Plasma Fluctuations, theory & observations

Short review of past and current research results from laser produced plasmas of relevance to inertial confinement fusion, laboratory astrophysics, and examined by means of theory and measurements of the particle noise.

Wojciech Rozmus

Department of Physics, University of Alberta

Preface

Eur. Phys. J. H **43**, 421–458 (2018).

Wave-particle and wave-wave interactions in hot plasmas: a French historical point of view

Guy Laval, Denis Pesme, and Jean-Claude Adam
Centre de Physique Th´eorique, Ecole polytechnique, CNRS, Universit´e Paris-Saclay,
91128 Palaiseau, France

Abstract. The first researches on nuclear fusion for energy applications marked the entrance of hot plasmas into the laboratory. It became necessary to understand the behavior of such plasmas and to learn how to manipulate them. Theoreticians and experimentalists, building on the foundations of empirical laws, had to construct this new plasma physics from first principles and to explain the results of more and more complicated experiments. Along this line, two important topics emerged: wave-particle and wave-wave interactions. Here, their history is recalled as it has been lived by a French team from the end of the sixties to the beginning of the twenty-first century.

In addition to collisionless, wave-particle and wave-wave interactions, processes of particle transport are needed to understand and model hot, fusion related and laser produced plasmas in general.
For example thermal transport is critical for the fusion schemes and ignition.

Theory of plasma fluctuations provides a useful tool in description of particle transport and collisions as well as waves and plasma turbulence. Modern diagnostic techniques, such as Thomson scattering, based on scattering of light from electron density fluctuations are indispensable in measuring plasma parameters and plasma processes.

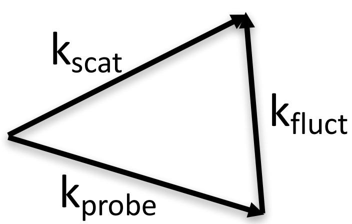
Fluctuations & Thomson scattering

Thomson scattering (TS) cross section is proportional to the dynamical form factor $S(\vec{k},\omega)$. For stable plasmas (but not necessary in equilibrium) particle discretness gives rise to electron (small amplitude) density fluctuations and their correlation function, as follows (J. Feyer, Can. J. Phys. (1960); J. Renau, J. Geophys. Res. (1960); J. Daugherty, D. Farley, Proc. Roy. Soc. (1960); E. Salpeter, Phys. Rev. (1960).

$$S(\vec{k},\omega) = \frac{\langle \delta n_e^2 \rangle_{k,\omega}}{n_e} = \frac{2\pi}{k}\left\{ \left|1-\frac{\chi_e}{\epsilon}\right|^2 f_{e0}\left(\frac{\omega}{k}\right) + \sum_{j(ions)} \frac{Z_j^2 n_j}{n_i}\left|\frac{\chi_e}{\epsilon}\right|^2 f_{j0}\left(\frac{\omega}{k}\right)\right\}, \quad n_i = \sum_j n_j$$

where linear response functions evaluated using distribution functions f_{e0}, f_{j0}, are

$$\epsilon = 1 + \chi_e + \sum_j \chi_j$$



$$\omega_s = \omega_0 + \omega$$

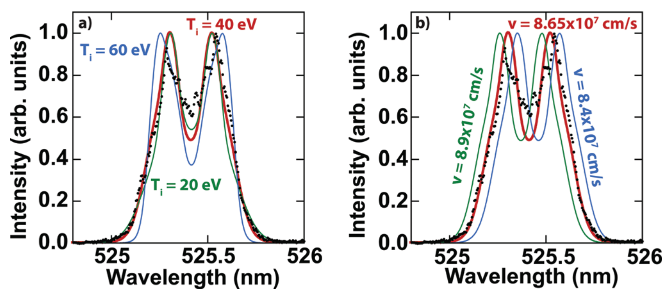


FIG. 4. The Thomson scattering cross section is fit to the measured Thomson scattering ion feature at 5.5 ns to determine the ion temperature and plasma flow velocity. The best fit to the experimental data (red line) is calculated using an electron temperature and density determined from the electron feature (100 eV and $5.6 \times 10^{18} \mathrm{cm}^{-3}$), ion temperature of 40 eV, and a plasma flow velocity of $8.65 \times 10^7 \mathrm{cm/s}$. (a) The ion temperature is increased to 60 eV (green line) and decreased to 20 eV (blue line) to demonstrate the sensitivity of the fit. (b) The plasma flow velocity is varied from $8.9 \times 10^7 \mathrm{cm/s}$ (green line) to $8.4 \times 10^7 \mathrm{cm/s}$ (blue line) as well.

Example from the paper by S. Ross *et al*. Phys. Plasmas **19**, 056501 (2012) on interpenetrating plasmas. Two ion acoustic peaks are shown and are fitted with the $S(\vec{k},\omega)$ and Maxwellians

Thermal transport

Electron heat flux is poorly described by the classical diffusive model, $q_{SH}=-\kappa\nabla T_e$, in many laser produced plasmas. Thermal transport requires kinetic theory or nonlocal closure when reduced to hydrodynamical description.

