Mutual impedance experiments as a diagnostic for magnetized space plasmas

Pietro Dazzi [1,2],

Pierre Henri [1,3], Francesco Califano [4], Luca Bucciantini [1], Federico Lavorenti [3,4], Gaëtan Wattieaux [5]

[1] LPC2E, CNRS, Univ. Orléans, CNES, Orléans
[2] LESIA, Observatoire de Paris
[3] Laboratoire Lagrange, Observatoire de la Côte d'Azur
[4] Dipartimento di Fisica "E.Fermi", Universita di Pisa
[5] Laboratoire Plasma et Conversion d'Energie, Université de Toulouse, CNRS

Objective of this work

Objective of this work: obtain a plasma diagnostic from *in situ* mutual impedance measurements performed by spacecraft, in an environment where the magnetic field influences said measurements.

State-of-the-art instrumental models provide access to plasma diagnostic for plasma density and electron temperature, in an unmagnetized plasma.

$n_e \quad T_e$

In support of **future space missions**, embarking mutual impedance experiments:

BepiColombo

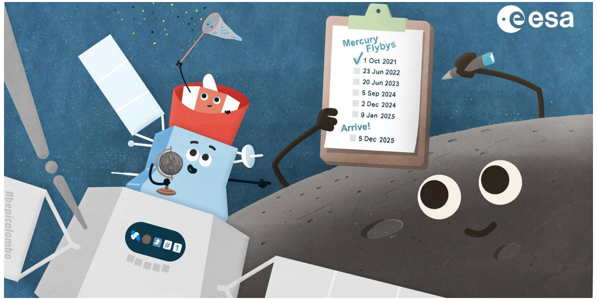


Image credit: ESA/ATG medialab

JUICE

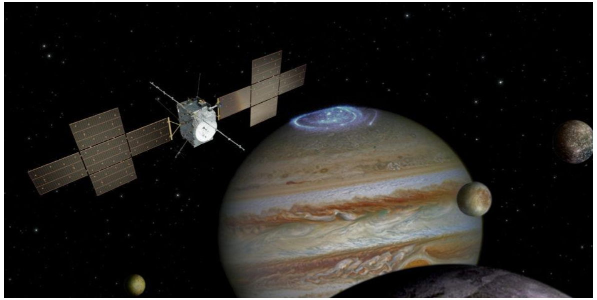


Image credit: ESA/ATG medialab

Nanosats, e.g. CIRCUS, SPEED

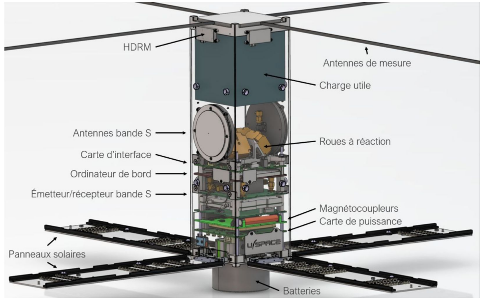
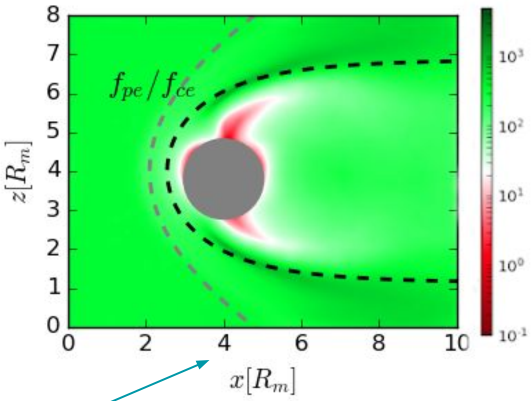


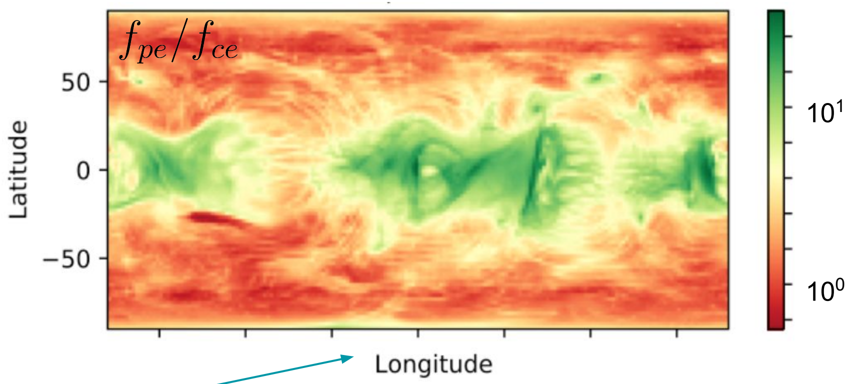
Image credit: U-SPACE

Need to generalize current instrumental models

Mercury

See presentation from F. Lavorenti, Friday!





Ganymede

Adapted from Carnielli et al. (2019)

BepiColombo

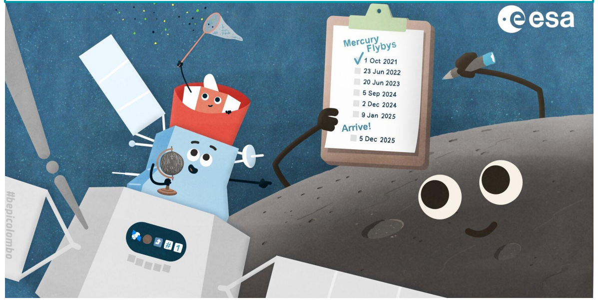


Image credit: ESA/ATG medialab

JUICE

Image credit: ESA/ATG medialab

Nanosats, e.g. CIRCUS, SPEED

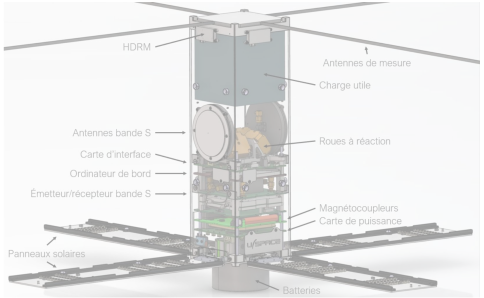
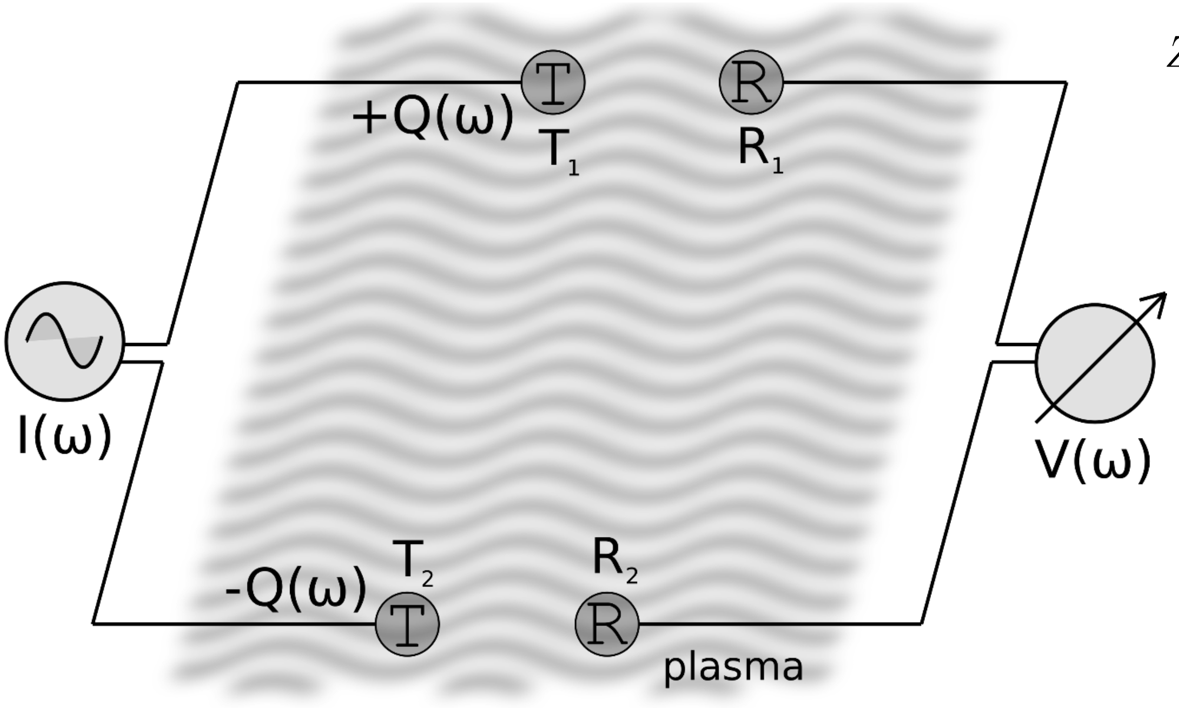


Image credit: U-SPACE

Mutual impedance experiments

Mutual impedance experiments exploit **electric antennas** onboard space missions to measure the mutual impedance, an electric quantity defined for a pair of antennas. This quantity is connected to the plasma properties.

