Low-Pressure RF Plasma Sources for Industrial Applications

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PPPL School on Plasma for Microelectronics
and Quantum Information Science

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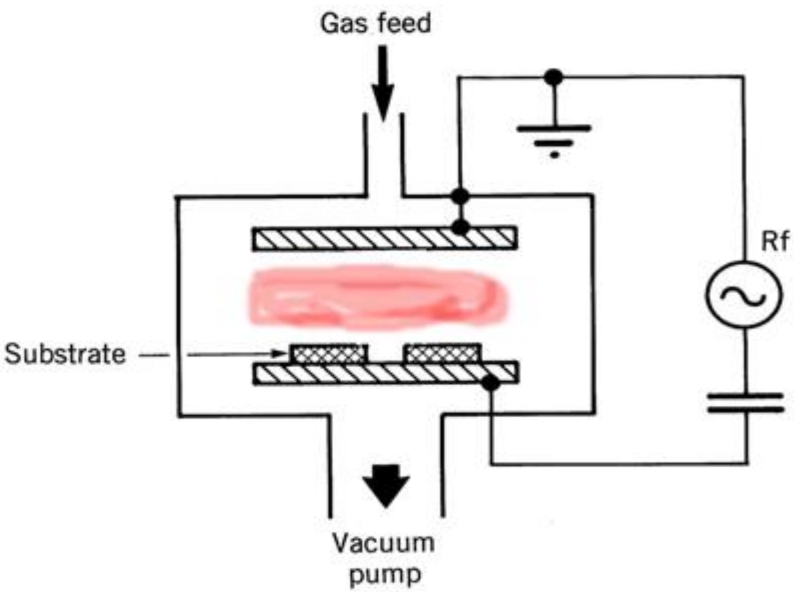
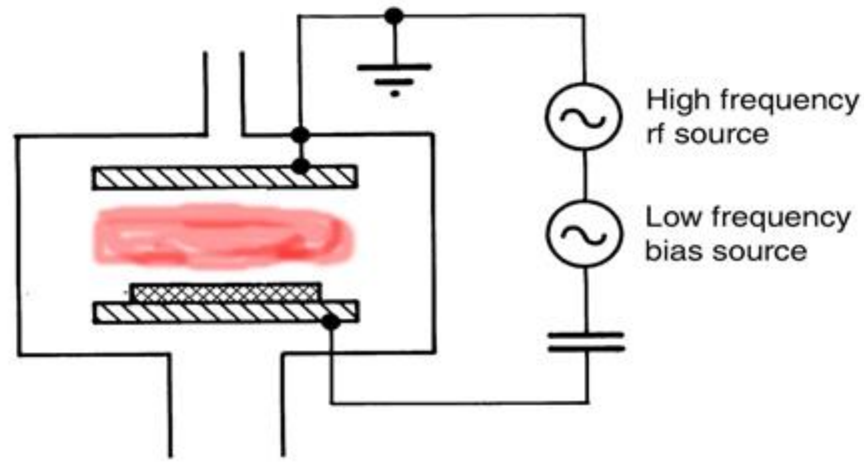
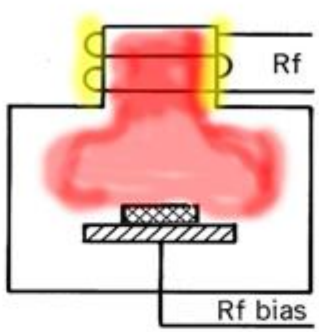
Main Plasma Sources in Processing of Materials



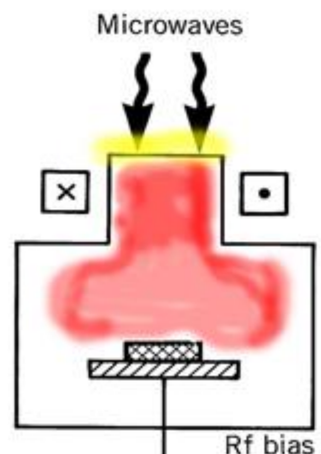
Capacitive
(Anisotropic etch)



Dual frequency capacitive discharge



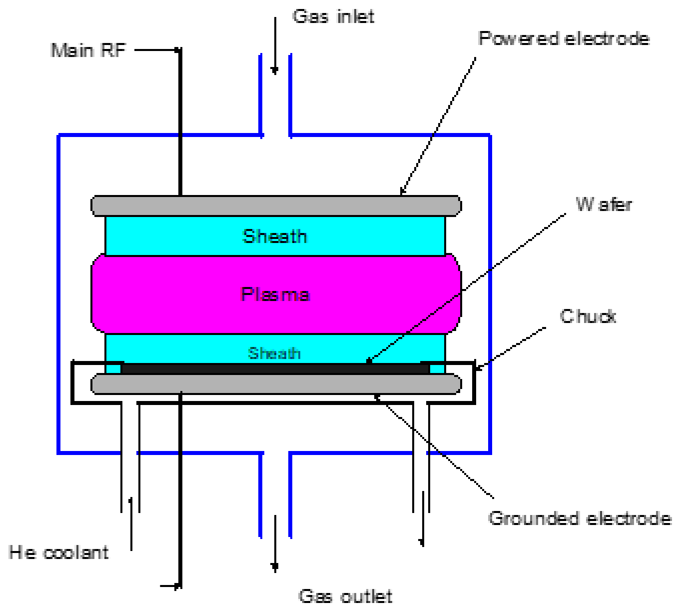
Inductive



ECR

M. Lieberman's lecture, 2007

CCP in Plasma Processing



F. F. Chen, AVS, 2003

Capacitive Coupled Plasmas (CCP) at 13.56 MHz were the first in plasma processing applications

In CCP the discharge current and plasma density are controlled by the electrode rf sheaths at the plasma boundary

- Good plasma uniformity due to rf sheath ballasting effect*
- Simple and relatively inexpensive construction

b u t:

- No independent control of ion flux and ion energy
- Low plasma density at low gas pressure
- At large rf power and low gas pressure, most of power goes for ion acceleration rather than for plasma production

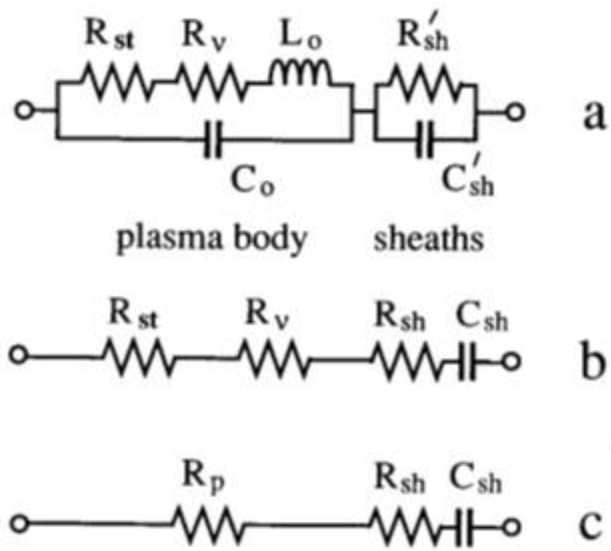
*Sheath stabilizing effect is due to different sheath and plasma impedance dependence on plasma density, $Z_p \sim N_p^{-1}$, while $Z_{sh} \sim N_p^{-1/2}$ (a good subject for study)

CCP equivalent circuit and CCP analytical model

General

@ $\omega^2 + \nu_{en}^2 << \omega_{e0}^2$

$V_{pl} << V_{rf}$



$R_\nu = L/\sigma_p A$, $\sigma_p = eN/m(\nu_{en} + j\omega)$,

$C_{sh} = A/\varepsilon_0(S_1 + S_2)$

A combination of the CCP equivalent circuit with ionization and electron energy balances resulted in analytical ICP mode.

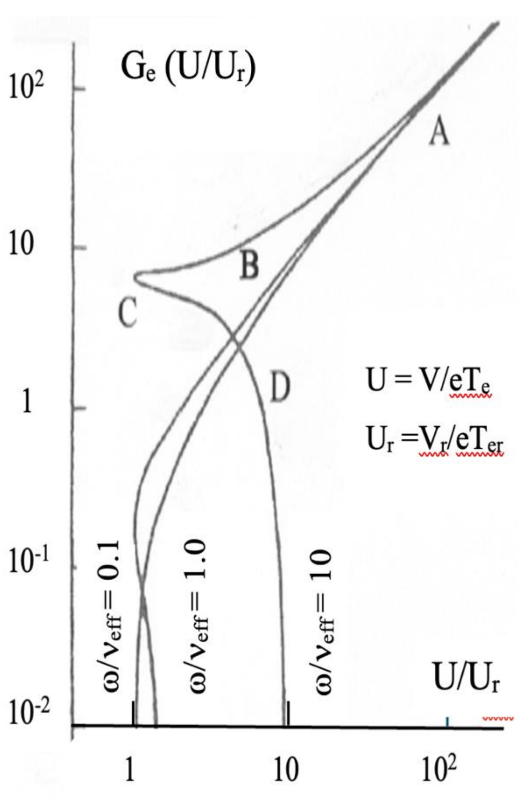
$P_{rf} = P_p + P_i$; Since in plasma

$E_p \approx$ const, $N_p \sim I_d$ and $V_{dc} \sim V_{rf}$

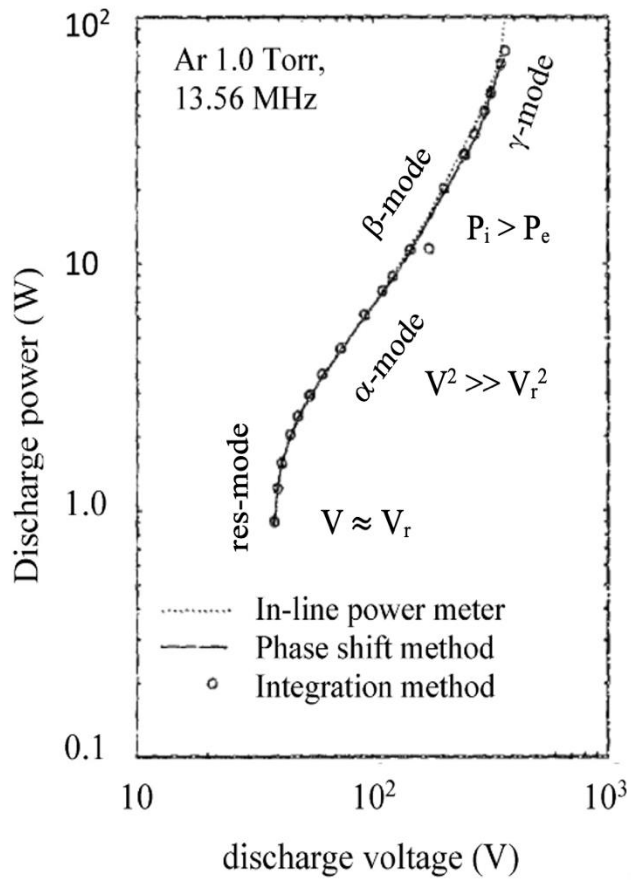
$P_p \sim I_d$ and $P_i \sim I_d^2$

This model predicted a variety of CCP features, later confirmed in experiments and numerical simulations.

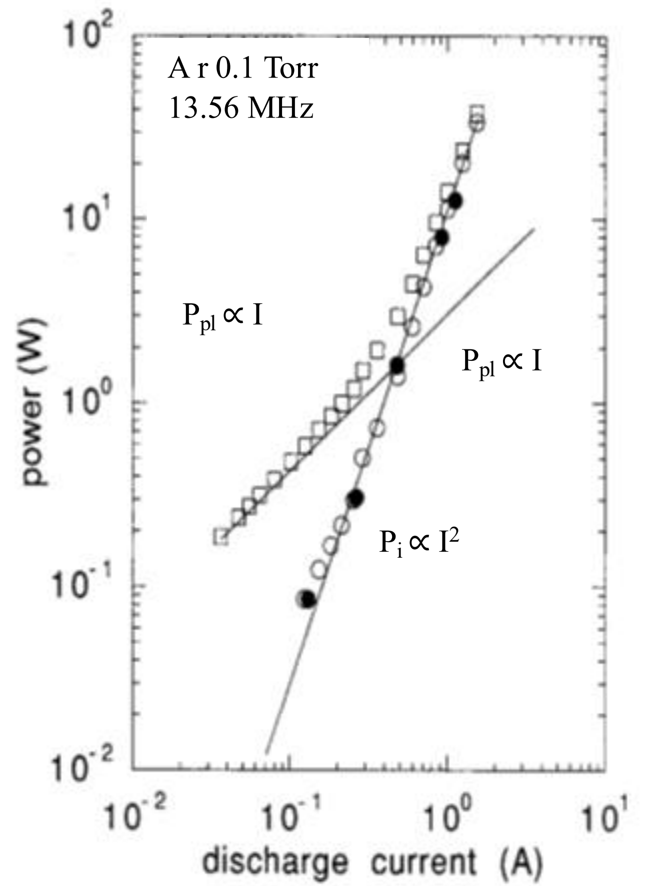
CCP Discharge Power and Volt/Ampere Characteristic



The theoretical universal function of an ICP discharge current and rf power



Discharge power P as a function of the discharge voltage V.



Discharge power absorbed by plasma electrons, Ppl, and by ions accelerated in rf sheaths P_i.

Main CCP Features Predicted by the CCP Theory.

With assumptions: (A uniform ion distribution, $\nabla N_i = 0$; And opaque plasma, $\omega_{0i}^2 << \omega^2 << \omega_{0\varepsilon}^2$)

- Double-value of CCP current I(V) and power P(V).
- Minimal $V = V_r$ corresponds to the series plasma-sheath resonance at $\omega_r^2 = \omega_{0e}^2 (S_1+S_2)/L$.
- At $I < I_r$, CCP has an inductive and a significant negative differential impedance.
- At $V >> V_r$, plasma density $N \propto V$, $\propto I$, $\propto \omega^2$, & $V_{dc} \propto V$, $P_i \propto V^2$, $\cos\varphi << 1$.
- At resonance, $N \propto \omega^3$, $\cos\varphi = 1$, and $dN/dV \rightarrow 0$

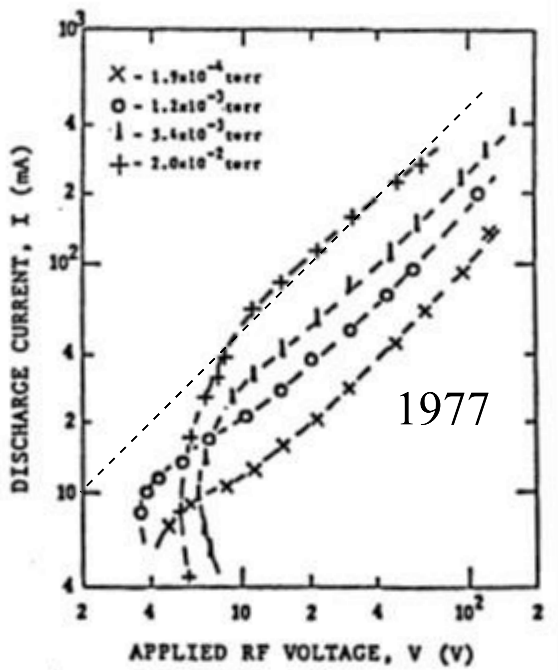
  The discharge current very weakly depends on gas pressure
- At symmetrical drive, $V_{pl\omega} = 0$, while $V_{pl2\omega} = 0.1V$.

