Report of the Panel on Frontiers of Plasma Science

I.D. Kaganovich

Princeton Plasma Physics Laboratory, NJ

Presented to PPPL on August 26th, 2016

PPPL
PRINCETON
PLASMA PHYSICS
LABORATORY

Extreme States of Matter and Plasmas

Recent progress has witnessed the development of the tools and techniques for creating plasma states with unprecedented temperature and density. Experiments to determine plasma behavior in these states will test new physics in parameter regimes where, in many cases, various models offer diverging predictions. These extreme states of matter and plasmas that we form and control in the laboratory may shed light on the age of our galaxy and mimic the dynamics of complex and correlated plasmas that exist in the cosmos.

Understanding the Physics of Coherent Plasma Structures

One of the major challenges of nonlinear science is to understand and control the synchronization of interacting particles. This phenomenon is common in diverse types of biological, chemical, and physical systems. In plasmas, synchronization typically involves the formation of physical space or phase space coherent structures, and has linear and nonlinear regimes. These structures are created through the electrical self- fields of the plasma and its interactions with waves. Examples include: complex environments such as planetary magnetospheres, plasma devices, electric propulsion. Moreover, understanding the phase space dynamics of charged particle beams with intense self-fields may lead to new classes of accelerators that may be used for scientific and industrial applications.

The Physics of Disruptive Plasma Technologies

New technologies are emerging which exploit the powerful and controllable interactions that occur between plasmas and electromagnetic fields. The field of relativistic plasma engineering—the shaping of plasmas by lasers to create customized structures for acceleration, pulse compression, radiation generation and other applications—has matured from its infancy over the last decade. This ability to shape plasmas on nano to femto-second time scales has motivated many groups to set out on the quest for plasma-based compact particle acceleration and x-ray sources, for ultra-intense pulse generation, and for new photonic systems.

Plasmas at the Interface of Chemistry and Biology

Low-temperature plasmas (LTPs) enable processes that have led to profound breakthroughs that revolutionized and enabled modern societies: the microelectronics industry, which is enabled by beneficial plasma-surface interactions that deposit and remove materials with nm resolution in the fabrication of microprocessors and other devices. Other examples include low cost, high-efficiency lighting technologies, low-cost solar cells, and bio-compatible human implants.

New sub-fields: plasma medicine to High Energy Density (HED) chemistry with promising applications for health, food, and water.

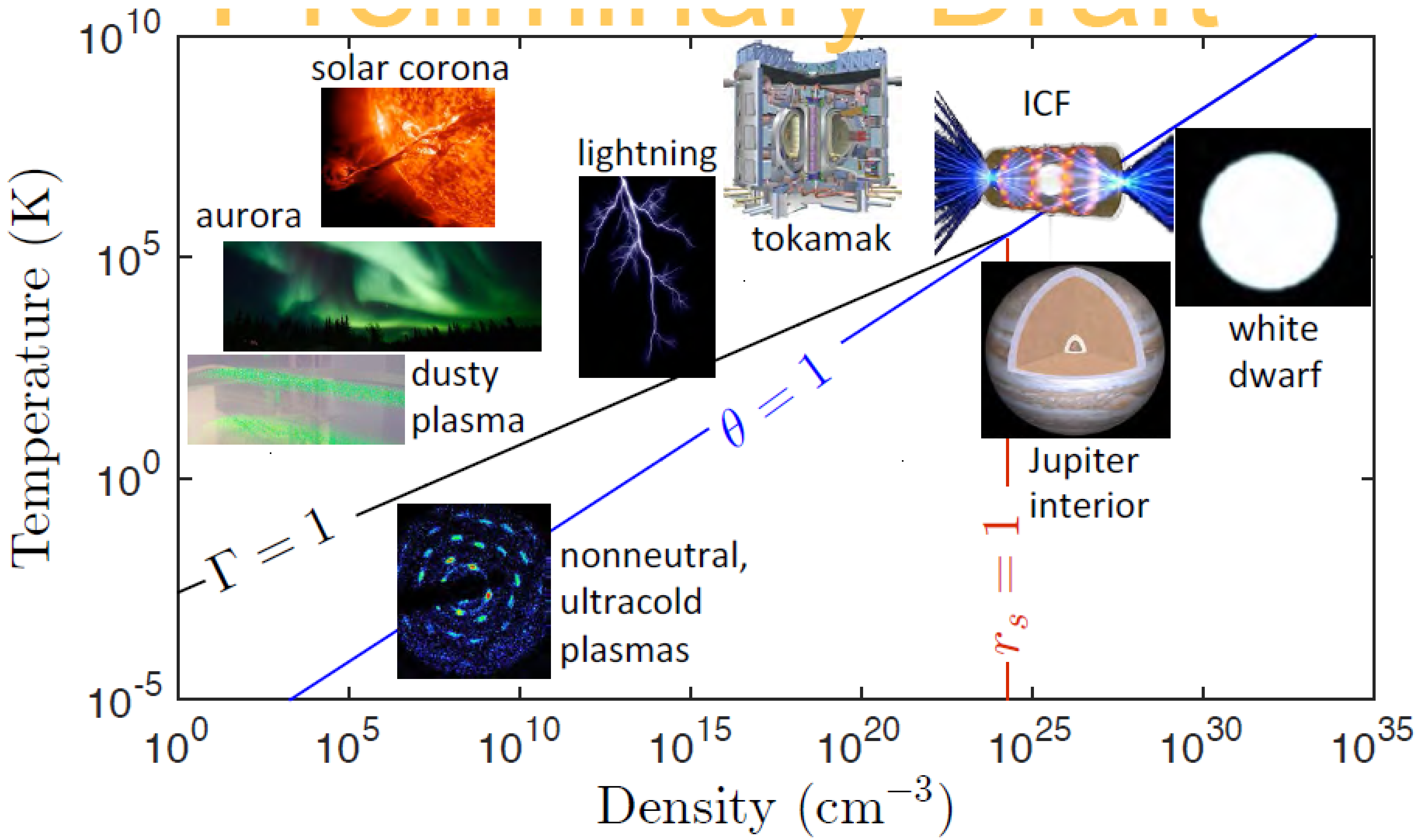
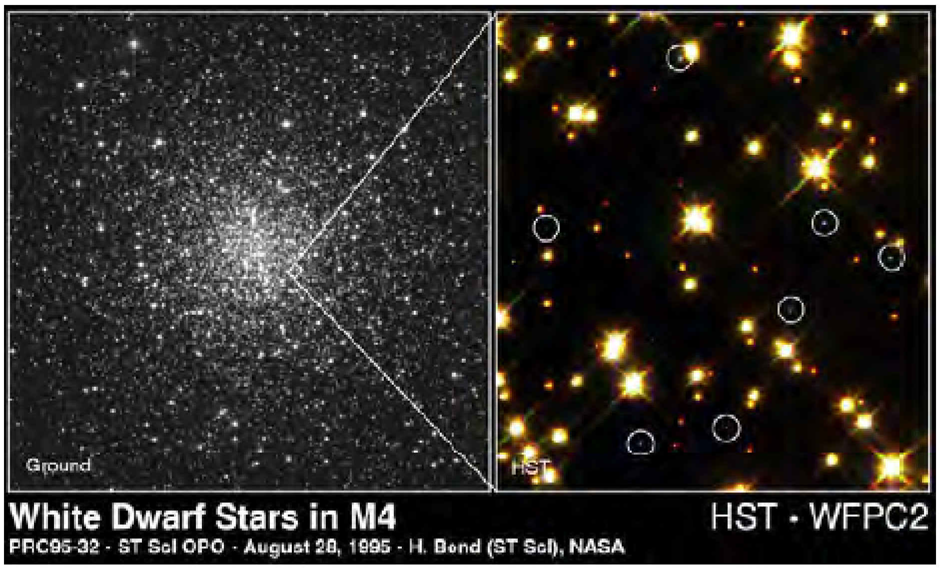


Figure 1. Extreme conditions with strong coupling and quantum degeneracy can dominate the behavior of plasma in astrophysical and laboratory settings. With strong coupling, charged particles collide often with nearest neighbors, allowing self-organization as in crystals, liquids or non-ideal gases. With quantum degeneracy, the spatial extent and wave-like nature of electrons influence plasma properties. This diagram, for equilibrium conditions, divides parameter space into four portions according to temperature and number density of charged particles. Traditional plasmas, which are weakly coupled and non-degenerate, are found in the upper left corner with colder more highly coupled dusty plasma of interest in this chapter found below. Extreme conditions of interest for this chapter are to the right. Warm dense matter is characterized by classical strongly coupled ions, and degenerate weakly-to-moderately coupled electrons. This region is found near the intersections of the lines in this figure. At very high energy density, electromagnetic fields can spark electron-positron pairs from the vacuum.

Extreme States of Matter and Plasmas

Warm Dense Matter and the Age of the Galaxy.

