Aula 3

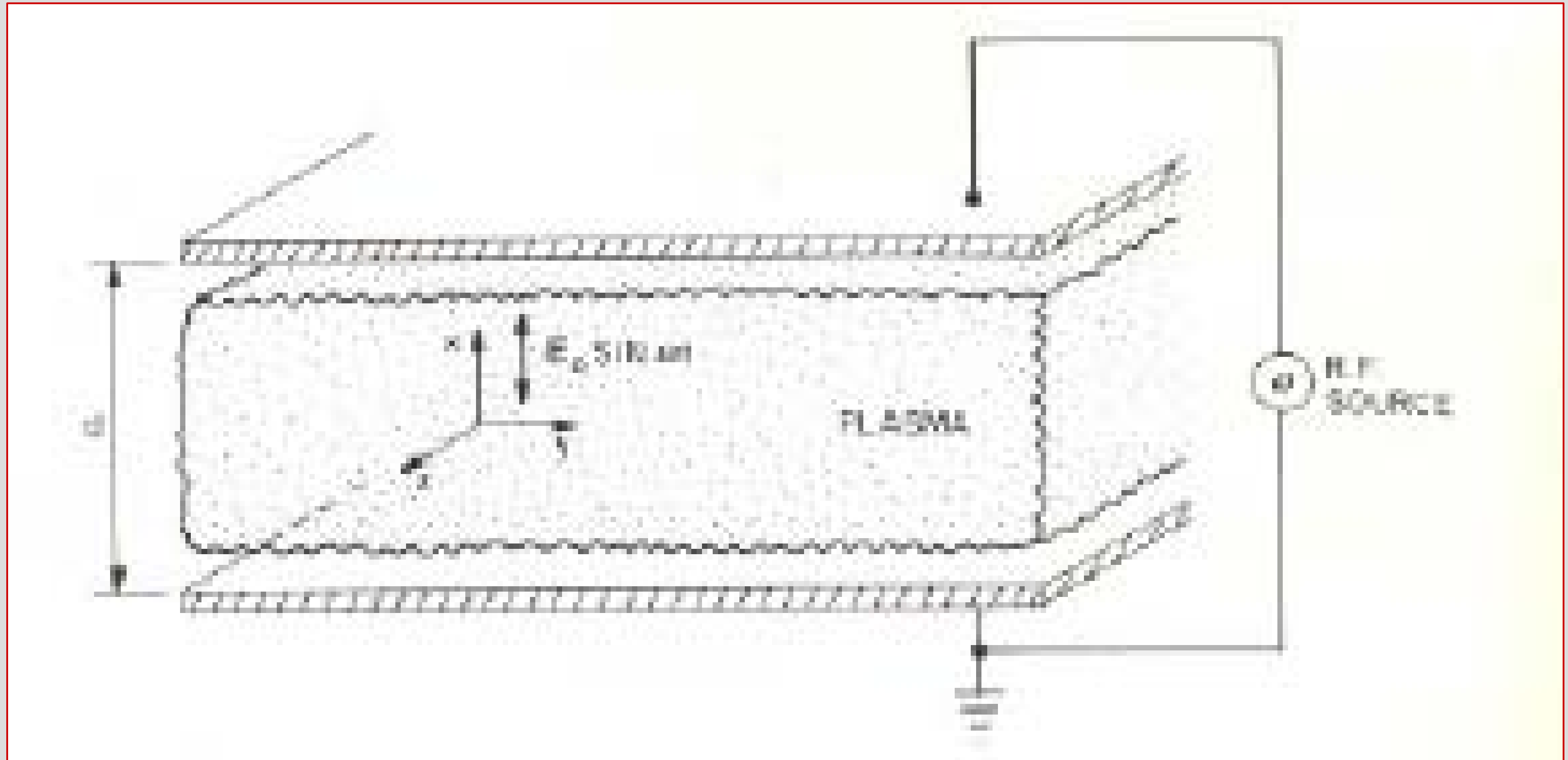
Plasmas RF

Plasmas Capacitivos

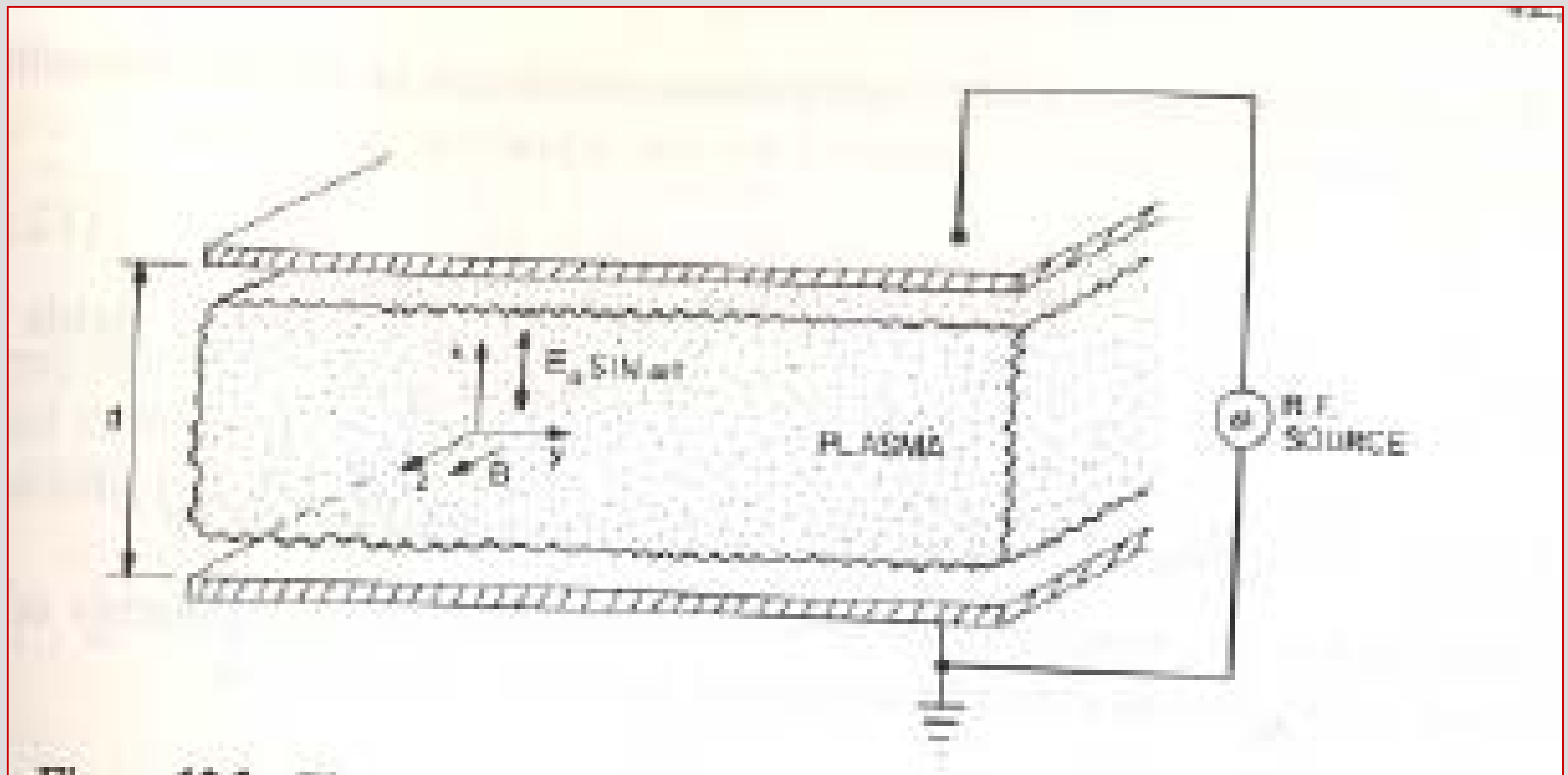
Plasmas capacitivos

- Plasmas capacitivos, talvez sejam os mais empregados na indústria atualmente, no entanto são os menos entendidos. Pois muitas das suas características são aproximadas aos de plasmas DC. Mas algumas características são singulares, como a espessura das bainhas, a energia dos íons, a perda de potência na bainha, e o surgimento de partículas nas regiões proibidas.

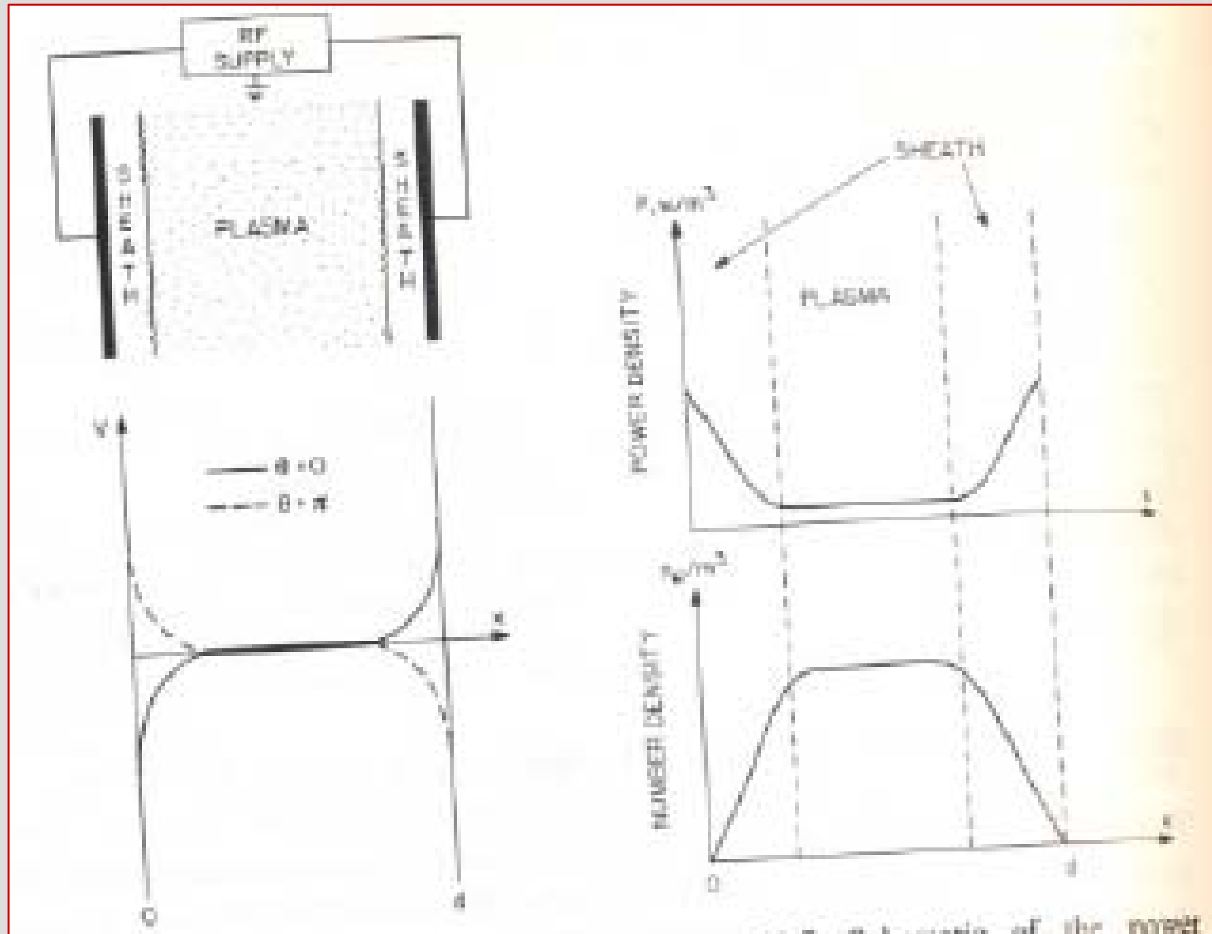
Plasma RF com campo puramente elétrico



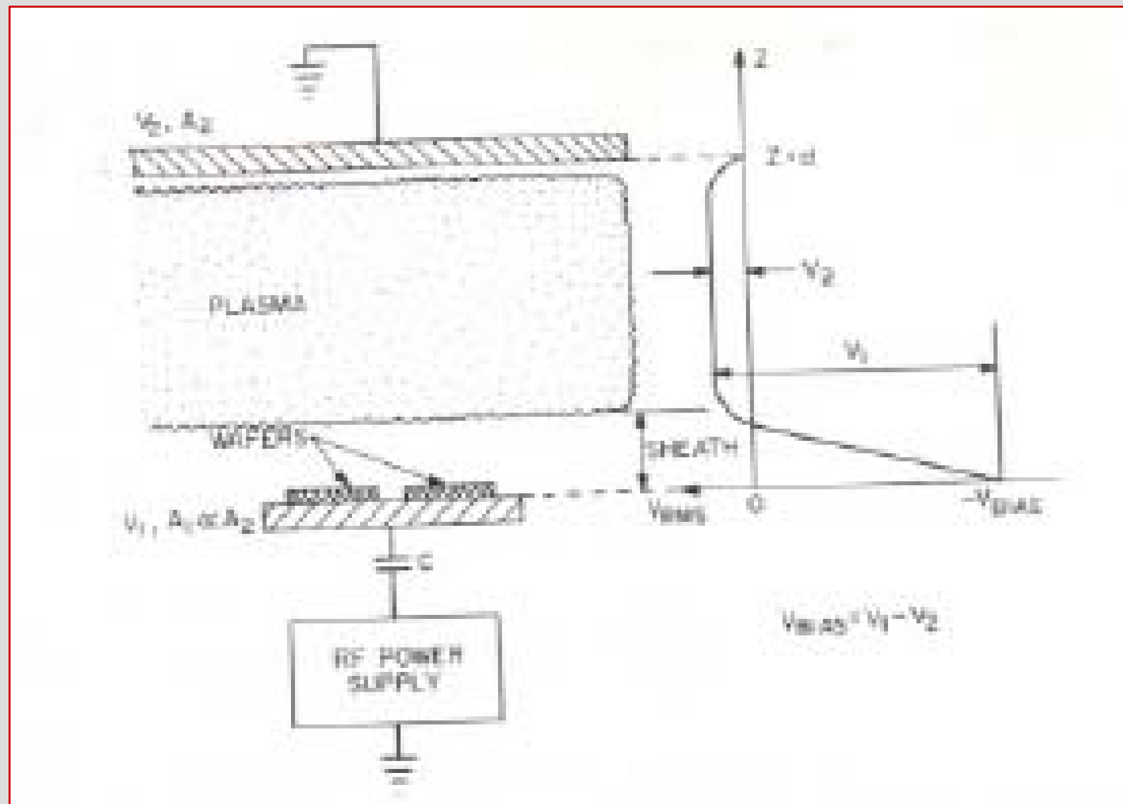
Plasma RF com campo puramente eletromagnético



