Concept of ambipolar diffusion and non-ambipolar flows

Igor D. Kaganovich

Plasma Physics Laboratory
Princeton University

Outline

- **Ambipolar diffusion**
- **Transport in magnetized plasma**
- **Transport in multicomponent plasma**
  - **Formation of plasmoids with sharply delineated edges in discharges**
  - **Formation of ion-ion plasma in afterglow**
  - **Ball lightning**

Drift-Diffusion Equations

$$-\nabla p + en\mathbf{E} - Mn\nu_{ia}\mathbf{u} = 0$$

$$\Gamma = n\mathbf{u} = \frac{-\nabla p + en\mathbf{E}}{Mn\nu_{ia}} = \frac{-T_i\nabla n_p + en\mathbf{E}}{Mn\nu_{ia}}$$

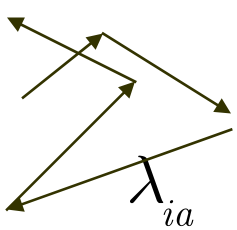
$$\Gamma_p = -D_p\nabla n_p + en_p\mu_p E$$

$$D_p = \frac{T_i}{M\nu_{ia}} = \frac{v_{Ti}^2}{\nu_{ia}} = \frac{v_{Ti}^2}{\nu_{ia}^2}\nu_{ia} = \lambda_{ia}^2\nu_{ia}$$

$$\mu_p = \frac{e}{M\nu_{ia}}$$

Ion mean free path is small =>inertia is neglected.

Here, n_p is the positive , ion density. P is ion pressure, T_i is the ion temperature, D is the diffusion coefficient, μ is the ion mobility.



Electron fluxes are much bigger than ion fluxes

$$\Gamma_p = -D_p \nabla n_p + e n_p \mu_p E$$

$$\Gamma_e = -D_e \nabla n_e + e n_e \mu_e E$$

$$D_p = \frac{T_i}{M\nu_{ia}} \qquad \mu_p = \frac{e}{M\nu_{ia}}$$

$$D_e = \frac{T_e}{m\nu_{ea}} \qquad \mu_e = \frac{e}{m\nu_{ea}}$$

Here, subscript *p* stands for the positive ions; subscript e for electrons. M is the ion mass, m is the electron mass.

$$\frac{M}{m} > 1800$$

=> Electron fluxes thousand times larger than ion fluxes.

Ambipolar Diffusion Equation

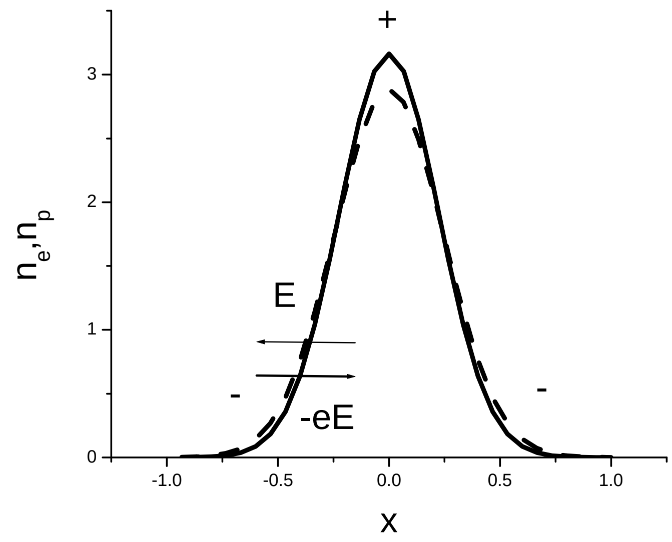
$$\frac{\partial n_e}{\partial t} = -\frac{\partial}{\partial x}\left(-D_e \frac{\partial n_e}{\partial x} - e n_e \mu_e E\right)$$

$$\Gamma_e \approx 0$$

$$\mathrm{eE} = \frac{-D_e \nabla n_e}{\mu_e n_e} \approx -T_e \frac{\nabla n_e}{n_e}$$

Electrons generate electric field and pull ions!

Ambipolar condition mean electron and ions have to move together, otherwise large fields appear and pull electrons to ions.

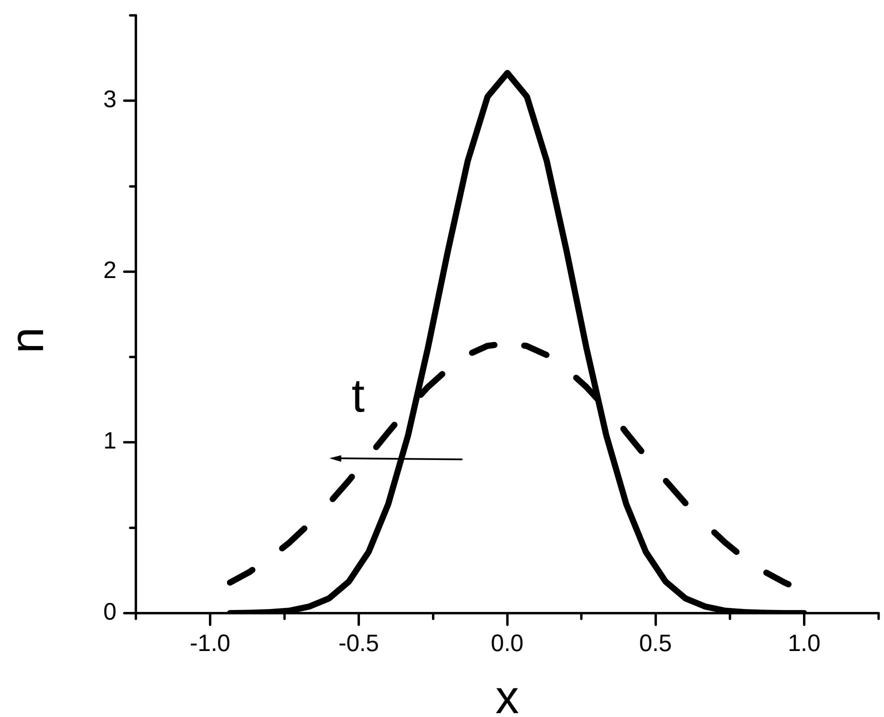


Ambipolar Diffusion Equation

$$\frac{\partial p}{\partial t} = -\frac{\partial}{\partial x}\left(-D_p \frac{\partial n_p}{\partial x} - n_p \mu_p T_e \frac{\partial n_e}{n_e \partial x}\right)$$

- $n_p = n_e$

$$\frac{\partial n_p}{\partial t} = \frac{\partial}{\partial x} \mu_p (T_e + T_i) \frac{\partial n_p}{\partial x}$$



Walter H. Schottky (1886-1976)

Quasineutrale
elektrische Diffusion im ruhenden und strömenden Gas.

Von **W. Schottky** in Rostock und **J. v. Issendorff** in Charlottenburg.

Mit acht Abbildungen. (Eingegangen am 14. Dezember 1924.)

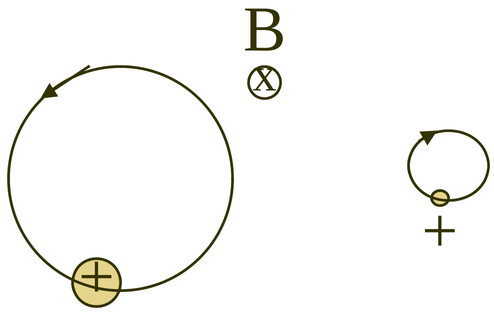
Worked at Universities of Jena, of Würzburg and of Rostock 1923-27) , Siemens Research Laboratories (1914-19, 1927-58).

Known for:

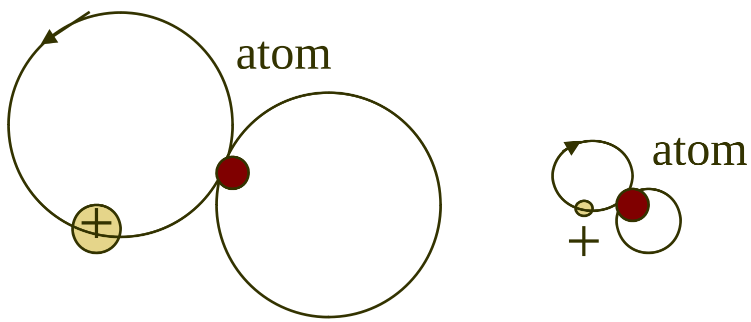
Schottky effect, Schottky barrier, Schottky contact, Schottky anomaly, Screen-grid vacuum tube, Tetrode, Ribbon microphone, Ribbon loudspeaker, Theory of Field emission, Shot noise.

Transport in magnetized plasma

Ion gyroradius is much larger than electron's



$$r_{Li} = \frac{v_{\perp i}}{\omega_{ic}} = \frac{\sqrt{T_i / M}}{eB / Mc} \qquad r_{Le} = \frac{v_{\perp e}}{\omega_{ec}} = \frac{\sqrt{T_e / m}}{eB / mc}$$



$$D_p = \nu_{ia} r_{Li}^2$$

$$D_e = \nu_{ea} r_{Le}^2$$

=> Electron fluxes across magnetic field thousand times smaller than ion fluxes.

