Non-Equilibrium EEDF in Gas Discharge Plasmas

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Workshop on Nonlocal, Collisionless Electron Transport in Plasmas

Plasma Physics Laboratory, Princeton University, Princeton, New Jersey August 2-4 2005

Electron Temperature in gas Discharge

(Uniform electric field, Maxwellian EEDF and direct ionization)

Ionization balance (continuity and momentum eqs.) in a steady-state, self-sustained bounded plasma defines Z, resulting in: $T_e^0 = T_e^0(p\Lambda)$, independently on P_d and n^0.

Electron energy balance, $P_d = \int_V 3/2 T_e^0 n^0 \xi dv$, results in: $Re(E_p^0) = E^0(p\Lambda) = const$, $n^0 \sim P_d$ independently on P_d and a specific mechanisms of electron heating.

$$\xi = \nu 2m/M + \Sigma 2\nu^* \varepsilon^*/3T_e^0 + Z\{2\varepsilon^i/3T_e^0 + (4/3) + ⅓\,[1 + \ln(M/2\pi m)]\}$$

plasma parameters are in equilibrium with electric field (spatial and temporal locality)

At given P_d and $p\Lambda$, T_e^0 and n^0 should be the same for all kinds of discharges

Non-Maxwellian EEDF in E-field

In elastic energy range ($\varepsilon < \varepsilon^*$):

f(ε) is effected by $\nu(\varepsilon)$, ω and by ν_{ee}

In inelastic energy range ($\varepsilon > \varepsilon^*$):

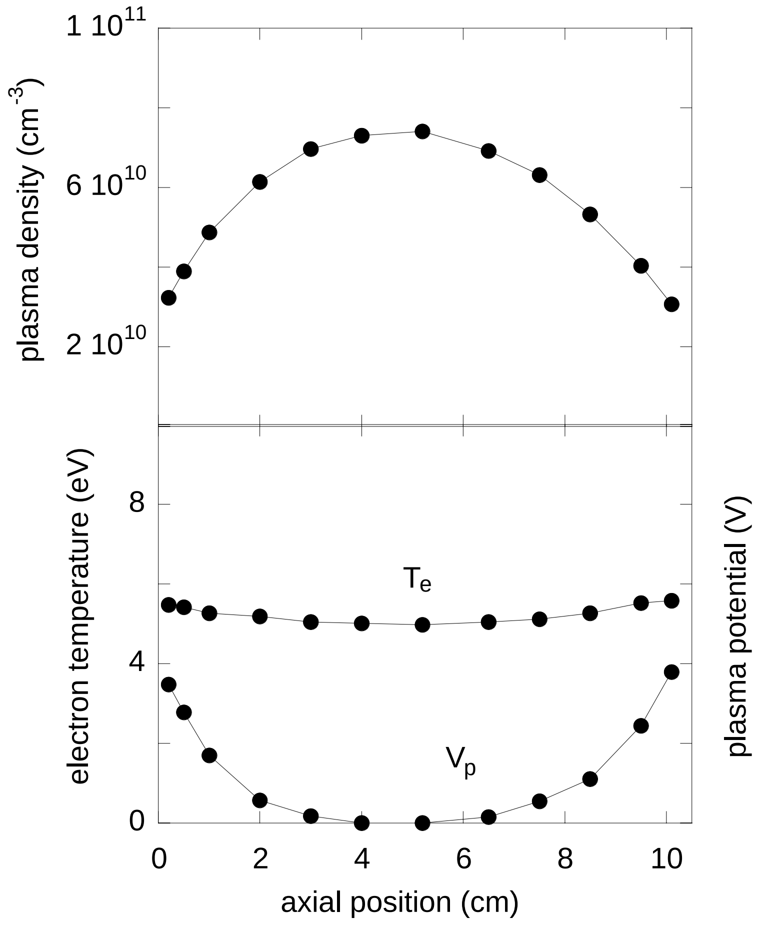
f(ε) is efected by $\nu_{in}(\varepsilon)$ and by wall loss

Electric field non-uniformity occur typically for $\omega << \omega_p$ when external electromagnetic field is localized at the plasma boundary, $\delta << L$.

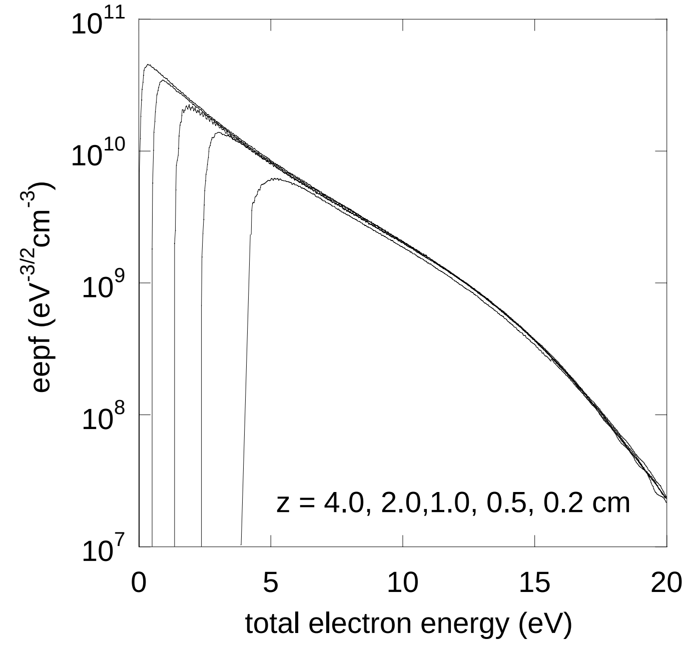
At low gas pressure when $\lambda_T >> \delta$, f(ε) and its scalar integrals (T_e, n, Z, ν) are not local functions of E. Plasma parameter distributions are practically not correlated with the heating electric field distribution.

Electrons behave as a gas with infinite thermo conductivity.

