Plasmas micro-onde basse pression

et

Procédés associés

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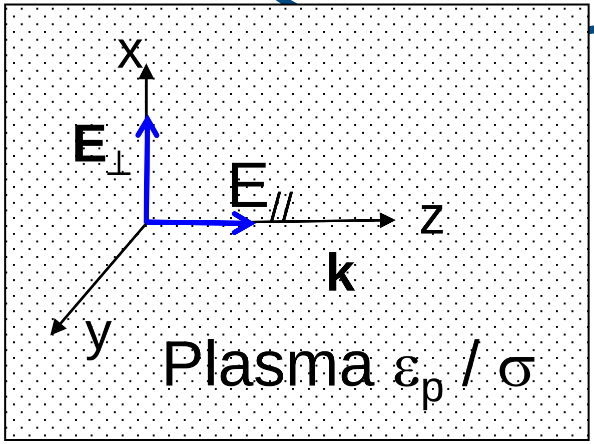
La Rochelle, 2014

PLAN DE PRESENTATION

- **Onde-Plasma (absorption d'énergie du champ E par les électrons dans le domaine basse pression $\nu << \omega$)**
  - Plasma infini (onde de volume)
  - Plasma limité (onde de surface)
- **Dispositifs de production du plasma (exemples)**
  - Dispositifs de couplage (guide, surfatron, fentes, coax,…)
- **Couplage Onde-Plasma**
  - Mode coupleur-plasma
  - Impédance
- **Procédés plasma micro-onde basse pression**
- **Avantages / inconvénients**

Onde / Plasma – milieu infini

- <u>Onde</u> caractérisée par l'équation de dispersion



$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}\,e^{i(kz-\omega t)}$$

$$\left[\left(\frac{\omega}{c}\right)^2 \overline{\overline{\varepsilon}}_p - k^2\right]\mathbf{E}_\perp + \left(\frac{\omega}{c}\right)^2 \overline{\overline{\varepsilon}}_p\,\mathbf{E}_{//} = 0$$

Onde transversale (EM)

$$k_z^2 = \left(\frac{\omega}{c}\right)^2 \varepsilon_{pxx} = \left(\frac{\omega}{c}\right)^2 \left[1 + \frac{\sigma_{xx}}{-i\varepsilon_0\omega}\right]$$

Onde longitudinale (EP)

$$\varepsilon_{pzz} = \left[1 + \frac{\sigma_{zz}}{-i\varepsilon_0\omega}\right] = 0$$

- <u>Plasma</u> (approche fluide ou cinétique) conductivité : **v**
- <u>Onde-plasma</u> **J** = σ**E** (Ohm) ∇.**E** = ρ/ε_0 (Poisson) : **v** → σ → ε_p → k

Onde / Plasma – milieu infini

- ***Onde transversale EM*** **($v_{th} << v_\varphi$)**

- ***Ondes longitudinale*** **EP (cas $\nu = 0$)**

$$\sigma = i\frac{\omega_p^2 \varepsilon_0}{(\omega + i\nu)}$$

Plasma / conducteur

$$\sigma = i\frac{\omega_p^2 \varepsilon_0}{\omega\left(1 - \frac{3}{2}\frac{v_{th}^2}{v_\varphi^2}\right) + i\nu}$$

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega}\frac{1}{(\omega + i\nu)}$$

Plasma / Diélectrique

$$\varepsilon_p = 1 - \frac{\omega_{pe}^2}{\omega\left(\omega\left(1 - \frac{3v_{th}^2}{2v_\varphi^2}\right) + i\nu\right)}$$

Impédance plasma

$$Z_p = \frac{Z_0(\omega, \text{géométrie applicateur})}{\varepsilon_p(\omega, \omega_p, \nu)}$$

$$k^2 = \left(\frac{\omega}{c}\right)^2\left[1 - \frac{\omega_p^2}{\omega^2(1 + i\,\nu/\omega)}\right]$$

Onde / dispersion

$$\omega^2 = \omega_p^2 + \frac{3}{2}v_{th}^2 k^2 \quad (\nabla p \neq 0)$$

Champ électrique

$$E = E_0 e^{i(k_R + ik_I)z}$$

$$E = E_0 e^{ik_R z} e^{-k_I z}$$

Propagation

Atténuation

$$\delta = k_I^{-1}$$

Épaisseur de peau

Onde / Plasma – milieu infini

❑ PROPAGATION / ATTENUATION - ABSORPTION de puissance de l'onde par les électrons

- Absorption collisionnelle ($\nu > \omega$)

  Plasma moyenne et haute pression

- Absorption résonnante ($\nu << \omega$)

  Plasma basse pression ($p < 100$ mTorr)

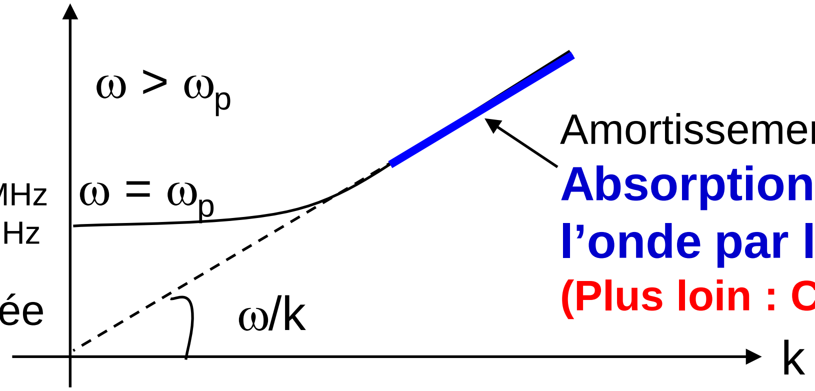
❑ ONDE PLASMA ($E // k$)

❑ ONDE LONGITUDINALE ($E \perp k$)

Onde Plasma (EP) cas $\nu \ll \omega$ - Résonance

- **Equation de dispersion (approche fluide)** $\sigma = i\dfrac{\omega_p^2 \varepsilon_0}{\omega}\left(1+\dfrac{3}{2}\dfrac{v_{th}^2}{v_\varphi^2}\right)$

$$\omega^2 = \omega_p^2 + \frac{3}{2} v_{th}^2 k^2 \qquad (\nabla p \neq 0)$$



Propagation ($n < n_c$)

$n_c \approx 5\times10^{8}$ cm^{-3} @ 13.56 MHz
$n_c \approx 7\times10^{10}$ cm^{-3} @ 2,45 GHz

Onde coupée

Amortissement Landau

Absorption résonante d'énergie de l'onde par les électrons $v_{th} \approx \omega/k$

(Plus loin : Conversion EM → EP)

- **Equation de dispersion (approche cinétique)**

$$\sigma = i\frac{ne^2}{m\omega}\left(1+\frac{3}{2}\frac{v_{th}^2}{v_\varphi^2} + i\pi\frac{\omega^2}{k^2}\left.\frac{\partial F_0}{\partial w_{//}}\right|_{\frac{\omega}{k}}\right) \qquad \omega^2 = \omega_p^2\left(1+\frac{3}{2}\frac{v_{th}^2}{v_\varphi^2} + i\pi\left(\frac{\omega}{k}\right)^2\left.\frac{\partial F_0}{\partial w_{//}}\right|_{\frac{\omega}{k}}\right)$$

Terme supplémentaire → partie réelle de la conductivité ⇒ absorption de puissance

$$P = \frac{1}{2}\mathrm{Re}\left\{\sigma E^2\right\}$$

Onde Electromagnétique (EM)

$$\sigma = i\frac{\omega_{pe}^{2}\,\varepsilon_0}{(\omega + i\nu)} \qquad \varepsilon_p = 1 - \frac{\omega_{pe}^{2}}{\omega(\omega + i\nu)} \qquad k = \frac{\omega}{c}\sqrt{\varepsilon_p} = \frac{\omega}{c}\sqrt{1 - \frac{\omega_{pe}^{2}}{\nu^2 + \omega^2} + i\frac{\nu}{\omega}\frac{\omega_{pe}^{2}}{\nu^2 + \omega^2}} = k_R + i\,k_I$$

$$\frac{|\sigma|}{\omega\varepsilon_0} = \frac{\omega_{pe}^{2}}{\omega^{2}\sqrt{1 + (\nu/\omega)^2}} \qquad E(r,t) = E\,e^{ik_R z}e^{-z/\delta}$$

Domaine élastique

Plasma **non-collisionnel** **$\omega >> \nu$**

Fréquences dispersives $\omega > \omega_p > \nu$

$\frac{|\sigma|}{\omega\varepsilon_0} << 1$ (courant de déplacement non-négligeable)

Fréquences réactives $\omega_p >> \omega > \nu$

$\frac{|\sigma|}{\omega\varepsilon_0} >> 1$ (impédance plasma - inductif)

Domaine résistif

Plasma **collisionnel** **$\omega << \nu$**

Milieu dilué $\omega^2_p < \nu\omega$

$\frac{|\sigma|}{\omega\varepsilon_0} << 1$ (courant de déplacement non-négligeable)

Milieu dense $\omega^2_p > \nu\omega$

$\frac{|\sigma|}{\omega\varepsilon_0} >> 1$ (impédance plasma - résistif)

Domaine d'intérêt (plasma dense n > n_c, basse pression)

Onde Electromagnétique (EM)

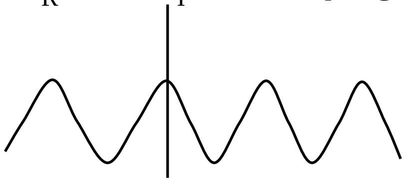
Plasma non-collisionnel : $\omega \gg \nu$

$$\sigma = i\sigma_I \qquad \varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2} \qquad \omega^2 = \omega_p^2 + c^2 k^2$$

Fréquences dispersives $\omega > \omega_p > \nu$

$n < n_c$ (7.5×10^{10} cm^{-3} @2.45 GHz)

$k = k_R + 0\,k_I$ **Propagation** sans atténuation



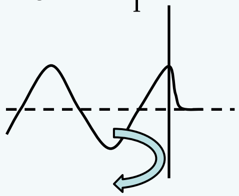
$$\delta = \infty$$

Fréquences réactives $\omega_p > \omega > \nu$

$n > n_c$

Onde évanescente

$k = 0 + i k_I$



$$\delta \cong \frac{c}{\omega_p} \ll \frac{\lambda_0}{2\pi}$$

5 mm ($n = 10^{12}$ cm^{-3}, 100 mTorr)

Pas de chauffage ohmique (collisionnel)

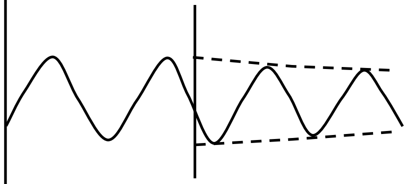
Plasma collisionnel : $\omega \ll \nu$

$$\sigma_R = \sigma_{DC} = \frac{\omega_p^2 \varepsilon_0}{\nu}$$

Milieu dilué $\omega^2_p < \nu\omega < \nu^2$

$n < n_c$

$k \cong k_R + i k_I$ **Propagation** + faible atténuation



$$\delta = \frac{2c\nu}{\omega_p^2} \gg \frac{\lambda_0}{2\pi}$$

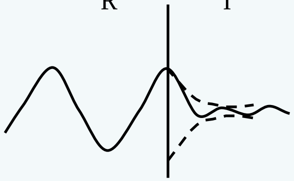
30 cm
($n = 10^{10}$ cm^{-3},
p = 4 Torr)

Milieu dense $\omega^2_p > \nu\omega$, $\omega_p > \omega$, $\omega < \nu$

$n > n_c$

Propagation + forte atténuation

$k \cong k_R + i k_I$



$$\delta = \frac{c}{\omega_p}\sqrt{\frac{2\nu}{\omega}} = \sqrt{\frac{2}{\mu_0 \omega \sigma_{DC}}} \ll \frac{\lambda_0}{2\pi}$$

8 mm ($n = 10^{12}$ cm^{-3}), p = 4 Torr

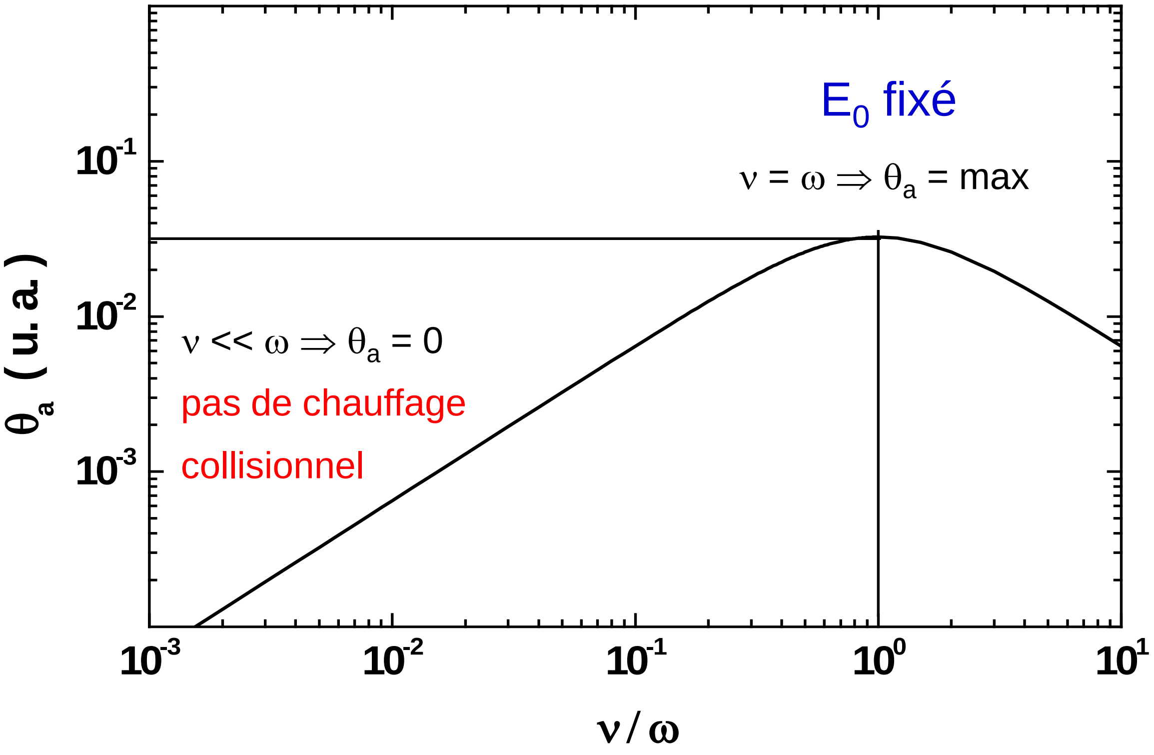
Chauffage ohmique (collisionnel)

Onde Electromagnétique (EM)

$$P\left(W/m^3\right) = n\frac{e^2|E|^2}{2m_e\nu}\frac{\nu^2}{\nu^2+\omega^2} = n\,\theta$$

- θ puissance moyenne (sur une période) absorbée par un électron nécessaire au maintien d’une paire électron-ion dans le plasma

$$\theta_a = \frac{e^2}{m_e\nu}\frac{E^2}{2}\frac{\nu^2}{\nu^2+\omega^2}$$

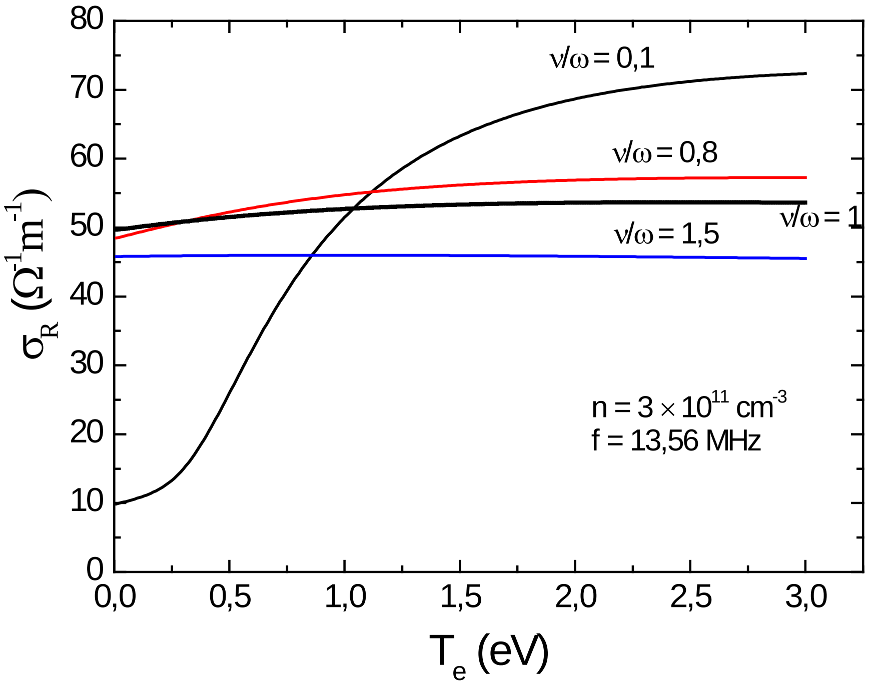


- Pour $\nu \ll \omega$ (basse pression) chauffage par d’autres mécanismes :
  - **Résonances du type Landau (EP-onde plasma, EM-onde elmg.)**
  - **Onde de surface (plasma limité, cf. suite)**
  - ECR si $B \neq 0$

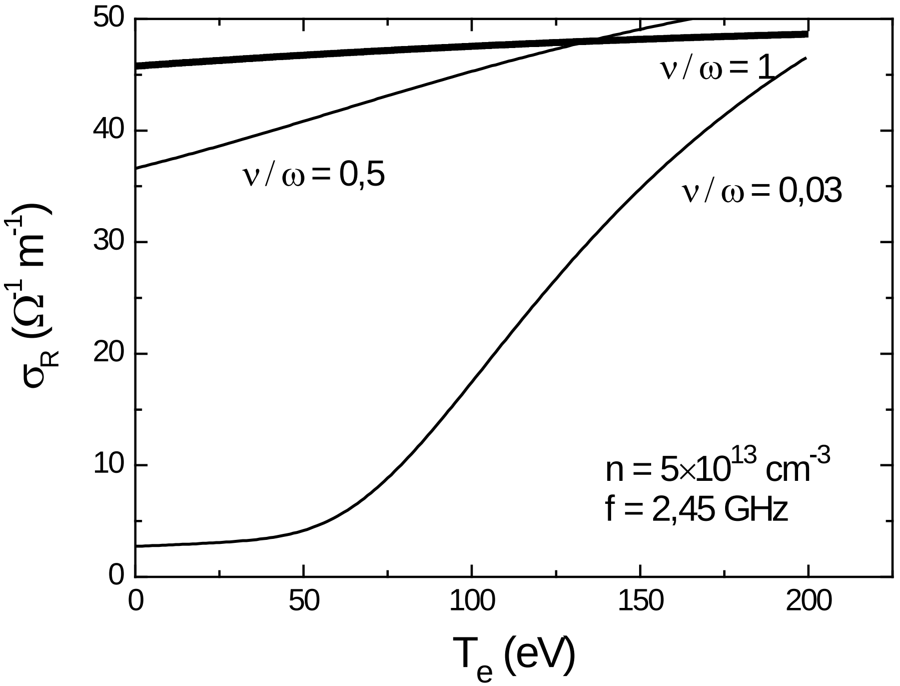
Onde Electromagnétique (EM) cas $\nu << \omega$ Résonance (type Landau)

- **Approche cinétique**

$$\sigma_\perp = i\frac{ne^2}{m}\frac{1}{\omega}\left(1+\frac{3}{2}\left(\frac{kv_{th}}{\omega}\right)^2 - i\sqrt{\pi}\left(\frac{\omega}{kv_{th}}\right)e^{-\frac{w^2}{v_{th}^2}}\Bigg|_{\frac{\omega}{k}}\right)$$



Domaine RF *(S. Rauf et al. , PSST 6 (1997)*



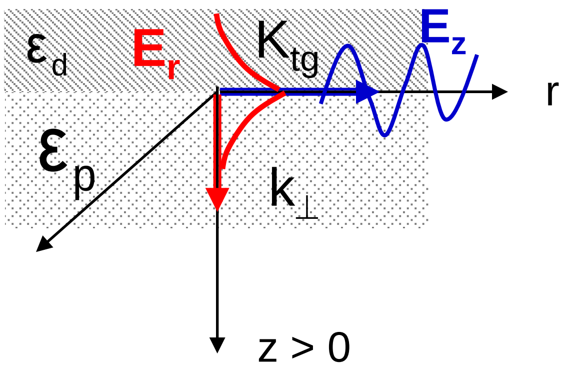
Domaine micro-ondes

Peu probable pour les conditions habituelles

- T_e faible $\Rightarrow$ $\sigma_R = \sigma_{R\ froids}$ due aux électrons froids (chauffage collisionnel)
- $T_e > 1$eV $\Rightarrow$ $\sigma_R = \sigma_{R\ froids}\,(1 + W)$ où W = contribution des électrons chauds (chauffage non-collisionnel) qui est d'autant plus grande que ν / ω est faible.

