Physique des réacteurs plasmas radiofréquence

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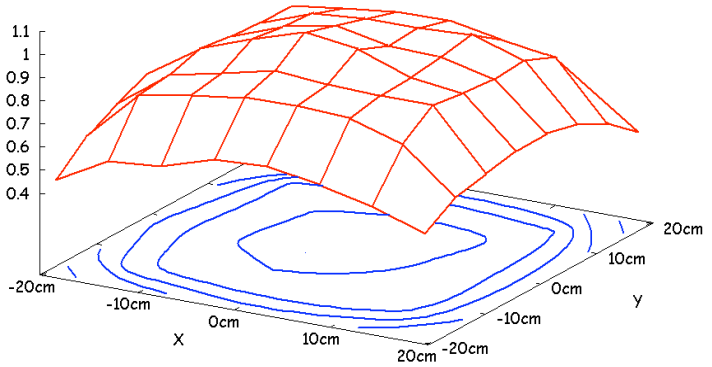


Programme

- Quelques mots sur les plasmas radiofréquence: Pourquoi s'y intéresser/Enjeux industriels

- Electrodynamique de base

- Les plasmas capacitifs: Faut-il augmenter la fréquence? Pourquoi une excitation multifréquence?

- Les plasmas inductifs: Faut-il diminuer la fréquence?

- Conclusions

Pourquoi s'intéresser aux plasmas RF?

1) Parce que les chercheurs du réseau PF adorent ça

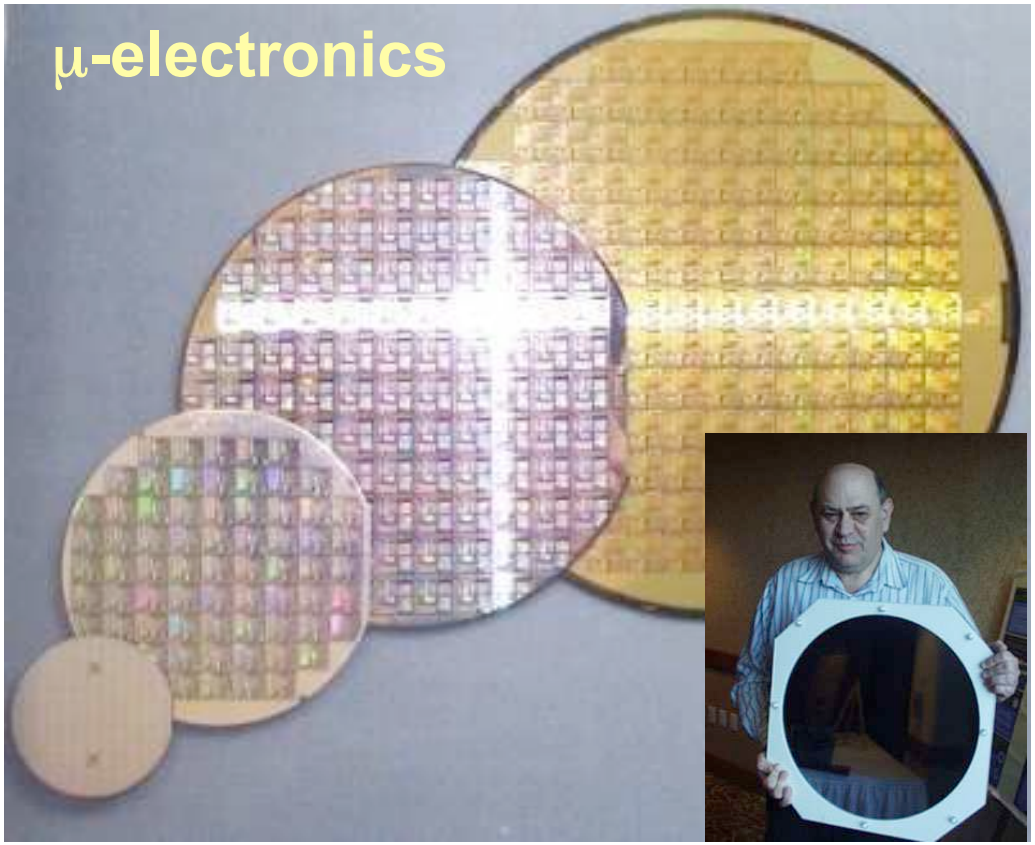
- Guy Cernogora : Plasmas capacitifs/Plasmas poudreux
- Jean-Paul Booth : Plasmas capacitifs multifréquence/Gravure
- Pascal Brault: Plasmas inductifs/dépôt/pulvérisation
- Gilles Cunge: Plasmas inductifs/Gravure
- Gilles Cartry: Plasmas inductifs/Source d'ions et de neutre

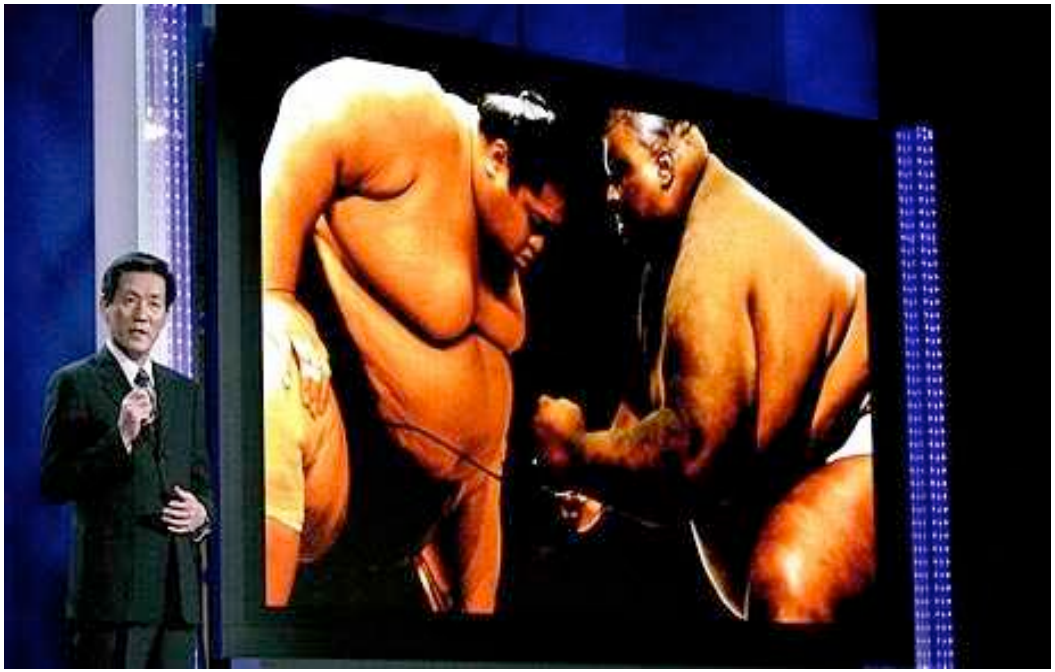
1) Accessoirment, il sont à la base de:

- Microélectronique/Photonique/MEMS/NEMS etc.
- Ecrans plats/Photovoiltaique etc.
- Dépôts en tous genre

Tendance générale

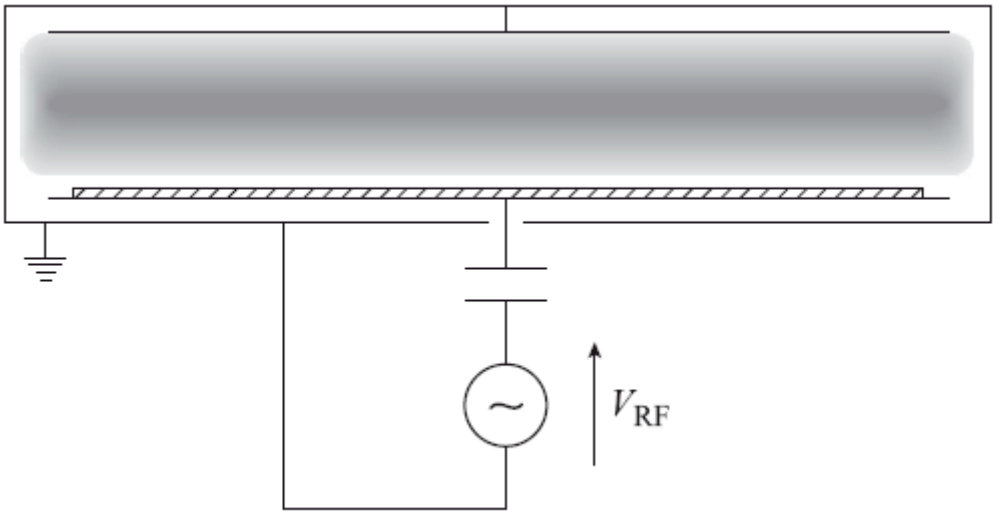
- Diminution des motifs (stabilité/contrôle extrême)
- Augmentation de la taille des substrats (uniformité)



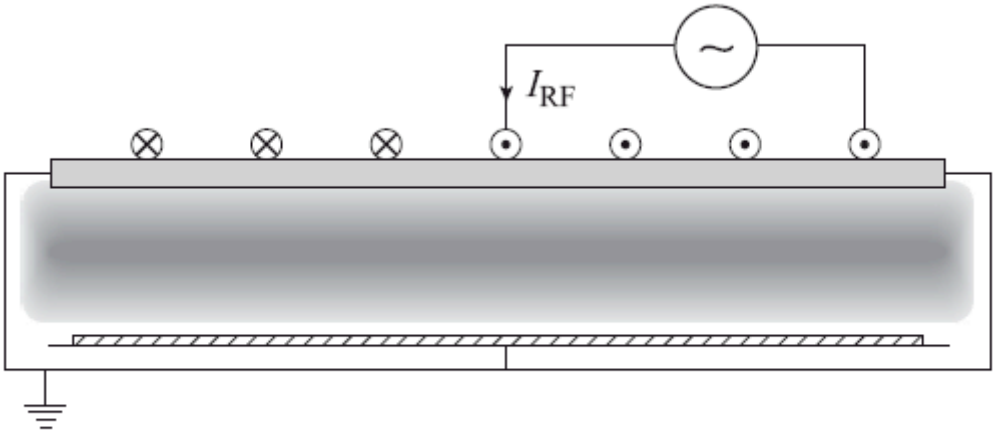


LCD - Flat Panel Displays

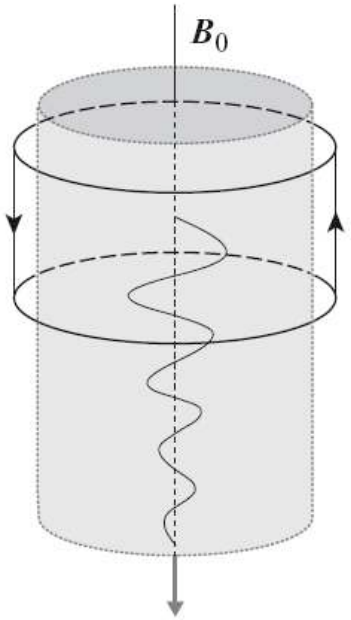
Plasmas radiofréquence: Trois types de couplage de l'énergie



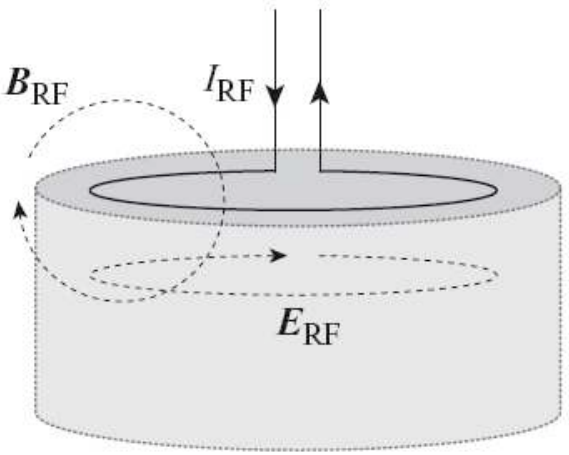
(a) **Electrostatique: capacitif**



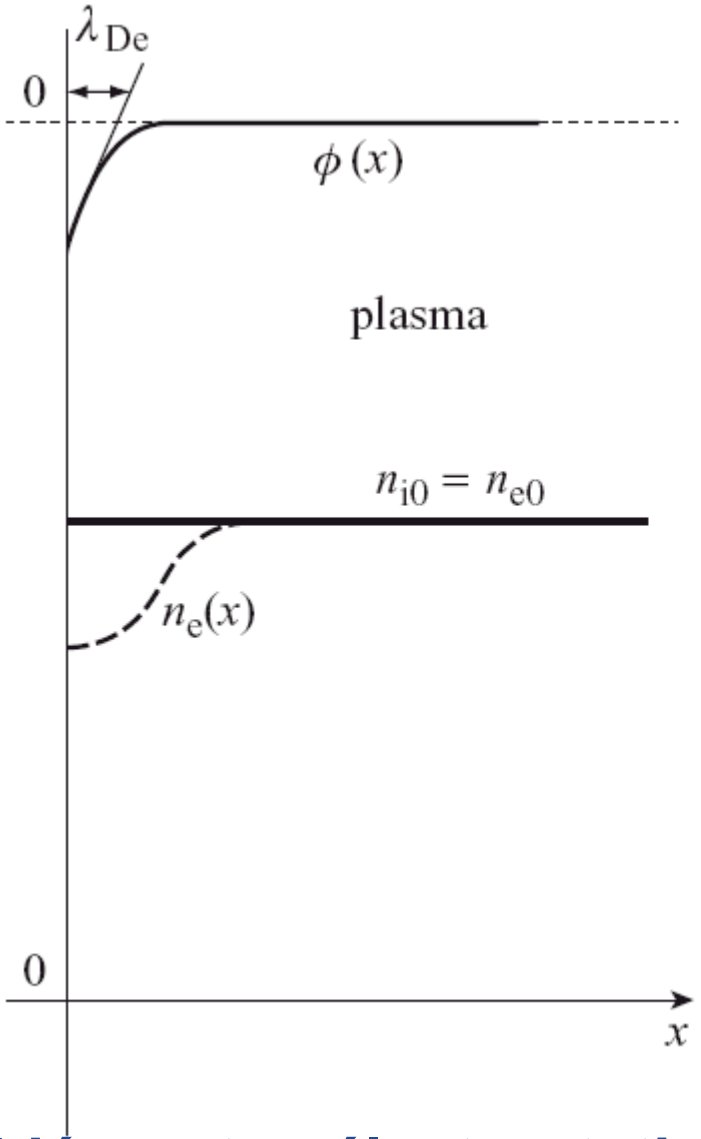
(b) **Electromagnétique evanescent: inductif**

