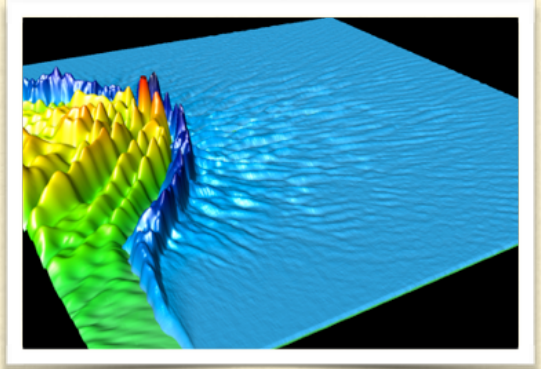
Application Of Parallel Kinetic Simulations To Laser & Electron Transport Through HED Plasmas



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F.Fiuza

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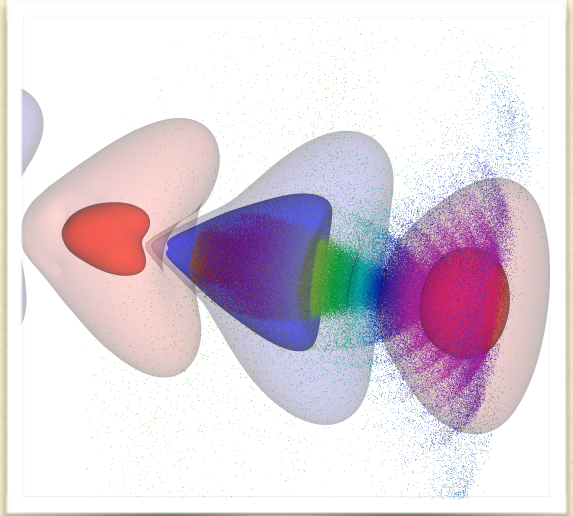
In memory of Mike Meyers



Work supported by DOE-NNSA: DE-NA0001833

What is high energy density plasma physics?

- The kinetic energy density of a plasma is its pressure. The dimensionless parameter N_D is related to the plasma pressure via the following relation:

$$\frac{4\pi}{3} n \lambda_d^3 \equiv N_D = 2.1 \times 10^3 \frac{T_{keV}^2}{P_{MBar}^{1/2}}$$

- When the plasma pressure exceeds >1MBar, then N_D can be finite and the discrete nature of the plasma becomes important.

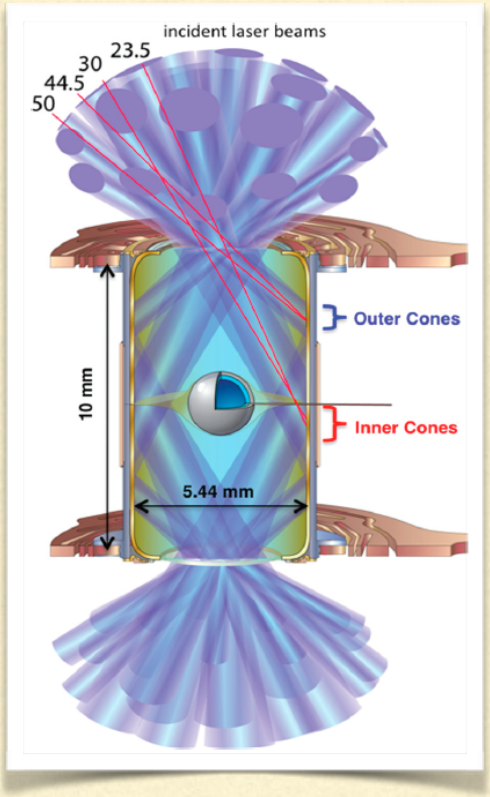
- Discreteness makes the underlying plasma physics, and the modeling of these plasmas difficult, and a wide range of models are needed, including:

  - particle-in-cell (PIC) models for *nearly* collisionless plasmas

  - collisional PIC models

  - Vlasov Fokker Planck (VFP) models

NIF/IFE is incredibly complicated with much fundamental science



~2 MJ into holhraum, ~ 200KJ turns into x-ray, but just ~10's KJ into compressed fuel

Requires very symmetric compression
Requires very symmetric x-ray drive
Requires correct time dependence to this drive

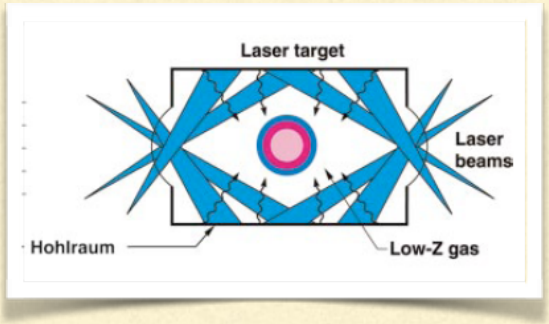
Lasers must hit where they are aimed!

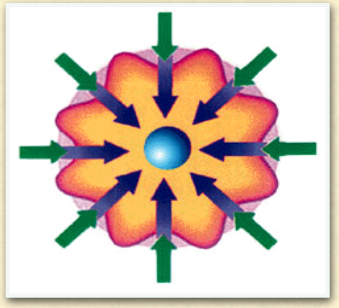
The high foot results* represented an exciting scientific milestone (i.e., scientific breakeven with 10's KJ yield)

To push towards breakeven w.r.t. the 1MJ laser drive, or even ignition, will require better understanding and control of laser plasma interactions

* O. A. Hurricane *et al*, *Nature*, **506**, pp. 343-348 (2014).

Laser and electron transport is important to IFE and NIF, **and** it is basic science: excellent for graduate students and post-doctoral researchers





