Development of a spectro-tomography diagnostic in the visible for the study of plasmas

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Opération XPM

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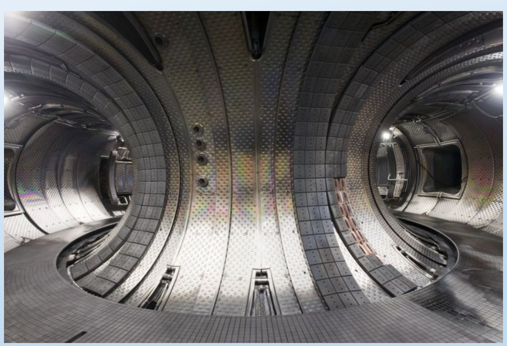
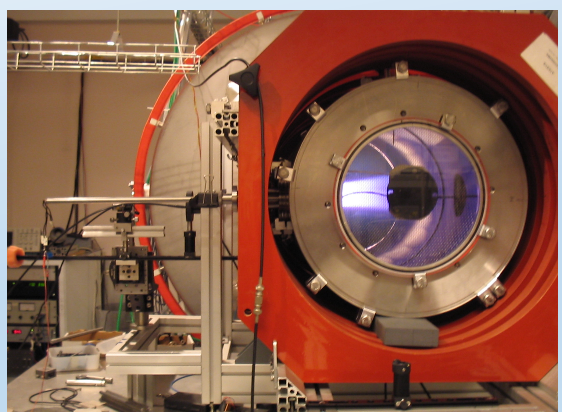




Cross-field ExB plasma instability

ExB plasma configuration:

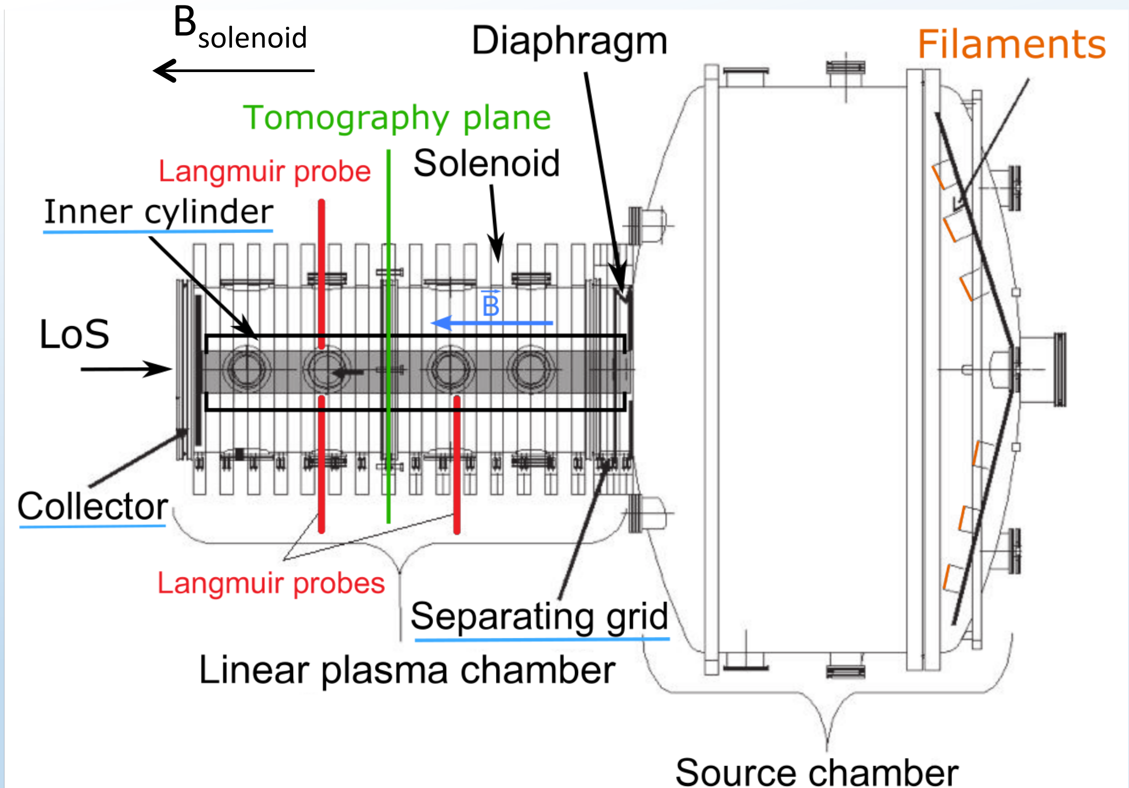
- Hall thruster,
- Magnetron discharges,
- Penning gauges,
- Tokamaks…

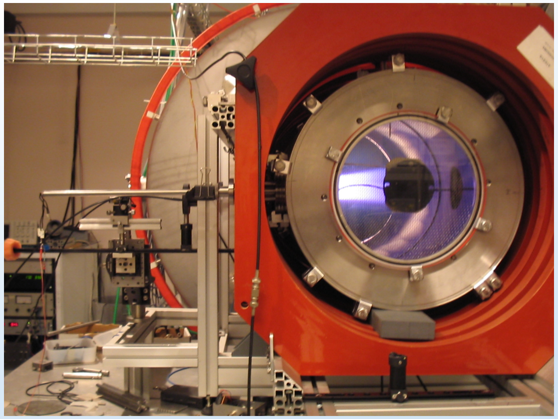
→Particles drift in the ExB direction:
→**Anomalous transport coefficient in the perpendicular direction**
problem for the tokamaks ☹, advantage for the thrusters ☺
→Need for a better undestanding of the physics.

→ The Mistral experiment has been created for the study of ExB instabilities

The Mistral experiment

- Created by **G. Leclert** and **Th. Pierre,**
- Electrons magnetized ; ions poorly magnetized,
- Ionizing primary electrons,
- **Cylindrical symetry,**
- « Stable » plasma state during several hours.

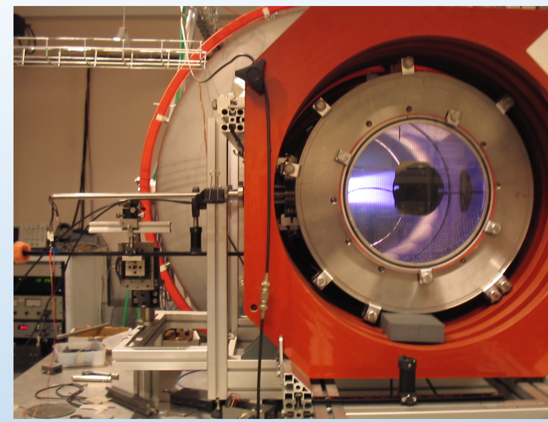


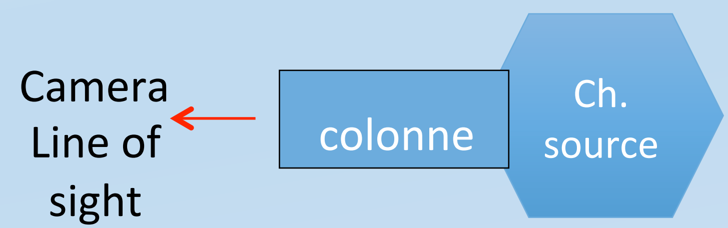


- **L = 1.2m**
- **r_{plasma} =36 mm**
- **5.10^{-5} mbar < P < 10^{-3} mbar**
- **$B_{solenoid}$ < 25 mT**
- **Gaz : He, Ne, Ar, Kr, Xe**

The Mistral experiment: observation of regular instabilities

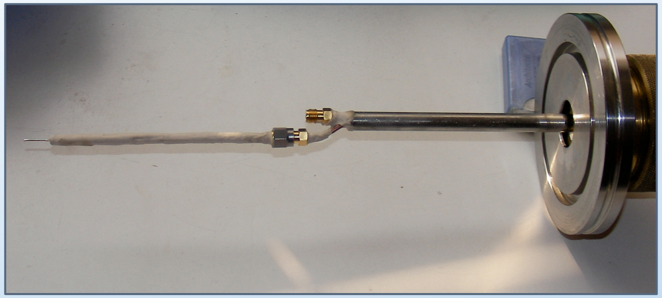
Flute modes around the central column with constant rotation frequency (m = 1 - $\nu \approx$ a few. kHz)

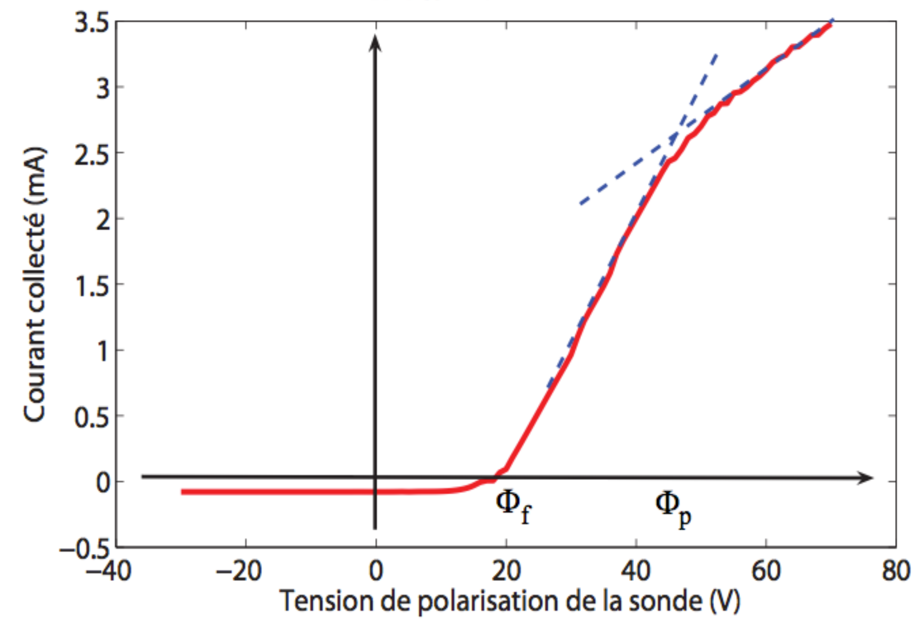




Studying plasmas with Langmuir probes

→Simple installation: ne, Te, V_{plasma}…
→BUT the results interpretation can be complicated
→The probes are perturbative for the plasma.





→ Development of optical diagnostics

First step: optical tomography

→ ***P. David*** *Phd*

→Advantages of tomography:

- 2D spatial structure analysis

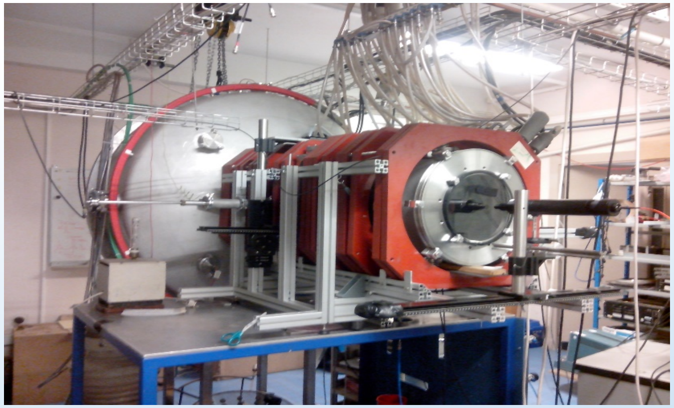
Without hypothesis,

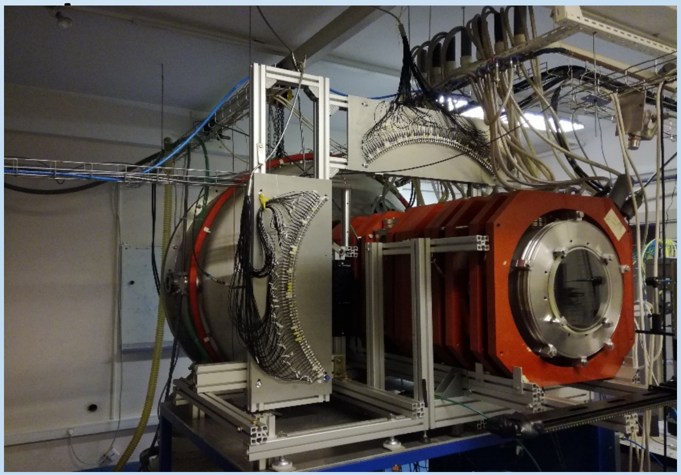
- Non intrusive methods.

→ Study of turbulent plasma states (no symetry)

→Validation: symetric flute $\nu_{mode} \approx 1$ -

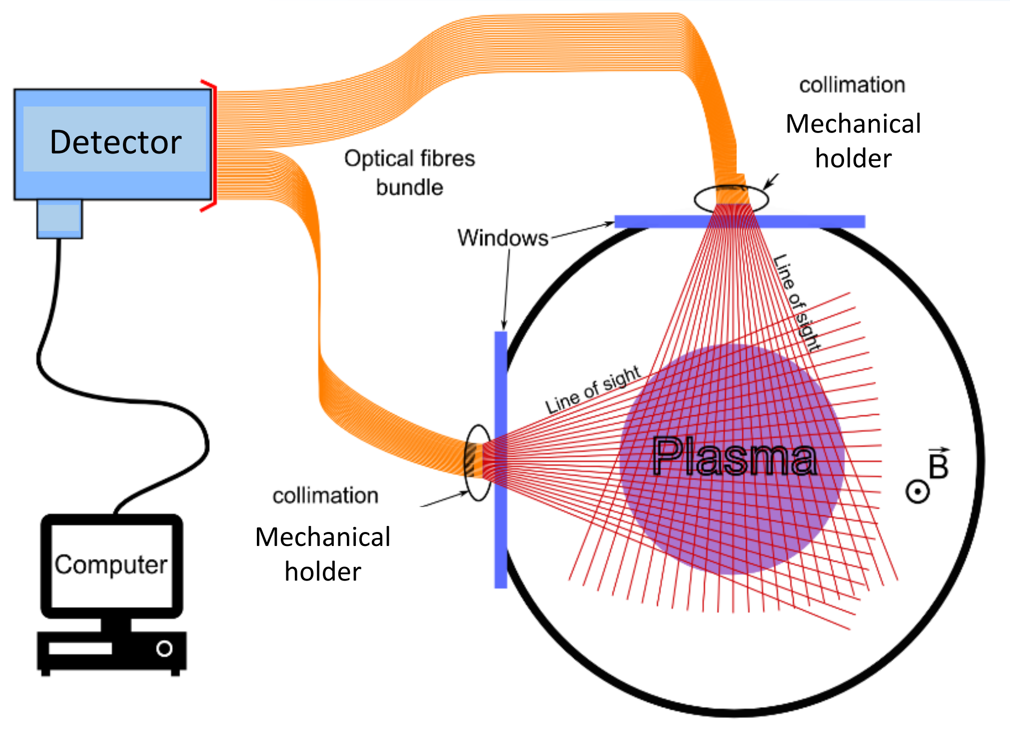
→2x64 channels, ν_{acq} = 1 MHz

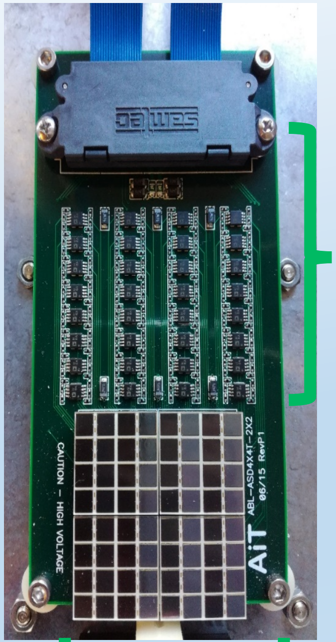




Optical tomography

→→ 2x64 channels, ν_{acq} = 1 MHz, SiPM sensors (gain > 10^6)





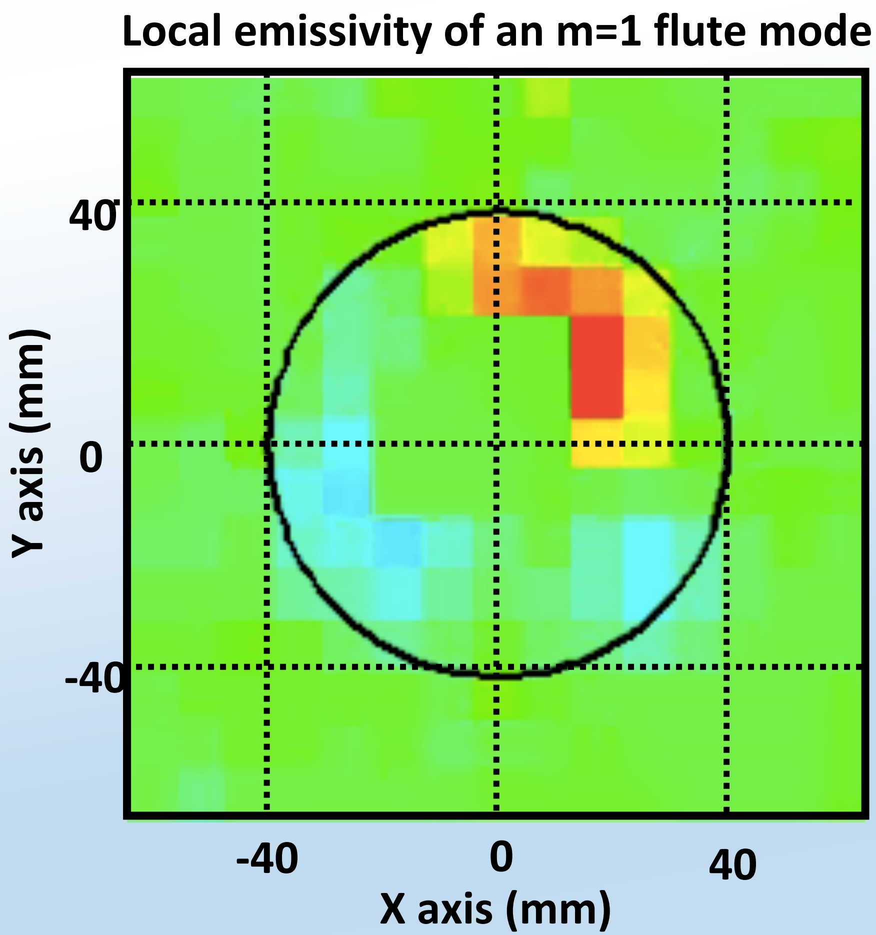
Amplification stage

8x8 matrix detector

Tomography: results for a periodic structure

→« One shot » time evolution
→Analysis of structures without symetry
→BUT no spectral resolution

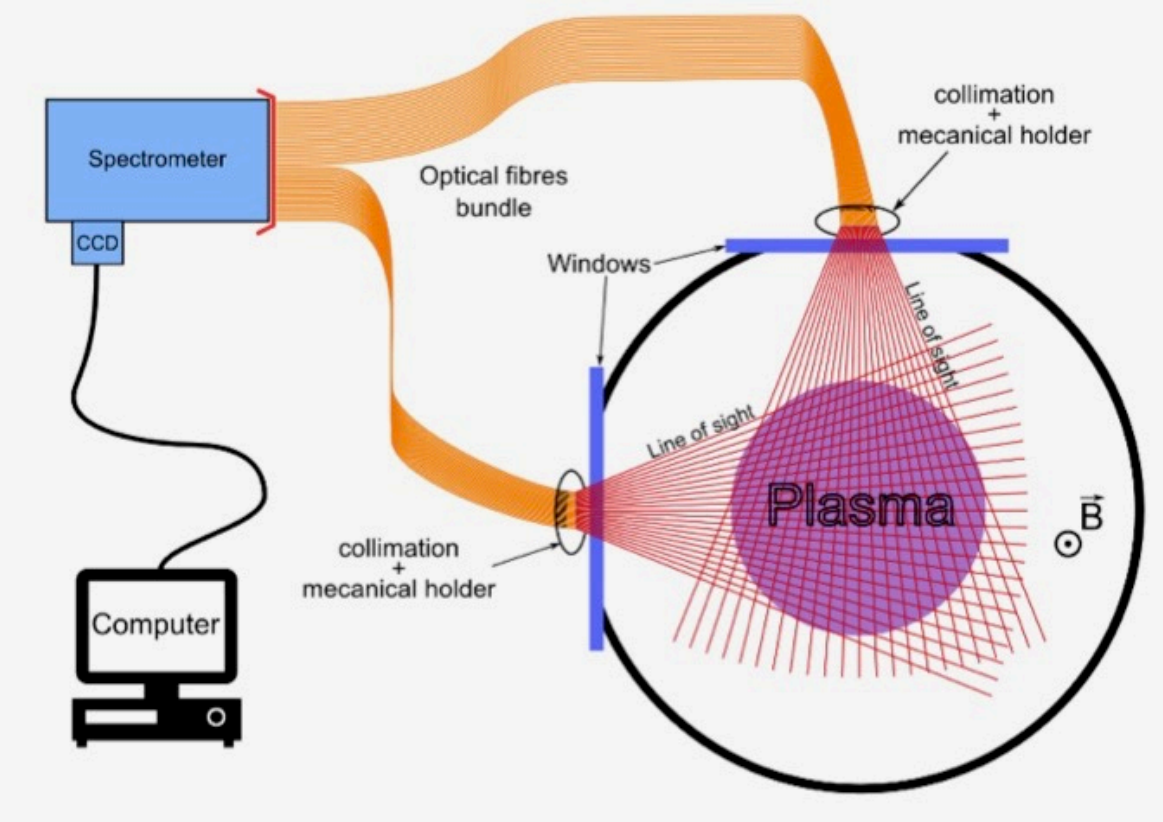
[P. David POP 2016 ; P. David RSI 2017]