Nonlocal effects in a low pressure ICP



Ar, 1-10 mTorr, 6.78 MHz, 50-200 W

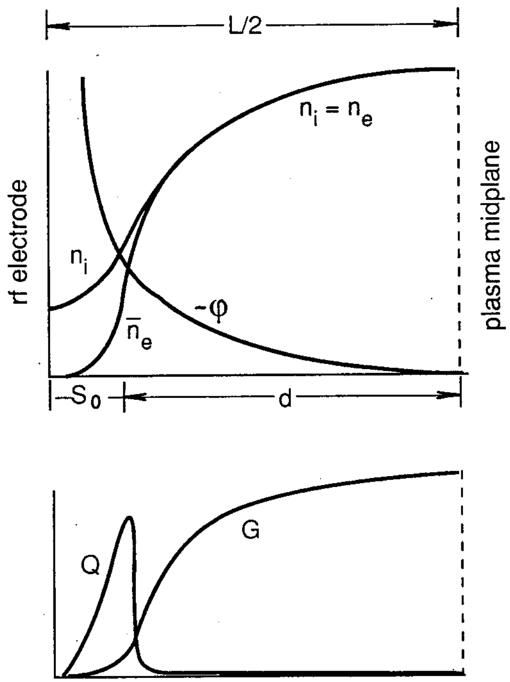


Spatial and Temporal Nonlocality

Spatial nonlocality:

Cathode glow of DC discharge

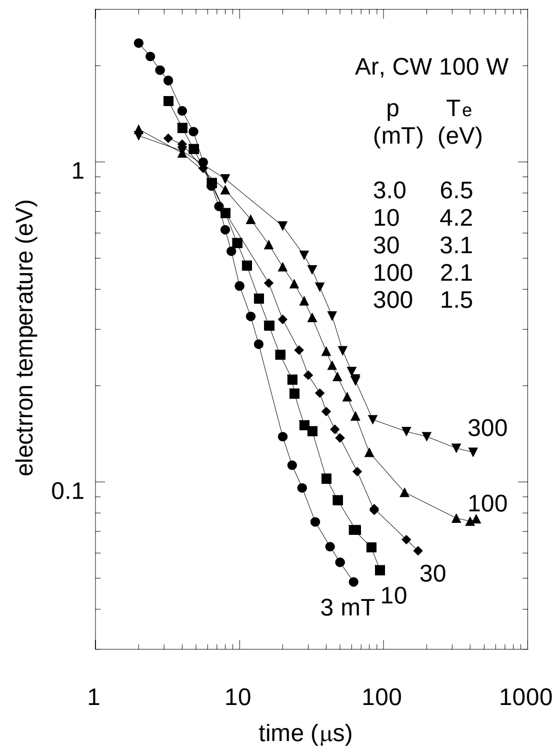
CCP in the γ and α modes



Temporal nonlocality:

Low frequency (ω < Z or ξ)

Pulse discharges

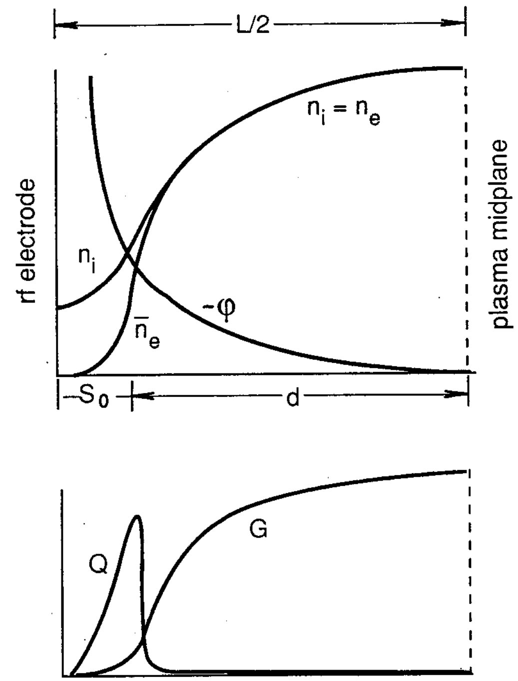


EEDF and plasma parameters are not in equilibrium with heating electric field

Hot electrons generated in a narrow zone δ << L (cathode fall, rf sheath or skin layer)

Led to cool down of main body of electrons in adjacent plasma. This occurs only if there is some segregation mechanism that prevents heating of low energy electrons.

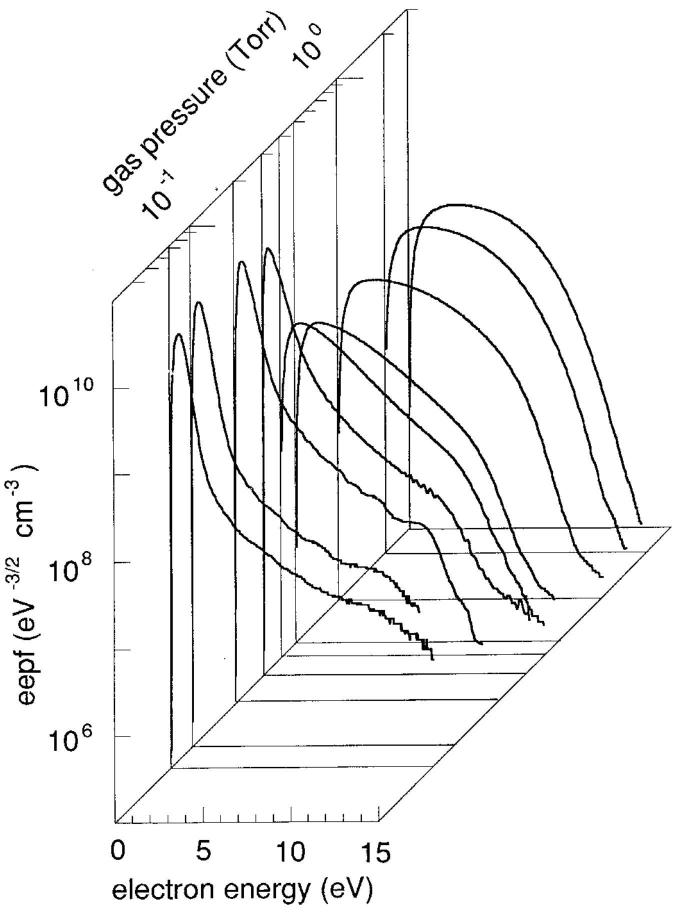
- Plasma created by electron beam (outside beam, E=0)
- Cathode glow and Faraday space (E=0, ambipolar φ)
- CCP, especially in the γ mode (E=0, ambipolar φ)
- ICP in anomalous skin effect (selective electron heating)