Onde Electromagnétique / Plasma limité

☐ **ONDE DE SURFACE** (Mode TM: $H_z = 0$, continuité du E_{tg} à l'interface)



☐ E_z se propage le long de l'interface diélectrique plasma (**onde de surface**)

$$k_{tg} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_p \varepsilon_d}{\varepsilon_p + \varepsilon_d}}$$

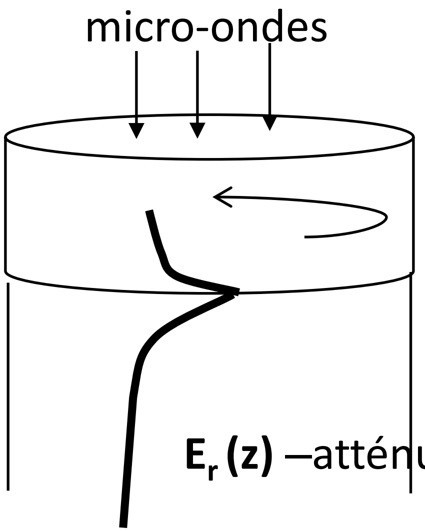
☐ Basse pression ($\nu \ll \omega$) $\varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2}$

☐ **Propagation si $n > n_c$ ($\omega > \omega_p$)**

☐ **Résonance** ($k_{tg} \to \infty$) si $\frac{\omega_p}{\omega} = \sqrt{1 + \varepsilon_d}$

☐ Si **$n > n_c \to E_r$ évanescente dans la direction $k_\perp$**

$$k_{\perp p(d)} = \frac{\omega}{c}\frac{\varepsilon_{p(d)}}{\sqrt{\varepsilon_p + \varepsilon_d}}$$

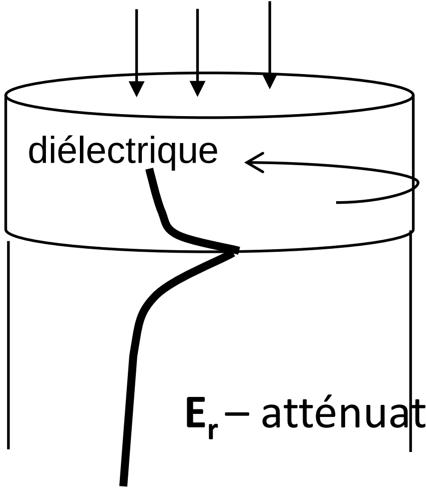


E_z (r) – propagation sur la surface séparatrice (onde de surface)

E_r (z) –atténuation sur $\delta = c/\omega_p$

Onde Electromagnétique / Plasma limité

- ☐ Si **n > n_c → onde EM de surface**
- ☐ Si **n < n_c → onde EM en volume**



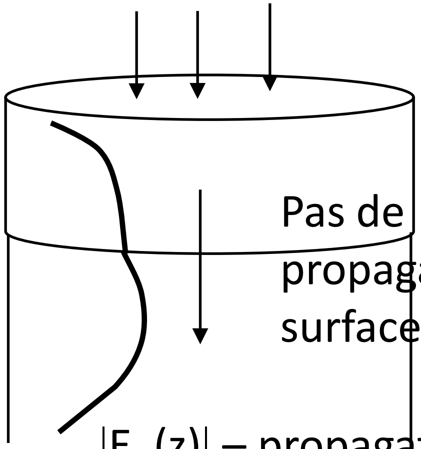
micro-ondes

diélectrique

plasma n < n_c
(onde propagative)

E_z (r) – propagation sur la surface séparatrice (onde de surface)

E_r – atténuation sur $\delta = c/\omega_p$



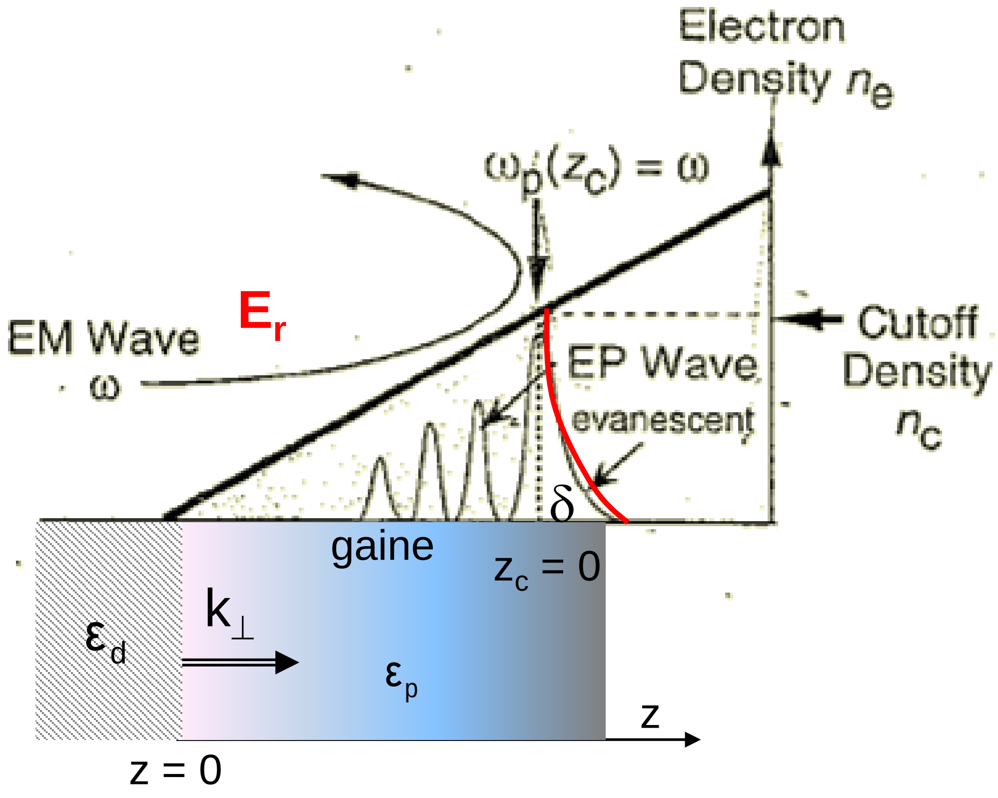
micro-ondes

Pas de propagation sur la surface séparatrice

$|E_r (z)|$ – propagation en volume

Onde Electromagnétique / Plasma limité

❑ ONDE DE SURFACE : mécanismes de chauffage



H. Sugai et al. PSST 7 (1998)
(3 mTorr, n= 10^{12} cm-3)

❑ $\omega \approx \omega_p$ (résonance) → Pic du champ E_z (onde de surface) dans une zone de résonance $\Delta \ll \delta$ → les électrons acquièrent de l'énergie si temps de transit $\tau \sim 2\pi/\omega$

$$\delta/v_{th} \sim (4\times10^{-10}) \rightarrow v_{th}\ T_e \approx 1\ \text{eV}$$
$$\Delta/v_{th} \sim (4\times10^{-10}) \rightarrow v_{th}\ T_e \approx \text{mV}$$

**L. Alves et al, Phys. Rev. E 79, 2009*
*** Terebessy et al. Appl. Phys 77 (18) 2000*

❑ Conversion de l'onde EM en onde EP ($n < n_c$, $\nabla n \neq 0$), et absorption par effet résonant (Landau)

**Y.M. Aliev et al, Phys. Scr. 48, 1993*
***H. Sugai et al. PSST 7 (1998)*
****O. Boudreault et al. Phys. Rev. E 86 2012*

Conclusion
Chauffage à basse pression ($\nu << \omega$)

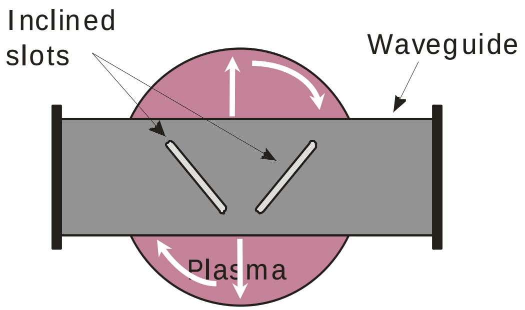
- ☐ Onde PLASMA ($E_{//}$ // k) – **(volume)** Propagation pour **$n < n_c$**
  - ➢ Absorption d'énergie résonnante (Landau) par les électrons *chauds* ($v_{th} \approx \omega/k$)
- ☐ Onde ELECTROMAGNETIQUE ($E_{\perp}$ // k) – **(volume)** Propagation pour **$n < n_c$**
  - ➢ Absorption résonante possible par les électrons $v_{th\,//} \approx \omega$ / k de l'onde ($v_{\perp}$) , mais peu probable pour 2.45 GHz et n ~ 10^{12} - 10^{13} cm^{-3}
- ☐ Onde ELECTROMAGNETIQUE ($E_{\perp}$ // k)–**(surface)** Propagation pour **$n > n_c$**
  - ➢ Absorption lors de la traversée de la zone de résonance si $\tau \sim 2\pi/\omega$. Renforcement du champ de l'onde de surface (pics de champ E résultant de l'inhomogénéité du plasma) dans une zone $\Delta << \delta$ près de surfaces où $\omega \approx \omega_p$.
  - ➢Absorption résonnante d'énergie de l'onde EP après conversion EM → EP ($\nabla p \neq 0$)

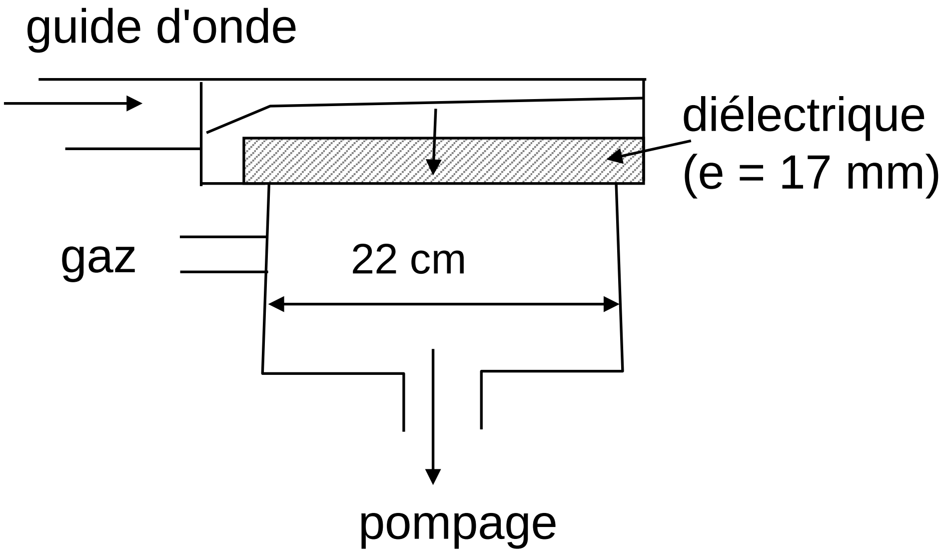
Réacteurs plasma micro-onde basse pression

- **Structures à onde de surface (absorption sur L > λ)**
    - Excitation par le haut
        - Guides d’onde avec ouvertures (fentes ou antennes) distribuées sur une longueur ou une surface
    - Excitation latérale
        - Surfaguide ou Surfatron
        - SLAN (excitation par fentes dans un guide)
- **Structures à absorption d’onde localisée (absorption sur L > λ)**
    - Excitation par antennes individuelles (applicateurs micro-onde)

Excitation par le haut

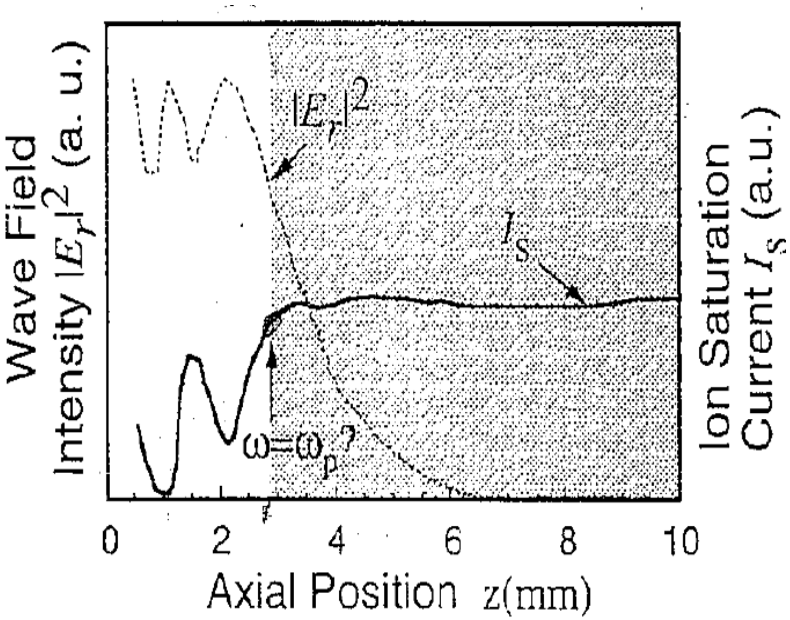
Onde de surface planaire - champ rayonné par fentes





H. Sugai et al. PSST 7 (1998)

f = 2,45 GHz, p = 3 mtorr - 1 torr (Ar, CF_4), P = 0,2-1,5 kW
n = 10^{12} cm^{-3} (@z = 16 mm) $\delta \sim 3$ mm



Accord entre la distribution axiale du champ radial et le profil du courant ionique prouve la production des ondes plasma dans la gaine.

Excitation par le haut

Onde de surface planaire - champ rayonné par fentes suivant un anneau

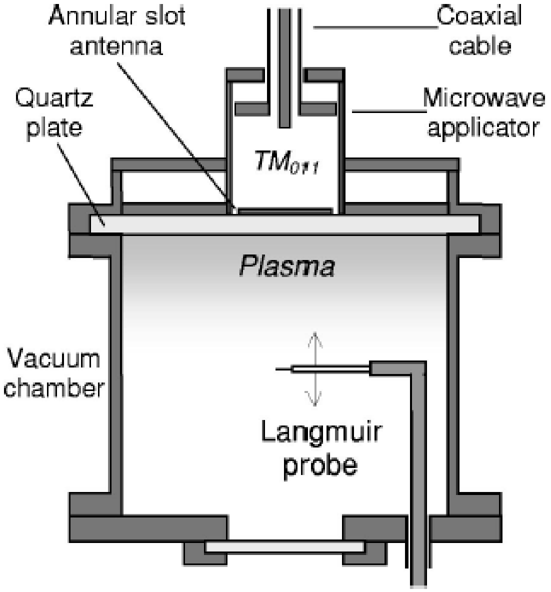


FIG. 1. Schematic view of the experimental apparatus.

*** Terebessy et al. Appl. Phys 77 (18) 2000*

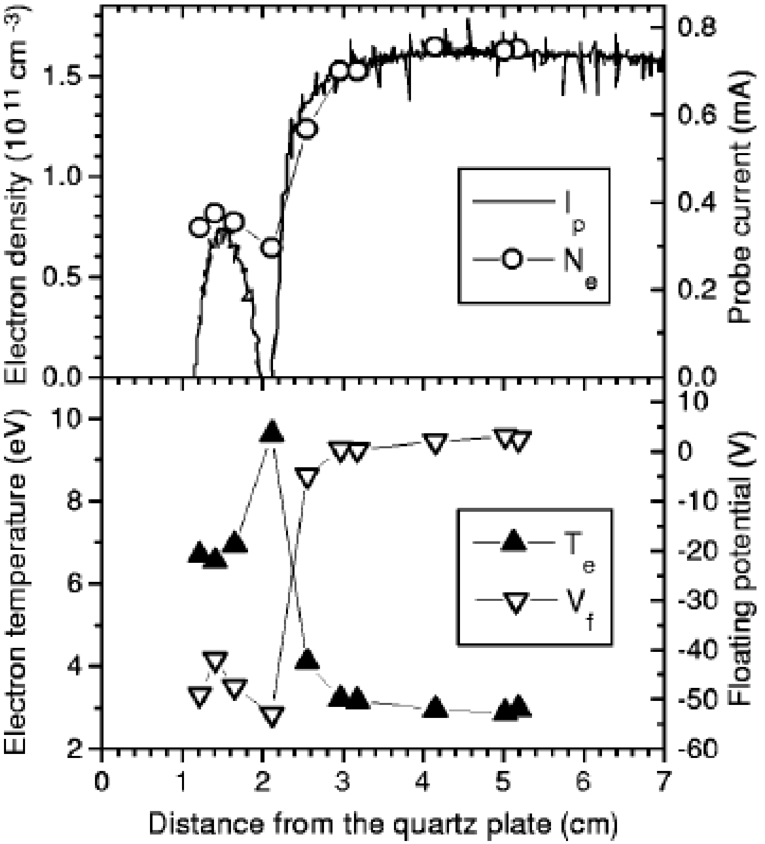
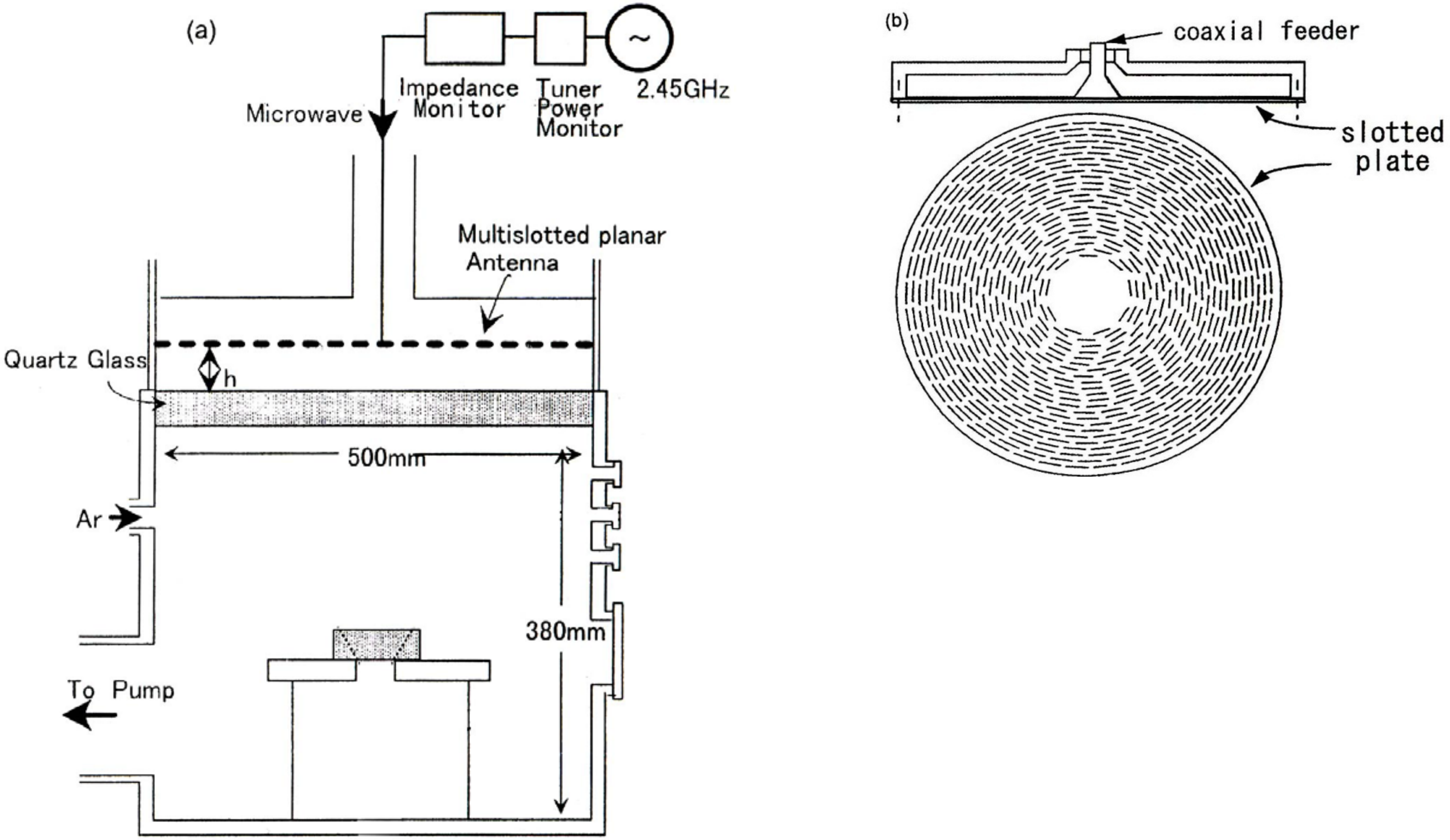


FIG. 6. Axial plasma parameter and probe current ($V_p = -50$ V) profiles measured on the chamber axis in argon discharge at 2.5 mTorr and 1380 W.