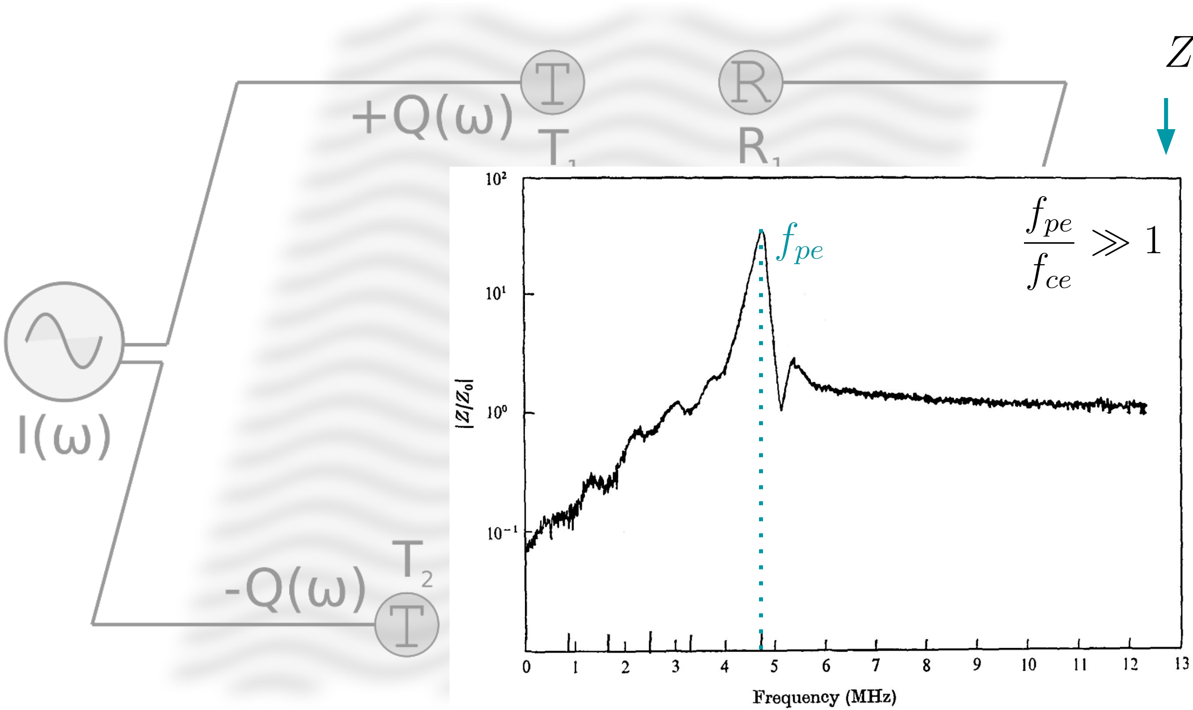


$$Z(\omega) = \frac{V(\omega)}{I(\omega)}$$

Mutual impedance experiments

Mutual impedance experiments exploit **electric antennas** onboard space missions to measure the mutual impedance, an electric quantity defined for a pair of antennas. This quantity is connected to the plasma properties.

$$Z(\omega) = \frac{V(\omega)}{I(\omega)}$$



$$f_{pe} \leftrightarrow n_e$$

Image credit: Chasseriaux et al., 1972

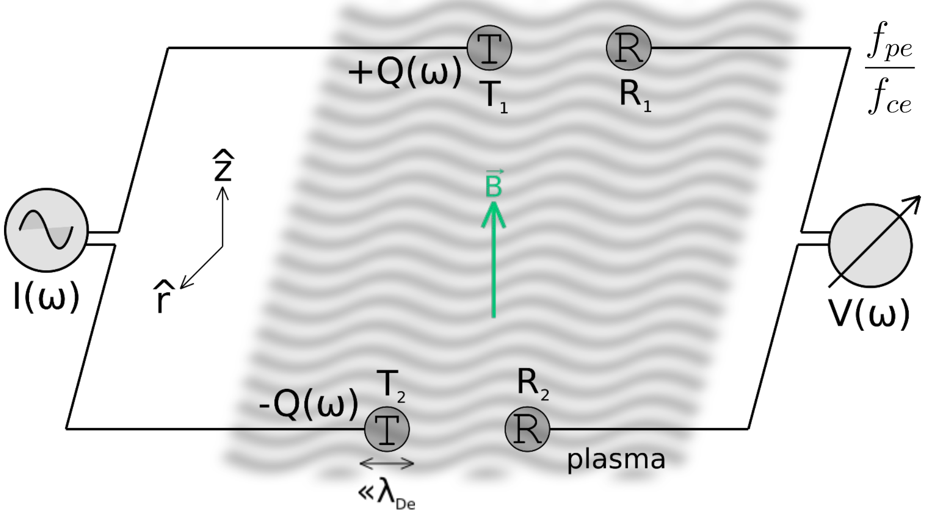
Outline of the instrumental model

The model is based on the computation of the **electric potential** generated by the electric charge deposited by the current imposed on the emitter antenna.

- Kinetic (Vlasov) model,
- electrostatic approximation,
- linear dielectric.

$$\begin{cases} \dfrac{V}{V_0} = \dfrac{\sqrt{r^2+z^2}}{\pi} \displaystyle\int_0^{+\infty} dk_r \int_0^{+\infty} dk_z \dfrac{k_r J_o(k_r r)\cos(k_z z)}{k^2 \varepsilon_L(k_r,k_z,\omega)} \\ \varepsilon_L(k_r,k_z,\omega) = 1 + \dfrac{1}{\lambda_{De}^2 k^2}\left[1 + \dfrac{\omega e^{-r_{Le}^2 k_r^2}}{\sqrt{2} v_{th.e} k_z} \displaystyle\sum_{n=-\infty}^{+\infty} I_n\left(r_{Le}^2 k_r^2\right) Z\left(\dfrac{\omega - n\omega_{ce}}{\sqrt{2} v_{th.e} k_z}\right)\right] \end{cases}$$

Previous talk	*This talk*
1D	3D
electrostatic, without B	electrostatic, with constant B
non-linear	linear