Plasma diffusion across magnetic field

$$D_{\perp} = \nu_{ea} r_{Le}^2 \sim \frac{1}{B^2}$$

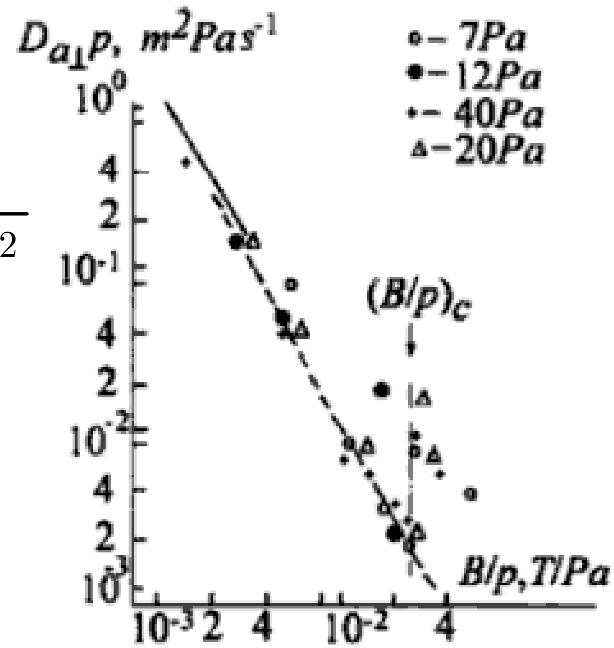
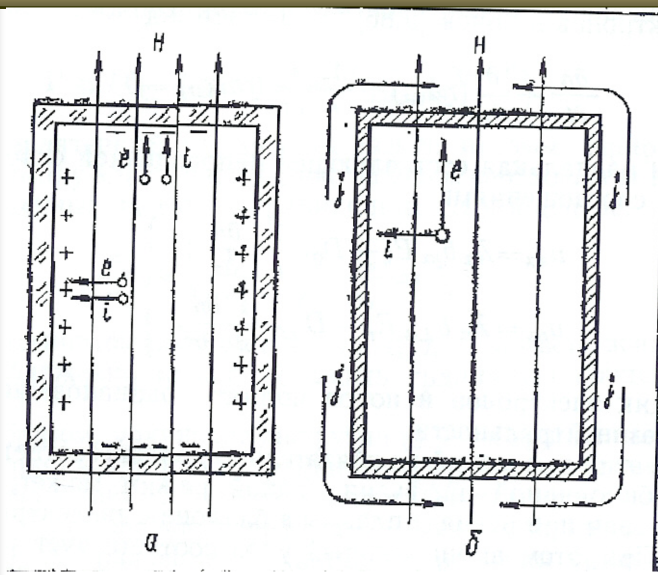


Figure 7.2. Dependence of the transverse ambipolar diffusion coefficient in a helium plasma on the magnetic field; sharp increase at $B = B_c$ is due to transition to the turbulent state. Dashed line corresponds to the classical theory, a=2cm, L=75-80cm, solid line are data of [5].

[5] K.H. Gessler, Phys. Rev. 171, 179 (1968)

Short-circuit effect



In a vessel with conducting walls electrons can escape along magnetic field and ion can diffuse across magnetic field freely, which lead to 1000 times increase in plasma decay times.

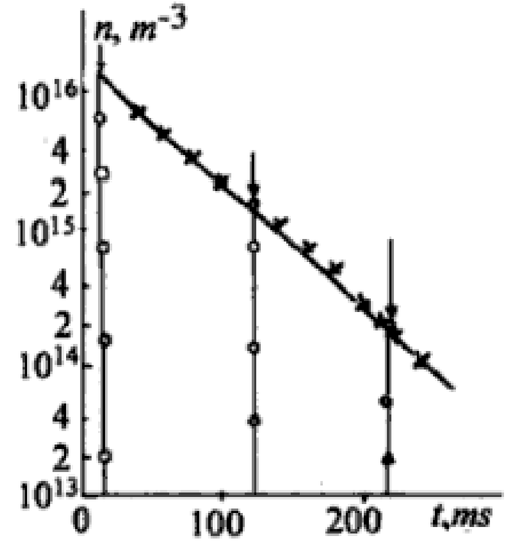


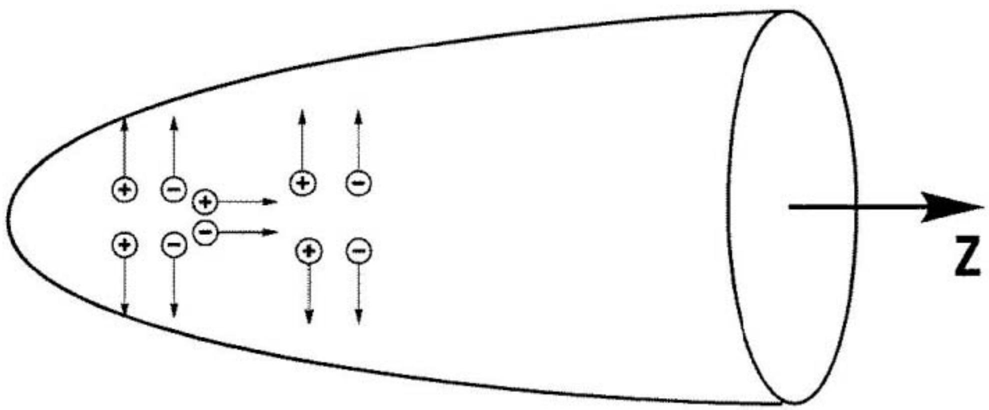
Figure 7.6. Decay of helium plasma in a metallic chamber [13]; *a*=2cm, *p*=13.3Pa, B=0.2T. The end electrode was simulated by a cylinder in a weak field. Arrow indicates moment when the end and side electrodes are connected; x - ambipolar decay, o - short circuited walls.

Plasma Expansion Along Magnetic Field Lines (1/2)

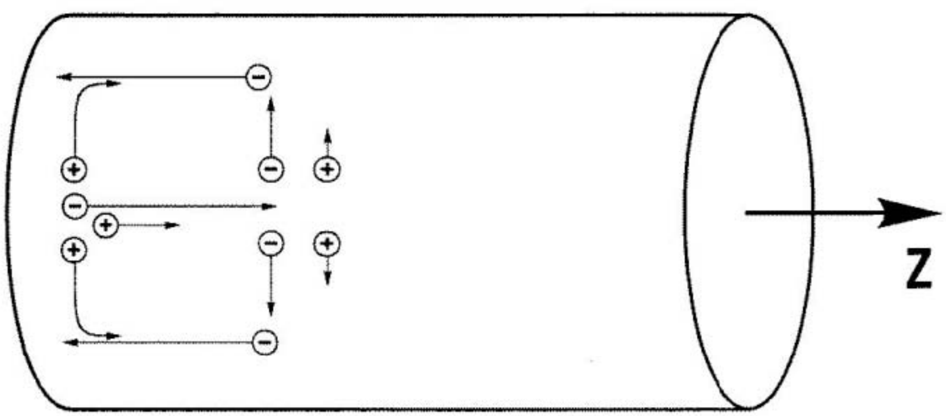
The scheme of non-ambipolar diffusion accompanied by short-circuiting currents. Arrows show the electron and ion motion. The arrow length represents the value of particle fluxes.

(a) Hypothetical ambipolar expansion.

(b) Real non-ambipolar fluxes.



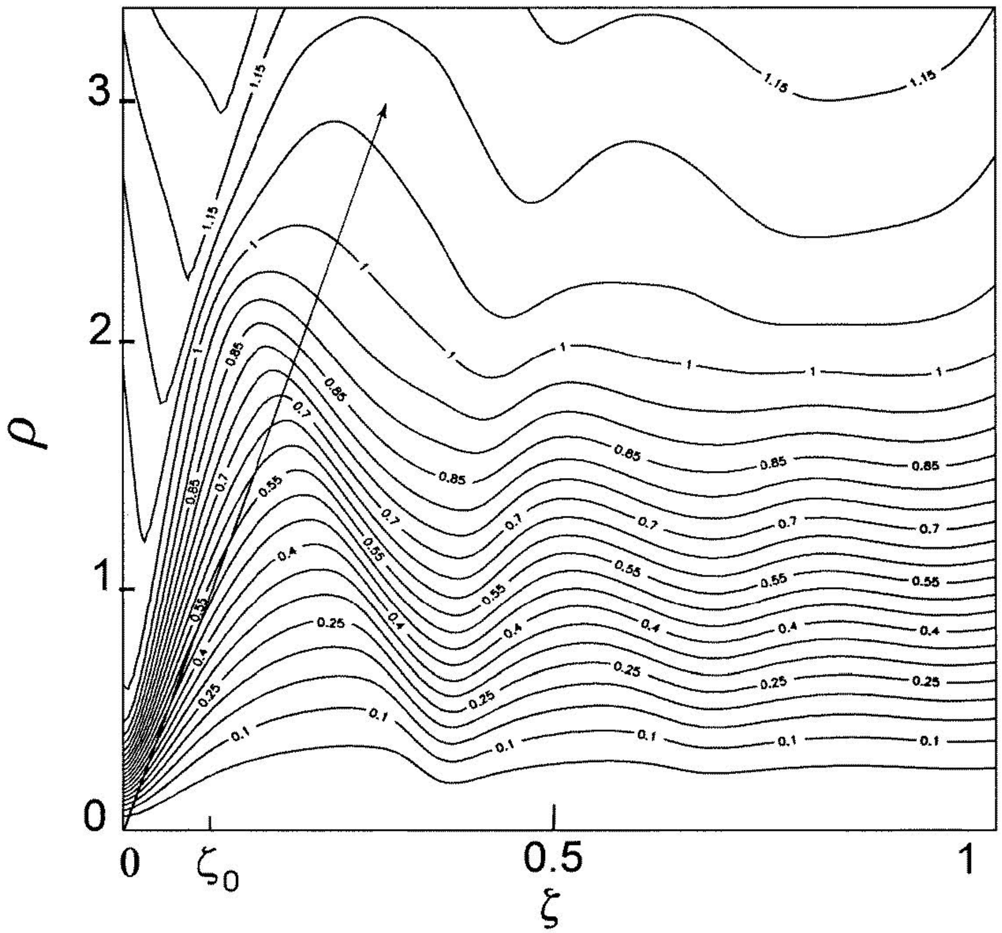
a)



b)