Chauffage local lors du passage des électrons dans la zone de résonance.

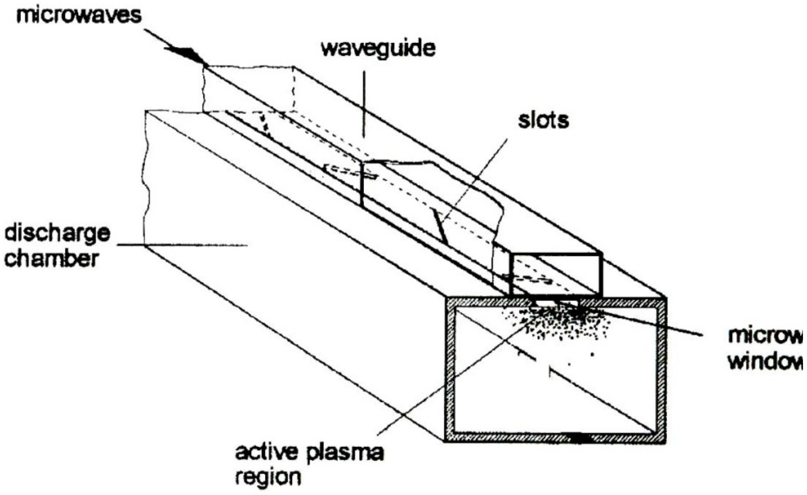
Excitation par le haut

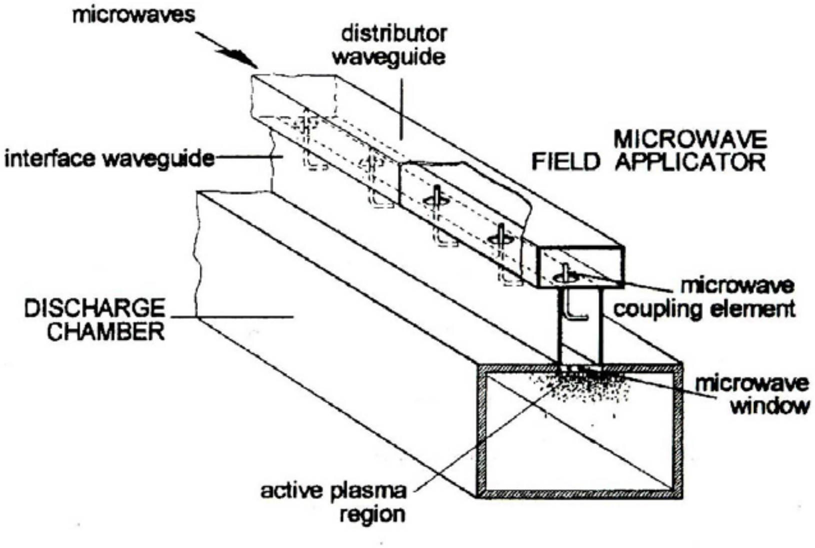
Onde de surface planaire - champ rayonné par fentes distribuées sur grande surface



Excitation par le haut

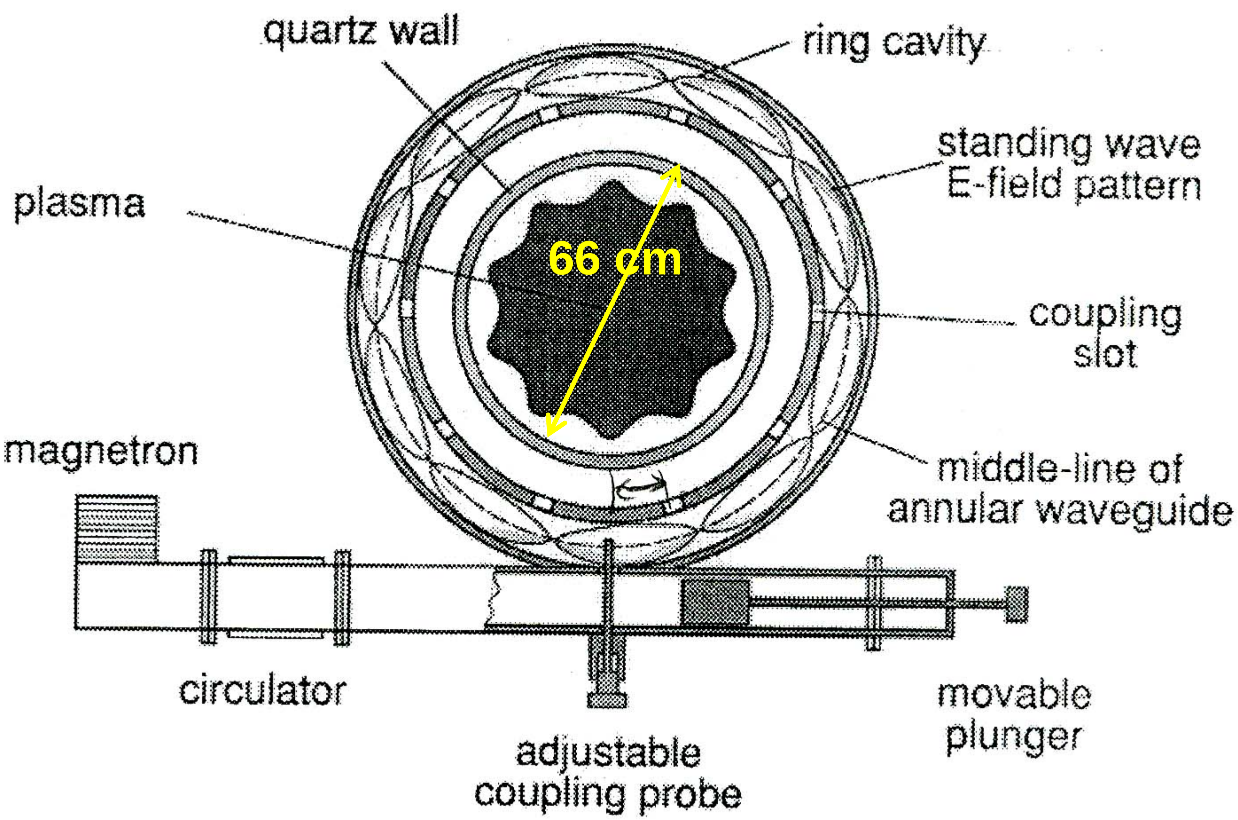
Onde de surface planaire - champ rayonné par fentes ou antennes

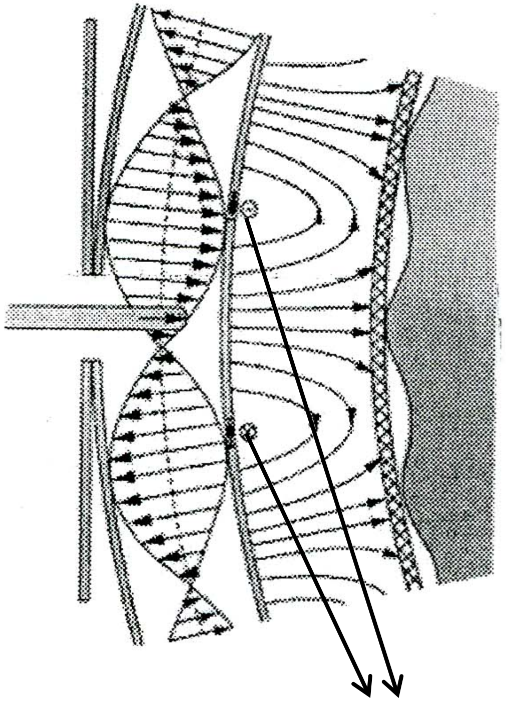




Excitation latérale

Excitation latérale (SLAN - SLot ANtenna) - plasma grand volume (p < 800 mTorr)



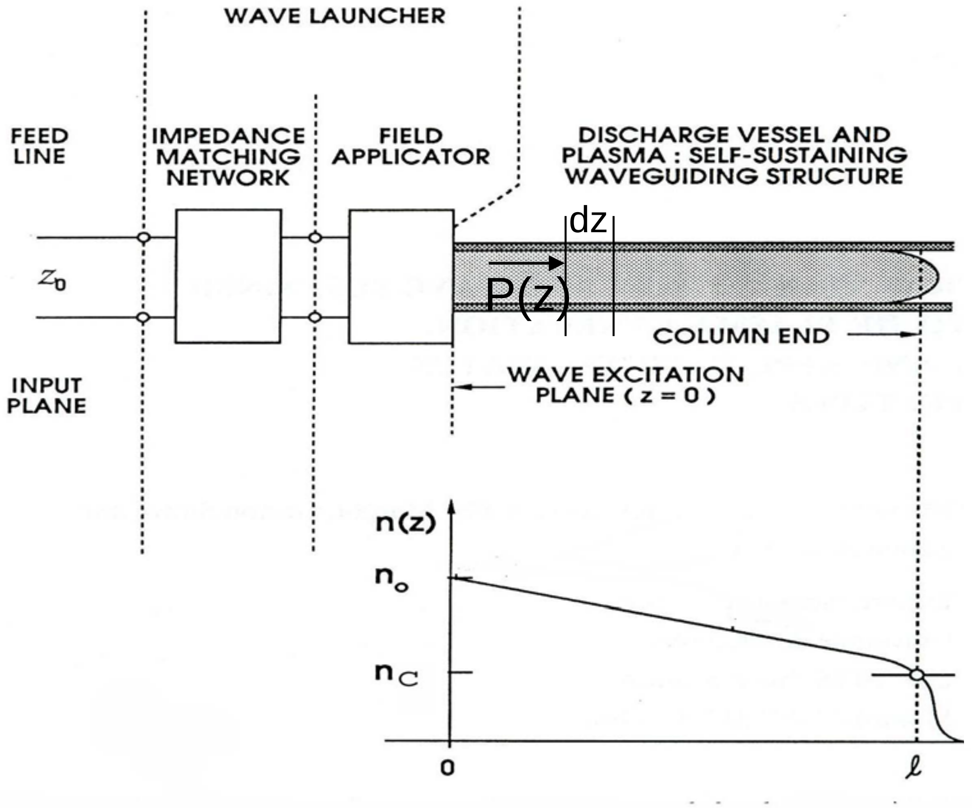


Fentes @ $\lambda_g/4$ dans en guide en anneau

Slot-antenna SW excited cylindrical plasma source

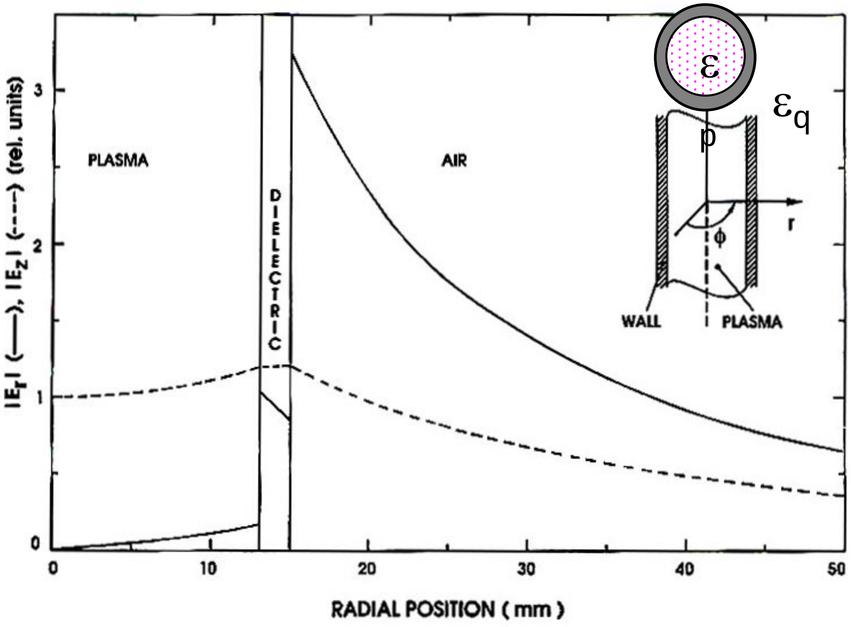
(F. Werner & al. Plasma Sources Sci. Technol. 3, 1994, 743)

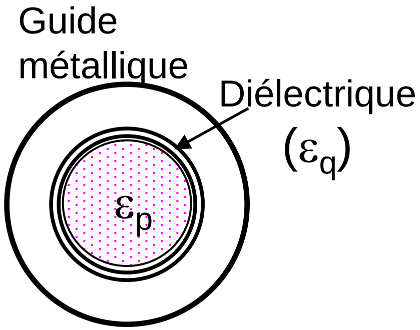
Excitation latérale



Mode plasma TM_{00}

$n = 5^{1/2}\, n_c$, f = 600 MHz





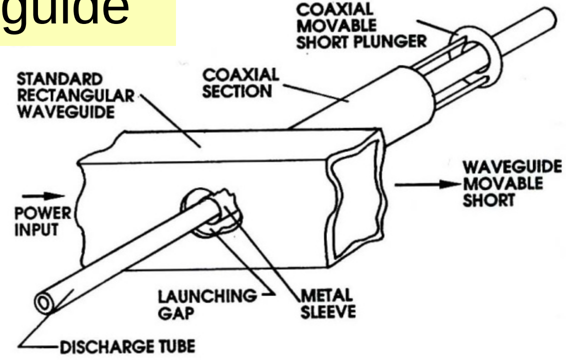
- ❑ Structures les plus répandues
- ❑ Plasma le plus modélisé (si 1 mode excité)
- ❑ Plus appropriées aux procédés en volume (colonne de plasma = volume important)

ϕ_{quartz} = 12 cm, 0.1-5 Torr, 2 kW, 10^{11}-10^{12} cm^{-3}

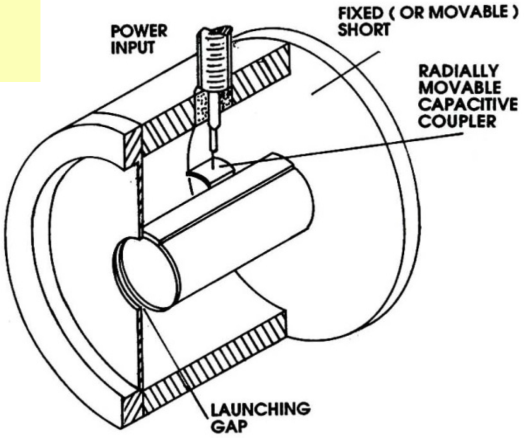
Excitation latérale

Configurations de l’excitateur

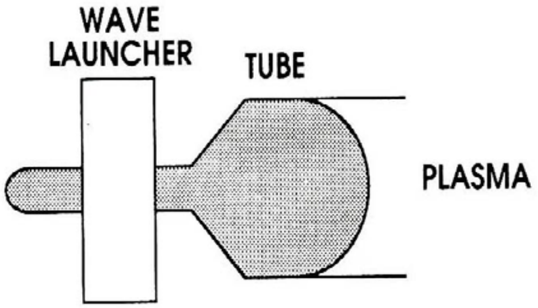
surfaguide

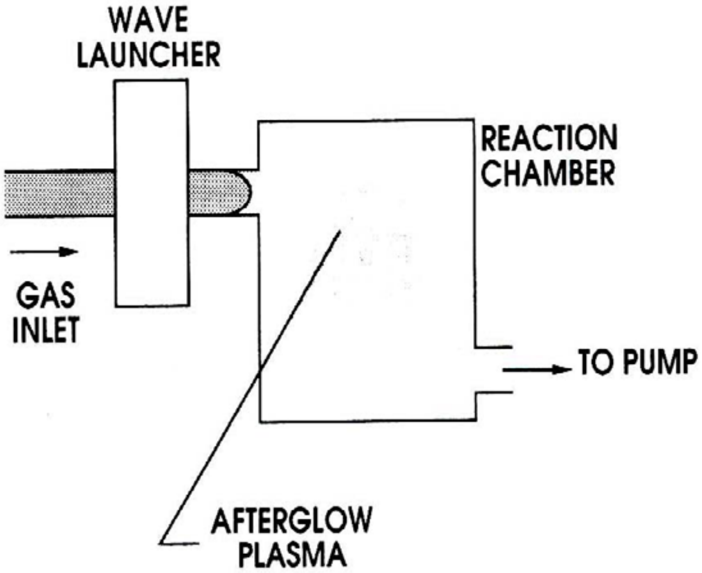


surfatron

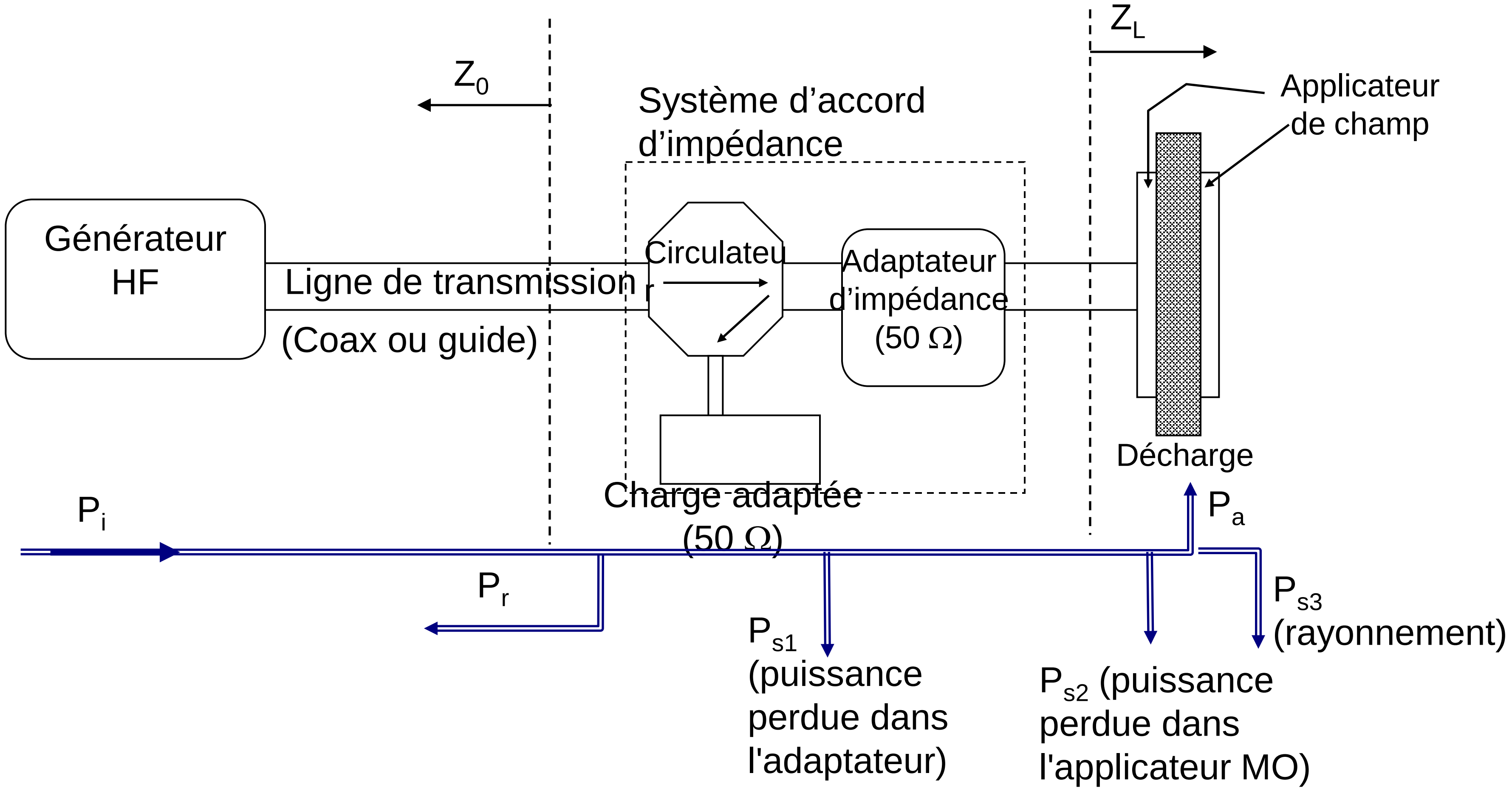


Configurations pour traitement de surface





Circuit micro-onde



Z_0

Z_L

Système d'accord d'impédance

Applicateur de champ

Générateur HF

Ligne de transmission

(Coax ou guide)

Circulateur

Adaptateur d'impédance (50 Ω)

Charge adaptée (50 Ω)

Décharge

P_i

P_r

P_a

P_{s1} (puissance perdue dans l'adaptateur)

P_{s2} (puissance perdue dans l'applicateur MO)