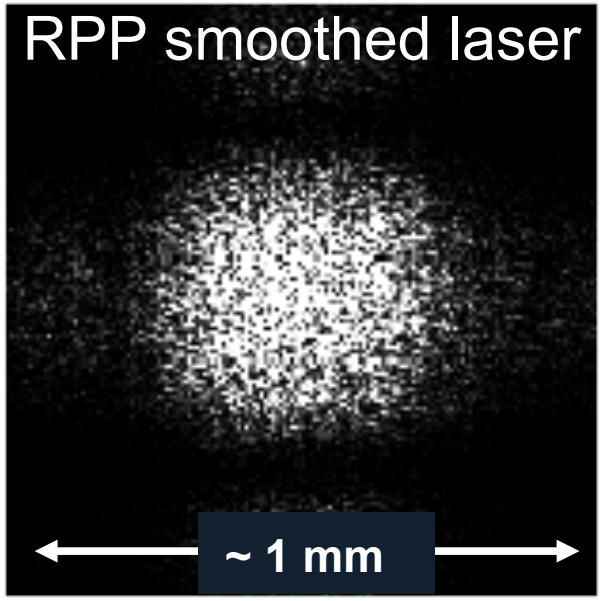
- Laser and electron transport in HED plasmas is challenging and basic research.
  - In underdense plasmas, the laser undergo LPI, including SRS and TPD. The LPI problem is rich in basic science, including:
    - propagation of a single wave packet up (or down) a density gradient.
    - wave-wave interactions (e.g., excitation of ion waves from multiple EPW's)
    - wave-particle interactions (generation of energetic electrons via nonlinear EPW's)
  - The energetic electron can reach the dense core and be collisional absorbed by the dense core. In shock ignition fusion, the energetic electrons created by LPI's can be used to drive shocks in the core and increase yield. Kinetic effects in transport (for both electrons & ions) is both rich in basic science and an important topic for IFE.
  - The UCLA simulation group is in a unique situation to have a full suite of SELF-DEVELOPED suite of kinetic tools to study the transport of lasers & energetic particles in HED plasmas

Summary

- 2D OSIRIS simulations of laser plasma interactions in IFE plasmas
  - Simulation of BSRS in magnetized plasmas, understanding the roles magnetic fields (// or ⊥ to the laser) have on LPI's under NIF relevant conditions.
  - Identifying the importance of HFHI instabilities in direct drive or shock ignition plasmas
- Study of non-local transport of electrons using the VFP code OSHUN
- Open source codes (including multi-level parallelization for running on the largest supercomputers) with near term releases w/ different physical and numerical models:
  - OSHUN (VFP)
  - UPIC (PIC with EM, ES and Darwin field models)
  - UPIC-EMMA (EM-PIC)
- Examples of broader impacts in our current code developments — algorithms that eliminate numerical Cherenkov radiation in LWFA simulations are also used to study relativistic shocks & other HED plasmas. (impacts will be much broader once our codes become open)
- Training experimental and simulation students and post-docs in HED science and advanced computing.

Simulations of LPI's under IFE conditions are computationally challenging.

- Although the SRS problem 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 the 4 lasers can have same or different polarizations. And the LPI's inside these hotspots can trigger LPI activities elsewhere via the following mechanisms, and therefore the multi-speckle problem is inherently 2D and even 3D.
  - "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.

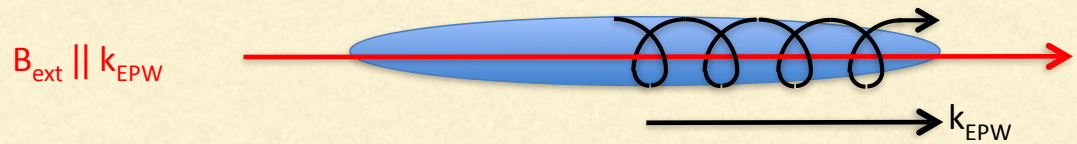


Post 1990's

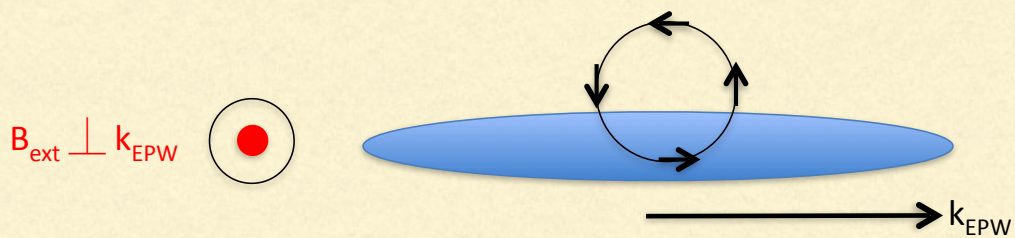
- 2D multi speckle simulations and 3D simulations with only 2 speckles will take up to 10's of millions of hours, and 3D multi-speckle simulations will take ~ 1 billion CPU hours! (> 2 months on the largest supercomputer today)

Simulations of SRS in magnetized plasmas under NIF relevant conditions (poster by Dr. 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 due to the interaction of multiple speckles, also the magnetic field can increase the plasma temperature, and Landau damp the driven plasma waves.



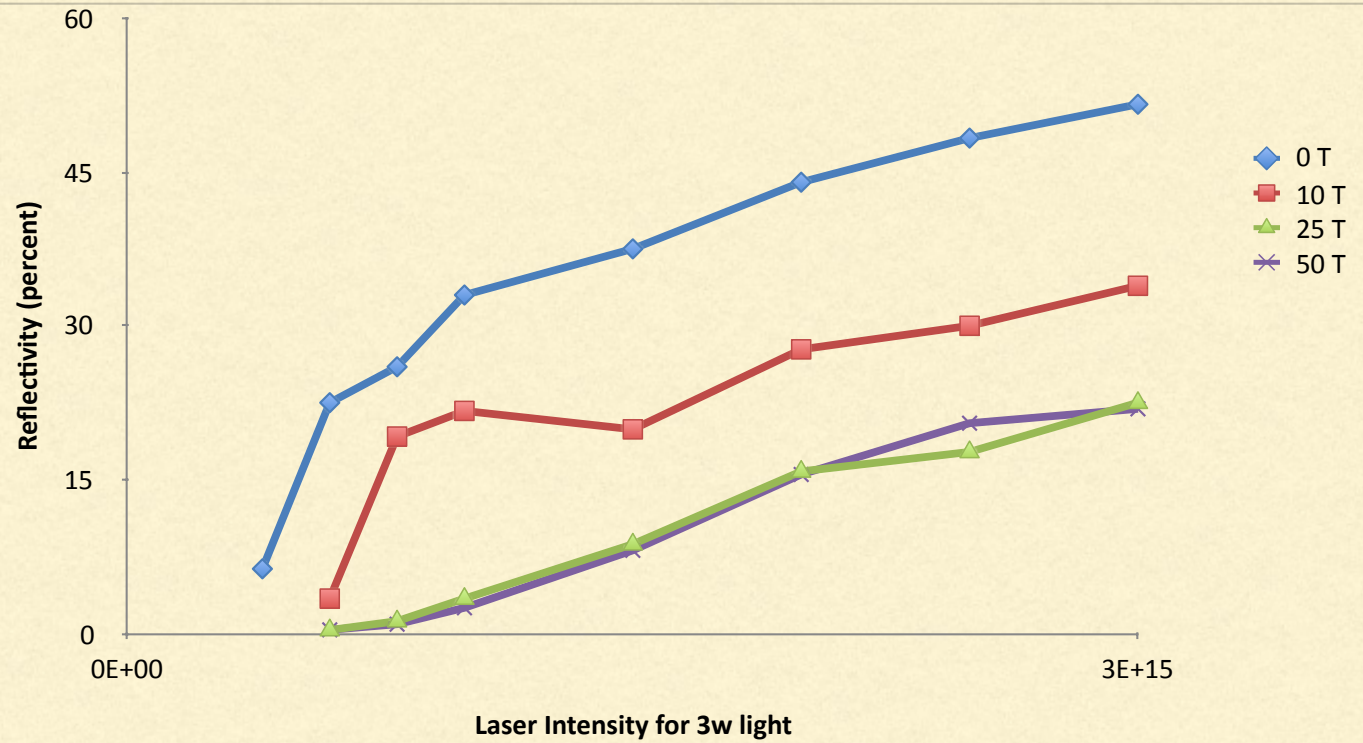
- A perpendicular B-field can detrap particles in both physical space and velocity space, which can change the growth and the saturation mechanism of electron plasma waves. This mechanism is much more complicated and require PIC simulations.