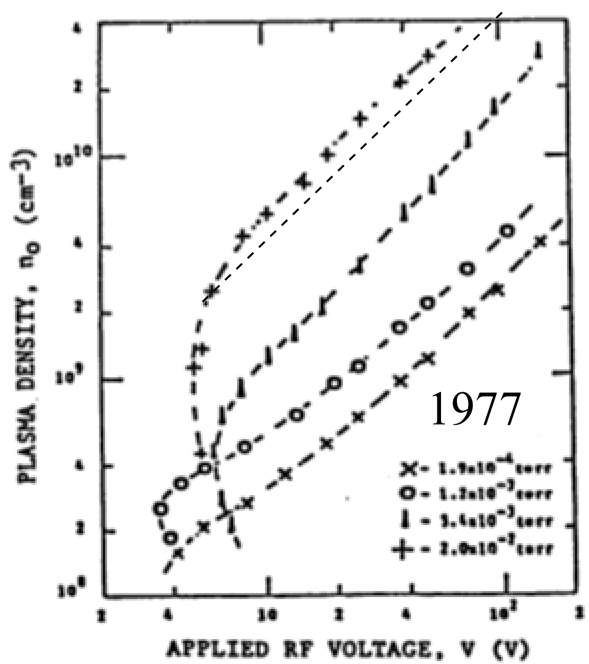
According to the CCP analytical model, assuming a uniform ion distribution between electrodes

$$P_d \propto I_d \propto N_p \propto \omega^3 \nu_{eff} L^2/V_p\{1 \pm (\nu_{eff}/\omega)[(V_{rf}/V_p)^2 - 1]^{1/2}\}$$

where $V_p = \mathrm{Re}(E_p L)$ is the minimal discharge sustaining voltage, and at large ($V_{rf} >> V_p$), $I_d \propto N_p \propto V_{rf}\omega^2$; $S_{sh} \sim \omega^{-1}$; bi – value of I(V) and negative V/A characteristic and inductive impedance of CCP !

CCP in Hg vapors at 40.8 MHz shows a linear V/A characteristic at $V_{rf} >> V_p$



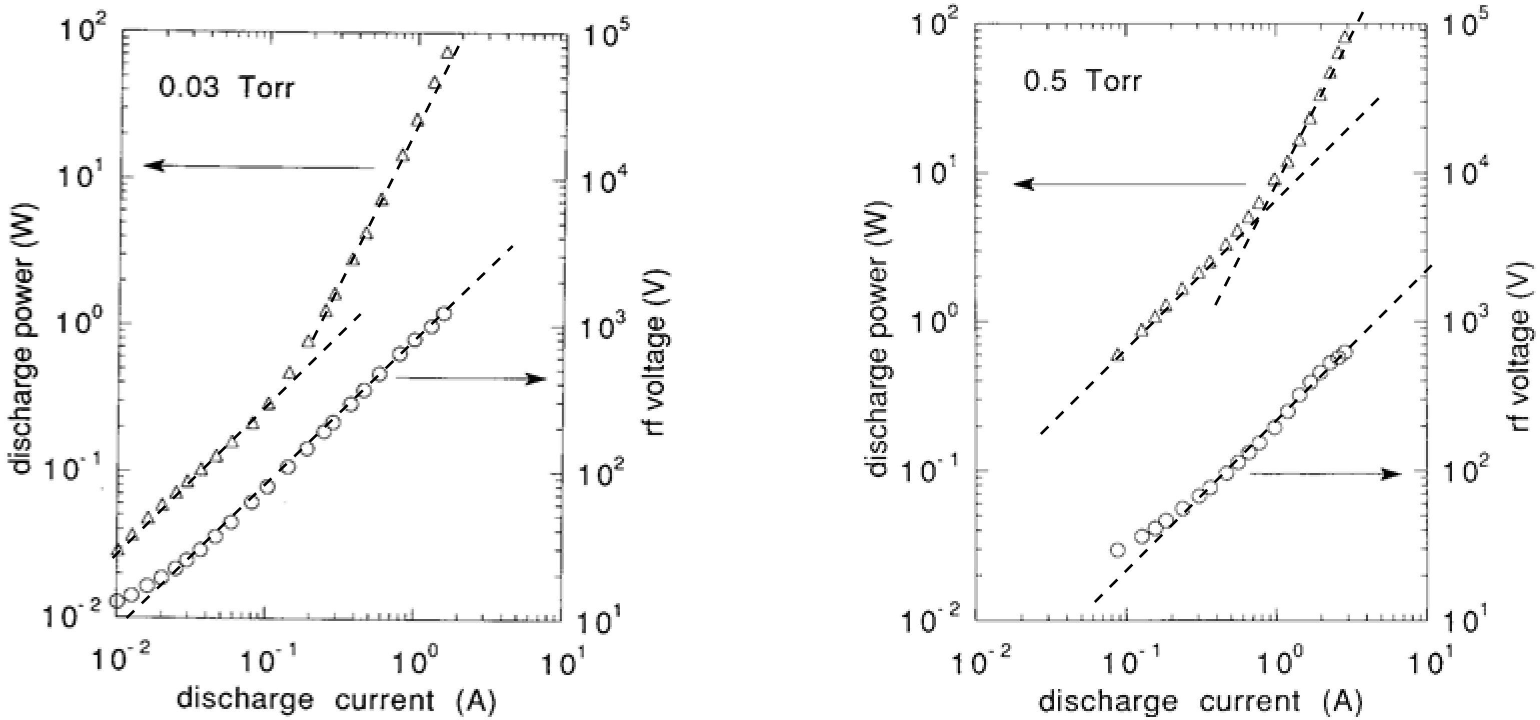


Due to large M , f, andrelatively small rf voltage, Pi is negligibly small

V. Godyak et al, in proceedings of XII ICPIG, p. 347, Berlin, Germany (1977).

Electrical characteristics of a symmetrical CCP, Argon, 13.56 MHz

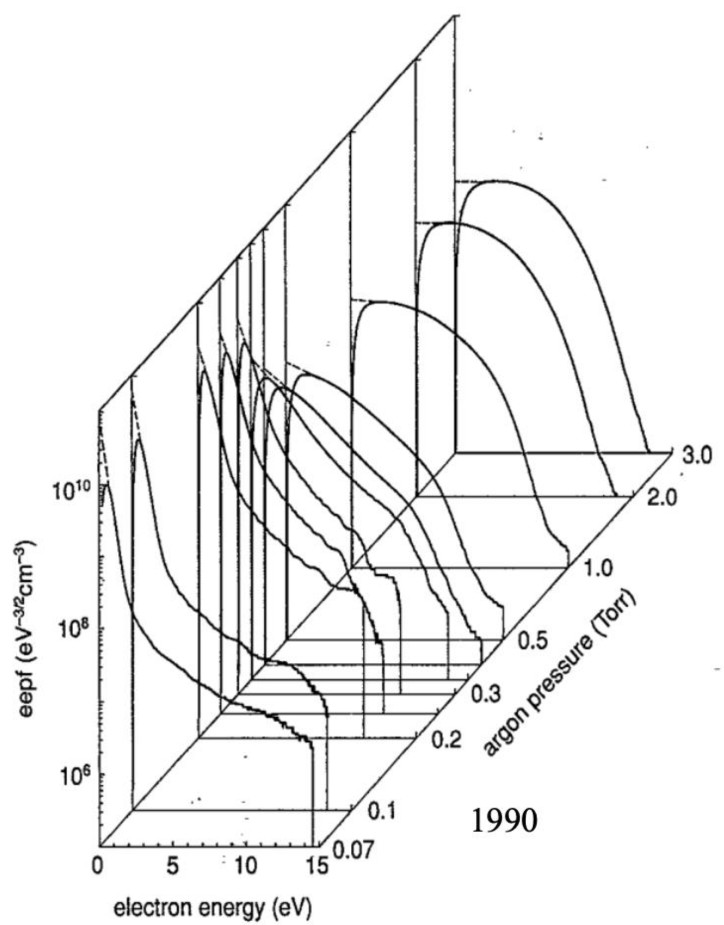
L=6.7 cm, D = 16 cm

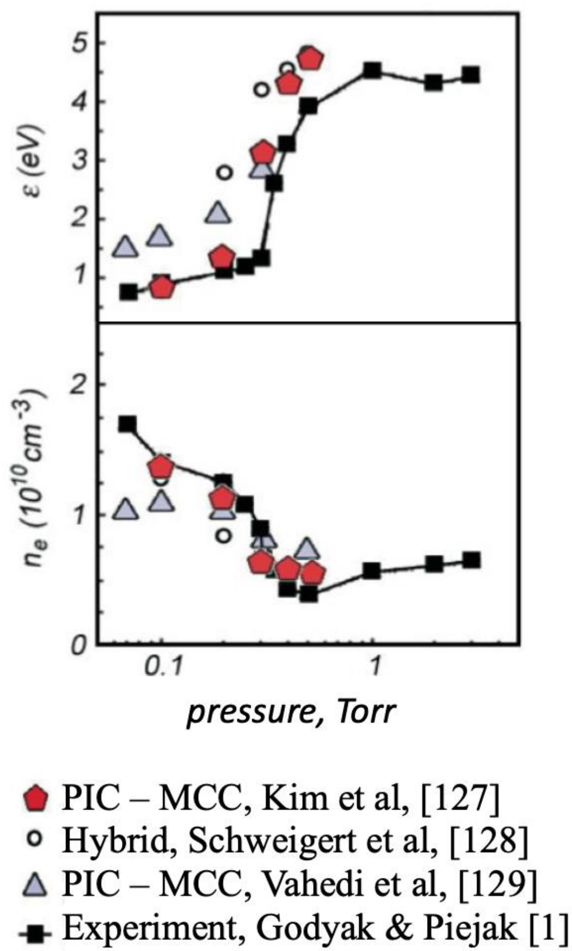


For moderate rf voltage ($V_p < V < 1$ kV), V/A discharge characteristics are nearly linear, that does not obey to Childs-Langmuir law followed from Lieberman rf sheath model.

V. Godyak et al, IEEE Trans. PS, ***19****, 660, 1991*

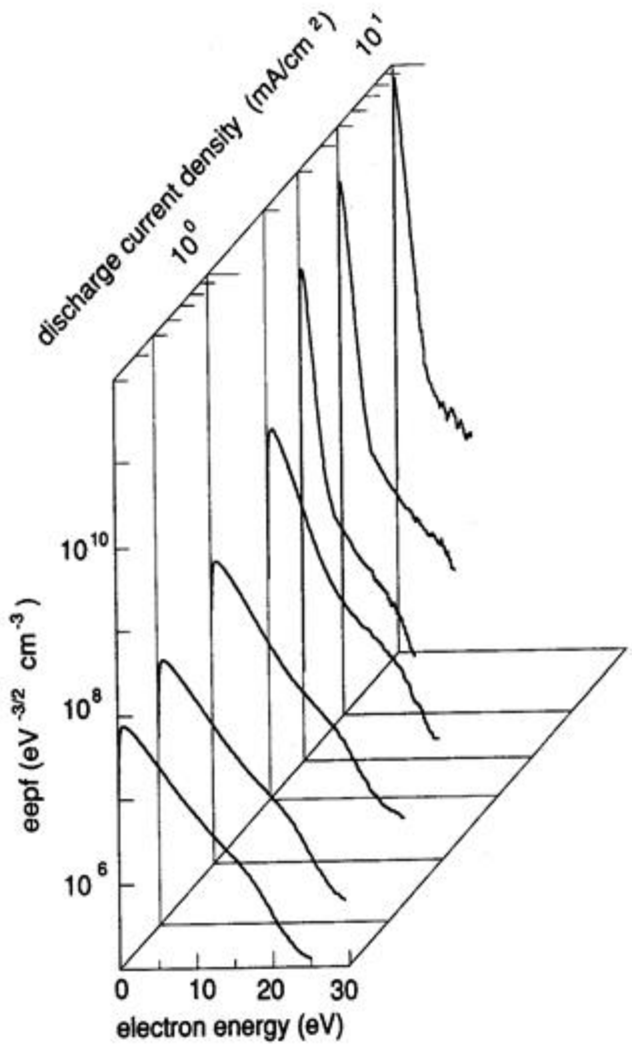
CCP mode transitions. Volume/boundary heating mode transition, argon 13.56 MHz, L= 2 cm, D = 16 cm

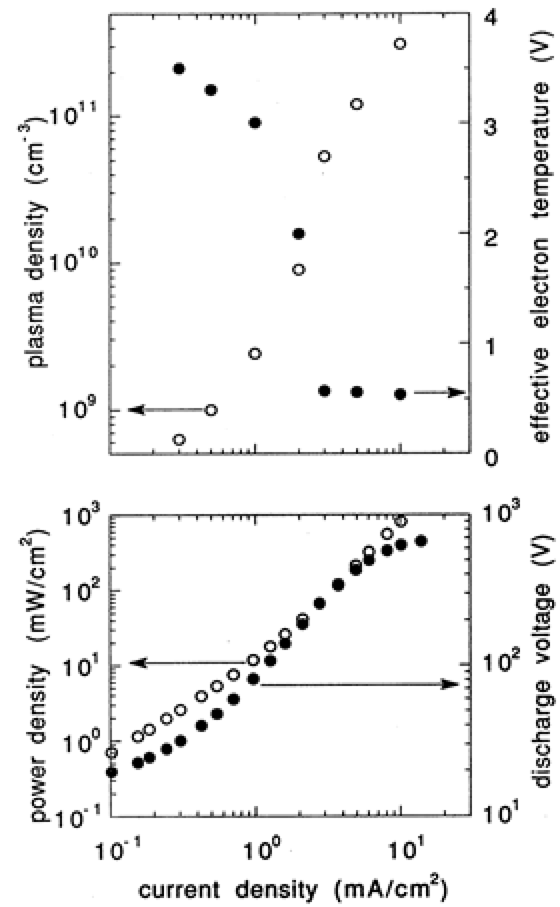




V. Godyak & R. Piejak PRL ***65****, 996, 1990*

2. α to γ-mode transition (13.56 MHz, He, 0.3 Torr)





