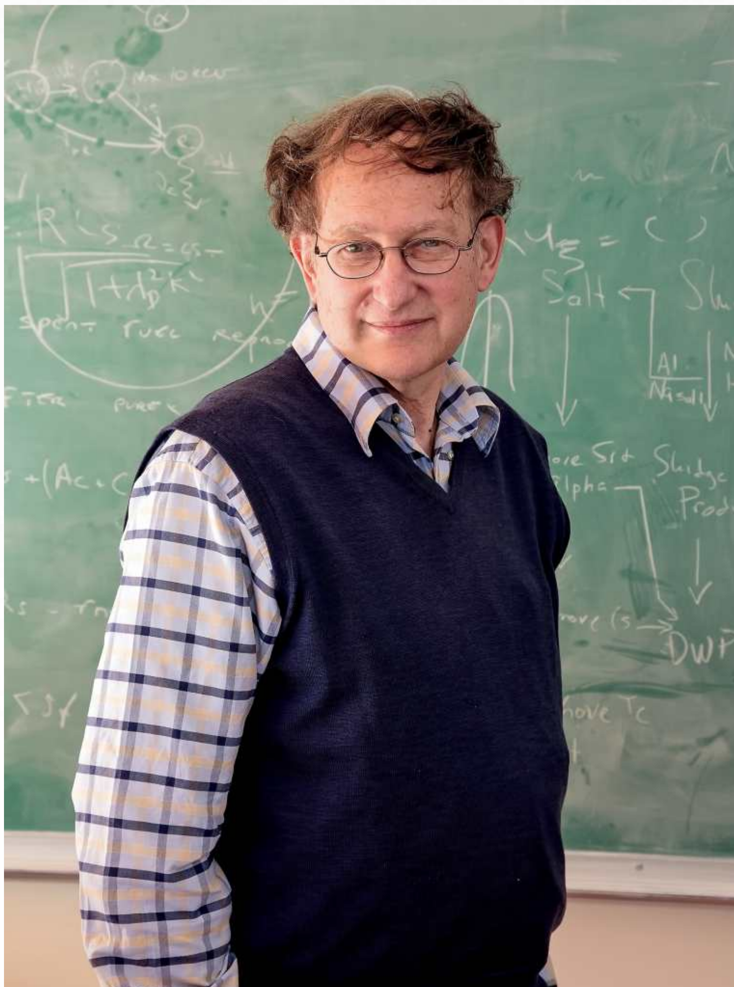
March 28-30, 2016
Princeton, New Jersey

Solved and Unsolved Problems in Plasma Physics

A symposium in honor of Nathaniel J. Fisch

Photo by Elle Starkman, PPPL



Book of Abstracts

March 28-30, 2016
Princeton, New Jersey

https://fisch-fest2016.pppl.gov/

Invited Talks

Synchronization: What Can a Plasma Physicist Say about Generic Collective Behavior

Thomas Antonsen
University of Maryland

Abstract not submitted

The Most Unsolved Problem in Plasma Physics: Demonstrating a Burning Plasma in the Laboratory*

Riccardo Betti
Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14623, USA

The recent results from the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory raise the hopes for producing a thermonuclear burning plasma in the laboratory for the first time. A plasma is defined as "burning" when the self-heating from the fusion reactions is the main energy input to the plasma. A burning plasma represents the stage before thermonuclear ignition. Assessing the degree to which fusion alpha particles contribute to the fusion yield is essential to assess when the plasma is burning. The recent results from indirect-drive implosions on NIF [1,2] show that the total alpha energy is comparable to the input energy to the central hot spot of a compressed core. The level of alpha heating [3] of NIF indirect-drive implosions is inferred from the measurements of areal density and neutron yield, and compared to the results achieved by other approaches to nuclear fusion. An approach [4] is also developed to extrapolate fusion yields, including alpha heating from current direct-drive experiments on OMEGA at tens of kilojoules of incident laser energy to megajoule drivers such as the NIF assuming the same illumination configuration. The extrapolation assumes that the implosion hydrodynamic performance is unchanged at higher energies. It is estimated that the current best-performing OMEGA implosion [5] extrapolated to a 1.9 MJ laser driver would produce over 100 kJ of fusion energy [4] and similar levels of alpha heating [3] than current indirect-drive NIF implosions. While not included in this analysis, the predicted performance can be significantly degraded if laser-plasma instabilities become more detrimental at the larger energy scales.

