NON-MAGNETIC-FUSION PLASMA SCIENCE APPLICATIONS

Presented by

Ronald C. Davidson

Princeton Plasma Physics Laboratory
Princeton University
Princeton, NJ 08543

at
PPPL Theory Program Review
June 1-2, 2000

Plasma Science Applications

FESAC Goal

Advance fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.

Five-Year Plasma Science Applications Goal

Advance the forefront of plasma science across a broad range of applications synergistically with the development of fusion science.

Areas of Research

Nonneutral Plasmas and High-Intensity Accelerators

- Heavy ion fusion
- Proton storage rings (SNS)

Laser-Plasma Interaction Physics

- ICF-scale plasma simulations
- Plasma-based advanced accelerators

Industrial Applications

- Plasma display panels
- Synthetic fiber production
- Hall thrusters

Space Plasma Physics

- Magnetospheric and ionospheric plasmas
- Solar plasmas

Nonneutral Plasmas and Nonlinear Beam Dynamics

Objectives

•Develop advanced analytical and numerical models describing the nonlinear dynamics and collective processes in intense nonneutral beams:

-- Next-generation accelerators for heavy ion fusion.

-- Proton storage rings (Spallation Neutron Source).

•Experimental and theoretical studies of heavy ion beam propagation and beam-plasma interactions in the target chamber.

•Basic experimental and theoretical investigations of nonneutral electron plasmas confined in a Malmberg-Penning trap (funded by ONR).

Personnel

R.C. Davidson, P. Efthimion, L. Grisham, I. Kaganovich, W.W. Lee, S.F. Paul, and H. Qin

Heavy Ion Fusion

Selected Recent Accomplishments

- Developed and applied kinetic (Vlasov-Maxwell) model to describe intense nonneutral beam propagation:
  - -- Nonlinear stability theorem.
  - -- Hamiltonian averaging techniques.
  - -- Electron-ion two-stream instability.
- Application of test-particle model to investigate chaotic particle dynamics and halo formation.
- Development of new nonlinear 2D and 3D δf simulation schemes:
  - -- Beam Equilibrium, Stability and Transport (BEST) code.
  - -- Application to quiescent beam propagation, and two-stream instability.
- Application of macroscopic warm-fluid model to collective instabilities driven by pressure anisotropy.

PDF

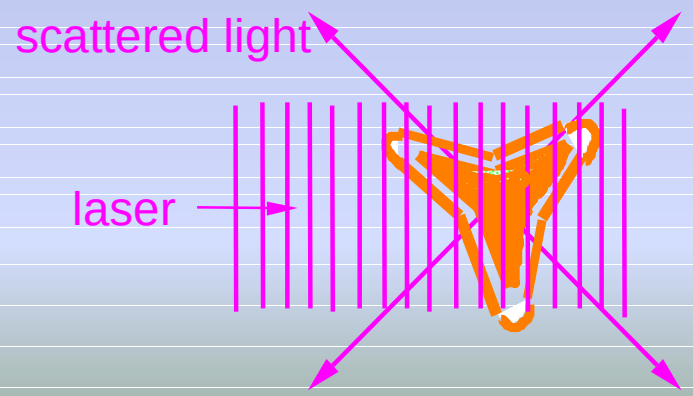
AMTEX CRADA on Diagnostic for Synthetic Fibers

Objectives:

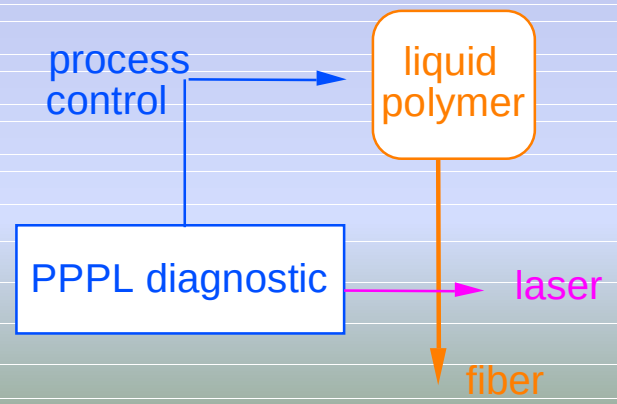
- On-line diagnostics are needed by synthetic textile industry.
- Properties of textile polymers vary with molecular orientation.
- Application of 3D scattering theory to determine birefringence and fiber diameter.