PHYSICAL REVIEW LETTERS **121,** 125001 (2018)

Observation of Nonlocal Heat Flux Using Thomson Scattering

R. J. Henchen,[1,2,*] M. Sherlock,[3] W. Rozmus,[4] J. Katz,[1] D. Cao,[1] J. P. Palastro,[1] and D. H. Froula[1,5]

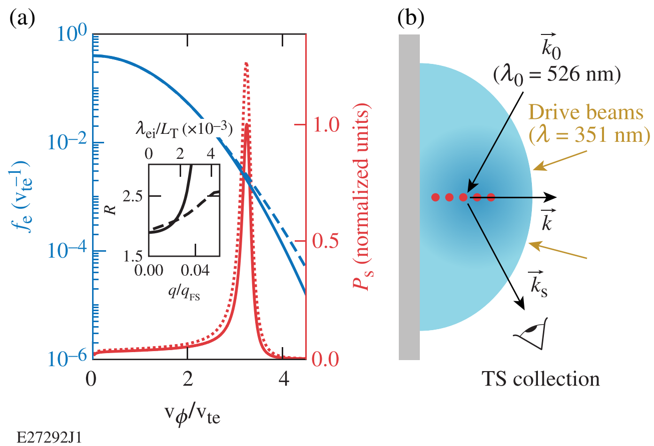
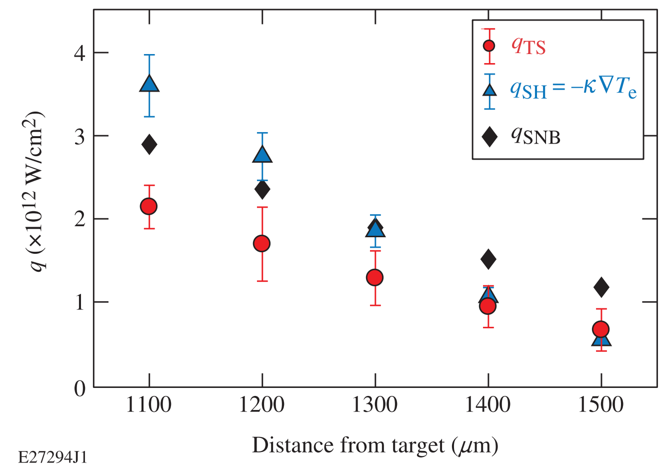


FIG. 1. (a) Calculated Thomson-scattering features (red curve, right axis) from electron plasma waves [Eq. (1)] are shown ($v_\phi = \omega/k$) using a Maxwellian (solid blue curve, left axis) electron distribution function and the non-Maxwellian (dashed blue curve) distribution that accounts for classical SH heat flux ($\lambda_{ei}/L_T = 2.2\times10^{-3}$, $q/q_{FS} = 3\%$). Inset: For a fixed normalized phase velocity, the ratio (R) of the peak scattered power of the up- and downshifted features are shown for calculations that use classical SH (solid curve, top axis) and nonlocal (dashed curve, bottom axis) distribution functions over a range of heat flux. (b) A schematic of the setup is shown.



- Asymmetry of resonances associated with electron plasma waves propagating with and against the heat flux in $S(\vec{k},\omega)$ is used to measure q_{TS} by employing results of Vlasov-Fokker-Planck simulations.
- SNB is G. Shurtz, Ph. Nicolai, M. Busquet, Phys. Plasmas **7**, 4238 (2000) – current standard in nonlocal transport implementation into radiation hydrodynamics.

Wave-wave interactions by TS

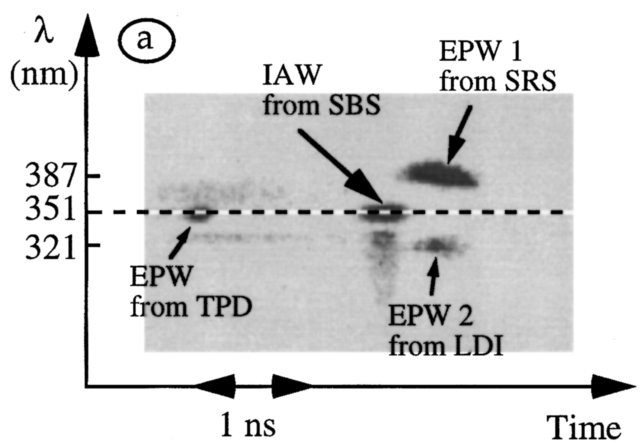
Nonlinear electron plasma waves driven by the stimulated Raman scattering undergo further decays that contribute to saturation of the scattering instability.

