## Nonlinear transport of negative ions in plasma sources

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## Spontaneous Plasma Stratification into Regions of Different Ion Composition

FOR MORE INFO...

I.D. Kaganovich, *et.al.,* Phys. Rev. Lett. **84**, 1918 (2000).
I.D. Kaganovich, Phys. of Plasmas – invited papers of APS DPP 2000, **8,** 2540 (2001).

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## Negative-ion-rich Plasmas

- **Negative-ion-rich (electronegative) plasmas are of great importance in many fields, including semiconductor manufacturing, negative ion sources, D-layer in the lower ionosphere, etc..**
- **Pulsed plasmas in electronegative gases have been shown to offer important advantage for semiconductor manufacturing. We focused on physical phenomena associated with plasma diffusion to the wall in afterglow. The possibility to predict this time is of crucial importance for plasma applications that utilise negative ions extracted from the plasma.**

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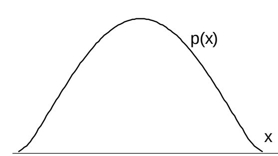
## Ambipolar Diffusion Equation

- **$p=n_e$**

$$\frac{\partial p}{\partial t} = \frac{\partial}{\partial x}\mu T_e \frac{\partial p}{\partial x}$$

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## Plasmas with Negative Ions
versus two-component plasmas

- **Two-component**
  - diffusion
  - linear
  - mixing
- **Multi component**
  - diffusion & convection
  - nonlinear
  - self-separation

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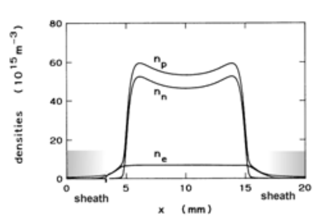
## Numerical Modeling




Gas $CF_4$
J.D.Passchier and W.J. Goedheer, J.Appl. Phys. **73** (1993) 1073

FIG. 1. Electron and ion densities at $\omega t=0$ for $p=500$ mTorr and $L=2$ cm.

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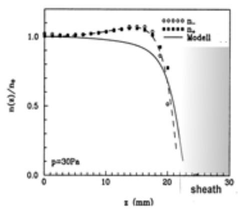
## Experimental Results




Symmetrical RF discharge CCP, P=0.21Torr, O2
U. Buddemeier, Ph.D. Thesis, 1998 Ruhr-University Bochum

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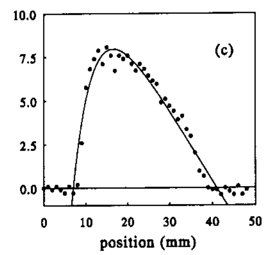
## Experimental Results




Asymmetrical RF discharge CCP, P=100mTorr, $O_2$
D. Vender et. al., Phys. Rev. E **51**, 2436 (1995)

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## Ion and Electron Densities Evolution are Described by Drift-diffusion Equations

$$\frac{\partial n}{\partial t} - \mu \frac{\partial}{\partial x}\left( T_i \frac{\partial n}{\partial x} + eEn \right) = 0 \qquad \frac{\partial p}{\partial t} + \mu \frac{\partial}{\partial x}\left( -T_i \frac{\partial p}{\partial x} + eEp \right) = 0$$

$$n_e = p - n \qquad E = -\frac{T_e}{e}\frac{d\ln(n_e)}{dx}$$

Ion mean free path is small => drift diffusion
Here, $p$, $n$, $n_e$ are positive , negative ion and electron densities,
$T_i$ , $T_e$ are ion and electron temperatures, $\mu$ is ion mobility

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## Analysis of Nonlinear Convection

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}(un) = 0 \qquad u = \mu T_e \frac{\partial \ln n_e}{\partial x}$$

negative ion velocity

$$\frac{\partial n_e}{\partial t} - \frac{\partial}{\partial x}\left(D_{eff}\frac{\partial n_e}{\partial x}\right) = 0$$

$$D_{eff}\left(\frac{n}{n_e}\right) = \frac{\mu T_e (n_e + 2n)}{n_e}$$

Electron effective diffusion coefficient

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## Final Form: Nonlinear Convection

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x} u(n) n = 0$$

$$u(n) = -\Gamma_e \frac{\mu_n}{\mu_n n + \mu_p p}$$

convective velocity is explicit function of density

$$\Gamma_e = -T_e \frac{\mu_n n + \mu_p p}{n_e}\frac{\partial n_e}{\partial x}$$

electron flux is nearly conserved in narrow negative ion perturbations

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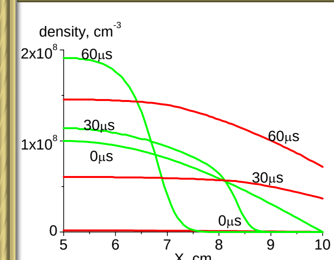
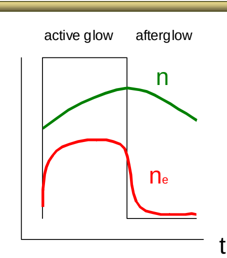
## Evolution of Electron and Negative Ion Densities in Early Active Glow




Fronts form near the n=0.

