Posters

Study of Alpha Channeling with Lower Hybrid Waves in a Shaped Plasma

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Abstract not submitted

Beyond Nonlinear Saturation of Backward Raman Amplifiers

Ido Barth
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Backward Raman amplification is limited by relativistic nonlinear dephasing resulting in saturation of the leading spike of the amplified pulse. Pump detuning is employed to mitigate the relativistic phase mismatch and to overcome the associated saturation. The amplified pulse can then be reshaped into a mono-spike pulse with little precursory power ahead of it, with the maximum intensity increasing by a factor of two. This detuning can be employed advantageously both in regimes where the group velocity dispersion is unimportant and where the dispersion is important but small.

Plasma-Surface Interaction with Strong Electron Emission — A New Solution to an Old Problem*

Michael Campanell
Lawrence Livermore National Laboratory

The first solution to the fundamental sheath-presheath problem with strong emission was reported a half century ago by Hobbs and Wesson. In their original theory [1], it was assumed for any emission coefficient that the floating sheath potential is negative and the presheath accelerates ions to the sound speed, similar to the case without emission. This "space-charge limited" (SCL) model has long been used to predict the plasma-surface interaction at strongly emitting surfaces in applications. However, recent theory and simulation studies demonstrated a new type of solution where the sheath potential is positive, repelling ions. In this inverse regime [2], the dynamics of electrons and ions in the sheath and presheath, as well as their fluxes into the surface, drastically differ from the SCL theory. Very recently, it was shown that SCL states are unstable when the emission coefficient exceeds unity and therefore only inverse states should exist [2]. This could have significant consequences for applications where intense emission is possible including tokamak divertor plates, Hall thruster channel walls, emissive probes, dust grains, hot cathodes and the lunar surface.

[1] G. D. Hobbs and J. A. Wesson, Plasma Phys. 9, 85 (1967).

[2] M. D. Campanell and M. V. Umansky, *Strongly Emitting Surfaces Unable to Float Below Plasma Potential*, to appear in Phys. Rev. Lett.

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On the Value of the Reconnection Rate

Luca Comisso
Princeton University

Magnetic reconnection is a fundamental plasma process that changes the connectivity of the magnetic field lines and has profound consequences in a wide variety of different phenomena in laboratory, space and astrophysical plasmas. Therefore, it is essential to know the rate at which magnetic reconnection occurs. In the last two decades it has been consistently shown from numerical simulations that magnetic reconnection in the collisionless regime can be characterized by a reconnection rate (normalized to the electric field upstream of the reconnection layer) as fast as 0.1. This has been observed with very different physical models and different initial conditions. However, the deep physical understanding of this particular value of the reconnection rate has remained a mystery. Here we want to identify some key points that may be crucial to the solution of this open problem.

Sudden Viscous Dissipation in Compressing Plasma

Seth Davidovits
Princeton University

Compression of turbulent plasma can amplify the turbulent kinetic energy, if the compression is fast compared to the viscous dissipation time of the turbulent eddies. A sudden viscous dissipation mechanism is demonstrated, whereby this amplified turbulent kinetic energy is rapidly converted into thermal energy, suggesting a new paradigm for fast ignition inertial fusion.

Effects of Nonlinear Modification of LHCD and ECCD on Tearing Mode Stabilization

Ge Dong
Princeton University

RF driven current can control neoclassical tearing mode by compensating for bootstrap current inside the island. The power deposition of the waves has a nonlinear dependence on the perturbed temperature. Equilibrium solution of the heat diffusion equation with nonlinear source term inside the island shows a regime where perturbed temperature at the o-point increase dramatically, resulting in a larger local current density, and therefore much stronger suppression of the magnetic island. In drift kinetic simulation of the electrons with collision and modeled current drive, electron phase space evolution results in a nonlinear increase in perturbed power deposition, confirming the theoretical picture.

