RF antennas as plasma monitors

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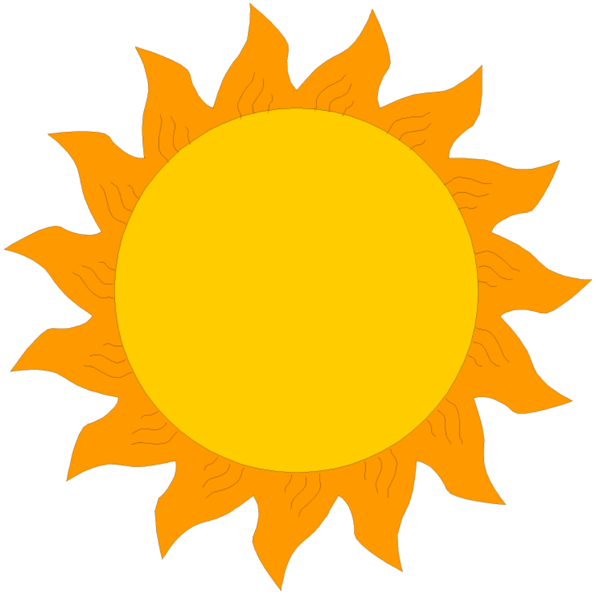
Porquerolles Island, France

Outline of talk

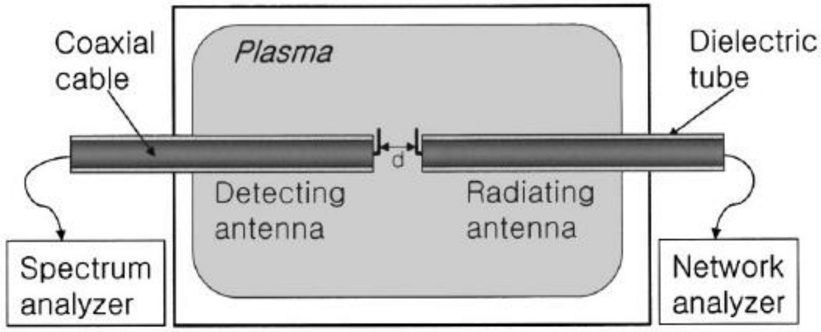


- Review: RF antenna diagnostics
- Inductively-coupled plasma (ICP)
- Planar resonant RF antenna "new" device
- Partial inductance "new" concept
- Complex image method "new" theory
- RF antenna ICP diagnostic

} new to plasma

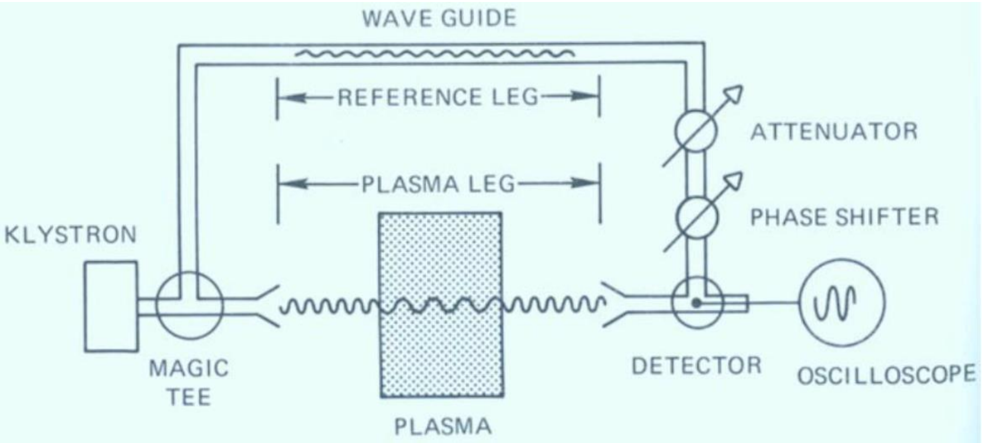
Brief review: RF antenna diagnostics

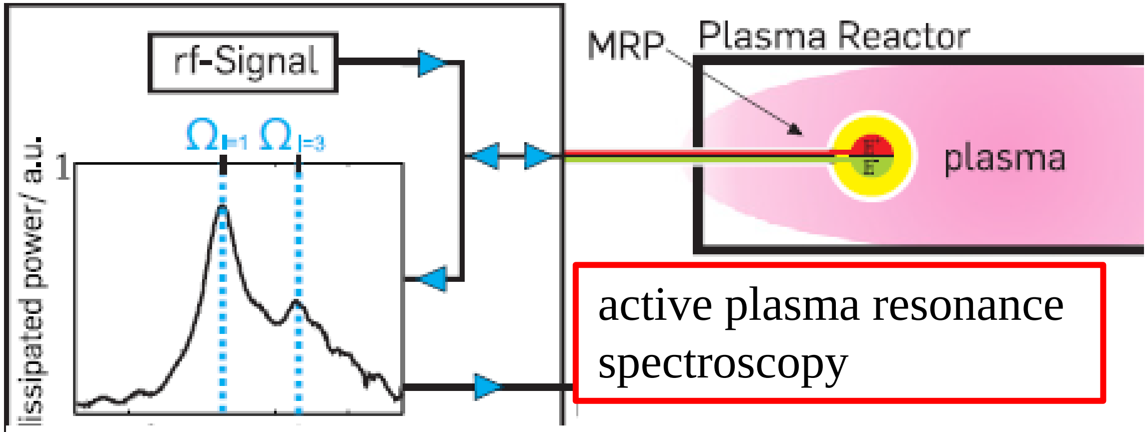
wave cutoff method



J H Kim et al, *Appl. Phys. Lett*. **83**, 4725 (2003)

microwave interferometer





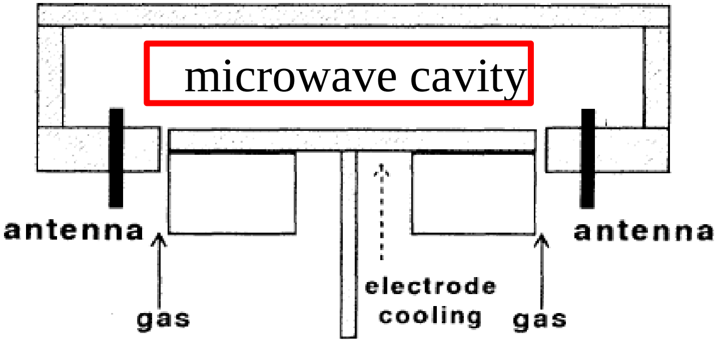
active plasma resonance spectroscopy

T. Styrnoll et al, *Pl. Sources, Sci. Technol*. **23**, 025013 (2014)

$$\epsilon_r = 1 - \left(\frac{\omega_{pe}}{\omega}\right)^2, \ \omega_{pe} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}$$

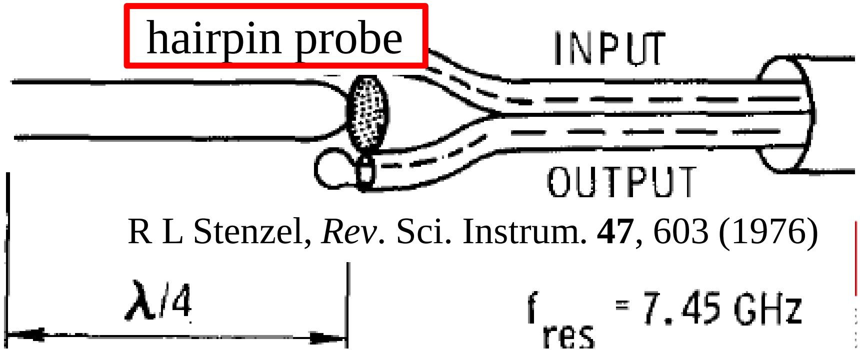
relative dielectric constant of plasma

microwave cavity



E Stoffels et al, *Phys. Rev. E* **51**, 2425 (1995)

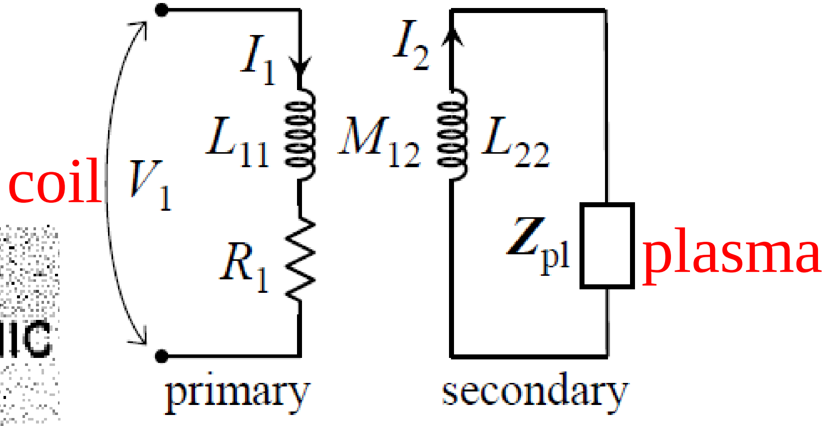
hairpin probe

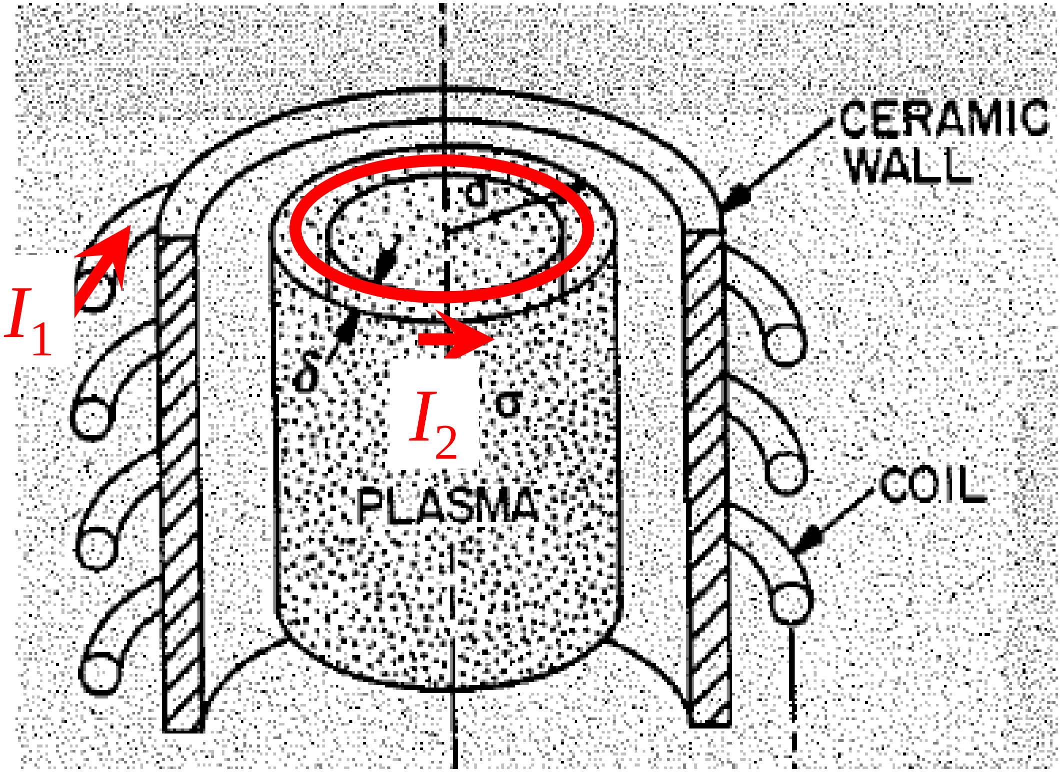


R L Stenzel, *Rev*. Sci. Instrum. **47**, 603 (1976)

Inductively-coupled plasma diagnostic?