[1] O. Hurricane *et al.*, Nature 503, 346 (2014).

[2] T. Doppner et al, Phys. Rev. Lett. 115, 055001 (2015).

[3] R. Betti *et al.*, Phys. Rev. Lett. 114, 255003 (2015).

[4] A. Bose *et al.*, submitted to Phys. Rev. Lett.

[5] S. Regan *et al.*, submitted to Phys. Rev. Lett.

* Work supported by the US Department of Energy under cooperative agreements DE-FC02-04ER54789 and DE-NA0001944.

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

The Unsolved Problem of the Ubiquitous Spectral Gap in Lower Hybrid Current Drive

Paul Bonoli
Plasma Science and Fusion Center, Massachusetts Institute of Technology

Abstract not submitted

Whence US Science

William Brinkman
retired from the DOE Office of Science

Abstract not submitted

Philanthropy, Science and Society

Robert Conn
The Kavli Foundation

Abstract not submitted

Ionization in Atomic and Solid State Physics

Paul Corkum
University of Ottawa, Canada

Ionization is an atomic molecular and optical physics process that has important implications for plasma physics. What one field learns has significance for the other. Atomic ionization (and inter band transitions in solids) by infrared light is well approximated by tunnelling. After ionization, the electron and ion motion is equally well approximated by semi-classical physics – bringing the electron back to its origin (recollision) and creating coherent XUV (or soft X-ray light) whose duration is controllable and can be as short as a few 10's of attoseconds.

In plasmas, oscillating electrons can also lead to XUV radiation, but incoherent radiation, called bremsstrahlung. This same process in plasmas contribute to "air lasing" in N_2 molecular ions and it can help pump an inversion in highly charged ions. In molecules ionization, followed by recollision image a molecules structure and that of its valence electrons and to follow chemical dynamics. In solids, we can determine the band structure of semiconductors all optically.

In my talk, I will discuss some of these implications.

When Do Tokamaks Explode?

Steven Cowley
Culham Centre for Fusion Energy

Abstract not submitted

A Fresh Look at Solar Coronal Heating

Jill Dahlburg
Naval Research Laboratory

Abstract not submitted

Challenge in LHCD Capability at High Density Regime

Bojiang Ding
Institute of Plasma Physics, Chinese Academy of Sciences,
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Abstract not submitted

Basic Aspects of Fast Ion Transport in Burning Plasmas

Ambrogio Fasoli
EPFL – Swiss Plasma Center SPC, Switzerland

Abstract not submitted

Spheromaks and How Plasmas May Explain the Ultra High Energy Cosmic Ray Mystery

T. Kenneth Fowler
University of California, Berkeley

In recent papers published in the Astrophysical Journal, we show how accretion disks around massive black holes could act as dynamos producing magnetic jets similar to the early stages of plasma gun injection creating spheromaks in the laboratory. In a third paper in preparation, we show how these jets evolving at a velocity $0.01c$ naturally produce runaway ion beams accelerated to 10^{20} eV or more, finally ejected as Ultra High Energy (UHE) cosmic rays long regarded as one of the mysteries of astrophysics. Each step of the acceleration process is due to a hyper-resistive electric field: first by MRI turbulence in the accretion disk, then MHD kink mode turbulence in the jet, and finally electrostatic kinetic modes occurring at the nose end of the jet. It is these kinetic modes, perhaps overlooked by astrophysicists, that account for most of the acceleration. The model correctly predicts several observables, including the observed synchrotron radiation, the cosmic ray energy spectrum and UHE cosmic ray intensity on Earth.