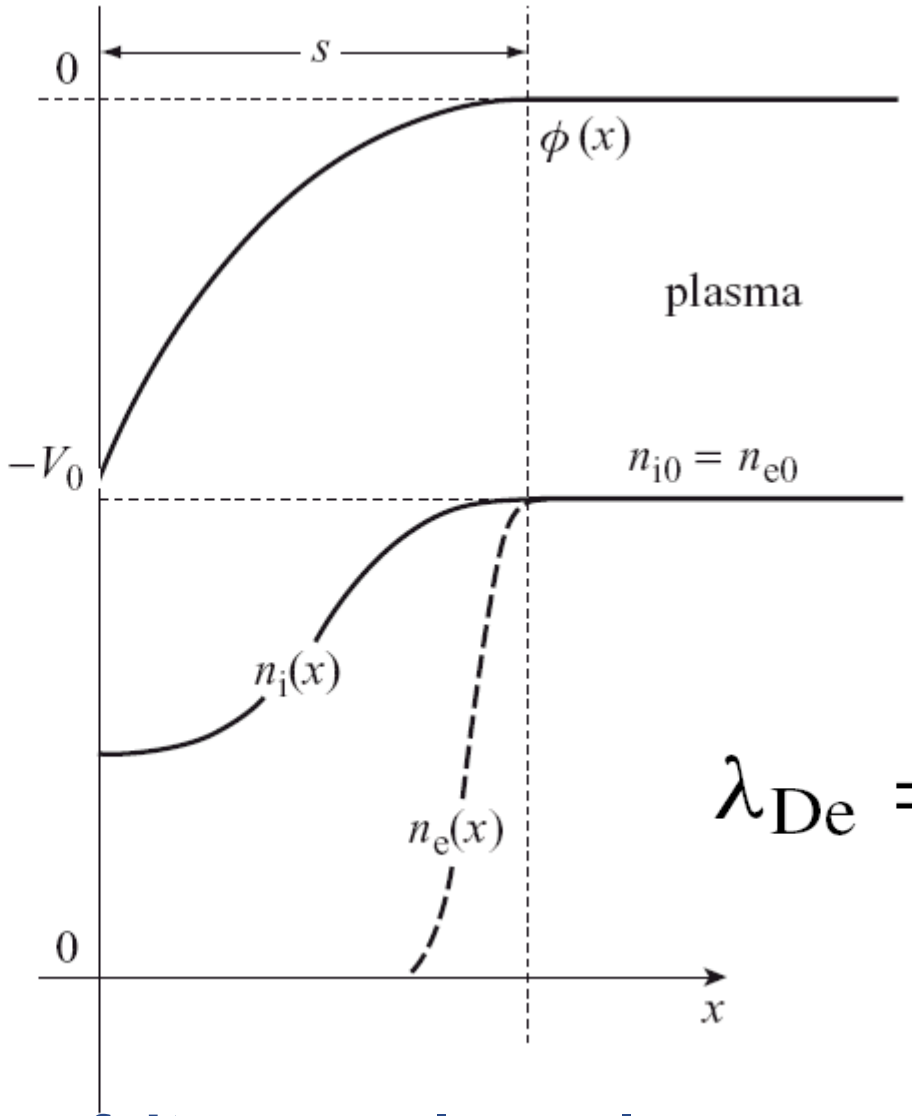


Electromagnétique propagatif: hélicon



Couplage électrostatique: écrantage de Debye et loi de Child



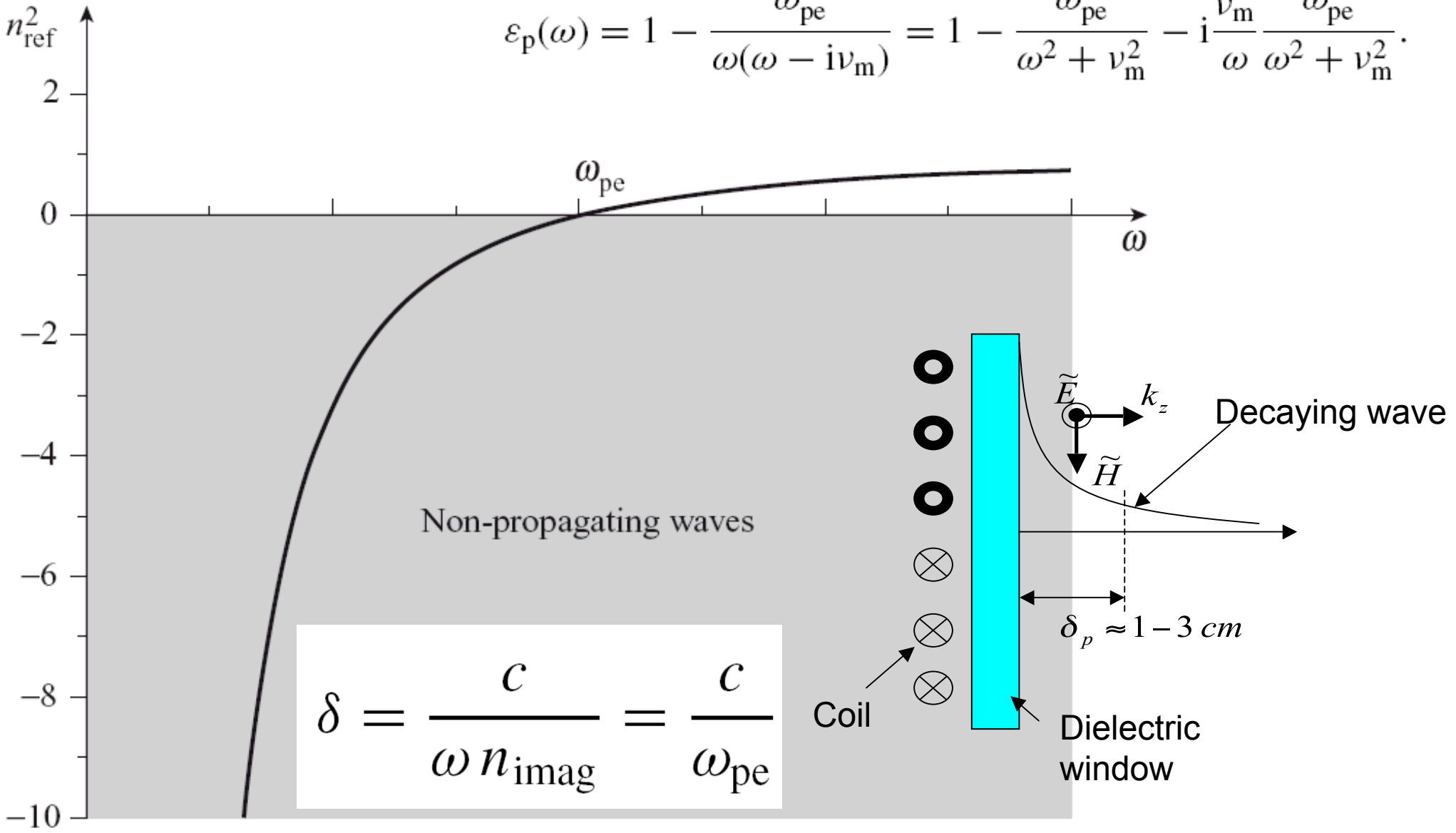


$$\lambda_{De} = \frac{v_e}{\omega_{pe}}$$

L'écrantge électrostatique se fait sur quelques longeurs de Debye

Couplage électromagnétique évanescent: profondeur de peau

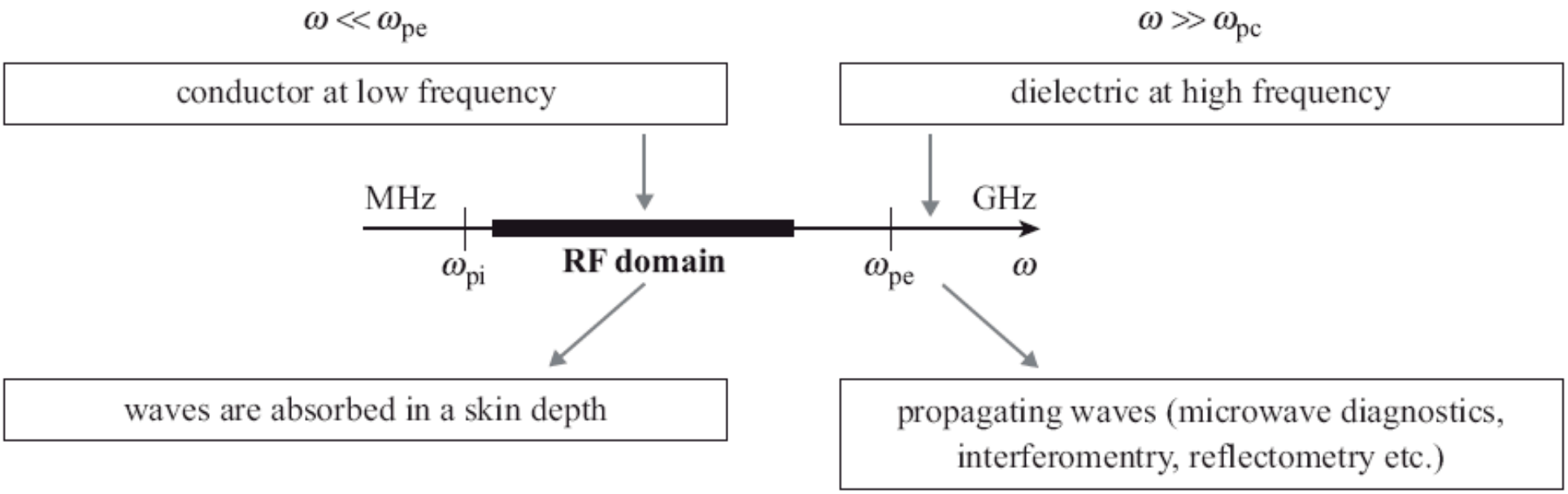
$$\varepsilon_p(\omega) = 1 - \frac{\omega_{pe}^2}{\omega(\omega - i\nu_m)} = 1 - \frac{\omega_{pe}^2}{\omega^2 + \nu_m^2} - i\frac{\nu_m}{\omega}\frac{\omega_{pe}^2}{\omega^2 + \nu_m^2}.$$