Plasma Expansion Along Magnetic Field Lines (2/2)

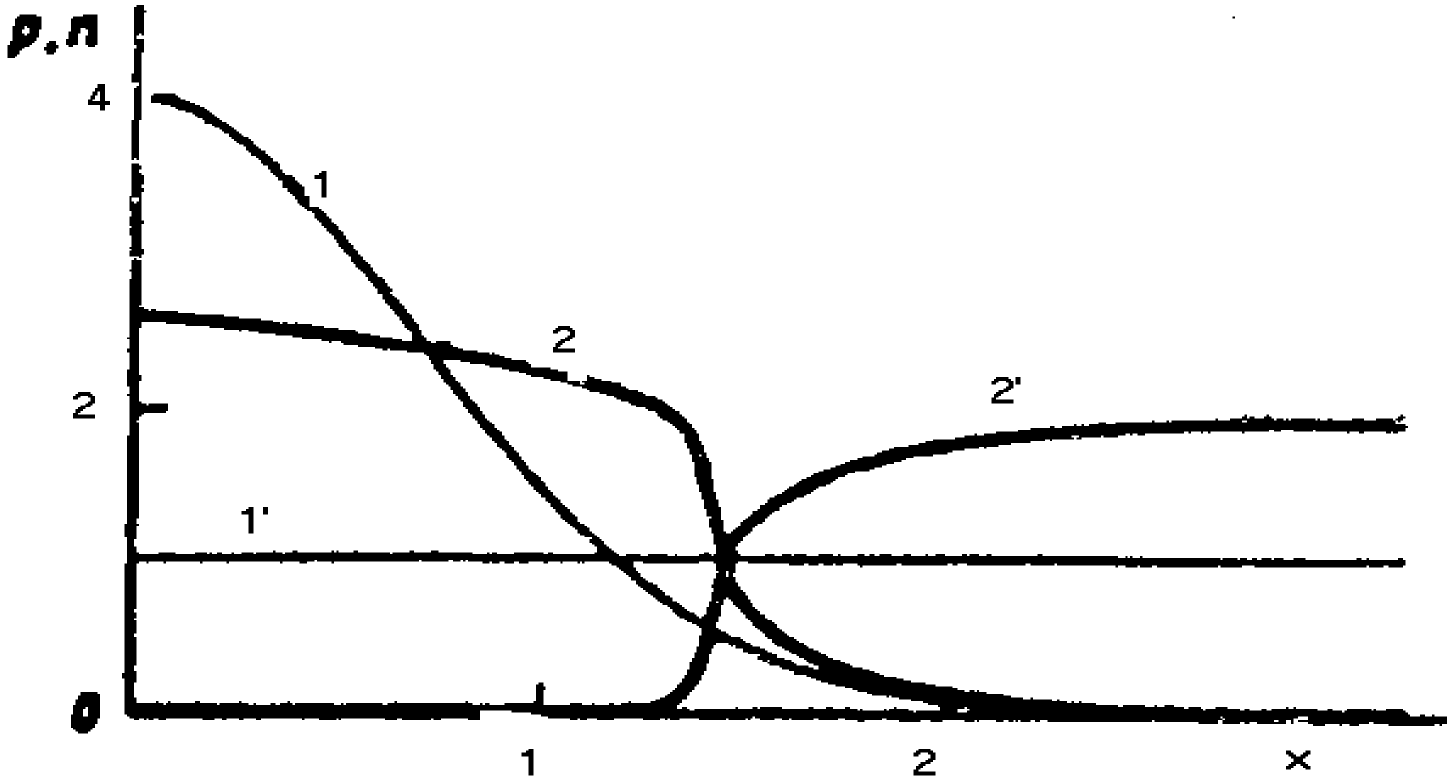
Ion trajectory (streamlines of ion flow) in cylindrical geometry. Ion jet propagates with a supersonic velocity along ζ and expands radially due to the electron temperature. The arrow shows th characteristic angle of plasma expansion at the sound velocity.



For more info: IEPC-096;

Kaganovich, I.D., et al, Plasma Sources Sci. Technol. **5**, 743 (1996).

Temporal Evolution, Self-separation of Positive Ions



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Periodic table (1/2)

Electron affinity, E_f, for negative ions

Group period	I	II	III	IV
1	H 0.75			
2	Li 0.62	Be 0.004*	B 0.28	C 1.2
3	Na 0.54	Mg 0.004*	Al 0.44	Si 1.4
4	K 0.5	Ca 0.02	Sc 0.19	Ge 1.2
5	Rb 0.49	Ba 0.15	Sr 0.11	Sn 1.1
6	Cs 0.47	Ra	Ba 0.15	Pb 0.36

Periodic table (2/2)
Electron affinity for negative ion formation

Group period	V	VI	VII	VII
1				He 0.075*
2	N 0.2*	O 1.45	F 3.4	Ne 0.095*
3	P 0.75	S 2.08	Cl 3.61	Ar 0.17*
4	As 0.81	Se 2.02	Br 3.36	Kr 0.65*
5	Sb 1.1	Te 1.97	I 3.06	Xe 1.25*
6	Bi 0.95	Po 1.9	At 2.8	Rn

Most elements including noble gases form negative ions!!!
Metastable negative ions life time ~0.5ms

Applications of Plasmas Containing Negative Ions

- **Common plasma: Te ~3eV =>**
  - **negative ions in oxygen and halogens.**
    - **Semiconductor manufacturing,**
    - **Negative ion sources,**
    - **D-layer in the lower ionosphere.**

- **Colder Electrons, Te ~1eV =>**
  - **negative ions in most other elements.**
    - **H^- negative ion sources**

