Modelling of dual-frequency capacitive discharges

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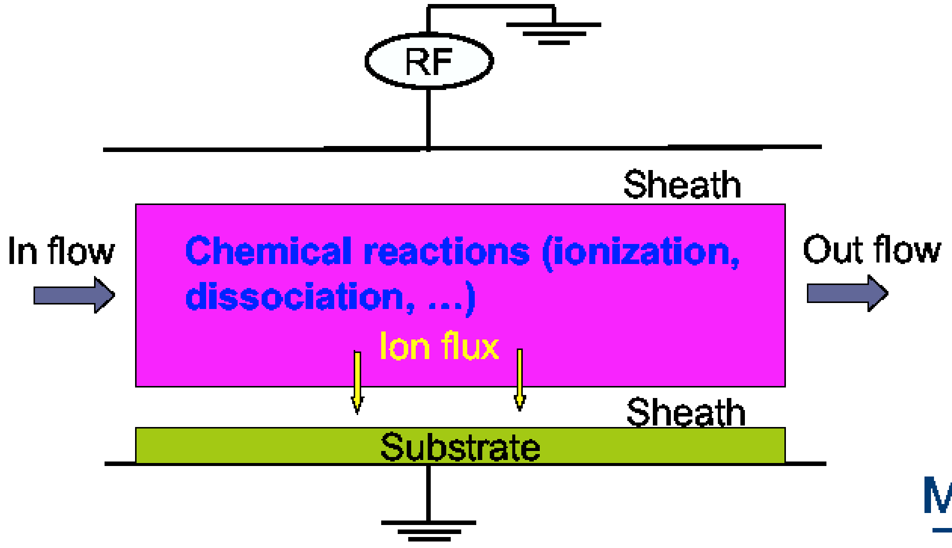
Towards simple models for multi-frequency discharges

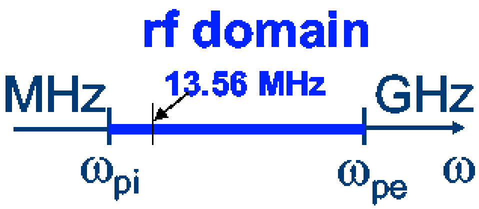
- Capacitive discharges dominated by sheath physics:
  1. Electron heating
  2. Ion acceleration
  3. Impedance
  4. Volume (very often)
- Research programme:
  1. Sheath model
  2. Electron heating model
  3. Global model

Capacitive Discharges



Plasma processing systems

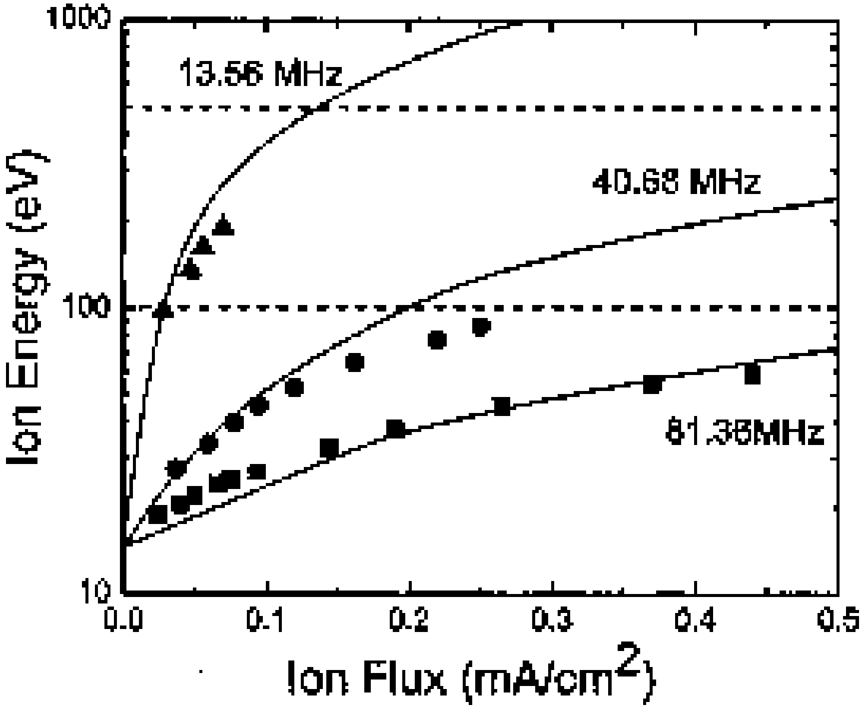
- Materials etching
- Thin film deposition



