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Modeling Nonlinear Optics Of Plasmas (Relevant To IFE)

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Summary/Conclusion

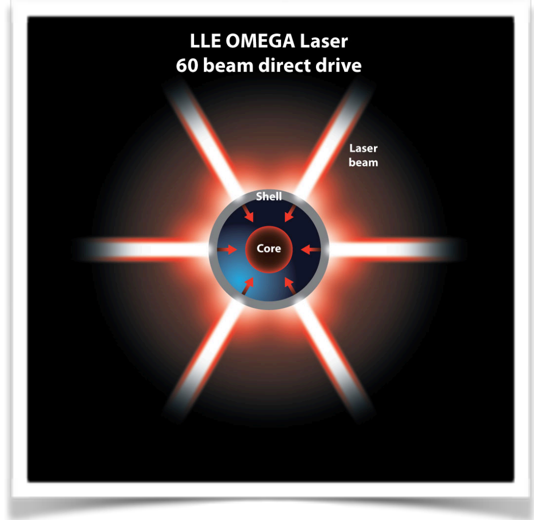
- Introduction
- Recent/Current Results:
  - 1D Simulation of SRS Relevant to IFE
  - Importance of Higher Dimensional Effects:
    - Using temporal bandwidth to suppress SRS & TPD
    - Using External Magnetic Fields to Suppress SRS
- Future Needs

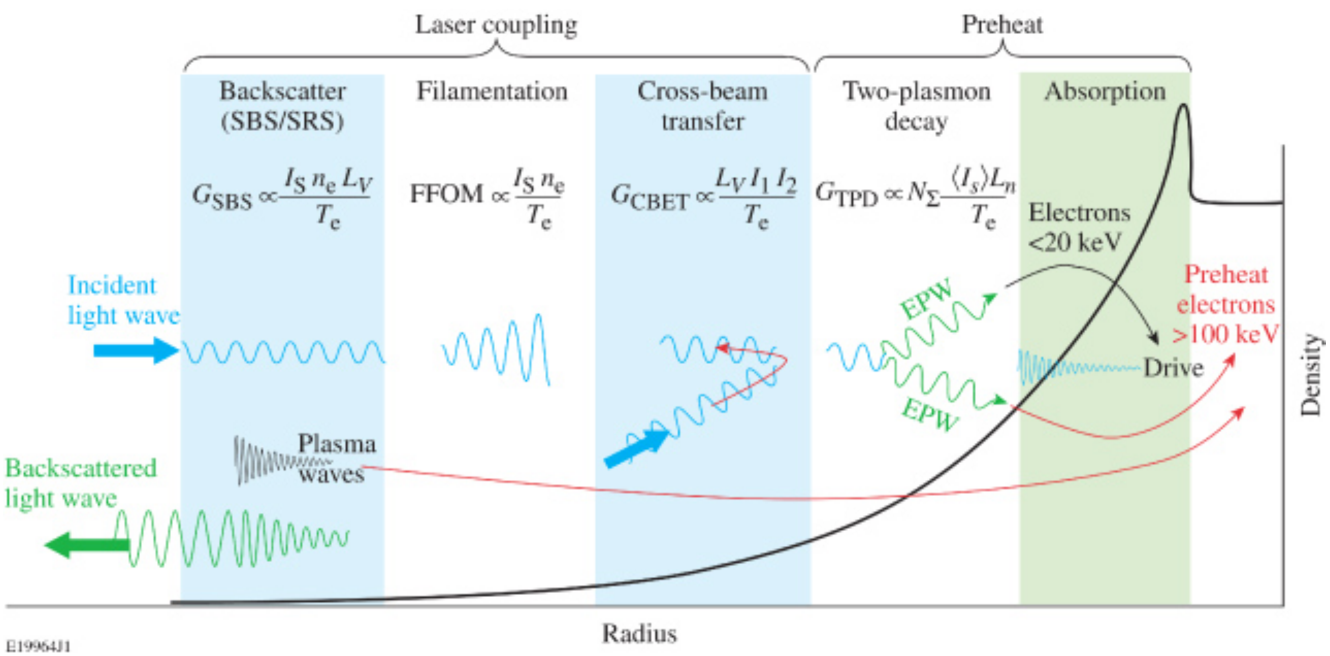
Laser Plasma Interactions in IFE

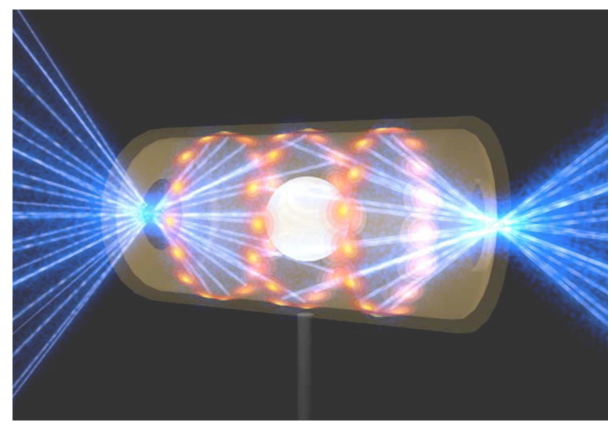
- IFE (inertial fusion energy) uses lasers to compress fusion pellets to fusion conditions. The goal of these experiments is to extract more fusion energy from the fuel than the input energy of the laser. The plasma in the laser path can produce a large number of LPI's (shown below). In this case, the excitation of plasma waves via LPI (laser plasma interactions) is detrimental to the experiment in 2 ways.
  - Laser light can be scattered backward and cannot reach the target
  - LPI produces hot electrons which heats the target, making it harder to compress.

