Rotating spokes study in the Mistral experiment: recent results

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PhDs :

- ***C. Rebont** (07/2010)*
- ***S. Jaeger** (10/2010)*
- ***T. Lefèvre** (02/2012)*
- ***P. David** (02/2017)*

and post-doc. :

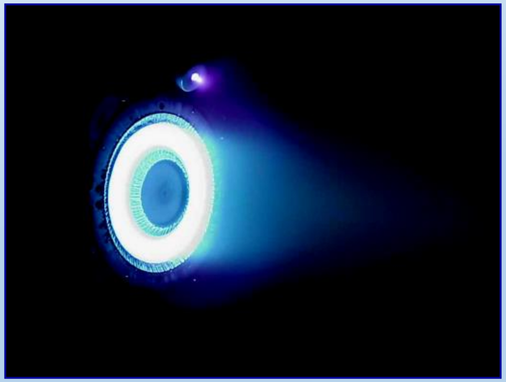
- ***R. Baude** (2015-2017)*

Plasma instabilities in ExB fields

Plasmas in ExB fields:
- Plasma thrusters
- Magnetron discharges
- Penning gauges…

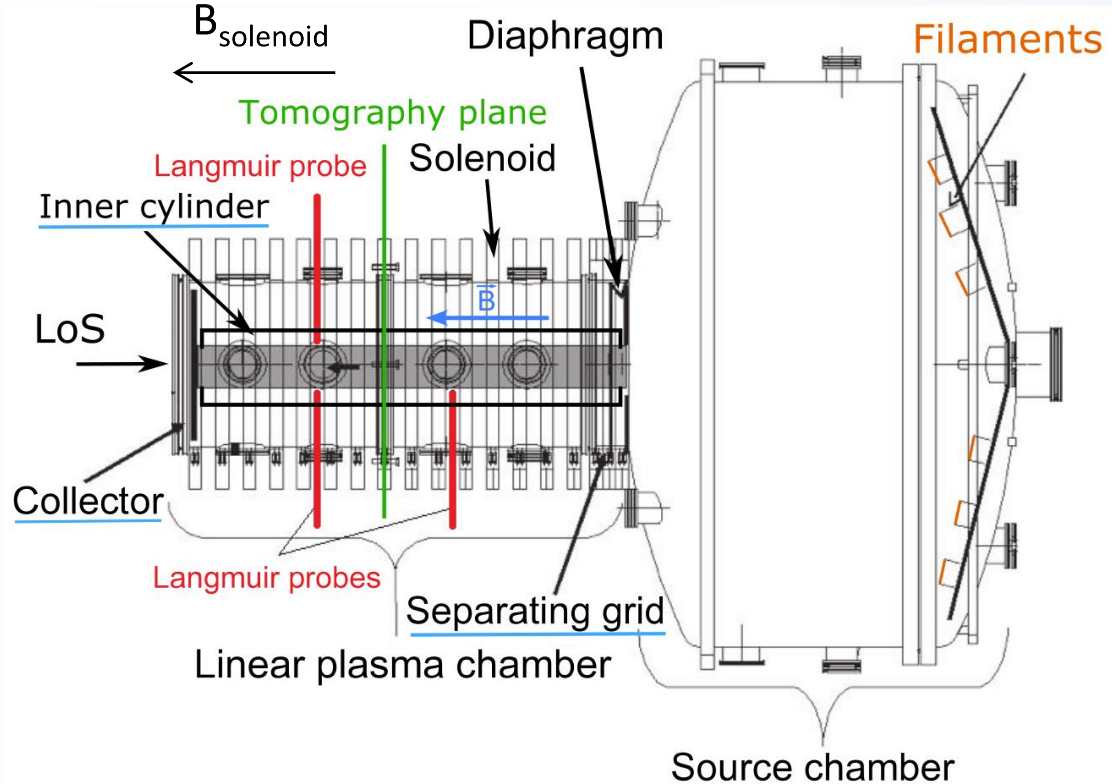
→ Charged particles drift in ***E x B*** *direction*.
Interesting when azimuthal drift

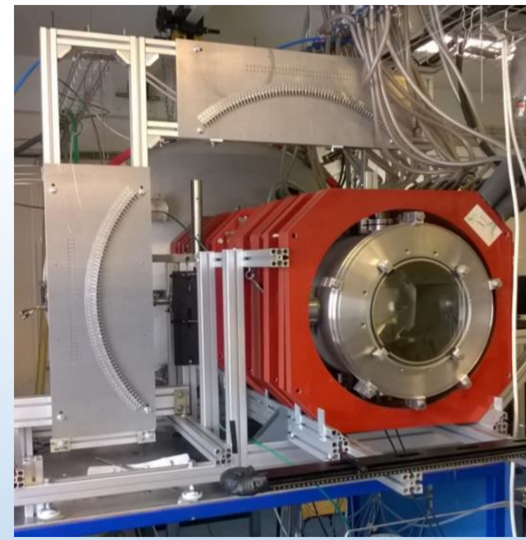
→ But configuration undermining development of « anomalous » transport of electrons across B (Tokamak fusion problem, favorable in plasma thrusters).



MISTRAL experiment

- Machine built by **G. Leclert** and **Th. Pierre**
- Weakly ionized ions
- Presence of **ionizing (primary) electrons**
- « **Stable** » plasma state during several hours

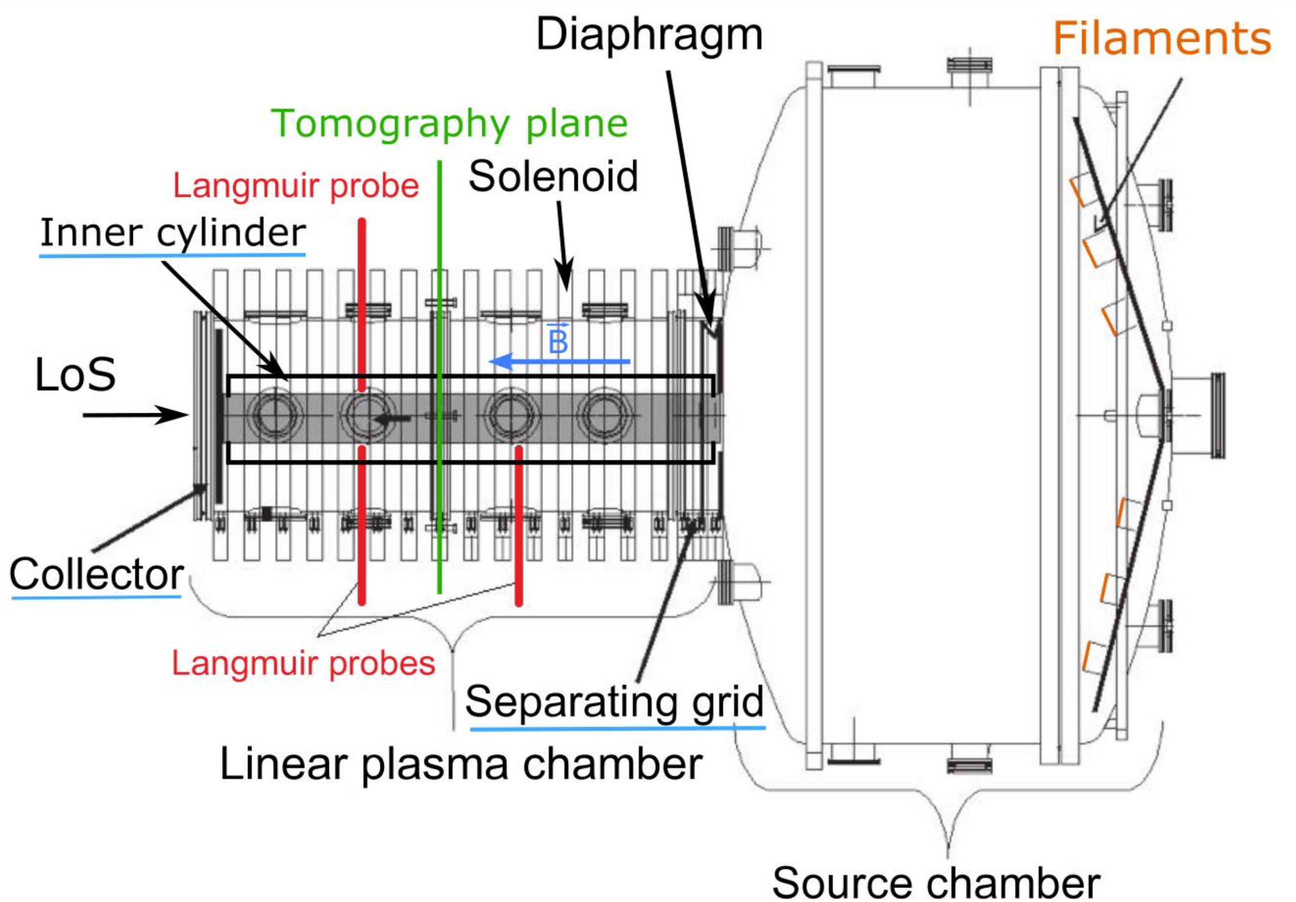




- **L = 1.2m**
- **$r_{inner\ cylinder} = r_{plasma}$ =36 mm**
- **5.10^{-5} mbar < P < 10^{-3} mbar**
- **$B_{solenoid}$ < 25 mT**
- **Gaz : He, Ne, Ar, Kr, Xe**