Descarga RF em reator simétrico

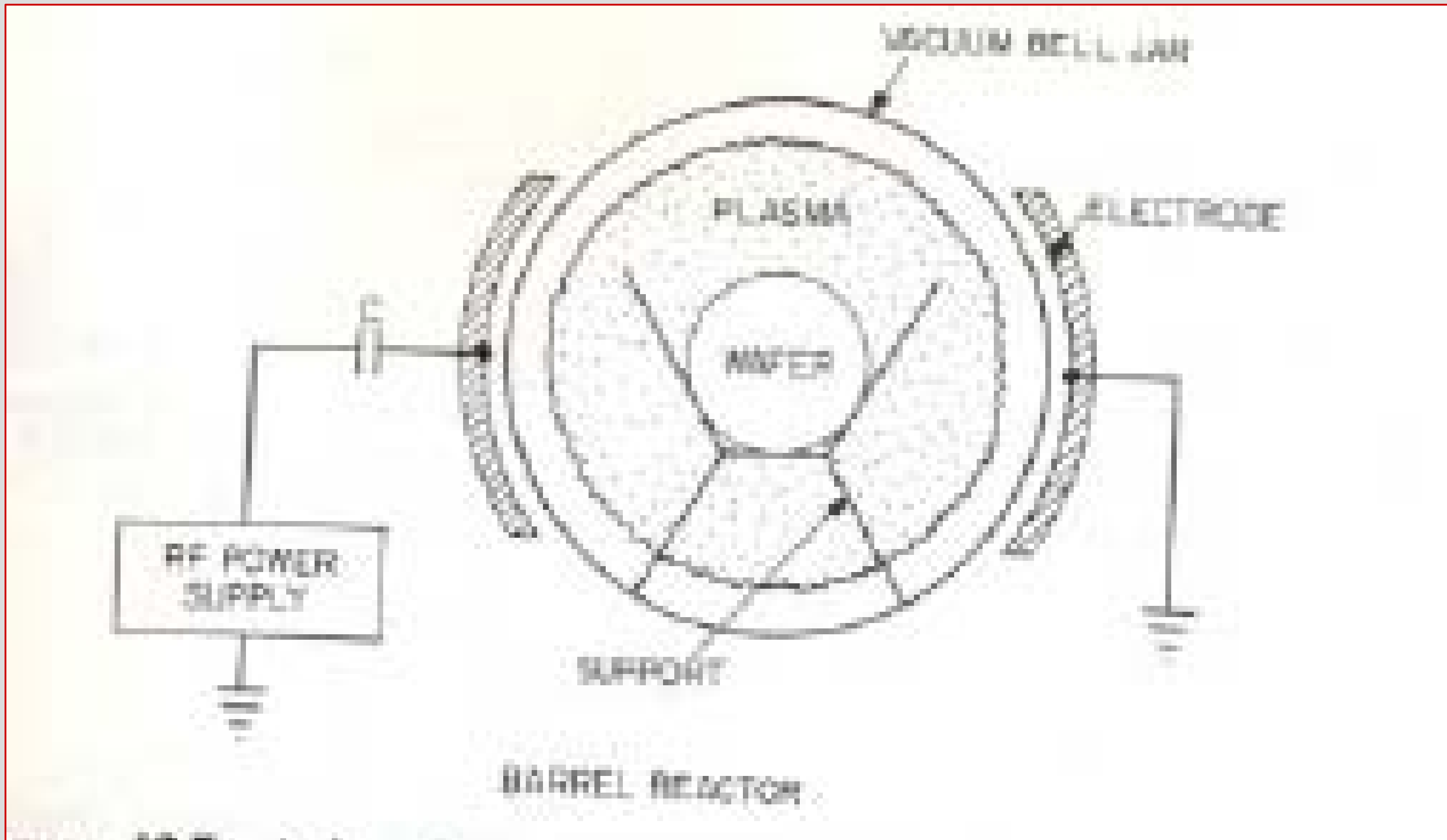


Reator assimétrico de plasma



Tipos de reator capacitivos

Reator tipo Barril



Reator hexagonal

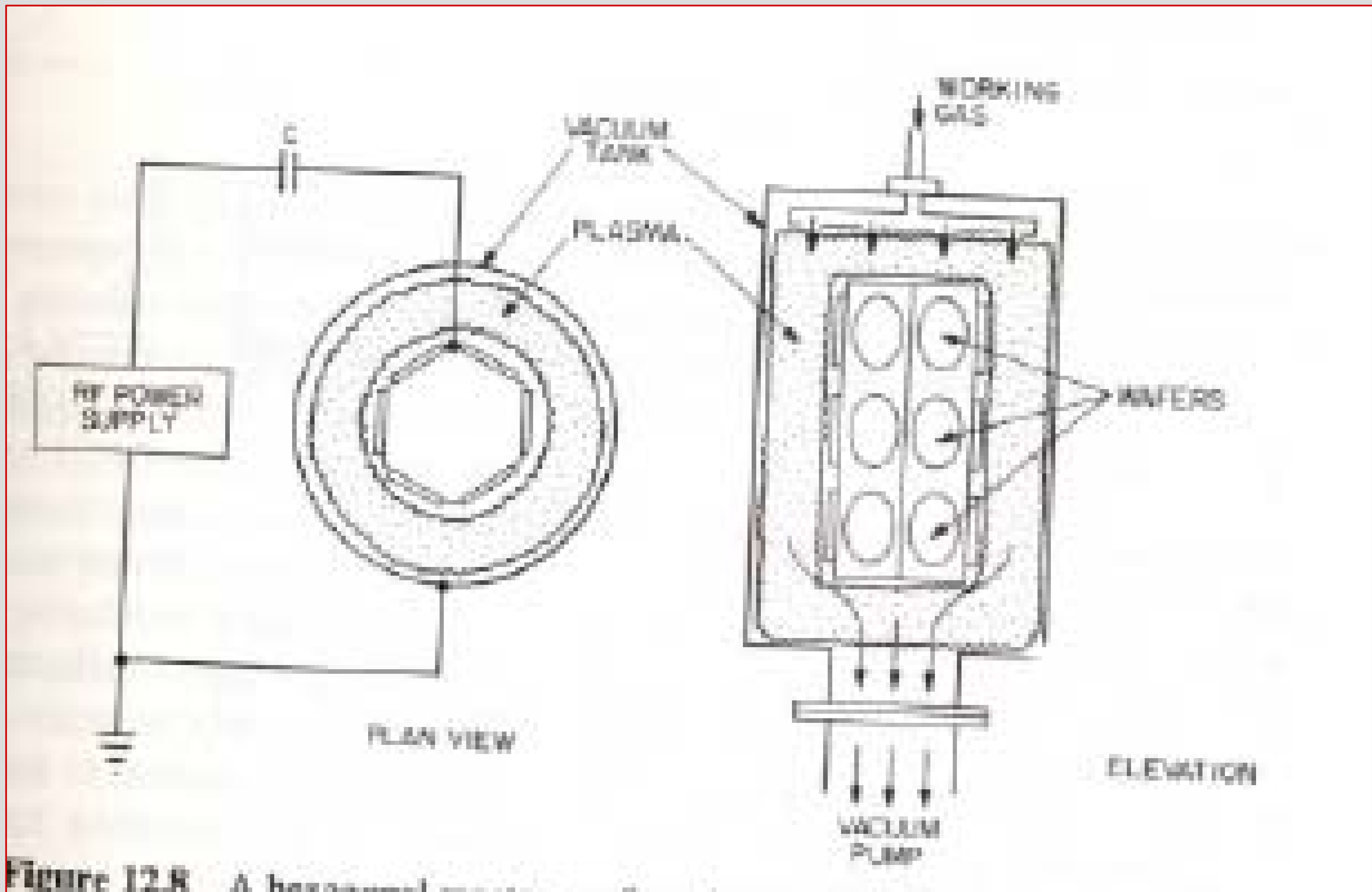
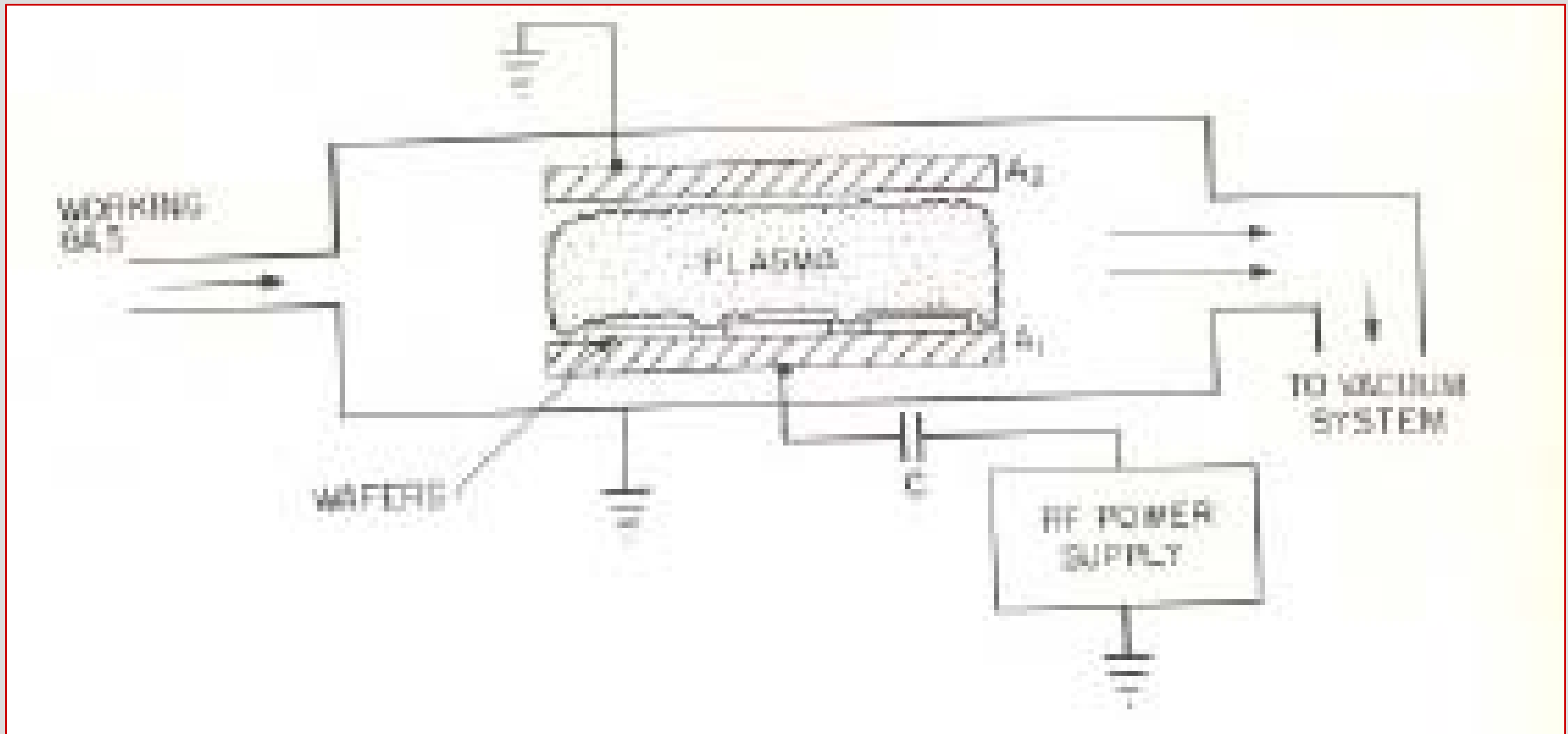
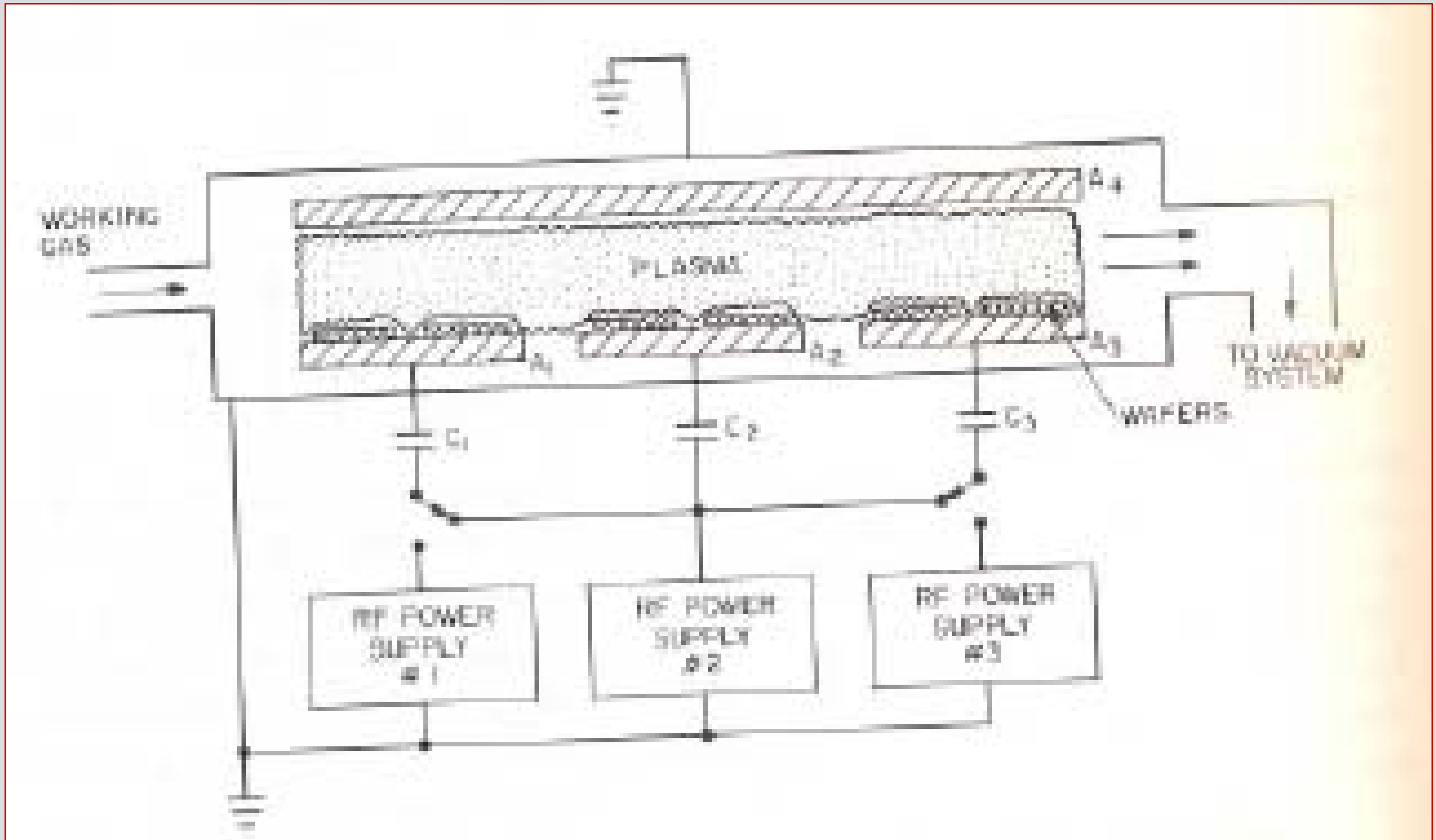


Figure 12.8 A hexagonal

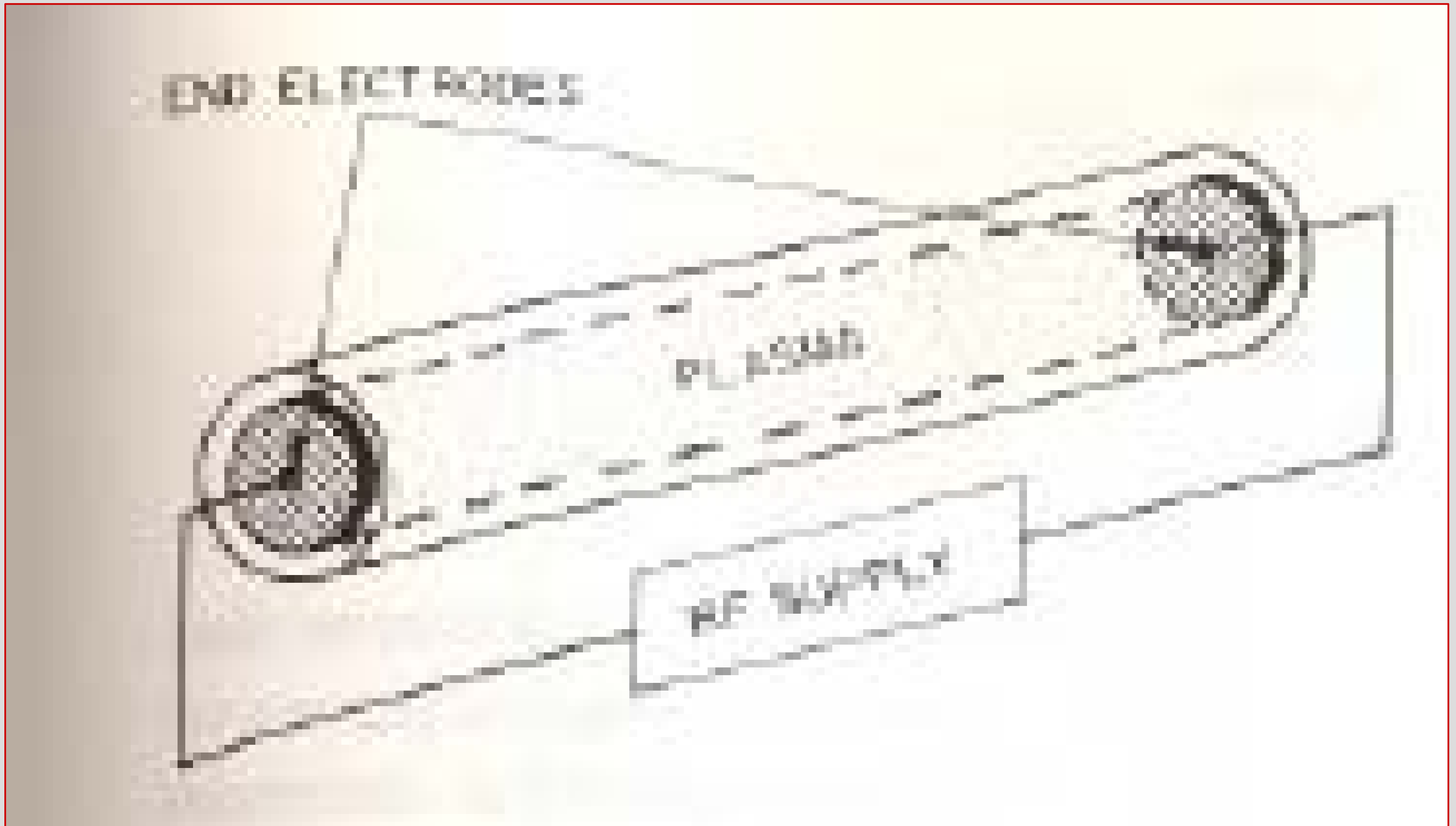
Sistema tipo *Reative Ion Etching* (RIE)



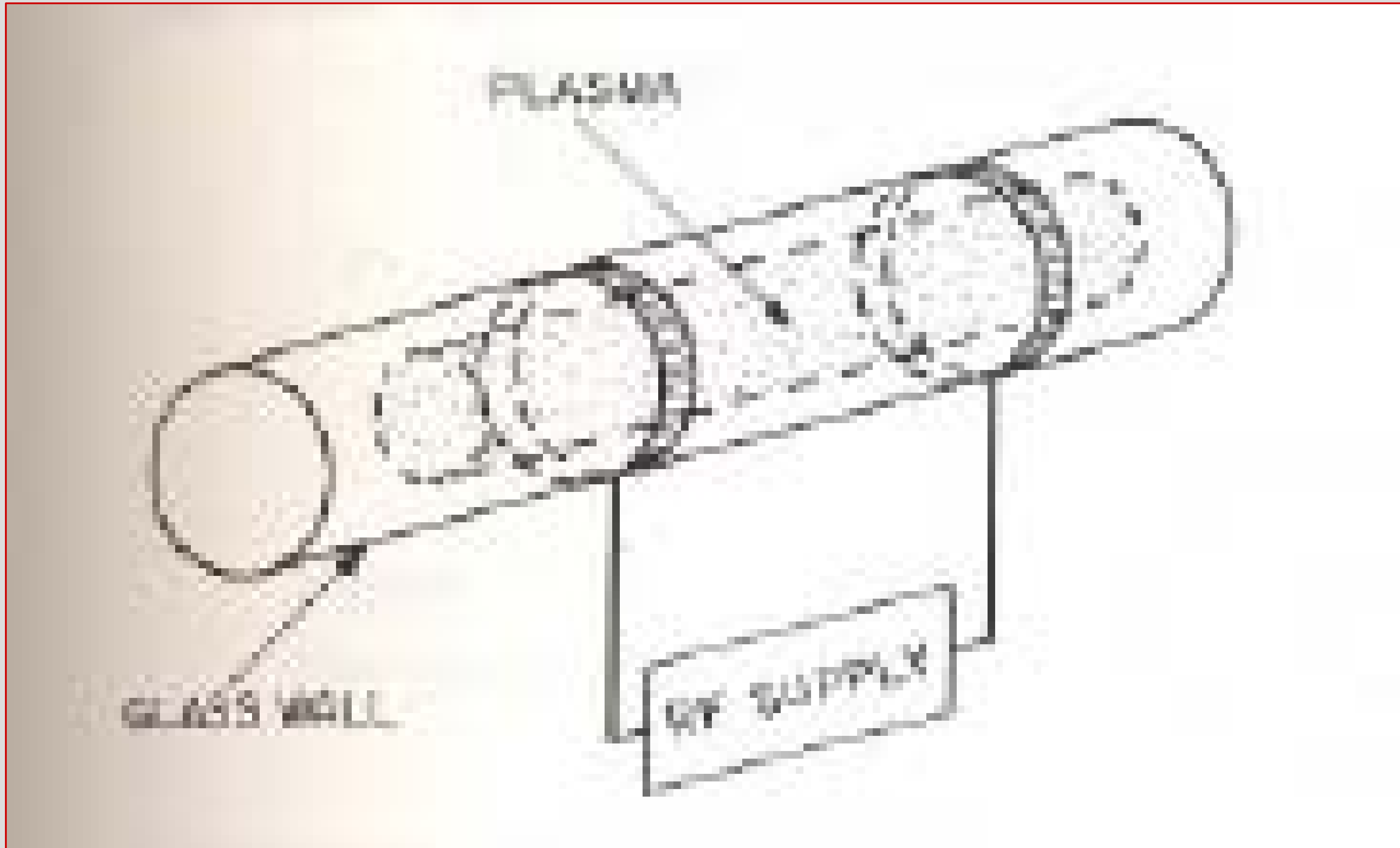
Sistema tipo (RIE) com multiplos eletrodos



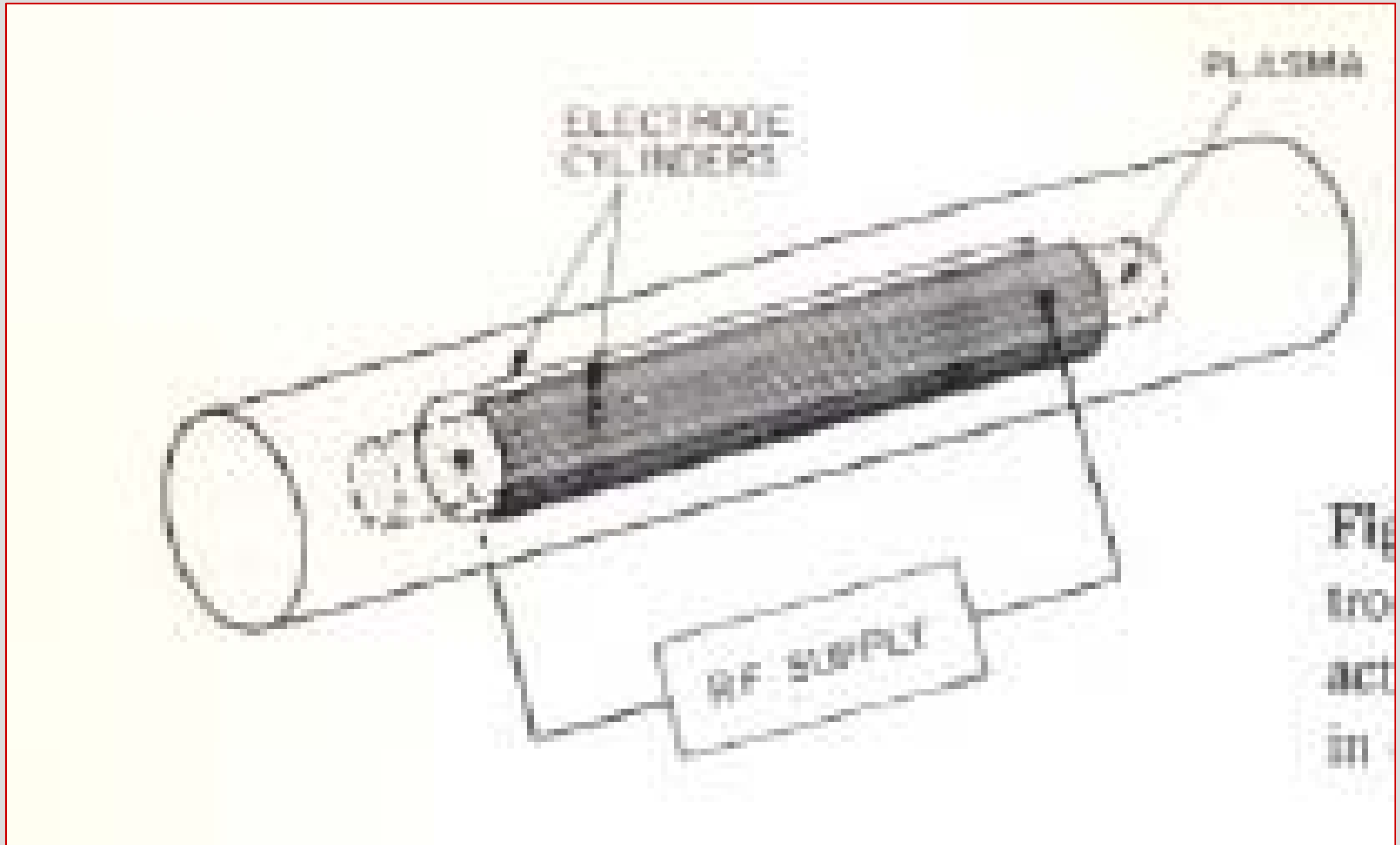
Reator cilíndrico com eletrodos internos



