Electron Temperature Modification in Gas Discharge Plasma

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Electron Temperature in Gas Discharge

(Uniform electric field, E•grad(n) = 0, Maxwellian EEDF and direct ionization)

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

- Ionization balance (continuity and momentum eqs.) in a steady-state, self-sustained .

bounded plasma defines z, resulting in: $T_e = T_e(p\Lambda)$, independently on P_d and n.

- Electron energy balance, $P_d = \int(3/2)VT_e n\xi dV$, results in: $\mathrm{Re}(E_{pl}) = \mathrm{const}(p\Lambda)$, $n \sim P_d$

Here ξ is the characteristic frequency of electron energy loss, $\xi = v_e/\lambda_\varepsilon$

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

The fundamental relations for the electric field E and the total number of electrons/ions N_p follows from the electron energy balance:

$$E^2 = 3T_e m\xi\upsilon_{eff}(1+ \omega^2/\upsilon^2_{eff}) \quad \text{and} \quad N_p = \langle n\rangle V = 2P_d/3\xi T_e$$

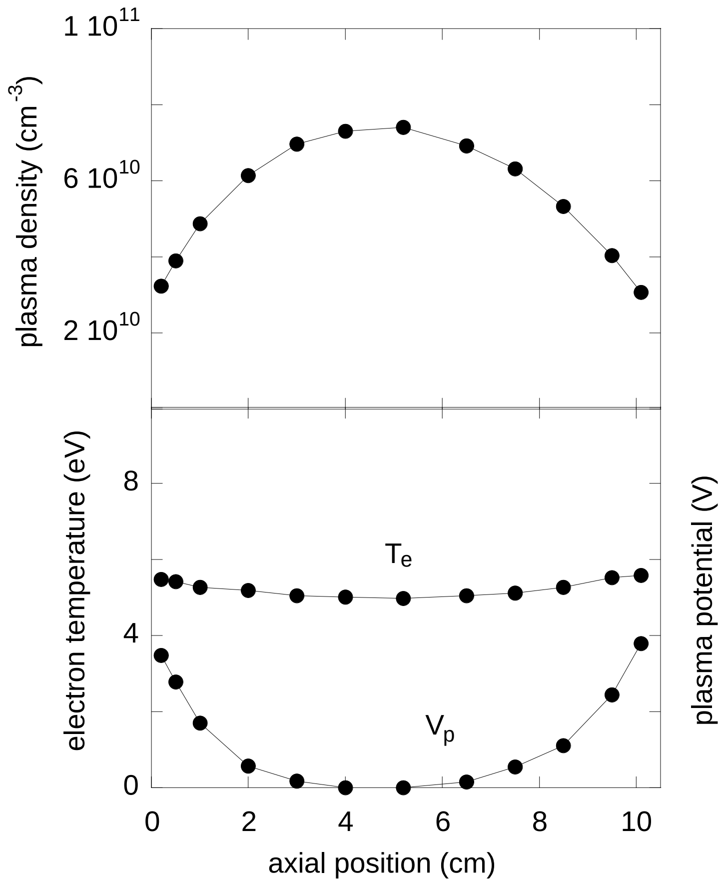
Thus, for given P_d and $p\Lambda$, T_e and n should be the same for all kinds of discharges

These are basically true for non-Maxwellian EEDF and with non-linear processes

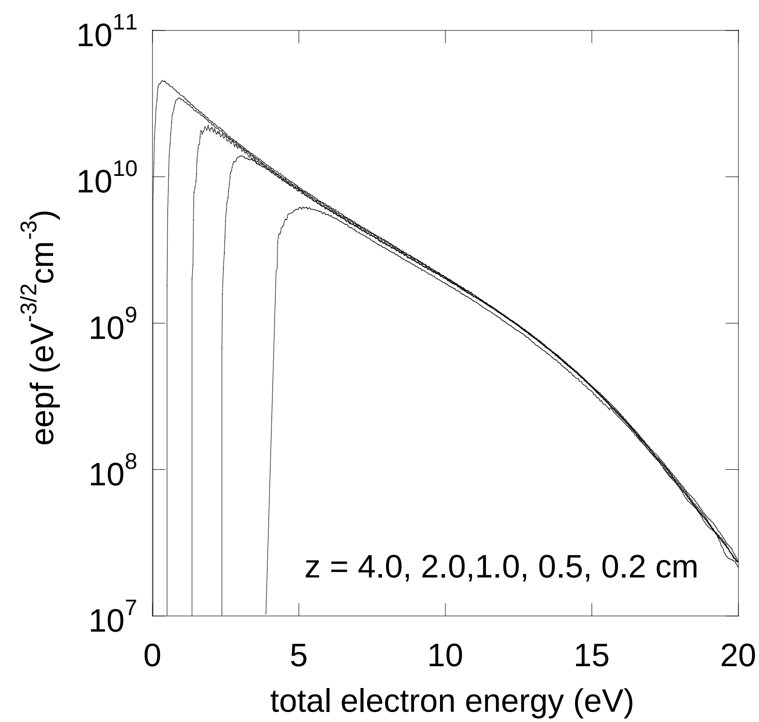
Non-local electron kinetics

In gas discharge plasmas, electrons are not in equilibrium with molecules and ions, $T_e >> T_i, T_g$, they are not in equilibrium within their own ensemble, non-Maxwellian,
and when $\lambda_\varepsilon = v_e/\xi > L$, they are not in equilibrium with a non-uniform heating electric field E.

The last is domain of electron non-local kinetics where plasma parameters are not local function of the field, $\mathrm{grad}(T_e) \approx 0$ and $df_e(\varepsilon + eV)/dr \approx 0$



Nonlocal effects in a low pressure ICP

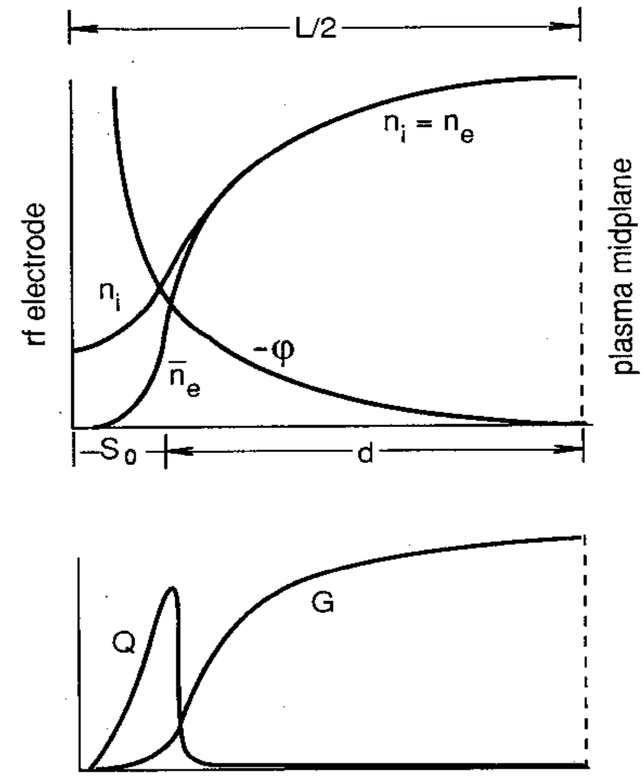


EEDF in a non uniform E-field

At $\omega \ll \omega_p,$ the external electromagnetic field is localized at the plasma boundary, S, $\delta \ll L$, and in plasma bulk $E \infty n^{-1}$ when $E \bullet \text{grad}(n) \neq 0$