transformer coupling model



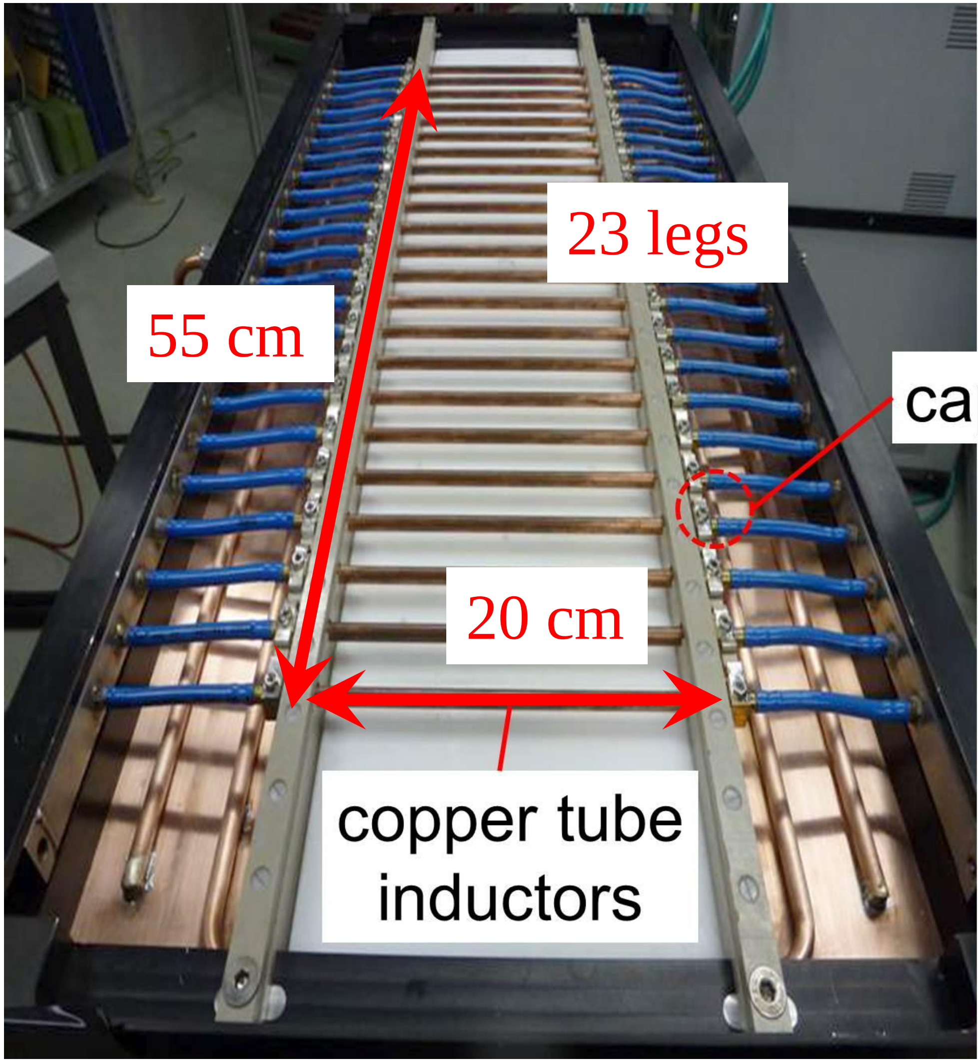


measure the change in primary impedance
to deduce plasma conductivity
(electron density and collision frequency)

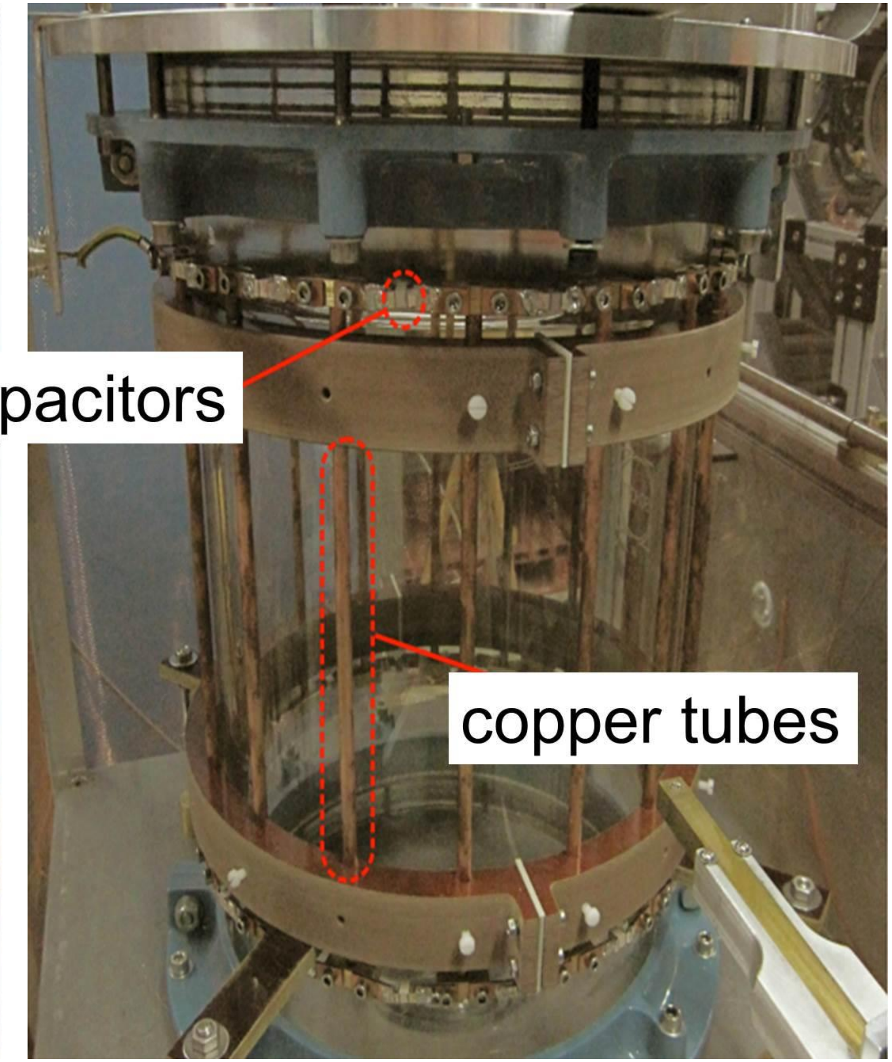
OK only for simple geometries!

Planar resonant network

Ph. Guittienne et al, *Pl. Sources, Sci. Technol*. **23**, 015006 (2014)

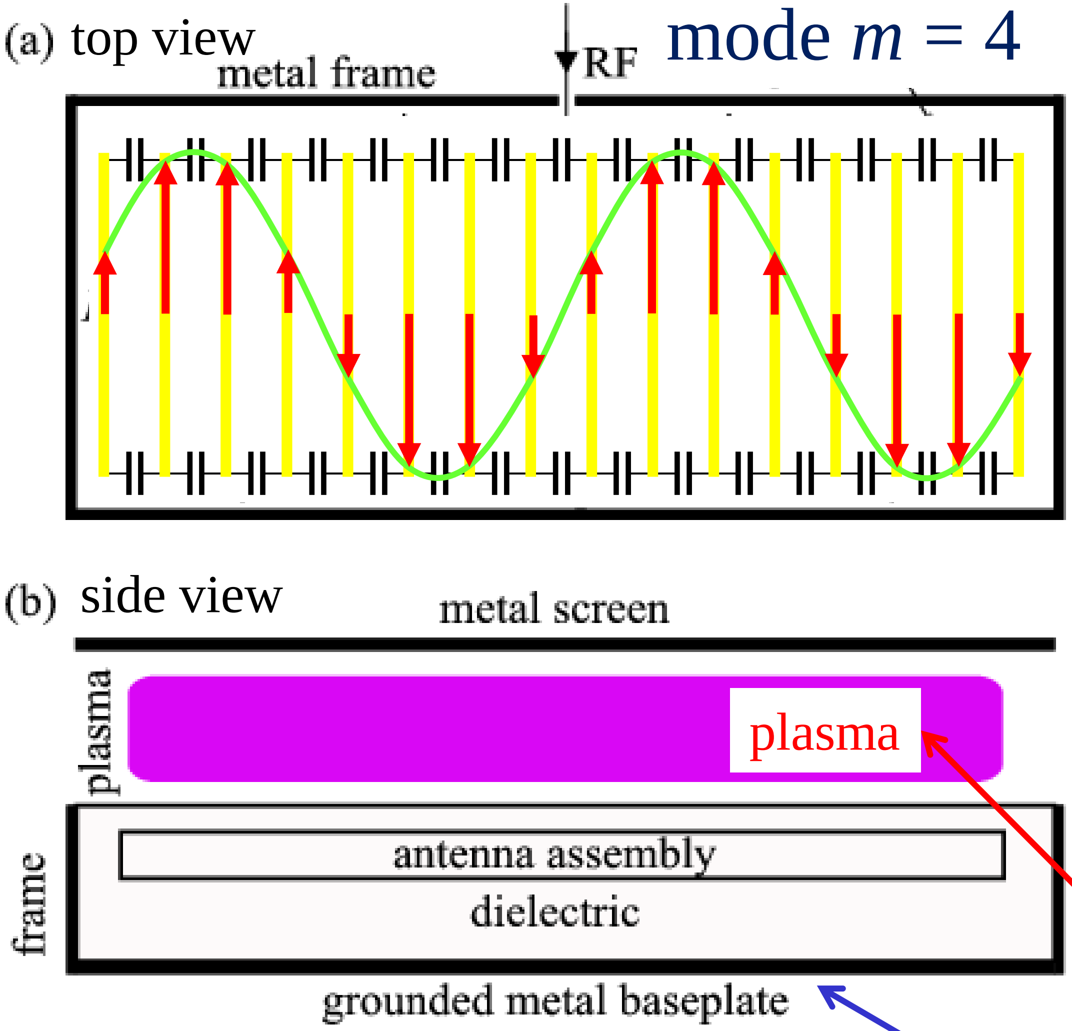


Cylindrical (birdcage)



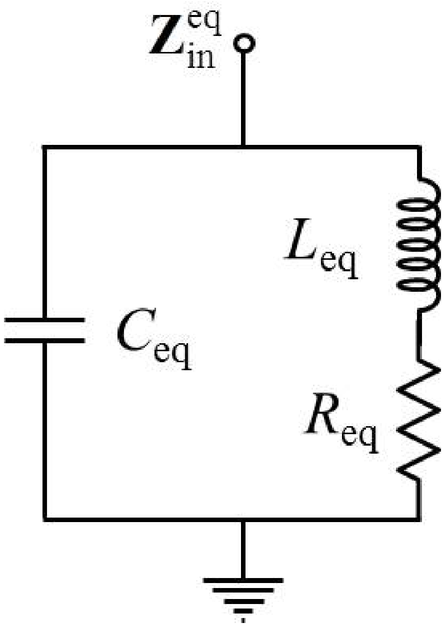
How to model inductive coupling with plasma?

Planar resonant network, *N* legs, (*N*-1) resonances



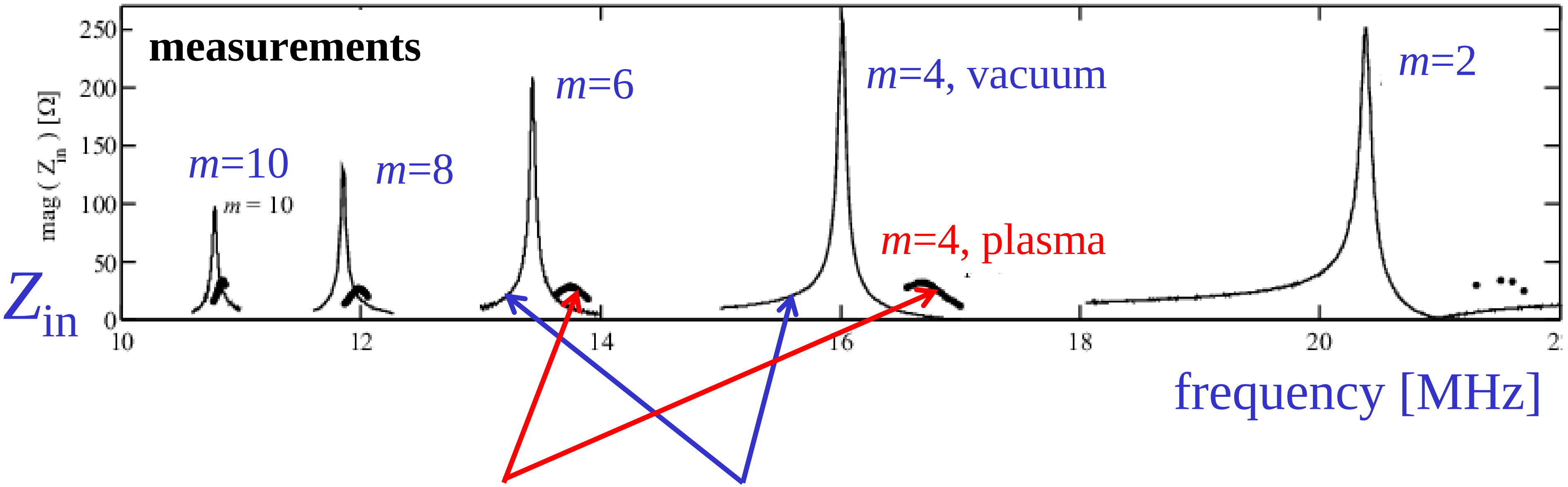
mode *m* = 4

For each resonance: single ***LC*** parallel resonant circuit



How to model inductive coupling with screen & plasma?