Phys. Plasmas **5** (1), January 1998

Time-resolved measurements of secondary Langmuir waves produced by the Langmuir decay instability in a laser-produced plasma

C. Labaune, H. A. Baldis,[a)] and B. S. Bauer[b)]
Laboratoire pour l'Utilisation des Lasers Intenses, Ecole Polytechnique, Centre National de la Recherche Scientifique, 91128 Palaiseau cedex, France

V. T. Tikhonchuk[c)] and G. Laval
Centre de Physique Théorique, Ecole Polytechnique, Centre National de la Recherche Scientifique, 91128 Palaiseau cedex, France

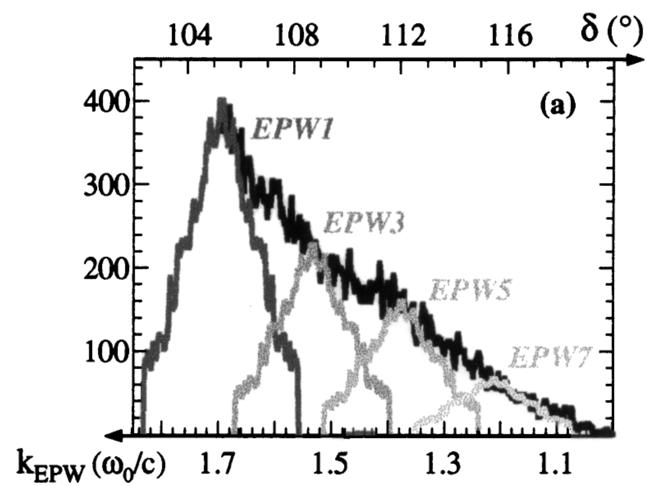


TS from enhanced electrostatic fluctuations and unstable plasmas

VOLUME 89, NUMBER 4 PHYSICAL REVIEW LETTERS 22 JULY 2002

Langmuir Decay Instability Cascade in Laser-Plasma Experiments

S. Depierreux,[1,*] C. Labaune,[1] J. Fuchs,[1] D. Pesme,[2] V. T. Tikhonchuk,[3] and H. A. Baldis[4]



TS spectrum of epw cascade reconstructed from the experimental data using instrumental spectral width for each component of the cascade.

Nobel prize in physics 2018

Left to right: Arthur Ashkin, Gérard Mourou, and Donna Strickland. Credits: Bell Labs, Alexis

"During the 1990s, a kind of revolution occurred in the little world of laser-plasma interaction. The simultaneous development of high energy lasers for fusion and of the chirped pulse amplification allowed a huge jump in accessible laser light intensities."

G.Laval, *et al*. EPJ H **43**, 421 (2018)

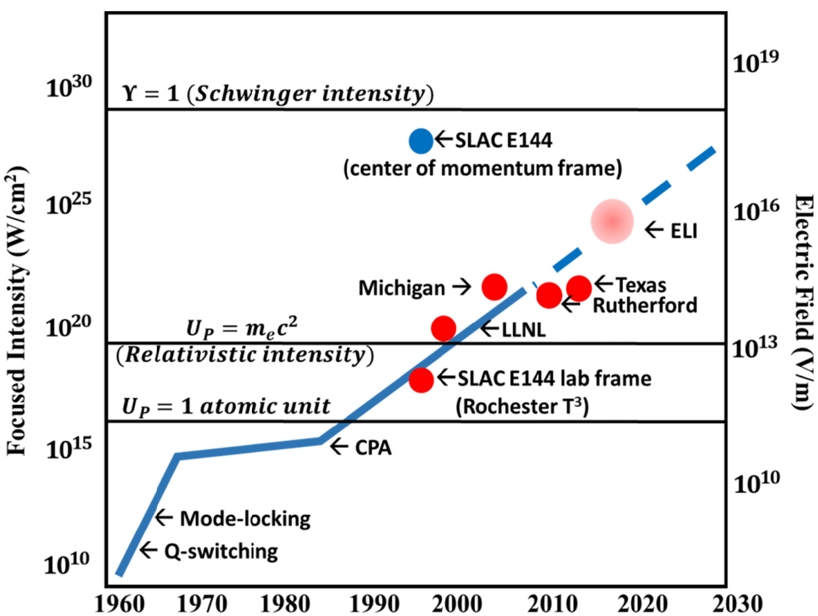
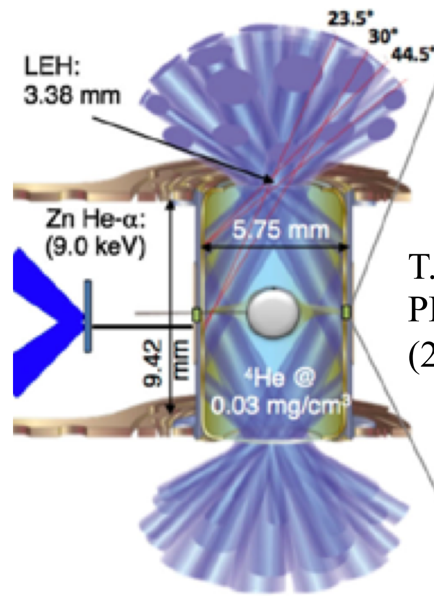