I. Kaganovich, et.al. PRL **84**, 1918 (2000).

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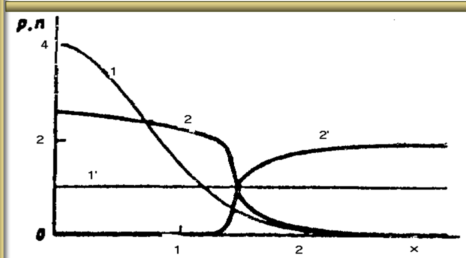
## Temporal Evolution, Self-separation of Positive Ions




1 - p(x)=4exp(-x$^2$), 2 - n(x)=1 the profiles,
1' and 2' corresponds to a time t=5,
the ratio of ion mobilities of 1 to 2 is 0.1

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## Kinetic Code for Calculation of EEDF and Plasma Parameters

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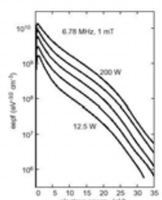
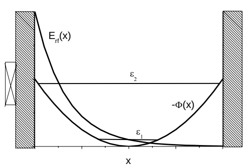
## Electron Distribution Function is not Maxwellian




**Measured EDF shows departure from a Maxwellian:**
**Cold electrons are trapped in a small rf electric field.**

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## Overview

- **Calculate nonlocal conductivity in nonuniform plasma**
- **Find a nonMaxwellian electron energy distribution function driven by collisionless heating of resonant electrons**
- **What to expect: self-consistent system for kinetic treatment of collisionless and nonlocal phenomena in inductive discharge**

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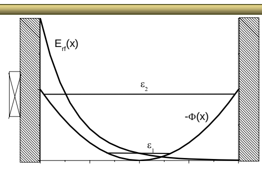
## Inductive Discharge




The transverse rf electric field is given by

$$\frac{d^2E_y}{dx^2}+\frac{\omega^2}{c^2}E_y=-\frac{4\pi i\omega}{c^2}[j(x)+I\delta(x)]$$

The electron energy distribution is given by

$$-\frac{d}{d\varepsilon}D_\varepsilon\frac{df_0}{d\varepsilon}=S^*(f_0)\,,$$

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## Bibliography

I. D. Kaganovich et al "Anomalous skin effect for anisotropic electron velocity distribution function", to be published in Phys. Plasmas (2004).

I. D. Kaganovich, et al , "Landau damping and anomalous skin effect in low-pressure gas discharges: self-consistent treatment of collisionless heating", to be published in Phys. Plasmas (2004).

I. D. Kaganovich and O. Polomarov, "Self-consistent system of equations for kinetic description of low-pressure discharges accounting for nonlocal and collisionless electron dynamics", Phys. Rev. E 68, 026411 (2003).

B. Ramamurthi, et al " Effect of Electron Energy Distribution Function on Power Deposition and Plasma Density in an Inductively Coupled Discharge at Very Low Pressures", Plasma Sources Sci. Technol. 12, 170 and 302 (2003).

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# Nonlocal Conductivity

- •PIC code is inefficient: limited by electron time step,
- •while discharge develops at ion time scale =>
  - •implicit description of the rf electric field
  - •solved by spectral method

$$J_y(x)=\frac{e^2 n_{e0}}{m}\left(\int_0^x G(x,x')E_y(x')dx'+\int_x^L G(x',x)E_y(x')dx'\right)$$

Nonlocal conductivity G(x,x') is a function of the EEDF $f_0$ and the plasma potential φ*(x)*.



# Kinetic Equation Is Averaged over Fast Electron Bouncing in Potential Well

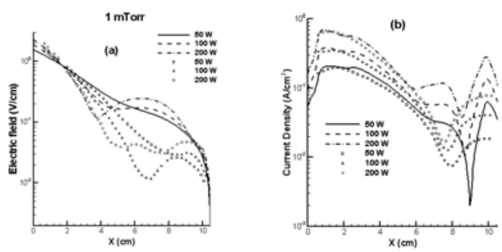
$$-\frac{d}{d\varepsilon}(D_\varepsilon+\overline{D_{ee}})\frac{df_0}{d\varepsilon}-\frac{d}{d\varepsilon}\overline{V_{ee}}f_0=\sum_k\left[\overline{\nu_k^*(u+\varepsilon_k^*)\frac{\sqrt{(u+\varepsilon_k^*)}}{\sqrt{u}}f_0(\varepsilon+\varepsilon_k^*)}-\overline{\nu_k^*}f_0\right],$$

**Energy diffusion $D_e$ coefficient is a function of the rf electric field $E_y$ and the plasma potential φ*(x)*.**

$D_{ee}$ $V_{ee}$ are from the electron-electron collision integral,
ν* is inelastic collision frequency,
upper bar denotes space averaging with constant total energy.



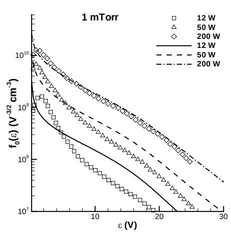
# Comparison with Experiment $\frac{c}{\omega_{ep}}<\delta<\frac{V_{Te}}{\omega}$

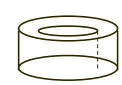



Experimental data (symbols) and simulation (lines)
(a) RF electric field and (b) the current density profiles for a argon pressure of 1 mTorr.



# Comparison with Experiment



R=10cm,L=10cm,
antenna R=4cm

**EEDF simulated (lines) and experimental data (symbols) for 1 mTorr. Data are taken from V. A. Godyak and V. I. Kolobov, *Phys. Rev. Lett.*, 81, 369 (1998).**