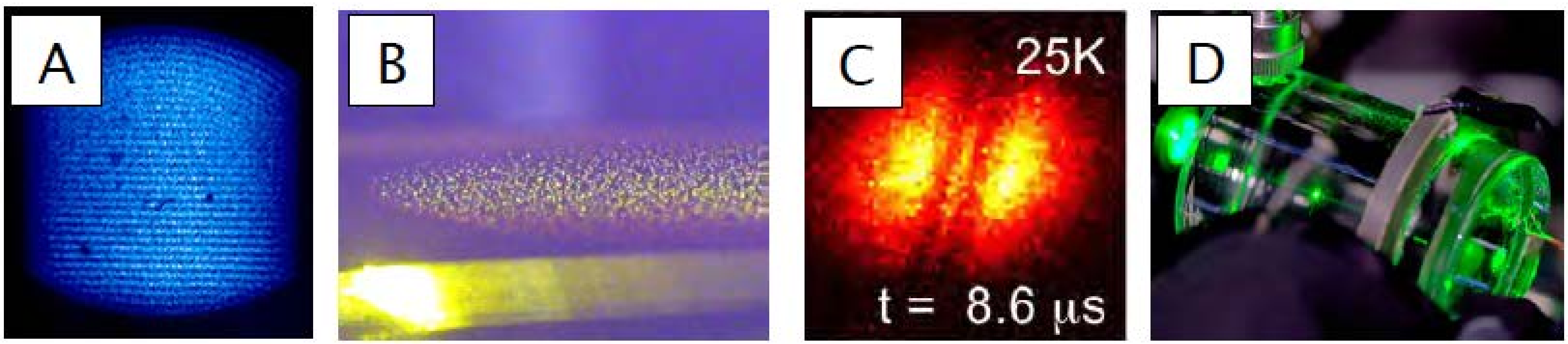


Stellar graveyard: view of Messier 4, the nearest globular cluster to Earth (7000 light-years away). The cluster contains hundreds of thousands of stars, of which an estimated 40000 are white dwarfs (circled in the right panel). Using white dwarf cooling models, the age of the cluster was determined to be 12.7 ± 0.7 billion years. (Image: http://hubblesite.org/newscenter/archive/releases/1995/32/)

White dwarfs are made of plasma, which varies tremendously from the surface to the center of the star. White dwarf temperatures can thus be used as "cosmic clocks" for constraining the age of our Milky Way galaxy and its components. The accuracy of these cosmic chronometers is limited by uncertainties in the rate of energy flow through the warm dense matter region in the white dwarf envelope.

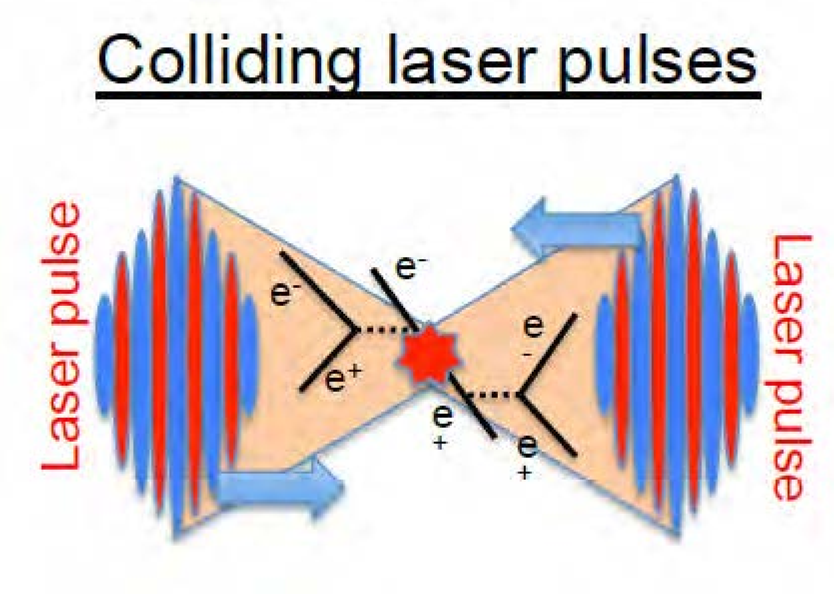
Extreme States of Matter and Plasmas

Experimental Approaches for Studying Classical Strongly Coupled Plasmas



A. Ions trapped by electric and magnetic fields can be laser cooled to a few millidegrees Kelvin to form strongly coupled non-neutral plasmas. (B) Dusty plasmas are formed of multiply charged, micron sized particles in a room temperature discharge plasma of background ions, electrons and neutral atoms. C) Ultracold neutral plasma (UCNP) is produced by laser photoionization of laser-cooled atomic gases or supersonic beams of atoms or molecules. (D) Sonoluminescence experiments can produce pulsed plasmas with temperatures and densities of 6,000-20,000 K and 1-10 x1021 cm-3.

Extreme States of Matter and Plasmas



Colliding laser pulses with intensities of about 1025 W/cm2 can “boil the vacuum”, forming electron-positron pairs. (Image: https://www.orau.gov/plasmawkshps2015/whitepapers/general-Bulanov_Stepan.pdf). Such a photon collider with significant production of electron-positron pairs (Breit-Wheeler process) concomitant with electron or positron emission (Compton effect) could result in an extreme pair plasma soup with sufficient number density for collective effects to be observed for the first time.

Understanding the Physics of Coherent Plasma Structures

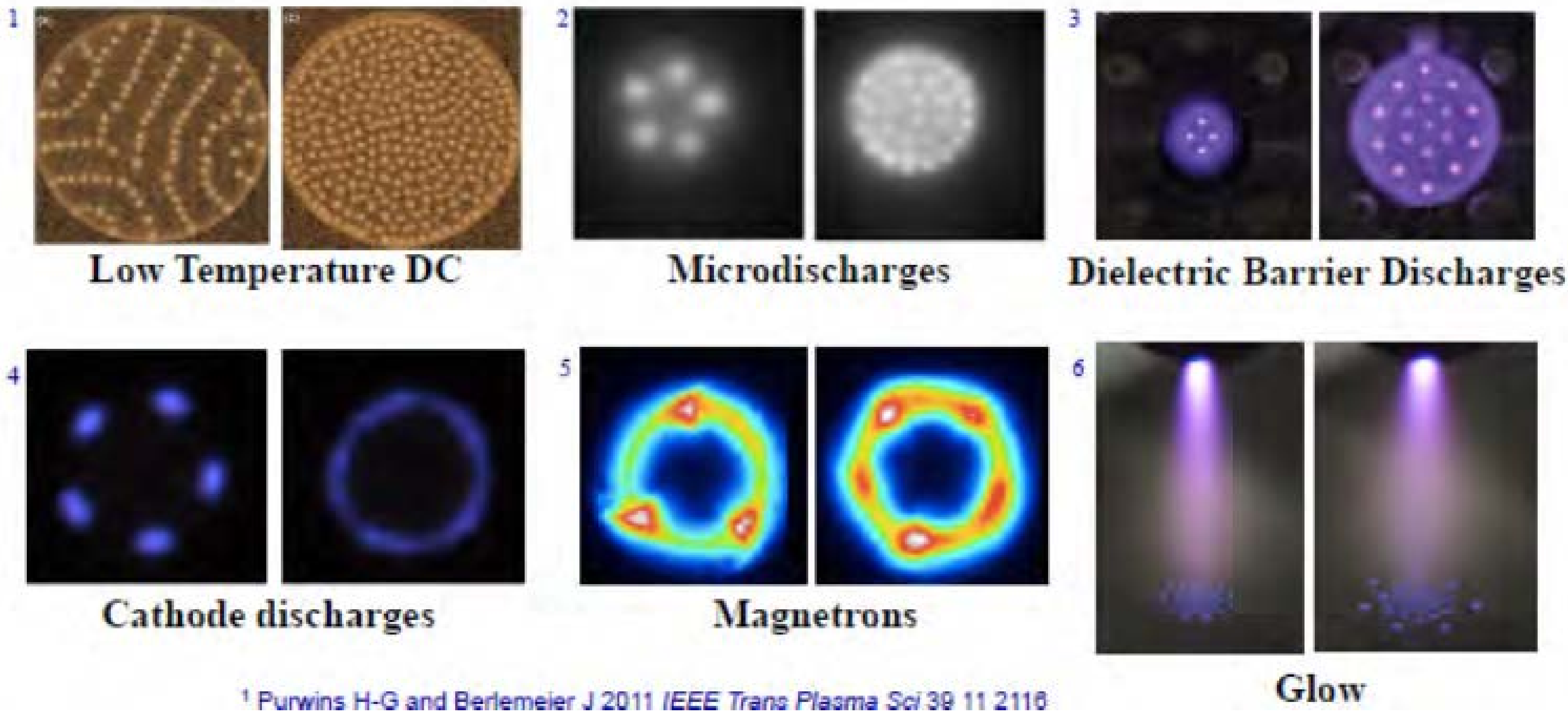


Figure Examples of structures formed transverse to the current flow direction. [Image from white paper of J. Trelles].