* Montgomery *et al*, *Phys. Plas.*, **22**, 010703 (2015). (experiment)

* 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

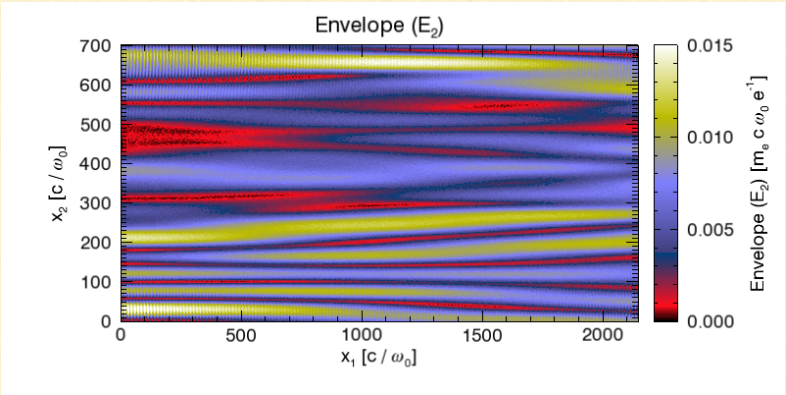


All points are for simulations with T_e = 3keV

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.



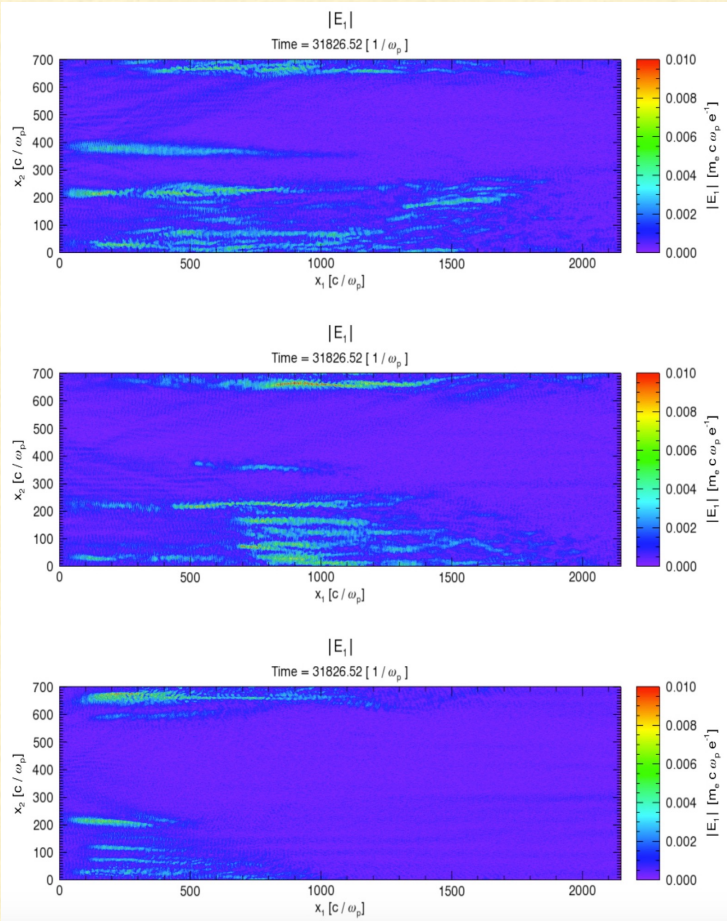
Laser direction
(continuously driven)

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
$B \parallel k_{EPW}$

$B_{ext} = 20$ T
$B \perp k_{EPW}$



	//	⊥
20T	11.3%	4.6%
50T	10.1%	0%

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

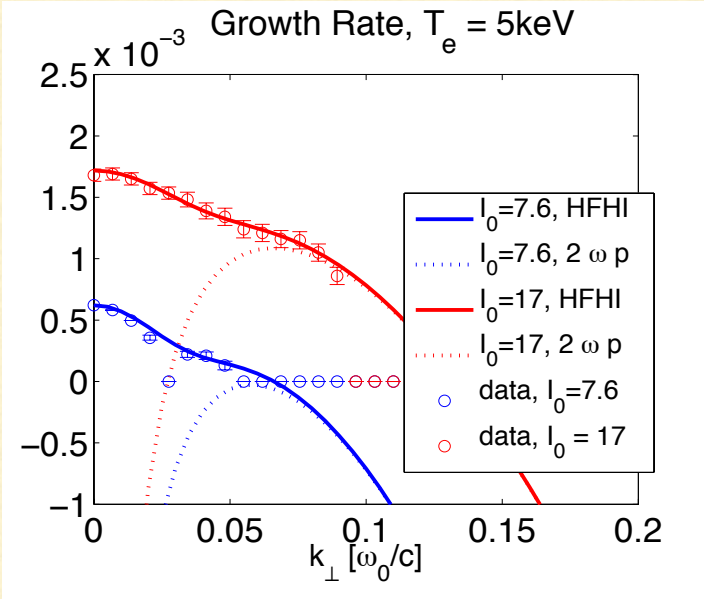
- $B \parallel k_{EPW}$ decreases SRS by limiting speckle interactions
- $B \perp k_{EPW}$ decreases SRS by altering the growth and saturation of EPWs by (v x B)
- In simulations with an external magnetic field of 50T perpendicular to laser propagation, SRS is completely eliminated.

