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Nonlinear Dynamics in Gas Discharges due to Coupled Ionization and Transport

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Nonlinear Dynamics in Gas Discharges due to Coupled Ionization and Transport

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Summer College on Plasma Physics
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Plasma sources (Helicon)

- Radio-Frequency discharges
- Size: 5 – 100 cm
- Gas pressure: mTorrs
- Electron temperature: eVs
- Plasma density:

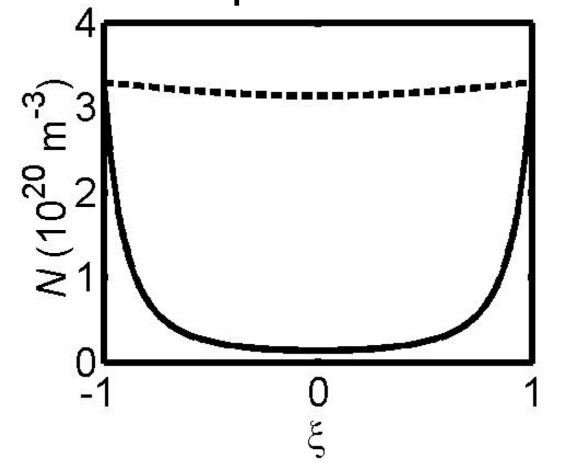
$$10^{15} - 10^{20}\ \text{m}^{-3}$$

- Magnetic field 50-500 G

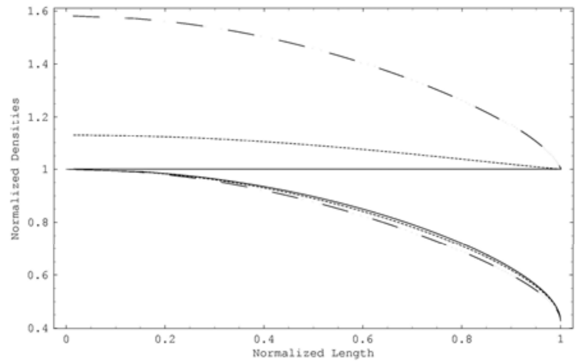
(H.I.T. plasma source built by Makrinich)

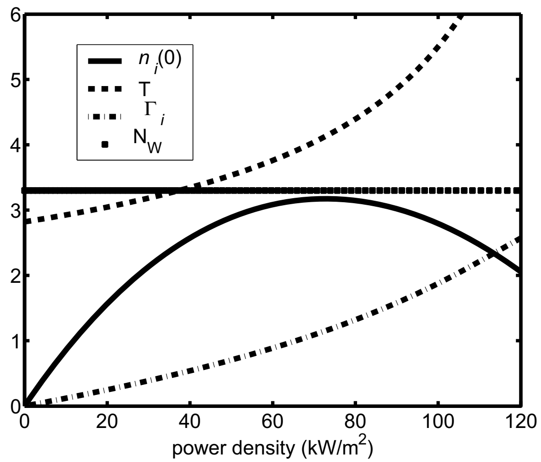
Highlights

depletion

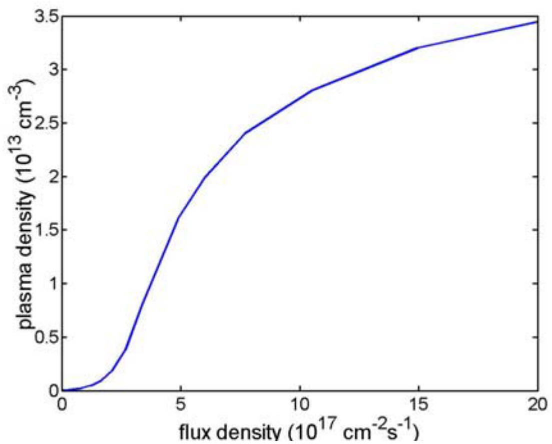


repletion





Nonmonotonic dependence



Density jump

Plasma Steady-State

Plasma particle balance:

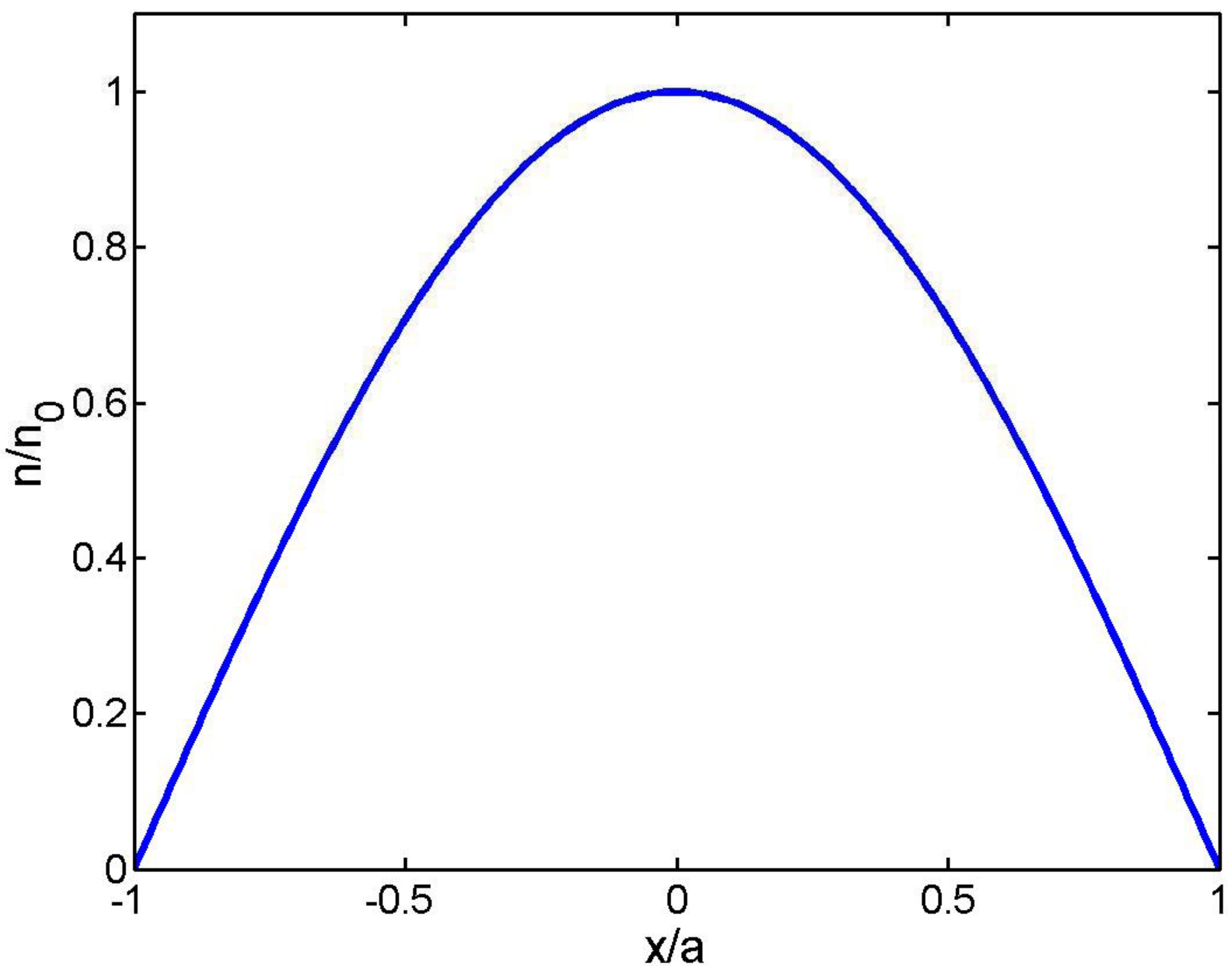
volume ionization is balanced by wall recombination.