“rf domain” ⇒ Time independent ion flow, Boltzmann electrons

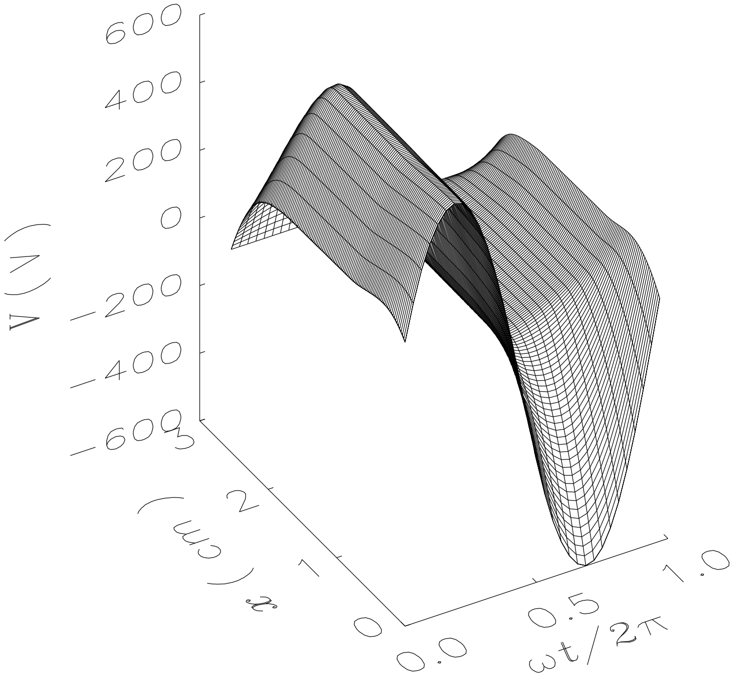
Capacitive Discharges

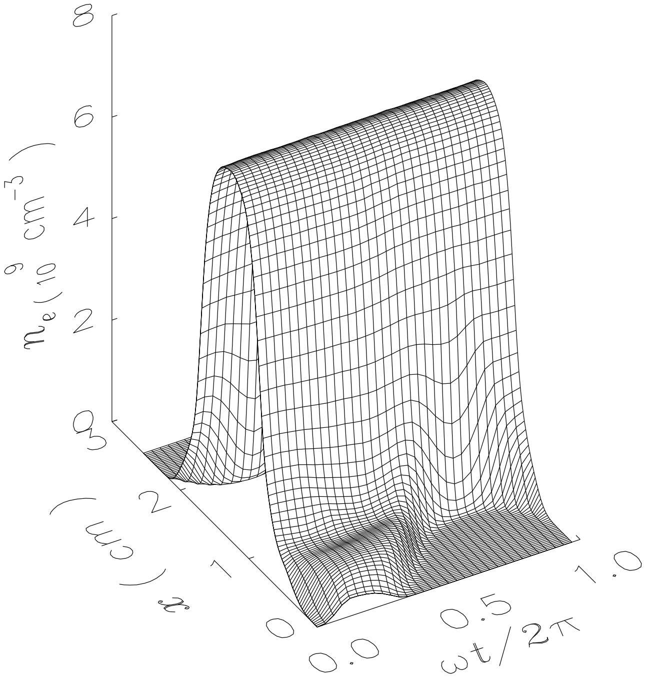
- Key parameters in most processes:
  1. Ion flux
  2. Ion energy
  3. Neutral radical flux
- Ion flux and energy related
- Relationship depends on frequency
- Two frequencies → much greater freedom



A Perret *et al*, Appl. Phys. Lett. 86, 021501 (2005)

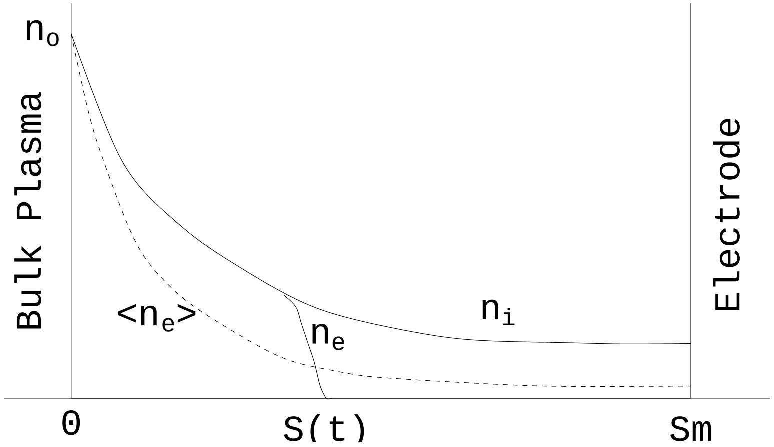
Capacitive Discharges: General Character





Sheath Model: What are we trying to understand?