Strongly Enhanced Stimulated Brillouin Backscattering in an Electron-Positron Plasma

Matthew Edwards
Princeton University

Stimulated Brillouin backscattering of light is shown to be drastically enhanced in electron-positron plasmas, in contrast to the suppression of stimulated Raman scattering. A generalized theory of three-wave coupling between electromagnetic and plasma waves in two-species plasmas with arbitrary mass ratios, confirmed with a comprehensive set of particle-in-cell simulations, reveals violations of commonly held assumptions about the behavior of electron-positron plasmas. Specifically, in the electron-positron limit three-wave parametric interaction between light and the plasma acoustic wave can occur, and the acoustic wave phase velocity differs from its usually assumed value.

Non-equilibrium Piezo-Thermal Effect in Spinning Gas

Vasily Geyko
Princeton University

A spinning gas, heated adiabatically through axial compression, is known to exhibit a rotation-dependent heat capacity. However, as equilibrium is approached, a new effect is identified here wherein the temperature does not grow homogeneously in the radial direction, but develops a temperature differential with the hottest region on axis, at the maximum of the centrifugal potential energy. This phenomenon, which we call a piezo-thermal effect, is shown to grow bilinearly with the compression rate and the amplitude of the potential. Numerical simulations confirm a simple model of this effect, which can be generalized to other forms of potential energy and methods of heating, namely, we checked this effect in the case of linear gravitational potential and self-generated potential of centrifugal force for spinning gas.

High Beta Tokamak Equilibria Using Fisch-Boozer and Ohkawa Current Drives

Pierre Gourdain
University of Rochester

High beta (> 0.25) equilibria in tokamaks exist if and only if the aspect ratio of the device is small ($A \sim 1$) or if the current density on the low field side of the plasma is much larger than the current density on the high field side. While the former condition simply constrains the geometry of the device, the later requires breaking the symmetry of the current profile. This poster will show why Fisch-Boozer and Ohkawa current drives are required to sustain stable high beta equilibria in large aspect ratio ($A > 2$) devices like ITER.

End Loss Analyzer System for Measurements of Plasma Flux at the C-2U Divertor Electrode

Martin Griswold
Tri Alpha Energy

An end loss analyzer system consisting of electrostatic, gridded retarding-potential analyzers and pyroelectric crystal bolometers was developed to characterize the plasma loss along open field lines to the divertors of C-2U [1]. The system measures the current and energy distribution of escaping ions as well as the total power flux to enable calculation of the energy lost per escaping electron/ion pair. Special care was taken in the physical and electronic construction of the analyzer elements so that they can be directly mounted to the divertor electrode. A laser-drilled stainless steel attenuation plate at the entrance to the gridded retarding-potential analyzer reduces neutral gas load and plasma density by a factor of 60 to prevent collisions and space charge limitations inside the device. This plate also withstands and attenuates high heat flux (up to 5 MW/m^2) without sacrificing its angular acceptance of ions. In addition, all of the electronics for the measurement are isolated from ground so that they can float to the bias potential of the electrode (up to 2 kV below ground). Preliminary measurements from the analyzer system will be presented.

[1] M. Binderbauer *et al.*, Phys. Plasmas 22, 056110 (2015).

Differential Confinement and Development of Plasma Mass Filtering Techniques at PPPL

Renaud Gueroult
Princeton Plasma Physics Laboratory

Legacy nuclear waste cleanup in the United States is estimated to cost over 280 billion dollars over the next 60 years [1]. In essence, cleanup is a matter of separating small volumes of high activity waste from much larger volumes of low activity waste. Physical separation techniques, such as plasma mass filtering, have the potential to significantly lower the cleanup cost while reducing the processing time [2]. To reach this potential, plasma devices that can efficiently separate elements at high throughput have to be developed. Since separation is a form of differential confinement, the development of such devices builds on the large body of work dedicated to the physics of magnetic confinement. In this paper, we review the ongoing effort towards the development of plasma mass separation techniques at PPPL.

[1] G. H. Friedman, *Special Report – Management Challenges at the Department of Energy – Fiscal Year 2015*, Technical Report DOE/IG-0924, U.S. Department of Energy, Office of Inspector General, Office of Audits and Inspections, 2014, p. 7.

[2] R. Gueroult, D. T. Hobbs and N. J. Fisch, Journal of Hazardous Materials 297, 153 (2015).