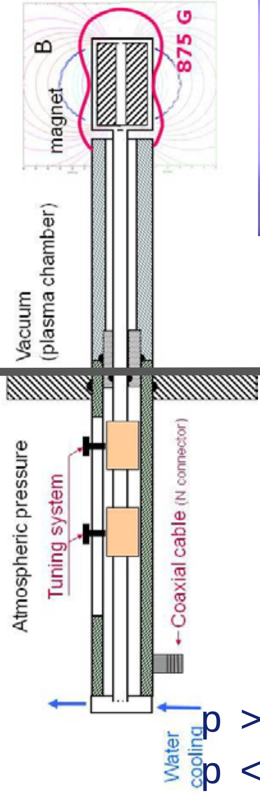
P_{s3} (rayonnement)

Excitation par antennes découplées

Sources plasma micro-onde à absorption localisée de puissance (absorption sur longueurs L < λ)

Configurations d'applicateurs (MWA)

Magnet-ended (dipolar)

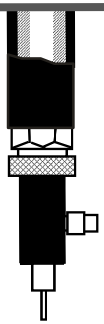


Vacuum

Air

p > 0.5 mTorr
p < 10 mTorr

Free-ended



p >100 mTorr
p < few Torr

Nouvelle conception
⇓
Extension des conditions opératoires

Efficacité énergétique améliorée

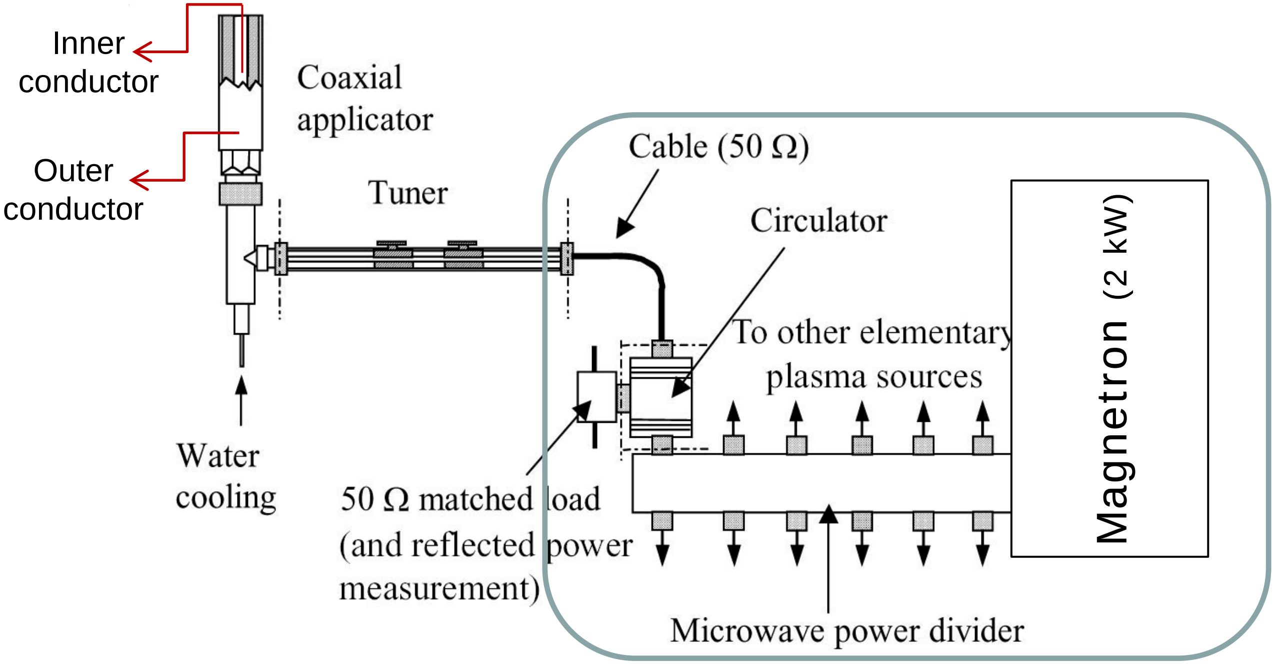
Magnet-ended (head-to-head) & Free-ended

p >0.1 mTorr
jusqu'à 65 Torr

Excitation par antennes découplées

- ❑ Chaque applicateur est alimenté individuellement via un guide diviseur de puissance
- ❑ Chaque type d'applicateur est constitué d'une structure coaxiale

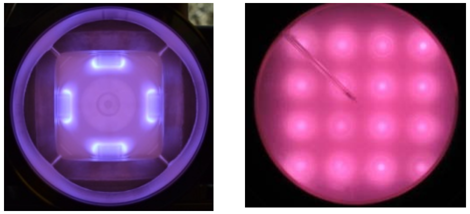
Different end-configurations according to operating parameters (power, pressure)

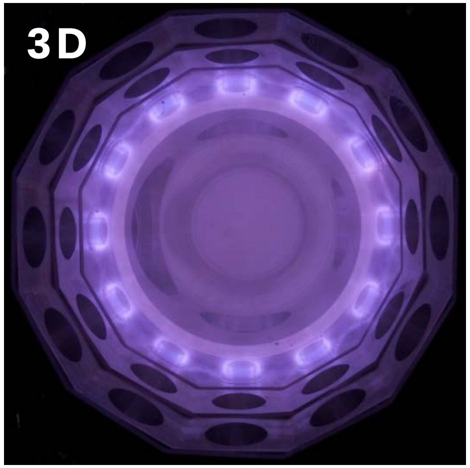


Excitation par antennes découplées
Réacteurs plasma micro-onde

Elementary plasma source (design depending on the application)

2D network distribution





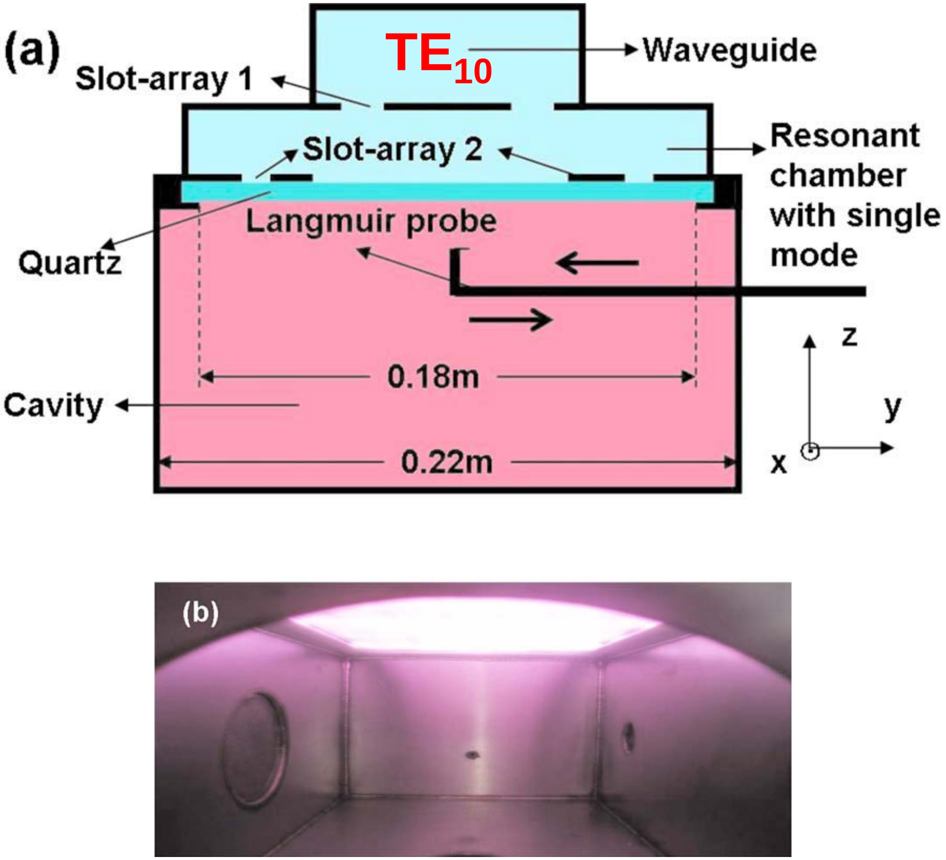
Elementary plasma sources distributed over multi-dimensional networks (0D to 3D)

Plasma set-up implemented according to the intended application

Couplage onde - plasma

- ❑ **Mode de propagation coupleur ≠ Mode dans le plasma**
  - – Composantes des champs différentes
  - – Rupture d’impédance
- ❑ **Objectifs pour avoir un « fort couplage »**
  - ❑ Avoir au moins une composante du champ dans le coupleur (guide, coax) égale à celle dans le plasma
  - ❑ Dans le plan de couplage onde-plasma, l’impédance du coupleur égale à l’impédance du plasma
- ❑ **Fort couplage : Puissance incidente (générateur) = Puissance injectée dans le plasma (exceptée les pertes d’insertion)**
  - ❑ Diminuer le nombre d’éléments de la ligne de transmission
  - ❑ Eviter la formation d’ondes stationnaires dans les adaptateurs d’impédance
  - ❑ Puissance injectée dans le plasma = puissance ohmique

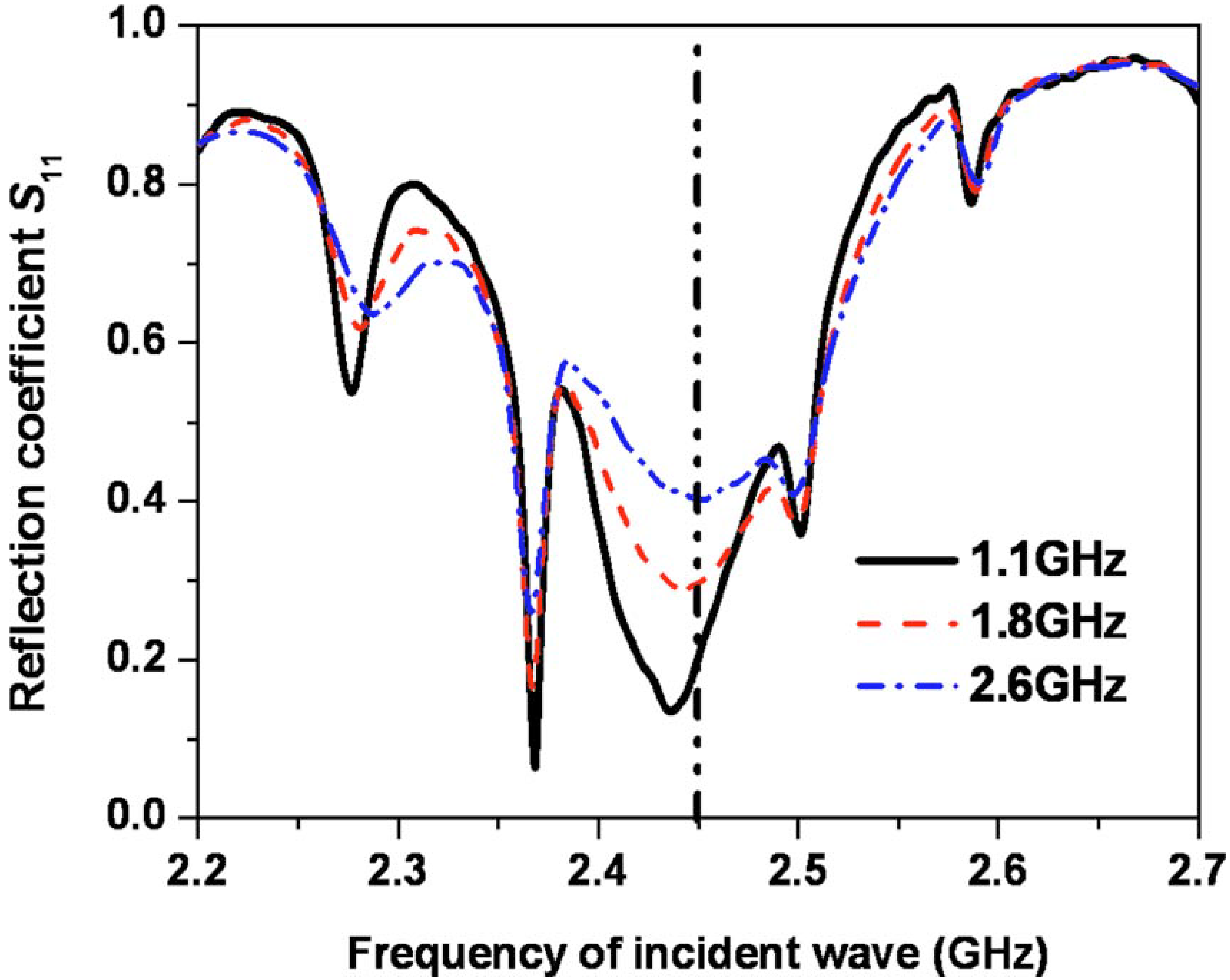
Couplage onde - plasma



Chen *et al.*, J. Appl. Phys. **106, 013314 2009**

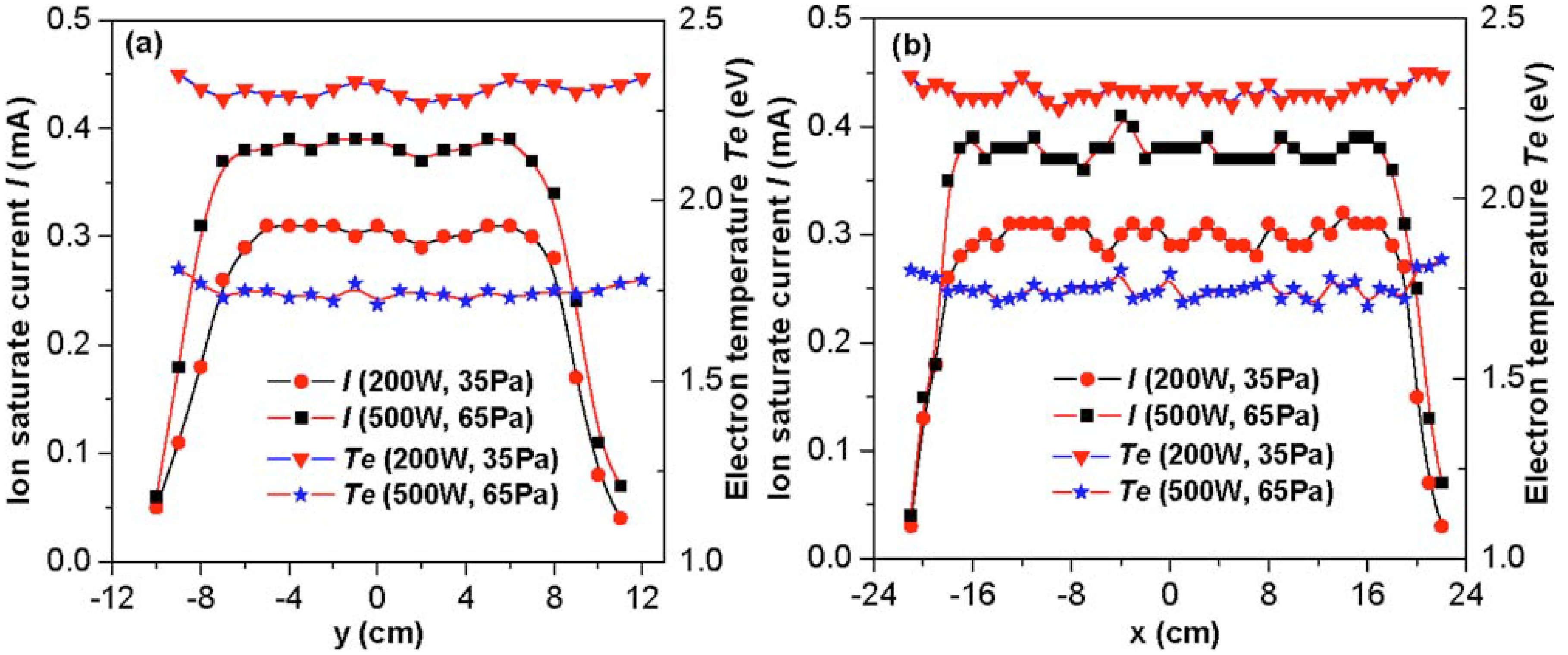
- ❑ **Objectif**
  - ➢ Transformer le mode TE_{10} guide en un seul mode TM_{110}
  - ➢ Obtenir le même champ E_z à l'interface chambre résonnante / diélectrique (adapter l'impédance)
- ❑ **Optimisation du coupleur**
  - ➢ Chambre (5 cavités résonnantes) entre le guide et la chambre plasma
  - ➢ Réseau de diffraction entre la chambre net le diélectrique
- ❑ **Résultat**
  - ➢ Fort couplage entre ondes incidente - diffractée - onde de surface
  - ➢ p = 200 – 500 mTorr

Couplage onde - plasma



Amplitude of the reflection coefficient *S11, varying*
along with the frequency of incident waves in different collision frequency.

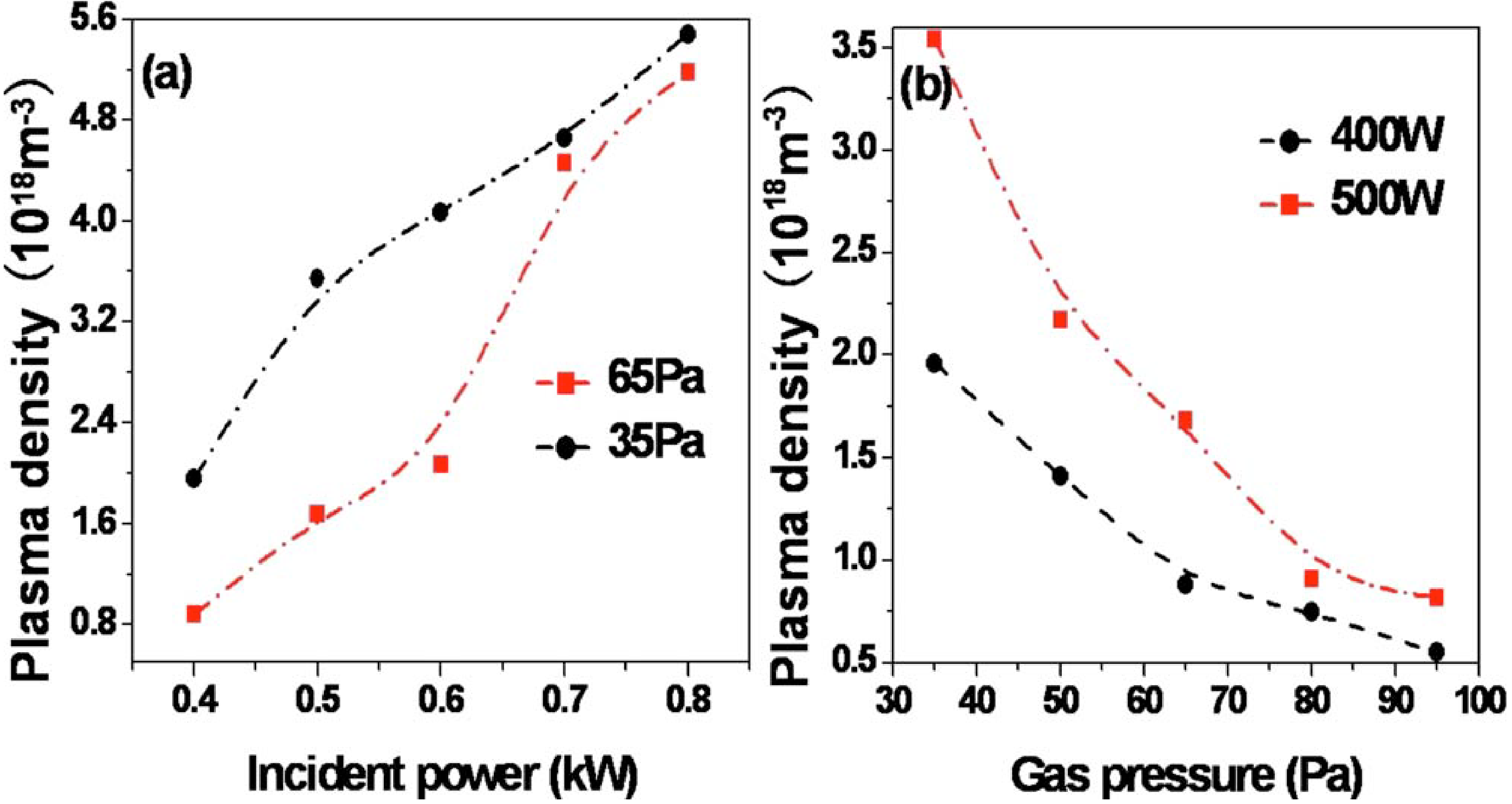
Couplage onde - plasma



Distribution of ion saturate current and electron temperature at z-axis of 3.5 cm under the quartz plate: (a) along y-direction with fixed x=−12 cm and (b) along x-direction with fixed y=0.