The Physics and Applications of Coherent Plasma Structures

Frontier: Formation of Coherent Structures is ubiquitous property of plasma due to long range interactions

Not just space, but phase-space structures

Challenge: Understand, predict and control structures

Key sub-areas: Beams, Nonneutral plasmas, Discharges, Space Plasma, Dusty Plasmas

Prepared for Frontiers of Plasma Science Workshops, Sponsored by the U.S. Department of Energy, Office of Fusion Energy Sciences

https://www.orau.gov/plasmawkshps2015/

Panel members:

A. Anders, A. Brizard, G. Ganguli, I. Kaganovich, V. Shiltsov, E. Thomas

Application Examples:

Spoke magnetrons, Penning discharges, Hall thrusters, contracted forms of discharges, diocotron modes,

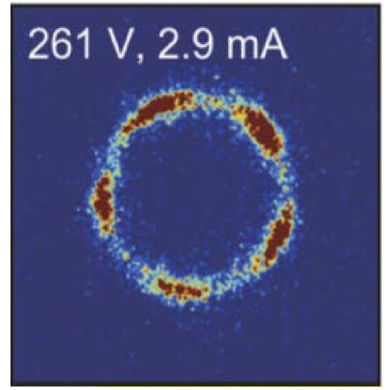
Voids, filaments in dusty plasmas,

phase-space holes, clumps, Keen waves,

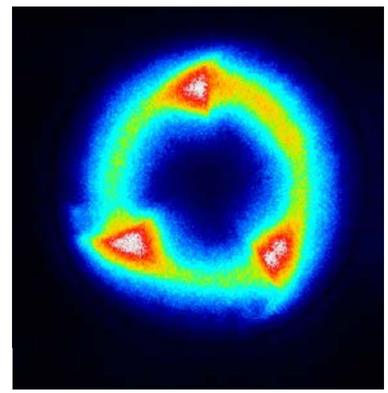
Physics of radiation belts in planetary magnetosphere

Coherent structures: How do coherent structures emerge from instability and/or turbulence and how do they impact dissipation?

- **<u>Importance</u>: Structures influence particle, energy, and momentum transport; plasma meta-materials**
- **<u>Why now</u>:**
  - **Ability to directly visualize coherent structures;**
  - **Advancements in the ability to simulate structures across temporal and spatial scales.**

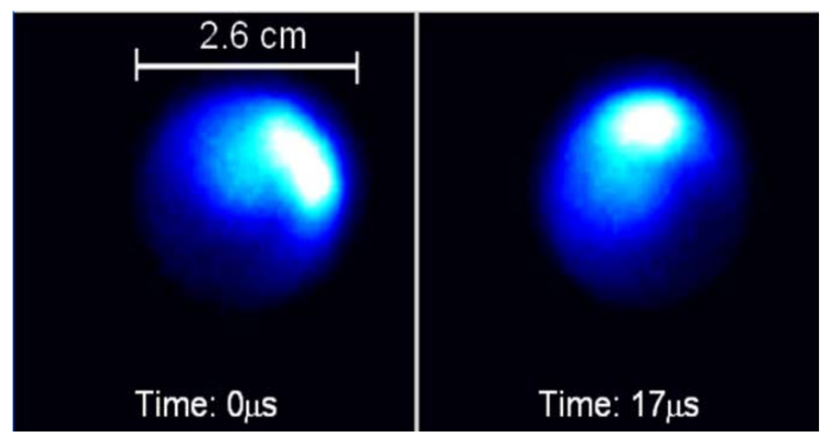


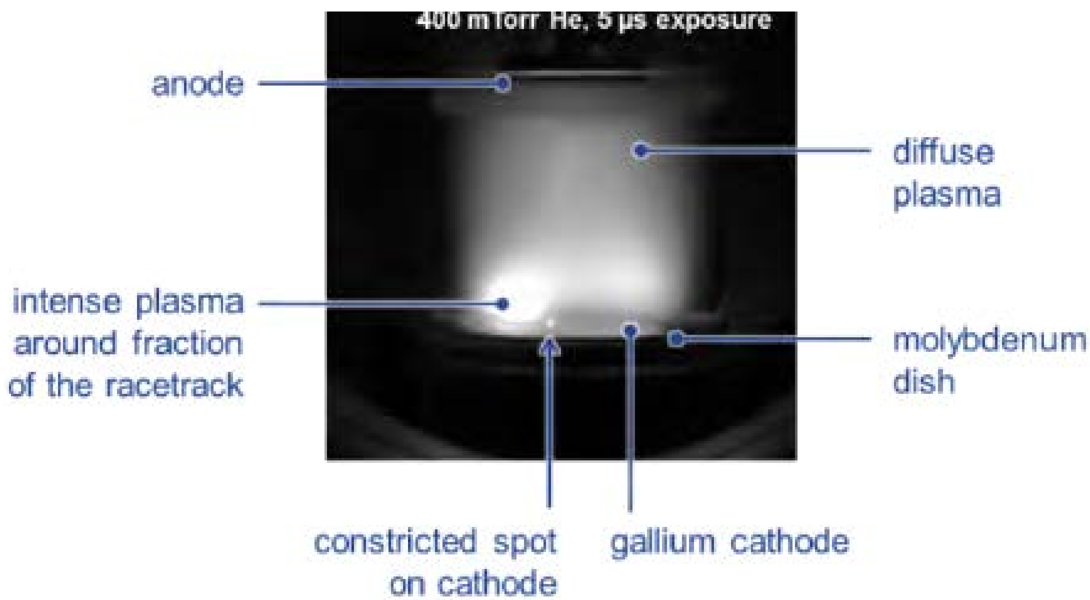
microplasma
2.9 mA



magnetron plasma
400 A

Hall thruster





Particle distributions functions at plasma boundaries and interfaces.

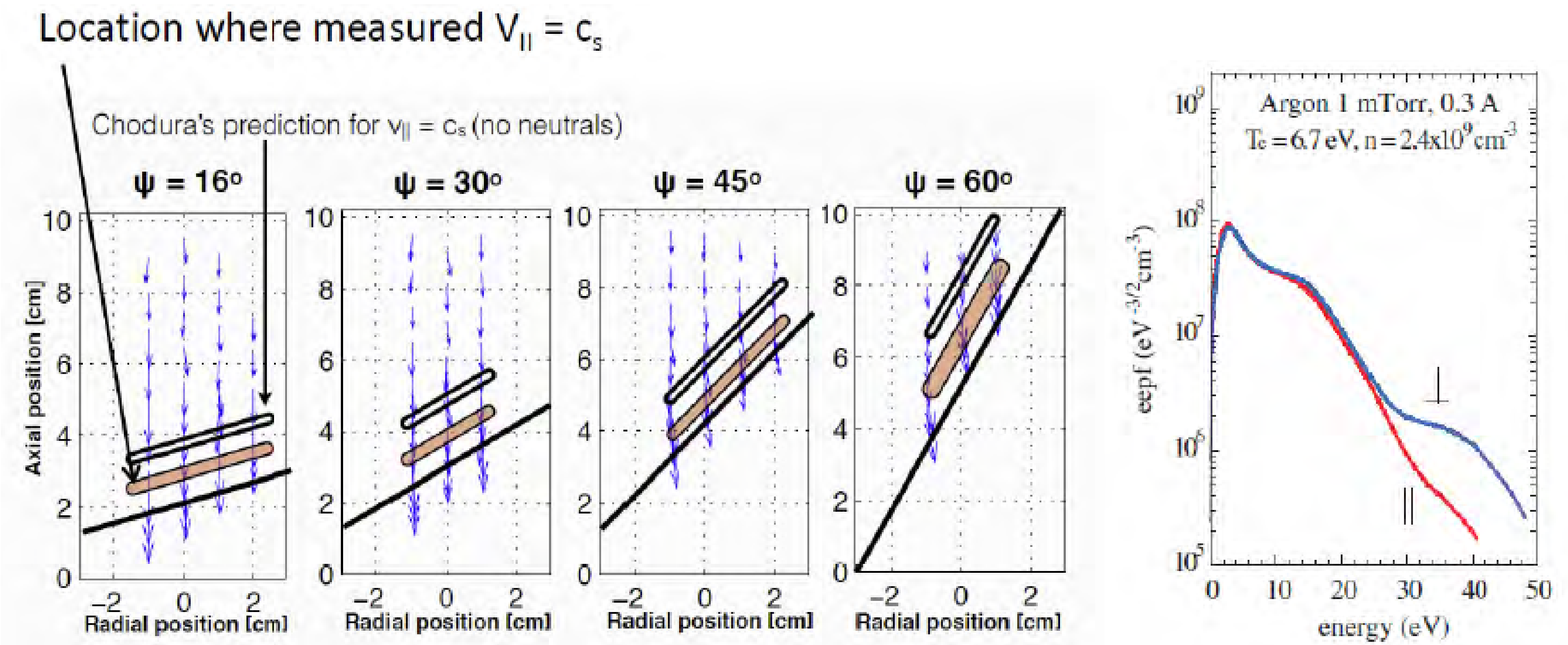


Figure 13. Examples of recent LIF and probe diagnostics. Left: Ion drift velocity along the perpendicular direction of an electrode plate; [Courtesy G. Severn, University of San Diego.] Right: Electron Energy Probability function measured in the positive column of Ar DC discharge. Red and blue correspond to radially and axially oriented cylindrical probe respectively. [Image from Plasma Sources Sci. Technol. **24** 052001 (2015).]