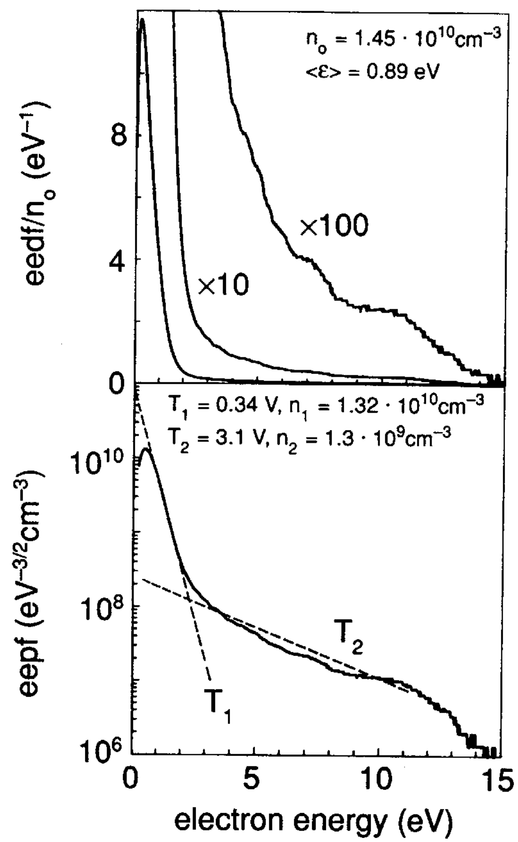


The adjacent plasma has features of a non-self-sustained discharge with typically low electron temperature

Heating mode transition in CCP

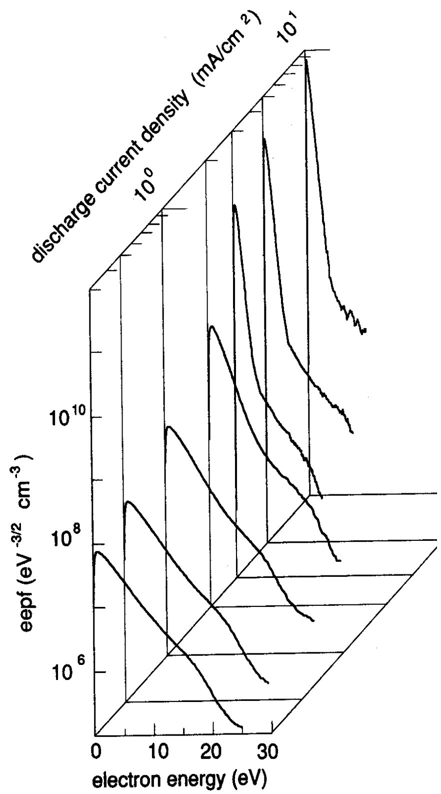
Ar CCP at13.65 MHz, L = 2 cm

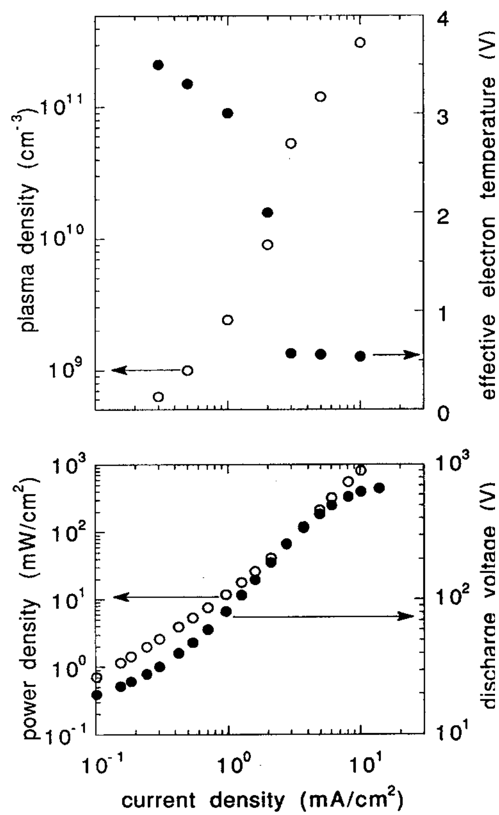




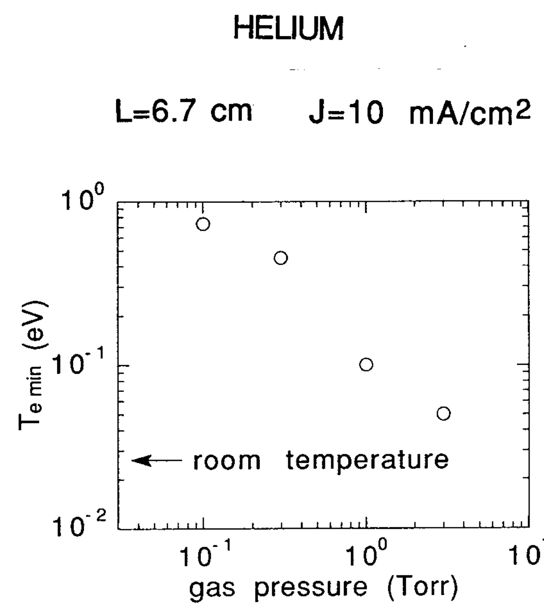
Transition to high plasma density (γ-mode)

