Capacitive and Inductive RF Plasma Sources for Industrial Applications

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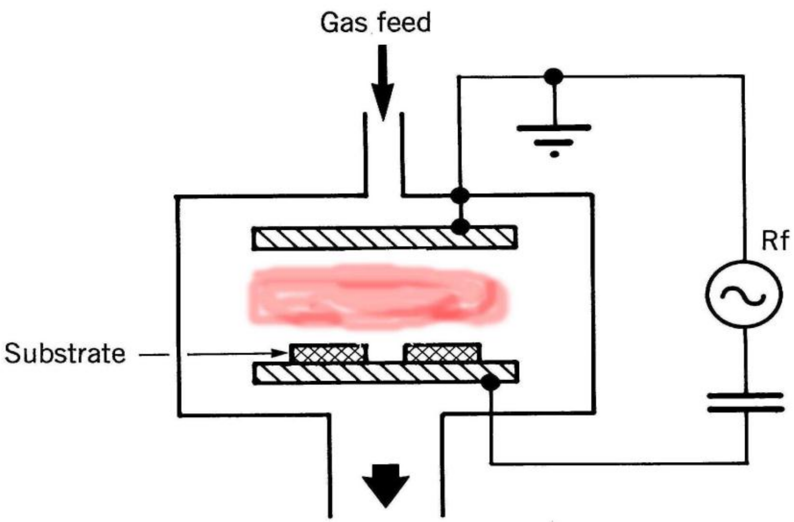
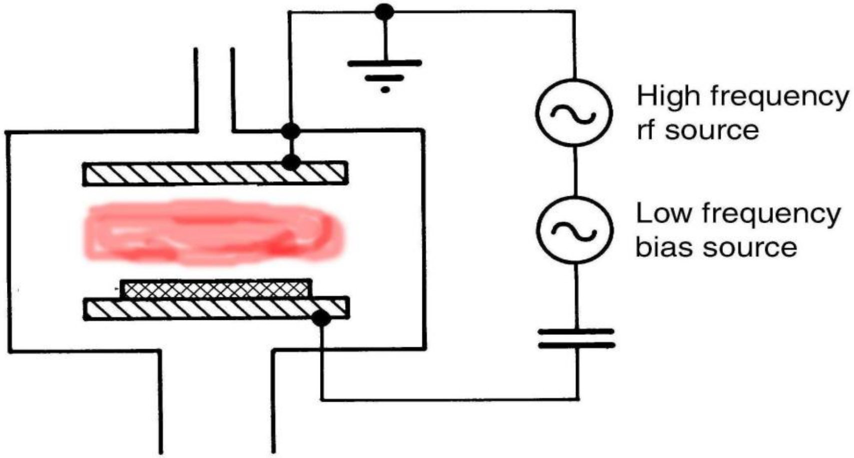
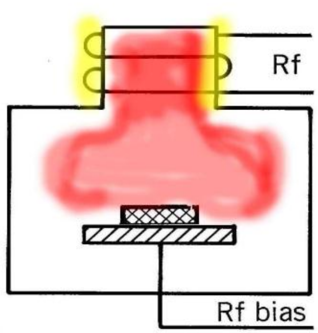
Main Plasma Sources in Processing of Materials



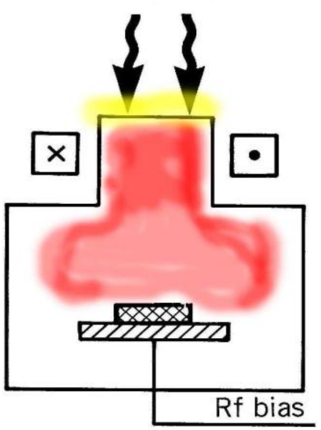
Capacitive
(Anisotropic etch)



Dual frequency
capacitive discharge



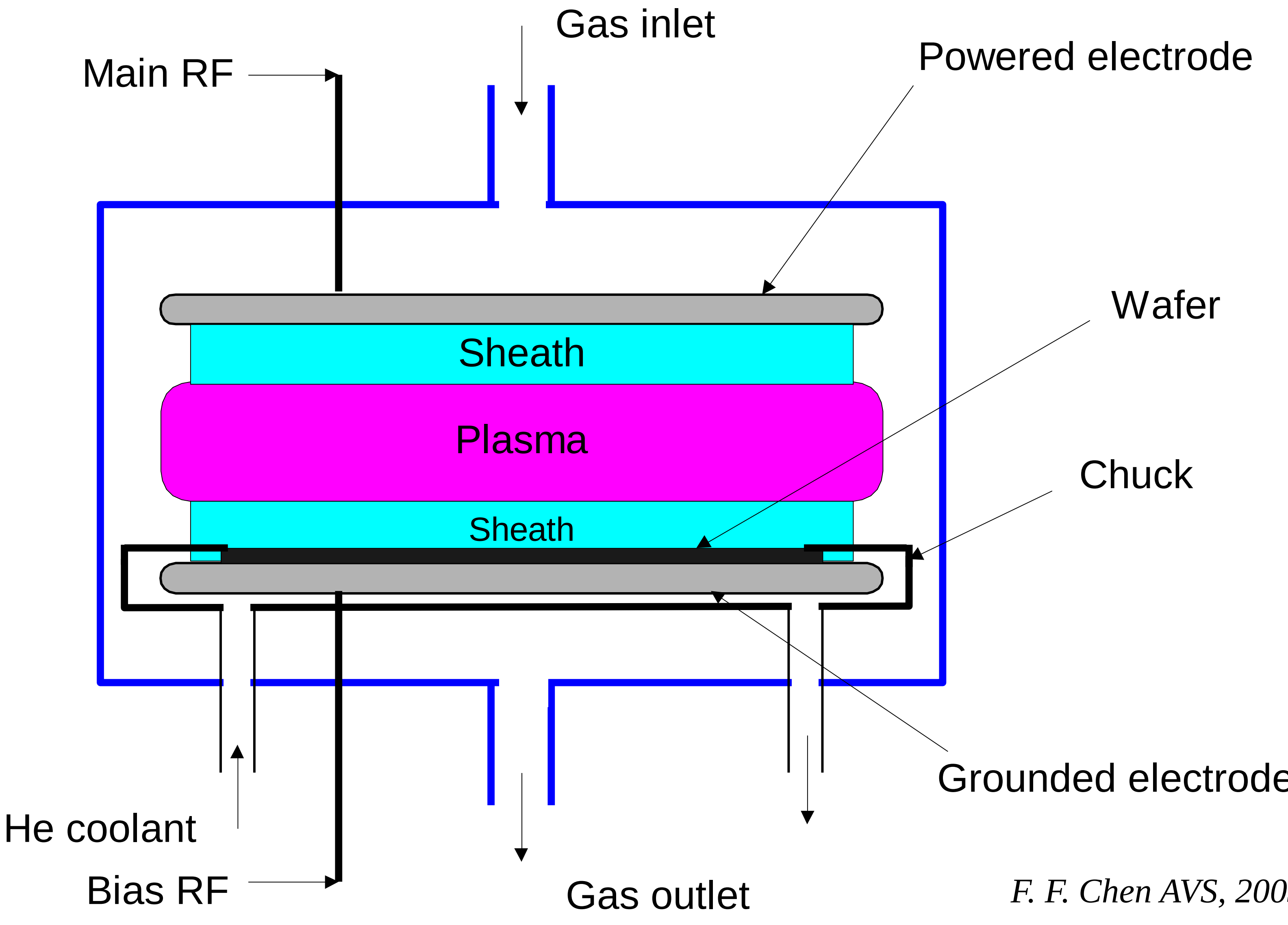
Inductive



ECR

M. Lieberman's lecture, 2007

Schematic of a CCP Processing Chamber



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

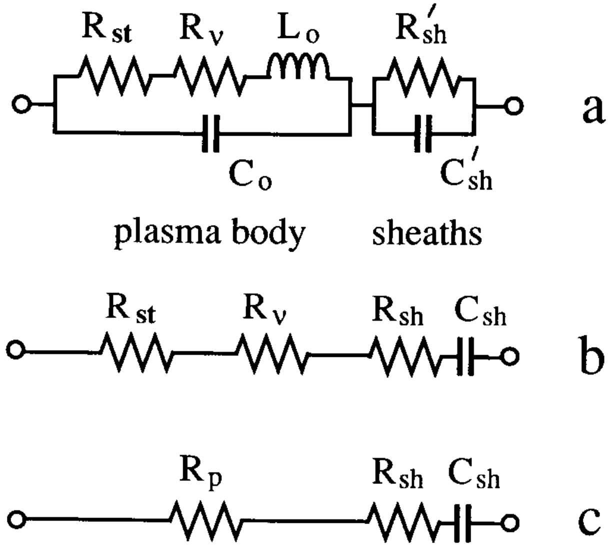
- Good plasma uniformity over processing wafer
- Simple and relatively inexpensive construction

b u t:

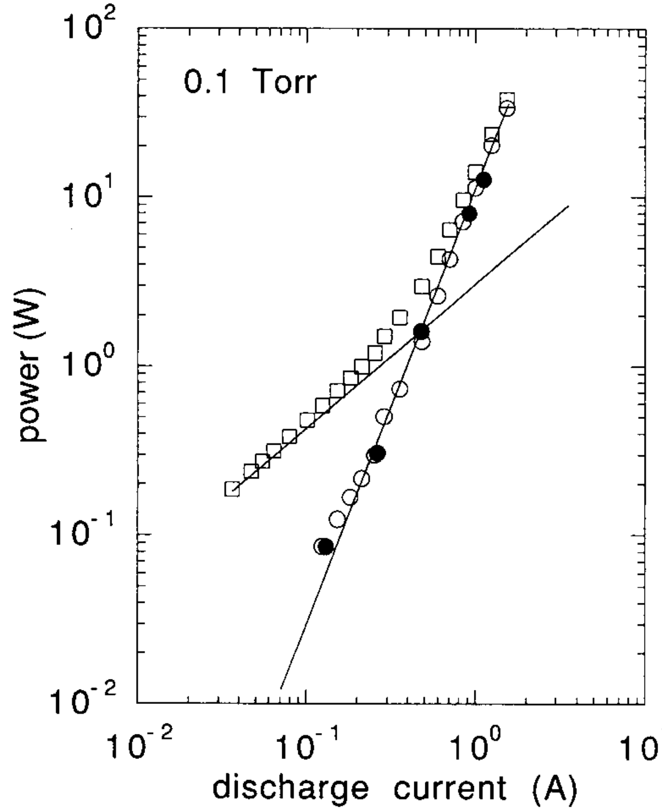
- No independent control of ion flux and ion energy
- Low plasma density at low gas pressure
- At large rf power, most of it goes for ion acceleration rather than for plasma generation

CCP equivalent circuit and rf power distribution between electron and ion heating

General



$\omega^2 << \omega_0^2$
$\nu_{en}^2 << \omega_0^2$
$V_{pl} << V_{rf}$



$P_{rf} = P_{pl} + P_i$ Since in plasma

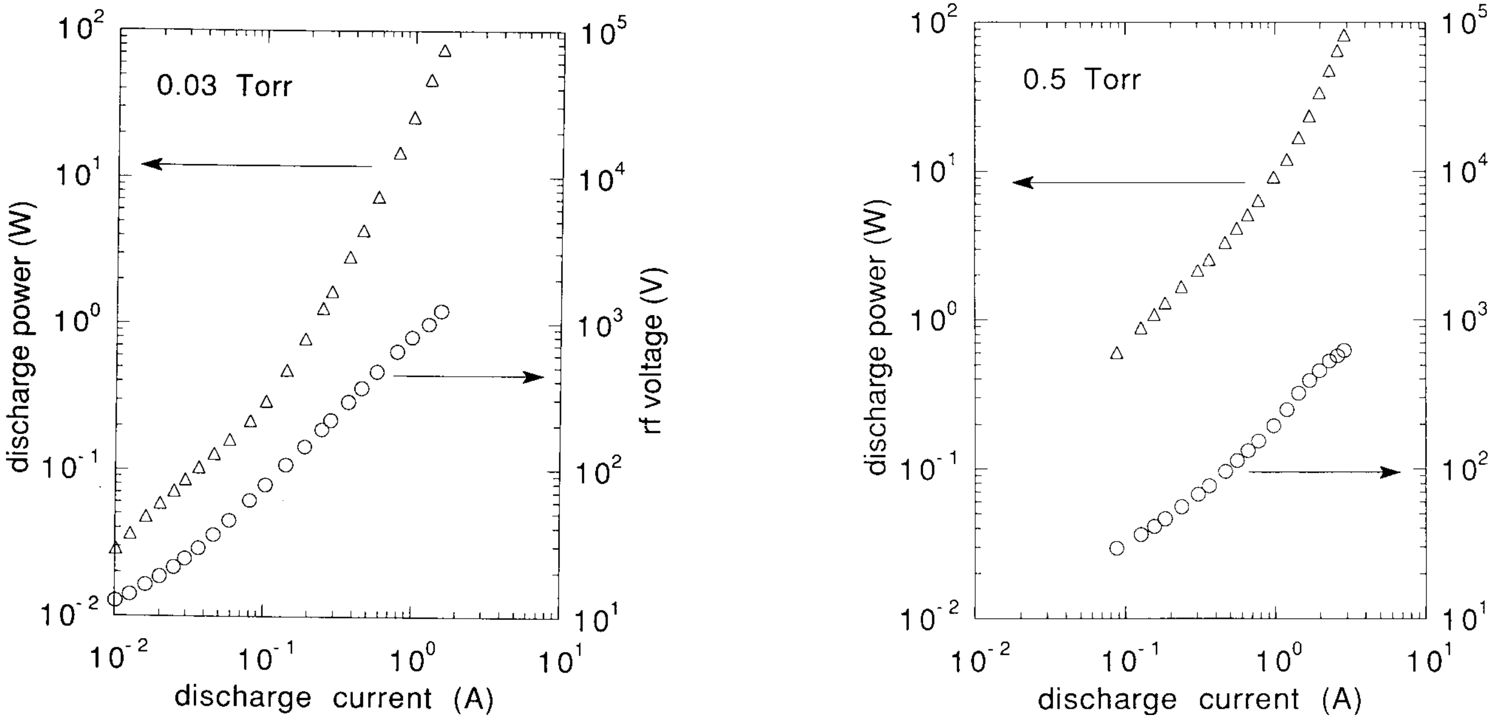
$E_p \approx$ conct, $N_p \sim I_d$ and $V_{dc} \sim V_{rf}$