- **Importance: All plasmas have boundaries, many properties of the plasma are determined by boundaries (sheath, presheath, double layers)**
- **Why now:**
  - **Advances in computation**
  - **Harder than assumed, still many unresolved issues**
  - **self-organization in presheath was underestimated**

Nonneutral plasmas in traps.

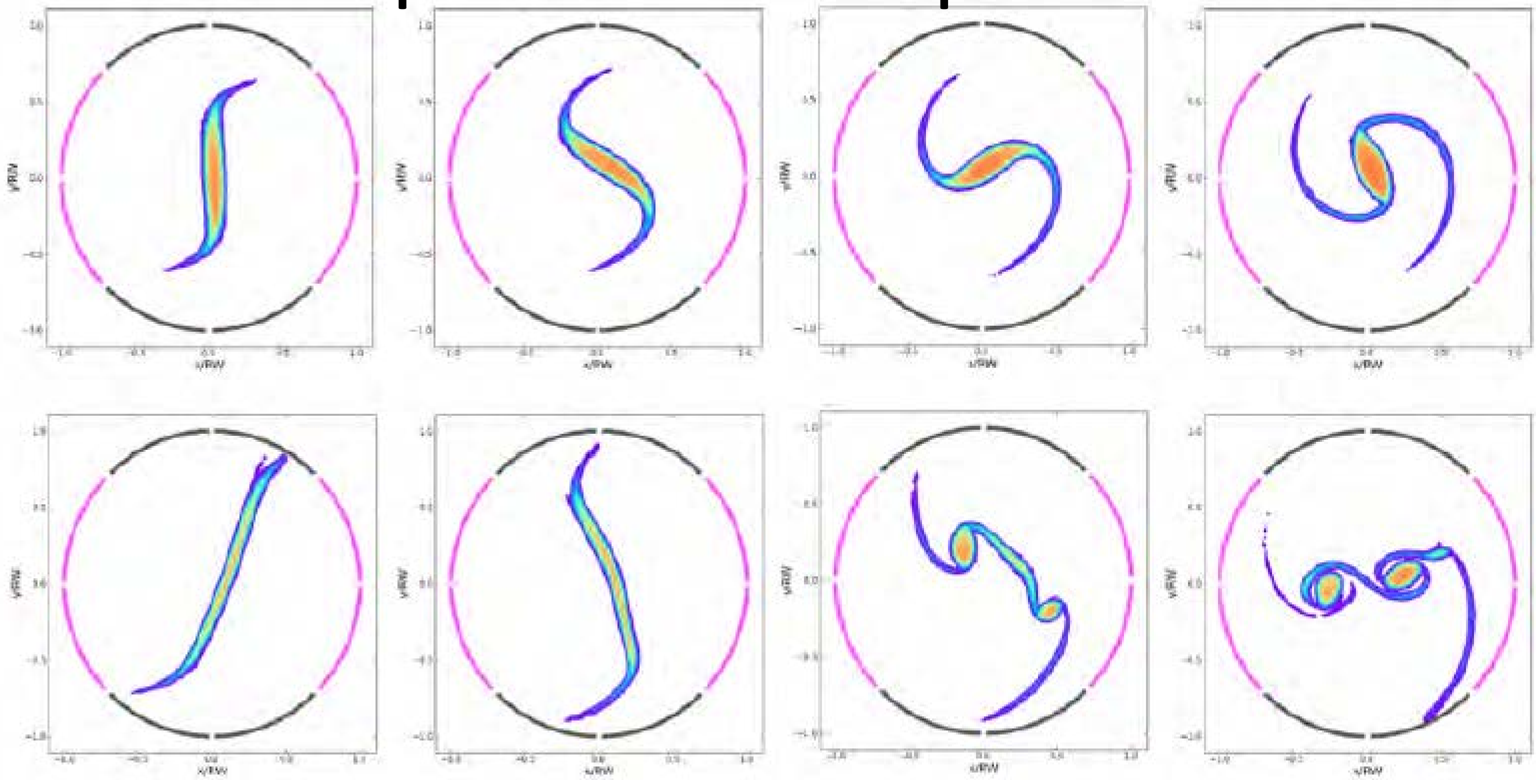


Figure 11 Two different vorticity distributions as subjected to the same externally-imposed flow. [Courtesy of N. Hurst, UCSD]

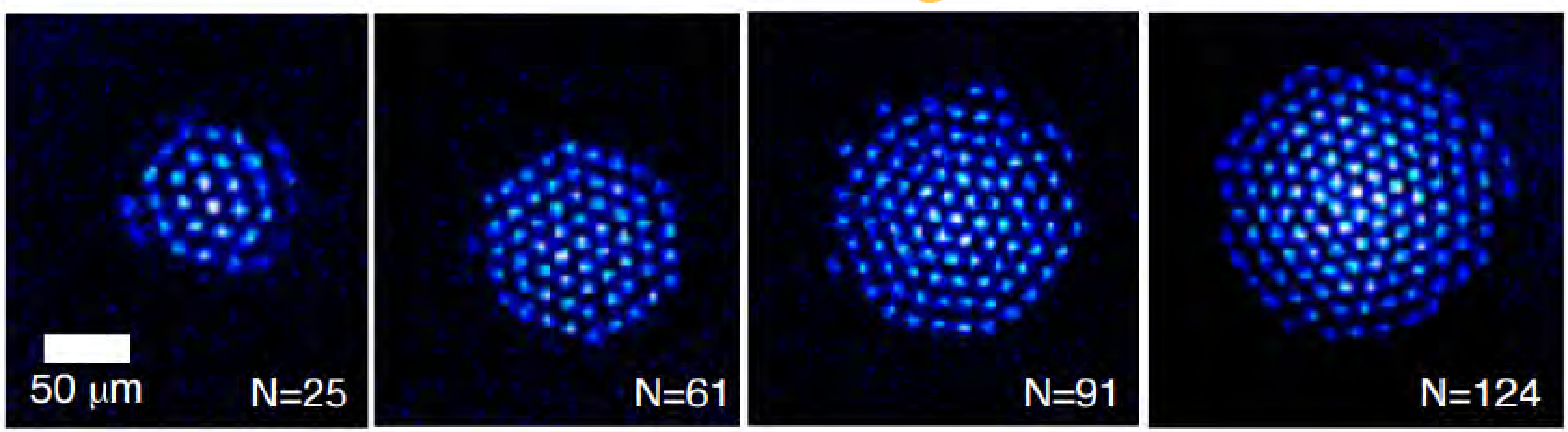
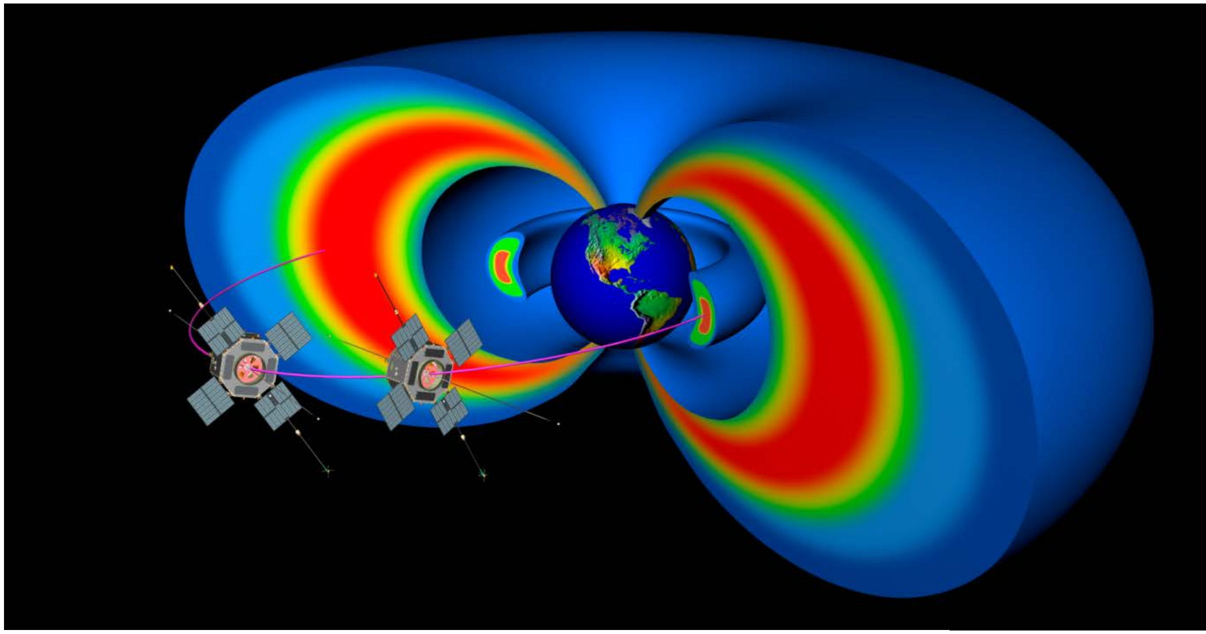


