Surface Waves and Landau Resonant Heating in Unmagnetized Bounded Plasmas

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Outline

- Introduction
  - Basic mechanisms, Homogeneous Model, Two Approaches
- Surface Waves
  - Cold Slab Model, Warm Non-Uniform Model, Modeling Results, Simulation Results
- Landau Resonant Heating
  - Observations, Traveling Wave, Standing Wave, Resonant Enhancement, Simulations
- Conclusion
  - Acknowledgments

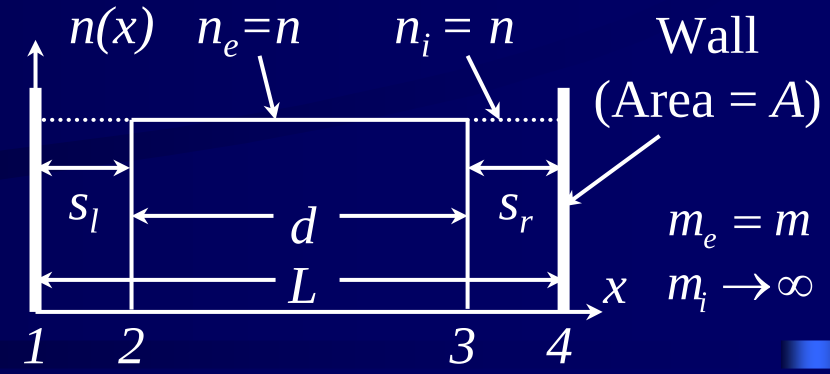
Introduction

- Understanding the plasma-wall interaction is critical in laboratory and industrial plasmas
- Large area plasmas pose difficult modeling, simulation and experimental problems.
- Surface Waves and Landau Resonant Heating can be exploited to generate plasmas with desirable properties:
    - Uniformity, low temperature, enhanced reactions

Mechanisms and Properties

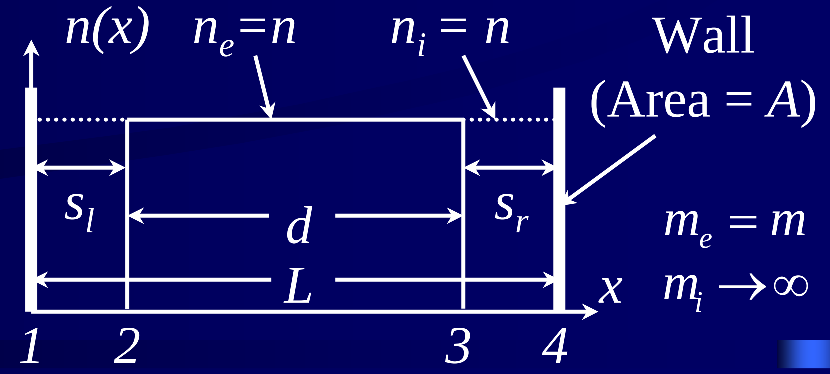
- Plasma Non-Uniformity
  - Capacitive sheaths, "Inductive" bulk (from e^- inertia)
  - Waves propagate near or below ω_{pe}
  - Strongest fields near plasma sheaths
- (Mostly) Longitudinal Waves
  - Waves exchange energy between e^- inertia and electric field
  - Waves of interest have slow group velocities, $v_{gr} \sim v_{th}$, and slow phase velocities, $v_{ph} << c$ (usually)
  - Compression of plasma: thermal effects - Bohm-Gross dispersion and Tonks-Dattner modes
- Wave-Particle Interactions
  - Wave fields suitable for trapping particles moving synchronously with the wave; Landau damping

Homogeneous Model



- Models the effects of space charge sheaths
  - Assume stationary uniform ions
  - Electrons are trapped in center of the plasma
  - Invoking quasi-neutrality, the bulk electron density is the same as the ion density
- Electron depleted sheaths at walls are ubiquitous in unmagnetized low temperature plasmas
  - Electrons mobility is far greater than ion mobility
- What is the relationship between the applied voltage and the device current?

Physical Viewpoint



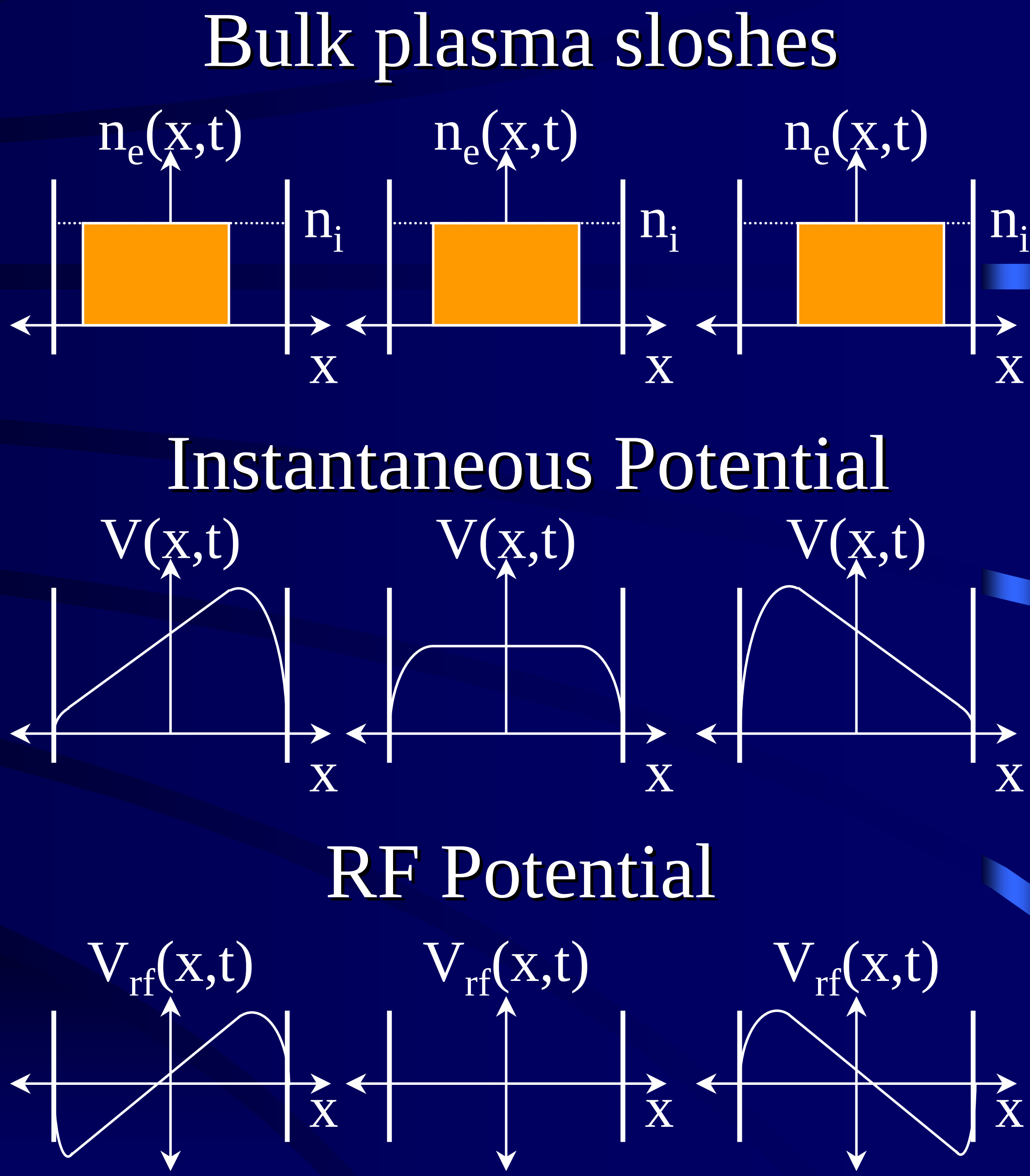
- From Poisson's equation, the electric field in the bulk (E_p) is constant in space
  - Ignoring thermal effects, e⁻'s move as a rigid slab
- Newton: $\frac{d^2}{dt^2}\tilde{s}_l = -\frac{e}{m}\tilde{E}_p - \nu_m \frac{d}{dt}\tilde{s}_l$
- Poisson: $\tilde{E}_p(t) = \frac{1}{L}\tilde{V}_{14}(t) - \frac{2en\bar{s}}{\varepsilon_0 L}\tilde{s}_l(t)$
- Damped SHO: $\frac{d^2}{dt^2}\tilde{s}_l + \nu_m \frac{d}{dt}\tilde{s}_l + \frac{2\bar{s}}{L}\omega_{pe}^2\tilde{s}_l = -\frac{e}{mL}\tilde{V}_{14}$
- Total Current: $\tilde{I}(t) = -enA\frac{d}{dt}\tilde{s}_l + \varepsilon_0 A\frac{d}{dt}\tilde{E}_p$