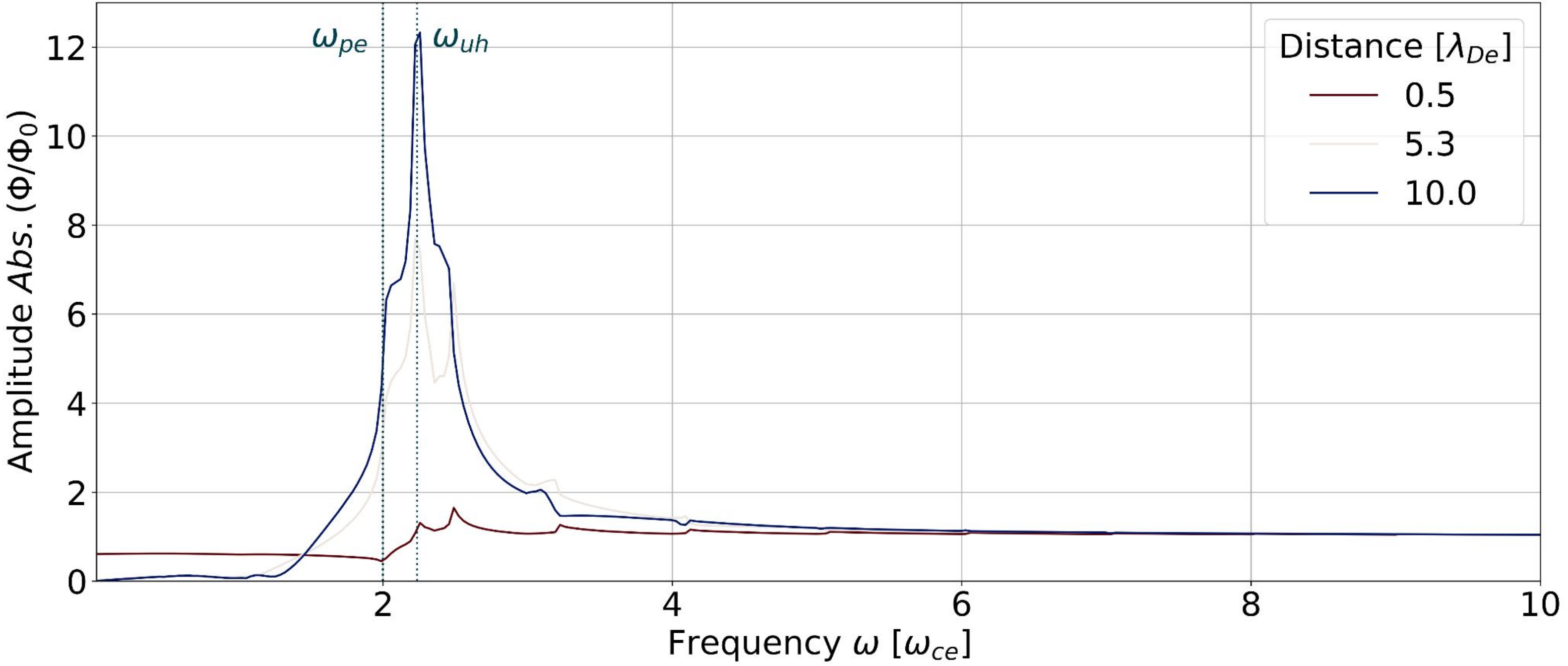
$$\frac{f_{pe}}{f_{ce}} \simeq 1$$

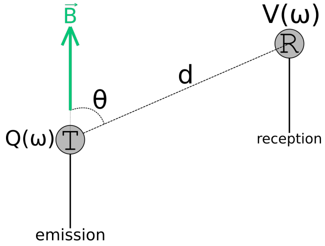
- T_e electron temperature
- n_e plasma density
- B magnetic field

Results of the model: oblique propagation

Is it possible to extract a **plasma diagnostic** from this model?

From this calculation, in the case of oblique propagation, the main maximum of the amplitude spectrum is located at the **upper-hybrid frequency**.





$$\omega_{pe}/\omega_{ce} = 2$$

$$\theta = 40^\circ$$

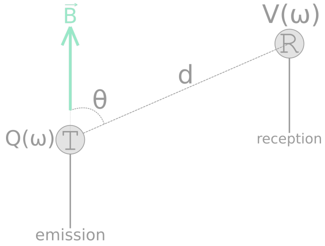
$$f_{uh} = \sqrt{f_{pe}^2 + f_{ce}^2}$$

Results of the model: oblique propagation

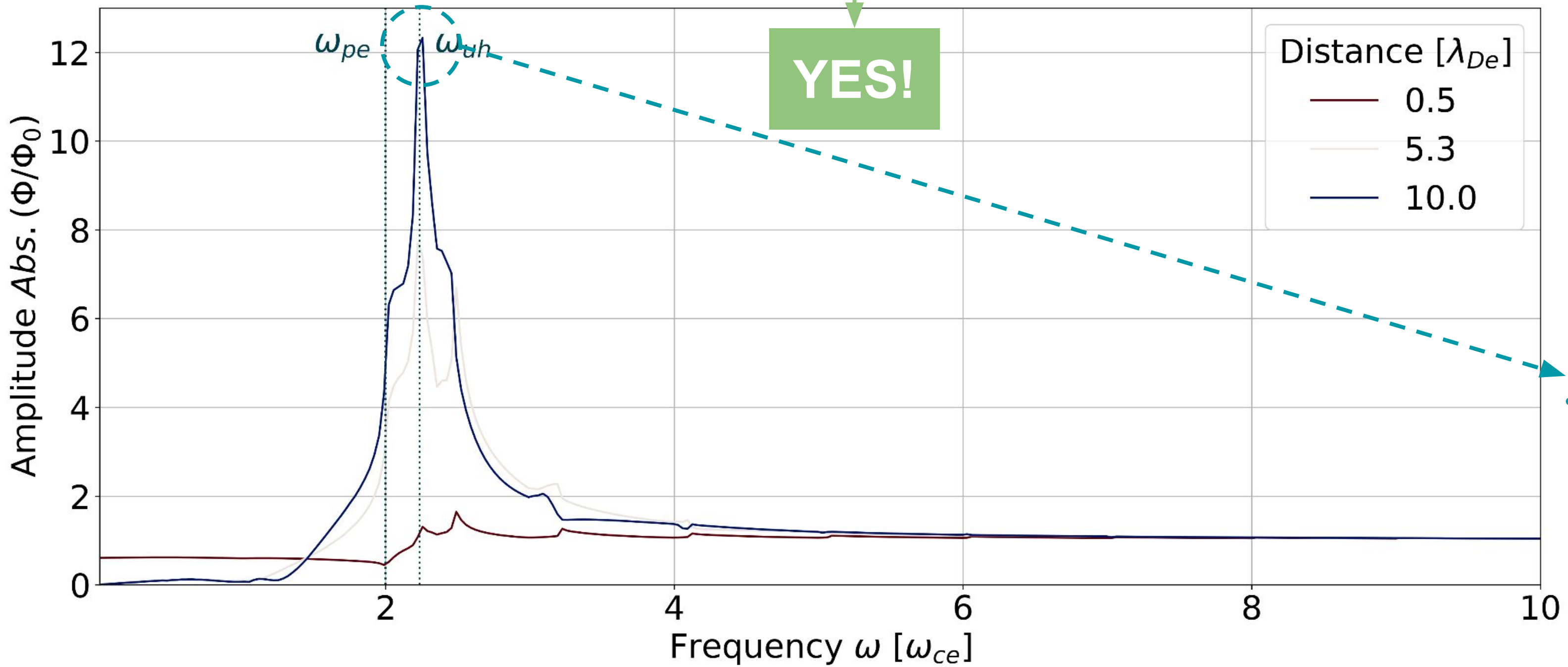
Is it possible to extract a **plasma diagnostic** from this model?

From this calculation, in the case of oblique propagation, the main maximum of the amplitude spectrum is located at the **upper-hybrid frequency**.

YES!



$$\omega_{pe}/\omega_{ce} = 2$$
$$\theta = 40^\circ$$
$$f_{uh} = \sqrt{f_{pe}^2 + f_{ce}^2}$$