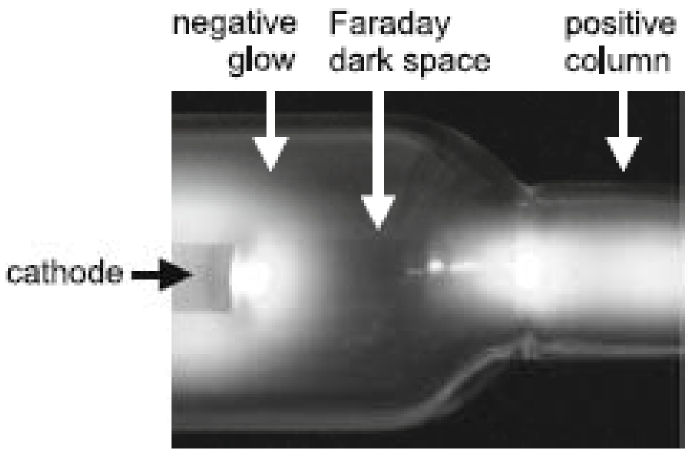
Electric field non-uniformity typically occurs when $\omega \ll \omega_p$ and electromagnetic field is localized at the plasma boundary, S, $\delta < L$, and in plasma when $E \bullet \text{grad}(n) \neq 0$

Hot electrons generated in the zone of strong electric field produce ionization in the area of week field. In the presence of some separation mechanism preventing new-born electrons mixing with hot electrons or/and to penetrate the heating zone, the new-born electrons remain cold. This results in EEDF having two electron groups (hot and cold) . This cold plasma has features of a non-self-sustained discharge



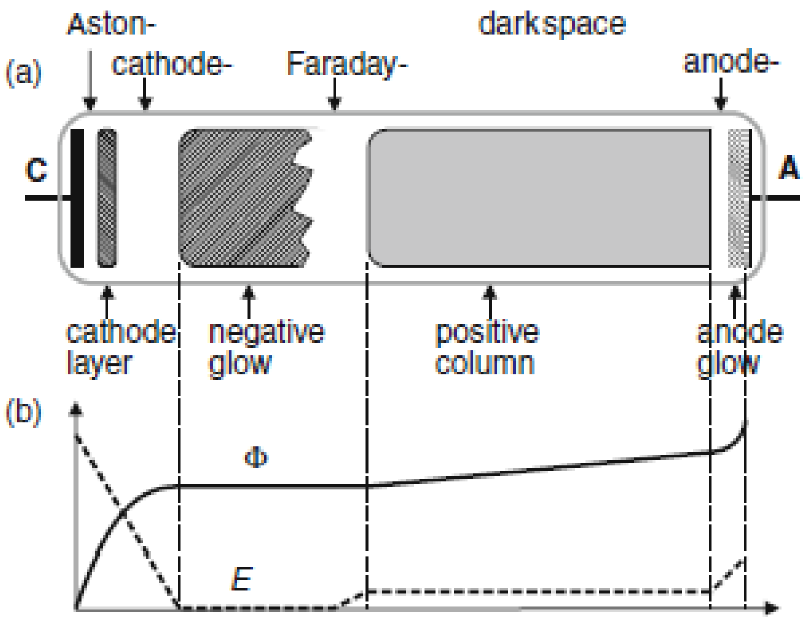
Thus, the local electron heating together with some separation mechanism result in plasma cooling

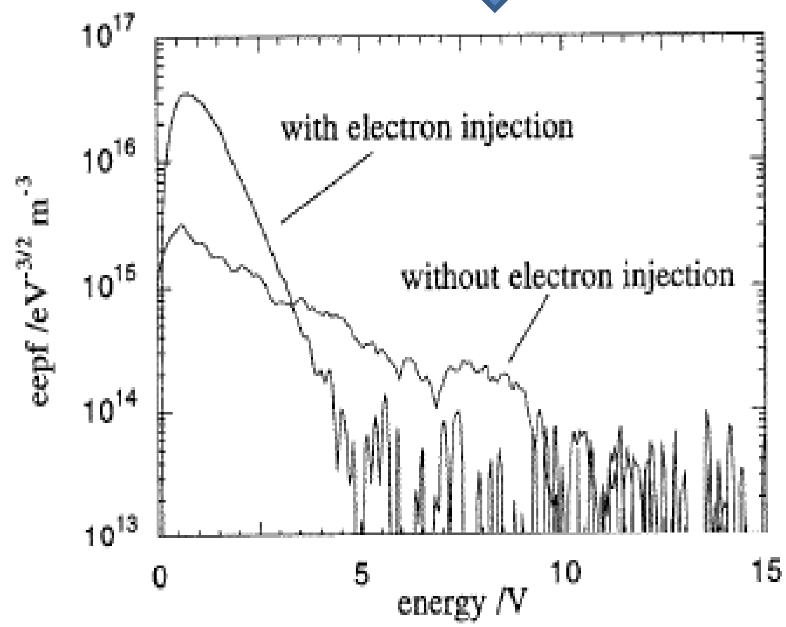
Electron cooling in negative glow of dc glow discharge



Solntsev et al, 8th ICPIG, p. 86, Vienna, 1967, have measured ultra-cold electrons (T_e = 0.04 - 0.3 eV, 1-2 orders of magnitude lower than that in the positive column. He, 0.6 - 4 Torr, I_d = 0.6 – 8 mA.

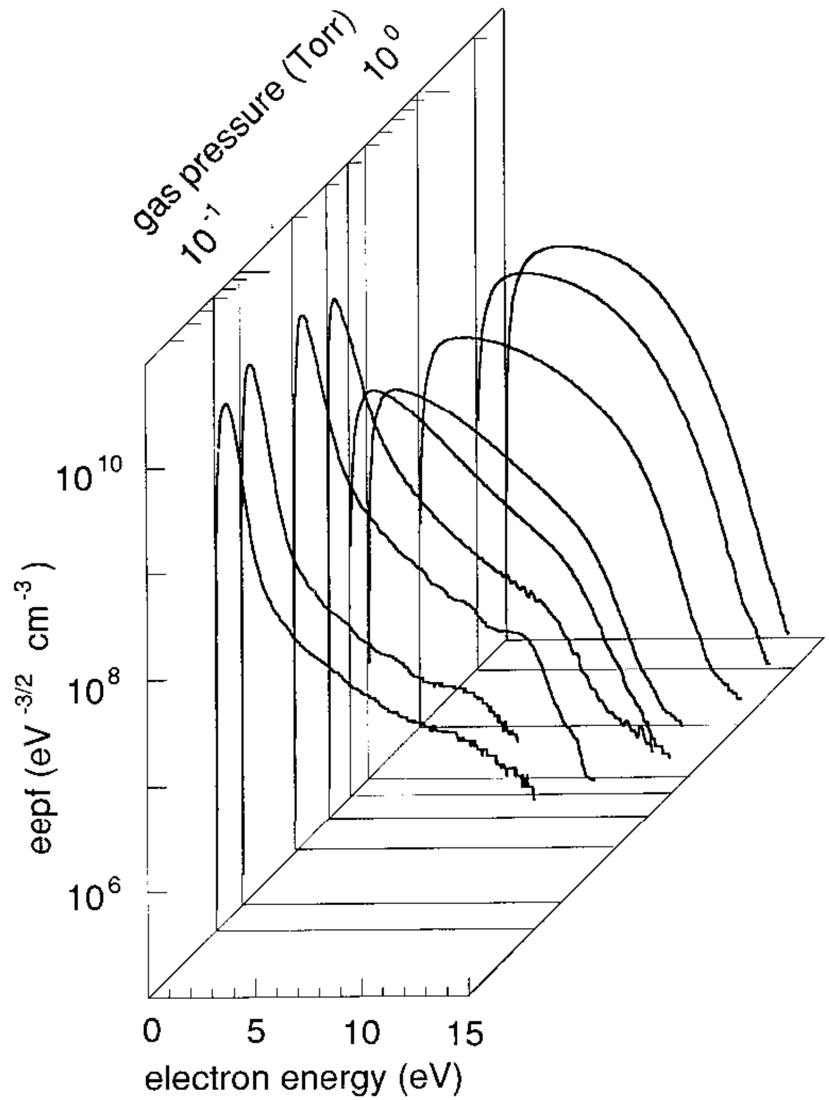
Haas et al, PSST. ***7****, 471, 1998,* have demonstrated plasma electron cooling by injecting 100 eV electron beam into CCP.