Governing Equation:

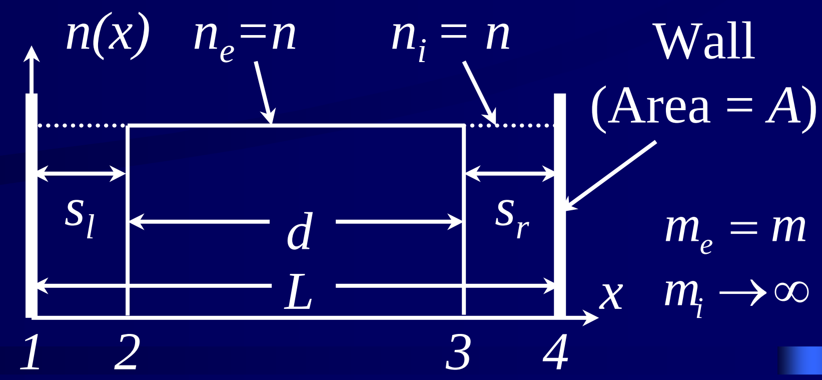
$$\frac{d^2}{dt^2}\tilde{I} + \nu_m \frac{d}{dt}\tilde{I} + \frac{2\bar{s}}{L}\omega_{pe}^2\tilde{I} = \frac{\varepsilon_0 A}{L}\left(\frac{d^3}{dt^3}\tilde{V}_{14} + \nu_m \frac{d^2}{dt^2}\tilde{V}_{14} + \omega_{pe}^2 \frac{d}{dt}\tilde{V}_{14}\right)$$

At the Series Resonance

- RF voltage drop across bulk plasma cancels sheath voltage drop
- Displacement current through bulk not negligible



Circuit Viewpoint

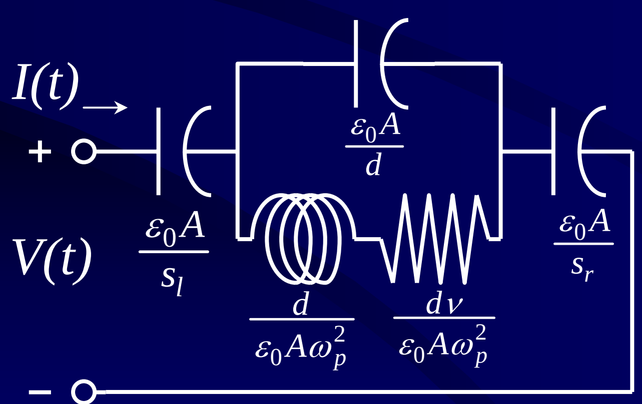


- In the plasma bulk: $\varepsilon_p = \varepsilon_0 \left(1 - \omega_{pe}^2 \big/ \omega(\omega - j\nu_m)\right)$

- Three capacitors in series:

$$Z(\omega) = \frac{\tilde{V}_{14}(\omega)}{\tilde{I}(\omega)} = \frac{s_l + s_r}{j\omega\varepsilon_0 A} + \frac{d}{j\omega\varepsilon_0 A\left(1 - \frac{\omega_{pe}^2}{\omega(\omega - \nu_m)}\right)} = \frac{L}{j\omega\varepsilon_0 A}\left(\frac{\frac{2\bar{s}}{L}\omega_{pe}{}^2 - \omega^2 + j\nu_m\omega}{\omega_{pe}{}^2 - \omega^2 + j\nu_m\omega}\right)$$

- High frequency equivalent circuit:



What We Learned

- A bounded plasma slab has a natural oscillation frequency for sloshing motion
  - Series resonance: $\omega_{sr}=\omega_{pe}(2s/L)^{1/2}$
- Near the series resonance the Z(ω) is resistive
- Treating the plasma as a stationary dielectric medium implicitly accounts for e^- motion
  - Calculations are easier from the circuit point-of-view but physical point-of-view has more insight

Surface Waves

A Simple Model and Asymptotes

A Better Model

Modeling Results

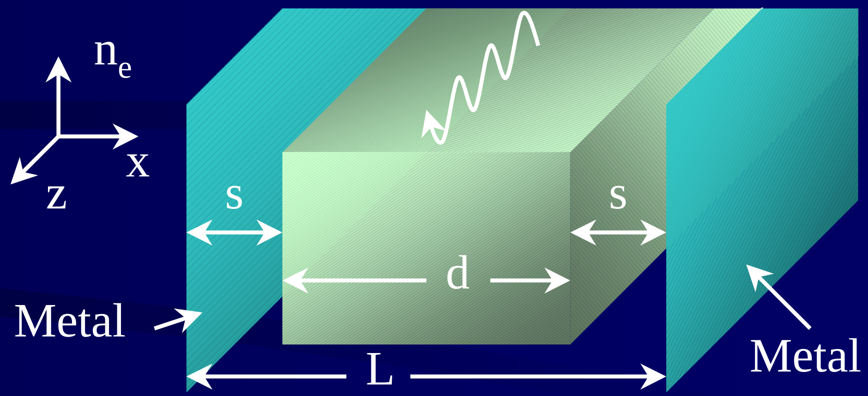
Theoretical Discussion

Electrostatic Simulation Results

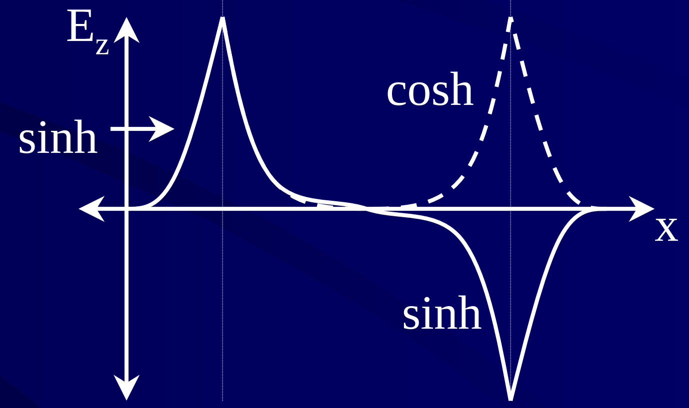
Electromagnetic Simulation Results

A Simple Model

- Treat as a dielectric loaded waveguide
  - Cold homogeneous bulk plasma
  - Vacuum sheaths
  - Longitudinal waves are TM polarized
  - Look for slow waves

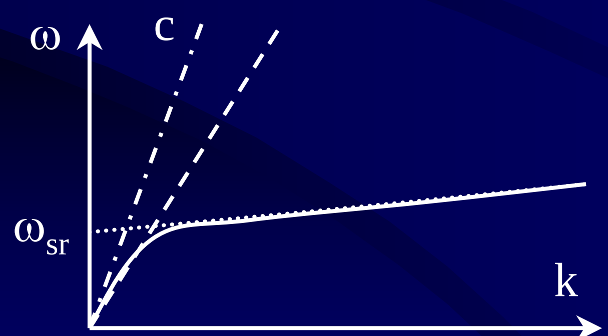


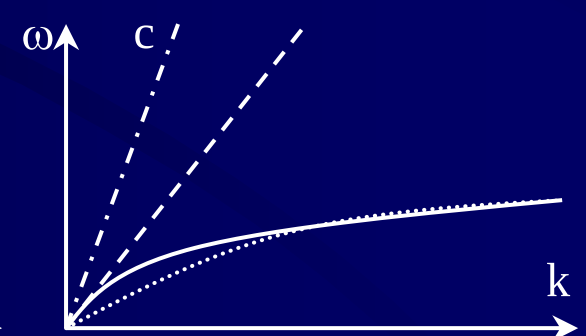
Mode Structure



Asymptotes

	Anti-symmetric	Symmetric
Small k	$\omega = kc / \sqrt{1 + \frac{c}{s\omega_{pe}} \tanh \frac{\omega_{pe} d}{2c}}$	$\omega = kc / \sqrt{1 + \frac{c}{s\omega_{pe}} \coth \frac{\omega_{pe} d}{2c}}$
Large k	$\omega^2 = \omega_{pe}^2 / 2$	$\omega^2 = \omega_{pe}^2 / 2$
Large k (thermal)	$\omega^2 = \omega_{pe}^2 / 2 + 3v_e^2 / 2$	$\omega^2 = \omega_{pe}^2 / 2 + 3v_e^2 / 2$
Electrostatic	$\omega^2 = \omega_{pe}^2 \left(\frac{\coth kd/2}{\coth ks + \tanh kd/2} \right)$	$\omega^2 = \omega_{pe}^2 \left(\frac{\tanh kd/2}{\coth ks + \tanh kd/2} \right)$
Electrostatic small k	$\omega^2 = \frac{2s}{L} \omega_{pe}^2 = \omega_{sr}^2$	$\omega = k\sqrt{sd\,\omega_{pe}^2 / 2}$