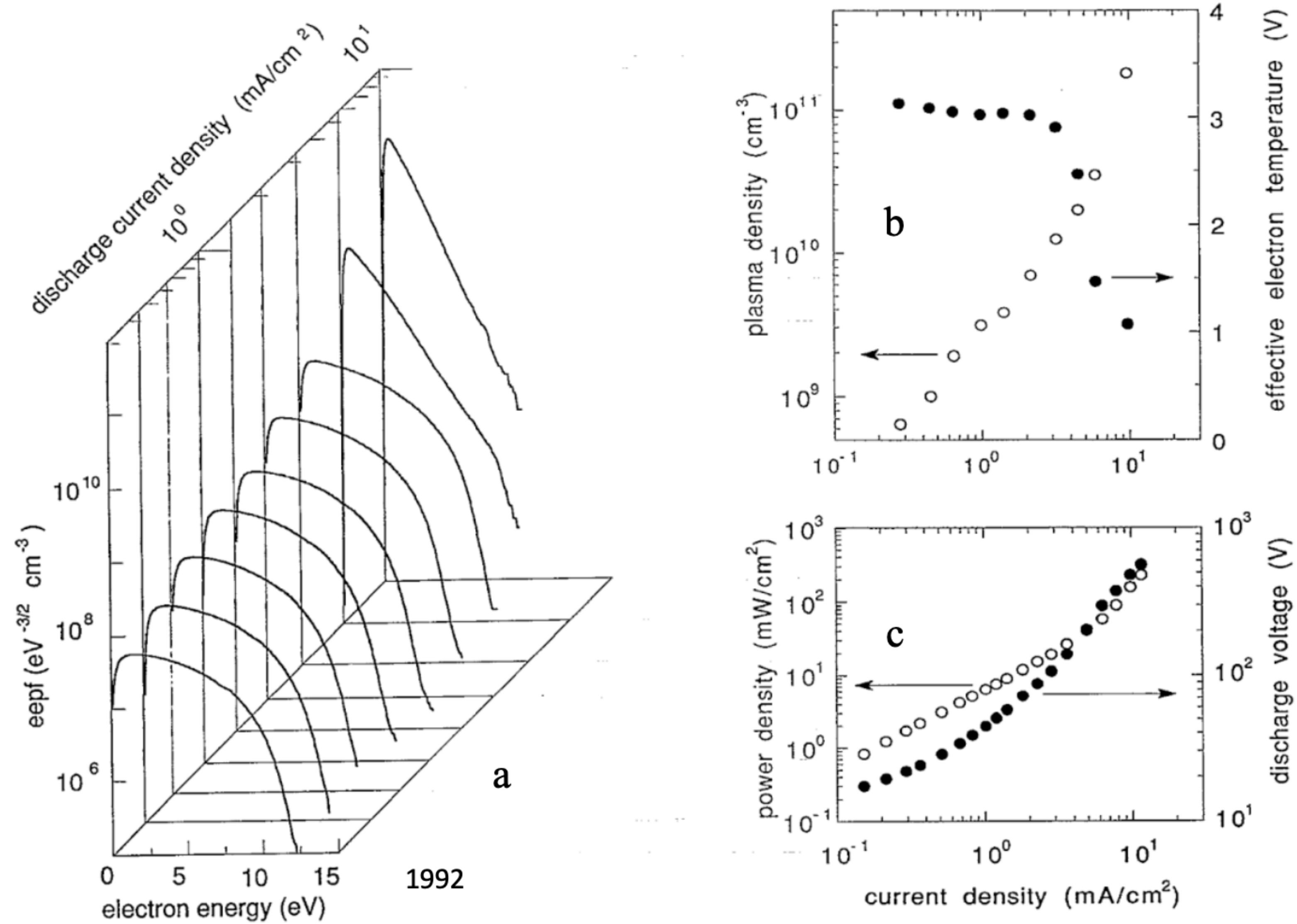
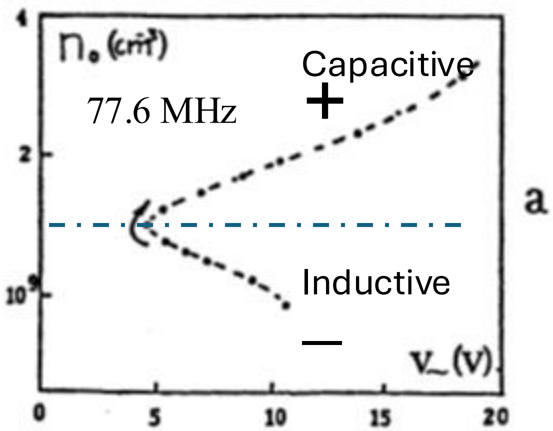


Fig. 61. a - EEPFs measured in the center of argon CCP at 13.56 MHz, 0.3 Torr. b - Plasma parameters. c – Discharge voltage and power density.

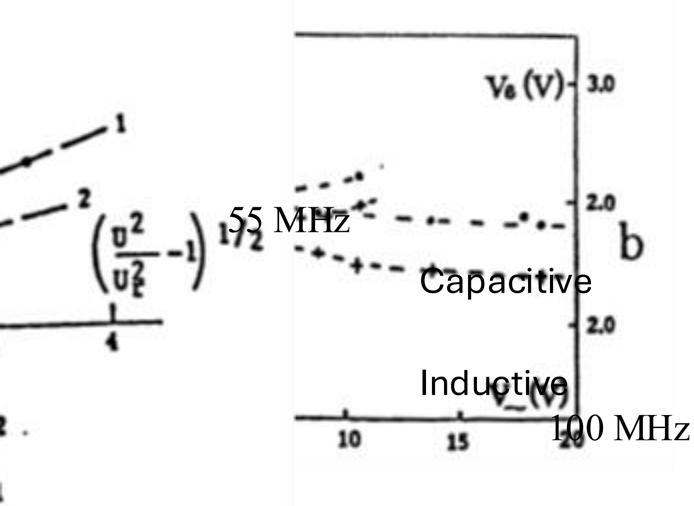
3. CCP resonant mode , (Hg 1.2 mTorr, L = 7.8 cm, D = 7 cm)



Peak discharge voltage

$$N_p \propto \omega^3\{1 \pm (\nu_{eff}/\omega)[(V_{rf}/V_p)^2 - 1]^{1/2}\}$$ *(1976)*

- Series (geometric) resonance of inductive plasma and capacitive sheath
- Double valued rf current and plasma density with capacitive and inductive discharge impedance
- Discharge parameters are not sensitive to discharge voltage when ω > veff
- In the resonance, the rf current does not depends on gas pressure, while Np ~ ω3

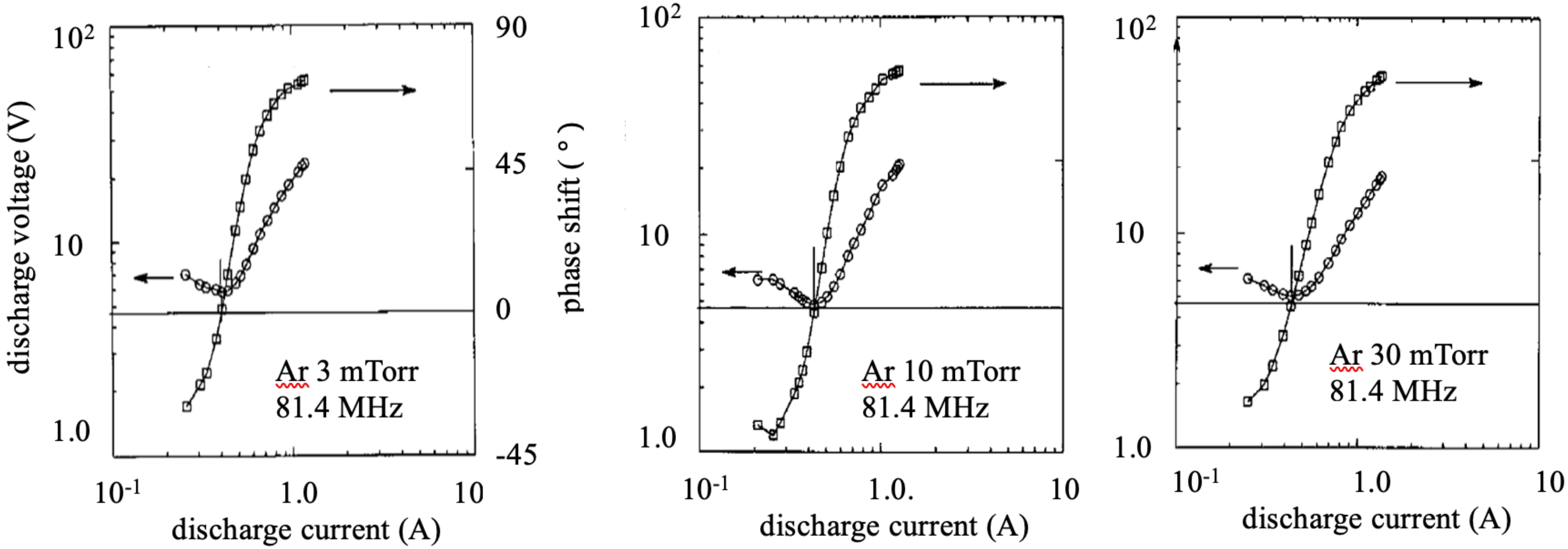


The analytic expression above and experiments suggest to utilize a higher frequency to achieve higher plasma density at fixed discharge voltage

V. Godyak & O. Popov, *Sov. J. Plasma Physics* ***3****, 238 (1977)*

Discharge voltage and phase shift between rf voltage and current in argon CCP

Practical independence of V/A and phase characteristics on argon pressure (3-30 mTorr) demonstrates the predicted by the theory effect of CCP self-stabilization at the resonance mode

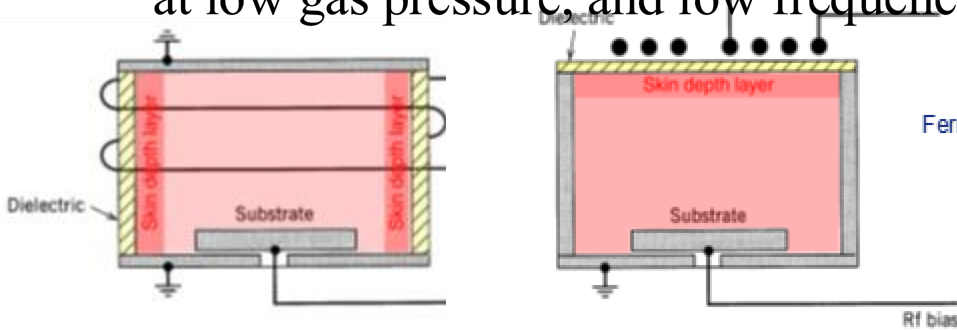


VHF CCP in many industrial plasma processing reactors are working in the close-resonance mode

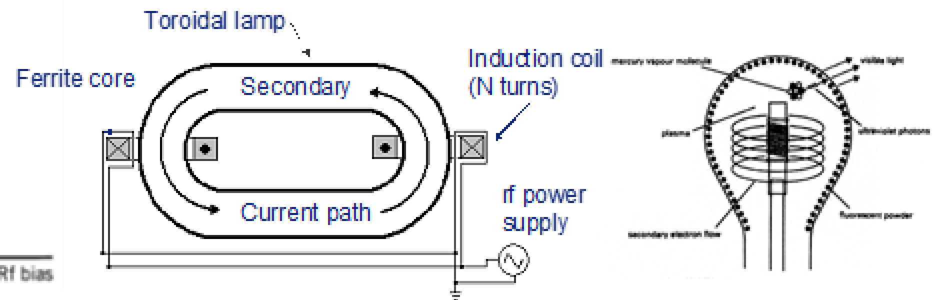
Inductively Coupled Plasma (ICP) Sources

Main ICP topologies in applications

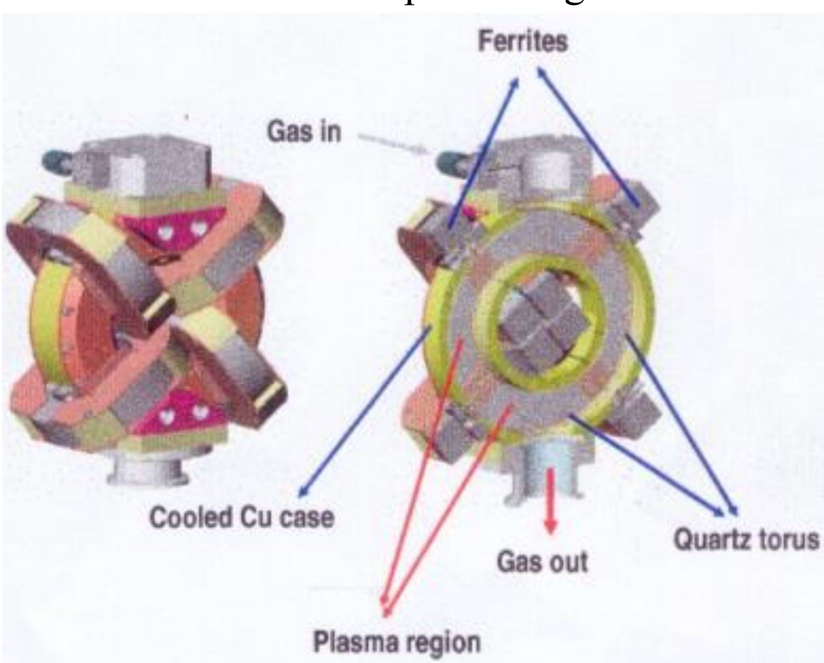
Advantages: Decouple plasma density and ion energy, the ability to work at low gas pressure, and low frequency with high plasma density

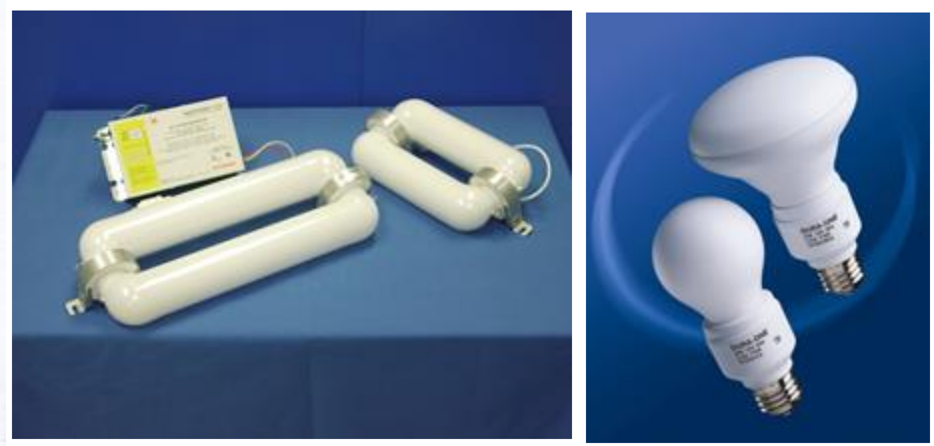


Wafer processing



Lighting





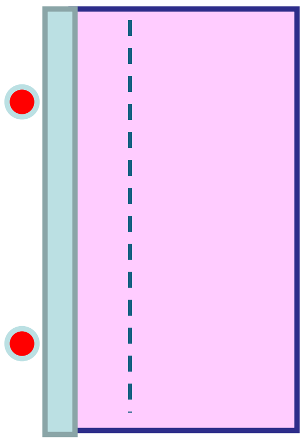
Lighting

Skin Effect, $\delta \equiv E(dE/dx)^{-1}$

In ICP, the rf current forms a closed loop within the plasma without rf sheath

Rf power absorption is localized within a skin layer at the plasma boundary

1. Geometric skin depth (the most important… and neglected) is due to the multidimensionality of the real ICP structure



2. High frequency SE, $\delta_0 = c/\omega_0$ @ $\omega >> \nu_{en}$ and $\omega >> v_{Te}/\delta$ *

3. Low frequency, normal SE, $\delta_n = \delta_0(2\nu_{en}/\omega)^{1/2}$ @ $\omega << \nu_{en}$ *

4. Anomalous SE @ ω and $\nu en << v_{Te}/\delta$ **

5. Non-linear SE @ $\omega << v_{rf}/\delta$ ** $(eB_{rf}v_{rf}/c > eE_{rf})$

* Formulae 2 and 3 are valid only for a uniform plasma with a planar boundary!