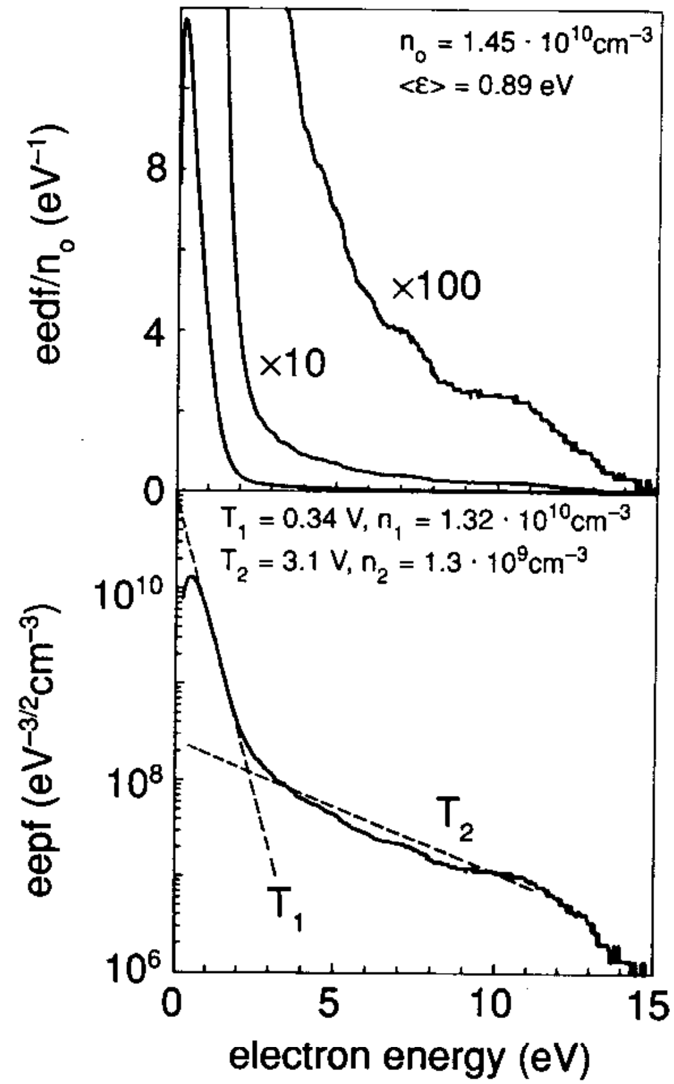




Heating mode transition in CCP

Ar CCP at13.65 MHz, L = 2 cm



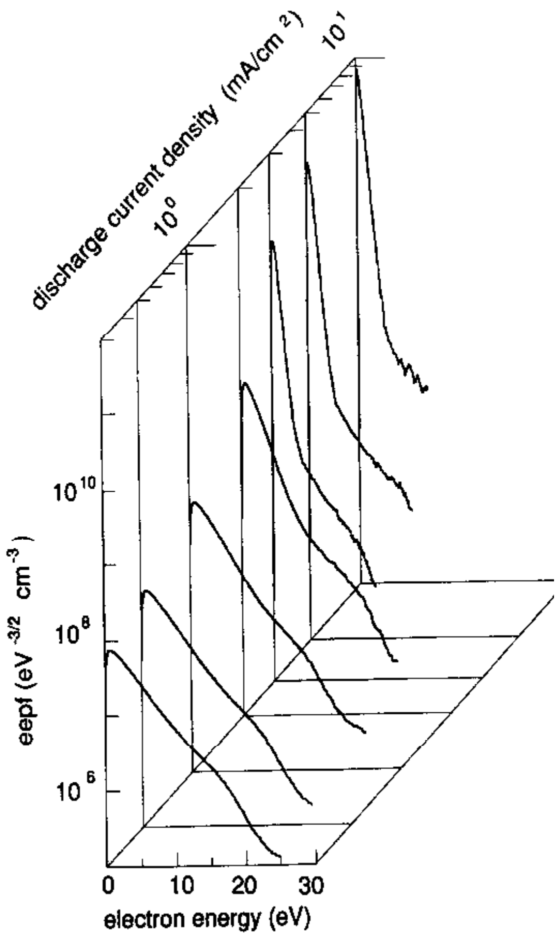


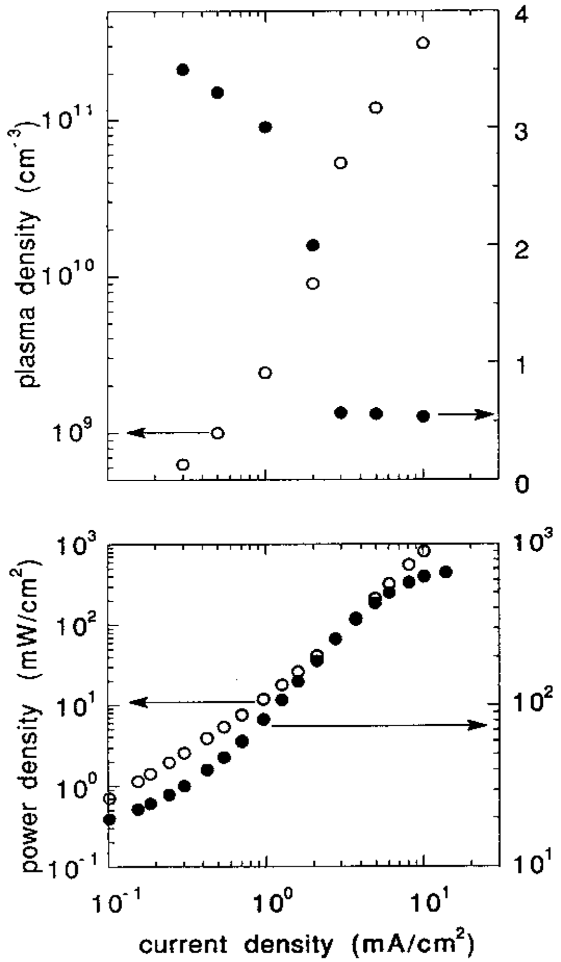
Godyak and Piejak, Phys. Rev. Lett. ***65****, 996, 1990*

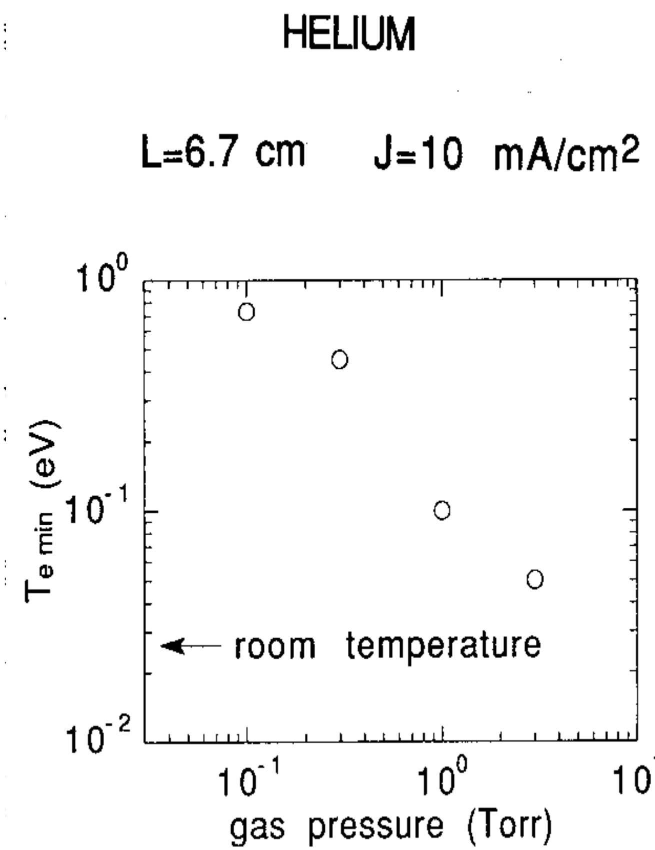
Transition to high plasma density (γ-mode)