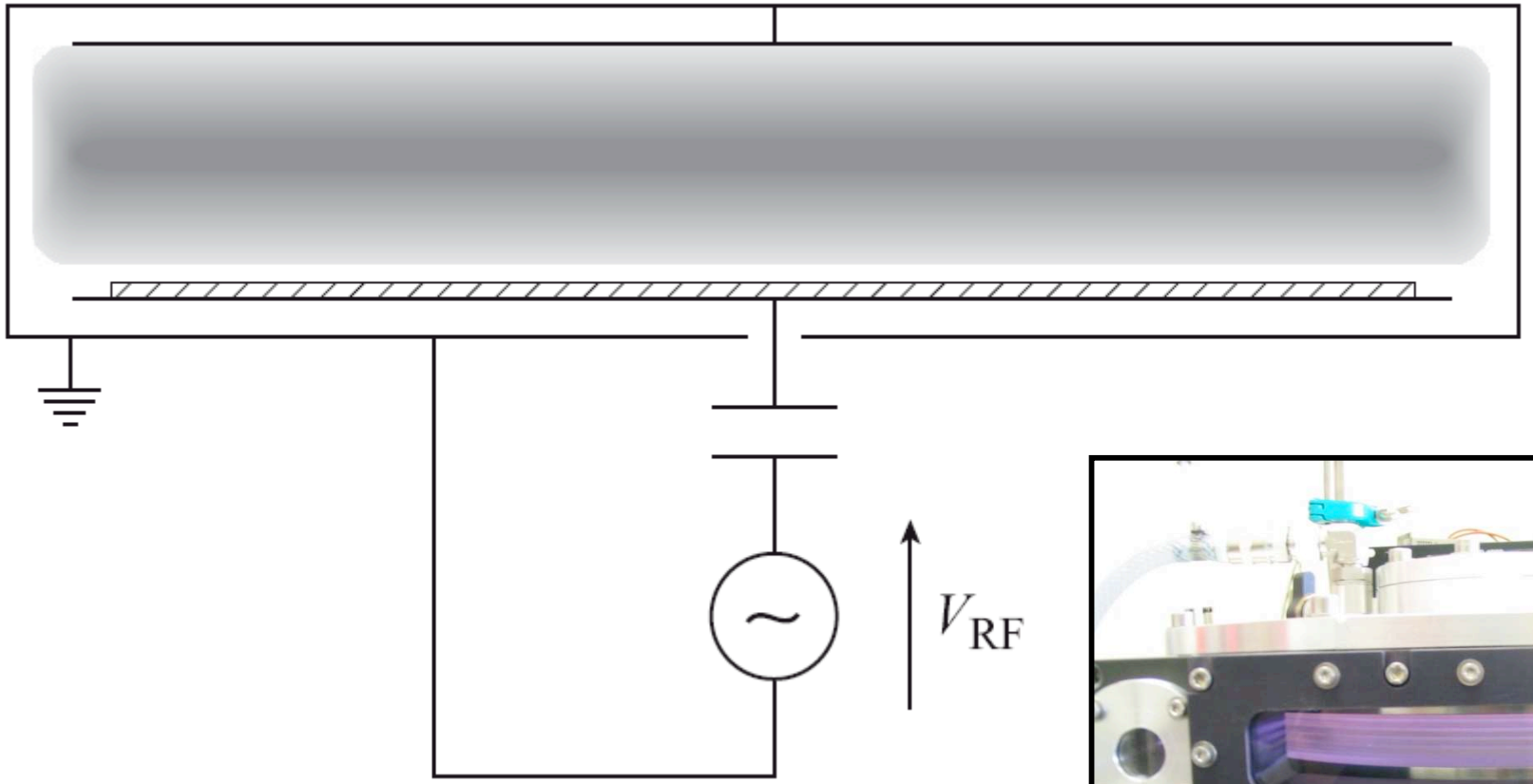
$$\delta = \frac{c}{\omega\, n_{imag}} = \frac{c}{\omega_{pe}}$$

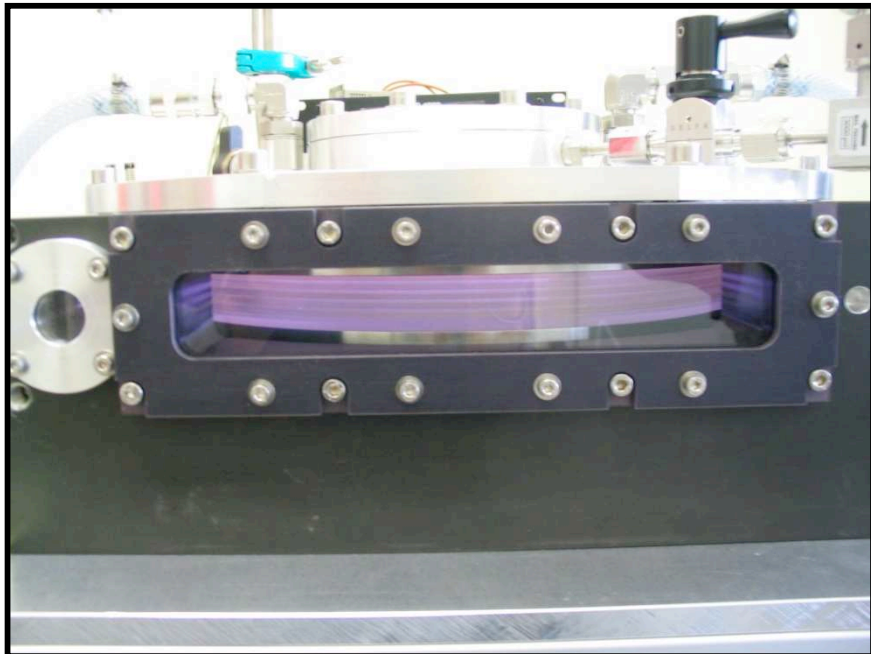
Résumé sur le domaine RF

- **Les ondes électromagnétiques sont moins écrantées que les perturbations électrostatiques**
- **Dans le domaine RF: les électrons suivent le champ instantané**
- **Dans le domaine RF: les ions ne suivent PAS le champ instantané**



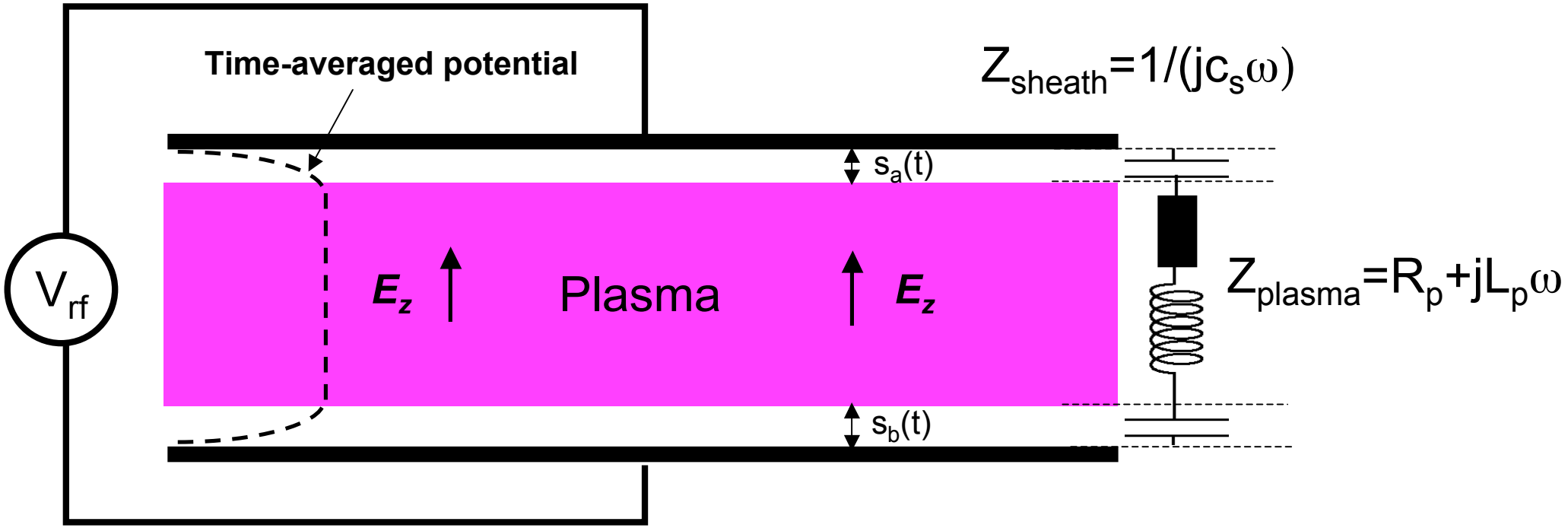
Décharges capacitives





Simple models of capacitive discharges

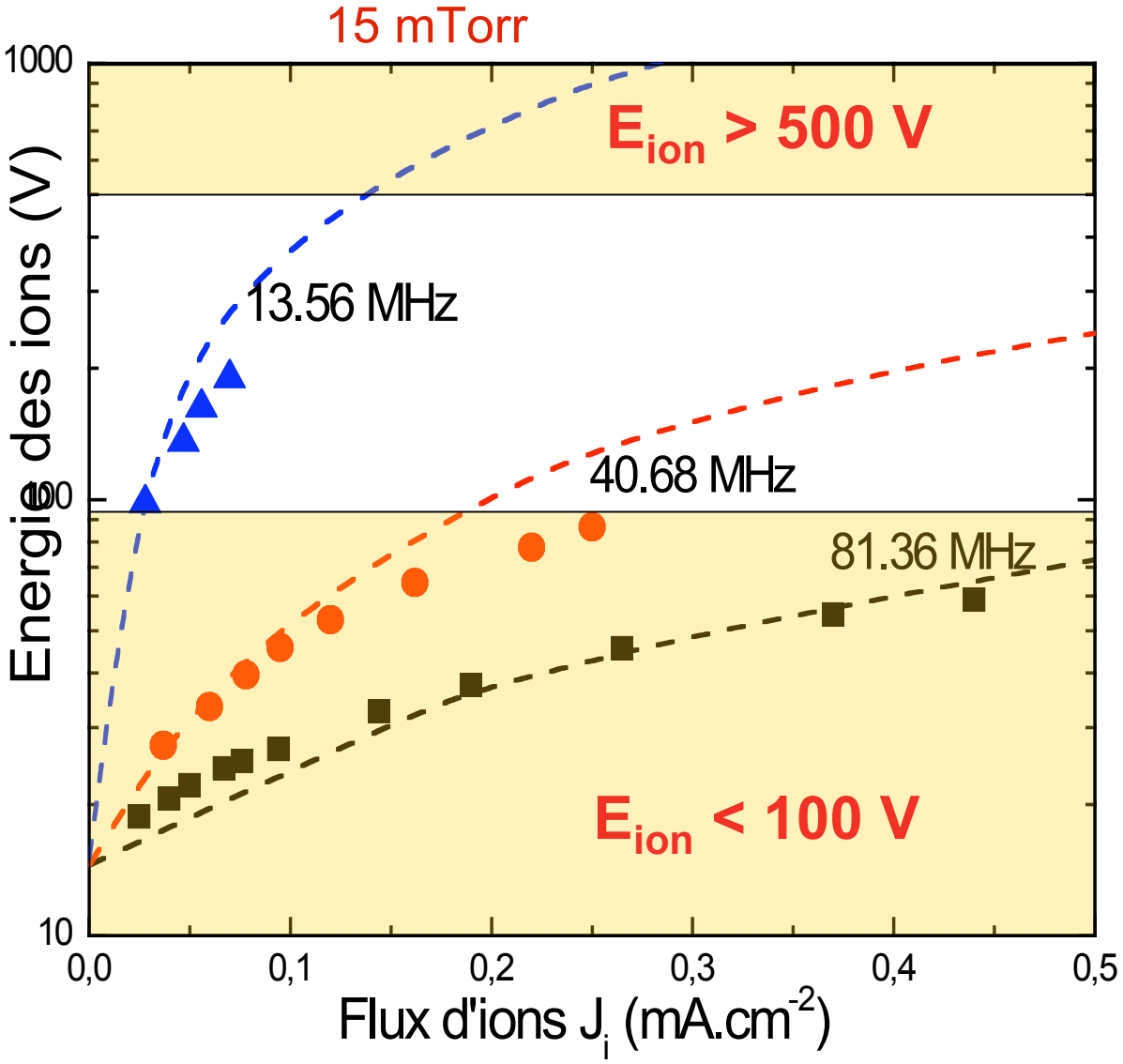
V.A. Godyak, "Soviet Radiofrequency Discharge Research", Delphic Associates, Fall Church, 1986
M.A. Lieberman, A.J. Lichtenberg, "Principles of Plasma Discharges and Materials Processing", 2nd Edition 2005



Impedance depends on :
- Voltage, V_{rf}
- Electron density, n_e
- Sheath size, s_m

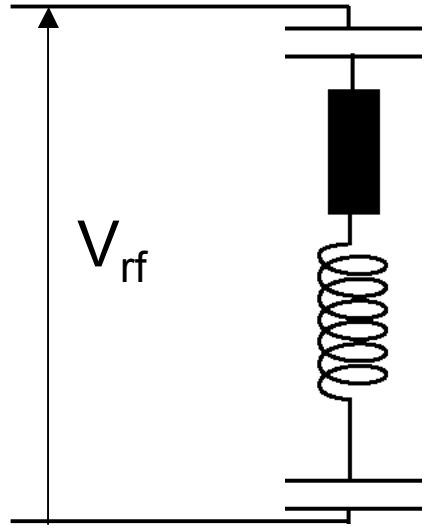
To find a self-consistent solution:
- Child law
- Particle balance
- Power balance