A Better Model

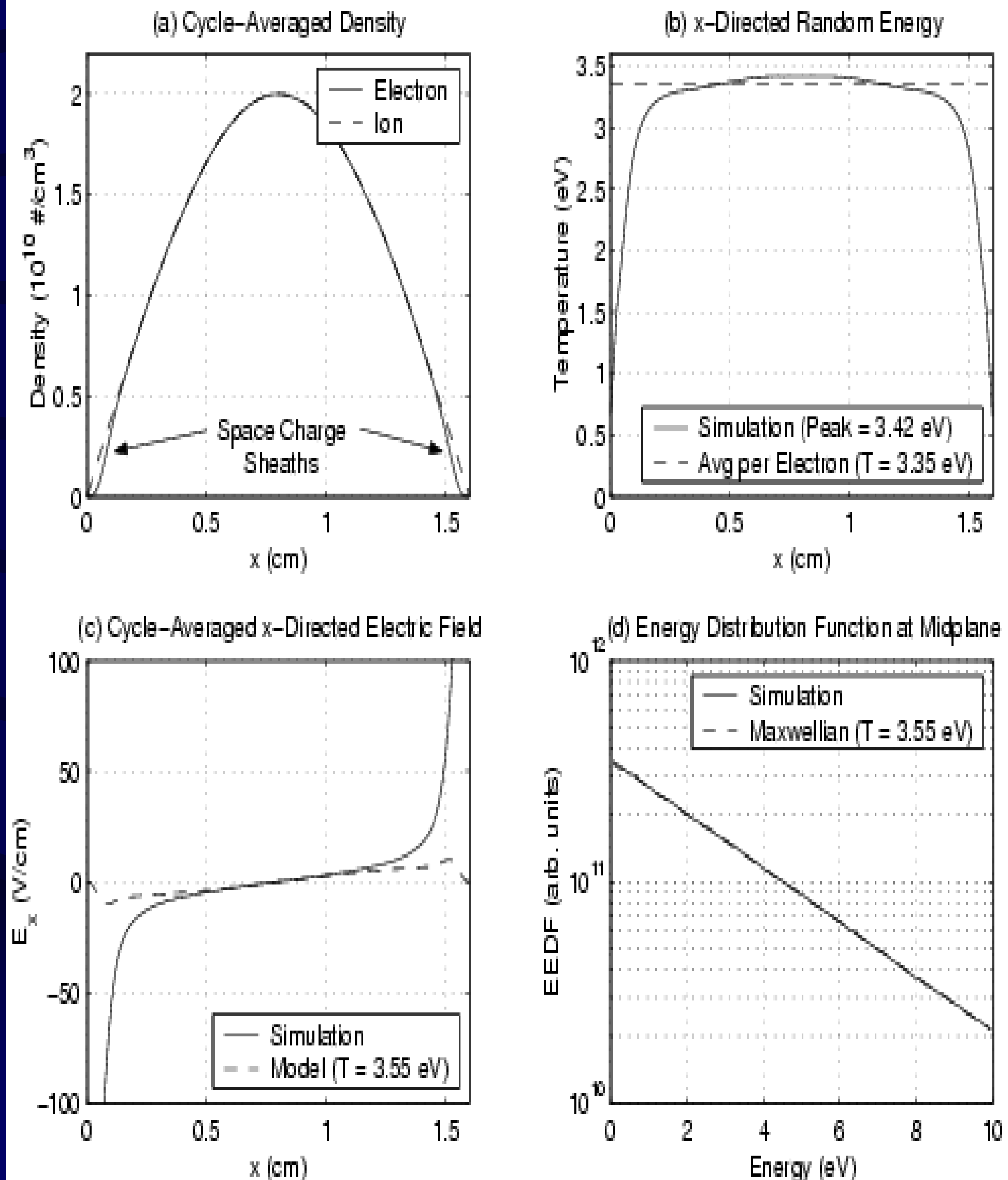
$$\hat{\varepsilon}_p = 1 - \frac{\omega_{pe}^2 f}{\omega(\omega - j\nu_m)} + \frac{\gamma_e v_{te}^2}{\omega(\omega - j\nu_m)}\nabla(\nabla\cdot[\,]) - \frac{v_{te}^2}{\omega(\omega - j\nu_m)}(\nabla \ln f)(\nabla\cdot[\,])$$

Cold Plasma Dielectric $\quad$ e^- Pressure $\quad$ Non-Uniformity

- Warm Non-Uniform Plasma Model
  - Linearized fluid theory. Uniform temperature. Ideal equation of state. Stationary ions. Model is expressed as a dielectric operator above.
  - Model first used to explain Tonks-Dattner resonances by Parker, Nickel and Gould (1964).
  - Captures thermal effects but not wave-particle effects.
  - Prior works were electrostatic and only could solve for plasmas a few tens of Debye lengths long
  - The thermal terms avoid singularities where the wave frequency matches local plasma frequency

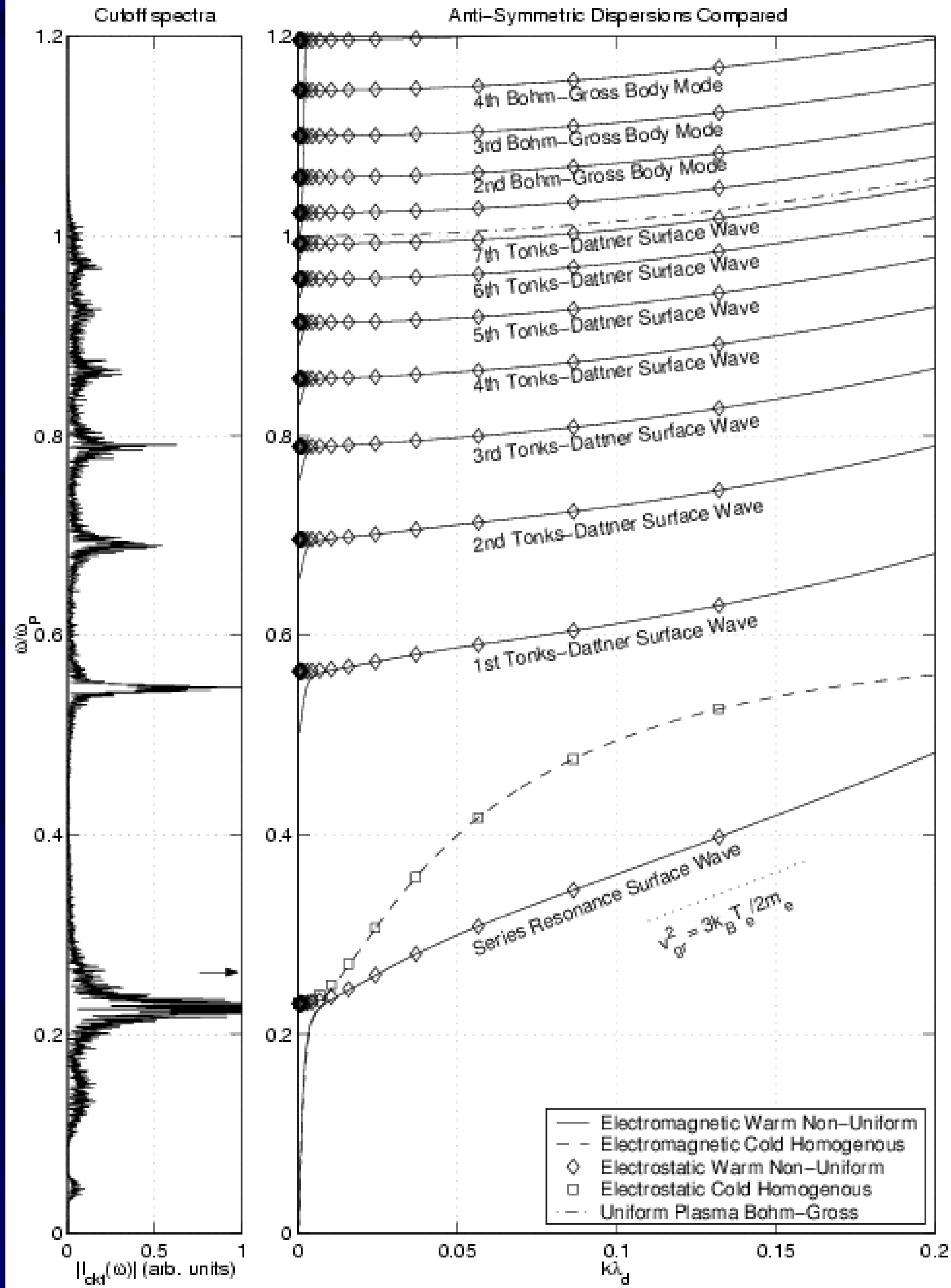
Modeling Results

- This profile is used for the results to follow
- Profile was obtained from an XPDP1 simulation of Tonks-Dattner resonances