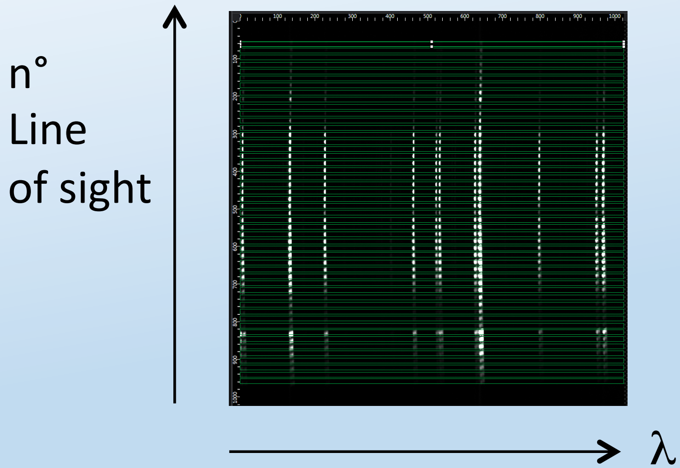


→ Coupling tomographie to emission spectroscopy

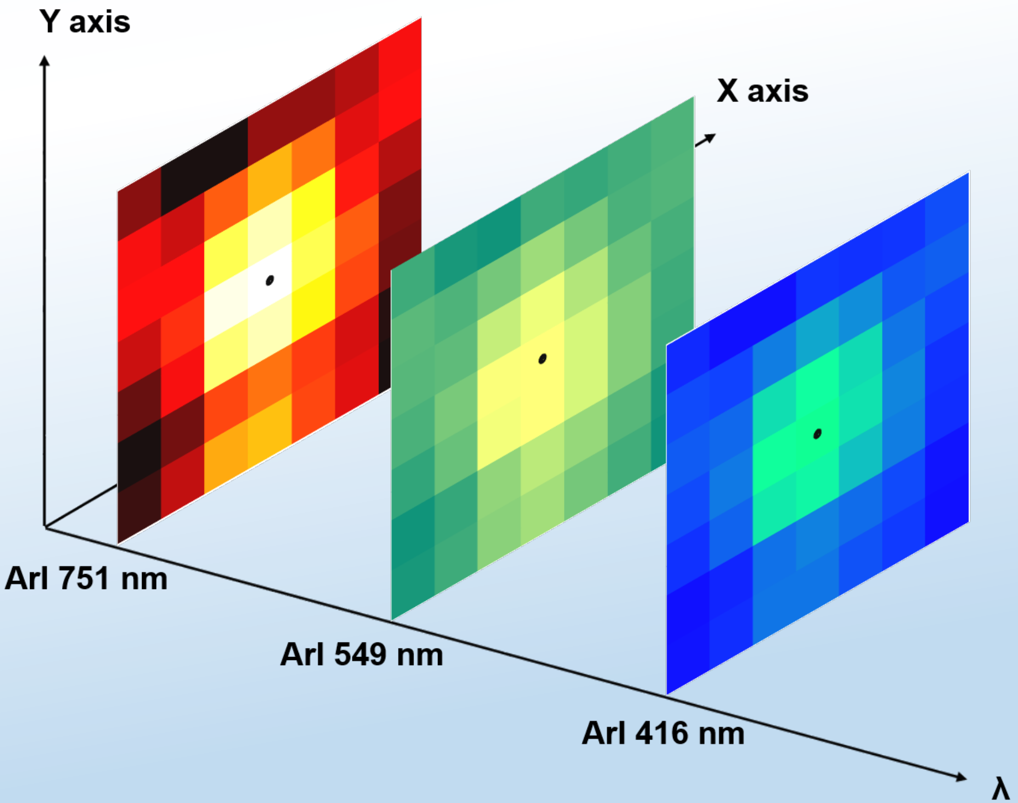
Spectro-tomography visible diagnostic

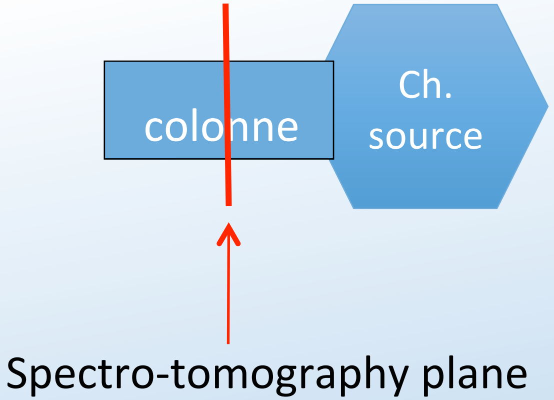
- 128 sensors → EMCCD camera
  + spectrometer
- Less line of sight : 49
  → 7x7 pixels





Spectro-tomography: results

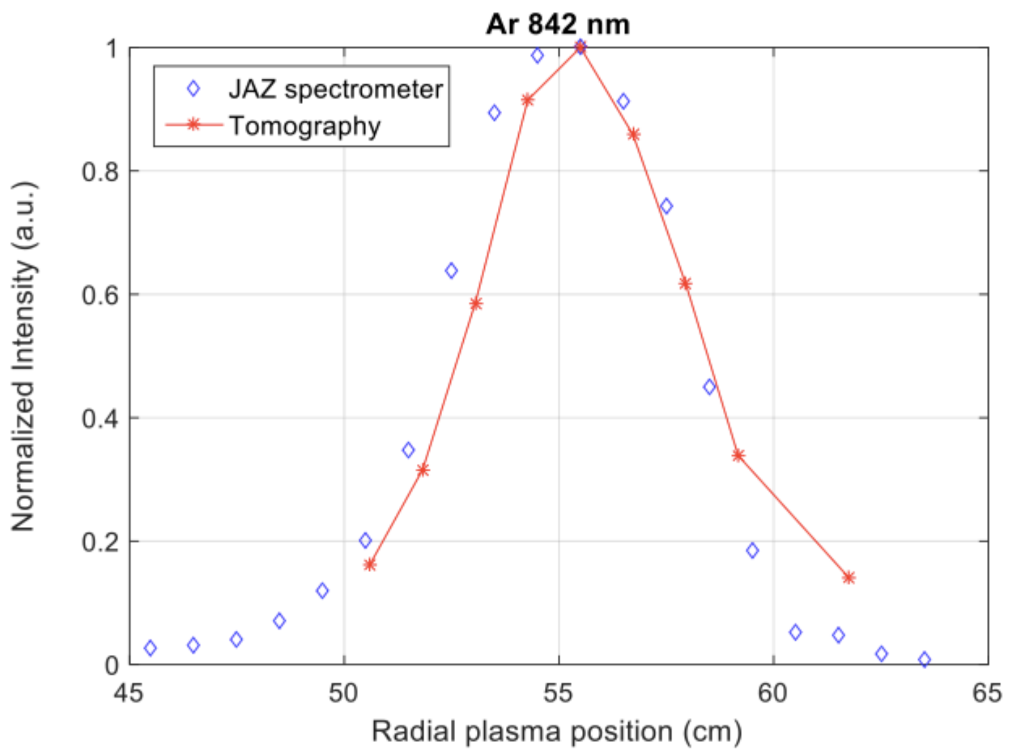


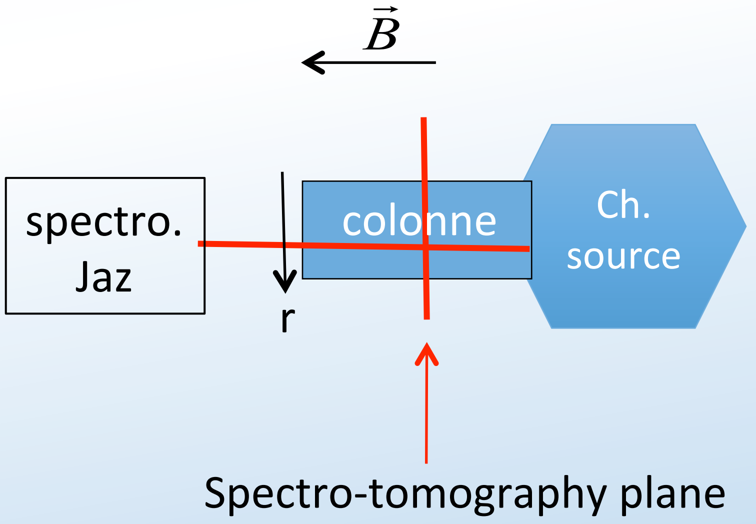


Spectro-tomography: validation

→ Homogeneous plasma along B

→ **Comparison with radial evolution of spectra along B.**



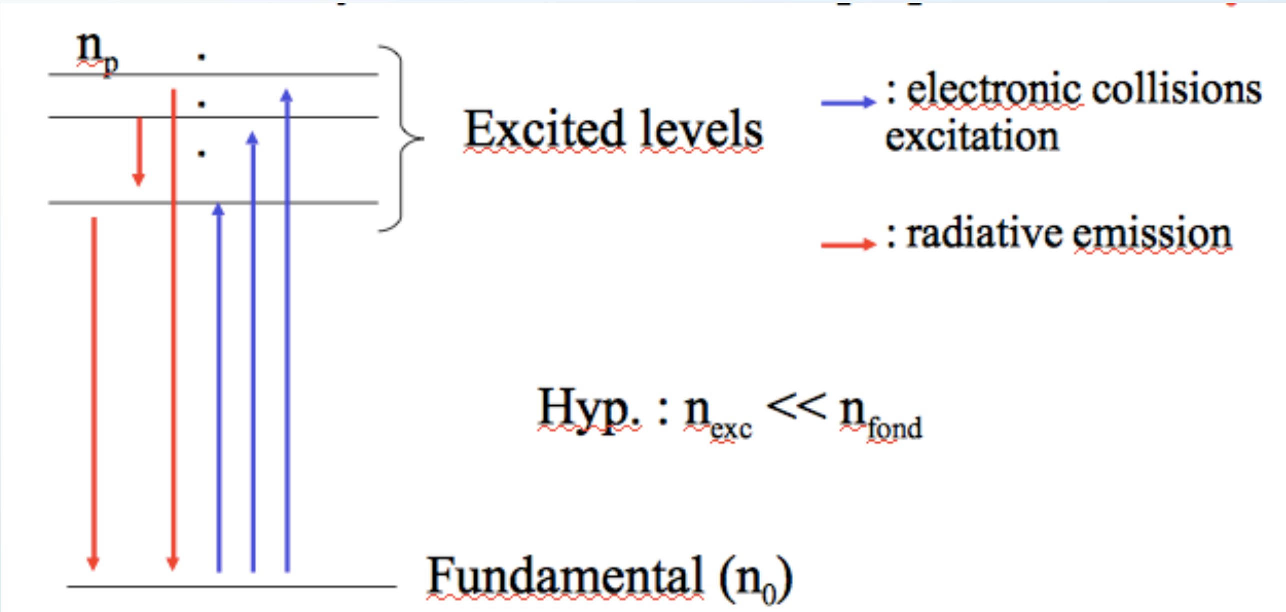


Plasma coronal model

→ Low density (n_e<10^{11} cm^{-3}) : ***coronal model***

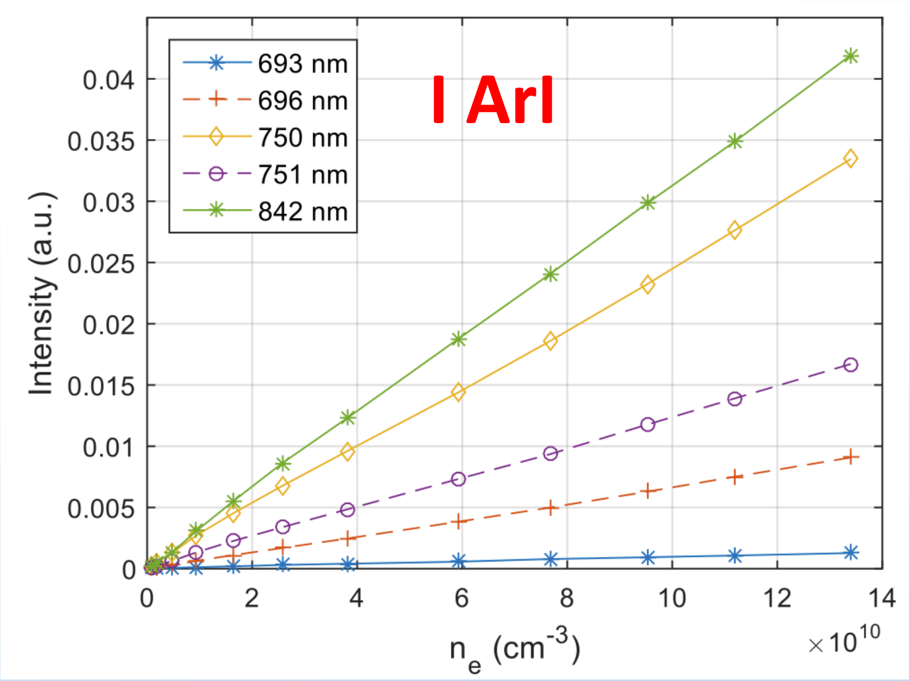
$$n_e\, n_0 \langle \sigma\, v_{0\to p} \rangle = n_p \sum_{r<p} A_{pr}$$

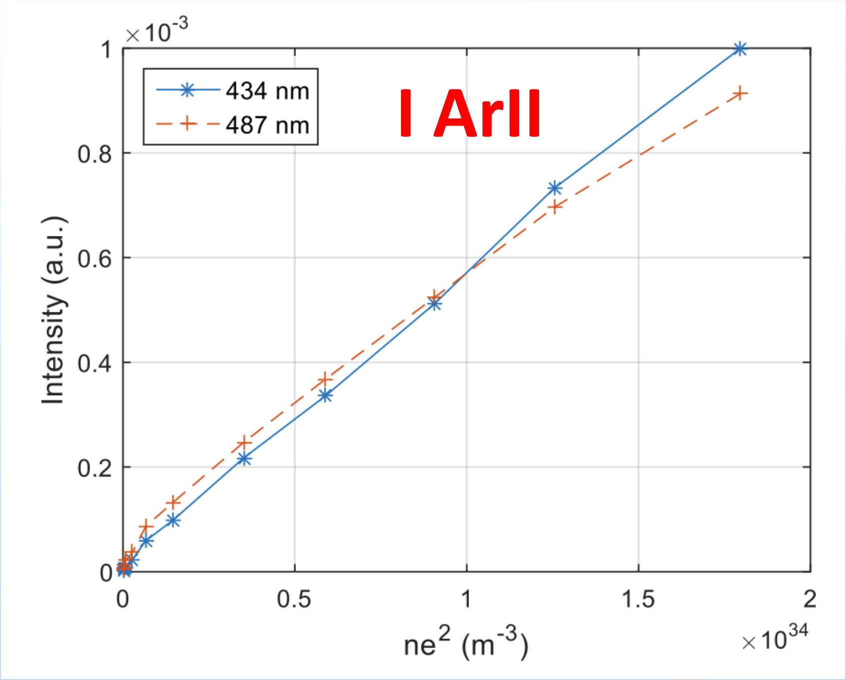
$$\rightarrow \quad I_{pq} = \frac{h\,\upsilon_{pq}}{4\pi}\, n_e\, n_0 \langle \sigma\, v_{0\to p} \rangle \frac{A_{pq}}{\sum_{r<p} A_{pr}} \quad W.m^{-3}.sr^{-1}$$



Coronal model: experimental validation

→ Experiments with n_e variations (and no T_e variations !)



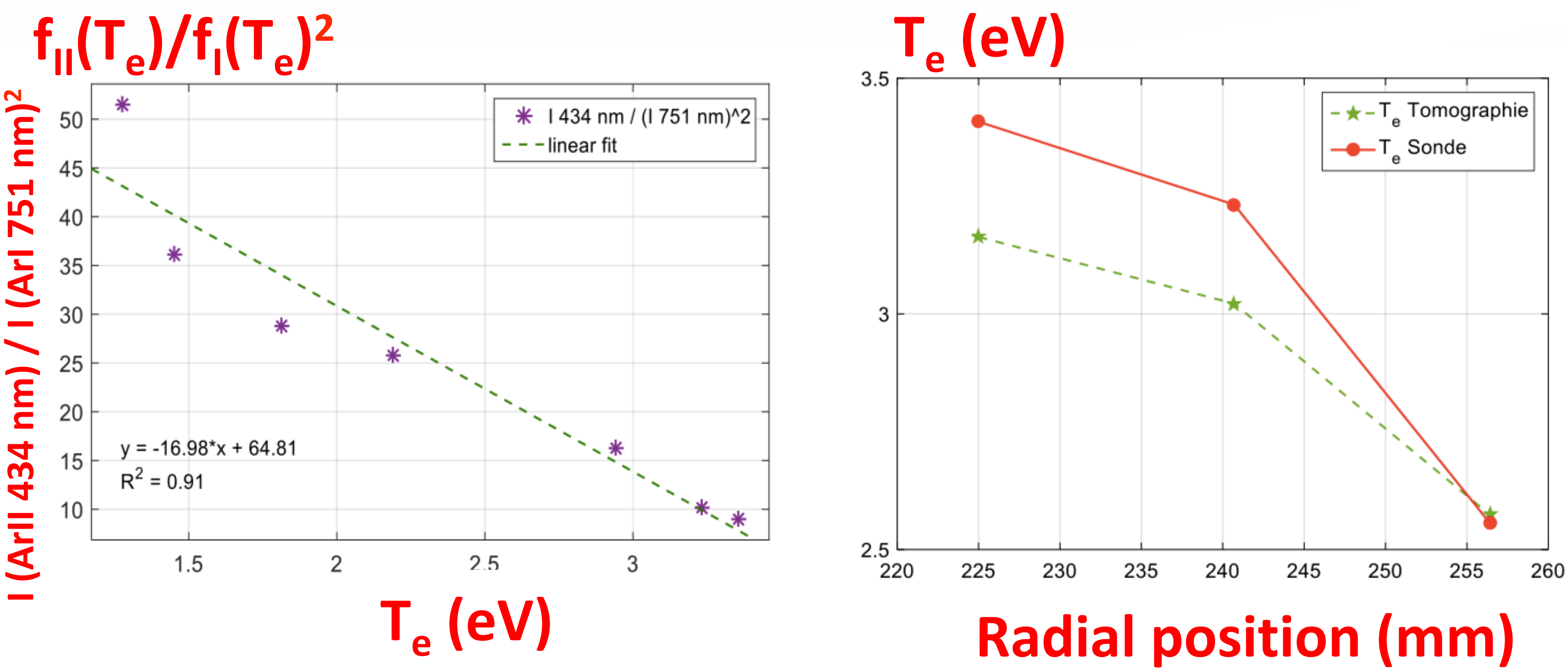


ArI α $n_e \times f_I(Te)$

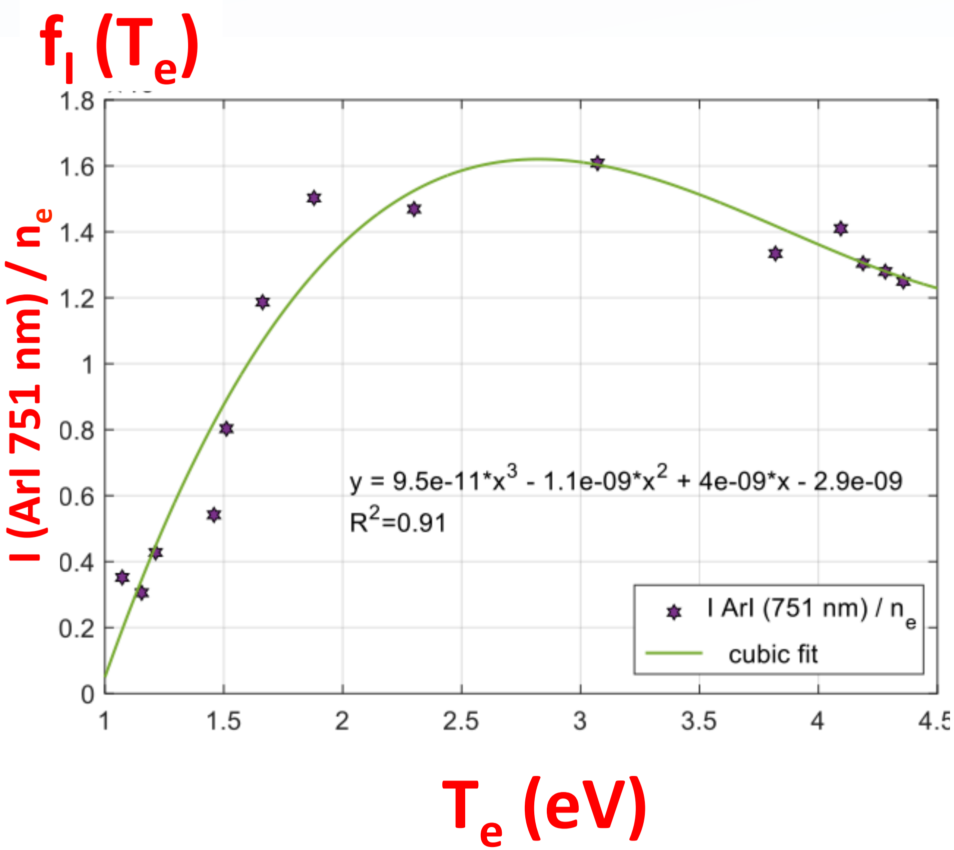
ArII α $n_e^2 \times f_{II}(Te)$

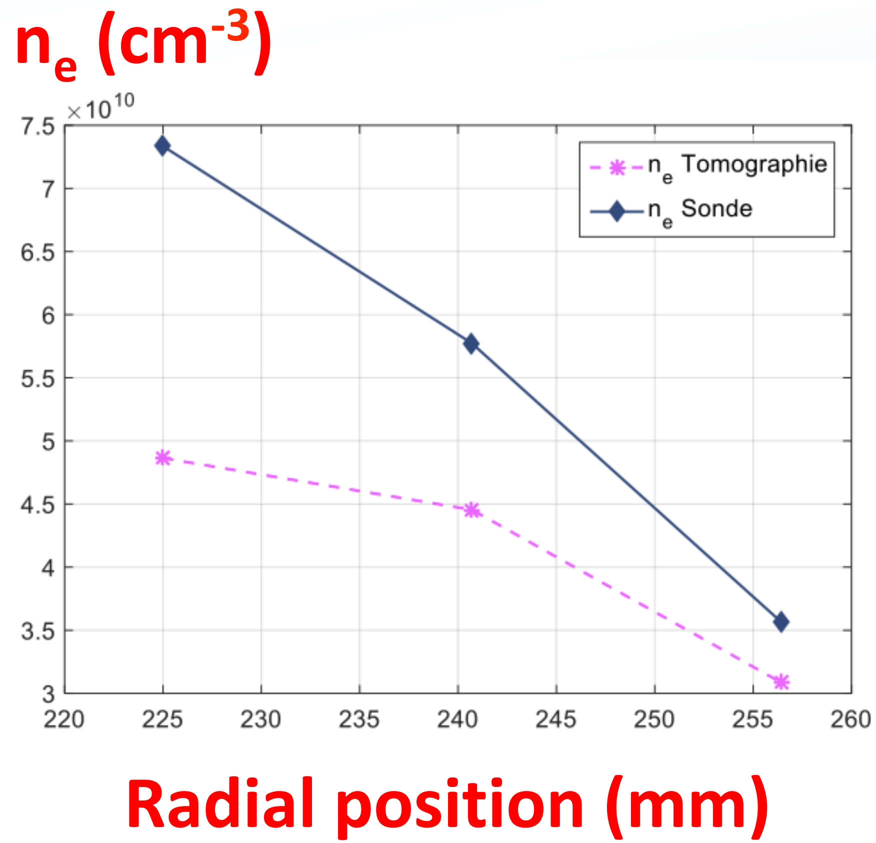
→ The coronal model is valid in the Mistral plasmas

Spectro-tomography T_e measurement



spectro-tomography n_e measurement

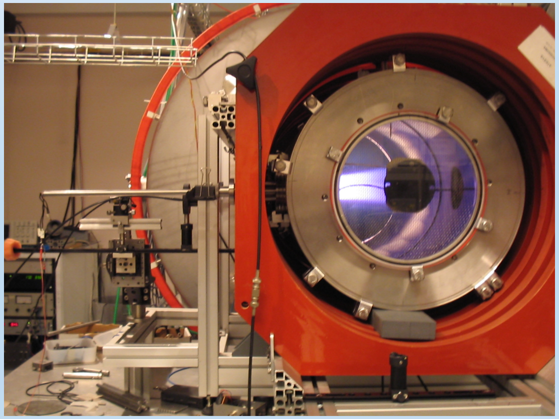




Conclusion

- ***Optical tomography***
  - temporal study of plasma instability
  - One shot acquisition of non flute modes

- ***Optical spectro-tomography***
  - Validation of the diagnostic
  - 2D measurement of n_e, T_e



Perspectives

- Tomography
  - Improvement of the spatial resolution
    → more lines of sight ?
  - Otical fibers → set of mirors around the plasma

- Spectro-tomography
  - 100 kHz acquisitions with a fast camera
  - Application to edge plasmas of Tokamak

