How to Control and Predict Plasma Parameters in Plasma Sources

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PPPL
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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...

- **Observed dependences of n_e,T_e on p, L**
- **Global model for n_e,T_e (p,L)**
- **Evaporating electron cooling in afterglow**
- **Fast kinetic code for plasma sources modeling**

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Godyak's Experiment is Benchmark.

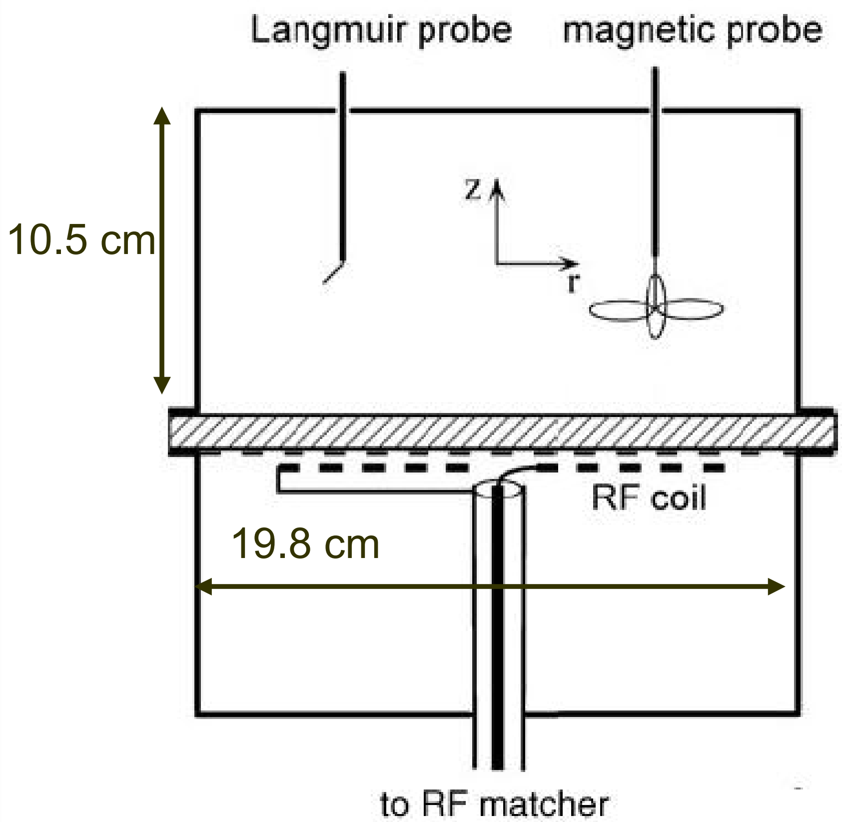


Figure 1. Experimental discharge chamber.

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

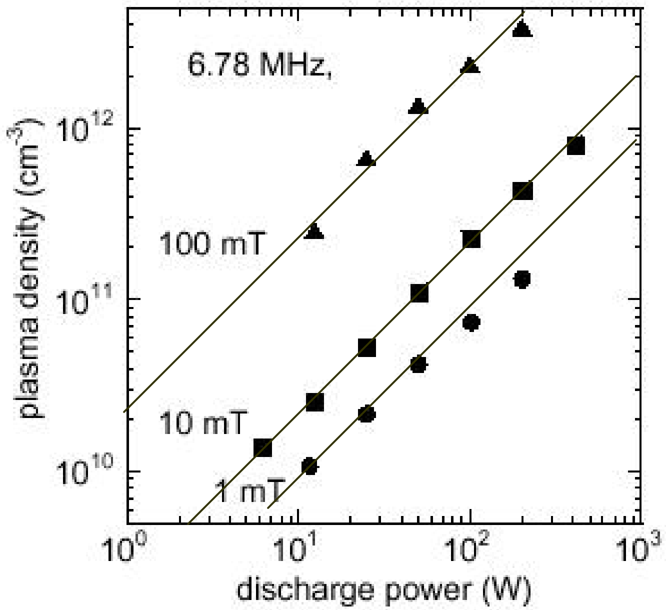
Measurements were made at

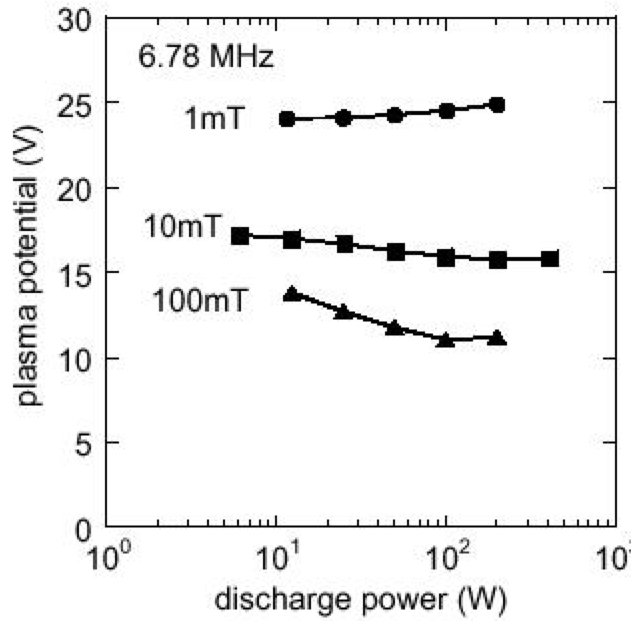
f=0.45-13.56 MHz

in argon gas pressures of 0.3-**300** mTorr **and**

rf power dissipation in the plasma 6-400 W.