MISTRAL experiment: plasma parameters

→ *Ions are poorly magnetized*



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

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

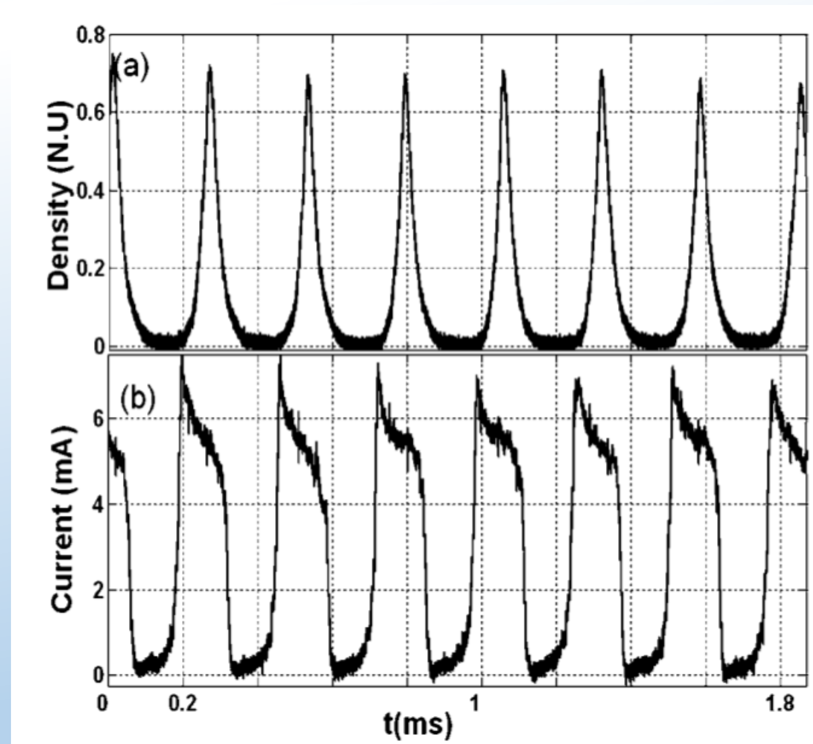
- $\rho_e = 3\ mm$
- $\rho_i = 25\ mm$ (He ; 160 G)
  = 56 mm (Ne; 160 G)
  = 80 mm (Ar ; 160 G)
  = 146 mm (Xe ; 160 G)

PIIM Aix✱Marseille université cnrs

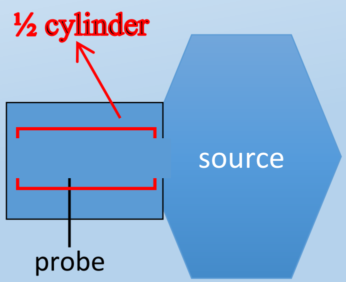
m=1, 2 regular modes rotating around plasma column

- 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

Vidéo mistral 11-22-27

Simon-Hoh instability (Phys. Fluids 1963)

ExB drift:

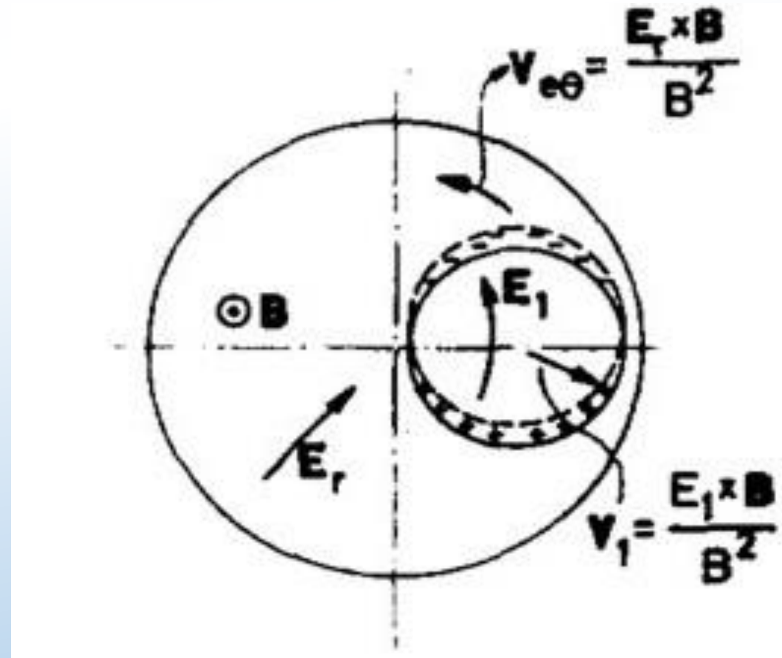
- Electrons : $v_{e\theta}$
- Friction forces (e-neutrals)

→ Ions slowed down:

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

→ Charge separation: E_1

→ Rotation frequency instability:



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

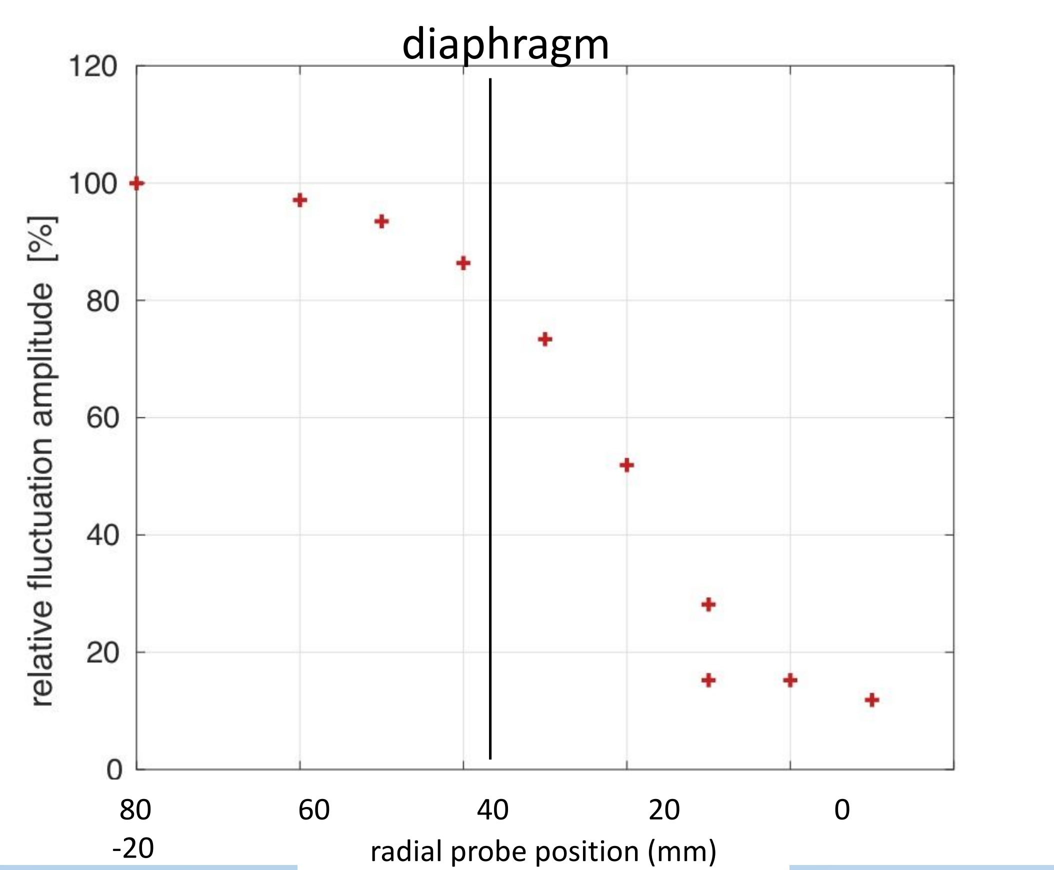
Smolyakov POP (2017)