Personnel: D. Mansfield, H. Okuda, P. Efthimion, and L. Meixler

Laser scattering process



Measurement concept

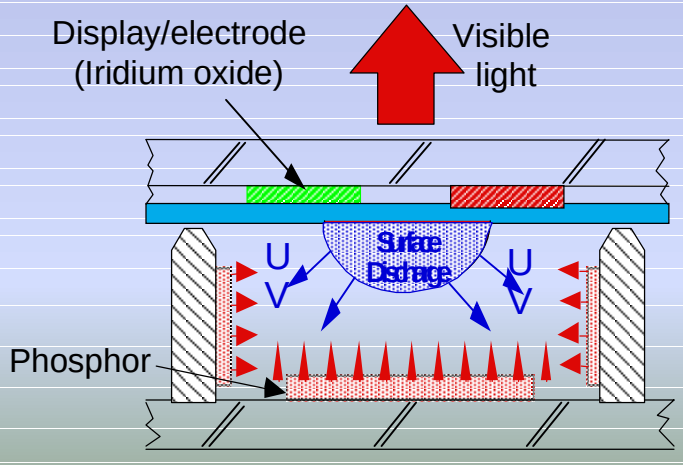


Plasma Display Panel (PDP) Research

Objective: Improve PDP technology to create HDTV display.

- Develop new "cavity ring-down" visible laser interferometer for cell.
- Use state-of-the-art in PIC modeling of plasma in cell.
- Compare experiment and modeling and optimize cell to obtain:
  - Higher plasma density - higher resolution
  - Low DC voltage operation - low energy consumption