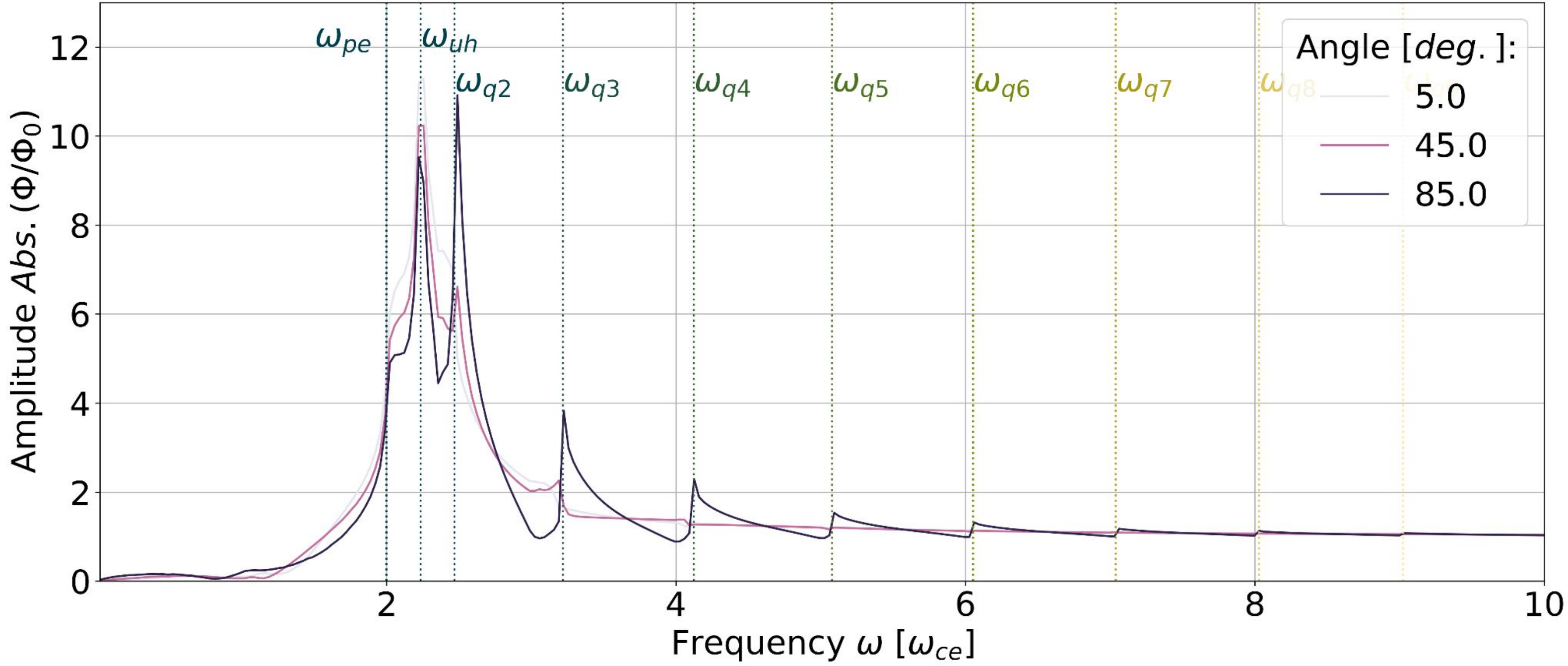


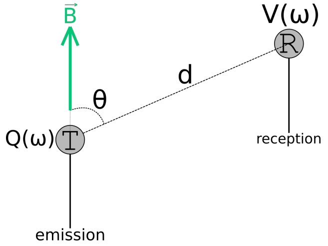
$$f_{uh} \leftrightarrow n_e, B$$

Results of the model: perpendicular propagation

Is it possible to extract a **plasma diagnostic** from this model?

From this calculation, in the case of quasi-perpendicular propagation, multiple maxima of the amplitude spectrum are located at the **zero group velocity Bernstein waves**.



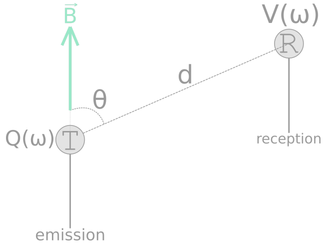


$$\omega_{pe}/\omega_{ce} = 2$$
$$d = 10\,\lambda_{De}$$

Results of the model: perpendicular propagation

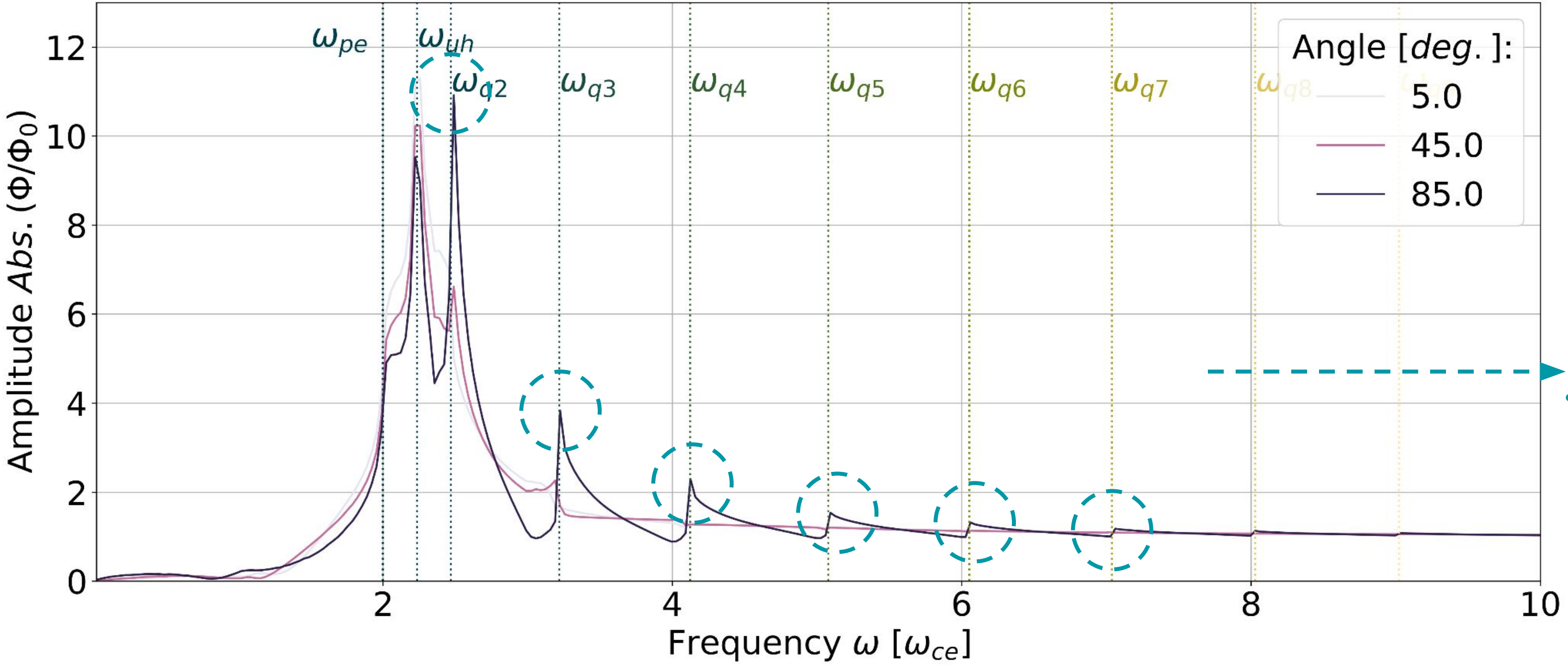
Is it possible to extract a **plasma diagnostic** from this model?

From this calculation, in the case of quasi-perpendicular propagation, multiple maxima of the amplitude spectrum are located at the **zero group velocity Bernstein waves**.



