Recent Advances in the Theory of Low-pressure Discharges

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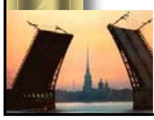

11/14/2005

Outline

May you have the hindsight to know where you've been, the foresight to see where you're going and the insight to know when you're going too far...

- **Introduction to low-pressure discharges.**
- **Nonlocal electron kinetics in low-pressure discharges.**
- **Nonlinear transport of negative ions in plasma sources.**

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Outline

- **Introduction to low-pressure discharges.**
- Nonlocal electron kinetics in low-pressure discharges..
- Nonlinear transport of negative ions in plasma sources.

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Applications of Glow Discharges

- **Plasma processing of materials**
- **Lighting**
- **Gas discharge lasers**
- **Plasmas for electric propulsion**
- **Plasmas for pollution control and reduction**
- **Plasma isotope separation**

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Plasma Parameters

- **Plasma density 10^8 - 10^{12} cm^{-3}**
- **Gas pressure few mTorr – atmosphere**
- **Small degree of ionization < 10^{-4}**
- **Electron temperature T_e - few eV**
- **Ion temperature T_i - 0.03 eV**
- **Spatial scale mm- m**

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Motivation

- ***Low temperature plasmas* are popular for technology.**
  - Most remote from thermodynamic equilibrium.
  - T_e(3eV) >> T_i (0.03 eV).
- **Parts of the EDF are very flexible and almost independent.**
  - EDF = several weakly connected populations.
  - Small degree of ionization < 10^{-4} => $\nu_{ee} << \nu_{\varepsilon}$.

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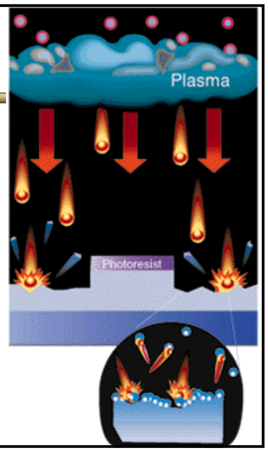
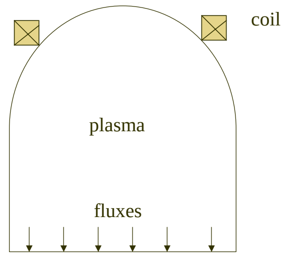
Plasma is Needed for the Etch Process



Plasma Can Produce Uniform Fluxes



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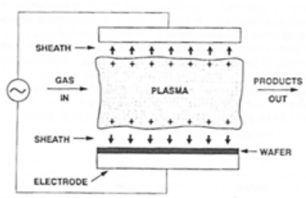
Schematic of Capacitive Discharge Plasma Reactor



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Needed Fluxes of Radicals and Ions

- **Composition**
- **Energy and angular distributions**
- **Uniformity**
- **Influence of external discharge parameters**

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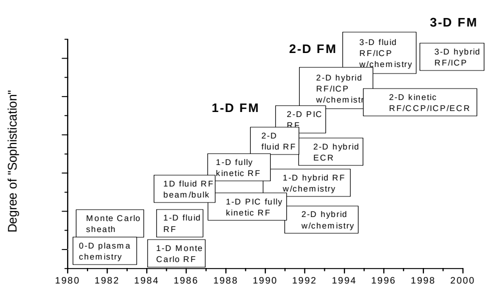
Timeline for Evolution of Plasma Equipment Models



After M. J. Kushner, Solid State Technology 1996 p.140

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Limitations in Numerical Procedures

Disparity of time scales

– **Etching**	**100s**
– **gas residence**	**0.1s**
– **ion residence**	**10^{-5}s**
– **ion residence in the sheath**	**10^{-7}s**
– **discharge voltage period**	**10^{-8}s**
– **electron residence in the sheath**	**10^{-9}s**

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Limitations in Numerical Procedures

Electric fields
- Sheath ~1 kV/cm
- Plasma ~1 V/cm

Spatial scales
- Debye radius ~ 10^{-3} cm
- Plasma slab ~ 10cm

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Is There Any Interesting Physics to Discuss

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Is There Any Interesting Physics to Discuss?