Personnel: H. Park and H. Okuda

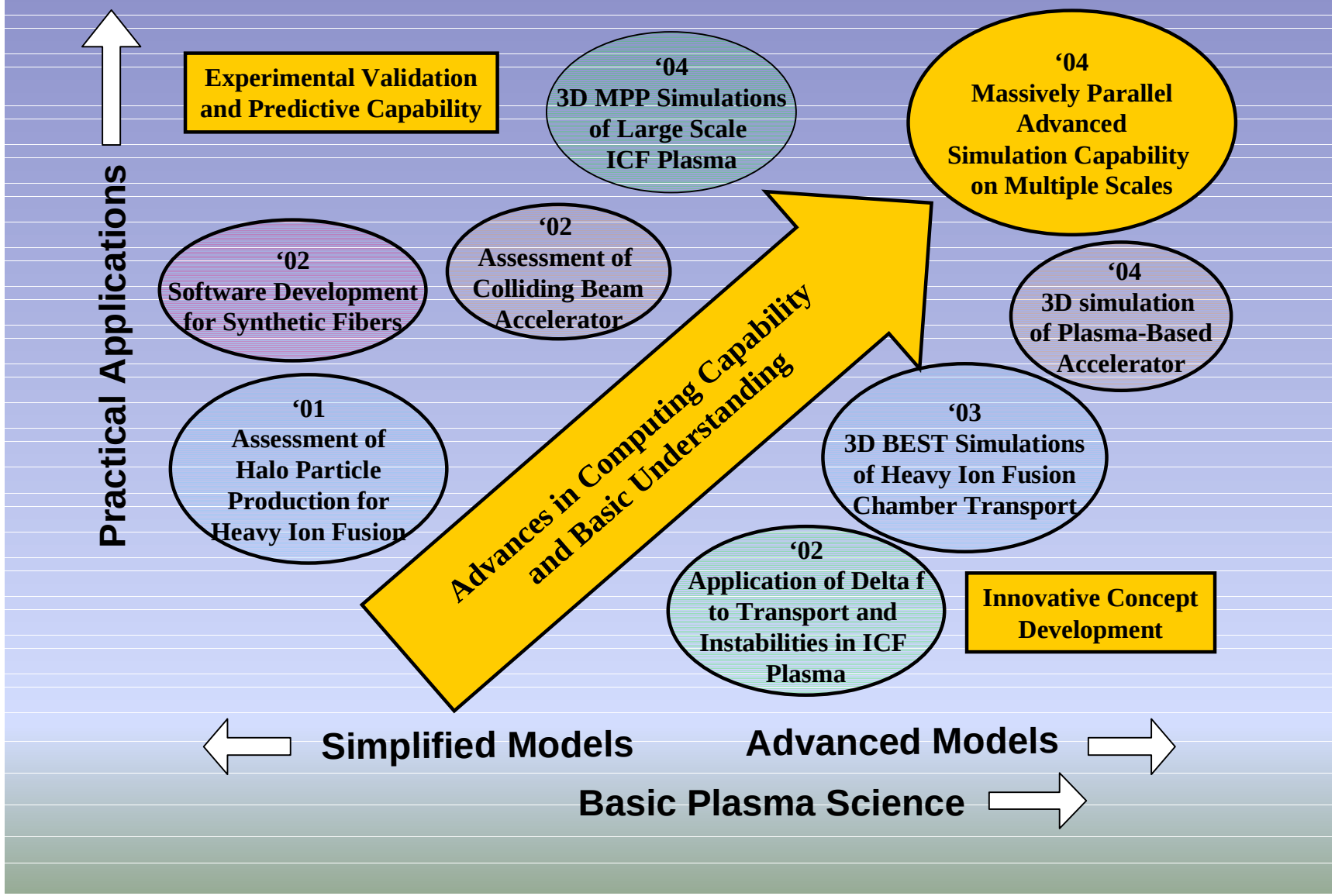


Hall Plasma Thruster Project

•Applications for satellite navigation, stationkeeping, satellite arrays.
•Supported by LPDA, AFOSR and DARPA.
•Development of segment electrode concept for efficiency improvement.
•Key recent achievements using segmented electrode approach.
- Created reduced "plume" in state-of-the-art Hall Thruster.
- Operated new cylindrical thruster scalable to micro-thrust regime.

•**Personnel**: Nat Fisch, Yevgeny Raitses

First-Principles-Based Plasma Science Applications



Plasma Theorists are Making Key Contributions in Plasma Science Applications

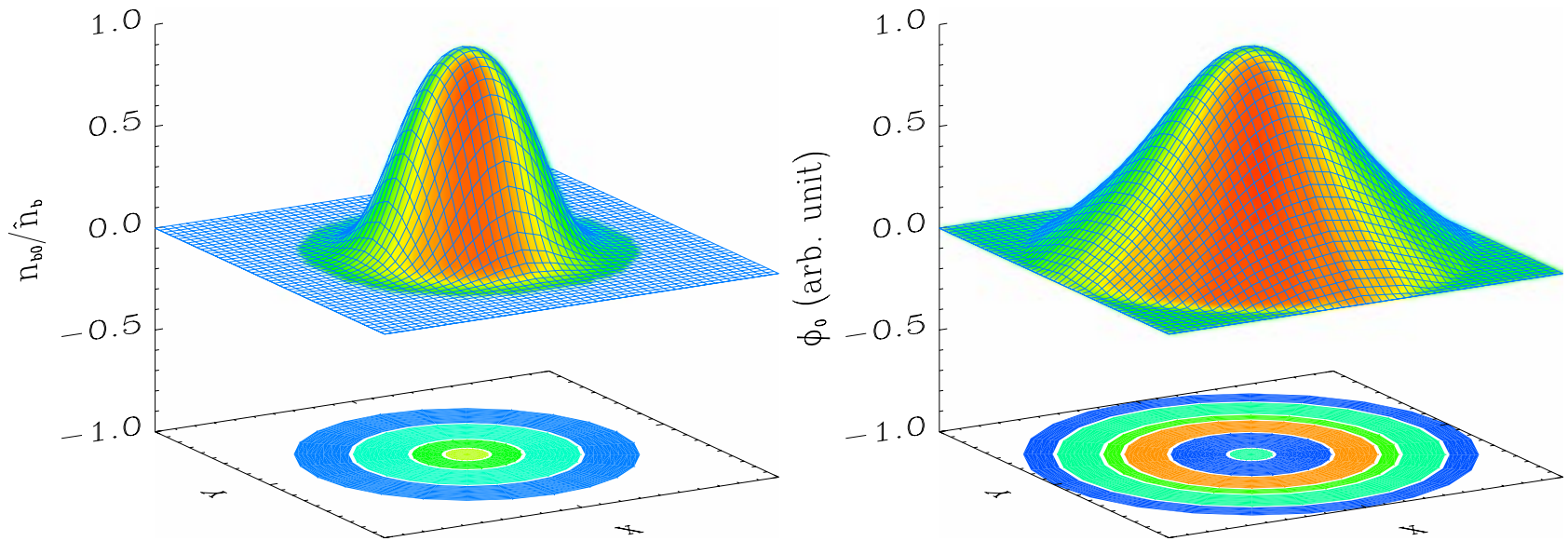
- Analytical and numerical techniques developed in magnetic fusion are finding wide application in accelerator physics, inertial fusion, laser-plasma interactions, space plasmas, and industrial applications.