Figure 12 Laser-cooled beryllium ions form strongly-coupled Coulomb crystals that can be used for quantum computing studies. [Image from http://arxiv.org/pdf/1512.03756v2.pdf]

Physics of Radiation Belts



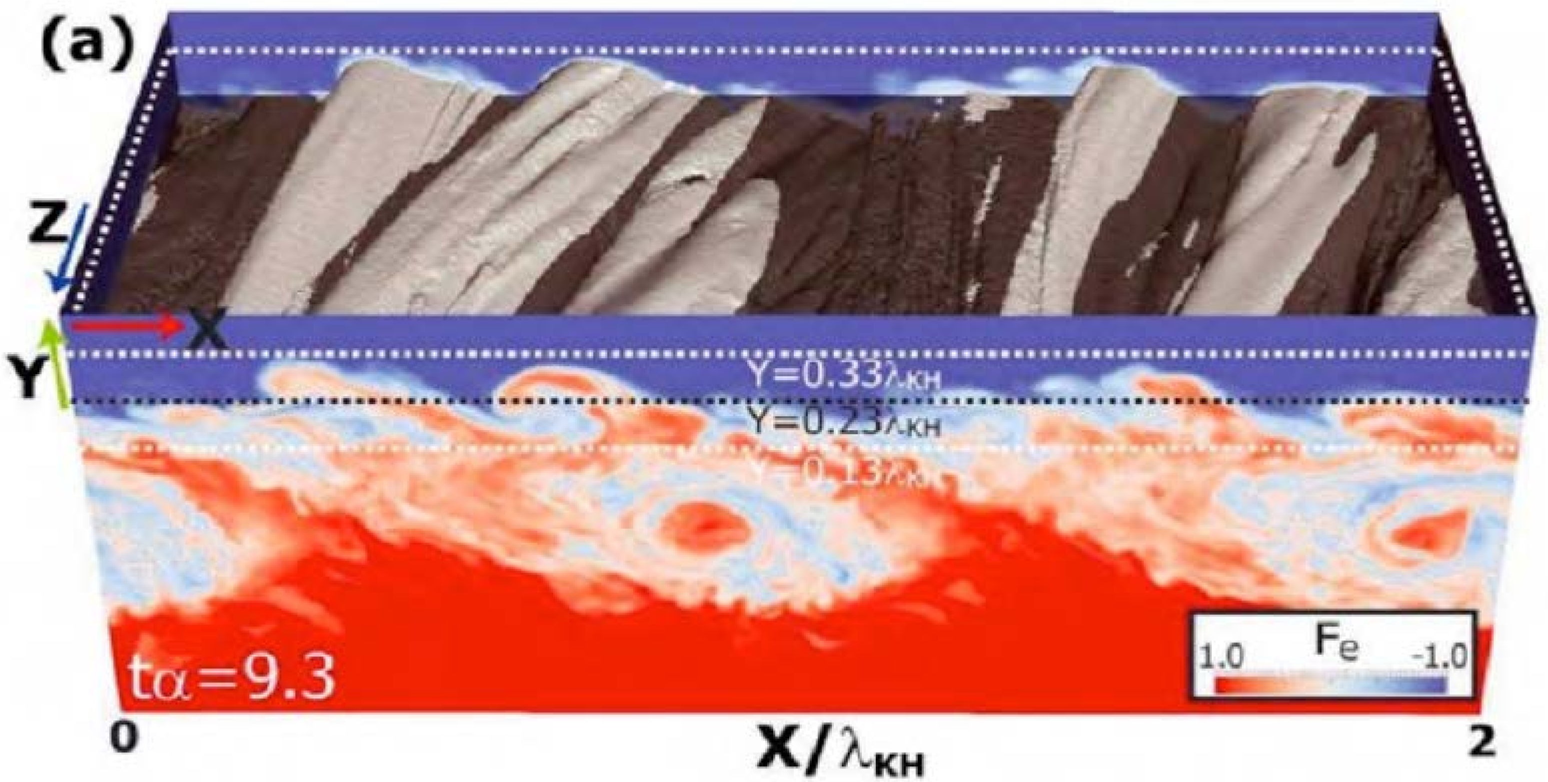
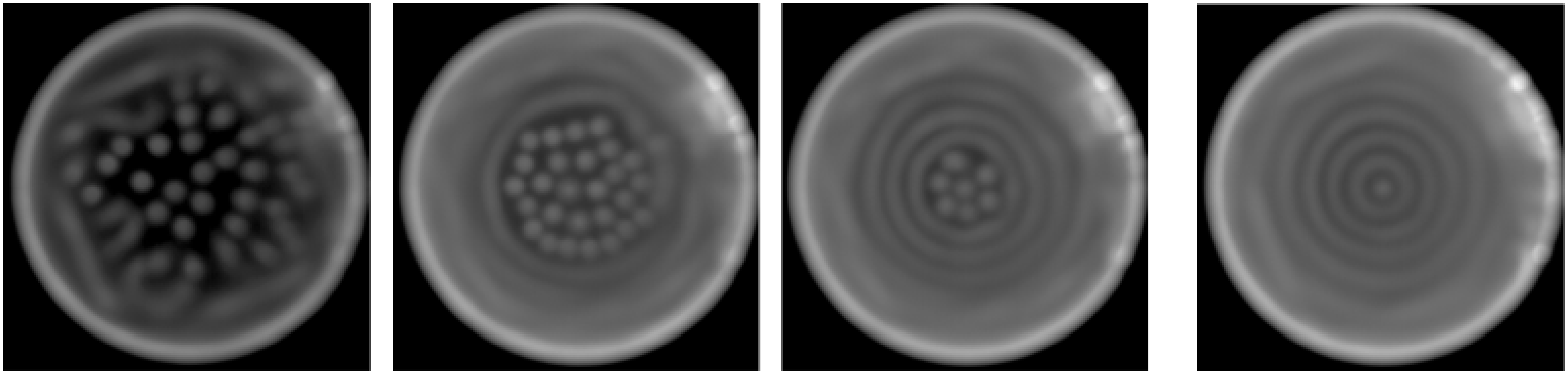


Figure 9. Three dimensional simulations of plasma structures forming at Earth's magnetospheric boundary [Image from Geophys. Res. Lett. **41**, 8704 (2014)].