[Hoh; Simon Phys. Fluids 1963 ; Jaeger PhD 2009]

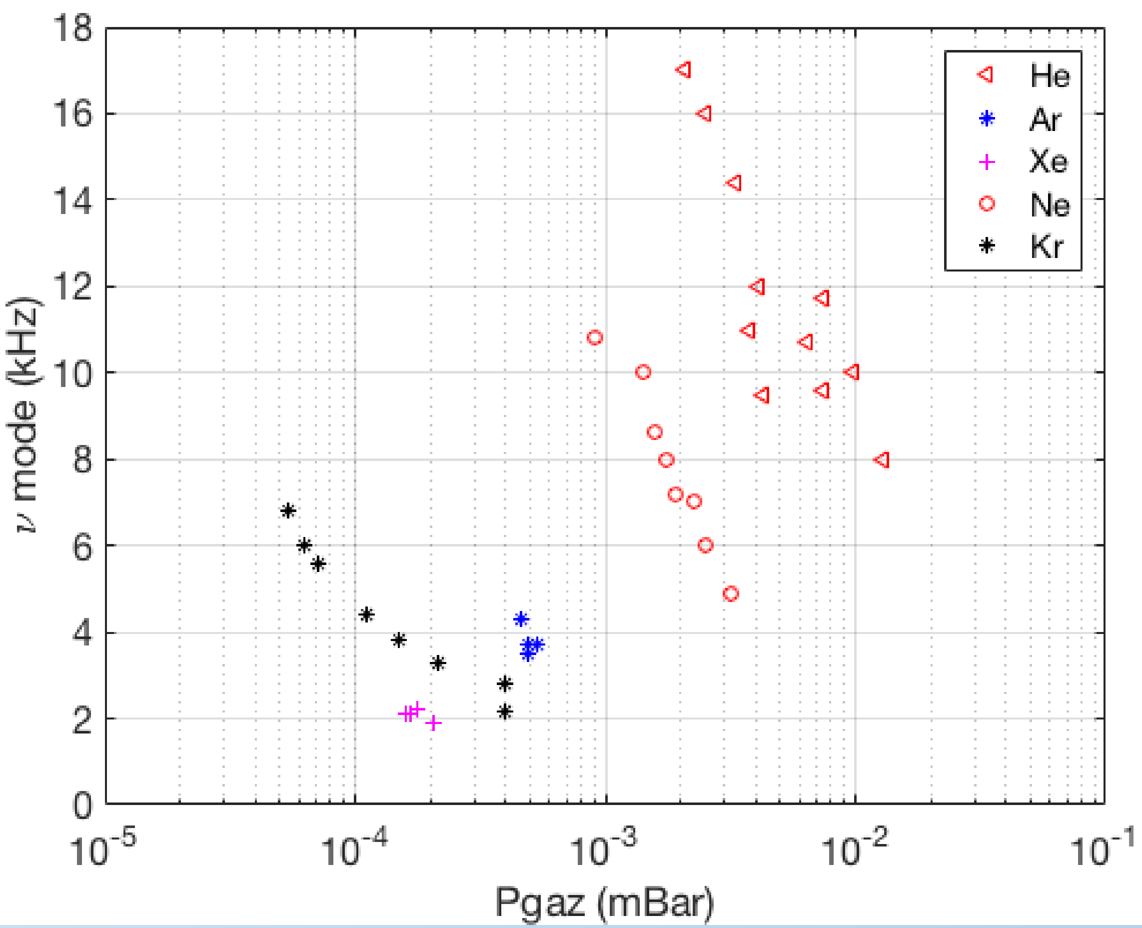
M=1 mode : radial evolution of the amplitude of the fluctuation

→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

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

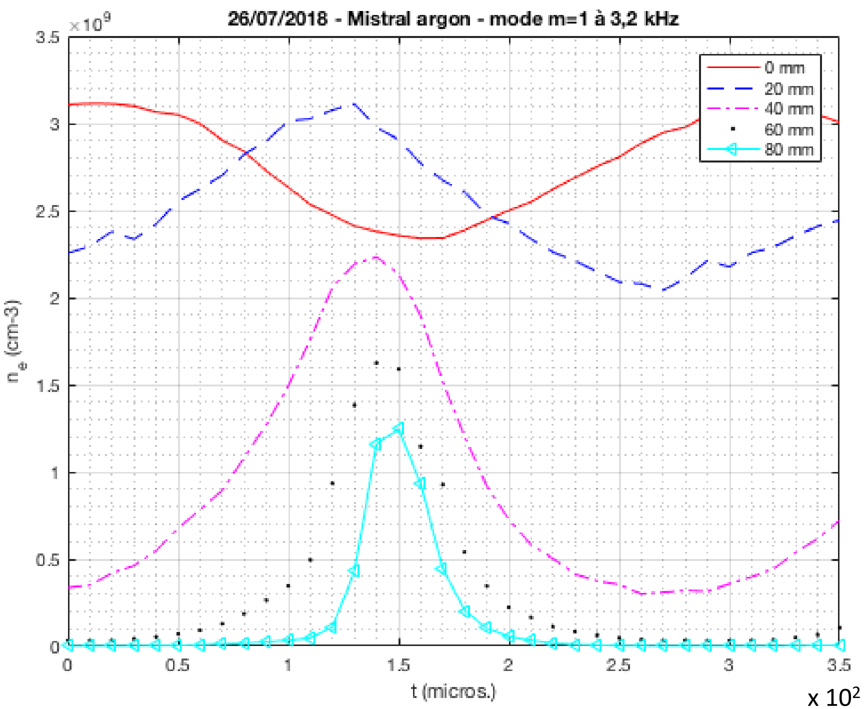
→ Role of E_r and grad(n_e) ?

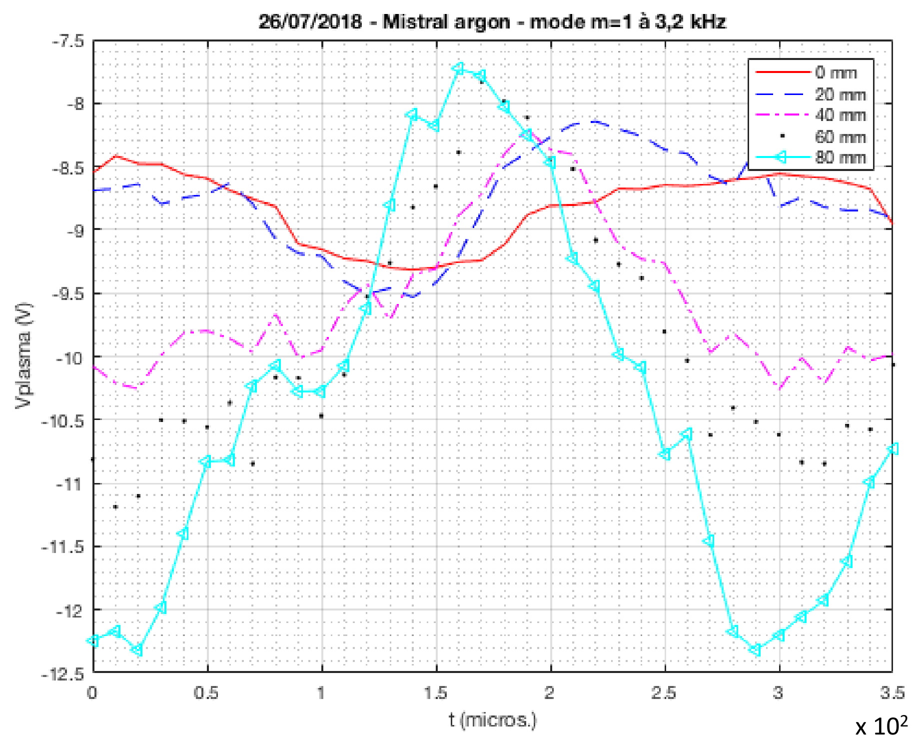
Spatial/time resolved study of a m=1 spoke in argon