- Research contributes significantly to broadening the intellectual foundations of plasma science, and broadens educational opportunities for graduate students.

- Research in these areas increases the value of plasma physics to the larger scientific and technological community.

- In turn, magnetic fusion benefits from the development of new models and tools.

BEST Simulation of Thermal Equilibrium Beam Propagation

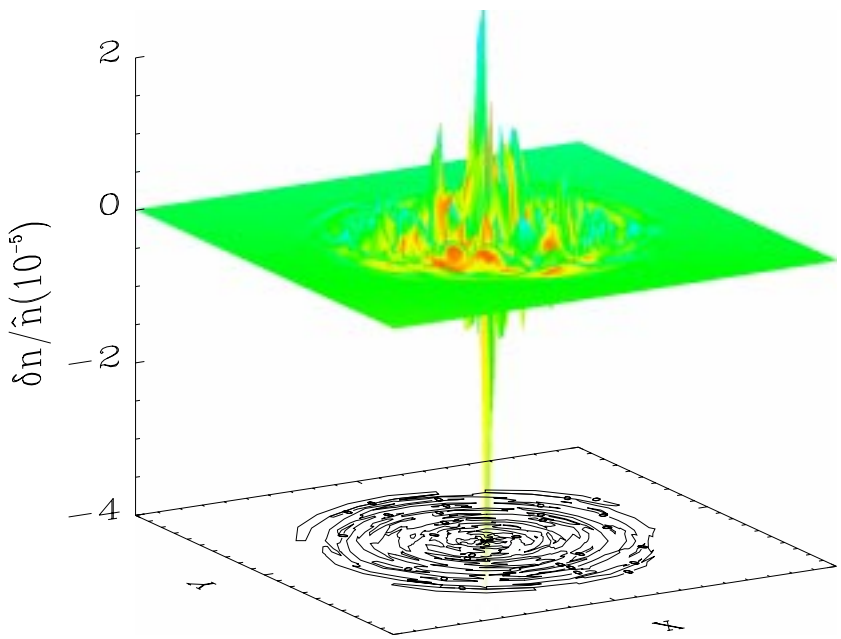


(a) Equilibrium Density (b) Equilibrium Space-Charge Potential

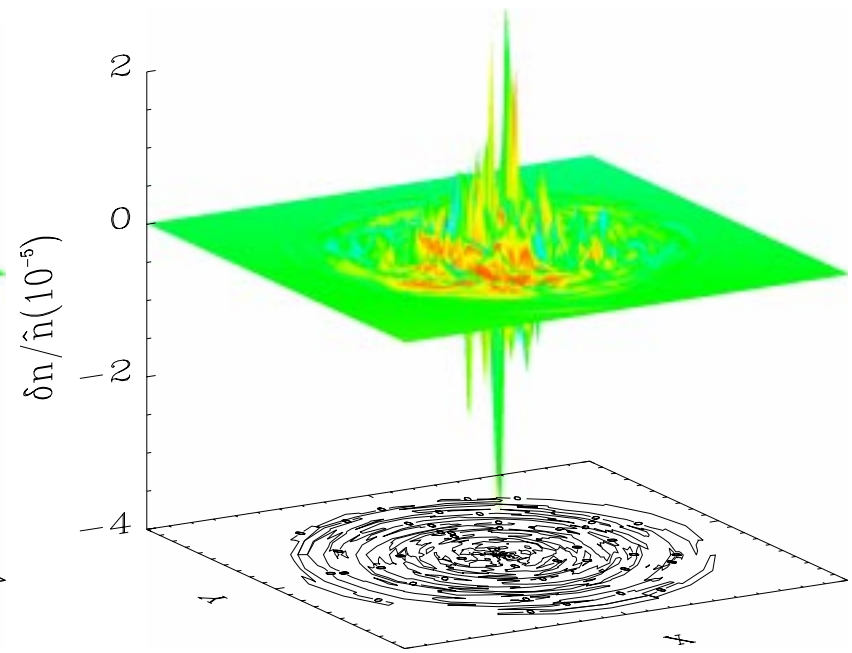
- Equilibrium solutions (ϕ_0, A_{z0}, f_{j0}) solve the steady-state ($\partial/\partial t = 0$) Vlasov-Maxwell equations with $\partial/\partial z = 0$ and $\partial/\partial\theta = 0$.