Mode impedance spectrum



plasma

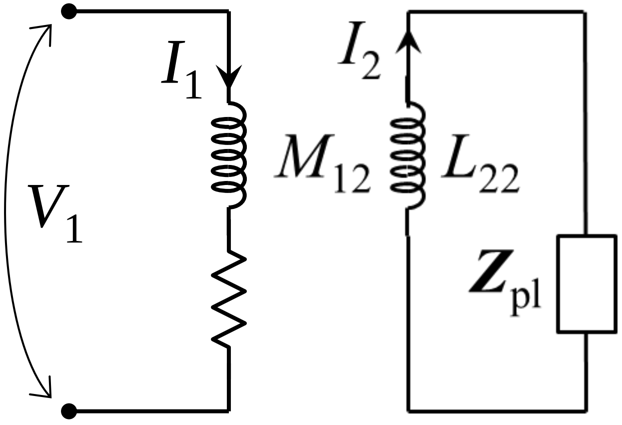
vacuum

Z_{in}

Z_{in}

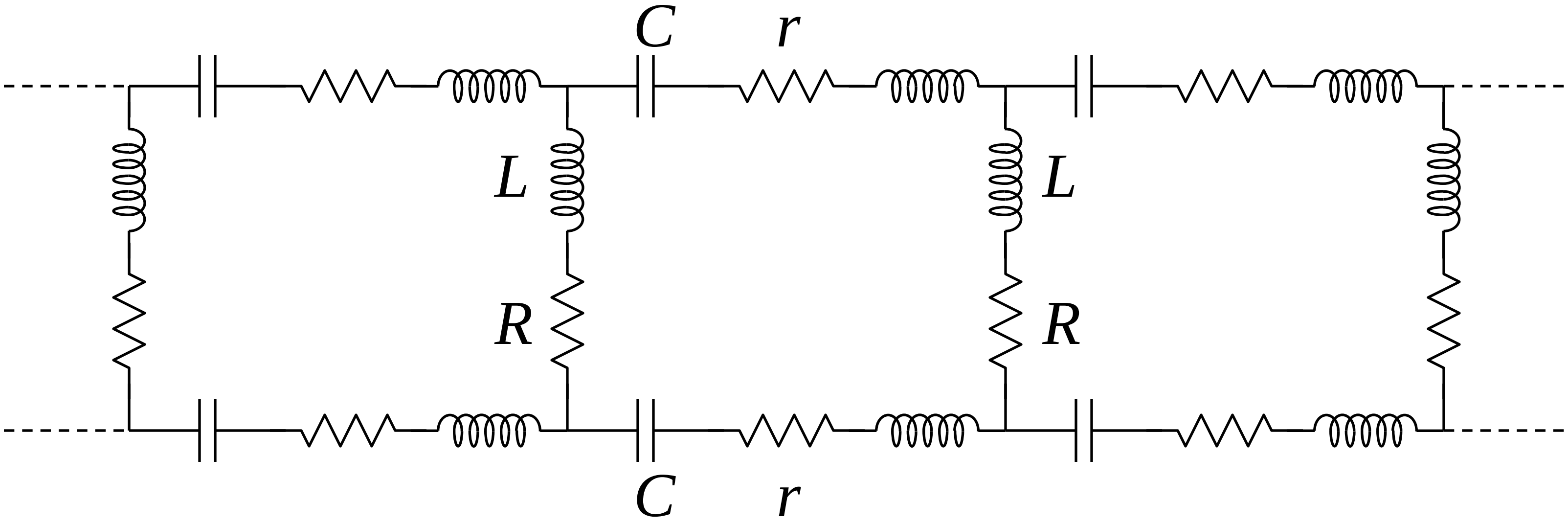
"Z-scan" probe

network analyser

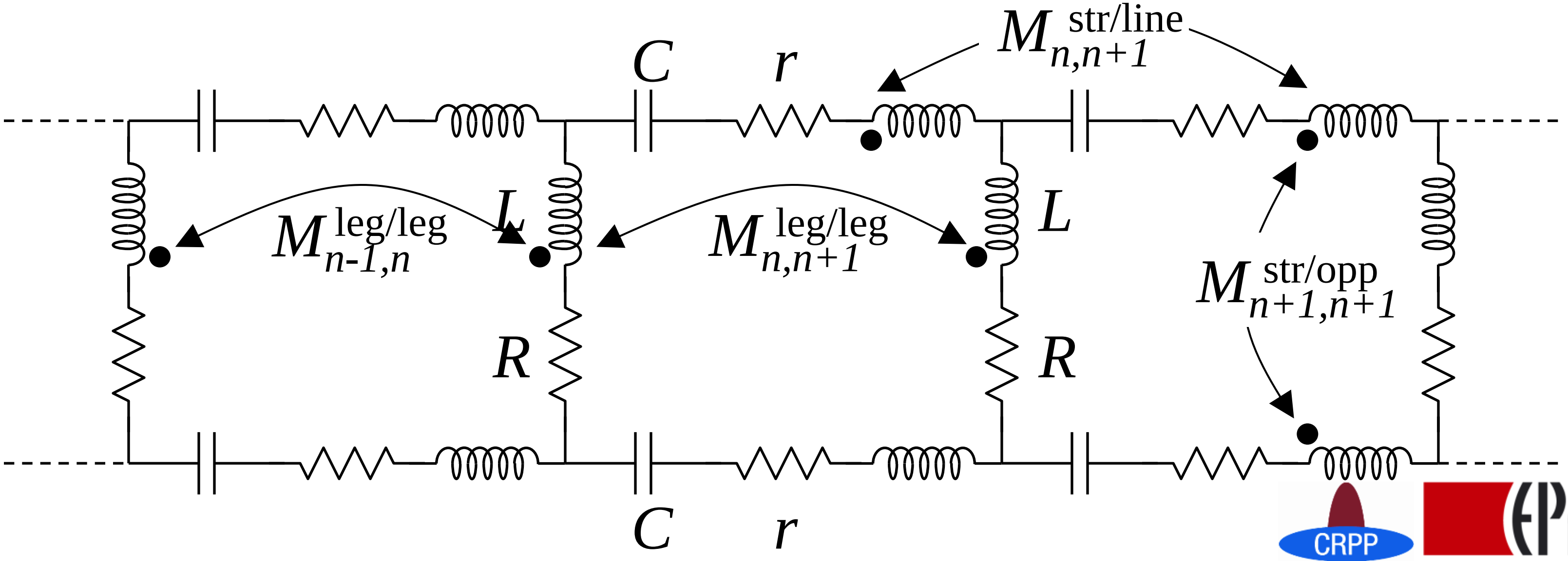


Strong effect of plasma = Basis for a plasma diagnostic

Planar resonant network



...must consider mutual inductances



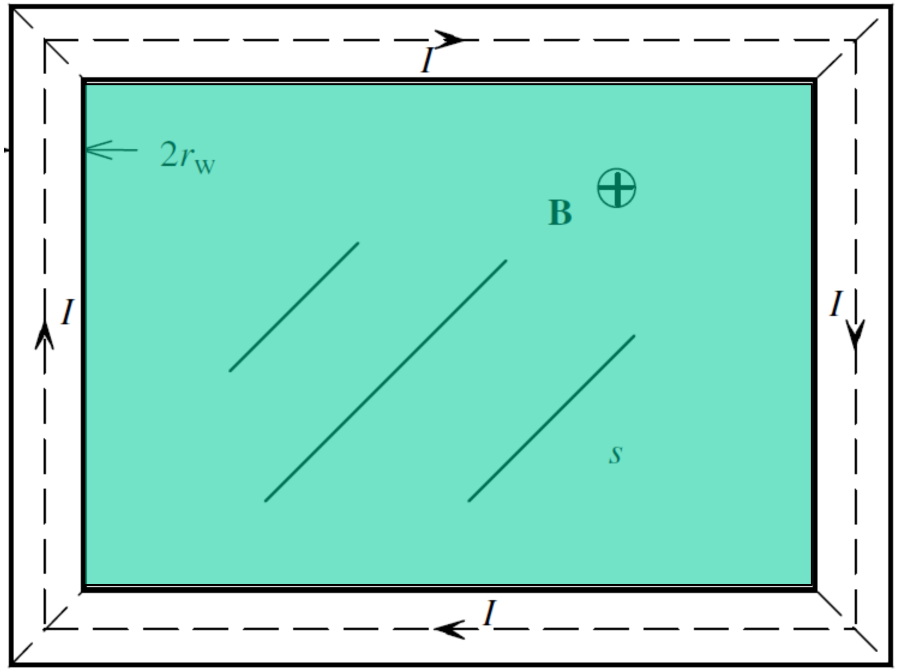
Loop and partial inductance – basic concepts

"Inductance: Loop and Partial" by Clayton Paul (2010)

What is the self inductance L of a metal leg?

Conventionally, (loop) inductance is only defined for a **closed** circuit

Consider a rectangular circuit:

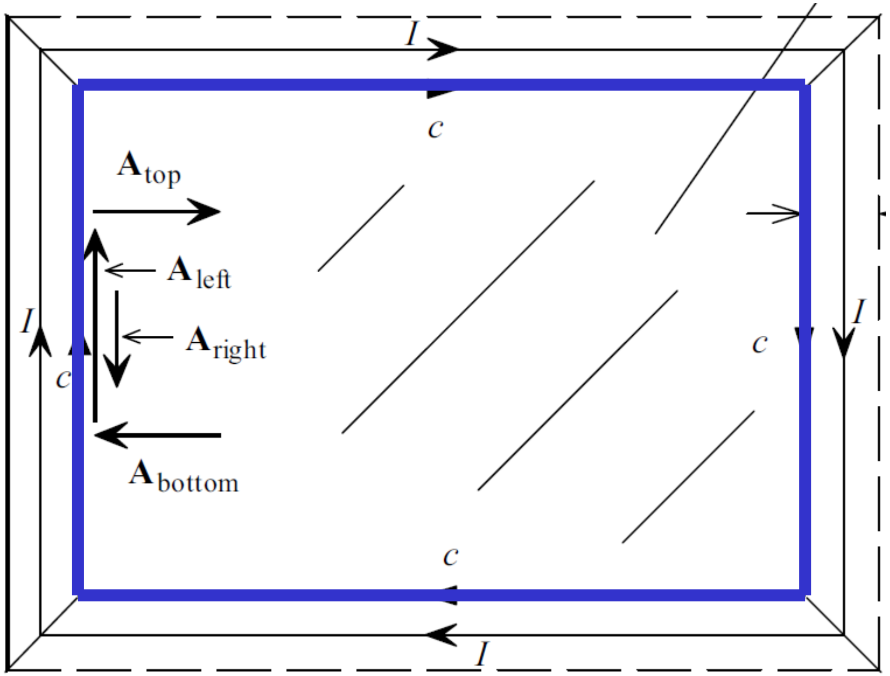


$$\psi = \int_s \mathbf{B} \cdot d\mathbf{s}$$

$$L = \frac{\psi}{I}$$

Loop self inductance

Alternative view of inductance...



$$\psi = \int_s \mathbf{B} \cdot d\mathbf{s}$$

surface integrals

$$= \int_s (\nabla \times \mathbf{A}) \cdot d\mathbf{s}$$

Stokes' theorem

$$= \boxed{\oint_c \mathbf{A} \cdot d\mathbf{l}}$$

line integral

$$L = \frac{\oint_c \mathbf{A} \cdot d\mathbf{l}}{I}$$

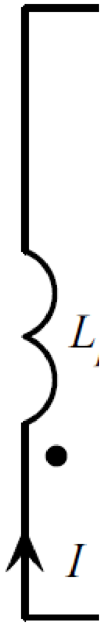
contribution to each segment of the closed loop

$$\boxed{L_i = \frac{\int_{c_i} \mathbf{A}_i \cdot d\mathbf{l}}{I}}$$

partial inductance

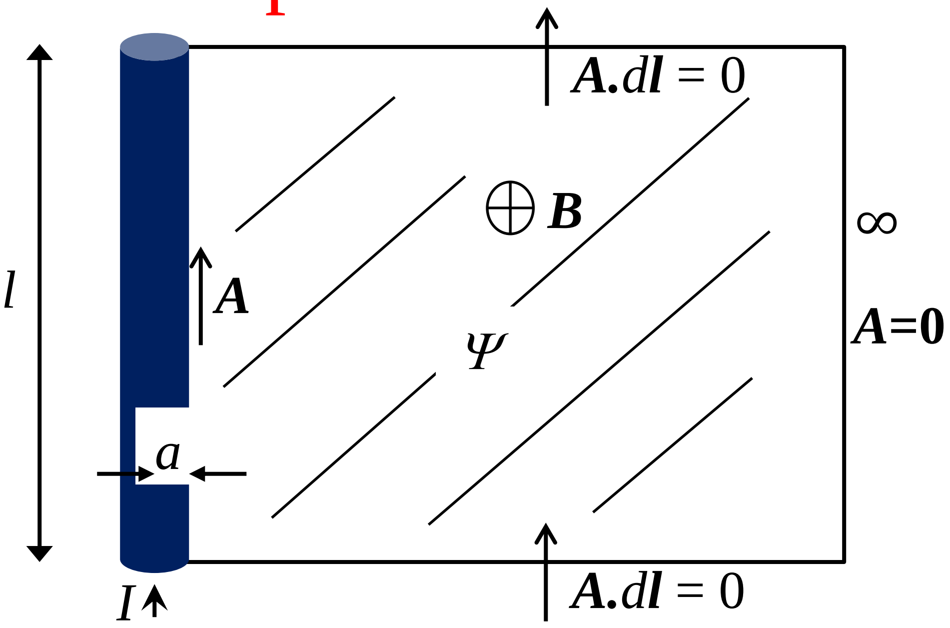
$$L_i = \frac{\int_{c_i} \mathbf{A}_i \cdot d\mathbf{l}}{I}$$

$$L_{\mathrm{p}}^{\mathrm{wire}} \approx \frac{\mu_0}{2\pi} l \left(\ln\left[\frac{2l}{a}\right] - 1 \right)$$