$\omega_{pe}/\omega_{ce} = 2$

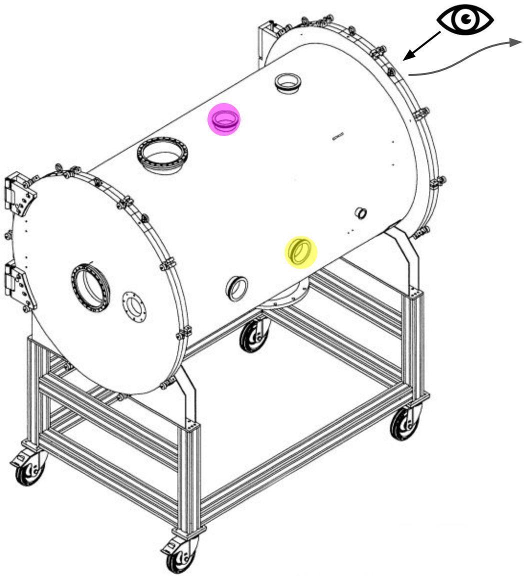
$d = 10\,\lambda_{De}$

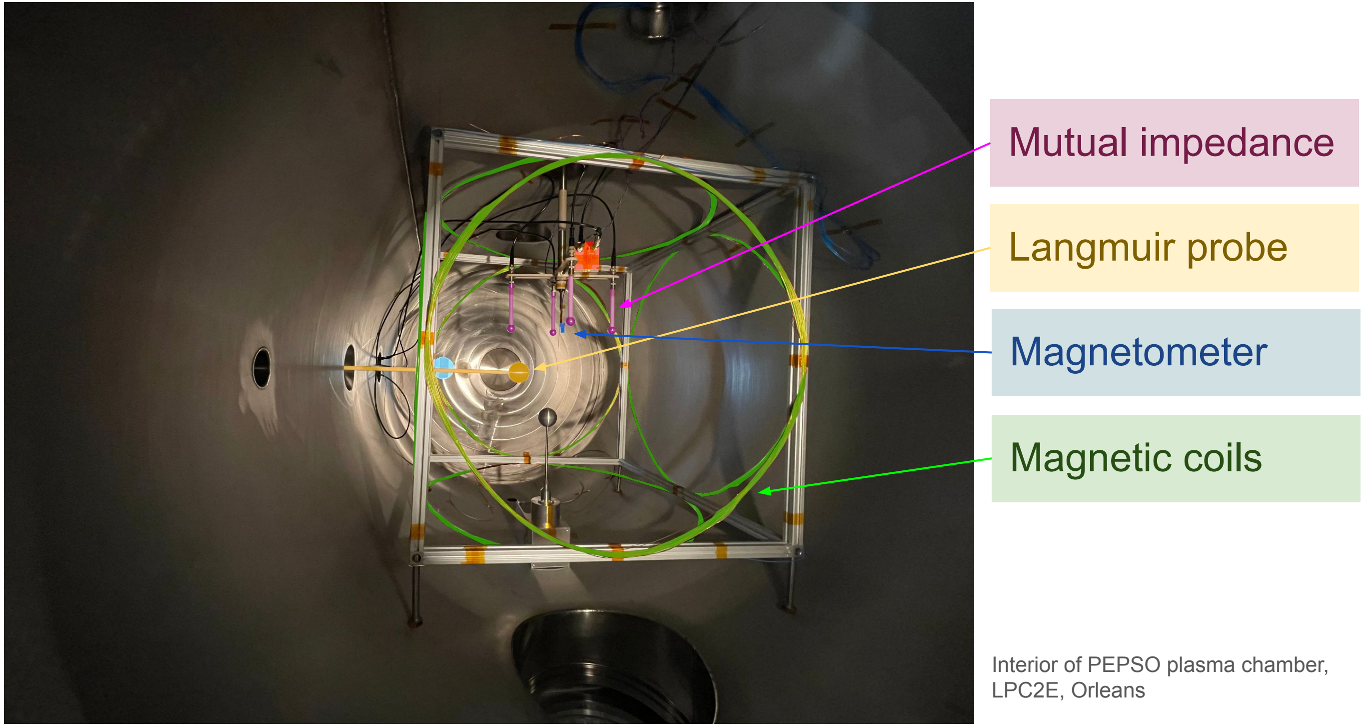


$\to f_{qn} \leftrightarrow n_e, B$

Experimental setup - PEPSO

The presence of a mutual impedance maximum located at the upper-hybrid frequency is used as plasma diagnostic for the plasma density, in the controlled setting of a plasma chamber.



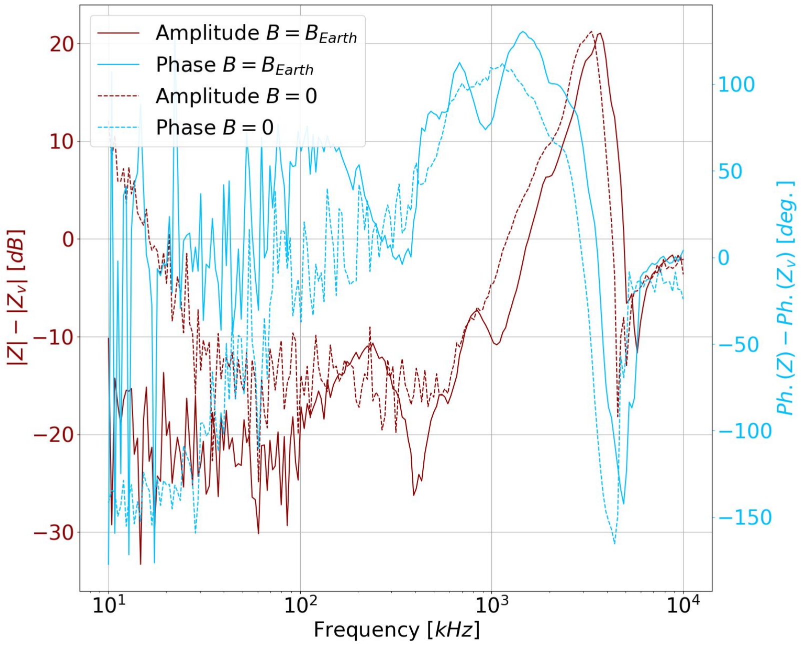


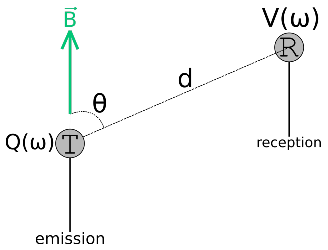
Interior of PEPSO plasma chamber, LPC2E, Orleans

Laboratory mutual impedance spectrum

Example of laboratory measurements of mutual impedance, **magnetized** and **unmagnetized** measurements.

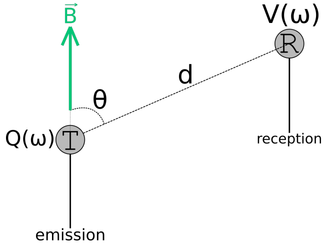
Electric field **amplitude** and **phase**



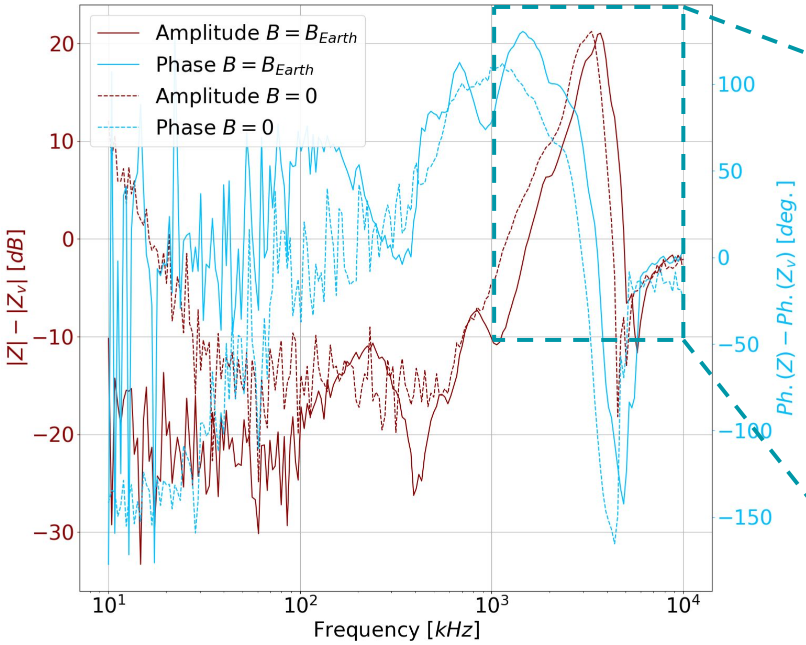


Laboratory mutual impedance spectrum

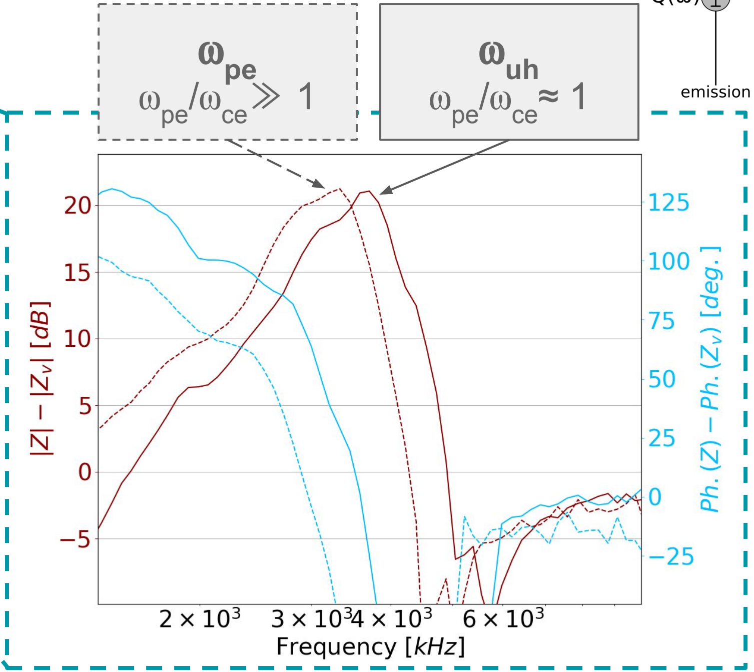
Example of laboratory measurements of mutual impedance, **magnetized** and **unmagnetized** measurements.