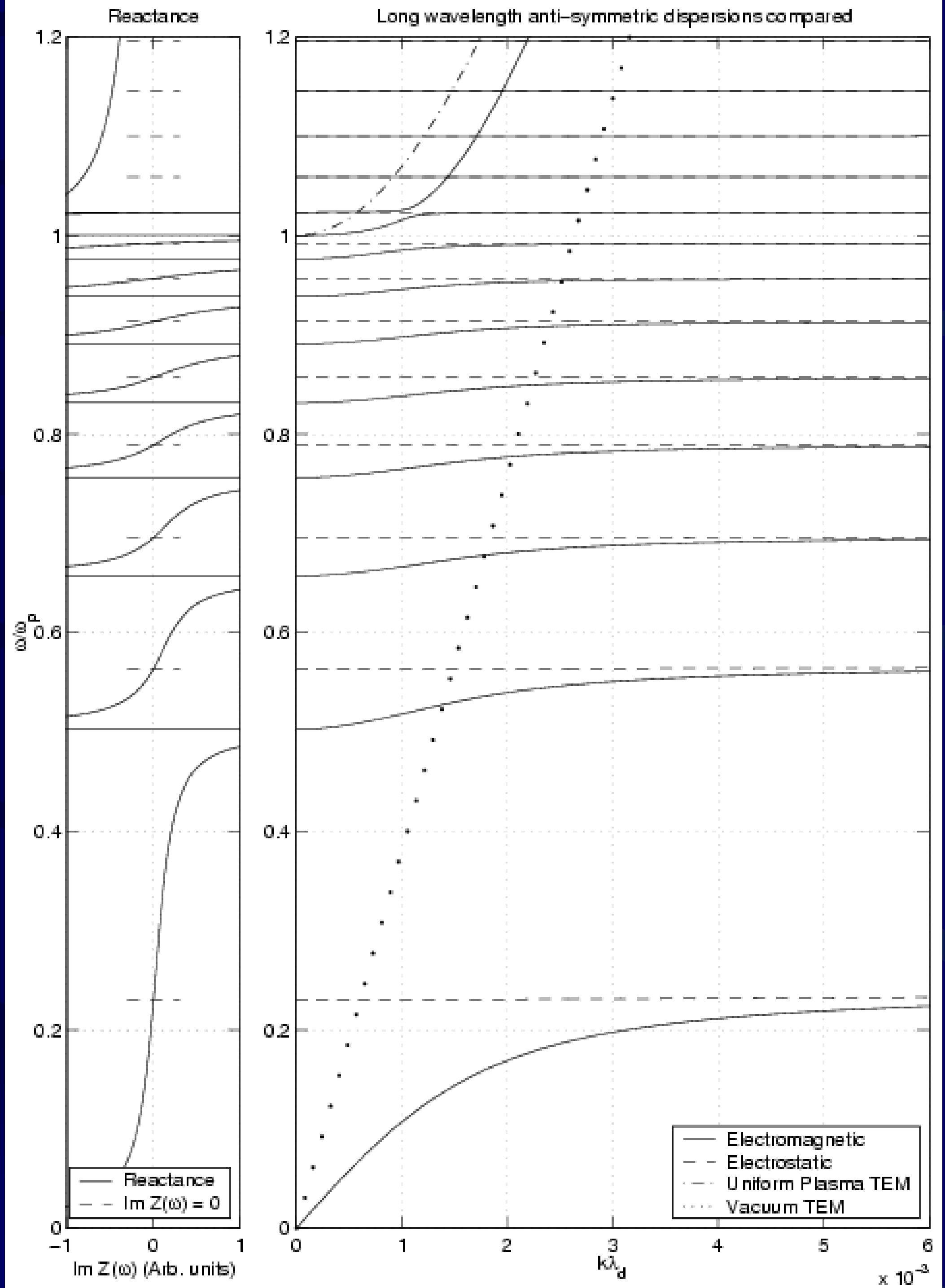
Anti-symmetric Results

- Cutoffs are Tonks-Dattner resonances
  - Agree within 5%
  - Series resonance wave very accurate
- "Knee" in the electromagnetic dispersion
- Bohm-Gross modes
  - Heavily Landau damped in the sim but not in the model



Closeup of “Knee”

- Only anti-symmetric modes exhibit this behavior
- Electromagnetic cutoffs are at poles in slab impedance
- Electrostatic cutoffs are at zeros

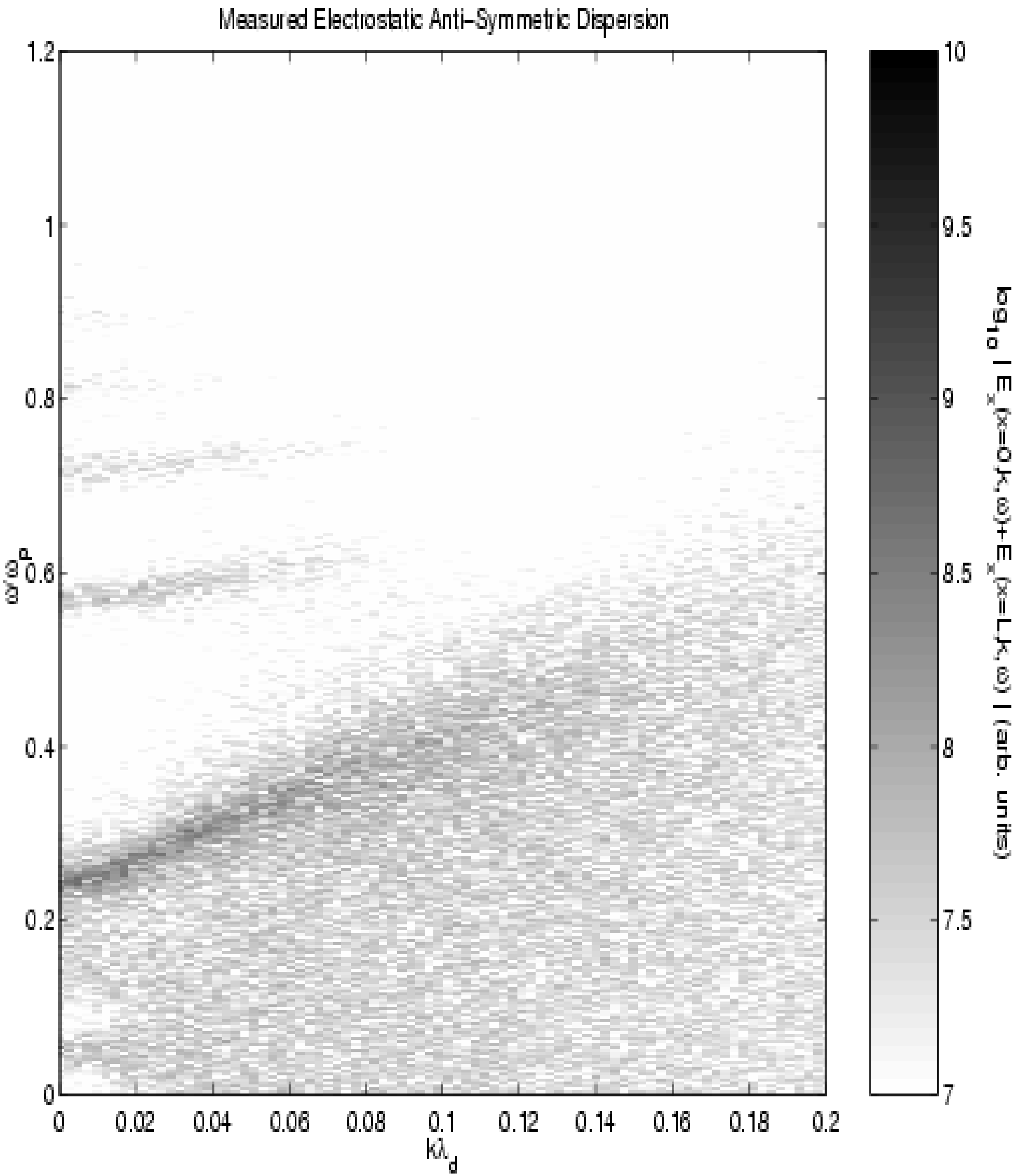


Discussion

- "Knee" was unexpected
  - Mathematically, knee is necessary to keep the magnetic field finite when no surface charges are added to the walls by plasma or external circuits (hence cutoffs at device Z poles).
  - Electrostatic model has no magnetic field, so there is no knee.
  - Electromagnetic model distinguishes between natural modes and modes driven by an external circuit (driven modes act similar to electrostatic model).
  - Theoretically, due to how charge continuity enforced.
  - Wave modes become TEM-like near knee.
- 1st Principles PIC Simulations confirm the "Knee"
  - 2d3v EM-PIC simulation of ~1 meter of plasma loaded parallel plate waveguide (tens of million of particles for tens of thousands of steps on home comp 6 yrs ago)
  - FDTD-EM solver that eliminates mesh Courant condition and damps transverse radiation PIC noise without altering charge conservation properties developed (~150X faster)
  - Cache optimal PIC techniques also developed (~1.5-2X faster)