- Development of an optical diagnostic of the electric field in a plasma

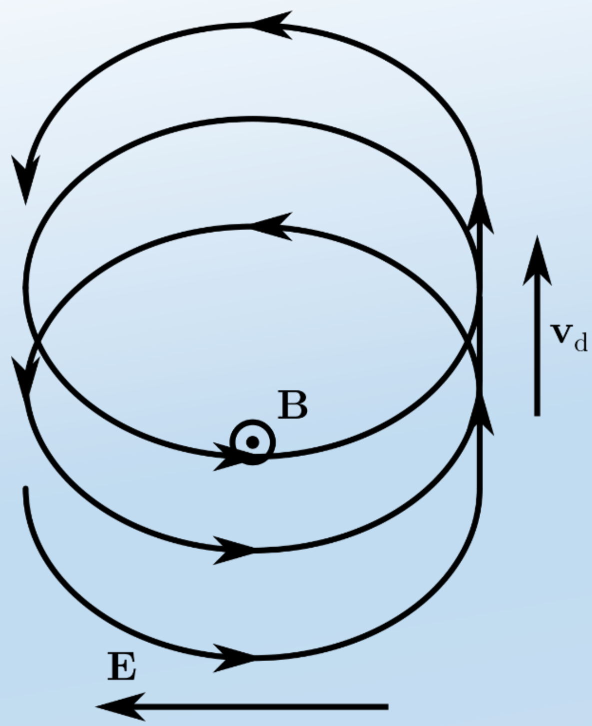
Thank you for your attention

Instabilités d'un plasma en champ croisé ExB

- Force de Lorentz : $\mathbf{F} = q(\mathbf{E} + v \times \mathbf{B})$
  - **B**: confine / guide
  - **E**: accélération / décélération

- Dérive quand $\mathbf{E} \perp \mathbf{B}$:

$$\mathbf{V} = \frac{\mathbf{E} \times \mathbf{B}}{\mathbf{B}^2}$$



La tomographie optique visible

Capteurs :

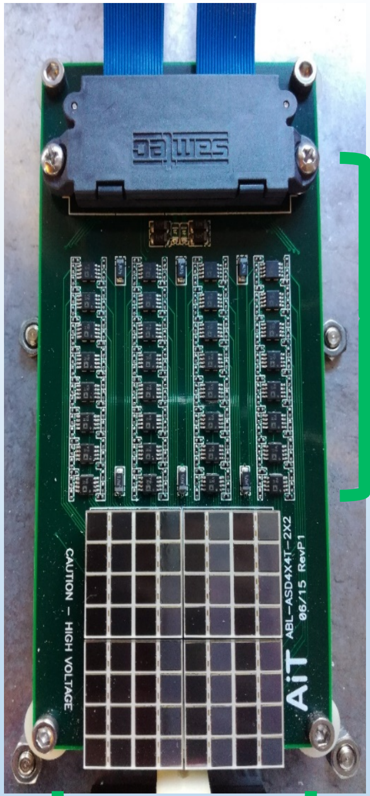
- **2 x 64 fibres Ø100 µm x 5 m**
- **128 détecteurs SiPM**
- **Gain (> 10^6, PDE > 30%) avec faibles tensions/PMTs (~ 20 to 40 V)**
    - **Tps. De réspone rapide <100 ps**
    - **ν_{acq} max. = 1 MHz**

Limitations :

- **Pas de résolution spectrale → mesures limitée des paramètres du plasma**
- **Bruit important (after pulse/cross talk)**

→Besoin d'ajouter la résolution spectrale

→Spectro-tomographie visible



Stage d'amplification

matrice de 8x8 détecteurs

Inversion tomographique

$$S_i = \sum_{j=0}^{N_p} t_{ij}.e_i$$

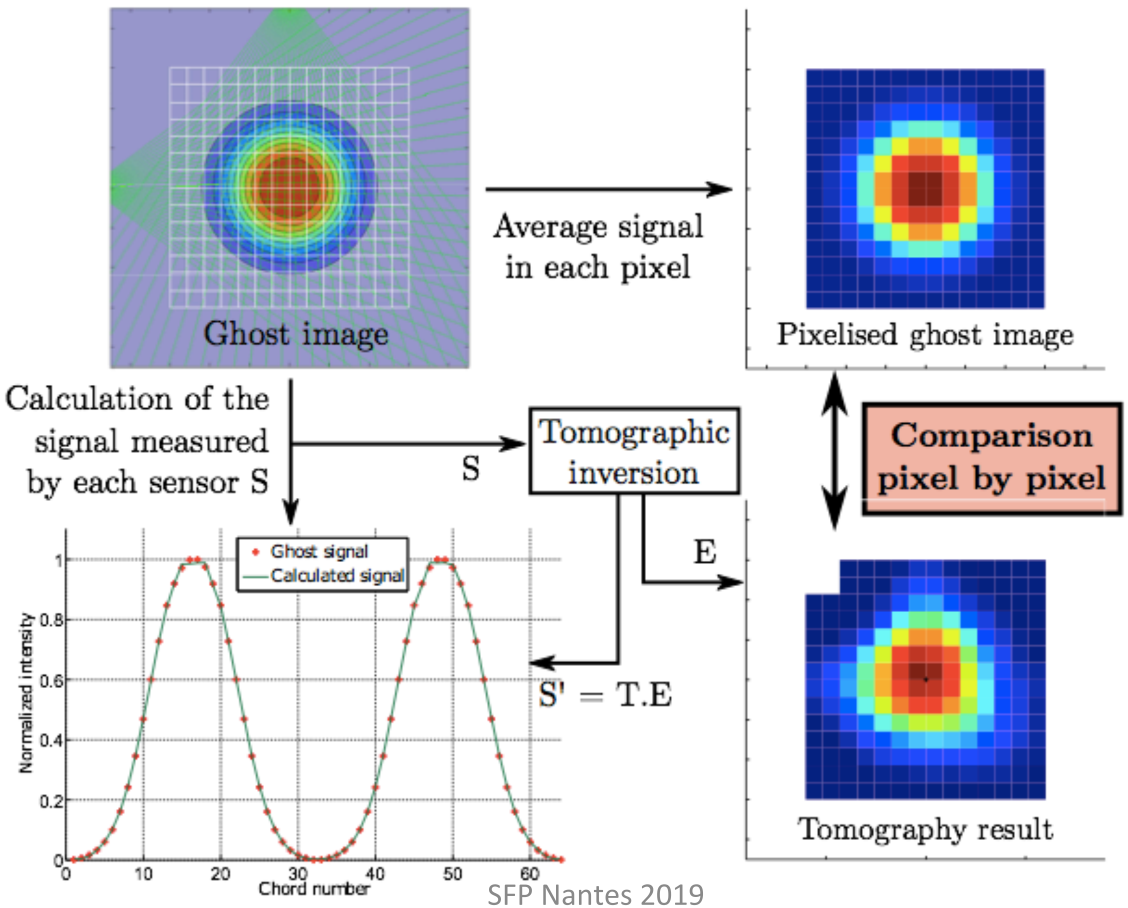
$$\Leftrightarrow \quad S = T.E$$

t_{ij} : coef. calibration, longueur de la ldv dans le $i^{ème}$ pixel

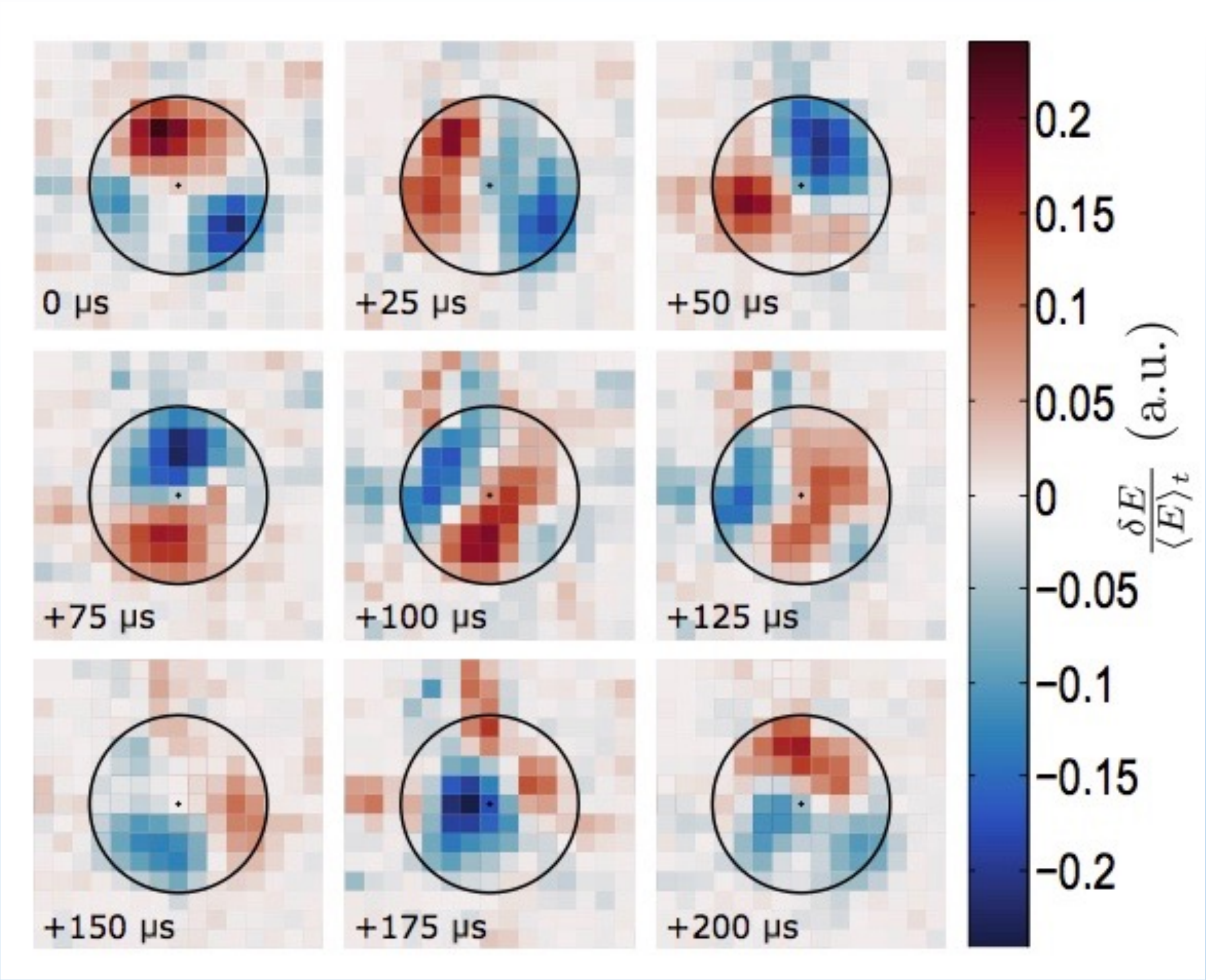
- Système linéaire :
  - $N_{equations} < N_{inconnues}$
  - Système mal conditionné : de petites erreurs sur les données entraînent de grandes erreurs sur les résultats.
- Régularisation de Tikhonov : min (½ $(T.E - S)^2 + \alpha R$)

R : fonction de régularisation

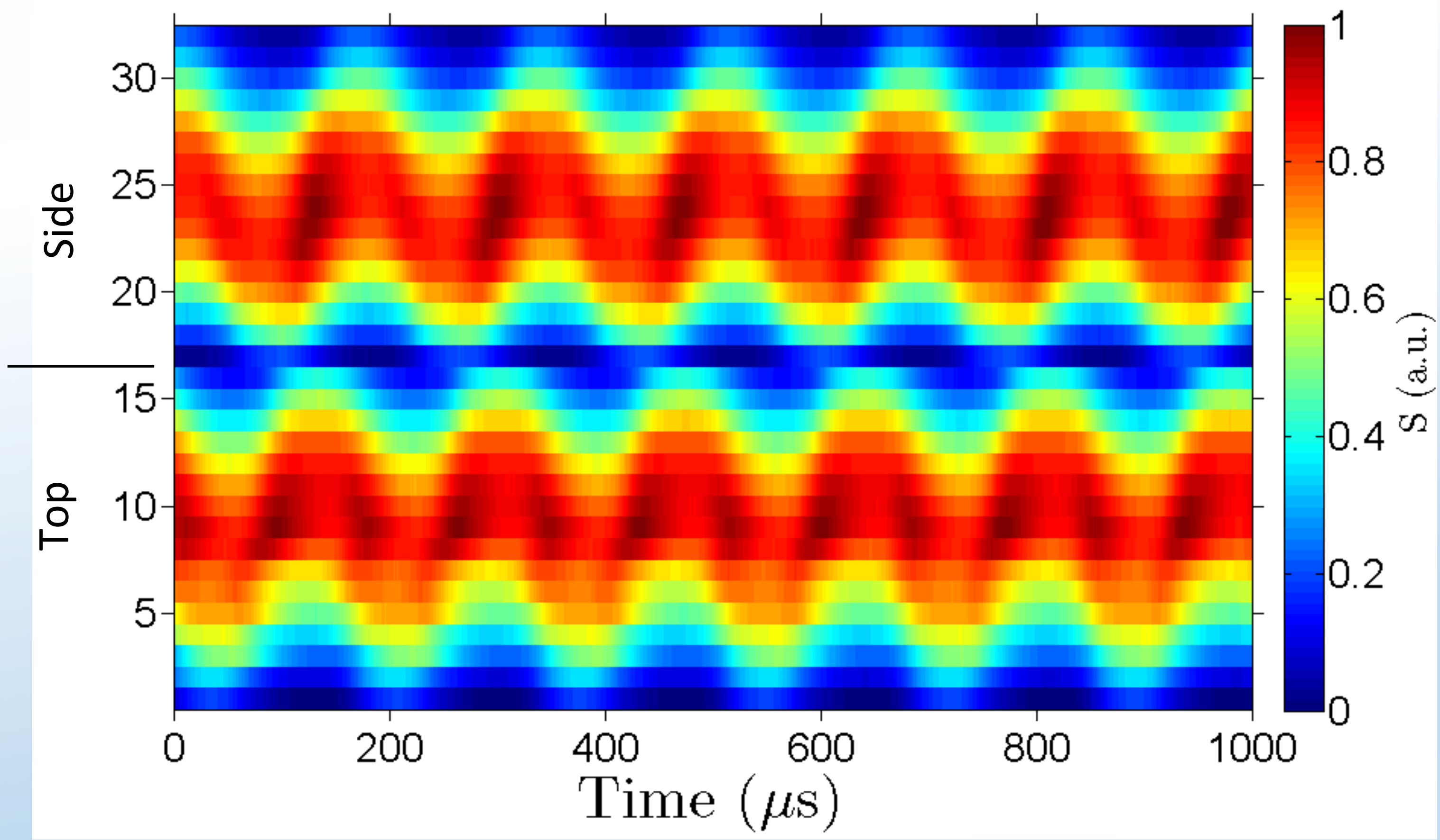
Tomography : validation of inversion code



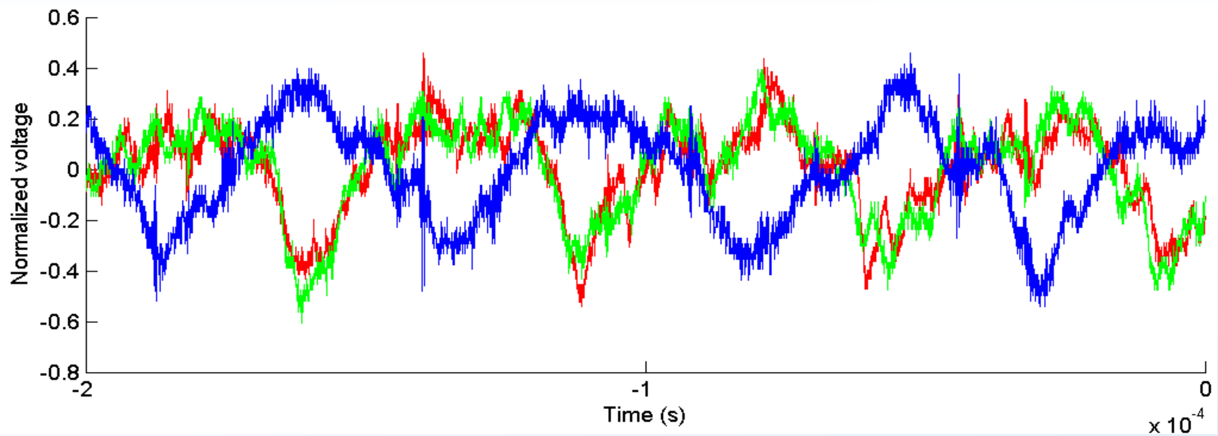
Tomographie : résultats

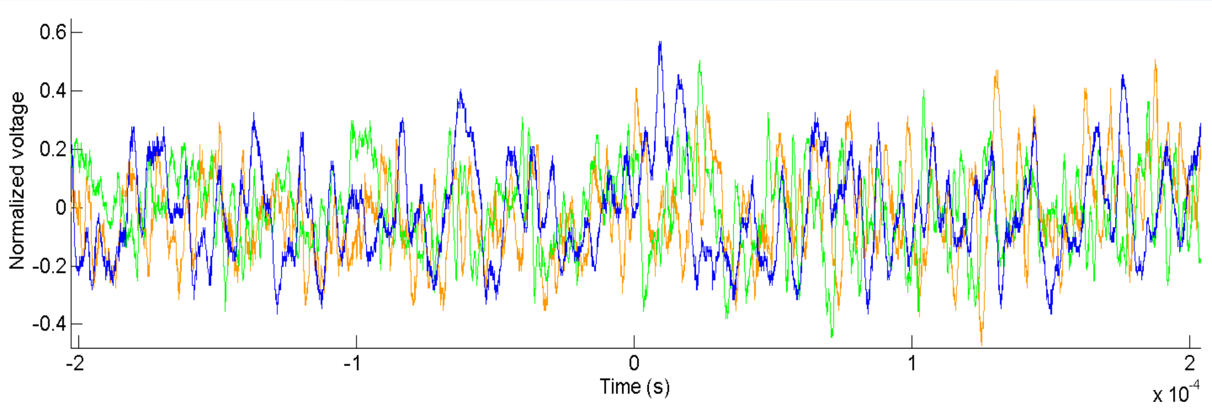


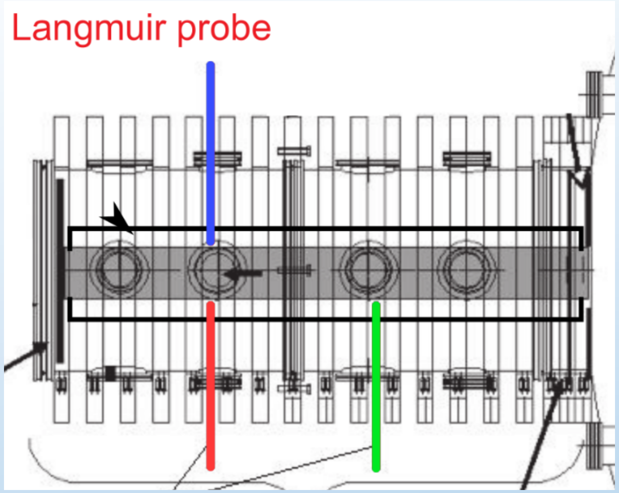
Tomographie : résultats bruts



Instabilités par sondes de Langmuir : symétrie cylindrique







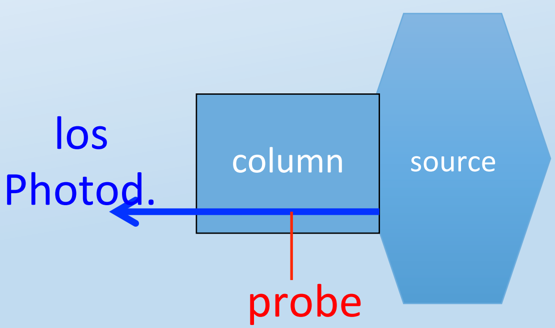
→ **Utilisation de cette symétrie pour valider la tomographie : comparaison avec caméra**

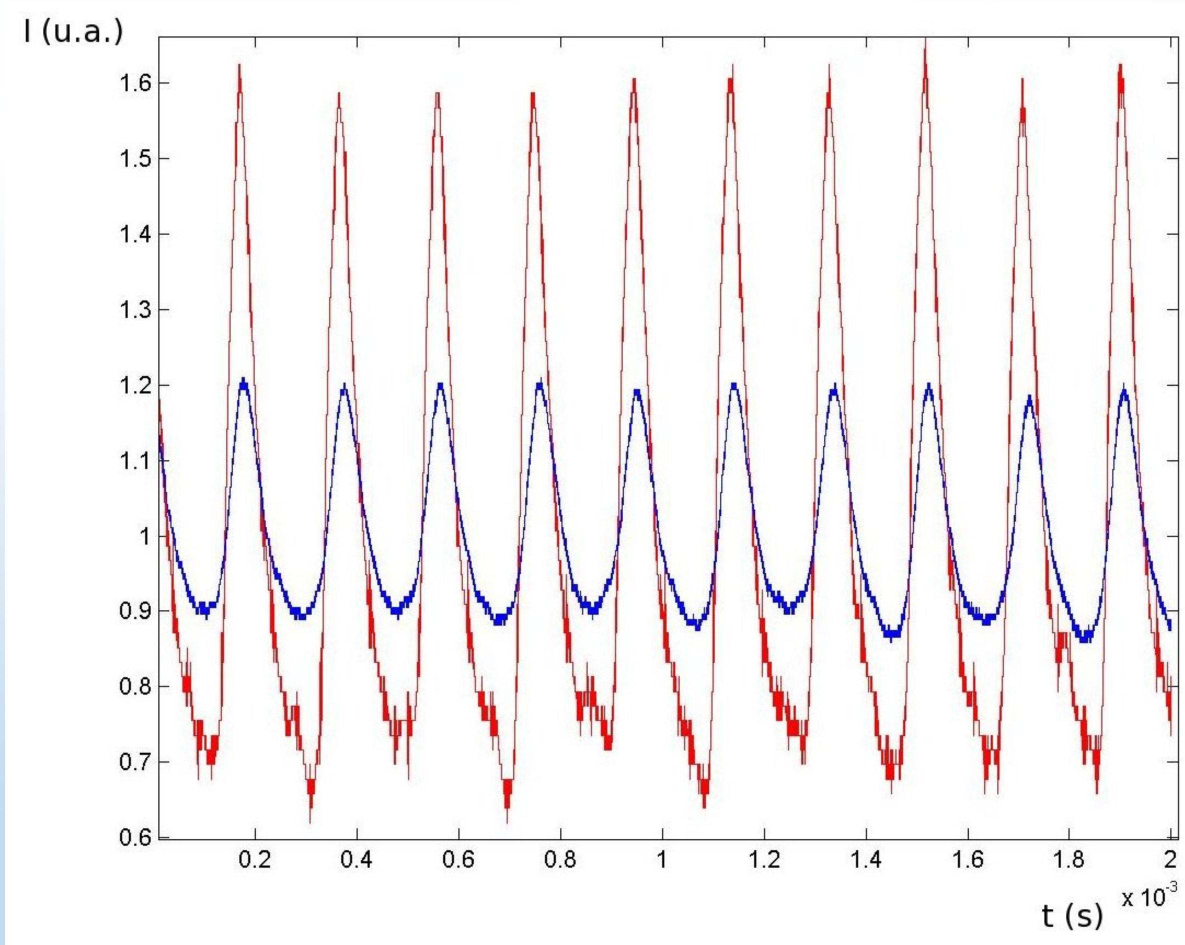
Low frequency instabilities : possible optical measurements…

→Strong correlation between probe and photo-diode signals

- : probe polarized at V > V_{plasma}

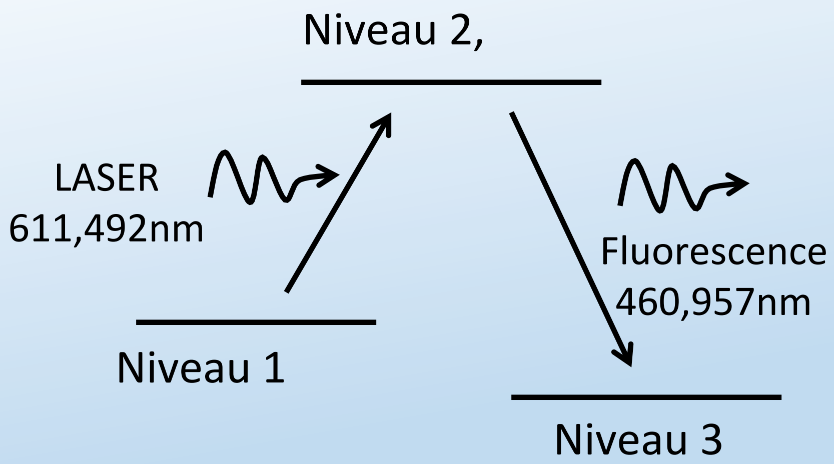
- : photo-diode (collimated los)





Principle of Laser Induced Fluorescence

- Measurement based on :
  - ➢Excitation and emission of photons by an atom or an ion. In our case, Ar^{+} ion.
  - ➢Doppler effect.