Electron Density and Plasma Potential Versus Power

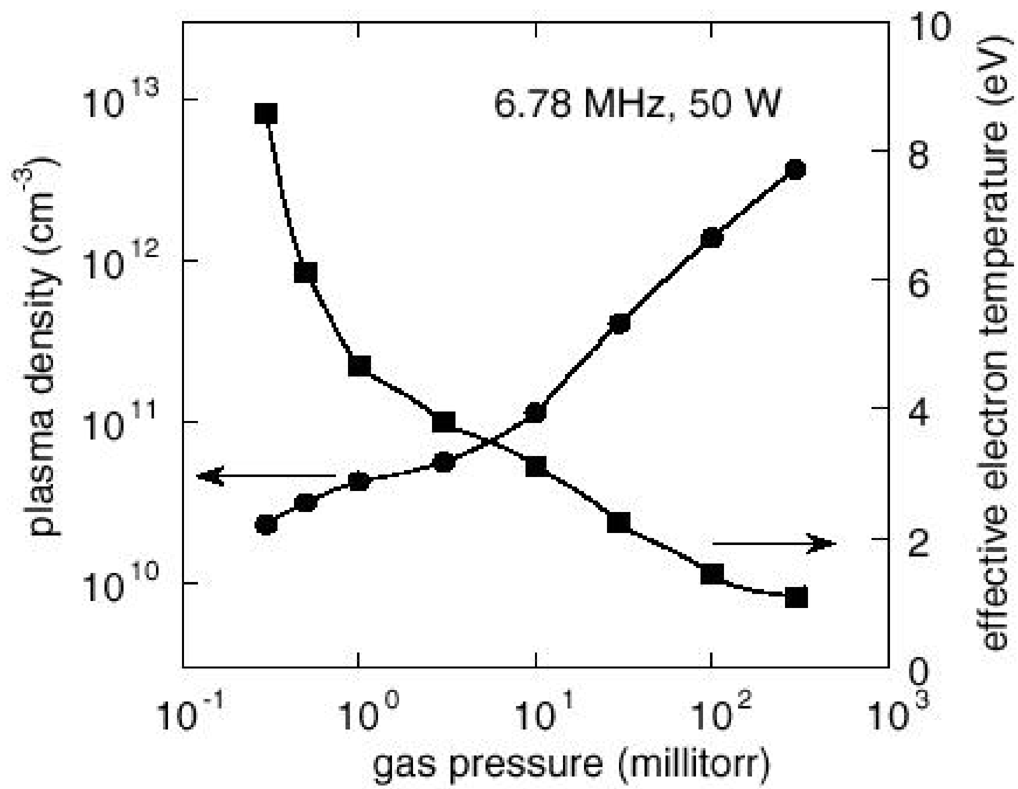




n_e ϕ_{pl} (~6 T_e) in the discharge center as a function of power (P) at f=6.78 MHz

n_e scales linear with P, whereas ϕ_{pl} and T_e ~const.

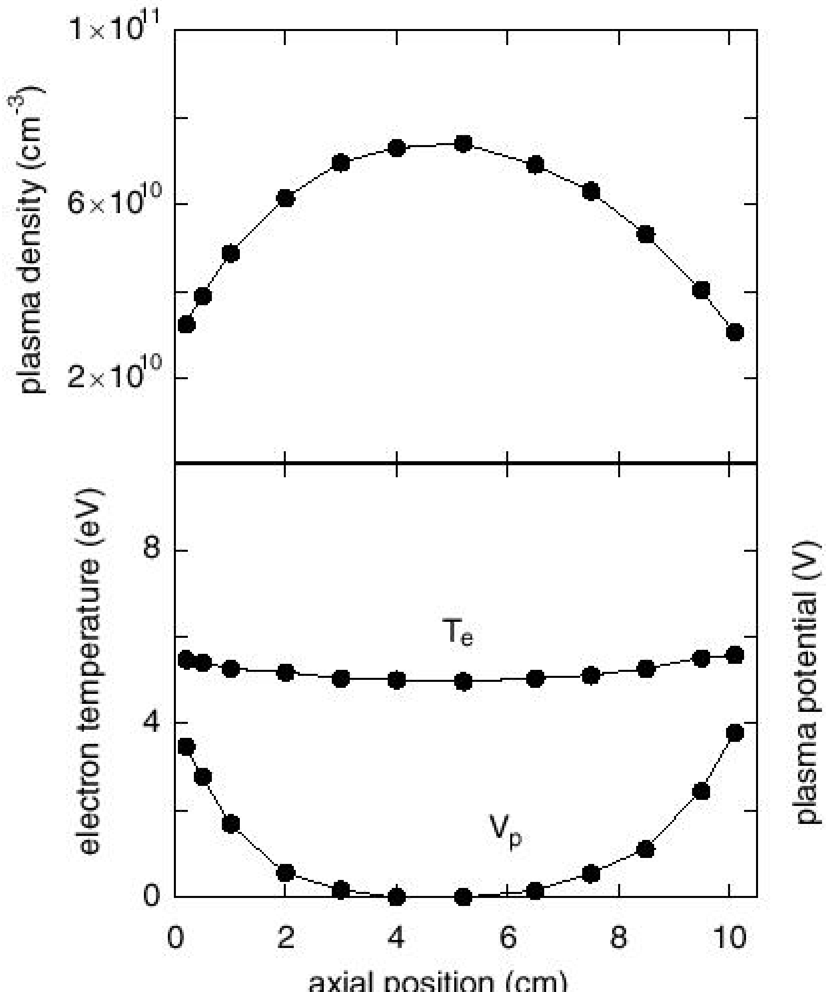
Electron Density and Plasma Potential Versus Pressure



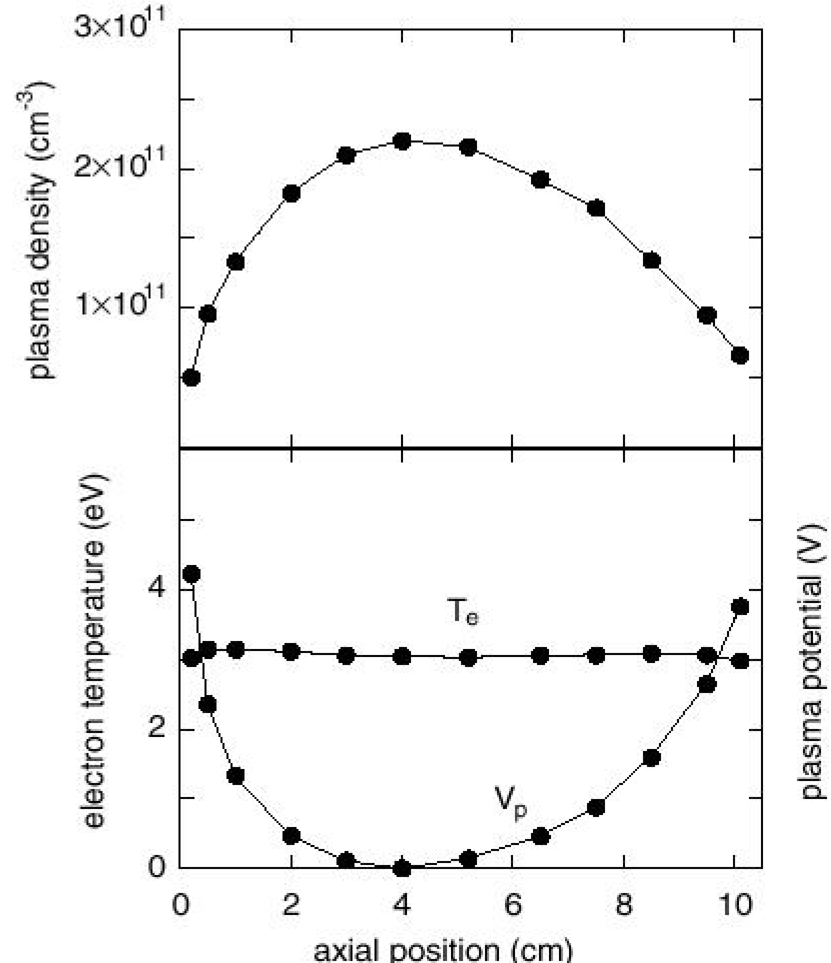
n_e,T_e in the discharge center at fixed power 50W, f=6.78MHz