CCP, 13.56 MHz, He 0.3 Torr



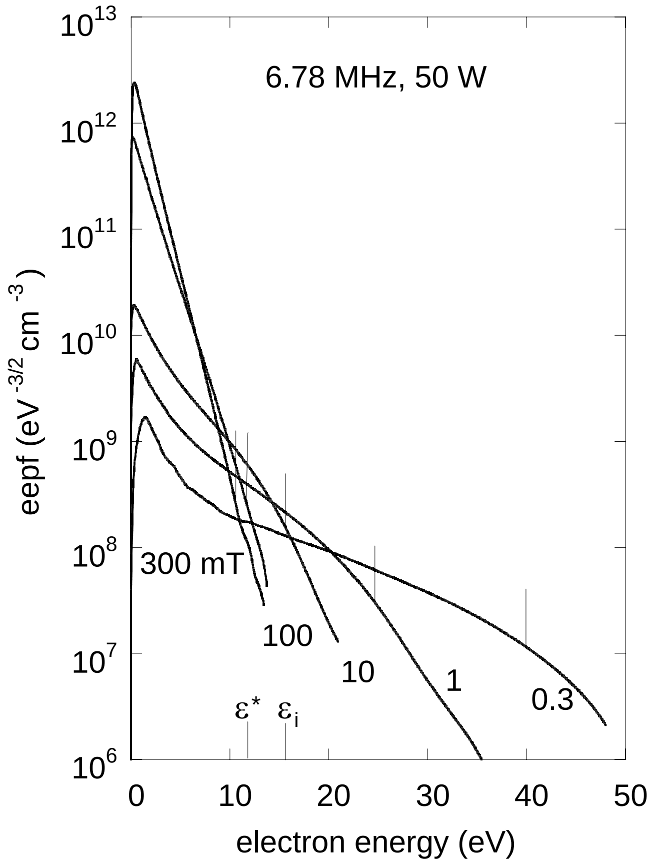


and T_e pressure dependence

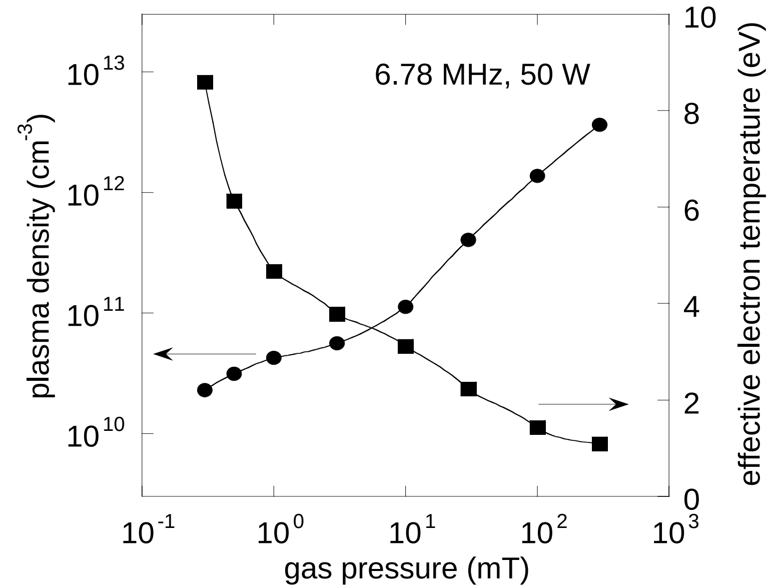


EEDF and plasma parameter in ICP

Center of Ar ICP, 2R=20 cm, L=10 cm

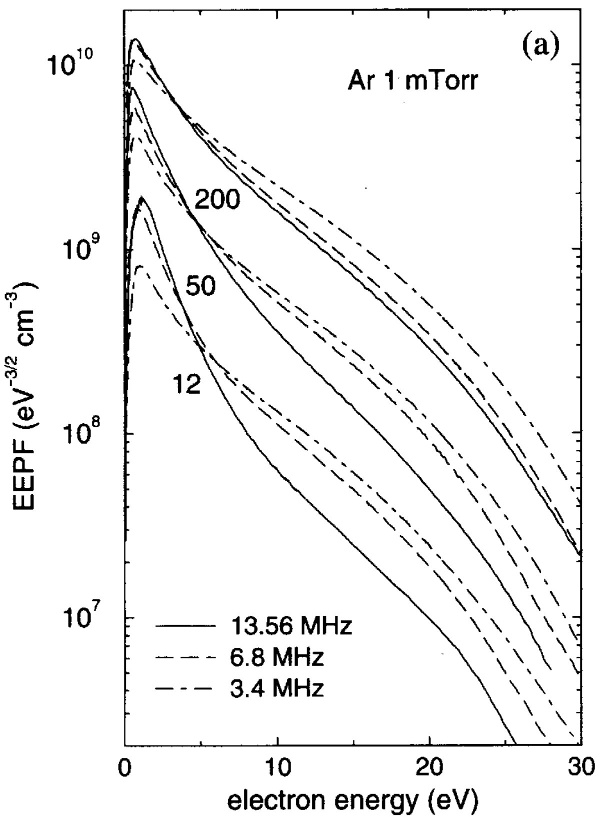


Myth #11: f(ε) is bi-Maxwellian in CCP and Maxwellian in ICP