1D, planar geometry – weakly ionized plasma

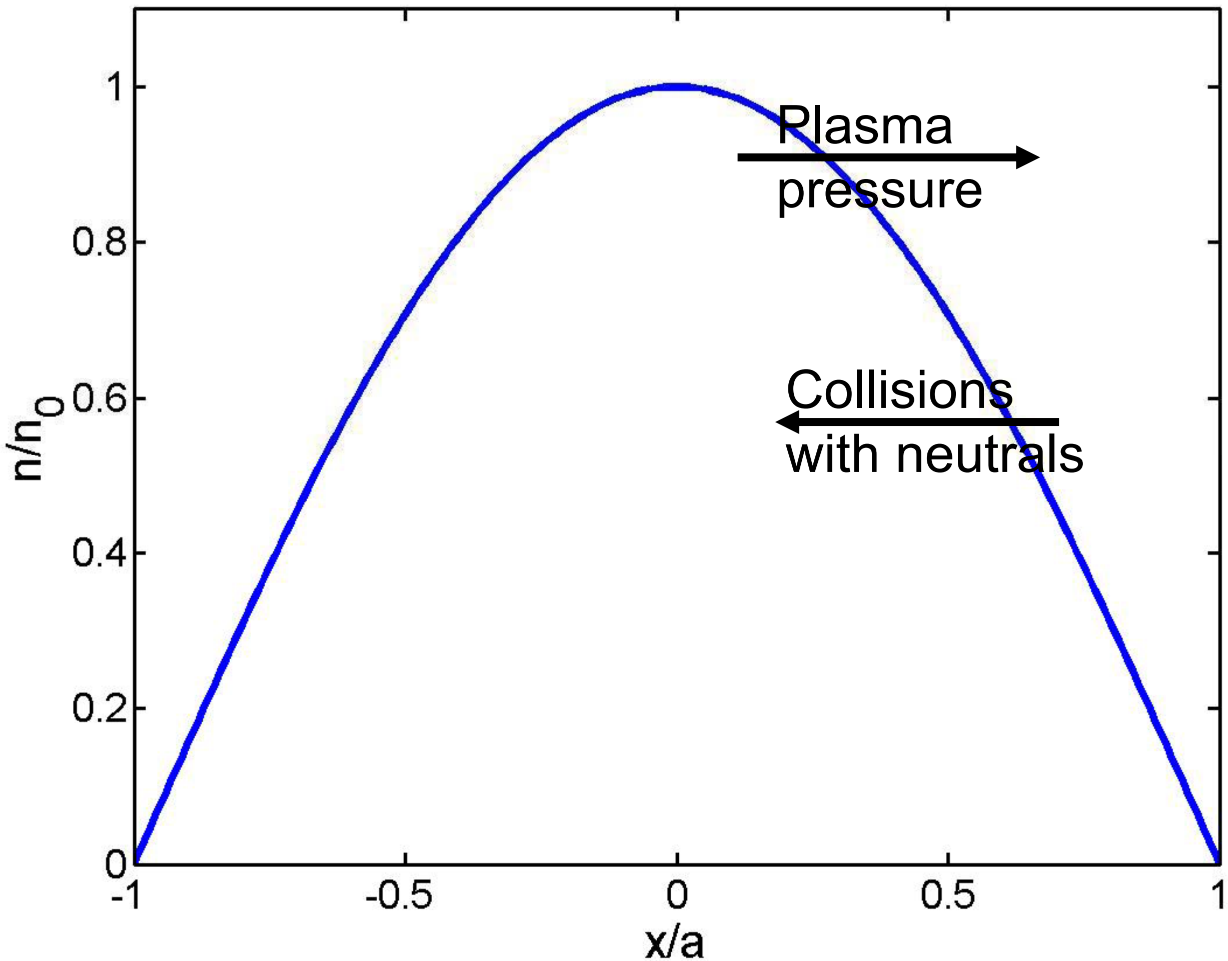
- The plasma dynamics is determined by diffusion.
- The profile of the plasma density is

$$n = n_0 \cos\left(\pi x / 2a\right)$$

Plasma density between two walls – a uniform neutral density



Forces on the plasma

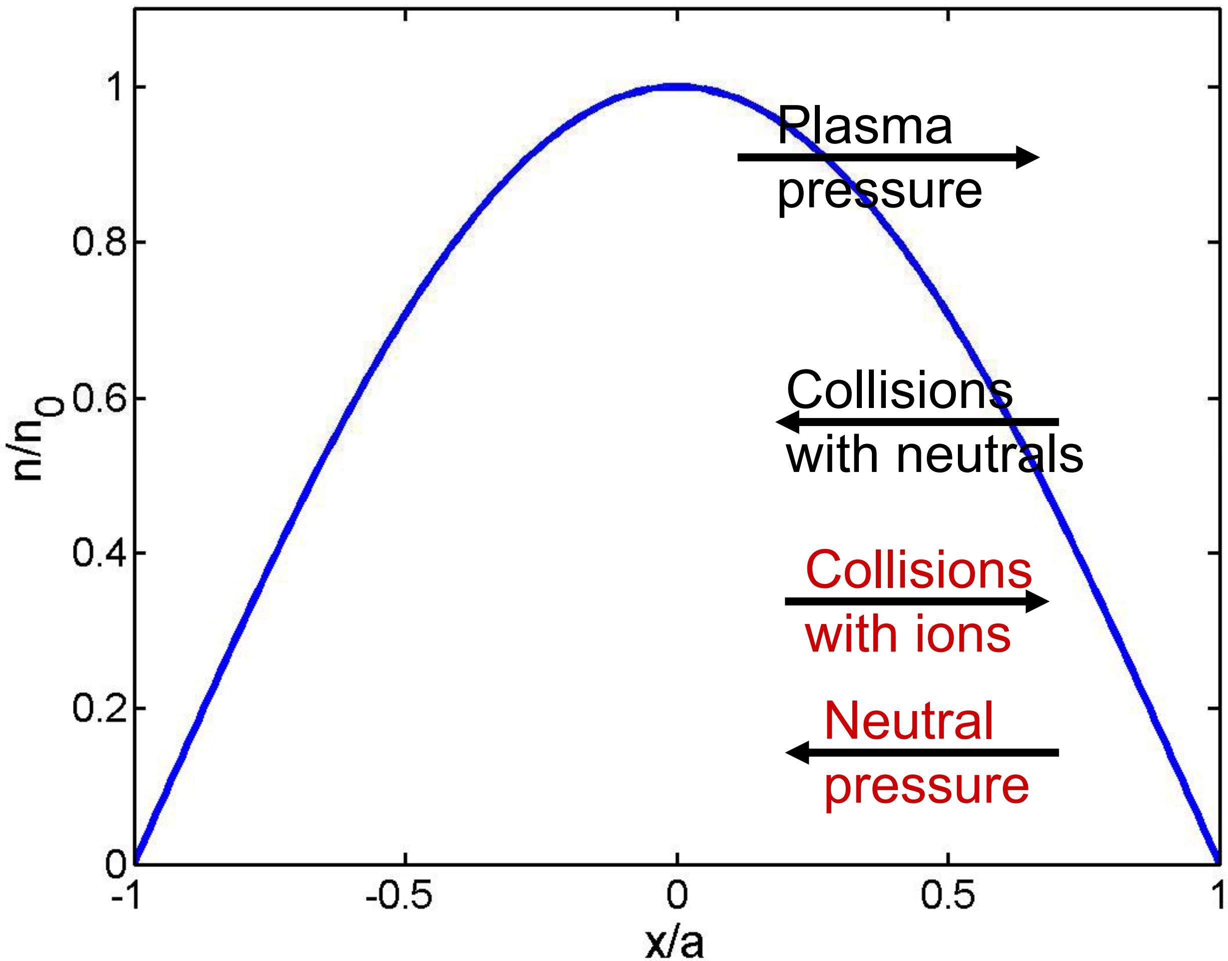


How is the neutral density modified

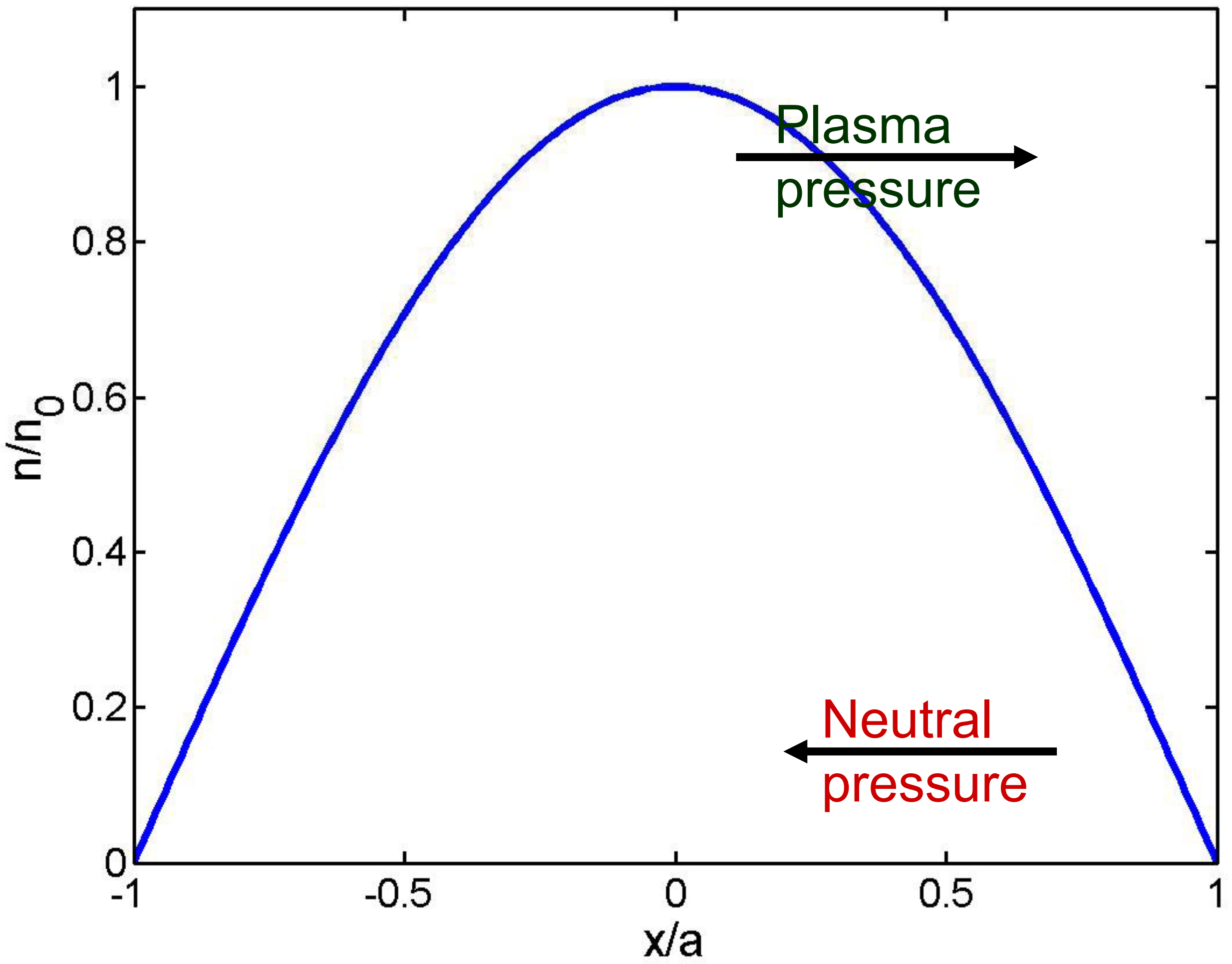
When ionization is intense?