$P_{pl} \sim I_d$ and $P_i \sim I_d^2$

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

Electrical characteristics of a symmetrical CCP, Argon, 13.56 MHz

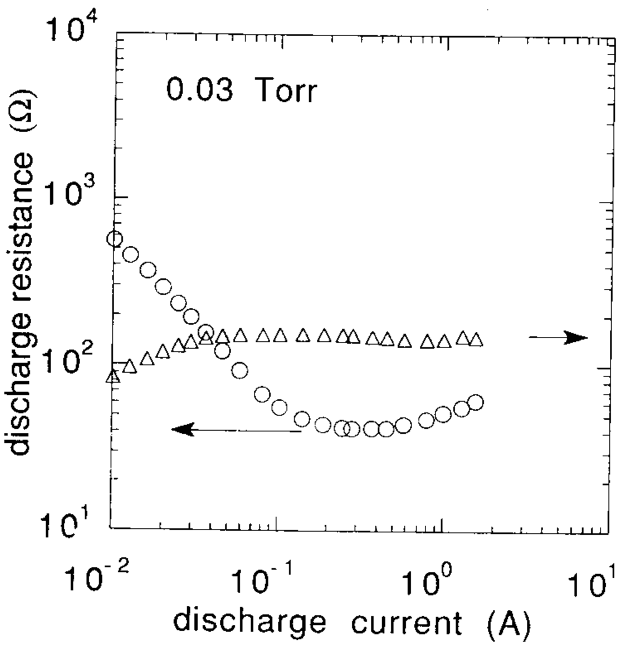
L=6.7 cm, D = 16 cm



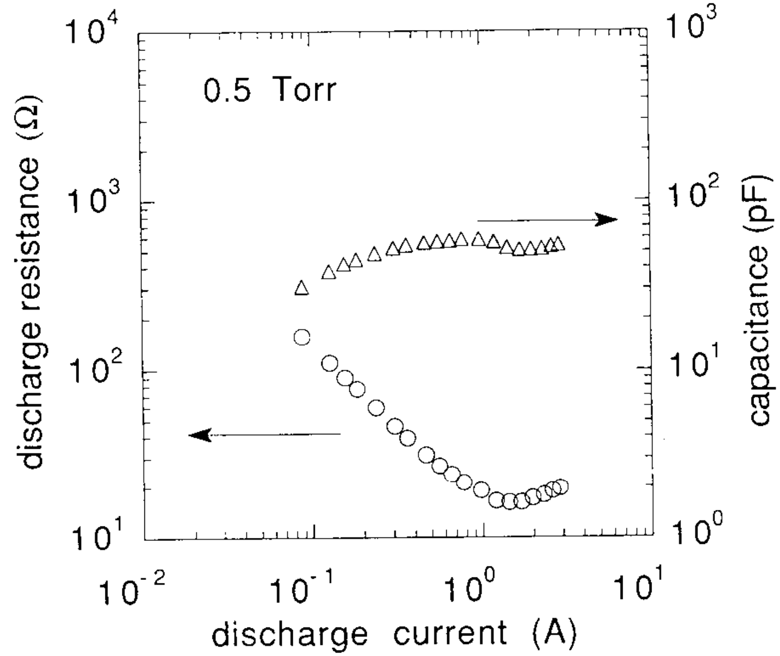
For moderate rf voltage (V < 1 kV), V/A discharge characteristics are nearly linear, does not obey to Childs-Langmuir law.

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

Sheath capacitance (or thickness) practically does not depend on discharge voltage and current



13.65 MHz



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

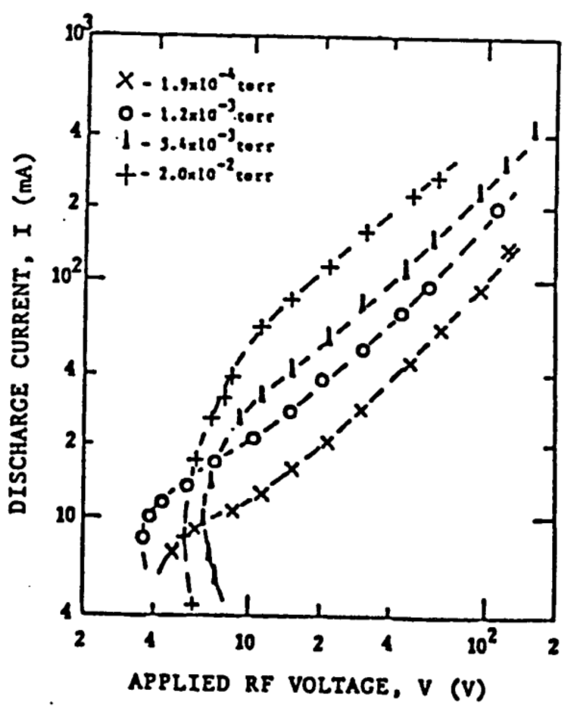
Experimental observations on CCP scaling plausibly correspond to an analytical self-consistent CCP model by *Godyak, Sov. J. Plasma Physics **2**, 78, 1976*

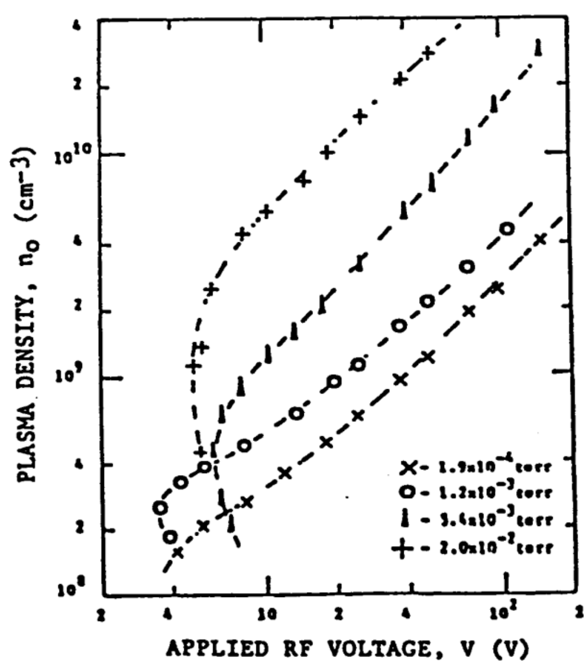
Basic CCP model assumes uniform ions (A = 1) and accounts for non-linear rf sheath dynamics, collisional and stochastic electron heating and energy balance V. *Godyak, Sov. J. Plasma Physics* **2**, *78, 1976*

$$N_p = (A\omega^3\nu_{eff}m^2L^2/8\pi e^3V_p)\{1 \pm (\nu_{eff}/\omega)[(V_{rf}/V_p)^2 - 1]^{1/2}\}$$

where $V_p = \mathrm{Re}(E_pL_p)$ is the minimal discharge sustaining voltage and A is a geometric factor accounting for ion space non-uniformity

At large voltage ($V_{rf} >> V_p$), $I_d \sim N_p \sim V_{rf}\omega^2$; $S_{sh} \sim \omega^{-1}$



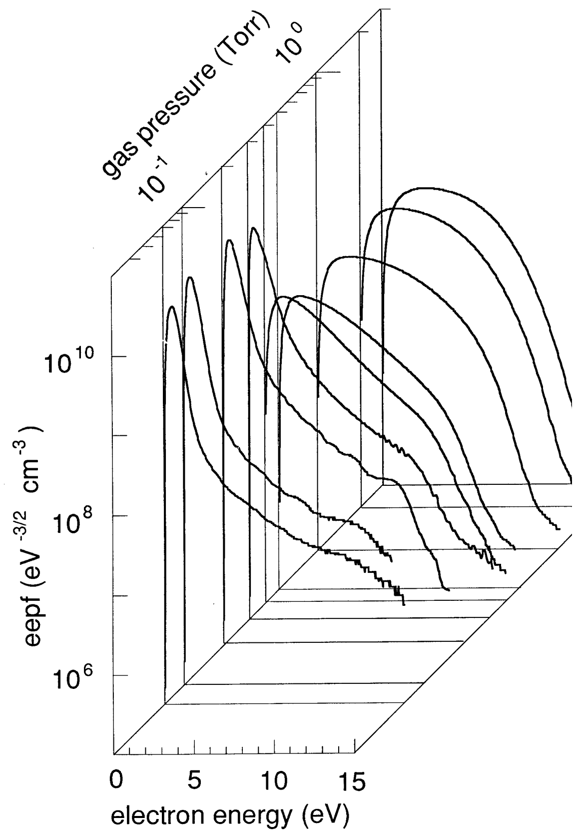


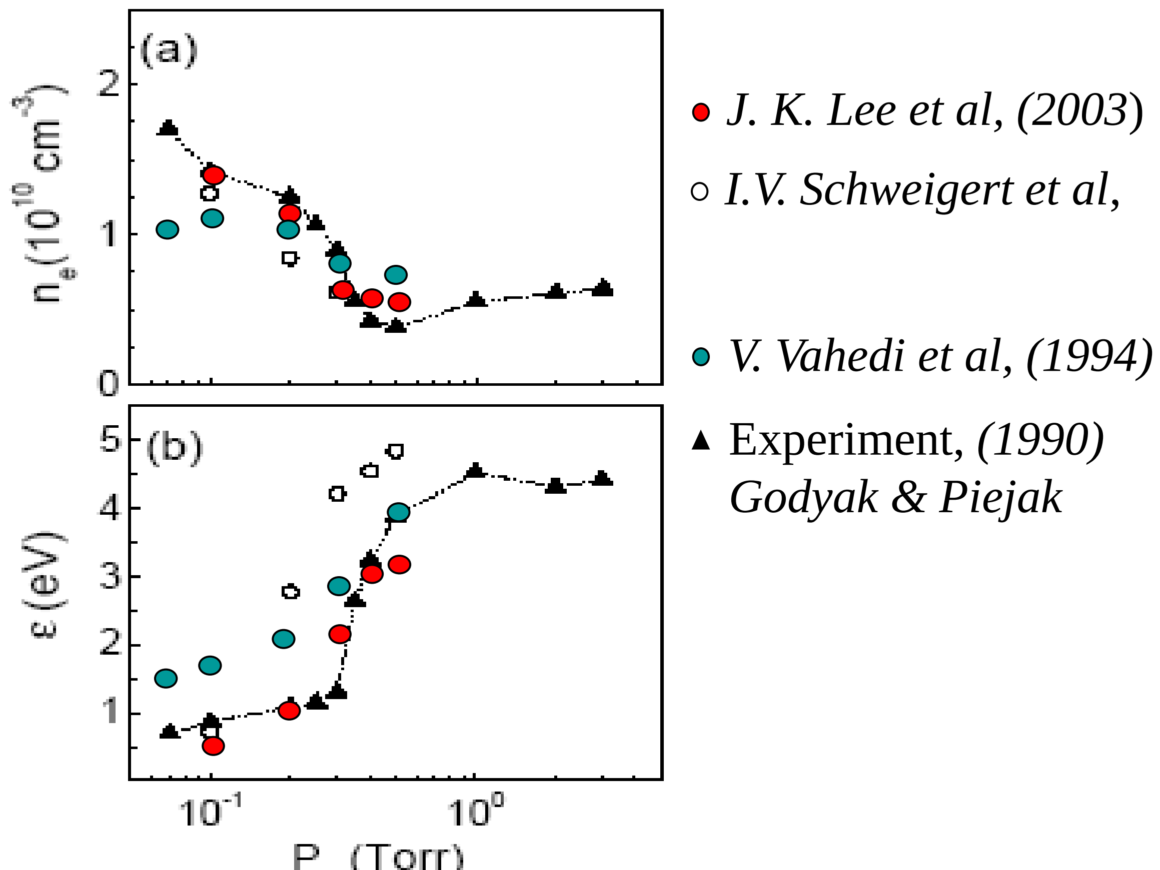
CCP in Hg vapors at 40.8 MHz shows a linear V/A characteristic at $V_{rf} >> V_p$