More gas, more plasma and smaller T_e

Electron Density, Temperature and Potential Profiles



1mTorr



10mTorr

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Plasma is Partially Ionized

Plasma density $n_e = 10^9 - 10^{13}$ cm^{-3}

Gas density $n_g = 3.5\ 10^{13}$ cm^{-3} p(mTorr)

- **Small degree of ionization $n_e/n_g < 10^{-3}$**
- **Collisions with gas atoms are dominant**

Particle Balance Determines T_e

$$\nu_{iz}(T_e) = \nu_{loss}(T_e)$$

- **Quasi-Steady-State =>**
  - **Rate of plasma production = rate of plasma loss, or**
  - **Ionization frequency = loss frequency to the wall**

Calculation of Ionization Frequency

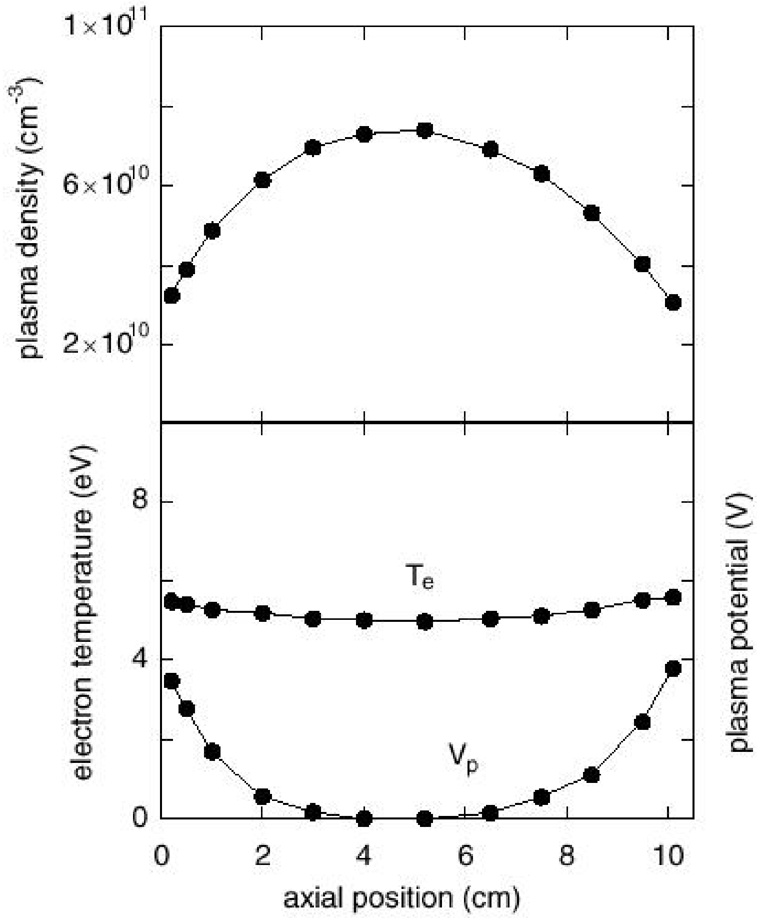
$$\nu_{iz} n_e = n_g \int_{m\mathbf{v}^2/2>I}^{\infty} |\mathbf{v}| \sigma_{iz}(\mathbf{v}) f(\mathbf{v}) d^3\mathbf{v},$$

$$\nu_{iz} = n_g V_T \sigma_{iz} e^{-I/T_e},$$

where I is ionization potential 15.8eV,

V_T is the electron thermal velocity.

Loss Frequency



Electrons are confined

$$n_e(x) = n_e(0)\exp(e\phi / T_e)$$

Potential of order T_e accelerates ions

$$C_s = \sqrt{T_e / M}$$

$$\nu_{loss} = \gamma C_s / L$$

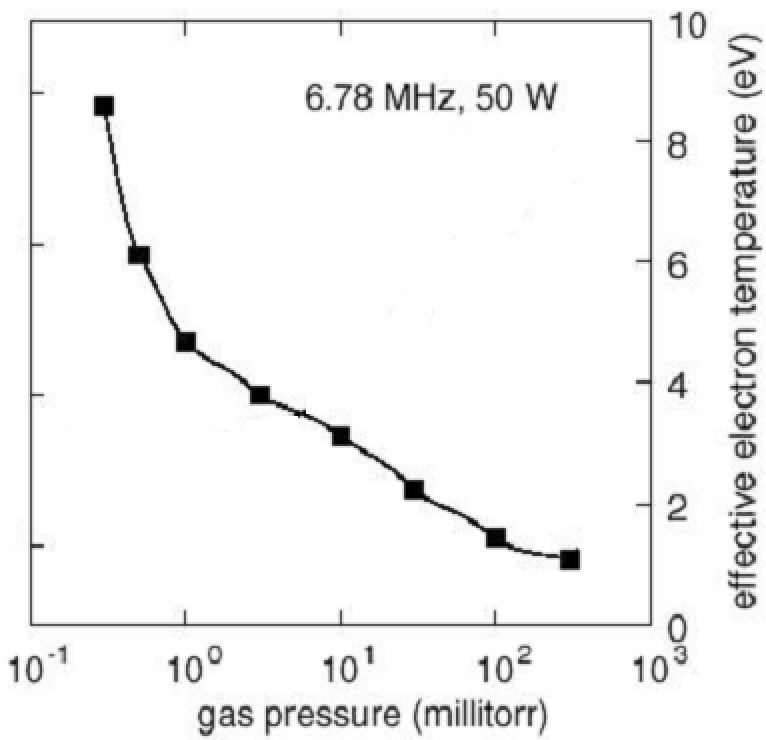
Particle Balance: T_e (PL)

