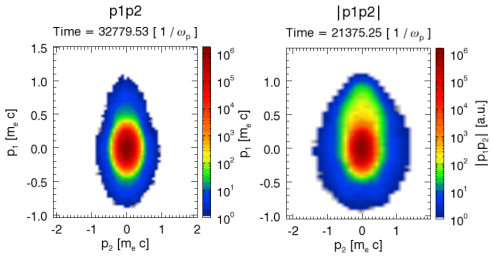
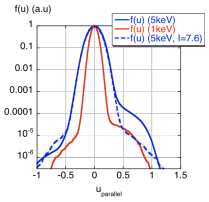
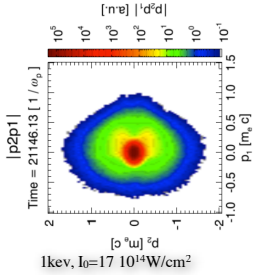
Hybrid modes with smaller k's lead to more hot electrons and more directed hot electrons



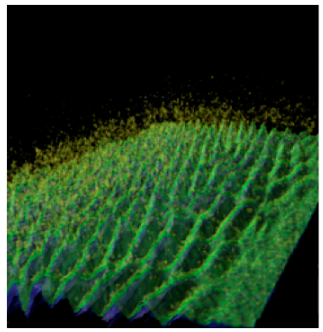
5kev, I_0=7.6 10^{14}W/cm^2

5kev, I_0= 17 10^{14}W/cm^2





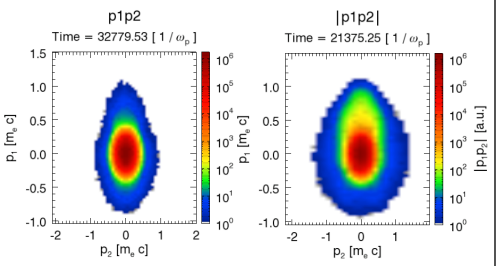
1kev, I_0=17 10^{14}W/cm^2



Electrons can bootstrap to higher energies from lower phase velocity waves at low density to higher phase velocity waves at higher densities

Hot electron spectrum for 1kev & 5keV, I=17 10^{14}W/cm^2

- In the 1keV simulation, the system is far above threshold, and many modes are excited, leading to a hot electrons spectrum with wide angular spread.
- In the 5keV case with identical intensity (1.7 10^{15}W/cm^2), the system is only 2 times above the threshold, and only a few modes are excited. These modes have mixed polarizations and have very small k_{perp}'s, and the electron are more directed.
- As intensity decreases, only k_{perp}~0 modes are excited, and far fewer hot electrons are generated, but the peak energy of the particles remain the same (due to k_{perp}=0 HFHI mode which has the highest v_{phase}), as shown the f(u) lineouts.



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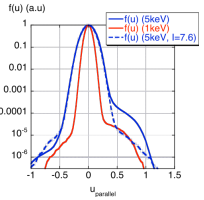
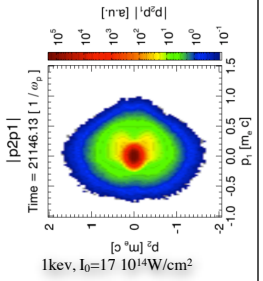
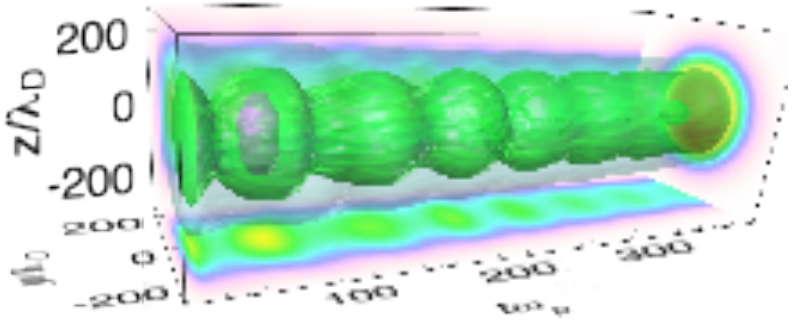




1kev, I_0=17 10^{14}W/cm^2

Nonlinear Plasma Wave Behavior in Multiple Dimensions Relevant to Stimulated Raman Scattering
Fahlen et al. to appear in PRE Rapid Communications



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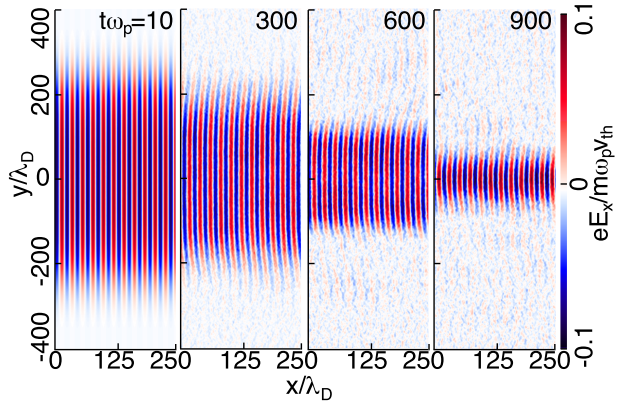
2D Finite Width Waves

Localization

A finite width plasma wave tends to localize around its center, losing energy at the sides while the center amplitude remains approximately constant.

L. Yin *et al*. (PRL **99**, 265004 (2007)) suggest that localization may cause SRS saturation and is due to nonlinear frequency shifts causing TPMI and wavefront bowing. Our simulations suggest instead that kinetic effects cause localization.



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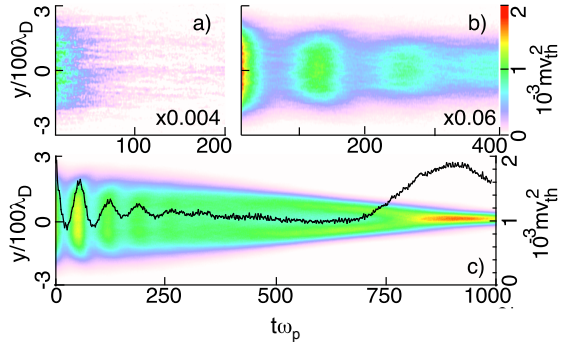
Wave Behavior Varies with Amplitude

a) For very small amplitudes, $\gamma_L >> \omega_B$, the wave Landau damps with essentially no multidimensional effects

b) At medium amplitudes, $\gamma_L \approx \omega_B$, the wave bounces

c) At large amplitudes, $\gamma_L < \omega_B$, the wave localizes at a fairly constant rate.



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We have made progress in:

- Understanding the onset, saturation, and recurrence in SRS
  - Physics continues to be identified that needs to be included in meso-scale models
- Understanding the behavior of plasma wave packets (localized both transversely and longitudinally)
- Understanding absorption and hot electron production from 2wp/HFHI: LPI near quarter critical density
- Understanding how an intense laser is absorbed at a sharp overdense plasma
- Understanding the wakes made by test charges in “collisional” plasmas
- Developing and maintaining a suite of parallelized particle-in-cell codes: OSIRIS/PARSEC/UPIC
- *Training students and post-docs in high-energy density science*