Fast Magnetic Field Penetration into Low Resistivity Plasma

Amnon Fruchtman
Holon Institute of Technology, Israel

Magnetic field penetration, much faster than expected by resistive diffusion, is observed in pulsed-power experiments for three decades [1]. The fast penetration is explained as a Hall-induced penetration that occurs when the Hall electric field becomes inductive due to non-uniformity of the plasma [2]. Large deviations from the frozen-in law in low-resistivity plasma have been explained by the formation of a shock with a narrow current layer. Despite the dominant role of the Hall penetration, basic issues remained unsolved. The magnetic field penetration is predicted by the theory to occur only if the current-carrying electron flows in the direction of the gradient of the electron density. In the opposite polarity, magnetic field expulsion out of the plasma instead of penetration is predicted. Such asymmetry in the penetration has not been observed. Moreover, the penetration seems to occur also in plasmas in which the initial density non-uniformity was small [3]. Energy conservation requires large magnetic field energy dissipation. The fate of the dissipated energy is not clear, however, as electron heating is small. An additional unexpected process of simultaneous magnetic field penetration and ion separation was discovered [4]. The ion separation was shown to consist of light-ion plasma being pushed ahead of, while heavy-ion plasma lags behind the magnetic piston. A model will be described that explains the combined fast magnetic field penetration and ion separation. With all the experimental and theoretical progress, this fast magnetic field penetration into low-resistivity plasma is only partially understood and is a puzzle that remains to be solved.

[1] R. Doron *et al.*, Phys. Plasmas 11, 2411 (2004).

[2] A. V. Gordeev, A. S. Kingsep, and L. I. Rudakov, Phys. Rep. 243, 215 (1994); A. Fruchtman, Phys. Fluids B3, 1908 (1991).

[3] A. Fruchtman and L. I. Rudakov, Phys. Rev. Lett. 69, 2070 (1992).

[4] A. Weingarten *et al.*, Phys. Rev. Lett. 87, 115004 (2001).

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

Running Away and Radiating

Tünde Fülöp
Chalmers University of Technology, Sweden

Abstract not submitted

Strong Journalism Turbulence and Four-Wave Mixing

James Glanz
The New York Times

Abstract not submitted

Current Drive for Stabilizing Magnetic Islands

Daniela Grasso
ISC-CNR, Italy

The magnetic island evolution under the action of a current generated externally by electron cyclotron wave beams is studied using a reduced resistive magnetohy-drodynamics plasma model. We investigate how the topological and geometrical aspects, related to the beam amplitude and width as well as to the island width and modifcation, influence the control effectiveness, revealing new features in comparison with the zero-dimensional model of the generalized Rutherford equation. In particular the occurrence of flip or Kelvin-Helmholtz instabilities when the current injection is applied to small or large magnetic islands respectively are features that need to be taken into account in designing tearing mode control systems based on radio frequency current-drive.