Frequency effect



■● ▲ : Experiments

----- : model



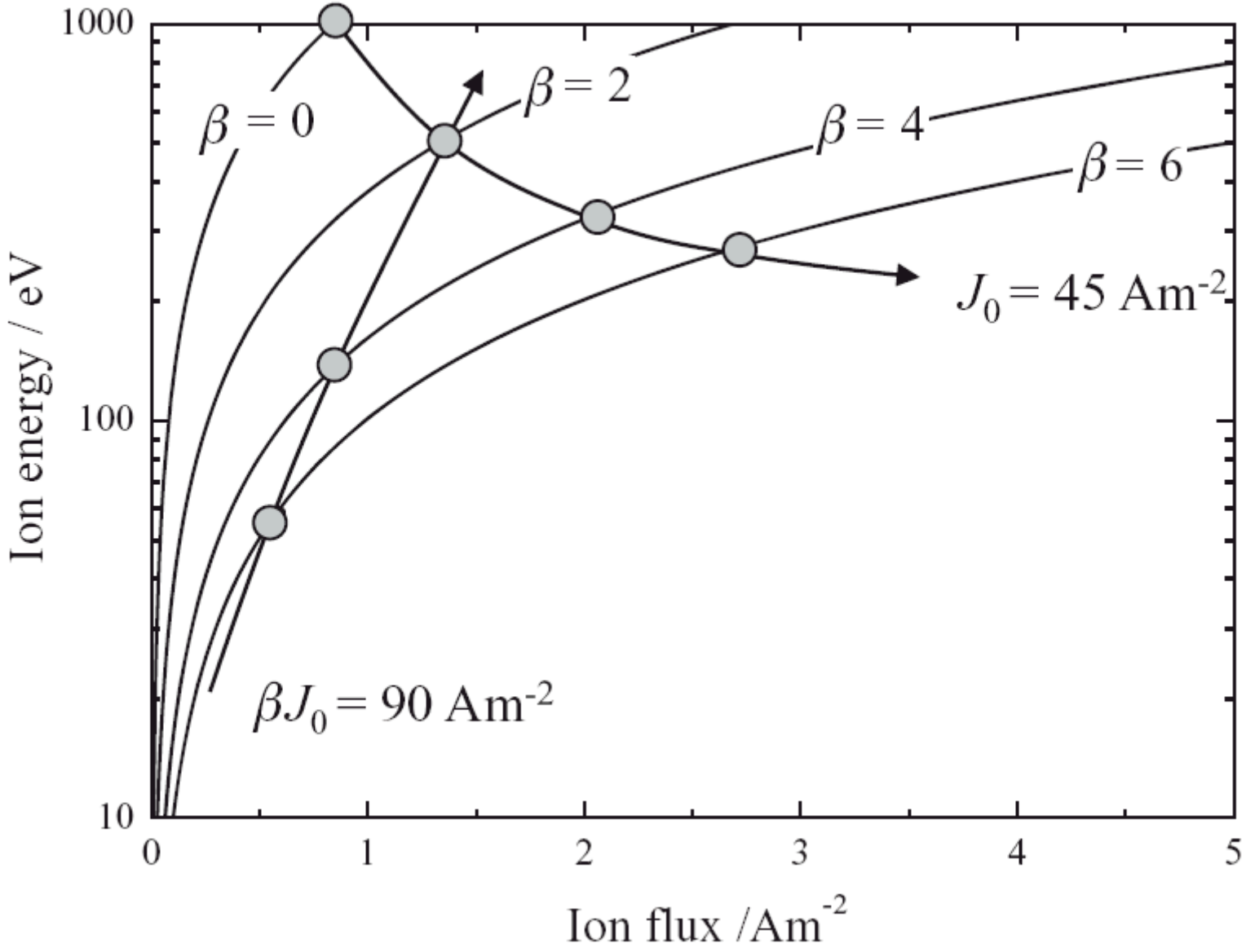
➔HF drive for high flux

➔LF bias for tunable ion energy

Dual Frequency Capacitive (DFC)

A. Perret et al., *Appl. Phys. Lett* ***86*** *(2005) 021501*

Independent control is not achieved



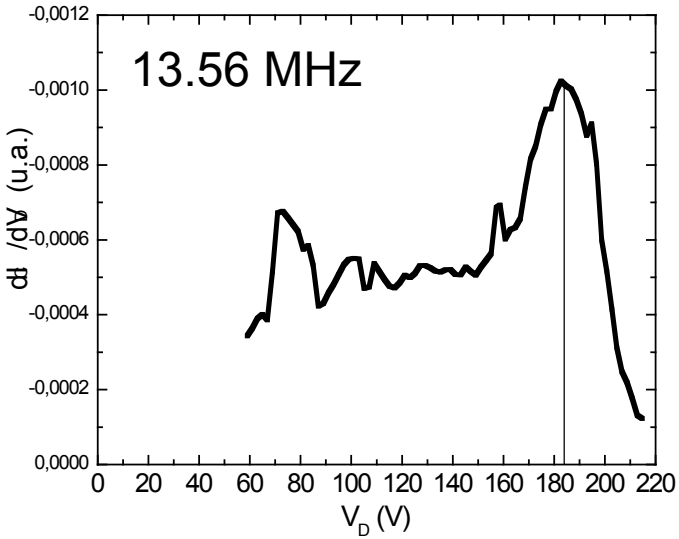
E_{ion} *vs.* J_i at the centre

15 mTorr

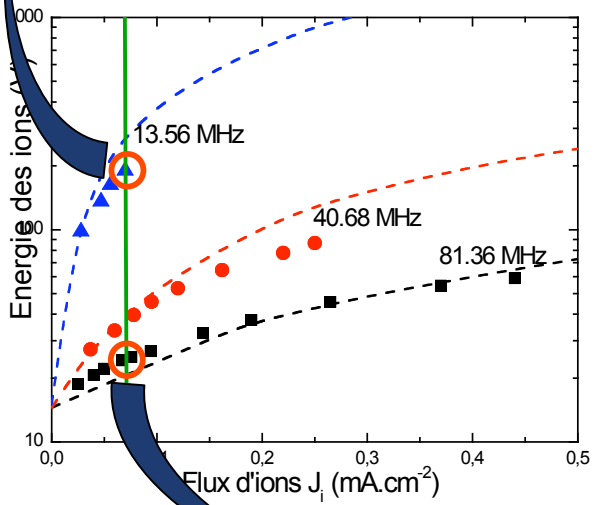
λ_i = 2 mm

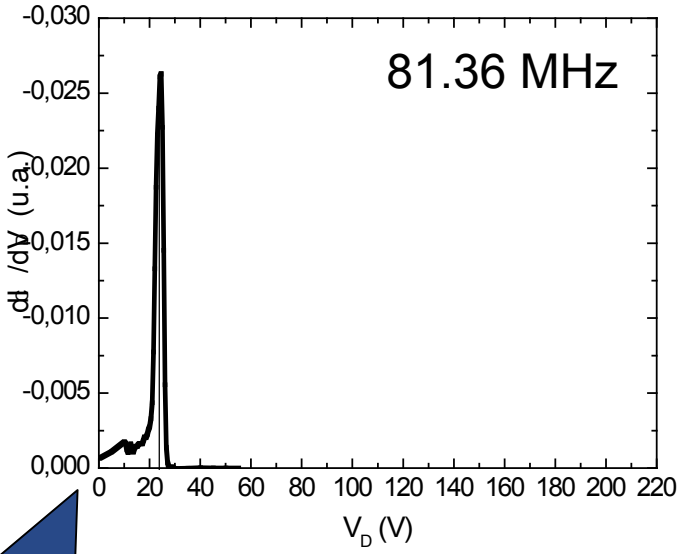
Analyzer :