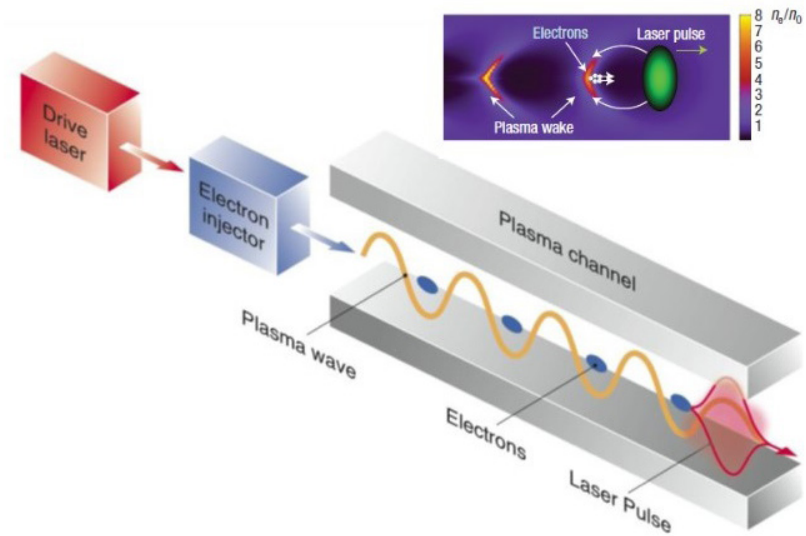
FIGURE 1.3 Highest focused intensities over time. CPA and solid-state laser technology have pushed the present peak intensity to the range of 10^{22} W/cm^2. The European ELI project will scale this up more than one order of magnitude in the near future. Also shown is a blue dot for the SLAC E144 experiment that achieved high intensity by boosting the laser-matter interaction into a relativistic frame. The three horizontal lines show the intensity for the ponderomotive (quiver) energy U_p of an electron in the focus of an 800 nm (Ti:Sapphire) laser to be equal to one atomic unit; or for U_p to be equal to the electron rest mass; or for the Schwinger intensity $Y = 1$ where the vacuum becomes unstable and light is directly converted to matter. SOURCE: Philip Bucksbaum, Stanford University.

Why laser produced plasmas?

- Lasers can deliver high powers of electromagnetic energy. Coupling with matter (plasma) is a complex and interesting problem.
- Almost from the very beginning (~1960) laser driven, inertial confinement fusion (ICF) was a main reason for studying laser plasma interactions.
- Indirect drive fusion is the leading experiment on ICF



T. Doppner *et al.* PRL, 121, 025001 (2018)



High intensity short pulse lasers:

- electron and proton acceleration,
- photon, positron, neutron sources
- nuclear physics applications
- extreme intensities, QED

Progress in ICF research

Inertial Confinement Fusion (ICF) was supposed to be attained in 2012 on the National Ignition Facility (NIF) in Livermore, CA. However, hydrodynamic instabilities and laser–plasma interactions that weren't foreseen in computer simulations have kept experimenters from achieving the uniform implosions that are required for the reaction. The recent milestone says:

PHYSICAL REVIEW LETTERS **120,** 245003 (2018)

Fusion Energy Output Greater than the Kinetic Energy of an Imploding Shell at the National Ignition Facility

S. Le Pape,[1] L. F. Berzak Hopkins,[1] L. Divol,[1] *et al.*

Experiments doubled previous records both for neutron yield (now at 1.9×10^{16}) and fusion energy output (now at 54 kilojoules) generated from capsules containing cryogenic deuterium–tritium fusion fuel. The progress was due largely to changes to both the capsules and the hohlraums, that helped maintain the symmetry of the fuel's implosion.

The latest shots have achieved 360 gigabars of pressure—exceeding that at the center of the Sun —which is around 70% of what's needed for ignition

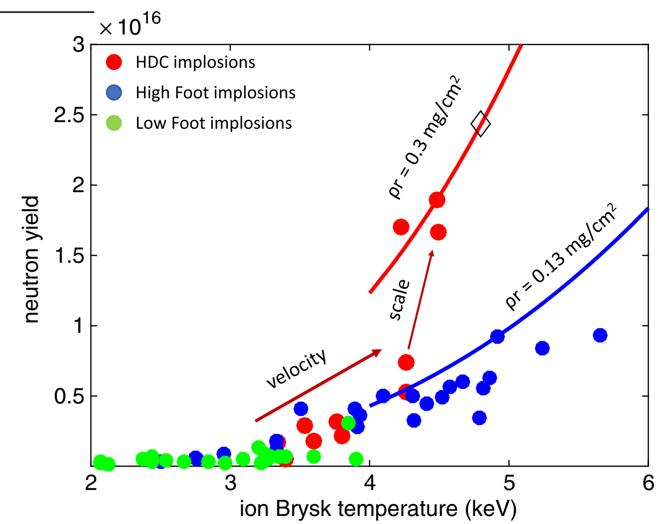
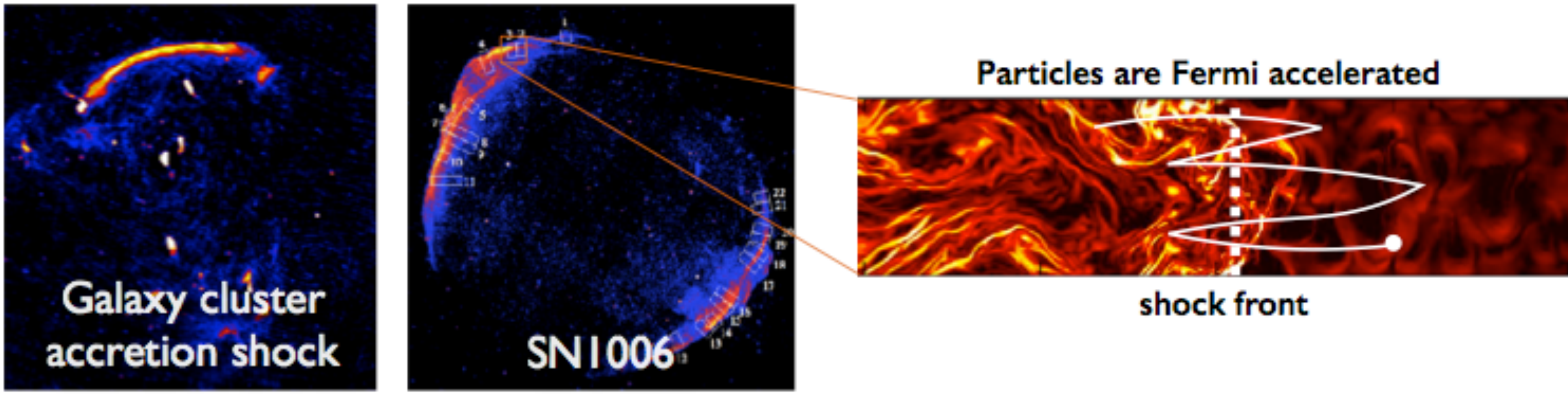