Electric field **amplitude** and **phase**



Zoom on the resonance:

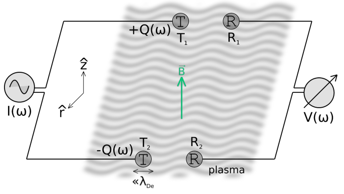


Summary and prospective

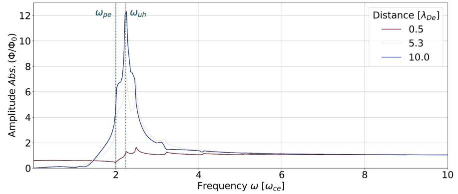
Objective*: obtain a plasma diagnostic from in-situ mutual impedance measurements of space plasma, in a magnetized environment, in support of future missions.*

During this work:

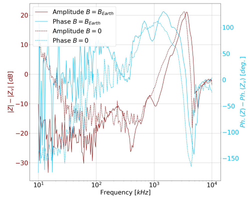
Model



Calculation: characterization of expected response



Experimental validation of model



Density diagnostic (+ magnetic field)

Prospective:

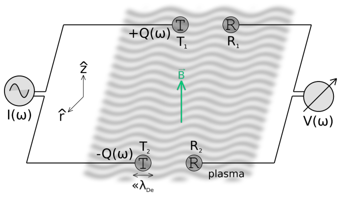
- Boundary conditions and spacecraft geometry effects,
- electron temperature diagnostic.

Summary and prospective

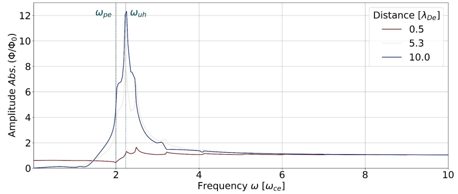
***Objective**: obtain a plasma diagnostic from in-situ mutual impedance measurements of space plasma, in a magnetized environment, in support of future missions.*

During this work:

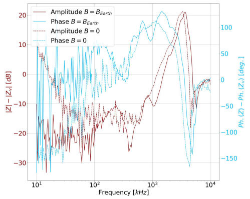
Model



Calculation: characterization of expected response



Experimental validation of model



Density diagnostic (+ magnetic field)

Prospective:

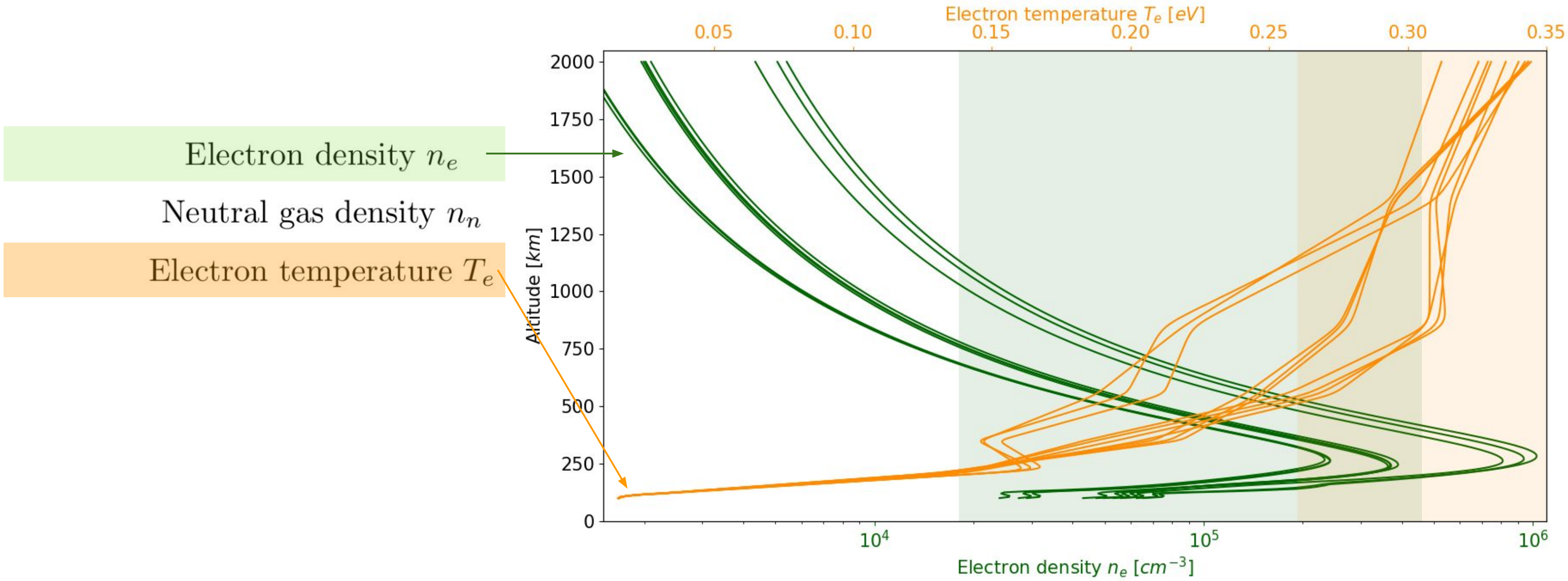
- Boundary conditions and spacecraft geometry effects,
- electron temperature diagnostic.

Mutual impedance and quasi-thermal noise models in magnetized space plasmas,
PhD with **Pierre Henri** (**LPC2E**) and **Karine Issautier** (**LESIA**).

Annex

Quantity	Minimum	Maximum	Uncertainty [%]
Working pressure (neutrals) P	$1.70 \cdot 10^{-5}\, mbar$	$5.50 \cdot 10^{-5}\, mbar$	2
Electron density n_e	$1.8 \cdot 10^{4}\, cm^{-3}$	$4.6 \cdot 10^{5}\, cm^{-3}$	13
Neutral gas density n_n	$4.13 \cdot 10^{11}\, cm^{-3}$	$13.37 \cdot 10^{11}\, cm^{-3}$	2
Electron temperature T_e	$0.26\, eV$	$2.1\, eV$	5
Electron plasma frequency f_{pe}	$1.20\, MHz$	$6.09\, MHz$	7
Debye length λ_{De}	$1.6\, cm$	$2.8\, cm$	5
Electron cyclotron frequency f_{ce} (B_{Earth})	$1.08\, MHz$	$1.11\, MHz$	3
Electron gyro radius r_{Le} (B_{Earth})	$3.15\, cm$	$8.95\, cm$	4
Electron neutral mean free path $l_{m.f.p.}^{e\rightarrow n}$	$3.7\, m$	$1200\, m$	10
Electron neutral scattering rate $\nu_c^{e\rightarrow n}$	$176\, s^{-1}$	$162 \cdot 10^{3}\, s^{-1}$	10