Formation of negative ions

- **Electron attachment**

  $e + A \rightarrow A^-$

energy, E_f, transfers to photons or third body

- **Dissociative attachment**

  $e + AB(*) \rightarrow A^- + B$

- **Charge transfer**

  $A^- + B \rightarrow A + B^-$

- **Clustering reactions**

  $A^- + B + C \rightarrow AB^- + C$

Destruction of negative ions

- **Electron detachment**

$e + A^- \rightarrow A + 2e$; $e + AB^- \rightarrow A + B + 2e$

- **Associative detachment**

$A^- + B \rightarrow AB + e$

- **Charge transfer**

$A^- + B \rightarrow A + B^-$

- **Positive-negative ion recombination**

$A^- + B^+ \rightarrow A + B^*$

Formation of plasmoids with sharply delineated edges in discharges

D. J. Economou, R. S. Wise, and A. A. Kubota, IEEE TPS **27,** 60 (1999). Chlorine plasma of ICP.

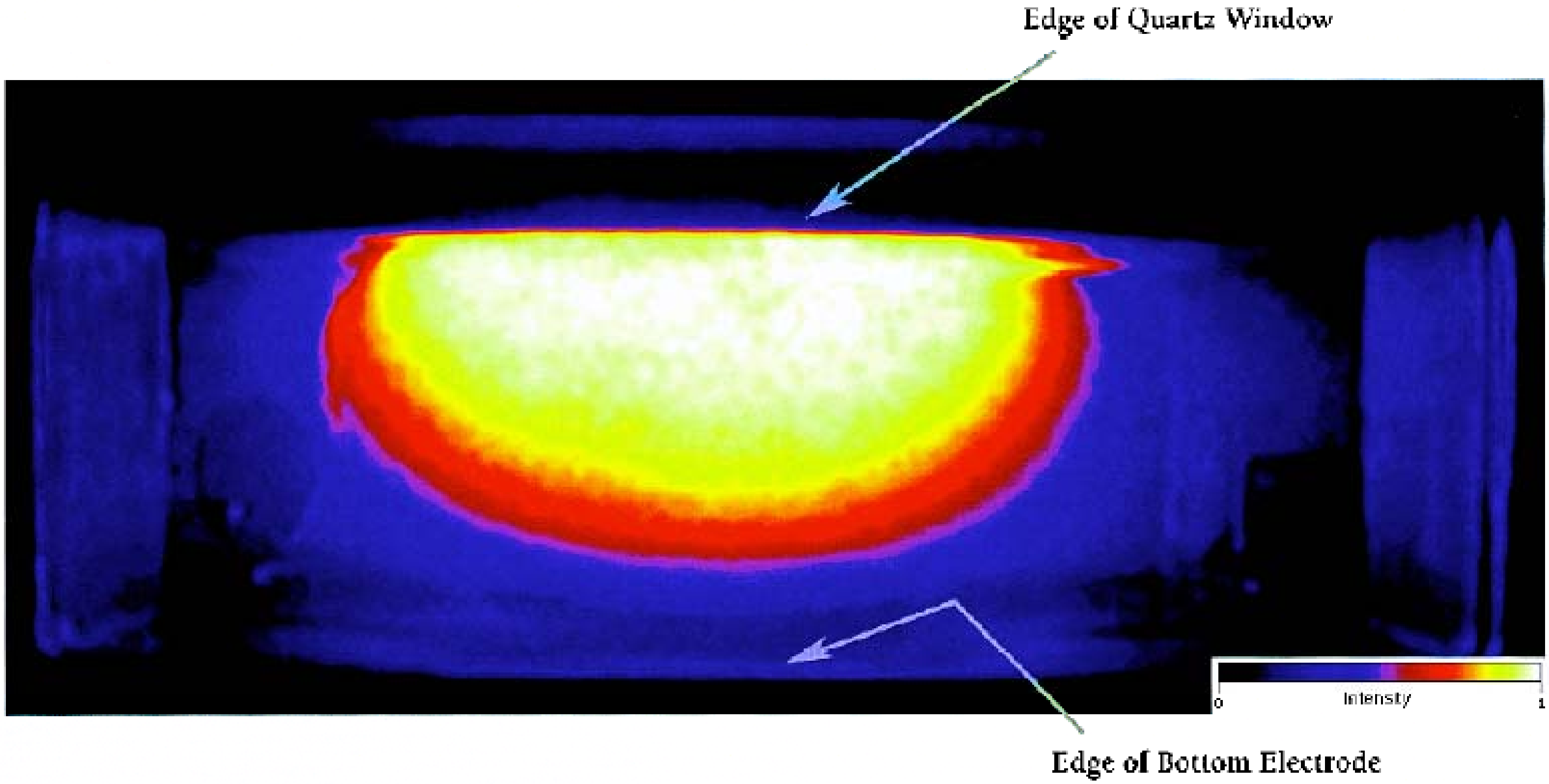
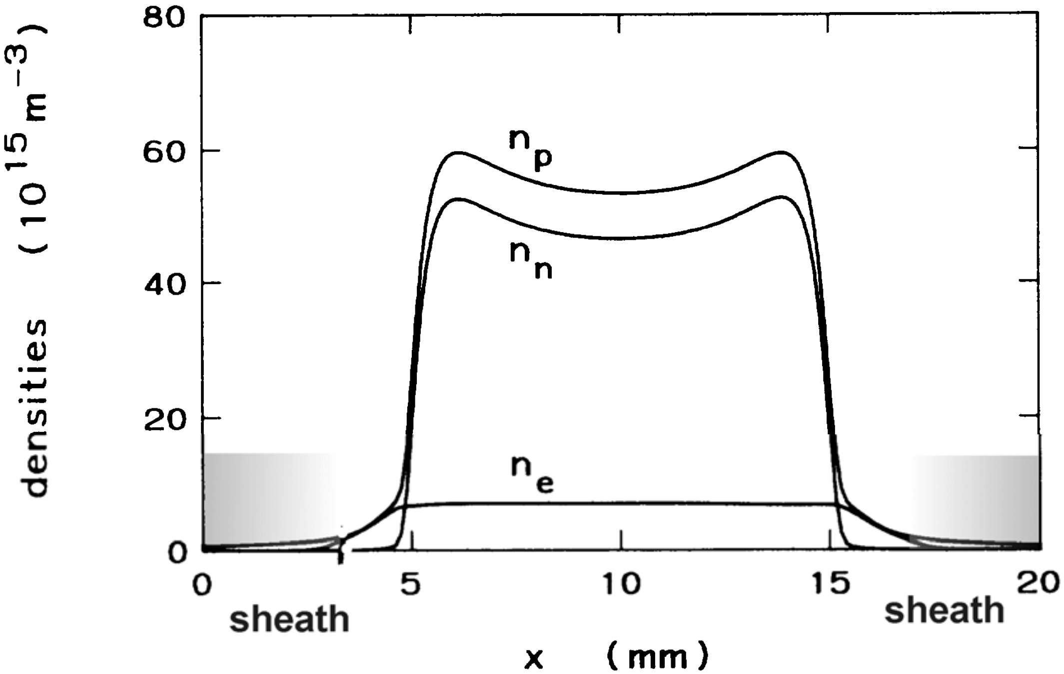


Fig. 1. Side view of a plasmoid formed at 5 mtorr. The bright structure is against the quartz window at the top and is well separated from the grounded bottom electrode. The spacing between the bottom electrode and the quartz window is 7.62 cm.

The ion densities profiles exhibit discontinuities / simulation. (1/4)



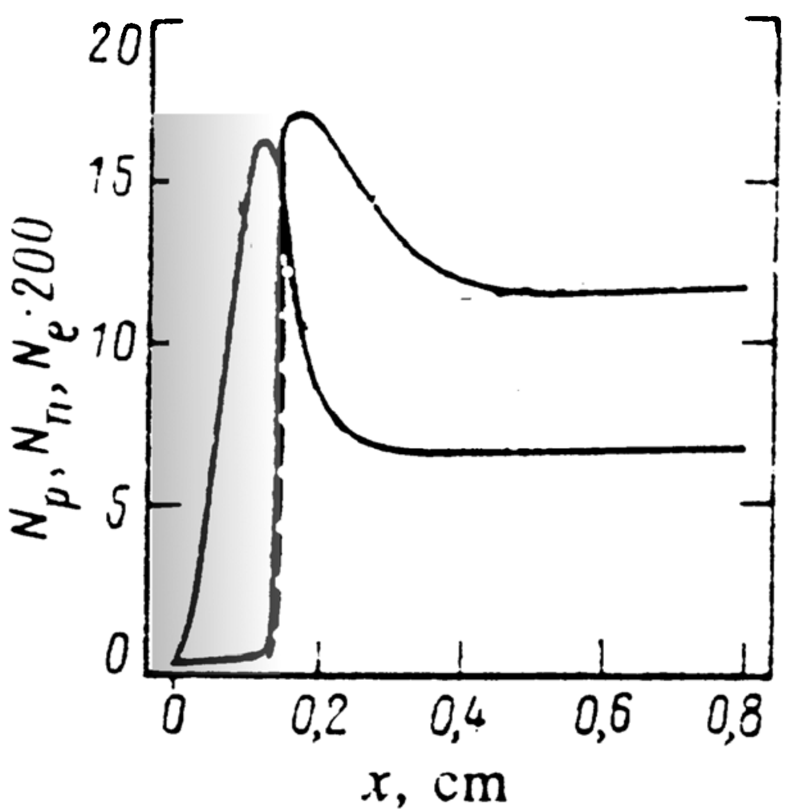
rf discharge,

0.5 Torr CF4, 13.6MHz.

Fronts form in the plasma bulk

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

The ion densities profiles exhibit discontinuities / simulation. (2/4)



rf discharge

0.1Torr SF_6

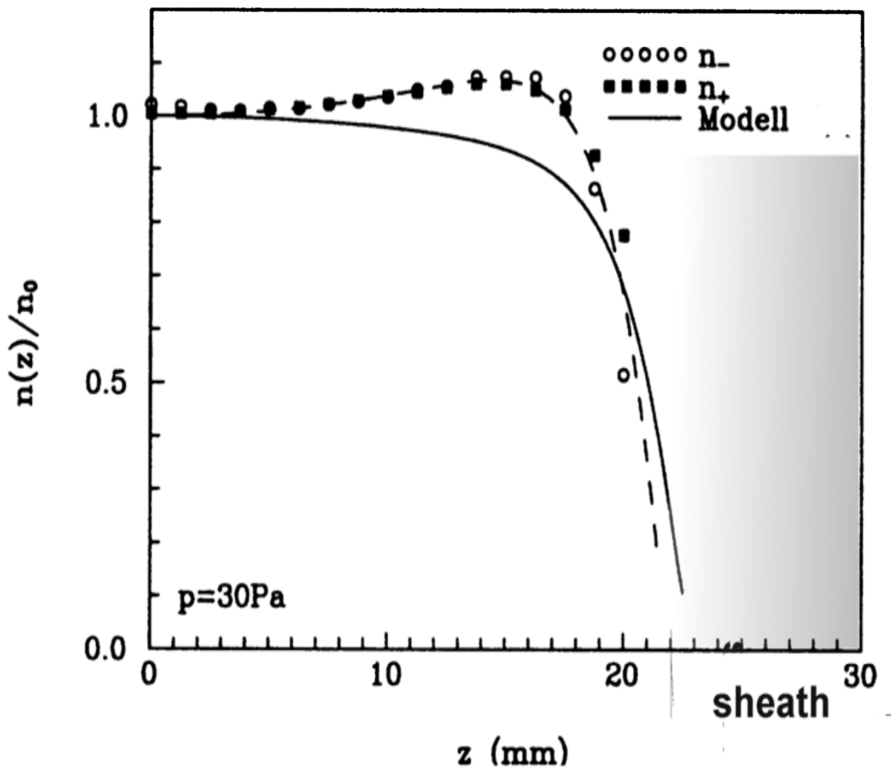
f=13.56 MHz

j=10mA/cm^2

Fronts form at the sheath edge

Simulation: V.A. Schveigert, Sov. J. Plasma Phys. **17,** 844 (1991).
Theory: I.D. Kaganovich, Sov. J. Plasma Phys. **5,** 410 (1995).