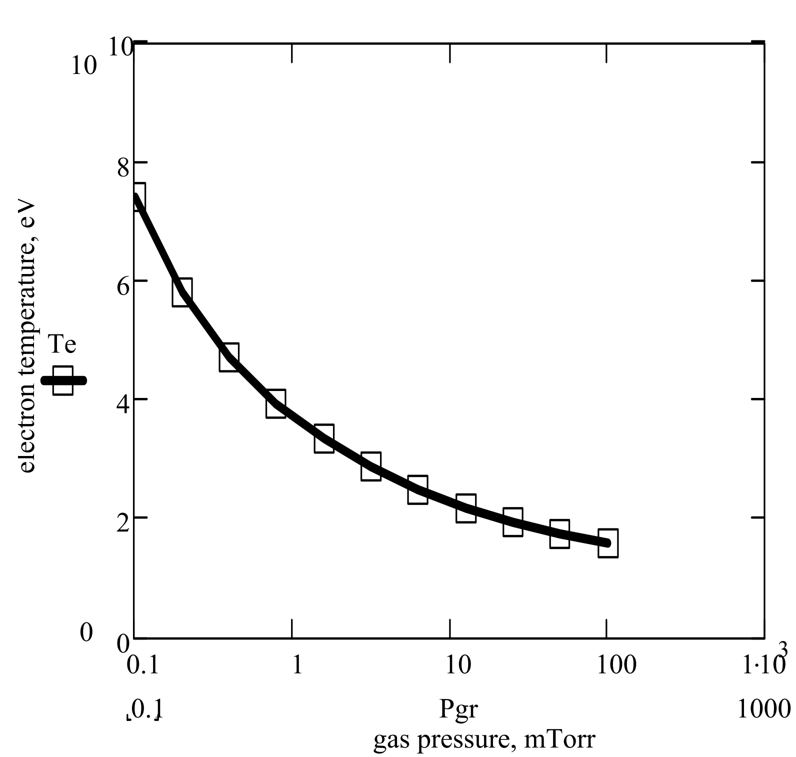
$$\nu_{iz}(T_e) = \nu_{loss}(T_e)$$

$$n_g V_T \sigma_{iz} e^{-I/T_e} = \gamma \frac{\sqrt{T_e / M}}{L}$$

More $n_g L$ less T_e

Experiment (left) and Global Model (right) Give Close Agreement





T_e as a function of gas pressure at f=6.78 MHz

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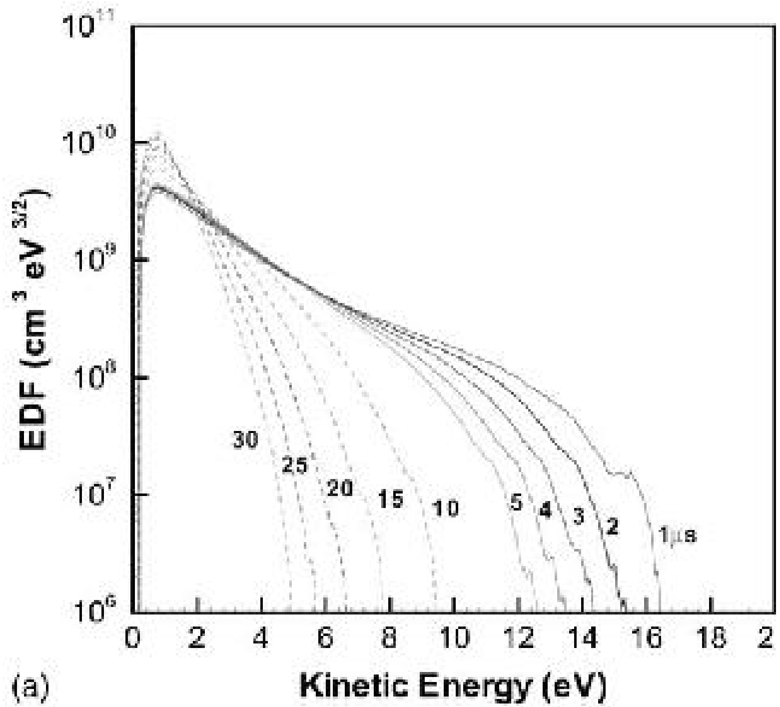
Evaporative Electron Cooling in Afterglow



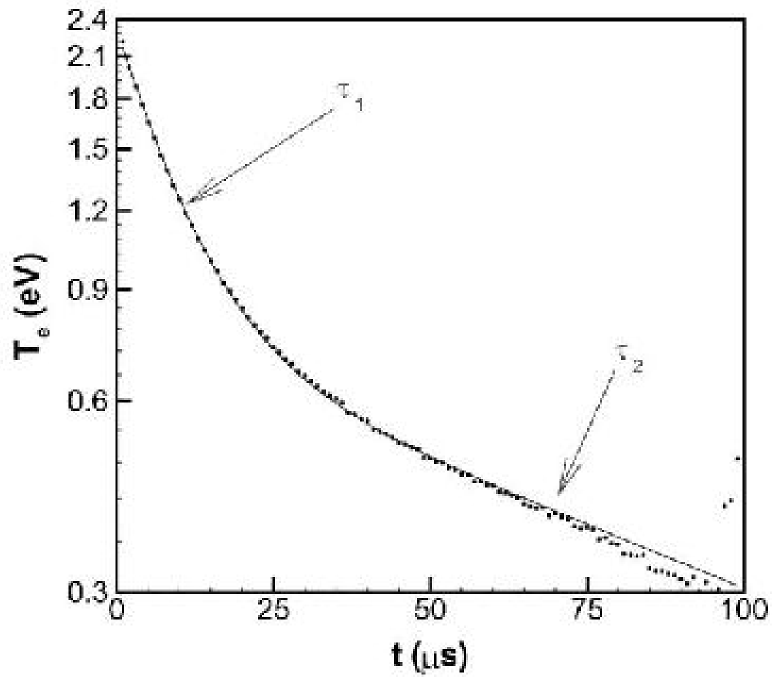
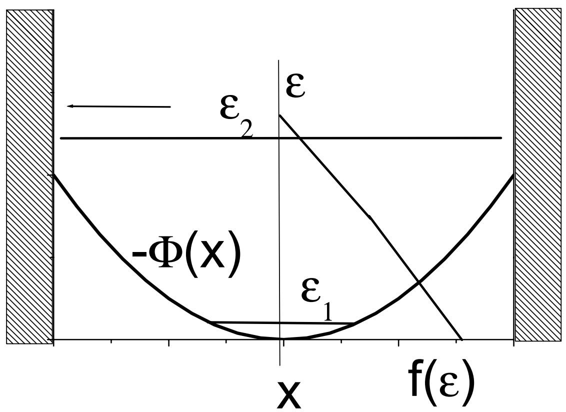


Fig. 7. Decay of the "electron temperature" at 15 mTorr.