Plasma Turbulence in Magnetic Fusion: What Is Needed to Predict and Reduce It?

Gregory Hammett
Princeton University

Abstract not submitted

Geometrical Constraints on Diffusion in Plasmas

Michael Hay
Princeton University

Waves propagating through a bounded plasma can rearrange the densities of states in the six-dimensional velocity-configuration phase space. Depending on the rearrangement, the wave energy can either increase or decrease, with the difference taken up by the total plasma energy. In the case where the rearrangement is diffusive, only certain plasma states can be reached. Because the plasma energy is a linear functional of the N state densities, the problem of energy minimization is reduced to characterizing the shape of the feasible region corresponding to the accessible plasma state space. In particular, the emphasis is on identifying and enumerating the vertices of this region in N-dimensional space.

X-ray Opacity of Hot Dense Plasmas: Solved or Unsolved?

Robert Heeter
Lawrence Livermore National Laboratory

Plasma "opacity", describing the absorption and re-emission of X-rays by partly-stripped ions, plays a critical role in stars and in many laboratory plasmas. Despite great progress in theory in recent decades, experiments on large lasers and Z pinches have not fully agreed with theory. One persistent disagreement involves experiments on the Sandia Z facility to study iron in conditions closely related to the solar radiation-convection transition boundary. An increased iron opacity, of the sort measured at Z, could help resolve a longstanding issue with the standard solar model. But this would require a radical departure for theory. To address this issue, a separate "platform" is in development to replicate the Z iron experiment using the National Ignition Facility. Specifically, a laser heated hohlraum "oven", able to produce iron plasmas at 160 eV and $7 \times 10^{21}\,\mathrm{cm}^{-3}$, will be probed with continuum X-ray radiation from the pulsed, point-like X-ray emission of a capsule implosion, and the resulting X-ray transmission spectra recorded on a specially designed Opacity Spectrometer. Preliminary experiments to develop the backlighter and hohlraum are underway, providing input data to calculations which illustrate how the NIF opacity platform is expected to perform.

First Experiments on Highly Relativistic Plasmas at the Upgraded Texas Petawatt Laser*

B. Manuel Hegelich
University of Texas at Austin

Advances in laser-based hadron generation, especially with respect to particle energy, as well as reaching the new regime of radiation dominated plasmas and non-linear QED, require laser fields of Petavolts per meter that preferably interact with very high density, overcritical plasmas. To achieve these conditions we are upgrading the Texas Petawatt Laser both respect to on-target laser intensity and laser-contrast, aiming to reach intensities of $\sim 5 \times 10^{22}\,\mathrm{W/cm^2}$ and pulse contrast parameters allowing the interaction with overcritical, yet ultrathin, sub-micron targets.

We will report on the planned experiments aimed at ion acceleration, neutron generation and the first experimental measurement of radiation reactions to motivate the chosen upgrade parameters. We will further report on the technical changes to the laser and present first measurements of the achieved intensity and contrast parameters.

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Differential Form for the Nonlinear Gyrokinetic Collision Operator

Eero Hirvijoki
Princeton Plasma Physics Laboratory

A Landau form for the nonlinear gyrokinetic collision operator, satisfying Boltzmann H-theorem and equipped with exact conservation laws, has been derived recently from the first principles [1]. In this work, we present a differential form for the nonlinear gyrokinetic operator, analogous to the Rosenbluth potential formulation in particle coordinates. We also discuss the numerical challenges one would expect in implementing either the Landau or the Rosenbluth formulation.

[1] J. W. Burby, A. J. Brizard, and H. Qin, Phys. Plasmas 22, 100707 (2015).