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

CCP modes and transitions between them

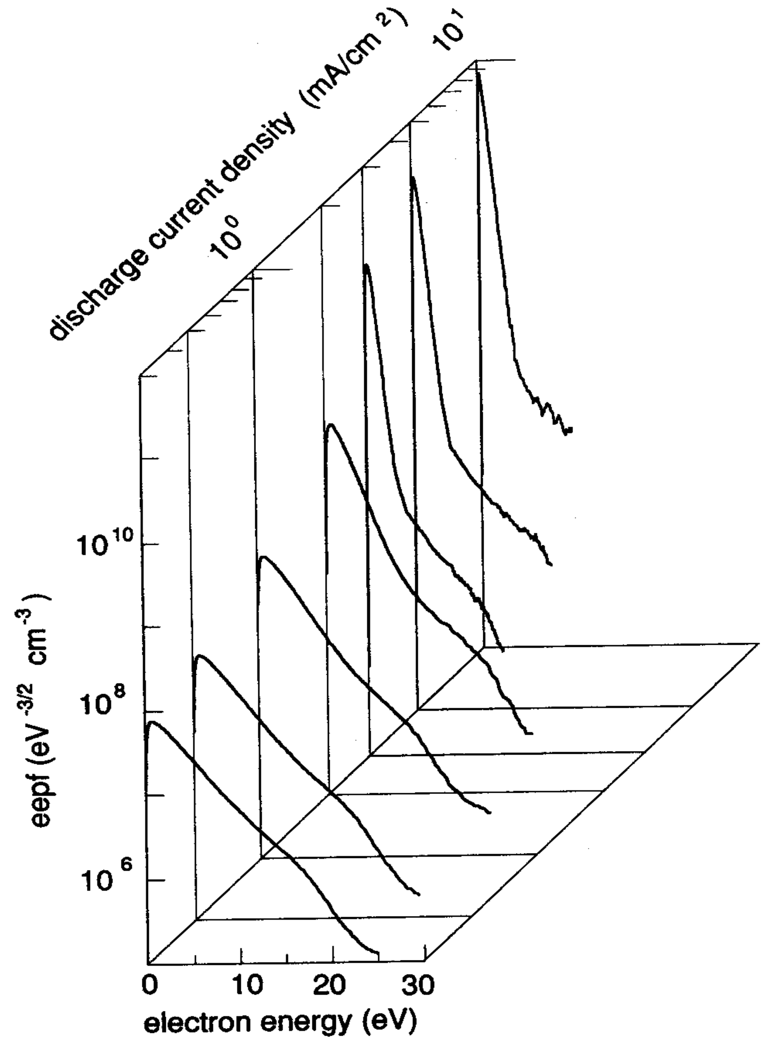
1. Volume/boundary heating mode transition, argon 13.56 MHz, L= 2 cm, D = 16 cm

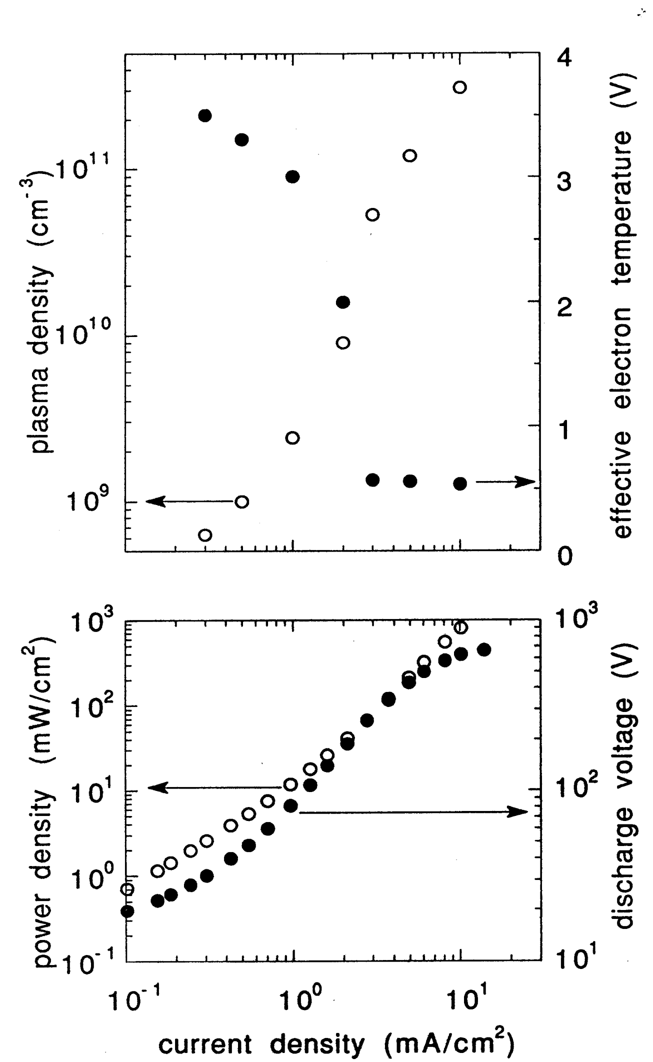




V. Godyak & R. Piejak PRL ***65****, 996, 1990*

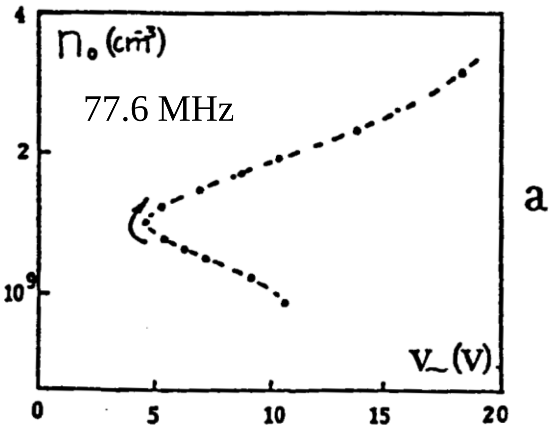
2. α to γ-mode transition (13.56 MHz, He, 0.3 Torr)



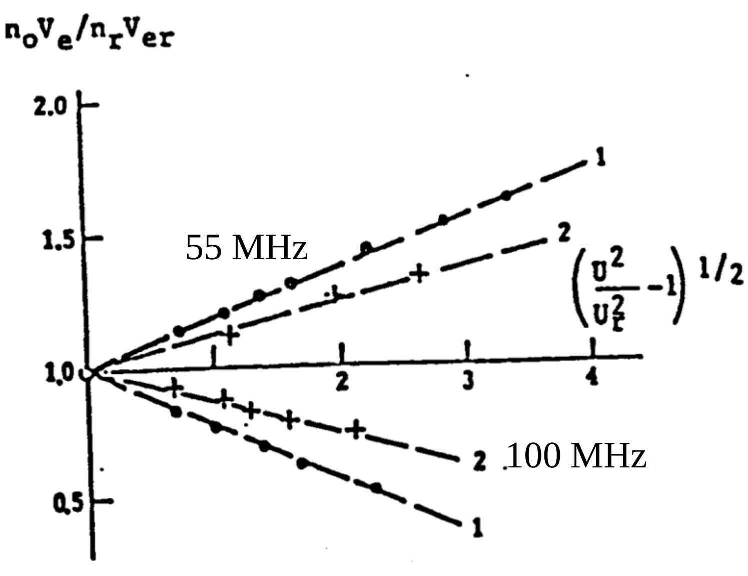


V. Godyak et al, PRL ***61****, 40,1992*

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



Peak discharge voltage



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

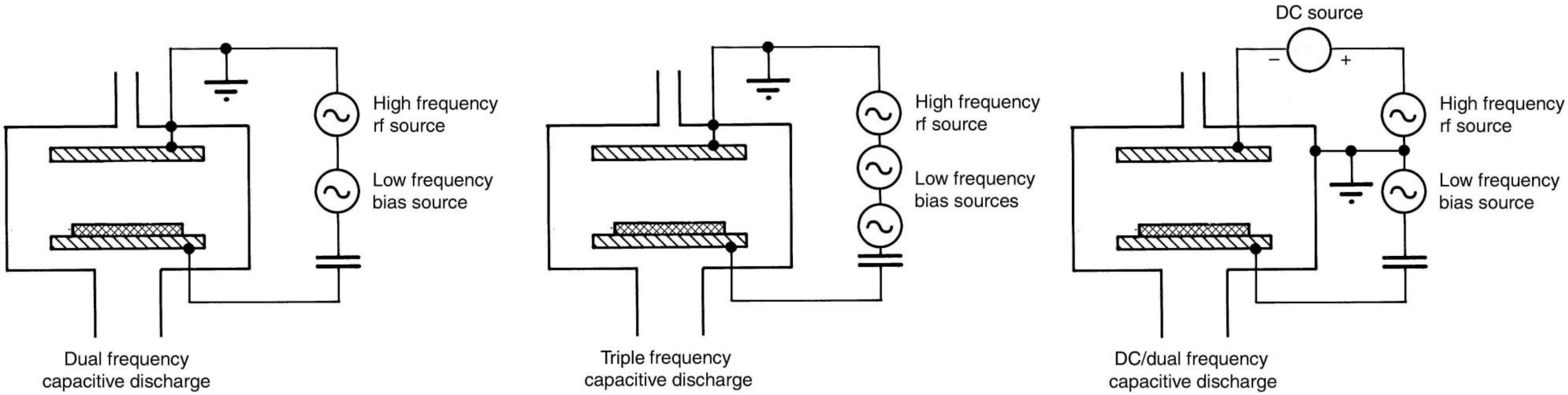
- Series (geometric) resonance of inductive plasma and capacitive sheath
- Double valued rf current and plasma density with capacitive and inductive discharge impedance
- Discharge parameters are not sensitive to discharge voltage
- In the resonance, the rf current does not depends on gas pressure, while $N_p \sim \omega^3$

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)*

Very High Frequency CCP (VHFCCP)

(Dual and triple frequency CCP)



M. Lieberman's lecture, 2007

Main concept:

High frequency f_h to control plasma density (ion flux),

while low frequency f_l to control ion energy and specter (IED)

F_h = 27-162 MHz f_l = 2-13.56, sometime 2 and 13.56 to tailor IED

Today, Dual (Triple) Frequency CCPs are the mainstream technology

VHF CCP problems

- Standing surface waves ($\lambda_r = [1+d/s]^{-1/2} \sim \lambda_o/3$, radial non-uniformity)
- Edge effect (enhances edge plasma density)
- Skin effect (radial non-uniformity when $\delta < 0.45d/R$)
- E to H transition (rf power is magnetically coupled to plasma, like ICP and produces plasma non-uniformity)
- Plasma-Sheath local resonances on F, 2F , 3F (destroy plasma uniformity)
- Resonance effects and mode jumps prevent smooth plasma control

All these problems became more severe at larger:

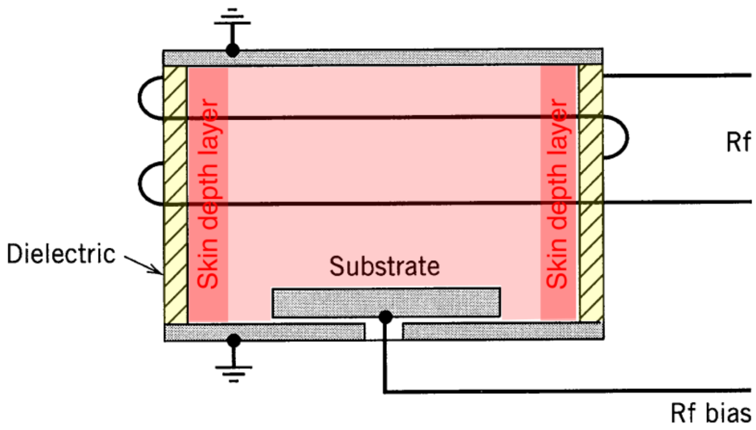
frequency, wafer size and plasma density

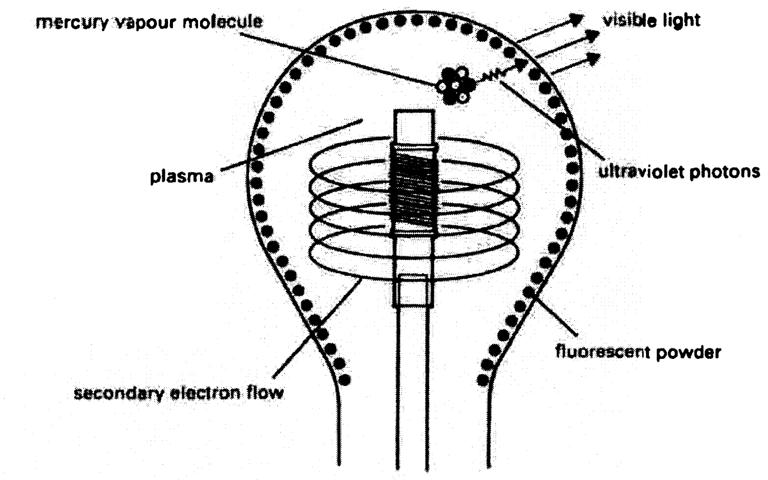
(Gas flow distribution, segmenting and profiling of rf electrode have limited successes)

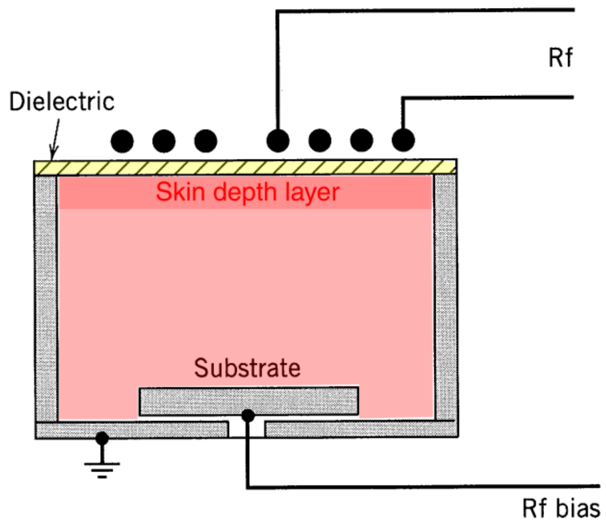
The variety of many fundamental electro-magnetic effects makes VHF CCPs too complicated for reliable their control in a wide range of parameters