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

Evaporative Electron Cooling in Afterglow



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

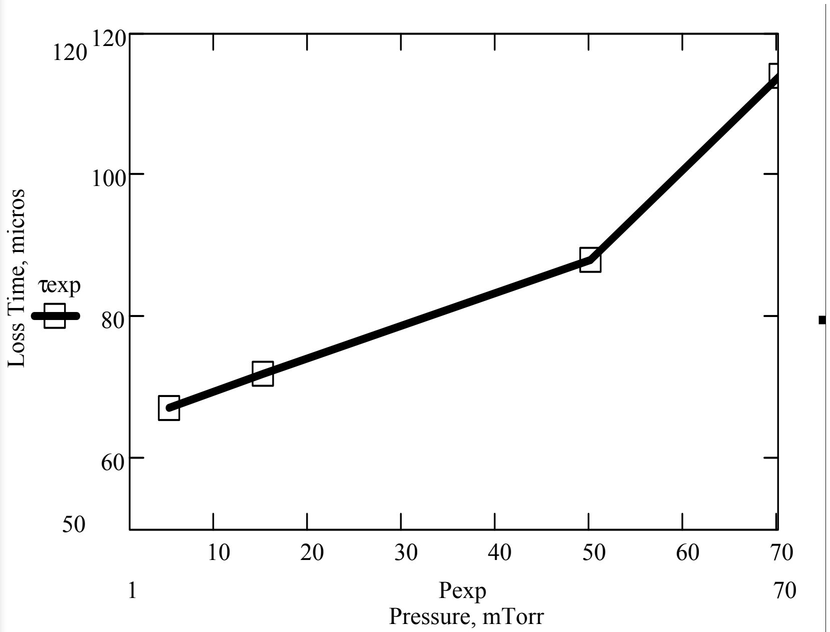
Inelastic Collisions (Ar Excitation) cool tail quickly

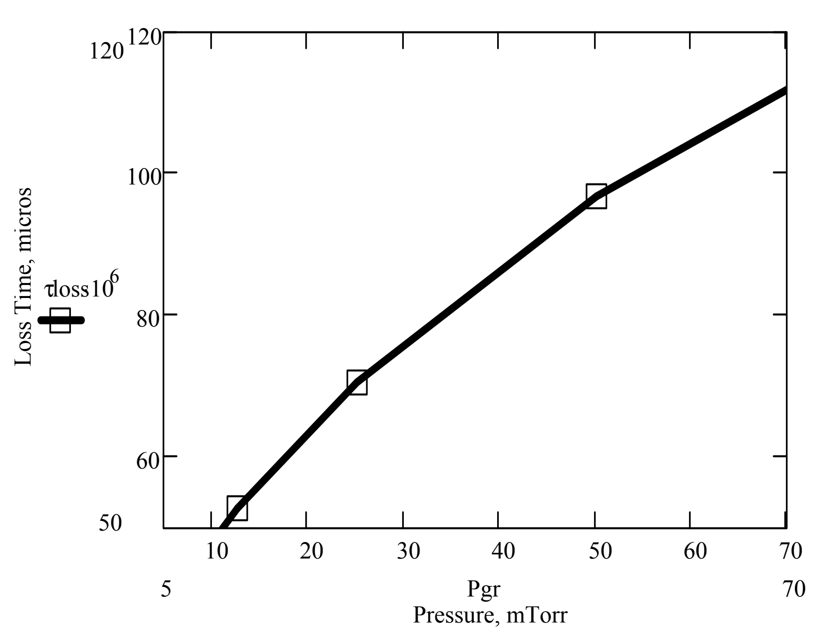
Than evaporated cooling as fast electrons leave fast

$\tau(T_e) \sim \tau(n_e)$

	T_e	n_e	inelastic	
τ,μs	10, 72	56	0.1	

Experimental Temperature Decay Time and Theoretical Estimate For Density Decay





Experiment T_e decay time in microseconds.

Theoretical estimate for n decay in microseconds.

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Bibliography

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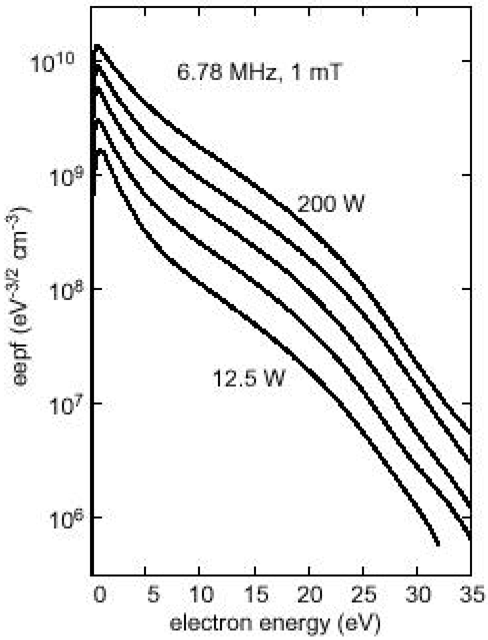
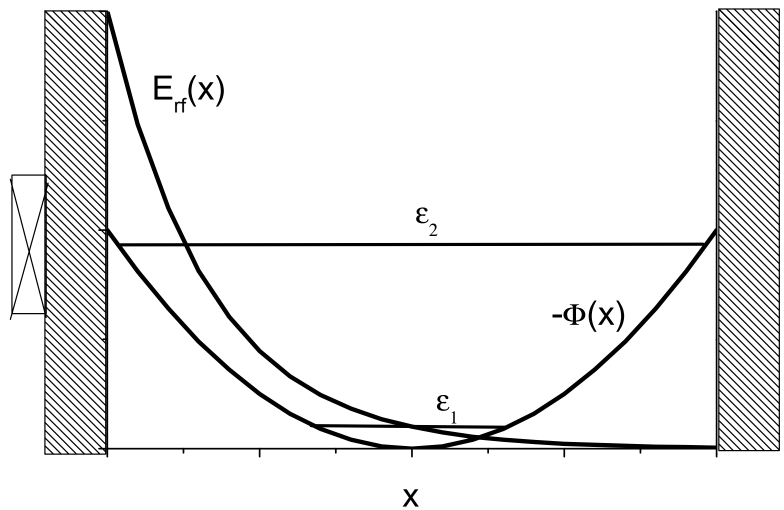
I. D. Kaganovich, et al , “Landau damping and anomalous skin effect in low-pressure gas discharges: self-consistent treatment of collisionless heating”, to be published in Phys. Plasmas (2004).

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).