- Parameters: $\tilde{J}_l, \tilde{J}_h, \omega_h, \omega_l, T_e, n_0$
- Results: $n_i(x), n_e(x,t), \Phi(x,t), s(t)$



Sheath Model: Technicalities

- Assume sheath adjoins semi-finite plasma with density n_0, electron temperature, T_e

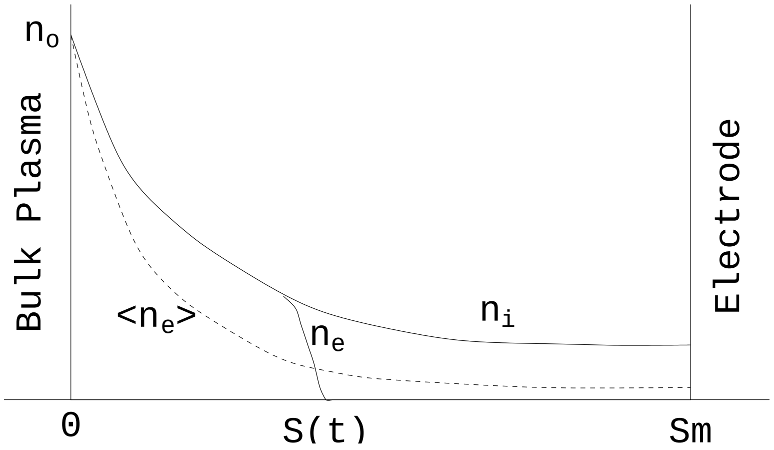
- Boltzmann electrons, time-independent ion motion

- Assume $s(t)$ is a point

  $\Rightarrow$ Sheath neatly divided into quasi-neutral and positive space charge regions

- Analytically solved for single-frequency case

  M. A. Leiberman, IEEE Trans. Plasma. Sci. 18, 638 (1988)

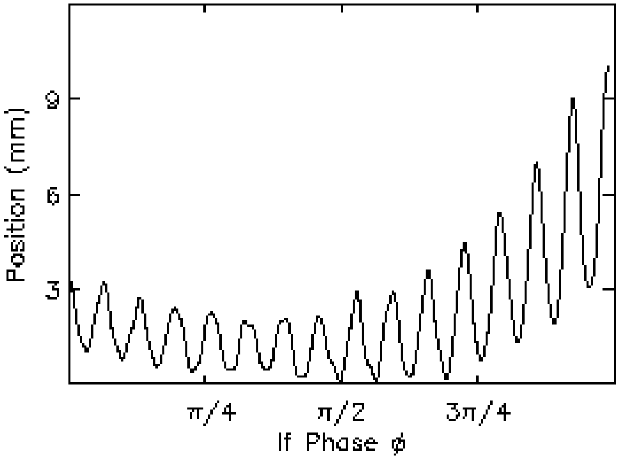


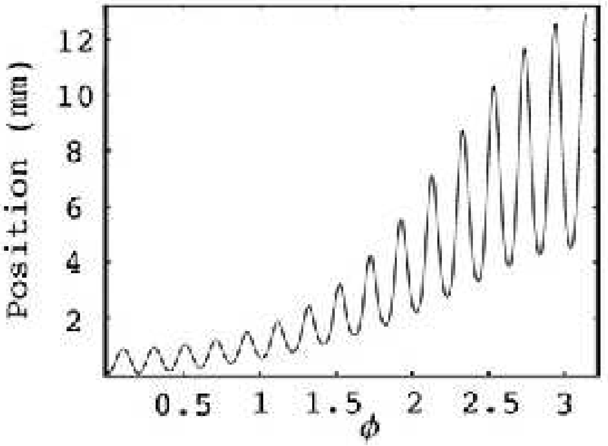
Robiche Sheath Model

- $J(t) = -\tilde{J}_h \cos\omega_h t - \tilde{J}_l \cos\omega_l t$
- Parameters $H = \tilde{J}_l^2 / e n_0 \pi \epsilon_0 \omega_l^2 T_e$, $\alpha = \omega_h/\omega_l$, $\beta = \tilde{J}_h/\tilde{J}_l$.
- One simple approximation: $\tilde{E}_h \ll \tilde{E}_l$
- True when $\alpha/\beta \gg 1$