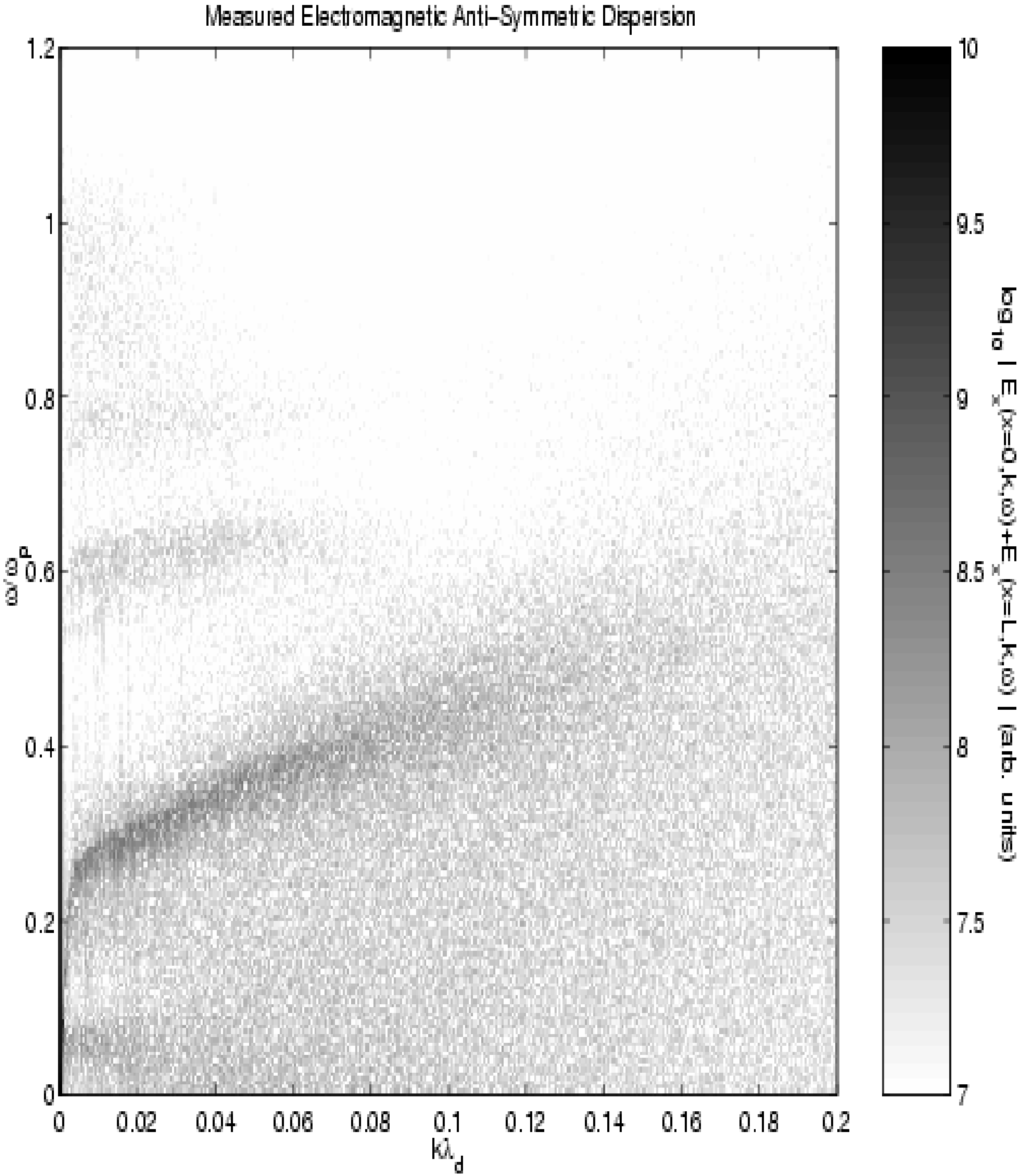
ES Simulation

- Series resonant surface wave and Tonks-Dattner surface waves visible



EM Simulation

- Knee clearly visible
- Simulation would not be feasible without implicit FDTD EM solver