Electron Distribution Function is not Maxwellian





Measured EDF shows departure from a Maxwellian:

Cold electrons are trapped in a small rf electric field.

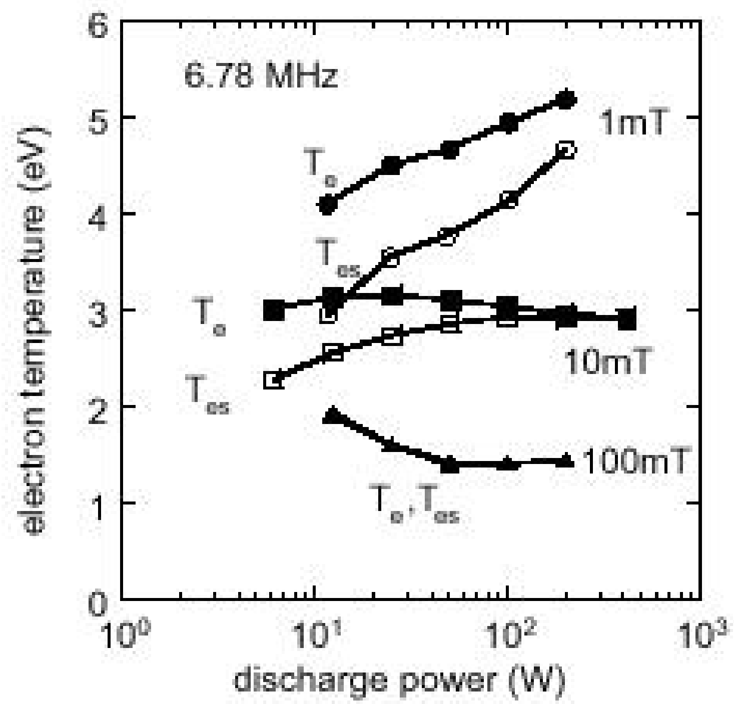
Concept of Screening Temperature

EDF is not Maxwellian, introducing T_{es}, so that

$$eE = -T_{es} d \ln(n_e)/dx$$

$$T_{es} = 2n\left[\int_0^{\infty} \varepsilon^{-1/2} f(\varepsilon) d\varepsilon\right]^{-1}$$

$$T_e = \frac{2}{3} < \varepsilon > = \frac{2}{3n}\int_0^{\infty} \varepsilon^{3/2} f(\varepsilon) d\varepsilon$$



Kinetic Code for Calculation of EDF and Plasma Parameters

In collaboration with

Oleg Polomarov, Constantine Theodosiou

University of Toledo, Toledo, Ohio

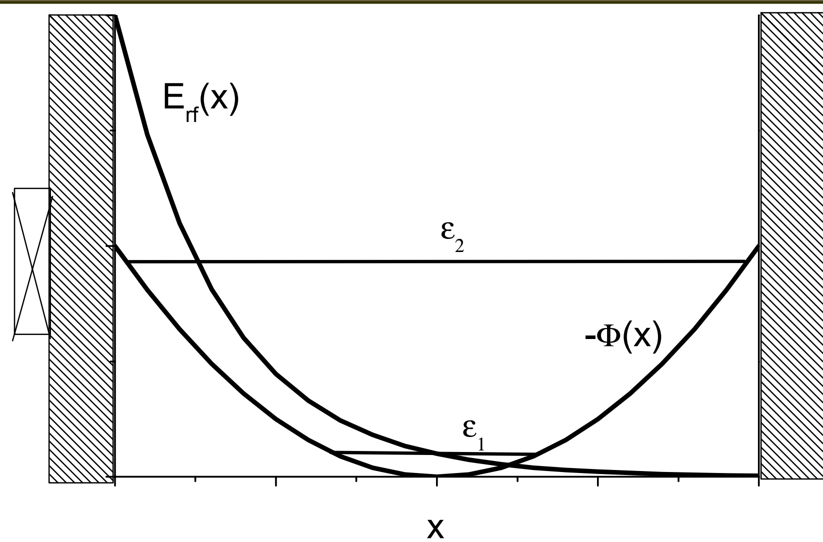
Badri Ramamurthi, Demetre J. Economou

University of Houston, Houston, TX

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**

Inductive Discharge



The transverse rf electric field is given by

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

The electron energy distribution is given by

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

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 $\varphi(x)$.

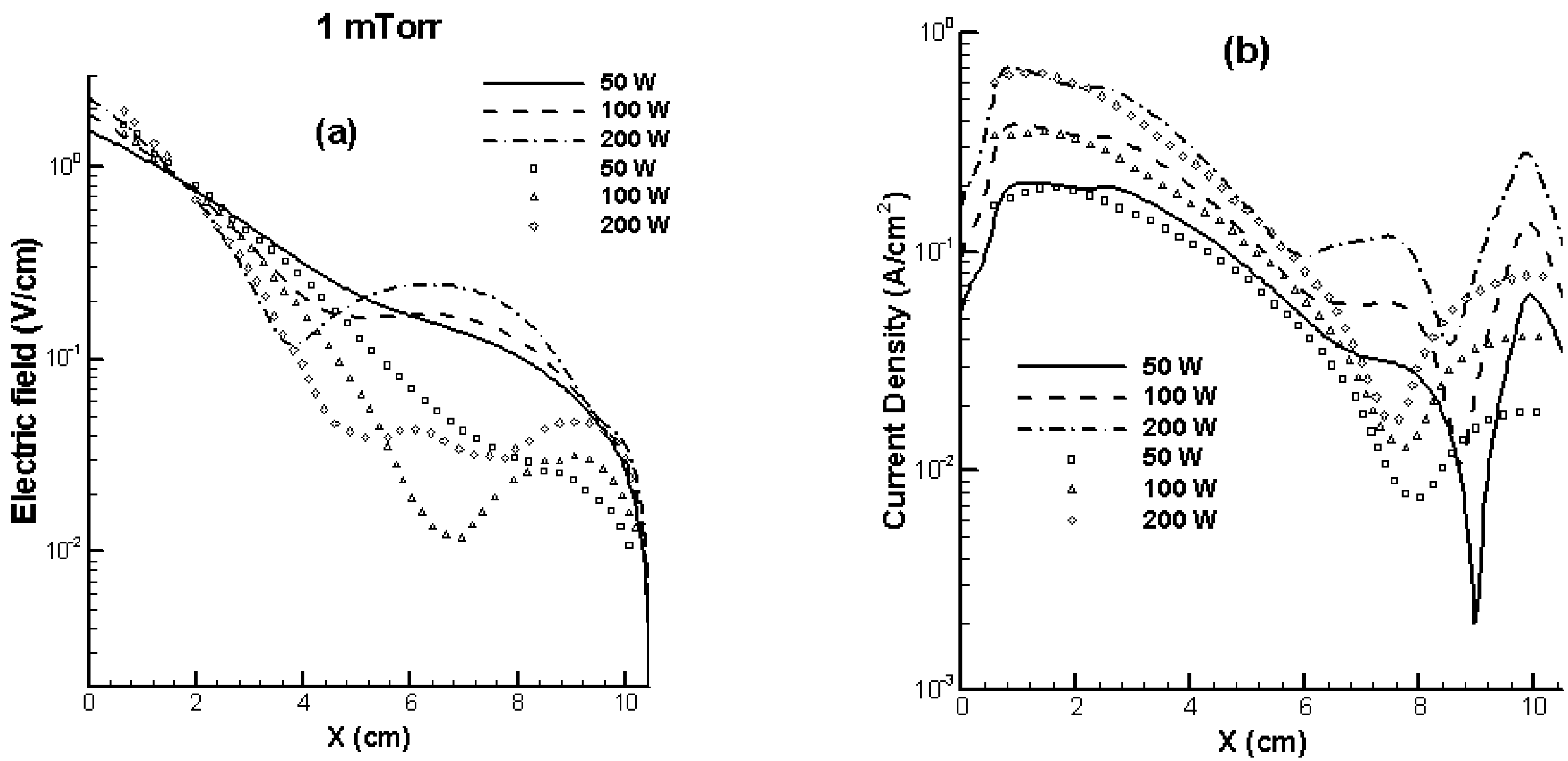
Kinetic Equation Is Averaged over Fast Electron Bouncing in Potential Well