Frequency dependence of EEDF in ICP with anomalous skin effect

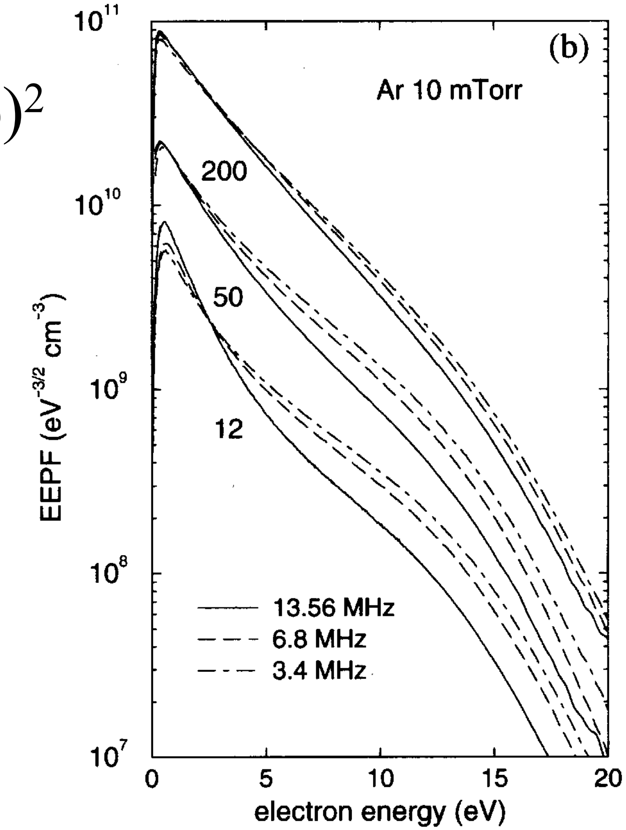
Selective electron heating. Collisionless heating occurs at $v/\delta > \omega$



$$\varepsilon_t \approx \tfrac{1}{2}m(\delta\omega)^2$$

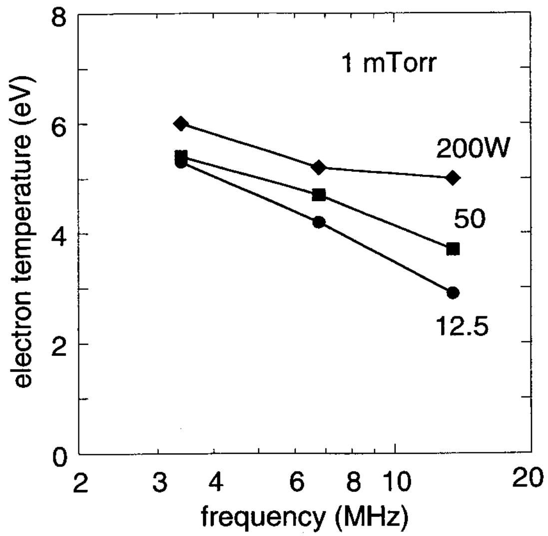
At P_d = 12 W

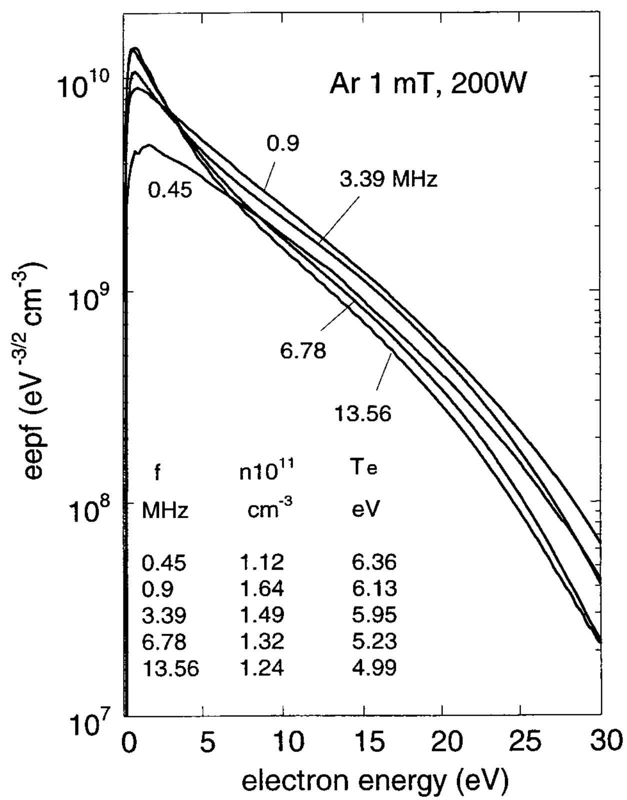
f (MHz)	ε_t(eV)
3.4	0.65
6.8	2.5
13.56	9.0