Laser Plasma Interactions

OMEGA
60 beams
40KJ







NIF
240 beams
1.8MJ Laser
~200KJ X-Ray

NIF
National Ignition Facility

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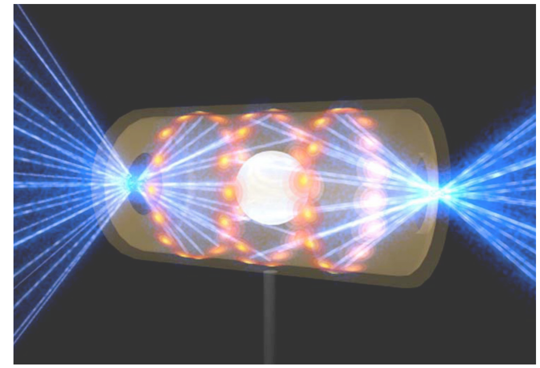
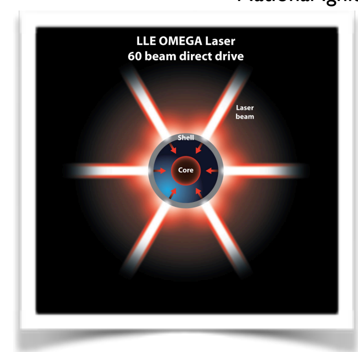
Laser Plasma Interactions in IFE (cont)

- The LPI problem is very challenging because it spans many orders of magnitude in time-scale & length-scale
  - The spatial scale spans from < 1 micron (which is the laser wavelength) to milli-meters (which is the length of the plasma inside the hohlraum).
  - The temporal scale spans 6-orders of magnitude from a femto-second(which is the laser period) to nano-seconds (which is the duration of the fusion pulse). A typical PIC simulation spans ~10ps.
  - 2D and 3D effects are also important, as we will discuss later, and 3D simulations will require billions of CPU hours and exa-scale supercomputers