CCP, 13.56 MHz, He 0.3 Torr

T_e pressure dependence



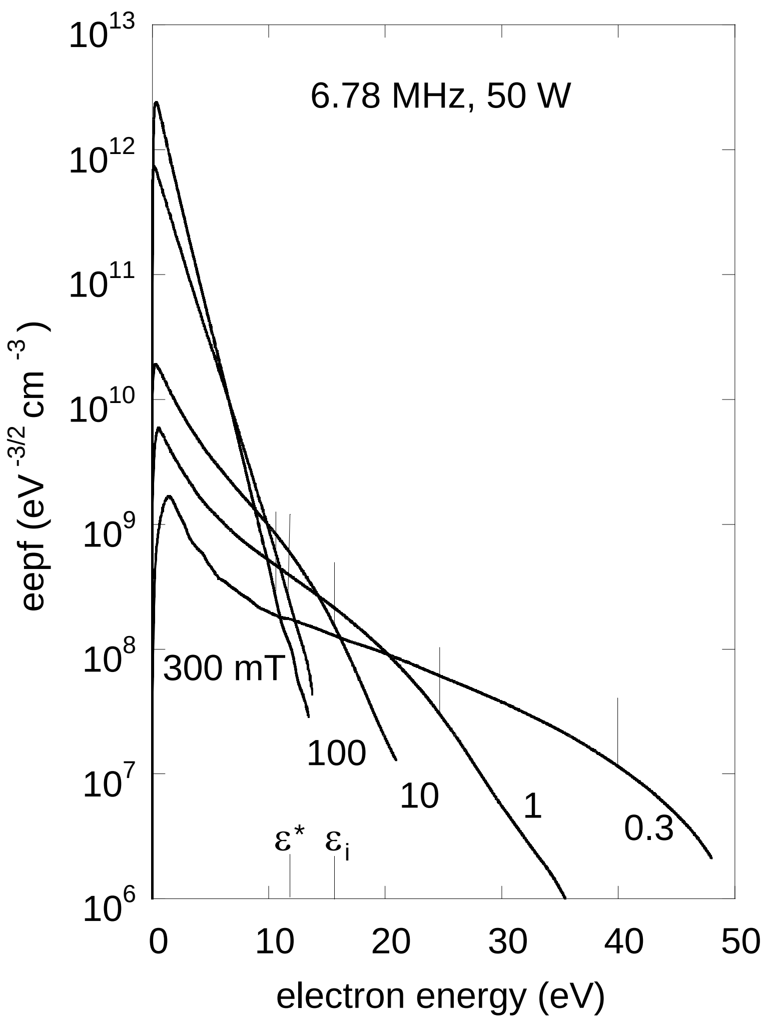




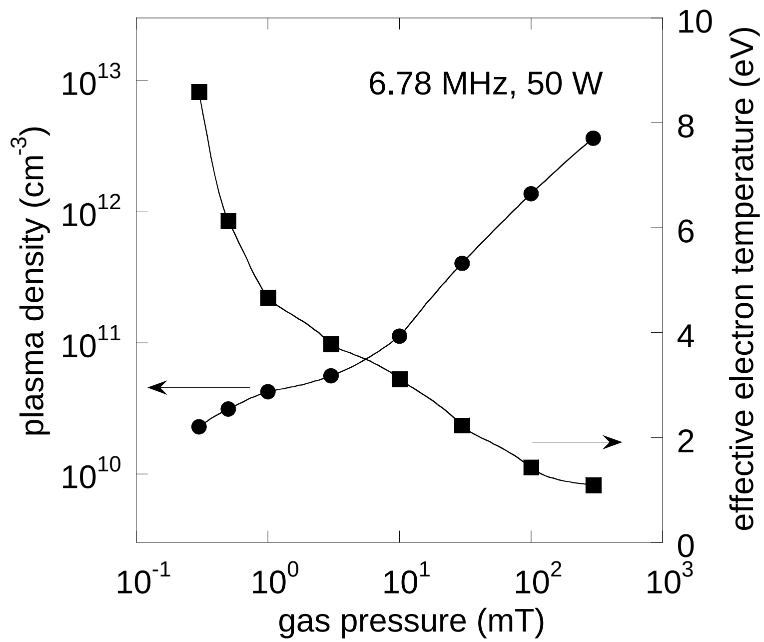
Godyak et al, *Phys. Rev. Lett.* ***68****, 49, 1992*

EEDF and plasma parameter in ICP

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



Three-temperature structure of EEDF is due to selective electron heating at the condition of anomalous skin effect. At high plasma density EEDF trends to Maxwellian distribution

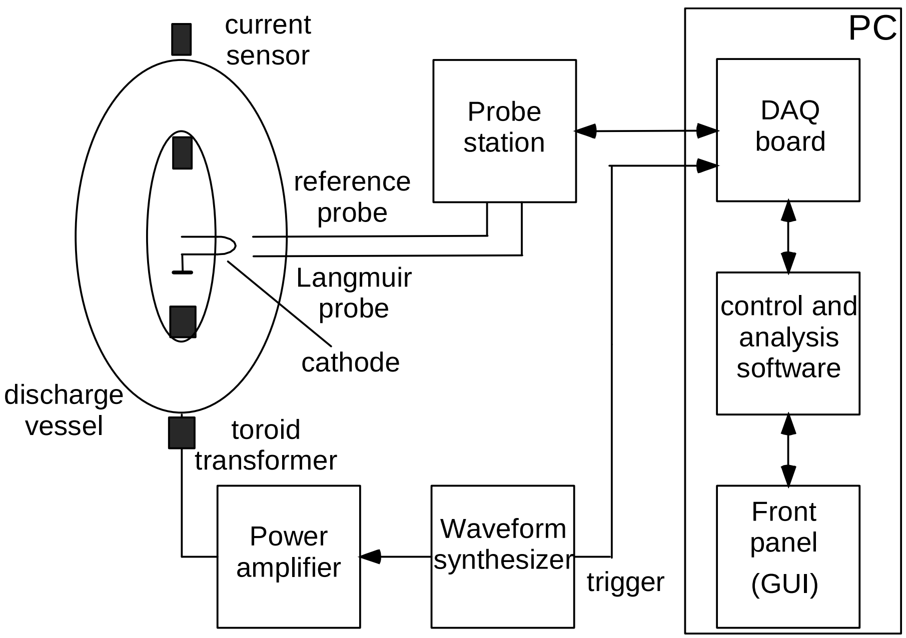


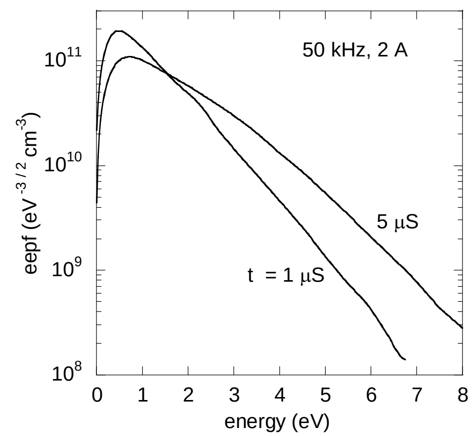
Godyak et al, PSST, ***11****, 525, 2002*