- System parameter are chosen to be: $\gamma_b = 1.08$, $A = 133$, and normalized beam intensity $s_b \equiv \hat{\omega}_{pb}^2/2\gamma_b^2\omega_{\beta b}^2 = 0.95$.

BEST Simulation of Thermal Equilibrium Beam Propagation



(a) Perturbed δn at $t = 0\tau_\beta$.



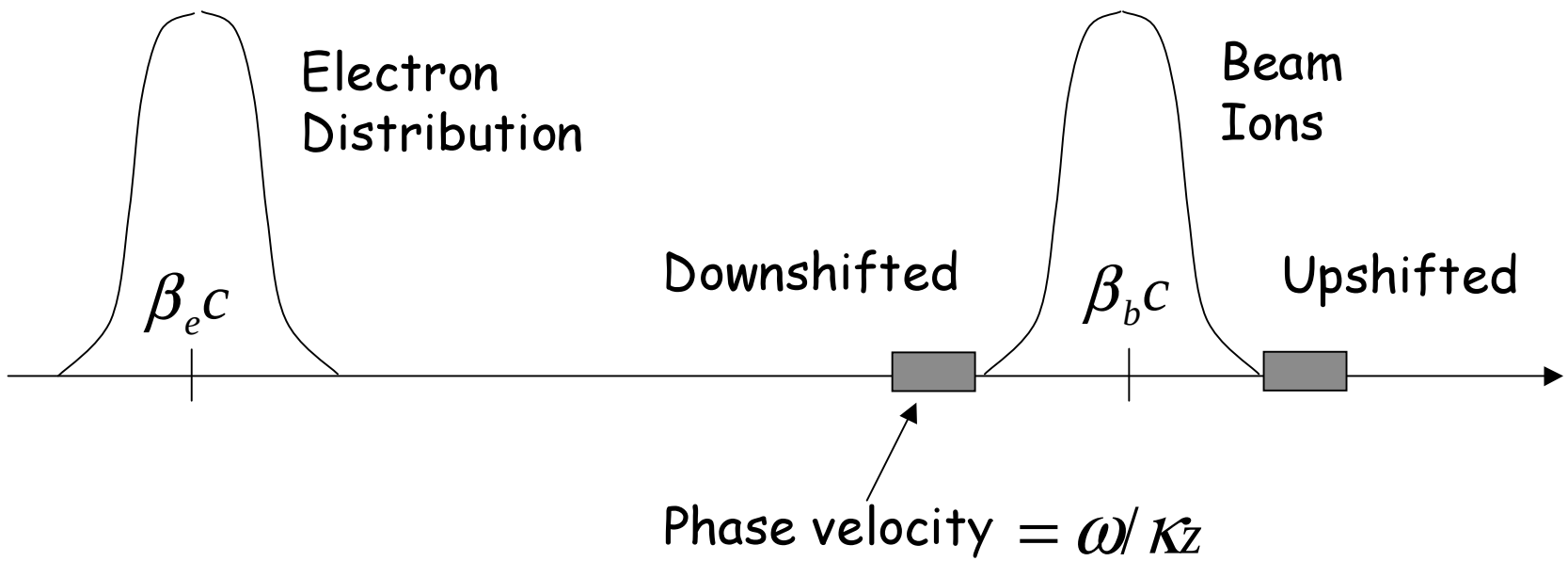
(b) Perturbed δn at $t = 1000\tau_\beta$.

- Random initial perturbation with normalized density amplitudes of 10^{-5} are introduced into the system.
- The beam is propagated from $t = 0$ to $t = 1000\tau_\beta$, where $\tau_\beta \equiv \omega_{\beta b}^{-1}$.