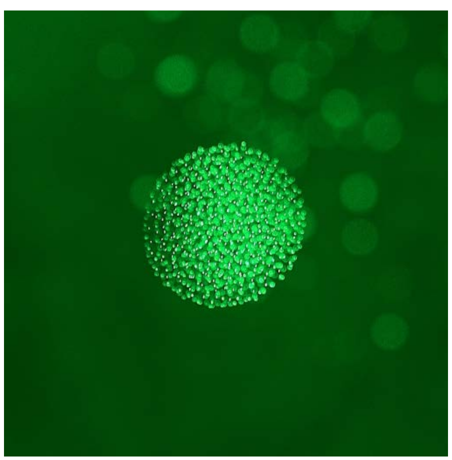
Strongly Magnetized Plasmas

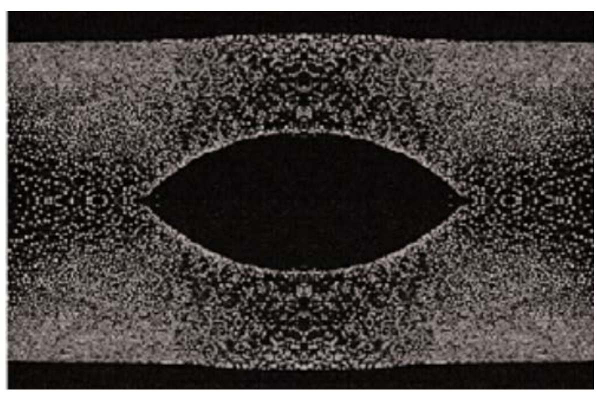


P = 2.7 Pa 3.9 Pa 4.7 Pa 6.9 Pa

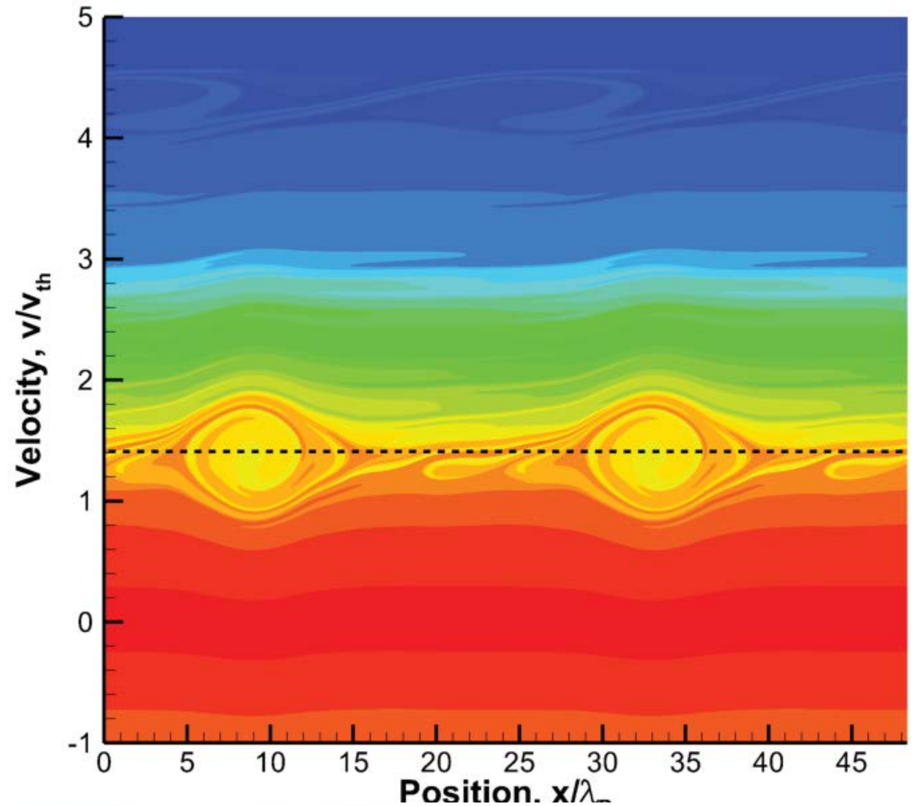
Top view of plasma filaments formed in an rf discharge plasma at B = 1 T

Dusty Plasma





Phase Space Structures



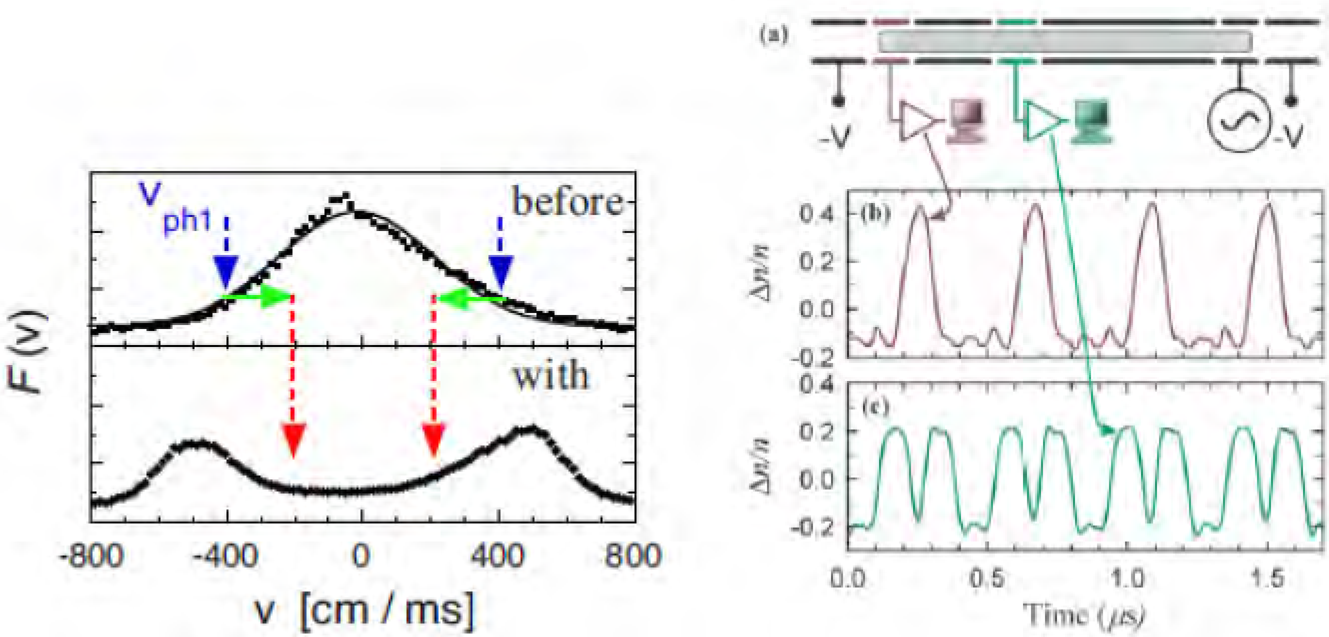
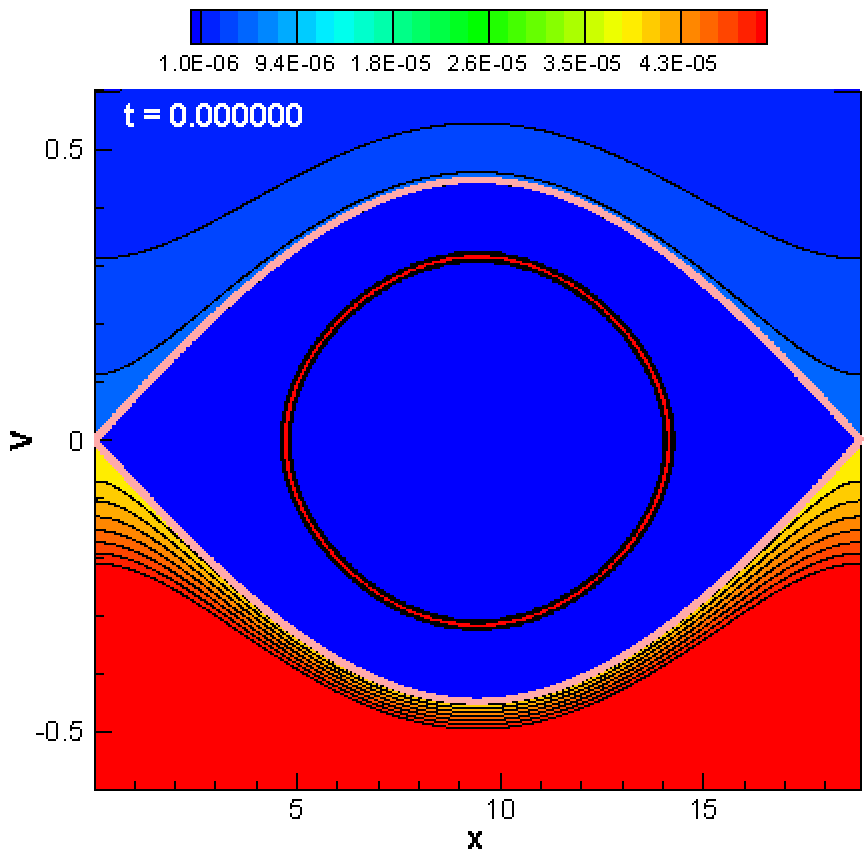
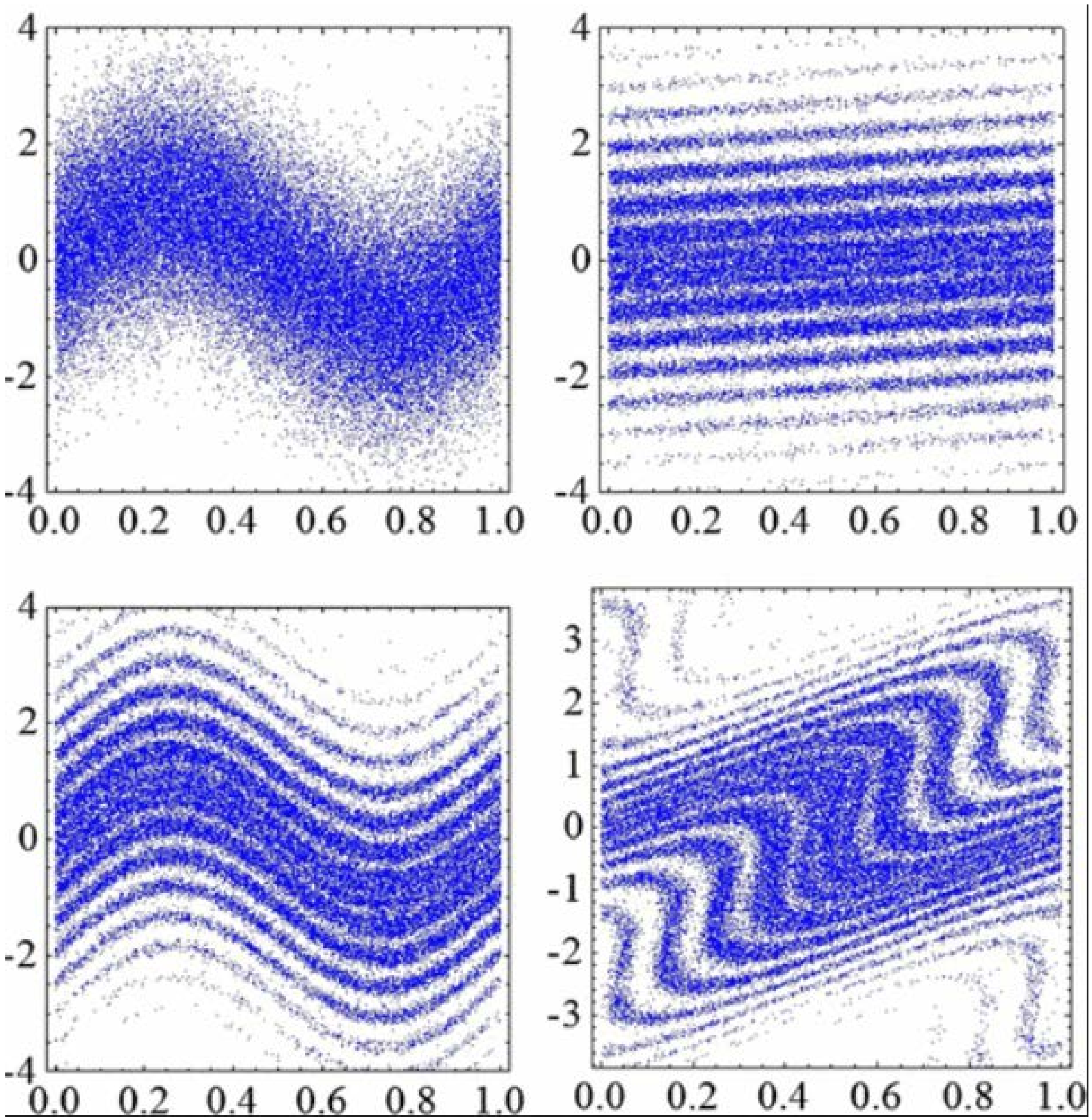