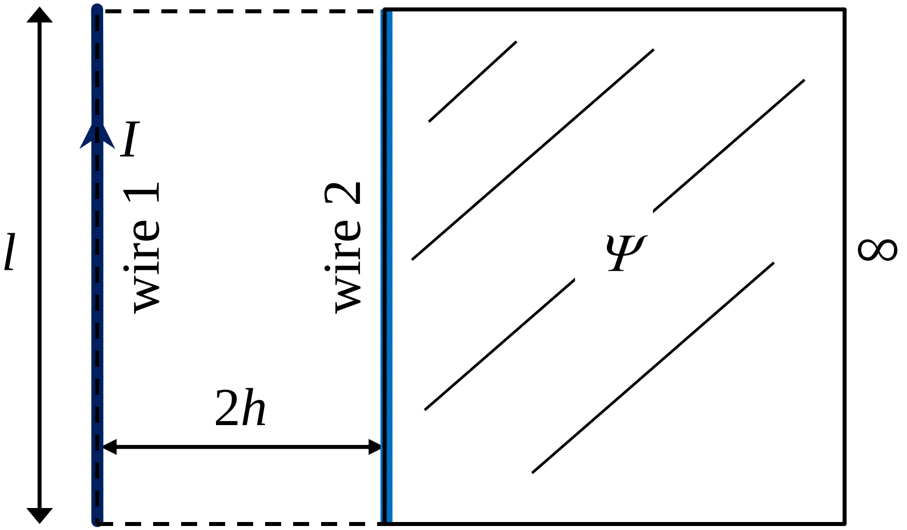


$$M_{\mathrm{p}}^{\mathrm{wire/wire}} \approx \frac{\mu_0}{2\pi} l \left(\ln\left[\frac{l}{h}\right] - 1 \right)$$

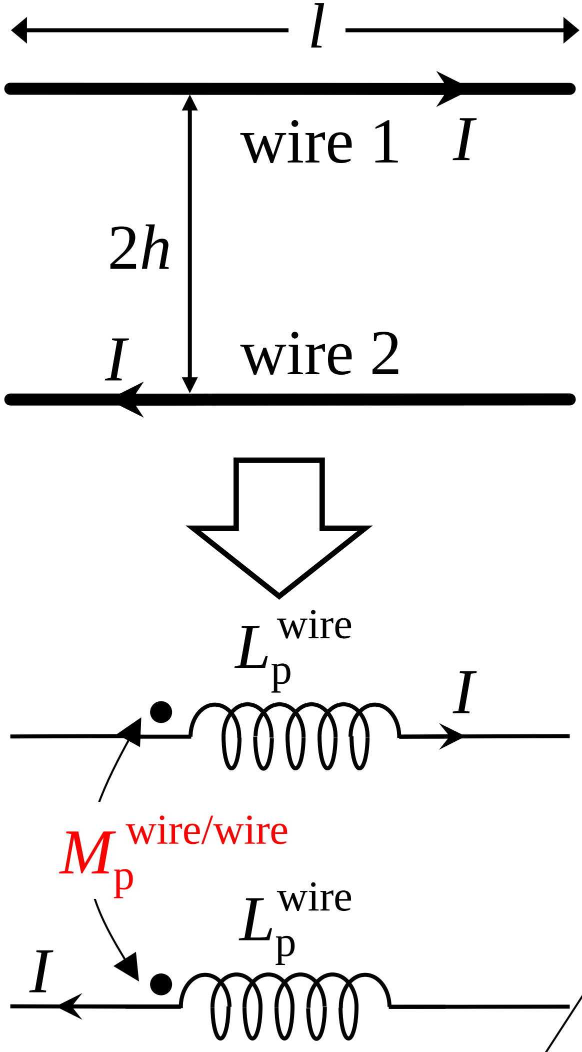
self partial inductance



mutual partial inductance



Mutual partial inductance between parallel wires



partial → loop inductance

loop ⇏ partial inductance

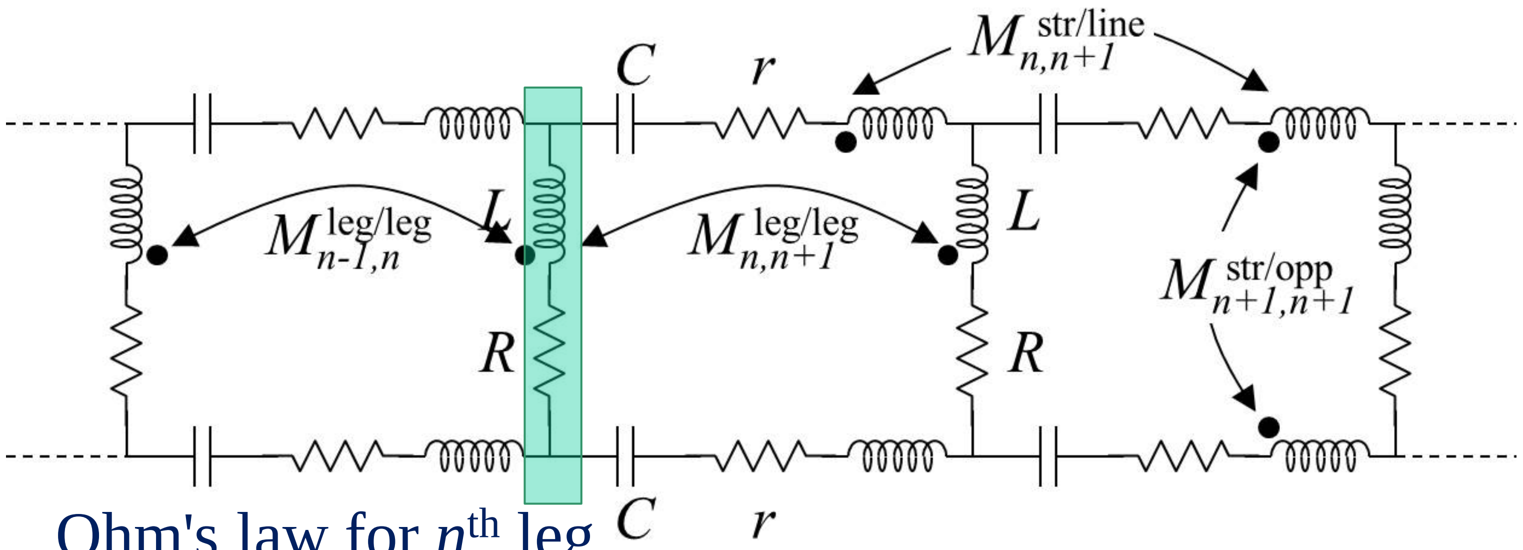
$$L_\mathrm{p}^\mathrm{wire} \approx \frac{\mu_0}{2\pi} l \left(\ln\left[\frac{2l}{a}\right] - 1 \right)$$

$$M_\mathrm{p}^\mathrm{wire/wire} \approx \frac{\mu_0}{2\pi} l \left(\ln\left[\frac{l}{h}\right] - 1 \right)$$

OK! ☺

$$L_\mathrm{loop}^\mathrm{wire/wire} = L_\mathrm{p11}^\mathrm{wire} + L_\mathrm{p22}^\mathrm{wire} - 2M_\mathrm{p12}^\mathrm{wire/wire} \approx \boxed{\frac{\mu_0}{\pi} l \ln\left[\frac{2h}{a}\right]}$$

Mutual partial inductances between antenna elements



Ohm's law for n^{th} leg

$$V_n = RI_n + \mathrm{j}\omega \sum_{q=1}^{N} (M_{nq}^{\text{leg/leg}}) I_q$$

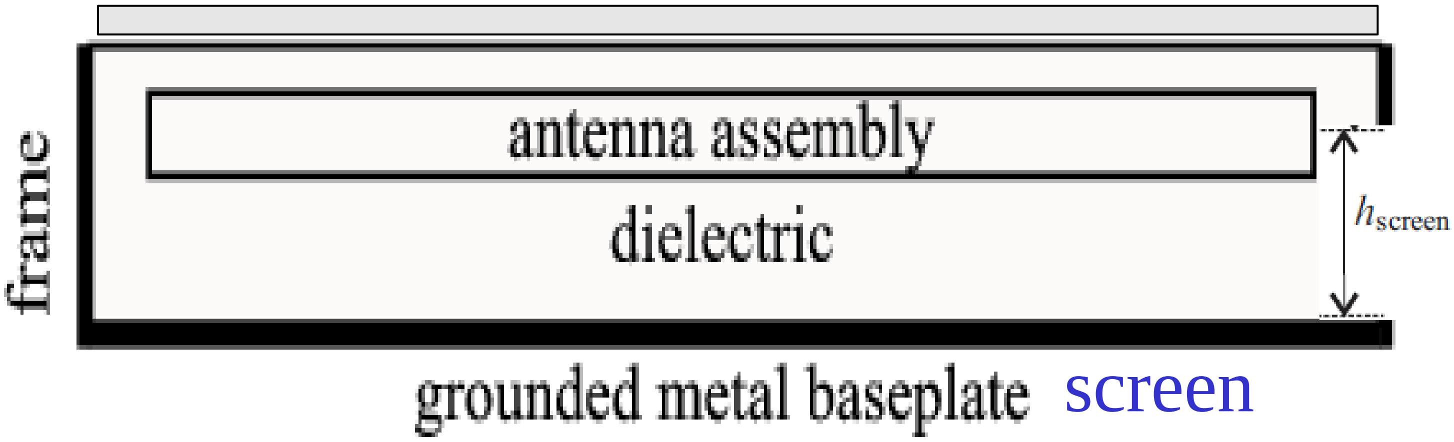
$$\mathbf{Z}_{\text{leg}} = R\mathbf{1} + \mathrm{j}\omega \left(\mathbf{M}^{\text{leg/leg}}\right)$$

$$\mathbf{M} = \begin{pmatrix} L_{\text{leg}} & M_{12} & \cdots & M_{1N} \\ M_{21} & L_{\text{leg}} & \cdots & M_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ M_{N1} & M_{N2} & \cdots & L_{\text{leg}} \end{pmatrix}$$

matrix impedance model

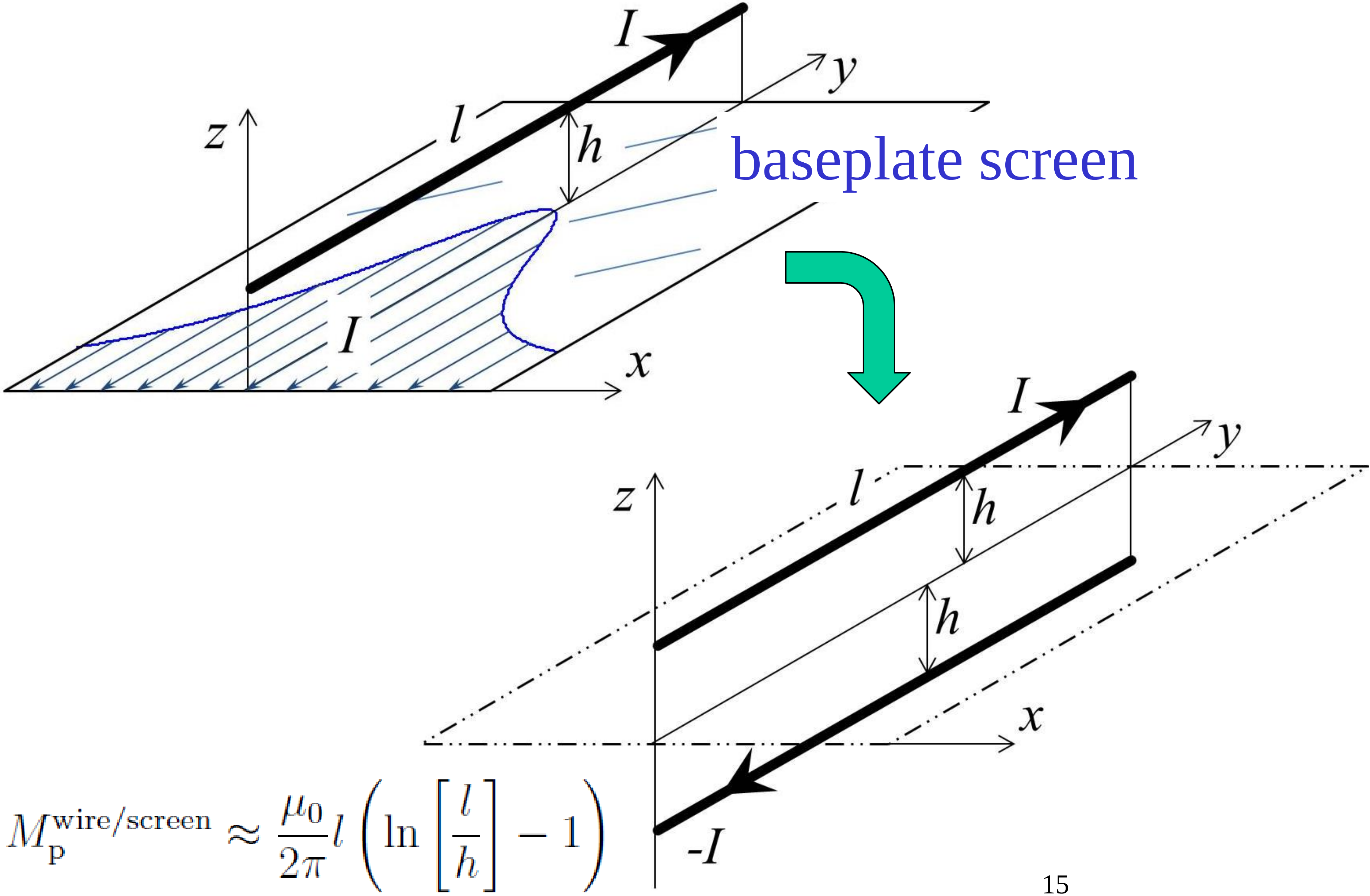
Mutual inductance with the baseplate screen in vacuum (no plasma)