Challenges and Opportunities in High Energy Density Physics

Mark Herrmann
Lawrence Livermore National Laboratory

Abstract not submitted

· · · To Be Determined · · ·

Rush Holt
American Association for the Advancement of Science

Abstract not submitted

Solved and Unsolved Physics Issues in Realizing a Plasma-Based Future Collider

Chan Joshi
University of California, Los Angeles

Abstract not submitted

Thermodynamic Approach to Far From Equilibrium Nonlinear Systems

P. K. Kaw
Institute for Plasma Research, Bhat, Gandhinagar 382428, India

Plasmas are typically born when intense violence is done to matter and are often observed in a far from equilibrium steady state. A thermodynamic approach holds the promise of defining features of the final observed state without analyzing the complex nonlinear dynamics of how it got there. One may distinguish between two kinds of steady states. Those that are born by intense and rapid rearrangement of the initial configuration on time scales so fast that the system has no significant matter or energy exchange with the external world. These isolated systems can be understood thermodynamically as nonlinear systems which minimize a properly identified free energy source subject to suitable constraints. Other steady states are driven steady states and acquire their characteristic configuration by constant exchange of matter and energy with the external world. There is no consensus on what the system is trying to optimize in the steady state. Here we show by making simple estimates that such "open configurations" in plasma physics are like negentropy machines which create a significant degree of order in their interior by ingestion of low entropy energy and expulsion of high entropy energy at the boundaries. We illustrate our ideas by making a quantitative comparison of negentropy generation by a tokamak with that generated by a piece of living matter and even with that generated by the whole web of life.

Ultrafast and Nanoscale Diodes

Yue Ying Lau and Peng Zhang
Department of Nuclear Engineering and Radiological Sciences
University of Michigan, Ann Arbor, MI 48109-2104

Charge carrier transport across interfaces of dissimilar materials (including vacuum) is the essence of all electronic devices. Ultrafast charge transport across a nanometer scale length is of fundamental importance in the miniaturization of vacuum and plasma electronics. With the combination of recent advances in electronics, photonics, and nanotechnology, these miniature devices may integrate with solid-state platforms, achieving superior performance. This talk review recent modeling efforts on electrical contact resistance, quantum tunneling and ultrafast electron emission and transport. Unsolved problems and challenges in these areas are addressed.

How to Do Particle-in-Cell Simulations – Dawson's Classical Algorithm vs. Qin's Modern Algorithm

Jian Liu
University of Science and Technology of China

Particle-in-cell (PIC) methods and simulations are widely applied in plasma physics and other fields. To solve critical physical problems and make full use of high performance computer clusters, new marvelous PIC algorithms with longterm accuracy and stability should be designed. To achieve this goal, based on Dawson's PIC schemes, the mathematical foundations of PIC methods are recently explored. Correspondingly, a series of Qin's modern algorithms are constructed and practiced successfully.

Experimental Discrimination between Thermal and Hydrodynamic Motions in High-Energy-Density Plasmas

Yitzhak Maron
Weizmann Institute of Science, Israel

Distinguishing between energy stored in the hydrodynamic motion of plasma and the thermal energy of ions is of fundamental significance for laboratory plasma physics, astrophysics, and hydrodynamics, including high-energy-density (HED) plasmas, where energy stored in the hydrodynamic motion contributes neither to radiation nor to fusion reactivity, whereas thermal energy does.

Yet, to the best of our knowledge, experimentally distinguishing ion temperature from hydromotion in HED plasmas had never been made prior to the studies described here.

Two novel spectroscopic methods have been developed and implemented.

The first method is based on determining the rate of heat transfer from ions to electrons by measuring the total ion kinetic energy, its dissipation rate, the total radiation from the plasma, and the electron density and temperature [1]. The second method [2] is based on the effect of the ion-ion coupling on the Stark line shapes [3].

The experiments were performed in z-pinch plasmas, investigated during both the implosion and stagnation stages. Required were observations with high resolution in spectrum, space, and time, augmented by detailed line shape and time-dependent plasma-kinetics modeling. Remarkably, the ion temperature in both stages was found to be significantly lower than the total ion kinetic energy. The dissipation time of the hydromotion was determined. The data also allowed for assessing reliably the pressure and energy balance in the stagnation stage of the imploding plasma [4]. Implications to various HED plasmas in large systems will be discussed.

[1] E. Kroupp *et al.*, PRL 98, 115001 (2007), PRL 107, 105001 (2011).

[2] D. Alumot *et al.*, ICOPS 2012, ICOPS 2013.

[3] E. Stambulchik and Y. Maron, JQSRT 99, 730 (2006).

[4] Y. Maron *et al.*, PRL 111, 035001 (2013).

Is There Order in the Catastrophic Collapse of Optical Beams?