$\Rightarrow$ Solution follows the Lieberman procedure

J. Robiche *et al*, J. Phys. D 36, 1810 (2003)





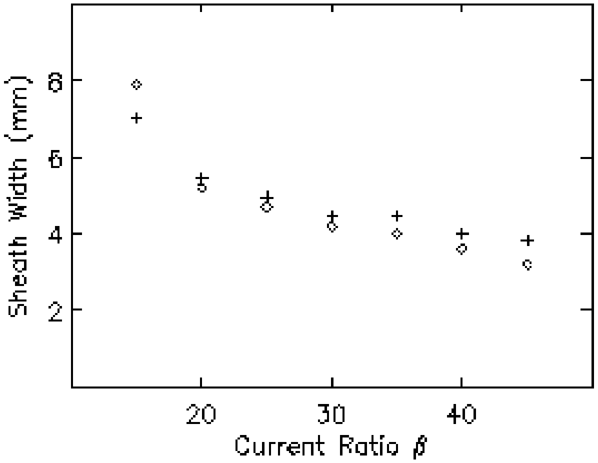
Models, Simulations, Scaling Laws

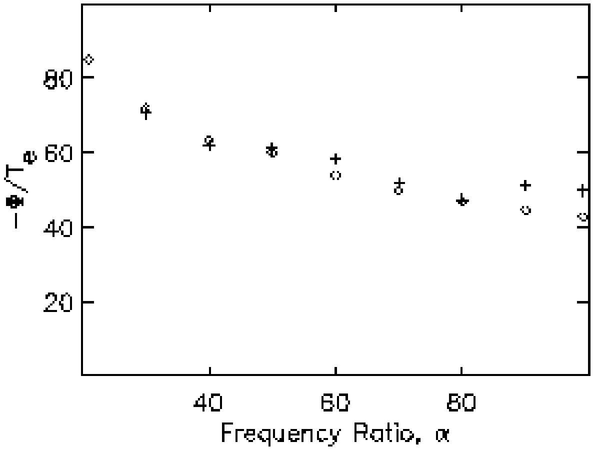
- Model agrees well with PIC simulations

- Scaling laws have been obtained by Franklin:

$$\begin{aligned} \frac{-\Phi_{\text{max}}}{T_e} &\sim \frac{9\pi^2H^2}{32}+\frac{3\pi^2HI}{4}+\frac{3\pi H}{4}+I+\frac{\pi^2I^2}{2} \\ \frac{s_{\text{max}}}{s_0} &\sim \frac{10\pi H}{24}+2+\frac{2I}{H} \qquad I\equiv H\beta/\alpha \end{aligned}$$