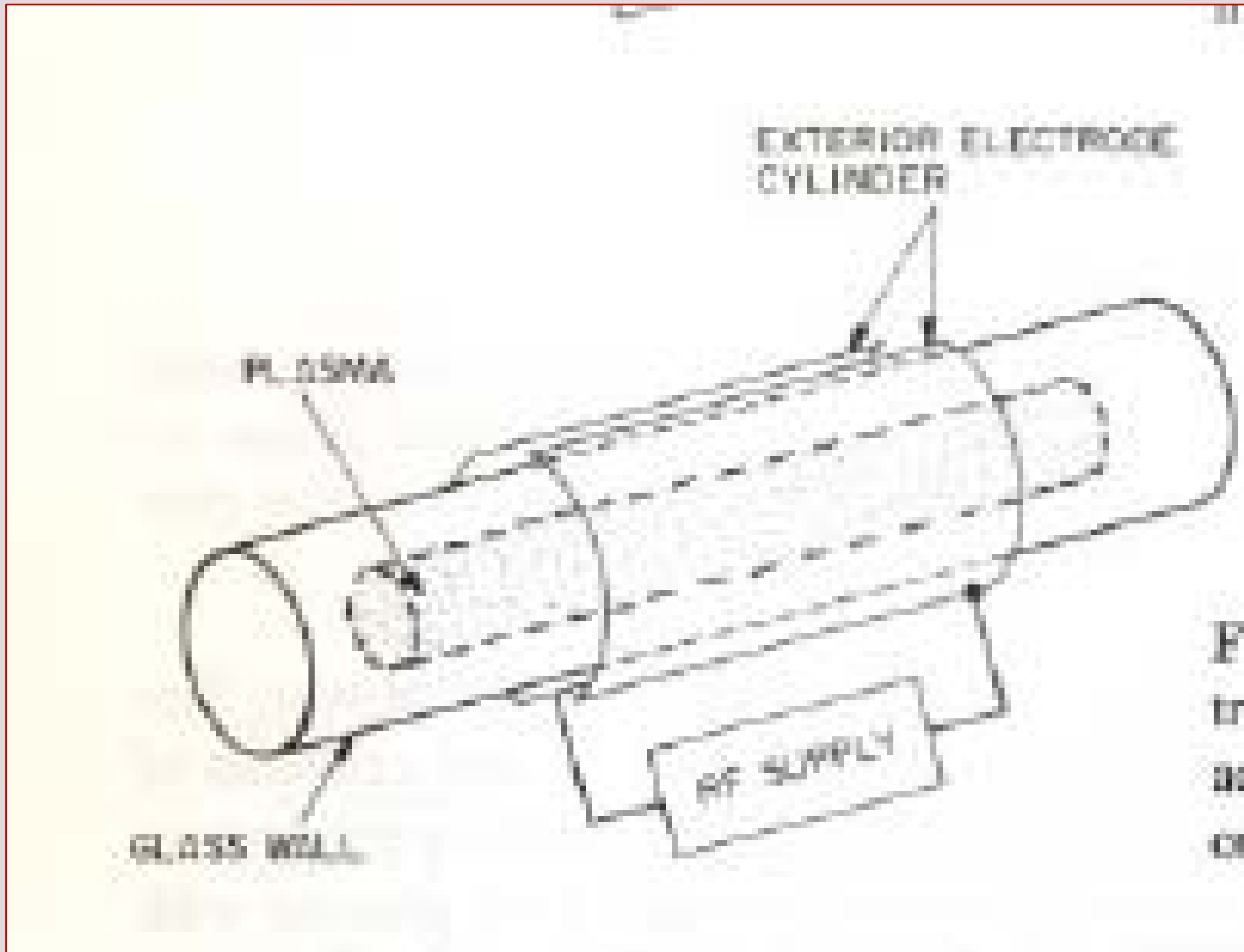
Reator cilíndrico com eletrodos externos



Reator com eletrodo longitudinal interno

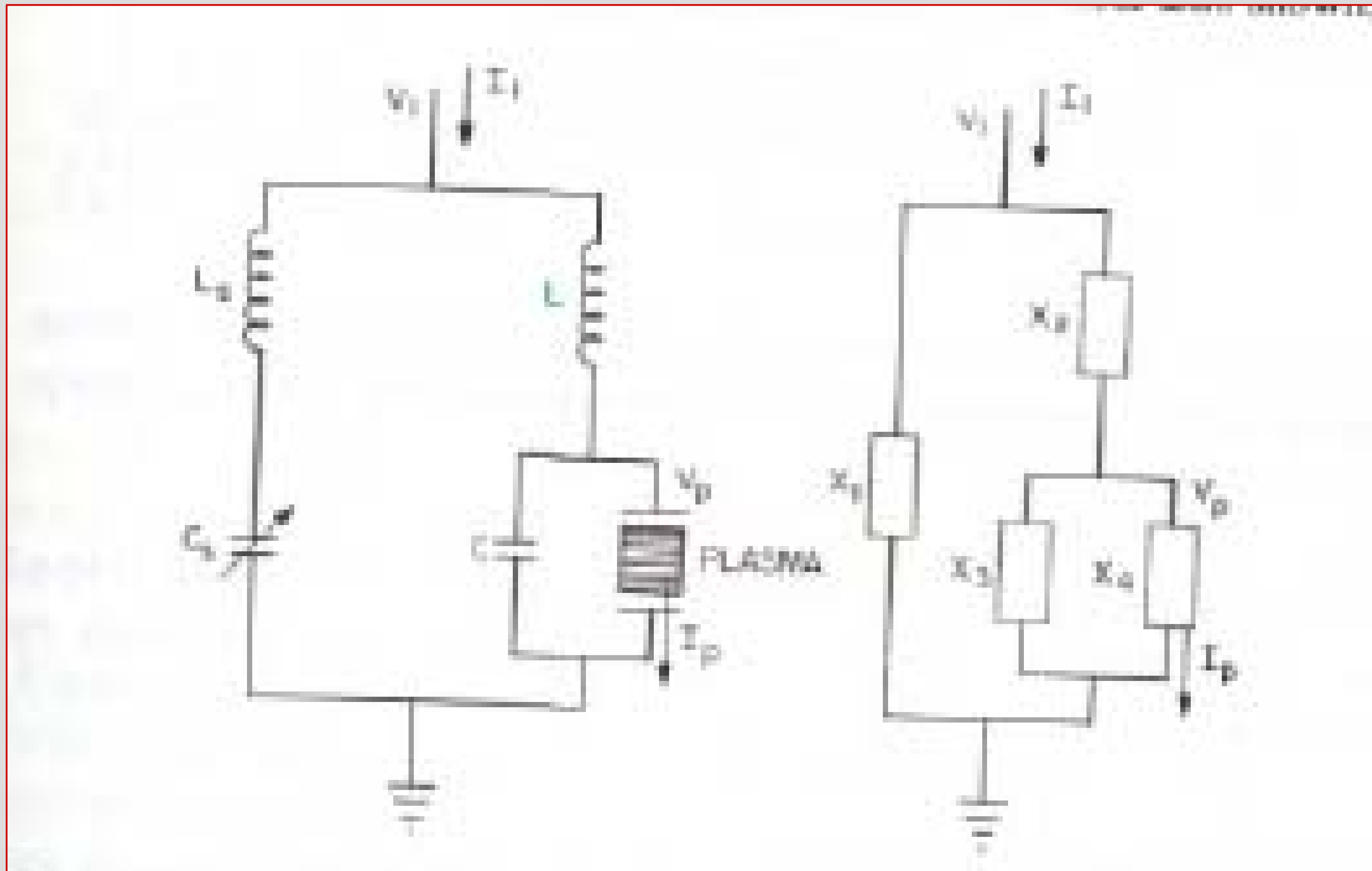


Reator com eletrodos longitudinais externo



Padronização de processos

Circuito equivalente de plasma

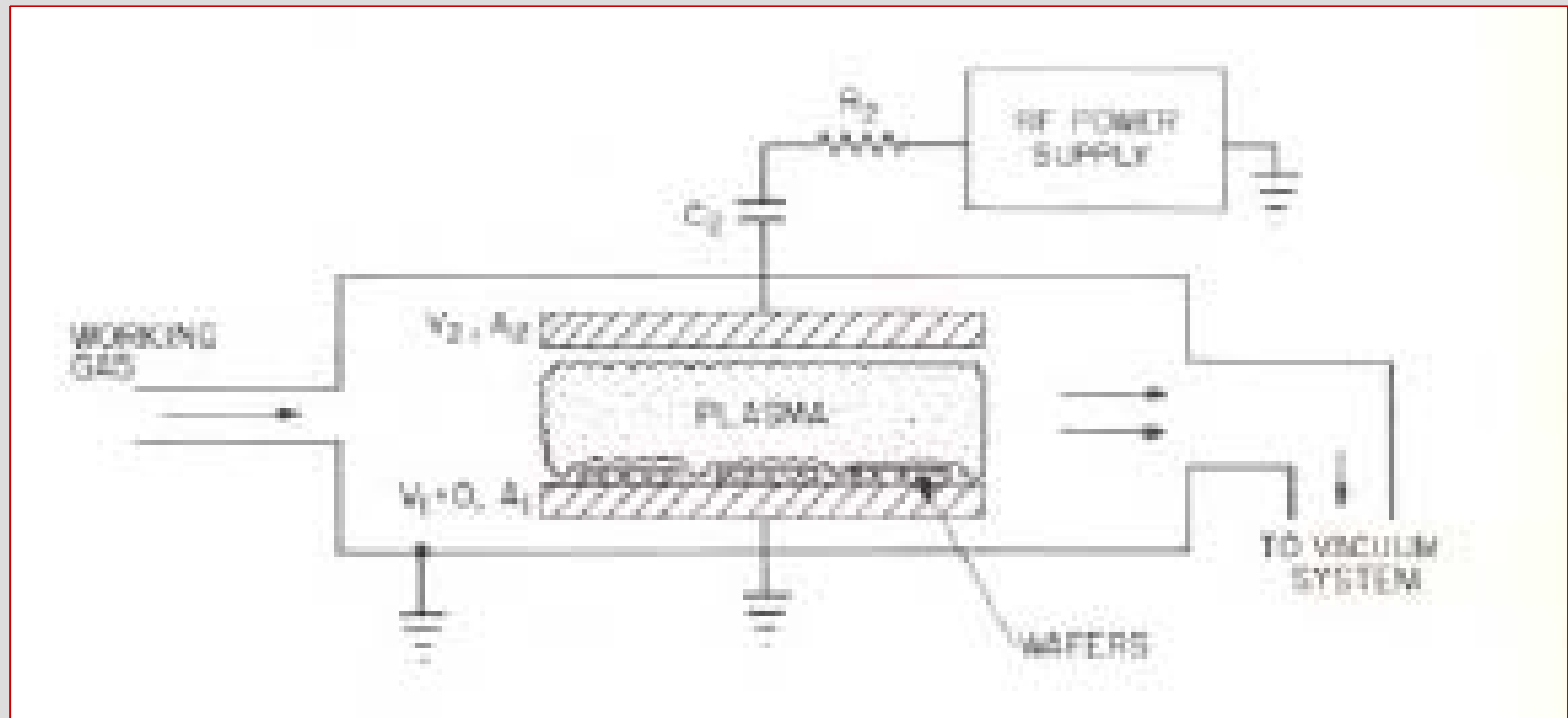


Faixa característica de referência para plasmas industriais

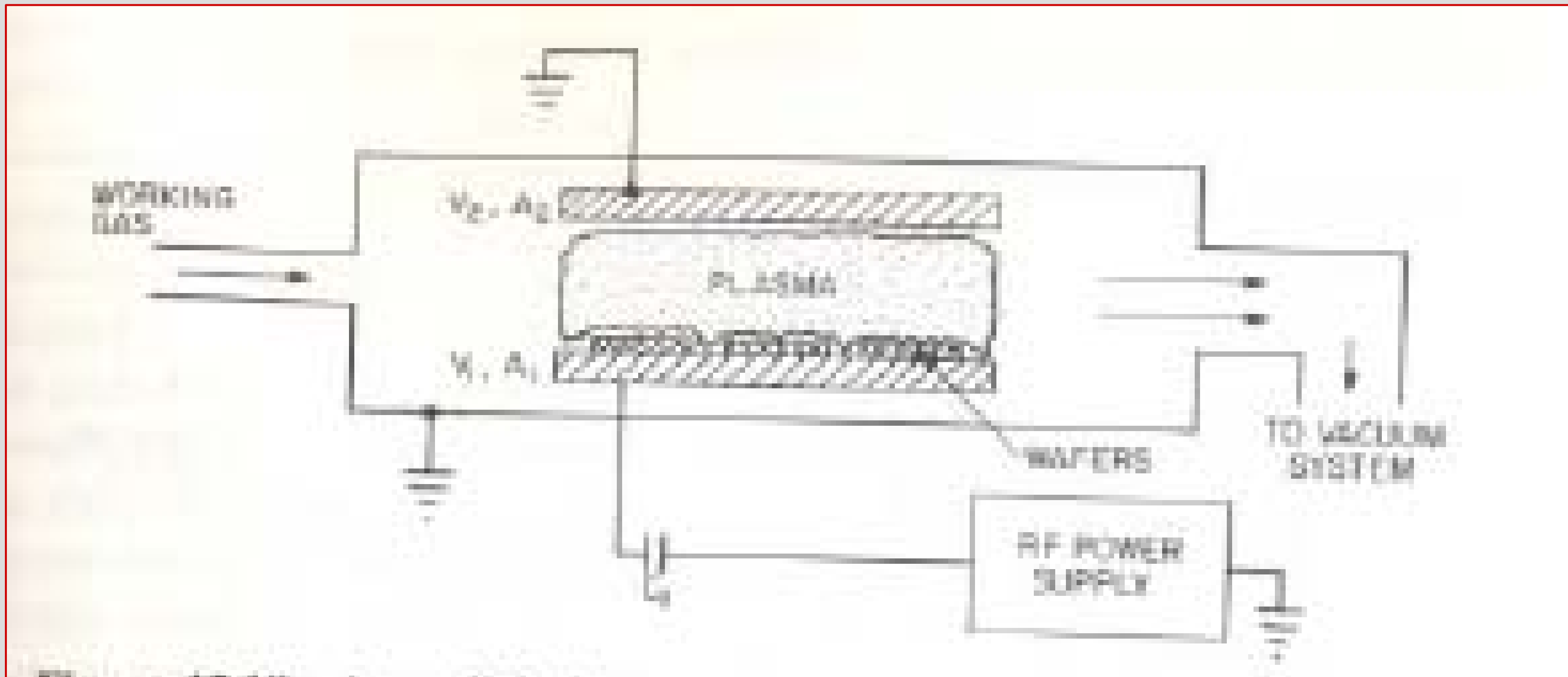
Characteristic	Low value	High value
Power	1 W	100 W
Bias voltage, DC	5 V	250 V
Electron density, n_e	10^{15} electrons/m^3	3×10^{17} electrons/m^3
Gas pressure, p_0	0.10 Torr	1 Torr

Reatores de multipla aplicação

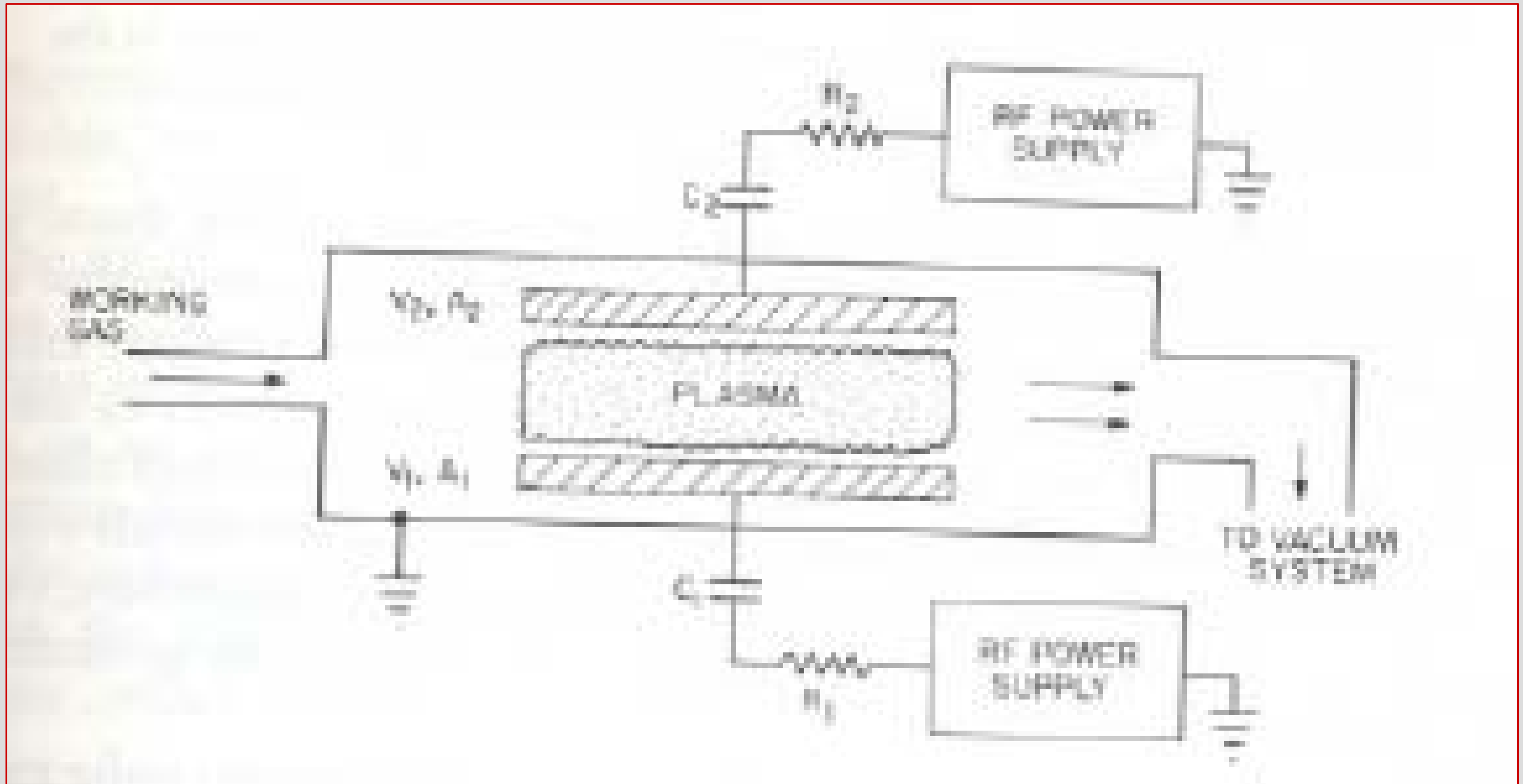
Reator do tipo *Plasma Etching* (PE)