Landau Resonant Heating

Early Observations

Overview

Traveling Waves

Standing Waves

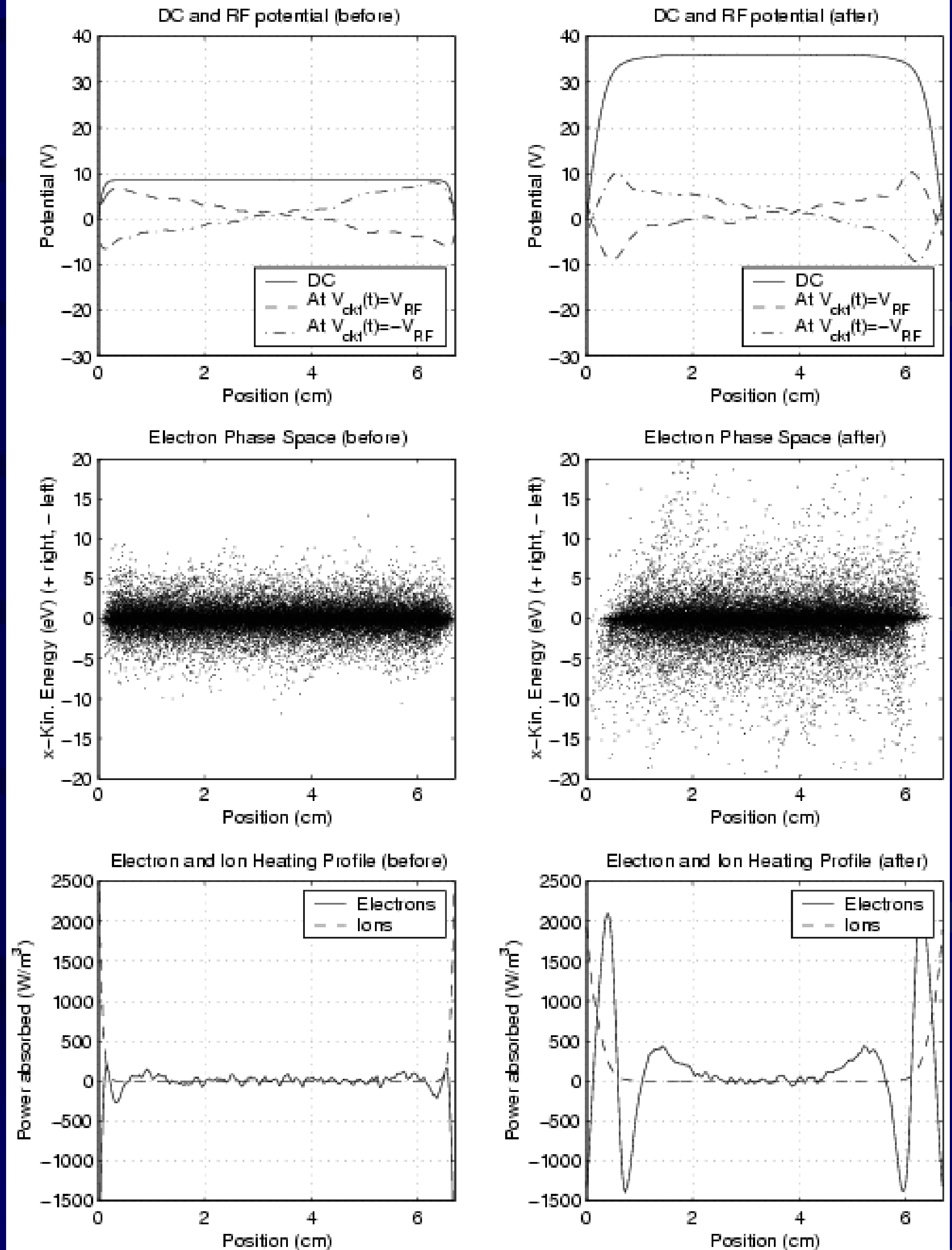
Reaction Enhancement

Bohm-Gross Demonstration

Surface Wave Demonstration

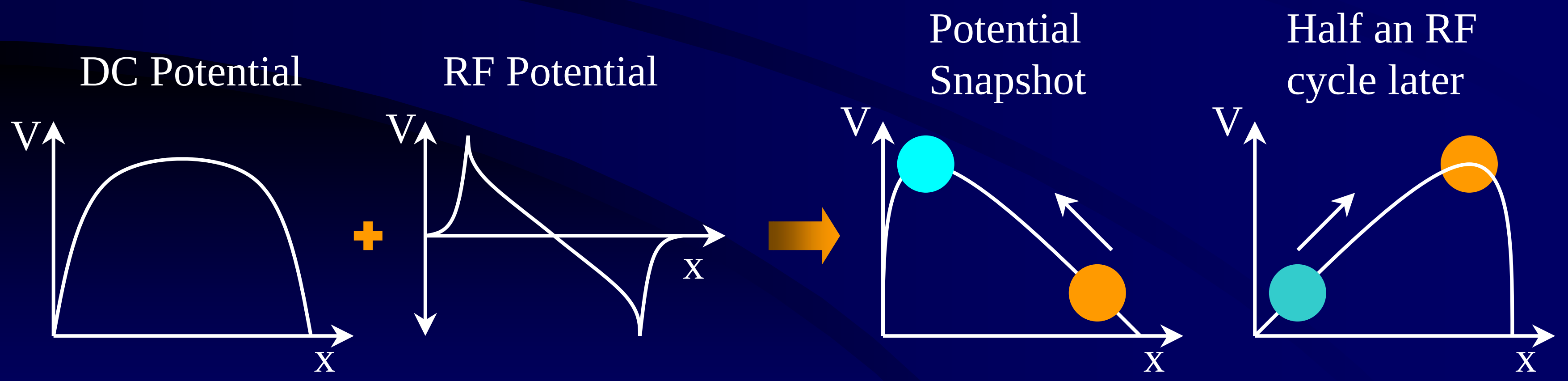
Resonant Discharge

- Unique Heating Mechanisms Observed in Simulations of Discharges Sustained at Cutoff of the Series Resonant Surface Wave Mode



Phase Space Bunching

- Mode potential interacts with the DC potential to form bunches of electrons.
- Half an RF cycle later, bunches are accelerated out of the sheaths
- What other heating mechanisms could surface waves exploit …

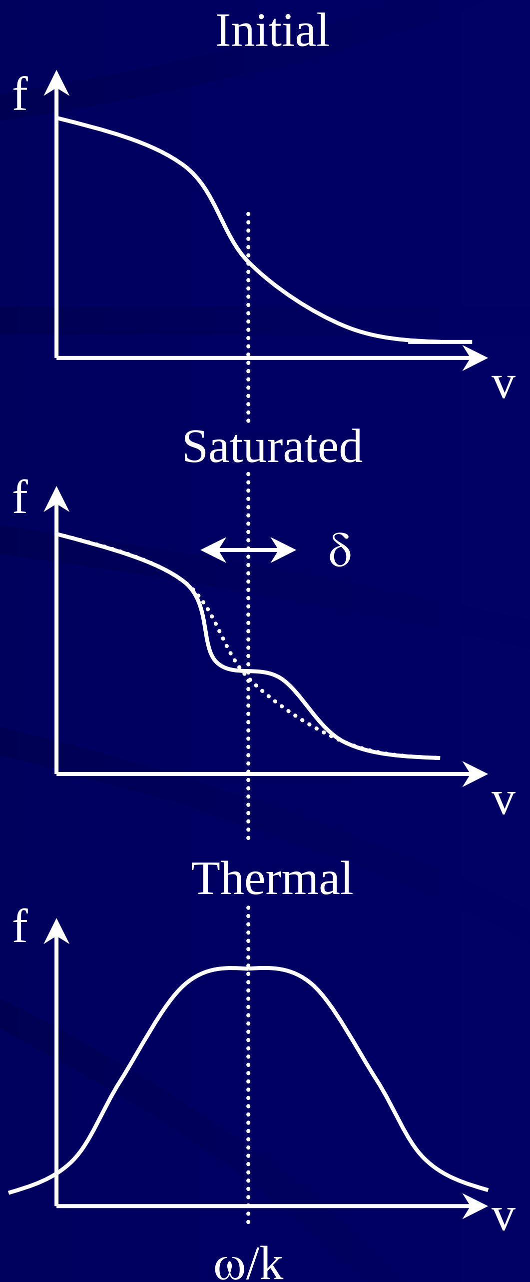


Landau Damping Overview

- Predicts that for monotonically decreasing EEDFs, a slow longitudinal wave will be damped from wave-particle interaction
  - Particles moving just below (accelerated) the wave phase velocity gain (lose) energy.
  - In linear stage, damping is exponential
  - In non-linear stage, particles trapped in wave potential wells phase mix (interesting …)

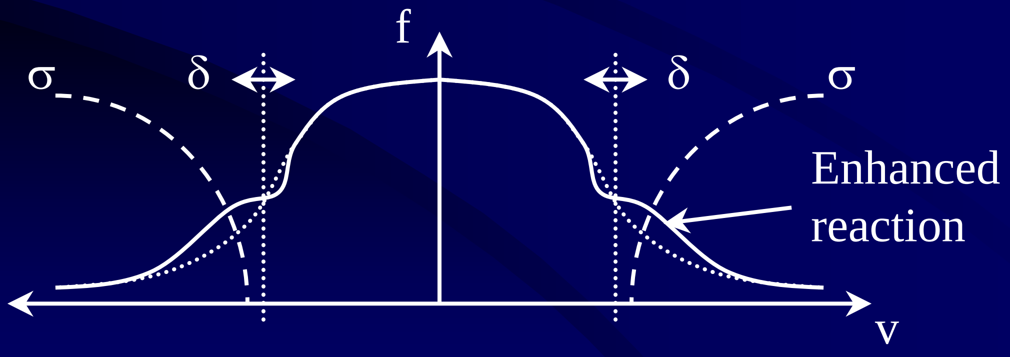
Landau Heating - Driven Traveling Wave

- If a wave is applied such that it does not damp, a non-thermal quasi-equilibrium will be established
- Saturated state reached after several Landau bounce times
  - Bounce time: $\tau = \sqrt{4\pi^2 m_e / ek^2 V_0}$
  - Plateau width: $\delta = \sqrt{16 eV_0 / m_e}$
- Thermal equilibrium usually not reached in effectively collisionless systems.



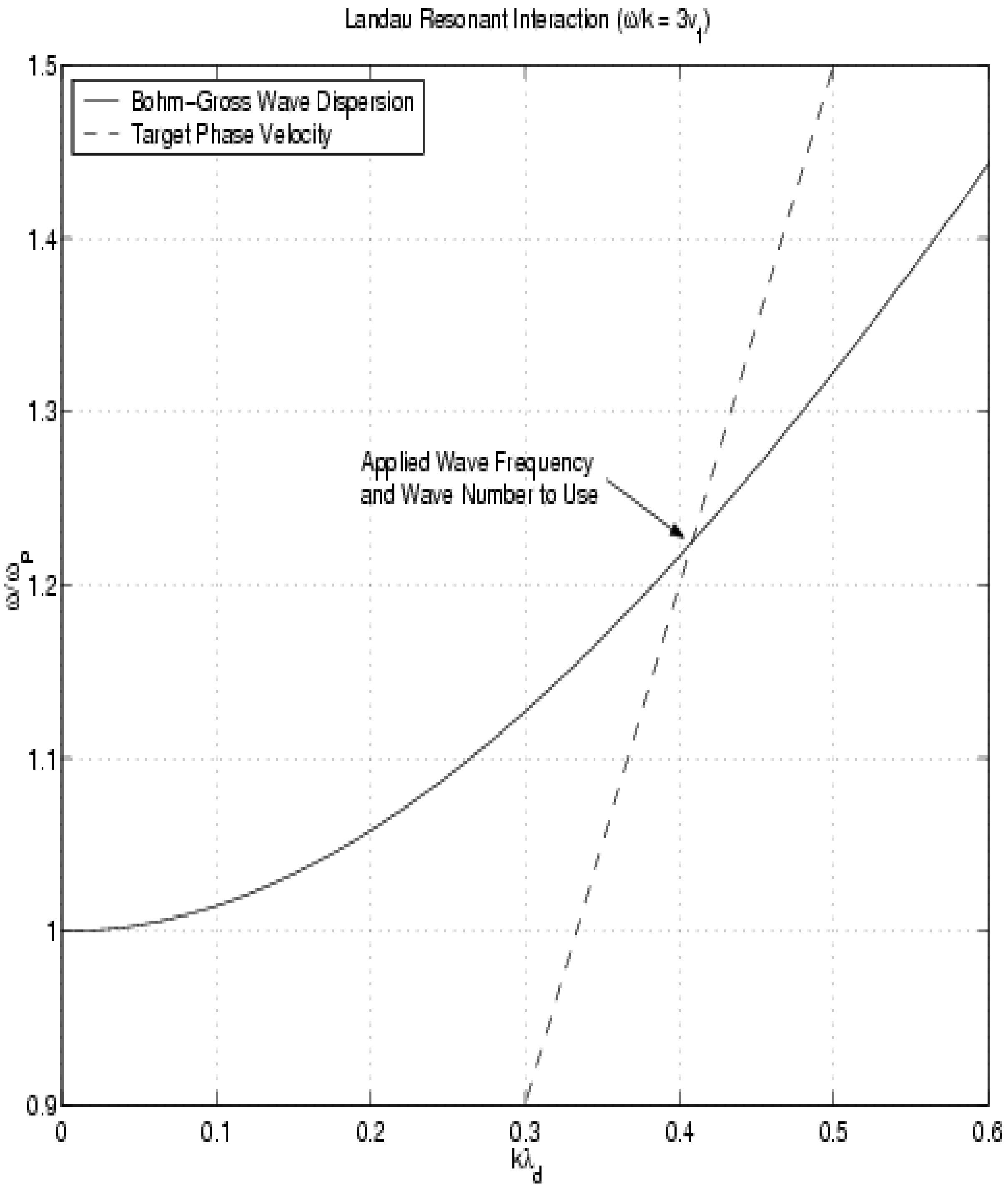
Landau Heating – Driven Standing Wave

- A standing wave consists of two oppositely directed traveling waves; each wave creates a (smaller) plateau
- No thermal equilibrium; the applied wave potential is time varying in all frames
- Reactions driven by electrons in the tail of the distribution function will have the reaction rate modified
- Landau Resonant Heating: If driven wave is resonant with natural plasma waves, plateau can be enhanced