FIG. 4. Total DT neutron yield as a function of ion temperature, red dots are doped HDC implosions, blue dots are high foot implosions, green dots are low foot implosions. The neutron yield is plotted against the lowest burn averaged DT ion temperature measured by NTOF detectors (Brysk temperature). For high foot implosions, the Brysk temperature is estimated to be up to a keV higher due to flows in the hot spot. Black diamond is the point where α deposited energy equals bremsstrahlung and conduction losses. Solid curves are a yield extrapolation with temperature using a constant ρr and adiabat.

Astrophysics in laboratory

Large scale fusion laboratories, OMEGA (Univ. Rochester), NIF, etc., have been used to investigate astrophysical processes, e.g. collisionless shocks and particle acceleration. Shocks were proposed as cosmic rays accelerators via Fermi mechanism [A. R. Bell, MNRAS 182, 147 (1978); R. D. Blandford, J. P. Ostriker, Astrophys. J. 221, L29 (1978)] .

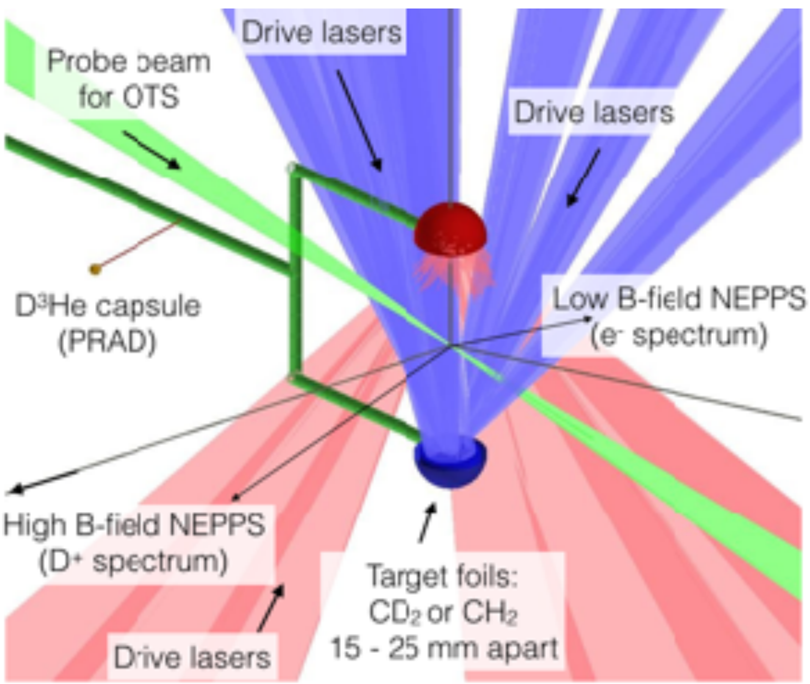


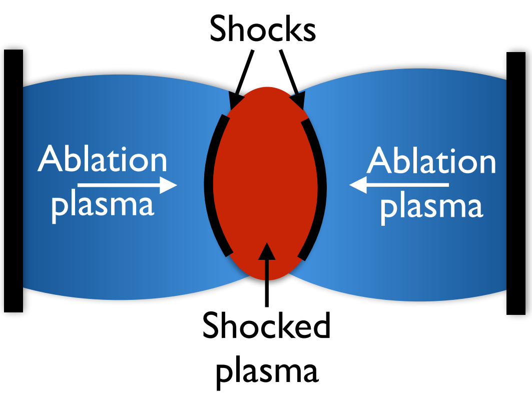
- In high Mach number shocks we need to understand how plasma instabilities mediate the shock formation and its structure.
- The onset of turbulence and injection of particles in the shock are critical elements of the cosmic ray acceleration scenario that are not yet understood.
- Laboratory experiments introduce rigor and constrain parameters of the shocks and plasma turbulence.