Prof. Nathaniel J. Fisch Symposium "Solved and Unsolved Problems in Plasma Physics", March 28-30, 2016
Poster Session

On the Generalization of Fluid Theory Including Kinetic Effects*

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One of the important unsolved problems in plasma physics is the unification between kinetic and fluid descriptions. The fluid description is advantageous because of its simplicity, its relatively light numerical demands and its use in reduced modeling. But, the existing fluid theory is always related to a steady-state Maxwellian. In contrast, the kinetic description has the advantage of including non-Maxwellian (NM) effects. As a result, after 20 years of code developing efforts by the community, very CPU-expensive kinetic codes dominate the field. A large part of the current work aims to expand the kinetic short time scale results to longer ones compatible with confinement time. It is therefore of great interest to develop undiscovered links between kinetic and fluid descriptions that have advantages of both: it would need relatively small numerical resources, it would be relevant to short and long time scales, and it would include NM effects. In this contribution we introduce some analytic NMs (particularly a new interpreted one), and predict analytic kinetic corrections due to a super-thermal population in a few fundamental theories relevant to fusion tokamaks including the Langmuir probe characteristic curve, the secondary electron emission and the statistical entropy. After revisiting the limitations of the current fluid theory, the second part generalizes it to include NM effects such as super-thermal tails with as few fluid equations as possible. The collisionless and collisional fluid closures from the nonlinear Fokker-Planck collision operator are discussed for an arbitrary collisionality. These new equations could initiate the next generation of fluid codes including kinetic effects and can be expanded to other scientific disciplines such as astrophysics, condensed matter or hydrodynamics.

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Distinguishing Raman and Strong-Coupling Brillouin Amplification for Short Pulses

Qing Jia
Princeton University

Strong-coupling Brillouin amplifier was recently suggested for the amplification and compression of short laser seed to ultrahigh intensities in the sub-quarter-critical density plasmas. With detailed spectral analysis of the kinetic simulation results, we demonstrate that it is the Raman backscattering amplification which is responsible for the leading spike where the most energy compression occurs in the suggested Brillouin amplifier, while the ion modes only affect the tail of the amplified pulse. Moreover, it is found that the amplification of the ultrashort pulse is the pure Raman effects. In addition, it is pointed out that sharper seed front leads to higher maximum amplitude since the Raman amplification determines the leading spike, and longer seed duration contributes to increasing the trailing pulse amplitude due to the enhanced Brillouin amplification.

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Abstract not submitted

Role of Drift Resistive Ballooning Modes on the H-Mode Pedestal Buildup in Alcator C-Mod Discharges*

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Tokamak edge physics plays a central role in controlling the global confinement of discharges. It is important to understand anomalous transport in the pedestal region in order to develop a comprehensive model for the H-mode pedestal. To advance our understanding of the anomalous transport in the H-mode pedestal region, five Alcator C-Mod discharges are analyzed. An objective of this study is to examine the possibility that modes, in addition to kinetic ballooning, impact the growth of the H-Mode pedestal width. In particular can drift resistive inertial ballooning modes (DRIBMs) [1] contribute to the development of the H-mode pedestal in CMOD discharges? Two alternative methods are used to illustrate the role of the DRIBMs in the C-Mod discharges considered. The first method is based on the stability analysis of the Alcator C-Mod equilibria using the DRIBM model in the TRANSP code. The second method is based on the interpretive analysis of anomalous transport using the additive flux minimization technique (AFMT) [2]. AFMT is used in the XGC0 code [3] to determine the anomalous fluxes that are needed in addition to the XGC0 neoclassical fluxes to reproduce the C-Mod profiles in the H-mode pedestal region. Neoclassical fluxes are computed self-consistently in the XGC0 code, and anomalous fluxes are computed using a simplified anomalous model. RMS deviations between computed and experimental temperature and density profiles are minimized using the gradient-based unconstrained optimization in the DAKOTA toolkit. In simulations carried out with the TRANSP code using the MMM7.1 anomalous transport model [4], it is found that the DRIBMs become more unstable in discharges with larger electron collisionality. In the studies using AFMT, it is shown that anomalous transport at the top of the pedestal increases with electron collisionality. This collisionality dependence of the plasma edge anomalous transport is consistent with the previous experimental results from Alcator C-Mod discharges [5]. The results of the studies carried out indicate that DRIBMs can compete with kinetic ballooning modes in determining the pedestal structure.