** Cases 4 and 5 process non-exponential spatial variation of **E** & **B**

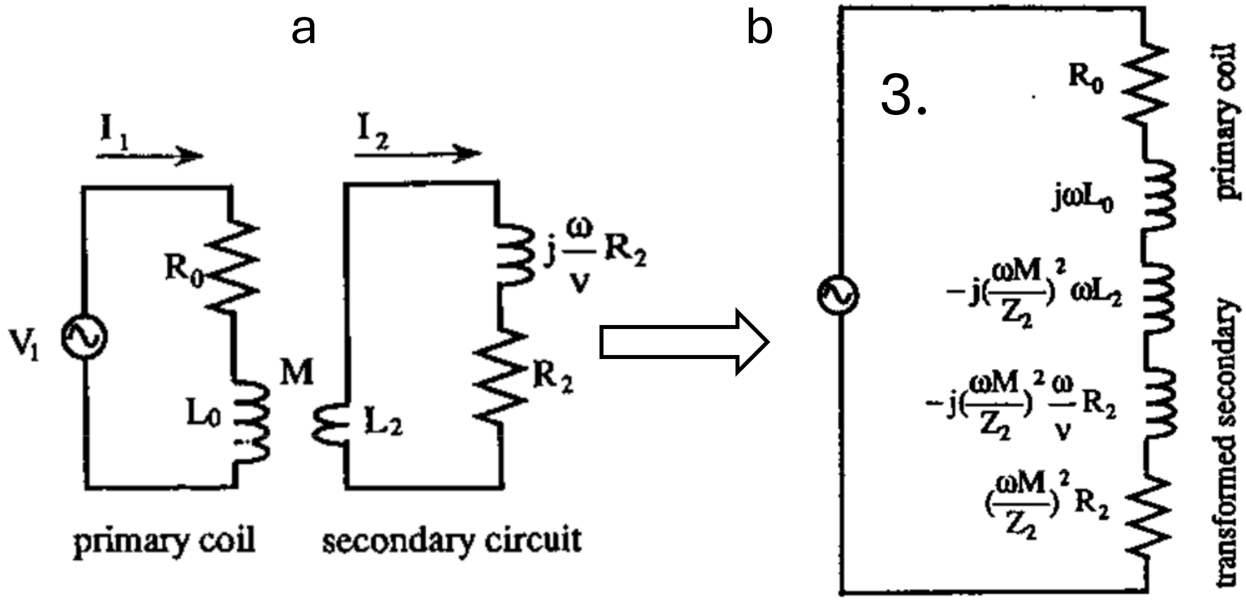
Analysis of ICP System

2.

a

b

3.



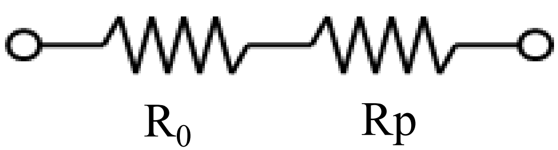
ICP equivalent circuit based on the transformer model;
a) - coupled primary and secondary circuits, b) – modified by plasma presence primary ICP circuit [1].

ICP plasma and electrical parameters

Electron temperature is defined by the ionization balance, $T_e = T_e(p\Lambda)$

- The plasma density is defined by the power absorbed by electrons, $N_p \sim P_p$.

- By measuring of the transmitted power to the coil P_0 and the current I_0 w/o plasma, and the same with the plasma (I & P), one can infer the power absorbed by plasma, P_p, and the power loss in antenna and surrounding hardware, P_C (in antenna, matcher, and chamber).



$P_0 = I_0^2 R_0$, $R_0 = P_0/I_0^2$

$P_c = P_0(I/I_0)$, $P_p = P - P_c$

$P_p = P - P_0(I/I_0)$

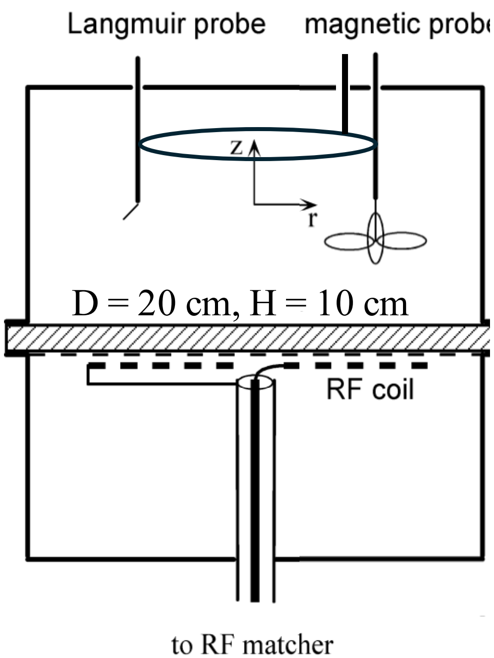
Measured: I_0, P_0, I, & P

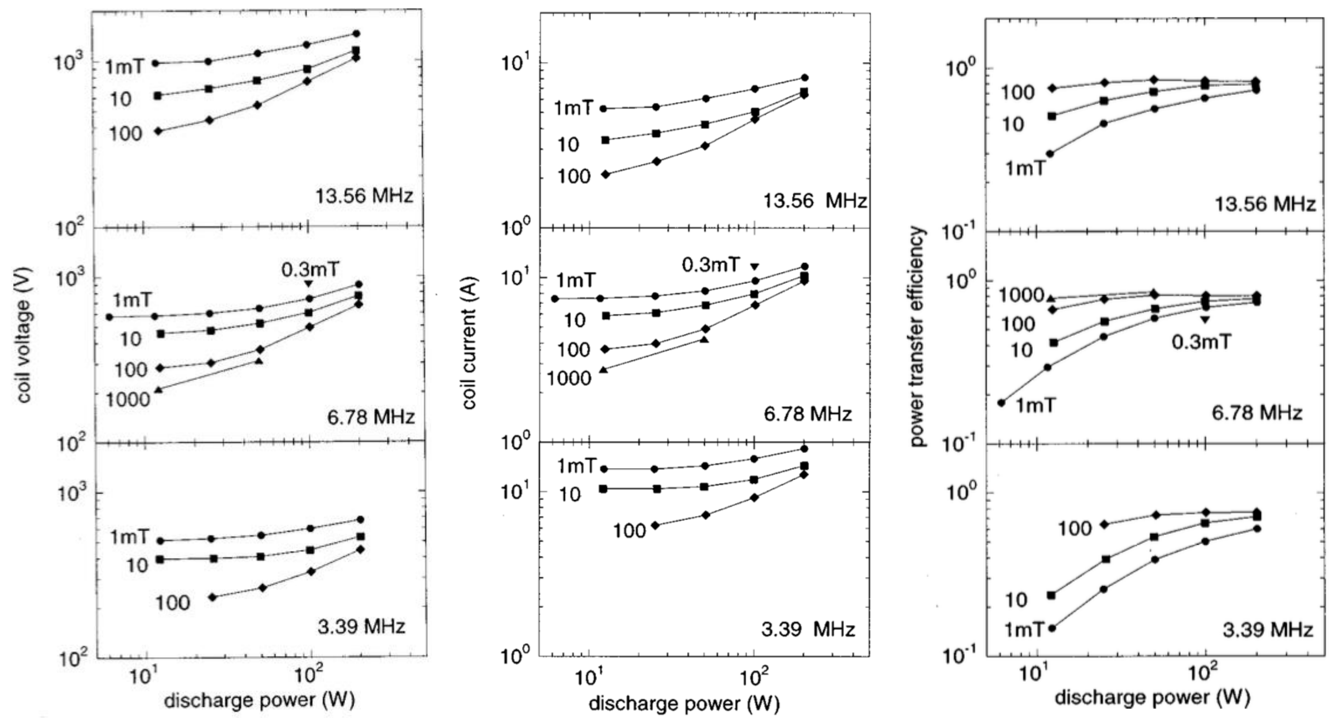
Calculated: P_0, P_c, P_p

Surprisingly, this simple RF diagnostics is neglected in the characterization of commercial plasma reac-reactors and in the overwhelming number of pub-publications, where plasma is characterized by the power consumed from the power source. The dis-charge power is always smaller (sometimes, signi-ficantly) than P_p, and is not proportional to P_p.

*R. Piejak et al, PSST **1**, 179, 1992*

Some experimental data measured in Ar ICP





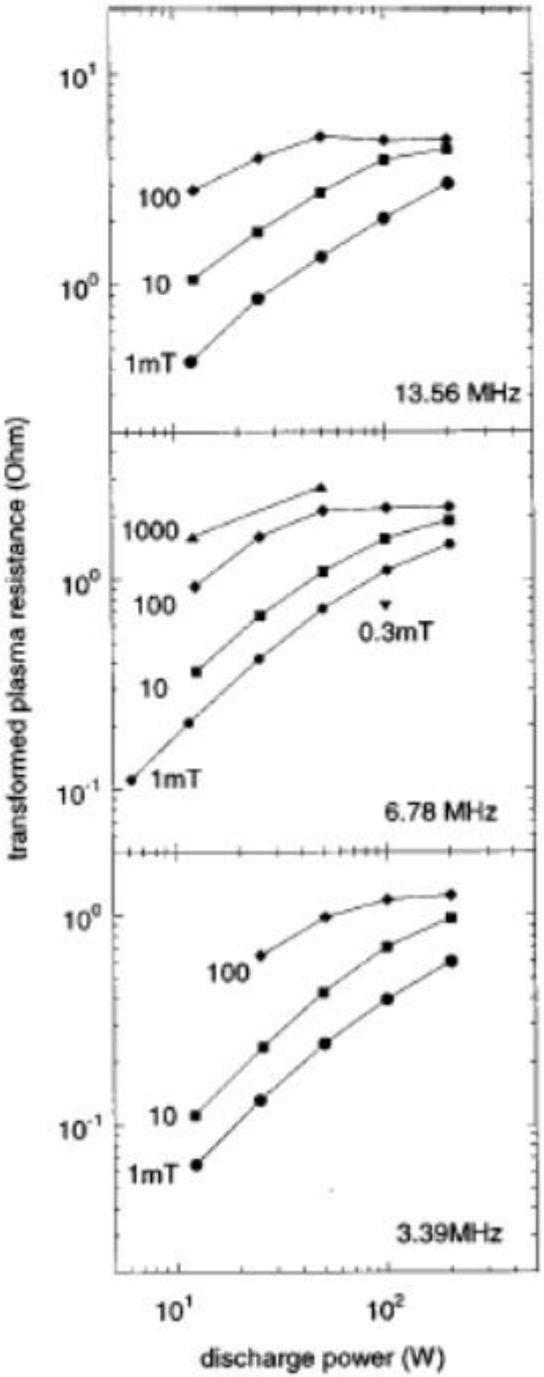
External parameter range
Diagnostics

Frequency MHz. 0.45; 0.9; 3.39; 6.78; 13.56; 81 Electrical I; V; P_d; P_c 29;

Ar pressure mTorr 0.3; 1.0; 3.0; 10; 30; 100; 300; 1T Magn. probe B; E; I_p; w_p

Power P_d W 12.5; 25; 50; 100; 200; 400; Langm. probe f[ε]; n; T_e; ν_{en};

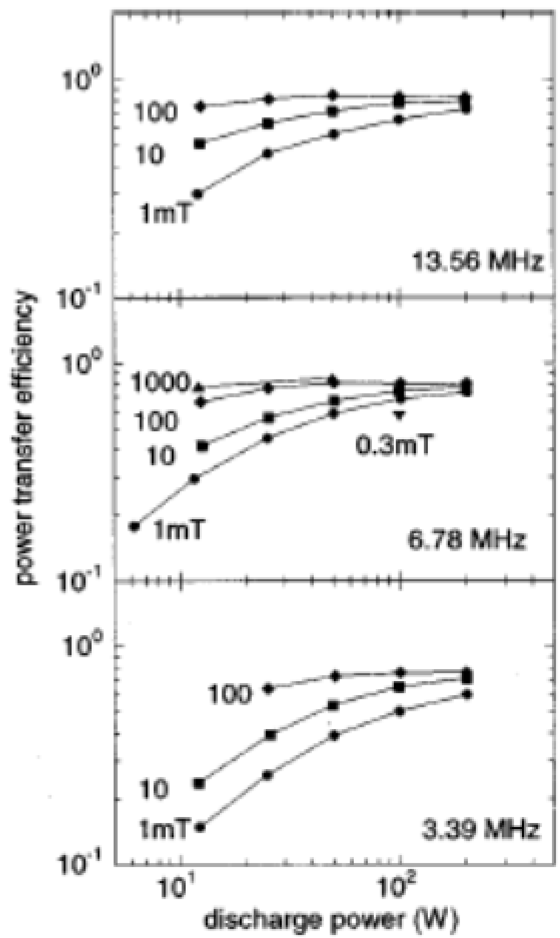
More electrical parameters



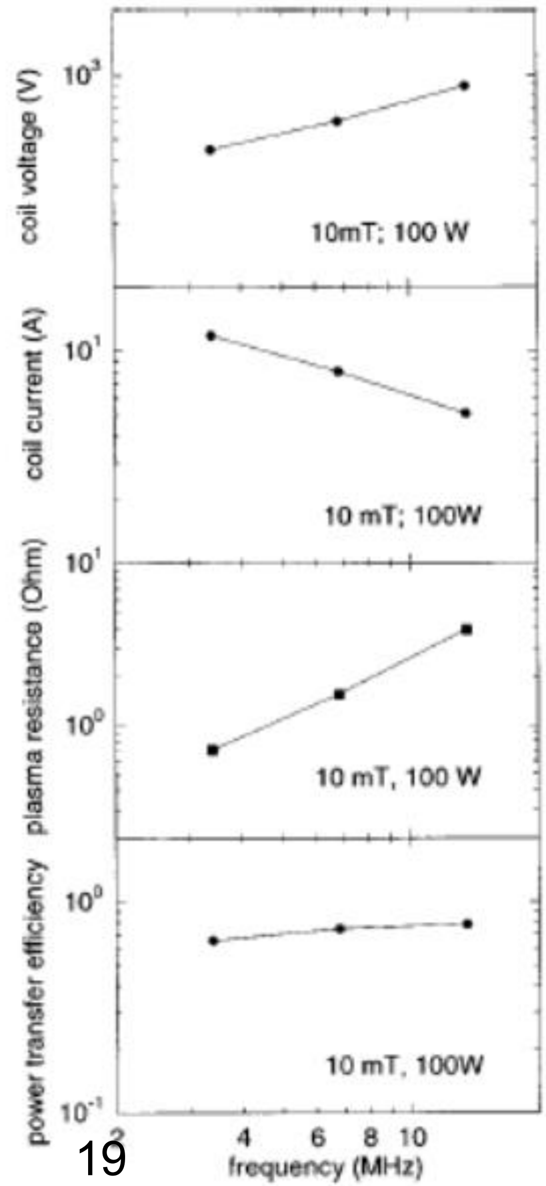
Transformed plasma resistance

←

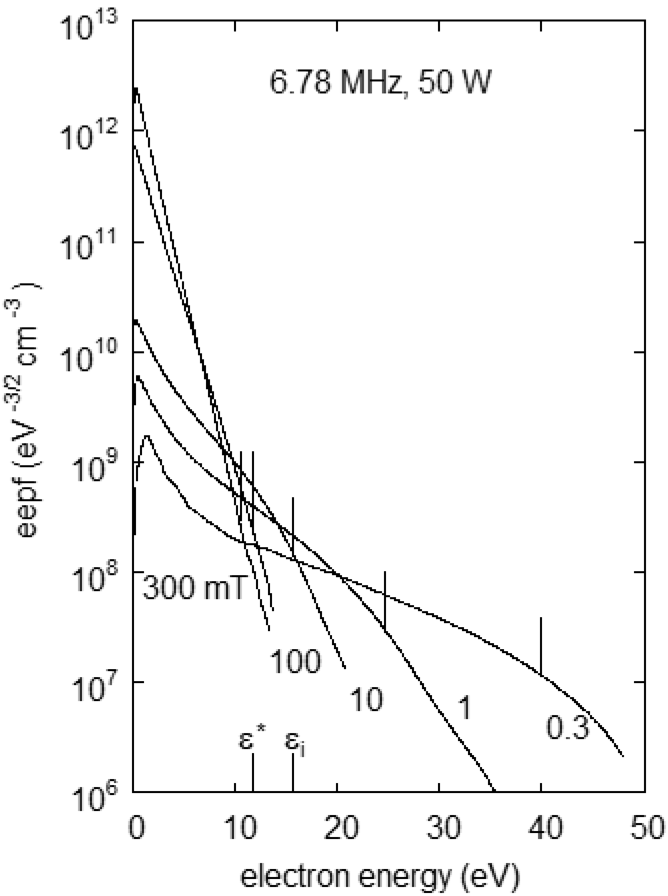
Power Transfer efficiency



Frequency dependence



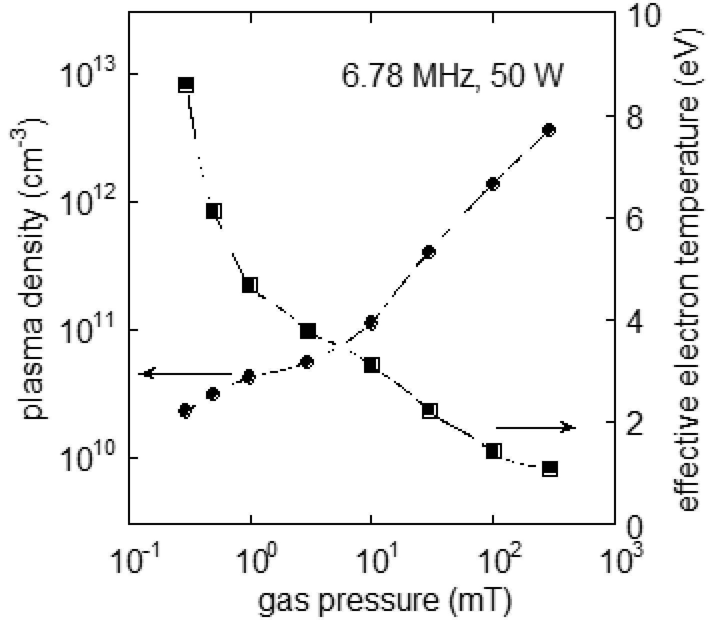
Argon pressure dependence of EEDF and plasma parameters in ICP driven at 6.78 MHz, 50 W