- 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

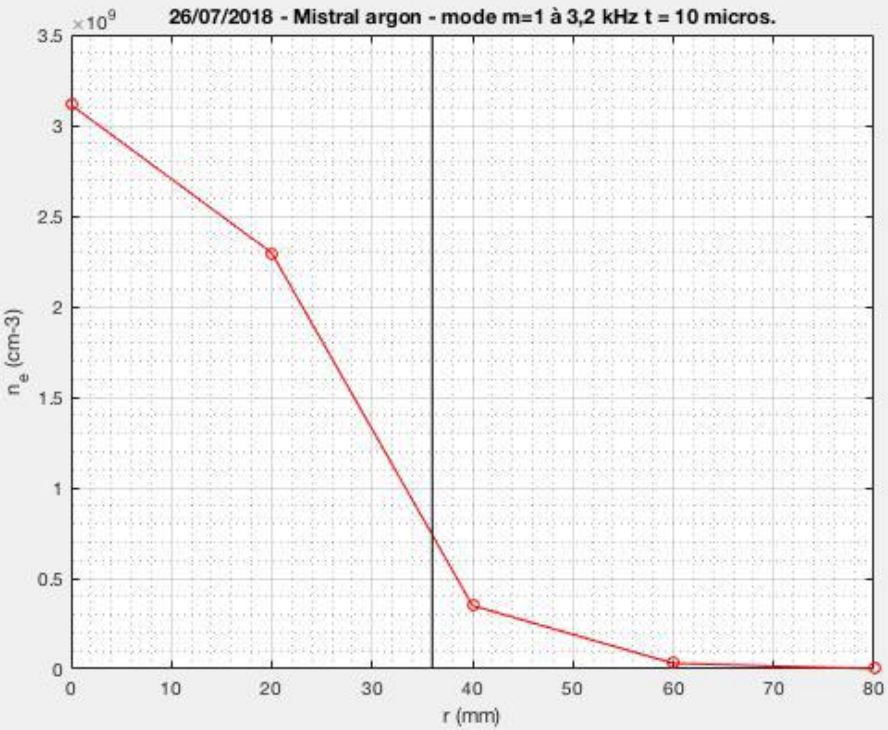
→ Phase shift (V_{plasma} /ne) ≈ π/2 in the shadow of the limiteur