[1] T. Rafiq *et al.*, Phys. Plasmas 17, 082511, (2010).
[2] A. Y. Pankin *et al.*, Phys. Plasmas 20, 102501, (2013).
[3] C. S. Chang *et al.*, Phys. Plasmas 11, 2649 (2004).
[4] T. Rafiq *et al.*, Phys. Plasmas 20, 032506, (2013).
[5] B. LaBombard *et al.*, Nuclear Fusion 40, 2041 (2000); Phys. Plasmas 8, 2107 (2001).

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Adjoint Fokker-Planck Equation and Runaway Electron Dynamics

Chang Liu
Princeton University

The adjoint Fokker-Planck equation method is applied to study the runaway probability function and the expected slowing-down time for highly relativistic runaway electrons, including the loss of energy due to synchrotron radiation. In direct correspondence to Monte-Carlo simulation methods, the runaway probability function has a smooth transition across the runaway separatrix, which can be attributed to effect of the pitch angle scattering term in the kinetic equation. However, for the same numerical accuracy, the adjoint method is more efficient than the Monte-Carlo method. The expected slowing-down time gives a novel method to estimate the runaway current decay time in experiments. A new result from this work is that the decay rate of high energy electrons is very slow when E is close to the critical electric field.

Extended Propagation of Powerful Laser Pulses in Focusing Kerr Media

Vladimir Malkin and Nathaniel J. Fisch
Princeton University

Powerful incoherent laser pulses can propagate in focusing Kerr media much longer distances than can coherent pulses, due to the fast phase mixing that prevents transverse filamentation. This distance is limited by 4-wave scattering, which accumulates waves at small transverse wavenumbers, where phase mixing is too slow to retain the incoherence and thus prevent the filamentation. However, we identify how this theoretical limit can be overcome by countering this accumulation through transverse heating of the pulse by random fluctuations of the refractive index. In these new regimes, the laser pulse propagation distances are significantly extended, making feasible a new class of random lasers, in particular, ultra-powerful random lasers in plasmas.

Two Unconventional Thoughts on Fusion and Climate

Wallace Manheimer
retired from the National Research Laboratory

This poster presents and explores two unconventional thoughts regarding controlled fusion and climate. First, the only way that fusion can contribute to midcentury power is by switching its goal from pure fusion, to fusion breeding. Doing so could lead to a sustainable, carbon free, environmentally and economically viable, midcentury infrastructure, with little or no proliferation risk, which could provide terawatts of power for the world. Second, while CO_2 input to the atmosphere may, at some point, become a concern to the earths climate, an Internet search shows that there is no evidence that we are anywhere near that point now and likely will not be before midcentury at the earliest. The timing could be serendipitous; the time necessary to develop fusion breeding could well match up to the time when it is needed so as to avoid harm to the earths climate and/or depletion of finite energy resources.

Energetic Electron "Pump-Out" by Combining ECRH and Interchange Transport in Magnetic Mirrors

Michael Mauel
Columbia University

Abstract not submitted

Intense Attosecond Pulse Emission from Relativistic Laser-Solid Interaction

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Many fields of science and technology quest for bright, high-quality light sources in the extreme ultraviolet (XUV) and x-ray spectral regions. These sources are key enabling tools for material science, chemistry, biomedicine, and plasma physics. The pursuit of brilliant sources of extremely short-pulsed (attosecond) x-ray beams that exploit the interaction between matter and laser fields can push the frontiers of real-time, high-resolution x-ray spectroscopy, imaging, and diffraction.

The interaction of intense, ultrashort-pulsed infrared light with solid targets results in target ionization and the momentary formation of a nanometer-sized electron "synchrotron": relativistic electrons moving at the target surface along synchrotron-like trajectories emit bursts of high-energy radiation within time intervals much shorter than the half-cycle of the driving light field. This process, also known as relativistic high-order harmonic generation, can be controlled by the details of how the incident field evolves with time. We explore the chance to enhance the intensity of coherent ultraviolet and x-ray emission from solids under extreme light fields by sub-cycle shaping of the driving laser pulse waveforms. The waveform shaping can be achieved through mixing the laser fundamental frequency with its second harmonic or higher frequency components. The effect of the energy distribution of different colors in the driving field as well as the phase delay between them on the radiation spectra is studied. The optimized solutions for driving waveforms, as well as the physical limits on the efficiency of the process are found. This study provides new insight into the dynamics of field-controlled electron oscillations in laser-produced solid-density plasmas. Ultimately, this approach may offer higher attosecond pulse intensities than those currently achieved, opening a pathway to advance ultrafast metrology toward time-resolved x-ray pump-probe spectroscopy.