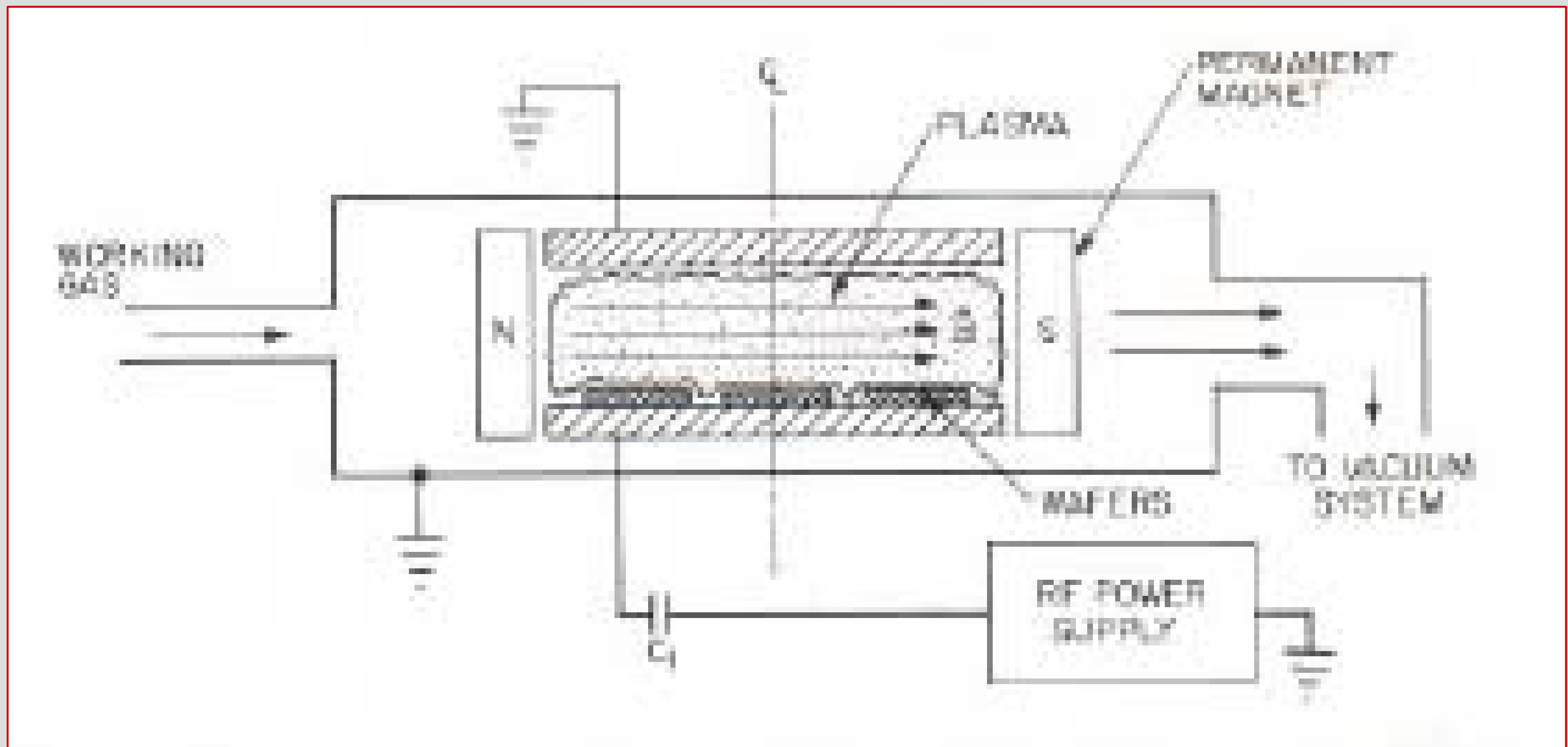
Reator do tipo RIE



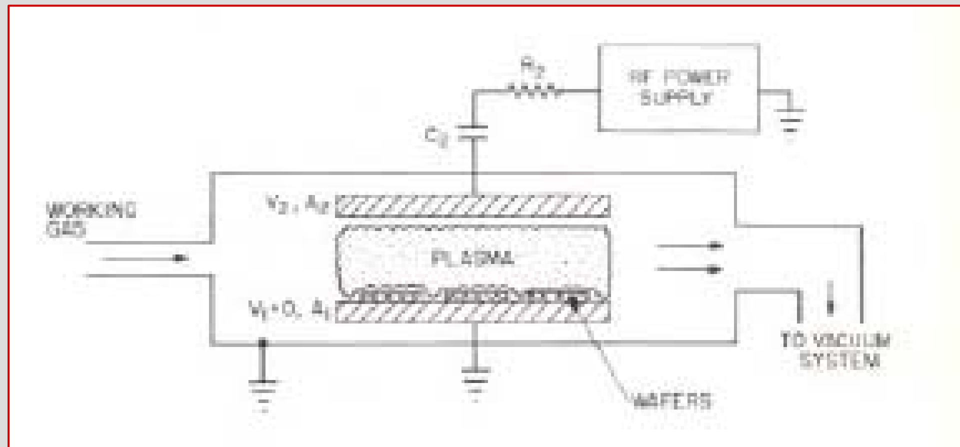
Reator do tipo Triodo

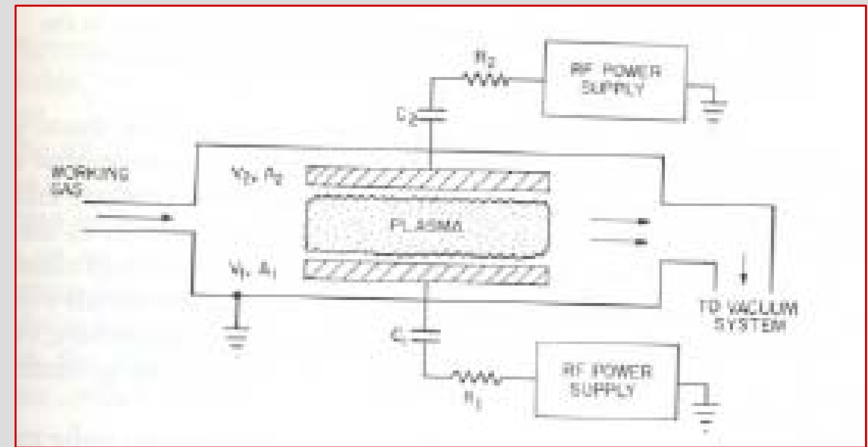


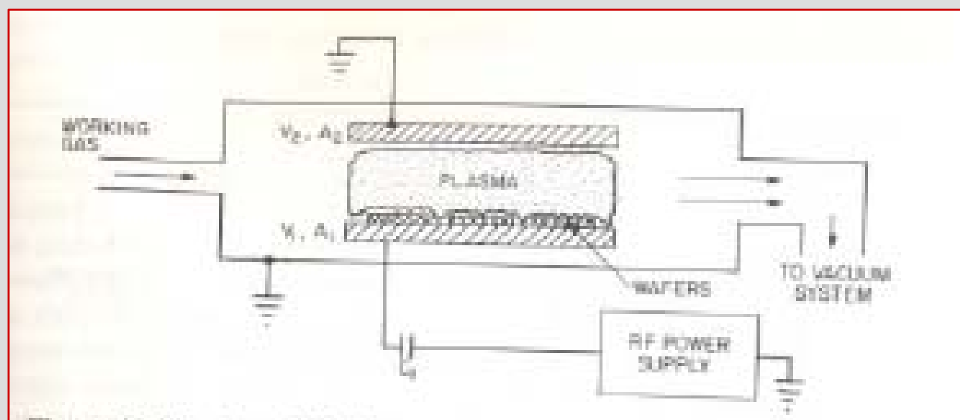
Reator do tipo Plasma enriquecido magneticamente

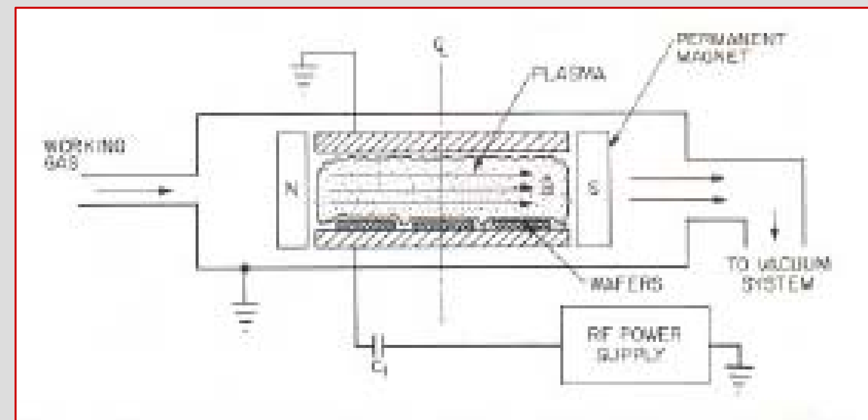


Comparação









Parâmetros característicos de plasmas RF capacitivos

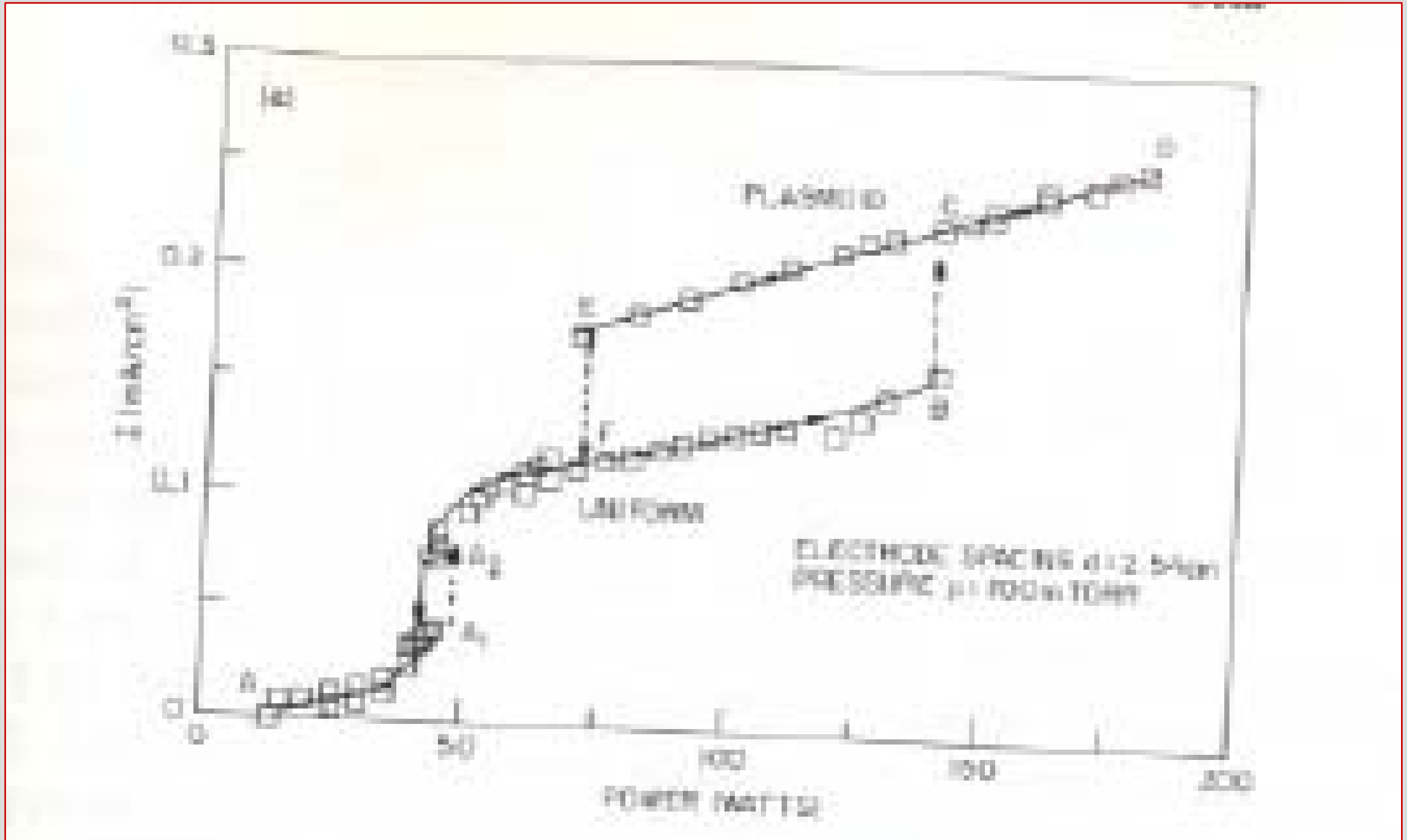
Parameter	Low value	Typical value	High value
Frequency	1 kHz	13.56 MHz	100 MHz
Gas pressure	3 mTorr	300 mTorr	5 Torr
Power level	50 W	≈ 200 W	500 W
rms electrode voltage	100 V	≈ 300 V	1000 V
Current density	0.1 mA/cm^2	≈ 3 mA/cm^2	10 mA/cm^2
Electron temperature, T_e	3 eV	≈ 5 eV	8 eV
Electron density, n_e	10^{15}/m^3	≈ 5 × 10^{15}/m^3	3 × 10^{17}/m^3
Ion energy, $\mathcal{E}_i$	5 eV	50 eV	500 eV
Electrode separation, d	0.5 cm	4 cm	30 cm

Transições em plasmas

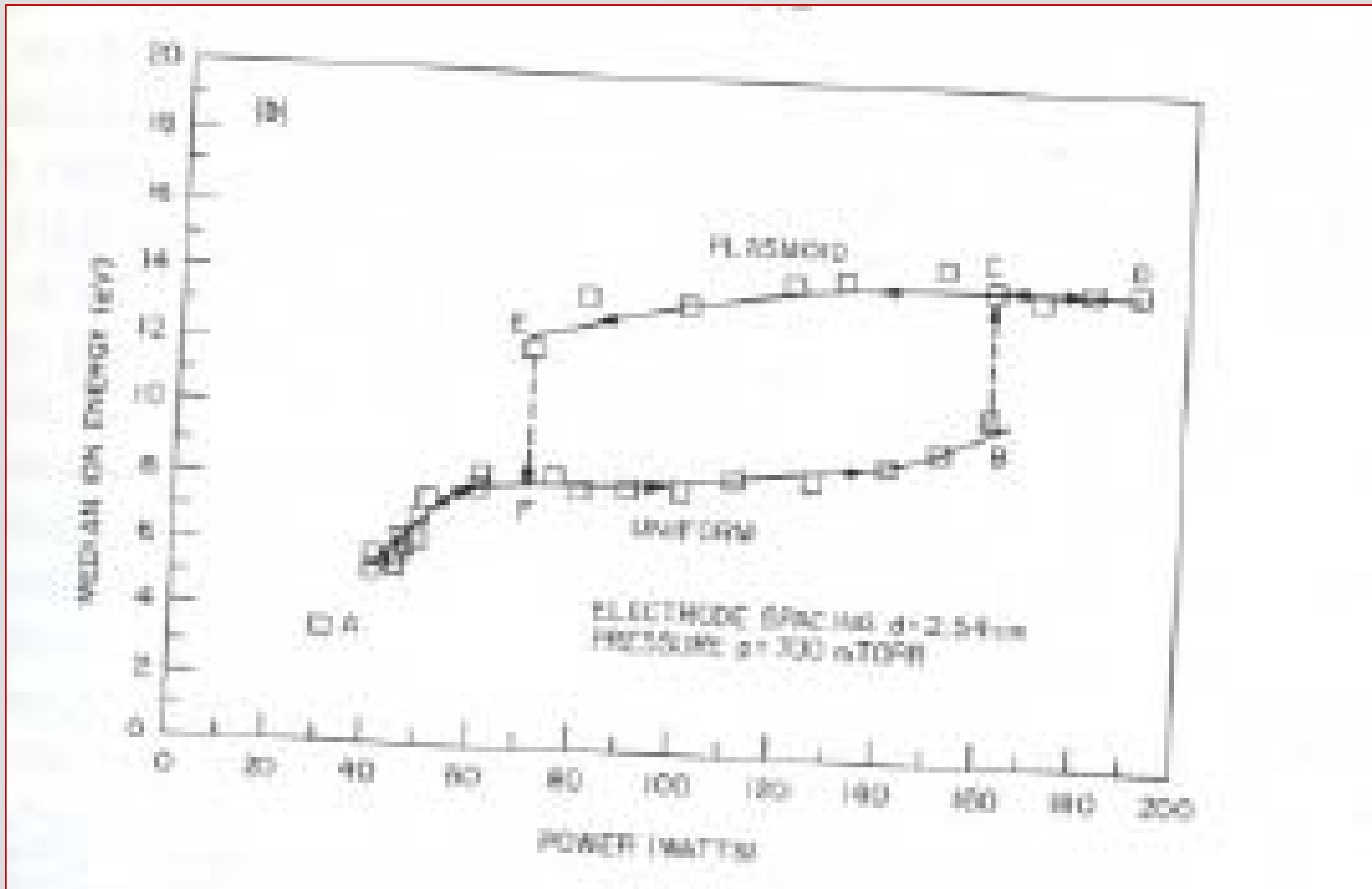
Transições em plasmas

- As transições de regimes em plasmas RF, não são completamente entendidas, e não se sabe que mecânismos são responsáveis por estas características, que são a mudança de acoplamento do modo E para o modo H abruptamente.