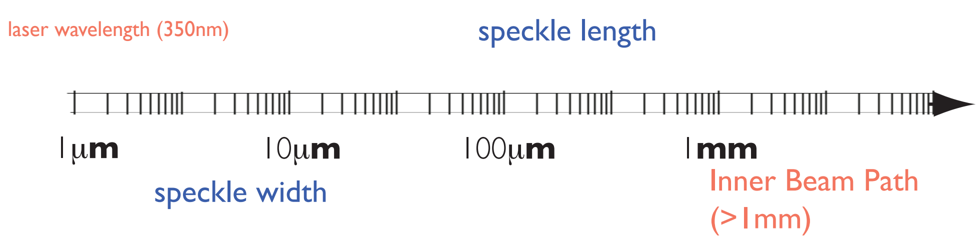
Laser Plasma Interactions



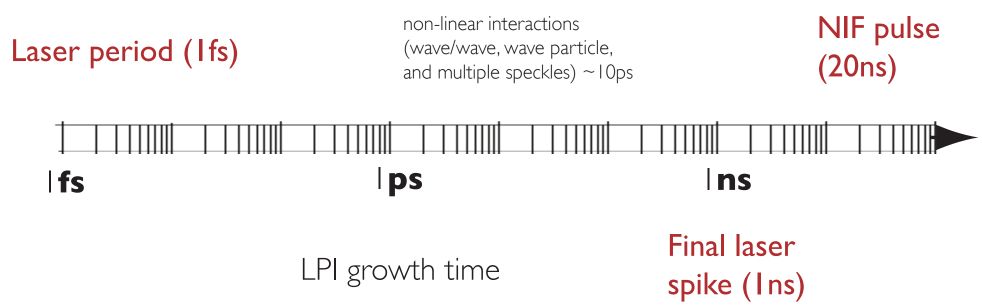
NIF
National Ignition Facility



Lengthscales



Timescales



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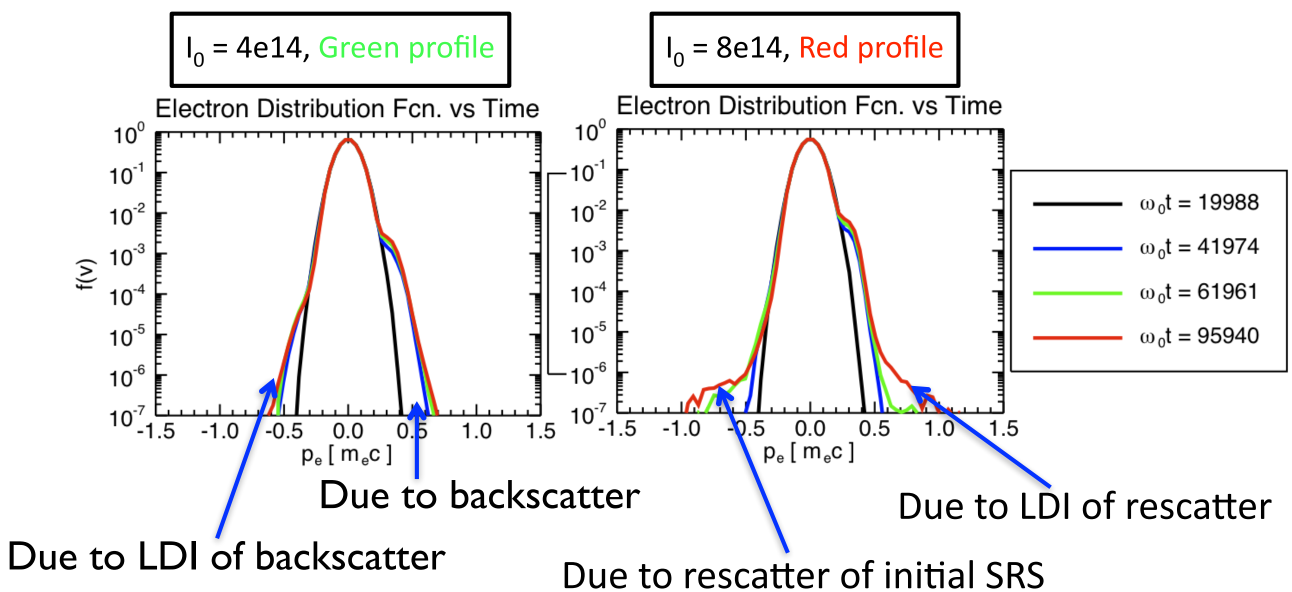
1D OSIRIS Simulation of a full NIF beam path is very modest and can reveal detailed kinetic physics

- Currently, after a NIF shot, scientists @ NIF can re-construct plasma conditions (such as density and temperature) using a hydro code. Using the "plasma map", theorists can use post-processors (e.g. NEWLIP) to predict the reflected spectrum as a function of time. Using the same "plasma map", we can perform a series of 1D OSIRIS simulations along each of the "beam path" indicated by the dash line, each taking a few hundred CPU hours.
- Spectrum of backscattered lights (which can be compared against experiments and NIF post-processors)
  - spectrum of energetic electrons (shown below). We can also identify the various physical processes responsible for the energetic electrons
  - energy partition, i.e., which is the detailed accounting of how the incident laser energy is converted to:
    - transmitted light
    - backscattered light
    - energetic electrons (and provides T_{hot}, which can be measured)