Case 1: neutrals collide with ions

Forces on neutrals

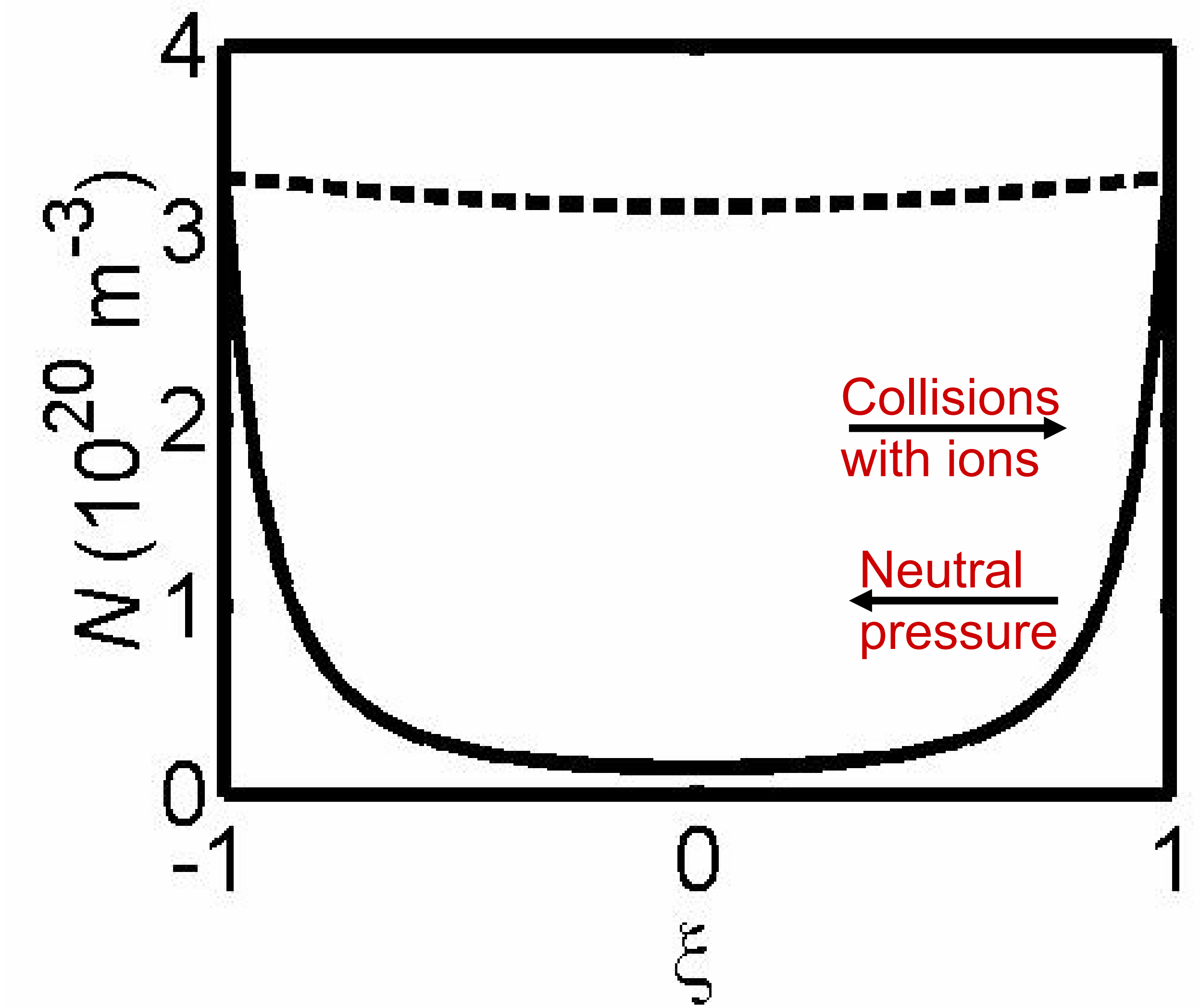


The neutral pressure gradient is opposite in direction to the plasma pressure gradient (pressure balance)



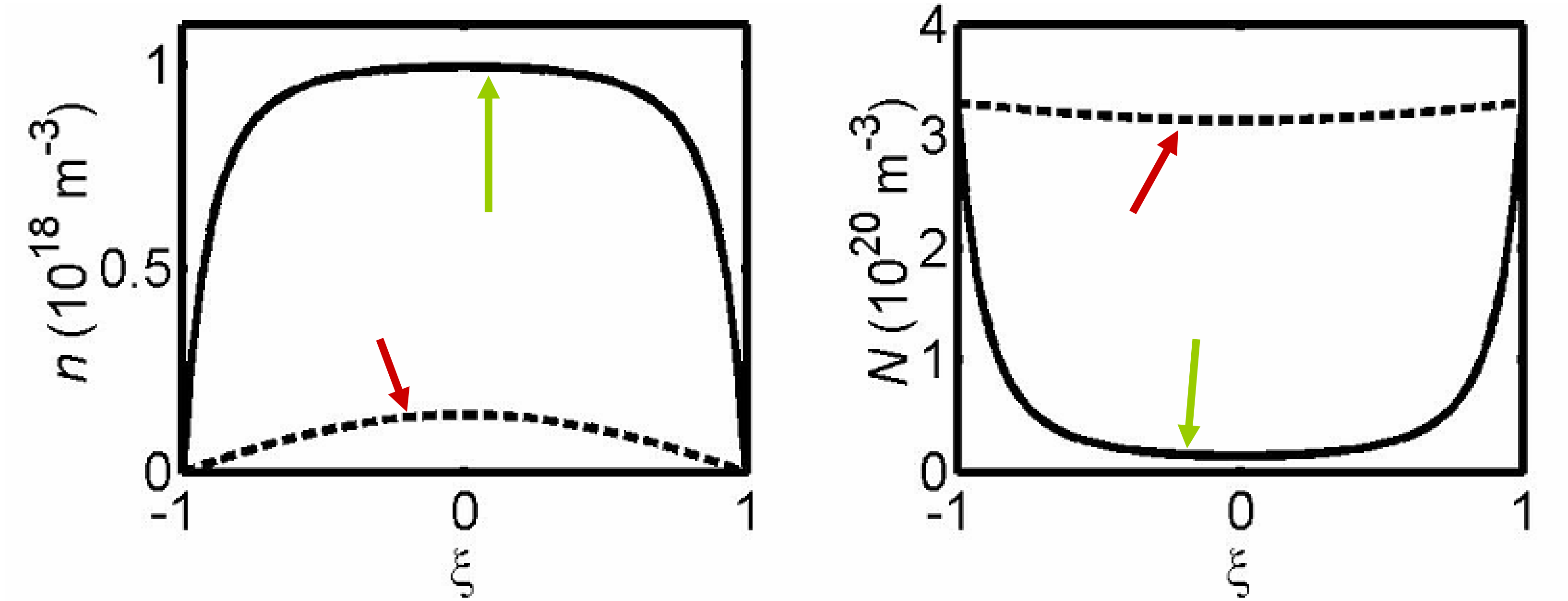
Neutral density proportional to pressure → $P_N = NT_g$

Neutral depletion



Plasma density

Neutral density



Low and high power

Argon

$N_W T_g = 10\,\mathrm{mTorr}$

$a = 5\,\mathrm{cm}$

Similar to experimental results:

Gilland, Breun, and Hershkowitz (1998)

Yun, Taylor, and Tynan (2000)

Nonlinear diffusion equation

$$\frac{\partial}{\partial x}\left[\frac{1}{N}\frac{\partial(nT)}{\partial x}\right]+m\beta_i\beta_c Nn=0$$

$$NT_g+nT=N_W T_g$$

nonlinear solution: $$\frac{\cos\theta-\sin\theta_0}{\sin\theta\cos\theta_0}=\cot\left[\left(\theta_0-\frac{\pi}{2}\right)\xi\right]$$

B.C. $\rightarrow$ a relation between plasma density n_0 and temperature T:

$$\frac{\pi}{2}-\theta_0=\alpha_L^{1/2}\cos\theta_0$$ Kepler's equation.