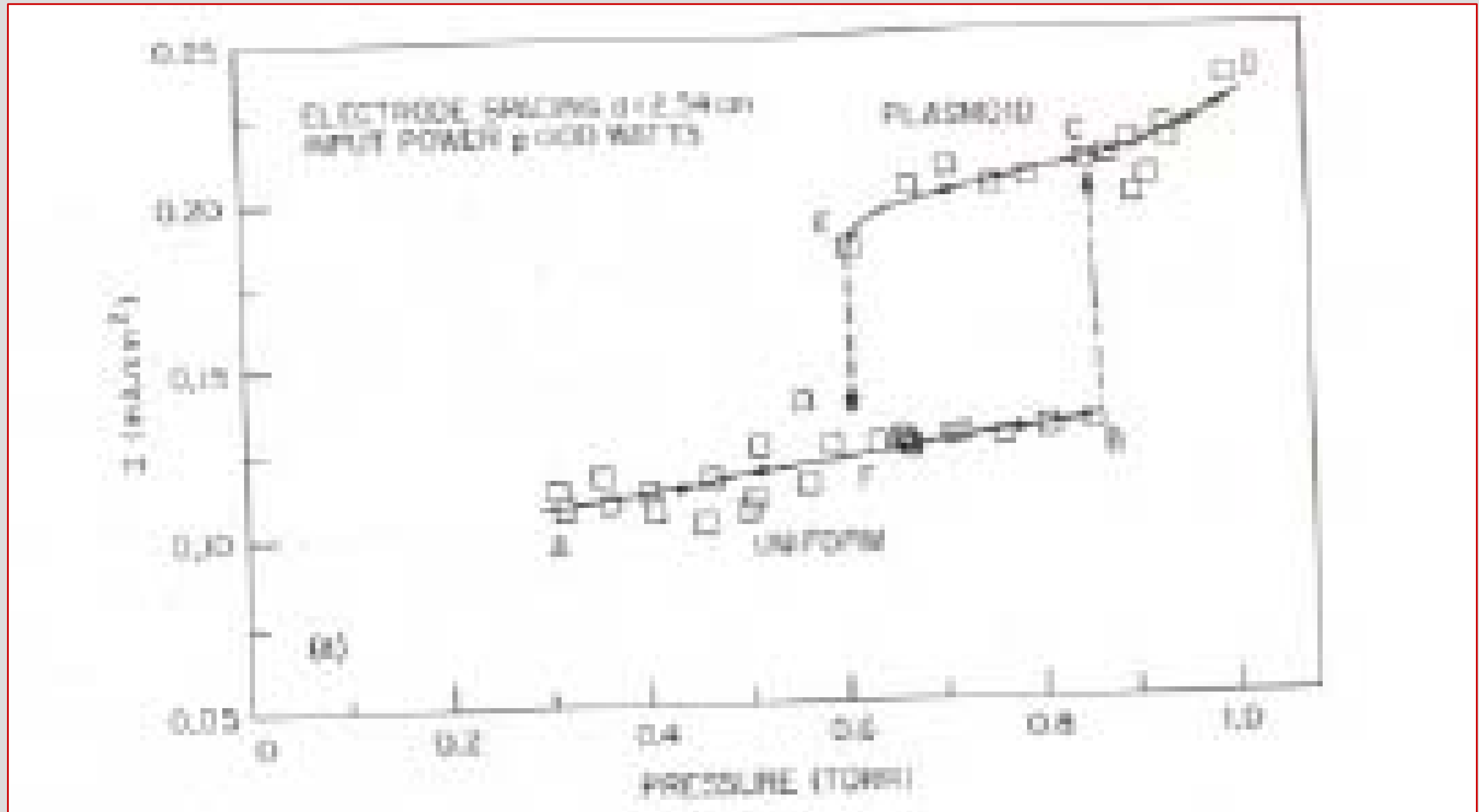
Transições em plasmas



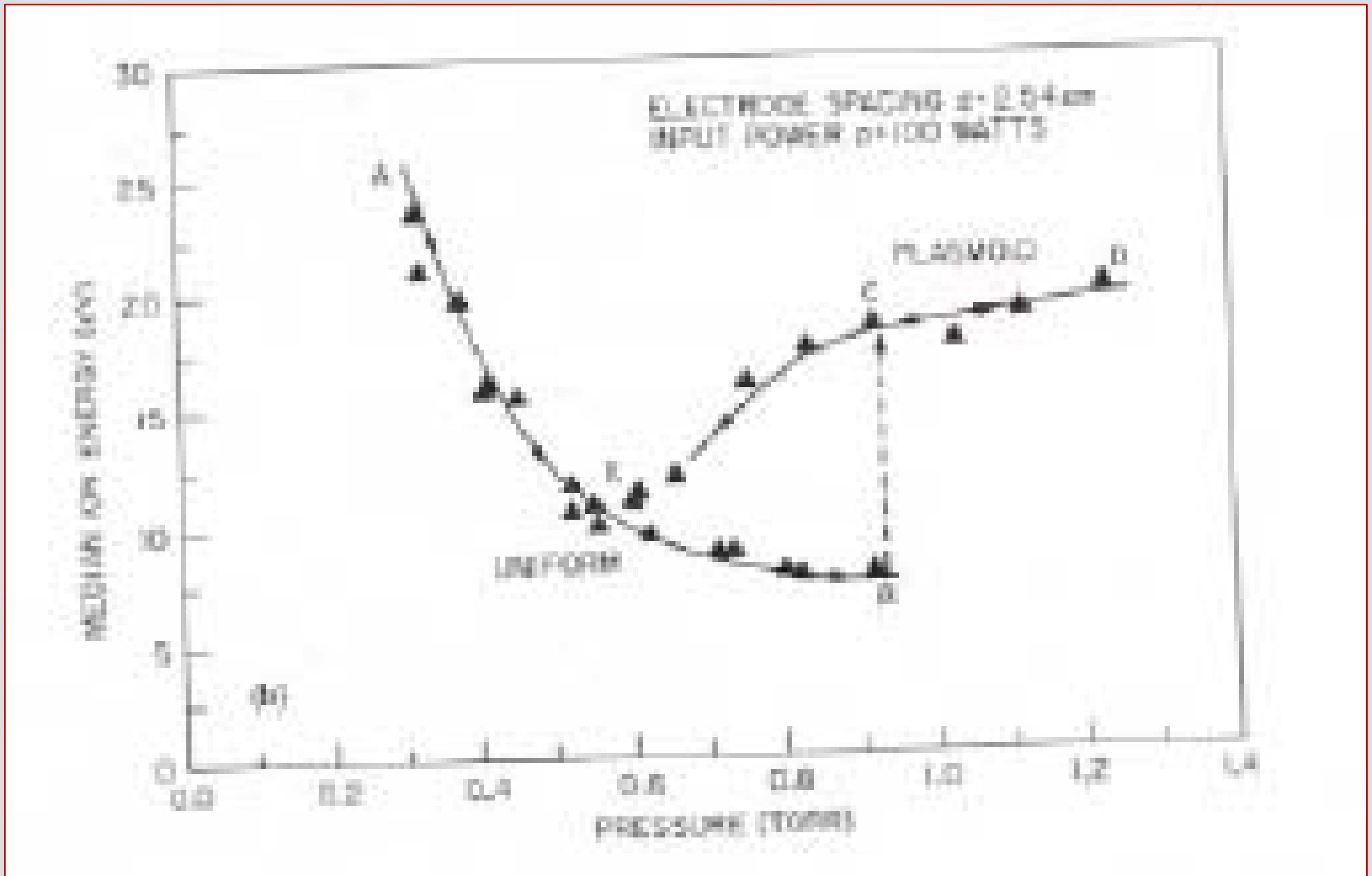
Transições em plasmas



Transições em plasmas



Transições em plasmas

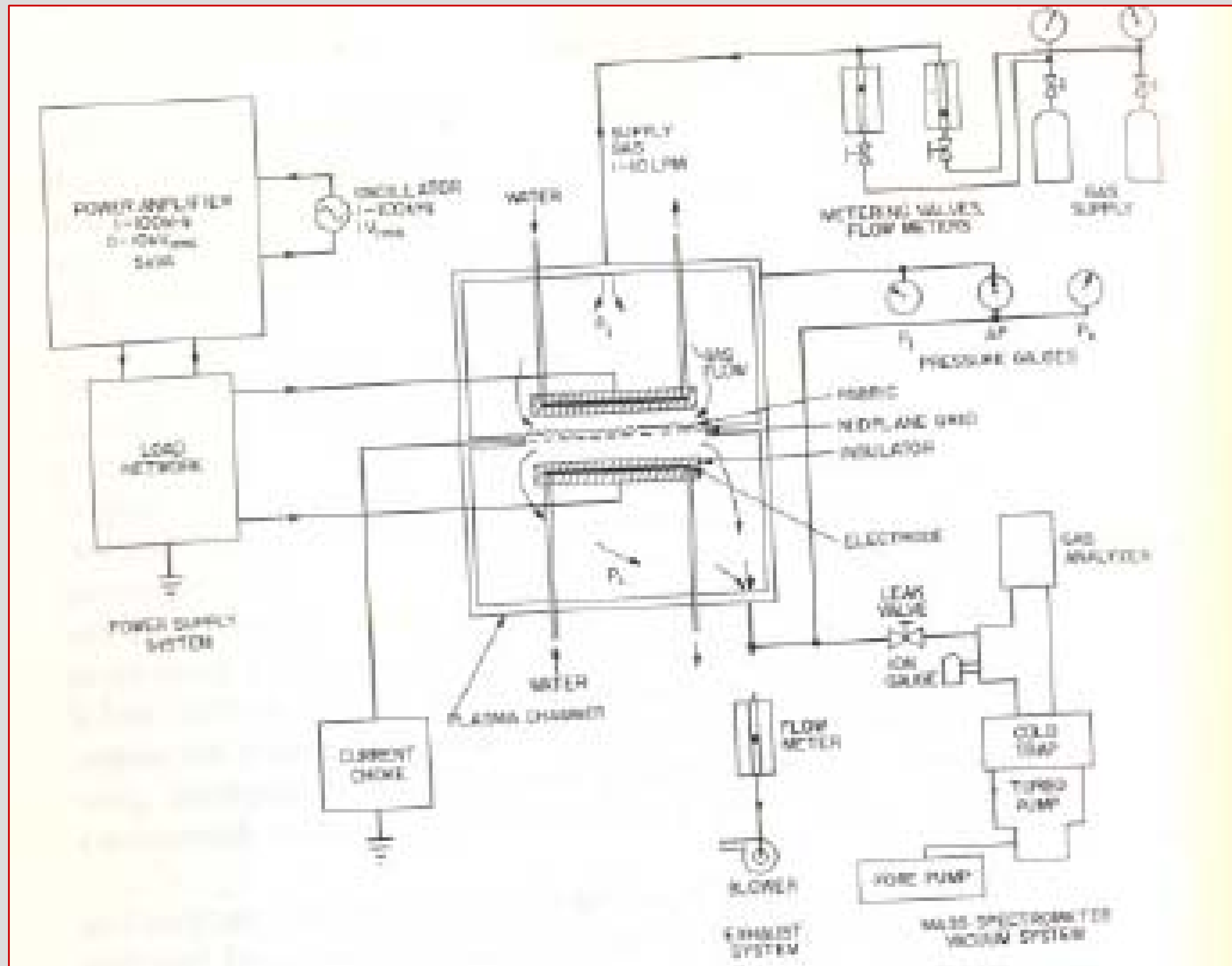


Plasmas capacitivos a pressão atmosférica

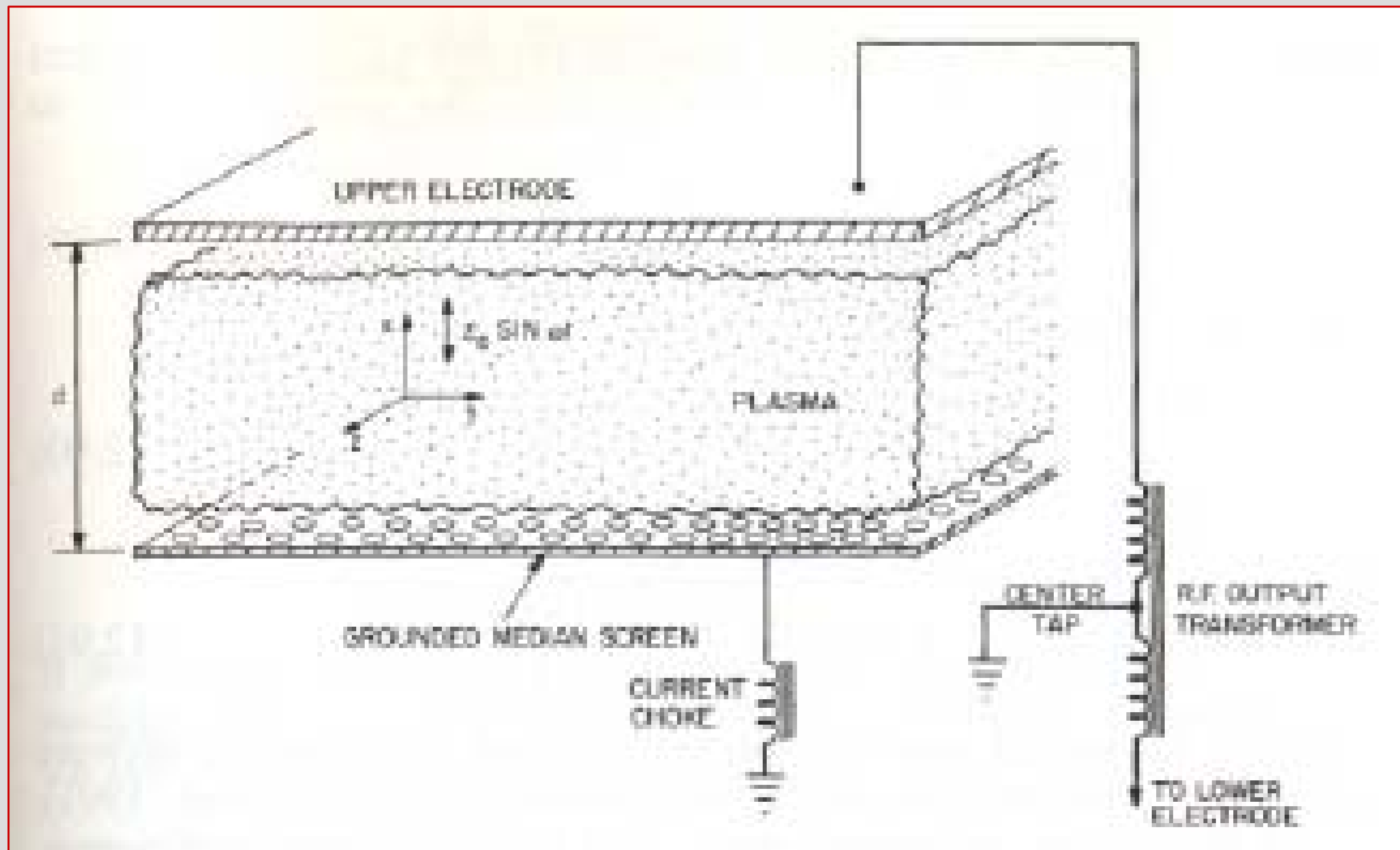
Plasmas a pressão atmosféricas

- Descobertos e descritos em 1991, utilizam frequências de alguns kilohertz e produzem descargas luminosas a pressão atmosférica , sem o uso de sistemas de vácuo.
- O campo elétrico aplicado deve ser superior a tensão de ruptura dielétrica dos gases utilizados.
- Seu maior emprego é em ativação de superfícies.

Descargas a pressão atmosférica



Reator a pressão atmosférica

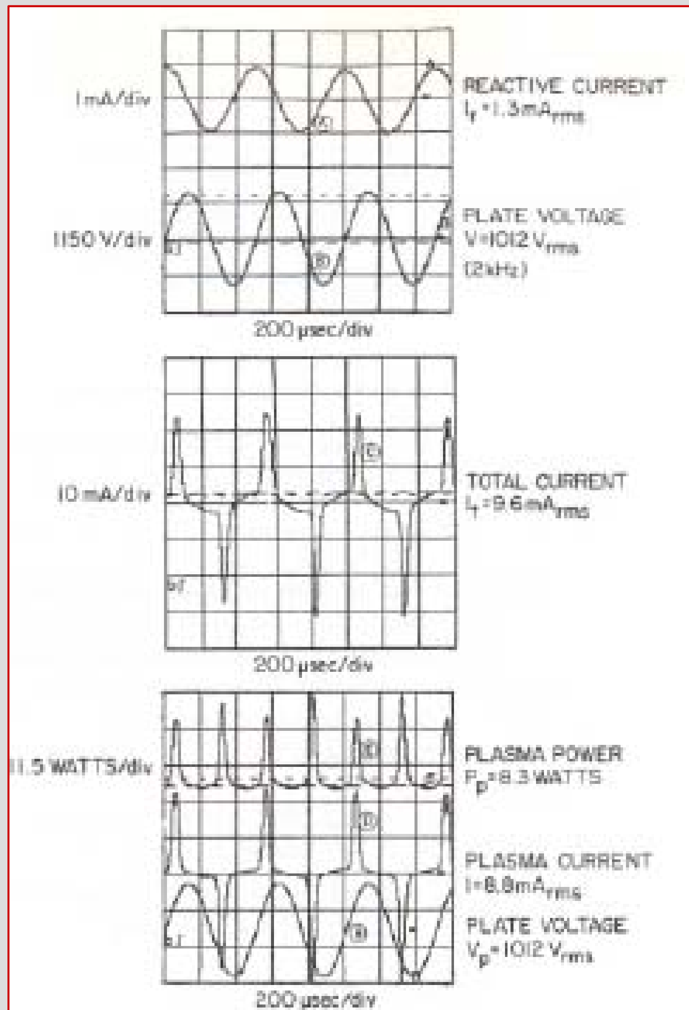


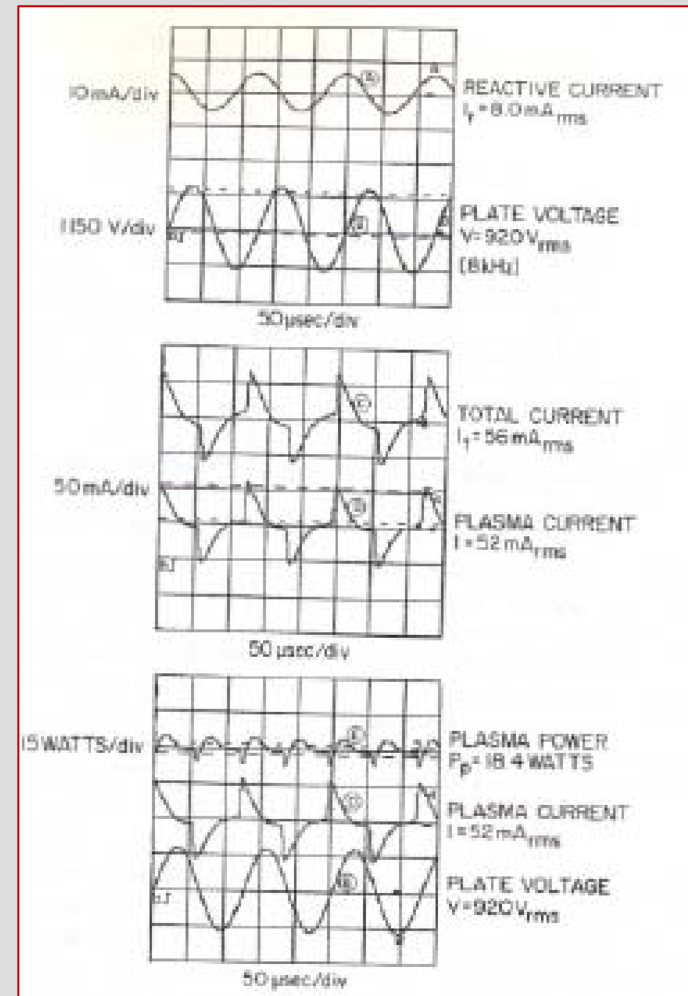
Características da descarga a pressão atmosférica

Table 12.3 Characteristic parameter ranges for uniform glow discharge operation of the UTK 1 atm plasma reactor, for various working gases: He; He+1.7%O_2; Ar; Ar+He; Ar+1.7%O_2; air.

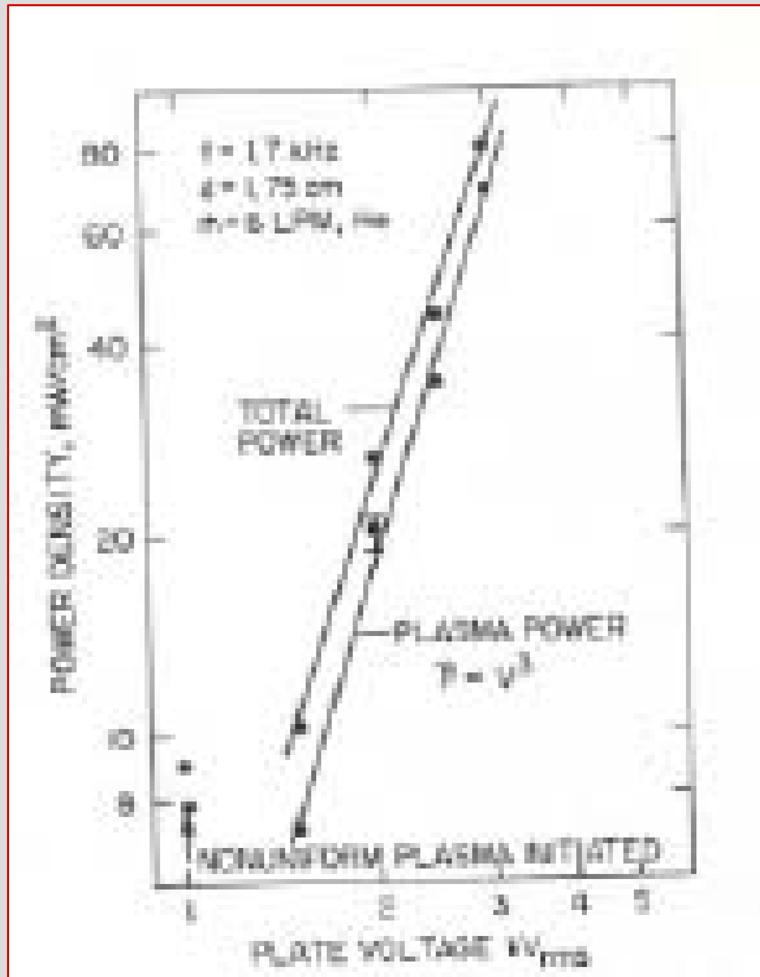
Frequency	1–20 kHz
Voltage	1.5–9.5 kV_{rms} plate to plate
Electrode gap, *d*	0.8–2.5 cm
Pressure	760 +15, −5 Torr
rms power	10–150 W
Power density	4–120 mW/cm^2
Plasma volume	0.7–2.4 liters