Howard Milchberg
University of Maryland

Abstract not submitted

Single Cycle and Exawatt Lasers

Gérard Mourou
École Polytechnique, France

Efficient compression toward the single-cycle regime of petawatt laser pulses, such as those becoming available at laser facilities around the world, holds the promise to open up an entirely new realm of fundamental and applied physics both directly and by driving exawatt, X-ray pulses. A shorter route to the generation of Schwinger intensities with current day technology is now envisioned with the capability of producing high energy radiation and particle beams of extremely short, sub-attosecond timescales. The energies and timescales involved are far from traditional laser regimes and offer a new intersection of laser technology with the study of the structure of vacuum and numerous applications to subatomic physics. With this vision in mind, a plan for petawatt pulse compression shall be presented and the potential applications for such pulses discussed.

Science at the Timescale of the Electron: Harnessing the Extreme Nonlinear Optics of High Harmonic Generation for Tabletop Coherent X Rays

Margaret Murnane and Henry Kapteyn
University of Colorado Boulder

Abstract not submitted

Challenging Tasks in Laser Wakefield Acceleration with PW Lasers

Chang Hee Nam*
Center for Relativistic Laser Science, Institute for Basic Science (IBS), Gwangju 61005, Korea and Department of Physics and Photon Science, GIST, Gwangju 61005, Korea

Laser-produced plasmas have been explored as media to accelerate charged particles. When an intense laser pulse is focused to a gaseous medium, the plasma wave excited can accelerate an injected electron bunch, called the laser wakefield acceleration scheme. Since the acceleration field in the plasma wave, ~ 1 GV/cm, is larger by several orders of magnitude than in a conventional accelerator, the laser wakefield acceleration can provide a means to construct compact high energy accelerators. Investigations on laser-driven particle acceleration have thus paved the route to develop compact particle accelerators and also radiation sources.

Recent advancement of ultra-high intensity lasers has offered opportunities to investigate laser-matter interactions in the relativistic regime. At CoReLS two PW Ti:Sapphire laser beamlines with powers of 1.0 PW and 1.5 PW at 30 fs were developed [1]. These PW lasers have been successfully applied to generate multi-GeV electron [2] and energetic proton beams [3]. One of the PW laser beamlines is being upgraded to a 4-PW laser, which will be utilized to generate a 10-GeV electron beam. In addition, we plan to carry out all optical Compton backscattering to generate MeV gamma-rays from the scattering between a laser-accelerated GeV electron beam and another laser beam – challenging tasks to explore nonlinear QED effects in photon-particle interactions.

[1] J. H. Sung *et al.*, Opt. Lett. 35, 3021 (2010).

[2] H. T. Kim *et al.*, Phys. Rev. Lett. 111, 165002 (2013).

[3] I J. Kim *et al.*, Phys. Rev. Lett. 111, 165003 (2013).

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Mechanisms for Loss of LHCD Efficiency at High Density

Ron Parker
Plasma Science and Fusion Center, Massachusetts Institute of Technology

Since the earliest experiments on lower hybrid current drive, an anomalous loss of efficiency has been observed at high density, i.e., at densities approaching but below the penetration limit. Possible losses include collisional absorption in the plasma scape-off-layer and effects resulting from parametric decay instabilities. New measurements confirm that, in this regime, power absorption does indeed occur near the edge, most likely just inside the separatrix in diverted configurations. Direct measurement of the launched wave, or pump, suggests that pump depletion is not strong enough to lead to near 100% absorption; consequently, if PDI are the root cause, the loss in efficiency must be a secondary effect, e.g., spectral broadening or development of a supra thermal component in the electron distribution function near the edge.

Advanced Fokker-Planck Calculations in Complex Magnetic Topologies

Yves Peysson
CEA, France

Abstract not submitted

Resonance and Rotation for Plasma Isotope Separation

Jean-Marcel Rax
Université de Paris XI, France

Plasma isotope separation schemes are based on the use of: (i) the ponderomotive force, (ii) the cyclotron resonance or (iii) magnetized plasma rotation with crossed static fields. We briefly analyze and review these processes. Then, we identify and describe a forth method where the plasma rotation is induced by a rotating field rather than a static field. As opposed to the classical rotation displaying a mass threshold associated with the two roots of the slow and fast modes, this later scheme presents a wider access to a mass threshold for separation.