The ion densities profiles exhibit discontinuities / experiment. (3/4)



Symmetrical RF discharge CCP

0.21Torr oxygen

S. Berezhnoi, et. al., Appl. Phys. Lett. **77**, 800 (2000).

Long lived metastables are important

The Nightglow as observed from Space. The lower left segment is the moon lit solid Earth, and the green arc above it is the Nightglow layer located about 100 km above the surface.

$O_2^* \Rightarrow O_2 +$ green light

www.yorku.ca/mcdade/

Ball lightnings

- **Long lived**
- **Observed in presence of aerosols or dust => negative ions**



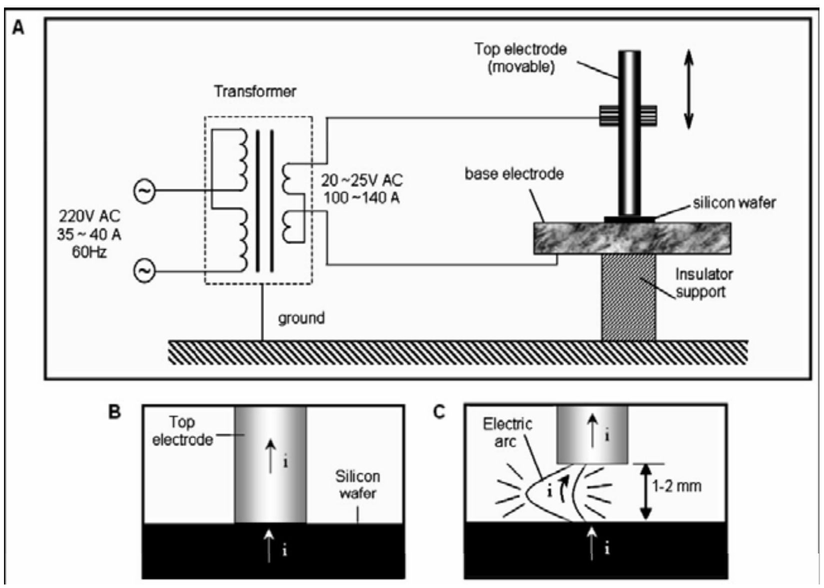
www.zeh.ru/shm/index_e.php

Ball lightnings in laboratory (1)

- **Eli Jerby and Vladimir Dikhtyar made lightning balls in the lab using a "microwave drill, "*Phys. Rev. Lett.* 96, 045002 (2006).**
- **The energy from the microwaves then produces a molten hot spot in the substrate. The solid substrate is made from glass, silicon, or other ceramics.**

Ball lightnings in laboratory (2a)

- **A Brazilian team made lightning balls in the lab using a dc arc, "*Phys. Rev. Lett.* 98, 048501 (2007).**
- **The energy from the arc produces silicon nanoparticles, which later burn.**



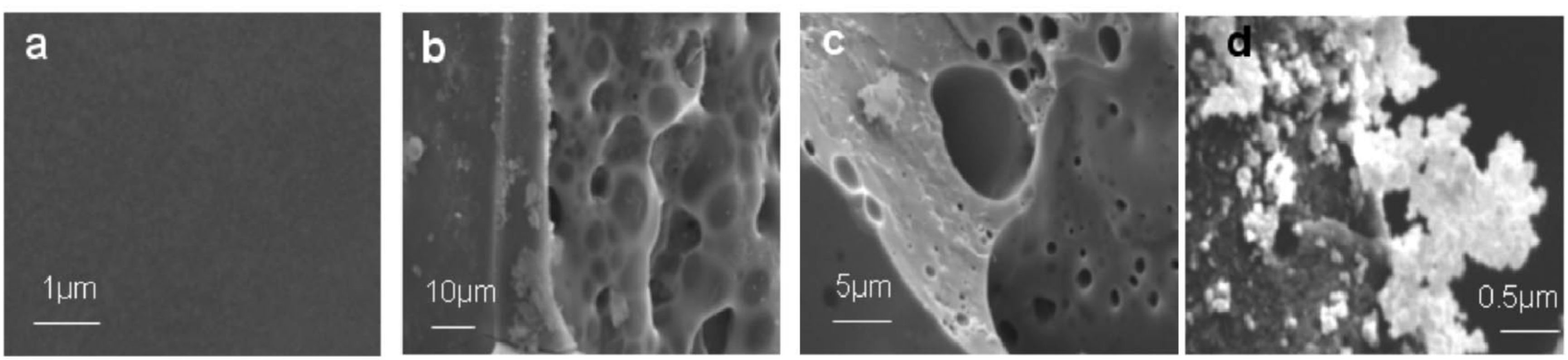
Ball lightnings in laboratory (2b)

- **Ball lightning goes under the cable**

Ball lightnings in laboratory (2c)

- **The energy from the arc produces silicon nano-particles.**

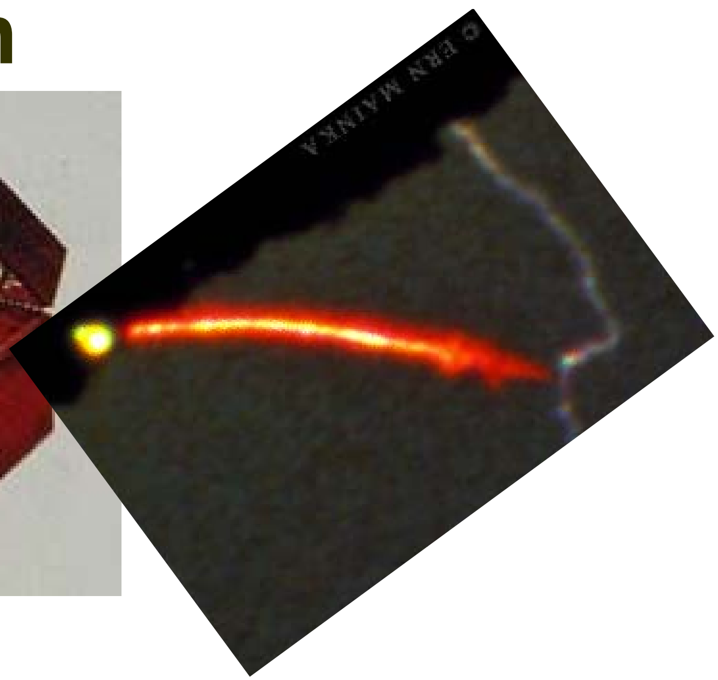
At the high temperatures created by the lightning strike, the carbon in the soil chemically reduces the Si oxides to the vaporized, metallic form of Si: SiO_2 +2C => Si + 2CO. As the hot vapor cools in the atmosphere, the Si condenses into an aerosol of nanometer-sized Si particles in the air.



SEM of the Si wafer before (a) and after electrical discharge (b), (c), (d). The surface of the samples subjected to electrical discharges shows holes (b), (c) and chains of micrometer-sized particles (d).

Ball lightnings per Larry Grisham

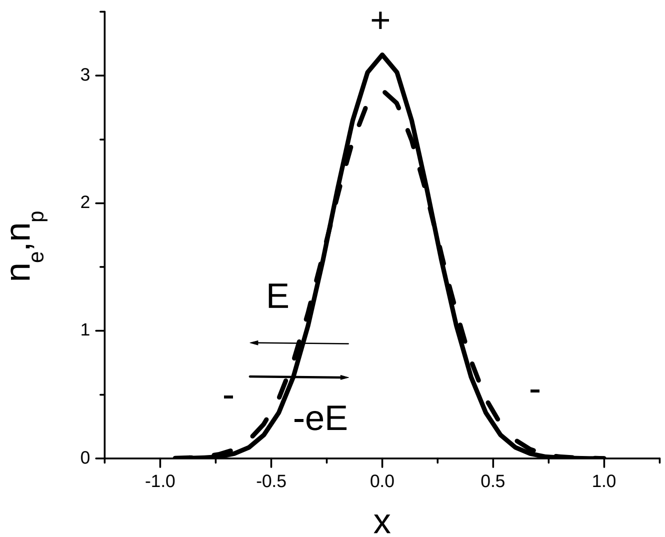
- lightning struck high-fidelity phonograph and repaired it.
- Larry’s mother saw fire ball crossing the room



Negative ions are pulled into the plasma center.

$$\frac{\partial n_n}{\partial t} - \mu_n \frac{\partial}{\partial x}\left(T_i \frac{\partial n_n}{\partial x} + eEn_n \right) = 0$$

$$\frac{\partial n_p}{\partial t} + \mu_p \frac{\partial}{\partial x}\left(-T_i \frac{\partial n_p}{\partial x} + eEn_p \right) = 0$$



$$n_e = n_p - n_n \qquad E = -\frac{T_e}{en_e}\frac{dn_e}{dx}$$

$$\Gamma_p = \mu_p n_p E = -\mu_p n_p \frac{T_e}{en_e}\frac{dn_e}{dx} = -\mu_p \frac{T_e(n_e + n_n)}{en_e}\frac{dn_e}{dx}$$