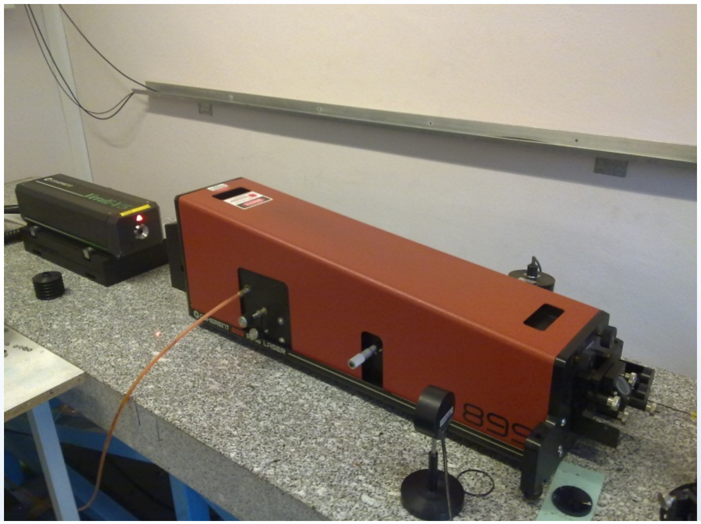


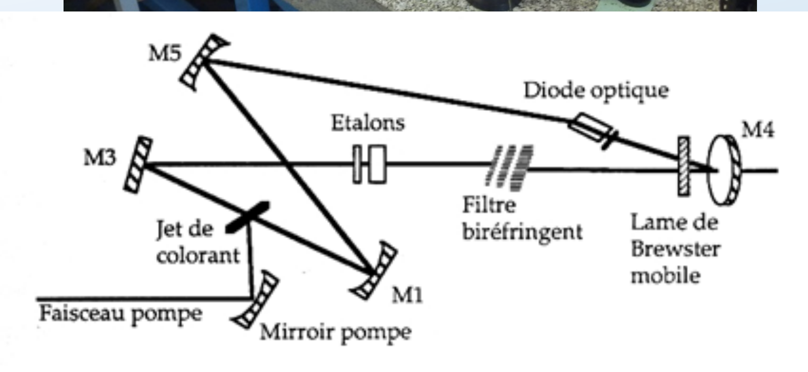
Level 1 to level 2 transition condition:
Laser frequency = transition 1-2 frequency

Emitted fluorescence proportional to the number of excited ions (atoms)

LIF instruments

Dye Laser



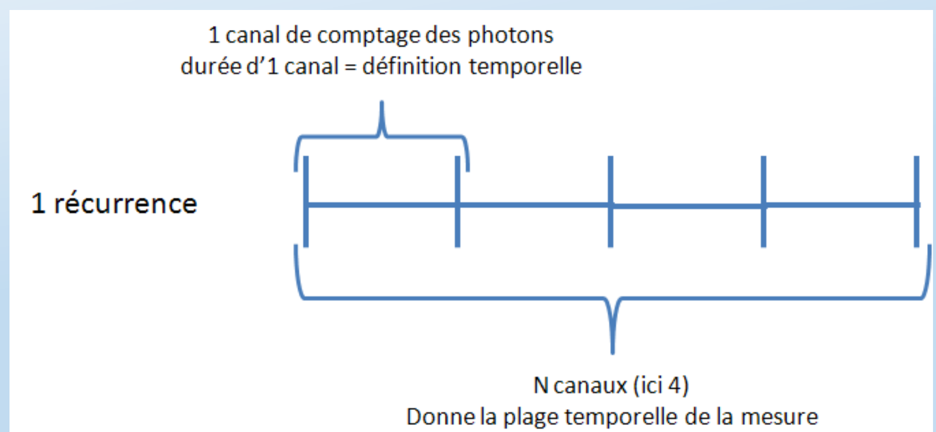


- Power : 400mW at 611,5nm
- Spectral width : 0,5MHz

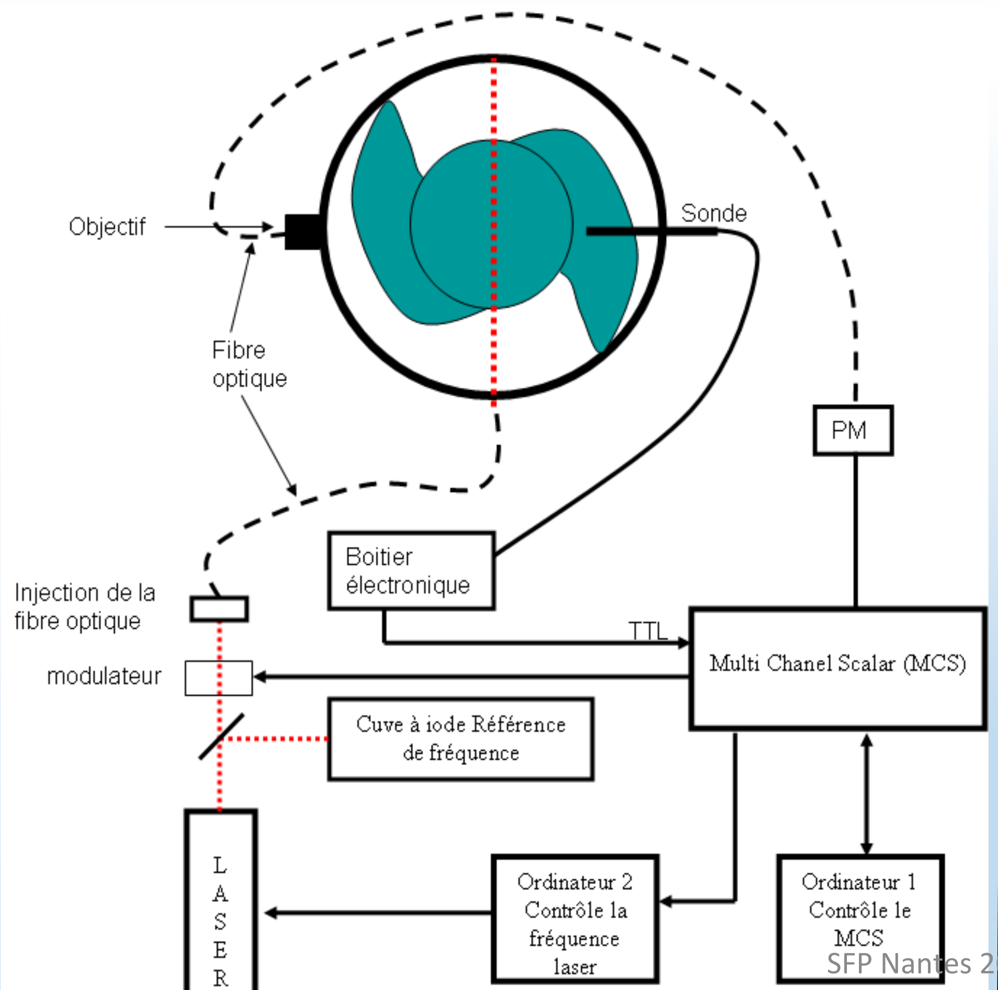
Multi-Channel Scaler (MCS)

The MCS allows to:
- Count photons (detected by a photomultiplier).
- Add temporal resolution to measurement.

Usual parameters:
- Temporal definition between 5ns et 65535s
- Between 4 et 16384 possible temporal channels.
- Up to 4 billions repetitions of measurement possible (increase S/B).



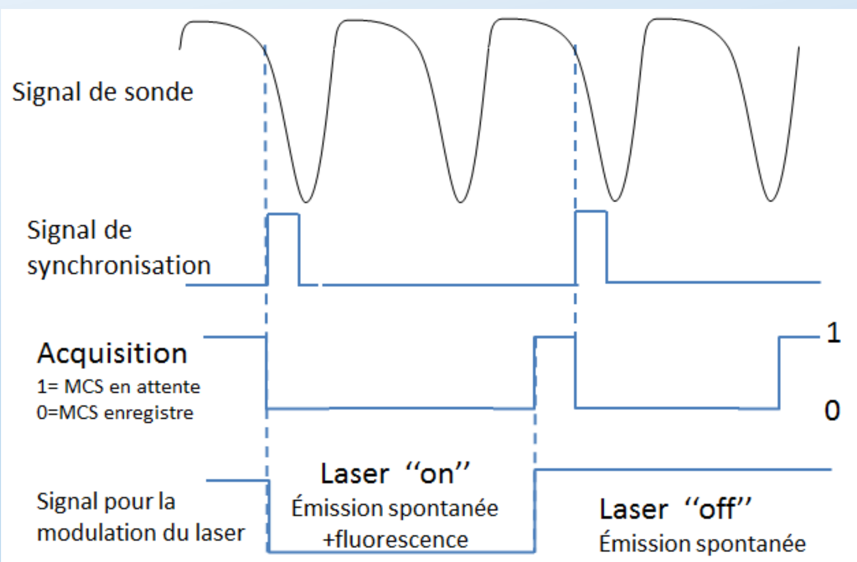
LIF on MISTRAL experiment



- 2 Measurements:
  - laser on
  - laser off

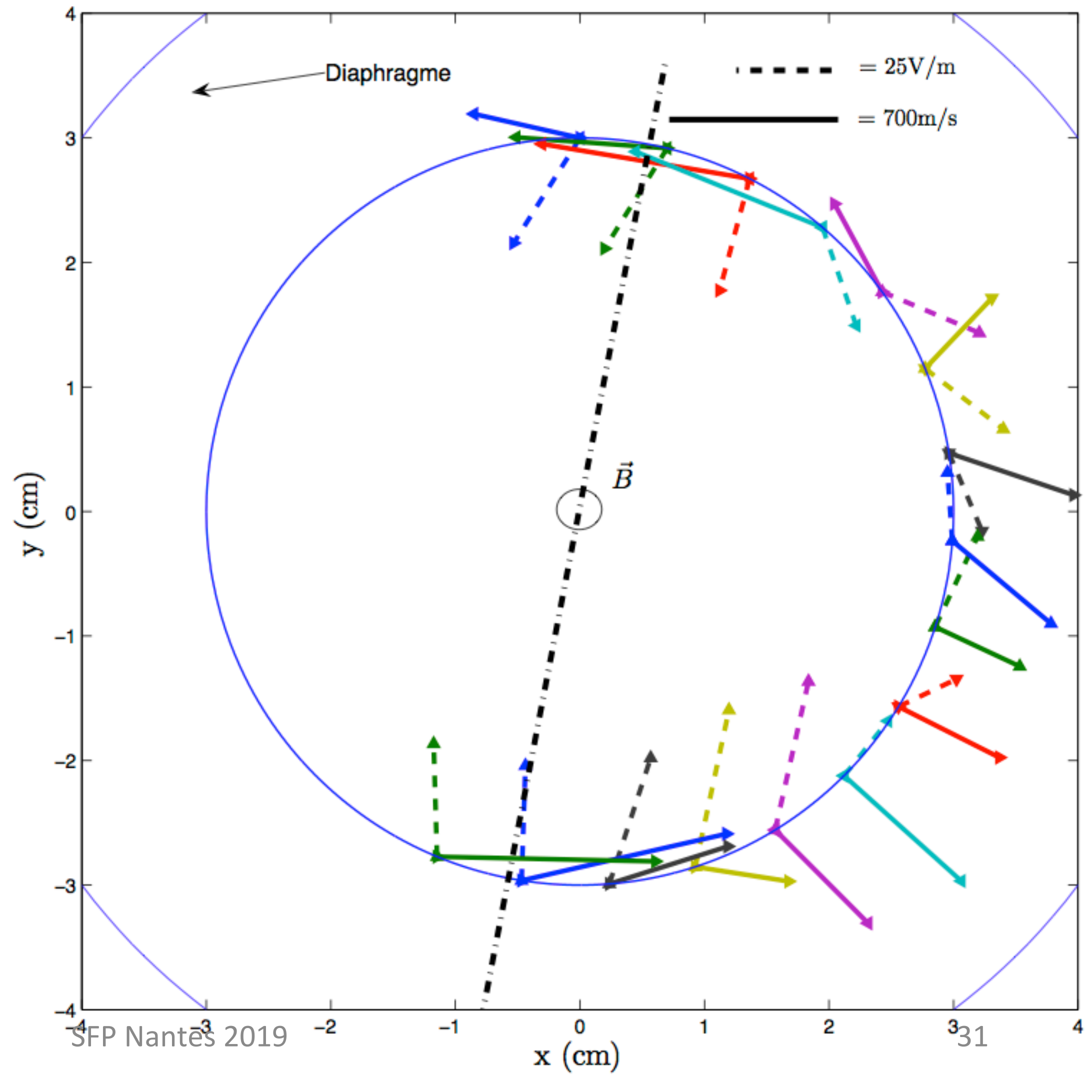
Allows to substract background signal (spontaneous emission)

- Synchronization with perturbation to keep temporal definition during recurrences.



LIF measurements in Mistral : m=2 mode

- : ion velocity (m/s)
-- : electric field (V/m)
-. : mode m=2 axis



→ No whole column ExB drift
→ No clear signature of instability

[Rebont PRL 2011]

Development of a diagnostic to measure directly electric field : EFILE

- Electric field → Emission Lyman-α of a probe H (2s) beam
- Measurement of static and/or fluctuating electric fields (vacuum or cold plasma, density 10^{11} cm^{-3}, sheaths) → **OK**

Project/Challenge :

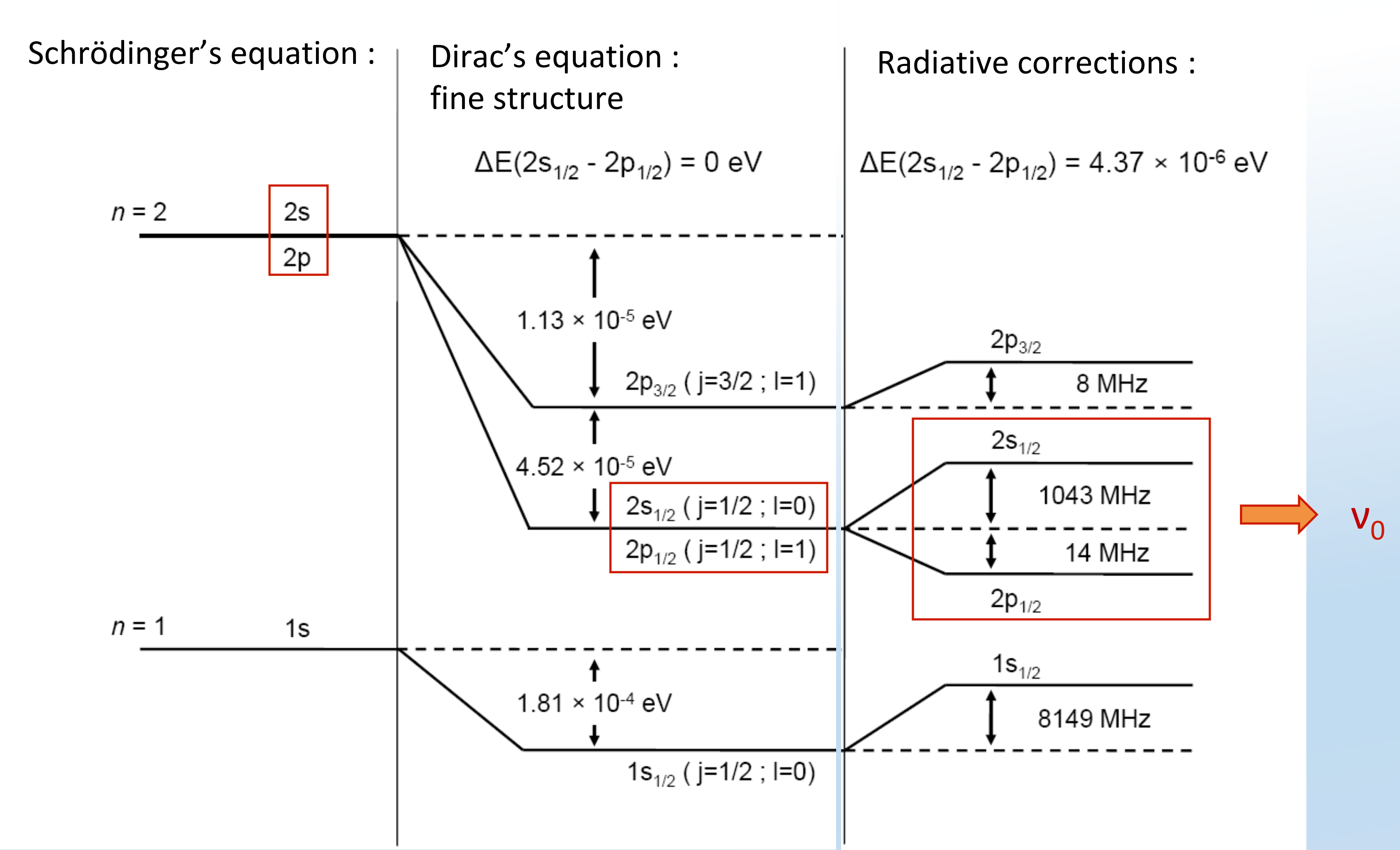
- Measurement of local electric field in Mistral
- Measurement of electric field in front of ICRF IShTAR (Ion cyclotron Sheath Test Arrangement) antenna

[Cherigier-Kovacic RSI 2015 ; Doveil PPCF 2016]

Lamb shift

- Second property of hydrogenoids :

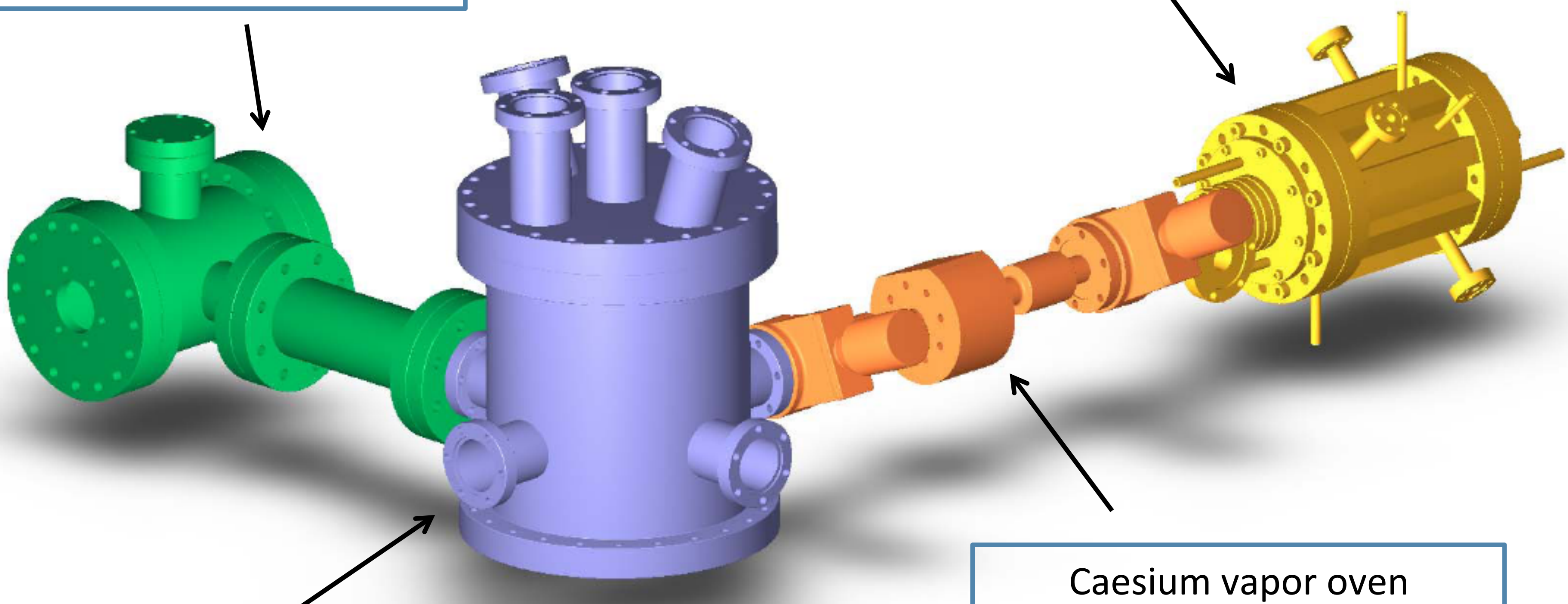
Lamb-shift due to radiative corrections



Schematic view of the EFILE experiment

Plasma source : multipolar device
+
Einzel lenses (extraction)