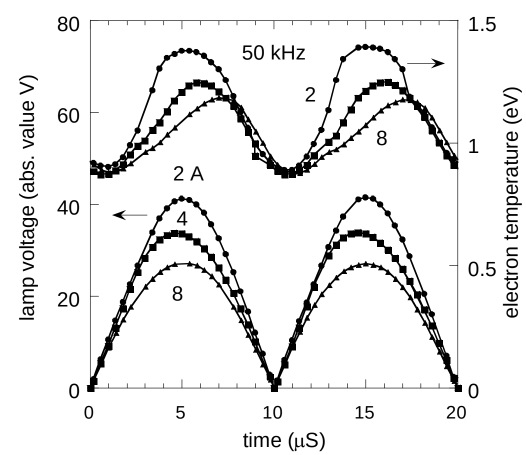
Temporal non-locality: Time resolved EEDF measurement

$$\omega \gg z \;\rightarrow dn/dt = 0,\;\; \text{but } \omega \approx \xi \;\rightarrow dT_e/dt \neq 0$$

Toroidal ICP driven with ferrite inductor at 50-250 kHz, Hg-Ar, 0.3 Torr



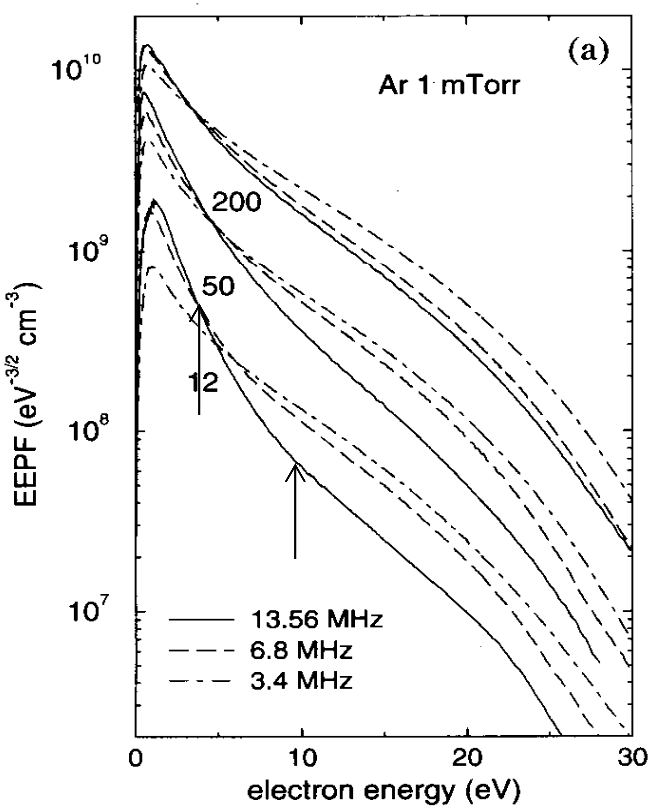




Alexandrovich et al, LS10, p. 283, Toulouse, France, 2004

Frequency dependence of EEDF in ICP with anomalous skin effect

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



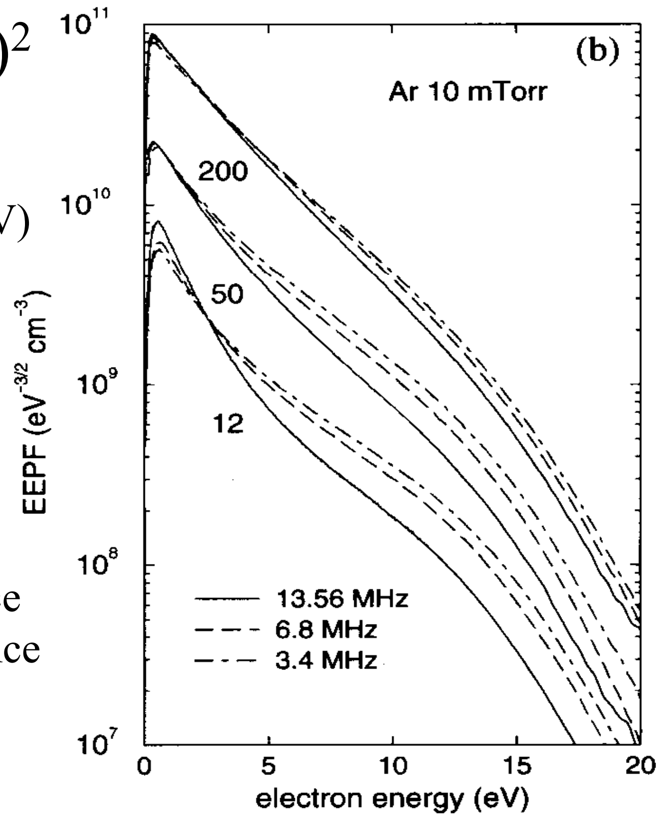
$$\varepsilon_t \approx \frac{1}{2} m(\delta\omega)^2$$

At P_d = 12 W

f(MHz)	ε_t(eV)	T_{eff}(eV)
3.4	0.65	5.4
6.8	2.5	4.2
13.56	9.0	2.9

At high plasma density, the difference in T_{eff} disappears, since

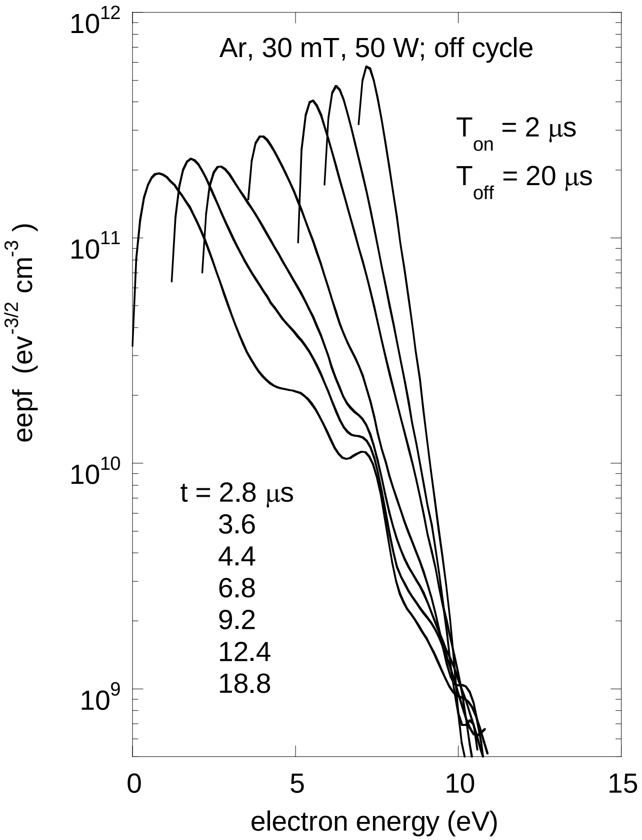
$$\nu_{ee} \sim n\varepsilon^{-3/2}$$



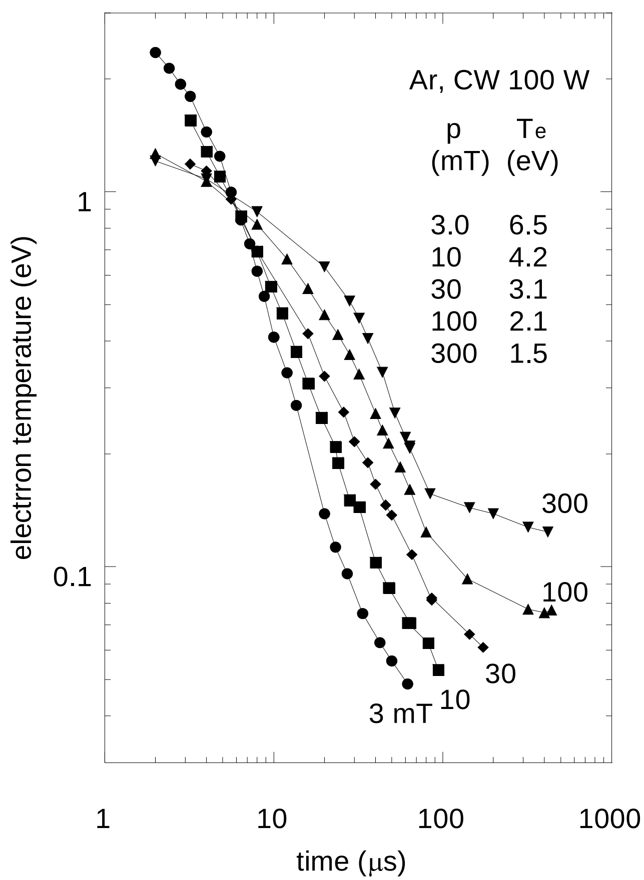
*Godyak and Kolobov, Phys. Rev. Lett., **81**, 369, 1998*