$$\cos\theta\equiv\frac{n}{n_0}\qquad \sin\theta_0\equiv\frac{n_0 T}{P_r}$$ Maximal plasma pressure / total pressure

$$\alpha_L^{1/2}\equiv\frac{(\beta_i\beta_c)^{1/2}N_w a}{c},\qquad \xi\equiv\frac{x}{a}$$

AF, Makrinich, Chabert and Rax, PRL (2005)

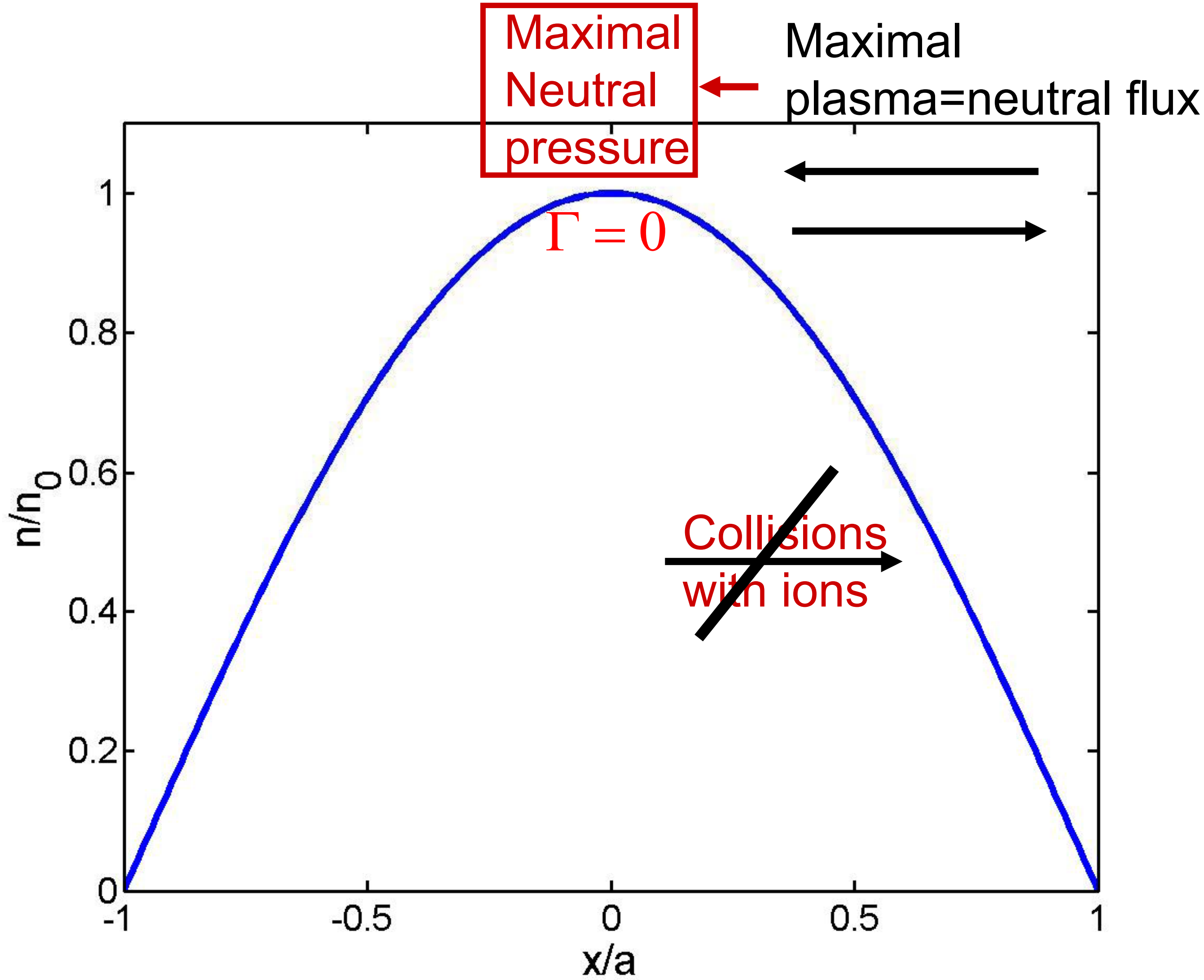
How is the neutral density modified

When ionization is intense?

Case 2: neutrals hardly collide with ions

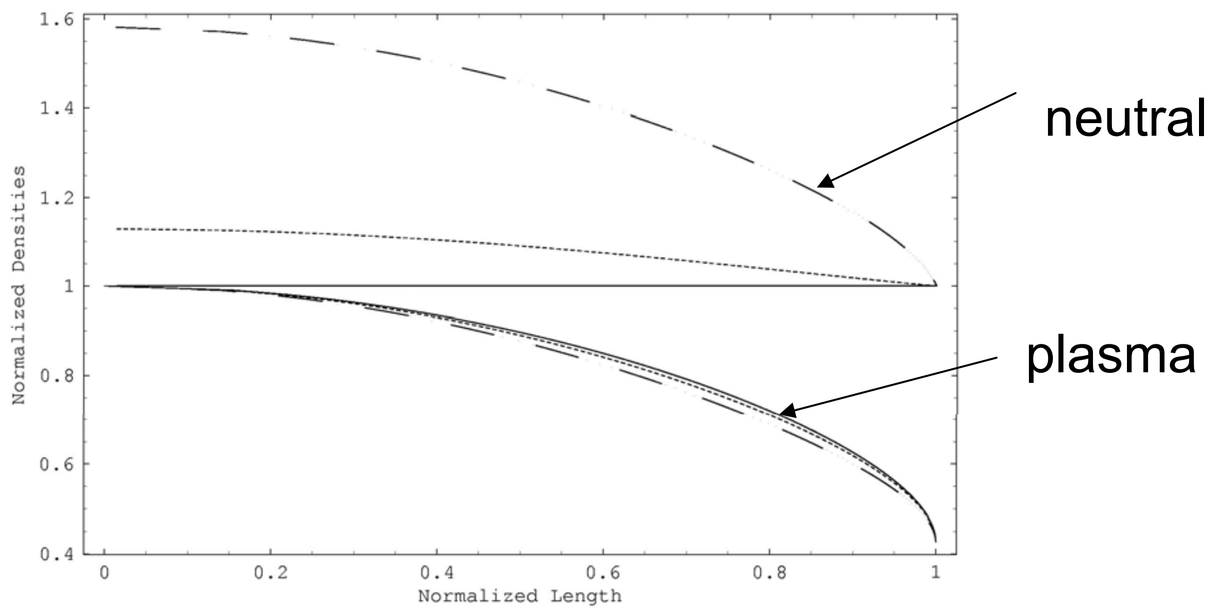
Negligible neutral collisions with ions

$$P_N + m\Gamma^2 / N = P_c$$



$$P_N = NT_g \Rightarrow \text{maximal density where maximum pressure}$$

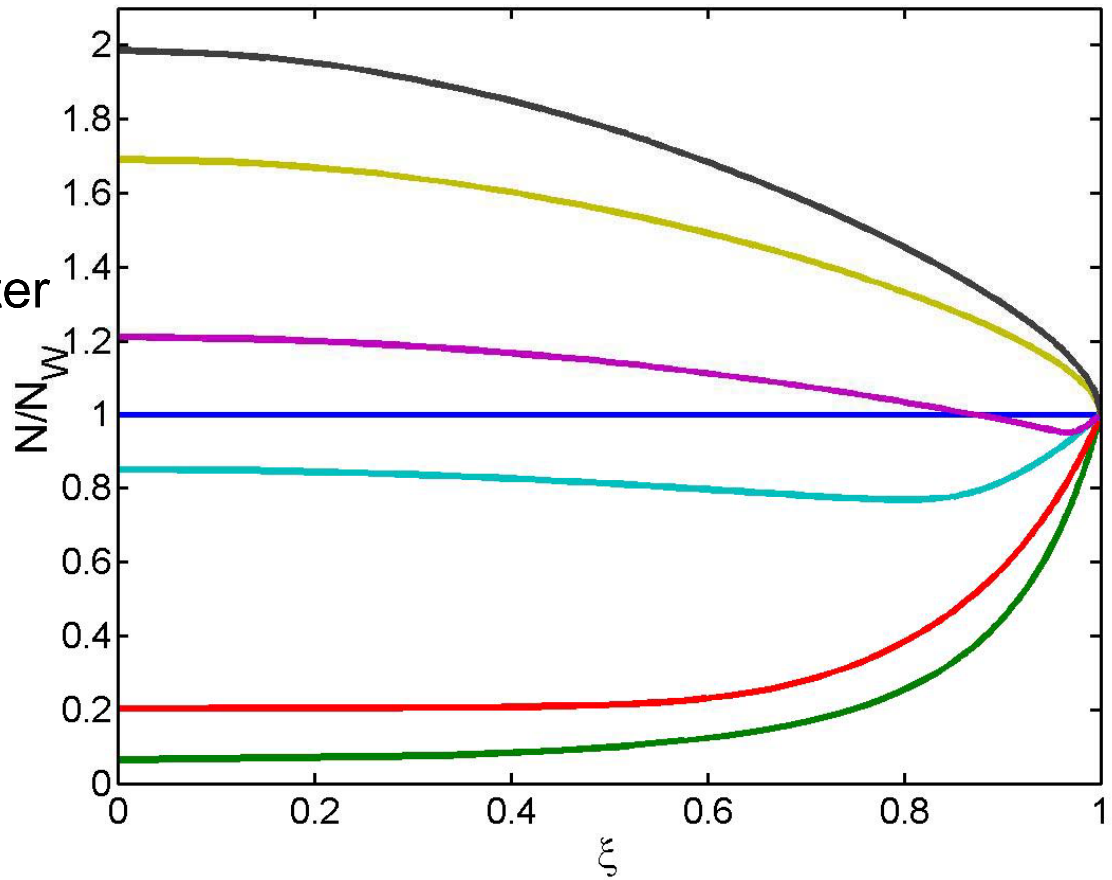
Neutral repletion – as gas is ionized more, its density at the center of the discharge increases



Raimbault, Liard, Rax, Chabert, AF, and Makrinich, PoP (2007)

from neutral depletion to neutral repletion

Discharge center



wall

Plasma flux increases, from depletion to repletion, AF and Rax (2009)

A different case of collisionless neutrals

- Again: neutrals hardly collide with ions
- Neutrals move ballistically
- Neutrals specularly reflected at the walls
- Ions and neutrals are coupled through ionization only

Neutrals Dynamics

Flux towards the wall to the right Γ_1
and to the left Γ_2 from the wall.