Collection of Lyman α emission

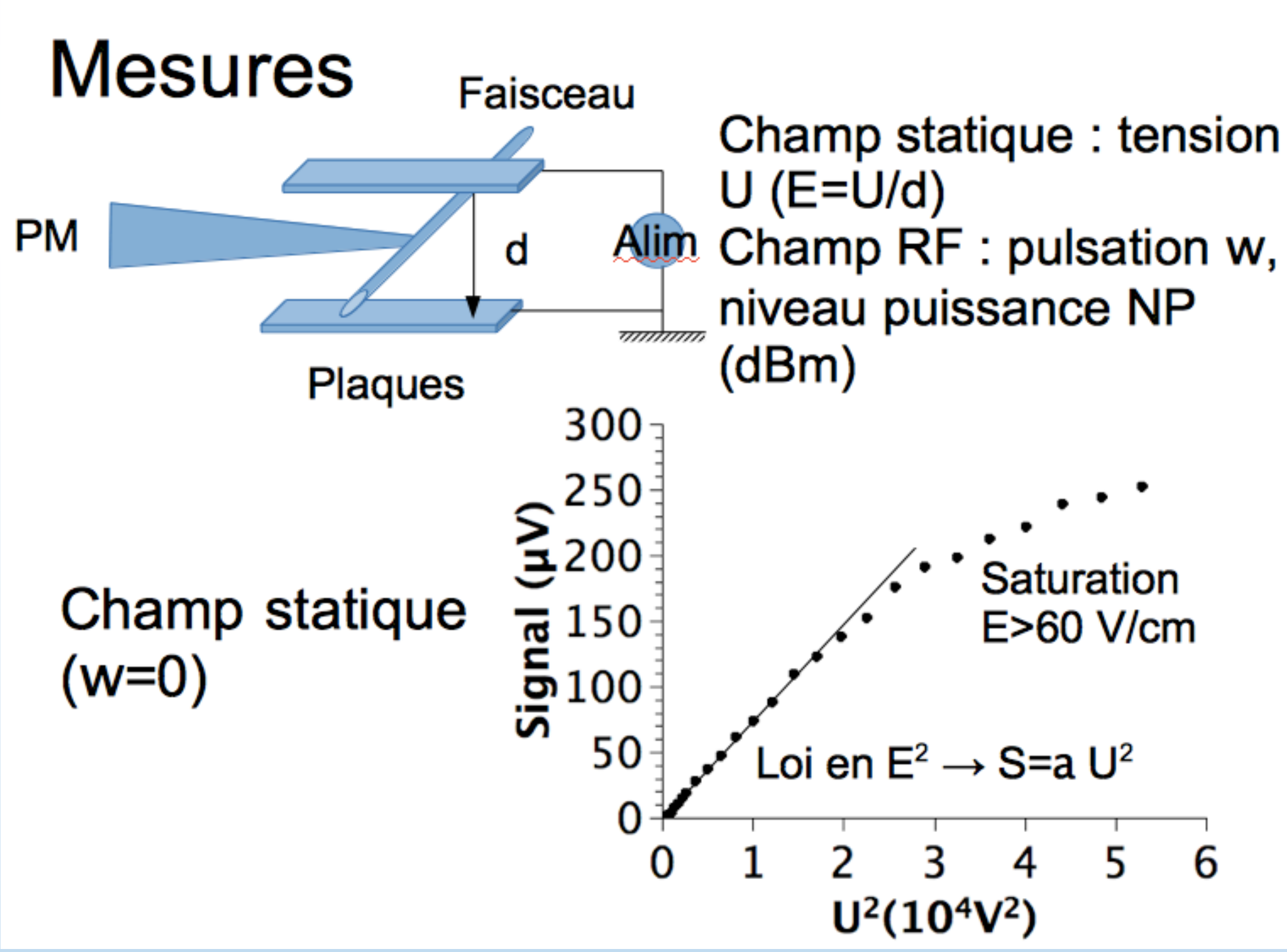


Caesium vapor oven (neutralization)

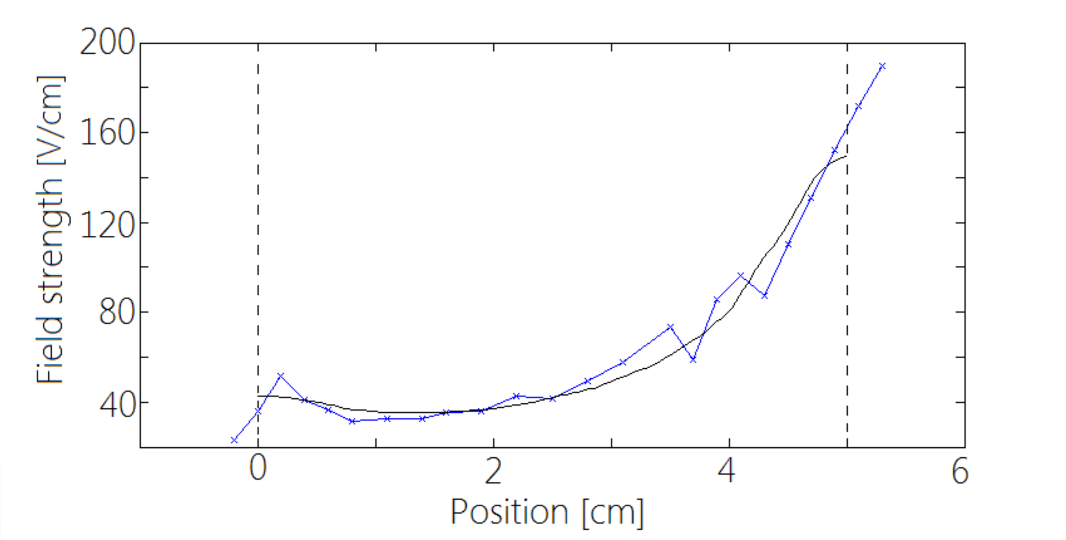
Test chamber: interaction probe beam – electric field + diagnostics* beam / plasma

* mass spectrometer, energy analyzer, Langmuir probes

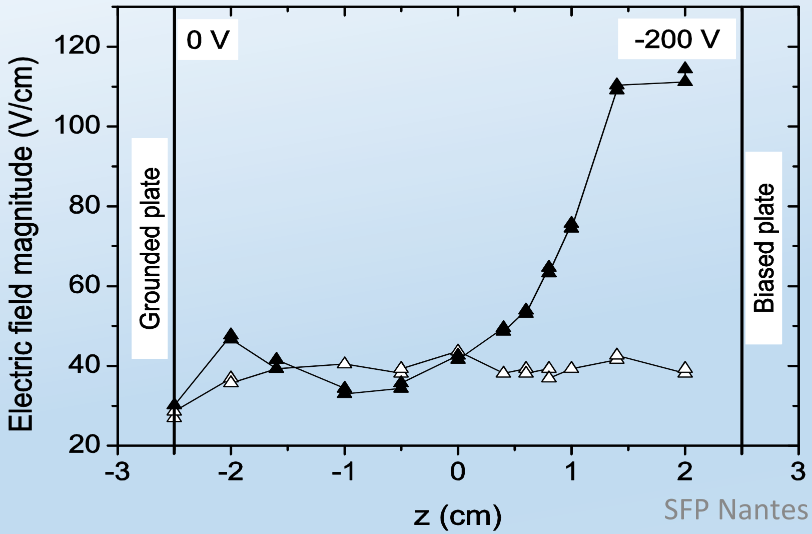
E measurement in the shadow of a limiter : principle



EFILE : results



Diagnostic EFILE in vacuum: comparison with numerical simulation FEM



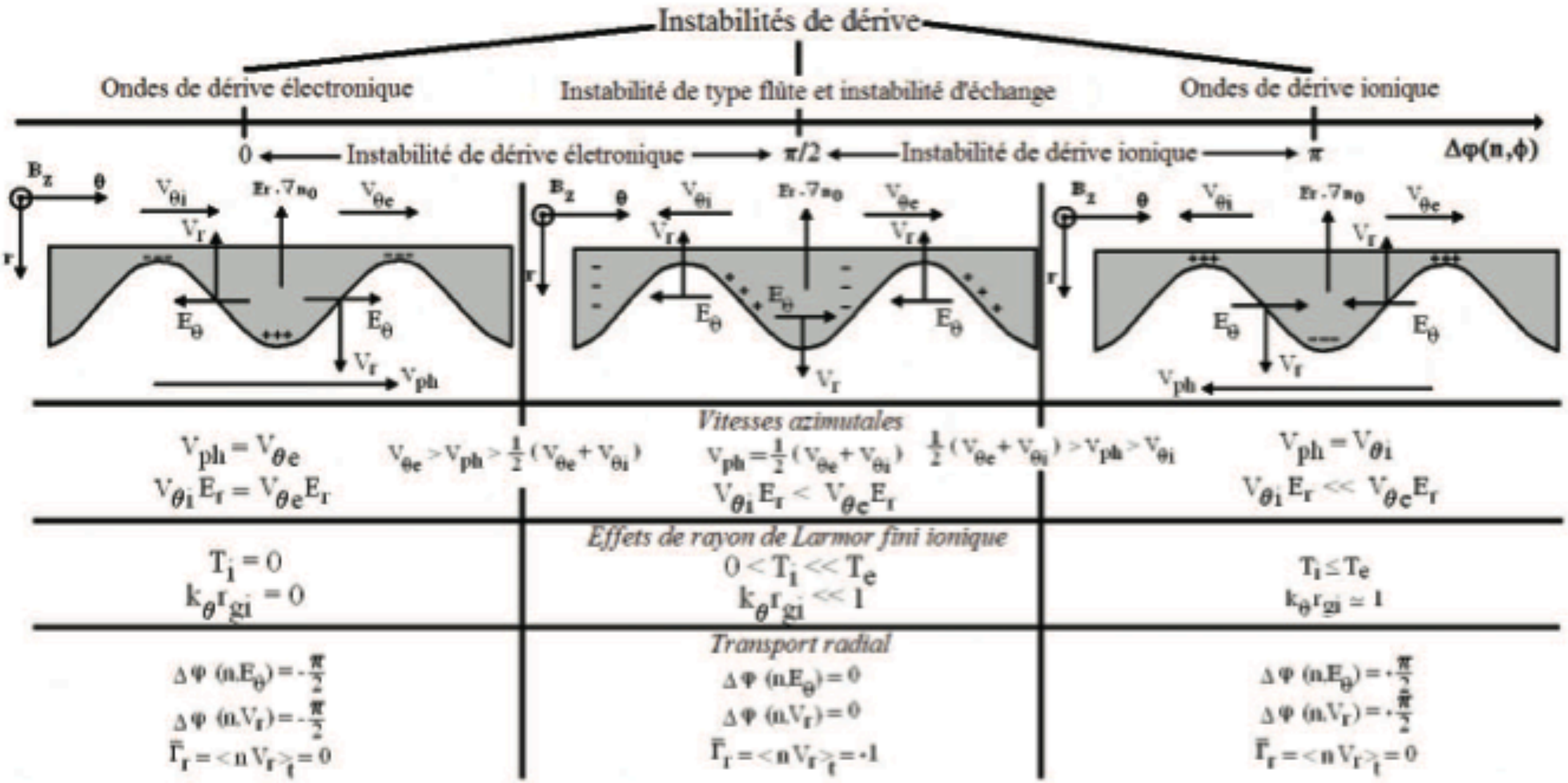
Diagnostic EFILE in plasma

Formation of a plasma sheath:

Electric field profile measured

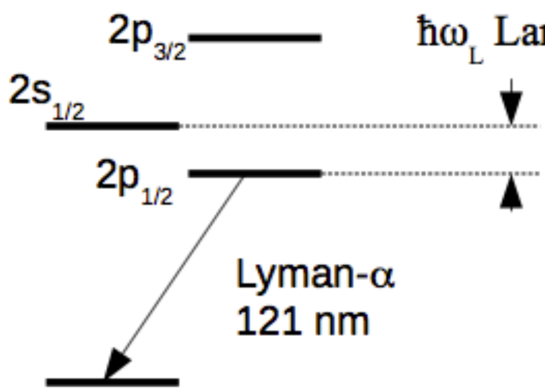
-in vacuum (white triangle)

-in test plasma (black triangle)


Instabilités de dérive
Ondes de dérive électronique
Instabilité de type flûte et instabilité d'échange
Ondes de dérive ionique
0 ← Instabilité de dérive életronique → π/2 ← Instabilité de dérive ionique → π
Δφ(n,ϕ)
Vitesses azimutales
$V_{ph} = V_{\theta e}$
$V_{\theta i} E_r = V_{\theta e} E_r$
$V_{\theta e} > V_{ph} > \frac{1}{2}(V_{\theta e} + V_{\theta i})$
$V_{ph} = \frac{1}{2}(V_{\theta e} + V_{\theta i})$
$V_{\theta i} E_r < V_{\theta e} E_r$
$\frac{1}{2}(V_{\theta e} + V_{\theta i}) > V_{ph} > V_{\theta i}$
$V_{ph} = V_{\theta i}$
$V_{\theta i} E_r \ll V_{\theta e} E_r$
Effets de rayon de Larmor fini ionique
$T_i = 0$
$k_\theta r_{gi} = 0$
$0 < T_i \ll T_e$
$k_\theta r_{gi} \ll 1$
$T_i \leq T_e$
$k_\theta r_{gi} \simeq 1$
Transport radial
$\Delta\varphi(n.E_\theta) = -\frac{\pi}{2}$
$\Delta\varphi(n.V_r) = -\frac{\pi}{2}$
$\bar{\Gamma}_r = \langle n V_r \rangle_t = 0$
$\Delta\varphi(n.E_\theta) = 0$
$\Delta\varphi(n.V_r) = 0$
$\bar{\Gamma}_r = \langle n V_r \rangle_t = -1$
$\Delta\varphi(n.E_\theta) = +\frac{\pi}{2}$
$\Delta\varphi(n.V_r) = +\frac{\pi}{2}$
$\bar{\Gamma}_r = \langle n V_r \rangle_t = 0$

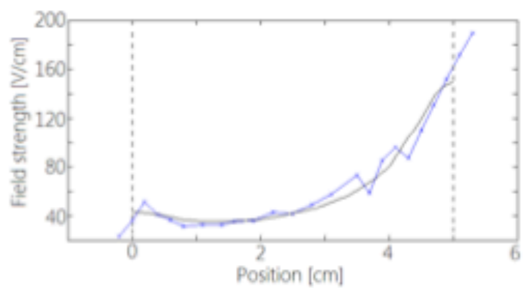
Mesure d'un champ électrique statique ou fluctuant

Principe physique : interaction entre un faisceau H(2s) et un champ électrique (E, ω) → émission Lyman-α par Stark mixing 2s, $2p_{1/2}$ = modification taux d'émission

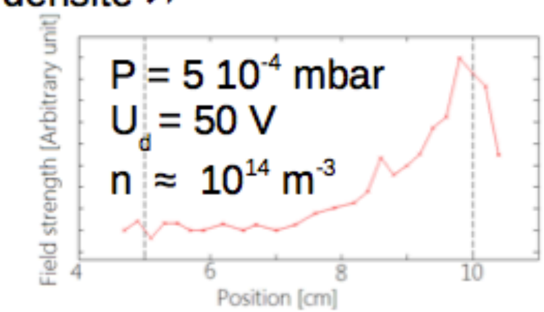


$$\gamma^{*}_{2s}(\omega) = \frac{9e^2 a_0^2 E^2}{h^2} \frac{\gamma_{2p}}{(\omega-\omega_L)^2 + \gamma_{2p}^2/4}$$

Champ statique dans le vide : profil entre les plaques en accord avec calcul numérique



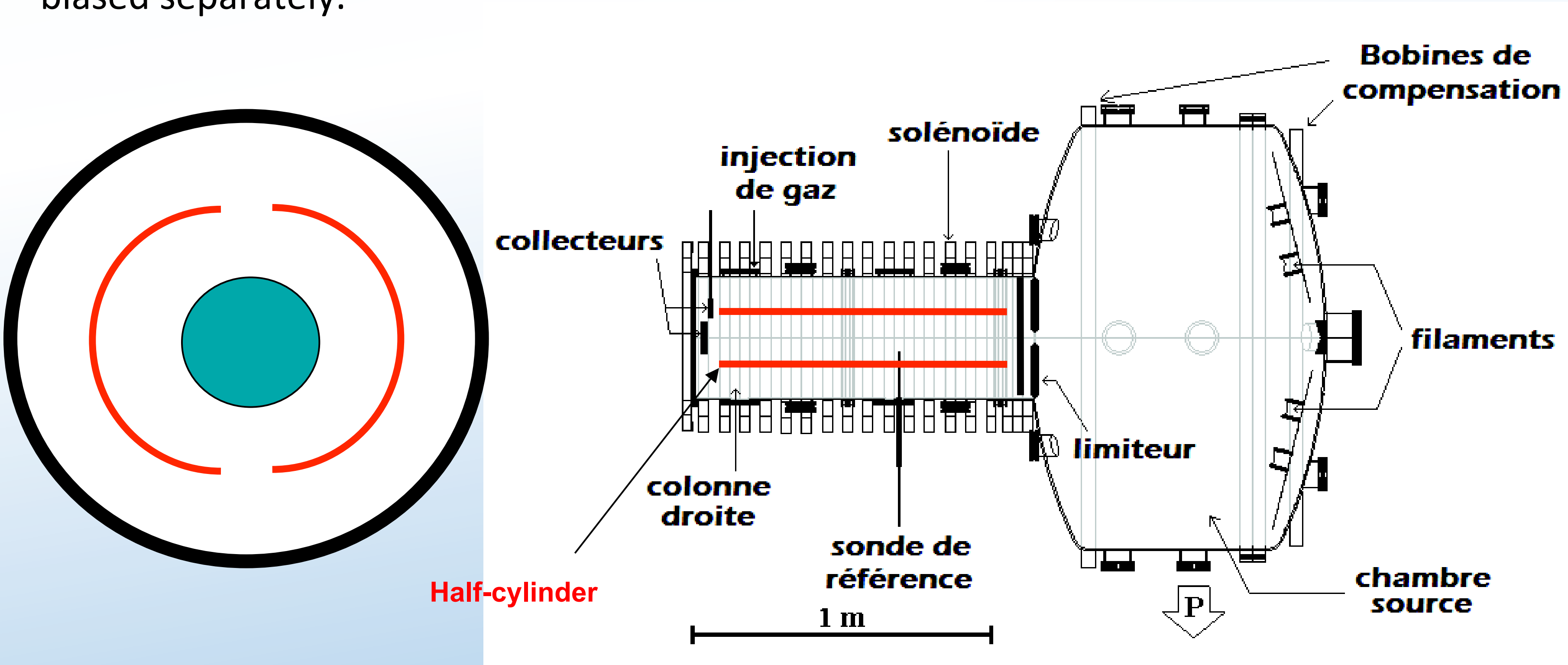
Champ statique dans un plasma : taille gaine ↘ quand densité ↗



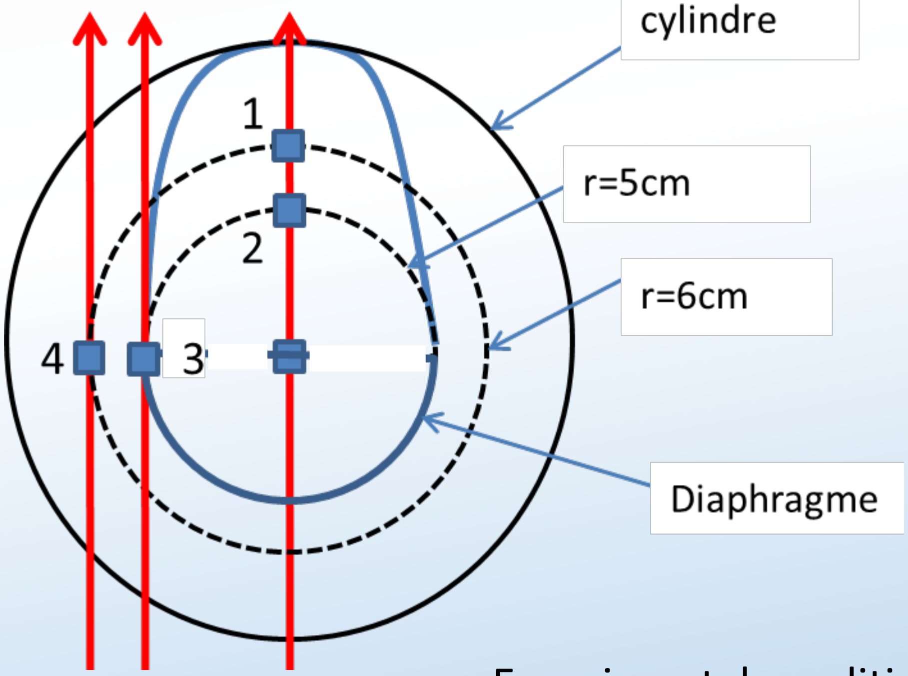
En cours : mesures RF, calibration
Développement : mesures en champ magnétique (MISTRAL)
Projet : mesure champ RF devant antenne ICRF chauffage plasma (Ishtar, Garching)

New configuration

Installation of 2 half-cylinders to measure radial current: each half-cylinder can be biased separately.



LIF measurements



- Measurement between r = 0 and 6 cm
- ΔX = 1 cm
- Mode frequency: 5 KHz < f_{ci}
- LIF Δt : 100 μs
- 150 000 repetitions
- Total acquisition time: 2 h for a time-resolved velocity distribution function

Experimental conditions:

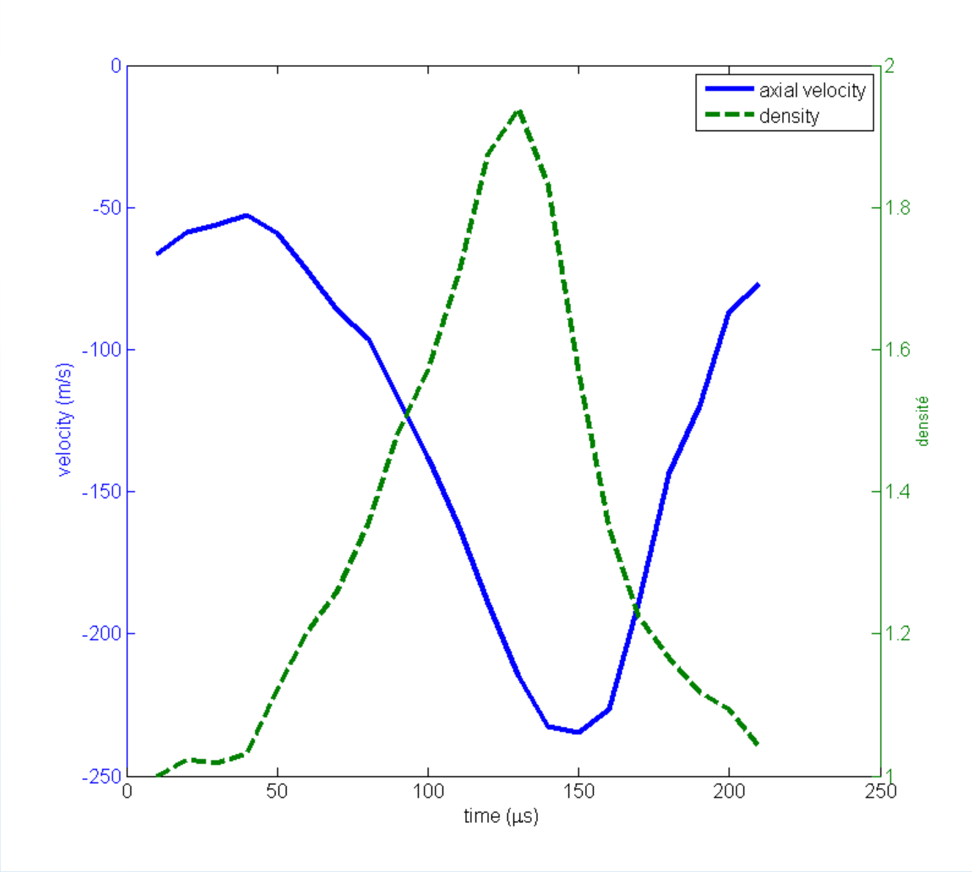
-Grounded half-cylinders

-Floating separatrix and collector (-30 V)

-P = 9 10^{-4} mbar

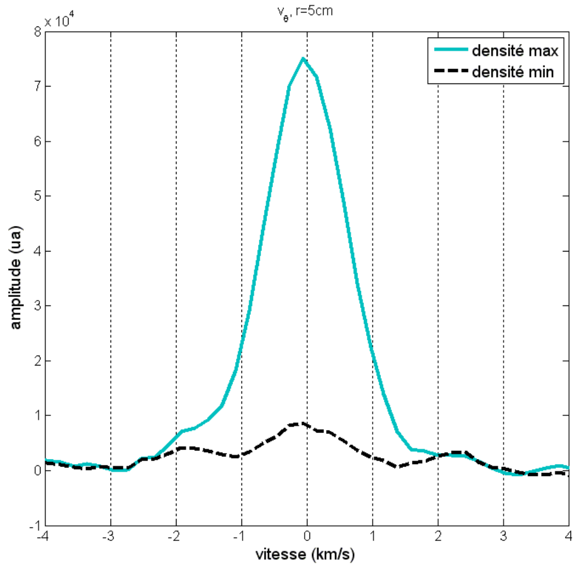
-B = 16 mT

Axial distribution function



Modulation of mean axial velocity at the same frequency as perturbation
➔ possible drift waves

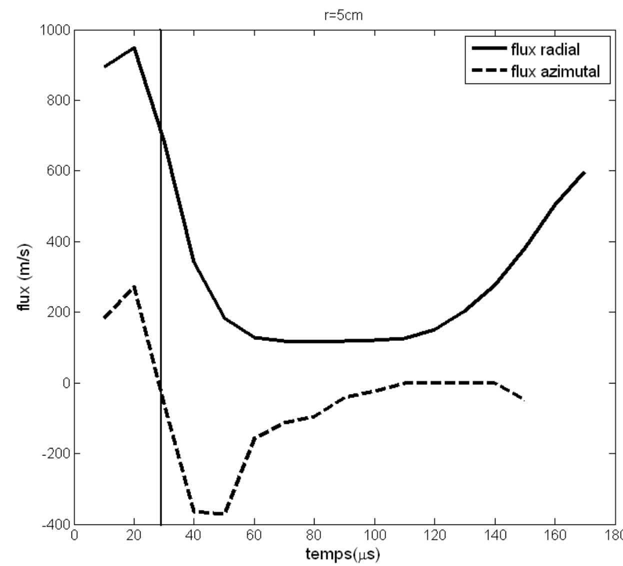
Results at r=5cm, ionization zone limit

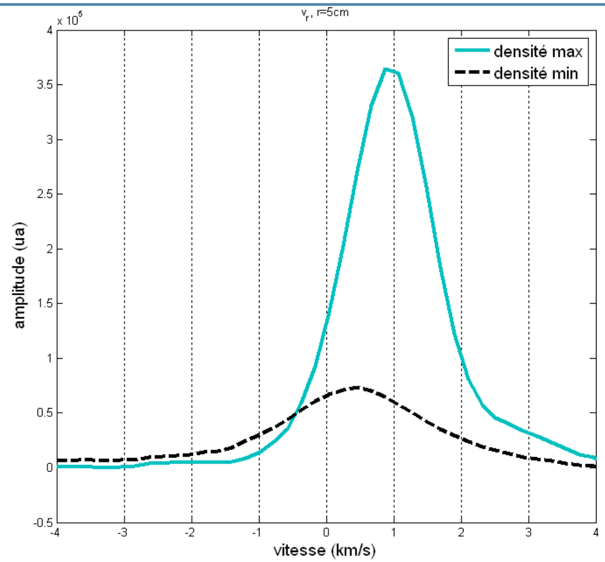


azimuthal

At max and min density ivdf centered at zero velocity.