Electron temperature control in ICP with anomalous skin effect

T_e reduction is desirable in plasma processing



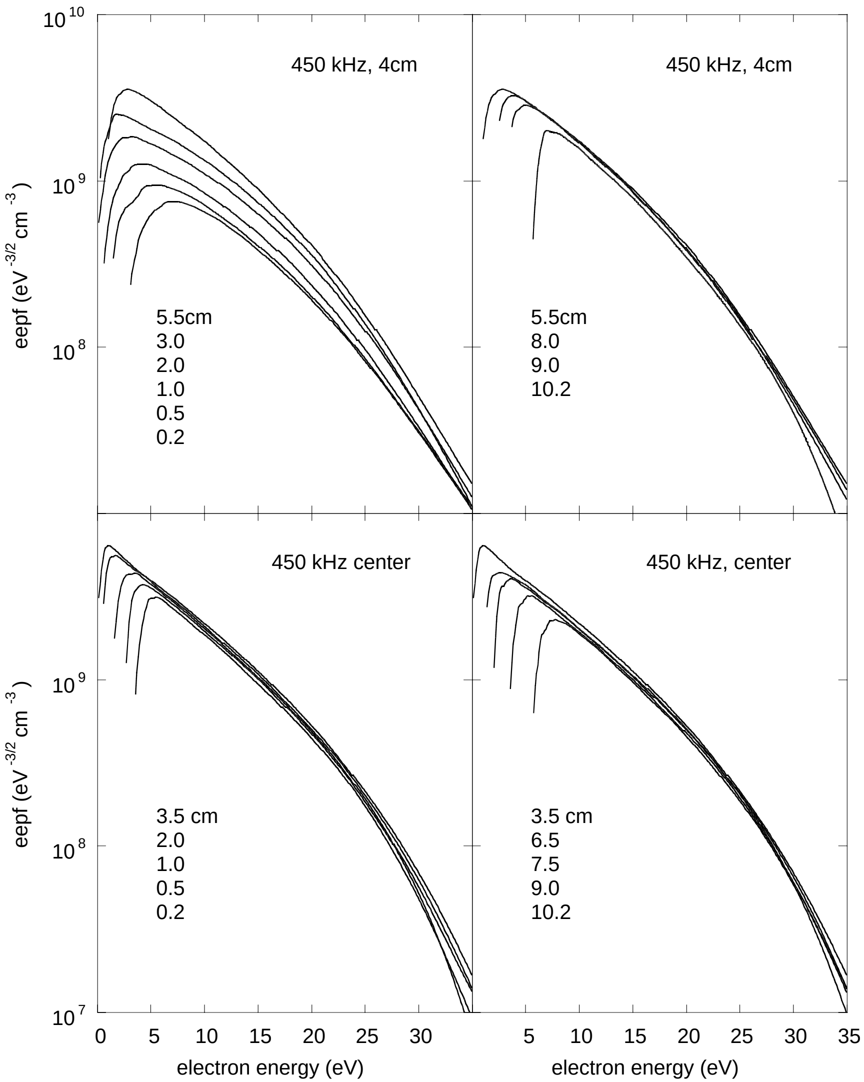


e-e interactions diminish frequency dependence of EEDF, approaching it to a Maxwellian distribution →

Landau damping of helicon waves at $v = \omega/k$ could be another mechanism of selective electron heating

Electron Energy Distribution of ICP in Nonlinear Regime

f(ε) is also affected by ponderomotive potential



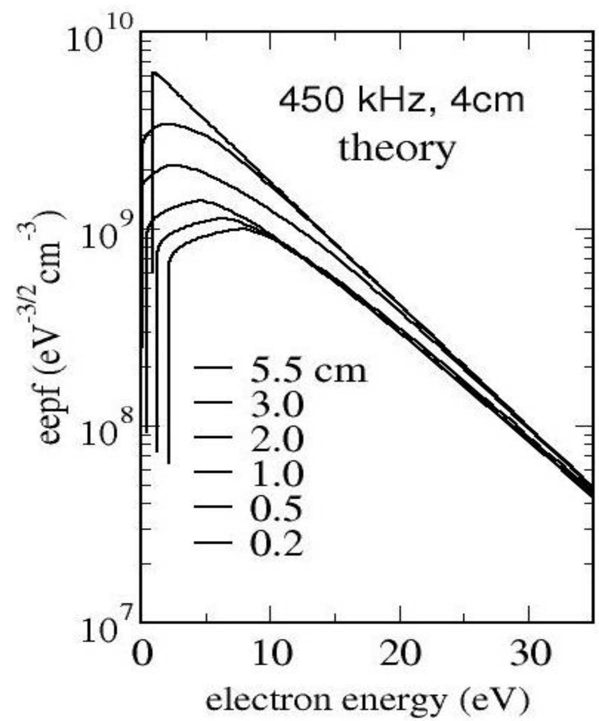
$F_L > F_E \rightarrow \omega_B > (\omega^2+\nu_{eff}^2)^{1/2}$

$B = -E/\delta\omega$, E is a weak function of ω, and thus $B \sim \omega^{-1}$

$v_e/\delta < (\omega^2+ \nu^2)^{1/2}$ - local

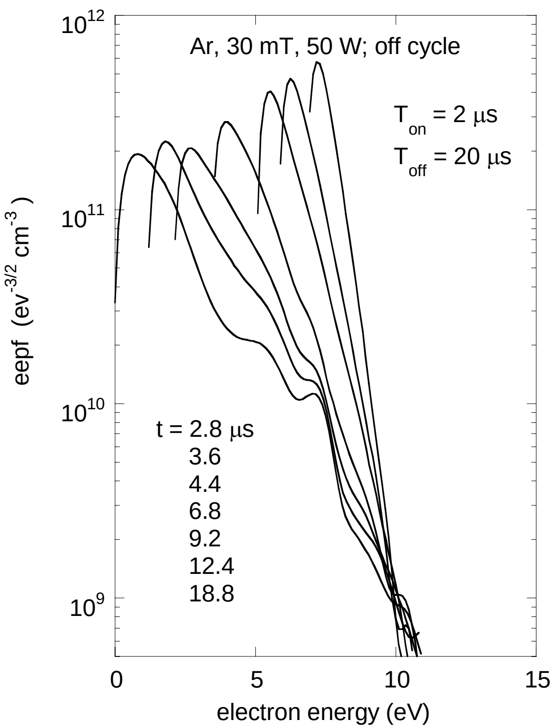
$v_e/\delta > (\omega^2+ \nu^2)^{1/2}$ - nonlocal