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Ian Ochs
Princeton University

Abstract not submitted

How Do Pulsars Shine?

Alexander Philippov
Princeton University

The modeling of pulsar radio and gamma-ray emission suggests that in order to interpret the observations one needs to understand the field geometry and the plasma state in the emission region. In recent years, significant progress has been achieved in understanding the magnetospheric structure in the limit of abundant plasma supply. However, the very presence of dense plasma everywhere in the magnetosphere is not obvious. Even the region where the observed emission is produced is subject to debate. To address this from first principles, we constructed global kinetic simulations of pulsar magnetospheres using relativistic Particle-in-Cell codes, which capture the physics of plasma production and particle acceleration. In this poster I will describe how plasma is produced in the magnetospheres of pulsars. I will show evidence that observed radio emission is powered by non-stationary discharge at the polar cap. In addition, I will also present modeling of high-energy lightcurves, calculated self-consistently from particle motion in the pulsar magnetosphere.

Development of Microtearing Mode Transport Model for Tokamak Plasmas*

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Microtearing modes (MTMs) have been identified as a source of significant electron thermal transport in high β tokamak discharges. A model for MTMs that can be installed in integrated whole device predictive modeling codes is needed in order to improve the prediction of electron thermal transport and, consequently, the evolution of the plasma in devices in which MTMs have a significant role. A unified fluid/kinetic approach is used in the development of a nonlinear model for the transport driven by MTMs. The derivation of the model includes the effects of electrostatic and magnetic fluctuations, collisionality, electron temperature and density gradients, magnetic curvature and the effects associated with the parallel propagation vector. The electron momentum, electron density, Maxwell equations, Ampere's law and quasi-neutrality condition are used in the derivation of a nonlinear fluid microtearing dispersion relation. An iterative nonlinear approach is used to calculate distribution function employed in obtaining the nonlinear parallel current and the nonlinear dispersion relation. The third order nonlinear effects in magnetic fluctuations are included in the development of the microtearing mode model, and the influence of third order effects on a three-wave system is considered. For the evolution of the nonlinear microtearing instability in time, the third order effects provide the possibility of saturation of the microtearing instability. In the limit of slab geometry and strong collisionality, the fluid dispersion relation for nonlinear microtearing modes is found to agree with the kinetic dispersion relation in Ref. [1]. An envelope equation for the nonlinear microtearing modes in the collision dominant limit is introduced.

[1] J. F. Drake *et al.*, Phys. Rev. Lett. 44, 994 (1980).

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Breaking the High Power Limits with Stimulated Raman Backscattering

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For high power laser systems, the scheme using stimulated Raman backscattering (SRBS) in plasma is an attractive candidate for overcoming the difficulties in increasing laser power and intensity to extreme levels. Feasibility of SRBS lasers was initiated and proved with theoretically studies and successful experimental demonstrations. Still, despite progresses of more than a decade, maximum amplified pulse energy so far obtained in experiments has been limited to a few millijoules, and the mechanisms constraining the output energy remains to be illuminated.

Here we report on Particle-in-Cell (PIC) simulations to confirm that the currently achieved SRBS energy seen in experiments is close to its maximum. We also extensively explored the SRBS power and energy limits. With detailed studies on the electron dynamics and their impact on the plasma wave, we identify early gain saturation mechanisms introduced by the spontaneous noise, which peaks ahead of the SRBS signal and effectively enhances stochastic-like phase shifts to the Langmuir wave. The magnitude of the Langmuir wave driven by the pump and seed of the SRBS drops and hence the rates of energy transfer between the pump and seed decrease with time. Eventually the Langmuir wave diminishes to the thermal background and the energy transfer between the pump and seed stops.