Flux: $\Gamma = n.V$



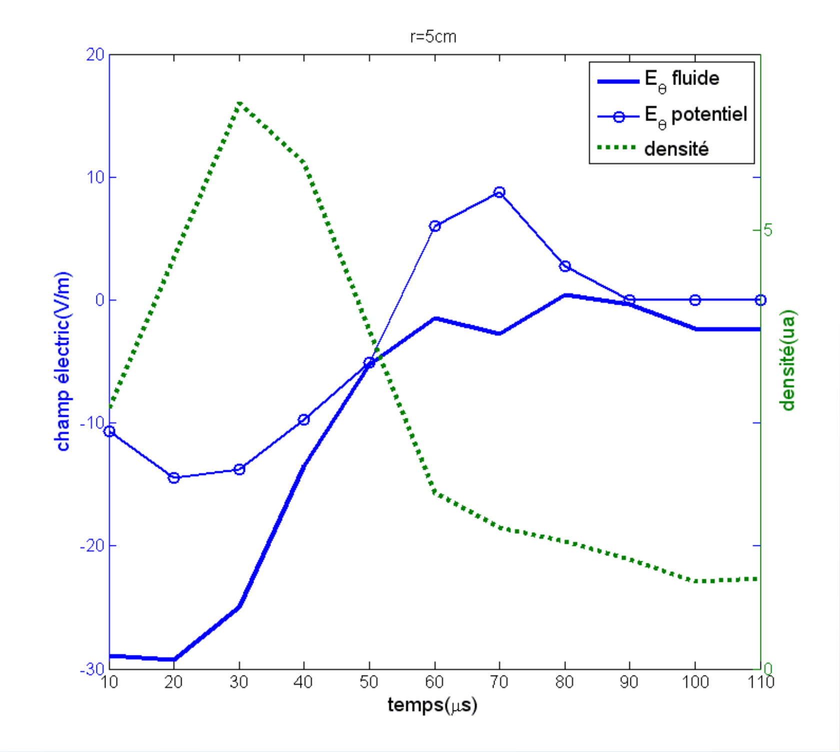


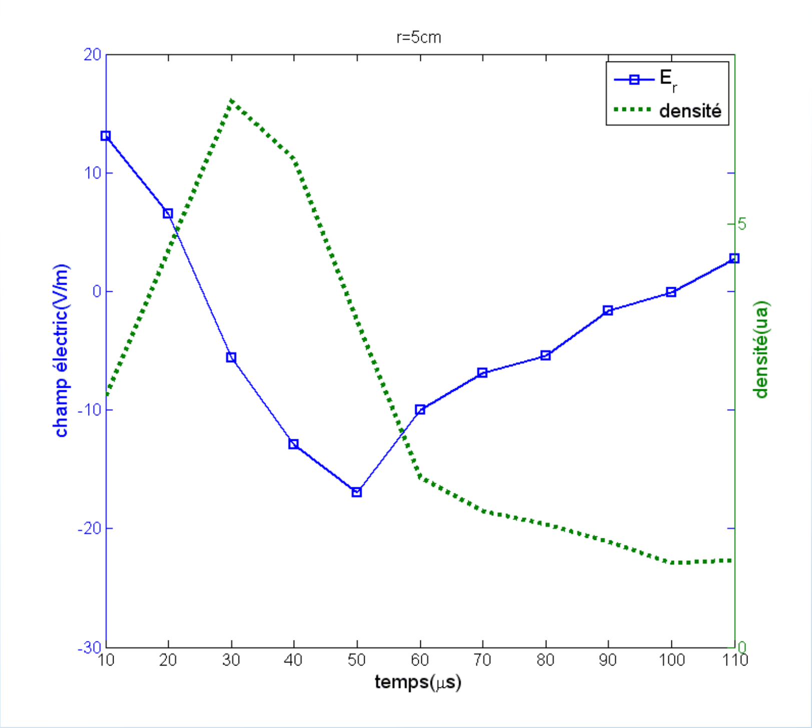
radial

Radial velocity always present.

Non-zero mean radial flux -> no drift wave

Results at r=5cm





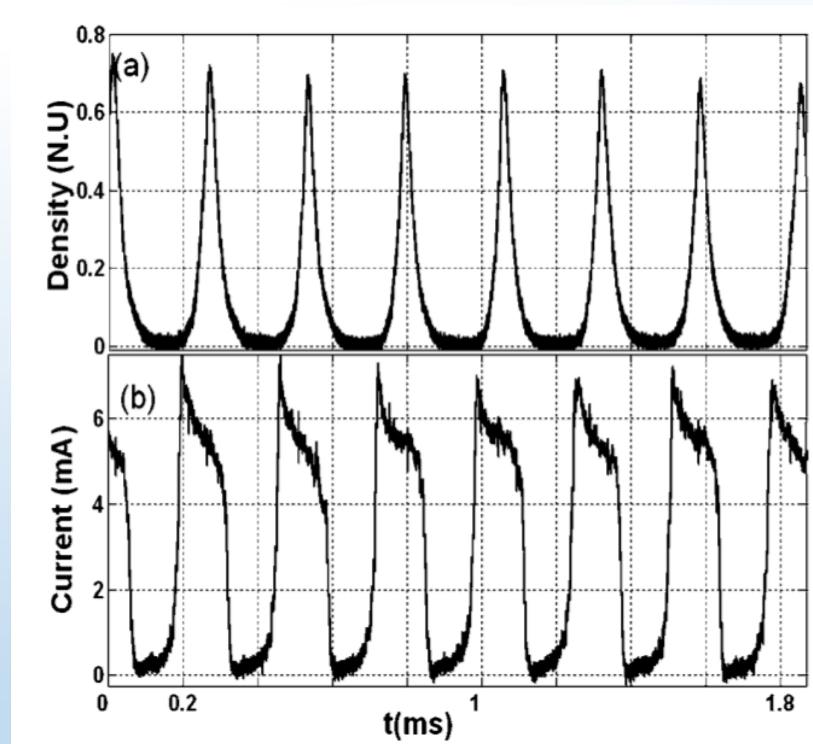
Azimuthal electric field shows:
-max on rising density front
-differences according to used method (change of sign for energy conservation method)

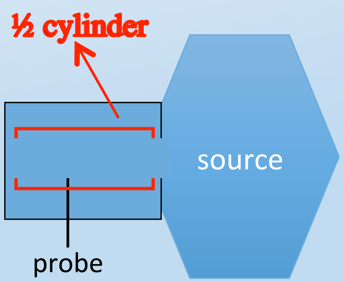
Radial electric field extrema on density fronts ➔ changes sign.

m=1, 2 regular modes rotating around plasma column

- Langmuir probe in the diaphragm shadow (V_{probe}>V_{plasma}) : n_e.
- 2 half-cylinders around the column : radial current I.

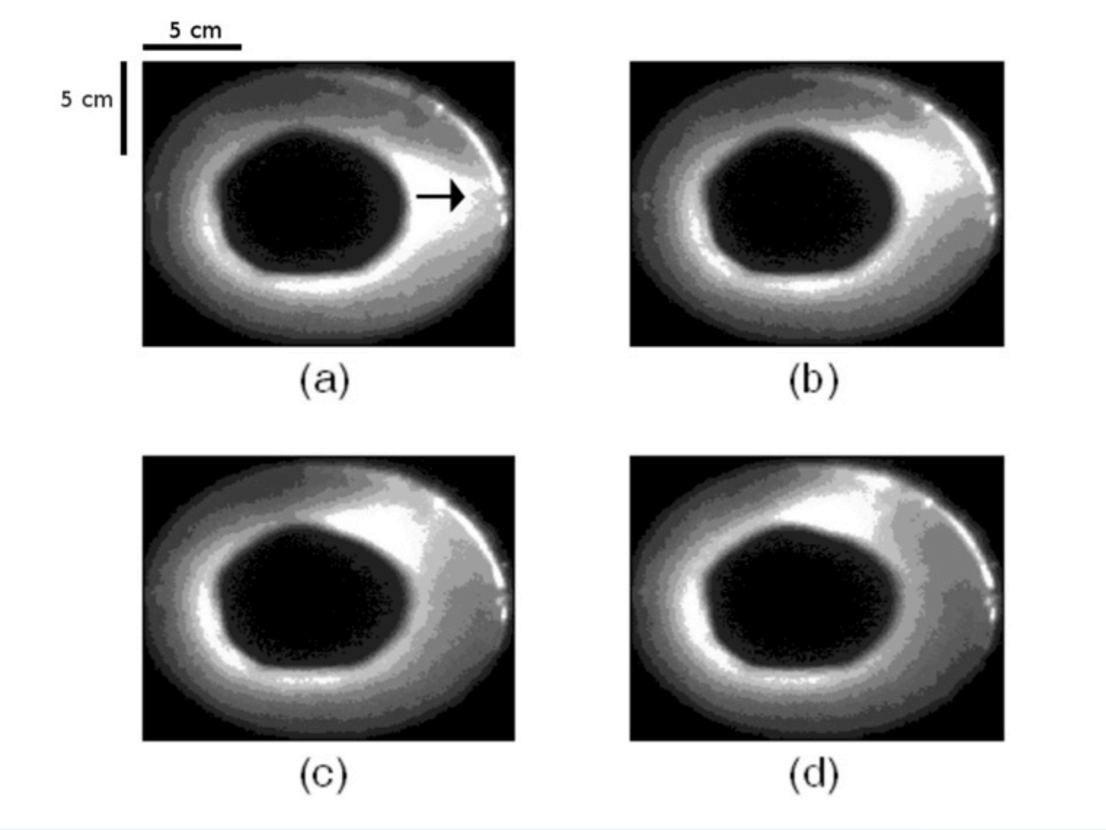
→ Observation of rotating structures (ν = a few kHz - sonification for live control)





[Jaeger POP 2009]

Fast camera results (end view of the plasma)



Simon-Hoh instability CSHI (Phys. Fluids 1963)

ExB drift:

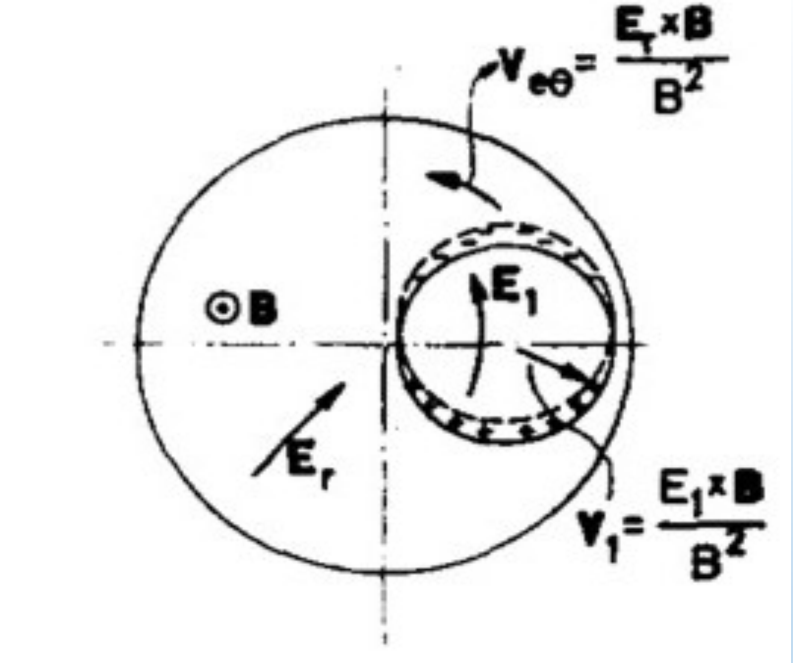
- Electrons : $v_{e\theta}$
- Friction forces (e-neutrals)

→ Ions slowed down:

$$v_{i\theta} < v_{e\theta}$$

→ Charge separation: E_1

→ Rotation frequency instability:

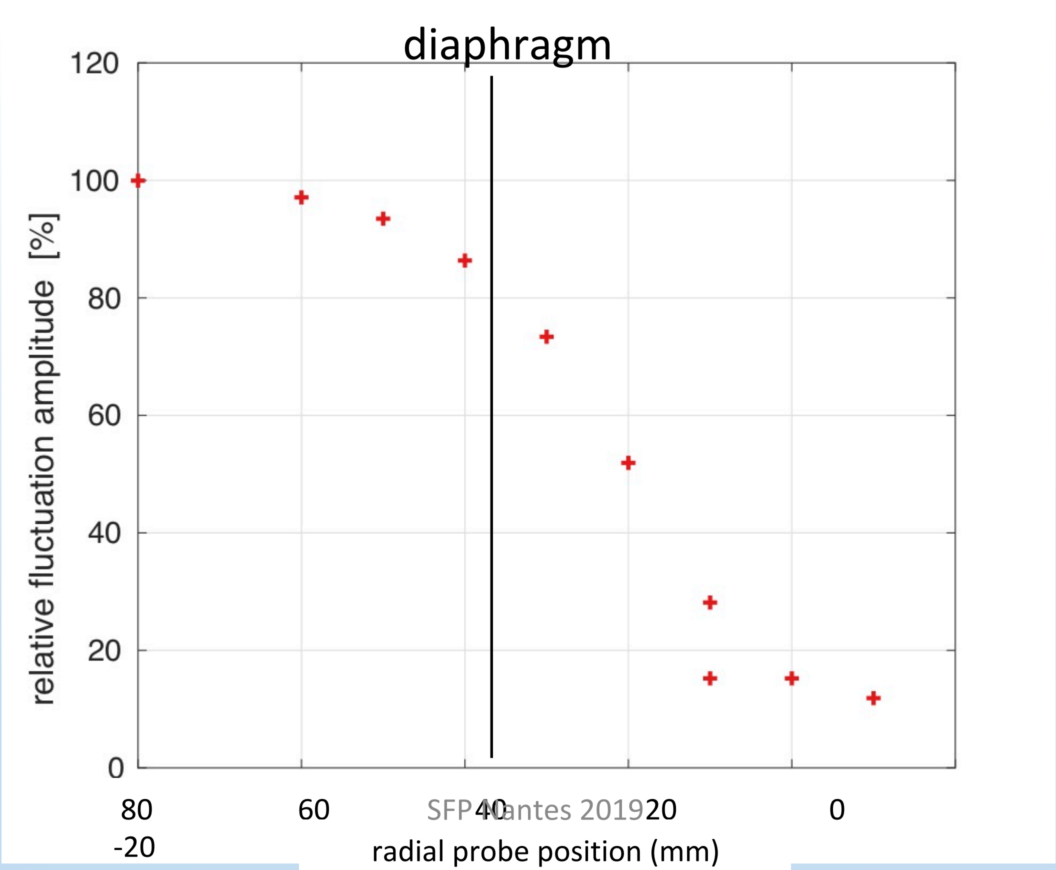


$$\upsilon_{spoke} = \frac{1}{\pi R_0}\sqrt{\frac{eE_r L_n}{m_i}} \qquad L_n = \frac{n_e}{\frac{\partial n_e}{\partial r}} \qquad \upsilon_{spoke} \propto \sqrt{B} \qquad E_r \propto B$$

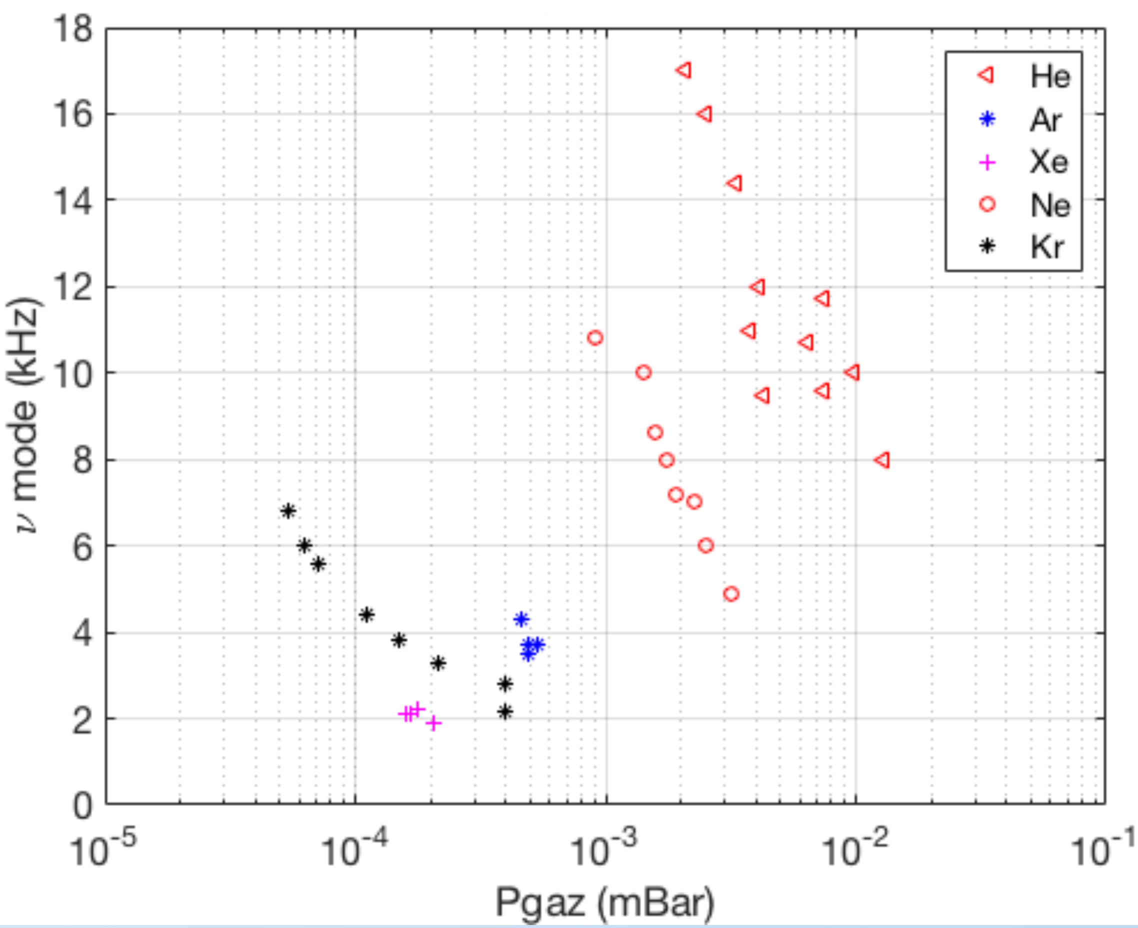
Smolyakov PPCF (2017) ; POWIS POP (2018) [Hoh; Simon Phys. Fluids 1963 ; Jaeger PhD 2009]

M=1 mode : radial evolution of the amplitude of the fluctuation

→10 % fluctuations inside the plasma column
→100 % fluctuations in the shadow of the limiteur



Rotation frequency of a m=1 spoke vs M_{ion}



Experimental:

- $\nu_{mode}(He)/\nu_{mode}(Ne) \approx 2.7$
- $\nu_{mode}(Ar)/\nu_{mode}(Kr) \approx 1.8$
- $\nu_{mode}(Kr)/\nu_{mode}(Xe) \approx 1.7$

Theory: collisionless Simon Hoh Instability (Smolyakov PPCF 2017) :

$$\nu_{mode} \alpha M^{-1/2}$$

$$(M_{Ne}/M_{He})^{1/2} = 2.2$$

$$(M_{Kr}/M_{Ar})^{1/2} = 1.4$$

$$(M_{Xe}/M_{Kr})^{1/2} = 1.3$$

→Difficult to overlap pressure ranges for ≠ M_{ion}

→ Possible transition m=1 to m=2 mode, when P increases : **the controlling parameter is not clear**.

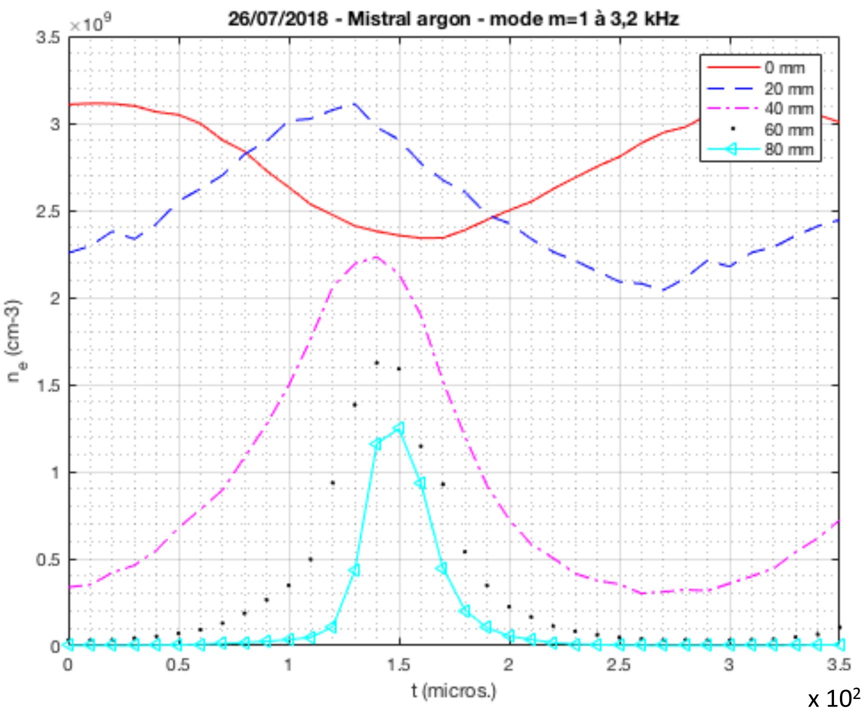
→ Role of E_r and grad(n_e) ?