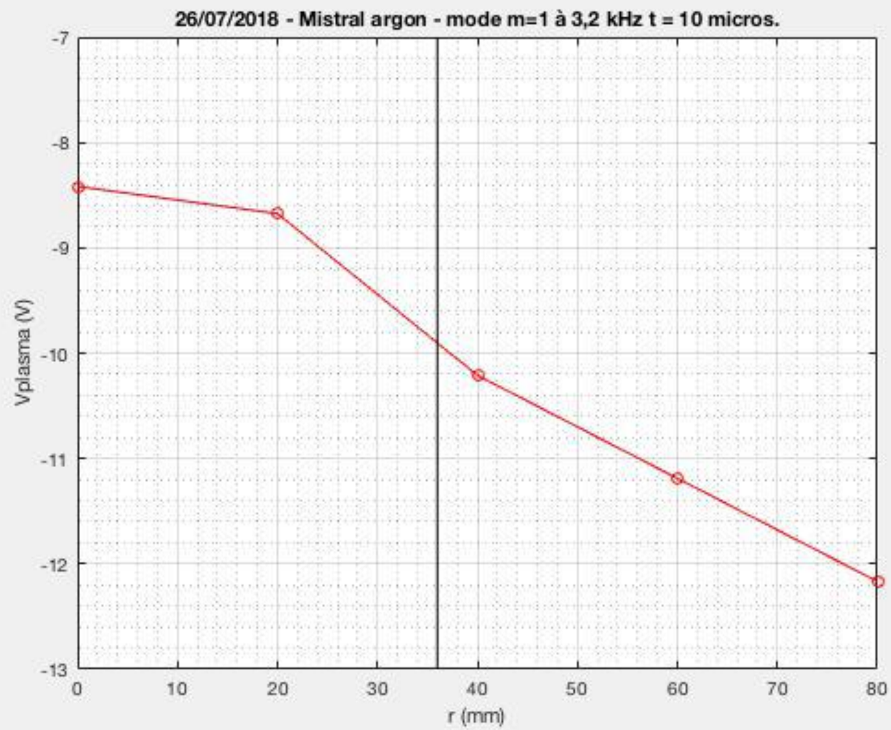




Time evolution of n_e and V_{plasma}

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

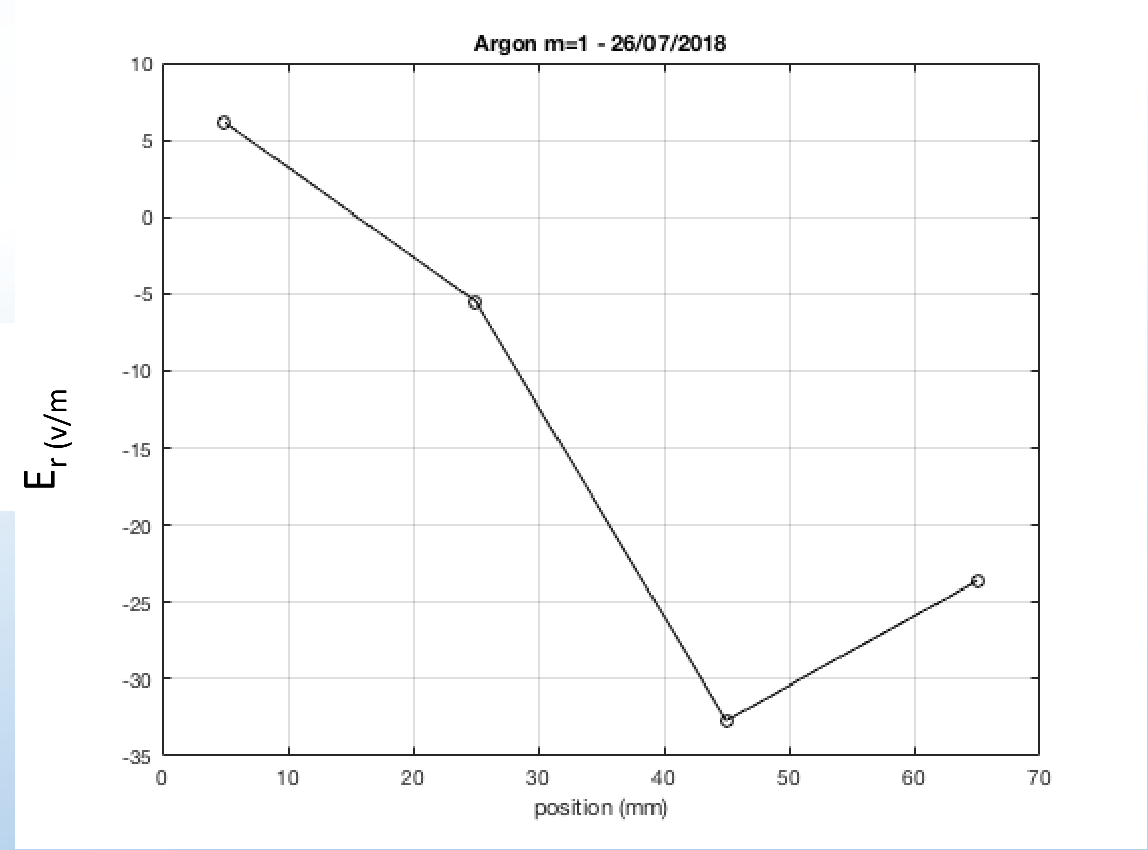




→ < E_r > is oriented outward…

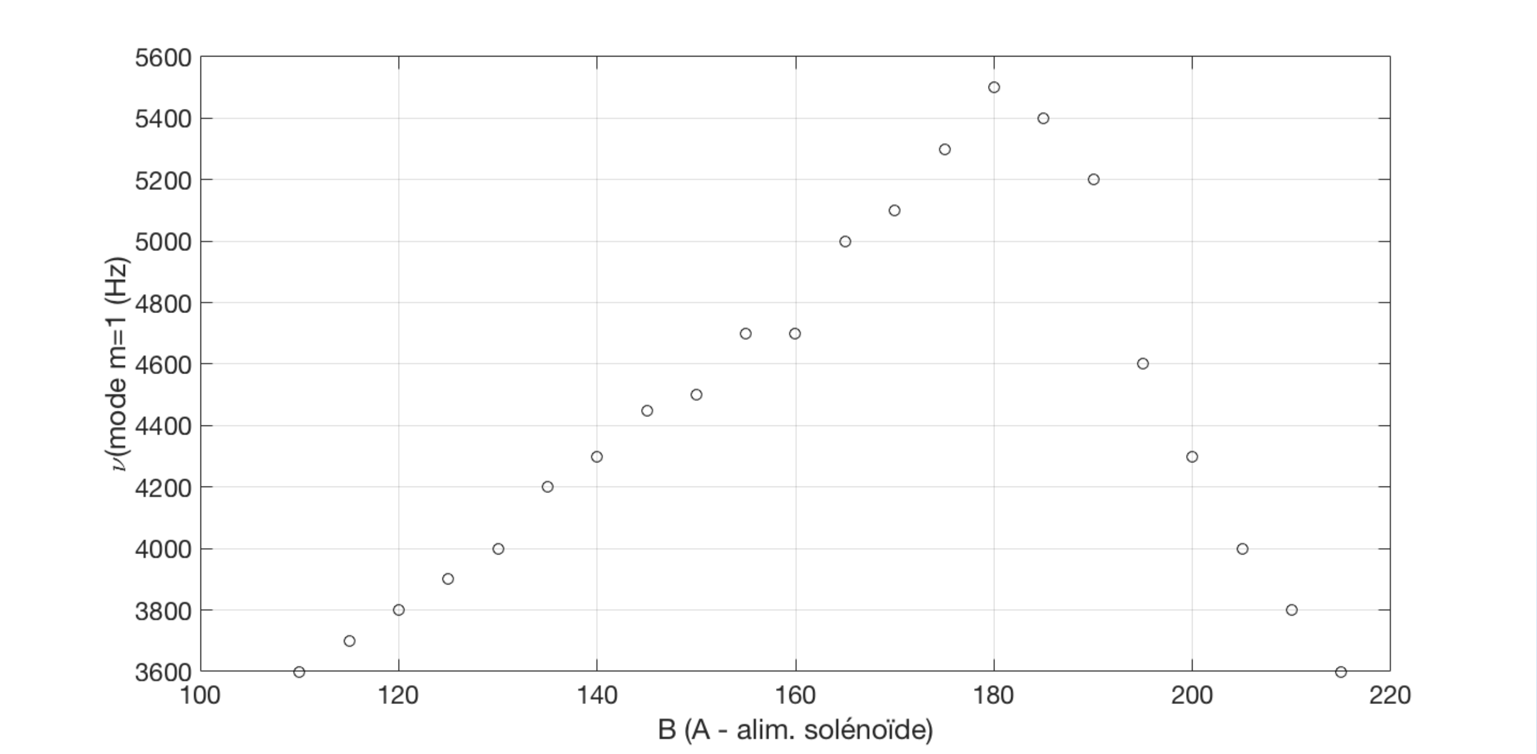
→But $E_r(r)$ is oriented inward inside the spoke, outward otherwise

Radial electric field E_r



→ Except in the center, inside the spoke, the radial electric field is oriented inward.
→ Coherent with LIF results (Claire POP 2018)

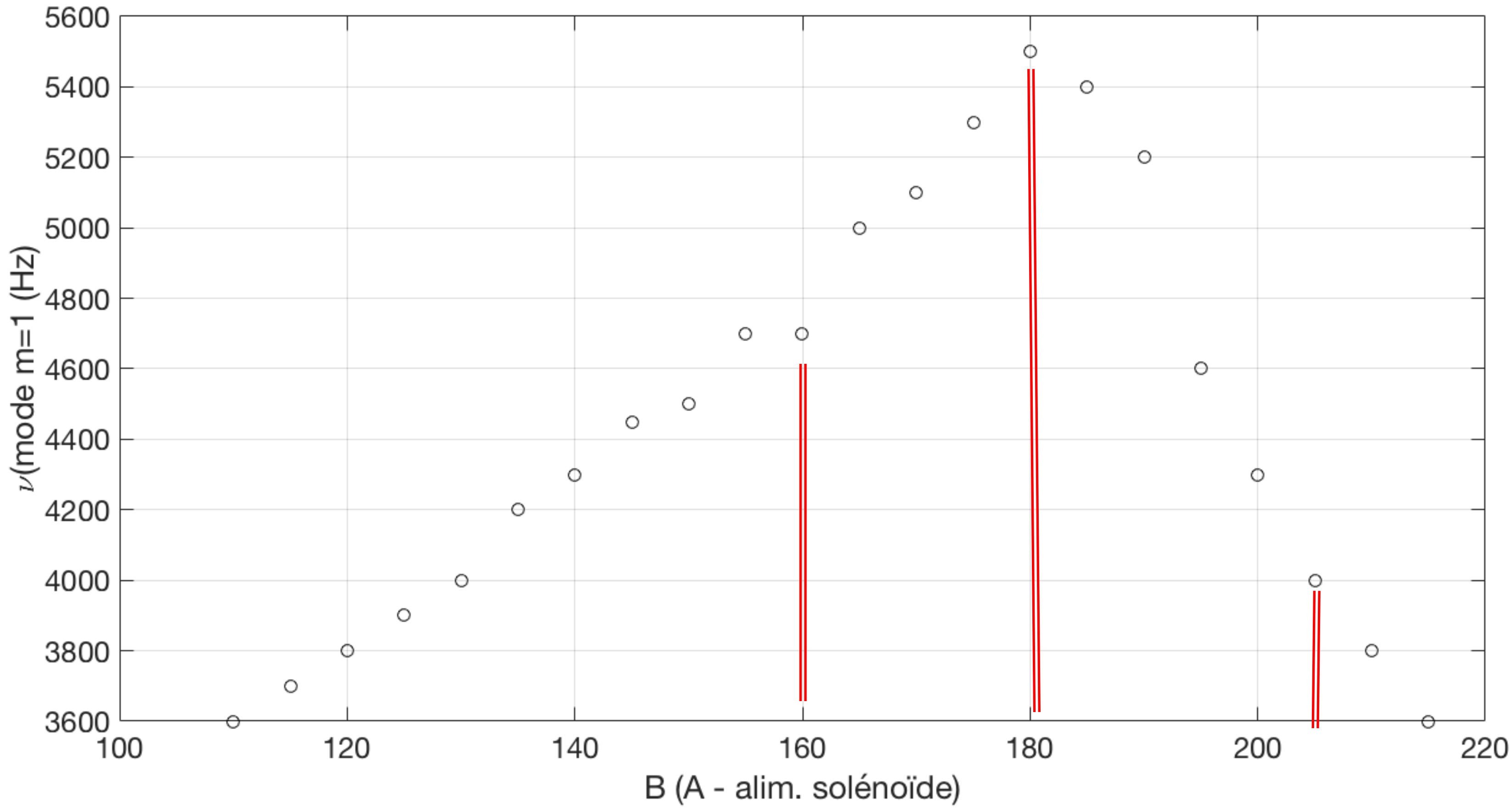
Spoke rotation frequency = f(B)