R. N. Franklin, J. Phys. D 36, 2660 (2003)



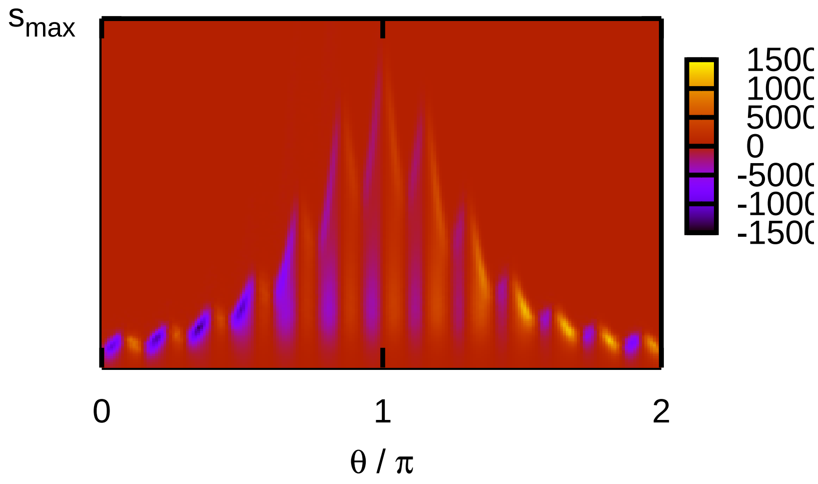


Electron heating

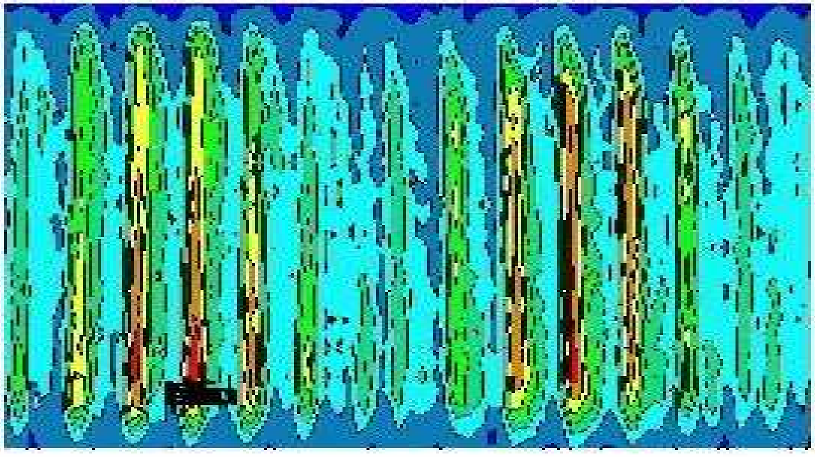
- Some mixture of stochastic and Ohmic

- Electron heating in sheath region

- Modulated by low-frequency

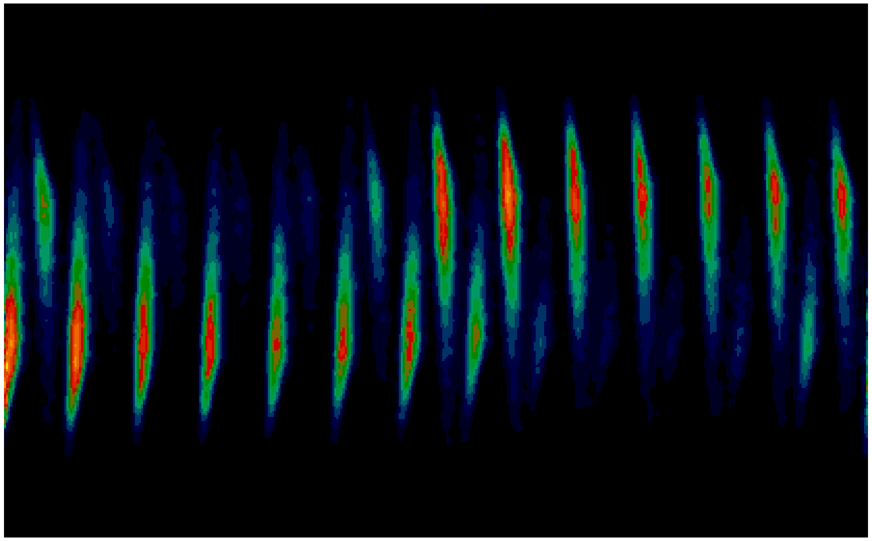


Experimental Evidence: Optical Emission



Exelan$^{\text{TM}}$ Experiment

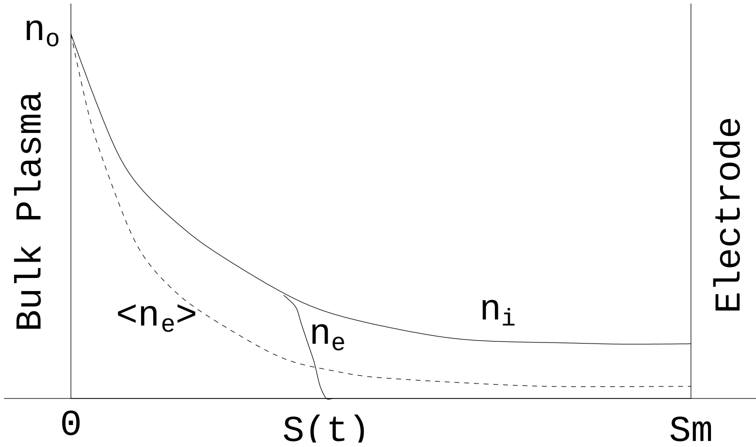
T. Gans *et al*, Appl. Phys. Lett. (submitted)



PIC Simulation

Collisionless Heating: Kinetic Moment Model

- Premise: *pressure effects*
- Fluid flow through density gradient
  $\Rightarrow$ Temperature changes
- Heat flux nonlinear function of temperature
  $\Rightarrow$ heating effect
- Calculation focuses on $0 \leq x \leq s(t)$