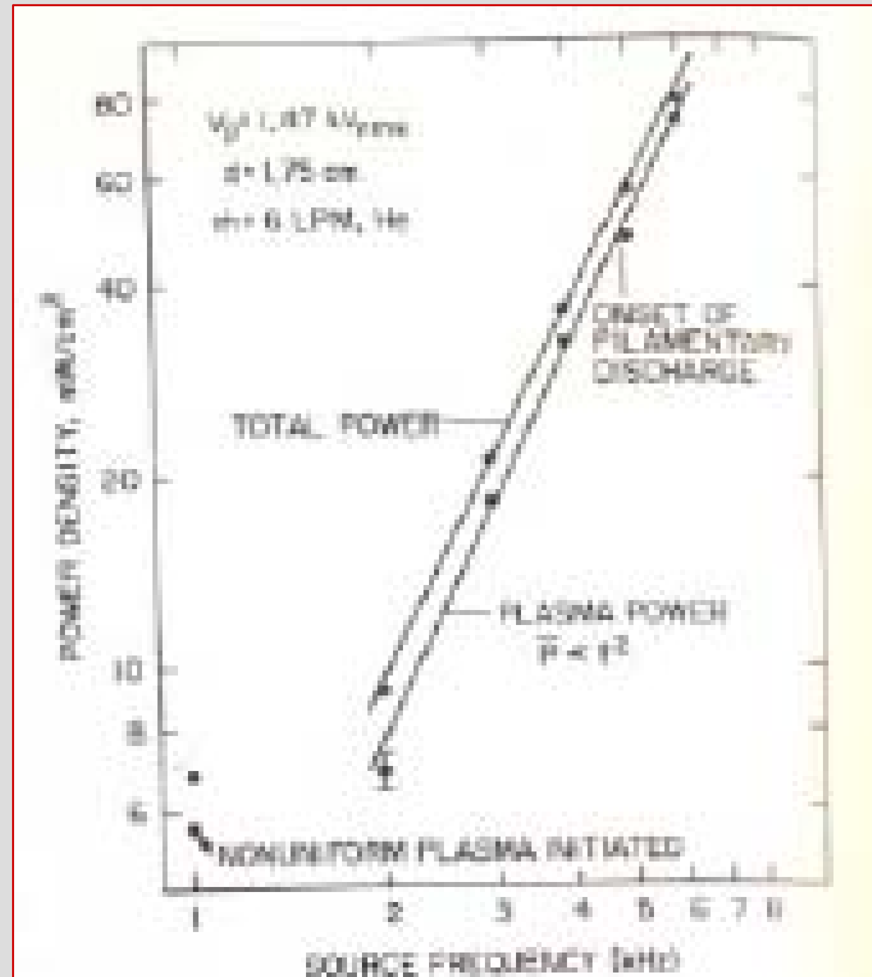
Descargas a pressão atmosférica a 2 kHz e a 8 kHz





Densidade de potência em plasmas a pressão atmosférica



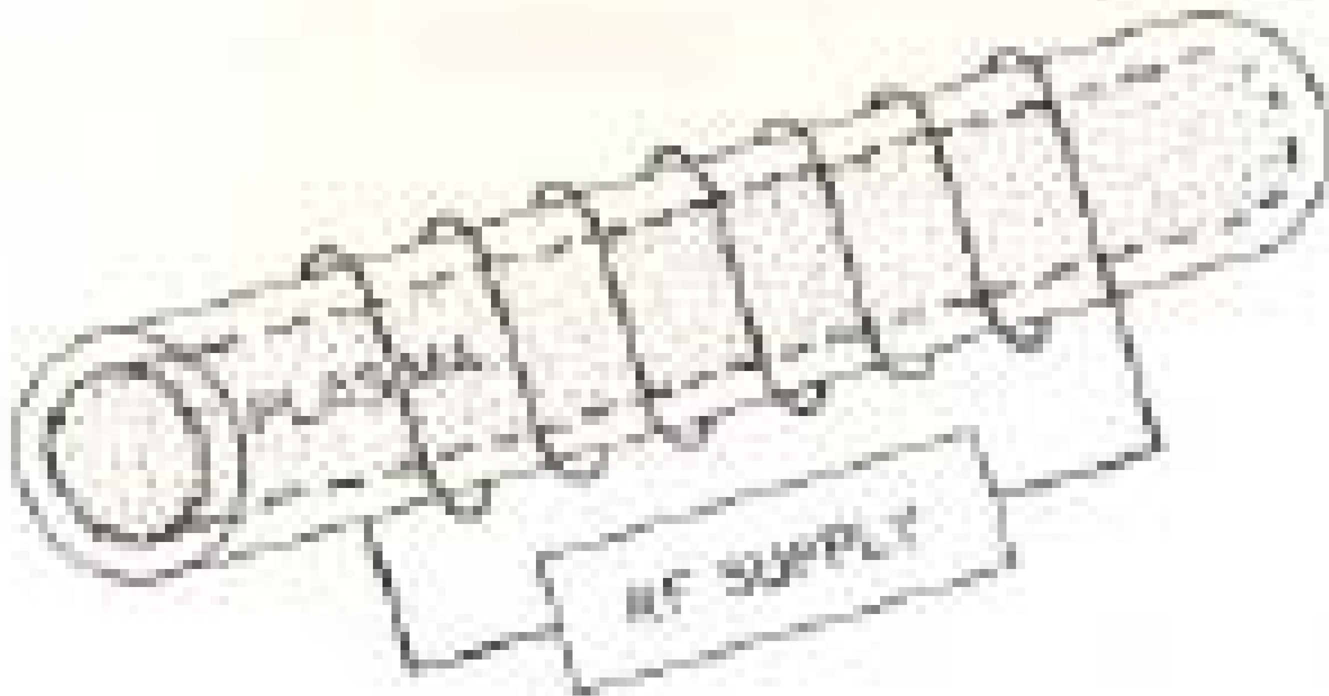


Plasmas Indutivos

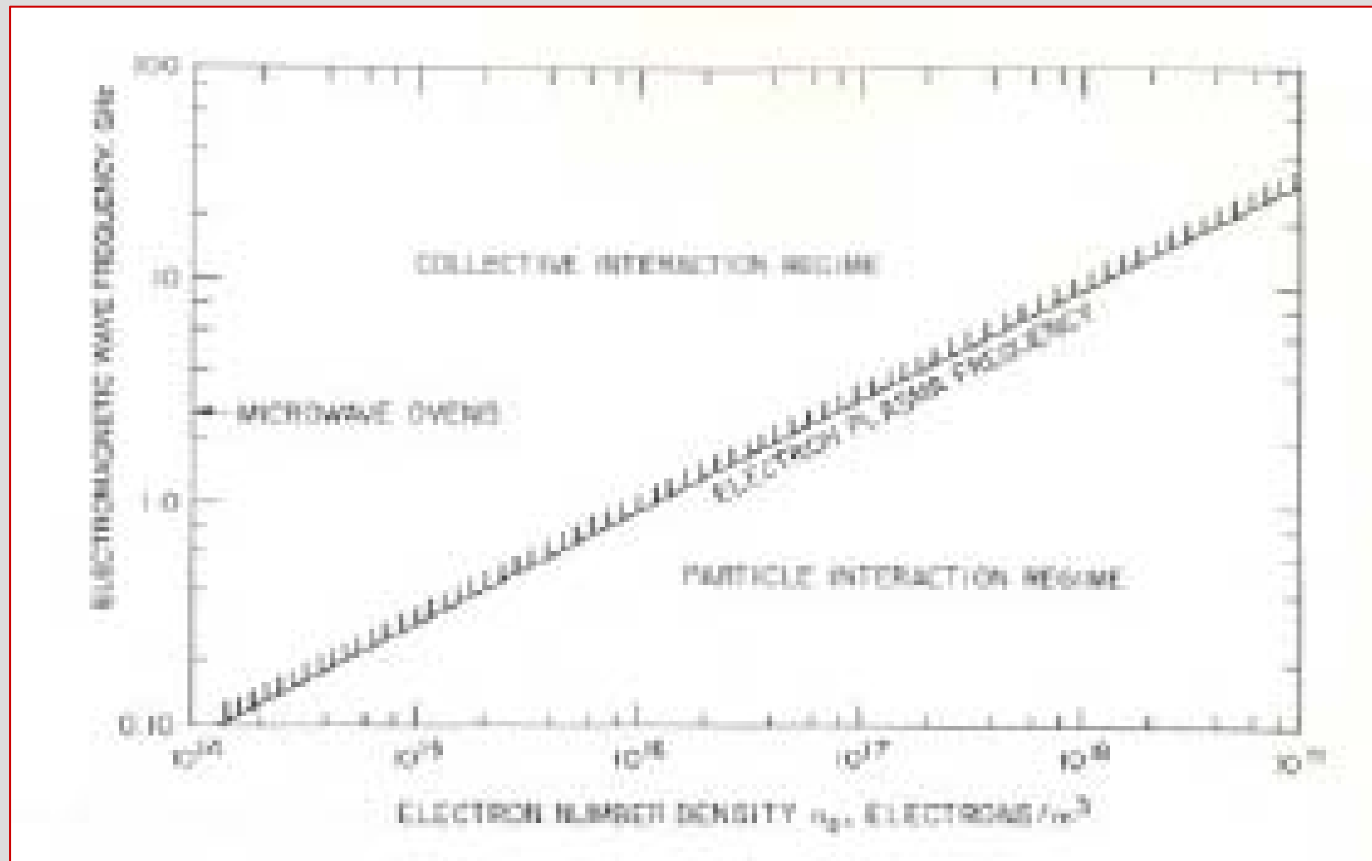
Plasmas Indutivos

- Plasmas indutivos foram os primeiros plasma RF criados e consistem principalmente de um indutor em torno de um dielétrico promovendo plasmas de alta densidade com baixa potência aplicada.

Reator acoplado indutivamente



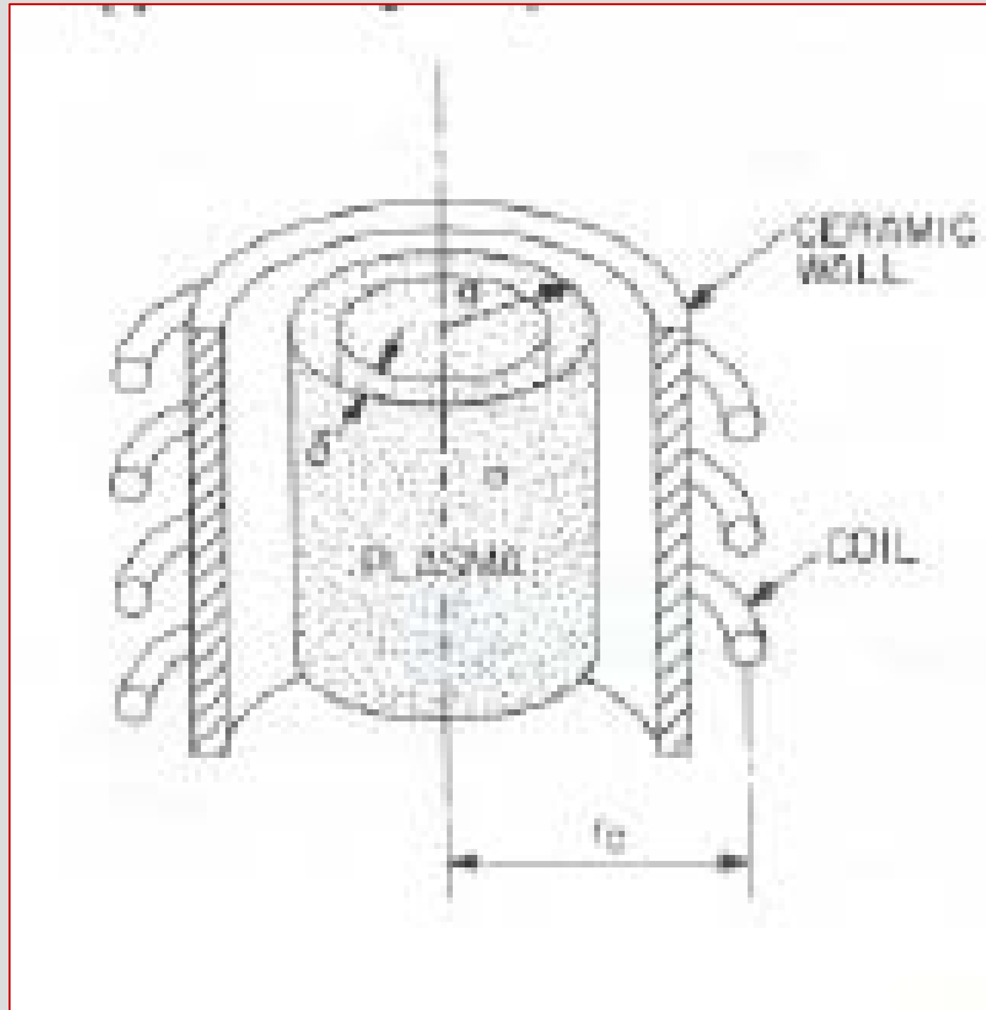
Densidade em função da frequência para plasmas indutivos



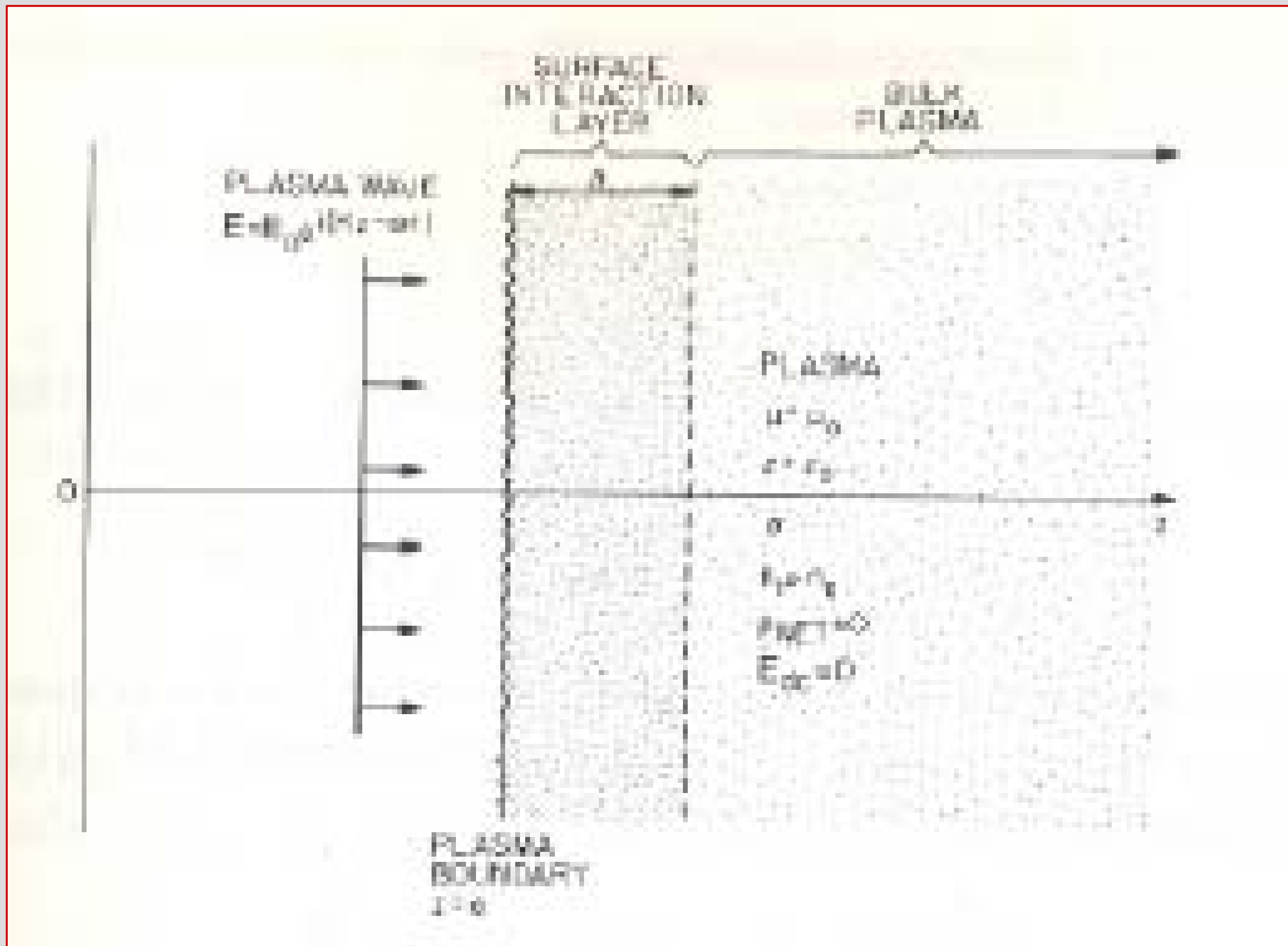
Características de reatores de plasma e alguns materiais

Material	Electrical conductivity σ (S/m)	Energy transfer frequency ν_κ (Hz)
DT fusion plasma, with $T_e = 10$ keV, $Z = 1.5$	$1\text{–}2 \times 10^{8}$	$2.26\text{–}4.52 \times 10^{20}$
Room temperature copper	$10^{7}\text{–}2 \times 10^{8}$	$2.26\text{–}45.2 \times 10^{18}$
Room temperature carbon	$3 \times 10^{4}\text{–}10^{5}$	$6.8\text{–}22.6 \times 10^{15}$
Room temperature iron	$3 \times 10^{4}\text{–}10^{5}$	$6.8\text{–}22.6 \times 10^{15}$
Argon plasma torch	$200\text{–}10^{4}$	$4.5 \times 10^{13}\text{–}2.3 \times 10^{15}$
Nitrogen plasma torch	400–2000	$9 \times 10^{13}\text{–}4.5 \times 10^{14}$
Hydrogen plasma torch	100–400	$2.3 \times 10^{13}\text{–}9 \times 10^{13}$
MHD generator plasma	10–100	$2.3\text{–}23 \times 10^{12}$
Saturated salt water	20	4.5×10^{12}
Bakelite	10^{-10}	23
Hard rubber	10^{-16}	2.3×10^{-5}