Chen *et al.,* J. Appl. Phys. **106, 013314 2009**

Couplage onde - plasma

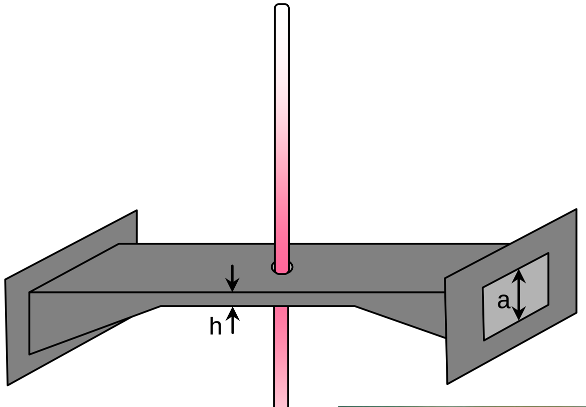


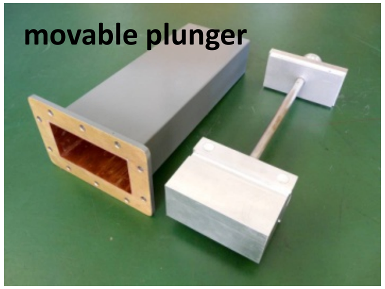
Distribution of plasma density varying along with (a) the incident power and (b) the gas pressure, at a position of probe: x= −12 cm, y=0, and z-axis of 3.5 cm under the quartz plate.

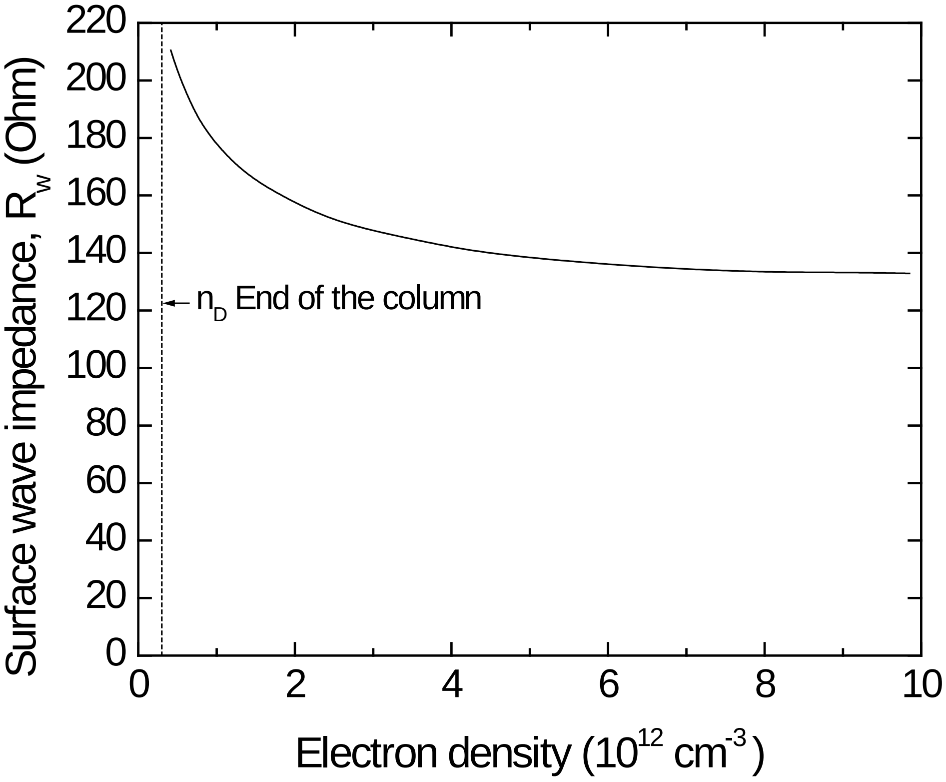
Chen *et al.,* J. Appl. Phys. **106, 013314 2009**

Couplage onde - plasma (impédance)

- ❑ Plasma column acts as a transmission line: calculated characteristic impedance value $\boldsymbol{Z_p \approx 140\text{-}160\ \Omega}$
- ❑ Reduced-height characteristic impedance: $\boldsymbol{Z_0 = 536\ \Omega \rightarrow Z'_0 = 186\ \Omega}$



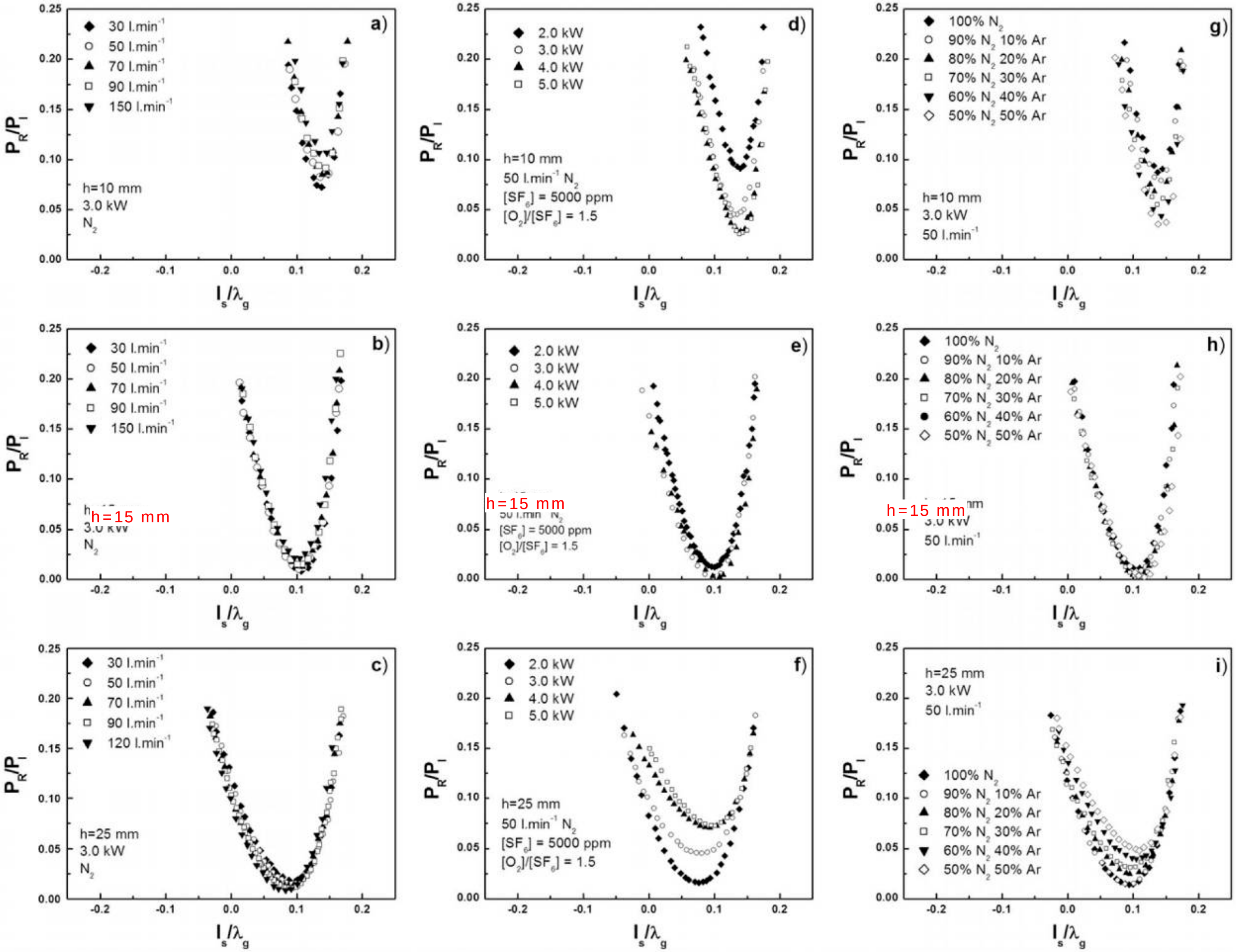


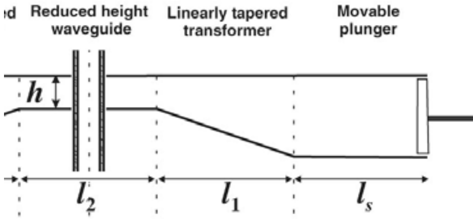


❑ n > $n_{critical}$ (sustaining condition of the surface wave) ⇒ little sensitivity on Z_p at plasma density variation (only small adjustments required)

Couplage onde - plasma (impédance)

Little sensitivity on operating conditions: gas nature, pressure and flow rate, MW power density



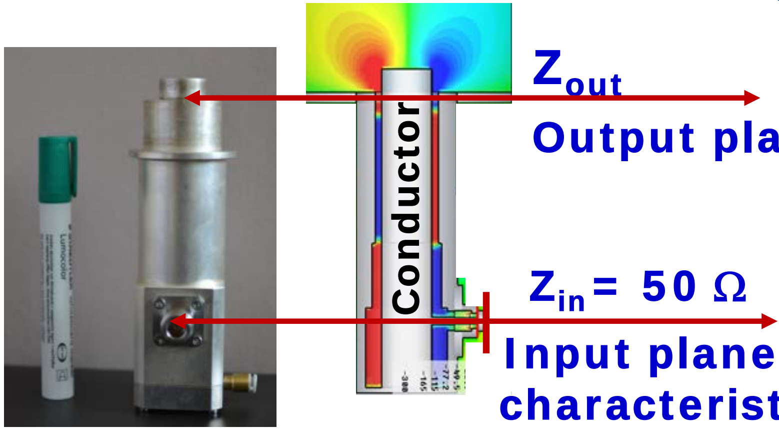


Smooth impedance tuning – movable plunger

Maximum insensitivity to operating condition changes achieved with adequate impedance transformer (h=15mm)

Couplage onde - plasma (impédance)

- **Impedance transformer**
  - Succession of several coaxial segments

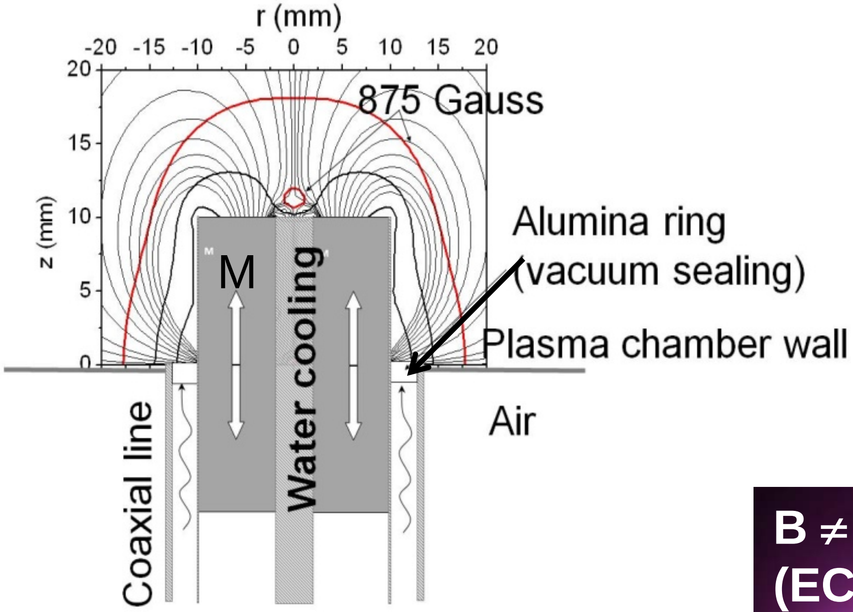


Z_{out}

Output plane

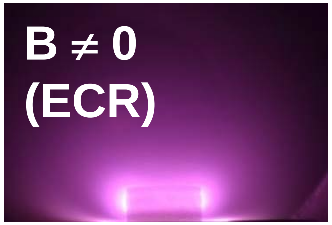
$Z_{in} = 50\ \Omega$

Input plane / Line characteristic impedance

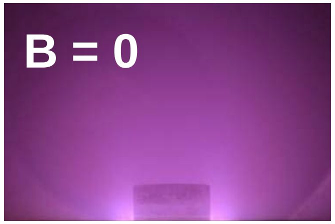


- Able to cover a **wide pressure range**
  - Magnet inserted into the central axis (**ECR** and **confinement** conditions)
  - Alumina window located at the level of plasma chamber wall (avoid plasma cavities)

Ar, P_i - P_r = 50 W



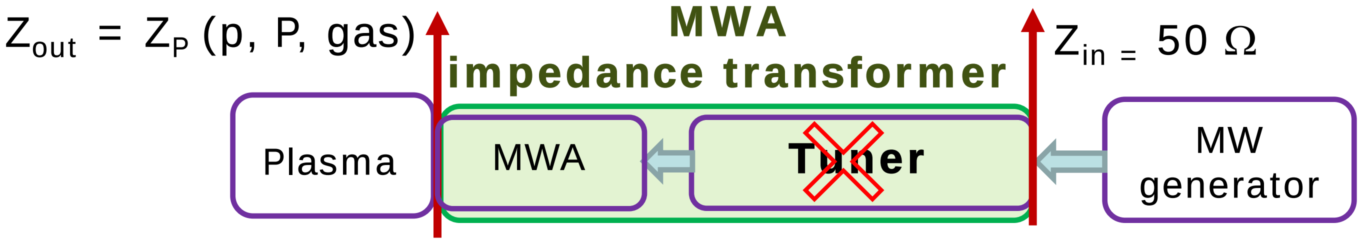
Magnet removed



p = 50 mTorr

p = 1 Torr (65 Torr)

Couplage onde - plasma (impédance)



Z_{out} = Z_P (p, P, gas)

MWA impedance transformer

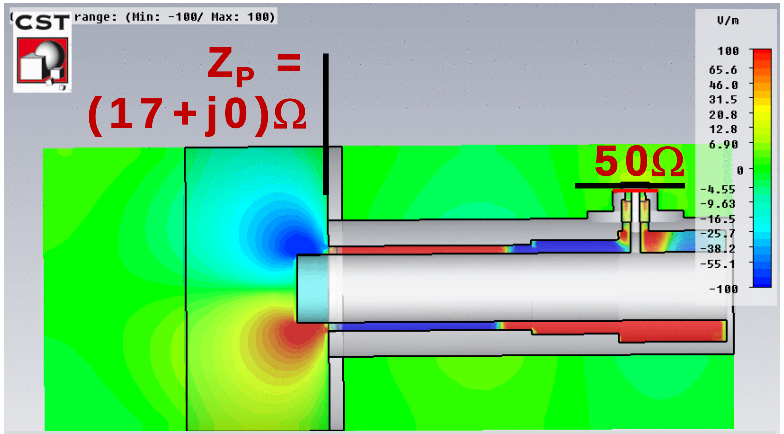
Z_{in} = 50 Ω

Plasma

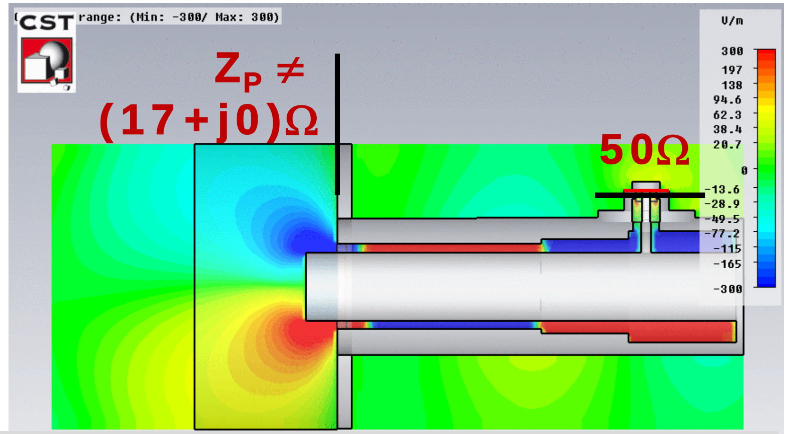
MWA

~~Tuner~~

MW generator



Progressive wave (P_r = 0)

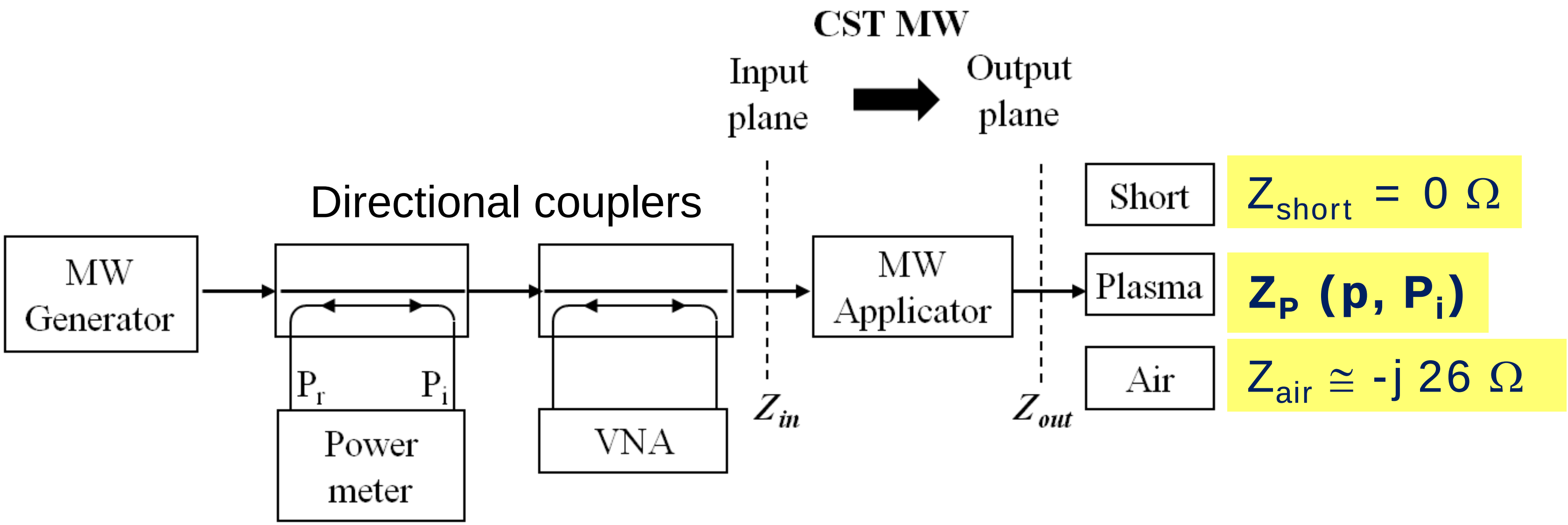


Stationary wave ($P_r \neq 0$)

- MWA designed to be adapted for Z_{out} = (17 + j0) Ω in the out plane ⇒ Progressive wave ⇒ **Maximum in power transfer (no reflection,** no more need of the tuner**)**
- **Z_p (p, P, gas, geometry) plasma impedance measurements are mandatory**
- The knowledge of the plasma impedance allows **re-designing new applicators over operating conditions range** (p, P, gas)

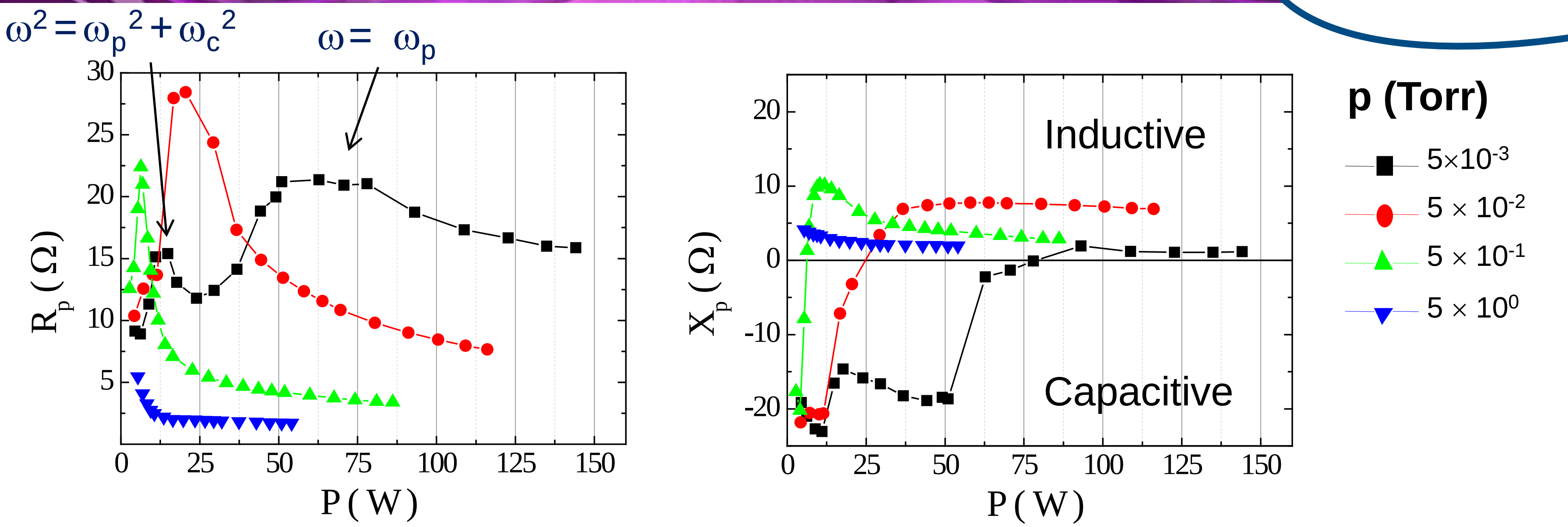
Couplage onde - plasma (impédance)