side view



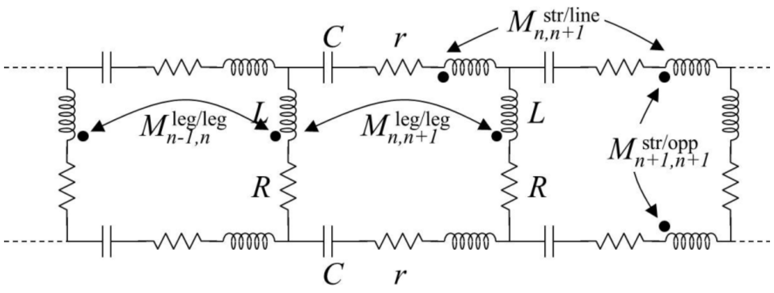
screen

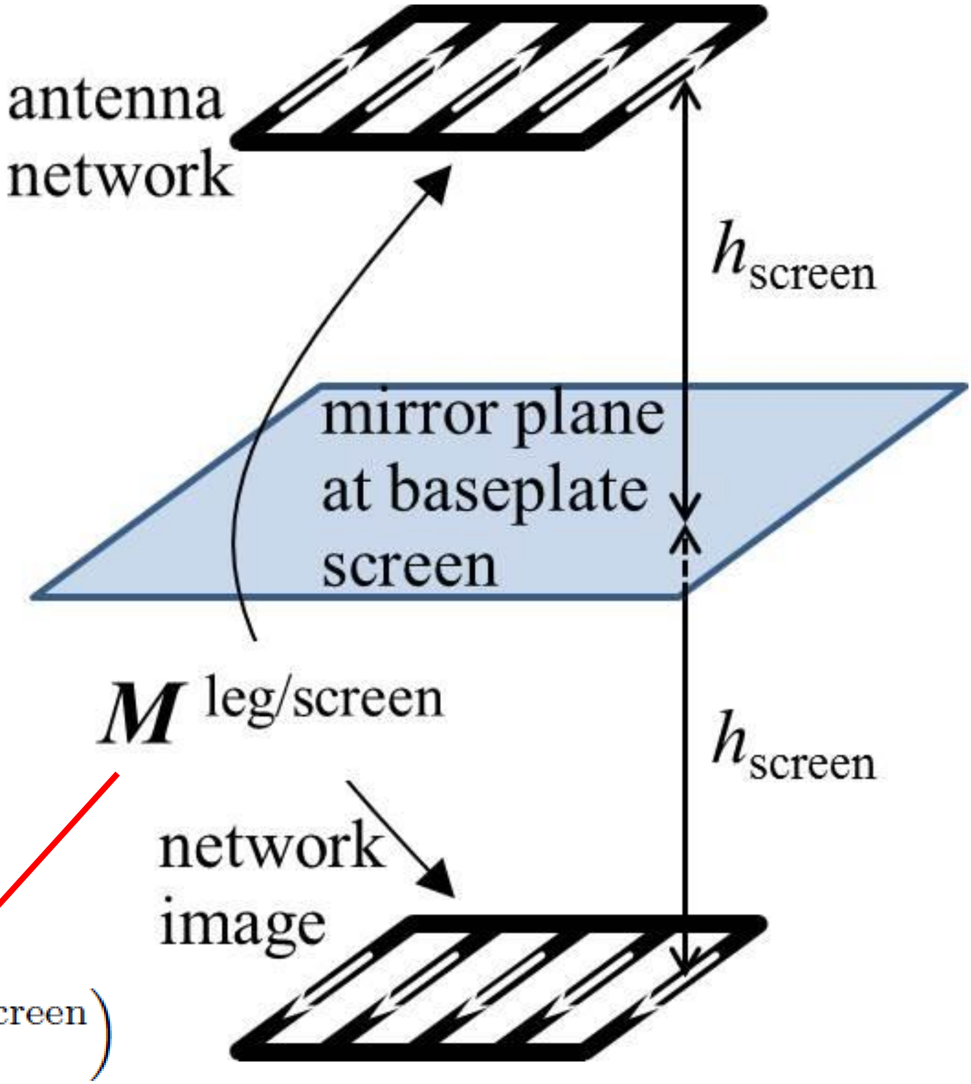
Method of images:



$$M_{\mathrm{p}}^{\mathrm{wire/screen}} \approx \frac{\mu_0}{2\pi} l \left(\ln\left[\frac{l}{h}\right] - 1 \right)$$

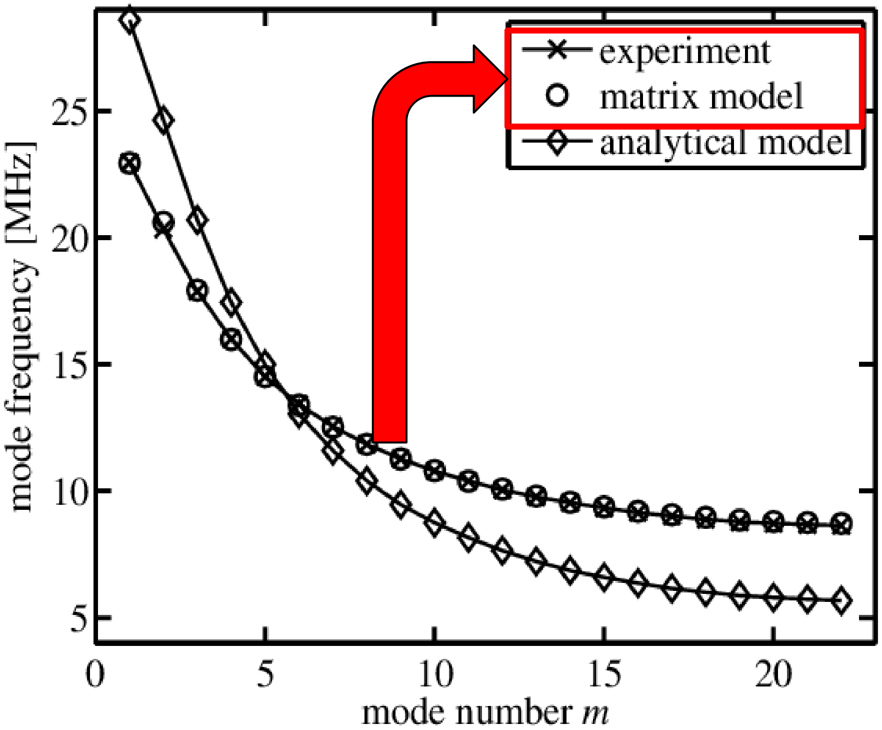
Method of images





$$\mathbf{Z}_{\text{leg}} = R\mathbf{1} + \mathrm{j}\omega\left(\mathrm{M}^{\text{leg/leg}} - \mathrm{M}^{\text{leg/screen}}\right)$$

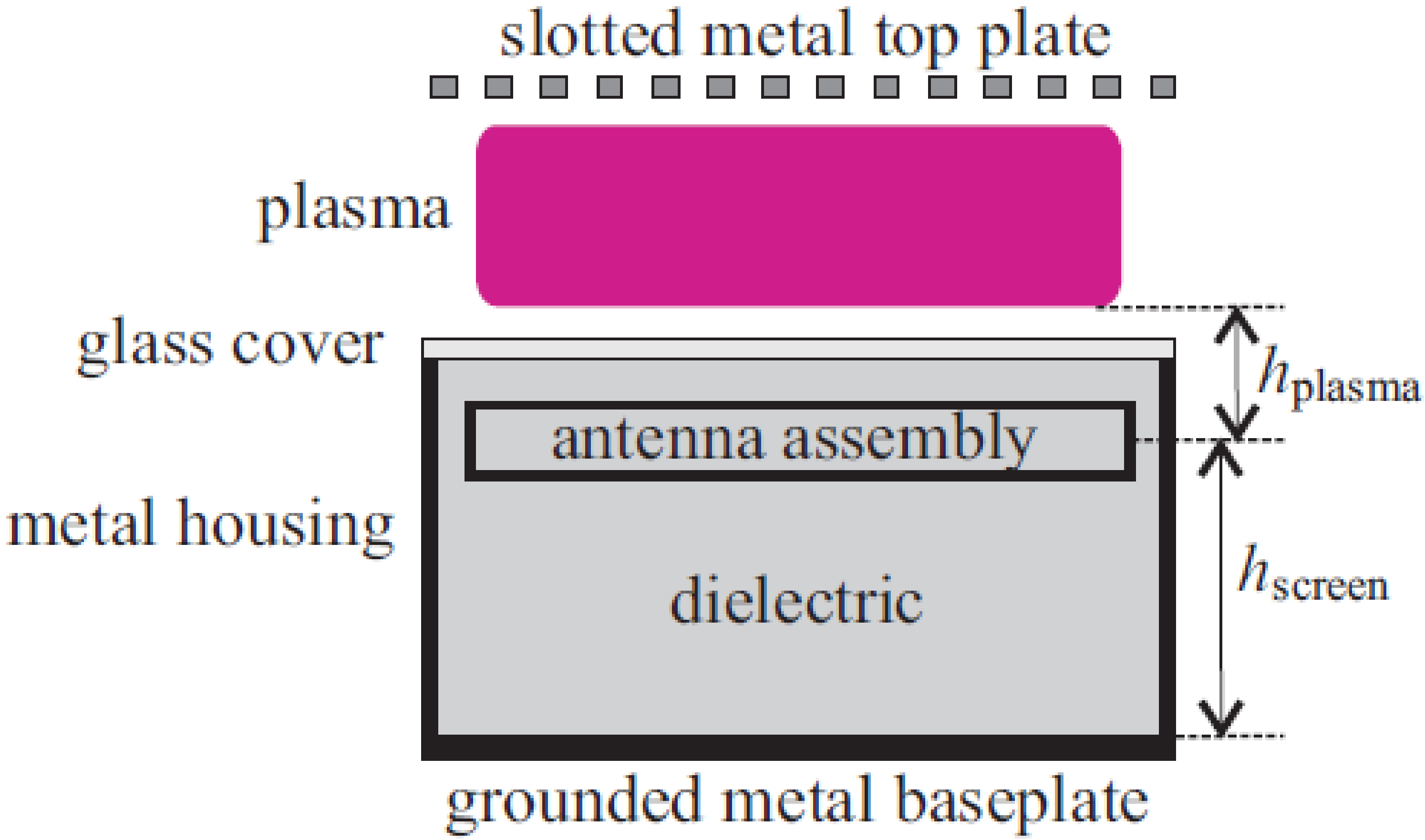
Planar resonant network – no plasma



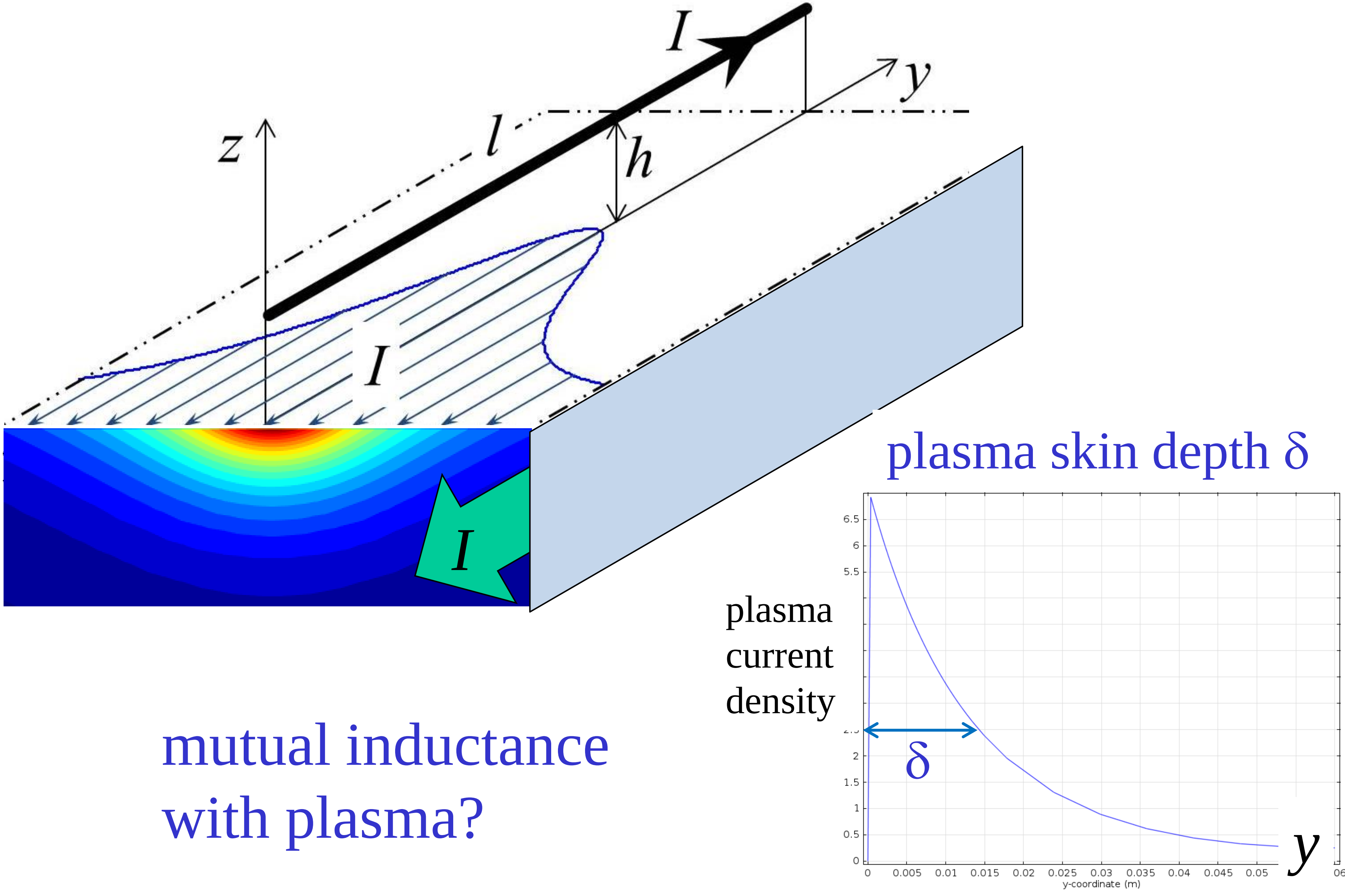
mode frequencies calculated by a matrix impedance model using partial inductances