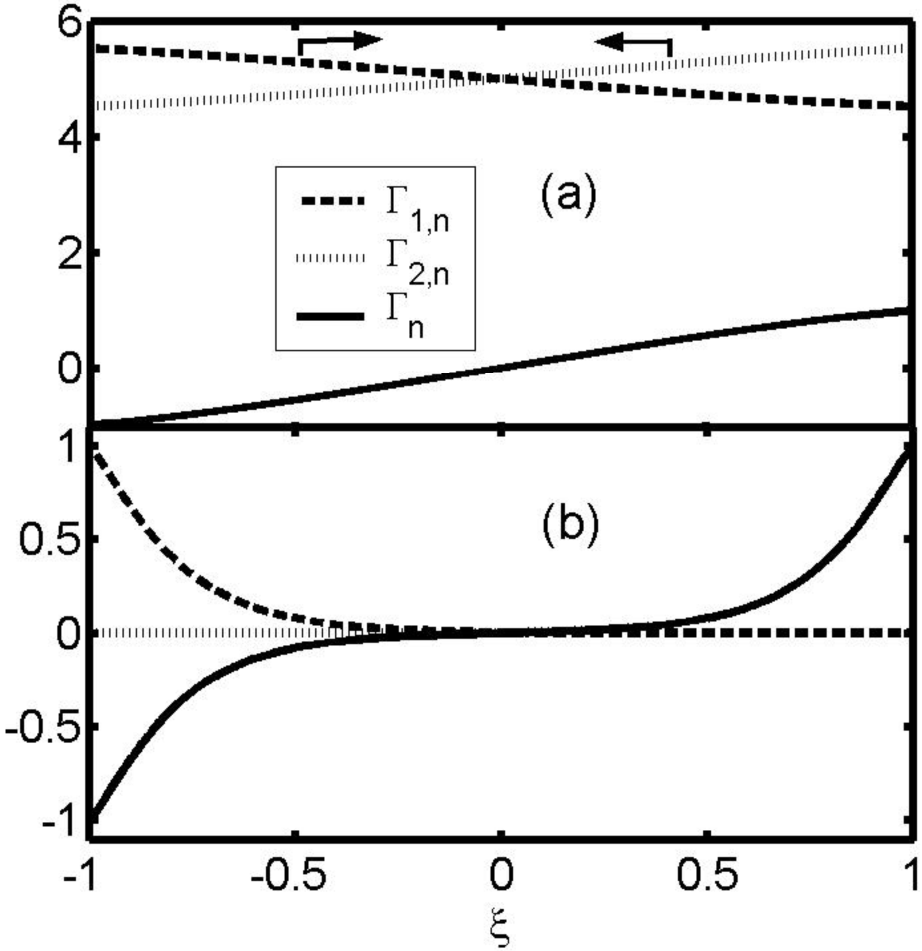
$$\Gamma_i + \Gamma_1 - \Gamma_2 = 0 \qquad \text{zero mass flow}$$

$$\frac{d\Gamma_1}{dx} = -\beta N_1 n, \quad \frac{d\Gamma_2}{dx} = \beta N_2 n \Rightarrow \Gamma_1 \Gamma_2 = \Gamma_0^2$$