Another important factor that affects the SRBS high power limit is the initial plasma temperature. In PIC simulations, we investigate the SRBS process with initial plasma temperature ranging from 5 eV to 400 eV. We find that with a higher initial plasma temperature, the SRBS process critically depends on the intensities of the seed pulse. Since at higher plasma temperatures, the magnitude of the Langmuir wave drops, although the growth of the spontaneous noise also slows down, this compensates the non-coherent effects from the spontaneous noise. The SRBS growth continues under the condition that the seed pulses are strong enough to keep the Langmuir wave above the thermal background. Based on these results, we develop a cascade SRBS scheme and proved through PIC simulations that the current SRBS saturation barrier can be effectively resolved this way.

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Relativistic Electron Acceleration in Surface Plasma Waves

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Surface plasma wave excitation on solid grating target enhances drastically the laser absorption in ultra-high intensity interaction regime and generates large currents of relativistic electrons. Motivated by this results different electron acceleration regimes in the evanescent field of a surface plasma wave are studied by considering the interaction of a test electron with the high frequency field of a surface wave. The non relativistic and relativistic limits are investigated. Simple scalings are found that show the possibility of efficient conversion of surface wave field energy into electrons kinetic energy. This mechanism of electron acceleration can provide a high frequency pulsed source of relativistic electrons with well defined energy. The most energetic electrons in the relativistic limit are obtained in the so called electromagnetic regime for surface waves. In this regime the particles are mainly accelerated parallel to the plasma-vacuum interface to velocities larger than the wave phase velocity.

Lagrangian Geometrical Optics of Classical Vector Waves and Particles with Spin

Daniel Ruiz
Princeton University

Linear vector waves, both quantum and classical, experience polarization-driven bending of ray trajectories and polarization dynamics that can be interpreted as the precession of the "wave spin." In this work, we present a universal Lagrangian theory, whose effective gauge Hamiltonian governs both mentioned phenomena and vanishes in leading-order geometrical optics [1]. When applied to classical vector waves, our theory correctly predicts, for example, the difference between the polarization-driven bending of left- and right-polarized electromagnetic waves in isotropic media [2]. When applied to quantum waves, the same general theory also yields a Lagrangian point-particle model for the Dirac electron, i.e. the relativistic spin-1/2 particle. The model captures both the Bargmann-Michel-Telegdi spin precession theory and the Stern-Gerlach spin-orbital coupling theory. Moreover, we present, for the first time, a calculation of the fully relativistic ponderomotive Hamiltonian for a Dirac electron in a vacuum laser field [3]. This Hamiltonian captures not only the usual relativistic mass shift but also spin effects.

[1] D. E. Ruiz and I. Y. Dodin, Phys. Lett. A 379, 2337 (2015).

[2] D. E. Ruiz and I. Y. Dodin, Phys. Rev. A 92, 043805 (2015).

[3] D. E. Ruiz, C. L. Ellison, and I. Y. Dodin, Phys. Rev. A 92, 062124 (2015).

Some Exotic Concepts of Magnetic Field Generation and Particle Acceleration in Plasmas

Chang-Mo Ryu
POSTECH, South Korea

Magnetic field generation and particle acceleration are two fascinating important subjects in plasma physics, which are not completely understood. Several ideas of magnetic field generation and particle acceleration such as dynamo mechanism, turbulence, reconnection, etc. are proposed and explored. Here, I would like to describe some exotic concepts which I have studied: 1) transport driven magnetic field generation. 2) turbulence acceleration. 3) magnetic field and particle acceleration in Weibel/filamentation instabilities.

Feasibility Study of Ultra-High Field Particle Acceleration in Nanostructured WDM with Laser-Pumped Electron Diffraction