good agreement for mode frequencies in *vacuum*

Planar resonant network – with plasma



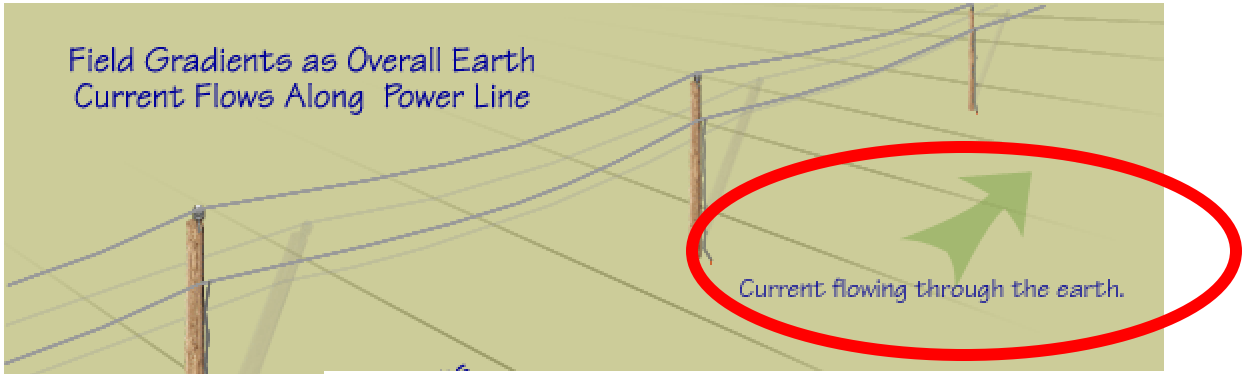
Induced current in a plasma

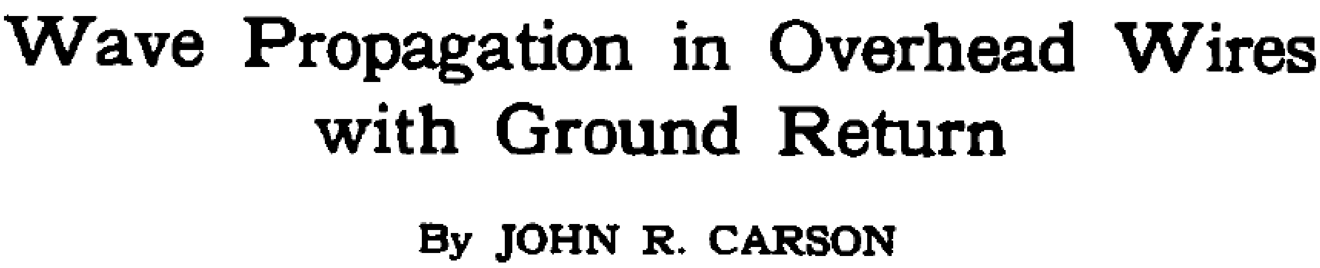


plasma
current
density

mutual inductance
with plasma?

Induced current in a resistive ground return

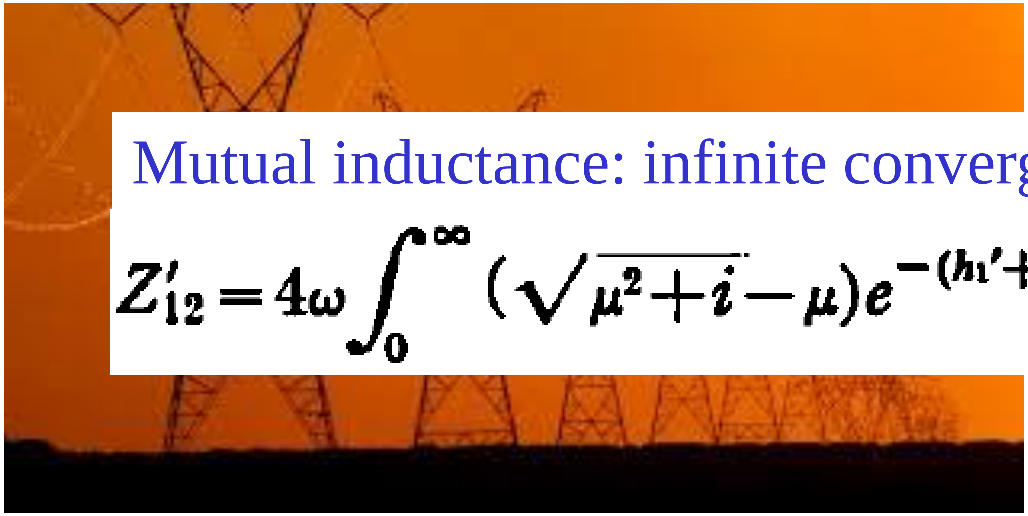




Wave Propagation in Overhead Wires with Ground Return

By JOHN R. CARSON

Bell Syst. Techn. J. **5**, 539 (1926)



Mutual inductance: infinite converging Fourier integrals

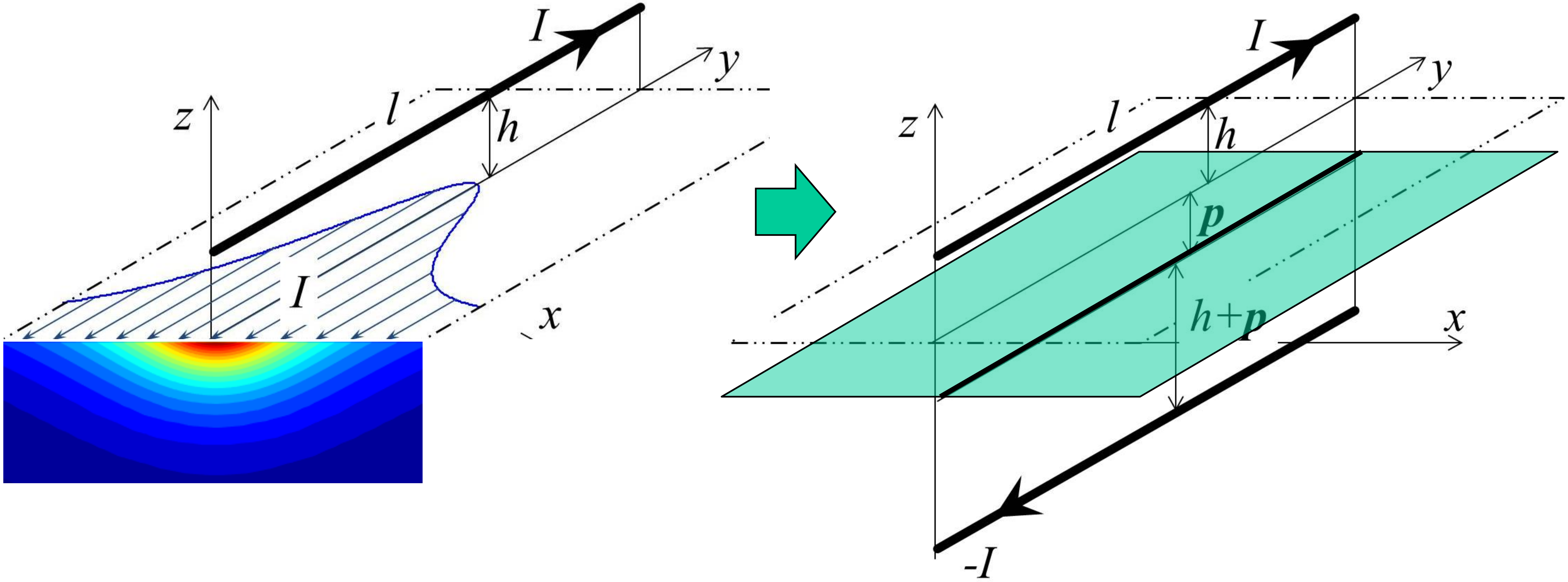
$$Z'_{12} = 4\omega \int_0^\infty \left(\sqrt{\mu^2+i}-\mu\right) e^{-(h_1'+h_2')\mu} \cos x'\mu \, d\mu.$$

Dubanton at Electricité de France (1976), & co.:

Complex image theory = real image current at a complex depth

Complex depth ***p*** = complex skin depth. Complex wavenumber = 1/***p***

$$H = H_0 e^{-z/\mathrm{p}} e^{\mathrm{j}\omega t} \qquad \frac{1}{\mathrm{p}} = \sqrt{\mathrm{j}\omega\mu_0\sigma} \qquad \delta = (\pi f \mu_0 \sigma)^{-1/2}$$

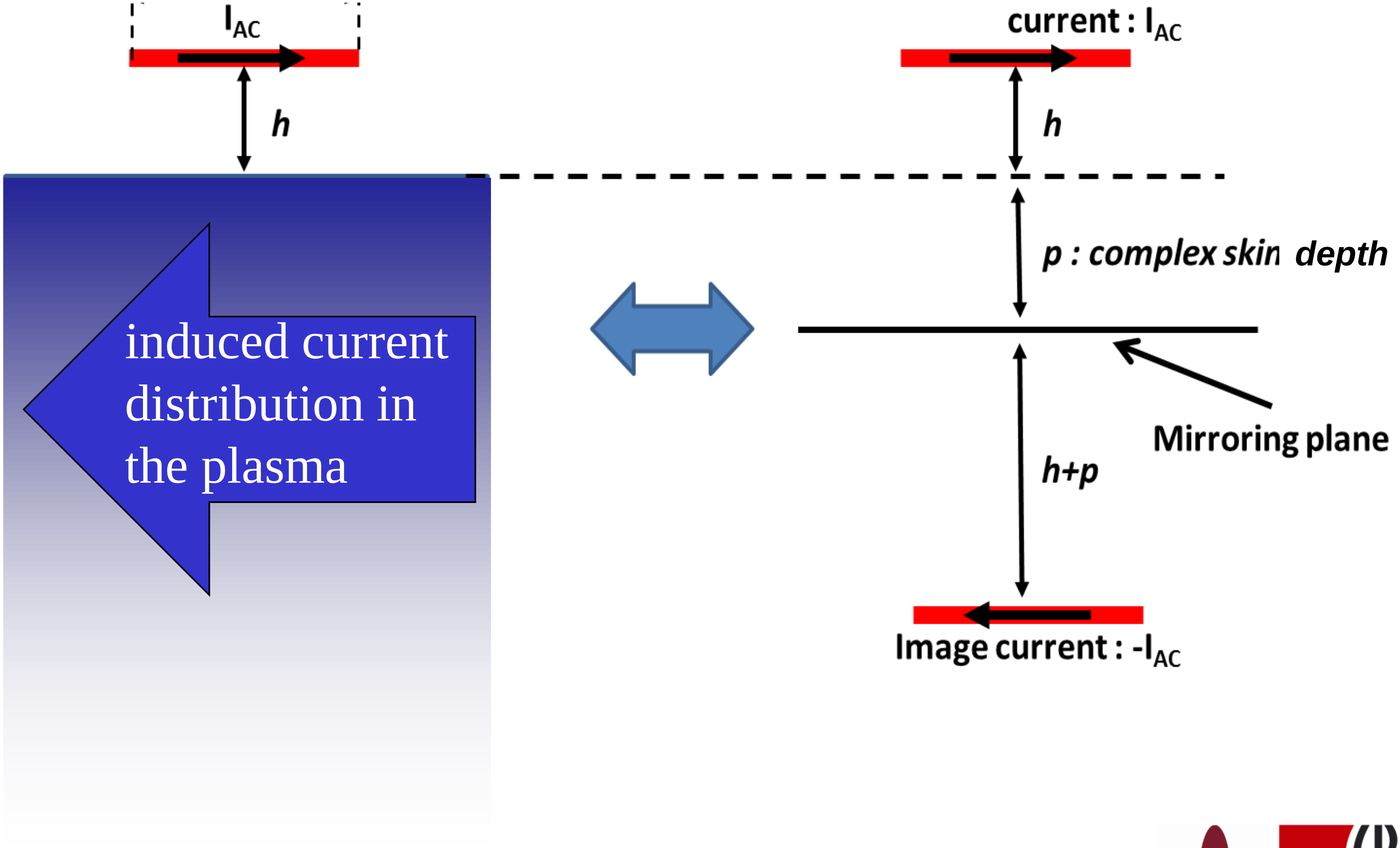


complex mutual inductance also includes ohmic dissipation:

$$\mathrm{M}_{\mathrm{p}}^{\mathrm{wire/plasma}} \approx \frac{\mu_0}{2\pi} l \left(\ln\left[\frac{l}{(h+\mathrm{p})} \right] - 1 \right)$$