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

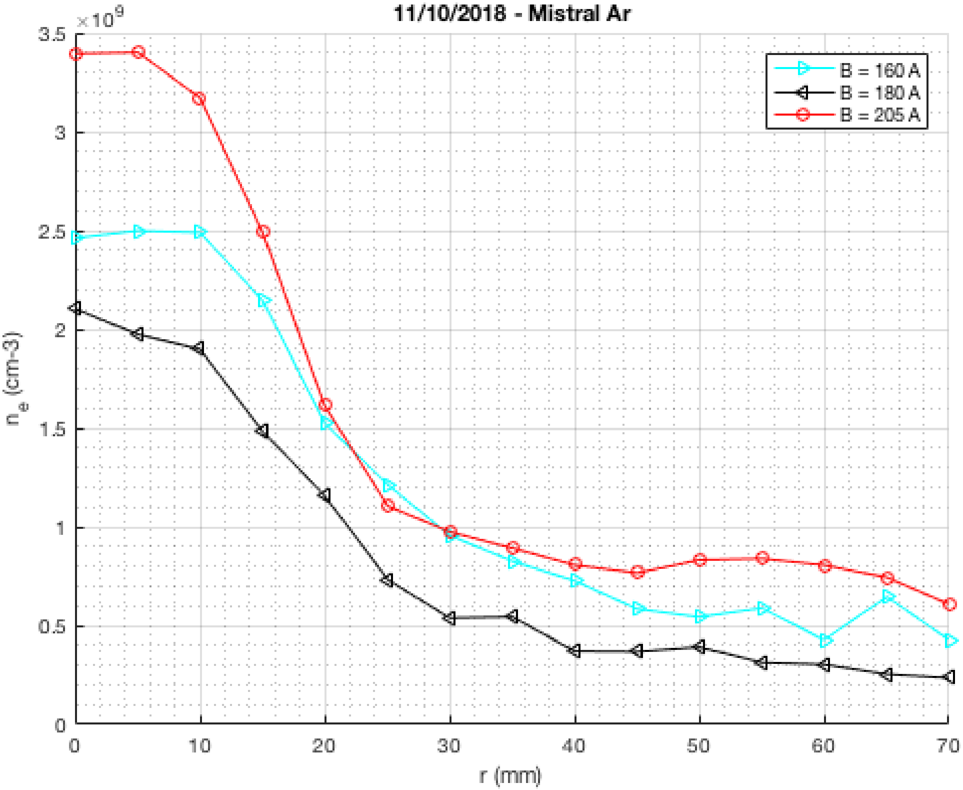
→Observation of a maximum at 180 G.

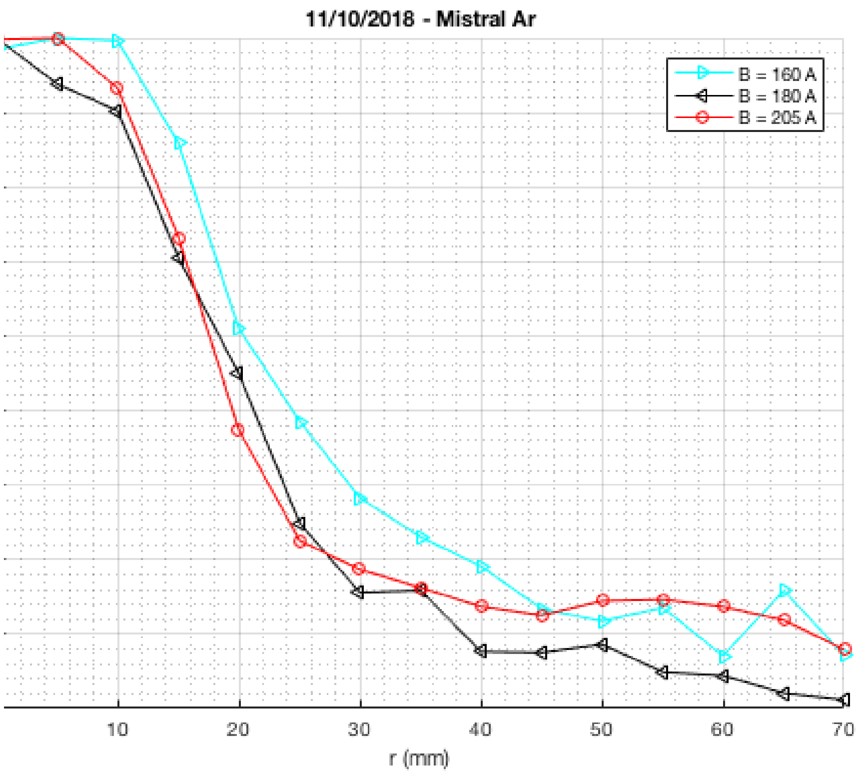
Spoke rotation frequency = f(B)



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

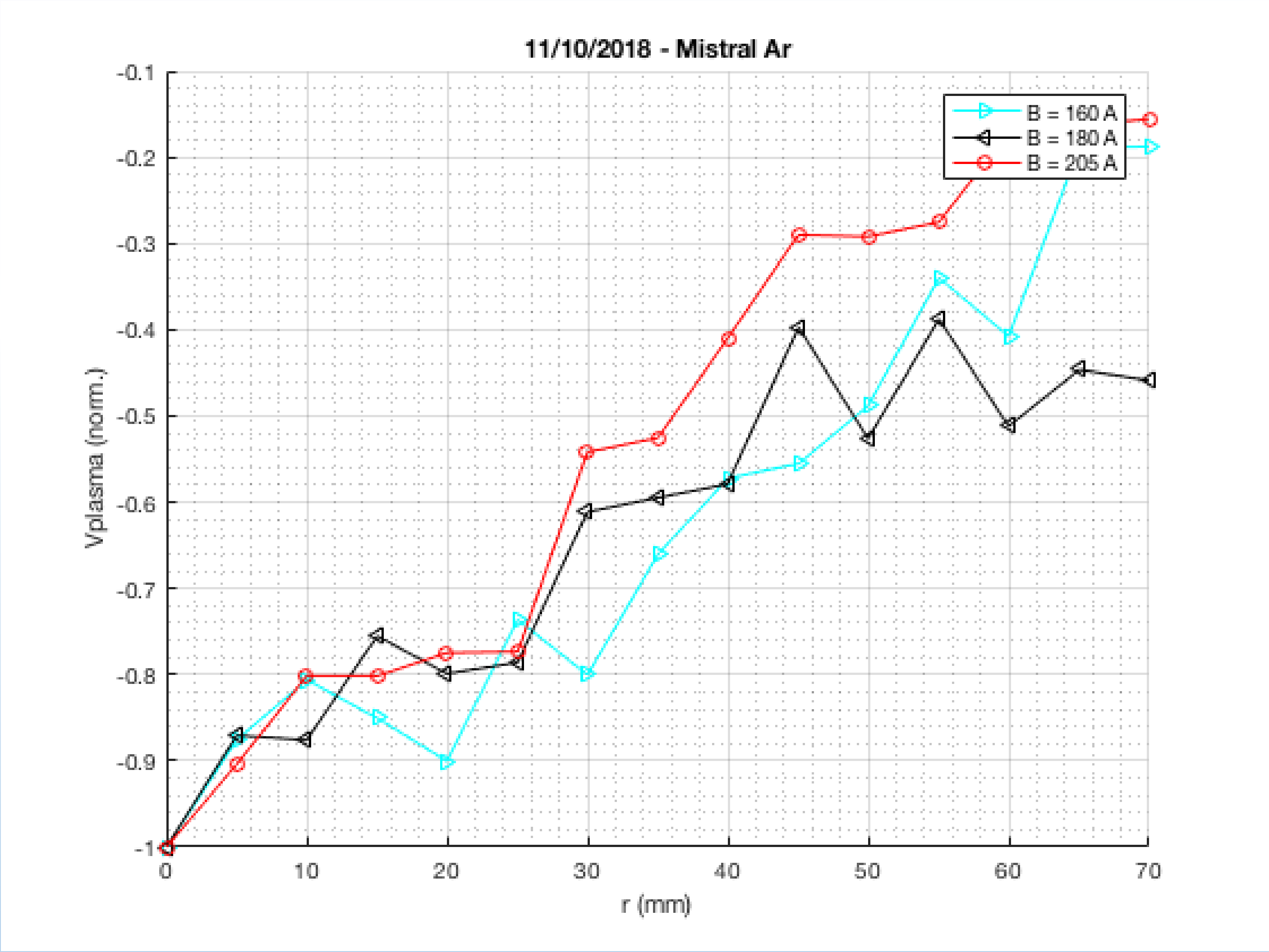
Comparison of ne(r)