Importance of the HFHI Modes @ Modest Temperatures (Poster by Tsung et al)

Near the quarter critical layer, the two plasmon decay (TPD) where the laser decays into two counter-propagating plasma waves can be important. In direct drive IFE, TPD can generate energetic electrons which can pre-heat the target and degrades compression.

However, even at modest temperatures, the high frequency hybrid instability (or HFHI) predicted by Afeyan and Williams* where the backward going daughter wave have both ES and EM components can be important. Our simulations showed that HFHI modes are important under direct drive & shock ignition conditions.

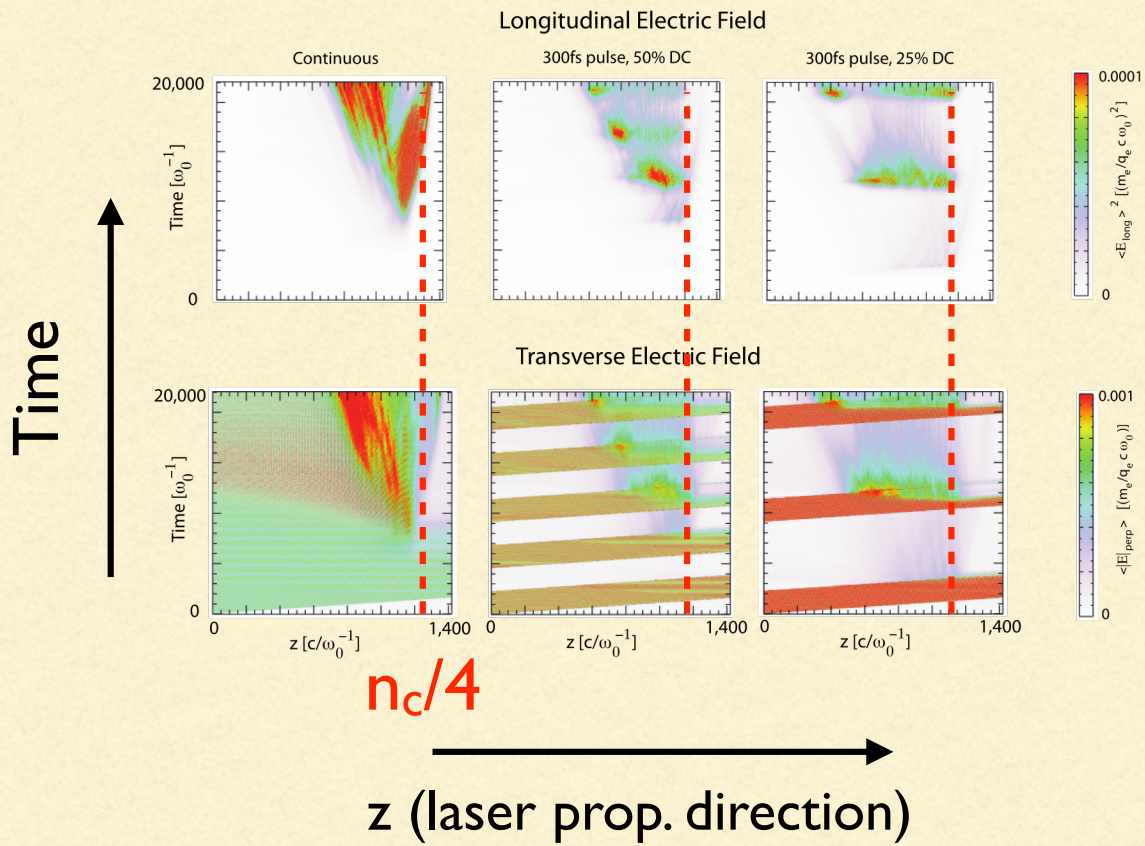
OSIRIS simulations have recovered the growth rate predicted by Afeyan and Williams in the early stages of the simulation (right), and we have shown that the saturation level, the temperature of the hot electrons, and laser absorption is controlled by ion waves driven by counter-propagating plasma waves, and it can be controlled by changing ion temperature, T_e/T_i. Details of this work was given at a poster @ this workshop.



measured growth rate (points) vs TPD theory (dashed lines) and HFHI theory (solid lines) for 5keV plasmas (see poster by Tsung *et al*)

* B. B. Afeyan, E. Williams, *Phys. Rev. Lett.*, **75**, 4218 (1995).

Control of TPD/HFHI instability by adding > THz bandwidth



Laser Profile	Transmitted Light
Continuous	<20
300fs, 25%DC	43.8
300fs, 50%DC	50.7

In addition to ions, we have looked at other mechanisms to control HFHI under shock-ignition relevant conditions. One possible mechanism is is the addition of temporal bandwidths to the incident laser light. (In our early simulations the laser bandwidth is being represented by a series of laser pulses whose pulse duration is proportional to the inverse bandwidth.

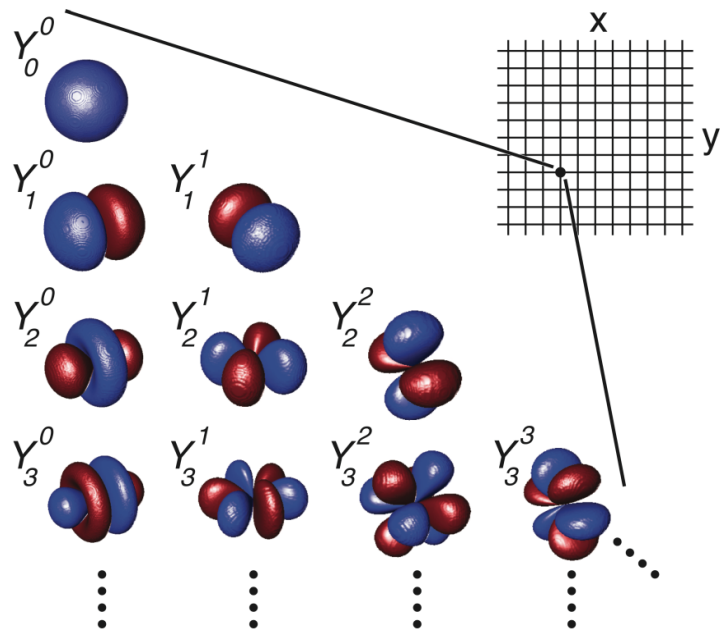
In simulations where the inverse temporal bandwidth is comparable to the growth time of the instability, simulations showed that:

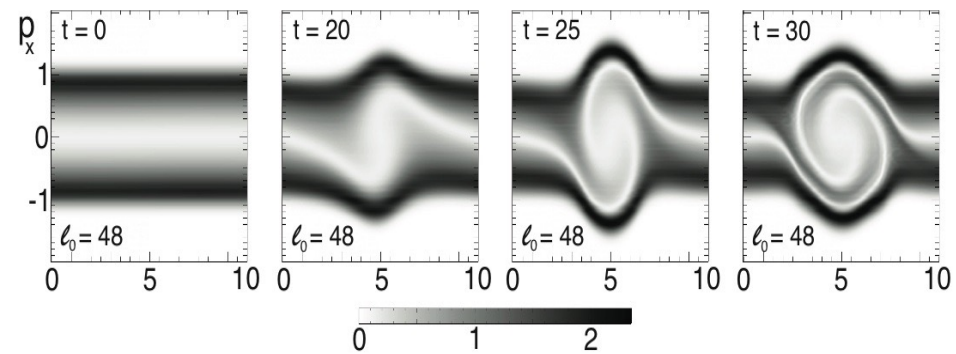
1. The plasma wave activity and the interaction region is much smaller with the addition of the temporal bandwidth, and

2. most of the light is transmitted during the linear phase of the instability, which leads to more of the lights going past the quarter critical layer and reaching the fusion target. In simulations without bandwidth, only ~20% of the light makes it to the target, and about 50% of the light makes it to the target when a 3THz bandwidth is present.

OSHUN – a VFP code for high energy density research

The transport and absorption of energetic electrons in collisional plasmas (e.g., the core of the fusion fuel) requires kinetic models with a collision operator, our VFP code OSHUN is well suited for this problem. We are working toward using OSHUN to study the transport of the energetic particles described earlier.



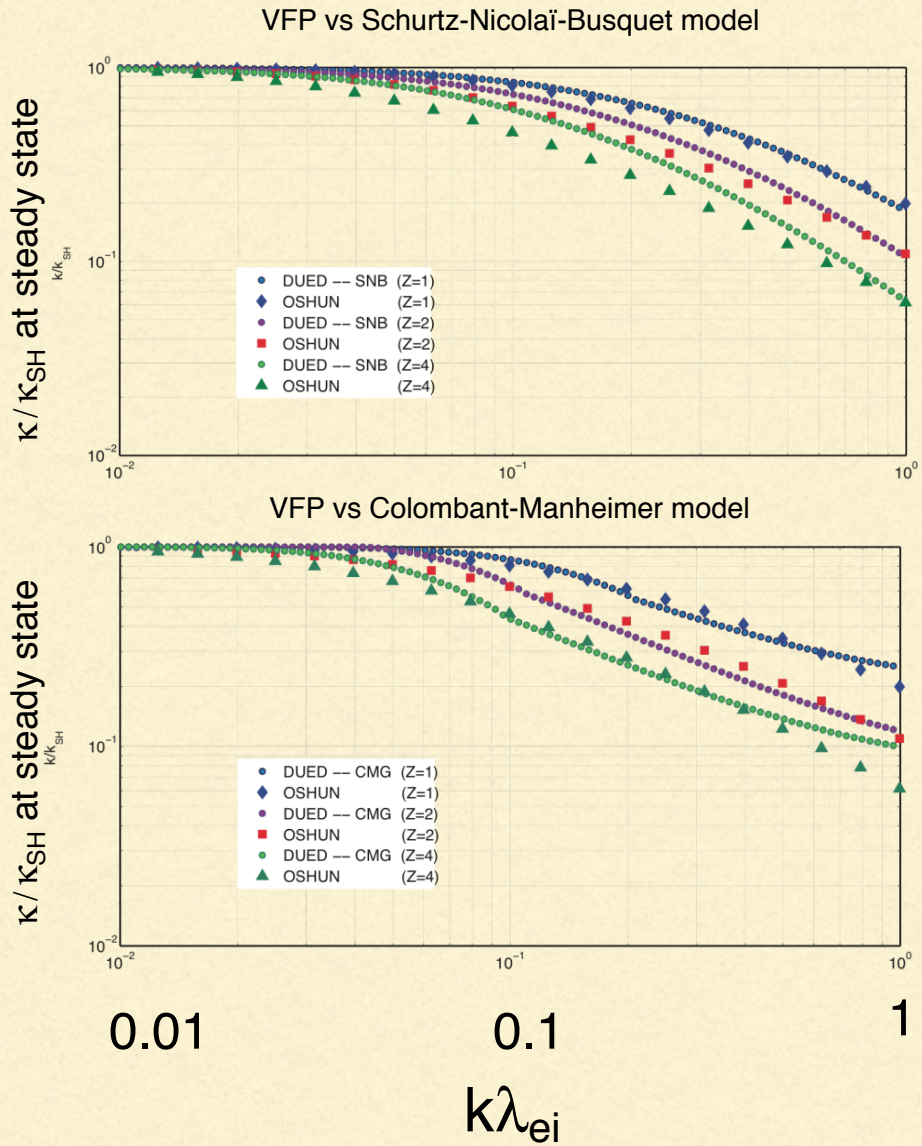


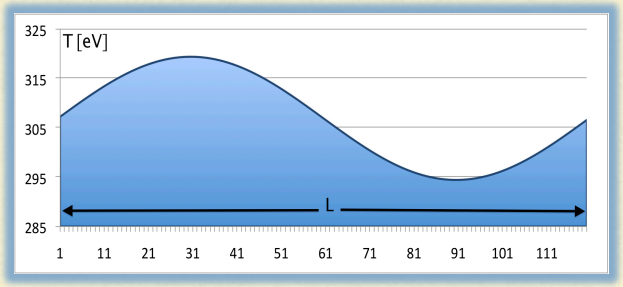
Spitzer heat conduction	Z = 1 **κ = 3.20**	Z = 2 **κ = 4.96**	Z = 4 **κ = 6.98**
VFP simul.	**3.21**	**4.93**	**7.00**

- ✓ **1D or 2D in X, 3P relativistic Vlasov**
- ✓ Spherical harmonics in **p**-space, cartesian mesh in **X**-space
- ✓ Energy conserving non-relativistic Fokker-Planck collision operator
- ✓ Models arbitrary degree of anisotropy, high collisionality —> inexpensive simulation
- ✓ **Parallel** with **GPU accelerated collision operator** (presented by Adam Tableman during poster session)

⋆ M. Tzoufras et al., JCP **270** (11) 6475-6494 (2011)

EX: OSHUN was used to benchmark various non-local electron transport models





- OSHUN was used to study non-local transport was used to benchmark two different non-local heat conduction models using a simple 1D initial value problem setup (see above).
- SNB overestimates Q for all k, but roughly recovers the functional form Q(k).
- CM overestimates $Q(k\lambda_{ei}\sim 1)$, but underestimates it for small $Q(k\lambda_{ei}<<1)$.