- Strategy:
  1. Write down moments of Vlasov equation
  2. Combine *with kinetic closure* to find temperature transport equation
  3. Assume $T(t)$, and integrate over sheath to find ODE
  4. Solve ODE with power series

- Moment equations:

$$\frac{\partial}{\partial t}\left(\frac{1}{2}nT\right)+\frac{\partial}{\partial x}\left(\frac{3}{2}nuT+Q\right)-u\frac{\partial}{\partial x}(nT)=0.$$

- Normalized ODE for T

$$\begin{aligned} & \delta_l\left[(1-\cos\theta)\frac{d\tau}{d\theta}-2\tau\ln\eta\sin\theta\right] \\ + \quad & \delta_h\left[\frac{1}{\alpha}(1-\cos\alpha\theta)\frac{d\tau}{d\theta}-2\tau\ln\eta\sin\alpha\theta\right] \\ + \quad & \tau(\tau-1)=0, \end{aligned}$$

with

$$\begin{aligned} \tau &= T/T_b \\ \theta &= \omega_l t \\ \alpha &= \omega_h/\omega_l \\ \delta_{l,h} &= \tilde{u}_{l,h}/\bar{v}_b \qquad \text{(Normalized current density)} \\ \eta &= n_s(x,t)/n_0 \end{aligned}$$

- Solution:

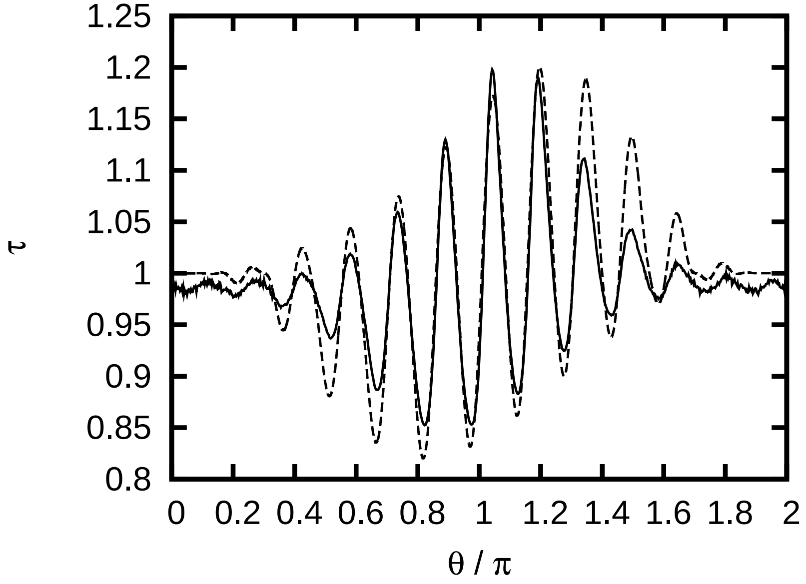
$$\tau(\theta)=1+\delta_h\tau_h^{(1)}(\theta)+\delta_l\tau_l^{(1)}(\theta)+\ldots$$

Model Results

- Analytical solution for τ agrees well with simulations
- A simple expression for the heating power follows:

  $$\langle S_{lh} \rangle \approx 2Q_b \left(\delta_l^2 + 1.1\delta_h^2\right) \frac{36H_l}{55 + H_l}$$