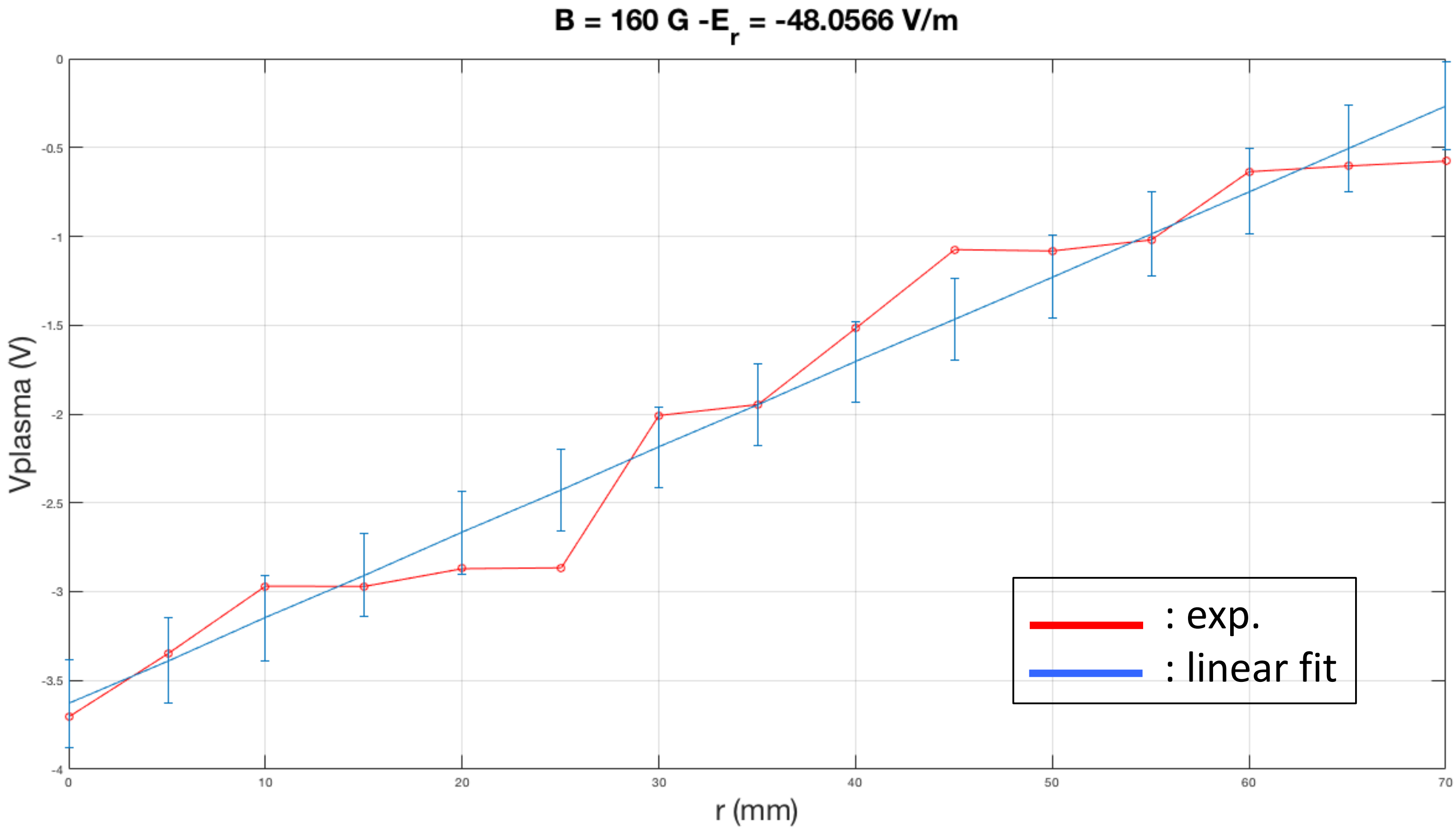


→ *similar radial behaviors*

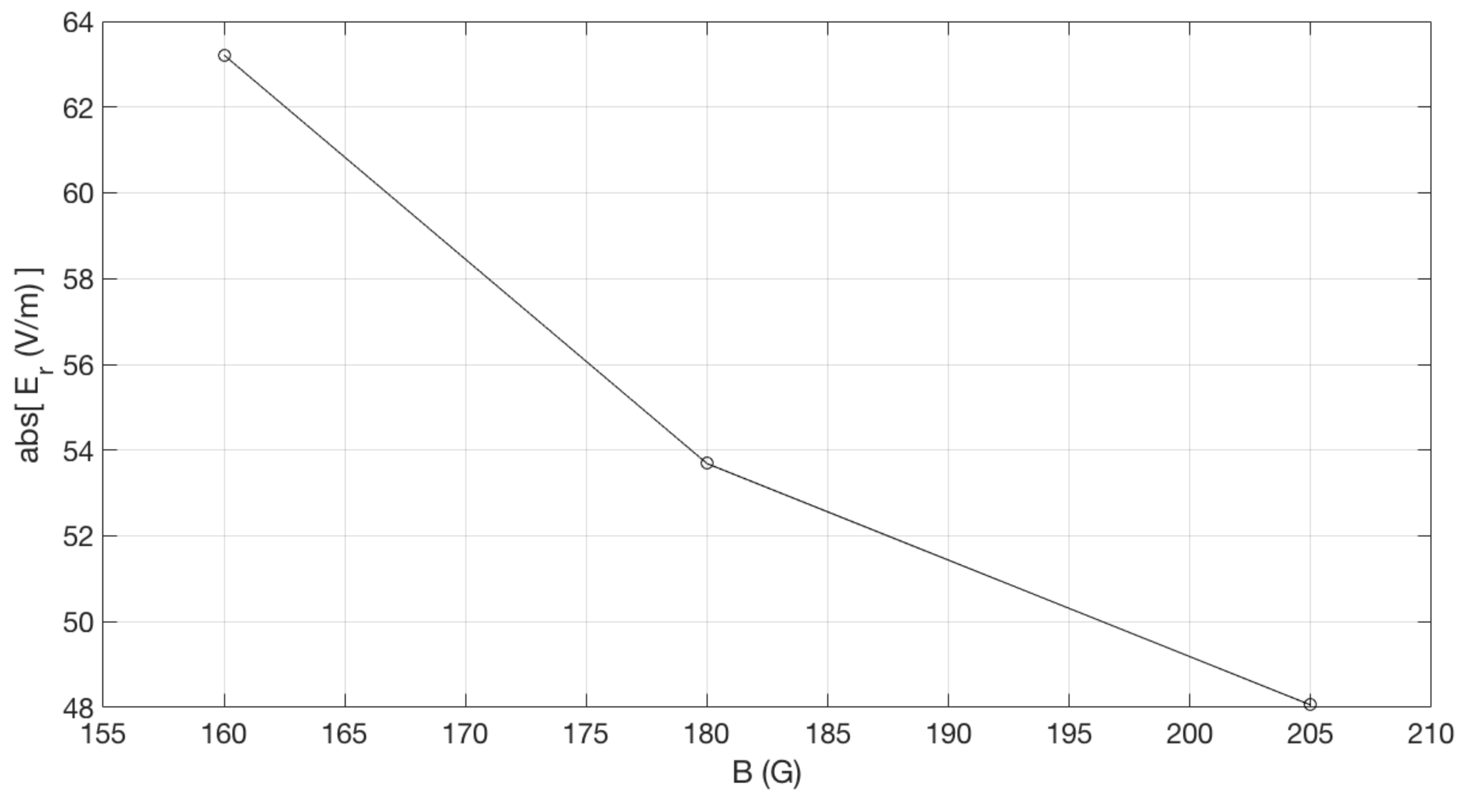
Comparison of $V_{plasma}(r)$



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



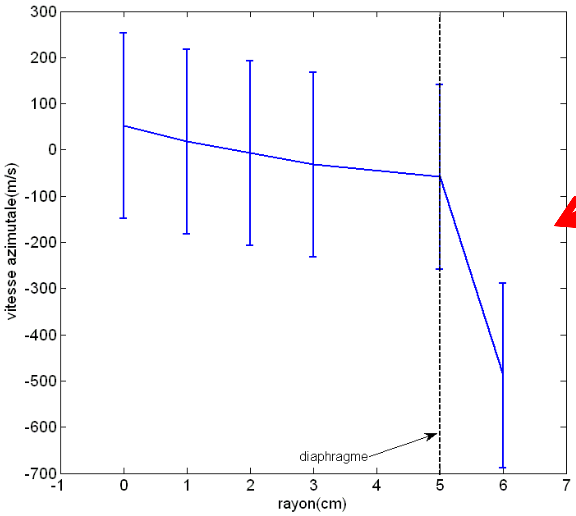
E_r estimation from the linear fit of $V_{plasma}(r)$



→ Except in the center, the radial electric field is oriented inward inside the spoke and is oriented outward between two spokes.