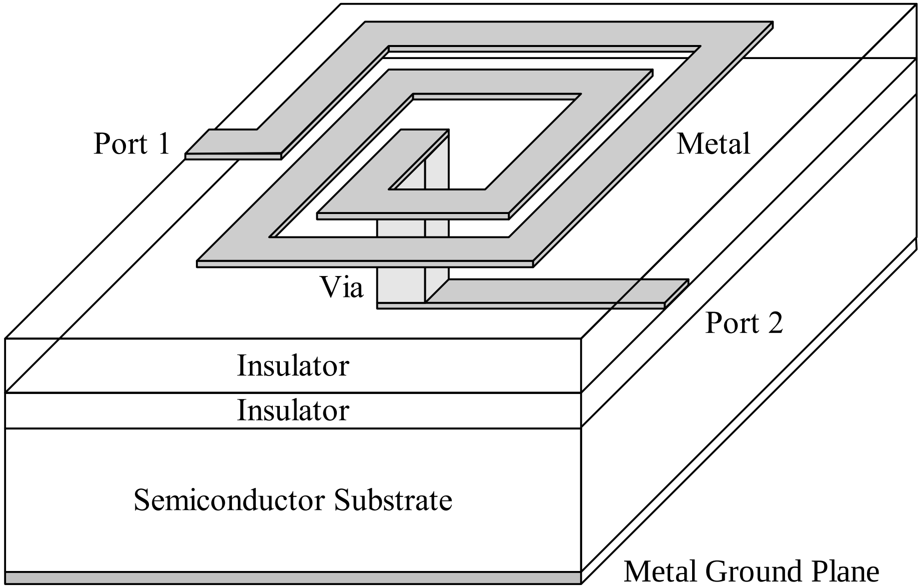
Complex image theory = real image current at complex depth...

...the magnetic field above the plasma is the same for both cases

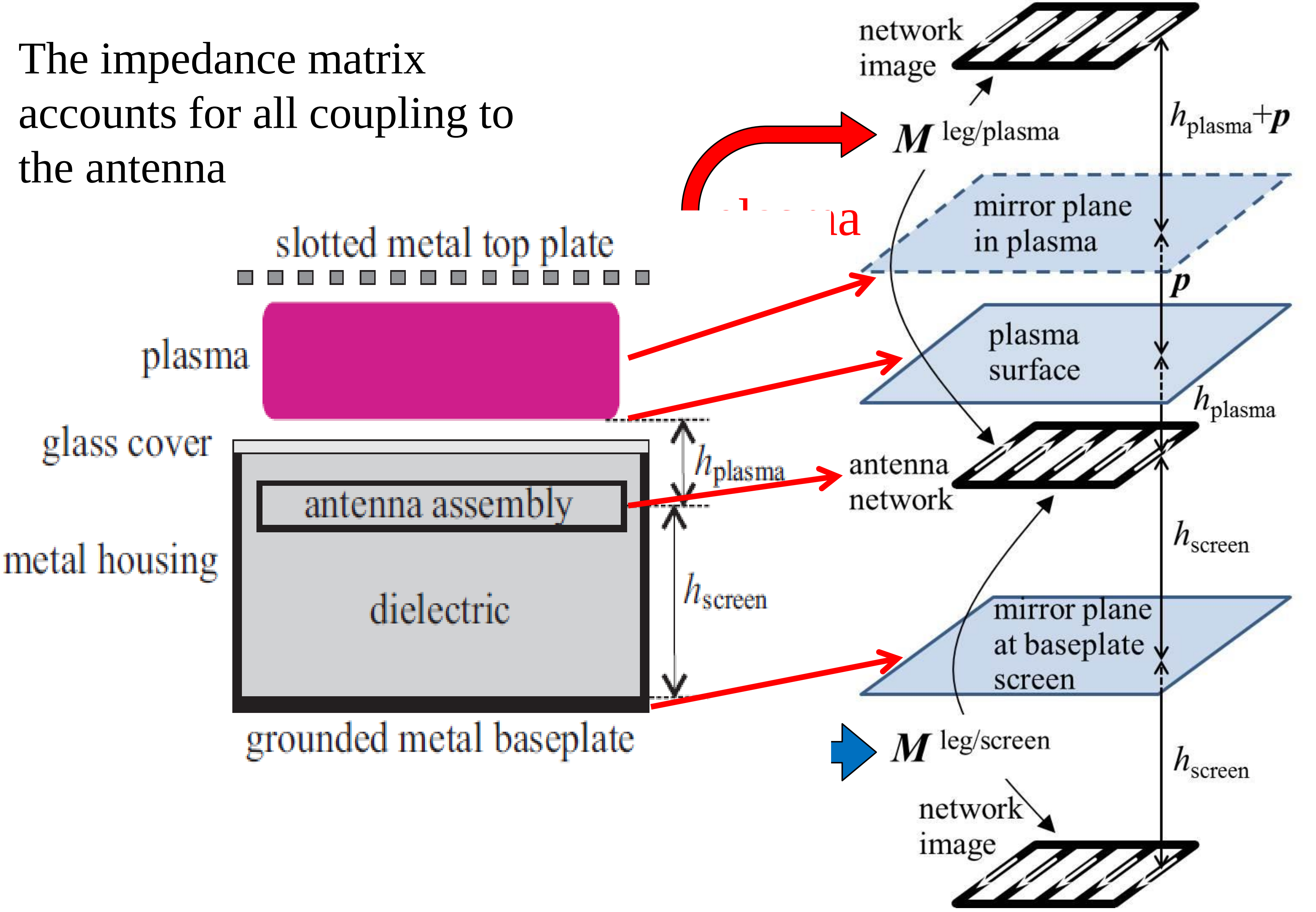


Complex image theory is used in several domains (but not plasma)

- power transmission
- telecommunications
- geophysics
- microelectronics



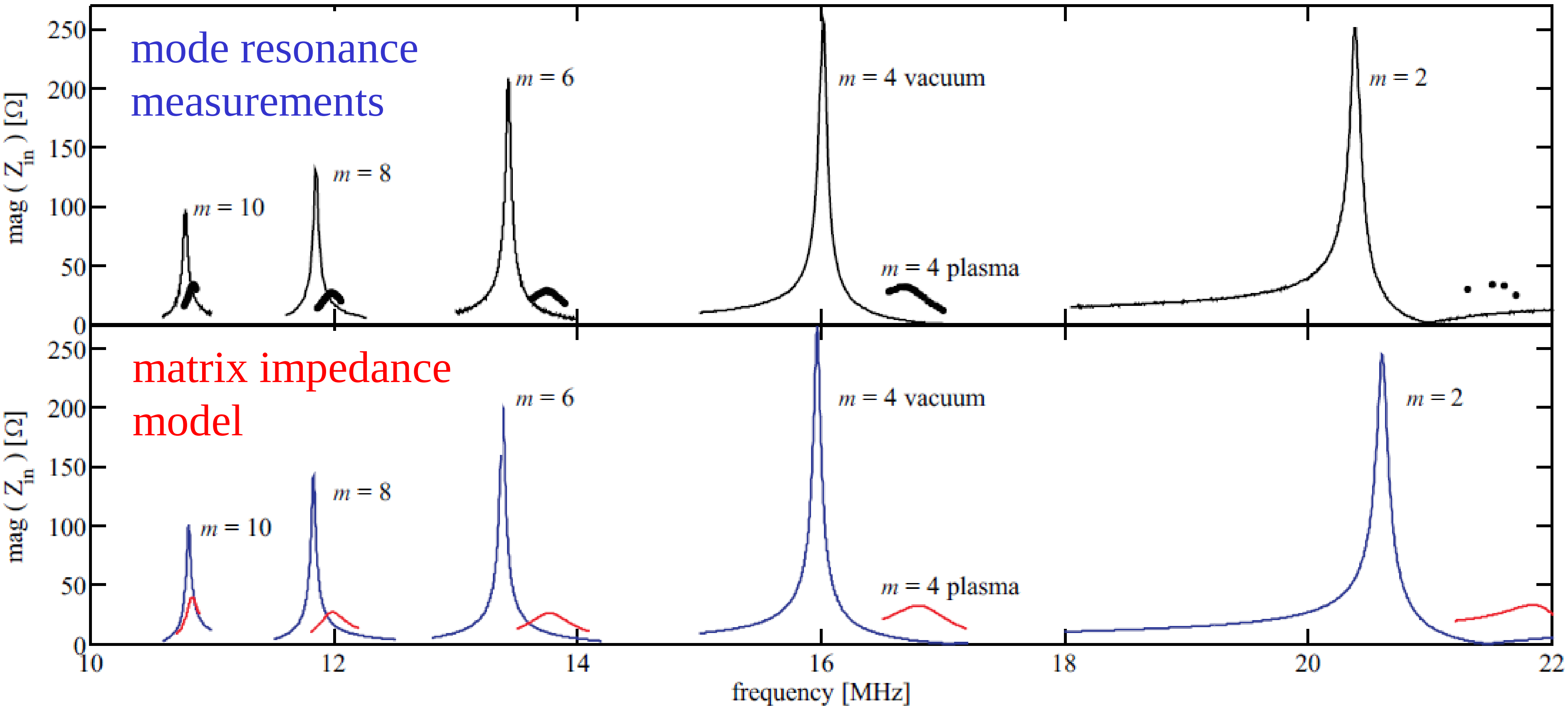
The impedance matrix accounts for all coupling to the antenna



Complex image method fits all 5 modes using only 3 physical quantities:

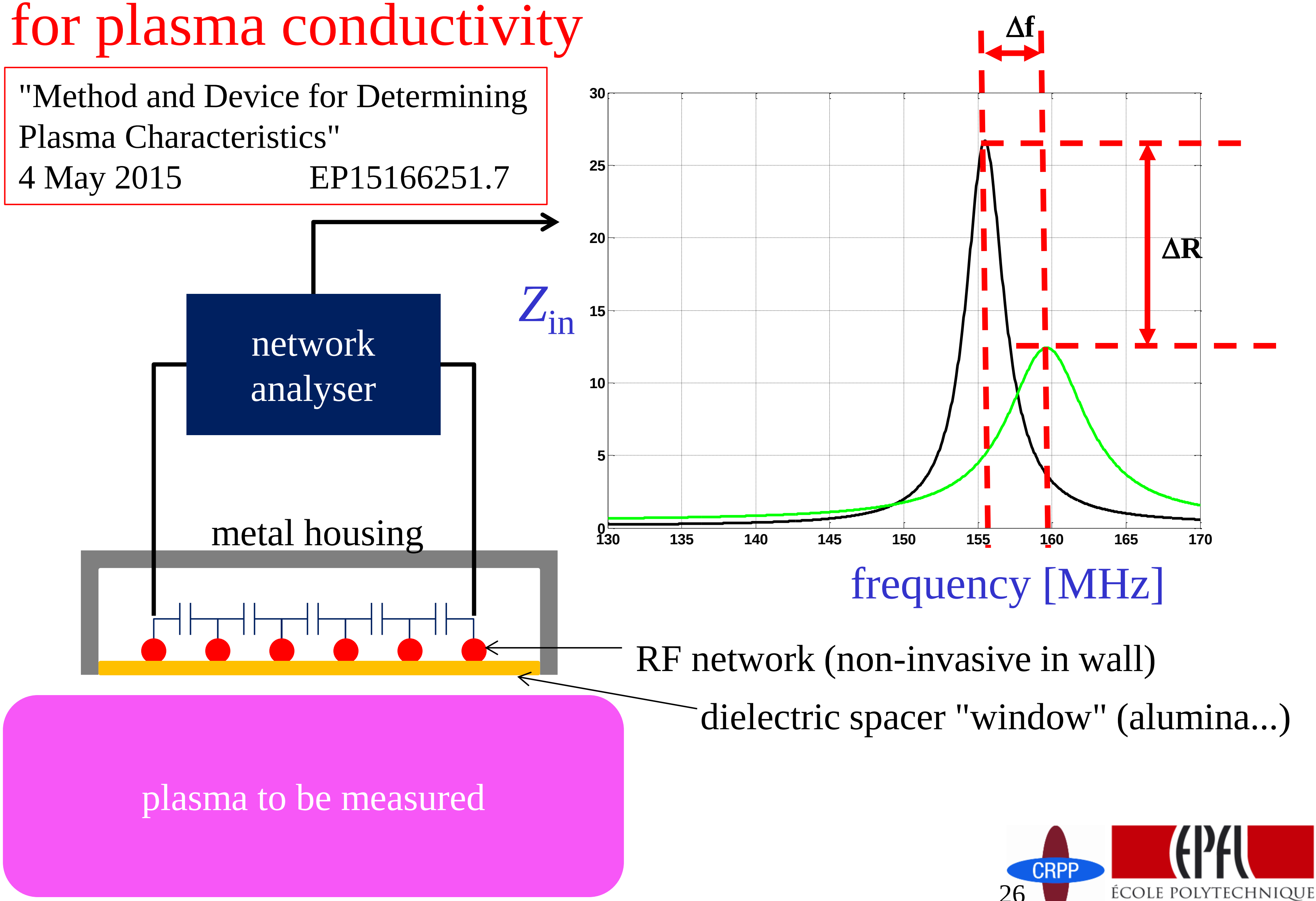
1) distance; 2) electron density; 3) collisionality

skin depth depends on: $\sigma_{\mathrm{pl}} = \dfrac{\sigma_{\mathrm{dc}}}{1 + \mathbf{j}\omega/\nu_{\mathrm{m}}}$, where $\sigma_{\mathrm{dc}} = \dfrac{n_{\mathrm{e}} q_{\mathrm{e}}^2}{m_{\mathrm{e}} \nu_{\mathrm{m}}}$