Figure 7. Examples of strong modifications of the velocity particles distribution functions in ion plasma and large amplitude plasma waves measured in electron plasma [lamge from white paper of F. Anderegg]


1.0E-06 9.4E-06 1.8E-05 2.6E-05 3.5E-05 4.3E-05
t = 0.000000
0.5
0
-0.5
v
5
10
15
x

K. Hara 2015

"Echo phase-space patterns in the 4th Generation X-ray FEL beams"



Generation and Control of Coherent Plasma Structures

1. Introduction

- What are different structures, mechanisms

  E x B spokes and filaments, Arc spots and constricted forms of discharges, Voids for dusty plasmas, Diochotron modes, Phase space structures, Thresholds and transitions to other modes, Van Allen Radiation Belts [Radiation belts in Planetary Magnetospheres]

2. **What are the origins of pattern formation?**

- a. Spontaneous vs. induced structures
- b. What are threshold conditions
- c. Structures – at boundaries and in the plasma
- d. Energy/Momentum/Angular Momentum transport (or redistribution)
- Phase space
- e. Robustness of structures

Generation and Control of Coherent Plasma Structures

3. How to control coherent structures?

- a. The inverse problem – how to obtain a desired structure in the plasma
- b. What parameters control these coherent structures?
- i. Fluid/global parameters – Pressure, B, E
- ii. Kinetic – pulsing / resonant particles

4. Requirements for advances

- a. Advanced diagnostics
- b. Numerical simulations
- c. Fundamental theory

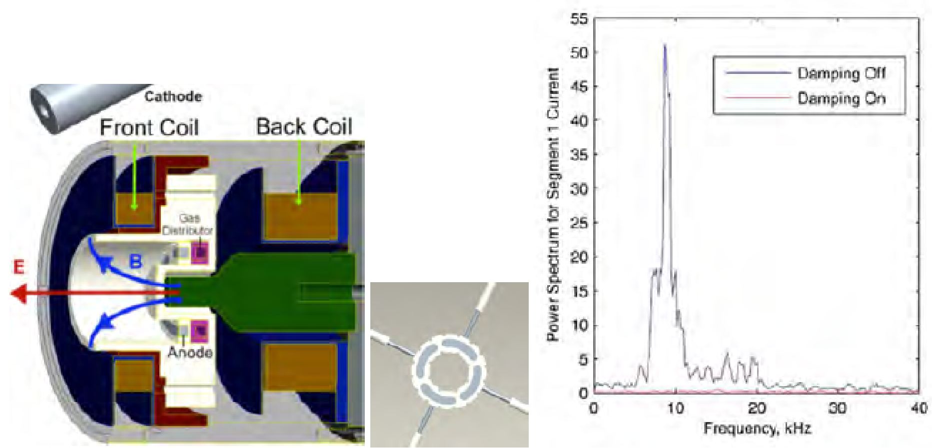


Figure14. Example of application of control of coherent structures in ExB discharge- Hall Thruster
in the left figure). When a feedback system is applied to the segmented anode (shown in the
figure) the spoke disappears as evident in the right figure. [Image from Phys. Plasmas **19**,
(2012).]

The Physics of Disruptive Plasma Technologies

The scientific challenges facing the realization of these ideas can be described as aspects of an overarching challenge

- How can efficient interactions between electromagnetic fields and particle motion be established and controlled?

This broad question naturally leads to both fundamental scientific and technical challenges for the different plasma-based technologies:

- How can ultra-high intensity (I ~ 10^{24} W/cm^{-2}) be reached in plasmas?
- Does Raman compression work in realizable plasmas at high efficiency?
- What are the limits on the brightness, wavelength, of plasma-based x-ray sources?
- What controls the acceleration of particles via collisionless shocks in laser produced plasmas?
- What are the limits to radiation pressure acceleration? Can it be used to accelerate ions to energies of 100's of MeV with lasers beyond the Petawatt level?
- What determines and limits the phase-space characteristics of laser generated particle beams? How can these characteristics (energy spread, peak current, transverse emittance) be tailored for specific applications?

The Physics of Disruptive Plasma Technologies

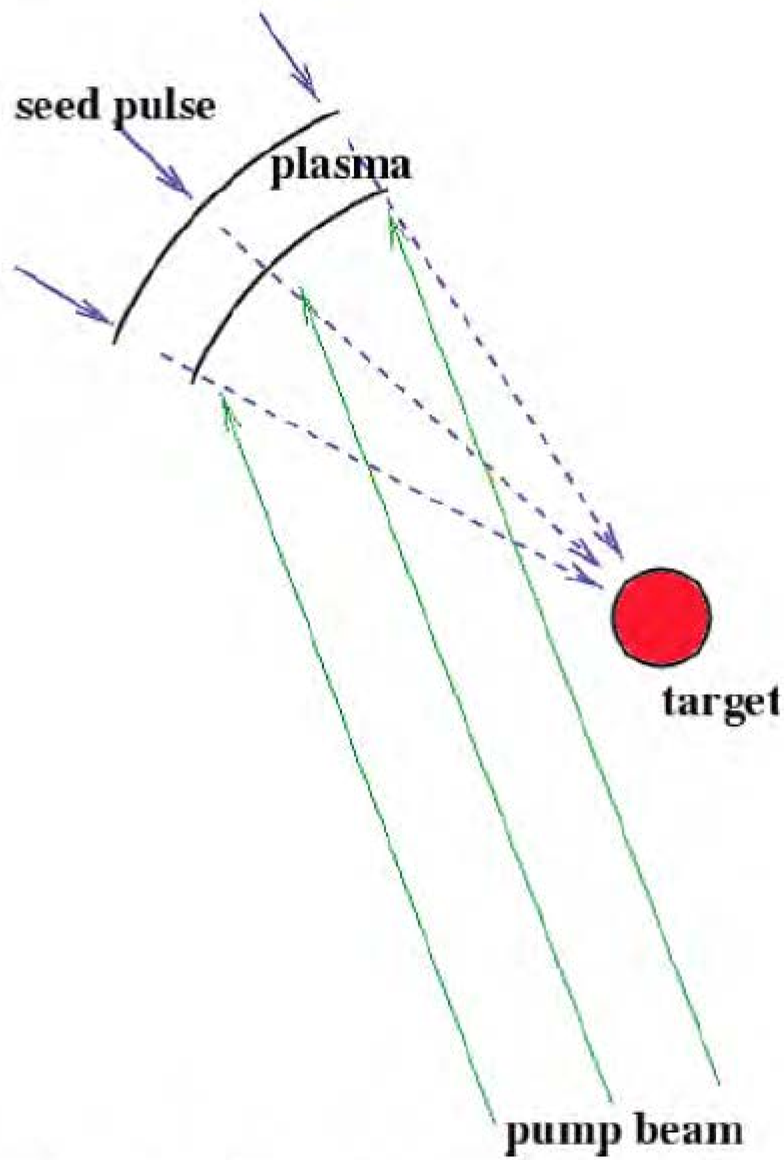


Figure 1. Schematic of Laser Compression in Plasma. [I

- The challenges of realizing a practical plasma-wave laser amplifier stem from the interactions of particles and the large amplitude plasma waves. These interactions lead to nonlinearities in the wave and particle dynamics that must be understood and ultimately carefully controlled.