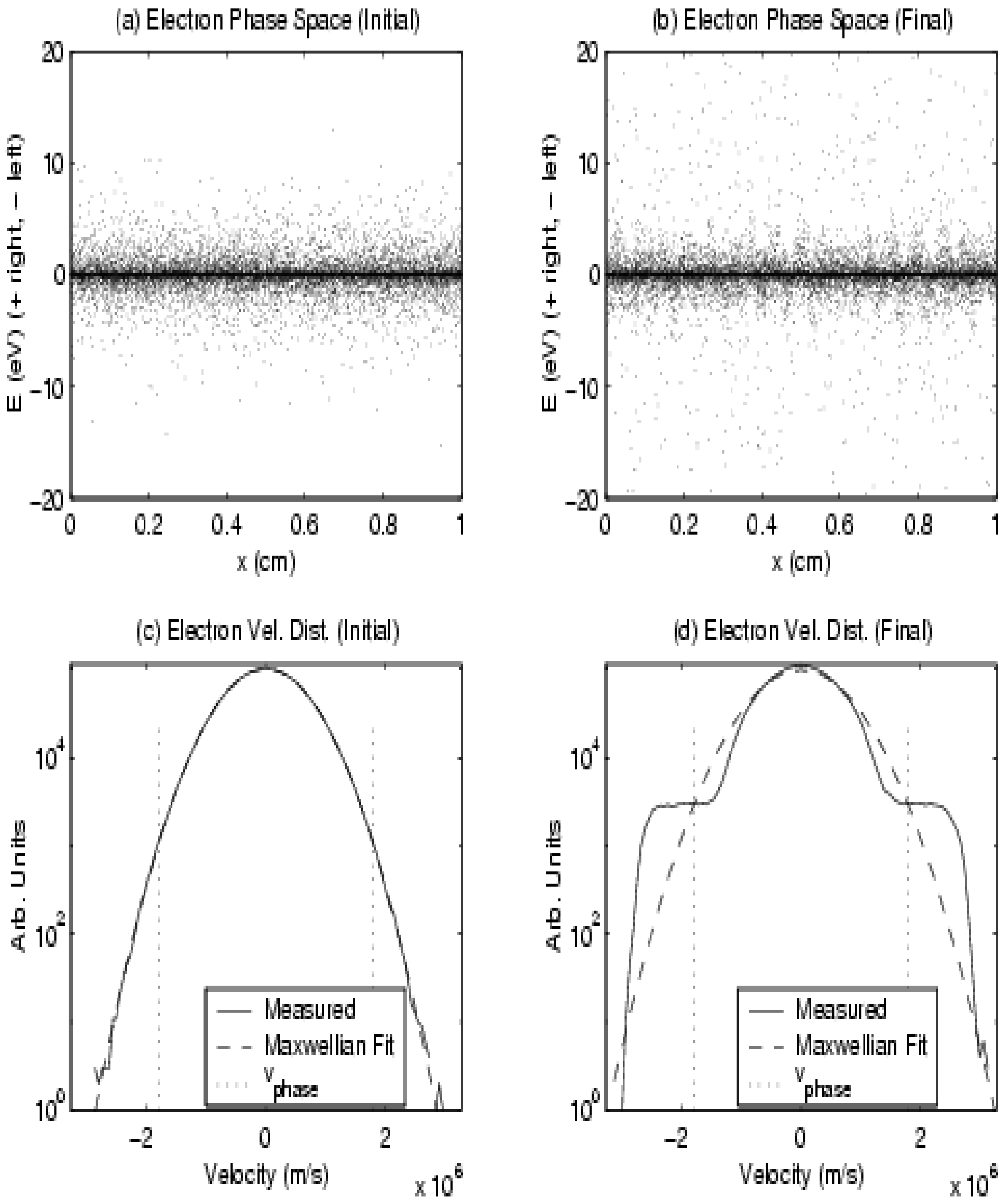
Bohm-Gross LRH Sim

- Plasma properties
  - $n_0 = 0.745 \times 10^{11}\ cm^3$
  - $T_e = 2eV$
- Interaction Point
  - $v = 3v_{th}$ ($E = 9T_e$)
- Wave properties
  - $f_{wave} = 3.00GHz$
  - $\lambda_{wave} = 0.588mm$
  - $V_{applied} = 0.2V$



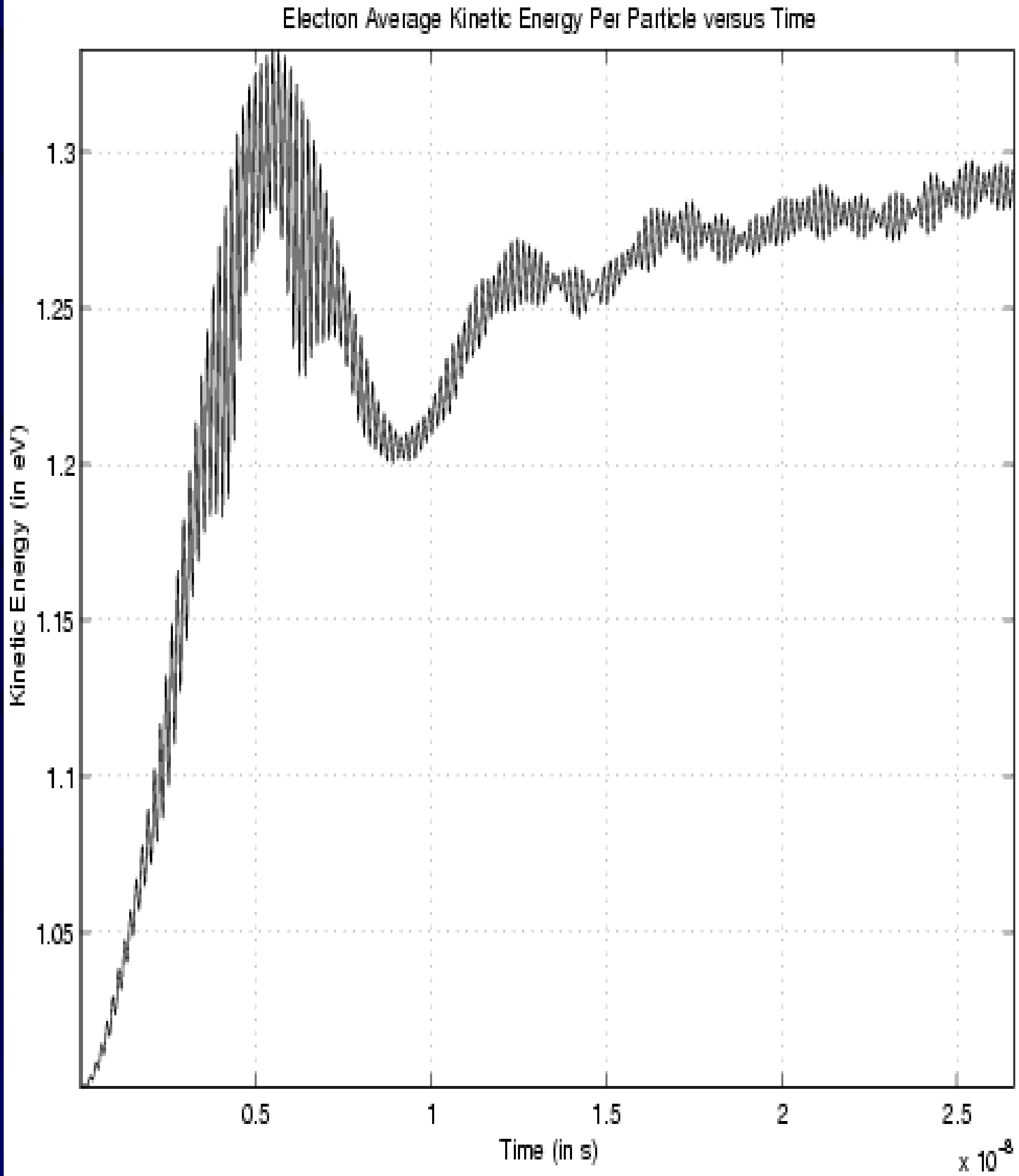
Before and After

- Nearly 100X enhancement of hot electron population at some energies
- Plateaus are much wider than the applied 0.2V