Yes!
Electron Energy Distribution Functions (EEDF)

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Outline

- Introduction to low-pressure discharges.
- **Nonlocal electron kinetics in low-pressure discharges.**
- Nonlinear transport of negative ions in plasma sources.

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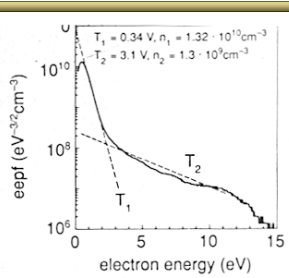
Non-Maxwellian Electron Energy Distribution Functions



2. The EEPF (lower) and normalized EEDF (upper), , obtained for p =0.1 Torr and I_d =0.3 A rms.

FOR MORE INFO...

V.Godyak R.Piejak PRL **65** 996
Argon 0.1Torr, f=13.56 MHz, L=2cm

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EEDF Can Drastically Change for Different Discharge Conditions

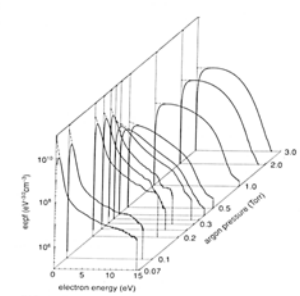

FIG. 3. The EEPF evolution with changing argon pressure, I_d =0.3 A rms.

FOR MORE INFO...

V.Godyak R.Piejak PRL **65** 996
Argon 0.1Torr, f=13.56 MHz, L=2cm

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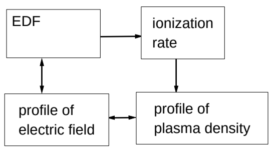
Why to Care About EEDF ?



"Heart-Body"= EEDF-Discharge

EEDF engineering = "Heart Surgery"

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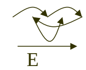
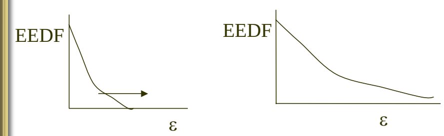
Mechanism of EEDF formation: Heating



Elastic collisions with mean free path λ =>
Random space diffusion yields =>
Diffusion in energy with energy kick eEλ



Diffusion in energy leads to heating

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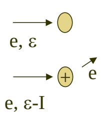
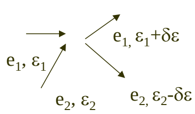
Mechanism of EEDF formation: cooling and mixing



Cooling is due to energy losses in inelastic collisions.



Mixing is due to electron-electron collisions.

It is the only mechanism to make EEDF a Maxwellian!

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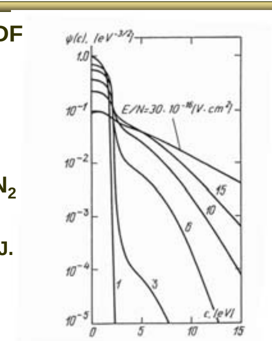
EEDF: stationary uniform E/P

1930 Druyvesteyn's EEDF for λ constant.

f~exp($-\varepsilon^2/\varepsilon_0^2$)

Real cross-sections in N_2

N.L. Alexandrev, et.al. Sov. J. Plasma Phys. 1978



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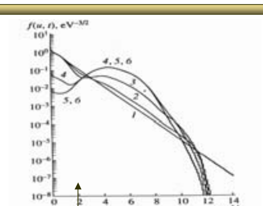
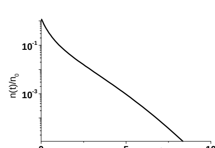
EEDF in decaying plasma



Strong energy losses



EDF afterglow Ar:NF_3, E/N=2 10^{-17}Vcm^2

- **1, 2, 3, 4, 5, 6.**
- **0, 0.25, 1, 3, 5, 10 ns.**

N.A. Dyatko, et.al. Plasma Phys.Rep. 1998

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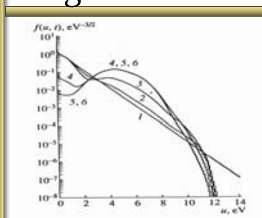
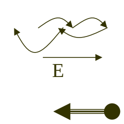
Non-monotonic EEDF yields Negative Plasma Conductivity!