F_L = is larger for slow electrons

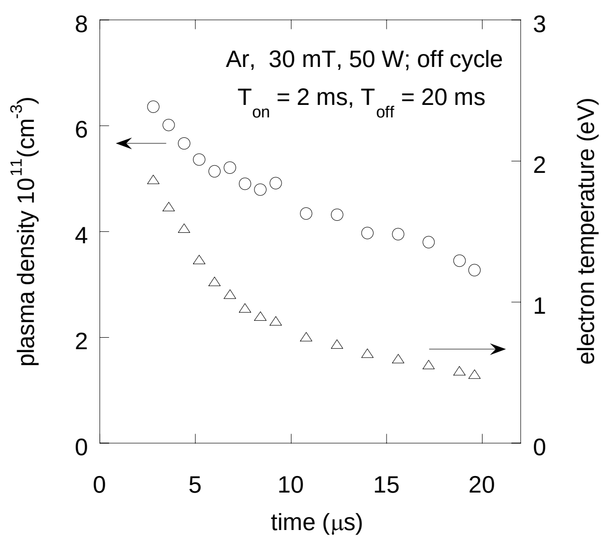


Electron temperature control in pulse rf discharge

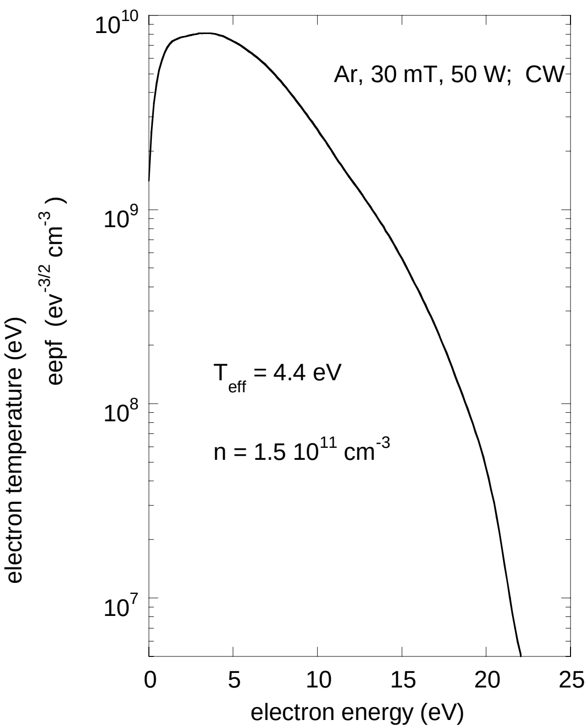
EEDF in afterglow stage



Evolution T_e and n in a periodically pulsed ICP

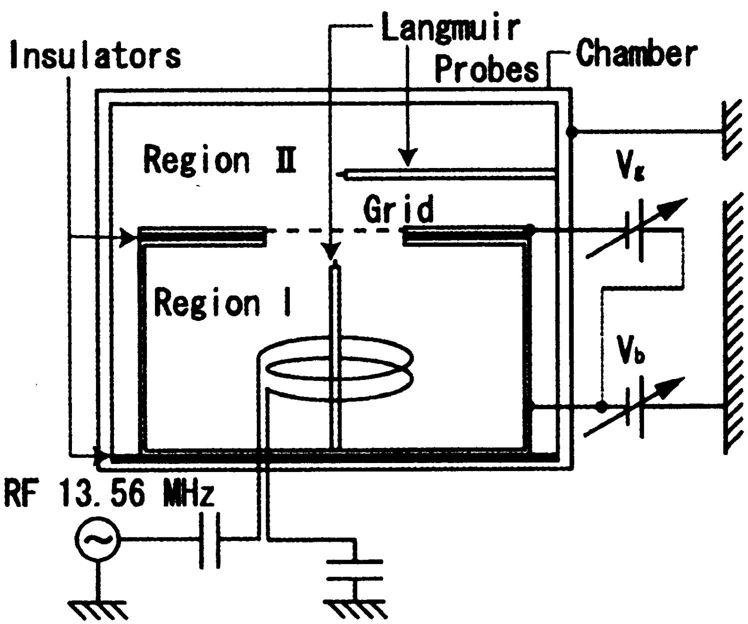


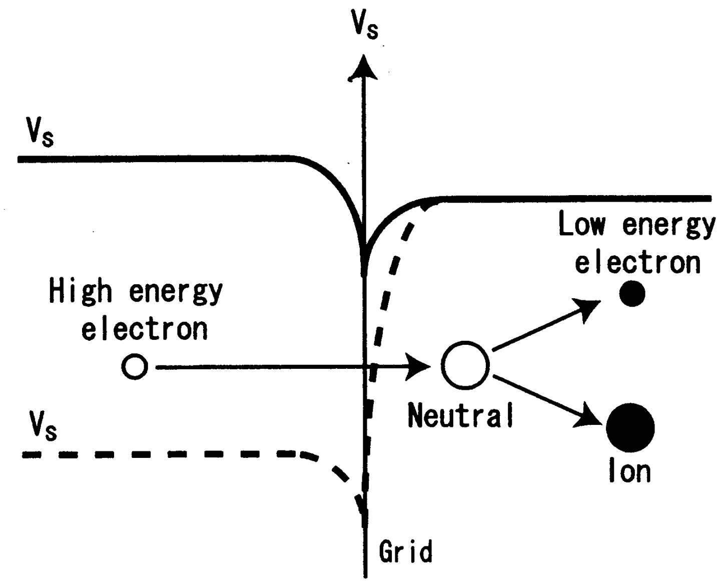
EEDF in CW mode



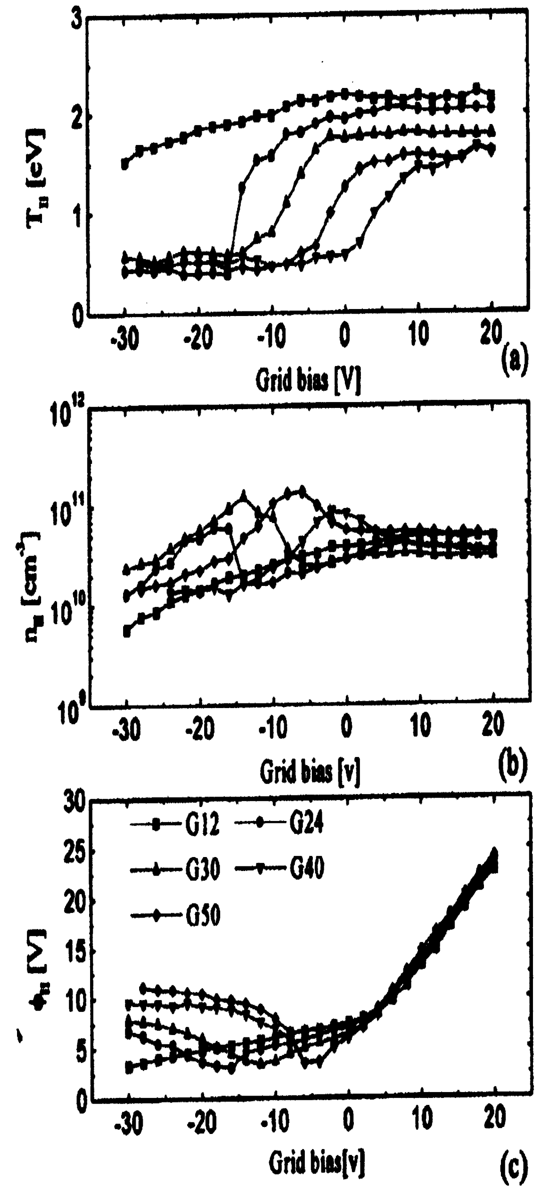
T_e control with negatively biased greed (Kato et al, 1993)