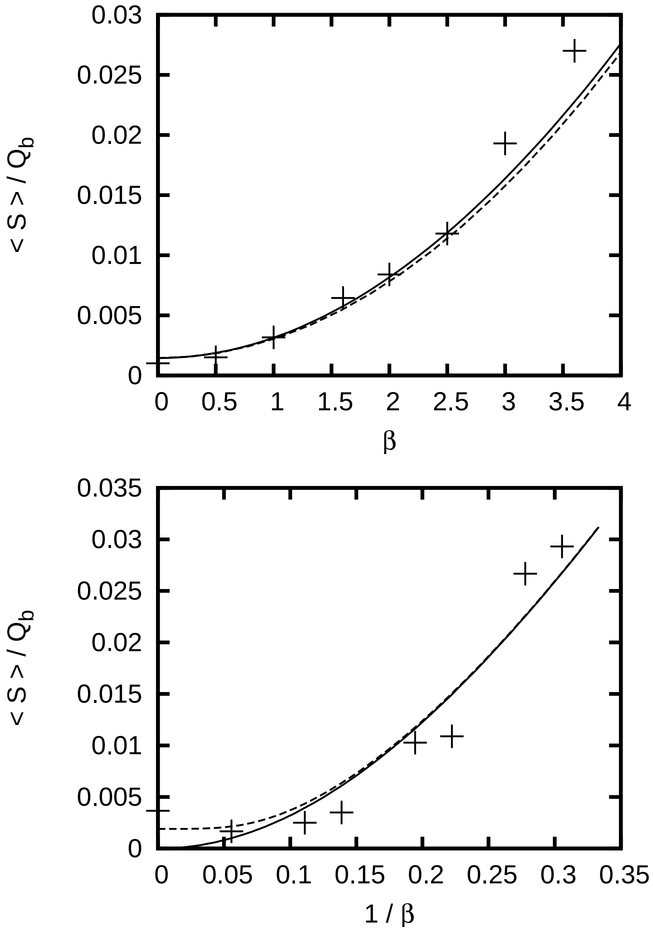
  where $H_l = \tilde{J}_l^2 / \pi T \omega_l^2 n_0$,
  $\delta_{l,h} = \tilde{J}_{l,h} / e n_0 \bar{v}_b$



Collisionless Heating: Model and Simulation

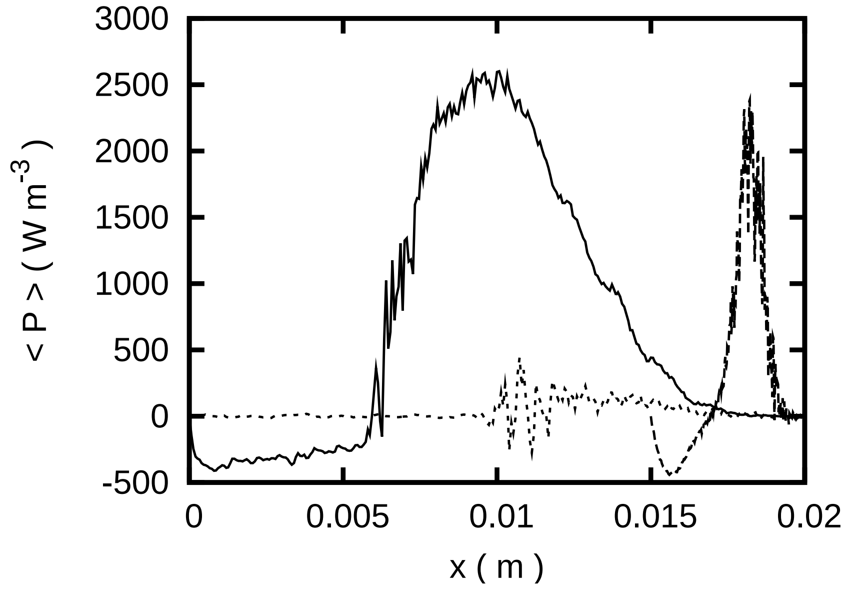
- Points—PIC
- Solid line—quadrature
- Dashed line—closed expression
- Heating strongly influenced by $\tilde{J}_l$

M. M. Turner and P. Chabert, Phys. Rev. Lett. 96, 205001 (2006)



Collisionless heating: Interpretation

- $\tilde{J}_l$ dominantly affects sheath structure
- Volume of sheath increases
- Dynamic range of density increases