I_{laser} = 2 – 8 x 10^{14} W/cm^2

λ_{laser} = 351nm,

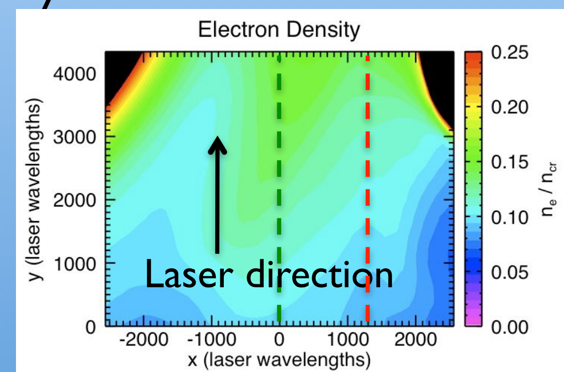
T_e = 2.75 keV,

T_i = 1 keV, Z=1,

t_{max} up to 20 ps

Length = 1.5 mm

Density profiles from NIF hydro simulations



14 million particles

~100's CPU hours per run

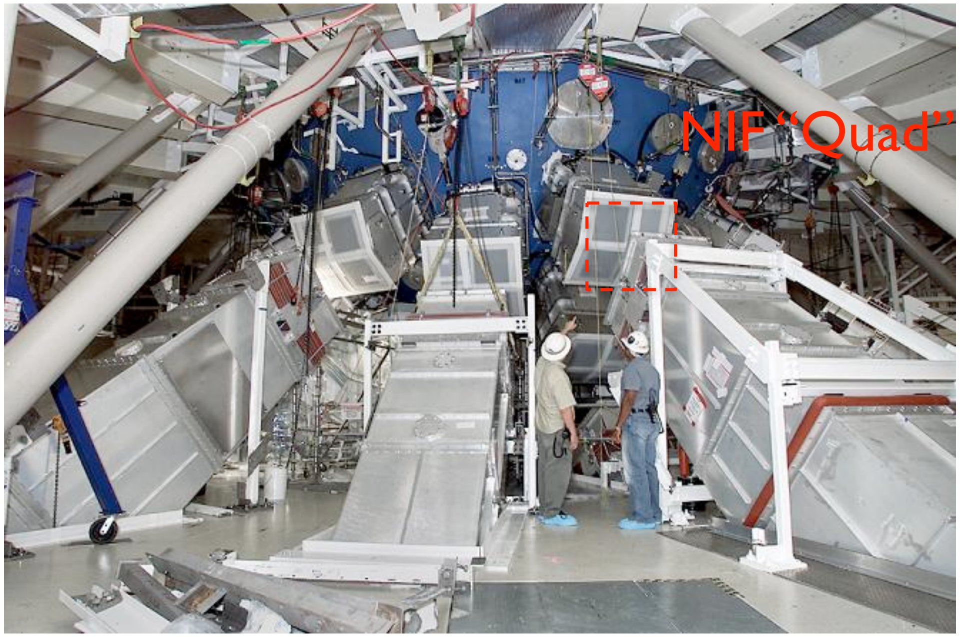
~1 hr on modest size local cluster (wallclock)

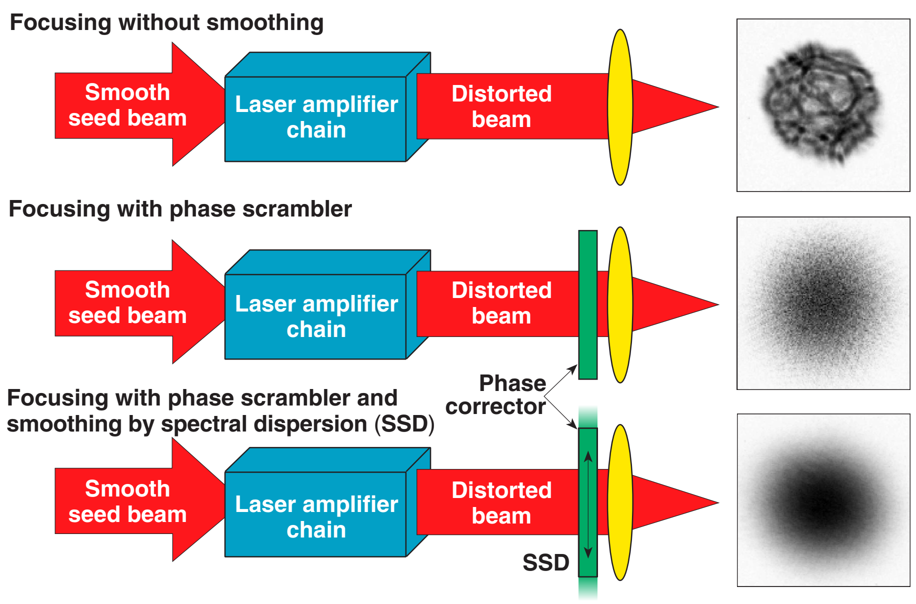
We have simulated stimulated Raman scattering in multi-speckle scenarios (in 2D)

- Although the SRS process is 1D (i.e., the instability grows along the direction of laser propagation). The SRS problem in IFE is not strictly 1D -- each "beam" (right) is made up of 4 lasers, called a NIF "quad," and each laser is not a plane wave but contains "speckles," each one a few microns in diameter. (And these speckles can move in time) These hotspots are problematic because you can have situations where 1D simulations and theory predict no LPI, but LPI occurs inside a high intensity hotspots and the LPI's in these hotspots can trigger activities elsewhere. The multi-speckle problem are inherently 2D and even 3D.

- We have been using OSIRIS to look at SRS in multi-speckle scenarios (both static speckles and speckles that move in time). In static multi-speckle scenarios, our simulations showed the excitation of SRS in under-threshold speckles via:
  - "seeding" from backscatter light from neighboring speckles
  - "seeding" from plasma wave seeds from a neighboring speckle.
  - "inflation" where hot electrons from a neighboring speckle flatten the distribution function and reduce plasma wave damping.

- Recently experiments and simulations have shown that external magnetic fields can reduce LPI activities. This is another source of higher dimensional effects, and another area of active research in our group.