- **Plasma impedance Z_p / Methodology**
  - Z_{in}: measurements by VNA (Vector Network Analyser)
  - $Z_{out} := f\,(Z_{in}, Z_{pq})$, Z_{pq} impedance matrix (intrinsic) elements by CST-software
  - Validation simulation / experiment ($Z_{out} = Z_{short}$ and Z_{air})
- **Coupling (transmission) efficiency $\eta = (P_i - P_r) / P_i$**
- **Heating (ohmic absorption) efficiency $\eta_a = P_a / (P_i - P_r) = f\,(Z_{out})$**



- **Domains explored**
  - f = 2.45 GHz, Argon, **p = 0.3 to 5000 mTorr**, **P_i = few to 200 W**

Plasma impedance & Energy efficiency



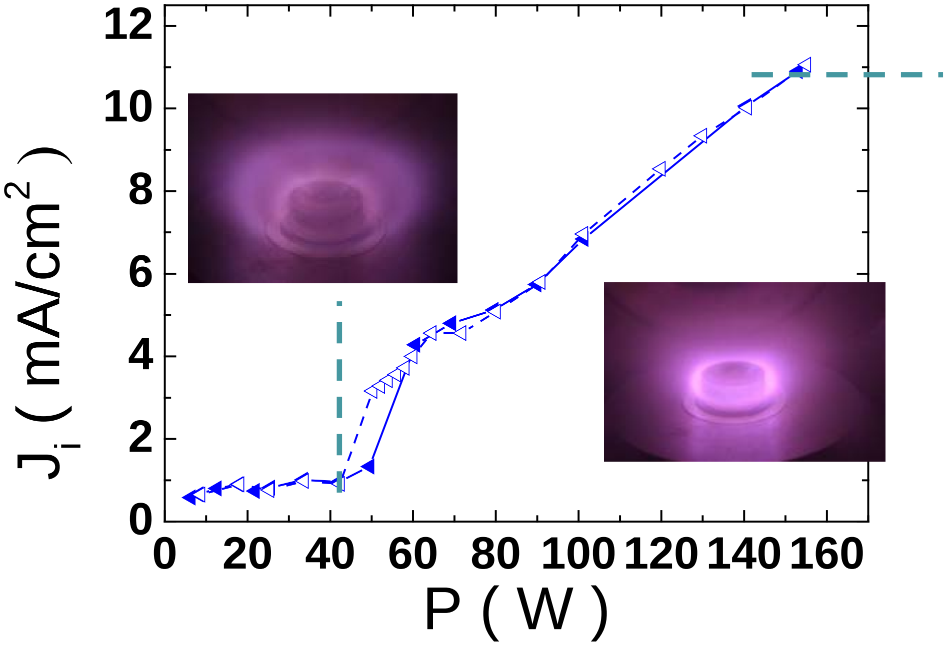
Real (R_p) and imaginary (X_p) of plasma Z_p as a function of transmitted power ($P = P_i - P_r$)

- **Reactive part** of plasma impedance
  - Capacitive → Inductive Transitions (shift to P↘ when p↗)
  - P ↘ ↘: Capacitive behavior governed by vacuum impedance $Z_{plasma} \approx Z_{air} = (0 - j\ 26)\ \Omega$
- **Real part** of plasma impedance
  - R_p peaks correlated with X_p jumps
  - Except peaks, normal behavior of $R_p = f(P, p)$
- **Jumps related to the changes in the propagation conditions** ($\omega= \omega_p$, $\omega^2=\omega_p^2+\omega_c^2$)

  EM mode → EP mode (attenuated within few millimeters in Landau damping)

Plasma impedance & Energy efficiency

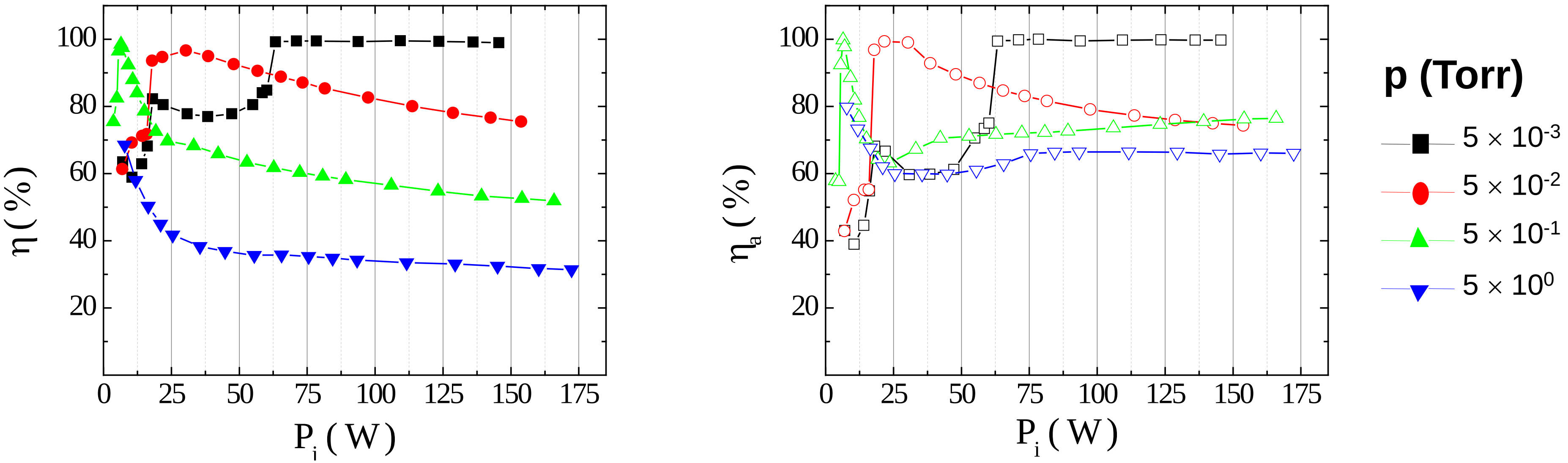
- Reactance jumps accompanied by
  - Jumps in ion current and plasma densities
  - Dimensional contraction of the plasma



$n_i \approx 10^{11}$ cm^{-3}
(50 mm away from source)

Ion current density J_i (50 mm away from source)
as a function of transmitted power $P = P_i - P_r$

Plasma impedance & Energy efficiency



Power transfer efficiency ⇒ ***Heating efficiency***

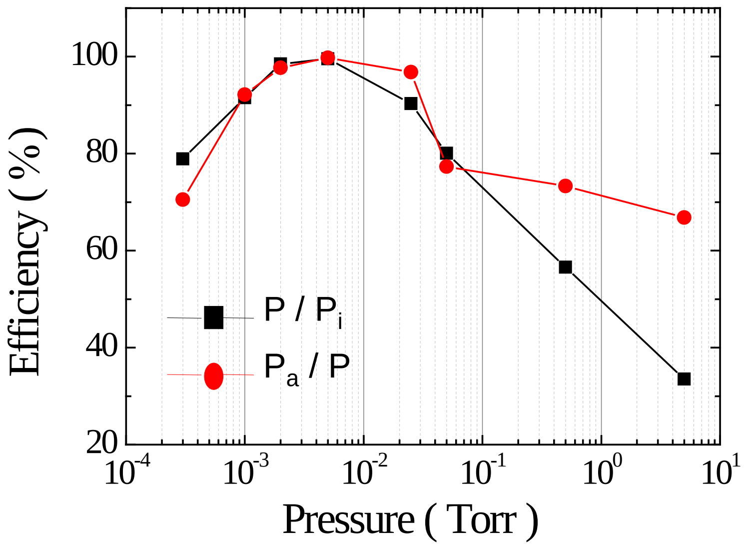
$$\eta = (P_i - P_r)/P_i = P/P_i$$

$$\eta_a = P_a / P = \frac{R_p}{\sqrt{R_p^2 + X_p^2}}$$

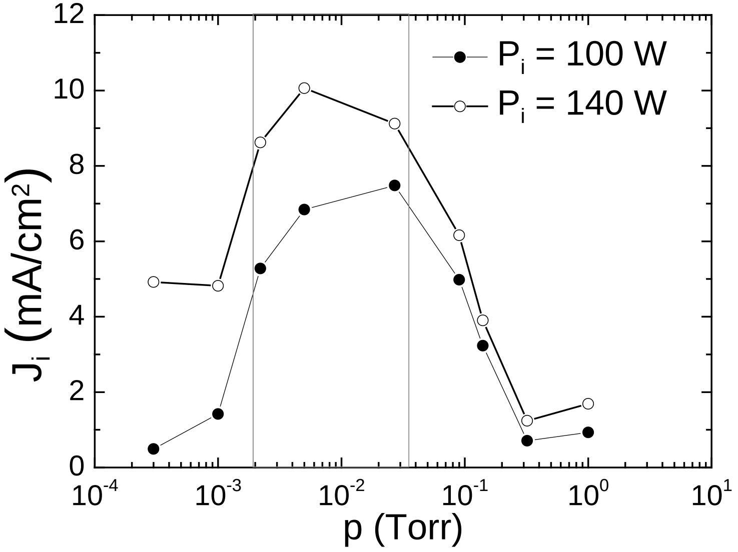
- ❑ Transmission efficiency $P/P_i \approx 100$ %
  - – Reached for several sets of pressure and power (p,P)
  - – **15 Ω < Z_p < 20 Ω** (MWA designed to be matched for Z_{out} = 17 Ω)
- ❑ Heating efficiency $P_a/P \cong$ 100 %
  - – $Z_p \rightarrow R_p$ +j0 (resistive plasma behavior)

Plasma impedance & Energy efficiency

- Power efficiencies greater than 90% - Plasma performance maximized for at least one order of magnitude of pressure (1-20 mTorr)



Transmission η = P/P_i and heating η_a = P_a / P efficiencies as a function of Ar pressure (P_i = 100 W)



Ion current density as a function of Ar pressure (@ 50 mm away from source)

Applications

☐ Gravure

☐ Traitement de surface (nettoyage)

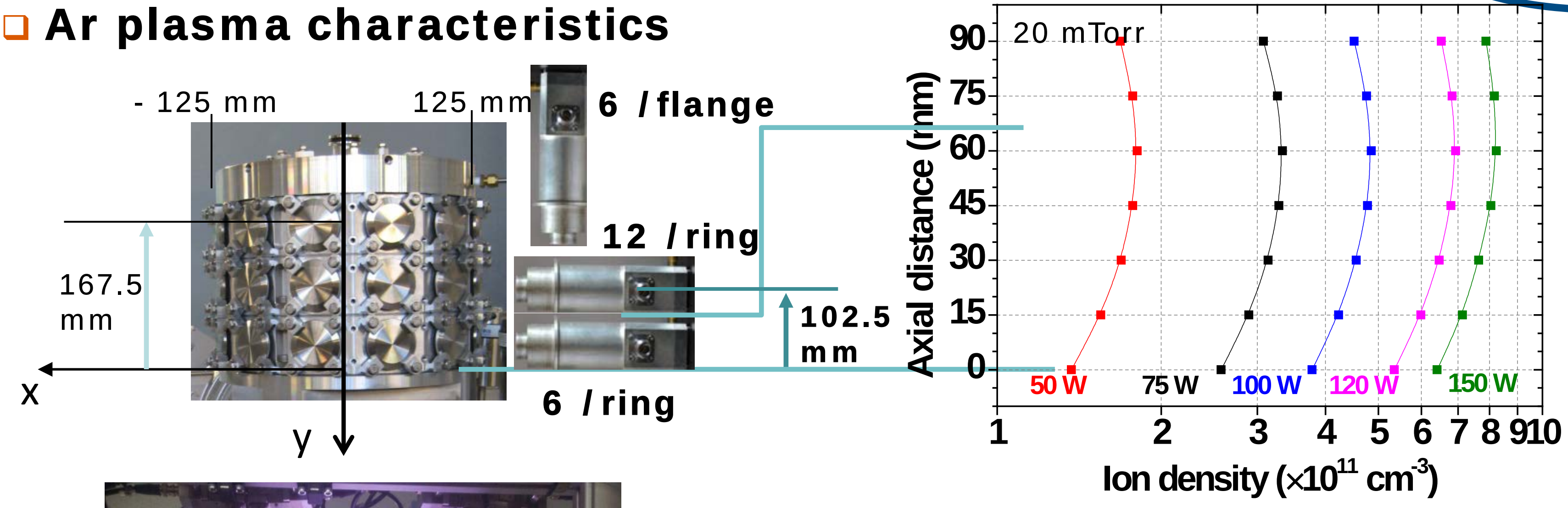
☐ Dépôt PECVD

☐ Dépôt par pulvérisation cathodique assistée par plasma micro-onde

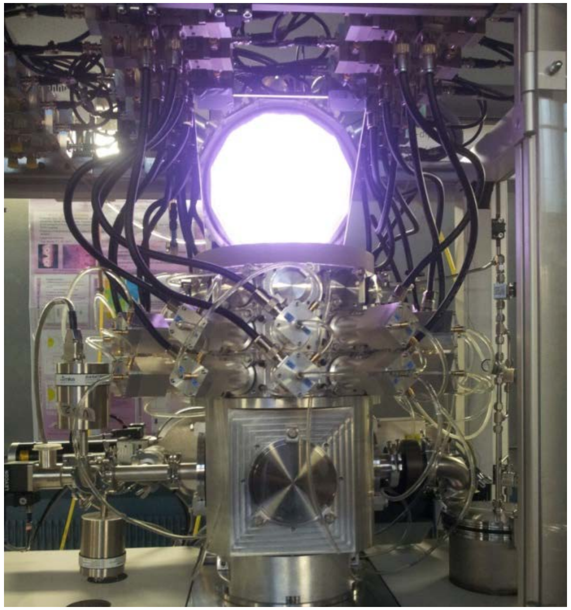
☐ Production d’espèces actives (« remote plasma »)

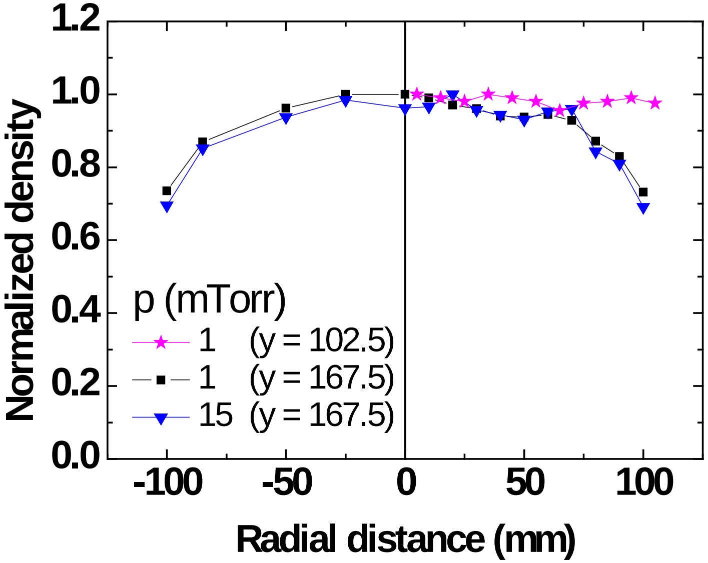
Microwave plasma / 3D configuration
High Density / Uniformity

❑ Ar plasma characteristics



High plasma density (~10^{12} cm^{-3}, 150 W / source)

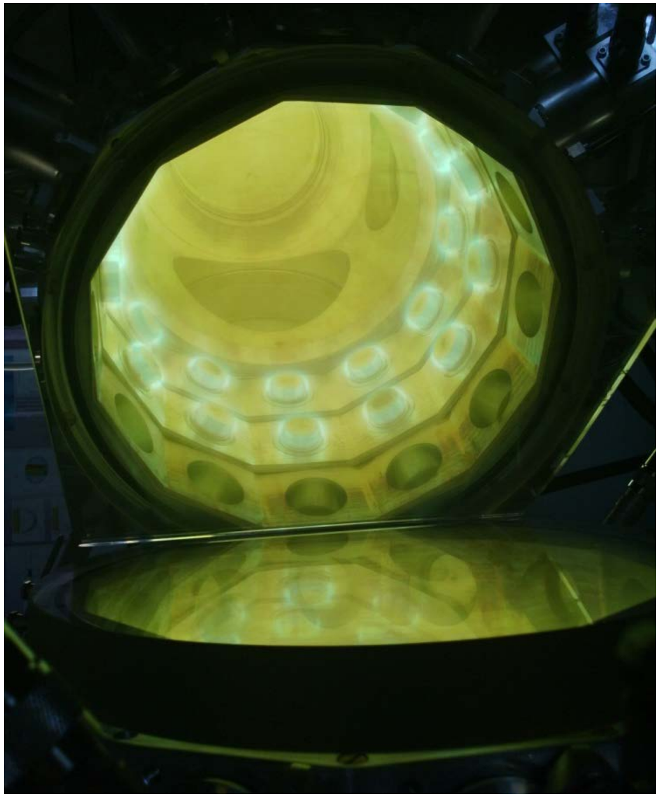




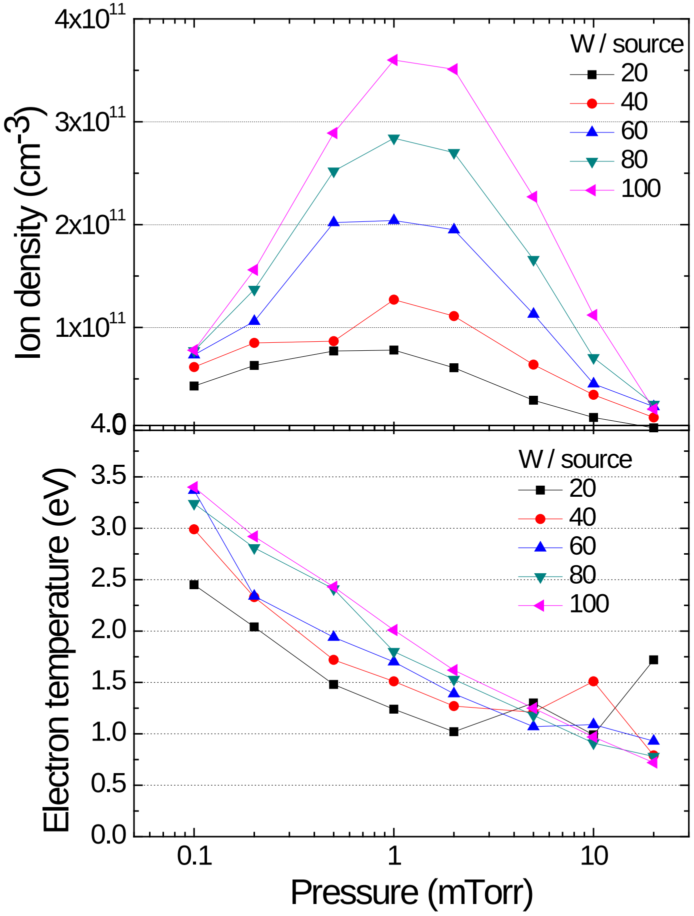
Uniformity over large size (∅ = 200 mm)

Microwave plasma / 3D configuration
Application to plasma processes (etching)

- Fundamental study of steric effects : Halide (F,Cl, **Br, I**) / 4st column (C, **Si, Ge, Sn**)



Iodine plasma (0.5 mTorr, 50 W/source)

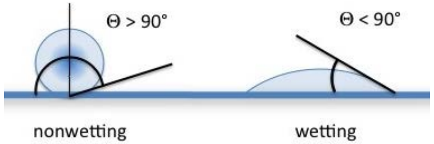


Iodine plasma parameters

- **Gravure polymères (O, autre gaz)**
- **Gravure diamant monocristallin (O+Ar)**
  11 μm / h