★ **"Comparison for non-local hydrodynamic thermal conduction models"**, A. Marocchino et al., *Phys. Of Plas.*, **20**, 022702 (2013).

UCLA Particle-in-Cell and Kinetic Simulation Software Center (PICKSC), NSF funded center whose Goal is to provide and document parallel Particle-in-Cell (PIC) and other kinetic codes.

http://picksc.idre.ucla.edu/
github: UCLA Plasma Simulation Group (currently closed)

Planned activities

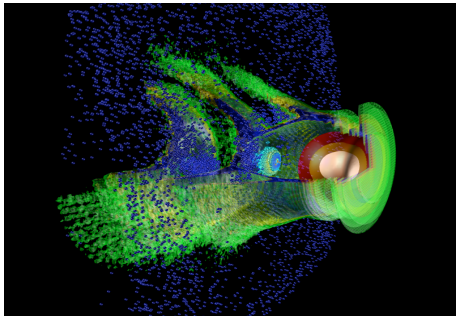
- Provide parallel skeleton codes for various PIC codes on traditional and new parallel hardware and software systems.
- Provide MPI-based production PIC (& VFP!!) codes that will run on desktop computers, mid-size clusters, and the largest parallel computers in the world.
- Provide key components for constructing new parallel production PIC codes for electrostatic, electromagnetic, and other codes.
- Provide interactive codes for teaching of important and difficult plasma physics concepts
- Facilitate benchmarking of kinetic codes by the physics community, not only for performance, but also to compare the physics approximations used
- Documentation of best and worst practices, which are often unpublished and get repeatedly rediscovered.
- Provide some services for customizing software for specific purposes (based on our existing codes)

Key components and codes will be made available through standard open source licenses and as an open-source community resource, contributions from others are welcome.

UCLA

UCLA develops and uses a set of PIC and fully kinetic codes to study high energy density plasma physics: Inertial confinement fusion, relativistic shocks, and plasma based acceleration

- **OSHUN (to be fully open source)**
  - **Vlasov Fokker Planck**
  - **Expands distribution function into spherical harmonics**

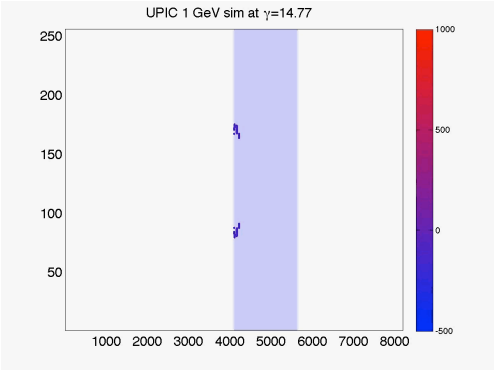


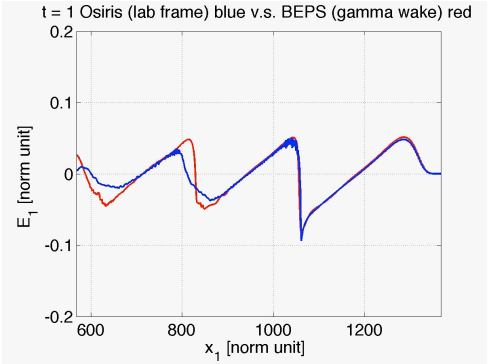
- **UPIC Framework (to be fully open source)**
  - **parallel Spectral solvers (ES, EM, Darwin)**
  - **Collisions**
  - **Gridless code**
- **UPIC-EMMA (to be open source)**
  - **EM PIC code optimized for the LWFA problem**