Inductively-coupled antenna used as a diagnostic for plasma conductivity

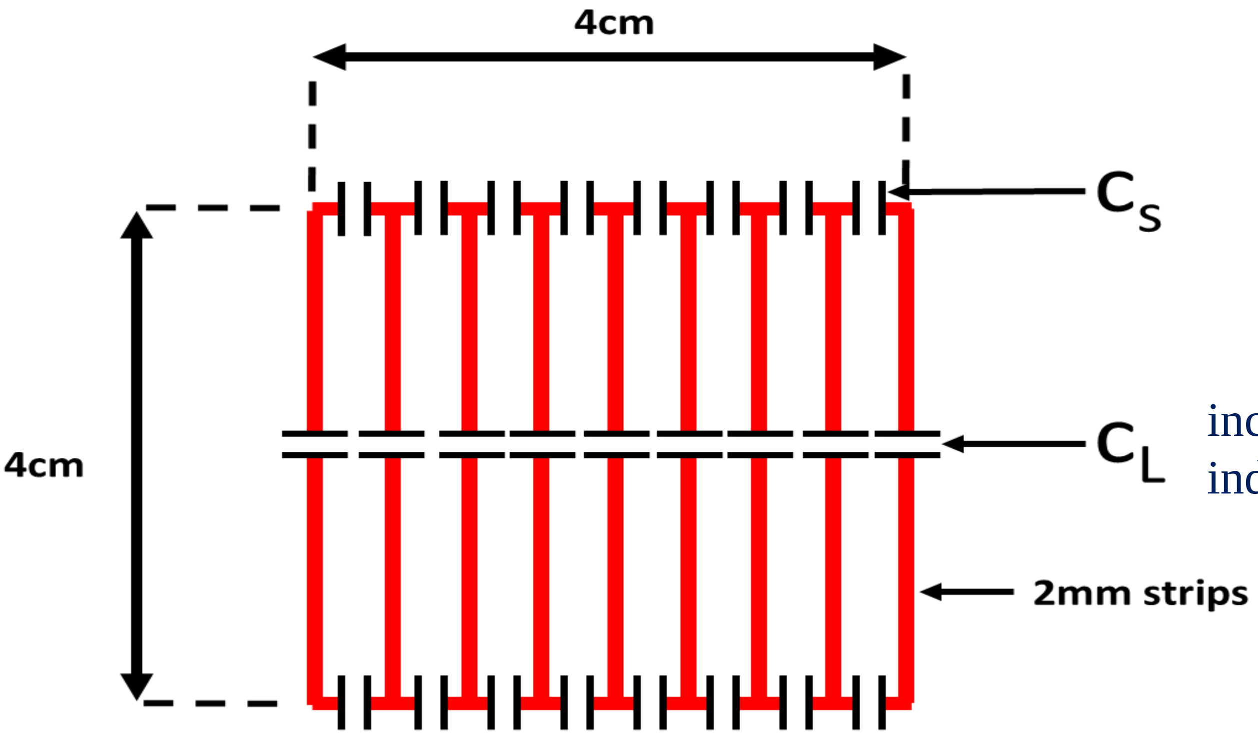
"Method and Device for Determining Plasma Characteristics"
4 May 2015 EP15166251.7



RF network (non-invasive in wall)

dielectric spacer "window" (alumina...)

A hybrid resonant network antenna probe on a printed circuit board



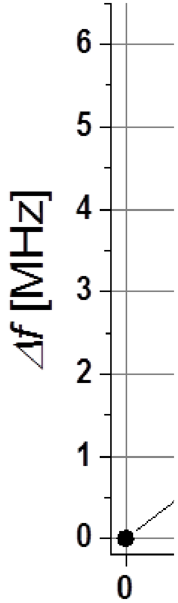
increases sensitivity to inductive coupling

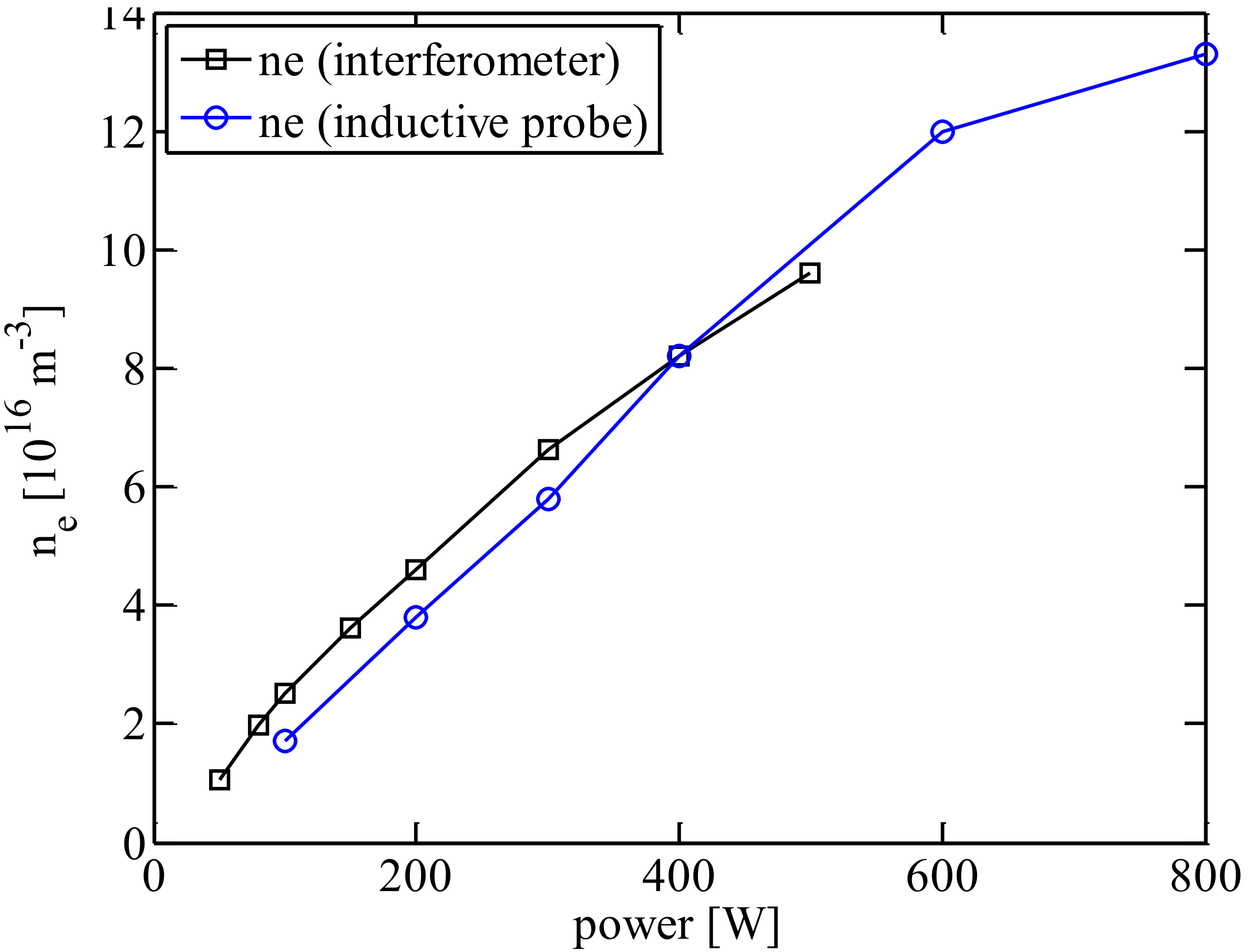
... and a large area 15 kW antenna (1.2 m^2) for large area deposition, etching, packaging applications, etc

Measurement of probe *Δf* as a function of the RF power of the plasma source.

The computed relation between the electron density and *Δf* (complex image method and mutual inductance matrix).

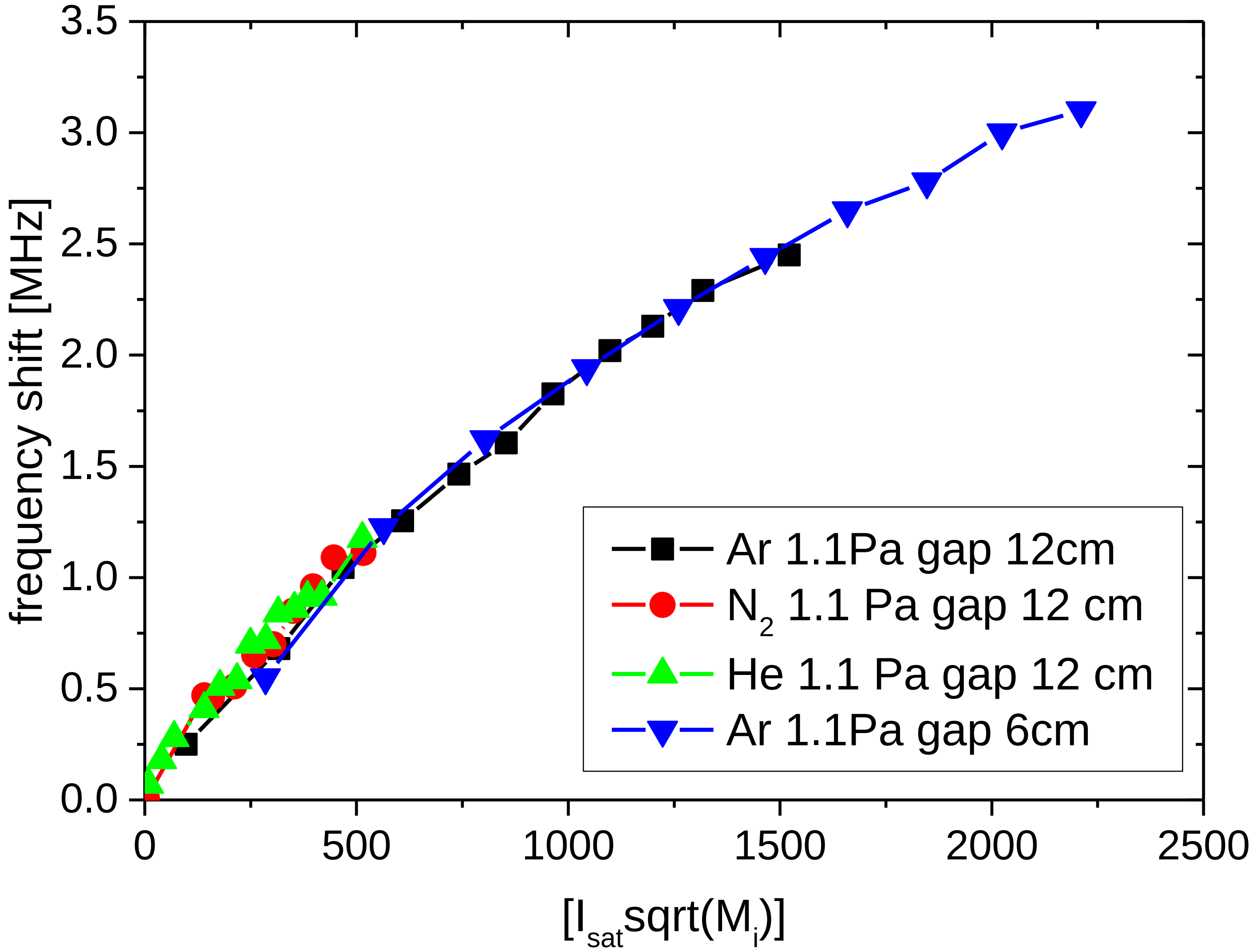
DEVICE + METHOD





The electron density as a function of the source injected power.

Inductive probe measurements using different gases



plasma density estimated with Langmuir probe

Conclusions

- Planar resonant antenna used as a plasma **source**
- Partial inductance method
- Complex image method
- Planar resonant antenna used as a plasma **sensor**
  - ❖ for plasma conductivity
  - ❖ general method for ICP