Collisionless shocks on NIF

Collisionless shocks require a specific scale length separation to form: $L_{inst} << L_{exp} << L_{mfp}$ where only by using energy of NIF lasers (~1 MJ) one can generate large enough collisionless plasma (L_{exp}) and short gain length for Weibel instability ($L_{inst} \sim c/\omega_{pi}$), while having large temperature to achieve large collisional mean-free-path.

Experimental platform



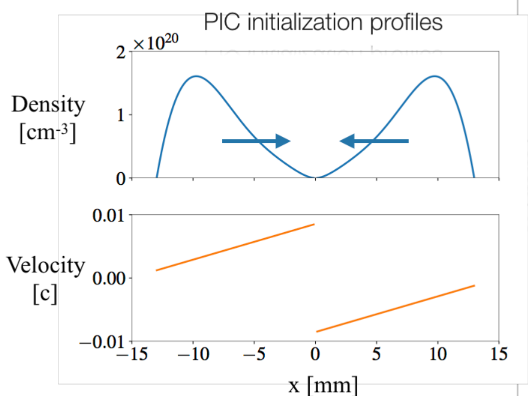


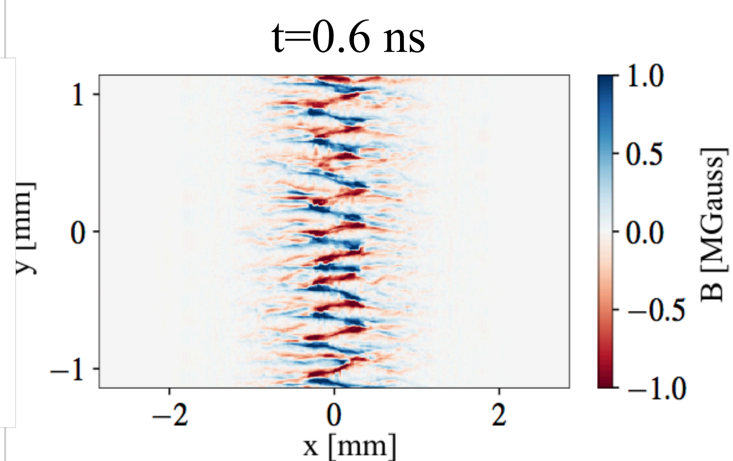
- Measurements of the shock width, Te/Ti, E and B fields, and nonthermal spectra of Particles will validate theoretical-astrophysical scenarios.
- Drive lasers ~450 kJ/foil, NEEPS – measure nonthermal tails of electron and ions, OTS- optical Thomson scattering will measure compression rate, temperatures.

Experiment in Feb. 2019, was a success – stay tuned for the results by F. Fiuza *et al*.