Optimized and scale well on largest computers

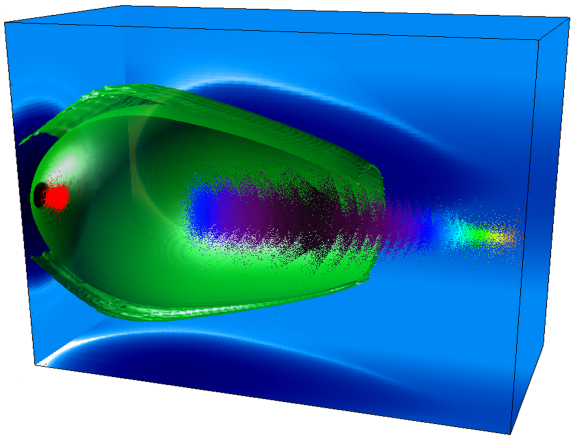
Dynamic Load Balancing

Works on GPUs/SIMD units

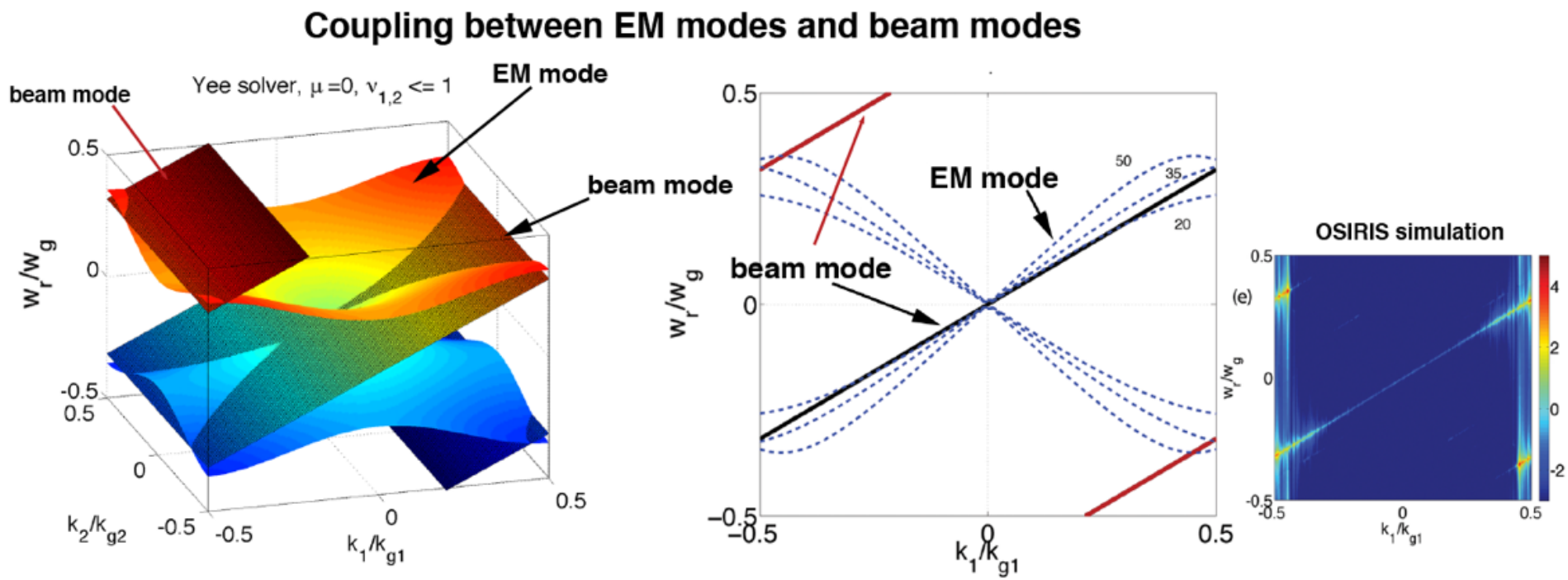




We feel that having a large base of developers will enhance the quality of our production codes (e.g., OSIRIS), for the rest of the talk, I will show you an example where development done on one code (UPIC-EMMA) for one application (LWFA) can have an impact on other codes (OSIRIS) for problems that are of interest to the HED community



Numerical Cherenkov Instability — Langmuir modes / EM modes coupling



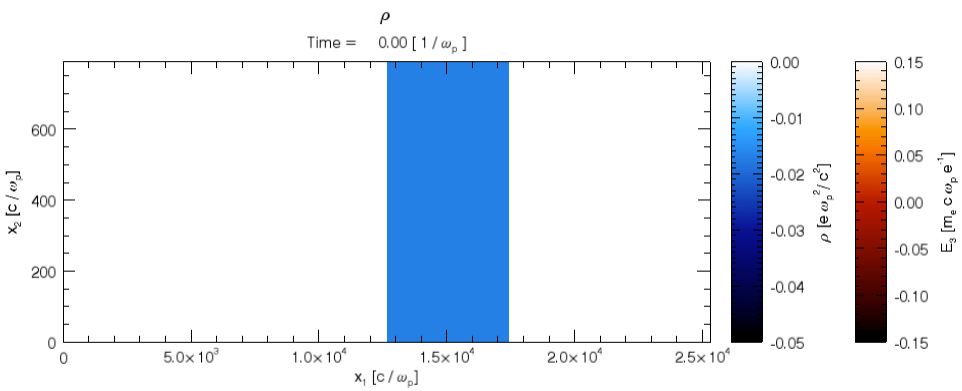
Numerical Cherenkov Instability (NCI) occurs when group velocity of the short wave EM modes is less than that of the beam velocity. The regions of instability can be predicted by looking at the intersection between the beam modes (shown as a flat surface on the left) and and the EM modes due to FDTD (shown as a slightly distorted cone) on the dispersion curve. This instability can leads to the unphysical radiation of relativistic beams in vacuum, and this was also observed in OSIRIS (see right).

A few years ago, we started looking at NCI in the context of doing LWFA simulations in Lorentz boosted frame, which is a technique that can provide ~2 order of magnitude savings in computation, but NCI can be an issue in these simulations.

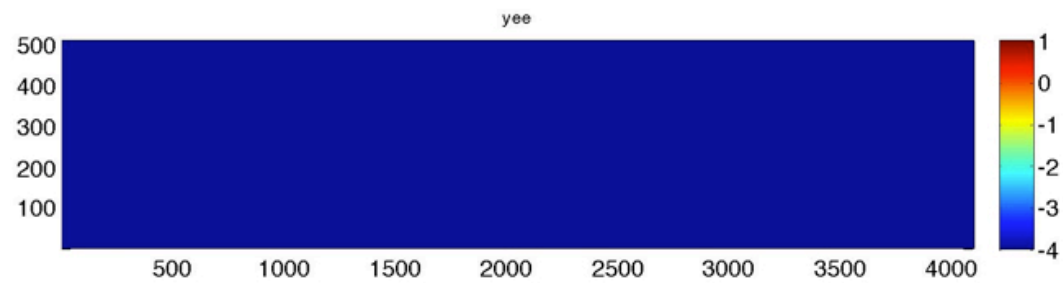
UCLA

Modeling relativistically drifting plasma in EM-PIC code*

LWFA in Lorentz boosted frame: A way to save time by studying a system in a Lorentz boosted frame. In this case, the plasma is moving near the speed of light.*



However, NCI is also observed in relativistic collisionless shock: In the simulation below, two relativistically moving plasmas collide with each other, and (nonphysical) radiation develops before the collision happens.