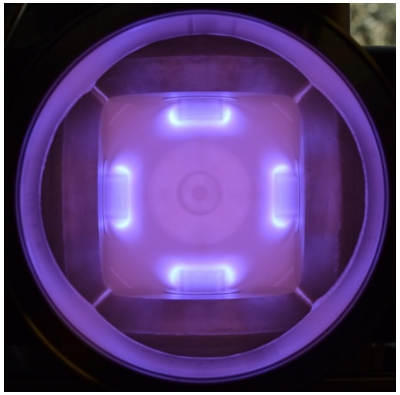
Microwave plasmas
Application to surface cleaning

- Thin films deposition by Plasma PVD on running stainless steel wire
  - Deposition chamber (cylindrical AC magnetron)
  - **Cleaning chamber (4 elementary MW plasma sources)**

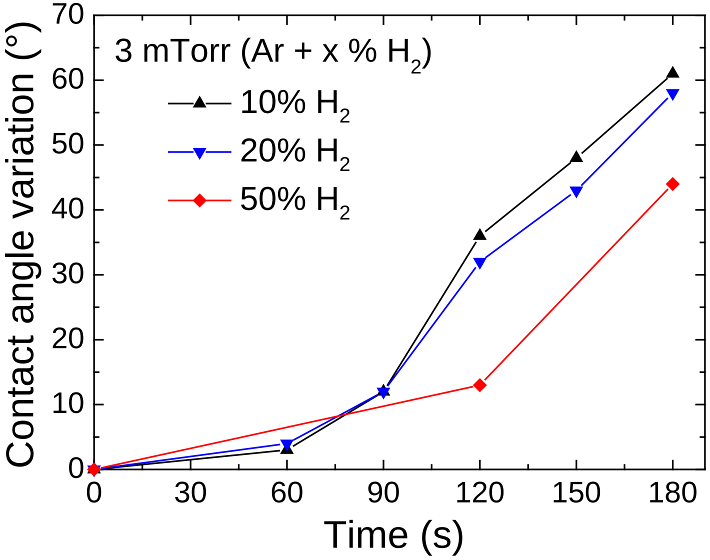


Deposition without cleaning

Deposition with cleaning



Plasma cleaning chamber
Ar, 20 mTorr, 200 W/source

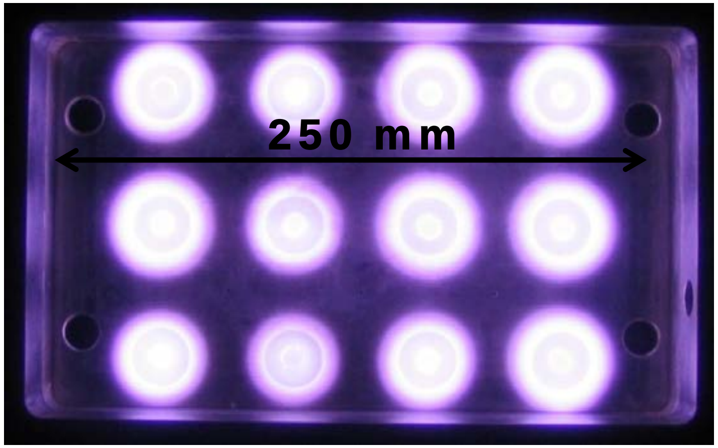


Contact angle variation Δθ = θ_{in} - θ_{fin}
as a function of time processing (200 W)

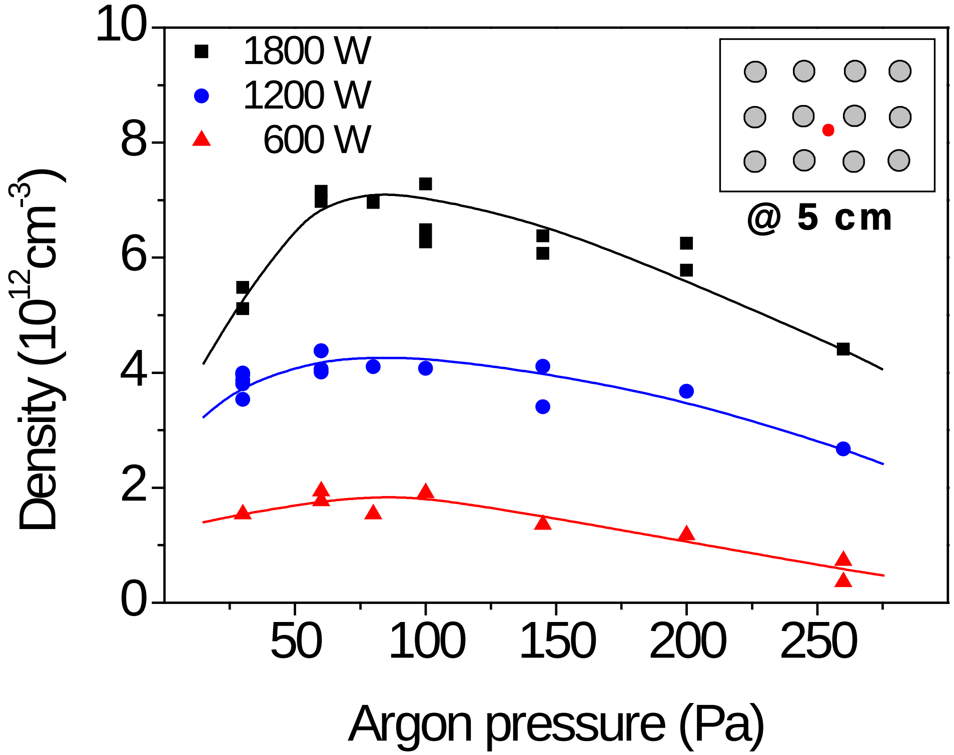
Measurements in ambient atmosphere
(2–5 minutes) ⇒ Recontamination

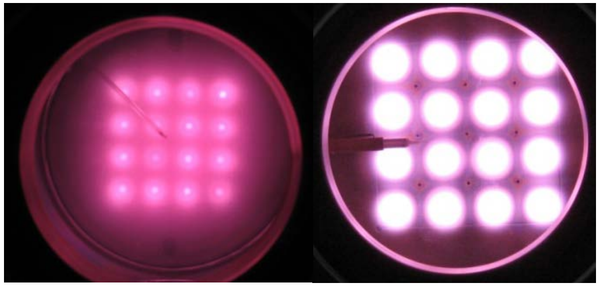
Microwave plasma / 2D- matrix configuration
Applications to PECVD deposition

- ❑ Application to surface processes with high processing rates
  - – High plasma density (> 10^{12} cm^{-3}) over 0.1 Torr - few Torr pressure range



Localized plasma
(500 W, 41.7 W/S)

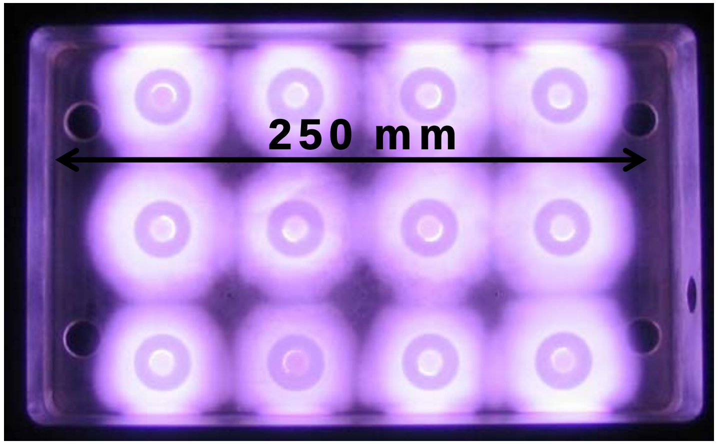




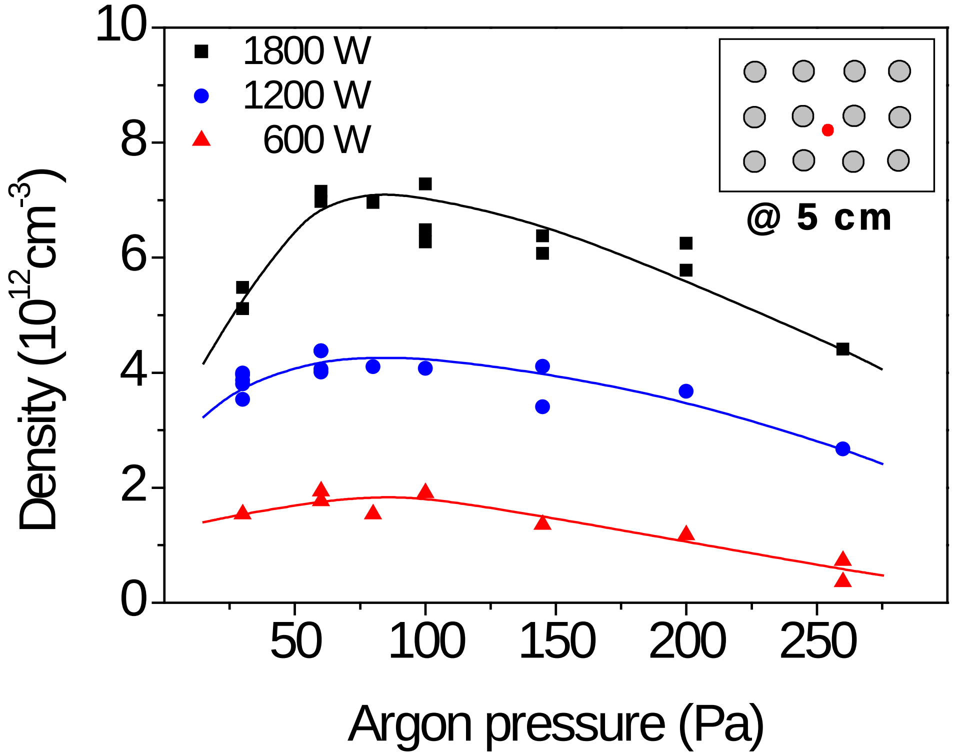
- ❑ **New application to large area polycrystalline diamond deposition** (LSPM - CNRS - University Paris 13)
- ❑ Photo : H_2, 0.2 and 1 Torr, 100 W/source

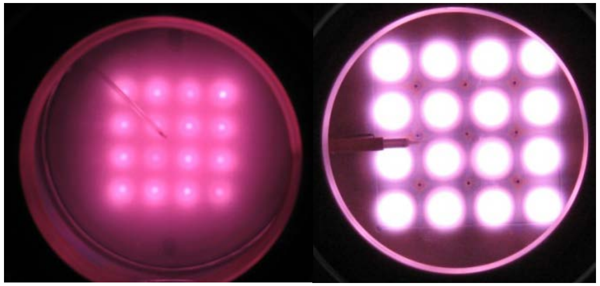
Microwave plasma / 2D- matrix configuration
Applications to PECVD deposition

- ❑ Application to surface processes with high processing rates
  - High plasma density (> 10^{12} cm^{-3}) over 0.1 Torr - few Torr pressure range



Plasma expansion (P ↑)



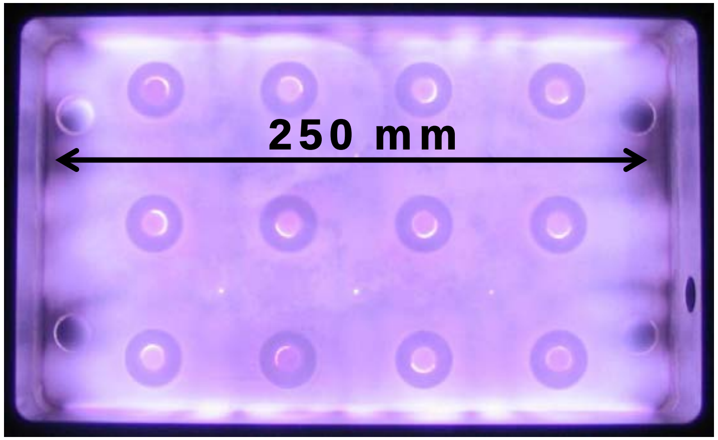


❑ **New application to large area polycrystalline diamond deposition** (LSPM - CNRS - University Paris 13)

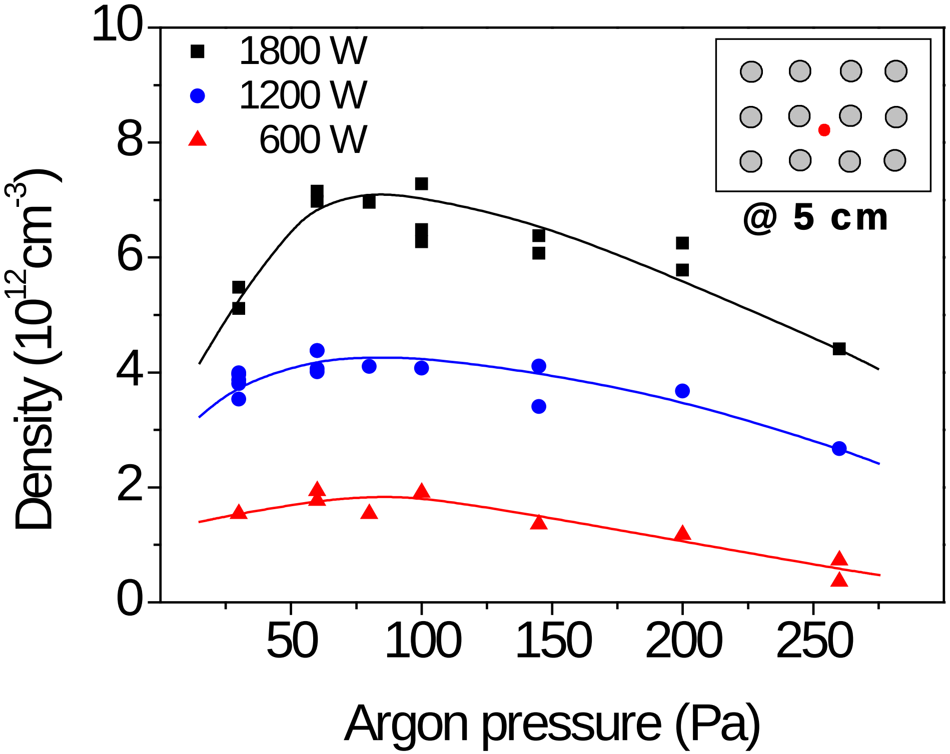
❑ Photo : H_2, 0.2 and 1 Torr, 100 W/source

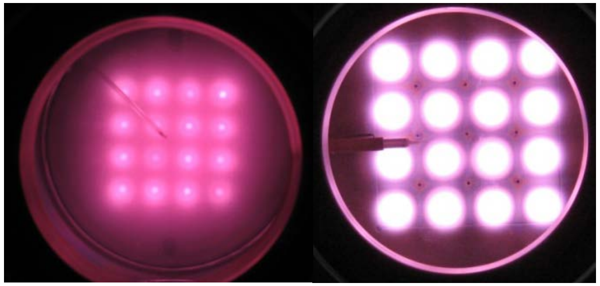
Microwave plasma / 2D- matrix configuration Applications to PECVD deposition

- ❑ Application to surface processes with high processing rates
  - – High plasma density (> 10^{12} cm^{-3}) over 0.1 Torr - few Torr pressure range



Uniform plasma
(1500 W, 125 W/S)

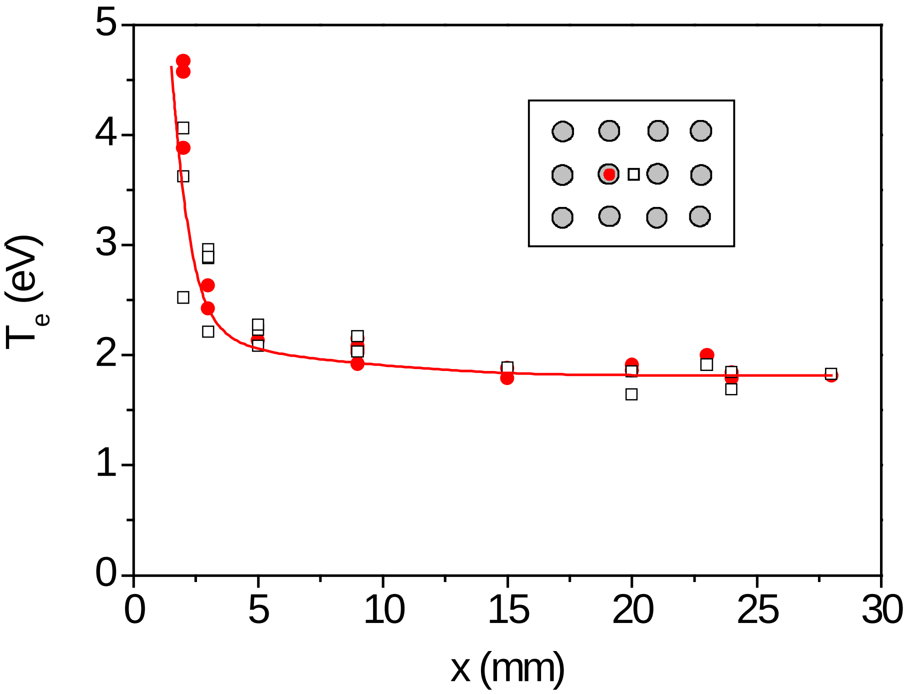


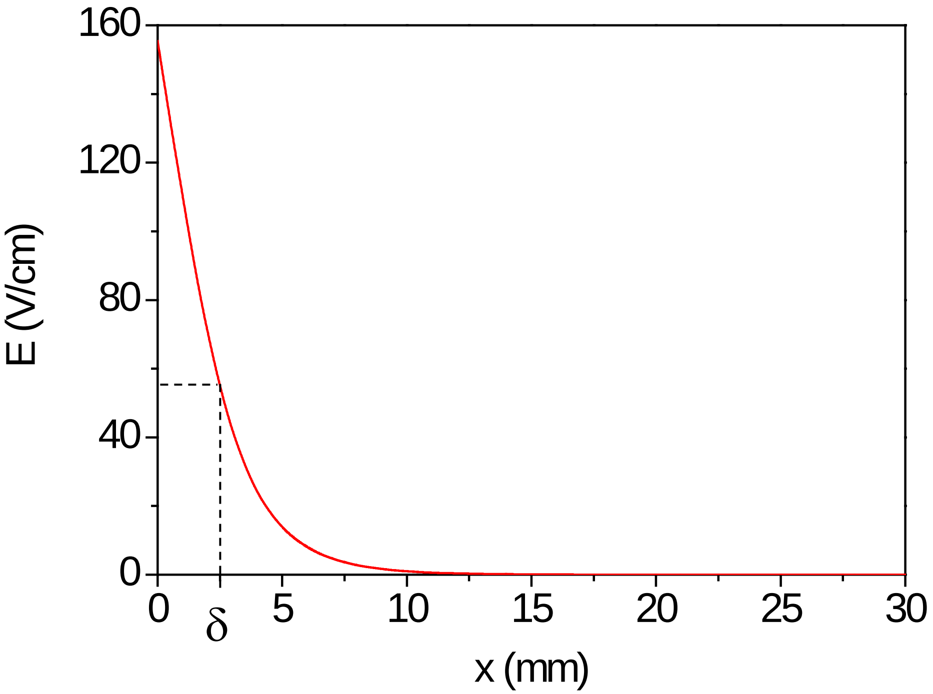


- ❑ **New application to large area polycrystalline diamond deposition** (LSPM - CNRS - University Paris 13)
- ❑ Photo : H_2, 0.2 and 1 Torr, 100 W/source

Microwave plasma / 2D- matrix configuration
Applications to PECVD deposition

Température électronique en fonction de la distance par rapport au plan de source



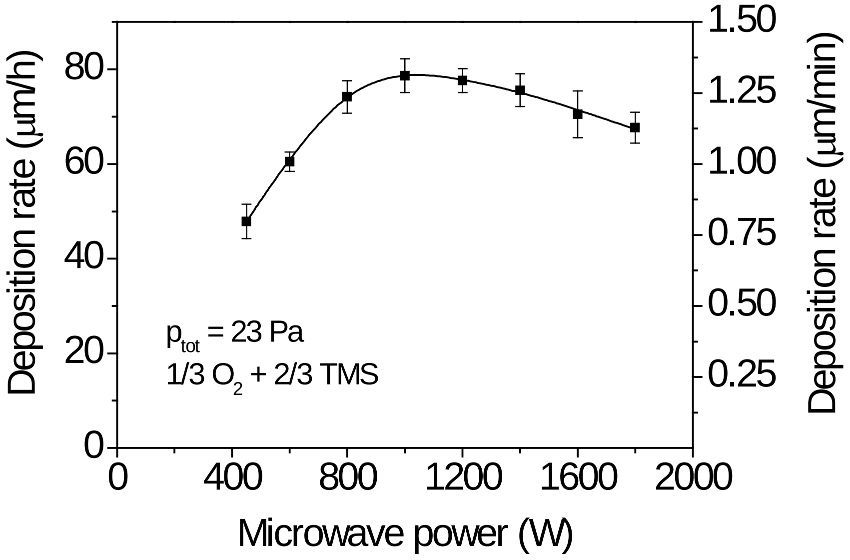


- T_e élevée à proximité du plan de source (fort champ HF)
- T_e constante dans le corps du plasma à partir de $x \geq \delta$ (épaisseur de peau)