Ohmic Heating

- Generally

$$P_{\text{ohmic}} = \frac{m_e \nu_e J^2(t)}{n e^2}$$

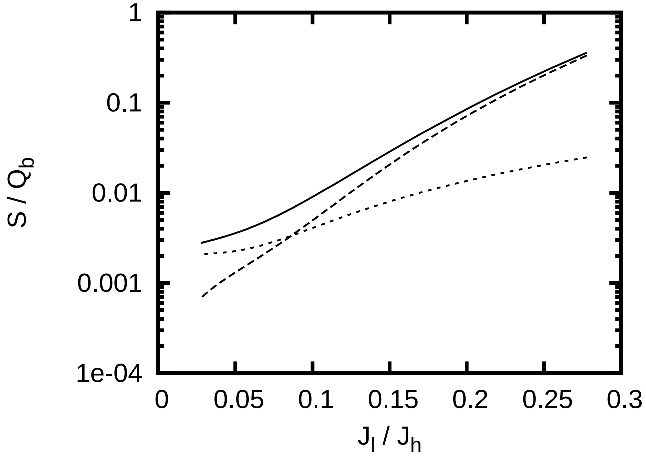
- Hence

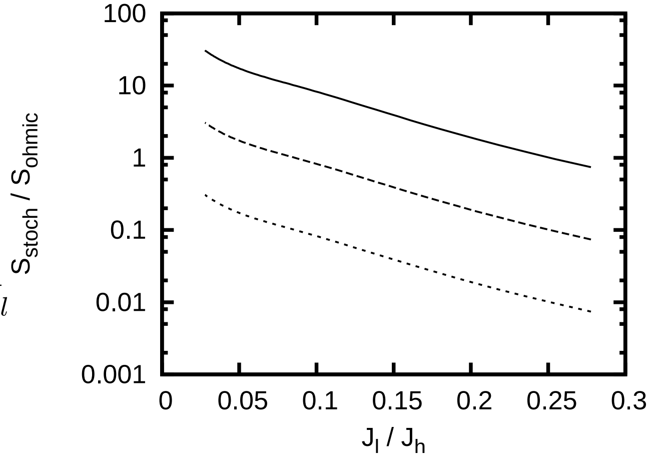
$$\begin{aligned} S_{\text{ohmic}}(t) &= \frac{m_e \nu_e J^2(t)}{e^2} \int_0^{s(t)} \frac{dx}{n(x)} \quad (1) \\ &= J^2(t) \frac{m_e \nu_e}{e^2} \int_0^{\phi(t)} \frac{d\phi'}{n(\phi')} \frac{dx}{d\phi'} \end{aligned}$$

$$\Rightarrow \bar{S}_{\text{ohmic}} = \frac{32}{\pi} Q_b \delta_l^3 \left(\frac{\nu_e}{\omega_l} \right) F_2(\alpha, \beta, H_l).$$

where

$$\begin{aligned} F_2 \approx & \left[\frac{1}{2} \left(1 + \beta^2 \right) + \frac{1}{\pi} \left(\frac{512}{675} + \frac{32}{27} \beta^2 \right) H_l \right. \\ & \left. + \left(\frac{14912}{165375} + \frac{1336}{3375} \beta^2 \right) H_l^2 \right]. \end{aligned}$$





Global Model

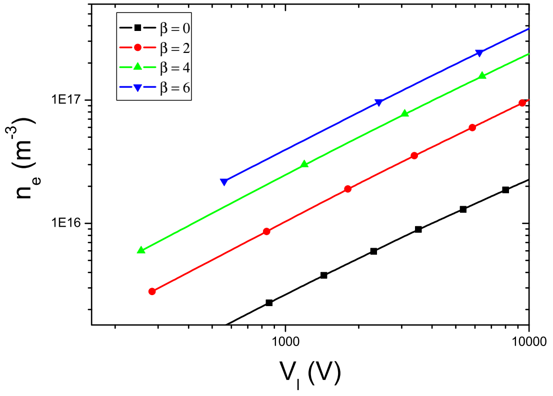
- Basic principles:

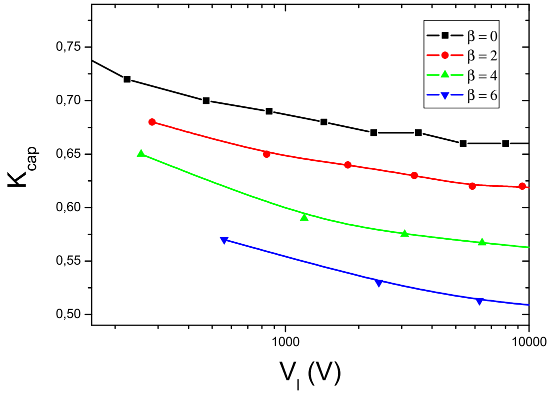
$$\begin{aligned} \text{Particle balance} &\Rightarrow T \\ \text{Power balance} &\Rightarrow n_0 \end{aligned}$$

- Control parameters N, $\tilde{J}_l$, $\tilde{J}_h$, ω_h, ω_l, L.

- Previous results for s_m, S_{stoch}, S_{ohmic}

- Predictions n_0, T, $K_{cap} = s_m C_{sym}/\epsilon_0$





Conclusions

- Sheath model agrees well with simulations
- Electron heating is a strong function of $\tilde{J}_l$
- Heating model agrees well with simulations
- Global model constructed (experimental tests pending)
- Multi-frequencies a simple extension
- Electromagnetic and resonance effects still to be studied