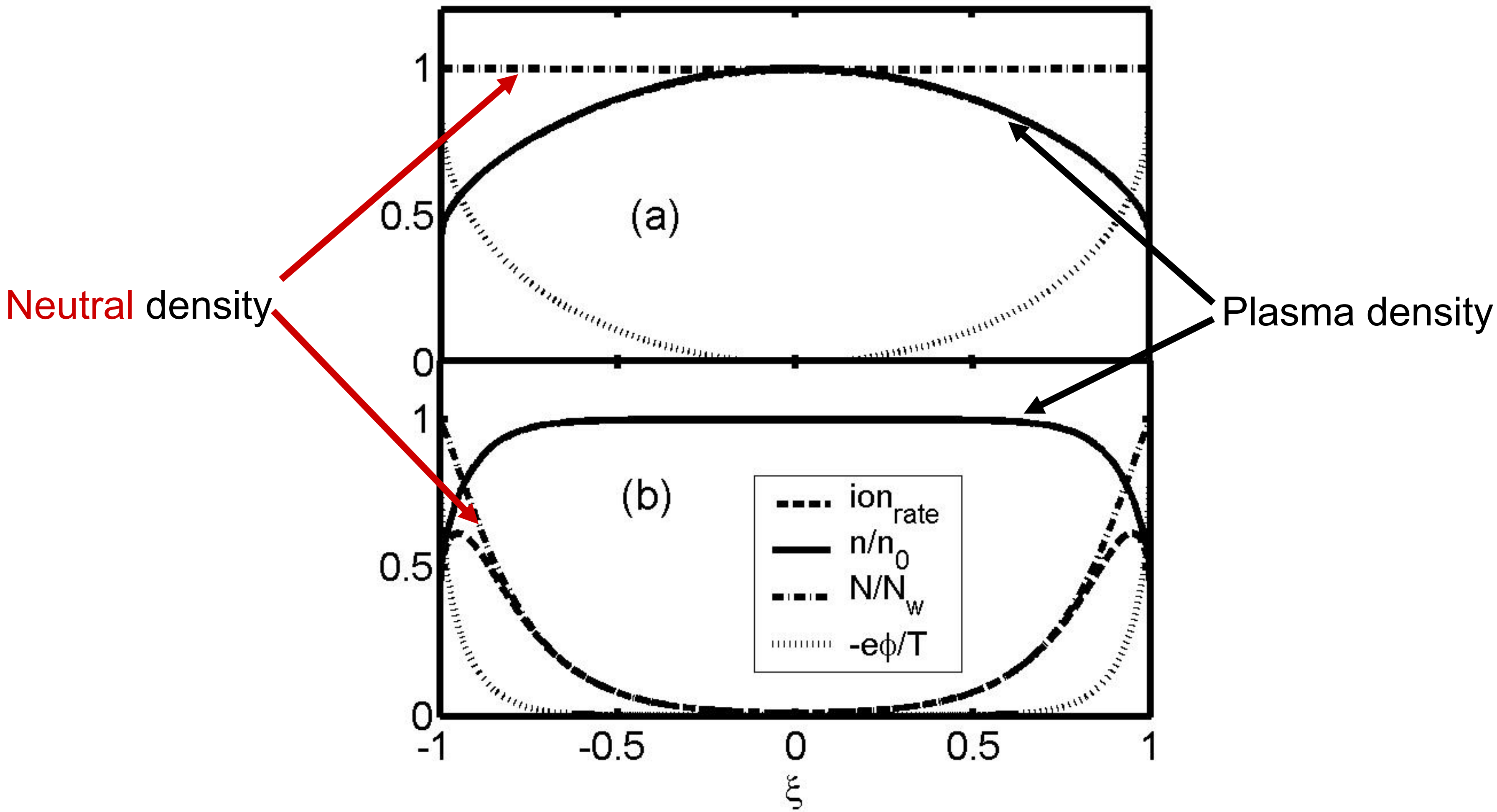
Two opposing neutral beams

Low ionization

High ionization

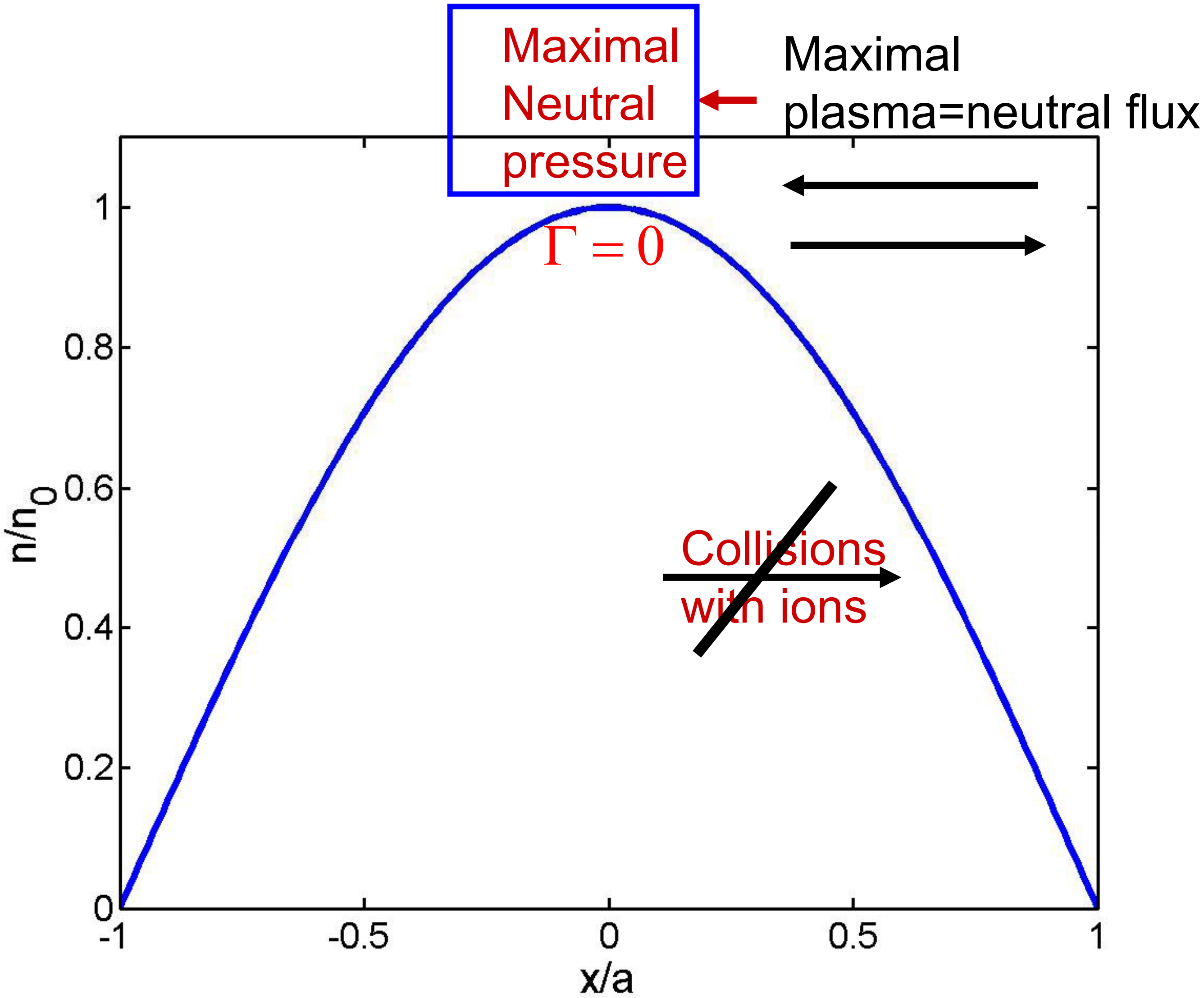


Neutral density is minimal at the center – neutral depletion

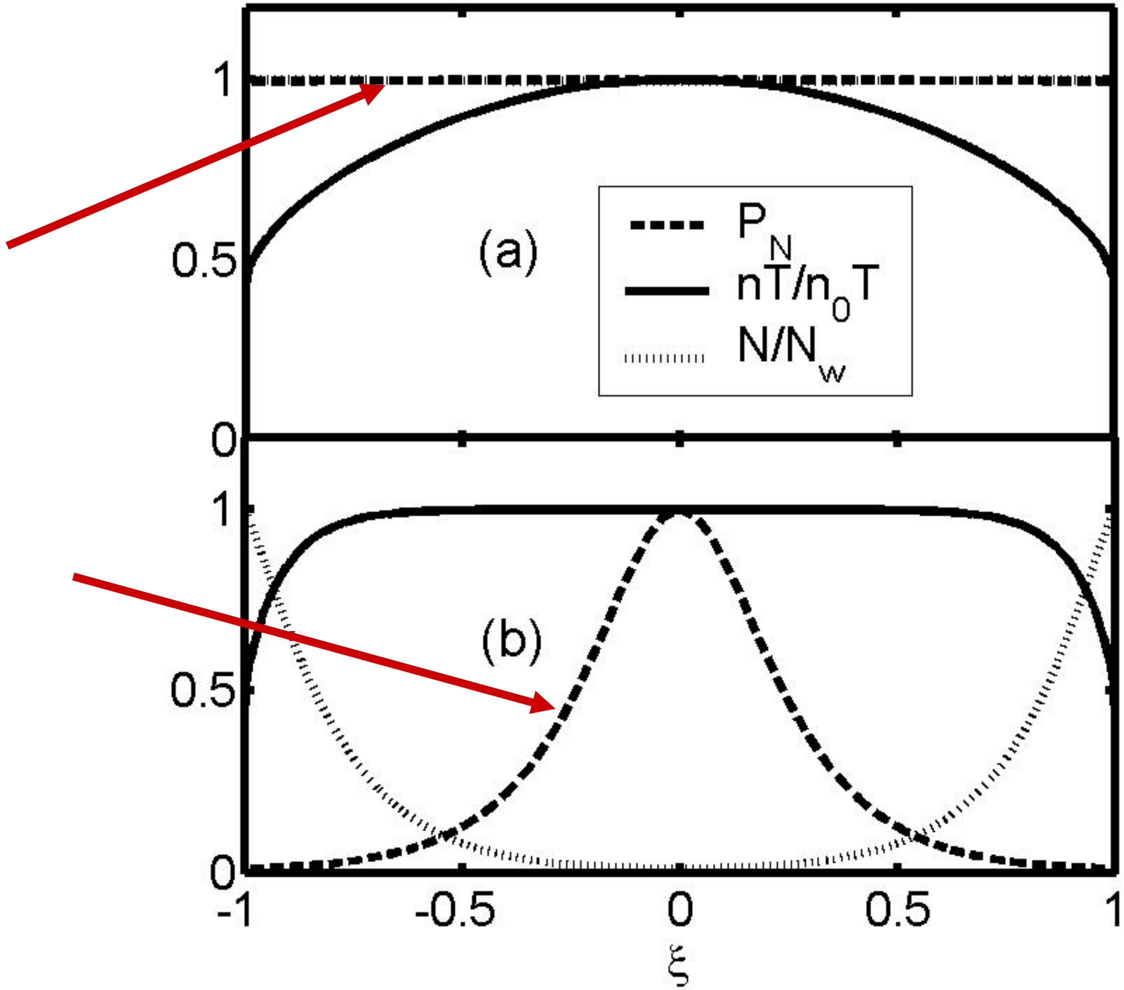


BUT!!! we said that: Negligible neutral collisions with ions

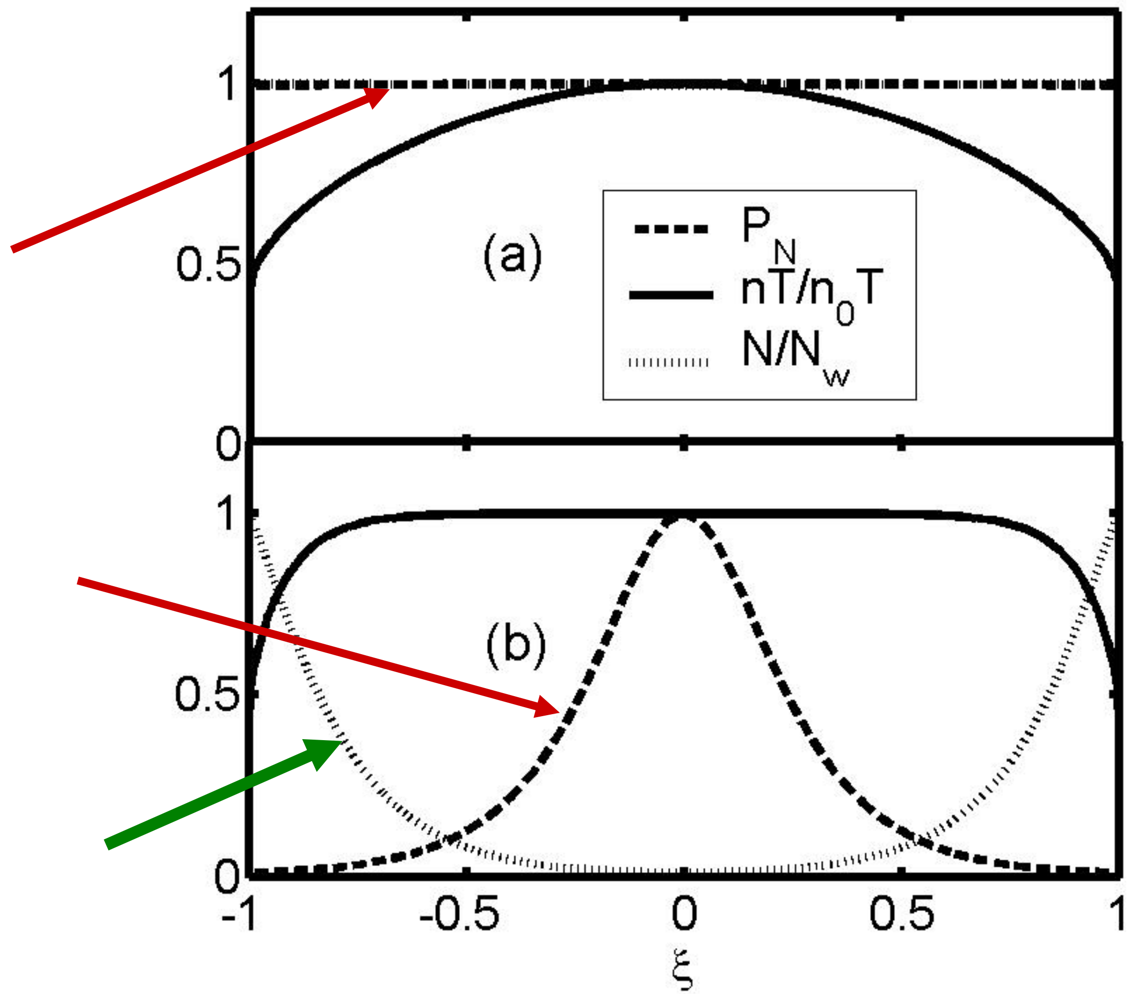
$$P_N + m\Gamma^2 / N = P_c$$



Neutral pressure is indeed maximal at the center



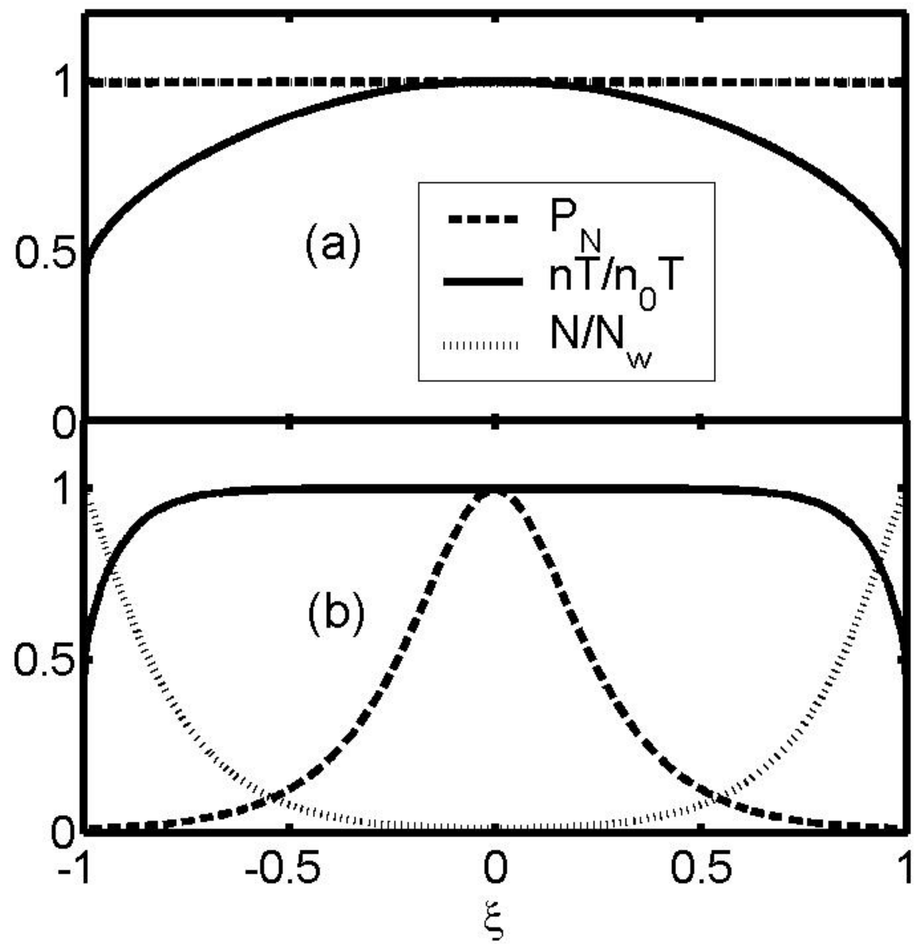
But neutral density is inversely proportional to neutral pressure and is minimal at the center



But neutral density is inversely proportional to neutral pressure and is minimal at the center

$$P_N \propto \frac{1}{N}$$

AF, IEEE TPS (2008)



How is the plasma density modified

When ionization is intense

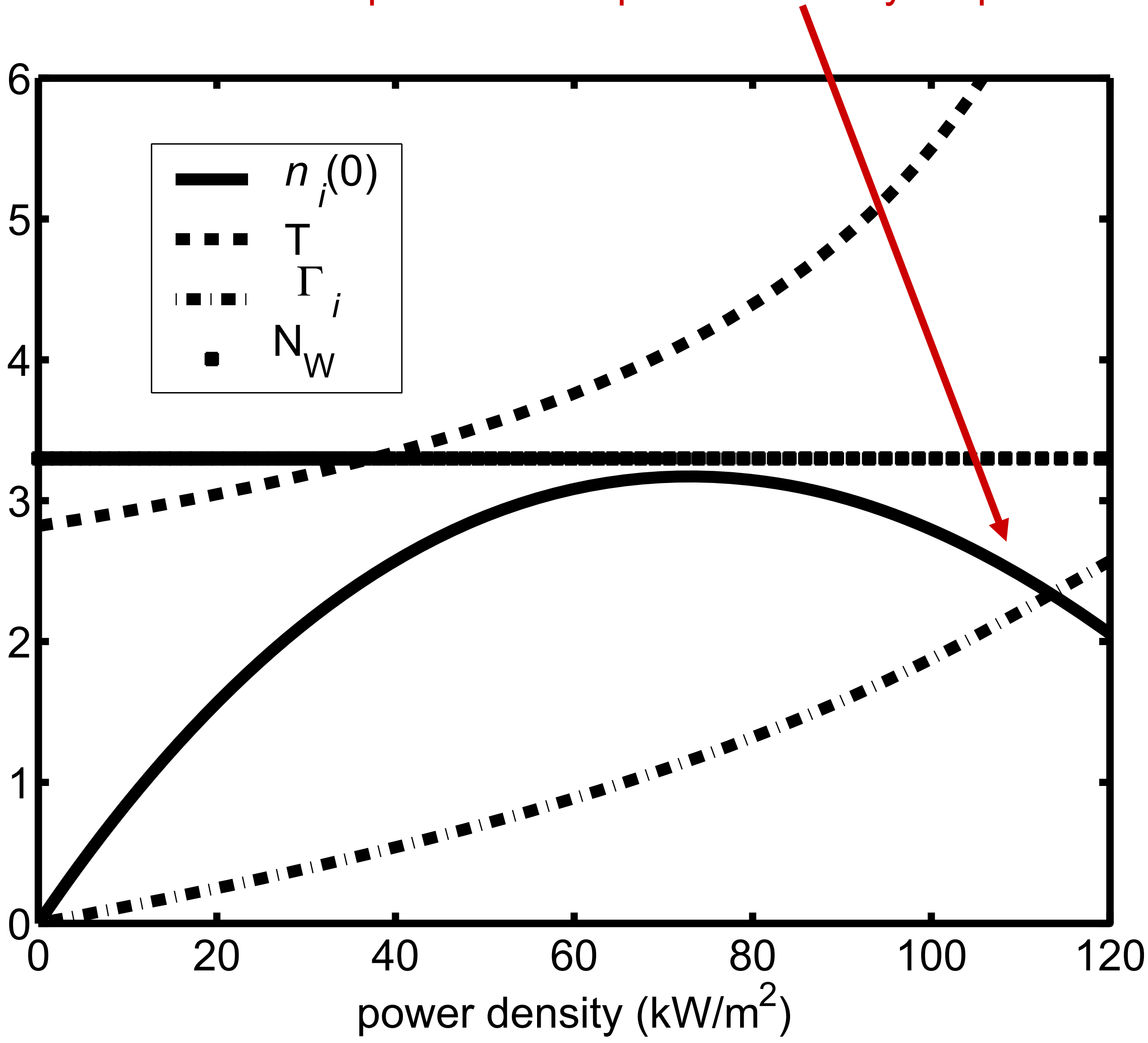
Due to neutral depletion

(neutral collisions with ions are important)

1D, planar geometry – weakly ionized plasma

- The plasma dynamics is determined by diffusion.
- The plasma density is linearly proportional to the ionization rate (and the plasma outward flux).
- The plasma peak density n_0 is linearly proportional to the plasma flux.
- What happens when neutrals are depleted?

Nonmonotonic dependence of plasma density on power



AF, Makrinich, Chabert and Rax, PRL (2005)

Increase of plasma flux and decrease of plasma density

- Neutrals are depleted $\longrightarrow$ less slowing-down collisions of ions with neutrals.
- Plasma transport is enhanced.
- Residence time of ions (and electrons) is reduced.
- The plasma density decreases even though the plasma flux increases.

Neutral depletion and cross-field diffusion

- When there is a magnetic field plasma collisions enhance cross-field transport.
- When electron-neutral collisions are dominant, neutral depletion reduces transport.
- The plasma residence time increases.
- The increase of plasma production is followed by a larger density increase.