The Physics of Disruptive Plasma Technologies

- **Generation of High---Flux High---Intensity X---Rays**

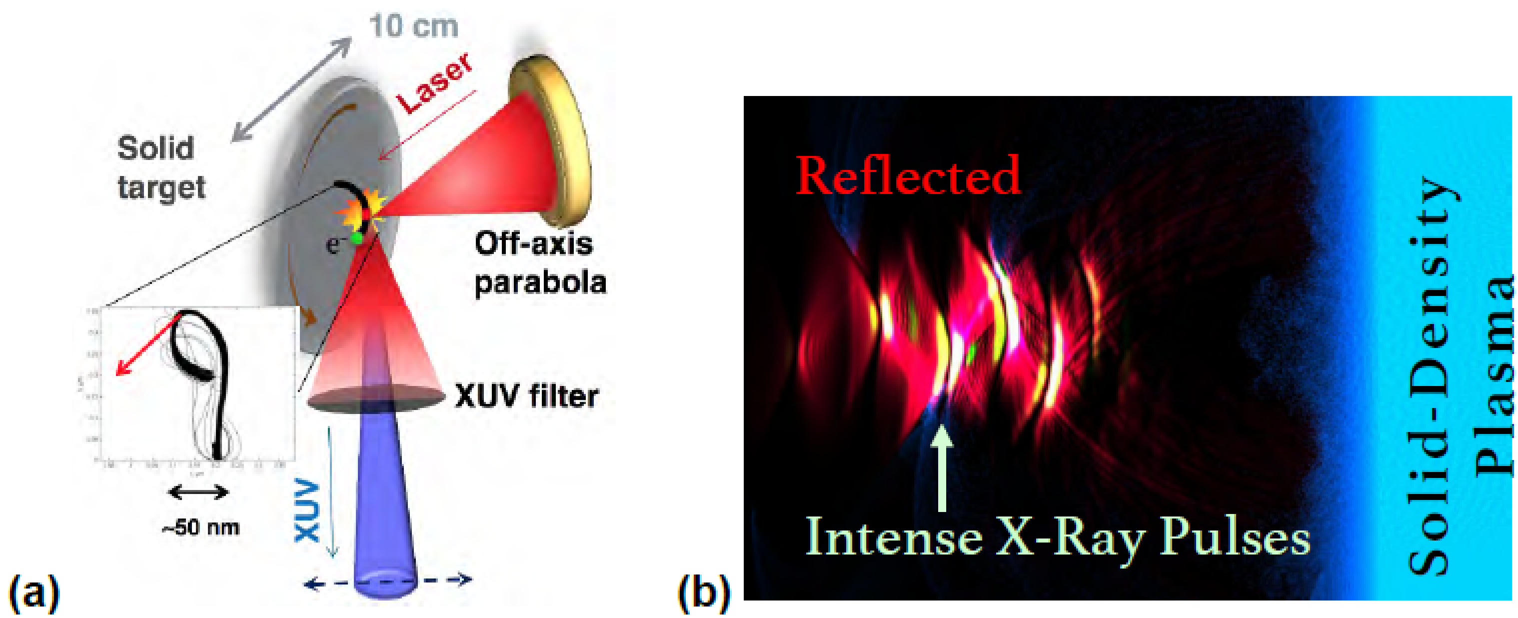


Figure 3. The interaction of relativistic-intensity lasers and dense plasmas can be used to create intense attosecond bursts of extreme ultraviolet and soft-x-ray radiation. (a) schematic of relativistic high-order harmonic generation experiment: a high-intensity laser (red) focused on the surface of a solid (grey disk) creates a solid-density plasma (yellow) with a steep density profile, and accelerates electrons that follow relativistic synchrotron-type trajectories near the target surface and coherently emit attosecond soft x-rays. (b) The process can be numerically studied with particle-in-cell simulations of plasmas, showing intense attosecond soft-x-ray pulses (white peaks) traveling with the laser (red) reflected from the solid-density plasma surface (blue). [Image courtesy of Julia Mikhailova Princeton University.]

The Physics of Disruptive Plasma Technologies

- **Plasma---Based Accelerators**

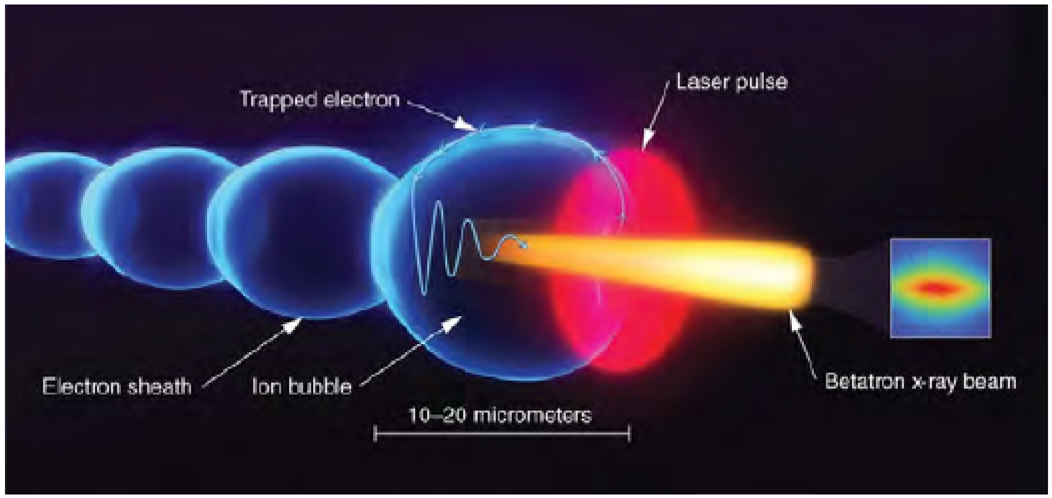


Figure 4. Principle of betatron x-ray emission. Electrons in a wake-field created by the laser in underdense plasma are subject to transverse and longitudinal electrical forces; they are subsequently accelerated and wiggled to produce broadband, synchrotron-like radiation in the keV energy range. From "Laser wakefield accelerator based light sources: potential applications and requirements. [Image from Plasma Phys. Control. Fusion **56,** 084015 (2014)].

The Physics of Disruptive Plasma Technologies

- **Plasma---Based Accelerators; Laser driven ion accelerators**

Fundamental physics questions in laser driven ion acceleration are:
• *At ultra-high intensity (I ~ 1024 W/cm-2) can relativistic protons beams (> 1 GeV) be directly generated from the laser plasma interaction? Can ultra-high power lasers be focused to such intensities in a plasma?*
• *What controls the acceleration of particles via collisionless shocks in laser produced plasmas?*
• *What are the limits to radiation pressure acceleration? Can it be used to accelerate ions to energies of 100's of MeV with lasers beyond the Petawatt level?*
• *What determines the emittance and beam quality of a laser generated proton/ion beam in the various acceleration regimes?*

The Physics of Disruptive Plasma Technologies

- **Ultra-high energy density laboratory plasmas**

Figure 7. Artistic representation of the generation of ultra-high energy density matter by intense ultrashort laser pulse irradiation of ordered nanostructure arrays. [Image from Nature Photonics **7**, 796 (2013)].

Recent experiments have shown that the irradiation of ordered nanowire arrays with femtosecond laser pulses of relativistic intensity can volumetrically heat plasmas with electron densities nearly 100 times greater than the typical critical density to multi-keV temperatures, generating dense ultra-hot plasmas with extreme degrees of ionization (eg. Ni+26, Au+52) for the atomic physics of highly charged ions at extreme density and temperature conditions.

These UHED plasmas also allow for the efficient conversion of optical laser radiations in to bright short flashes of X-rays.

Plasmas at the Interface of Chemistry and Biology

Figure 1 – Atmospheric pressure plasma jet incident onto a biological liquid. [[V. Columbo, D. Fabiani, M. L. focarete, M. Gherardi, C. Gualandi, R. Laurita and M. Zaccaria, "Atmospheric Pressure Non-Equilibrium Plasma Treatment to Improve the Electrospinnability of Poly(L-Lactic Acid) Polymeric Solution, Plasma Proc. Poly. 11, 247 (2013) DOI: 10.1002/ppap.2013.00141]

A. Interfacial Plasmas

Plasmas at the Interface of Chemistry and Biology

B. Plasmas for Human Healthcare

Building on the observations that plasmas can induce beneficial effects in biological systems – healing wounds and reducing cancer tumors – can we understand the complicated interaction pathways that provide such biological benefits?

- How can we control and understand interactions of plasmas at permeable, reactive, dynamic, charged interfaces exemplified by liquids (e.g., biological fluids), soft matter (e.g. cells and tissues) and polymers (e.g., biocompatible materials and scaffolding)?
- What is the effect of plasma (electric field, electrons, ions, photons, reactive oxygen and nitrogen species) on large molecules (including polymers and proteins), and on cell tissue?
- How do electrons and moderate energy ions (e.g., 10s of eV) cascade, deposit energy and modify chemistry within high density, amorphous materials such as water, polymer or bodily fluids?
- What are the synergetic effects of multiple reactive species, electric field, current and radiation in humid environments, and their combined effects on biological systems?

Plasmas at the Interface of Chemistry and Biology

- C. Control of Plasma---Electromagnetic Interactions
- D. Plasmas for the Environment: Plasma Catalysis
- E. Plasma Aided Combustion for improved energy Utilization
- F. Plasma Aided Aeronautics
- G. The Interface between Plasma and Solid---State Physics