L = 1 mm



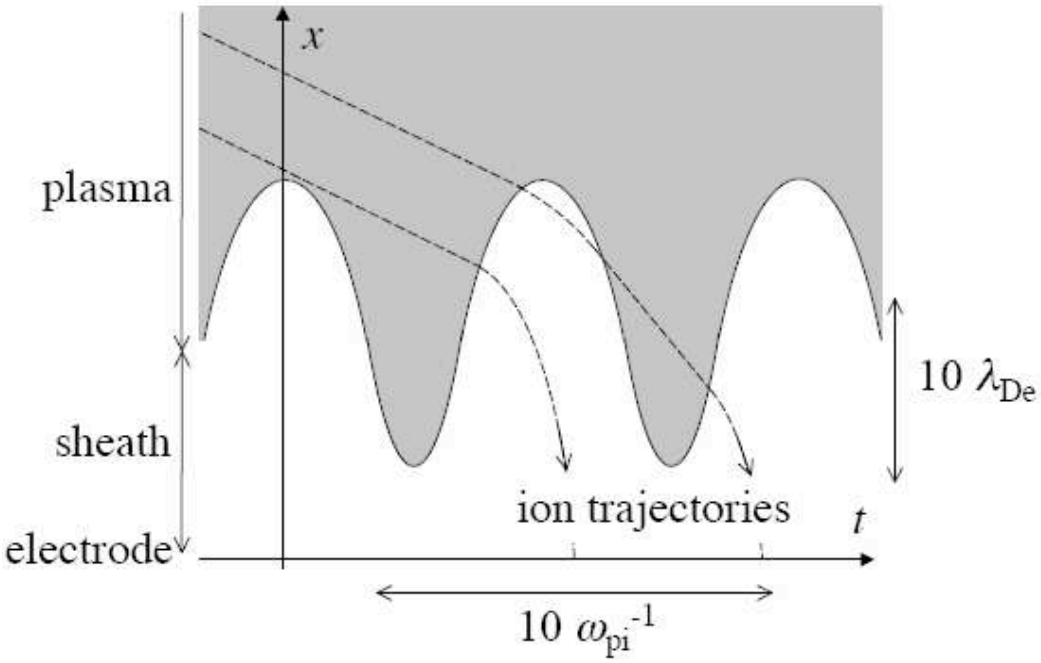
s_m = 7 mm



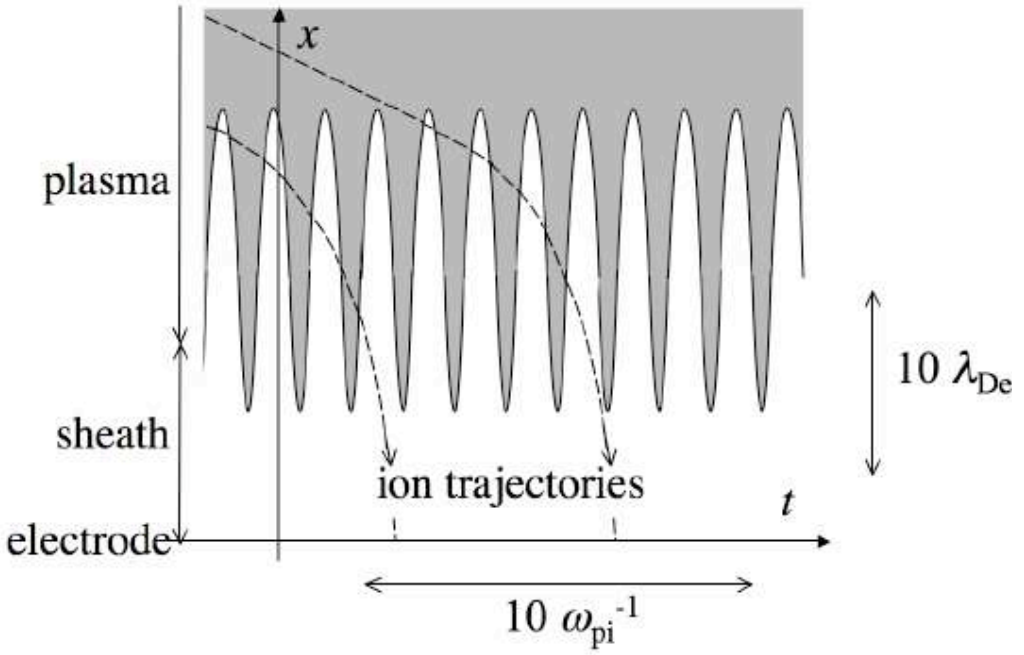


s_m = 1.2 mm

Ion trajectories in an RF sheath

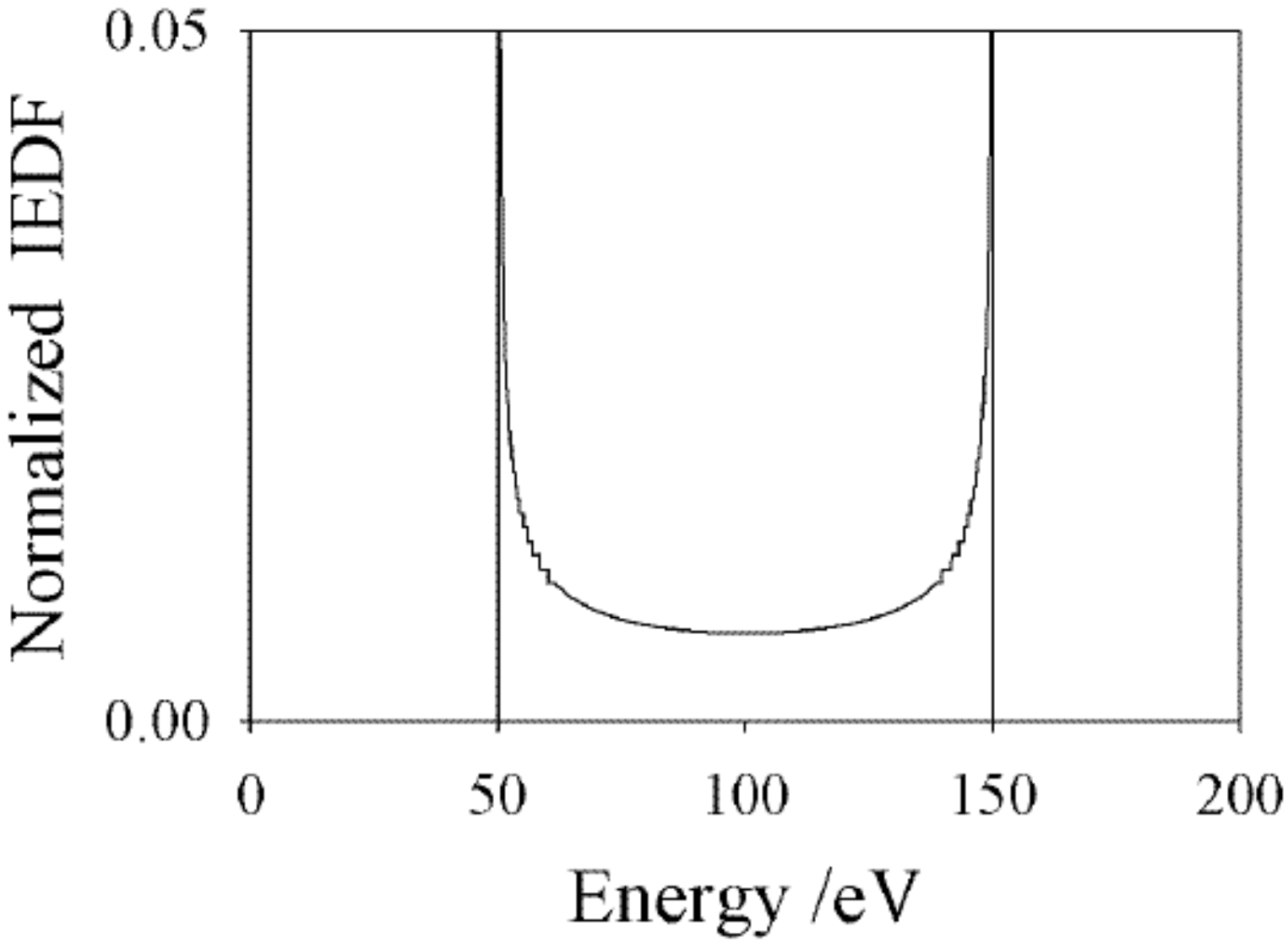


Intermediate frequency

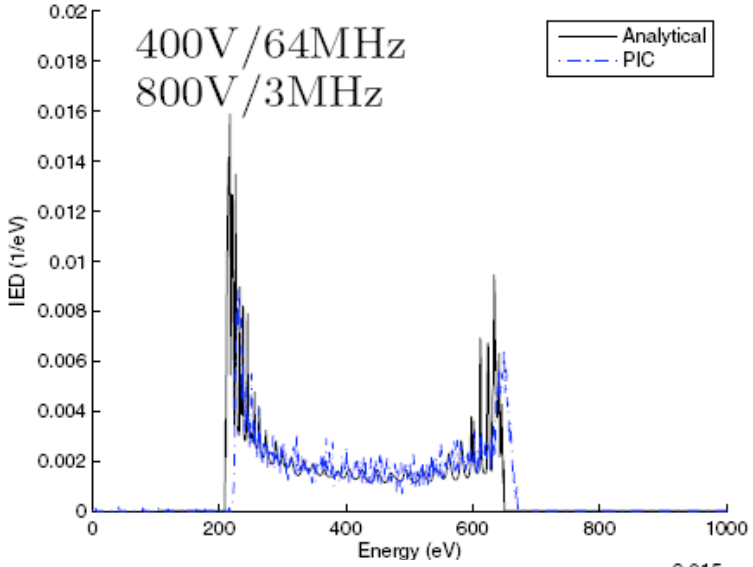


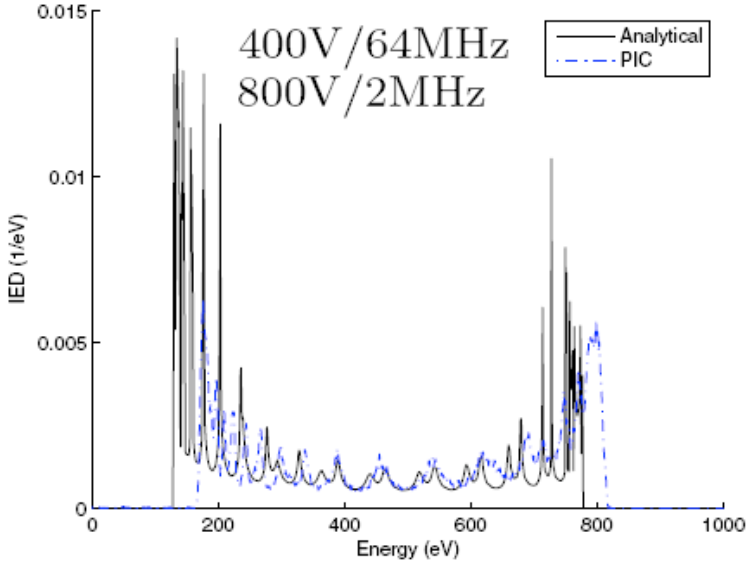
High frequency

Resulting "bi-modal" IEDF

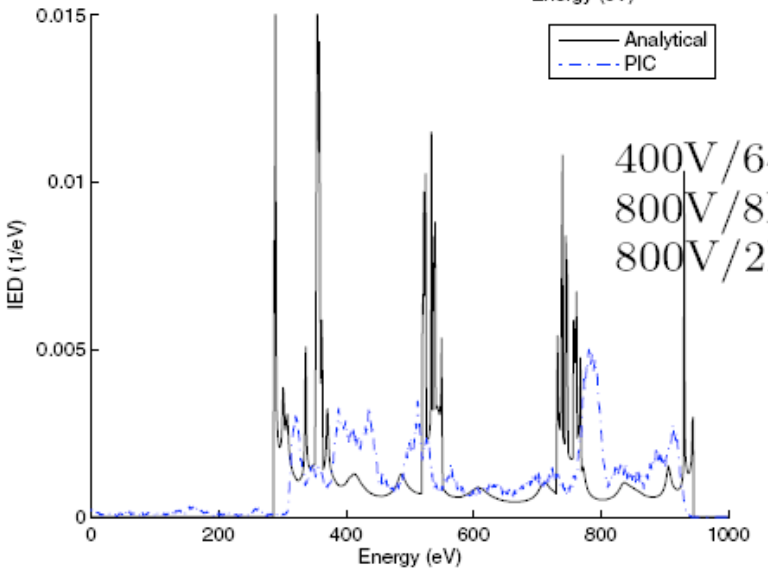


DUAL/TRIPLE FREQUENCY PIC SIMULATIONS



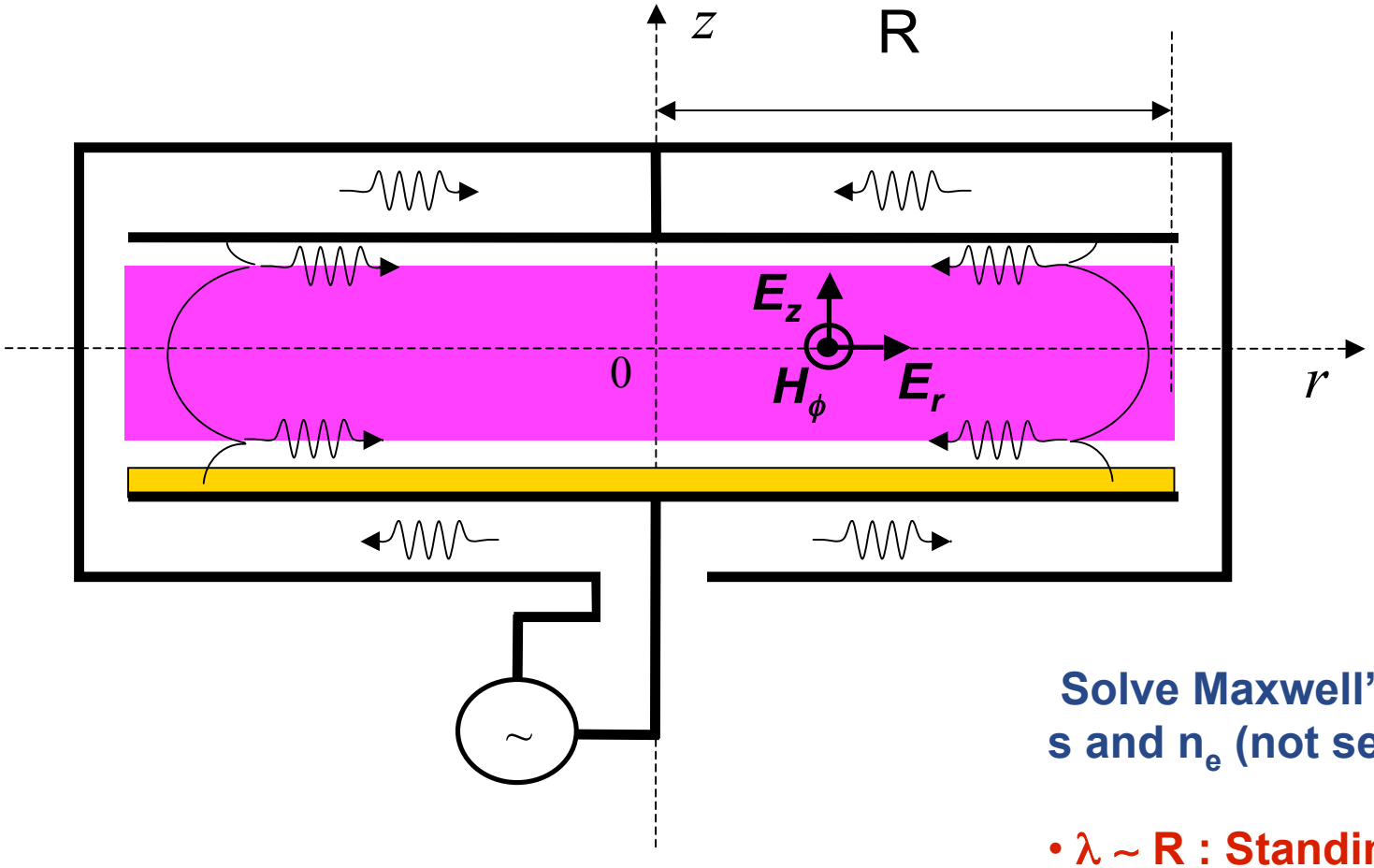


Gap=3 cm
p=30 mTorr
Collisionless ions



Electromagnetic regime: $\lambda \sim R$ and $\delta \sim d$

Fields are not radially uniform



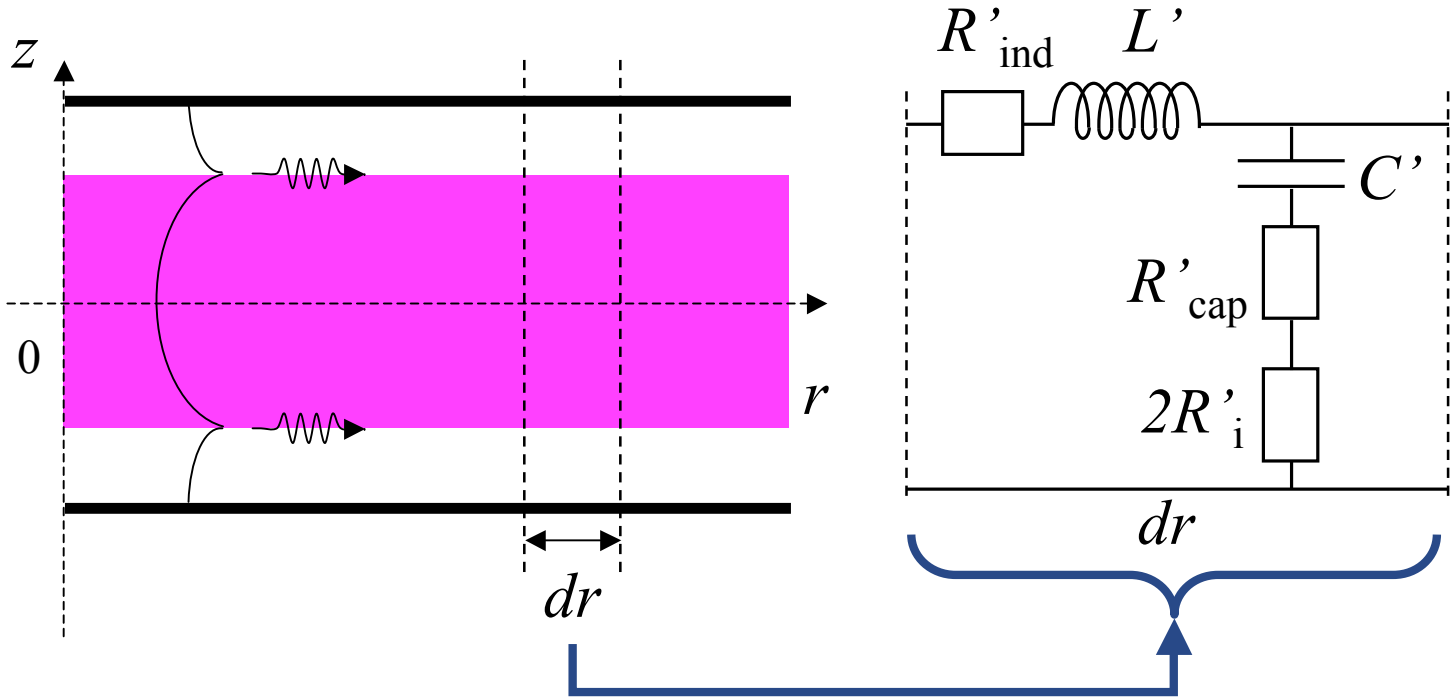
Solve Maxwell's equations for given s and n_e (not self-consistent):

- **$\lambda \sim R$: Standing wave effect (E_z)**
- **$\delta \sim d$: Skin effect (E_r)**
- **Edge effects**

M.A. Lieberman et al., *Plasma Sources Sci. Technol.* **11** (2002) 283

L. Sansonnens et al., *Plasma Sources Sci. Technol.* **15** (2006) 302

Transmission line model



$$\frac{d\tilde{V}}{dr} = -\left(R'_{\text{ind}} + jL'\omega\right)\tilde{I}$$

$$\frac{d\tilde{I}}{dr} = -\frac{jC'\omega}{1 + j(R'_{\text{cap}} + R'_i)C'\omega}\tilde{V}$$