Analysis of Nonlinear Convection

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

$$u = \mu T_e \frac{\partial \ln n_e}{\partial x}$$

negative ion velocity

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

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

Electron effective diffusion coefficient

Final Form: Nonlinear Convection

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

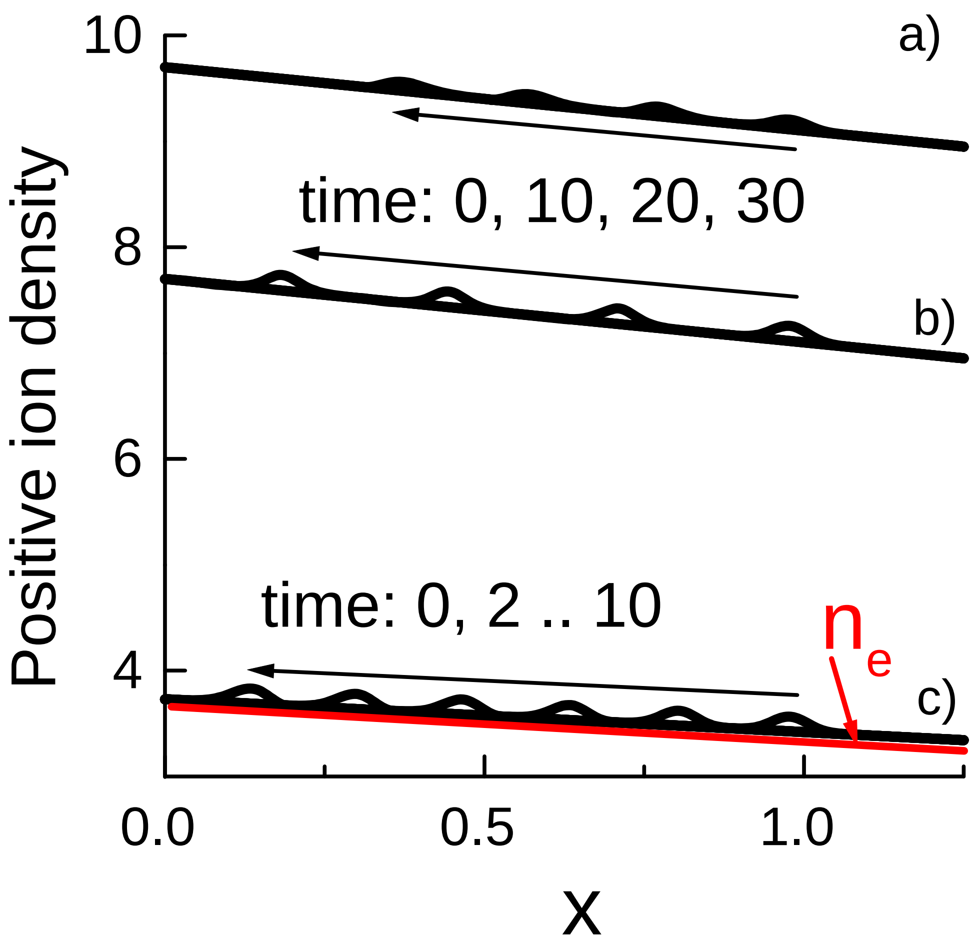
$$u(n) = -\Gamma_e \frac{\mu_n}{\mu_n n + \mu_p p}$$

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

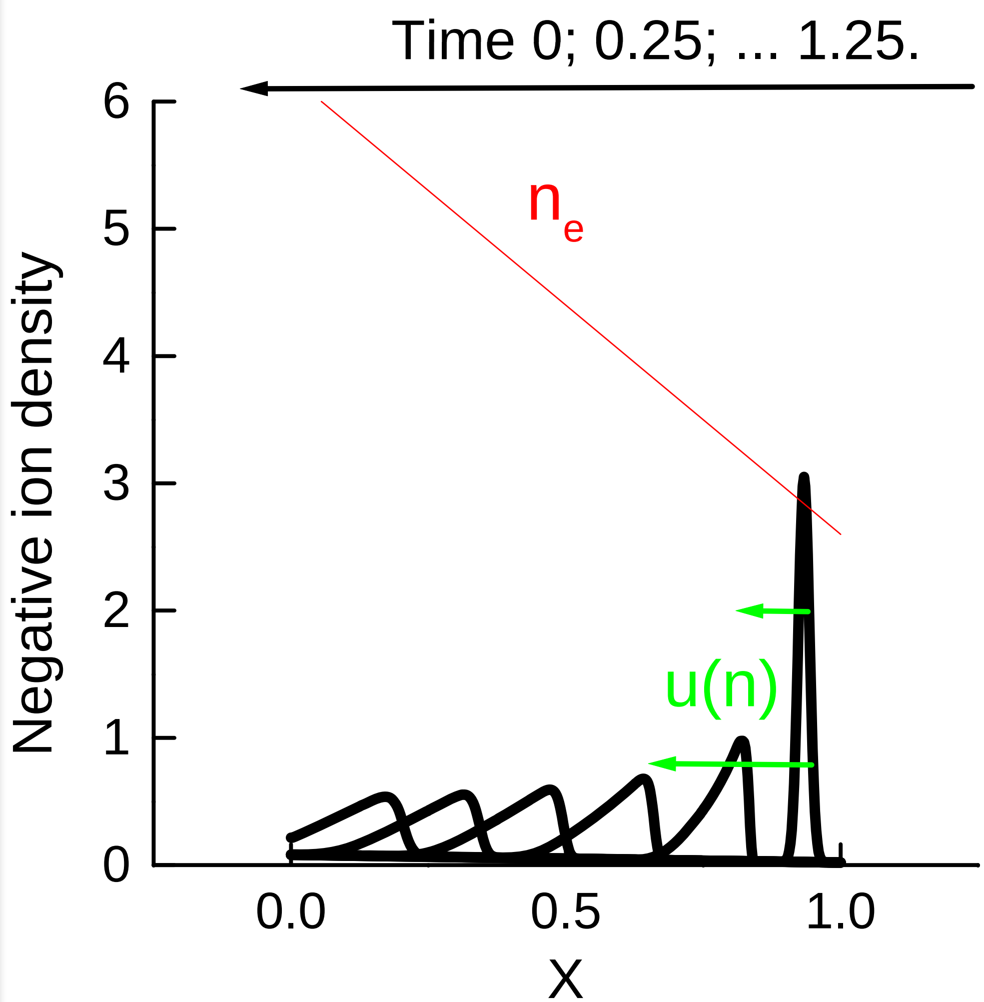
Propagation of negative ion density depends on electronegativity n/n_e.



- The same unperturbed electron density
  - ($n_e = 3.7 - 0.3\, x$)
- Different electronegativity
  - (a) $n = 6 - 0.3\, x$, $u_{eff} = 2.0$
  - (b) $n = 4 - 0.3\, x$, $u_{eff} = 2.7$
  - (c) $n = 0$, $u_{eff} = 8.1$.

$$u_{eff} = \frac{\mu_n \mu_p}{\mu_n n + \mu_p p} \frac{T_e \partial n_e}{\partial x}$$

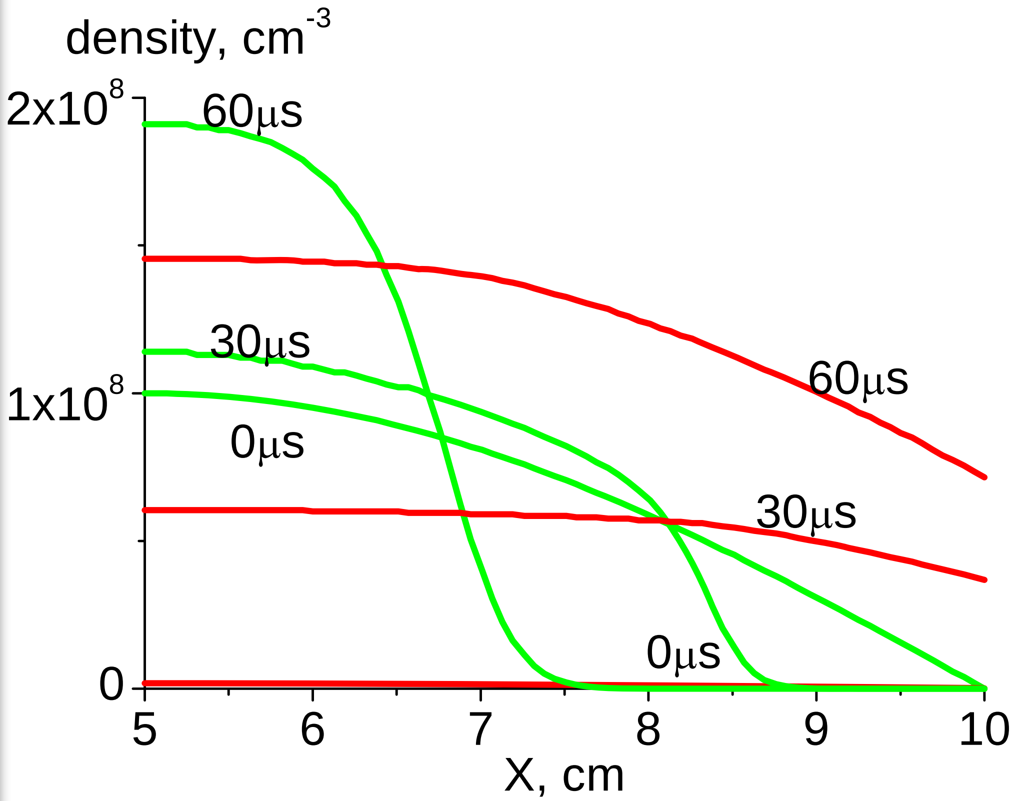
Large perturbations deforms during nonlinear convection.