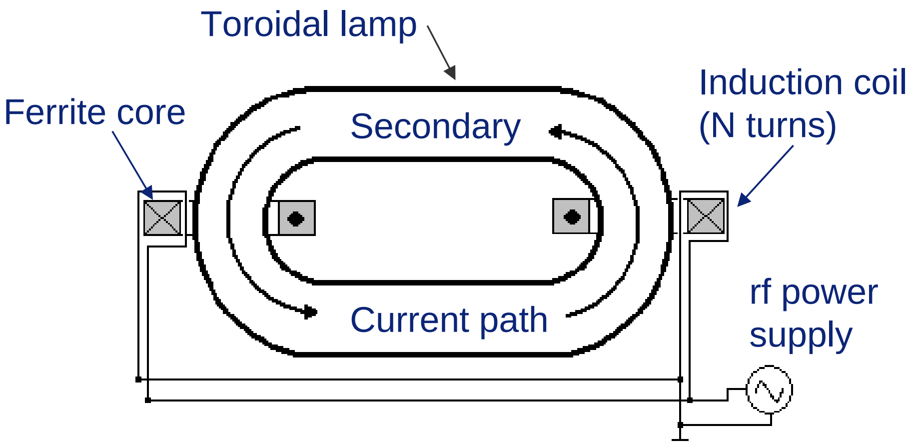
Inductively Coupled Plasma (ICP) Sources

Main ICP topologies in applications

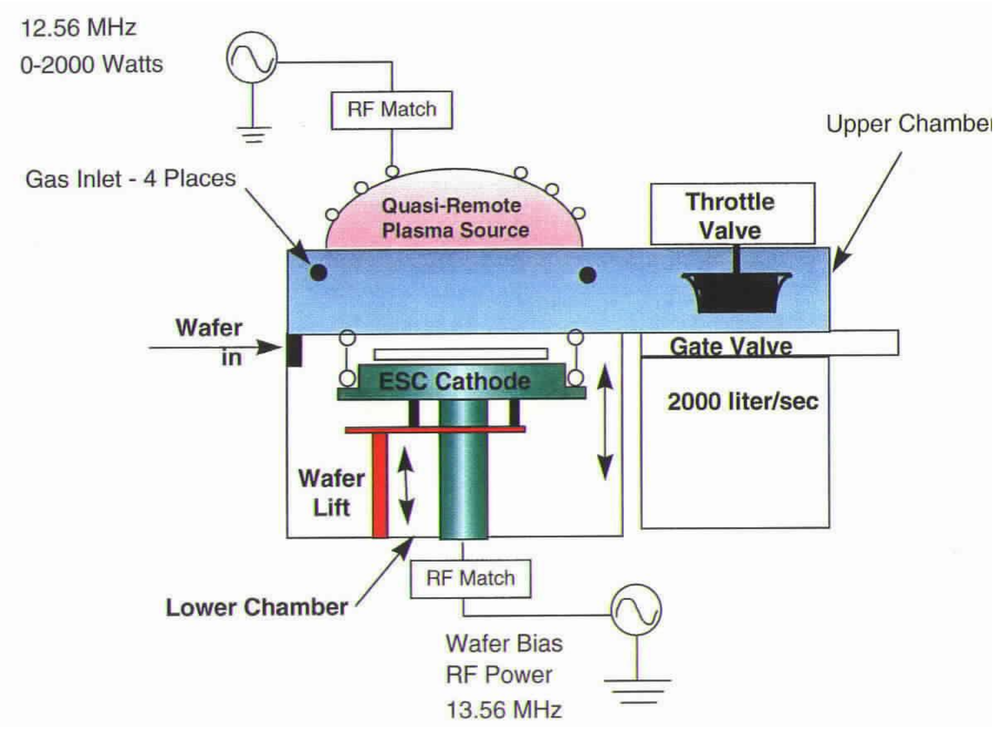








ICP in commercial products



ICP based plasma processing tool

150/100 W, 0.25 MHz fluorescent lamp

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

1. Geometric skin depth (the most important… and neglected) is due to multi-dimensionality 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, $\delta_n = \delta_0(2\nu/\omega)^{1/2}$ @ $\omega << \nu_{en}$ *

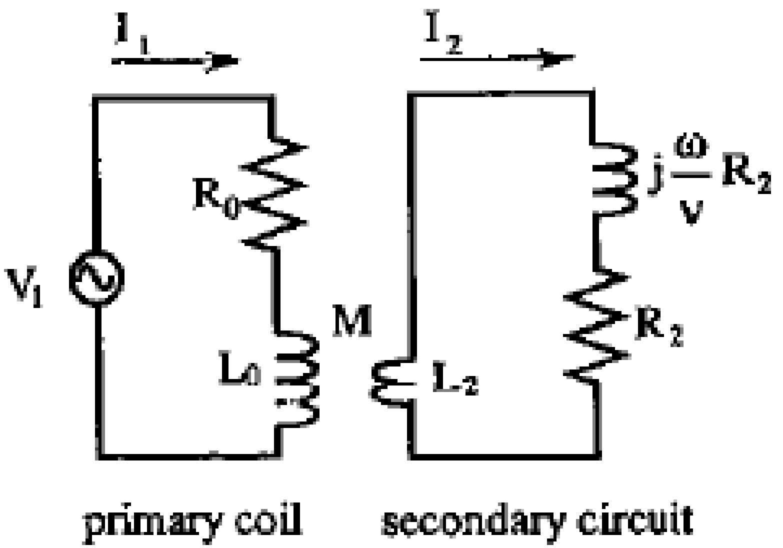
4. Anomalous SE @ ω and $\nu_{en} << v_{Te}/\delta$ **

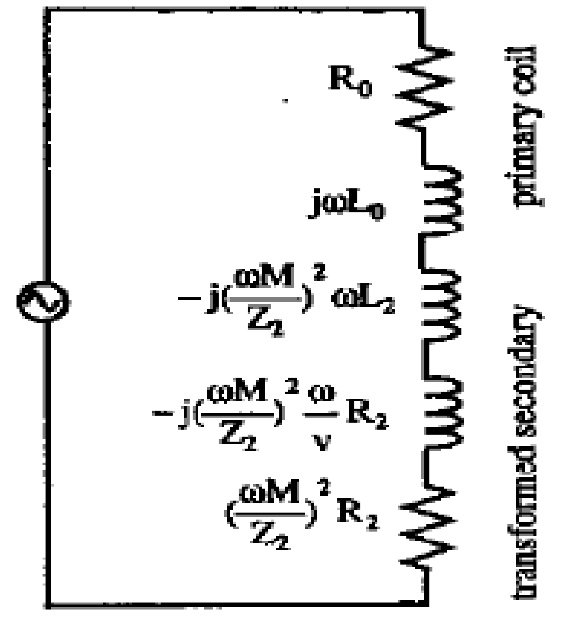
5. Non-linear SE @ $\omega << v_{rf}/\delta$ **

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

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

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





$$R_1 = R_0 + \omega^2 k^2 L_0 L_2 R_2 / Z_2^2$$

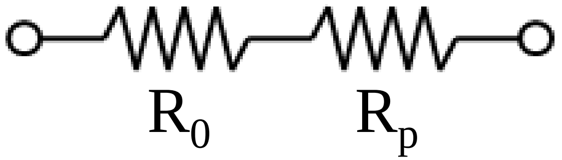
$$\text{where } M^2 = k^2 L_0 L_2,\ Z_2^2 = [\omega L_2 + (\omega/v) R_2]^2 + R_2^2$$

$$L_1 = L_0 - \omega k^2 L_0 L_2 [\omega L_2 + (\omega/v) R_2] / Z_2^2.$$

Physicists, do not be arrogant, these eqs. are integrals of Maxwell Equations, but result in some universal relationships between ICP integral parameter independently of ICP geometry and specific mechanism of electron heating in RF field.

ICP plasma and electrical parameters

- Electron temperature is defined by the ionization balance, $T_e = T_e\,(p\Lambda)$
- Plasma density is defined by power absorbed by electrons, $N_p \sim P_d$
- By measuring of transmitted power, P_{tr}, and the coil current I_c, with and w/o plasma, one can infer the power absorbed by plasma, P_p, and power loss in antenna and surrounding hardware, P_o (in antenna, matcher and chamber)



$$P_{tr} = P_i - P_r = I^2(R_0 + R_p); \quad P_0 = I_0^2 R_0$$

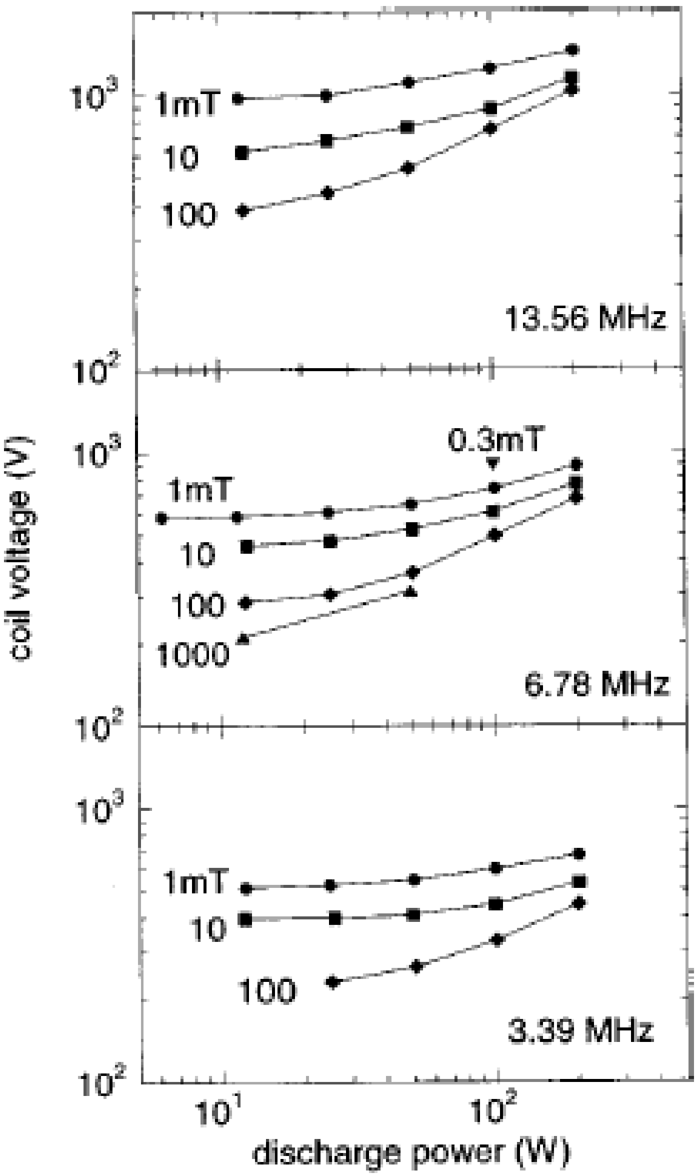
$$P_d = I^2 R_p = P_{tr} - P_0 I^2 / I_0^2$$

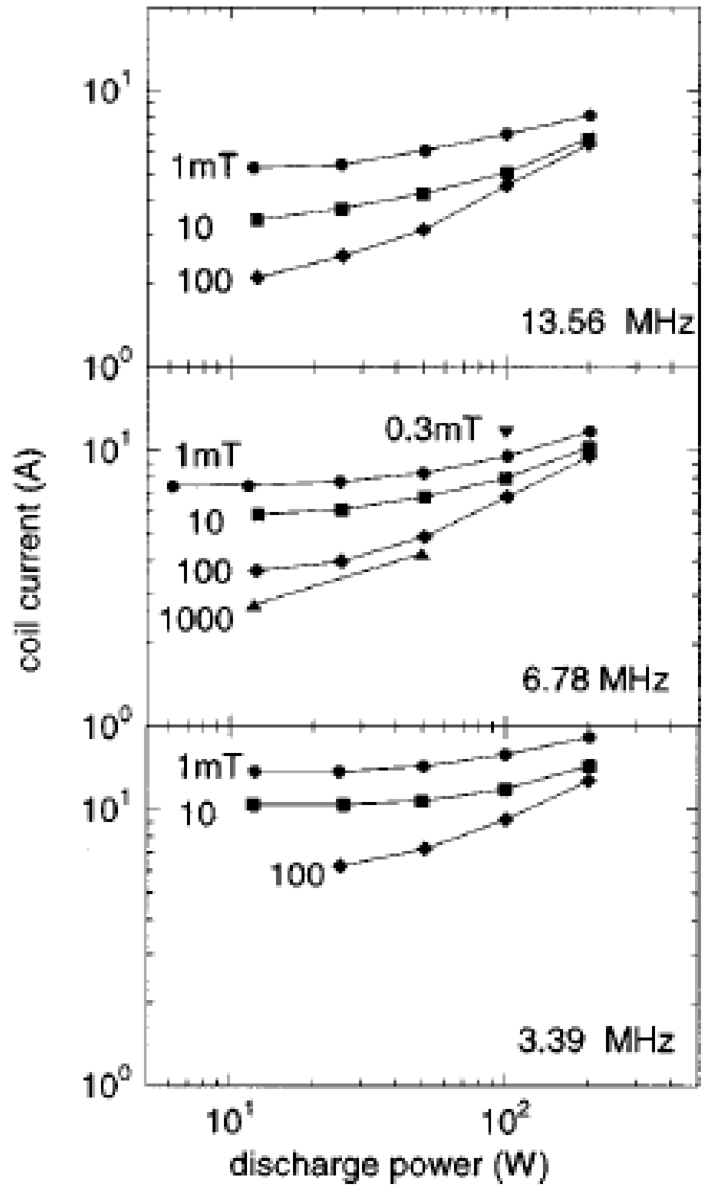
Surprisingly, tis simple RF diagnostics is neglected in characterization of commercial plasma reactors and of many laboratory rf plasmas, where plasma is characterized by the power consumed from the power source, P_{tr}. This power is always smaller (sometimes significantly) than P_d, and is not proportional to P_d