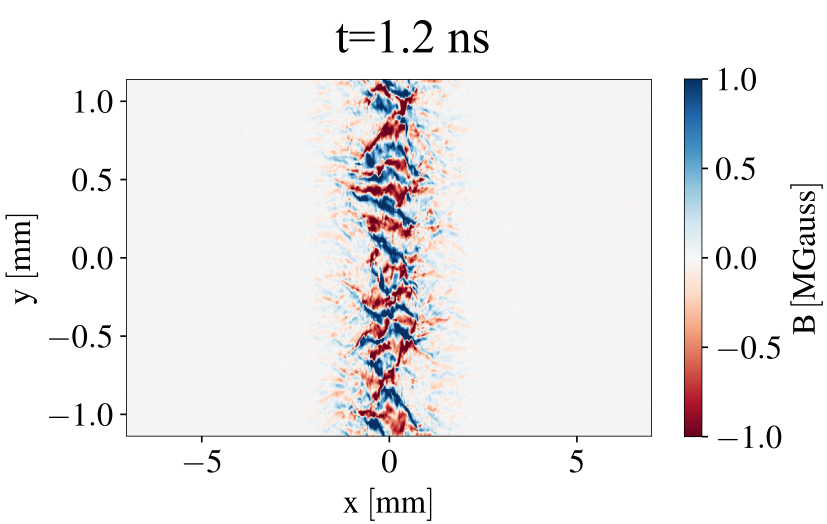
Magnetic field generation

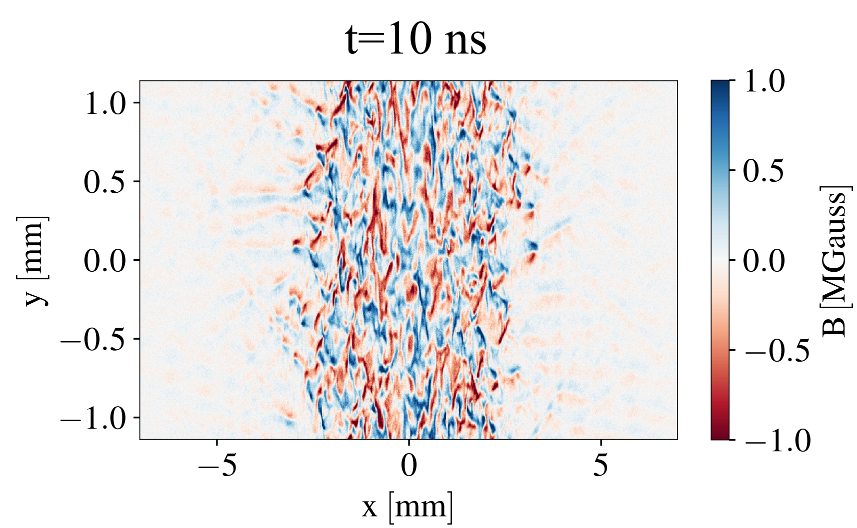
Anna Grassi, Frederico Fiuza, SLAC, described by 2D particle-in-cell (PIC) simulations Weibel instability of interpenetrating plasmas, magnetic field generation and collisionless shock formation





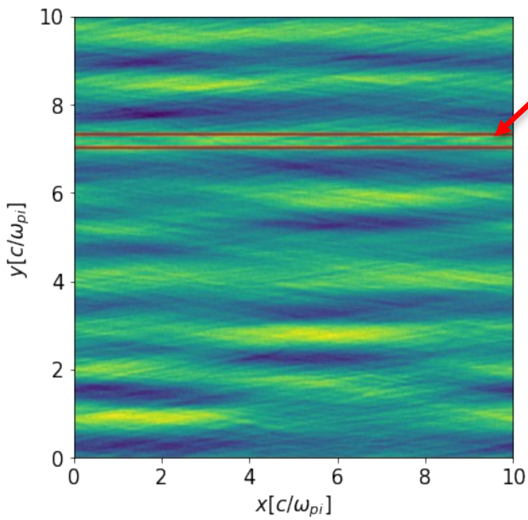
As a result of instability plasma flows are transversely modulated, give rise to current and B-field normal to the plane of simulations and shown at different times





Magnetic field measurement by TS

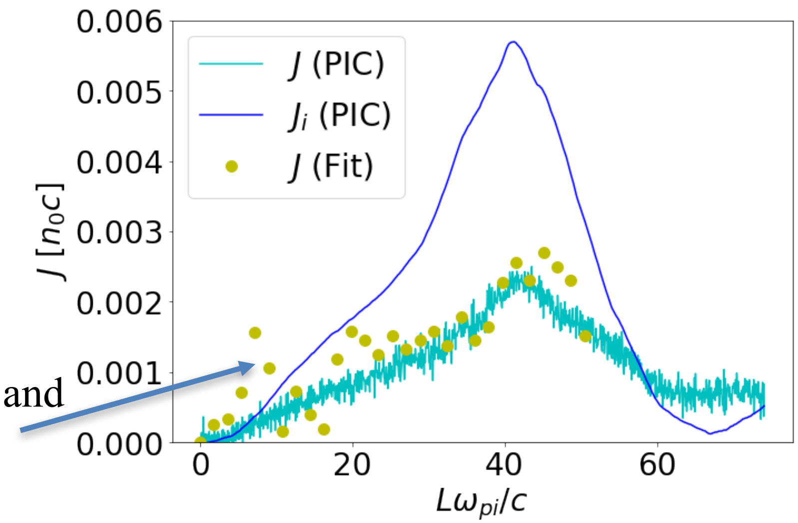
C. Bruulsema, F. Fiuza, W.R., G. Swadling, S. Glenzer, propose local measurement of magnetic field in Weibel unstable plasmas. TS spectra are used to calculate electric current, and B-field, assuming that electron density fluctuations and $S(\vec{k},\omega)$ are not affected by the electromagnetic instability. The method is first validated by PIC simulations.

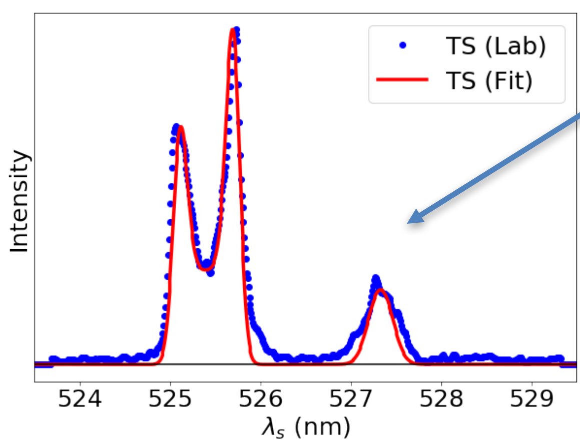


TS volume

Electric current in PIC simulations of the interpenetrating plasmas

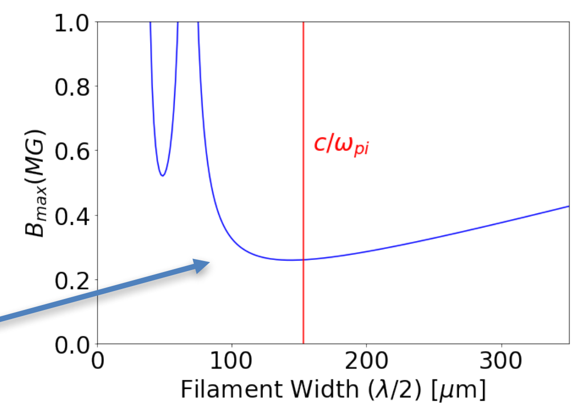
Comparison of PIC current and results from "synthetic" TS