Two-Stream Instability for Intense Ion Beams

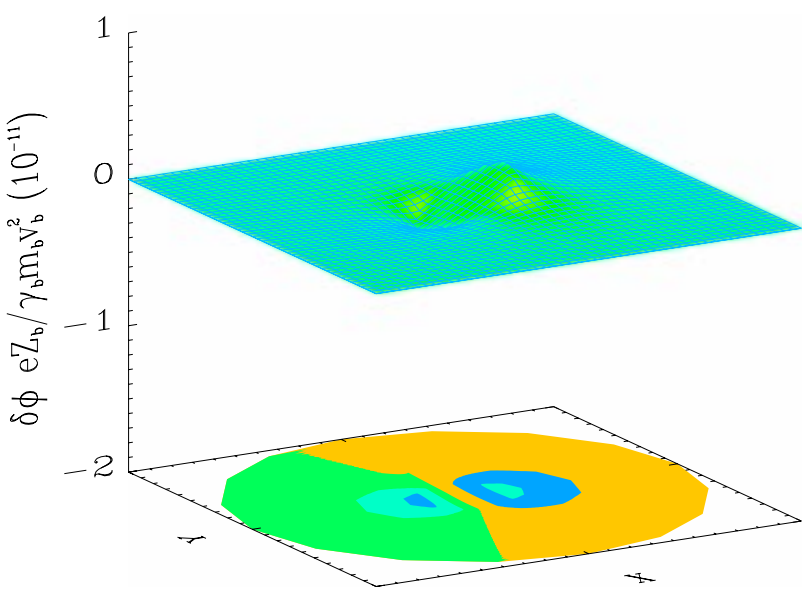
- In the absence of background electrons, an intense nonneutral ion beam supports collective oscillations (plasma oscillations) with phase velocity ω/k_z upshifted and downshifted relative to the average beam velocity $\beta_b c$.

- Introduction of an (unwanted) electron component (produced, for example, by secondary emission of electrons due to the interaction of halo ions with the chamber wall) provides the free energy to drive the classical two-stream instability.

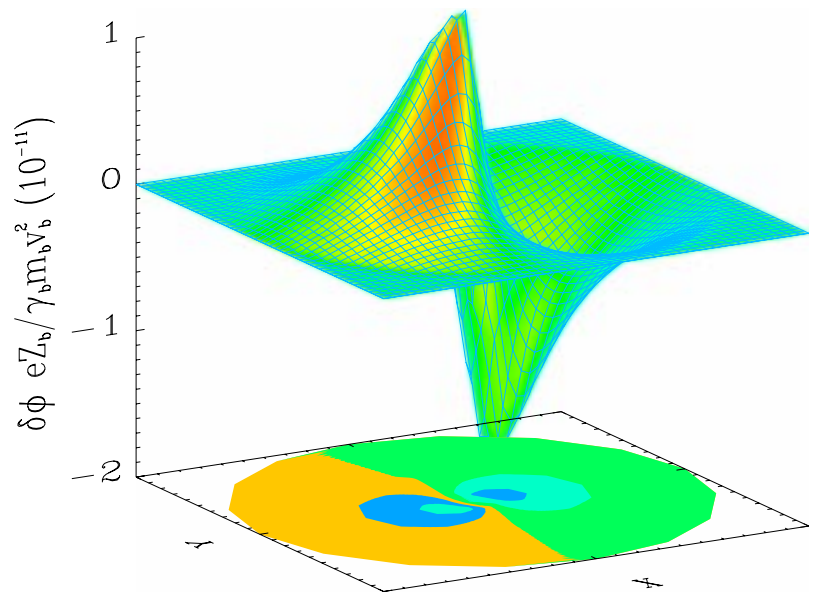


BEST Simulation of Two-Stream Instability

- When a background electron component is introduced with $\beta_e = V_e/c \simeq 0$, the $l = 1$ "surface mode" can be destabilized for a certain range of axial wavenumber and a certain range of electron temperature T_e.



(a) $t = 0$



(b) $t = 200/\omega_{\beta b}$

- Linear growth phase shows strong dipole mode structure.

Laser-Plasma Interaction Physics

Objectives

- Develop innovative techniques and codes for the accurate simulation of energy absorption and transport in dense plasmas driven by high intensity lasers, such as those found in inertial confinement fusion.

- Investigate the applicability of the nonlinear δf method for representing the nonthermal particle distributions arising under such conditions.

Personnel:

S. Brunner, E. Valeo, J. A. Krommes.

Laser-Plasma Interaction Physics

Recent Accomplishments

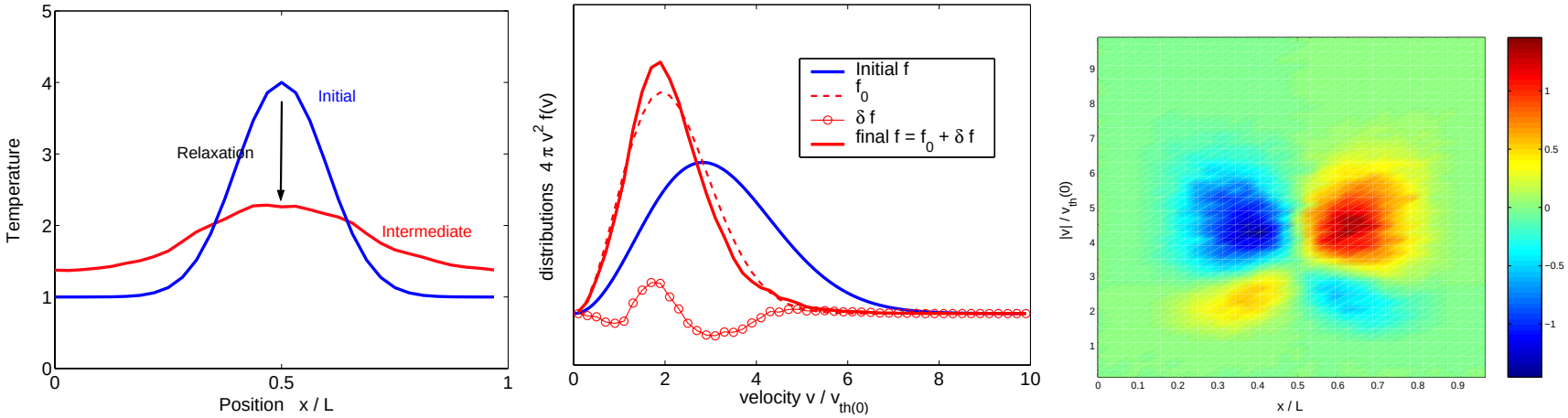
➪ Ion Driven Microturbulence:

- ❍ Developed a 2D, nonlinear δf code for simulation of Stimulated Brillouin Scattering (SBS).
- ❍ Significant reduction in the number of simulation particles compared to standard PIC simulations.

➪ Nonlocal Transport:

- ❍ Derived a nonlinear δf scheme with evolving background for transport time-scale simulations.
- ❍ Technique has been applied in 1D for computing linear and nonlinear, nonlocal electron heat transport.
- ❍ Results have been validated by comparison with previous hydrodynamic and Fokker-Planck calculations.

Laser-Plasma Interaction Physics



(a) Temperature profiles (b) Distributions at $x/L = 0.5$ (c) Heat flux

➪ Relaxation of an initial gaussian temperature profile through nonlocal electron heat transport. Mean free path/temperature gradient $\sim 1 - 10$.

High Intensity Laser Science and Applications

Objectives

- Discover and apply basic physical processes in ultra-intense laser-plasma interactions, including ponderomotive acceleration of electrons, inverse bremsstrahlung, and megagauss magnetic field generation.
- Develop advanced accelerator concepts based on femtosecond laser-plasma interactions for the needs of high-energy physics.
- Develop novel radiation sources in a broad range of frequencies (from FIR to X-rays) based on the interaction of intense lasers with plasmas.

Personnel: N. J. Fisch, G. Shvets.

Selected Recent Accomplishments

- Studied theoretically and computationally laser excitation of plasma waves in radially inhomogeneous plasma channels.

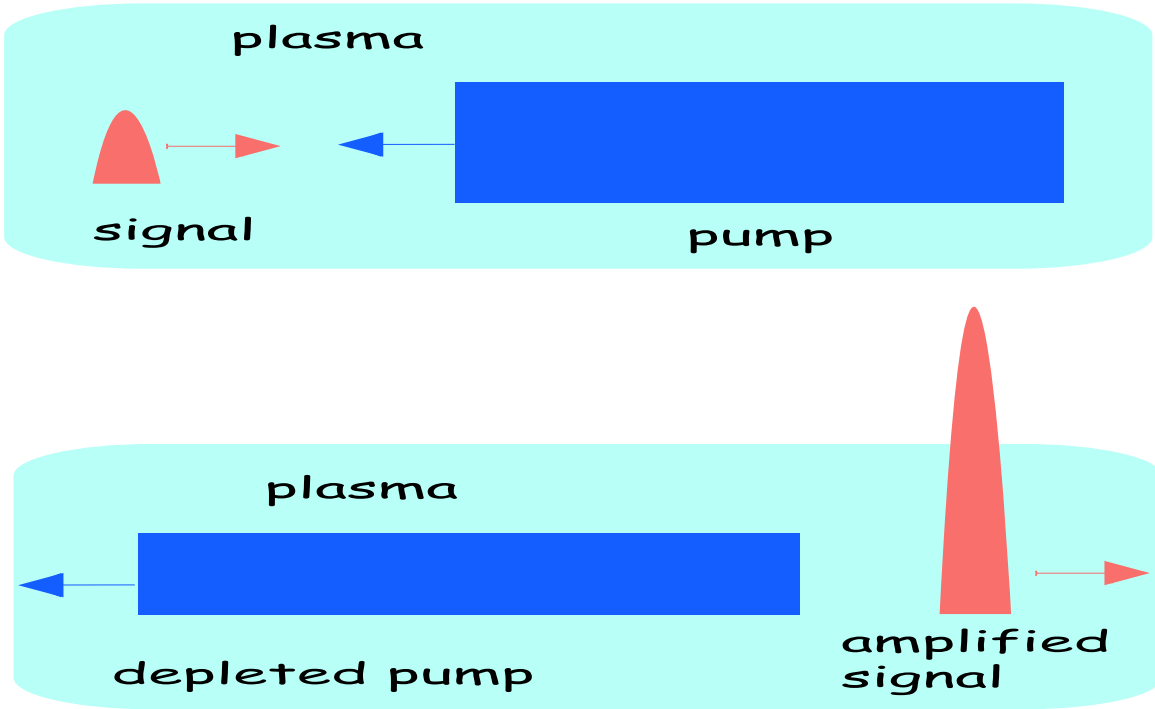
- Proposed to use nonlinear interaction between counter-propagating lasers in plasma to achieve several goals:

  - parametrically amplify a **short** pulse at the expense of a **long** counter-propagating beam thereby achieving energy compression $\Rightarrow$ superradiant amplification.
  - produce ultra-high accelerating gradients ($\approx$ 10 Gev/m) using modest intensity laser beams $\Rightarrow$ Colliding-Beam Accelerator.

- Proposed a novel plasma-based accelerator, the Beam-Channeled Laser Wakefield Accelerator, in which a high current electron beam guides an intense laser driver.

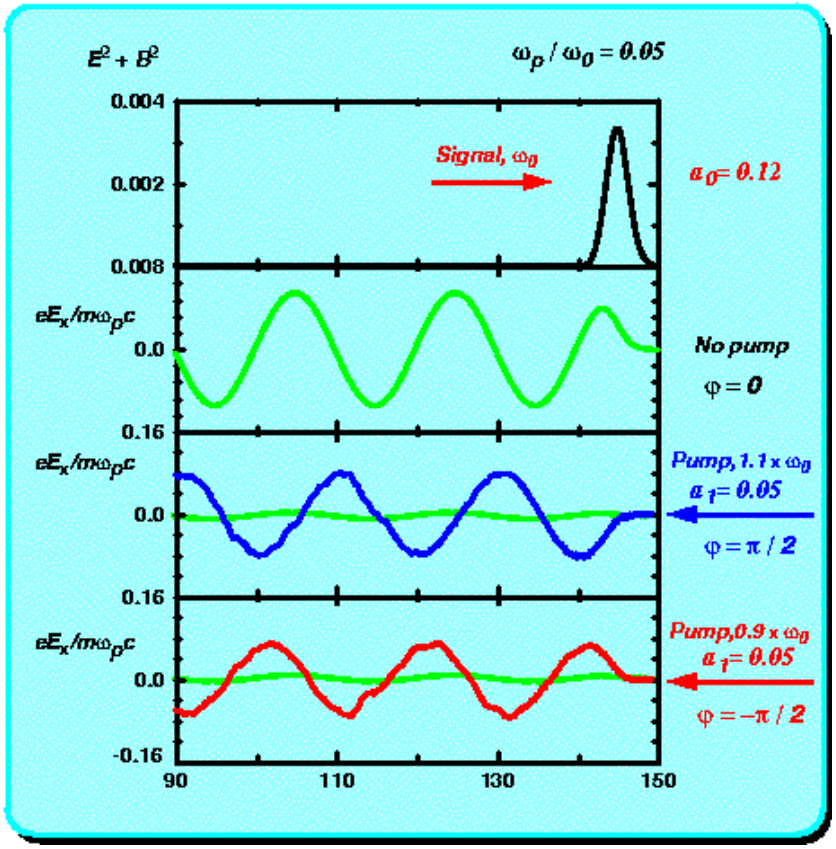
- Theoretical and computational studies of a laser-driven undulator source of infrared radiation.

Superradiant Pulse Amplification in Plasma



- Since $\tau_p \gg \tau_L$, $I_L \gg I_p$ – signifcant compression.

Colliding Beam Accelerator



- $I_0 = 4 \times 10^{16} W/cm^2$
- $I_{pump} = 6.7 \times 10^{15} W/cm^2$.
- Accelerating gradients$\simeq 10 GeV/m$.