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

Argon ICP electrical characteristics

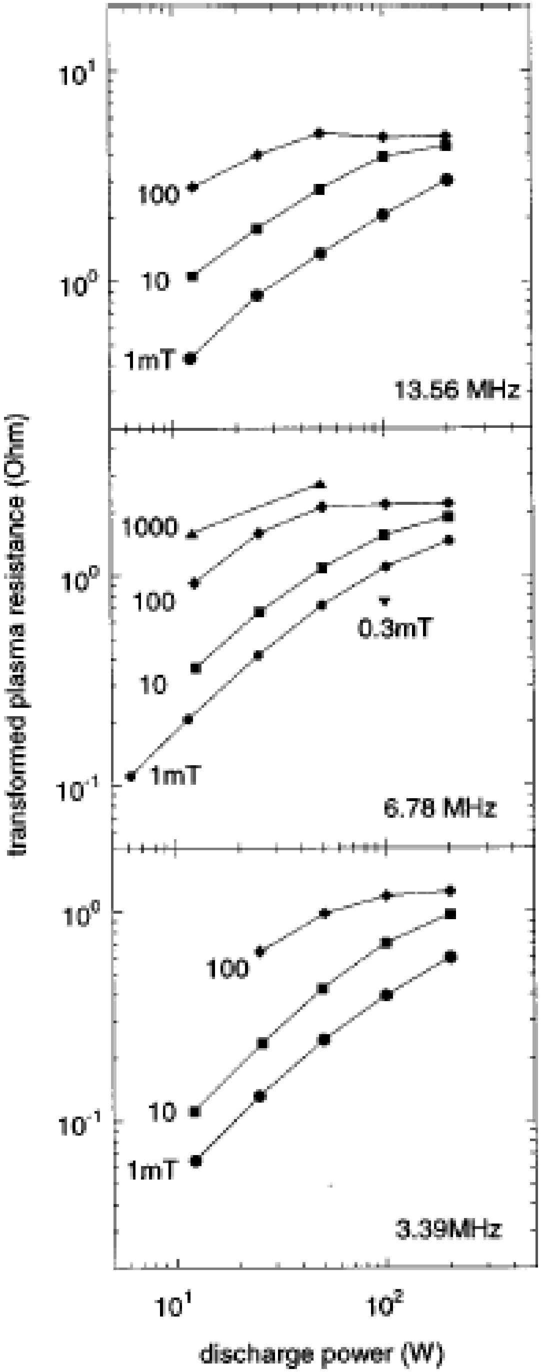
*(experiment, Godyak et al PSST, **11**, 525, 2002)*



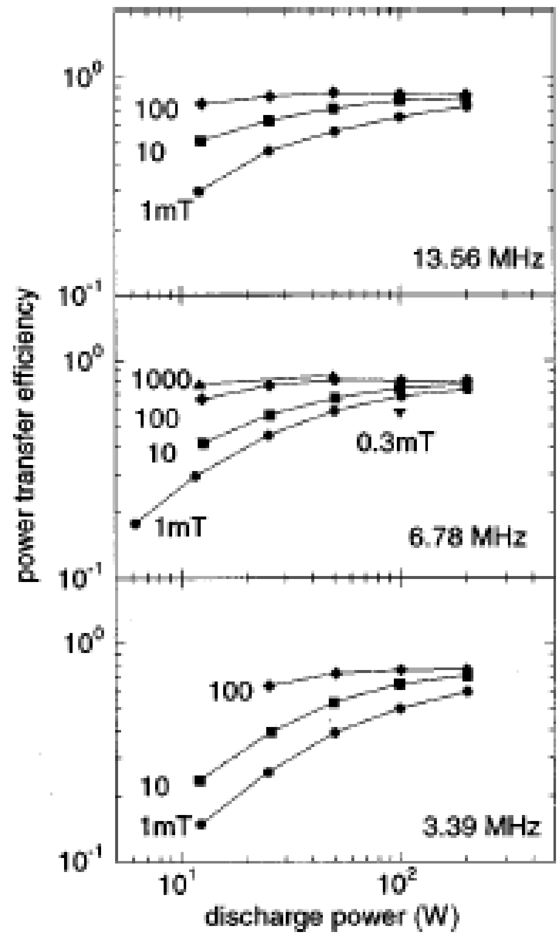


More electrical parameters

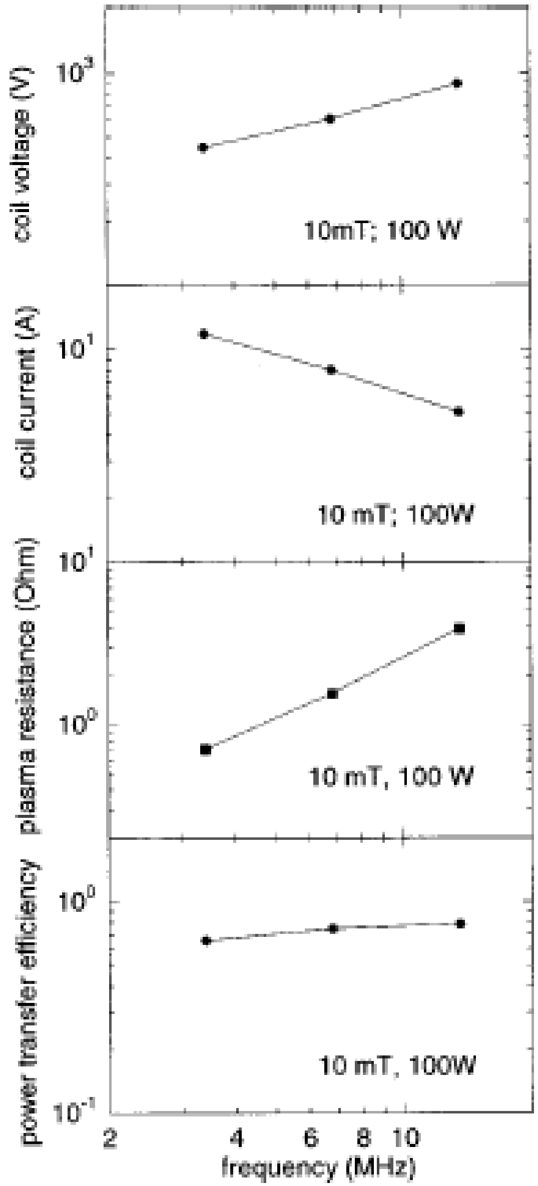
Transformed plasma resistance



Power Transfer efficiency



Frequency dependence



Power Transfer Efficiency and Frequency Effect

$P_c = I^2 r_c \sim E^2 = E_{dc}^2\,(1+\omega^2/\upsilon^2_{eff})$; excessive coil loss at $\omega > \upsilon_{eff}$

Power transfer efficiency, ξ

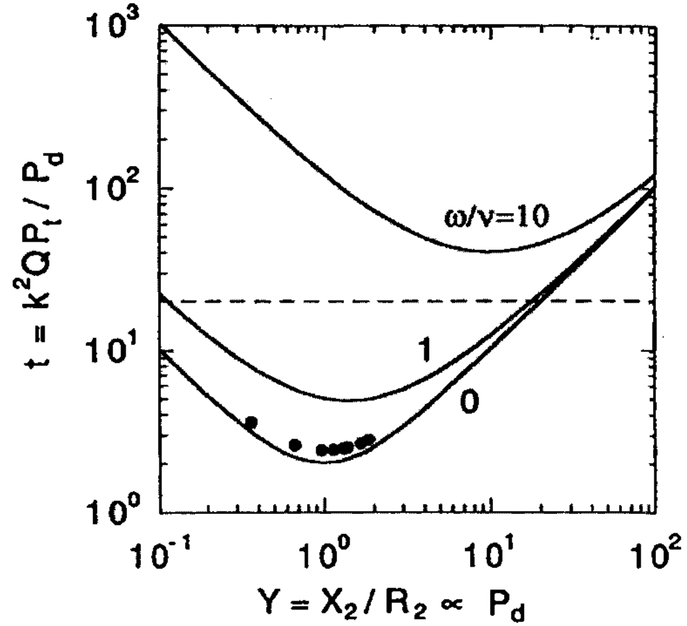
Conventional transformer

$\xi = P_2/P_1 \approx 1$

Conventional ICP

$\xi = P_{pl}/P_1 = 1 - P_c/P_1 \approx 0.05 - 0.8$

Relative power loss in ICP inductor $P_c/P_p \sim (1+\omega^2/\nu^2_{eff})/k^2Q_{10}$



$Y = (wL_0/\,kN_1^{\,2})/(P_{pl}/V^2_{pl})^{-1}$

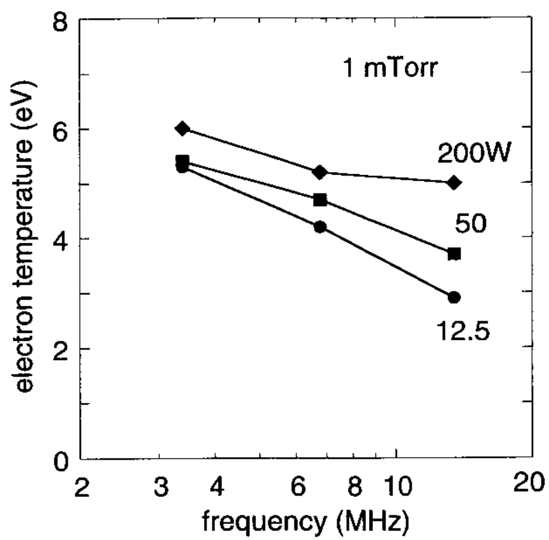
$t = k^2Q_{10}P_c/P_{pl}$

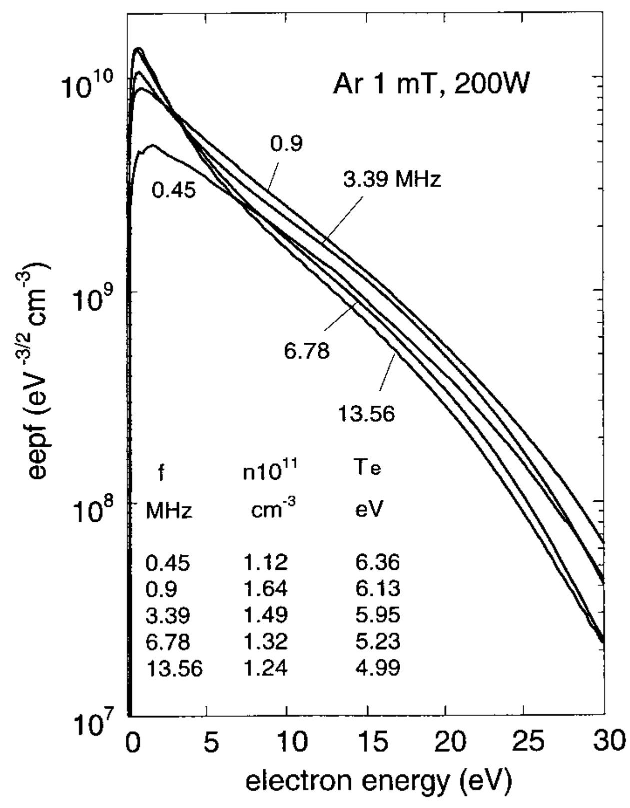
Weak coupling in plasma processing reactors together with high plasma impedance, typical for molecular and negative gases, prevents low - density ICP regime ($n \approx,> 10^{11}cm^{-3}$)

Frequency effect exists at low density plasma in anomalous skin effect regime, but disappears at larger plasma density due to e-e collisions.

Operation at lower frequency is desirable because:

- efficiency and lower cost of rf equipment
- Capacitive coupling and transmission line effect can be eliminated
- Easier management of rf power and simpler and more reliable electrical diagnostics





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

Pros and Cons of conventional ICP sources

Positive

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

Negative

- 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

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.