Electron-neutral collisions: from linear to exponential dependence

Low power:

$$n_0 = \frac{m_e \omega_e^2 a}{T_e k_{eN} N_W} \Gamma$$

High power:

$$n_0 = \frac{T_g m_e \omega_e^2}{T_e m_i k_{iN} k_{eN} N_W} \exp\left(\frac{a m_i k_{iN}}{2T_g} \Gamma \right)$$

Neutral depletion and cross-field diffusion

- However…..
- When neutrals are depleted and plasma density increases, electron–ion collisions dominate cross field diffusion.
- The plasma density increase is followed by an enhanced transport.
- The residence time decreases.
- The increase of plasma production is followed by a smaller density increase.

Electron-ion collisions: slow density increase

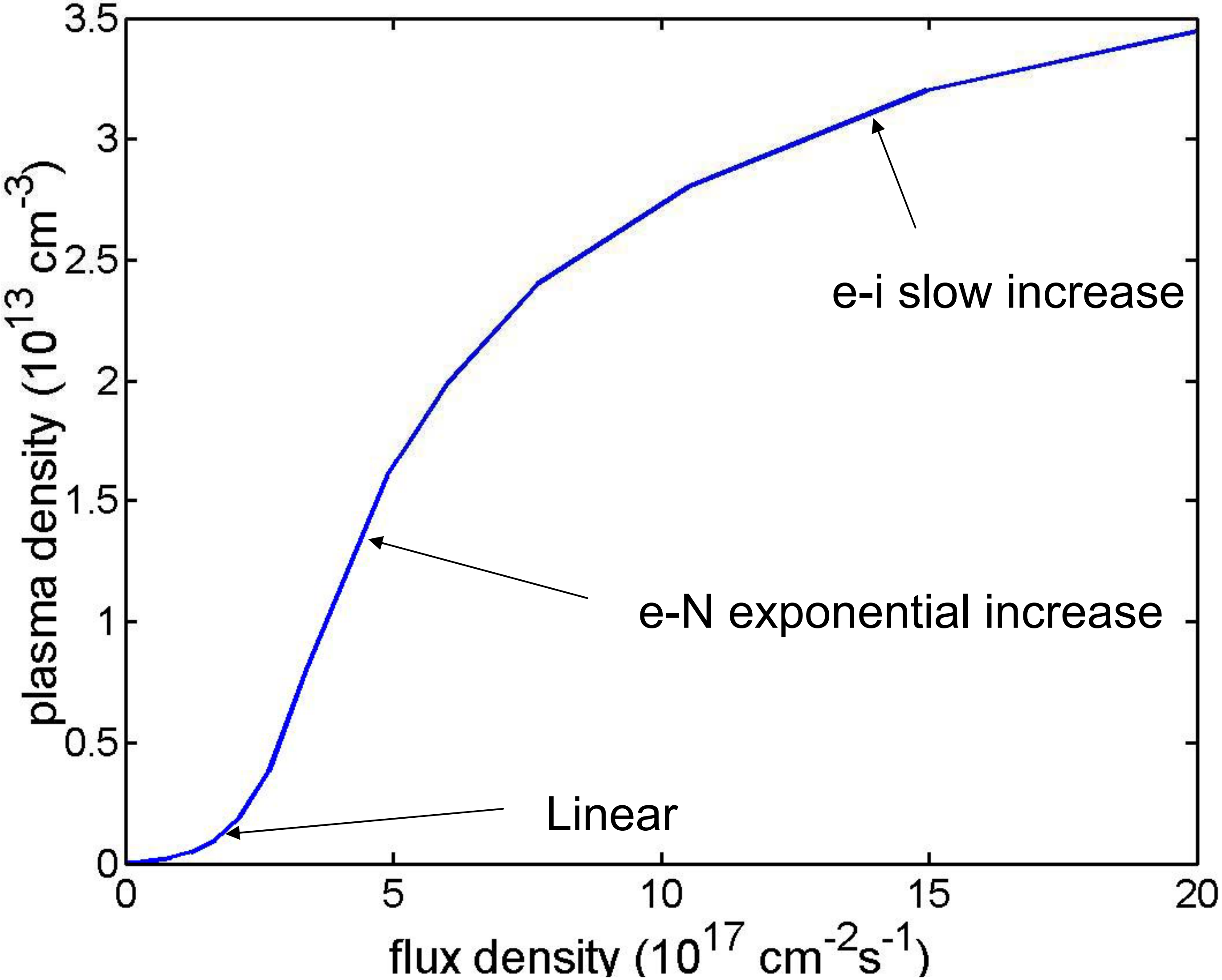
$$n_0 = \sqrt{2\frac{T_g m_e \omega_e^2}{T_e m_i k_{iN} k_{ei}} \ln\left(\frac{a m_i k_{iN}}{T_g}\Gamma\right)}$$

previously, electron-neutral collisions:

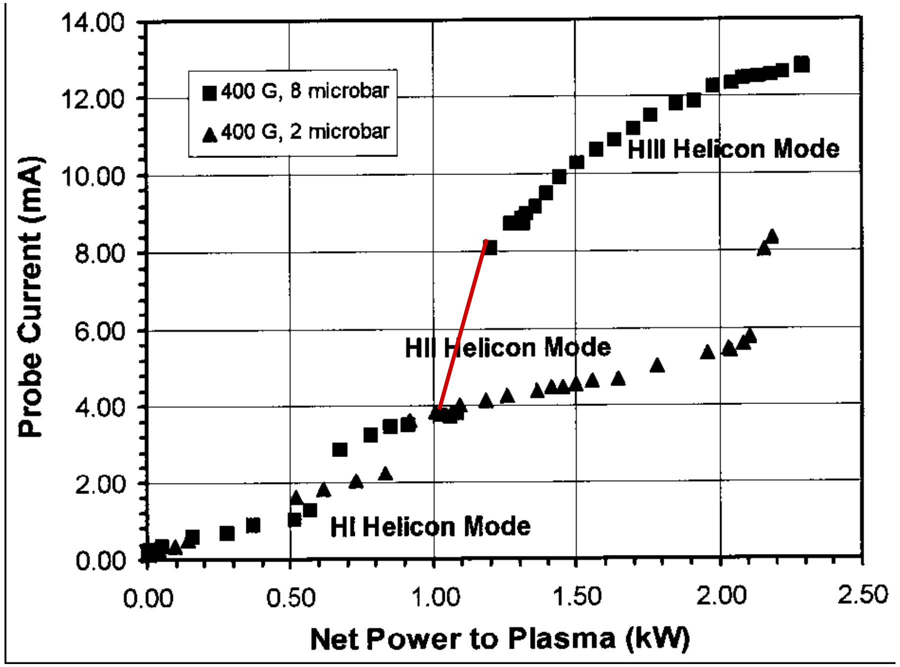
$$n_0 = \frac{T_g m_e \omega_e^2}{T_e m_i k_{iN} k_{eN} N_W} \exp\left(\frac{a m_i k_{iN}}{2T_g}\Gamma\right)$$

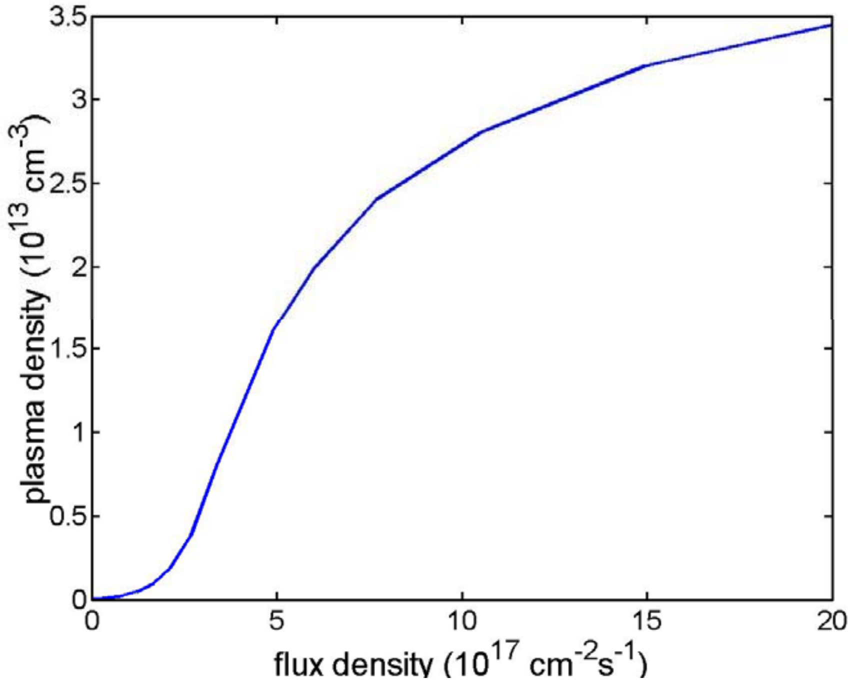
AF, PSST (2009)

Transport-induced density "jump"



Similar to density jumps seen experimentally





Summary

- The nonlinear dynamics due to coupled ionization and transport results in unexpected behavior.
- These unexpected effects are important for gas discharges.
- Perhaps also for other plasmas.