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

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

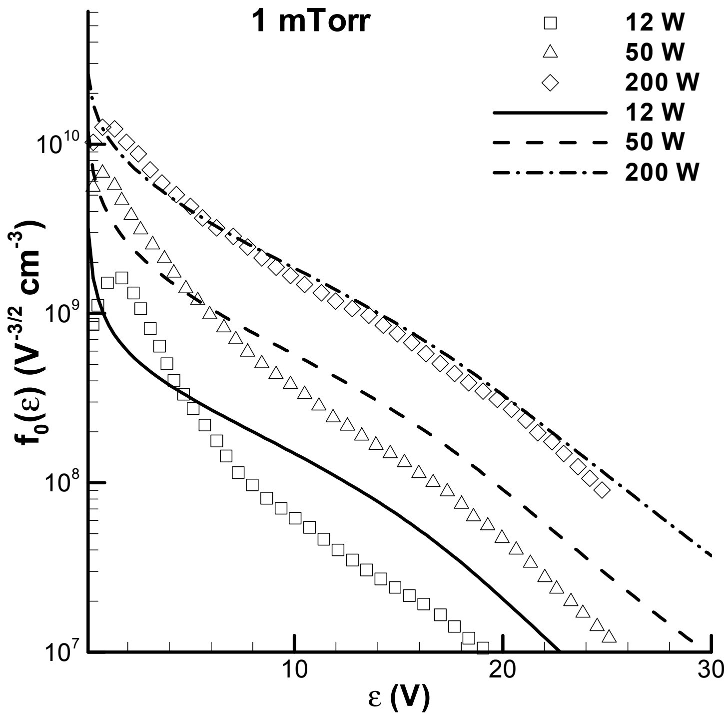
D_{ee} V_{ee} are from the electron-electron collision integral,
ν* is inelastic collision frequency,
upper bar denotes space averaging with constant total energy.

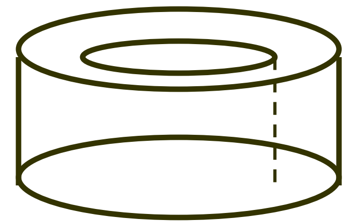
Comparison with Experiment $\frac{c}{\omega_{ep}} < \delta < \frac{V_{Te}}{\omega}$