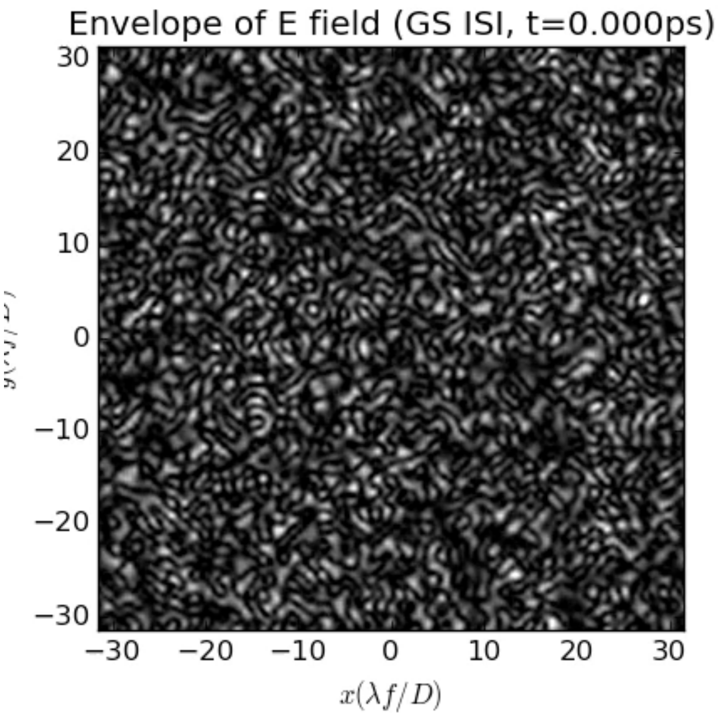




In the past year, we have added realistic beam effects into OSIRIS (Talk by Dr. H. Wen Yesterday)

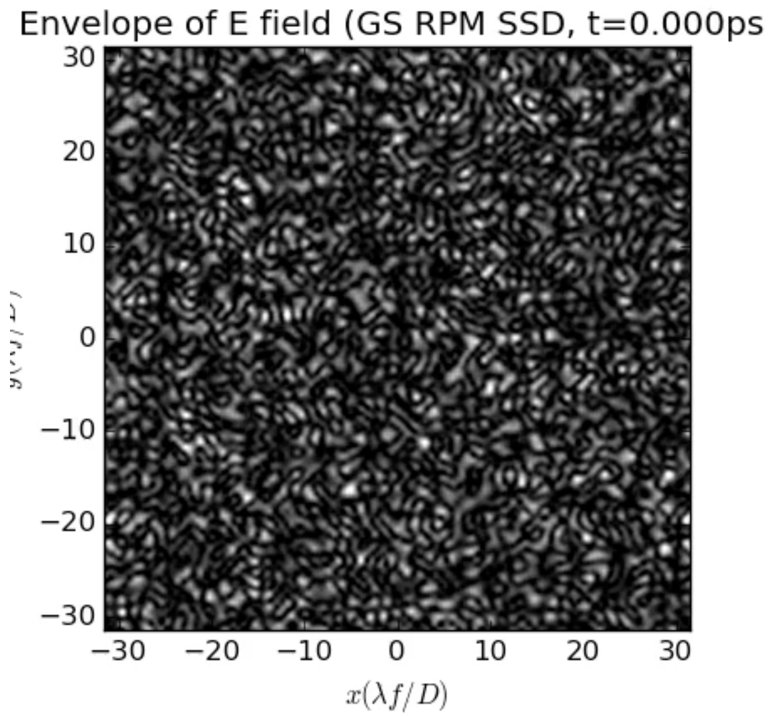
ISI

(Induced Spatial Incoherence)



SSD

(Smoothing by Spatial Dispersion)



& STUD

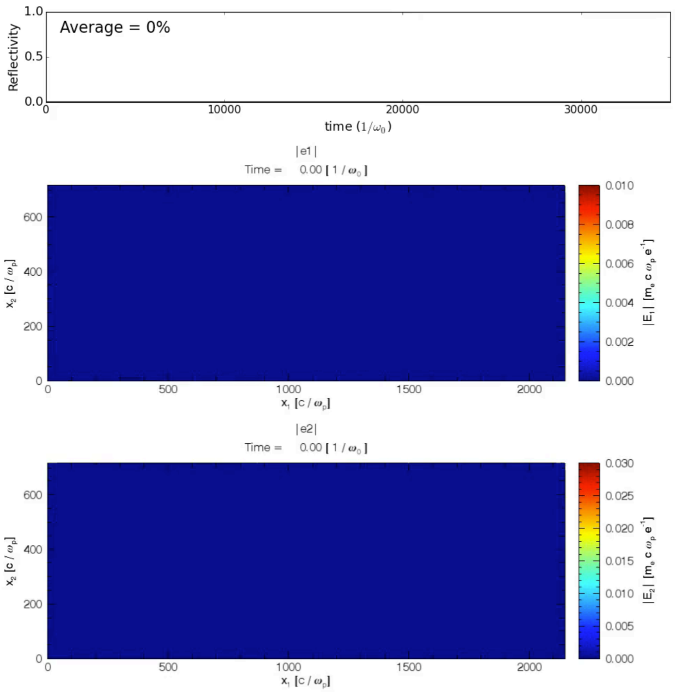
(Spike Train of Uneven Duration)