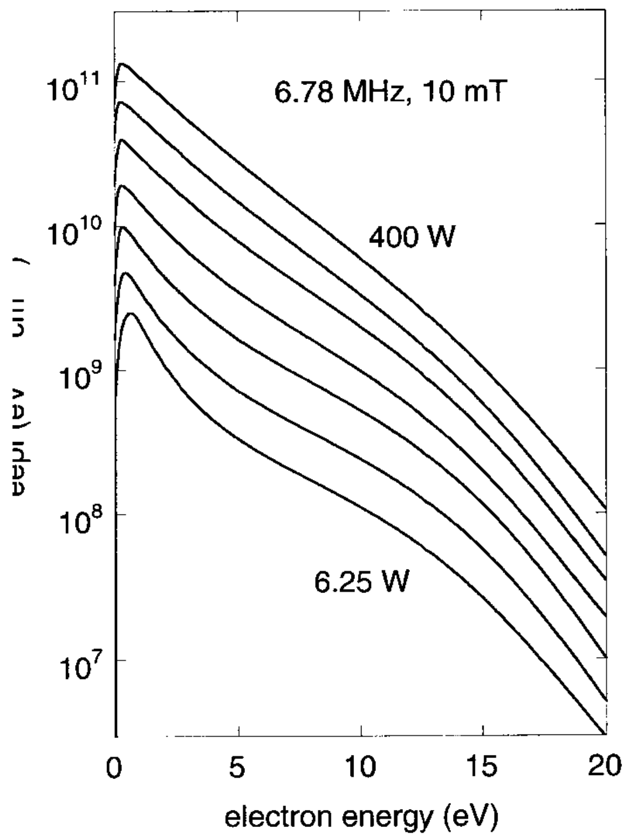
Contrary to prevailed lore:

- ICP can operate in inductive mode at small wattage and low plasma density
- ICP can operate with small gap (small residual time)
- ICP can provide uniformity control over the large processing area
- Capacitive coupling and transmission line effect can be eliminated
- ICP source can operate at much lower frequency, more efficient and 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

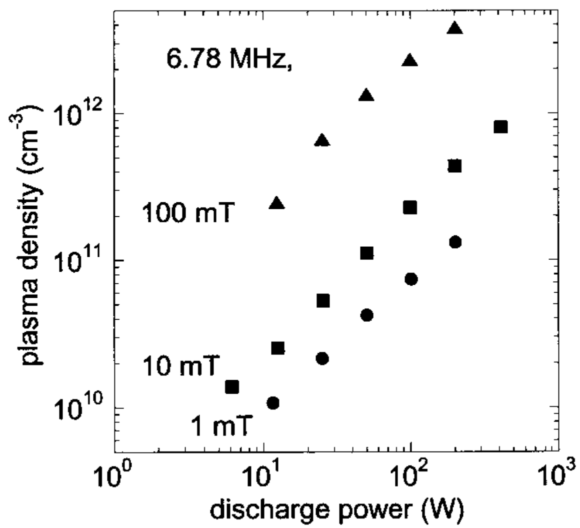
ICP does operate in inductive mode at low plasma density

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



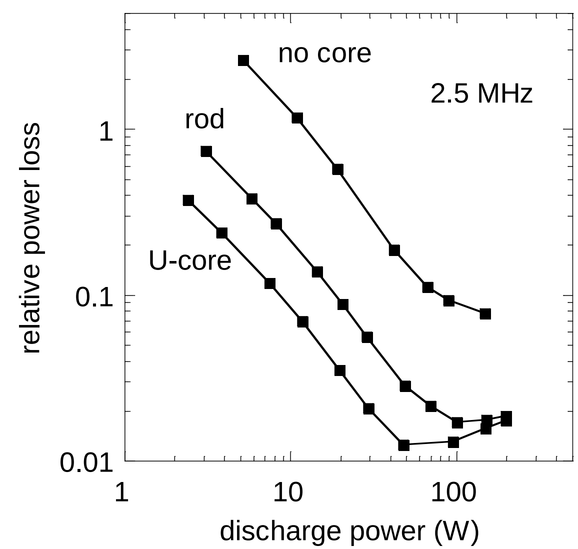
2R = 20 cm, L = 10 cm

r = 0, z = 5 cm



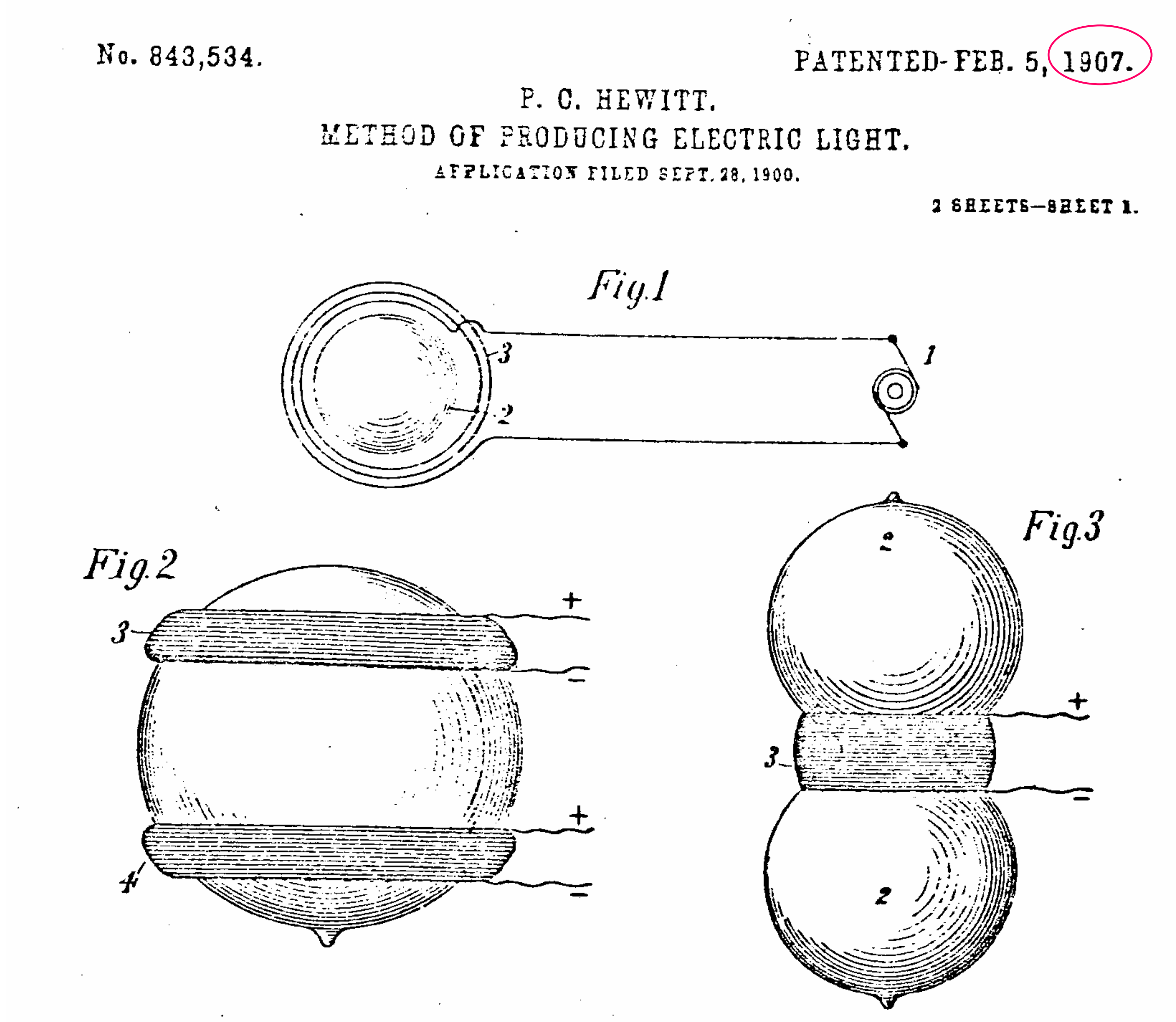
Spherical ICP
Ar-Hg at 0.5 Torr

$\eta = P_a/P_d$

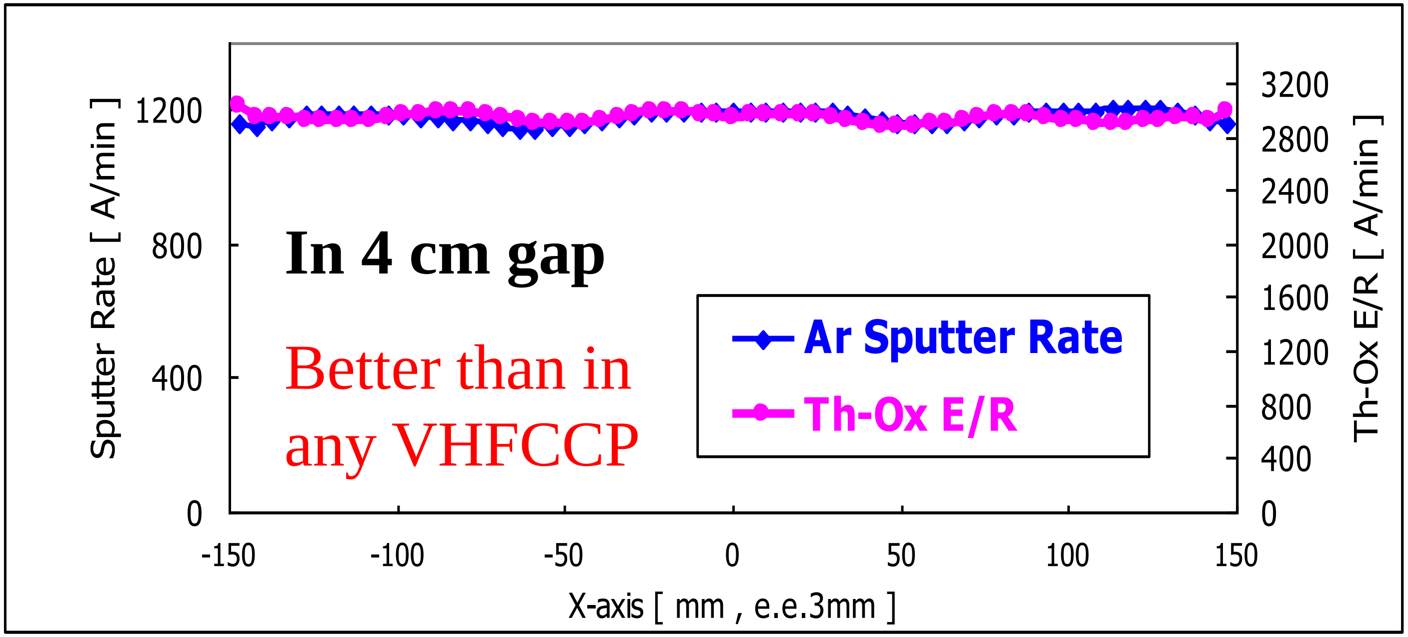


Inefficient coupling and huge antenna loss prevent low plasma density operation in commercial ICPs. $P_a \leq P_d \sim n$ is the condition for stable ICP operation

Today ICP reactor designs are based on 100 year old concept



Groovy ICP, Process : Ar/C4F_6/O_2. FOI (Japan)



Ar sputter rate uniformity : +/- 2.5%

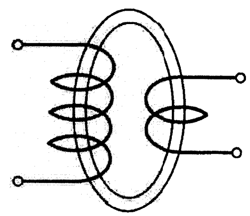
Th-Ox etch rate uniformity : +/- 2.6%

300 mm , Th-Ox wafer (blanket)

ICP with Ferromagnetic Core

What is the difference between:

a conventional transformer and a conventional ICP



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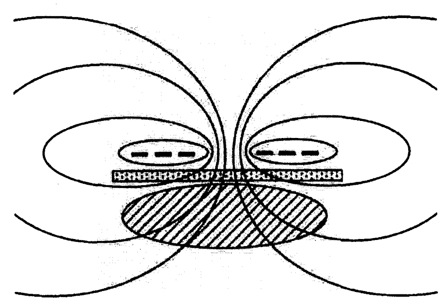
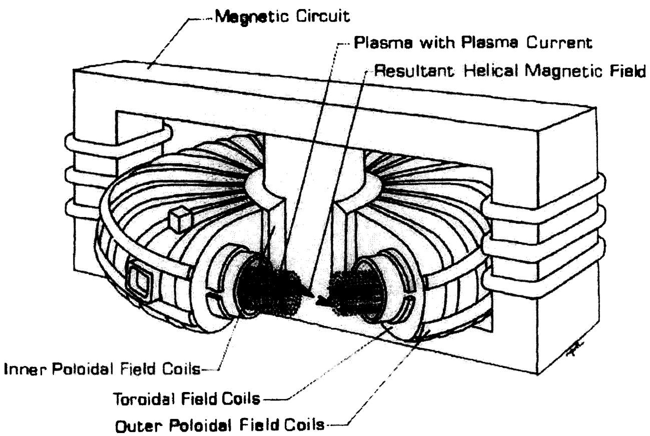


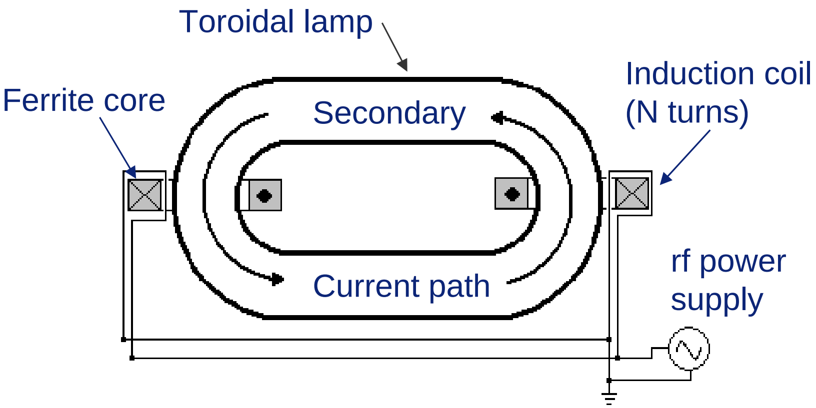
a conventional transformer	a conventional ICP
Ferromagnetic core (μ >>1) provides a strong coupling, $k \approx 1$	No core (μ =1), thus a weak coupling, $k = 0.2 – 07$, loss $\propto k^{-2}$!
$\omega L_s << R_1$, $Q_1 = L_{s1}/R_1 <<1$	$\omega L_s >> R$, $Q_1 >>1$, $\rightarrow$ $V_2 < V_1/N_1$
$V_1/V_2 = N_1/N_2$ $I_1/I_2 = N_2/N_1$	Needs a resonant matching network to compensate large $j\omega L_s \rightarrow \cos\varphi << 1$

Enhancement of ICP with ferromagnetic core makes it operate closer to an ideal transformer (more efficient and larger power factor)