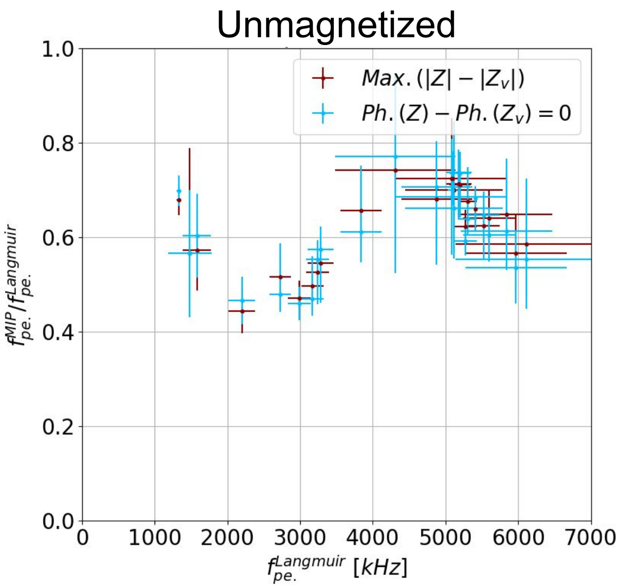
Annex



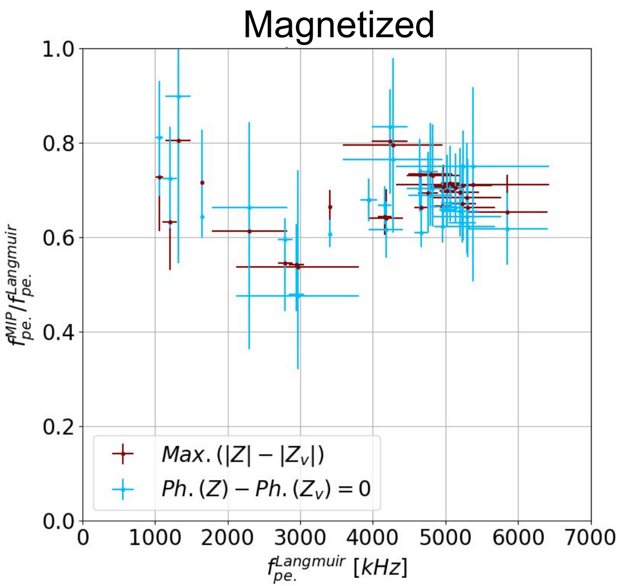
La densité du plasma est comparable à celle de **ionosphère terrestre** pour une altitude entre 400 km et 1100 km.
La température de plasma est comparable à celle de ionosphère terrestre pour une altitude entre 600 et 2000 km.

Annex

Comparison of plasma density measurements obtained from a Langmuir probe and a mutual impedance experiment, using the amplitude maximum as measurement for the plasma or upper-hybrid frequency.



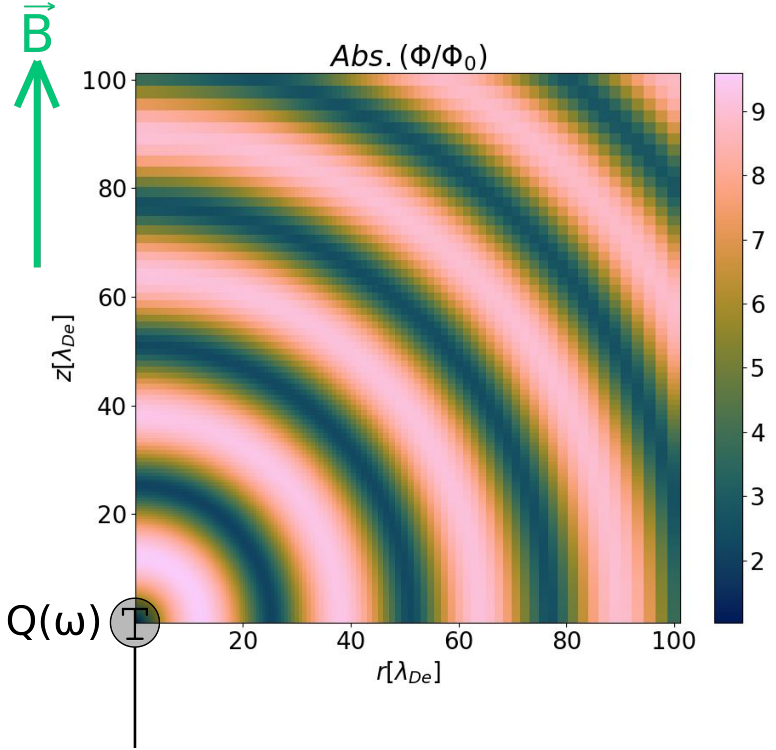
$\omega_{pe}/\omega_{ce} \gg 1$

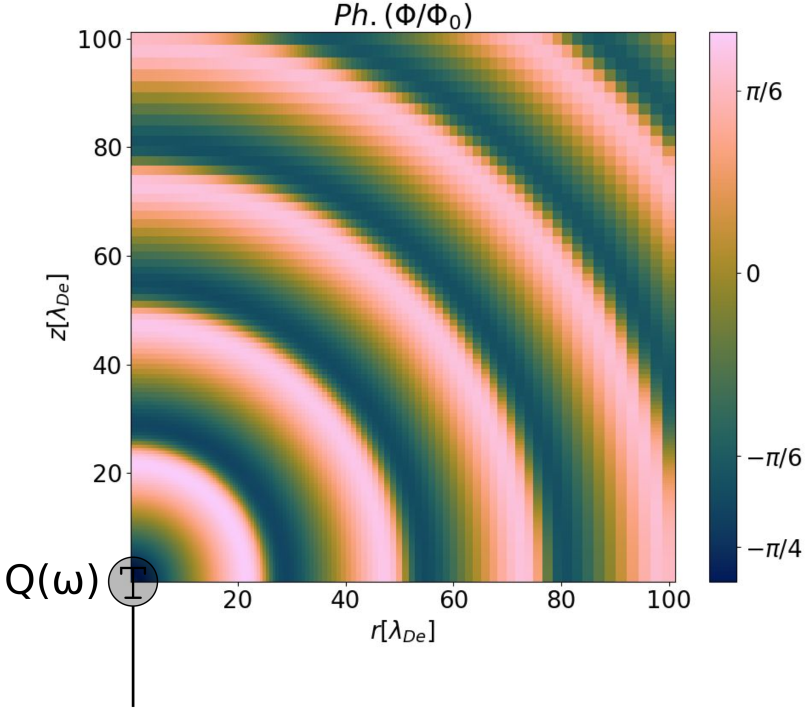


$\omega_{pe}/\omega_{ce} \approx 1$

Annex

$$\omega/\omega_{pe} = 1.1$$
$$\omega_{pe}/\omega_{ce} = 300$$





Annex

L'objectif de la **méthode numérique** est de calculer le potentiel en fonction de la position r, z, et des paramètres physiques n_e, T_e, B :

$$\frac{V}{V_0} = \frac{\sqrt{r^2+z^2}}{\pi} \int_0^{+\infty} dk_r \int_0^{+\infty} dk_z \frac{k_r J_o(k_r r)\cos(k_z z)}{k^2 \varepsilon_L(k_r, k_z, \omega)}$$

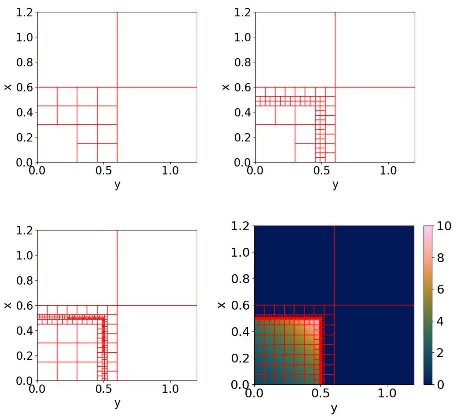
→ trois variables et un paramètre (normalisées) : $\begin{cases} r/\lambda_{De} \\ z/\lambda_{De} \\ \omega/\omega_{pe} \\ \omega_{pe}/\omega_{ce} \end{cases}$

Technique du calcul avec deux étapes :

fixé : $\begin{cases} \omega/\omega_{pe} \\ \omega_{pe}/\omega_{ce} \end{cases}$

Intégration adaptative ("**grid refinement**") avec une **seule position spatial** r, z :

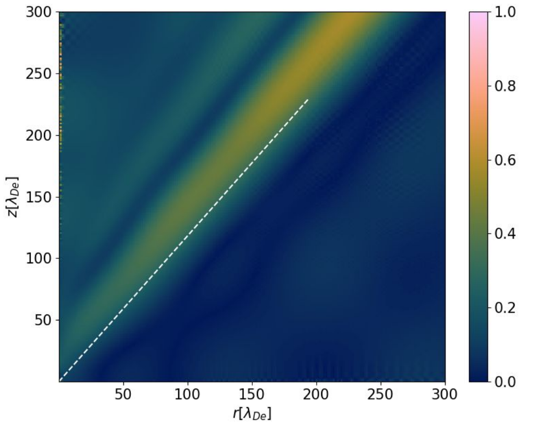
1



→

Intégration, avec la **même discrétisation**, sur toutes les positions spatiales :