LPI Simulation Results — Temporal bandwidth reduces LPI

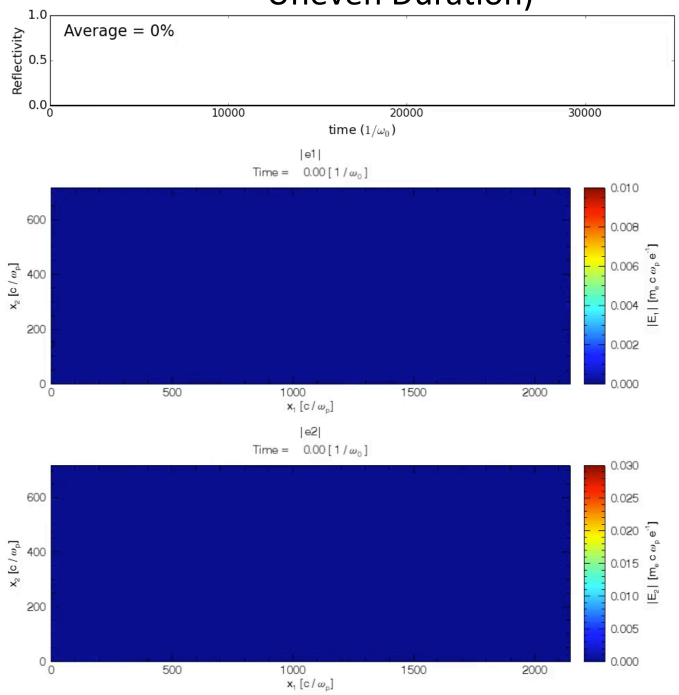
Temporal bandwidth can suppress SRS growth

- Small simulations (90k core-hours each) to identify interesting parameters before starting full simulations (<1 million core-hours each)
  - 15 speckles across and ~120 microns long.
  - ~100 million grids and ~10 billion particles each.
- Incorporating polarization smoothing can further reduce SRS reflectivity

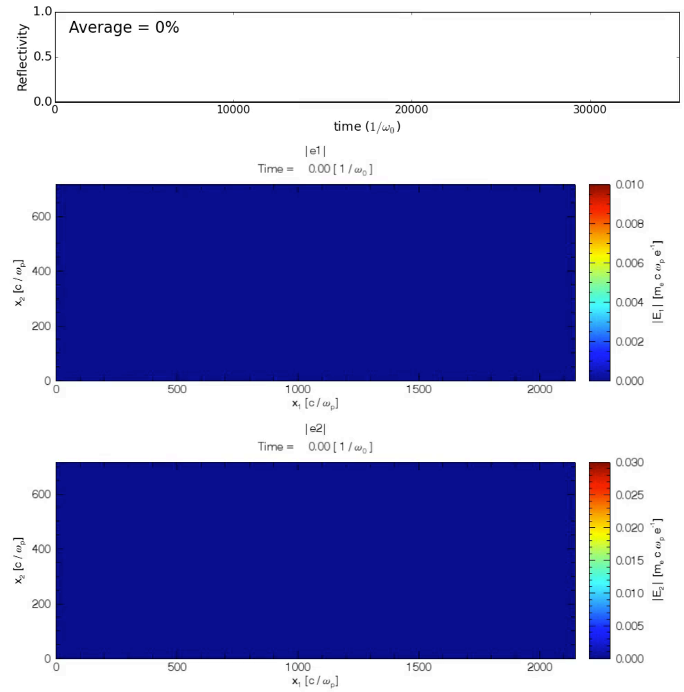
RPP



STUD (Spike Train of Uneven Duration)

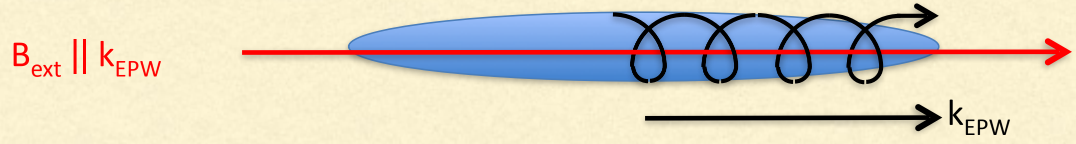


ISI

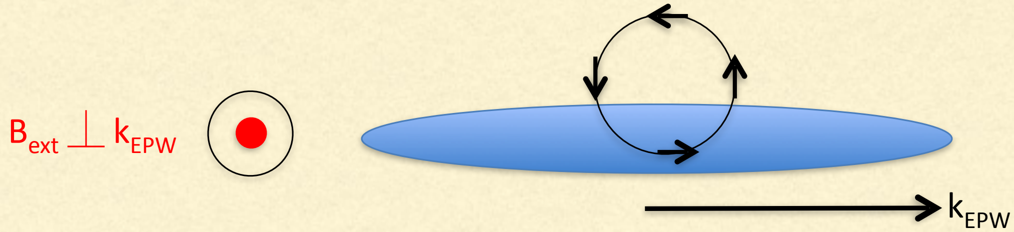


Simulations of SRS in magnetized plasmas under NIF relevant conditions (B. Winjum)

- A parallel B-field transversely constrains trapped particles
  - Yin et al* (with results for B = 114T) hypothesized that such fields would limit the collective SRS cascades in multiple speckles due to the interaction of multiple speckles, also the magnetic field can increase the plasma temperature, and Landau damp the driven plasma waves.