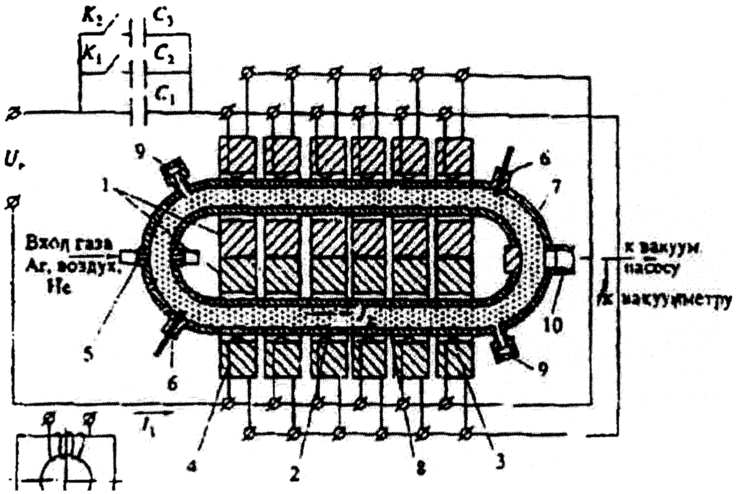
Toroidal ICP plasmas with ferromagnetic core in industrial applications



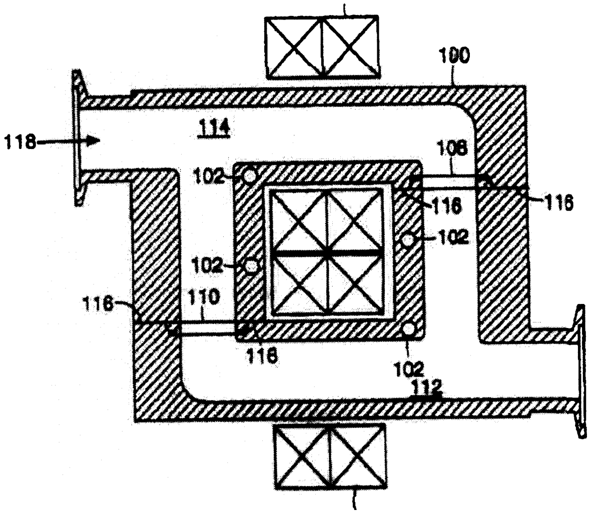
Toroidal plasmas for fusion, 1960



Induction lighting, Andersen, 1970



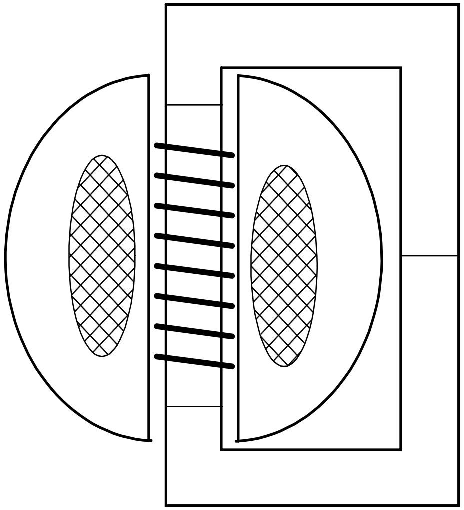
Kogan & Ulanov, 1993
100 kW, 10 kHz, 1 atm.

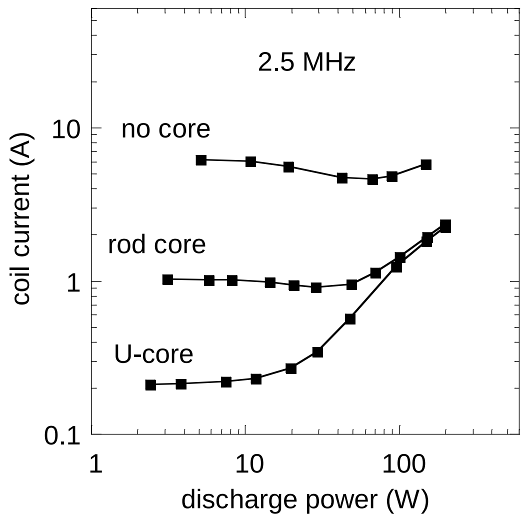


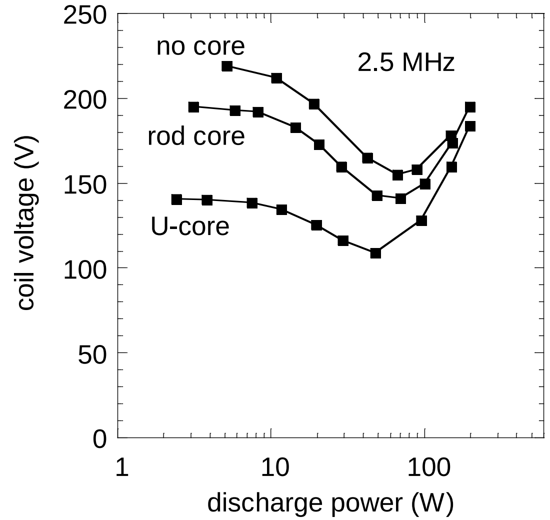
Smith et al, 1998
(5-10) kW, 400 kHz, 1-10 Torr

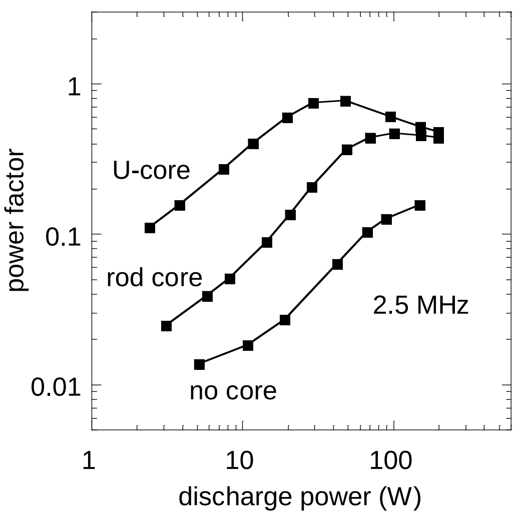
ICP enhanced with ferromagnetic core

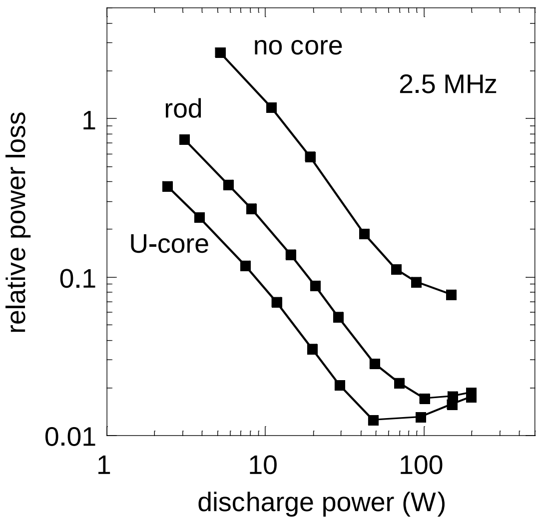
2.5 MHz, spherical ICP with internal inductor, D = 7 cm, Ar-Hg 0.5 Torr









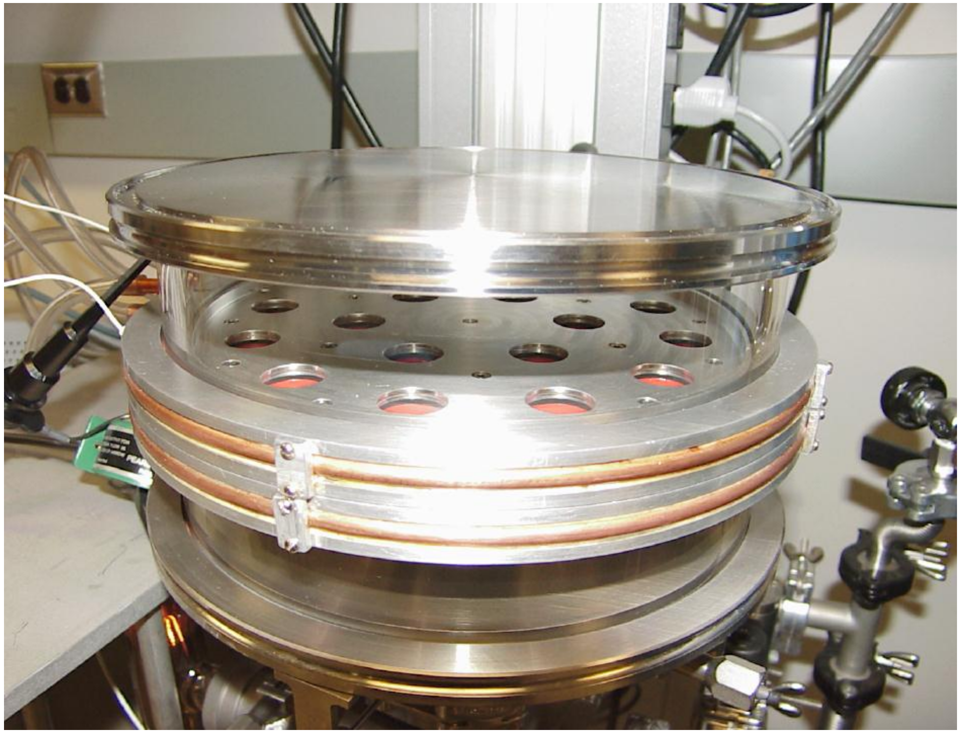


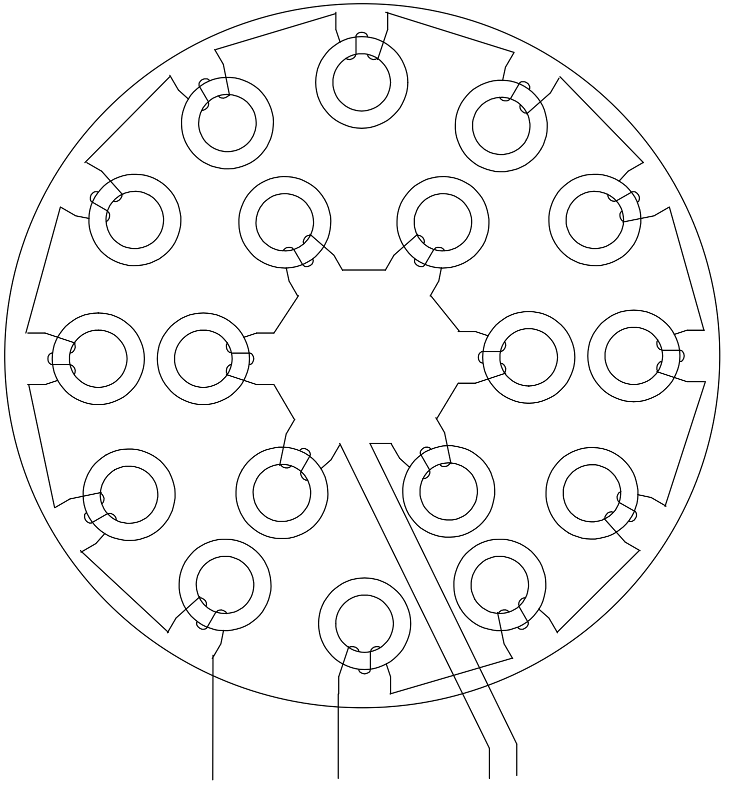
Introduction of a ferromagnetic core reduces antenna coil current and voltage, together with increasing ICP power factor (Cosφ) and power transfer efficiency