Sample of the experimental TS spectra and fits

Field strength from fit current



Plasma turbulence

- Influential monograph *Plasma Turbulence* by B.B. Kadomtsev was published in 1965 in English translation. It addressed not only quasi-linear and weak-turbulence theory but also sophisticated results about strong turbulence.
- Eq. (IV.18) from Kadomtsev's book describes evolution of the ion acoustic turbulence in terms of the spectral intensity I_k according to weak turbulence theory:

$$\frac{\partial I_k}{\partial t} - \frac{1}{k^2}\frac{\partial}{\partial k}\left(A k^7 I_k^2\right) = 2\gamma_k I_k - A k^4\, I_k^2,$$ giving stationary solution: $$I_k = \frac{\alpha}{2Ak^3}\ln\frac{k_0}{k}$$

where the linear growth rate of the ion acoustic instability, $\gamma_k = \alpha k$.

- This result has been refined and generalized, cf. V.Yu. Bychenkov, *et al*. Physics Reports **164**, 119 (1988). Subsequently several attempts have been made to incorporate it into main stream laser plasma interaction theory.

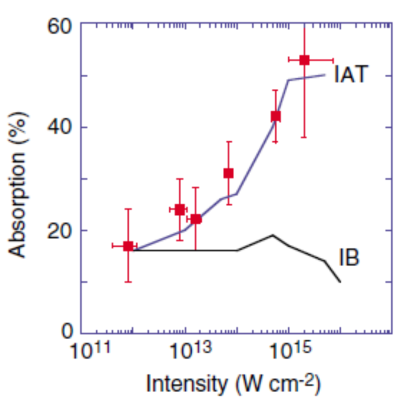


FIG. 4 (color). Absorption for various 2ω probe beam intensities. The comparison with two models show that inverse bremsstrahlung absorption (IB) is not sufficient to explain the measurements (squares). Good agreement can be seen when including ion acoustic turbulence (IAT).

VOLUME 88, NUMBER 23 PHYSICAL REVIEW LETTERS 10 JUNE 2002

Anomalous Absorption of High-Energy Green Laser Light in High-Z Plasmas

S. H. Glenzer,[1] W. Rozmus,[2,3] V. Yu. Bychenkov,[4] J. D. Moody,[1] J. Albritton,[1] R. L. Berger,[1] A. Brantov,[4] M. E. Foord,[1] B. J. MacGowan,[1] R. K. Kirkwood,[1] H. A. Baldis,[2] and E. A. Williams[1]

Ion acoustic turbulence (IAT) contributes to anomalous collision frequency that enhances absorption of laser light as compared to classical inverse bremsstrahlung (IB) mechanism. No direct observation of IAT spectra has been made.

Reduced model of IAT

Practical expressions for anomalous absorption and transport using Kadomtsev spectrum of the IAT have implemented in the radiation hydro codes (cf. M. Sherlock et al. 2017)

Linear threshold:

$$p_T^{SH}>1 \rightarrow \quad p_T^{SH} \approx \frac{3}{2}\frac{v_{Te}}{c_s}\frac{\lambda_{ei}}{L_T}>1, \quad \text{nonlocal threshold: } p_T^{NL}>1$$

$$\text{small ion damping}: \quad \gamma_e=\gamma_s\left(p_T-1\right)>\gamma_i$$

Knudsen number for IAT

$$K_N=\frac{6\pi\omega_{pe}^2\lambda_{Di}^2 R}{\omega_{pi}^2\lambda_{De}n_e T_e} \xrightarrow{J=0} 12\frac{T_i}{ZT_e}\frac{1}{m_e c_s\omega_{pi}}\left|\frac{\partial T_e}{\partial x}\right|$$

recall: $\vec{R}\equiv\hat{n}R=en_e\vec{E}_a-\vec{\nabla}\left(n_e T_e\right),$

Anomalous collision frequency

$$\nu_{an}=0.04\,\omega_{pi}\frac{ZT_e}{T_i}\left(\frac{1+9K_N^2}{K_N^2+\ln^2\left(\frac{1}{K_N}\right)}\right)^{1/2}$$

Enhanced IB absorption

$$\kappa_{IB}=\frac{\nu_{ei}+\nu_{an}}{c}\left(\frac{n_e}{n_c}\right)\left(1-\frac{n_e}{n_c}\right)^{-1/2}$$

Anomalous heat flux

$$q_{an}=fn_eT_ev_{Te},\quad f=0.18\sqrt{\frac{Z}{A}}\left(1+1.6\sqrt{K_N}\right)\approx 0.09$$

Au, $K_N<<1$

Necessary choice?