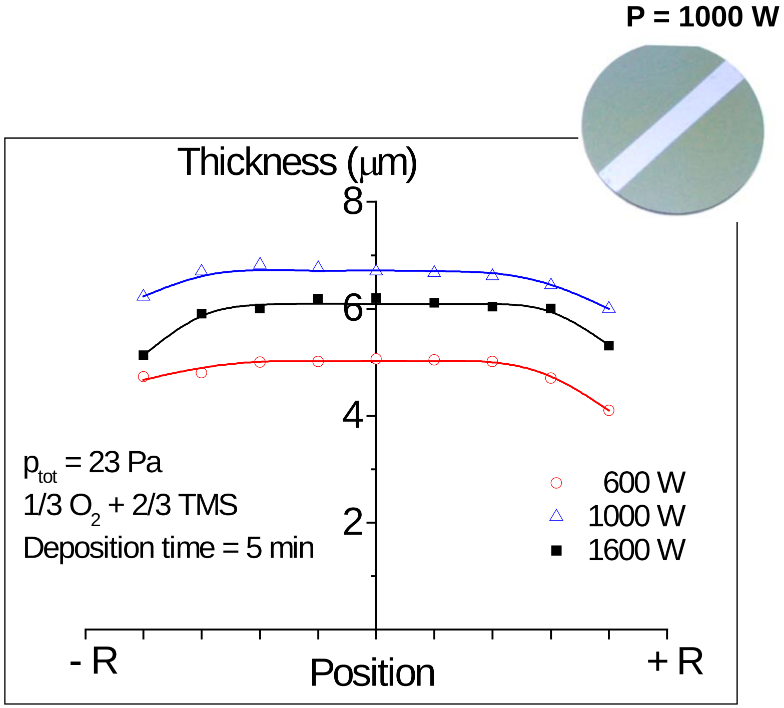
$p_{Ar} = 60$ Pa
$T_g = 500$ K
$P_W = 1200$ W

Microwave plasma / 2D- matrix configuration
Applications to PECVD deposition

- ❑ Evaluate deposition rate and uniformity of SiCH based films for anticorrosion or passivation applications
- ❑ SiOCH (O_2 /TMS, 20 to 70 Pa, 150 to 500 mTorr)

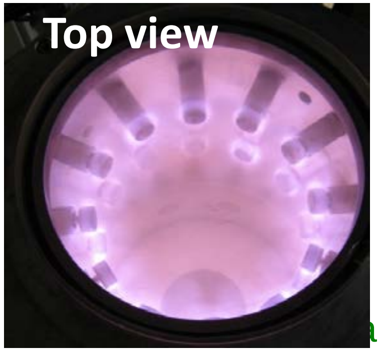


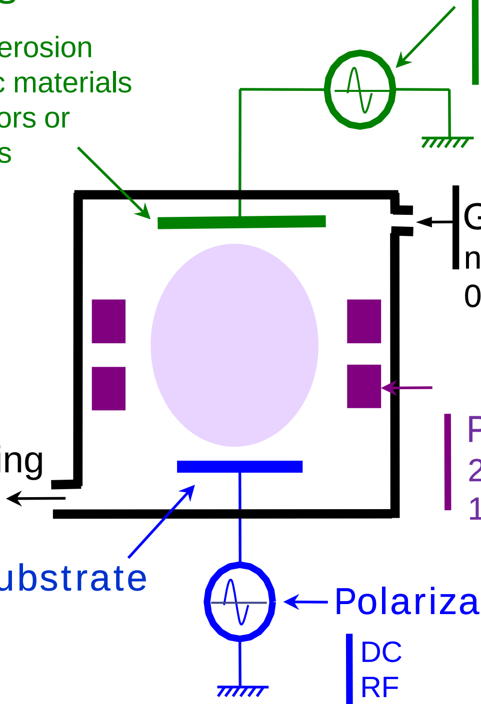
High deposition rate as a function of microwave power (O_2/TMS plasma)



Thickness uniformity of SiOCH films better than 5 % (O_2 /TMS plasmas, wafer 2R = 75 mm)

Plasma assisted sputtering: adequate technology for deposition of complex thin film materials





ation

DC
RF
Pulsed
DC

Targets

Uniform erosion
Magnetic materials
Conductors or insulators

Gas
neutral or reactive
0.5 to 10 mTorr

Plasma sources
24 MW Applicators
10 - 200 W/source

Pumping

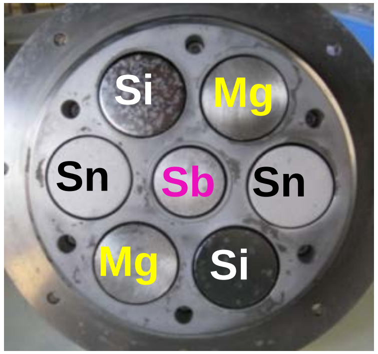
Substrate

Polarization / T_s

DC
RF
Pulsed DC

- **Features of the process**
  - Quasi-Independent control of process parameters
    - Particle flux (←microwave power)
    - Energy flux (← independent & individual bias)
    - Selective pulsed microwave power (plasma excitation mode)
  - In-situ processing (sequential steps in the same plasma chamber)
    - Substrate cleaning
    - Cleaning and conditioning of targets
    - Deposition process
  - No magnetic field behind targets
    - Reliability / No drift of process parameters
    - Sputtering of magnetic materials
- **Thin film materials**
  - Complex compounds (co-sputtering)
  - Fully controlled composition

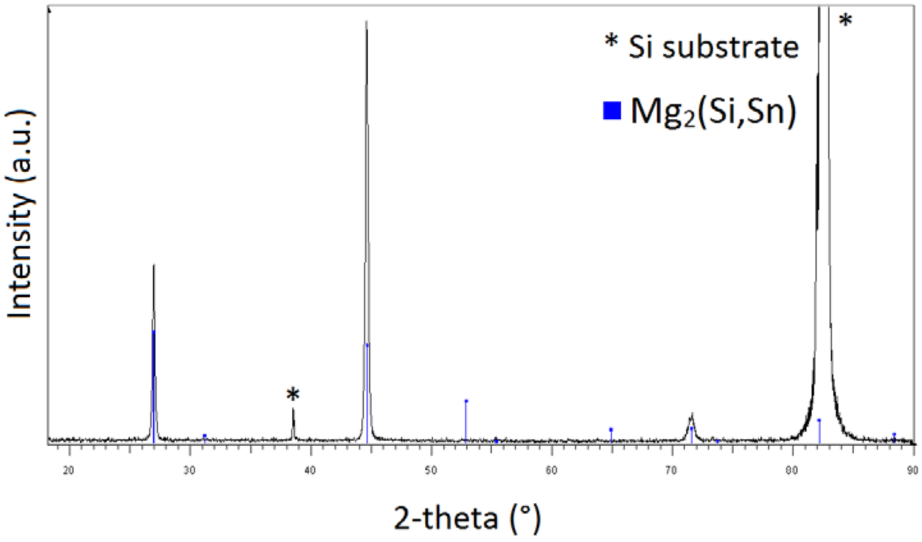
Plasma assisted sputtering: adequate technology for deposition of complex thin film materials



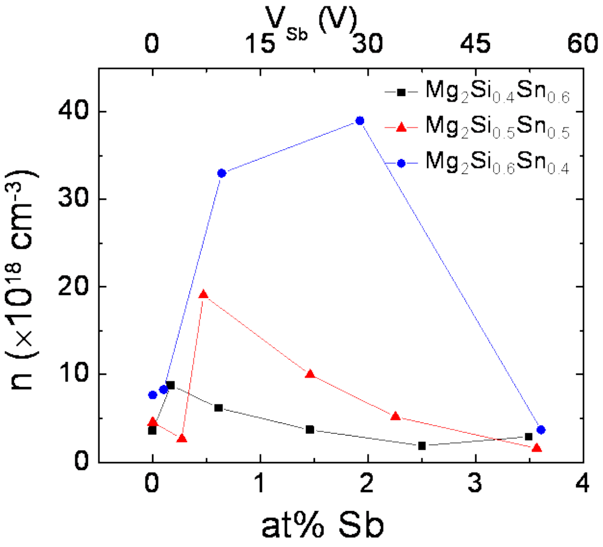
Ternary films grown - $Mg_2(Si,Sn)$ - Thermoelectric material

Process parameters : 2 kW, 1 mTorr, 350 /420/220 V (Mg/Si/Sn),
$V_S = V_f$, 2h, d = 12 cm

- **Fully controlled stoichiometry**
- **Controlled doping content**



X-ray diffraction pattern for $Mg_2Si_{0.4}Sn_{0.6}$ solid-solution

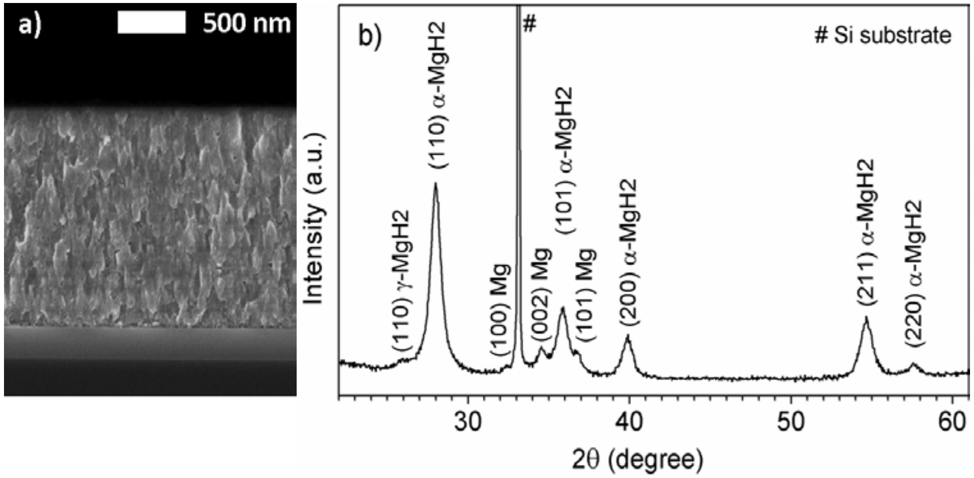


Variation of charge concentration with Sb doping

Plasma assisted sputtering: adequate technology for deposition of complex thin film materials

- Magnesium hydride **MgH_2 → Mg_7TMH_x hydrides** (**TM** - transition metal)
  - Lower desorption temperature (~160°C) than MgH_2 (360°C)
  - High storage capacity (i.e. ~5.5 wt.% for Mg_7TiH_x) comparable to MgH_2 (i.e. ~7 wt.%)

- **Methods for MgH_2 thin films synthesis**
  - Ex-situ process
    - Mg deposition+ High Pressure hydrogenation
  - In-situ process (direct synthesis)
    - RF reactive sputtering (mTorr Ar/H_2)
    - Activated RE (0.2 mTorr H)
- **Main issues**
  - MgTM no stable phase → in-situ hydrogenation is mandatory
  - In-situ process : incomplete hydrogenation (%MgH_2 ~40-80 mol%)

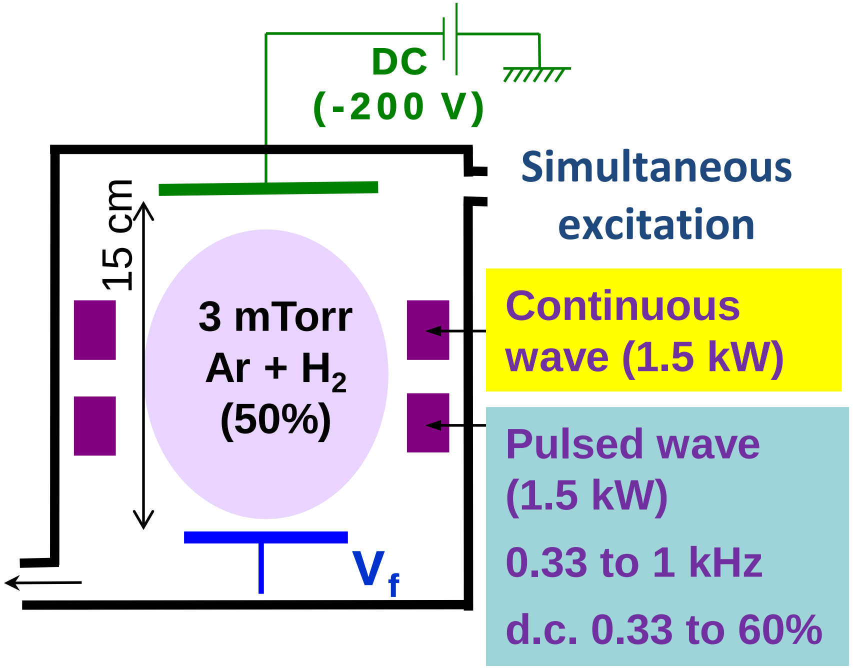


SEM fracture cross-sectional image (a) and XRD pattern (b) of film deposited in pulsed mode (see hereafter)

- **Microwave plasma / Process flexibility**
  - Higher control of the process **leading to the optimization** of the MgH_2 content

Plasma assisted sputtering: adequate technology for deposition of complex thin film materials

- **Magnesium hydride MgH_2 deposited by reactive sputtering**
- **Hybrid excitation mode:** control of the Flux & Energy flux of the most particles providing energy on the deposition surface



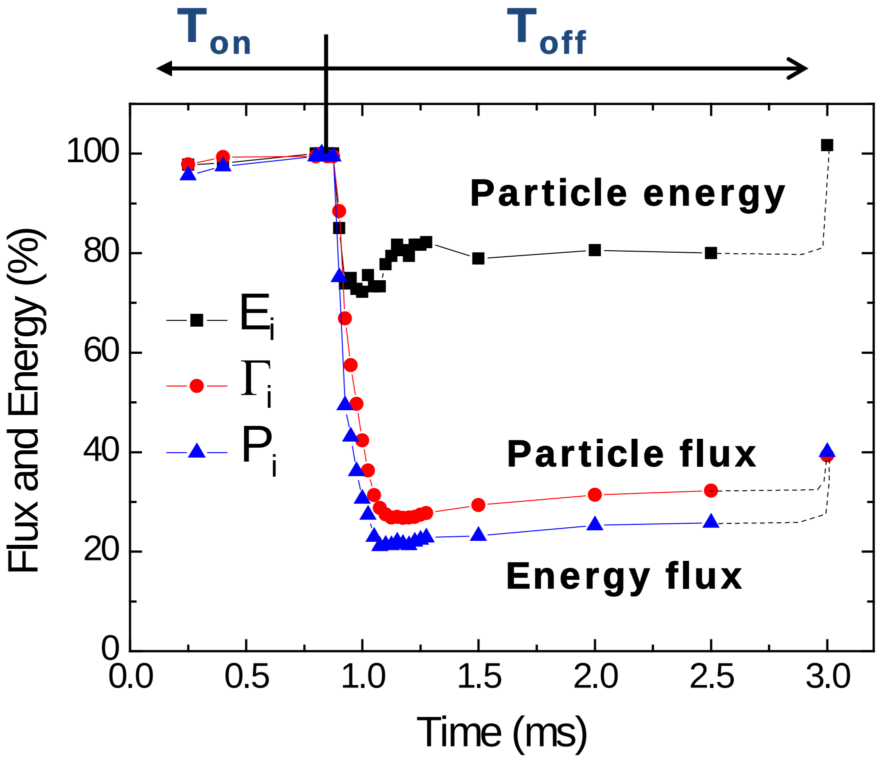
Simultaneous excitation

Continuous wave (1.5 kW)

Pulsed wave (1.5 kW)

0.33 to 1 kHz

d.c. 0.33 to 60%

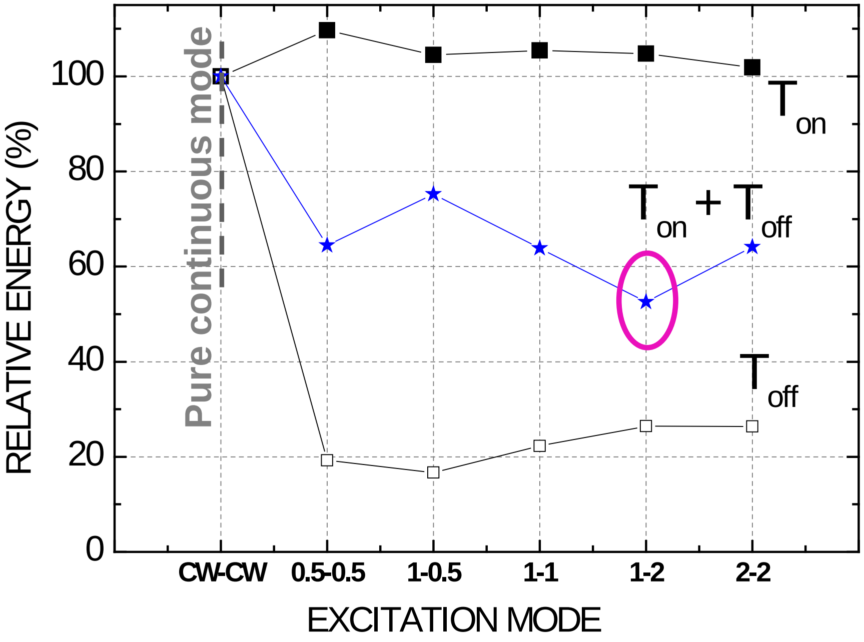


- Energy flux reduced of 80% - T_{off}

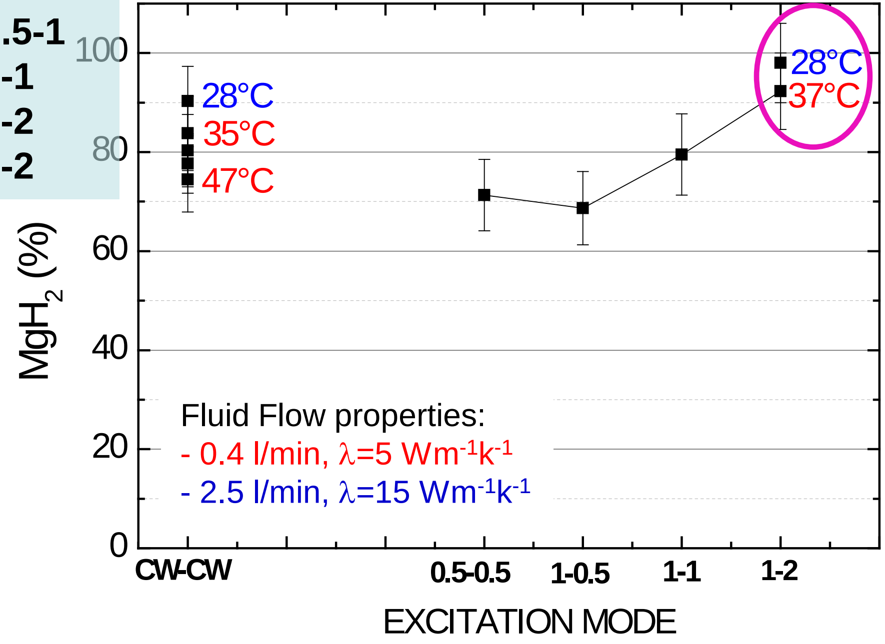
Plasma assisted sputtering: adequate technology for deposition of complex thin film materials

Cycles T_{on} - T_{off} (ms-ms)

0.5-0.5
0.5-1
1-1
1-2
2-2



Energy flux for different sets of T_{on} - T_{off} (normalized to the energy flux of the entirely continuous mode CW-CW)



MgH_2 content as a function of excitation mode for different substrate temperatures
[≥ 98 mol% for 1-2 (ms) cycle]

- Optimization of the MgH_2 content by the management of the energy through substrate temperature (thermal energy) and pulsed excitation mode (local and transient energy)

Plasmas micro-onde
Avantages et inconvénients

- ☐ **Avantages**
  - *Configurations très variées (compactes ou étendues) pour l'obtention des plasmas homogènes sur grandes dimensions*
  - *Absence d'électrodes - contamination limitée, pas de bombardement des surfaces (gaines)*
  - *Polarisation indépendante des surfaces sans incidence sur l'impédance du plasma (contrairement aux décharges RF capacitives)*
  - *Plasma pulsé sans problèmes d'accord d'impédance*
  - *Large domaine opératoire*
    - Haute densités (procédés grande vitesse) ou basses densités (fiable température de gaz)
    - Pression de 10^{-1} mTorr jusqu'à la pression atmosphérique
    - Puissance de 100 mW à 6 kW
    - Possibilité ECR (hautes densités à très basse pression)

- ☐ **Inconvénients**
  - *Fenêtre diélectrique (injection des micro-ondes, passage sous vide)*