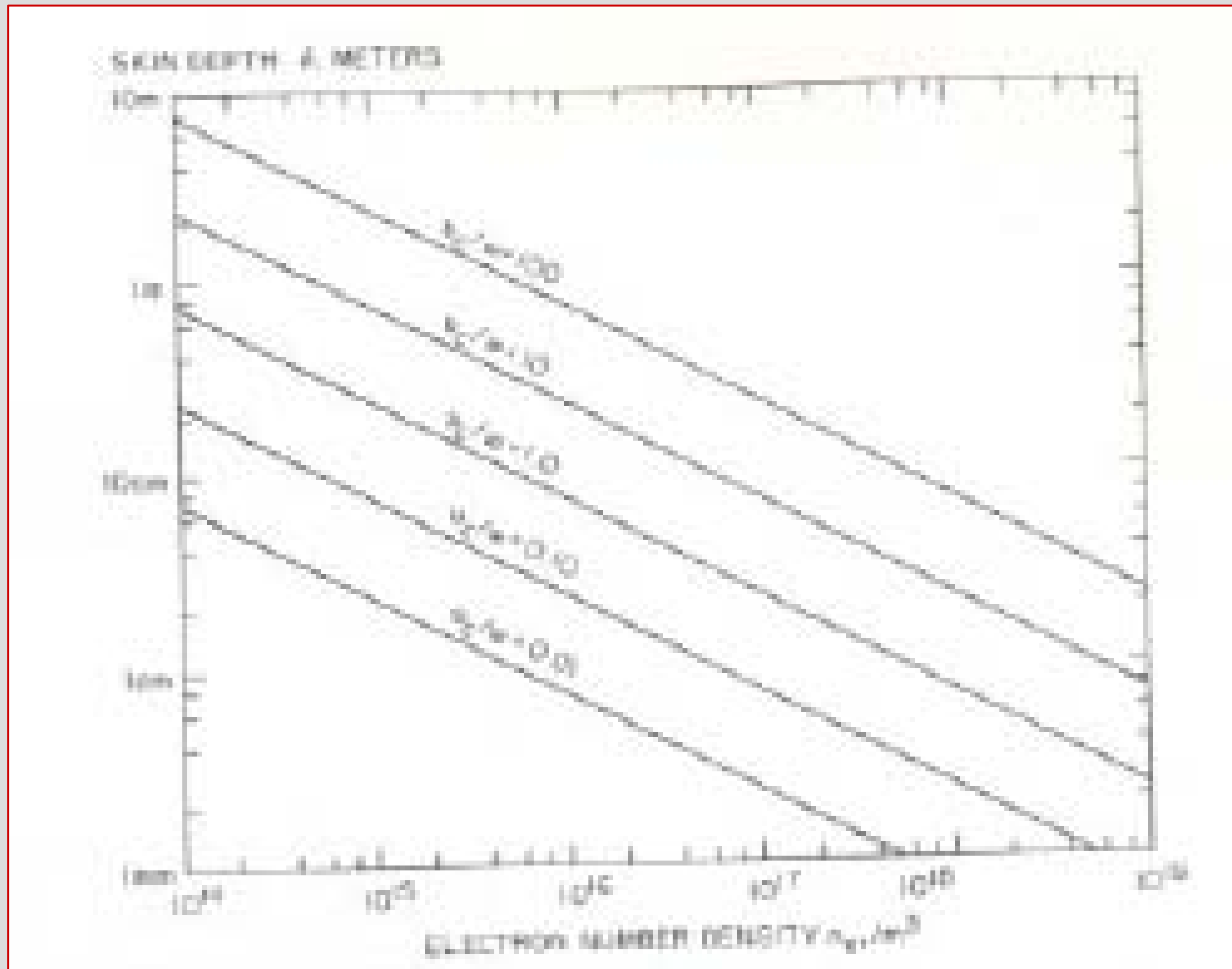
Características dos plasma indutivos



Bainhas em plasma indutivos

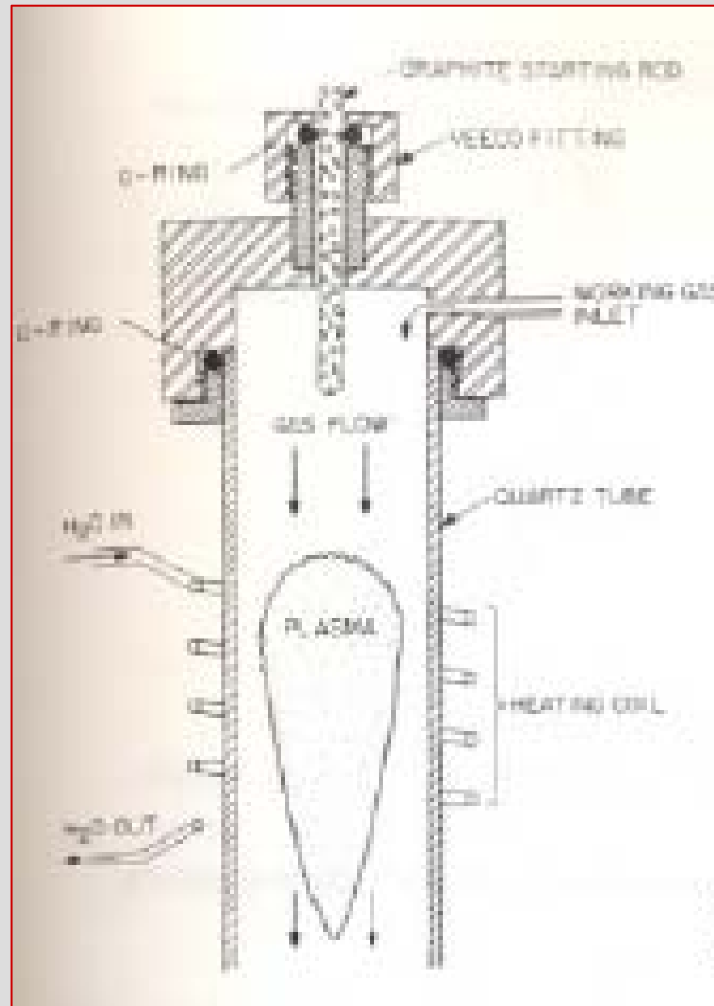


Bainhas em função da densidade de elétrons



Tochas de plasma

Tocha de plasma



Comparação entre tocha indutiva e tocha a arco

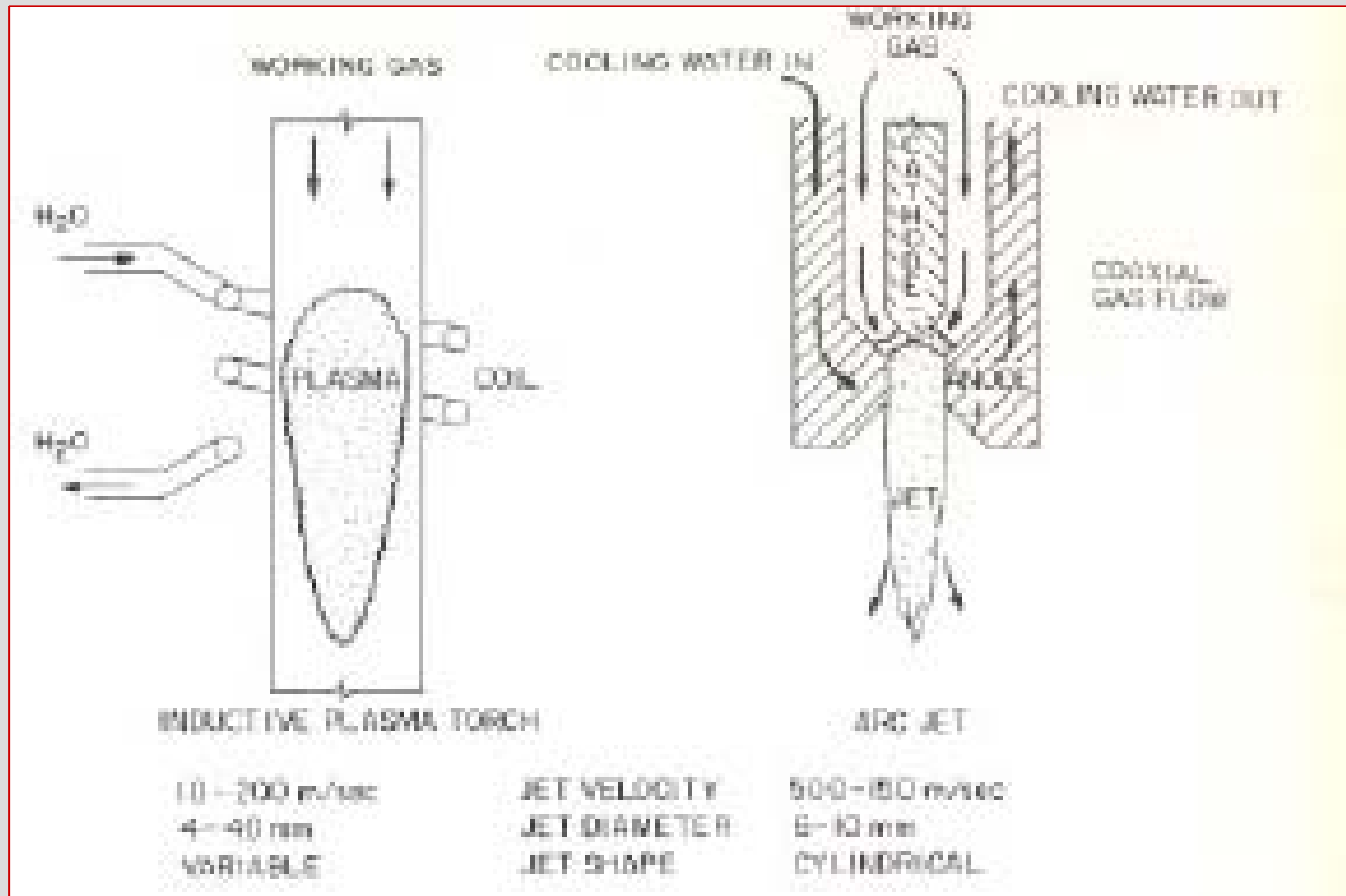
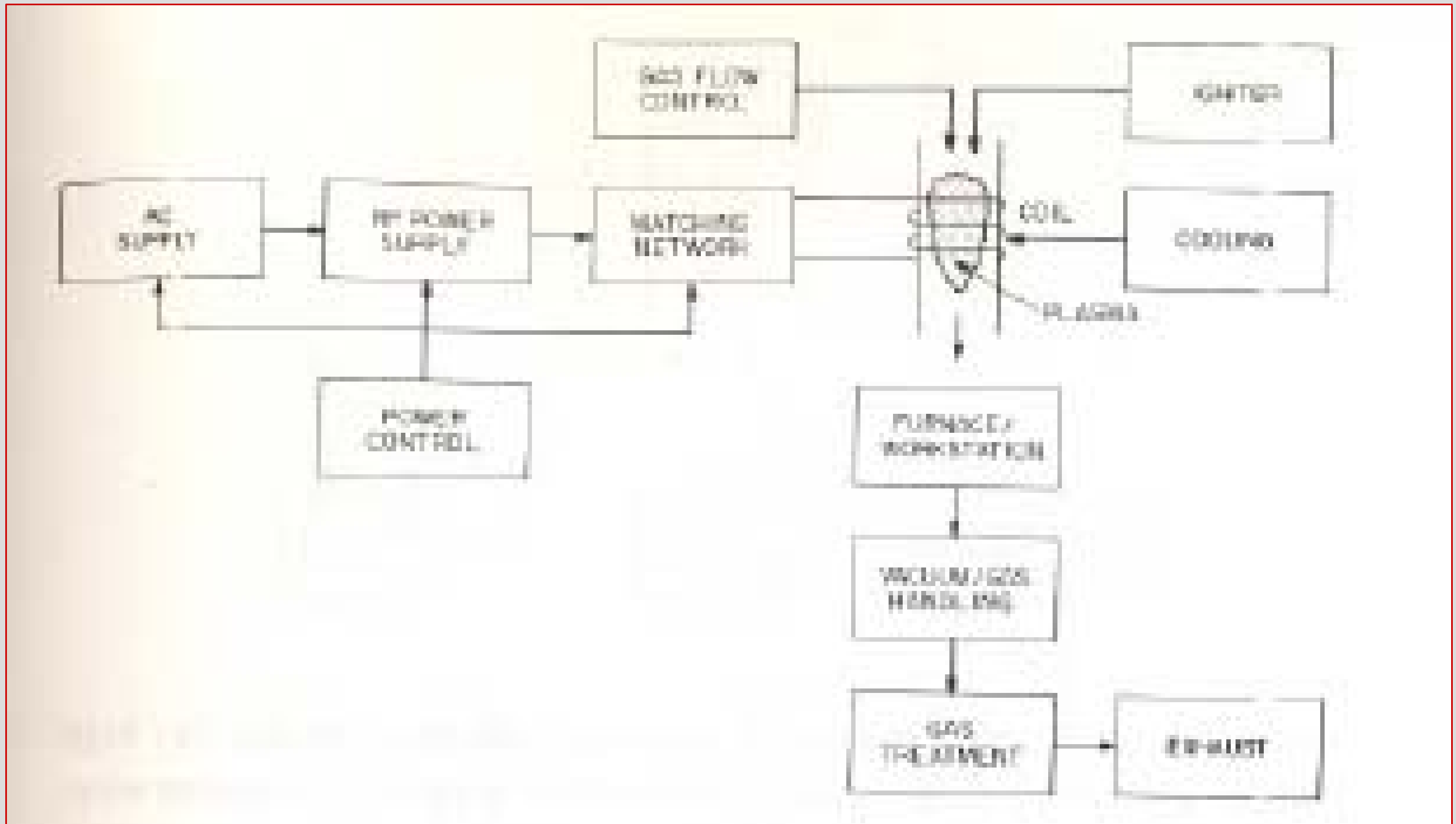
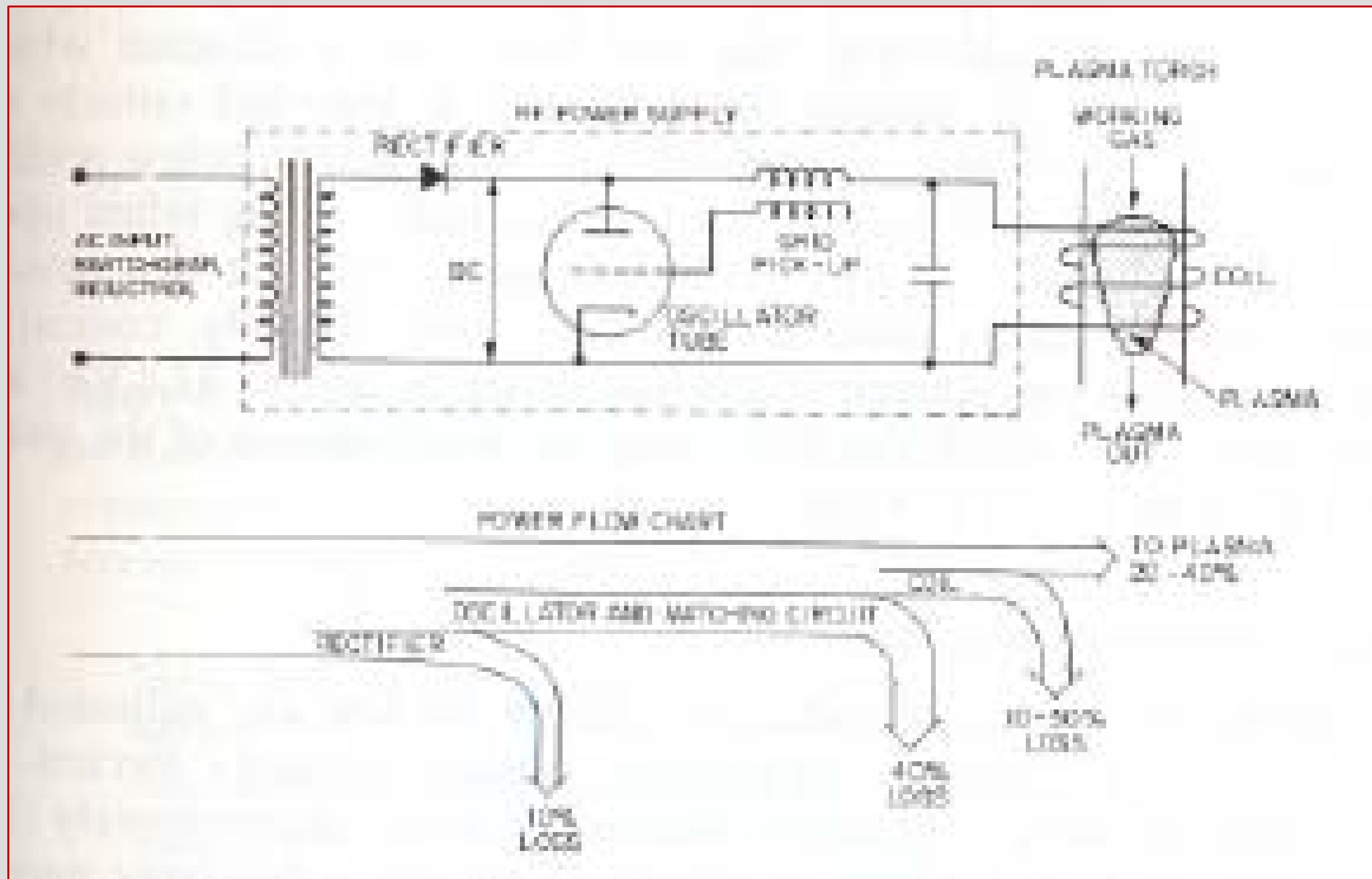


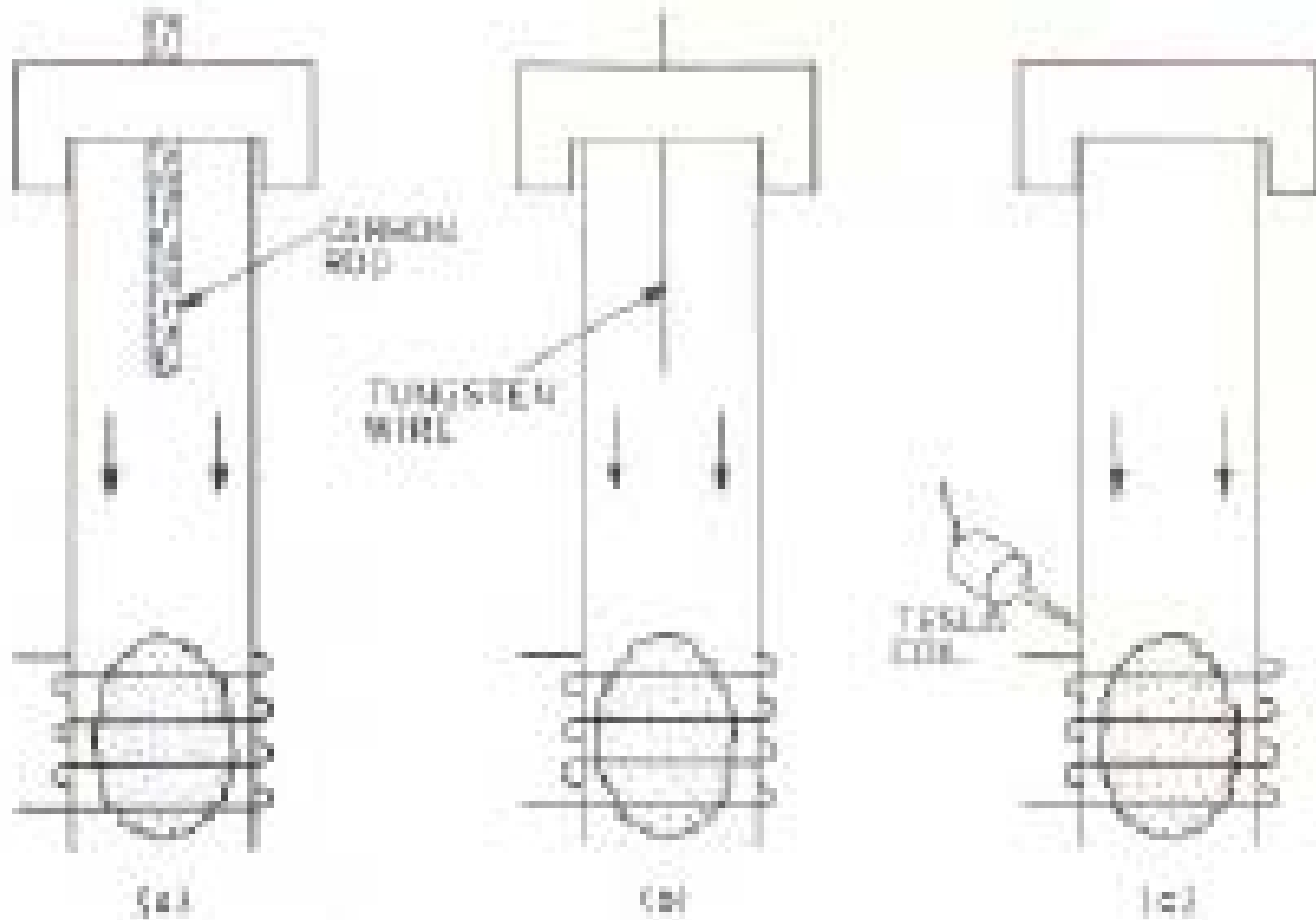
Diagrama em blocos de um sistema de tocha de plasma