Total electron flux is against the electric field

$$\mu = -\frac{2e}{3m}\int u^{1/2}\lambda \frac{df(u)}{du}du < 0$$

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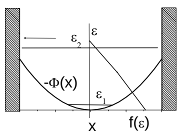
Evaporative Electron Cooling in Afterglow



In non-uniform plasmas
Low-energy electrons are trapped,
where as high-energy electrons can leave.

Electron temperature can cool to 30K! Biondi (1954)

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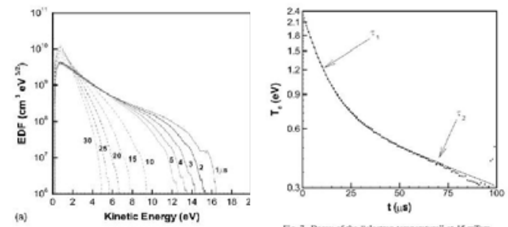
Evaporative Electron Cooling in Afterglow



Experiment: Kortshagen, et al. Appl. Surf. Sci. 192, 244 (2002)
Similar to Godyak's, but ID=14cm, L=10cm

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The Abrupt Formation of Large Population of Cold Electrons

- **Large population of cold electrons is typical in various glow discharges.**
- **"Paradoxical" electron cooling with power increase.**
- **Plasma density jumps.**

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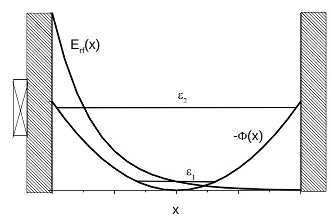
Cold Electrons: Explanation

- **Necessary conditions:**
  - **Non-locality**
  - **Non-linearity**



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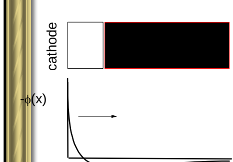
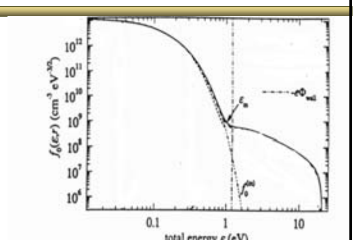
Cold Electrons in DC Discharge





Cathode fall

He 3.5 Torr, 0.85mA/cm², 260V, 0.62cm
Exp.: T_e=0.12eV
E.A. Hartog et. al. PRL 1989
Model.: R.Araslanbekov, A.Kudryavtsev PRE 1998

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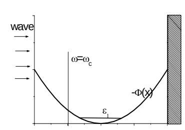
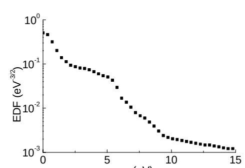
Cold Electrons in ECR discharge





Electron cyclotron resonance discharge

- **N_2 1mTorr, 0.14W/cm², 50cm**
- **Exp.: N. Bibinov et.al. Rev. Sci.Ins. 1998, 2004**
- **Model.: I. Kaganovich et.al. PRE 1999**

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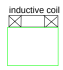
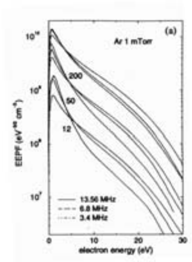
Cold Electrons: ICP



- Inductively coupled discharge
  - Argon 1mtor,
  - Pancake geom. 20x10.5cm
  - V A Godyak & V I Kolobov PRL 1998



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Godyak's Experiment is Benchmark.

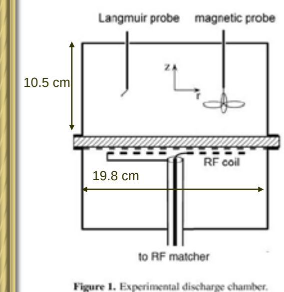

Figure 1. Experimental discharge chamber.

The Inductively Coupled Plasmas (ICP) in a cylindrical stainless steel chamber as shown in Fig.1.