Temporal nonlocality: Electron temperature variation in pulse discharge and Low frequency RF Discharge

EEDF in afterglow stage of ICP with internal coil



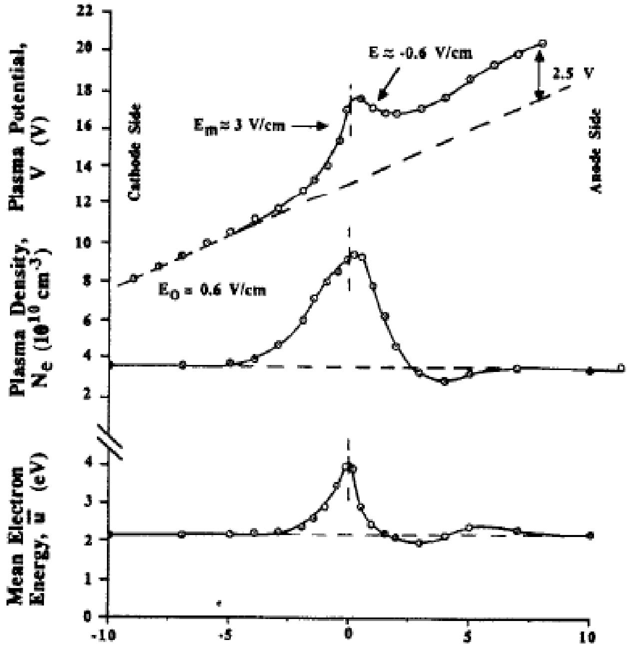
Evolution T_e and n in a periodically pulsed ICP

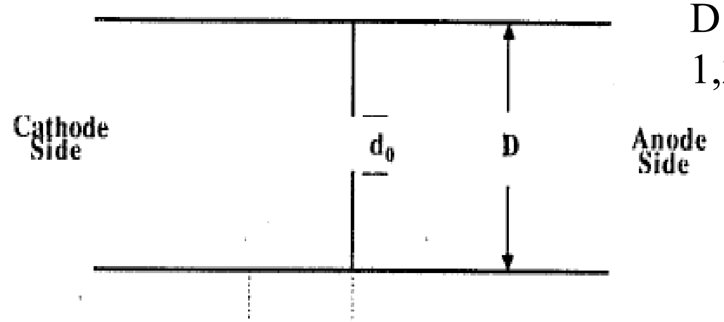


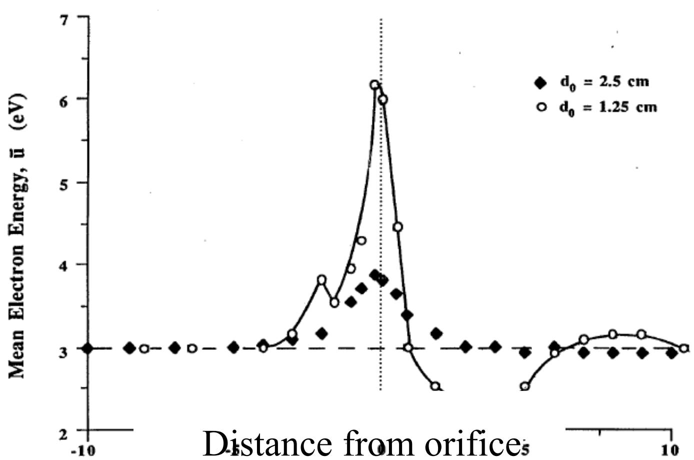
Godyak and Alexandrovich, XXVII ICPIG, vol. 1, p.221, Eindhoven, The Nederland, 2005

EEDF Modification with discharge current constriction

Ne/Hg p =1 Torr
D = 5 cm, d = 1,25 and 2.5 cm







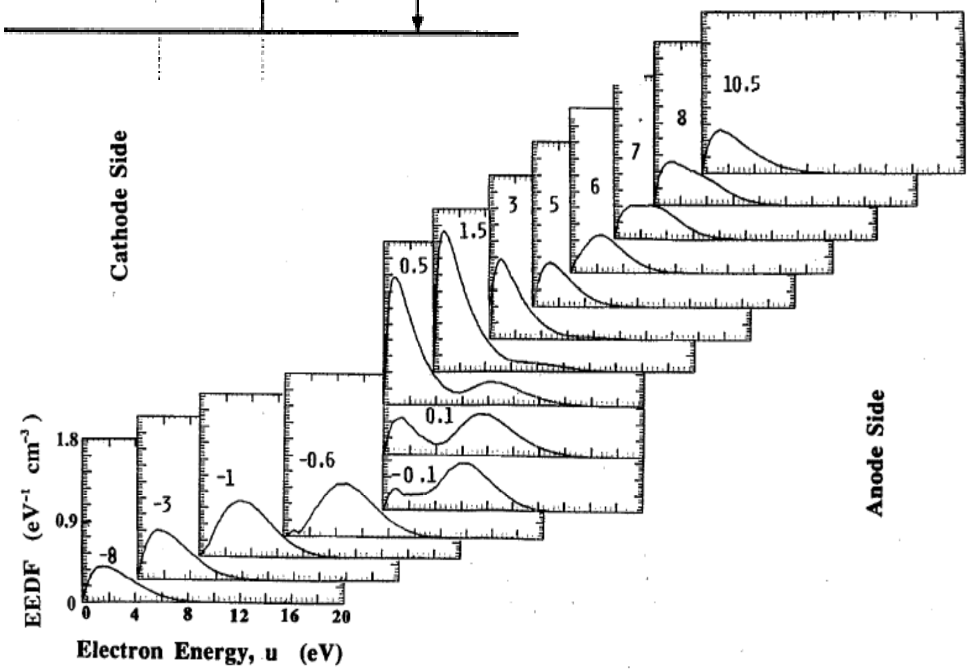
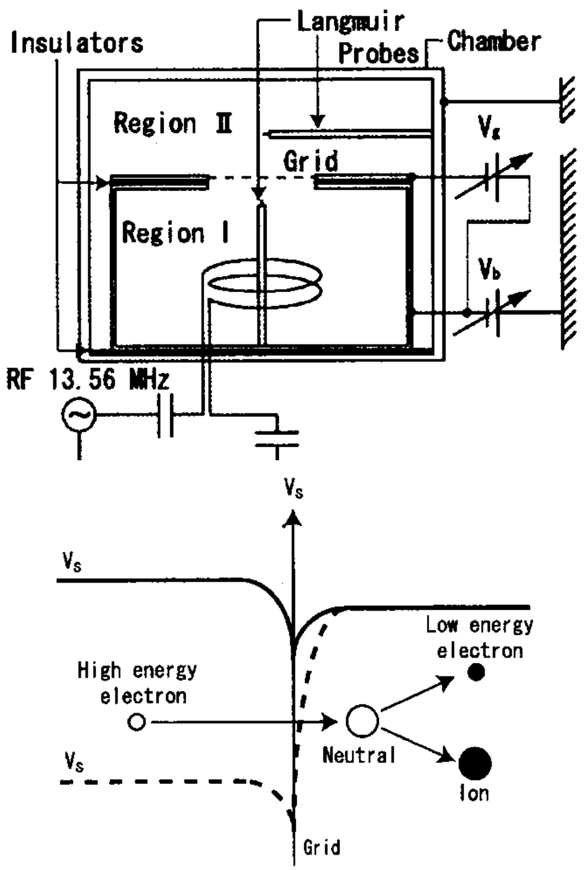