Why Compute?

Robert Rosner
The University of Chicago

Computational science is sometimes labeled the "third mode of science," complementing experiment and theory: To quote the Wikipedia, "The scientific computing approach is to gain understanding, mainly through the analysis of mathematical models implemented on computers." I will discuss a few example that illustrate a much more complex relationship between computer simulations and other ways of pursuing scientific problems, focusing on fluid dynamic problems that cross the boundaries between laboratory physics and astrophysics.

Solved and Unsolved Problems in Plasma Dynamo

Alex Schekochihin
University of Oxford, UK

MHD dynamo continues to be an interesting topic of current research but it can be viewed as solved in the sense that the basic mechanism is understood. Plasma (kinetic, collisionless) dynamo was until 2015 entirely unsolved in the sense it was not at all clear whether it worked at all. There are now first numerical results suggesting it does work. It may also be very close to an experimental test. However, the interplay between fluid (large) and kinetic (small) scales that gives rise to a working dynamo remains a difficult, fascinating and unsolved problem.

New and Emerging Concepts in Laser-Plasma Acceleration

Gennady Shvets
University of Texas at Austin

I will describe some of the recent work from several groups aimed at integrating direct laser acceleration (DLA) and laser wakefield acceleration (LWFA). While LWFA is an inherently near-field acceleration technique, the DLA is an example of a far-field accelerator that directly transfers the energy from the laser pulse to relativistic electrons undergoing betatron oscillation inside a plasma channel or a plasma bubble. One of the well-known limitations of LWFA is dephasing: the propensity of ultra-relativistic electrons to slip forward with respect to the wakefield, thereby advancing into the decelerating phase of the wake. Far-field accelerators, such as IFELs, suffer from their own limitations: the acceleration gradient rapidly falls as the function of the electron energy. I will demonstrate that these limitations of the far and near-field accelerators can be overcome in a hybrid laser wakefield/direct laser accelerators because these two accelerating mechanisms can operate simultaneously and synergistically, which implies two things. First, the distinct energy gains from the plasma wake and directly from the laser pulse are compounding, thereby increasing the total energy gain. Second, the energy gain from the wakefield is further increased because of the delayed dephasing caused by the DLA. I will show that the resulting phase space of self-injected plasma electrons is split into two, containing a subpopulation that experiences wakefield acceleration beyond the standard dephasing limit because of the multidimensional nature of its motion that reduces the phase slippage between the electrons and the wake. Several new concepts of combining DLA and LWFA will also be reviewed. One such concept involves combining a long-wavelength IR pulse ($\lambda \sim 2\mu$m) with a trailing short-wavelength ($\lambda \sim 0.8\mu$m) DLA laser.

Challenges in Plasma Physics at Ultra High Field Intensities

Luis O. Silva
Instituto Superior Tecnico, Portugal

Abstract not submitted

Pedestals and Thinking Outside the Box

Philip Snyder
General Atomics

This talk will discuss my experience working with Nat Fisch as a graduate student at Princeton, including lessons learned about how to approach physics problems, and how to use physics understanding in novel, perhaps "outside of the box," ways to benefit fusion and other applications. Some of these modes of thinking will then be applied to the problem of the H-Mode pedestal in tokamaks, the edge transport barrier whose "height" (pressure) is a key aspect of fusion performance. Moving beyond the local transport paradigm has enabled an understanding and quantification of important constraints on the pedestal that govern its structure. The resulting model (EPED) has been extensively compared to experiment, and also used to discover a new regime, called "Super H-Mode," that results from a bifurcation of the EPED solution. Finally, important open questions in pedestal research, and possible ways to apply out of the box thinking to the fusion problem, will be discussed.