V. Godyak, Proc. XV[th] 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

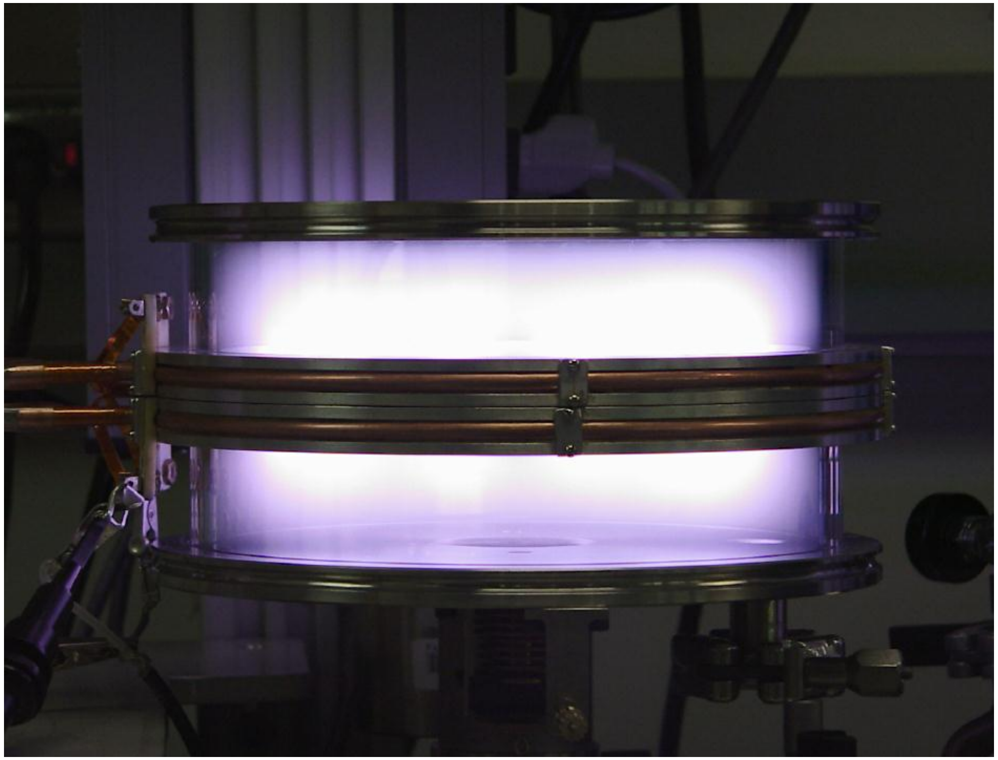


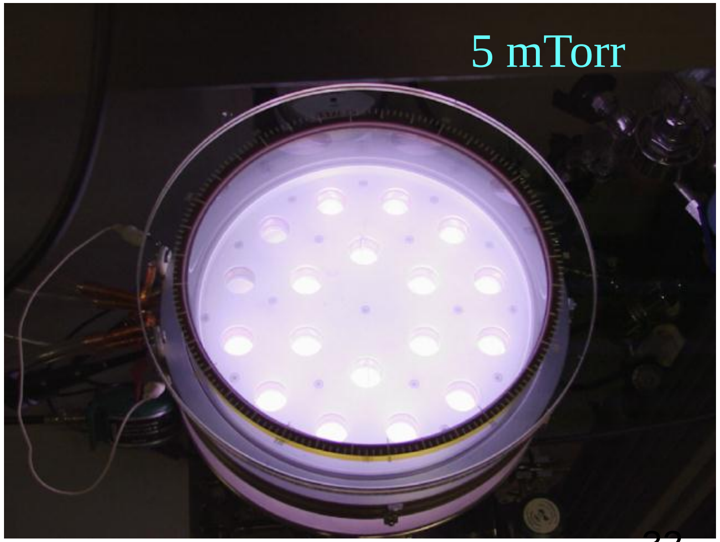


V. Godyak, PEUG, Santa Clara, 2003

18 core distributed ferrite ICP

Xenon, 400 kHz, 10 mTorr, 400 W



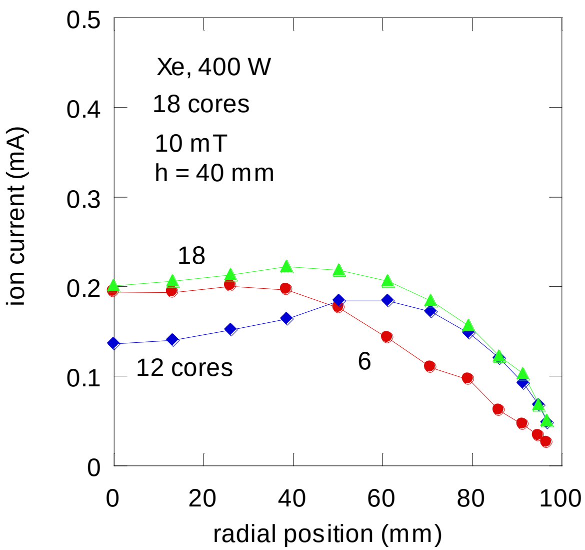


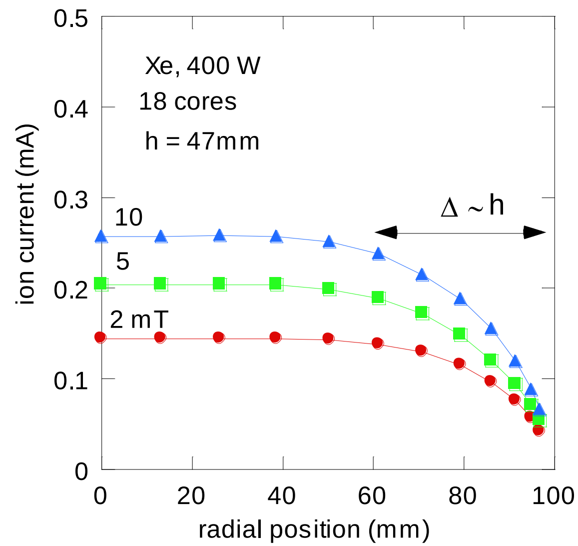
V. Godyak, PEUG, Santa Clara, 2003

Plasma uniformity control and coupler losses

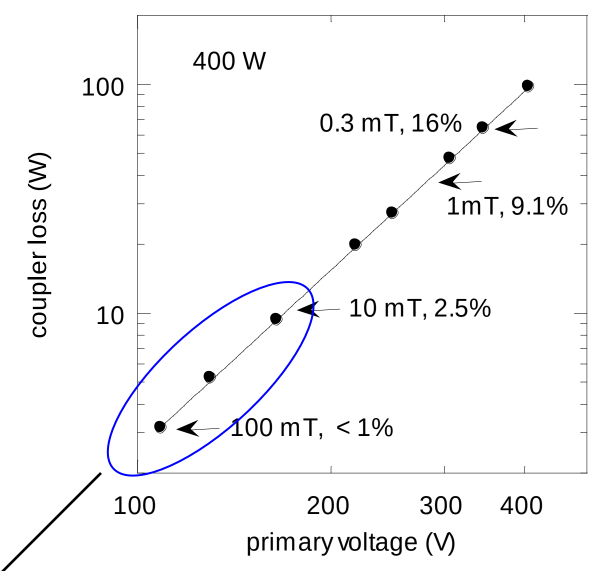
@ 400 W, p = 0.3-100 mT, Cosφ = 0.95-0.97 and P_o/P_d = (16 - 1)%

I_i @ 2 mm from the chamber bottom





Coupler loss versus coupler voltage

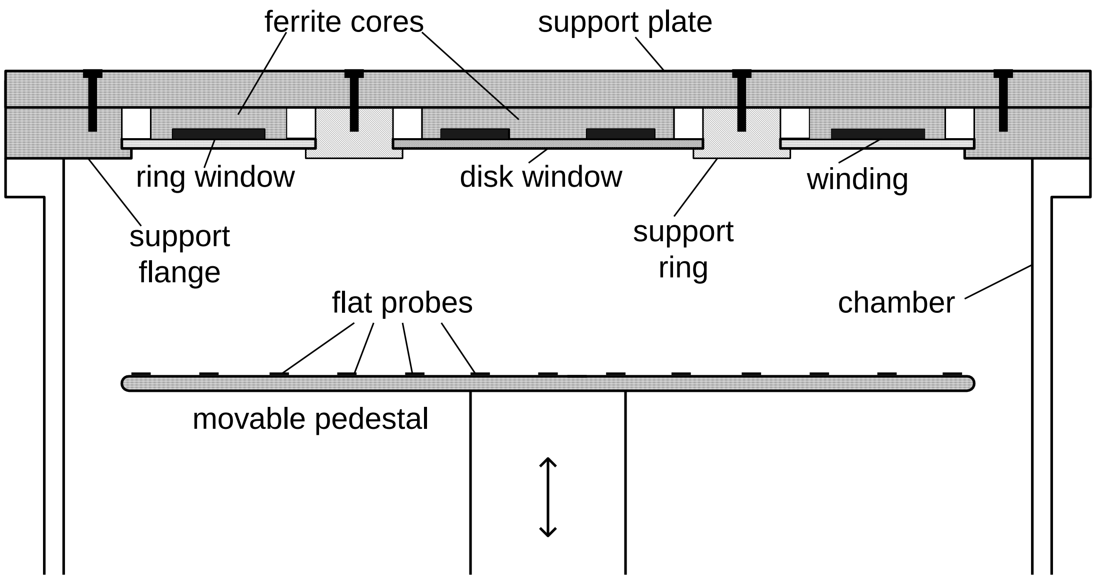


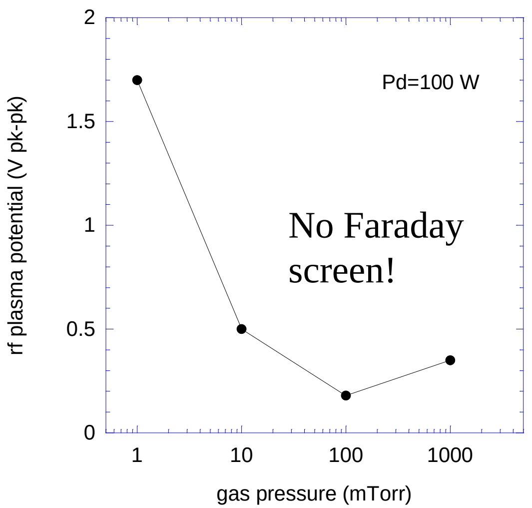
Power factor and efficiency exceed those in a conventional transformer at 60 Hz!

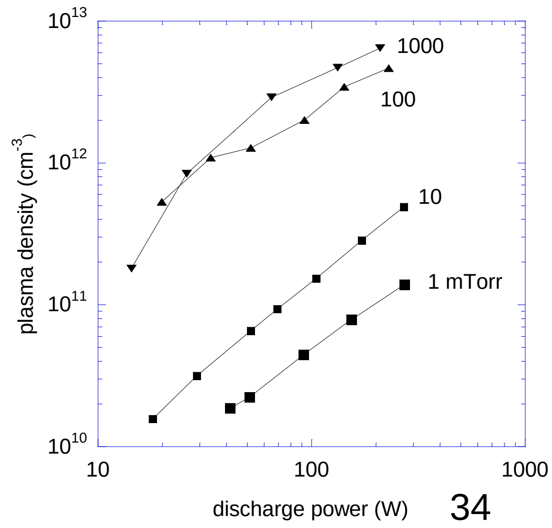
V. Godyak, PEUG, Santa Clara, 2003

ICP Enhanced with Ferrite Core, 2 MHz, argon, d = 1.5 - 8 cm

Increased coupling provides better plasma spatial control

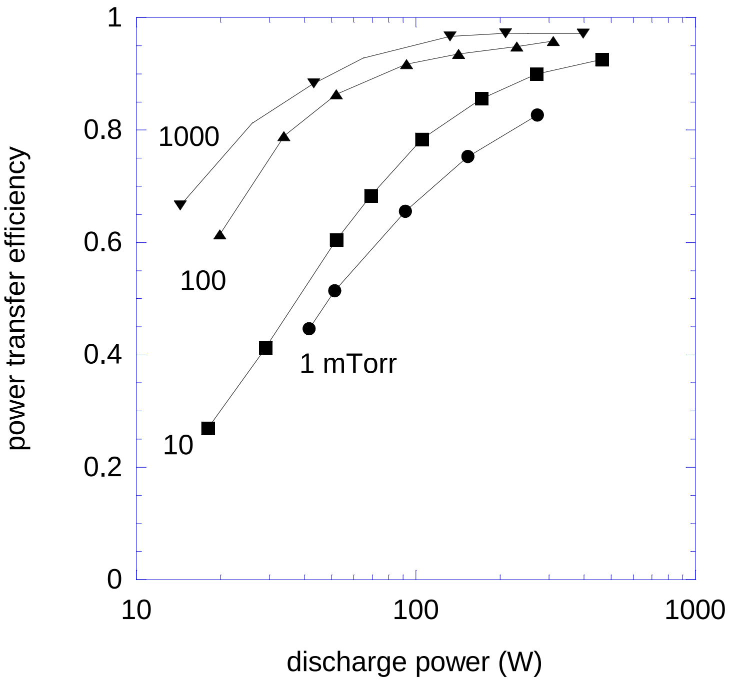


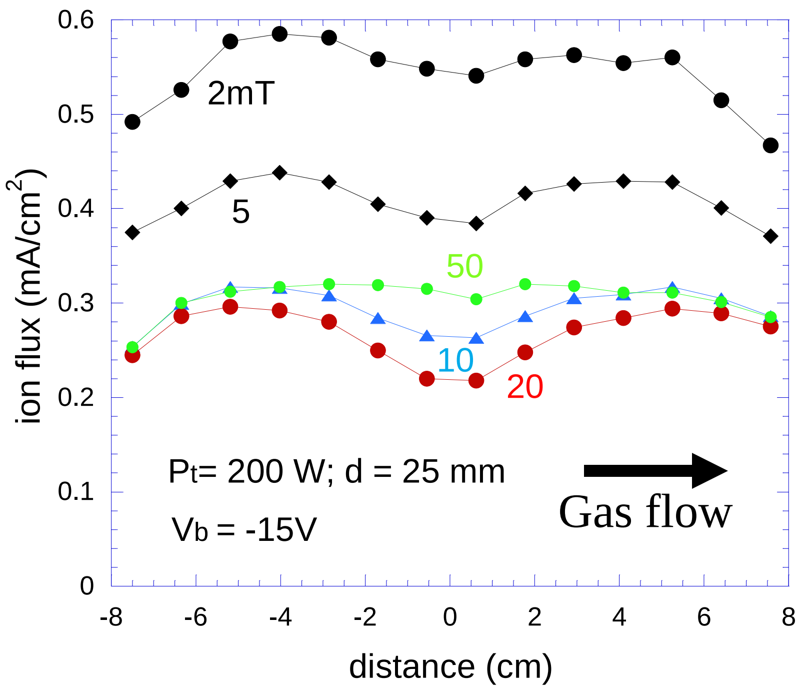




*V. Godyak, PSST **20**, 025004, 2011*

Power transfer efficiency and plasma density control





Commercial ICPs with two antennas do not produce peripheral maxima.

The reason is: too large gap between the window and the wafer and too low antenna to plasma coupling

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

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 rf coupling and poor gas flow management. They are far from the optimal design and thus have room for improvement

- Properly designed ICP can operate at low plasma density, small gap and provide good process uniformity control

- Low frequency distributed ICPs with ferromagnetic cores and free of capacitive coupling, transmission line effect can do everything that other plasma source do, but more efficiently and cost effective