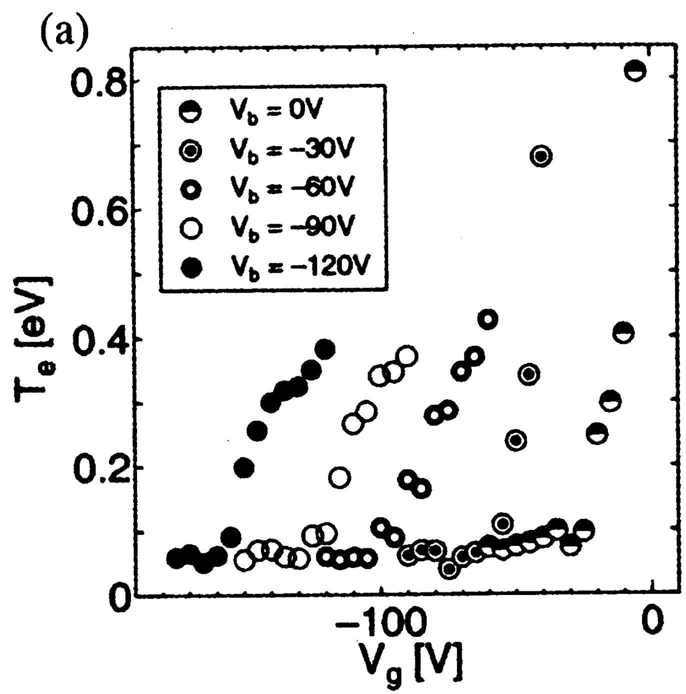
Experiments by Ikada et all, 2004





Experiments by Hong et al, 1999 →

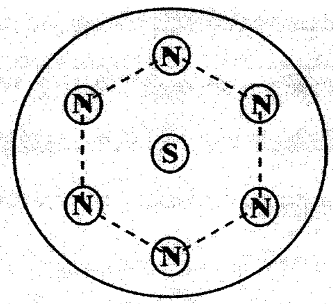


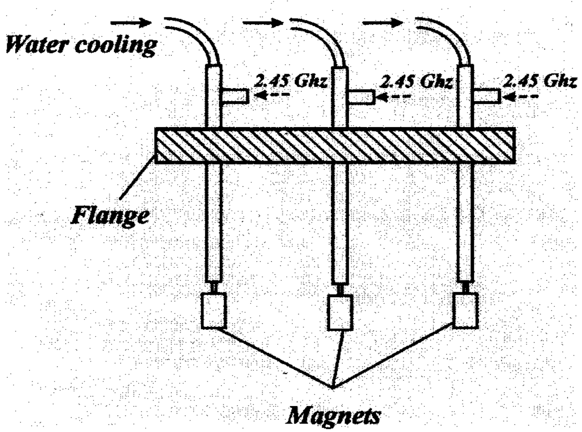


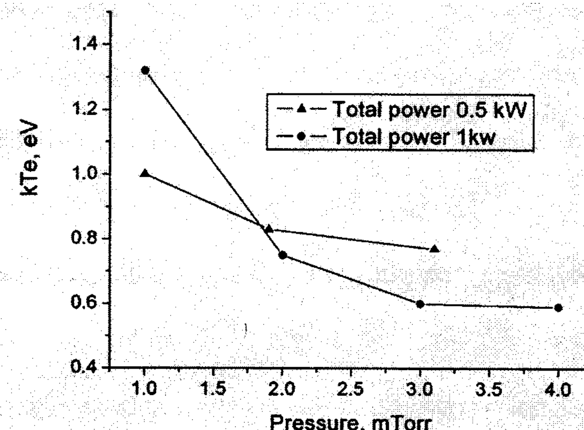
Experiments by Ikada et all, 2004

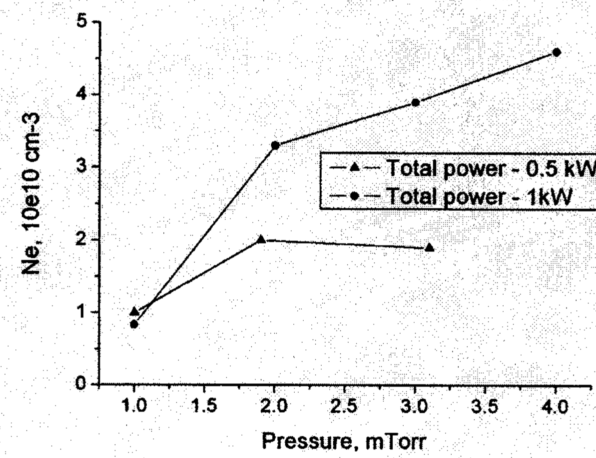
Localized ECR heating (Ivanov et al, 2004)

1-4 mTorr, multicusp magnetic confinement of fast electrons









Conclusions

• Plasma of a low pressure discharge ($\lambda_T >> \delta$ and large dE/dr) $f(\varepsilon)$ is not in local equilibrium with E-field, plasma parameters and the field distributions are decoupled and $df(\varepsilon+e\varphi)/dr \approx 0$.

• Generation of excess of high energy electrons may cool down the main body of electron population.

• Formation of highly non-equilibrium EEDF with two-temperature structure ($T_1 << T_2$) requires both, strong E-field localization (to produce fast electrons) and some separation mechanism preventing low energy electron heating and/or mixing with hot electrons.

• Non-equilibrium discharges with strong localization (in space and/or in time) of the heating field and with electron separation feature seems is the way for creation of plasma with controllable EEDF.