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Plasma-Material Interactions and RF Sustainment for Steady-State Tokamaks

Dennis Whyte
Plasma Science and Fusion Center, Massachusetts Institute of Technology

Abstract not submitted

The Plasma Techniques Enabling CPT and Gravity Tests with Antihydrogen

Jonathan Wurtele
University of California, Berkeley

Abstract not submitted

Understanding the L-H Transition in Fusion Plasmas

Guosheng Xu
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Abstract not submitted

Posters

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

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

Seung-Gyou Baek
Plasma Science and Fusion Center, Massachusetts Institute of Technology

Abstract not submitted

Beyond Nonlinear Saturation of Backward Raman Amplifiers

Ido Barth
Princeton Plasma Physics Laboratory

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.

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

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).

On the Generalization of Fluid Theory Including Kinetic Effects*

Olivier Izacard
Lawrence Livermore National Laboratory

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.

LLNL-ABS-681092

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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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Elijah Kolmes
Princeton University

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).

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, under Award Numbers DE-SC0012174, DE-FG02-92ER54141, DE-SC0013977, DE-SC0008605, and DE-FC02-99ER54512, using Alcator C-Mod, a DOE Office of Science User Facility. This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under contract No. DE-AC02-05CH11231.

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

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

Julia M. Mikhailova
Mechanical and Aerospace Engineering Department, Princeton University, USA

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.

[1] T. Tajima, and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979).

[2] I. Y. Dodin and N. J. Fisch, Phys. Plasmas 15, 103105 (2008).

[3] L. B. Fletcher *et al.*, Nat. Photonics 9, 274 (2015).

[4] Y. M. Shin, Appl. Phys. Lett. 105, 114106 (2014).

[5] Y. M. Shin, D. A. Still, and V. Shiltsev, Phys. Plasmas 20, 123106 (2013).

Transport-Driven Toroidal Rotation in the Tokamak Edge

Timothy Stoltzfus-Dueck
Princeton University

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

John Wright
Plasma Science and Fusion Center, Massachusetts Institute of Technology

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.

Alumni Talks

··· To Be Determined ···

Alain Brizard
Saint Michael's College

Abstract not submitted

Who Sits between Darwin and Maxwell?

Joshua Burby
Courant Institute of Mathematical Sciences

The Vlasov-Poisson (VP) and Vlasov-Darwin (VD) systems are Hamiltonian Galilean-invariant approximations of the Vlasov-Maxwell (VM) system. The small parameter used to justify these approximations is the ratio of a typical particle velocity to the speed of light. VP is obtained from VM in the limit where this parameter tends to zero; VD contains the next-order corrections. Are there systems that contain higher-order corrections than VD while still being 'simpler' than VM in some sense? I will argue that systems 'between' Vlasov-Darwin and Vlasov-Maxwell may be obtained by identifying an appropriate slow manifold of the Vlasov-Maxwell system. This slow manifold is a dynamically invariant subset of the Vlasov-Maxwell phase space. For states in this invariant subset, the electric and magnetic fields are determined completely by the single-particle distribution function. Higher-order approximations of the Vlasov-Maxwell system correspond to higher-order parameterizations of the slow manifold. Can these higher-order approximations be cast in Hamiltonian form? Do these higher-order approximations possess Galilean invariance, or perhaps some modified invariance principle?

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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Some Princeton Memes

Robert L. Dewar
The Australian National University

While Dawkin's idea [1] that "memes" (germs of ideas that can be passed from one mind to another) play a role in cultural evolution, analogous to that played by genes in ordinary evolution, may be of questionable scientific value, I have found it a useful organizing concept for tracing the influence of early influences on the evolution of one's research [2, 3]. I shall try to identify some of the memes I picked up during my graduate student, postdoc and research staff member years at PPPL.