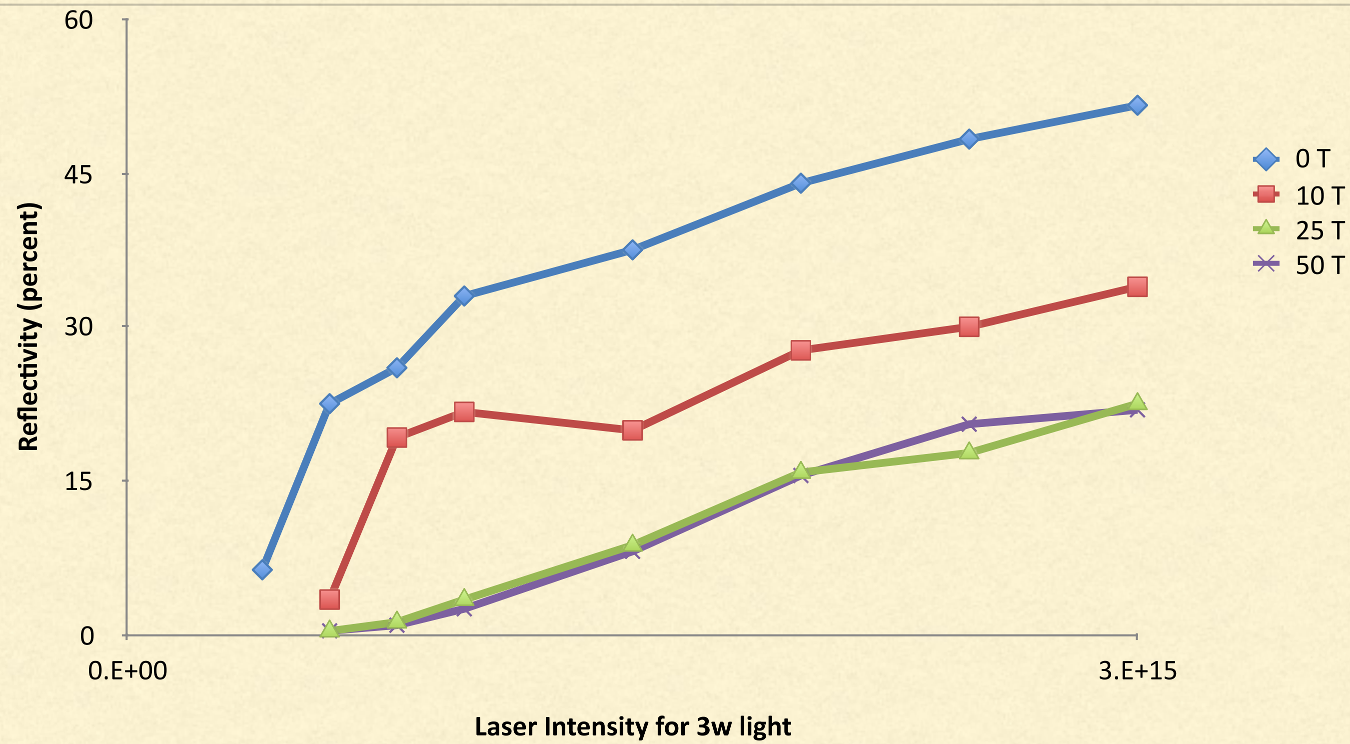


- A perpendicular (and modest) B-field can detrap energetic electrons in both physical space and velocity space, which can change the growth and the saturation mechanism of electron plasma waves. This mechanism is much more complicated and require PIC simulations.



* Yin *et al*, "self-organized coherent bursts of stimulated Raman scattering and speckle interaction in multi-speckle laser beams", *Phys. Plas.*, **20**, 012702 (2013). (simulation)

1D OSIRIS simulations showed reflectivity is reduced when a perpendicular B field is included

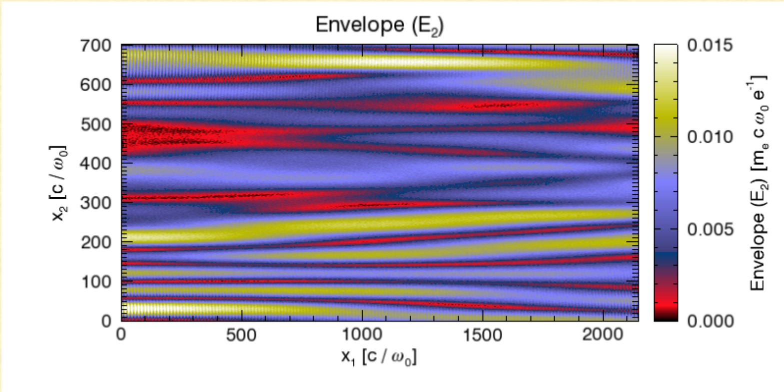


All points are for simulations with T_e = 3keV

1D simulations show that external magnetic fields can reduce the SRS reflectivity, and also delay the intensity onset of the SRS instability