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

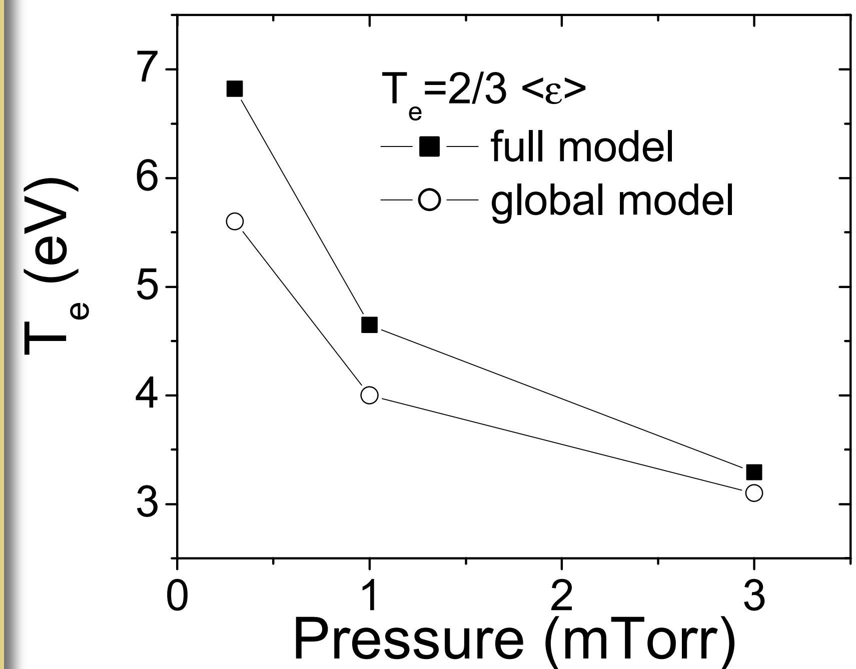


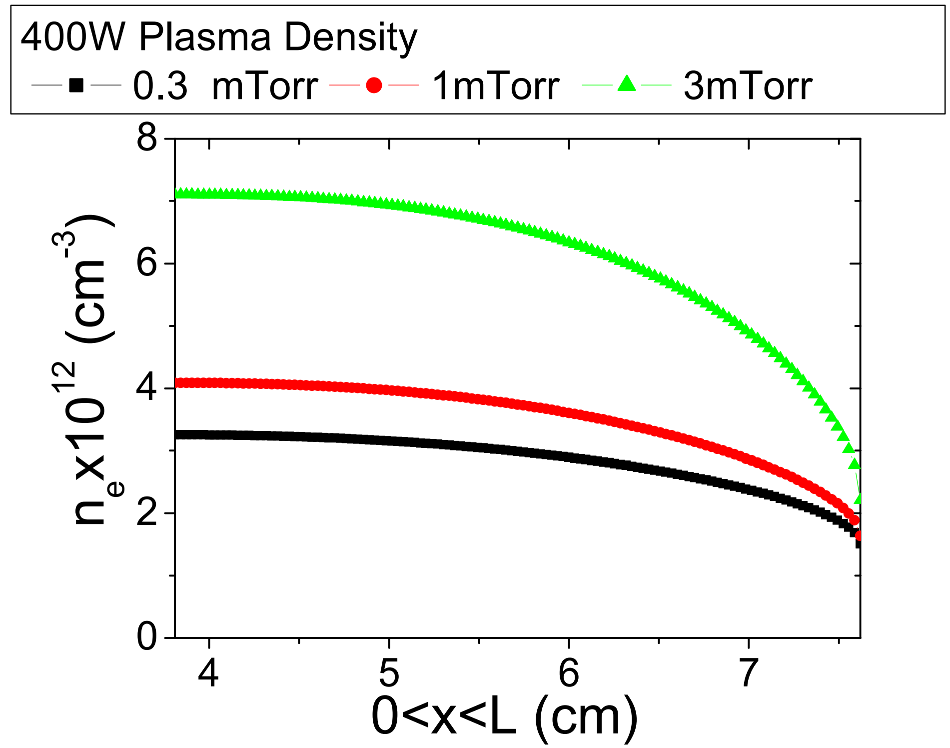


R=10cm,L=10cm, antenna R=4cm

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).

Predictions of the Code for PPPL Plasma Source





Predictions Using Power Balance for PPPL Plasma Source

Power deposited into plasma:

$P=0.5nC_s\ \varepsilon\ S$

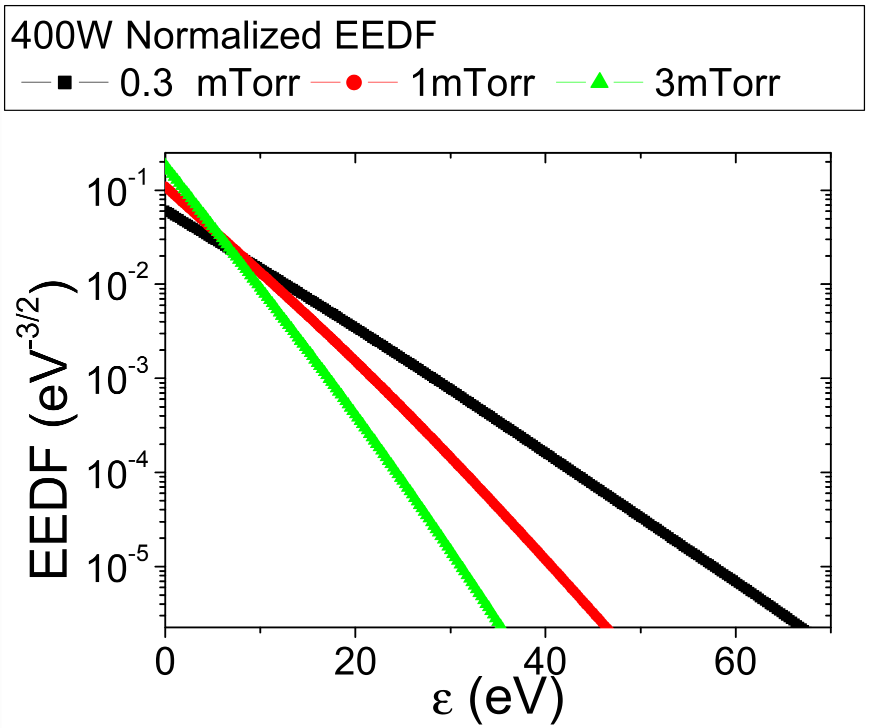
$$C_s = \sqrt{T_e / M}$$

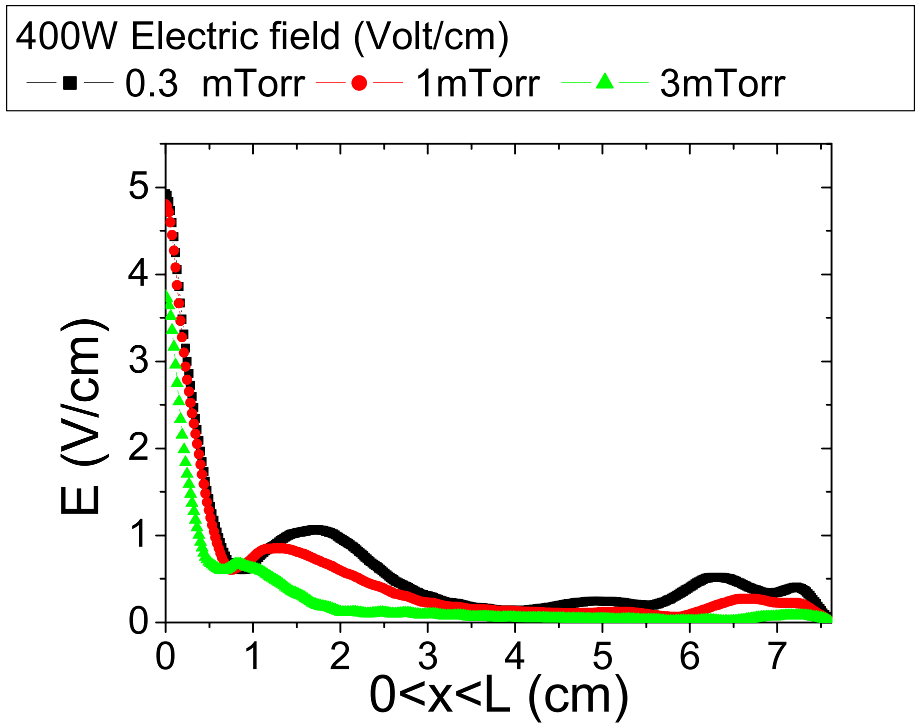
$\varepsilon \approx \varepsilon^* + 2I = 43eV$

N=4 10^{12} cm^{-3} at 1mTorr

needed power 0.4kW vs 2kW

Predictions of the Code for PPPL Plasma Source





EDF is Maxwellian due to high degree of ionization

Skin layer of 0.5 cm

Conclusions

- T_e 3-5eV for steady-state, P in mTorr range
- T_e decay time scale is 10-50 microseconds
- N=4 10^{12} cm^{-3} correspond to 0.4kW
- Skin layer about 1cm
- EDF is Maxwellian