Transition from normal to anomalous skin effect

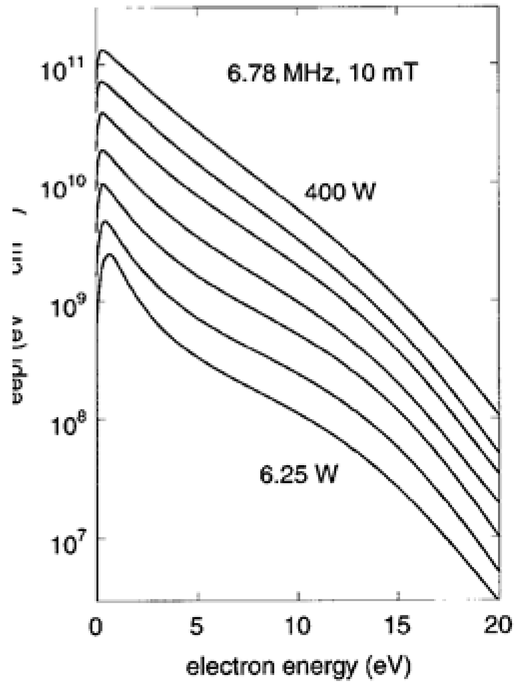
Collision dominated
Near-collisionless

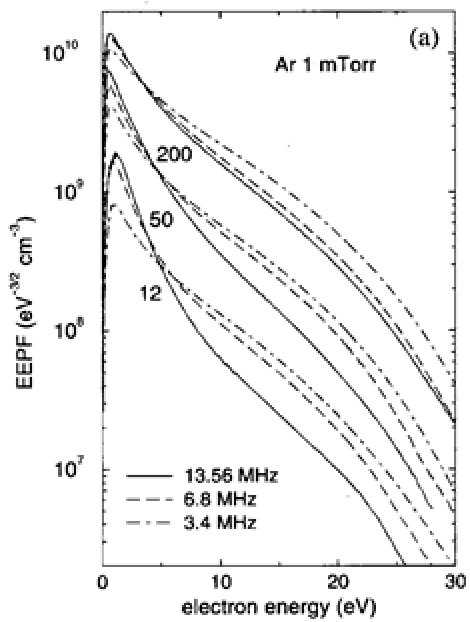
Inelastic collisions and escape to the wall

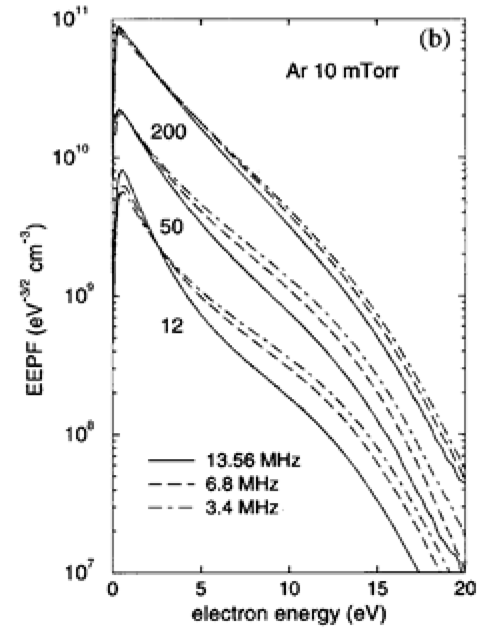


EEDF power and frequency dependence

In high-density plasmas, EEPF at low energy must be Maxwellian



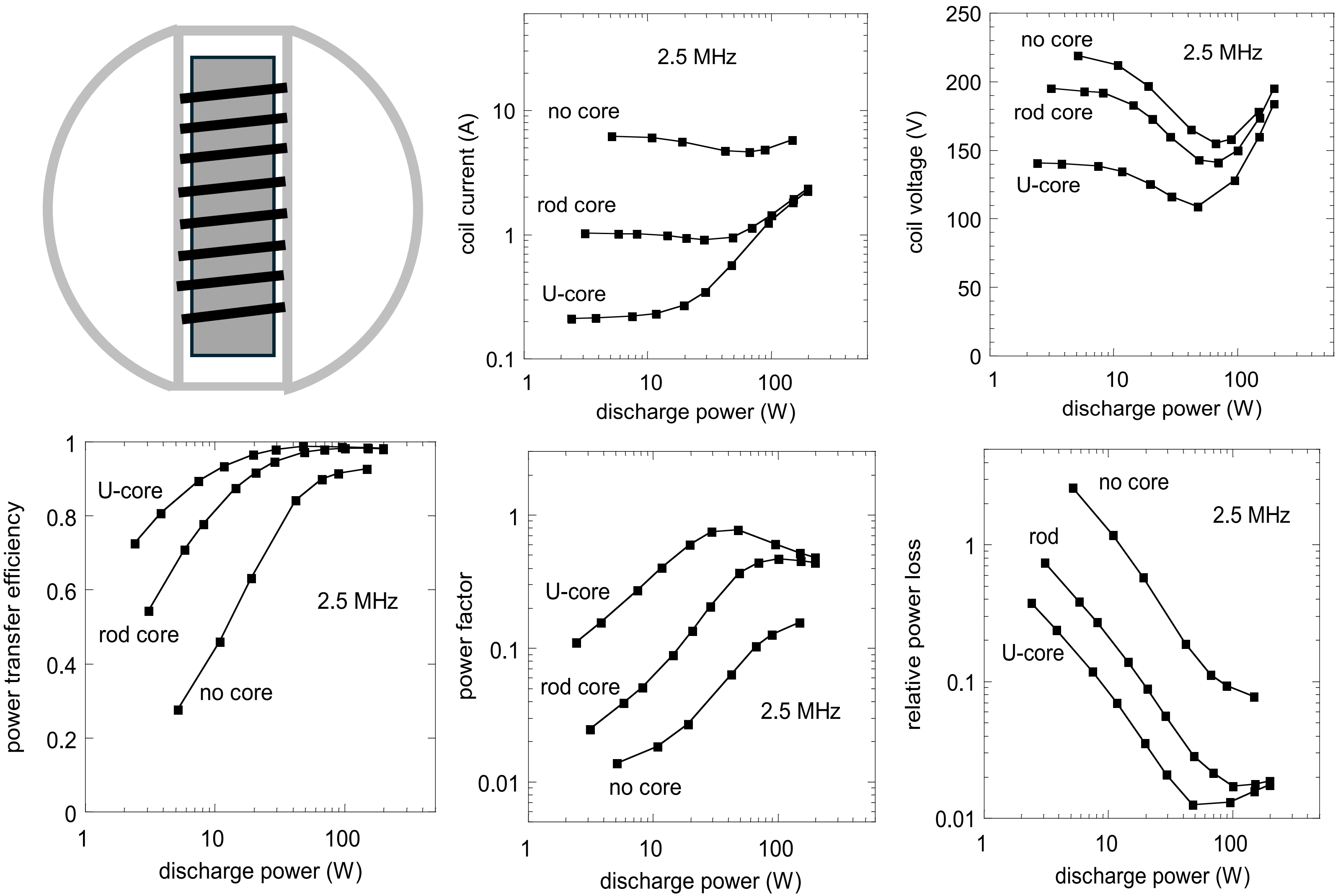




ε*

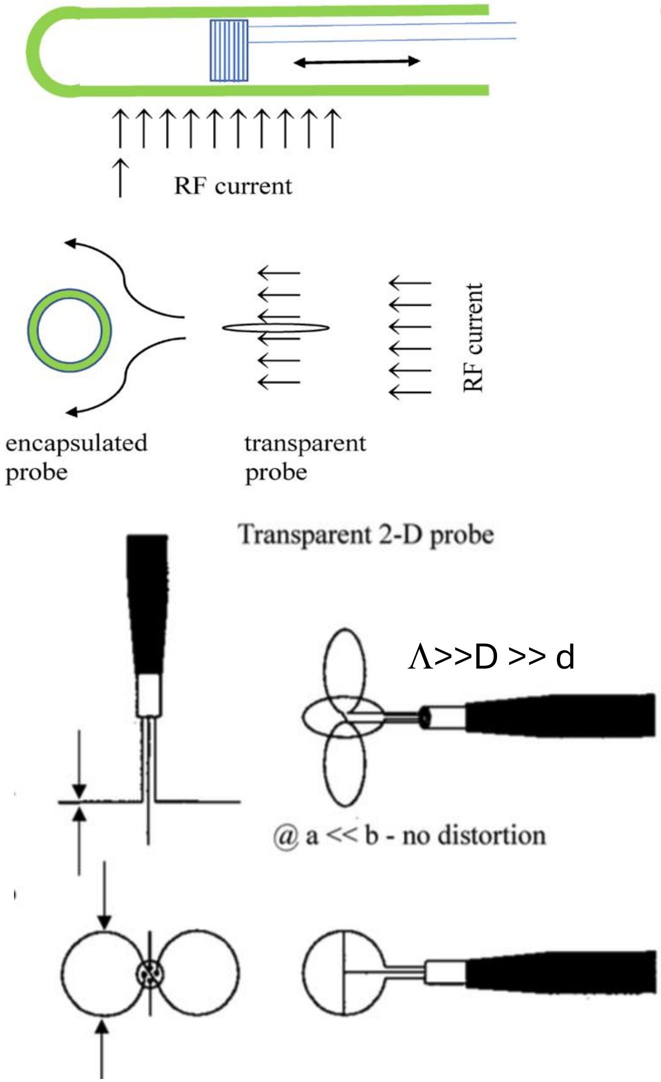
Electrical parameters of ICP enhanced with ferromagnetic core

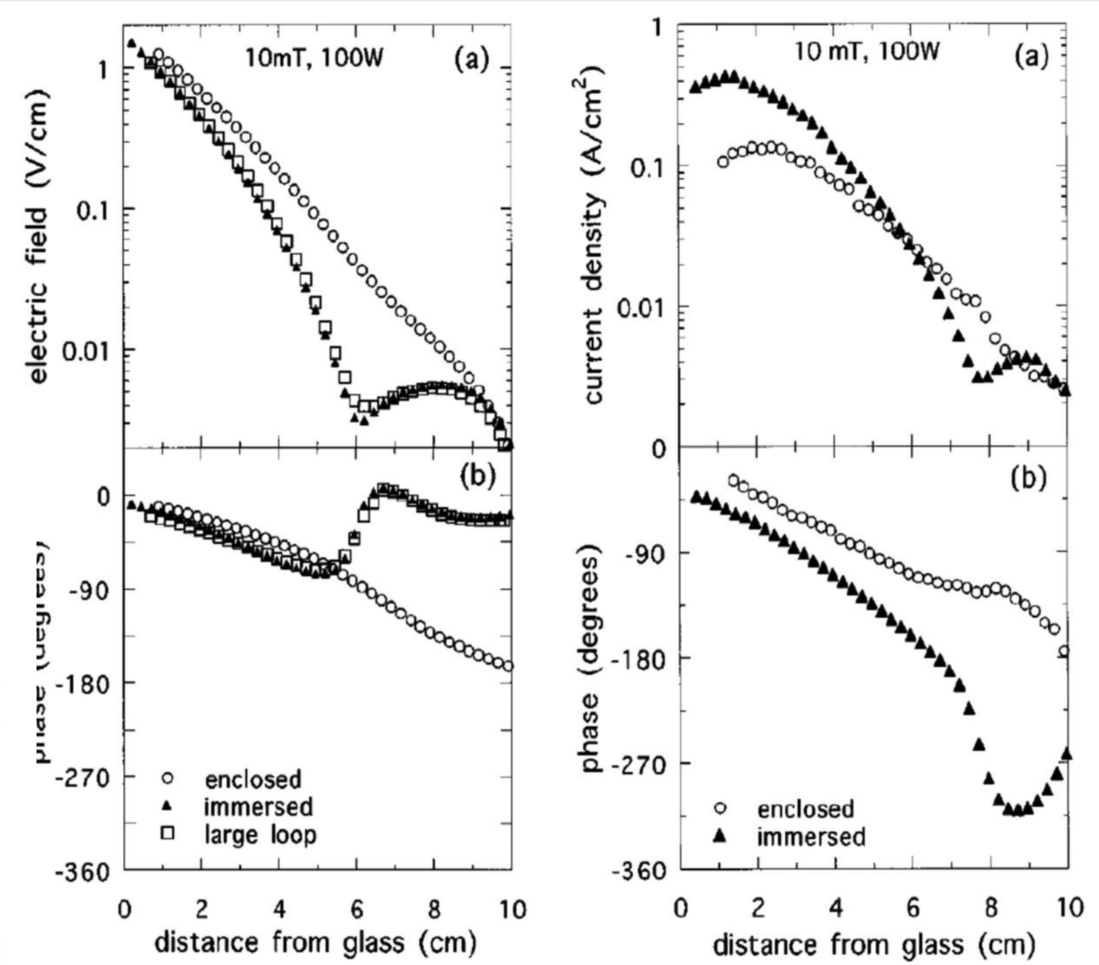
Kr-Hg , 0.5 Torr, 2.5 MHz, 2r = 2.2 cm, 2R = 7.5 cm, μ =100



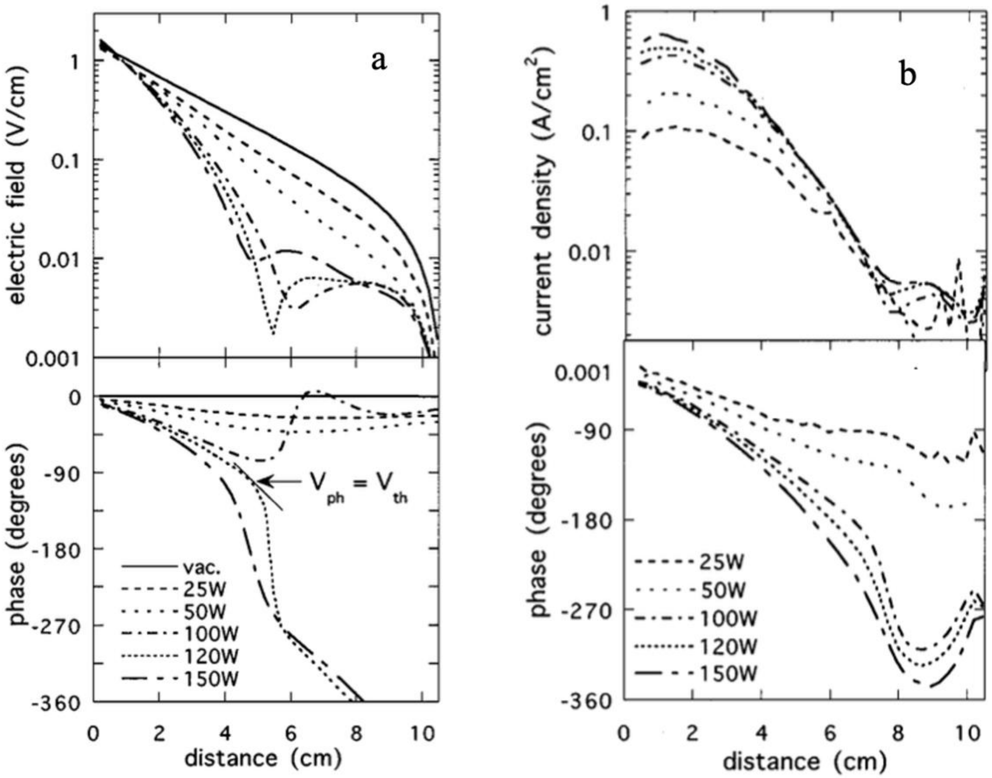
Magnetic and microwave probe diagnostics

Magnetic (b-dot) probes were used for measuring the time-varying magnetic field **B**(t,r) in pulsed and RF plasmas.