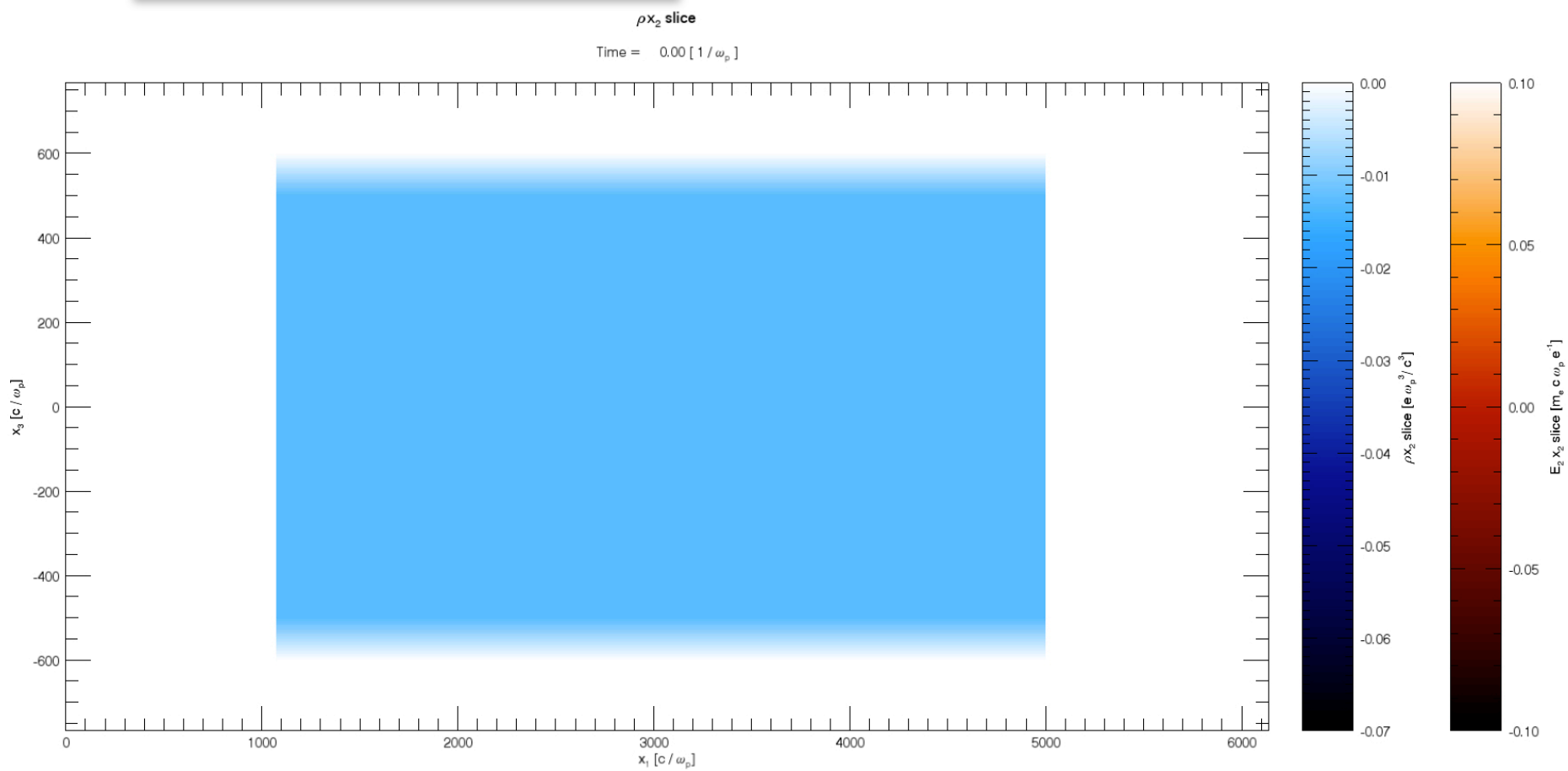
We've been working hard to remove NCI for this problem!

* X. Xu *et al*, *Comp. Phys. Comm.*, **184**, 2503 (2013).
* P. Yu *et al*, *Jour. Comp. Phys.* **266**, 124 (2014).
* P. Yu *et al*, *Comp. Phys. Comm.*, **192**, 32 (2015).

(Another example of NCI in HED plasmas is the transport of rela. electron beams in HED plasmas, where NCI can lead to numerically induced stopping of energetic electrons)

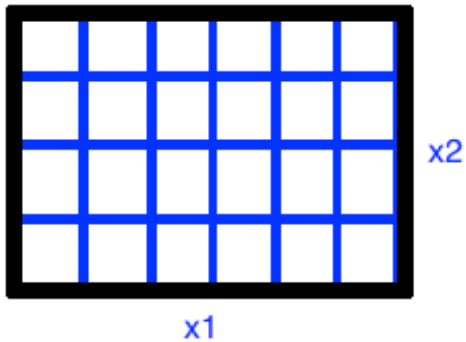
UCLA LWFA 3D boosted frame simulation

- 1.3 GeV 3D simulation
- NCI elimination applied
- 3D Simulation parameters
  - grid size: $\Delta x_{1,2,3} = 0.196$
  - time step: $\Delta t = 0.184 \Delta x_1$
  - Boosted frame: $\gamma = 15$



hybrid Yee-FFT solver

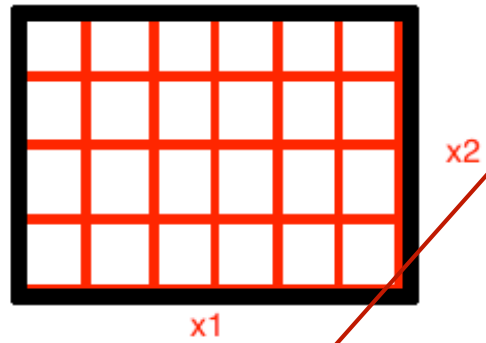
OSIRIS: FDTD solver



$$[k_1] = \frac{\sin(k_1 \Delta x_1/2)}{\Delta x_1/2}$$

$$[k_2] = \frac{\sin(k_2 \Delta x_2/2)}{\Delta x_2/2}$$

UPIC-EMMA: spectral solver + filter

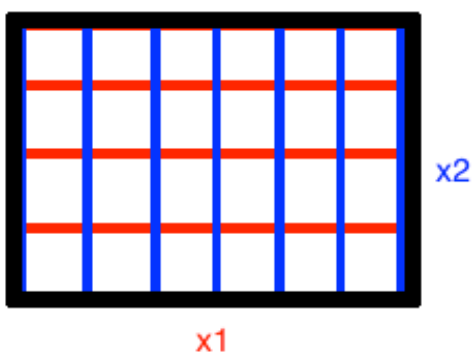


$$[k_1] = k_1$$

$$[k_2] = k_2$$

$$\frac{\partial}{\partial x_1} \quad \frac{\partial}{\partial x_2}$$

OSIRIS-H: Hybrid solver + filter



$$[k_2] = \frac{\sin(k_2 \Delta x_2/2)}{\Delta x_2/2}$$

$$[k_1] = k_1$$

- Can be extended to quasi-3D
- Can use flexible boundary condition in x2
- It eliminates NCI in OSIRIS and still maintains good parallel performance.

Our collaborators @ SLAC is now using this version of OSIRIS to look at relativistic collisionless shock,
Our open source effort will lead to rapid additions of new features to our open source codes, which can then be quickly added to our production codes.

This project has trained many students and post-docs in HED science, both in theory/computation and experiments, including

C. Huang 2006 LANL

J. Fahlen 2010 Arete Associates

B. Winjum 2010 UCLA

J. Ralph 2010 LLNL

M. Tzoufras 2010 Western Digital

T. Wang 2011 Raytheon

A. Pak 2012 LLNL

D. Haberberger 2012 U. Rochester

I. Ellis 2014 Northrup Grumman

Summary/Conclusions

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- Study of non-local transport models using the VFP code OSHUN
- Open source codes (including multi-level parallelization for running on the largest supercomputers) with near term releases w/ different physical and numerical models:
  - OSHUN (VFP)
  - UPIC (PIC with EM, ES and Darwin field models)
  - UPIC-EMMA (EM-PIC)
- Examples of broader impacts in our current code developments — algorithms that eliminate numerical Cherenkov radiation in LWFA simulations are also used to study relativistic shocks & other HED plasmas. (impacts will be much broader once our codes become open)
- Training experimental and simulation students and post-docs in HED science and advanced computing.