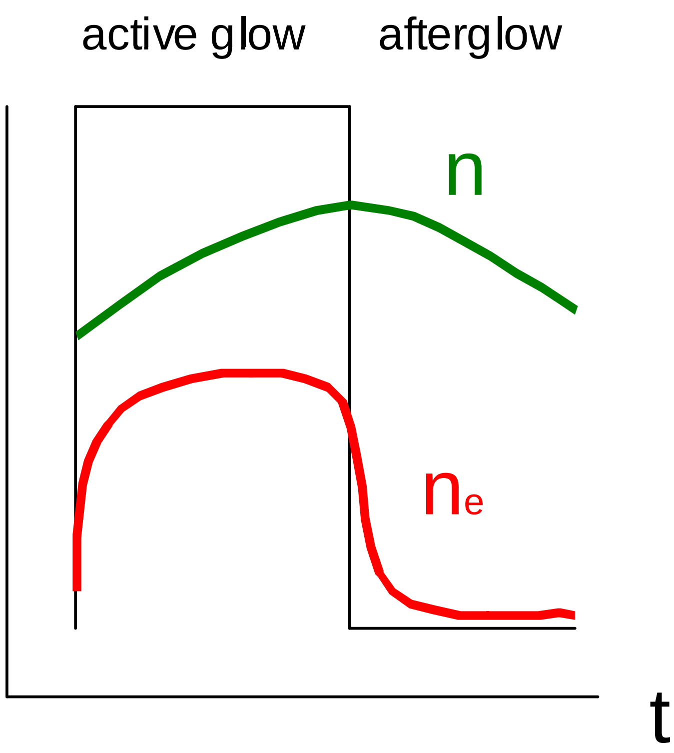


$$\frac{\partial n}{\partial t} + u_{eff}(n)\frac{\partial}{\partial x} n = 0$$

- Front profiles spreads,
- Back overturns

Evolution of Electron and Negative Ion Densities in Early Active Glow

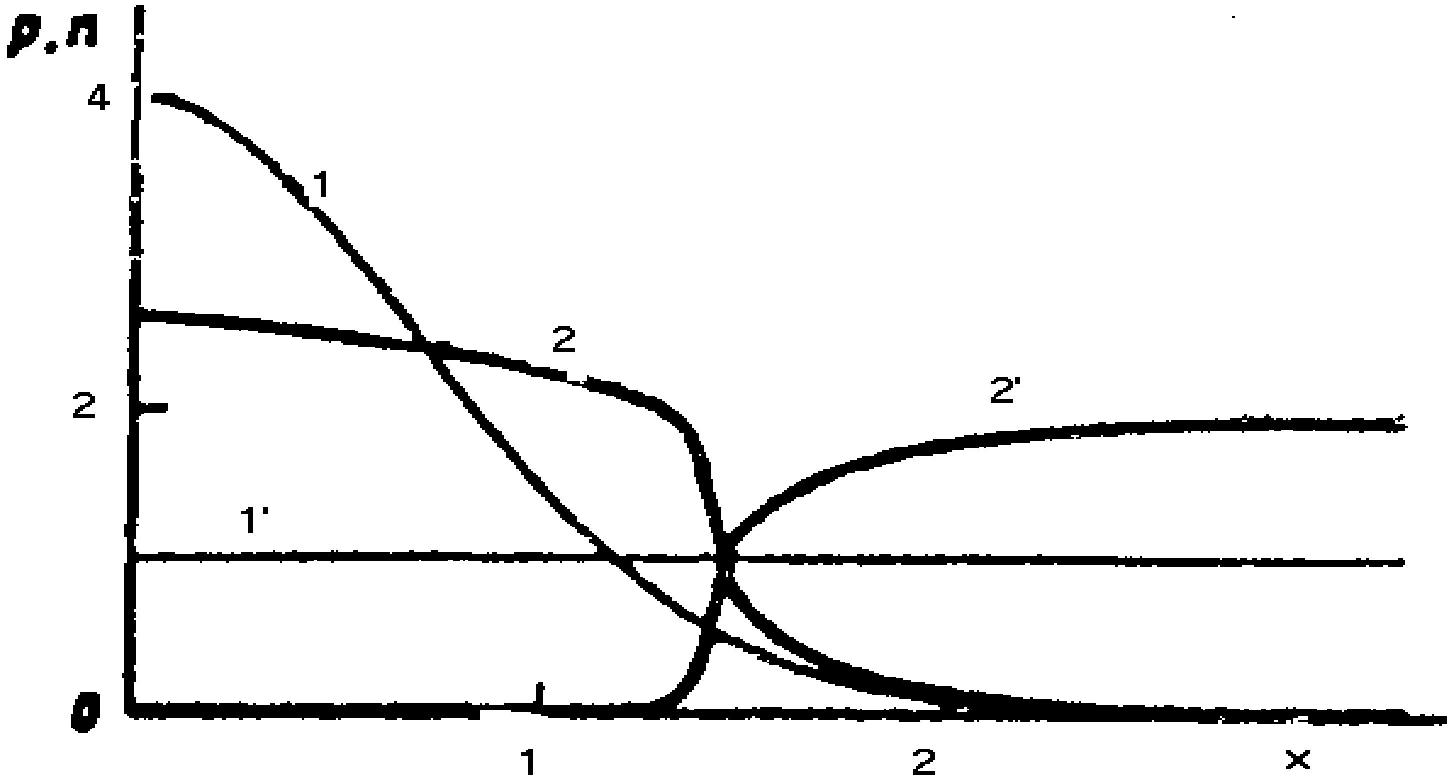




Fronts form near the n=0.