Axial distribution of RF electric field and current density

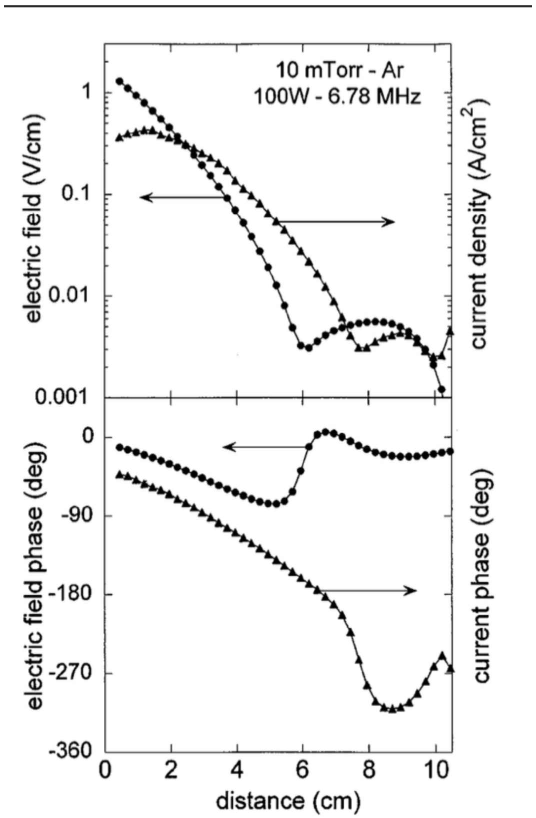


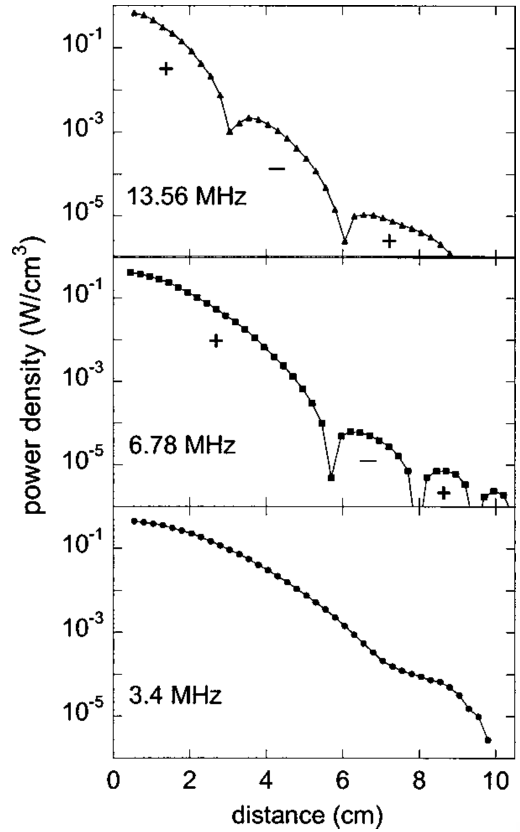
Ar ICP at 6.78 MHz, D = 20 cm, H = 10 cm

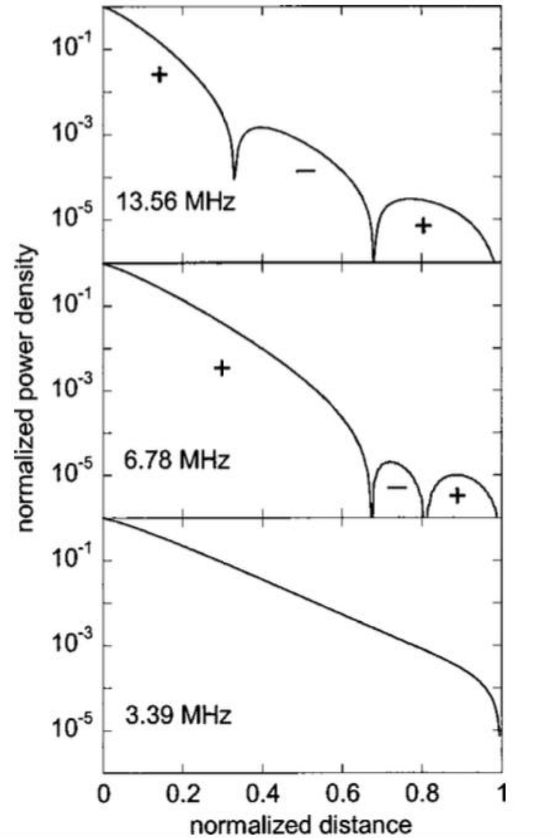
- Non-monotonic decay of E, J, and their phases bifurcation.
- Reverses of the field and current phases.
- Different skin depths for E and J, RF current diffusion, or spatial dispersion
- Phase bifurcation at the $v_{ph} = v_{th}$.
- The traditional encapsulated magnetic probe cannot resolve these phenomena.

These are the results of electron thermal motion, known as the anomalous skin effect, or non-local plasma electrodynamics.

Negative power absorption in ICP



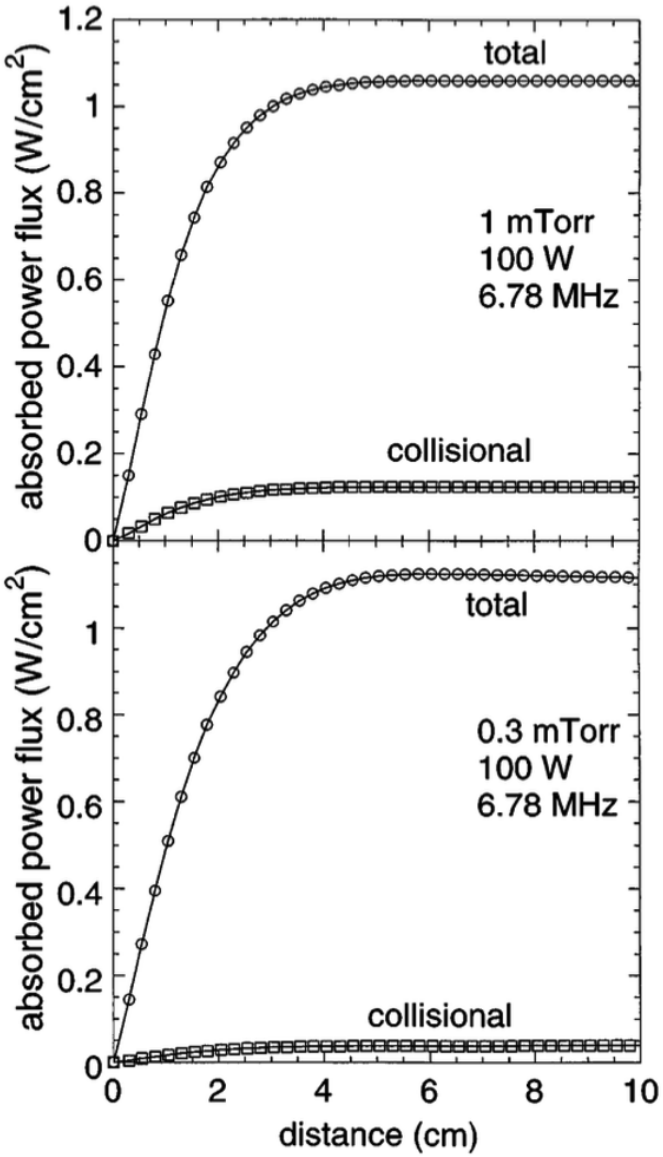


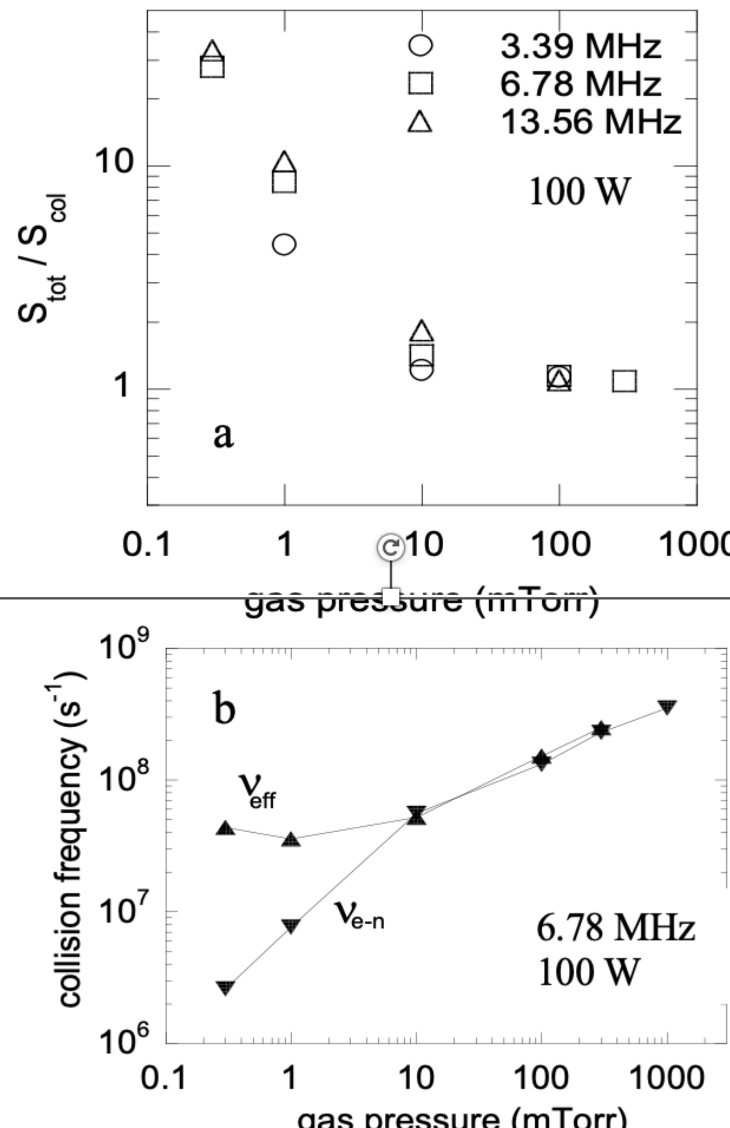


Experiment in Ar ICP

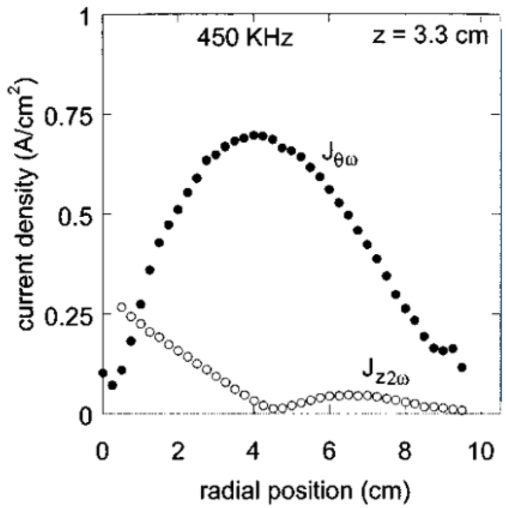
Simulation

Experimental proof of the collisionless RF power absorption in ICP





Second harmonic current in ICP at the nonlinear regime



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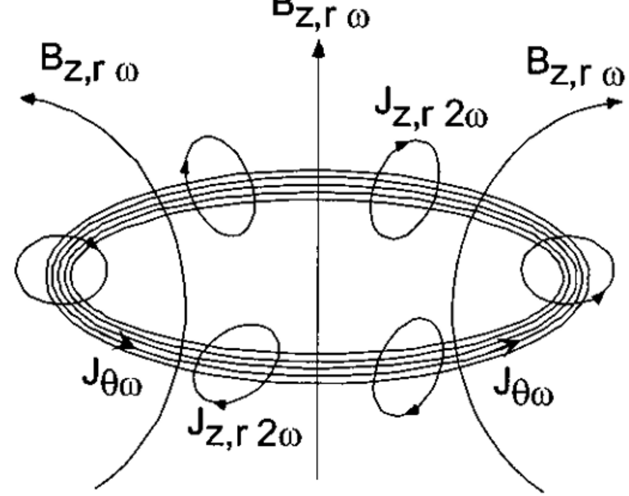
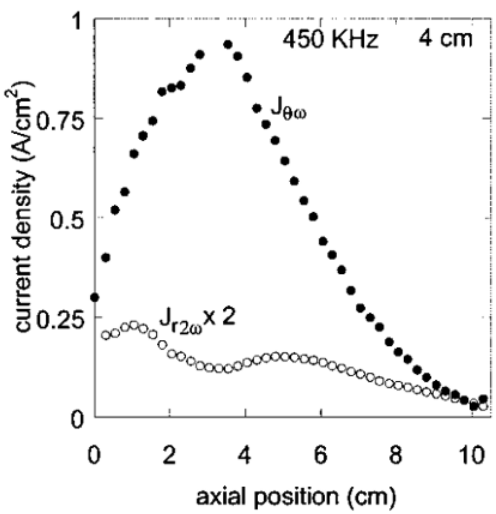
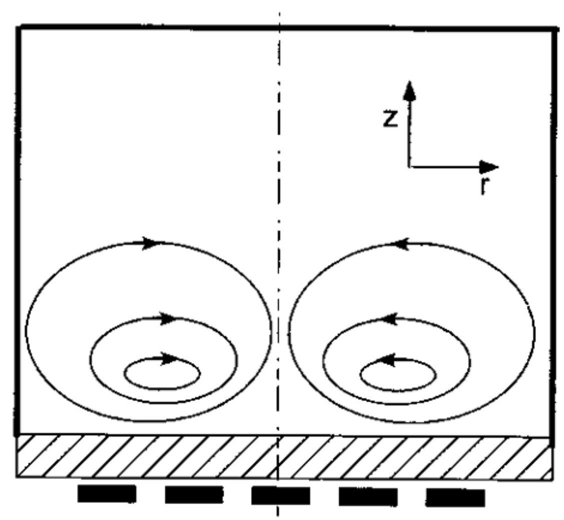




b



Pros and Cons of conventional ICP sources

Positive (expected)

- Independent control of ion flux and energy to the wafer
- Operates over a wide range of gas pressure.
- Relatively simple construction
- Operates in a wide range of frequencies.
- Possibility to operate at low frequency
- Possibility of plasma profile control with multiple coils?