Measurements were made at

f=0.45-13.56 MHz

in argon gas pressures of 0.3-300 mTorr and

rf power dissipation in the plasma 6-400 W.

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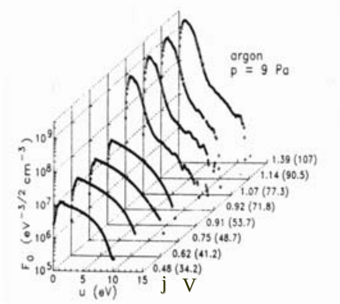
Explosive Generation of Cold Electrons in Capacitive Discharge

EEDF evolution with discharge current

Argon, 13.56MHz, 6cm, 9Pa

U. Buddemeier et.al. APL (1996)

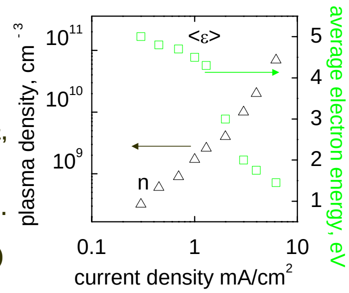


"Electron Refrigerator"

Plasma evolution with current

Argon, 13.56mHz, 6.7cm, 0.1torr

Symbols: exp. V.Godyak et. al. Plasma Sci. & Technol. (1992)



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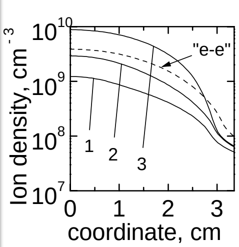
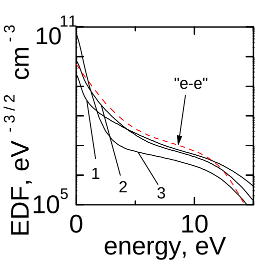
Modeling: Absence of Steady State





The EDFs and ion density profiles at three subsequent times

Solid lines: e-e collisions are ignored. 1 - t = 0 ms, 2 - t = 0.34 ms, 3 - t = 2.24 ms.

Dashed lines: with e-e collisions

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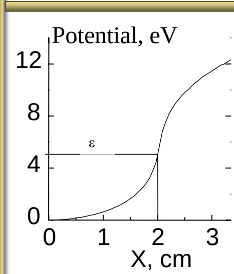
Nonlocal Approach -Averaging Over Fast Electron Bouncing



$$\varepsilon = \frac{mv^2}{2} + e\Phi(\vec{r})$$

$$F(\varepsilon)$$

I.B.Bernstein, T.Holstein. Phys. Rev. **94**, 1475 (1954).
L.D. Tsendin. Sov.Phys. - JETP, **39**, 805 (1974).

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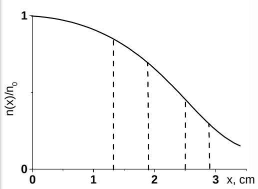
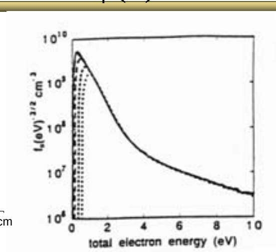
Nonlocal EEDF is a function of total energy ε=mv²/2-eφ(x)

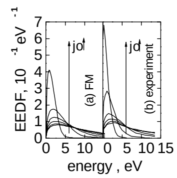


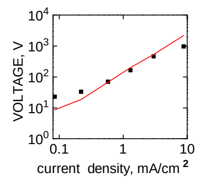


Experimental EEDF's at different positions

capacitively coupled RF discharge in argon 0.03 Torr, 13.56 MHz;
V A Godyak and R B Piejak, APL 1993

Results of Fast Modeling





He, p=0.1 torr, ω=13.56 MHz, L_0=3.35 cm.
Experimental data - filled squares, the FM results - solid line
j_0=0.085, 0.22, 0.58, 1.3, 6.0, 8.8 mA/cm².

Results of Fast Modeling

- **Speed up ~100-1000 times**
- **Consistent with experimental data and full scale modelling CCP, ICP and ECR**
- **Discovery of new phenomena**
  - **Explosive generation of cold electrons**