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

Temporal Evolution, Self-separation of Positive Ions



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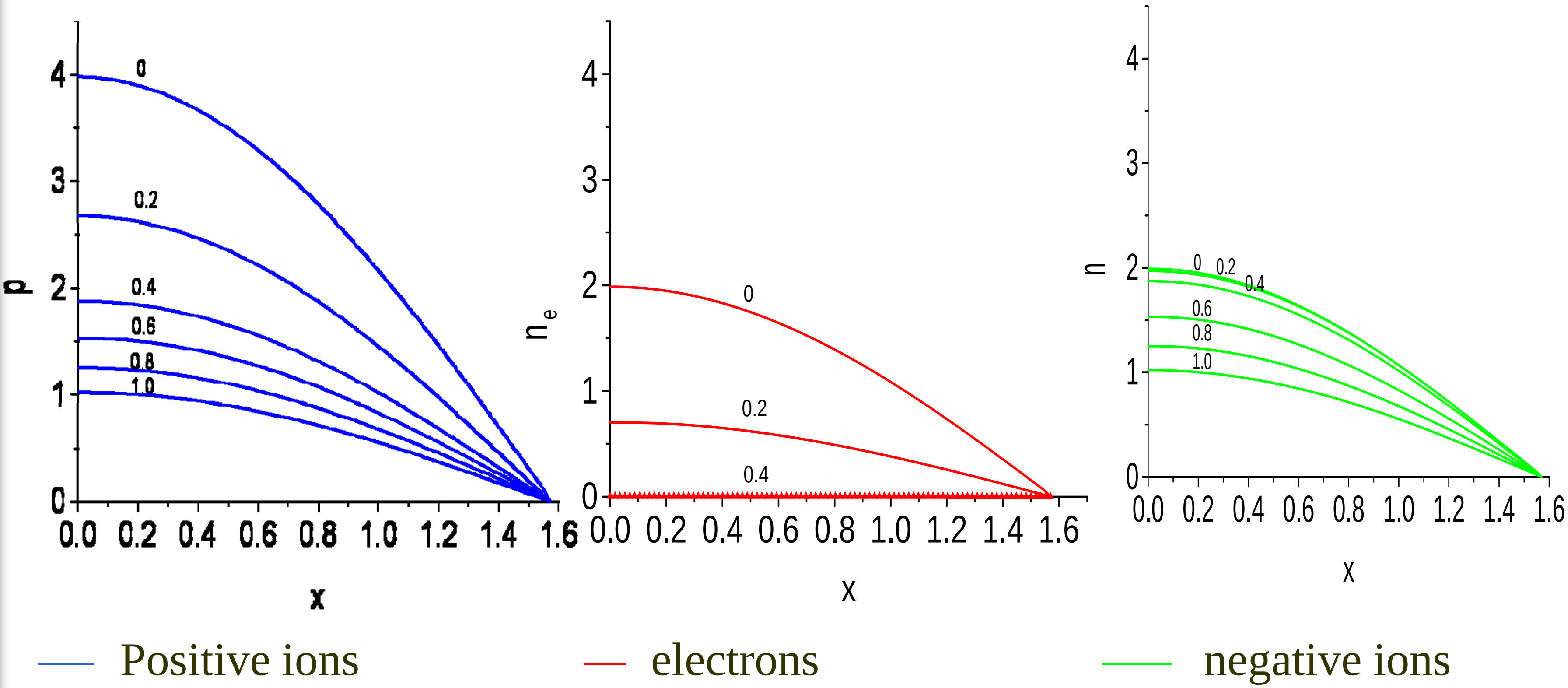
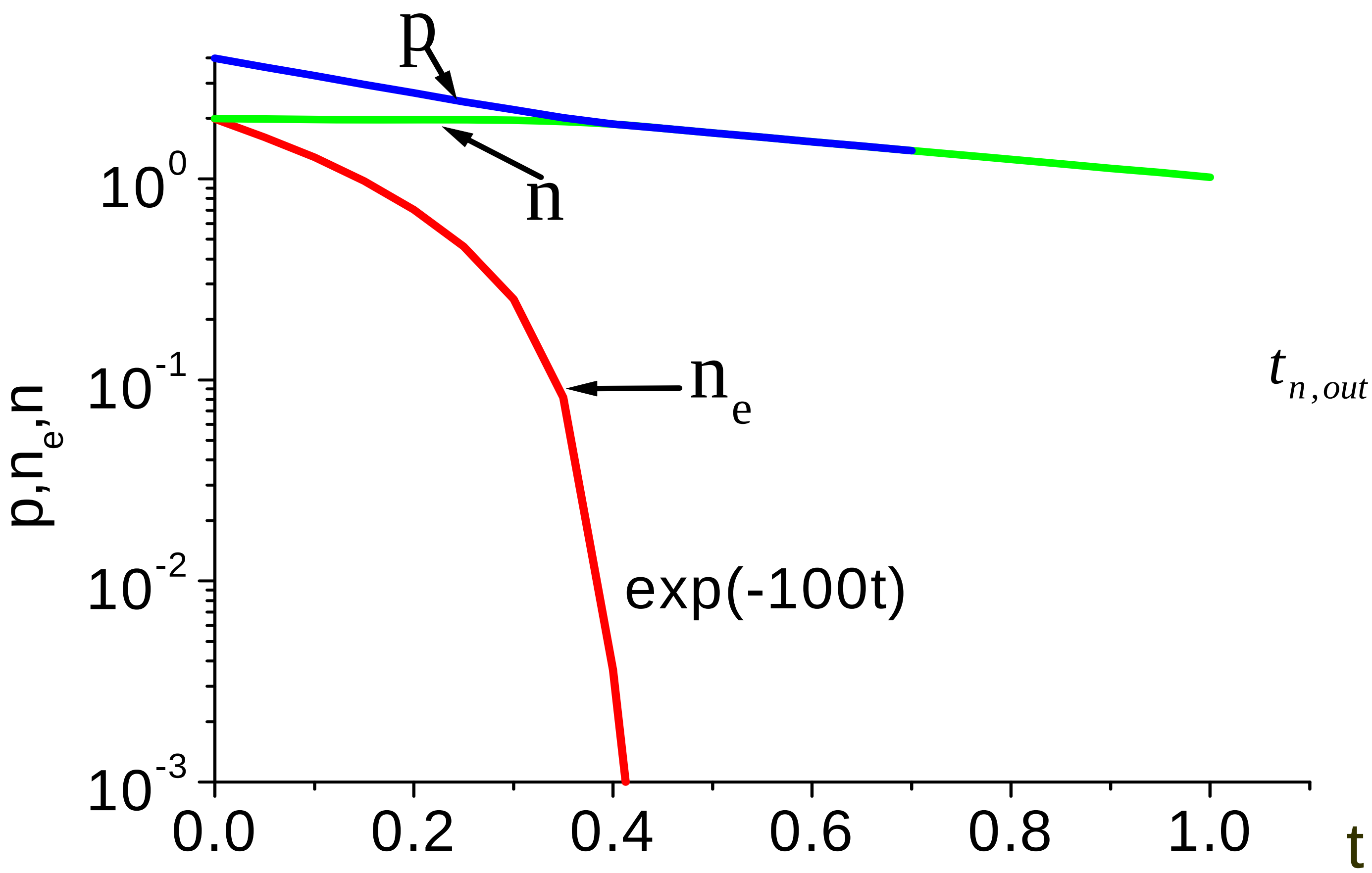
Formation of ion-ion plasma in afterglow: electrons can escape completely in finite time.



$T_e = T_i$, wall losses only.
Ions are present when electrons disappear.

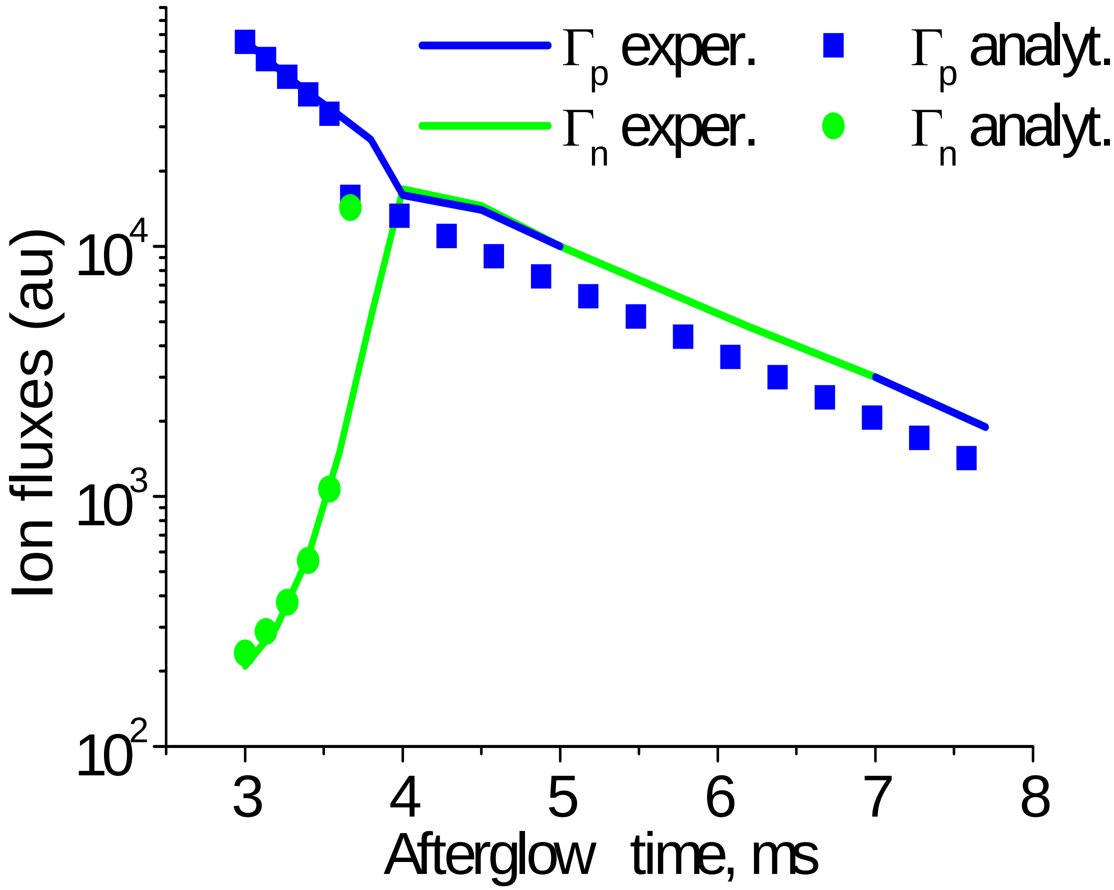
Electrons disappear in finite time.



$$t_{n,out} = 0.5\, ln(\frac{p_0}{n_0})$$

electron dominated plasma ion- ion plasma

Negative ions flow to the wall after electrons disappear.



Experiment:
$Kr:O_2$ 1:1 0.03Torr
R=5.5cm, L=18cm

D.Smith, et al. J. Phys. D: Appl. Phys., **7**, 1944 (1974).

Theory:
I.D. Kaganovich, et al. , APL, **76**, 284 (2000).

Summary: negative ions (1/2)

- **Low temperature plasmas containing negative ions exhibit many nonlinear phenomena.**

- **Plasma separation in time and space**

  into the regions with different ion composition is *universal property* of non- equilibrium plasma.

- **Formation of nanoparticles or droplets during melting and vaporization of solids may give rise to many new interesting phenomena like ball lightning and anomalous conductivity.**

Summary: transport in magnetized plasmas (2/2)

- **Transport in the magnetized plasmas is often non-ambipolar accompanied by short-circuiting currents.**
  - **These currents can lead to many nontrivial effects in plasma formation, e.g., cylindrical plasma jets instead of conical.**

Back-up explanatory slides

Small amount of electron density determines the electric field.

currentless plasma:

$$j = e(\Gamma_p - \Gamma_n - \Gamma_e) = 0$$

$$eE = \frac{-D_e \nabla n_e - D_n \nabla n + D_p \nabla p}{\mu_e n_e + \mu_p p + \mu_n n}$$

$$n_e \mu_e >> (\mu_p p + \mu_n n)$$

$$n_e \mu_e << (\mu_p p + \mu_n n)$$

- **electron dominated plasma**
- **ion-ion plasma**

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

$$if \;\; \mu_p = \mu_n \;\; E = 0$$