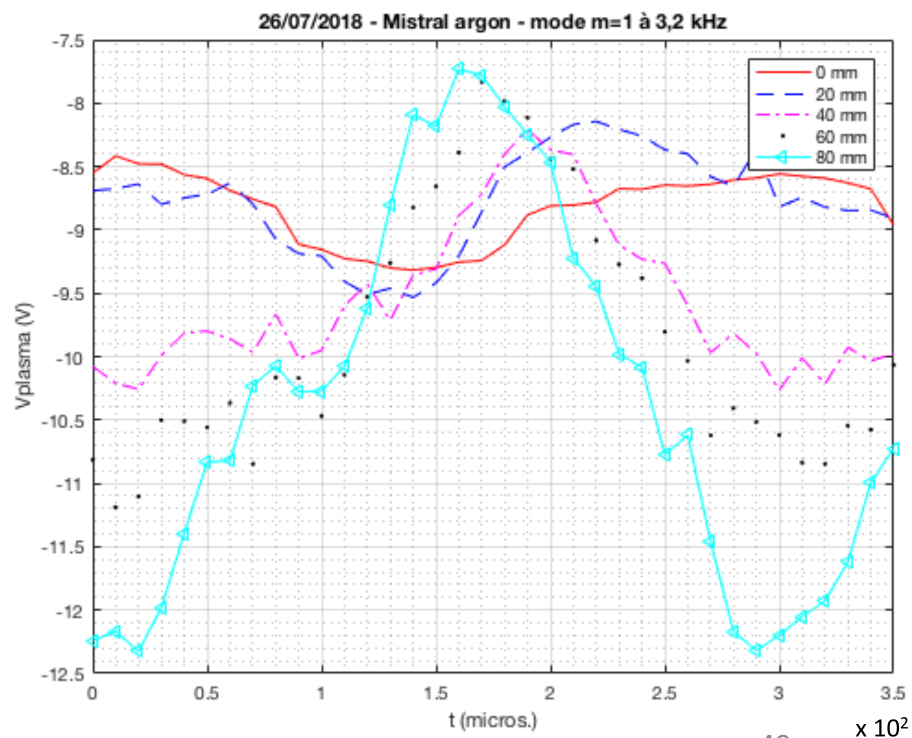
Spatial/time resolved study of a m=1 spoke in argon

- Synchronized Langmuir probe (perturbating…)
- r_{plasma} = 36 mm → the 2 first curves are inside the plasma column (red/blue)
- the 3 other curves are in the shadow of the limiteur (magenta/black/cyan)

→ ≈ Rigid body rotation

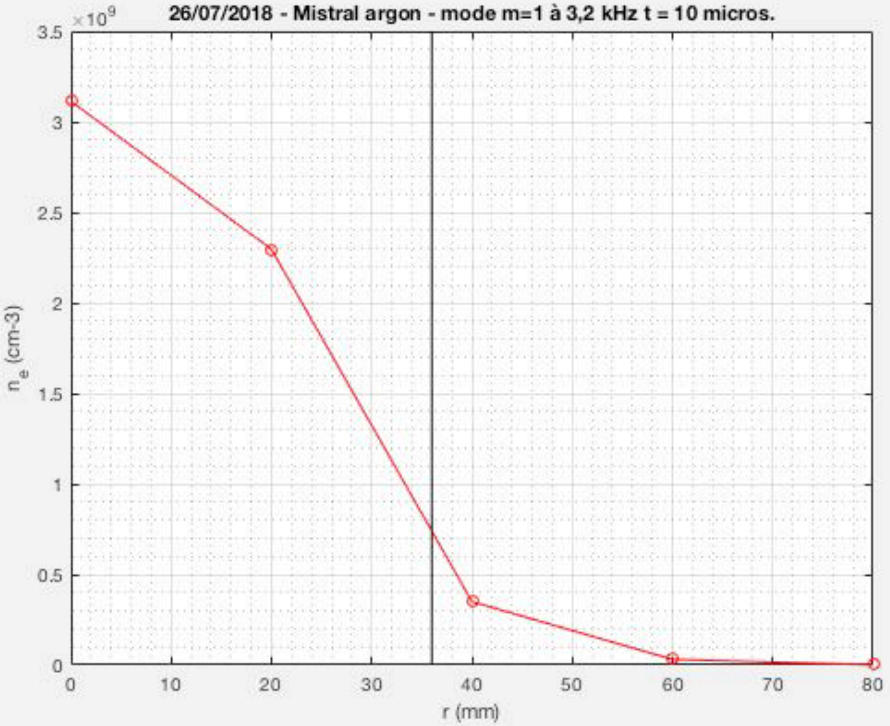
→ Phase shift (V_{plasma} /ne) ≈ π/2 in the shadow of the limiteur

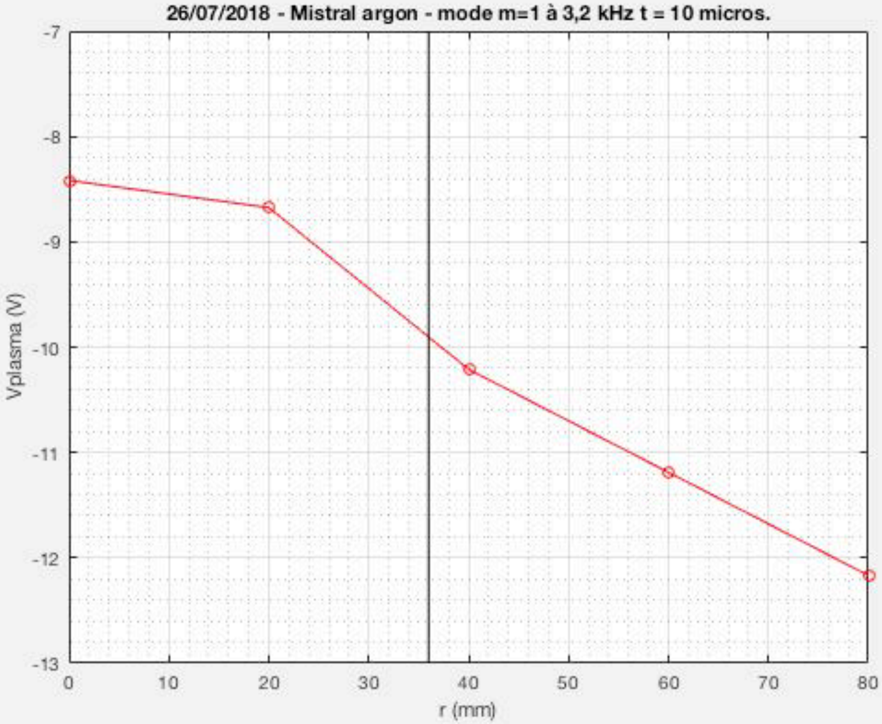




Time evolution of n_e and V_{plasma}

The rotating spoke is in front of the probe at **t = 150 µs**

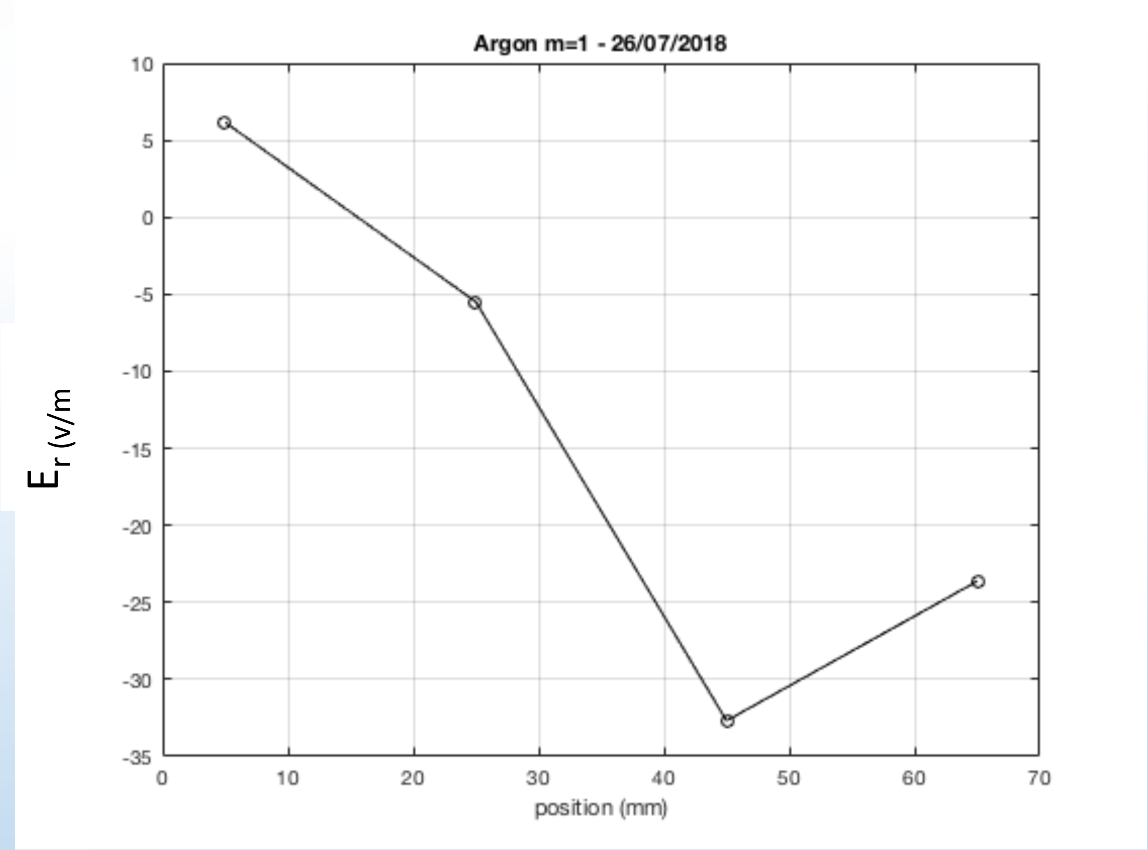




→ < E_r > is oriented outward…

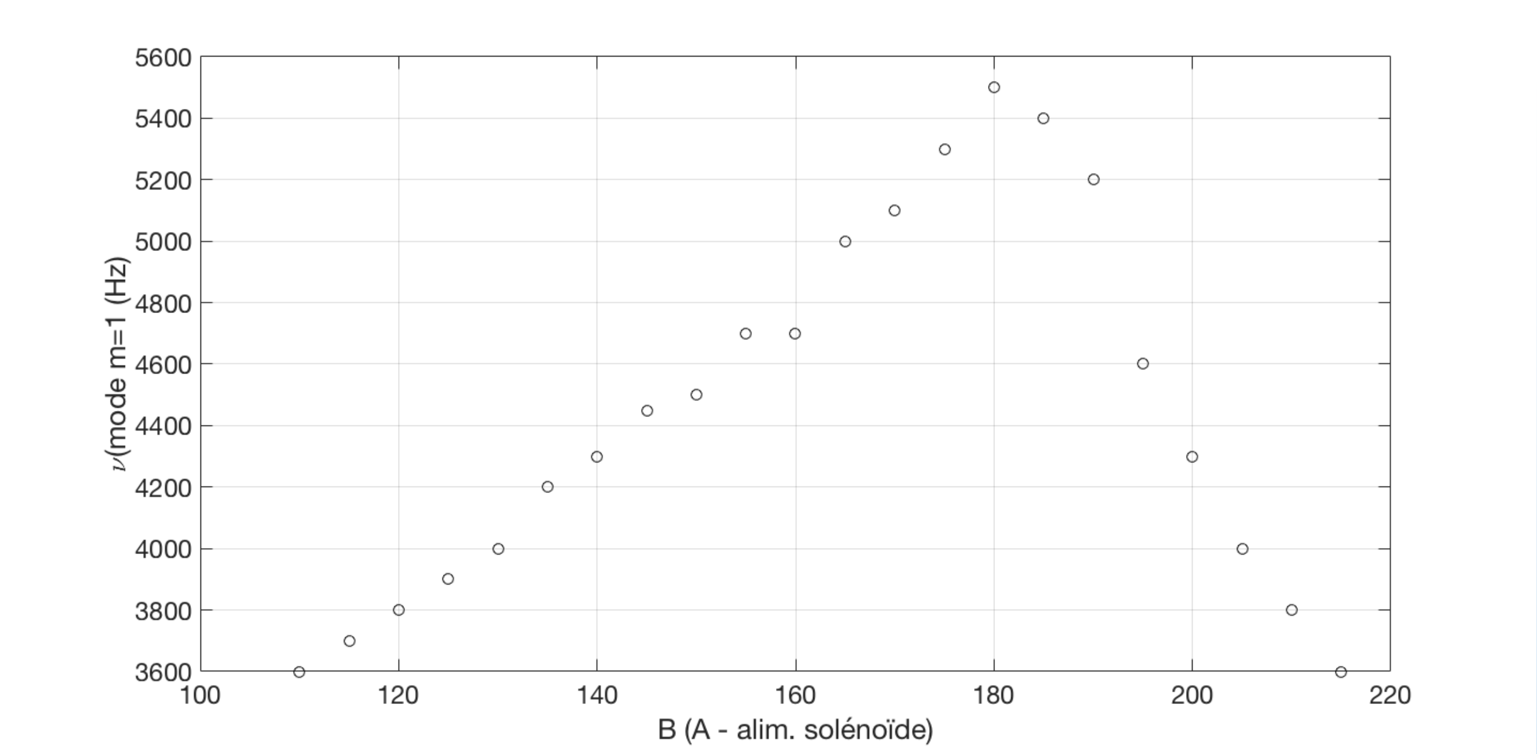
→But $E_r(r)$ is oriented inward inside the spoke, outward otherwise

Radial electric field E_r



→Except in the center, inside the spoke, the radial electric field is oriented inward.

Spoke rotation frequency = f(B)

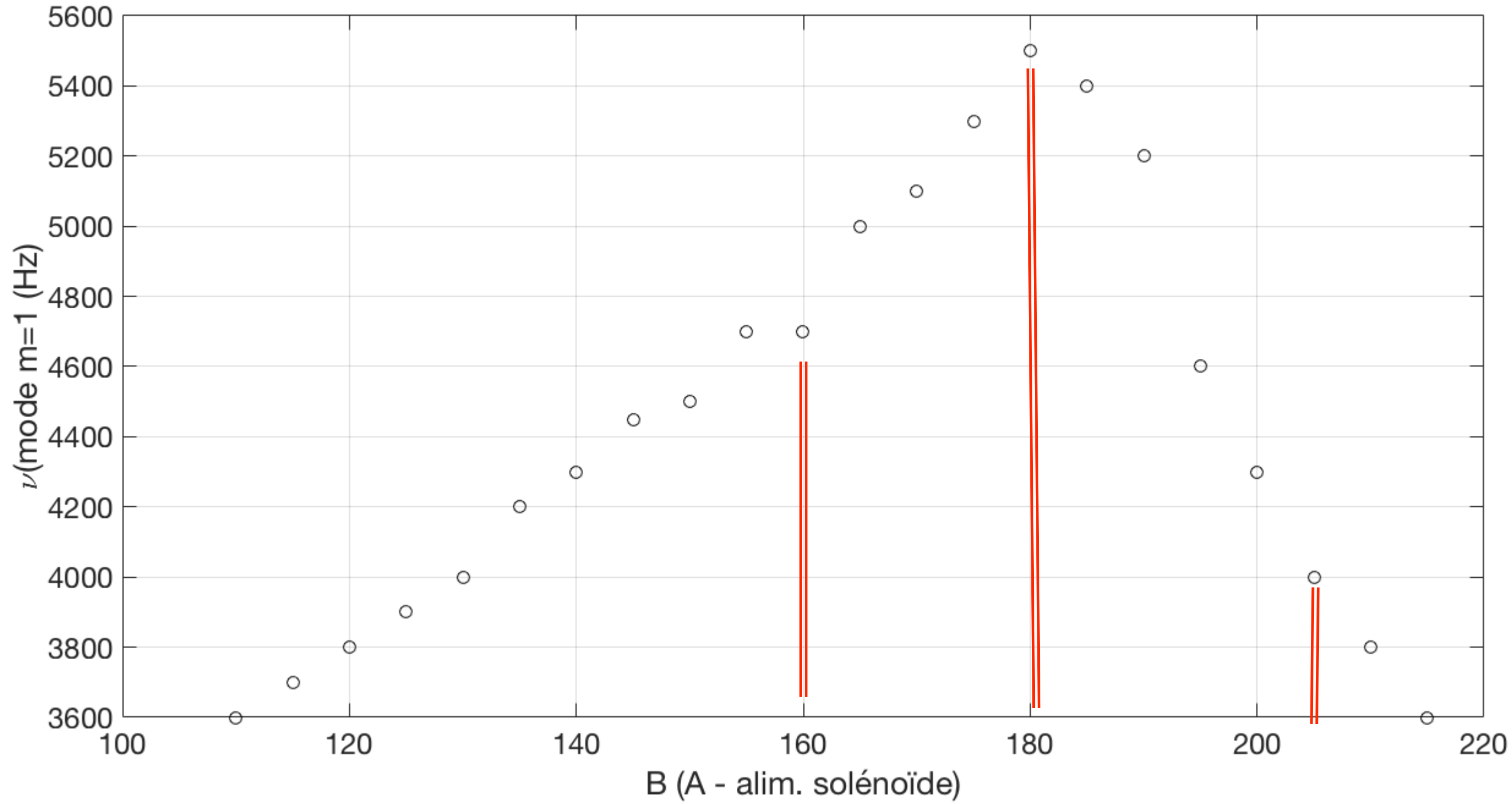


→Linear increase until B = 180 G – then, decrease ***with a different slope***.

→Observation of a maximum at 180 G.

→Coherent with CSHI ?

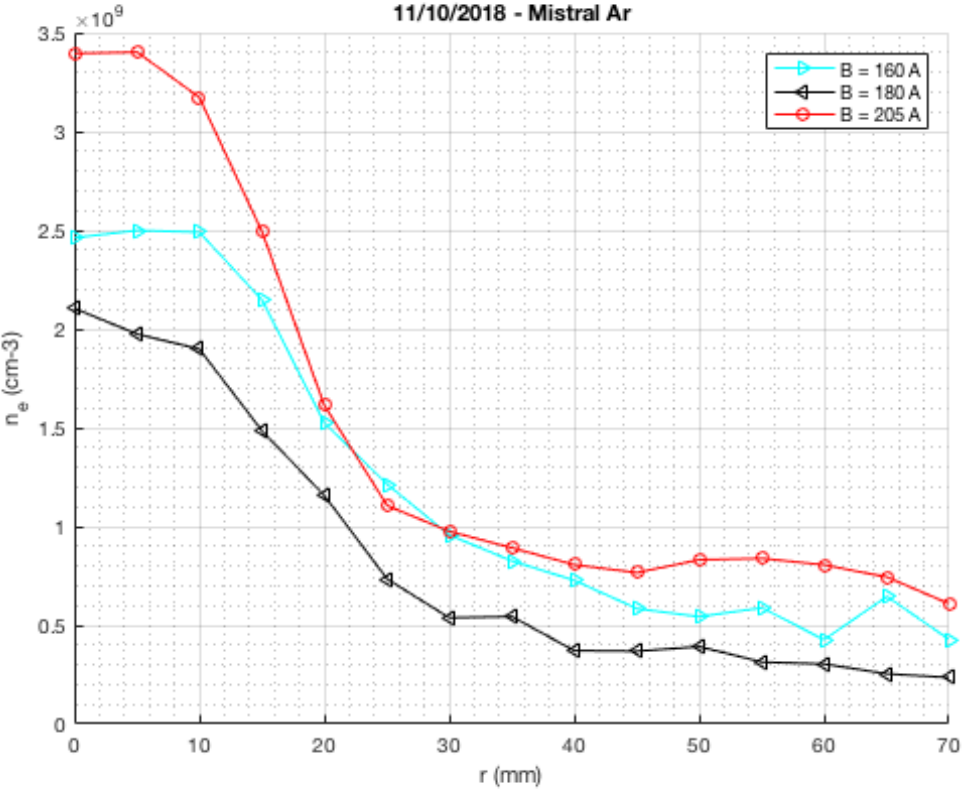
Spoke rotation frequency = f(B)

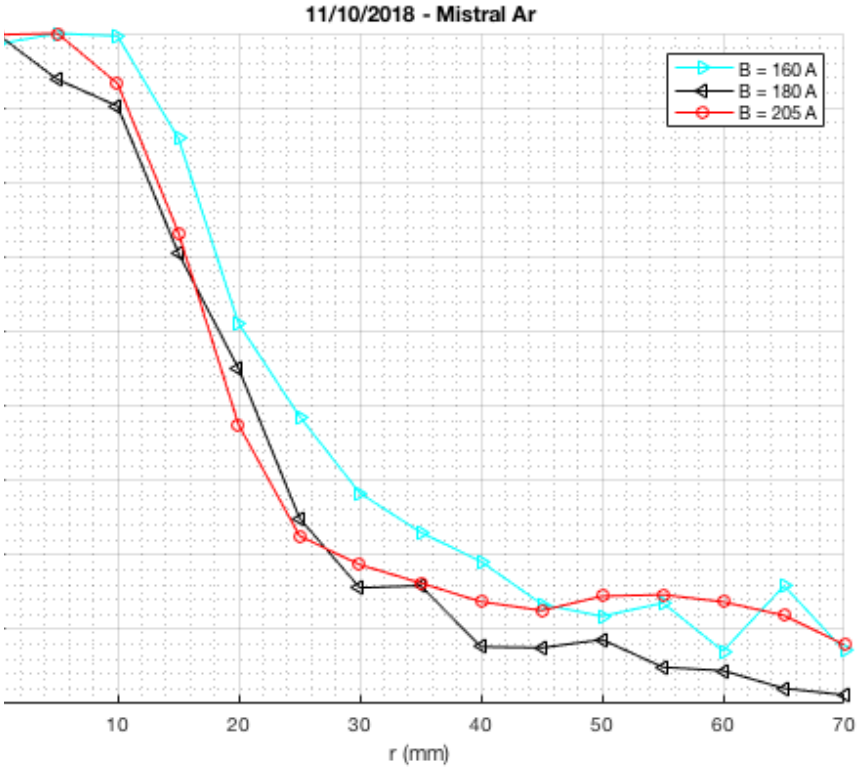


→Not coherent with CSHI theory. But do E_r and L_n change when B increases ?

→Detailed study of 3 cases at 160 G, 180 G and 205 G.