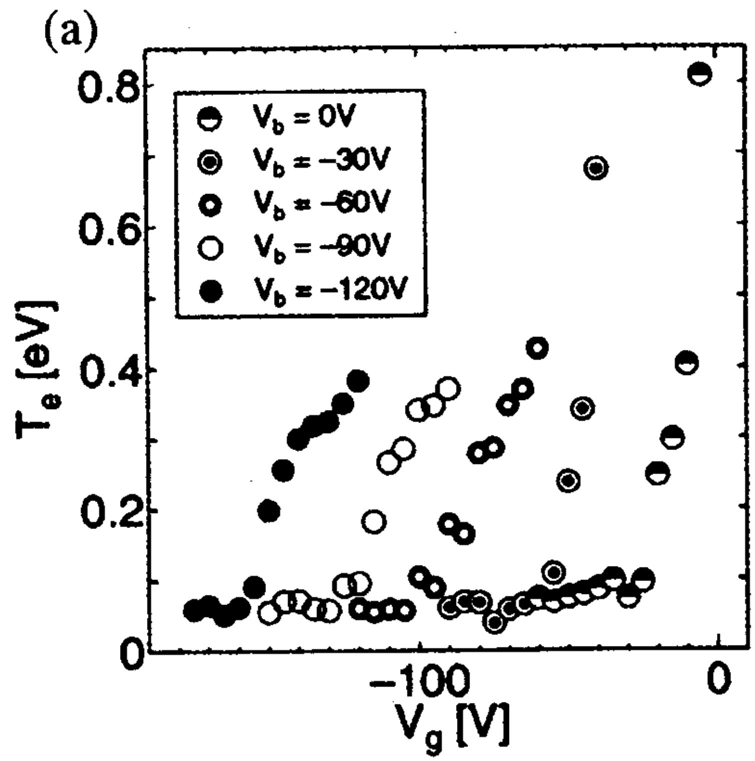
FIG. 7. Spatial evolution of the EEDF along the discharge (the numbers inside each rectangular box denote the distance from the orifice in centimeters. Here $P_{Ne}=1$ torr, $T_c=20$°C, $D=5.0$ cm, $d_o=1.25$ cm, $I=0.1$ A. The EEDF is expressed in units of 10^{10} eV^{-1} cm^3.

Godyak et al, Phys. Rev. ***A 38****, 2044, 1988*

T_e control with negatively biased greed (Kato et al, 1994)

Plasma source and diffusion zones are separated with negatively biased mesh



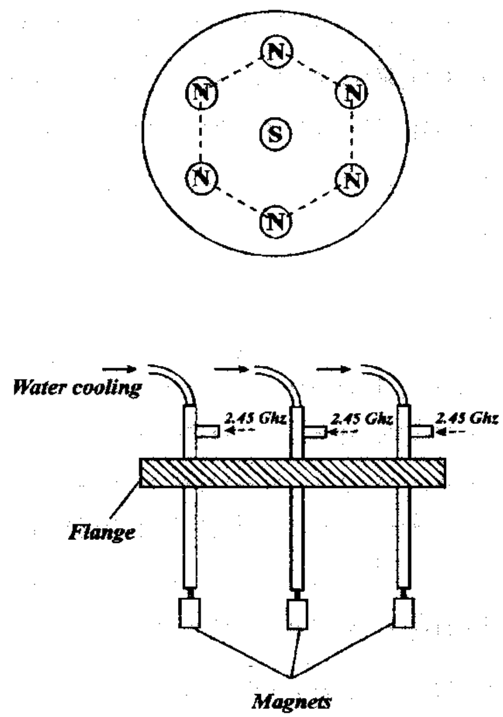


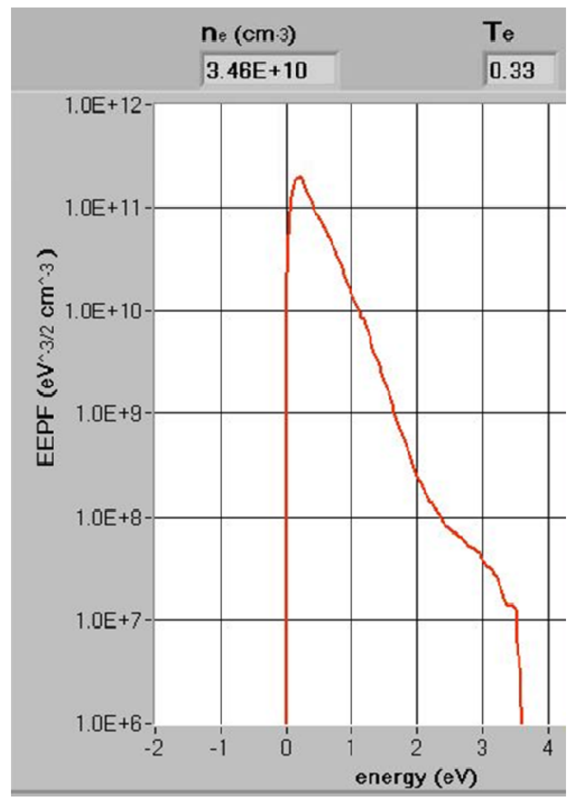
*Ikada et all, Thin Solid Films **457**, 55, 2004*

Localized ECR array reactor with trapped ECR plasma

Ar/SiF_4 at 10 mTorr with microcrystalline silicon deposition. Multicusp magnetic confinement of fast electrons. An order of magnitude T_e reduction in diffusion zone.

Local ESR electron heating with separation between hot and cold electrons provided by magnetic filters