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Crystals behave like a plasma, but at a relatively low temperature, if heated by a high energy source, which is called a warm dense matter (WDM). The WDMs contain much more free electrons available for plasma acceleration than gas-phase plasmas. Atomic channels in solid crystals are known to consist of $10 - 100$ V/Å potential barriers capable of guiding and collimating high energy charged particles and continuously focused acceleration by the exceptionally high electromagnetic fields. Relativistic particles, injected into a crystal orientation of a mono-crystalline target, undergo much lower nucleus and electron scatterings and stopping power. The density of conduction electrons in crystals, $n_0 \approx 10^{19} - 10^{23}\,\mathrm{cm}^{-3}$, is significantly higher than what was considered in gas-phase plasma, and correspondingly, the plasma waves possibly supports electric fields of up to 30 TV/m [1-3]. Nanostructured crystals such as carbon nanotube or graphene have a large degree of dimensional flexibilities and thermo-mechanical strengths. A laser-coupling condition into a WDM can be more readily controlled by flexible dimensions of nanostructures. Nano-channels of the synthetic crystals can accept a few orders of magnitude larger phase-space volume of channeled particles with much higher thermal tolerance than natural crystals. Normally, the electrons captured in a larger channel lose less energy through the betatron oscillations. The unique nature of nanostructures can thus possibly solve issues with atomic structures of natural crystals, limiting interaction parameters of accelerating ions in a crystalline plasma medium [4,5]. NIU and Fermilab will be investigating feasibility of ultra-high gradient particle accelerations in photo-excited crystal structures using time-resolved pump-probe electron diffraction technique. Princeton University will be in collaboration on the research with theoretical modeling and numerical analysis of experimental data.

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Transport-Driven Toroidal Rotation in the Tokamak Edge

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The edge of H-mode tokamak plasmas without external momentum input almost always rotates toroidally in the co-current direction, which has prompted a theoretical search for non-diffusive momentum transport mechanisms. In contrast to these efforts, the present model employs a kinetic ion transport equation for the pedestal and SOL containing only parallel free streaming, magnetic drifts, and spatially inhomogeneous but purely diffusive transport. The solution demonstrates that passing-ion orbits and spatially inhomogeneous diffusion interact to cause a variation of the orbit-averaged diffusivities that depends on the sign of the parallel velocity, typically resulting in preferential transport of counter-current ions. If the plasma at the boundary with the core is allowed to rotate toroidally to annihilate toroidal momentum transport, the resulting pedestal-top rotation reaches experimentally relevant values, is typically co-current directed, and has magnitude proportional to Ti/Ip. This mechanism is independent of the toroidal velocity and its radial gradient, representing a residual stress. The predicted rotation depends sensitively on the major-radial position of the X-point (Rx), with a more inboard X-point leading to stronger co-current rotation and rotation either vanishing or becoming counter-current for a strongly outboard X-point. To test the prediction, an Rx scan was conducted in Ohmic L-mode shots on TCV, in both USN and LSN configurations. The strong linear dependence on Rx was experimentally observed, as was the elimination of co-current edge rotation for outboard X-point. The core rotation profile shifted fairly rigidly with the edge rotation value, maintaining a relatively constant core rotation gradient. Core rotation reversals, triggered accidentally in a few shots, had little effect on the edge rotation velocity. Edge rotation was modestly more counter-current in USN than LSN discharges.

A Core to Edge Model for Radio Frequency Simulations in Tokamaks

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The finite element method (FEM) and the spectral approaches to simulation of ion cyclotron radio frequency (ICRF) waves in toroidal plasmas each have strengths and weaknesses. For example, the spectral approach (eg TORIC) has a natural algebraic representation of the parallel wavenumber and that can be used to calculate the wave dispersion but does not easily represent complex geometries outside the last closed flux surface, whereas the FEM approach (eg LHEAF or COMSOL) naturally represents arbitrary geometries but does not easily incorporate thermal corrections to the plasma dispersion due to the lack of an algebraic parallel wavenumber. The two domains: thermal core with flux surfaces and cold edge plasma with open field lines and complex plasma facing geometries may be combined in such a way that each approach is used where it works best. In this work, we demonstrate the method of mode matching for the domain decomposition. The method is non-invasive to the separate codes and approximately takes twice the computational effort as the original core solution. The net result is a core-to-edge model for RF simulations that is able to resolve wave interactions with plasma facing components and also calculate core interactions and power deposition in both the core and edge. We will present verification cases and initial applications to minority heating and discuss extensions to other frequency regimes and applications to other RF problems such as antenna loading and anomalous edge losses.