TL elements depends on:
- Local voltage and/or current (V_{rf}, I_{rf})
- Electron density, n_e
- Sheath size, s_m

Use:
- Child law
- Particle balance
- Power balance

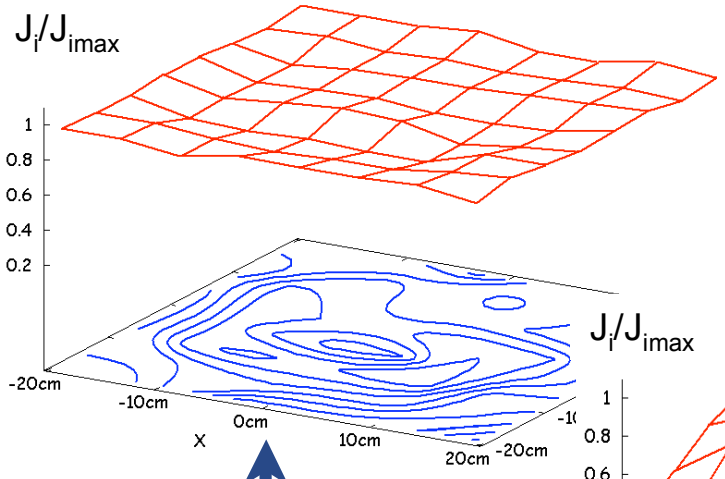
Self-consistent solutions for:
- $V_{rf}(r)$ and $I_{rf}(r)$
- $n_e(r)$
- $s_m(r)$

P. Chabert et al., Physics of Plasmas **11** (2004) 1775
P. Chabert et al., Physics of Plasmas **11** (2004) 4081

P. Chabert et al., Phys. Rev. Lett. **95** (2005) 205001

Standing wave effect (1/2)

50 W, 200 mTorr (local heating)

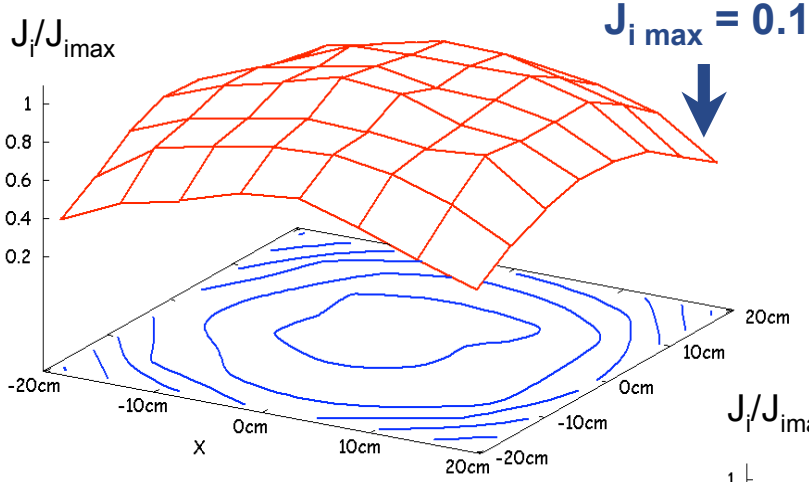


13.56 MHz

$J_{i\,max}$ = 0.07 mA.cm^{-2}

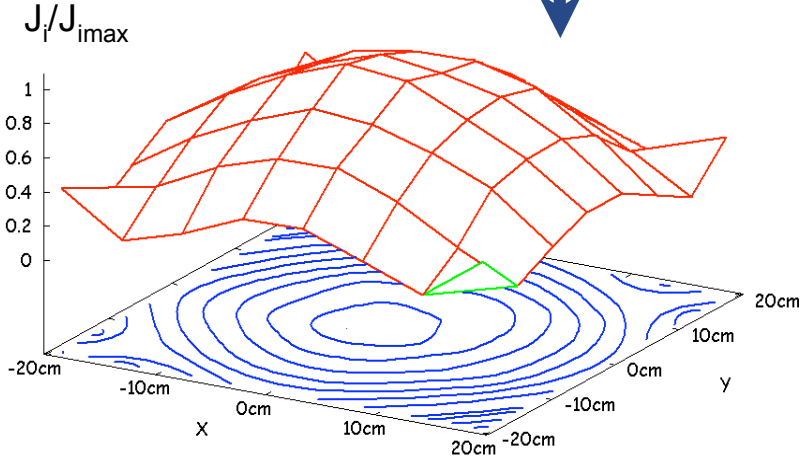
60 MHz

$J_{i\,max}$ = 0.15 mA.cm^{-2}



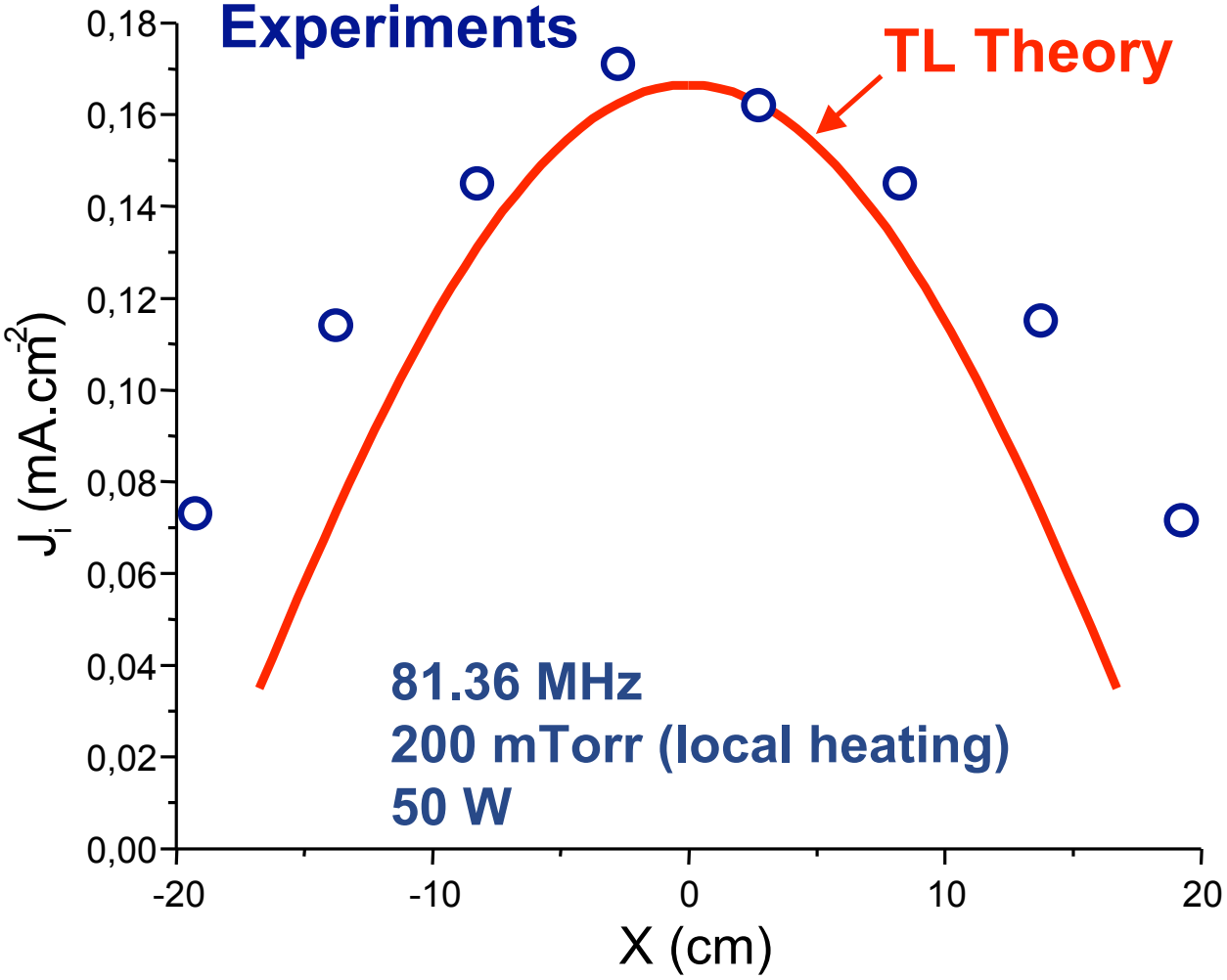
81.36 MHz

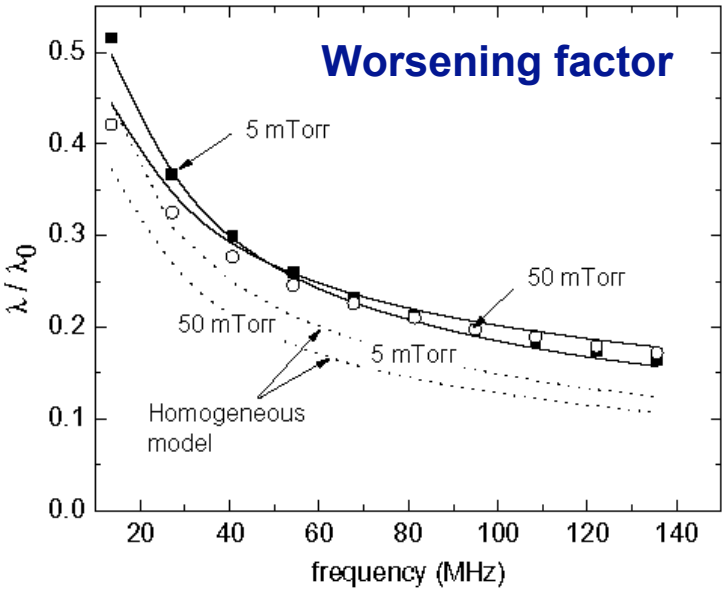
$J_{i\,max}$ = 0.17 mA.cm^{-2}



A. Perret et al., Appl. Phys. Lett ***83*** *(2003) 243*

Standing wave effect (2/2)



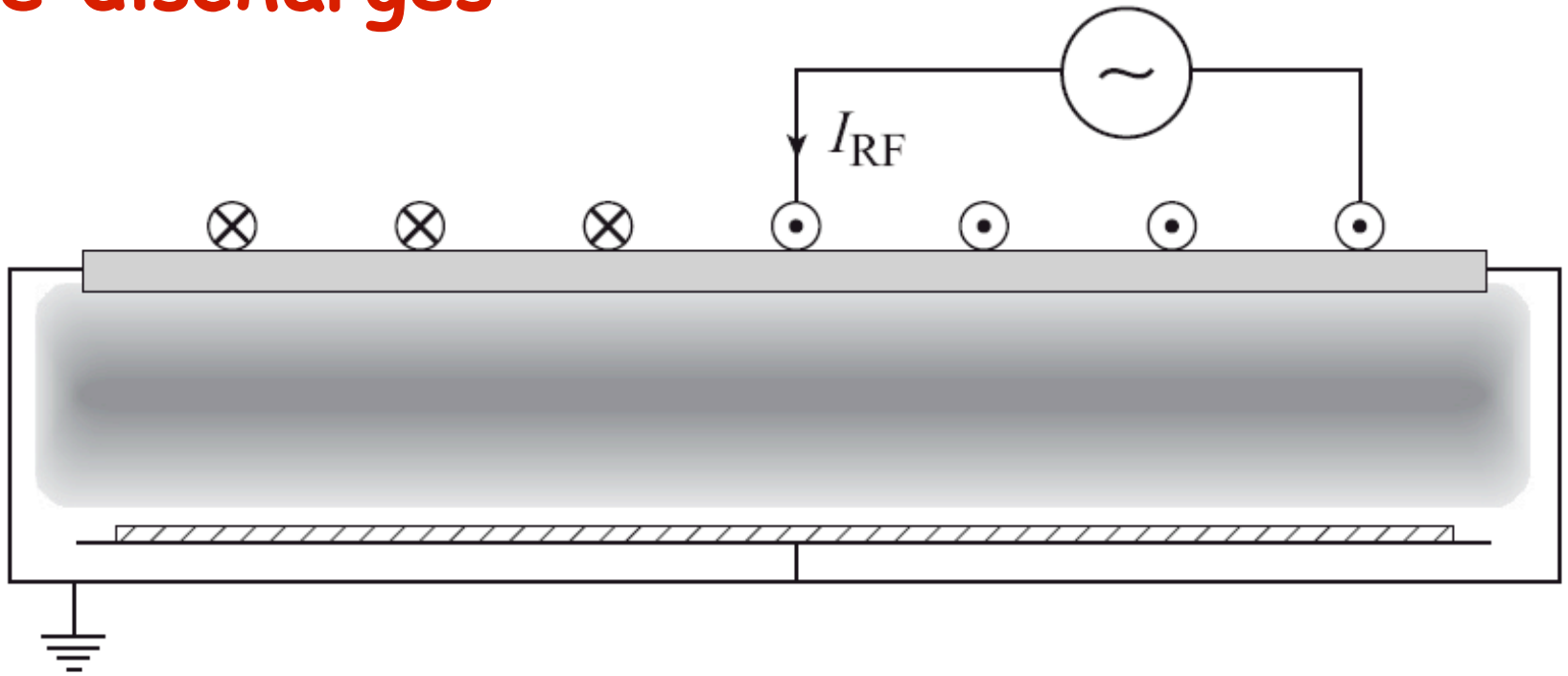


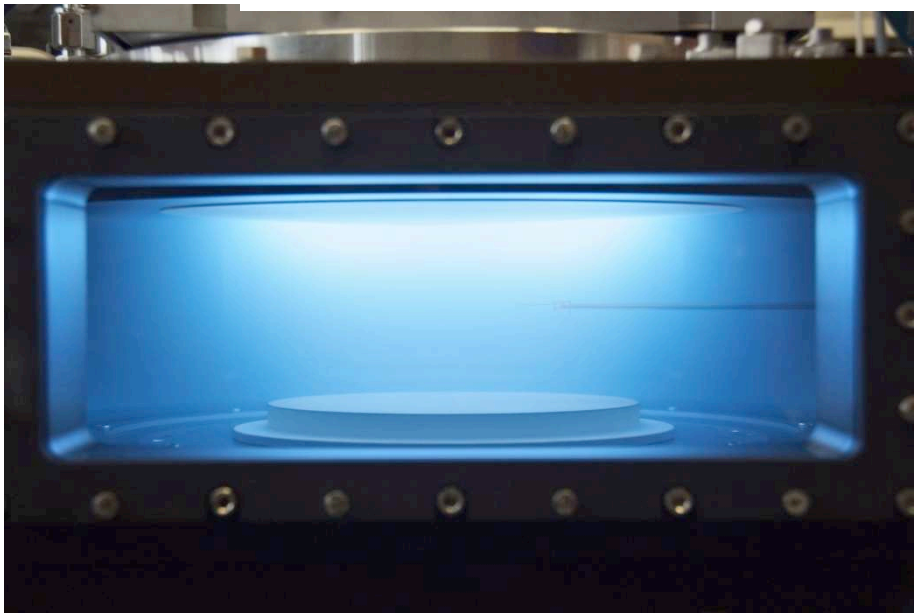
$$\frac{\lambda}{\lambda_0} \approx 40\, V_0^{1/10} l^{-1/2} f^{-2/5}$$