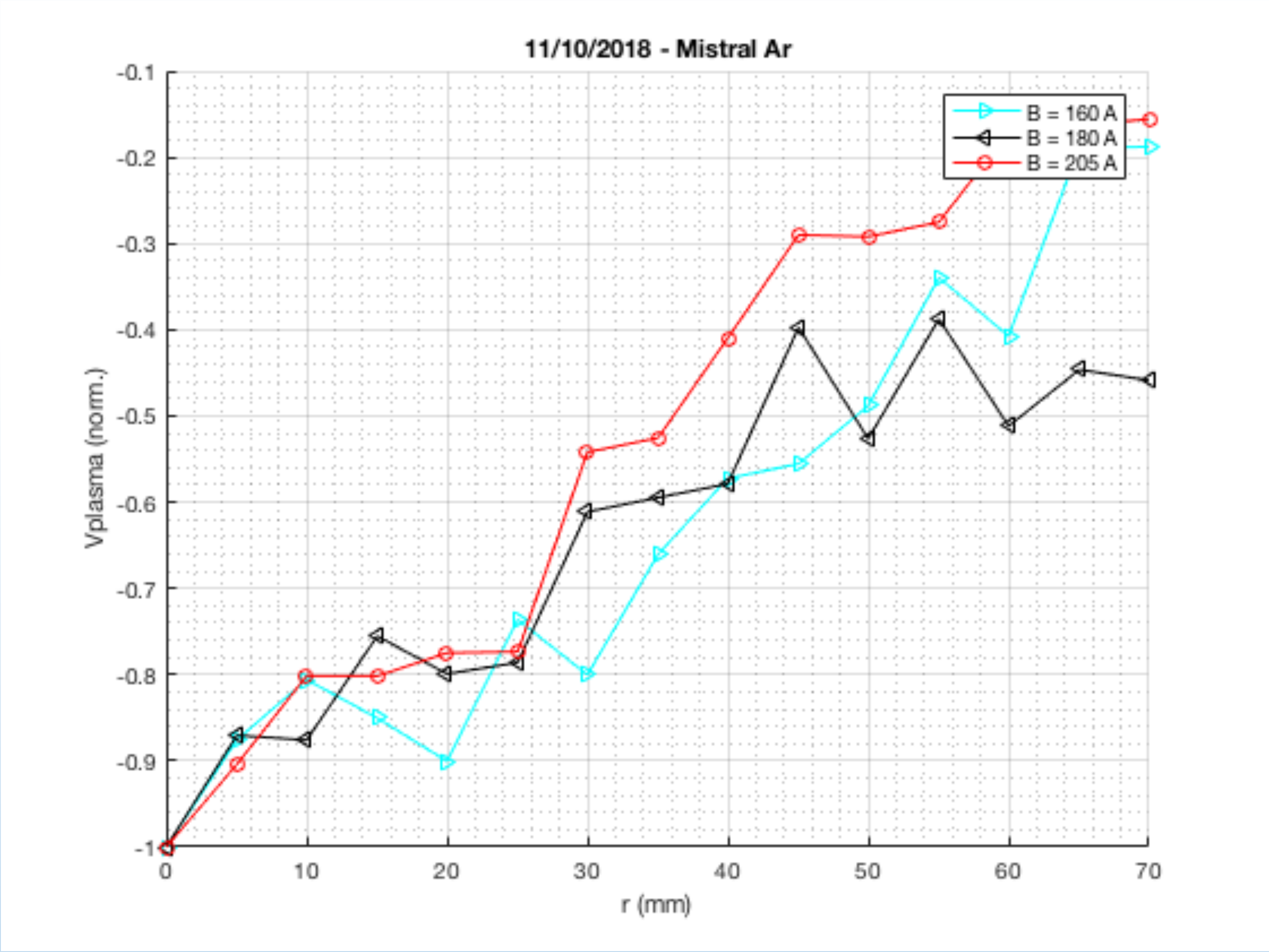
Comparison of ne(r)



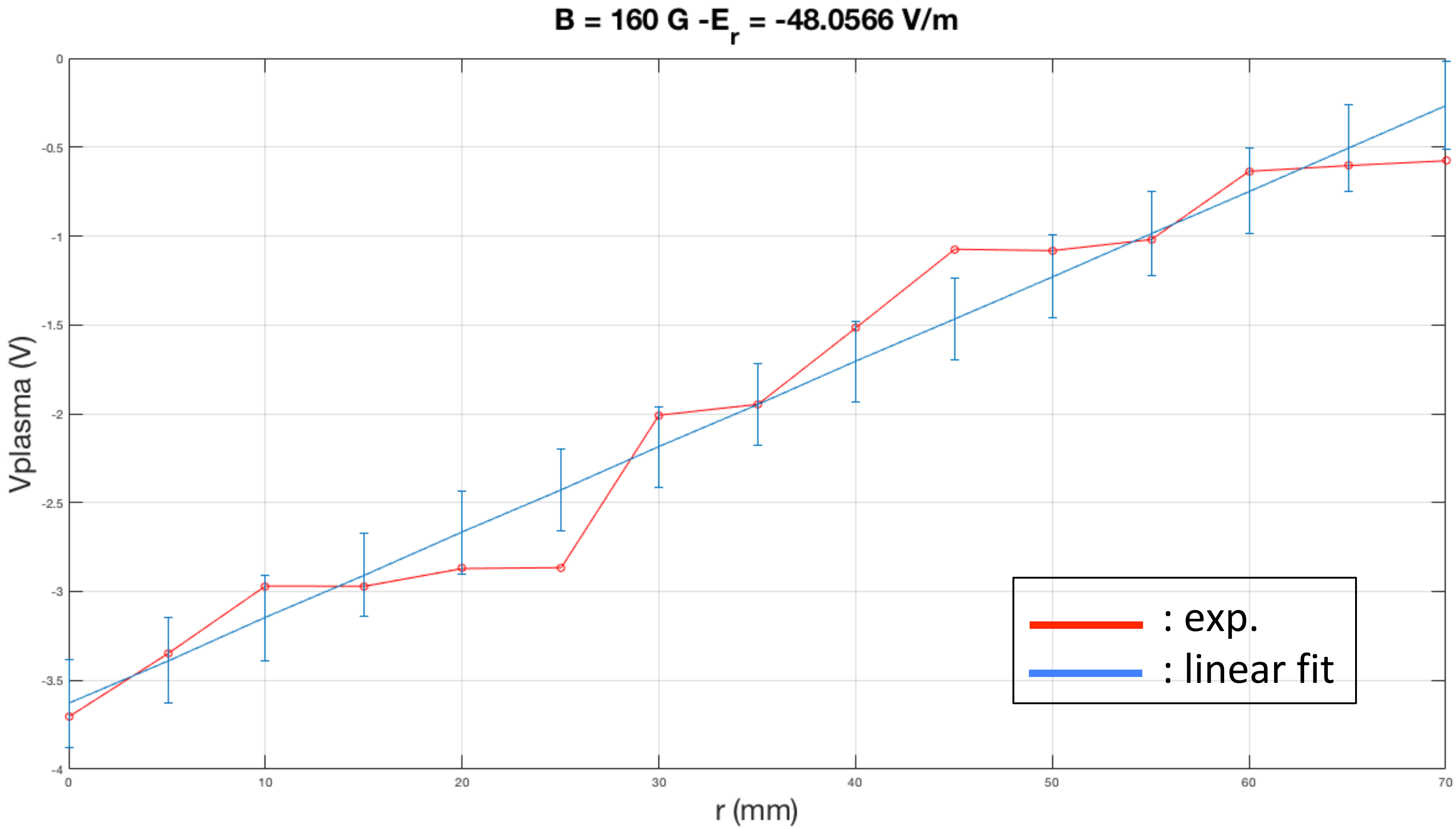


→ *similar radial behaviors*

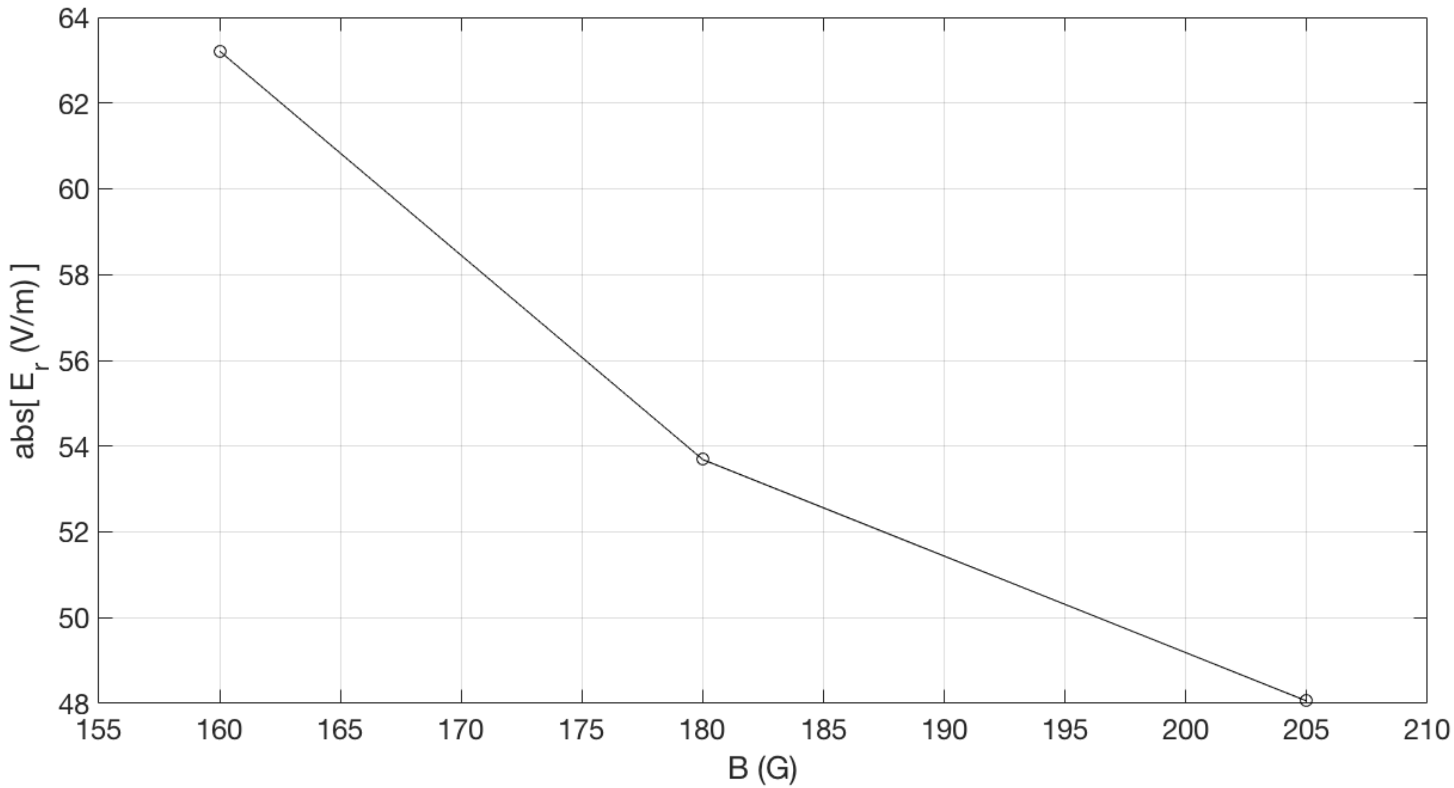
Comparison of $V_{plasma}(r)$



E_r estimation from the linear fit of $V_{plasma}(r)$



E_r estimation from the linear fit of $V_{plasma}(r)$

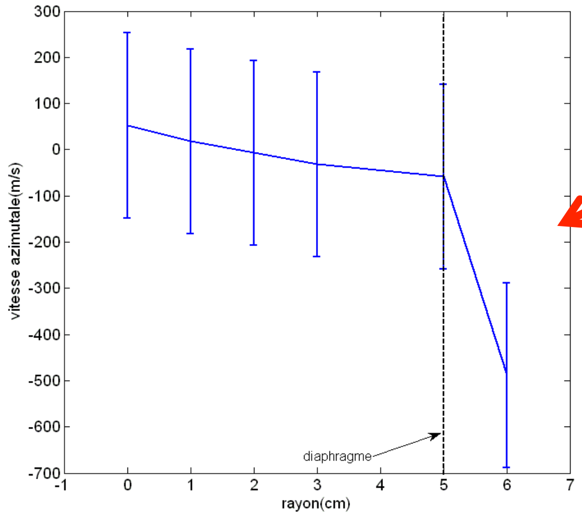


→ E_r and L_n do not seem to play a key role in $\nu = f(B)$

→ CSHI : E_r should increase with B….

Evolution of ion velocity in a m=1 spoke by LIF

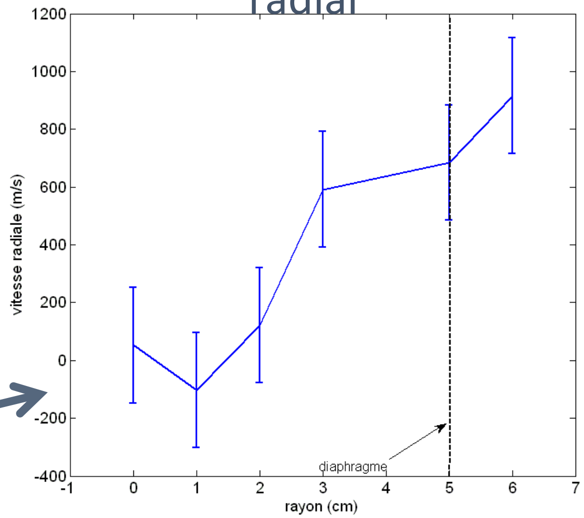
azimuthal



Mean velocity at density maximum

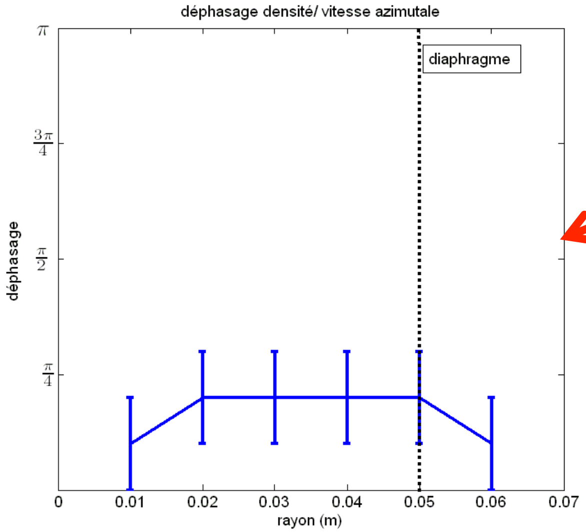
In the ionization zone, almost null velocity at any radius.
No « block » rotation.

radial

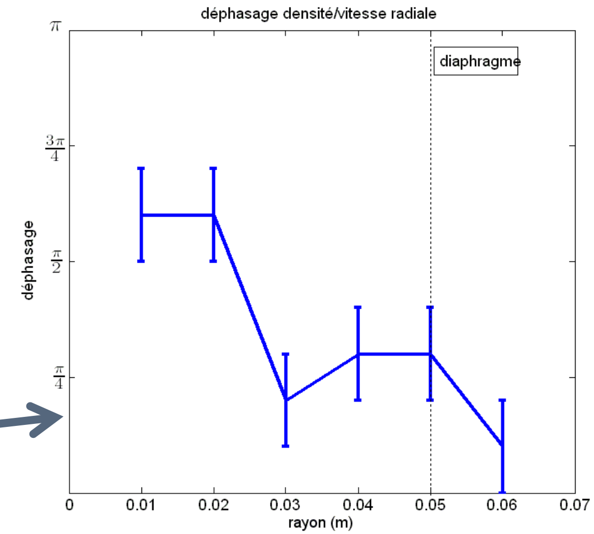


Linear evolution of radial velocity

Density/velocity phase



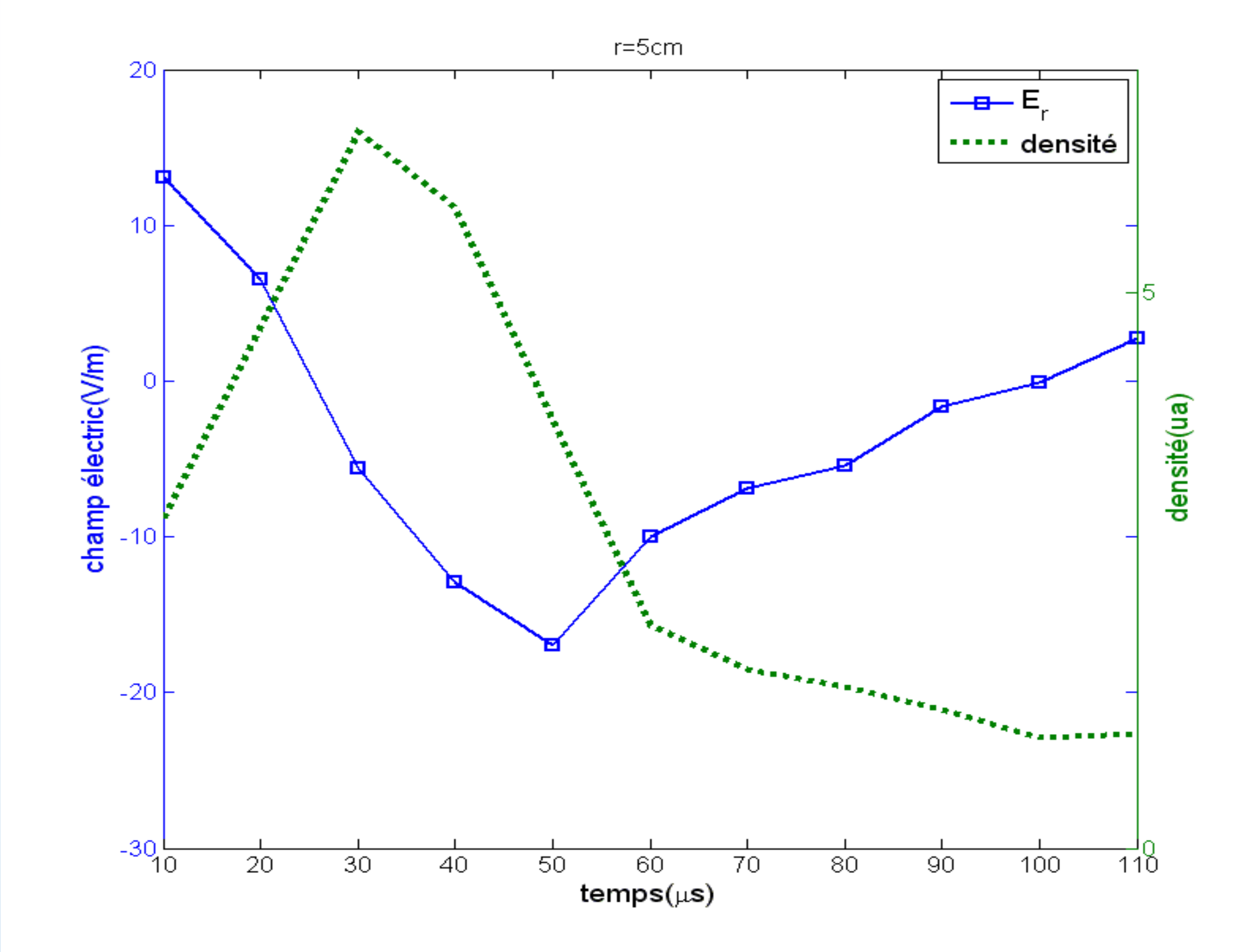
Constant phase close to π/4



Phase: π/2 at center,
0 outside ionization zone

N. Claire POP (2018)

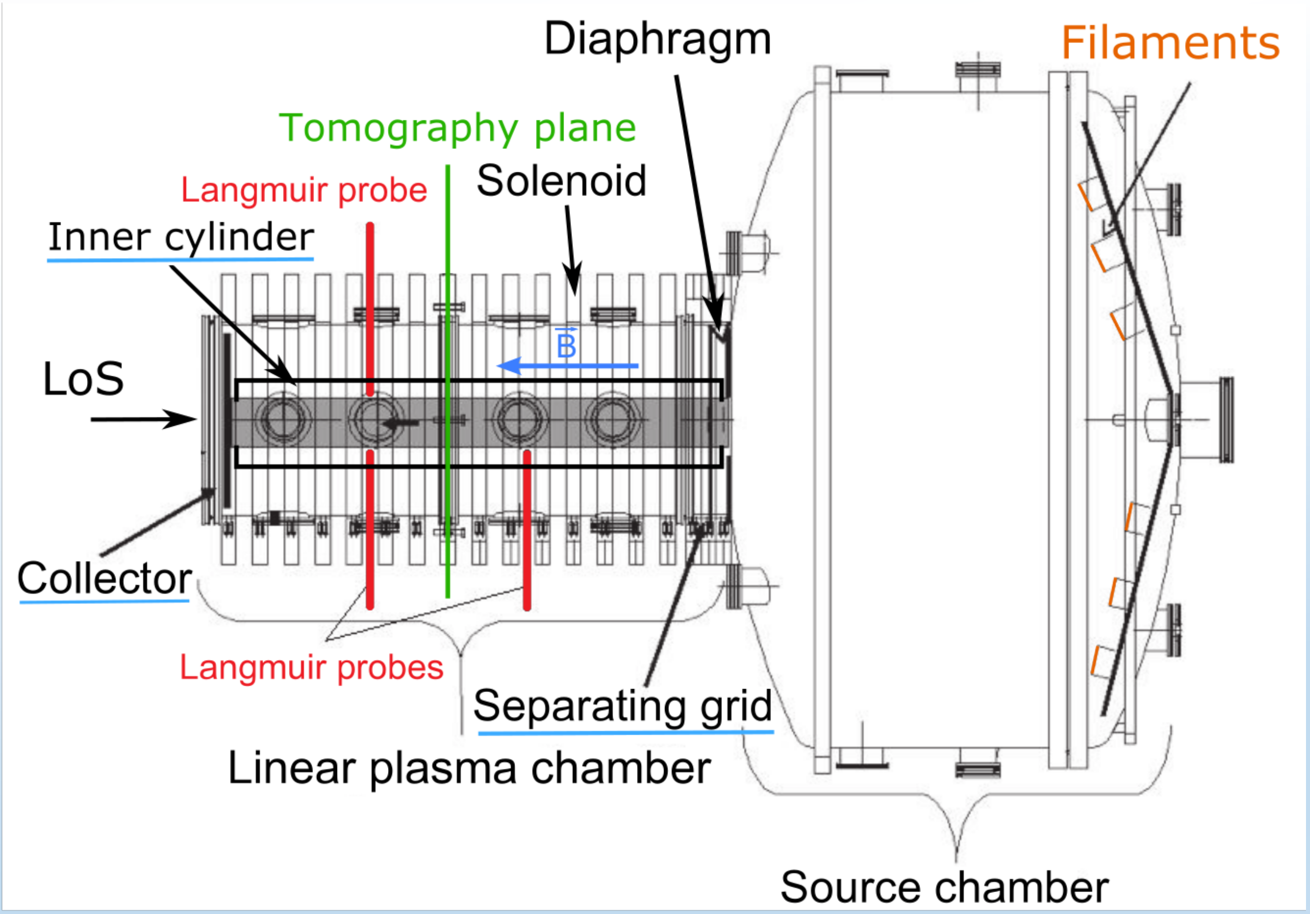
Electric field in a m=1 spoke by LIF



→ E_r measured by LIF is coherent with probe measurements

N. Claire POP (2018)

L'expérience MISTRAL



- **$1\ eV < T_e < 4\ eV$**
- **$10^{14}\ m^{-3} < N_e < 5.10^{16}\ m^{-3}$**
- $T_{Ar\ neutral} = 300\ K$
- $T_{Ar\ ion} = 1100\ K$
- $E_{primary\ electrons} \approx 40\ eV$

- $\nu_{ci} = 6\ kHz$ (Ar ; 160 G)

- $\rho_e = 3\ mm$
- $\rho_i = 25\ mm$ (He ; 160 G)
  $= 56\ mm$ (Ne; 160 G)
  $= 80\ mm$ (Ar ; 160 G)
  $= 146\ mm$ (Xe ; 160 G)