Negative (experienced)

- Inability to operate at low plasma density ($N_p < 10^{11}$ cm^{-3}) in inductive mode
- Can not operate with small gap (large residual time)
- Stray capacitive coupling (plasma non-uniformity and window erosion)
- Transmission line effect (plasma non-uniformity)
- Bead process uniformity control

VHF CCP problems

I. Low frequency bias significantly affects plasma parameters

II. Standing surface waves ($\lambda_r = [1+d/s]^{-1/2} \sim \lambda o/3$, radial non-uniformity)

III. Edge effect (enhances edge plasma density)

IV. Skin effect (radial non-uniformity when $\delta < 0.45d/R$)

V. E to H transition (rf power is magnetically coupled to plasma)

VI. Plasma-Sheath local resonances on F, 2F , 3F (destroy plasma uniformity)

VII. Resonance effects and mode jumps prevent smooth plasma control*

All these problems became more severe at larger:

rf frequency, wafer size, and plasma density

(Gas flow distribution, segmenting, and profiling of the RF electrode have limited successes)

The interplay of many fundamental electro-magnetic effects with resonant conditions makes VHF CCPs too complicated for reliable control in a wide range of their parameters

Mentioned above negative ICP features have promoted VHFCCP.

Many of negative opinions on ICP limitations are based on experience with poorly designed commercial ICP reactors.

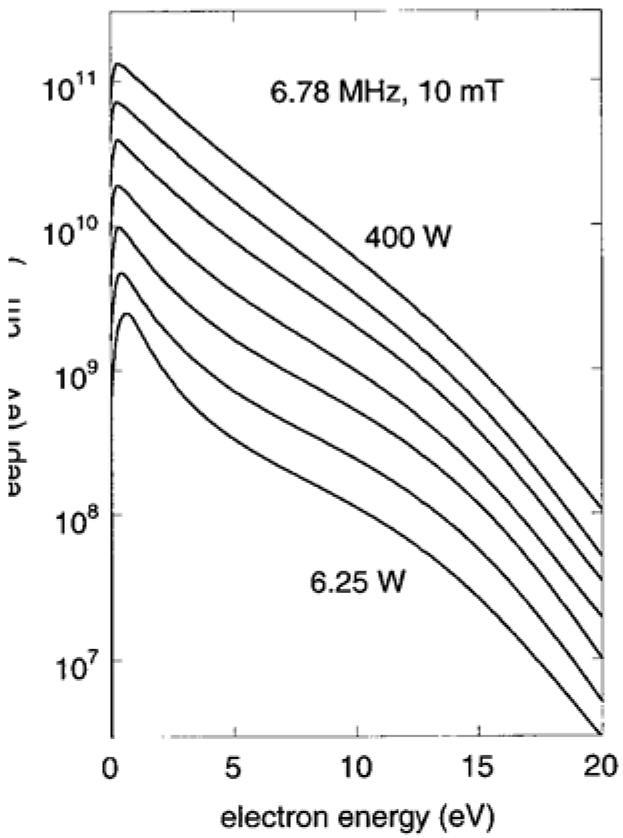
Contrary to prevailed lore:

- ICP can operate in inductive mode at small wattage and low plasma density
- ICP can operate with small gap (small residual time)
- Many commercial ICPs with two antennas do not produce peripheral maxima.
- ICP can provide process uniformity control over the large area
- Capacitive coupling and transmission line effect can be eliminated
- ICP source can operate at much lower frequency, more efficient and is less expensive than VHFCCP and ICP used today in the plasma processing of semiconductor materials

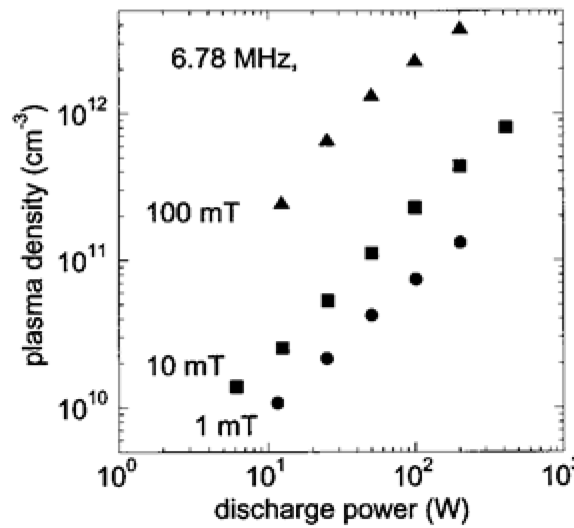
All above can be achieved by properly designed ICP source

ICP does operate in inductive mode at low plasma density

Small power ICP in RF lamps and in lab experiments, Pd < 2.5 W!

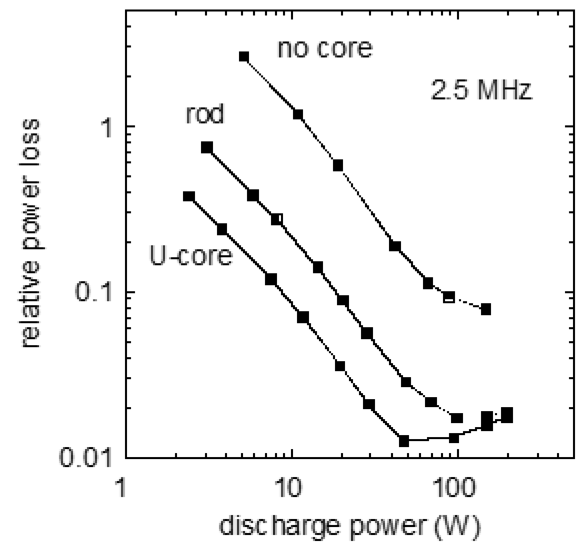


ICP pancake configuration
2R = 20 cm, L = 10 cm
r = 0, z = 5 cm



Spherical ICP with
and without ferrite
core Ar-Hg at 0.5 Torr

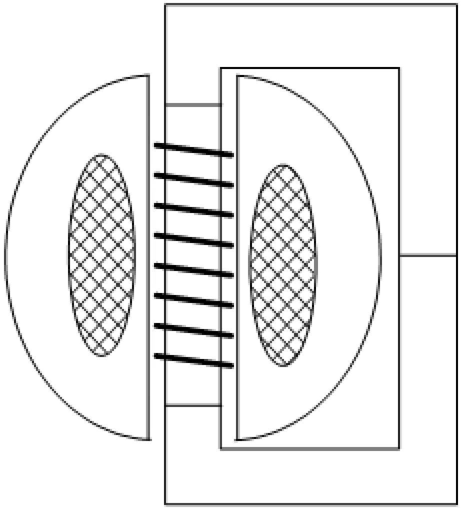
Pa/Pd

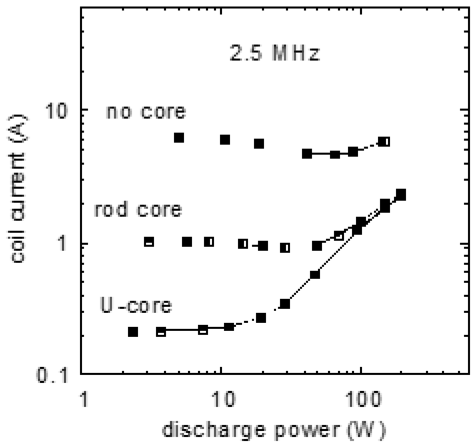


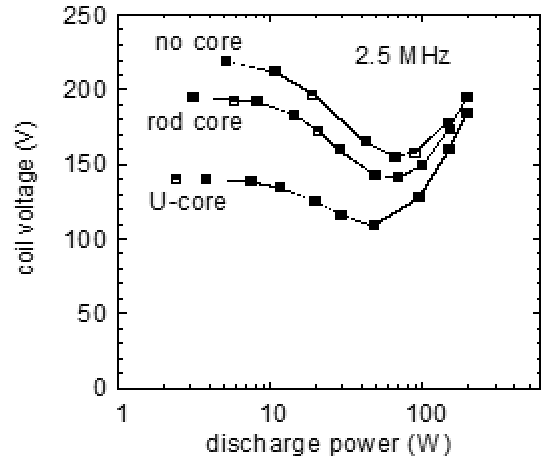
Inefficient coupling and huge antenna loss prevent low plasma density operation in commercial ICPs. $Pa \leq Pd \sim n$ is the condition for stable ICP operation

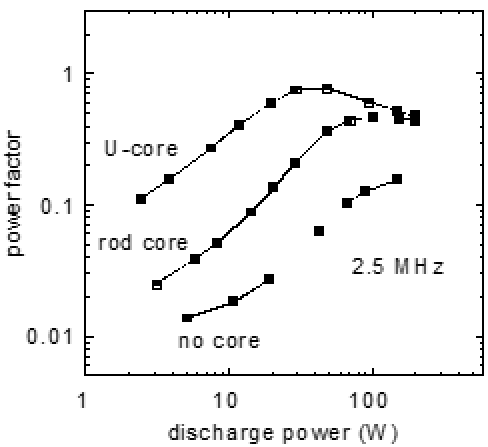
ICP enhanced with ferromagnetic core

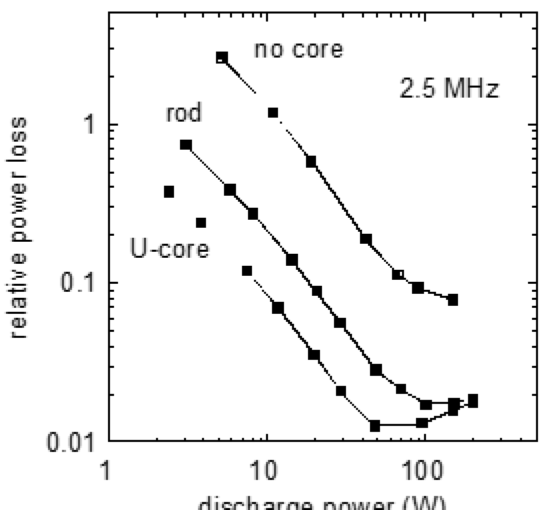
2.5 MHz, spherical ICP with internal inductor, D = 7 cm, Ar-Hg 0.5 Torr









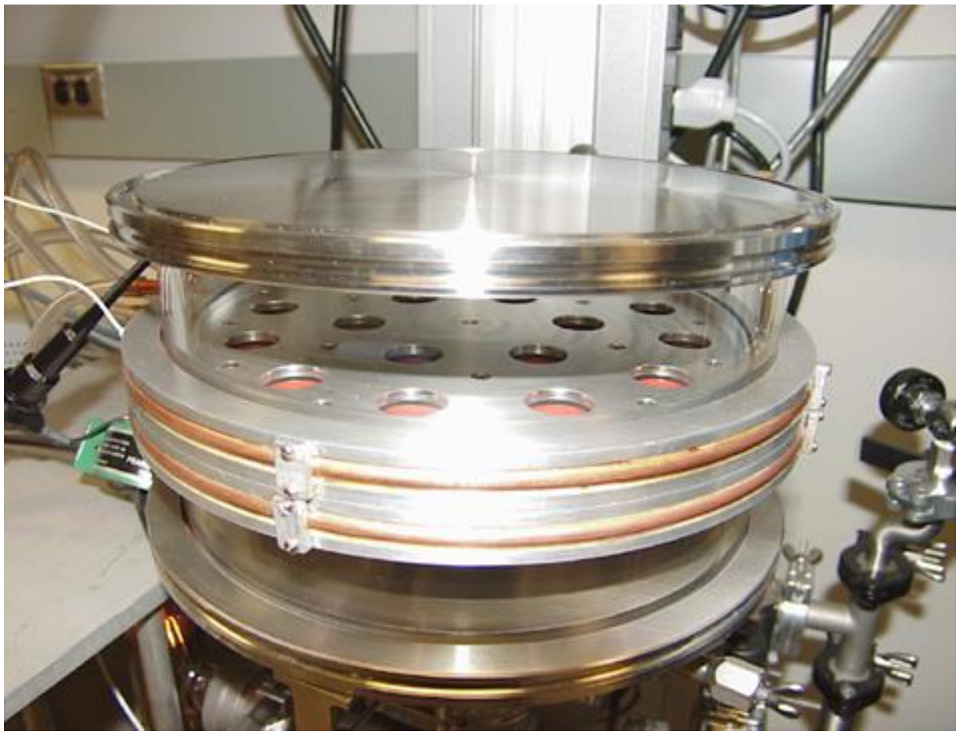


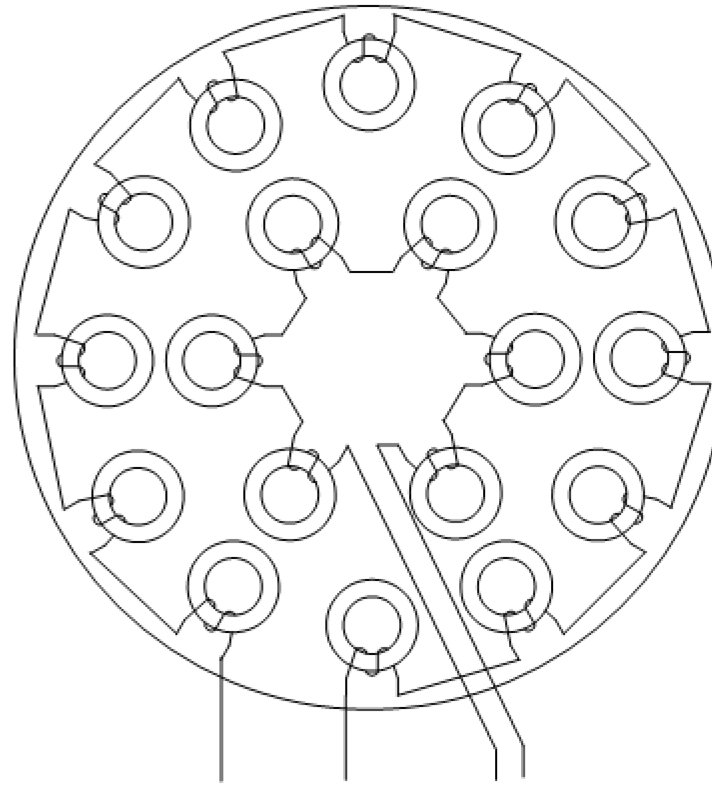
Introduction of a ferromagnetic core reduces antenna coil current and voltage, together with increasing ICP power factor (Cosφ) and power transfer efficiency