Electron Heating

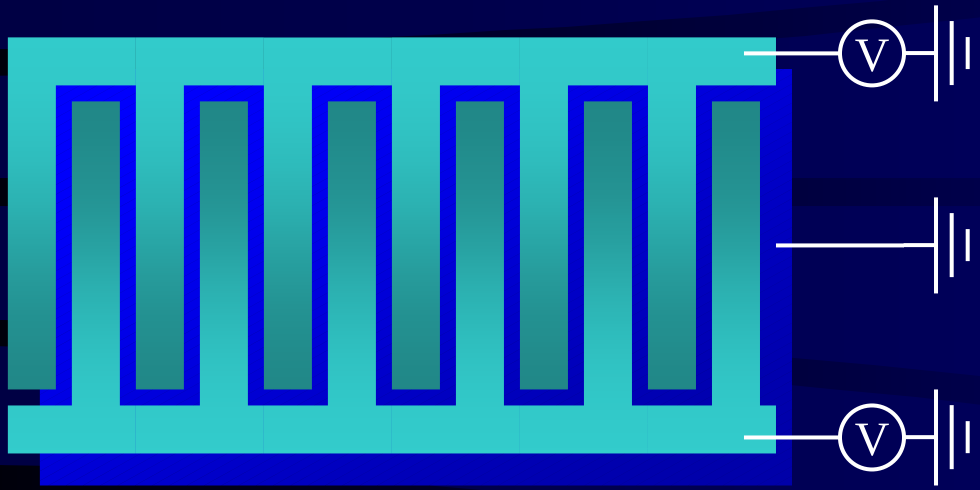
- Plateaus form and heating saturates in several hundred plasma oscillation times.

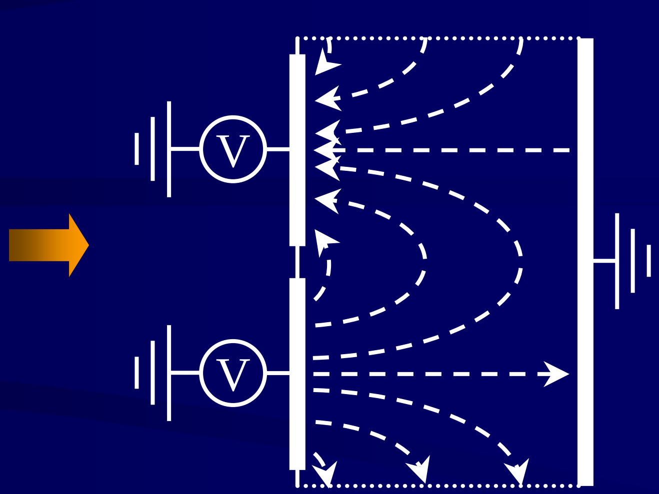


Demonstration with Series Resonant Surface Wave

- Series Resonant Surface Wave is ideal wave to use for Landau Resonant Heating in a practical device
  - Easy to excite with antennas / slow wave structures as its fields are edge concentrated
  - Mode cutoff is not dependent on thermal effects
- Goal: Enhance electron-impact ionization over a comparable non-LRH discharge
  - Background Gas: Argon (p = 3 mTorr, E_{iz} = 15.76 eV)
  - Plasma density: ~ 10^{10} / cm^3, width 3 cm
  - Initial electron temperature: 2eV (λ_{de} = 105 μm)
  - Target phase velocity: $v_{ph} = (2E_{iz}/m_e)^{1/2} = 2.35 \times 10^6$ m/s
  - Electrode: f = 315 MHz, λ = 0.75 cm, $V_{applied}$ = 10V

Device and Simulation Model

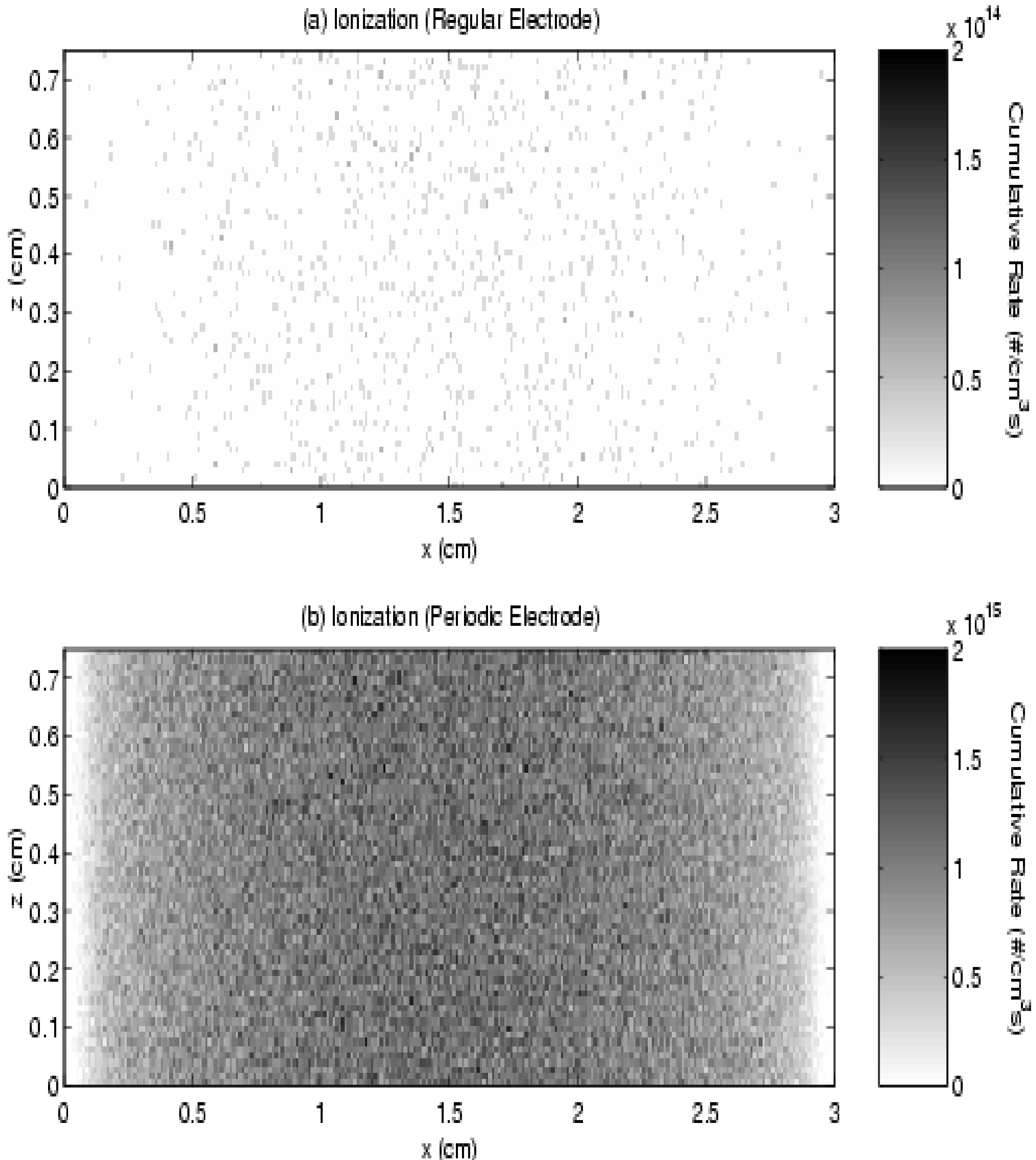




- 2d3v PIC-MCC simulation
  - Monte-Carlo collision package for atomic physics
- Non-LRH simulation operates structure at 0º phase difference between teeth (that is, a parallel plate capacitive discharge).
- LRH simulation operates structure at 180º phase difference between teeth.

Results

- Non-LRH simulation quickly extinguishes due to lack of ionization
- LRH simulation heats rapidly and is sustained



Conclusions

- Natural electromagnetic surface waves exhibit new phenomenology at long wavelengths (“knee”)
- Landau Resonant Heating permits the manipulation of the particle velocity space distribution functions.
- Surface waves may be used in conjunction with Landau Resonant Heating to manipulate the electron velocity space distribution function in order to modify electron reaction rates

Acknowledgments

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