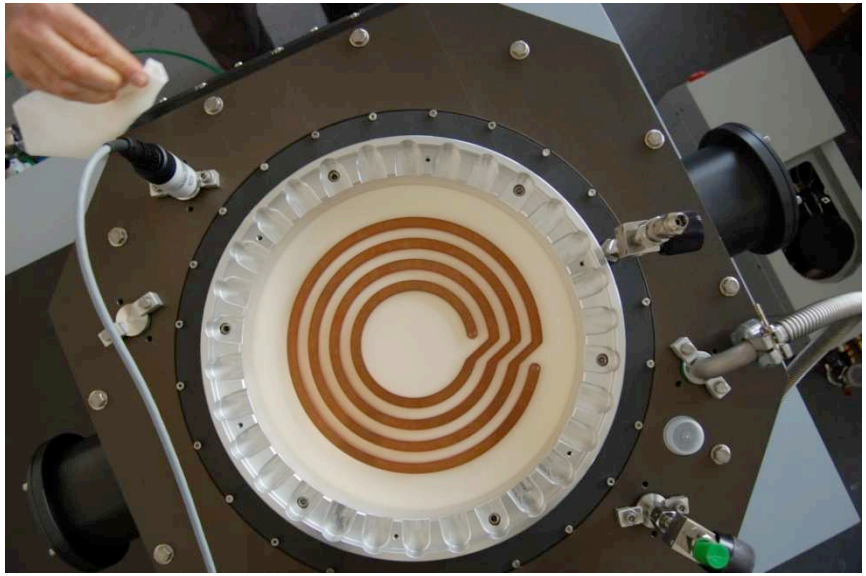
Fairly insensitive to the gas composition

P. Chabert et al., Physics of Plasmas **11** (2004) 1775

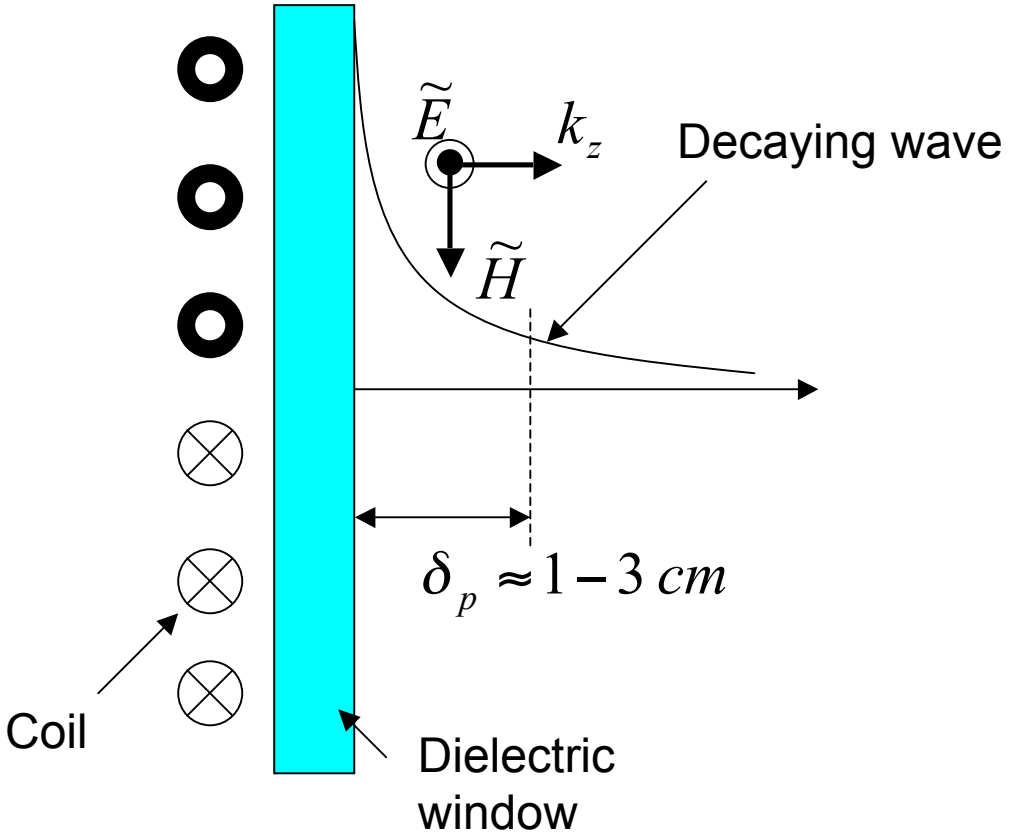
Inductive discharges







Inductive coupling



Inertial skin depth (low-pressure)

$$\delta_p = \frac{c}{\omega_p} = \sqrt{\frac{m_e}{e^2 \mu_0 n_e}}$$

Resistive skin depth (high pressure)

$$\delta_p = \sqrt{\frac{2}{\omega \sigma_p \mu_0}}$$

The transformer model

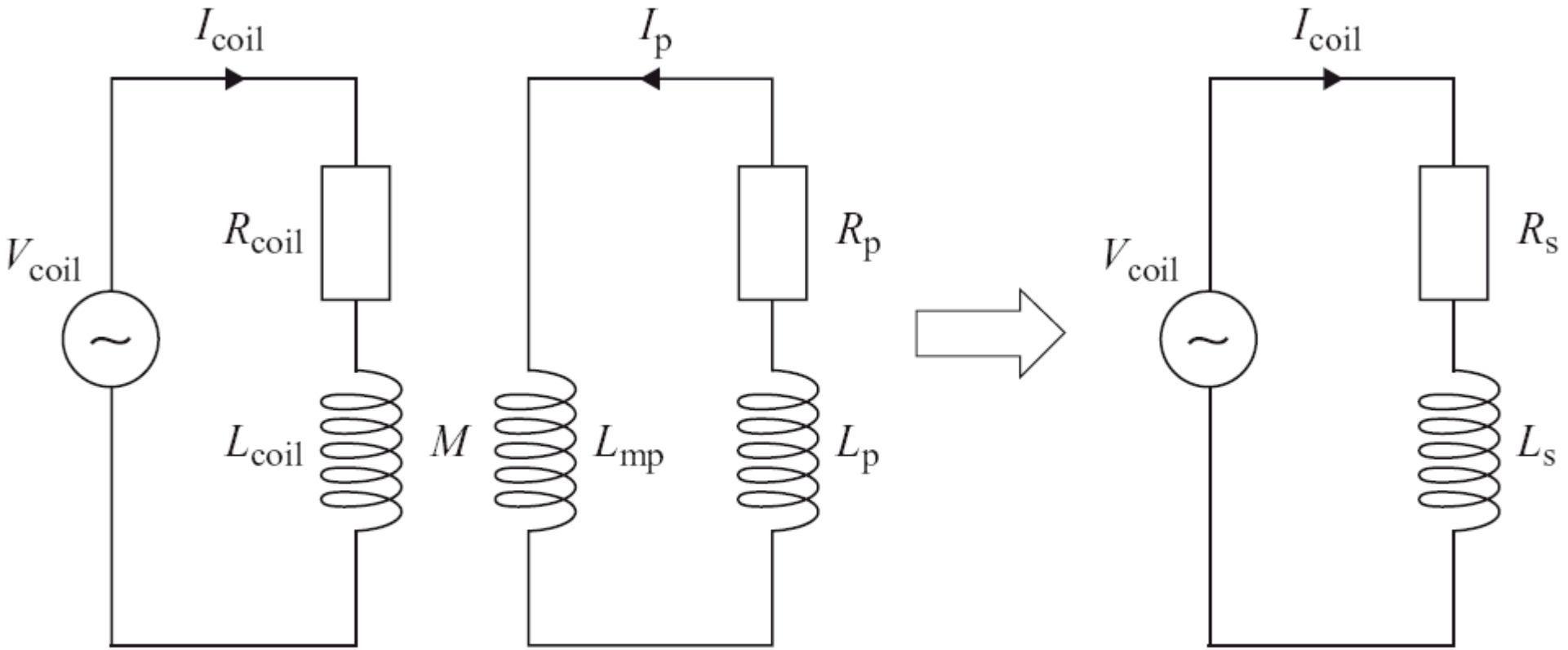
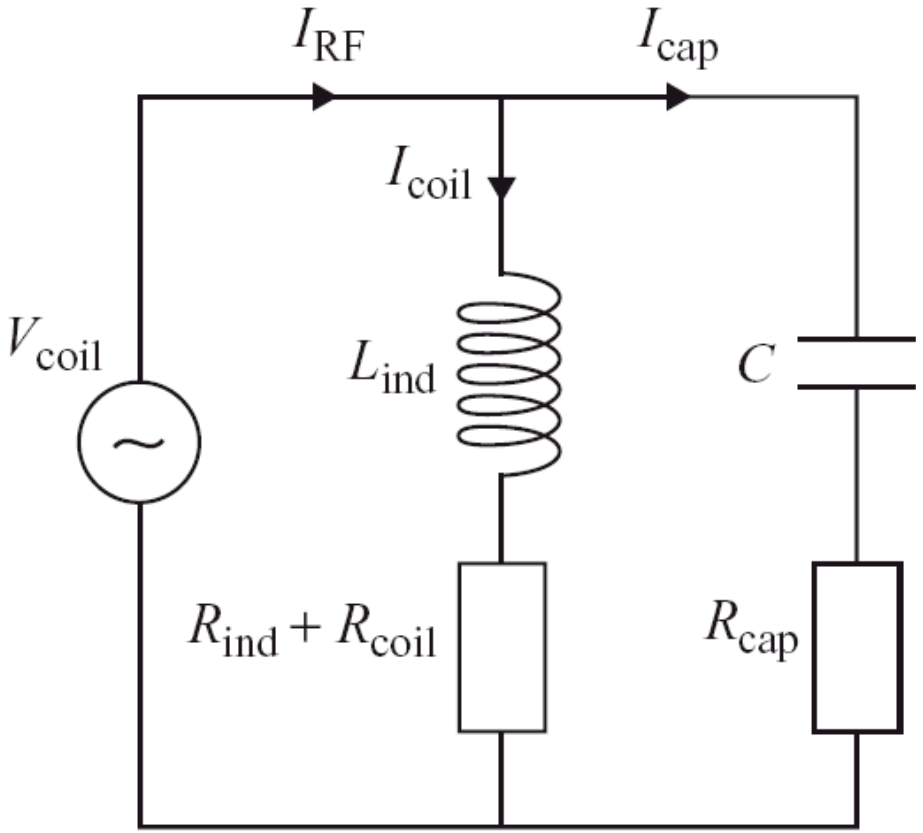
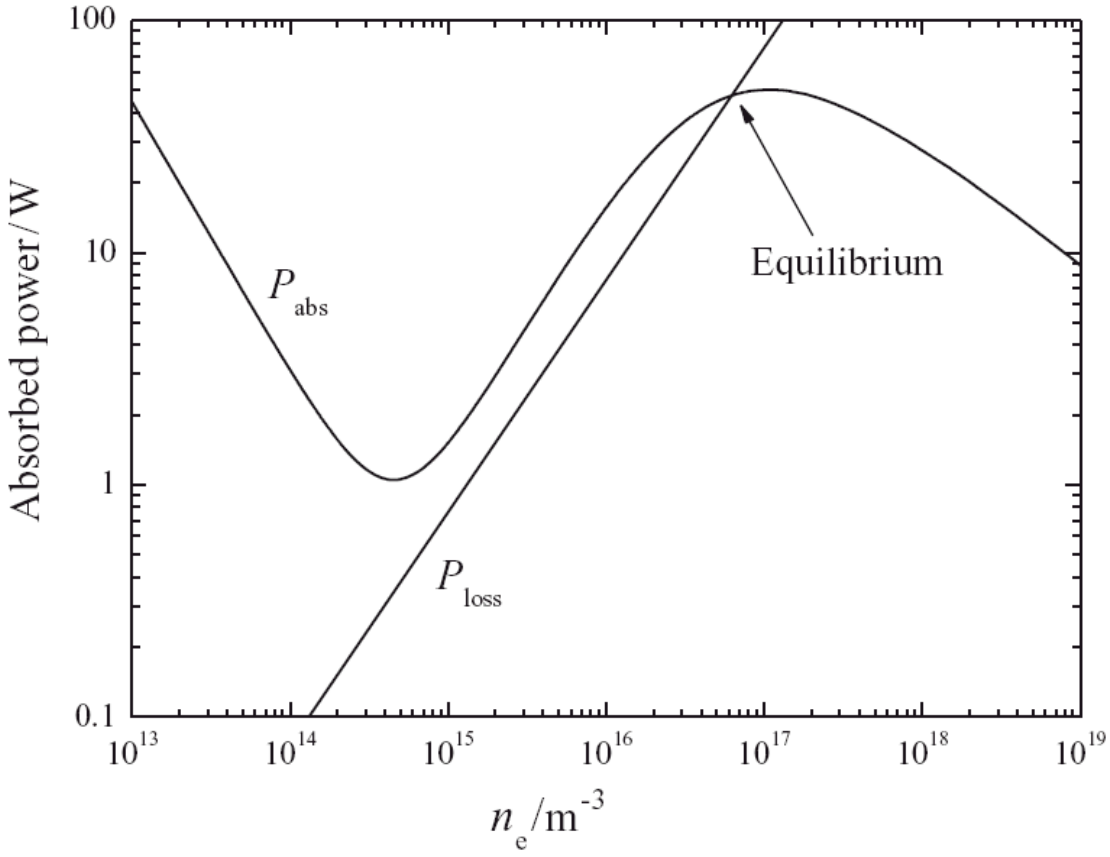