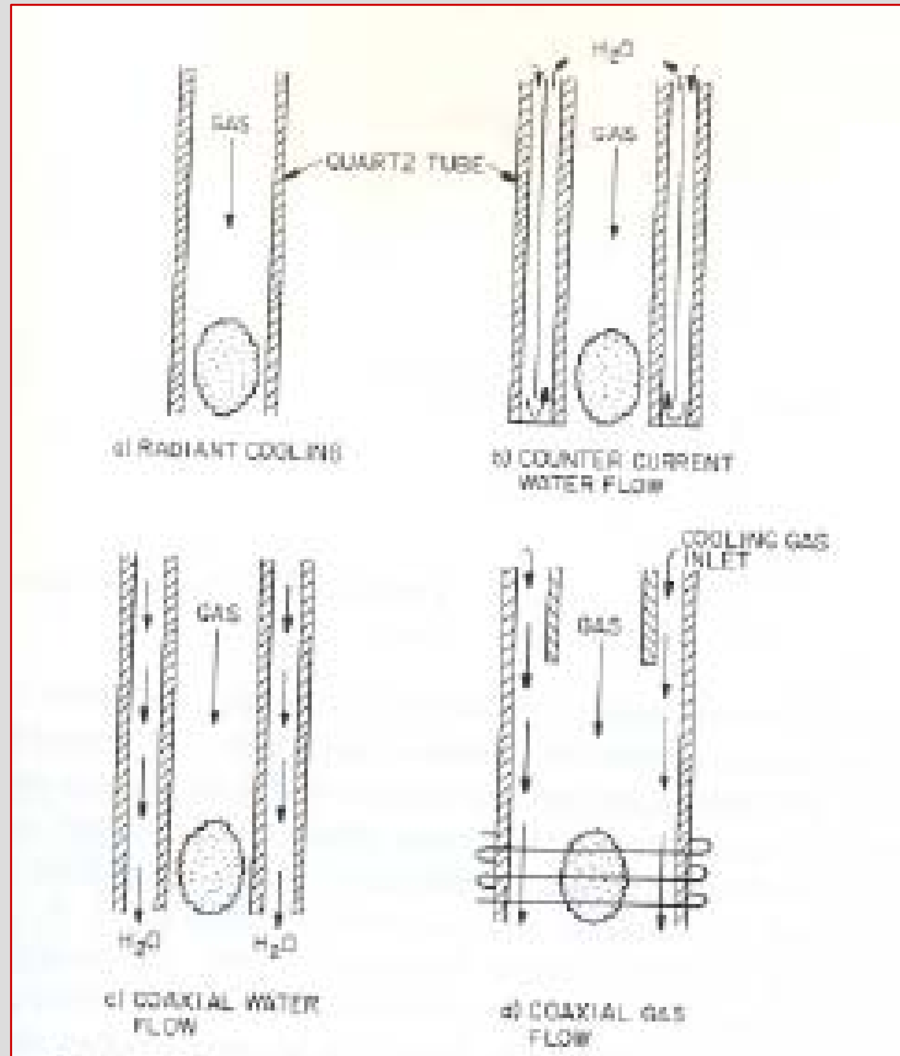
Circuito elétrico da tocha de plasma



Tipos de sistema de ignição de tochas



Sistemas de refrigeração em tochas de plasma

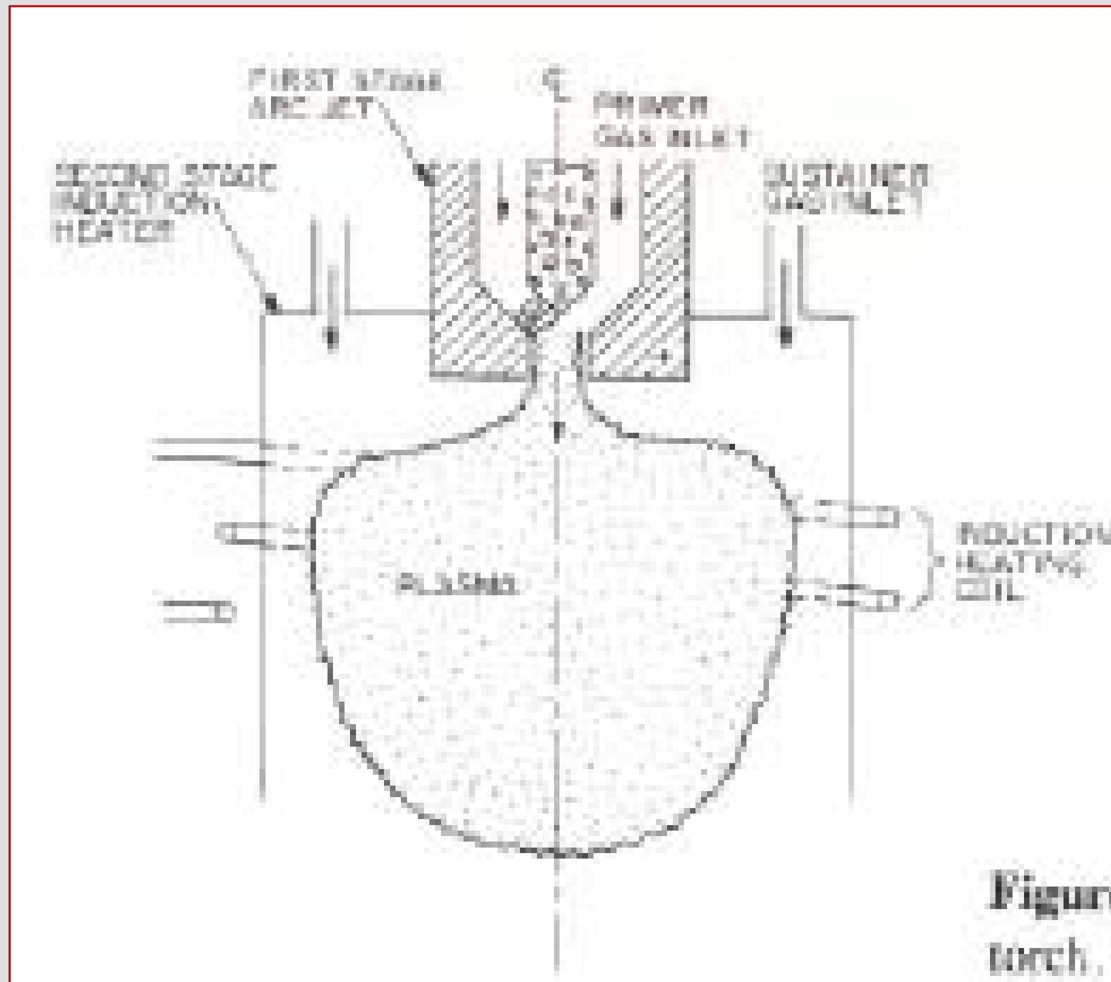


Características de tochas de plasma

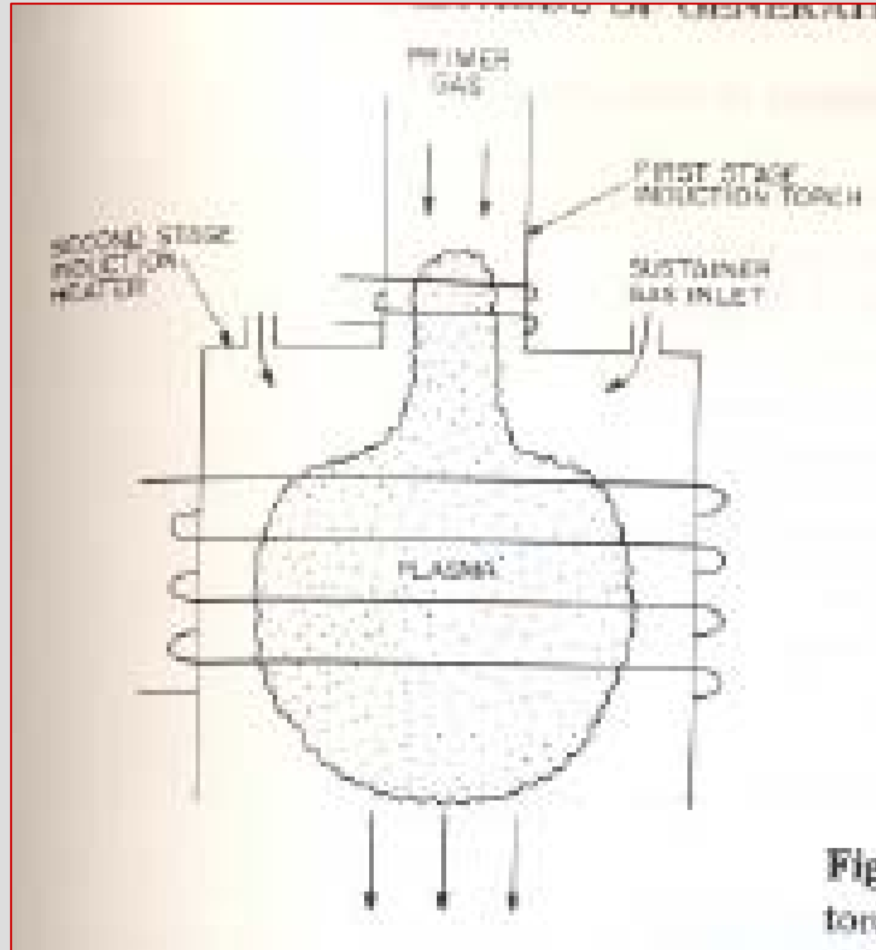
Parameter	Low	Characteristic	High
Frequency	10 kHz	13.56 MHz	100 MHz
Power	1 kW	30 kW	1MW
Efficiency	20%	35%	50%
Pressure	10 Torr	1 atm	10 atm
Gas temperature	1000 K	10^4 K	2×10^4 K

Sistemas alternativos

Sistema híbrido DC-RF



Sistema RF - RF



Empregos dos plasma indutivos

High purity materials production:
- Silica and other refractories
- Ultrafine powder
- Spherical fine powder
- Refining/purification

High temperature thermal treatment:
- Heat treatment
- Plasma sintering

Surface Treatment:
- Oxidation
- Nitriding

Surface Coating:
- Plasma flame spraying
- Surface coating of powder

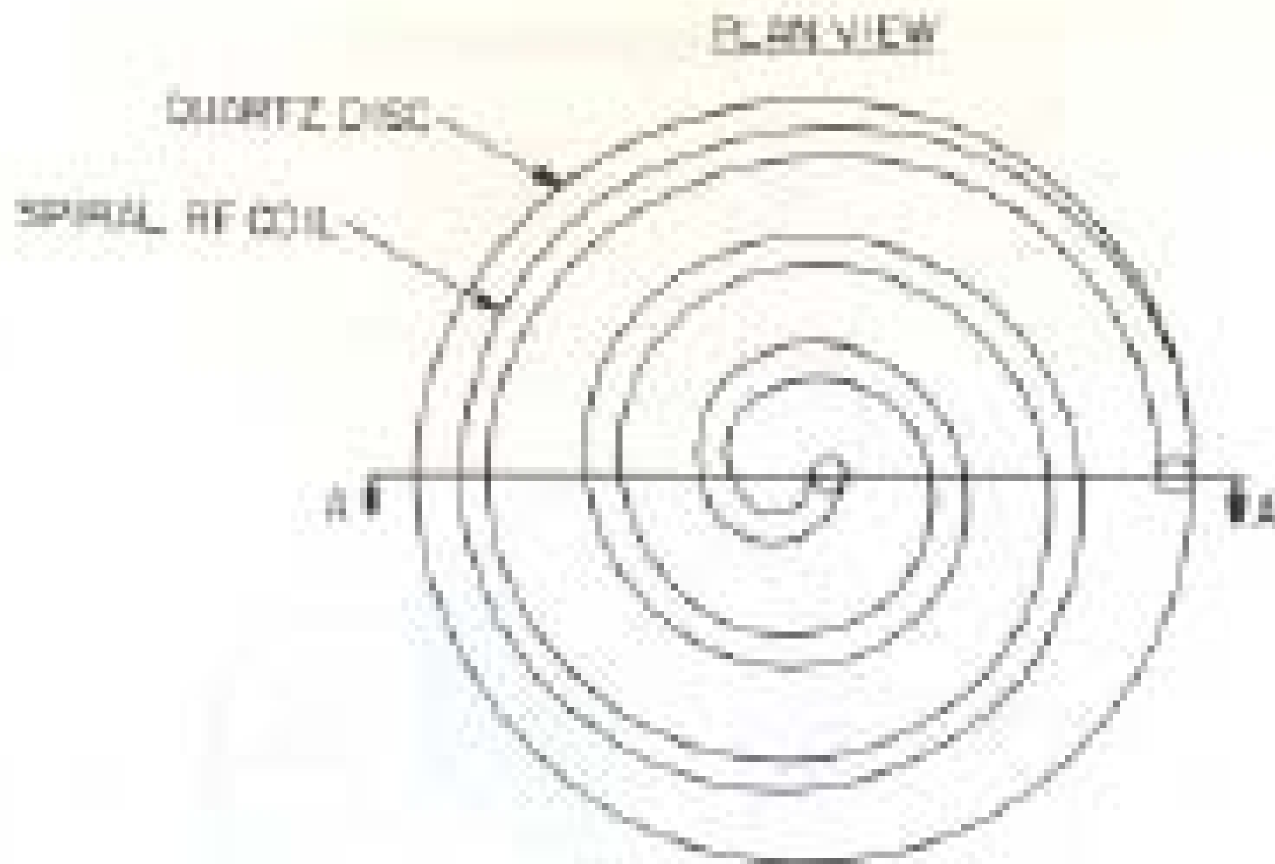
Chemical vapor deposition (CVD):
- At atmospheric pressure
- At reduced pressure

Chemical synthesis and processing

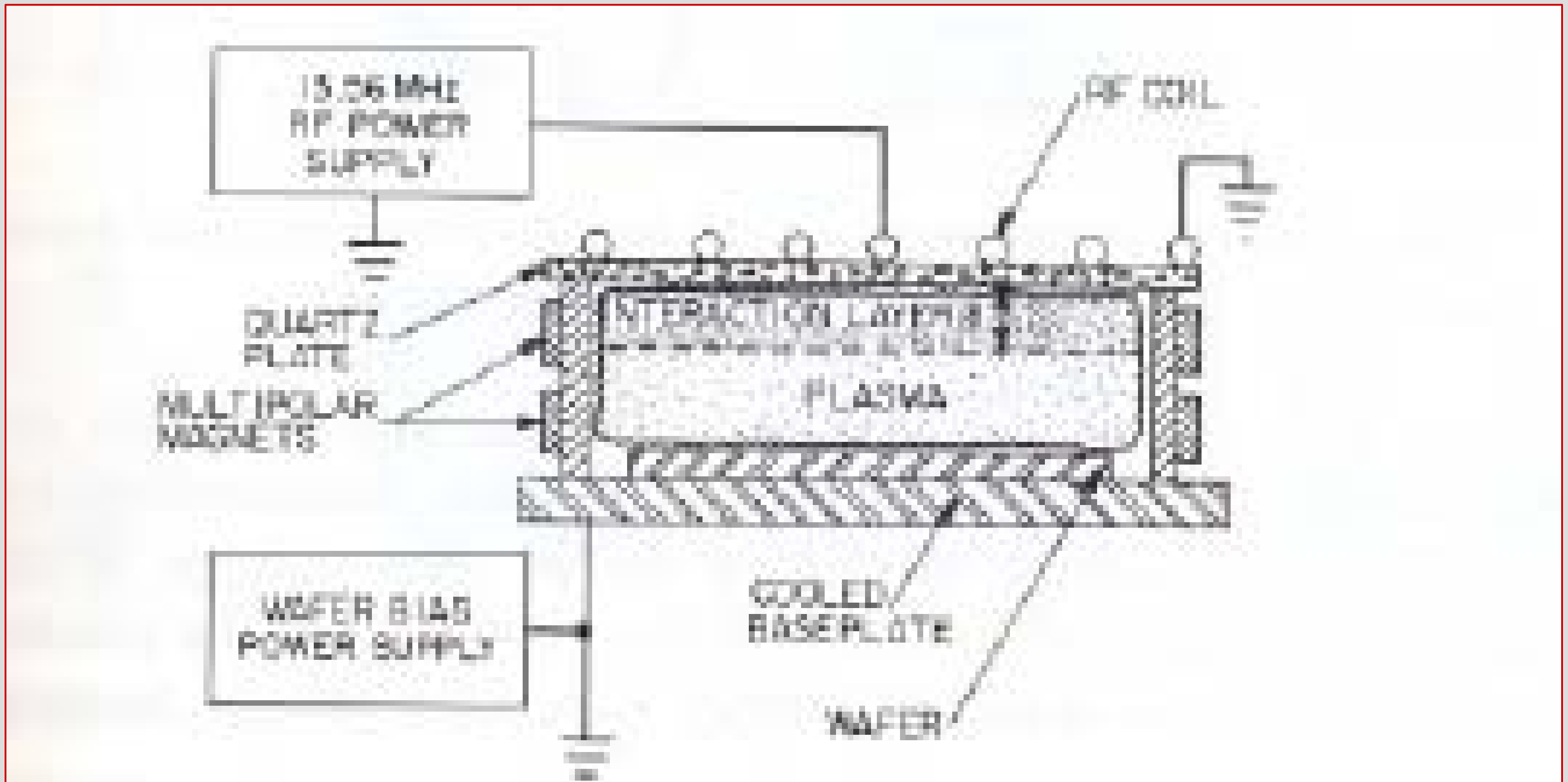
Experimental applications:
- Laboratory furnace
- High intensity light source
- Spectroscopic analysis
- Isotope separation
- Ion source
- High power density plasma source

HDPCVD plasmas

Indutores espirais

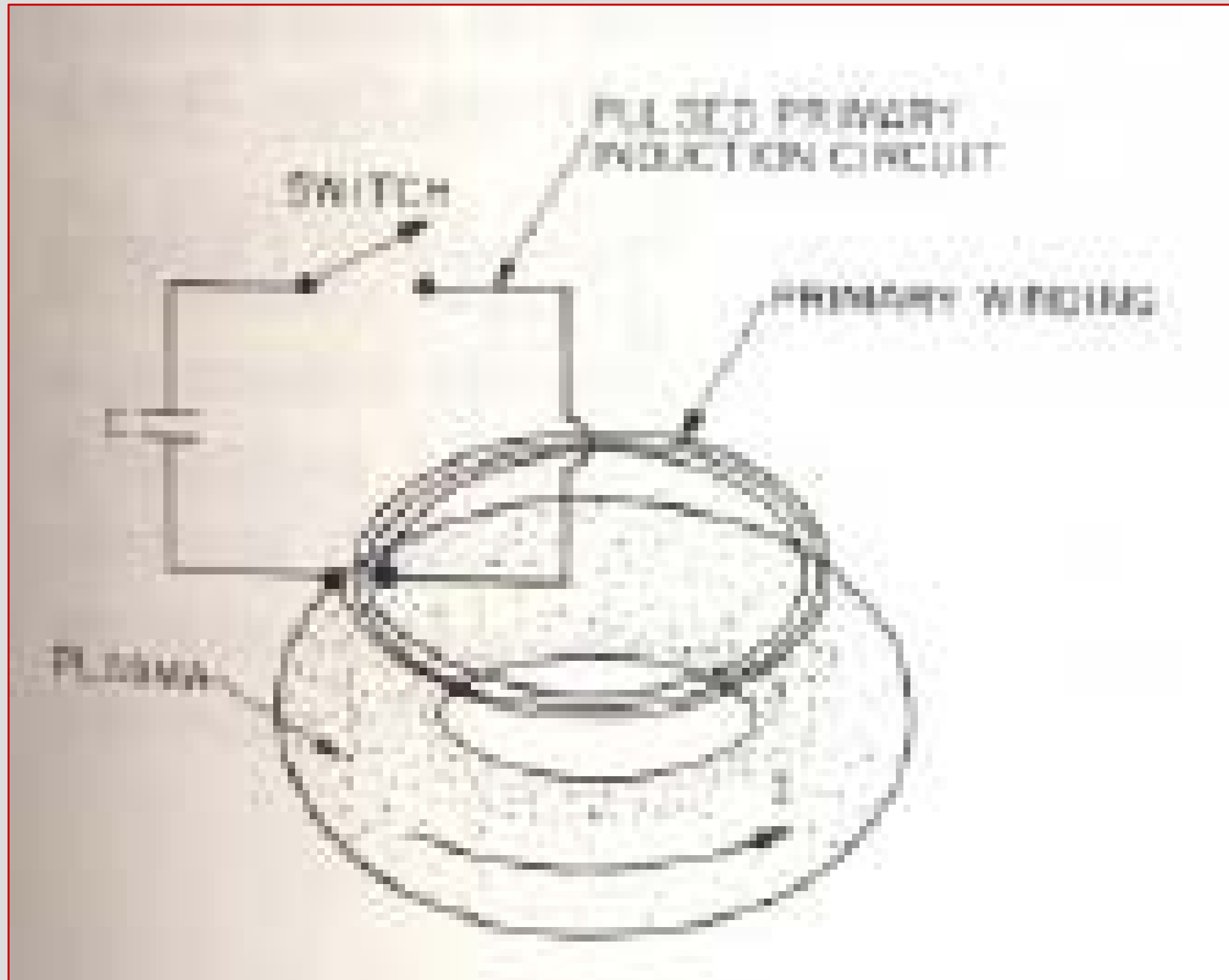


HDPCVD plasmas



Plasma Toroidais

Plasma toroidal de aquecimento ohmico



Plasma toroidal de frequência alternada (60Hz)