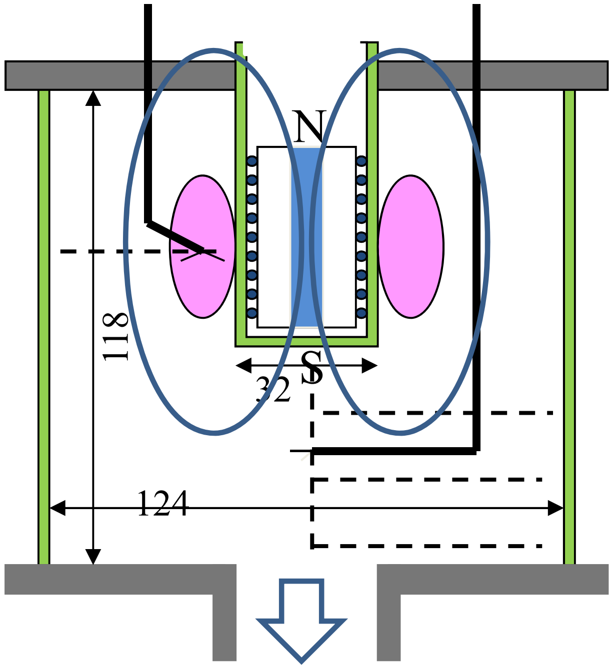


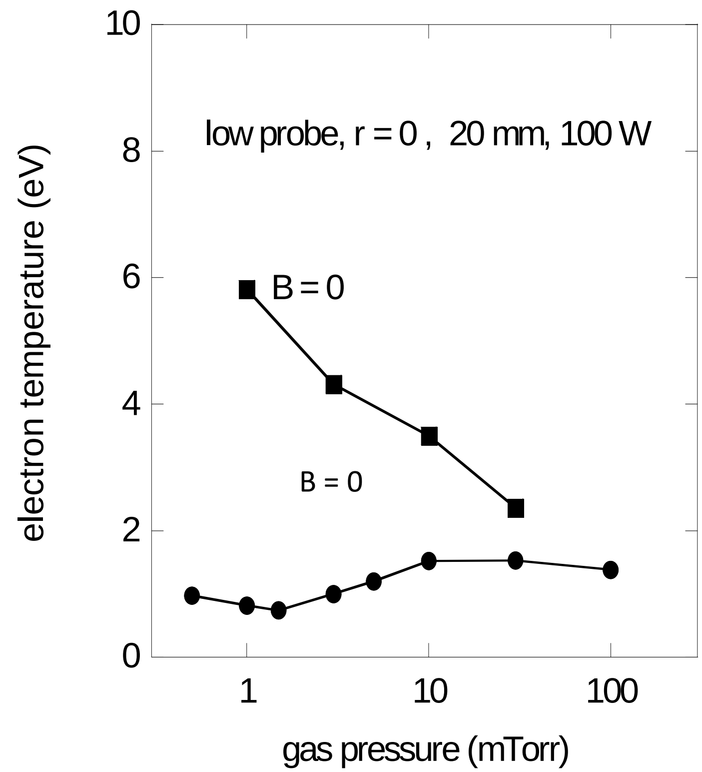


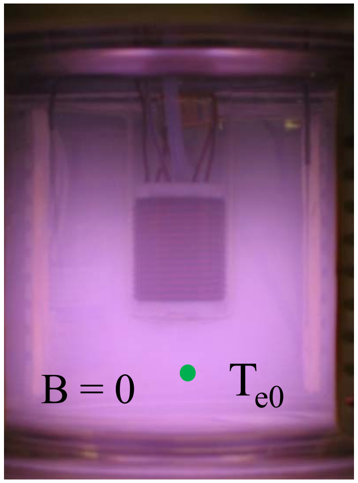
Measurement position

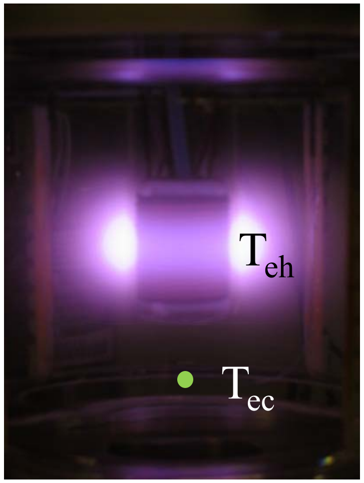
Bulkin et al, Ecole Polytechnique. 2010, to be published

Global magnetic filter with trapped ICP drive at 5 MHz







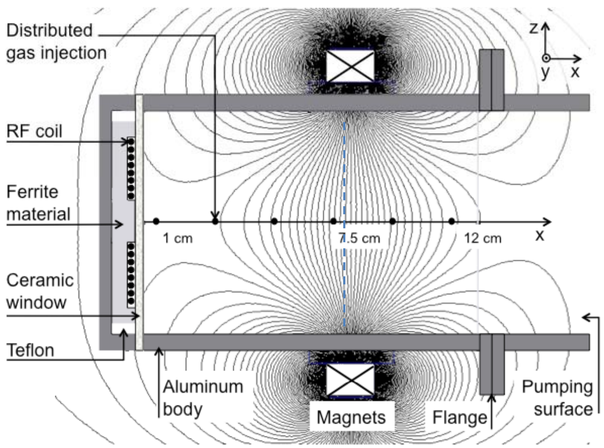


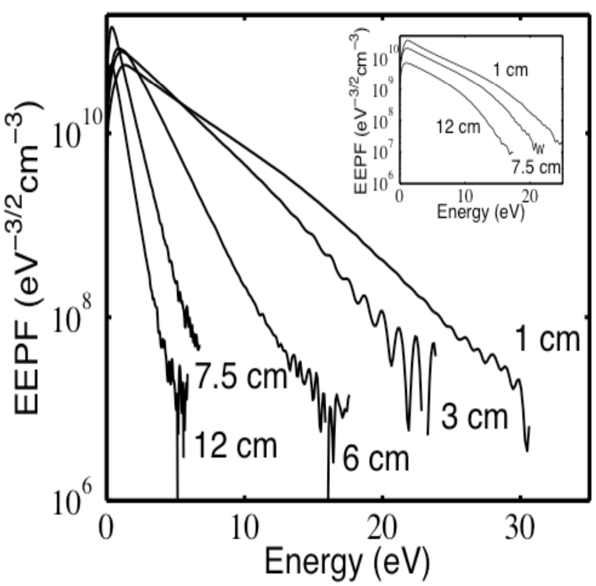
Magnetic field breaks non-locality in electron kinetics, leading to plasma stratification on hot (T_{eh}) and cold (T_{ec}) electron zones, $T_{eh} > T_{e0} > T_{ec}$

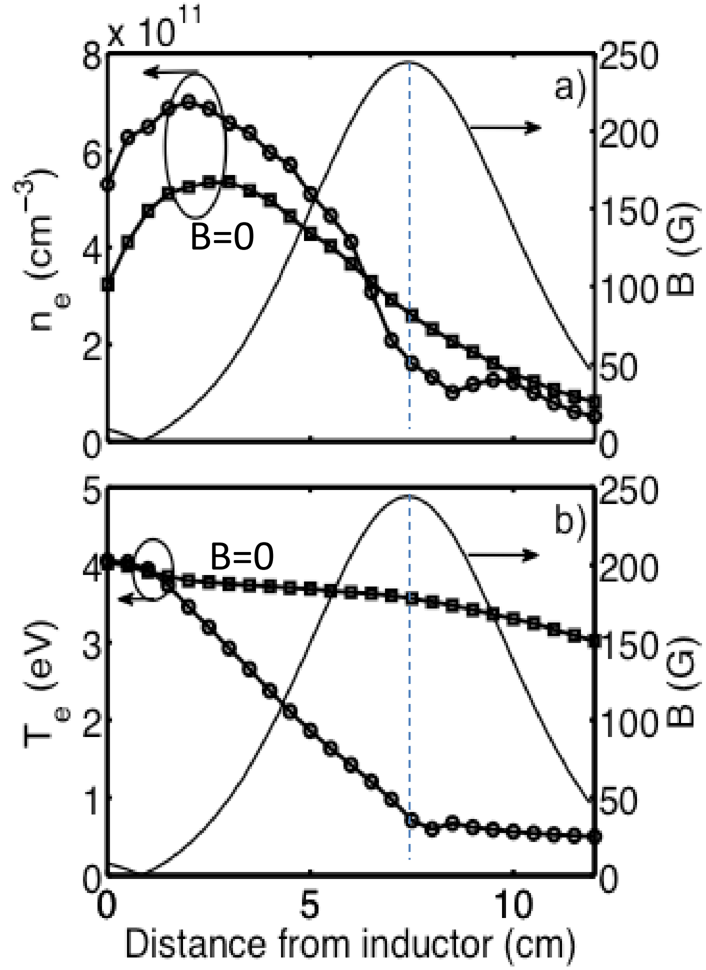
Godyak, 63 GEC, Paris, France, 2010

EEPF and plasma parameters along magnetic filter

Ecole Polytechnique







Aanesland et al, 2011, to be published

Conclusions

• In gas discharge plasma at $\lambda_\varepsilon >> \Lambda$ and large dE/dr, EEDF 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 cools down the main body of electron population leading to formation two electron groups

• Formation of highly non-equilibrium EEDF with two-temperature structure ($T_{e1} << T_{e2}$) requires both, strong E-field localization (to produce fast electrons) and some separation mechanism preventing low energy electron heating and 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 a viable way for creation of plasma with controllable EEDF.