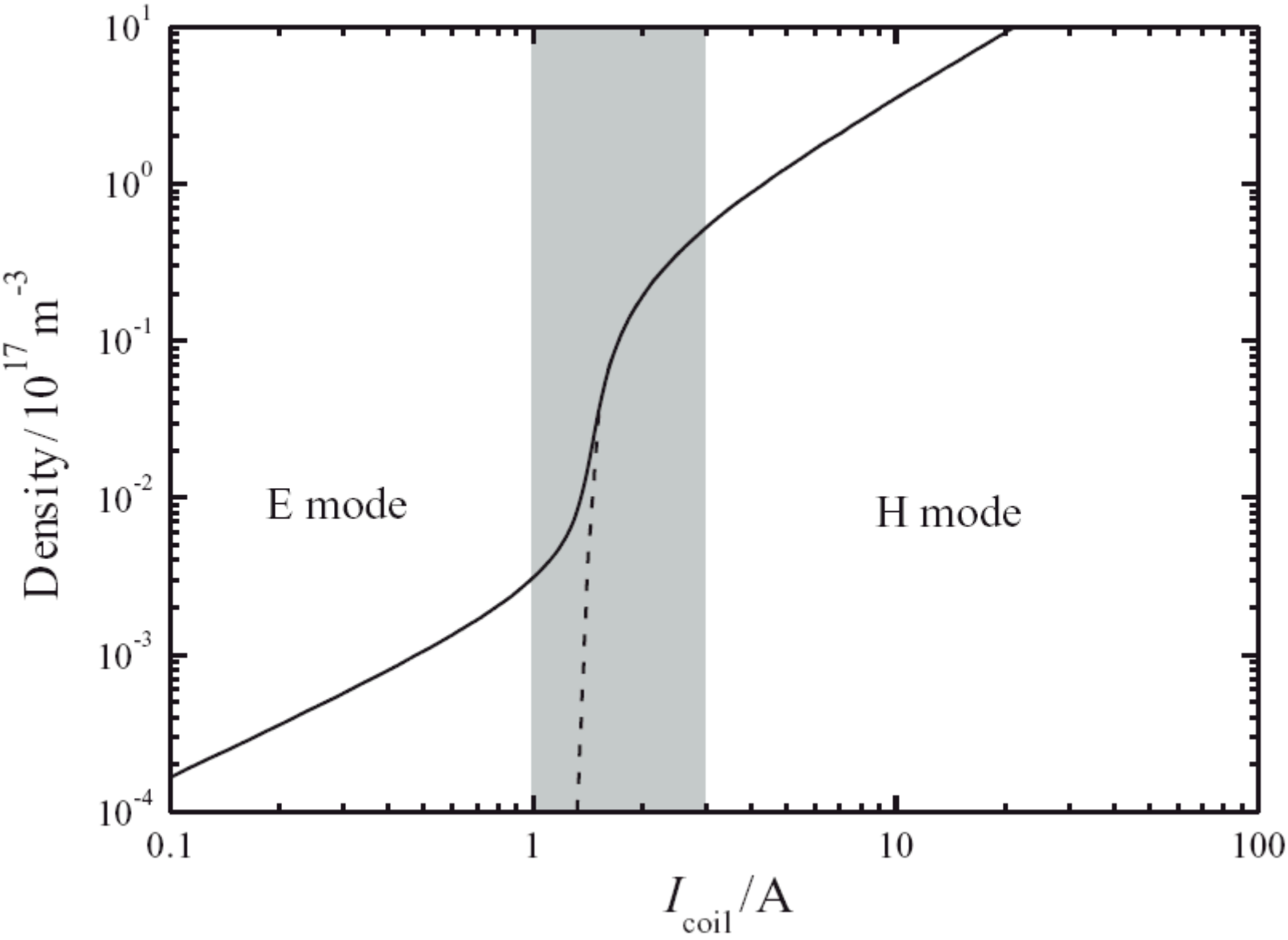
Figure 7.9 The transformer model of an inductive discharge. On the right, the secondary circuit has been transformed into its series equivalent in terms of the primary circuit current.

Equivalent circuit of real inductive discharges with capacitive coupling

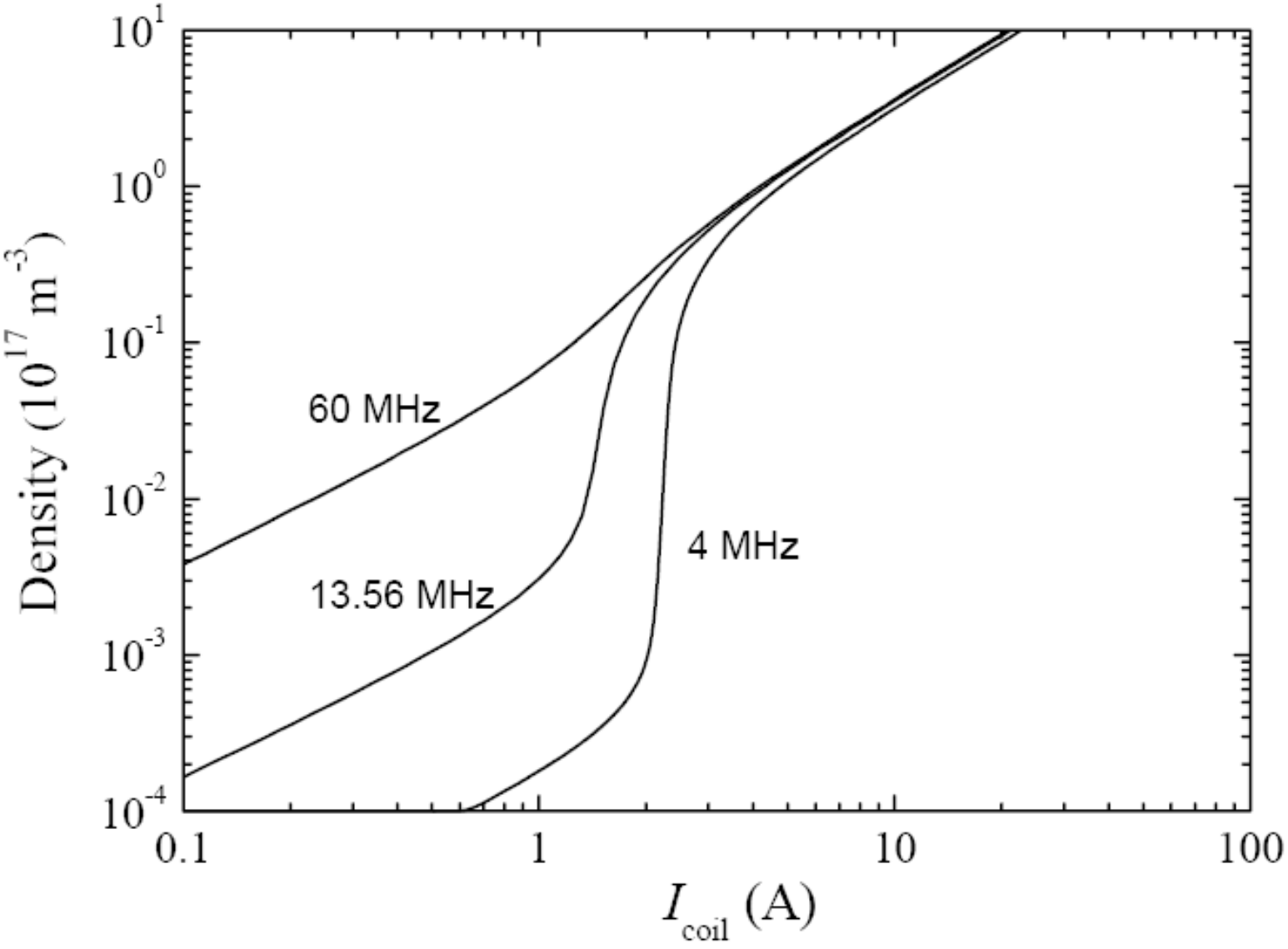




Electron density vs coil current



Frequency effect



In inductive mode, almost no effect of the driving frequency !

Conclusions

- Les décharges capacitives sont plus denses lorsqu'on augmente la fréquence d'excitation
- Malheureusement des problèmes d'uniformité apparaissent
- L'excitation multifréquence est nécessaire pour contrôler indépendamment (ou presque) le flux et l'énergie des ions

- Les décharges inductives sont naturellement denses car le chauffage électromagnétique est plus efficace
- Elles sont sujettes à des transitions de mode car il y a un couplage capacitif dû à la tension RF sur la bobine
- En mode inductif pur, la densité électronique est quasi indépendante de la fréquence à courant constant: Il semble donc plus astucieux de baisser la fréquence d'excitation

Pour en savoir plus…

Bibliography

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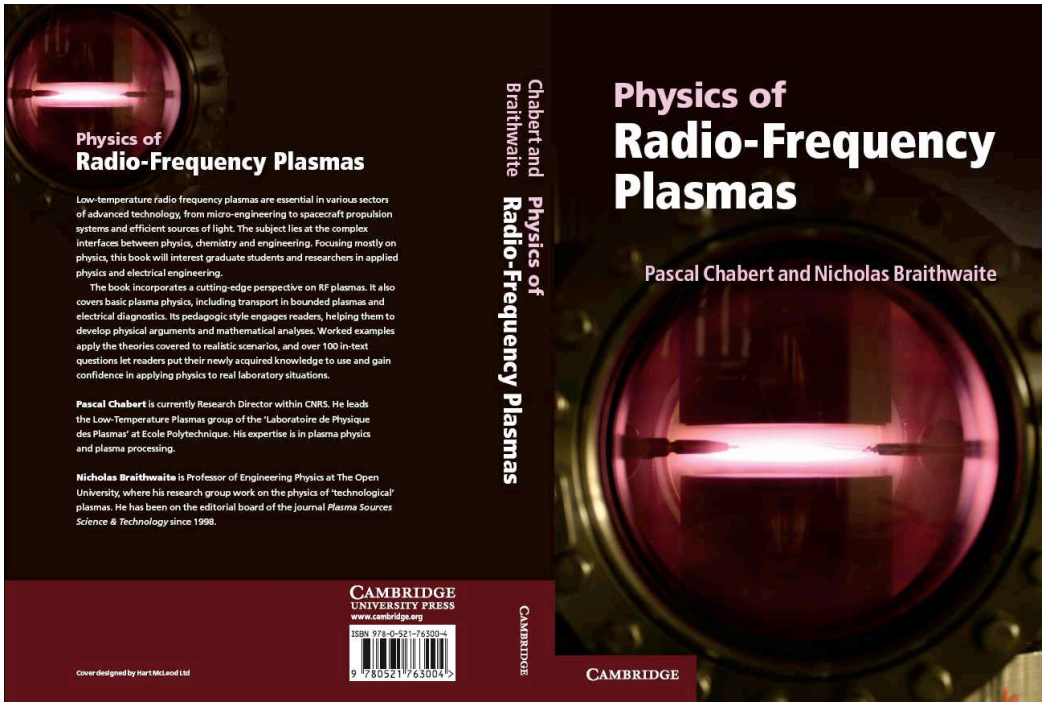
P. Chabert and N. Braithwaite,
Cambridge University Press, 2011



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