2



Annex

Parallèle k // B | Oblique | Perpendiculaire **k** ⊥ **B**

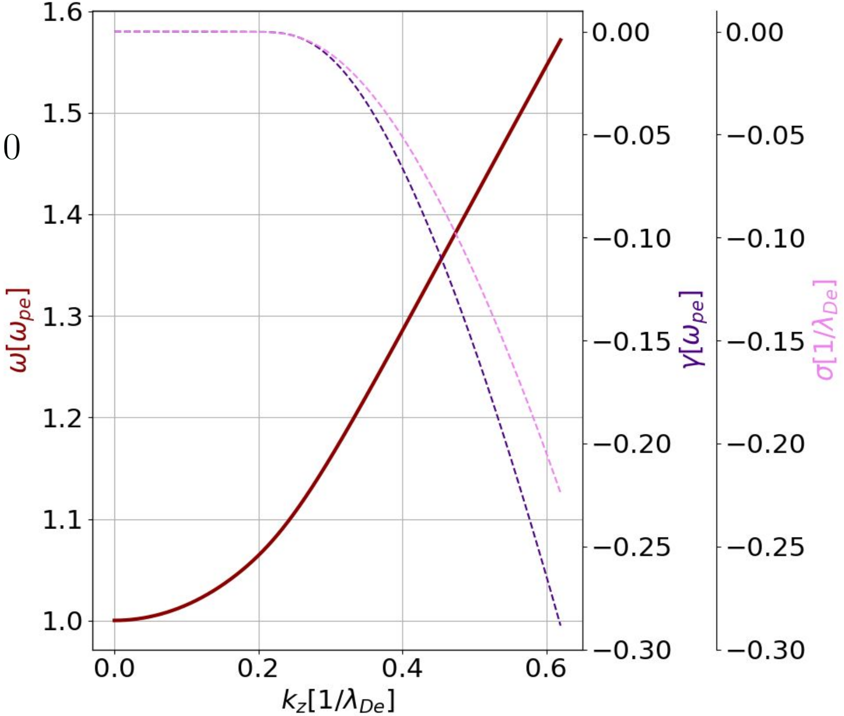
Dans le cas de **propagation parallèle** :

$$\varepsilon_L(k_r = 0, k_z, \omega) = 1 + \frac{1}{\lambda_{De}^2 k_z^2}\left[1 + \frac{\omega}{\sqrt{2}v_{th.e}k_z} Z\left(\frac{\omega}{\sqrt{2}v_{th.e}k_z}\right)\right] = 0$$

est la relation de dispersion des ondes de **Langmuir**

Fréquence caractéristique :

Fréquence du plasma ω_{pe}



Annex

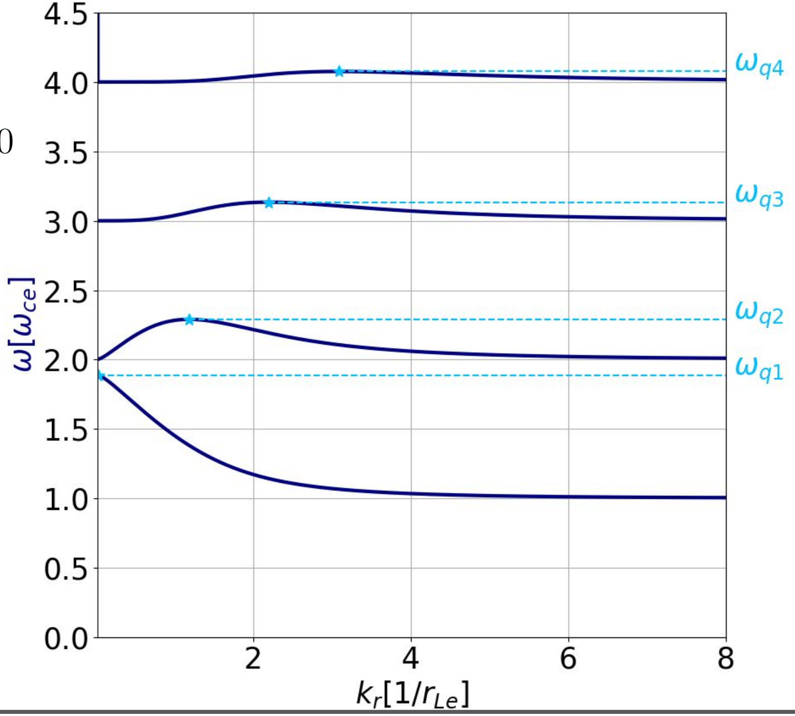
Parallèle **k** // **B** | Oblique | Perpendiculaire **k** ⊥ **B**

Dans le cas de **propagation perpendiculaire** :

$$\varepsilon_L(k_r, k_z = 0, \omega) = 1 - 2\frac{e^{-r_{Le}^2 k_r^2}}{\lambda_{De}^2 k_r^2} \sum_{n=1}^{+\infty} I_n(r_{Le}^2 k_r^2) \left[1 - \frac{\omega^2/\omega_{ce}^2}{\omega^2/\omega_{ce}^2 - n^2}\right] = 0$$

est la relation de dispersion des ondes de **Bernstein électroniques**

Fréquences caractéristiques :
Fréquences "de Hamelin" ω_{qn}



Annex

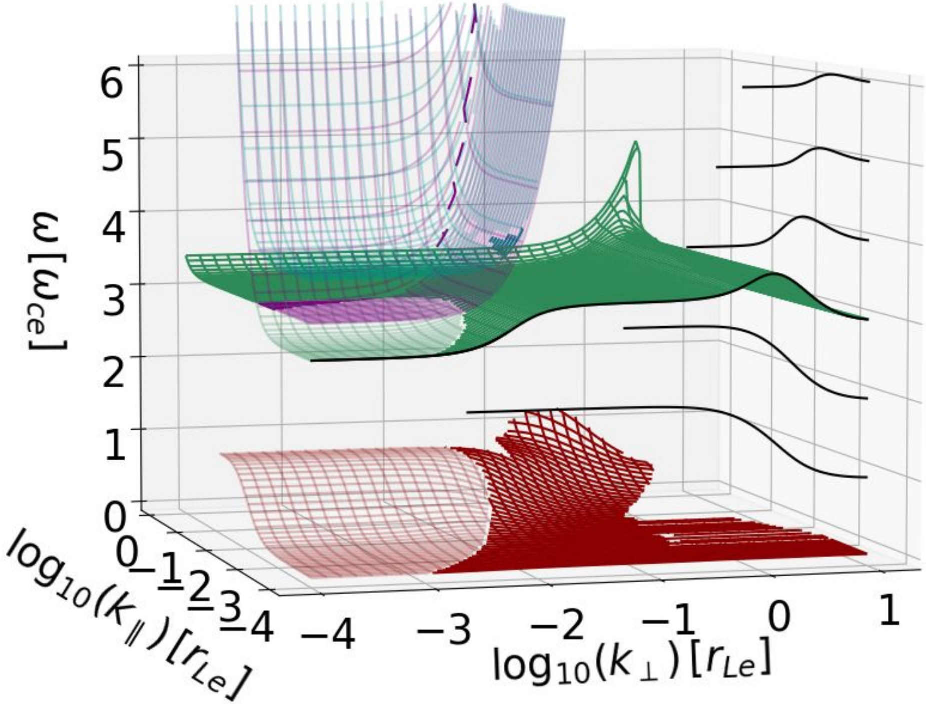
Parallèle **k** // **B** | Oblique | Perpendiculaire **k** ⊥ **B**

Dans le cas de propagation **oblique** :

$$\varepsilon_L(k_r, k_z, \omega) = 0 \rightarrow \omega = \omega(k_r, k_z)$$

la surface est autour de la fréquence **hybride haute**

Fréquence caractéristique :
Fréquence hybride haute ω_{uh}



Annex

Hamelin's diagram, relating the frequency of the Bernstein waves at zero group speed with the plasma to electron cyclotron frequency.