V. Godyak, Proc. XVth Intern. Conf. on Gas Discharge and their Appl. ***V. 2****, p. 621, Toulouse, France, 2004*

Distributed ICP with 18 core ferrite toroidal cores

2R = 10 cm, h = 4.7 cm, 400 kHz, 400 W, Xe 0.3-100 mT

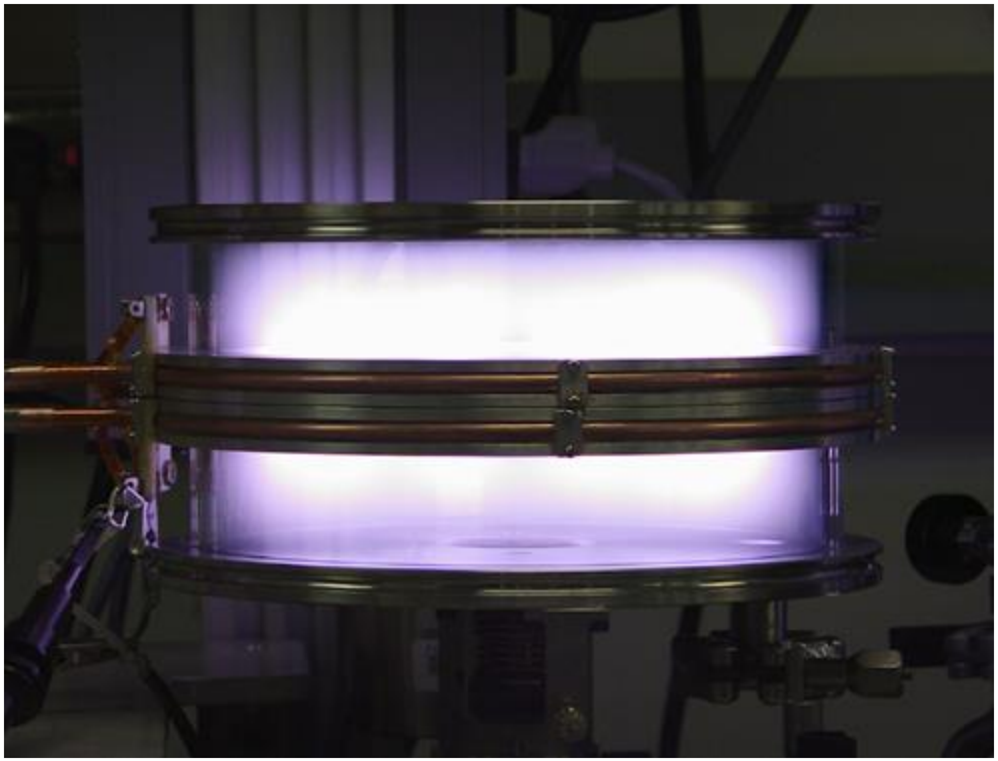


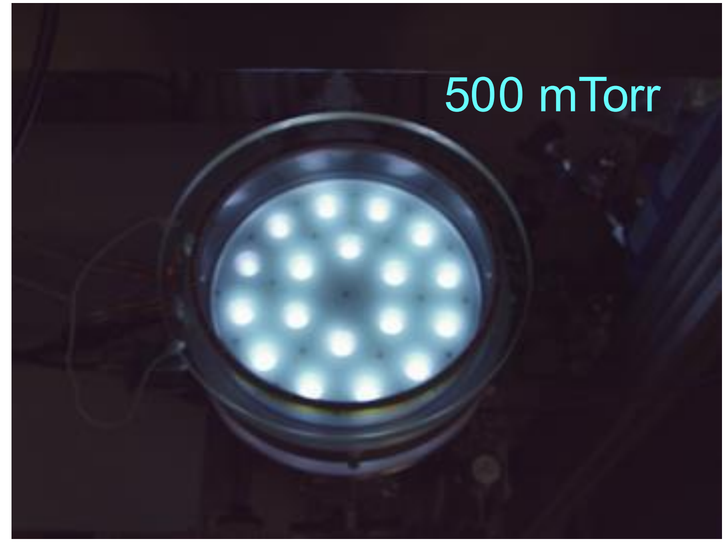


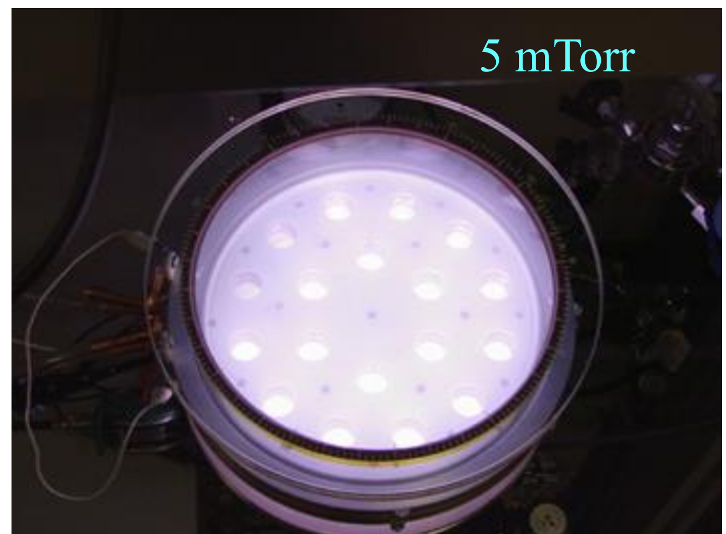
V. Godyak, PEUG, Santa Clara, 2003

18 core distributed ferrite ICP

Xenon, 400 kHz, 10 mTorr, 400 W





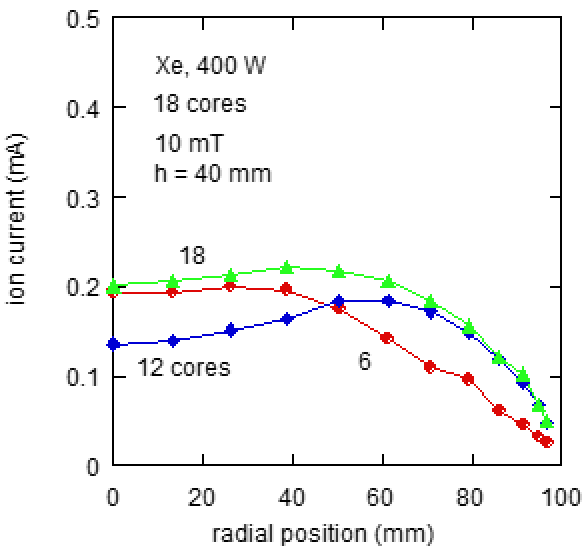


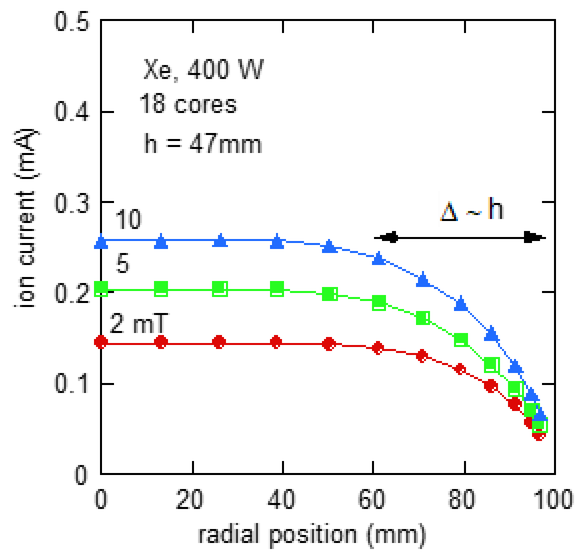
V. Godyak, PEUG, Santa Clara, 2003

Plasma uniformity control and coupler losses

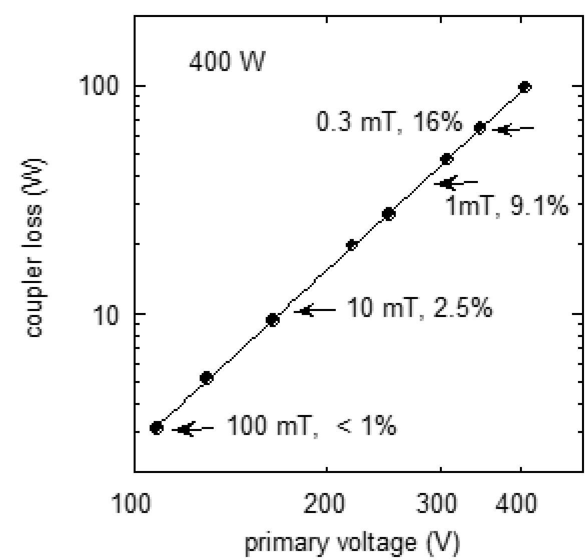
@ 400 W, p = 0.3-100 mT, Cosφ = 0.95-0.97 and Po/Pd = (16 - 1)%

Ii @ 2 mm from the chamber bottom.





Coupler loss versus coupler voltage

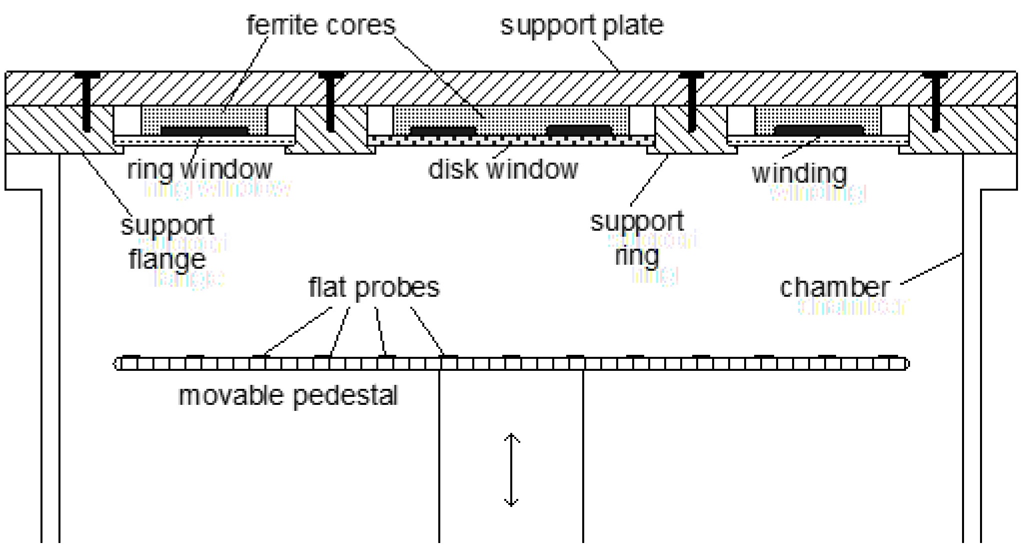


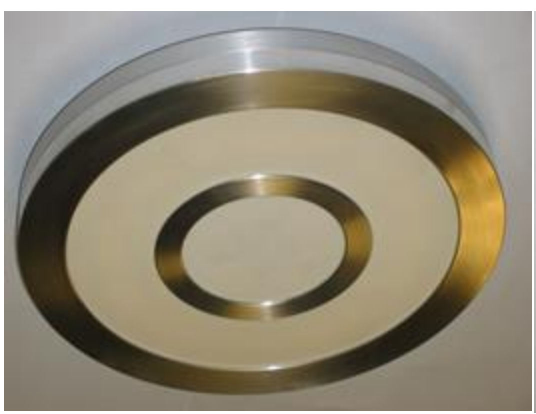
Power factor and efficiency exceed those in a conventional transformer at 60 Hz!

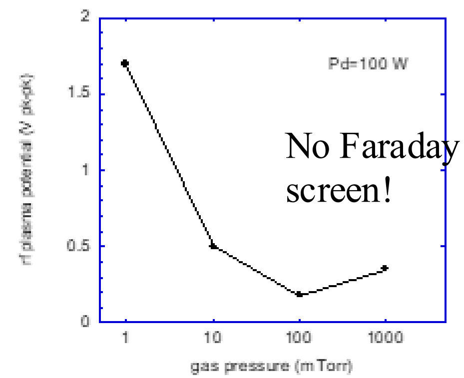
Low Frequency ICP Reactor Enhanced with Ferrite Core

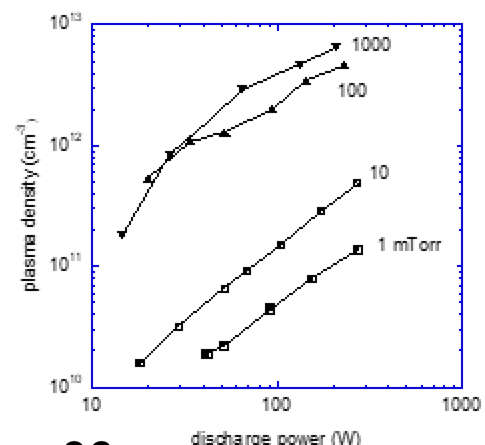
0.4-2 MHz, argon, d = 1.5 - 8 cm

Increased coupling provides better plasma spatial control



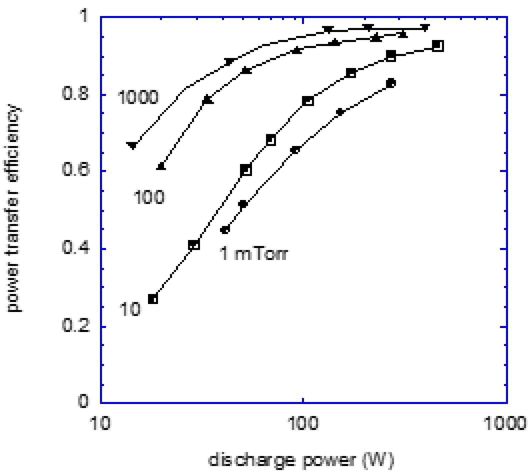


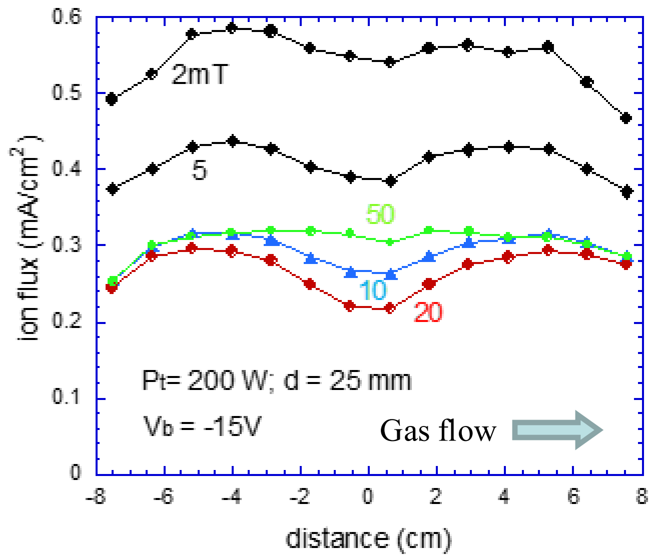




*V. Godyak, PSST **20**, 025004, 2011*

Power transfer efficiency and plasma density control





- No external EM interference
- No capacitive coupling
- No transmission line effect
- Low power (Np) operation
- Compact and simple construction
- Good plasma spatial control
- High power transfer efficiency
- High power factor
- Effective thermal management
- Wide processing window (mixture, pressure, power)
- Scaling up for uniform processing of large substrates

*V. Godyak, PSST **20**, 025004, 2011*

Twelve reasons why the future belongs to the distributed ICPs with ferromagnetic core

- No external E-M radiation (all E-M flux is directed to plasma)
- No capacitive coupling (no plasma rf potential, no window erosion)
- No transmission line effect (no azimuthal non-uniformity)
- Ability to operate at low power and low plasma density
- Low driving frequency (0.4 - 2 MHz) reduces cost of rf equipment
- Simple, compact and ridged construction
- Good plasma spatial control due to strong local coupling
- High power transfer efficiency reduces power dissipation in hardware
- High power factor allows for considerable simplification of matching network
- Effective thermal management due to large contact area of the rf inductor
- Wide processing window (mixture, pressure, plasma density)
- Possibility of scaling up for uniform processing of very large substrates

Summary

- VHFCCPs have fundamental limitations preventing them to scale up for next generation wafers processing (450-670 mm)
- The main problems in commercial ICPs are weak inductive and large capacitive coupling They are far from the optimal design and thus have room for improvement
- Properly designed ICP can operate without capacitive coupling and transmission line effect at low plasma density, small gap and can provide good process uniformity
- Low frequency distributed ICPs with ferromagnetic cores can do everything that other plasma source do, but more efficiently and cost effective

Thank you