[1] R. Dawkins, *The Selfish Gene* (Oxford University Press, 1976), http://en.wikipedia.org/wiki/The_Selfish_Gene.

[2] R. L Dewar, R. Mills and M. J. Hole, *MHD Memes*, J. Phys.: Conf. Series 169, 012004 (2009), http://dx.doi.org/10.1088/1742-6596/169/1/012004.

[3] R. L. Dewar and D. Leykam, *Dressed test particles, oscillation centres and pseudo-orbits*, Plasma Phys. Control. Fusion 54, 014002 (2012), http://arxiv.org/abs/1107.5201v2.

Irreversible Changes to the Plasma Physics Graduate Program

Bill Dorland
University of Maryland

I was in one of the first cohorts for Nat's irreversible course, I believe, and I would like to offer some memories from that time.

Plasma Turbulence in Magnetic Fusion: What Is Needed to Predict and Reduce It? (and Other Thoughts)

Gregory Hammett
Princeton University

Abstract not submitted

Curiosity-Driven Research – an Unsolved Problem in Plasma Physics

Vyacheslav (Slava) Lukin
National Science Foundation

Abstract not submitted

Kinetic Energy Principle since Newcomb

Jong-Kyu Park
Princeton Plasma Physics Laboratory

Energy principle is an elegant and efficient method for addressing global plasma stability contained in toroidal device. Since William A. Newcomb derived a cylindrical Euler-Lagrange equation in ideal MHD, its extension to include kinetic guiding-center motions of particles has been proposed and developed by Kruskal-Oberman, Rostocker-Rosenbluth, Taylor-Hastie, Antonsen-Lee, and again by Newcomb with one that is cited to be most precise but unpublished. Recent formulations show how these models are interconnected across non-axisymmetric neoclassical theory and 3D force balance, and enable precise calculations and predictions in full toroidal geometry. A subtlety arises due to dissipation represented by toroidal torque, which may not disappear even in the absence of collision, as will be briefly introduced.

Magnetized Liner Inertial Fusion (MagLIF) Research on Sandia's Z Pulsed Power Facility

Paul Schmit
Sandia National Laboratories

This talk will highlight briefly the campaign being undertaken at the worlds largest pulsed power facility, Sandia National Laboratory's "Z Machine," investigating the role magnetically-driven implosions can play in enabling laboratory inertial confinement fusion and magnetized target fusion.

C-2U Field Reversed Configuration Experiment at Tri Alpha Energy, Inc.

Artem Smirnov
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Tri Alpha Energy, Inc. is a privately funded company pursuing research of Field Reversed Configuration (FRC) plasmas for fusion reactor applications. Over the past decade, TAE has brought together world-class technical specialists in such fields as FRC plasma science, magnets, neutral beams, pulsed power, diagnostics, controls, electronics and fabrication. This group of over 150 full-time scientists, engineers and technologists is working at TAE's state-of-the-art plasma research facility in Orange County, California.

The core of the facility is the world's largest FRC device named C-2U. In the C-2U experiment [1], tangential neutral beam injection (15 keV hydrogen, 10+ MW total neutral power), coupled with electrically-biased plasma guns at the plasma ends, magnetic end plugs, and advanced surface conditioning, led to dramatic reductions in turbulence-driven losses and greatly improved plasma stability [2, 3]. Under such conditions, high-performance, advanced beam-driven FRCs were produced and sustained for times significantly longer (5+ ms) than all characteristic plasma decay times without the beams. The FRC sustainment is correlated with neutral beam injection, and confinement of fast ions is close to the classical limit. Collectively, these accomplishments represent a dramatic advance towards the scientific validation of the FRC-based approach to fusion. This presentation will provide an overview of the C-2U device and recent experimental advances.

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

[2] M. Tuszewski *et al.*, Phys. Rev. Lett. 108, 255008 (2012).

[3] H. Y. Guo *et al.*, Nature Comm. 6, 6897 (2015).

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.

Two-stream Instability in Electron Accelerators

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