Large 2D Multi-Speckle SRS simulations with external magnetic fields:

- Plasma:
  - Simulation Box: 120 microns x 40 microns (using 26 million grids and 7 billion particles)
  - Electron temperature: 3keV.
  - Plasma density: linear density gradient, $0.128n_c < n < 0.132n_c$
- Laser:
  - $I_{avg} = 8 * 10^{14}$ W/cm^{2} (3 ω light)
  - polarized in the plane of the simulation.
- External magnetic field:
  - 0, 20T, 50T, bot perpendicular and parallel to laser propagation.



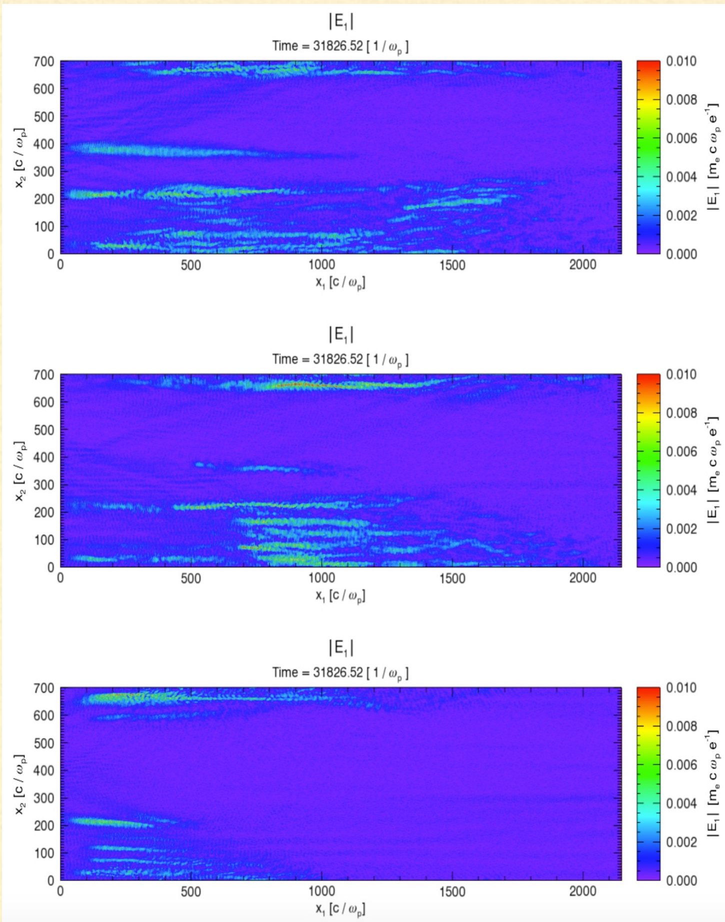
Laser direction
(continuously driven)

2D Multi-speckle SRS simulations showed that SRS can be limited by external **B** fields both parallel and perpendicular to laser propagation.

B_{ext} = 0

B_{ext} = 20 T
B || k_{EPW}

B_{ext} = 20 T
B ⊥ k_{EPW}



	//	⊥
20T	11.3%	4.6%
50T	10.1%	0%

Averaged reflectivity with external magnetic fields
(no field: 13.2%)

- B || k_{EPW} decreases SRS by limiting speckle interactions
- B ⊥ k_{EPW} decreases SRS by altering the growth and saturation of EPWs by (v x B)
- In simulations with an external magnetic field of 50T perpendicular to laser propagation, SRS is completely eliminated.

FUTURE NEEDS

PIC simulations of 3D LPI's is still a challenge, and requires exa-scale supercomputers, this will require code developments in both new numerical methods and new codes for new hardwares

	2D multi-speckle along NIF beam path	3D, 1 speckles	3D, multi-speckle along NIF beam path
Speckle scale	50 x 8	1 x 1 x 1	10 x 10 x 5
Size (microns)	150 x 1500	9 x 9 x 120	28 x 28 x 900
Grids	9,000 x 134,000	500 x 500 x 11,000	1,700 x 1,700 x 80,000
Particles	300 billion	300 billion	22 trillion
Steps	470,000 (15 ps)	540,000 (5 ps)	540,000 (15 ps)
Memory Usage*	7 TB	6 TB	1.6 PB
CPU-Hours	8 million	13 million	1 billion (2 months on the full Blue Waters supercomputer)

What are some features needed to perform large scale LPI simulations Relevant to IFE?

- Exascale capabilities (discussed yesterday)
- Collisional Absorption for KrF lasers (also discussed yesterday)
- In-situ diagnostics for exa-scale simulations
- Please bring your wish list to the discussion tomorrow.

THANK YOU AND I HOPE TO HEAR FROM YOU TOMORROW!