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

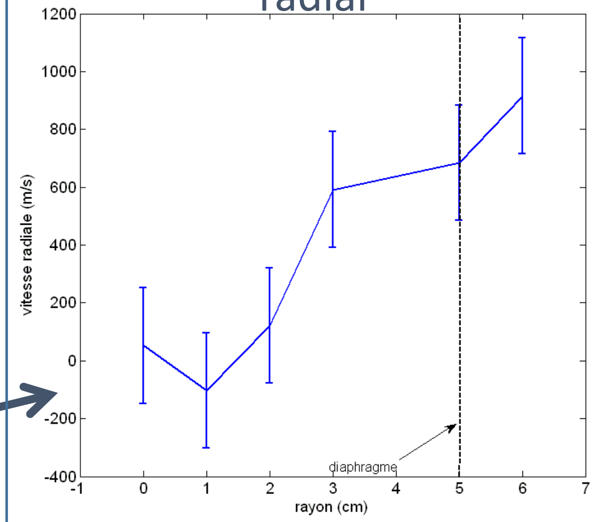
azimuthal



Mean velocity at density maximum

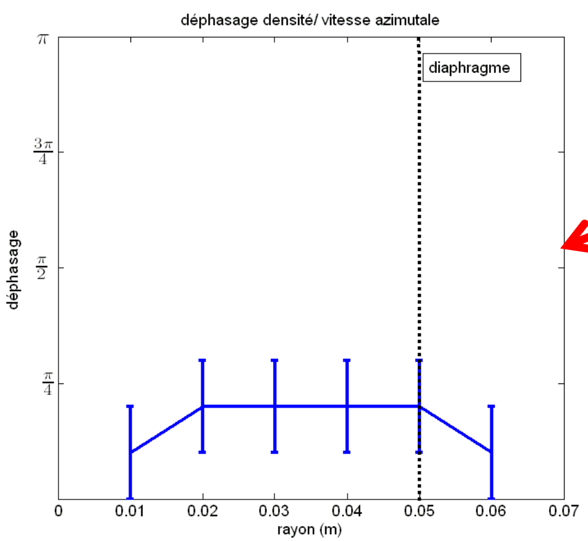
In the ionization zone, almost null velocity at any radius.
No « block » rotation.

radial

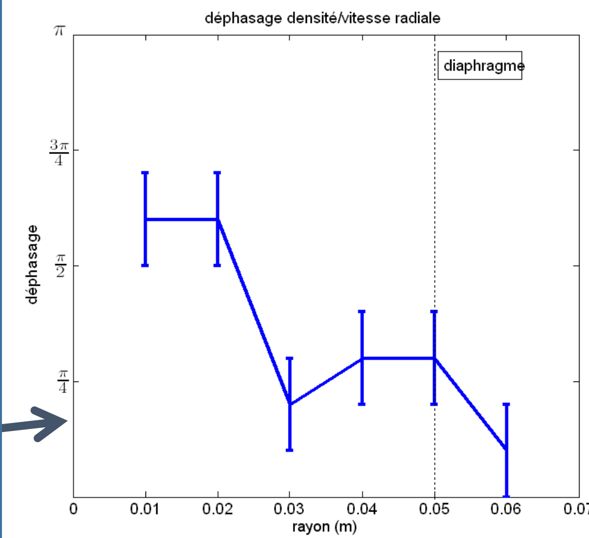


Linear evolution of radial velocity

Density/velocity phase



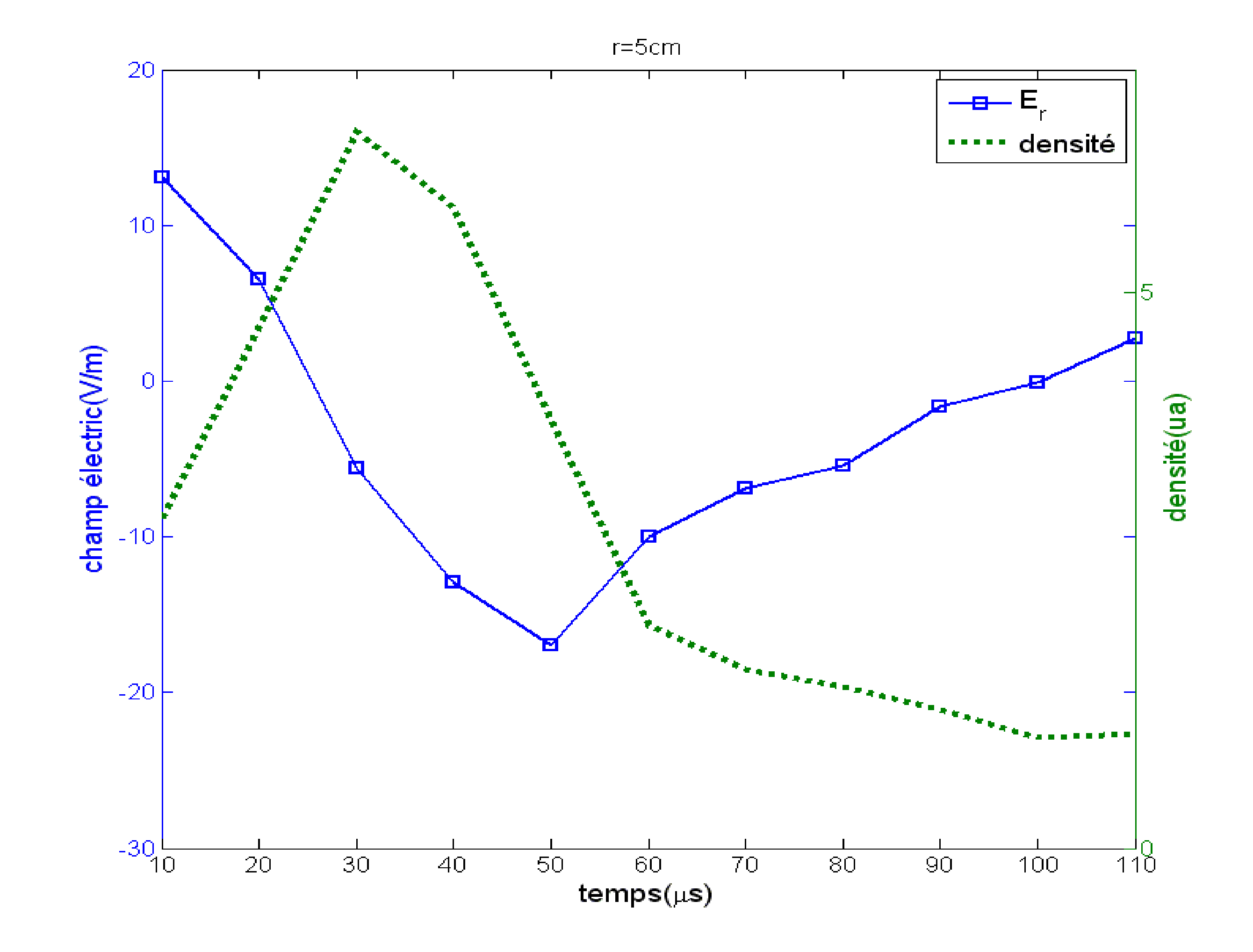
Constant phase close to $\pi/4$



Phase: $\pi/2$ 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)

Conclusion – m=1 spoke in Mistral

- **$V_{r\ ion}$**
  linear increase with r ; $\Phi(V_{r\ ion}, n_e) = \pi/2$ (center) ; 0 (shadow of limiteur)
- **$V_{\phi\ ion}$**
  null inside the column ; $\Phi(V_{\phi\ ion}, n_e) = \pi/4$
- **ν_{mode} = f(M)**
  Space/time resolved plasma parameters study for a m=1 spoke in Mistral : ν_{mode} = f(M) → OK with ICSH theory.
- **ν_{mode} = f(P)**
  Possible transition m=1 to m=2 mode, when P increases : controlling parameter ?
- **ν_{mode} = f(B)**
  Maximum at 160 G : role of ion-neutral collisions ?
- **E_r**
  oriented inward inside the spoke (probe and LIF)

Perspectives

- PIC simulations of Mistral plasma column

- Collaborations with Univ. Kyushu (PANTA), ENS Lyon (Von Karma plasma)

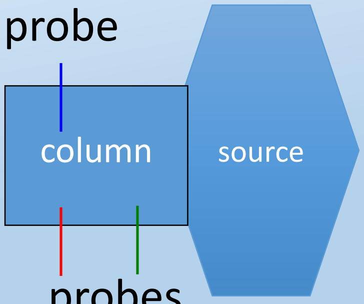
- Development of non intrusive diagnostics for instability study:
  - EFILE (non intrusive electric field measurement),
  - Tomography,
  - spectro-tomography.

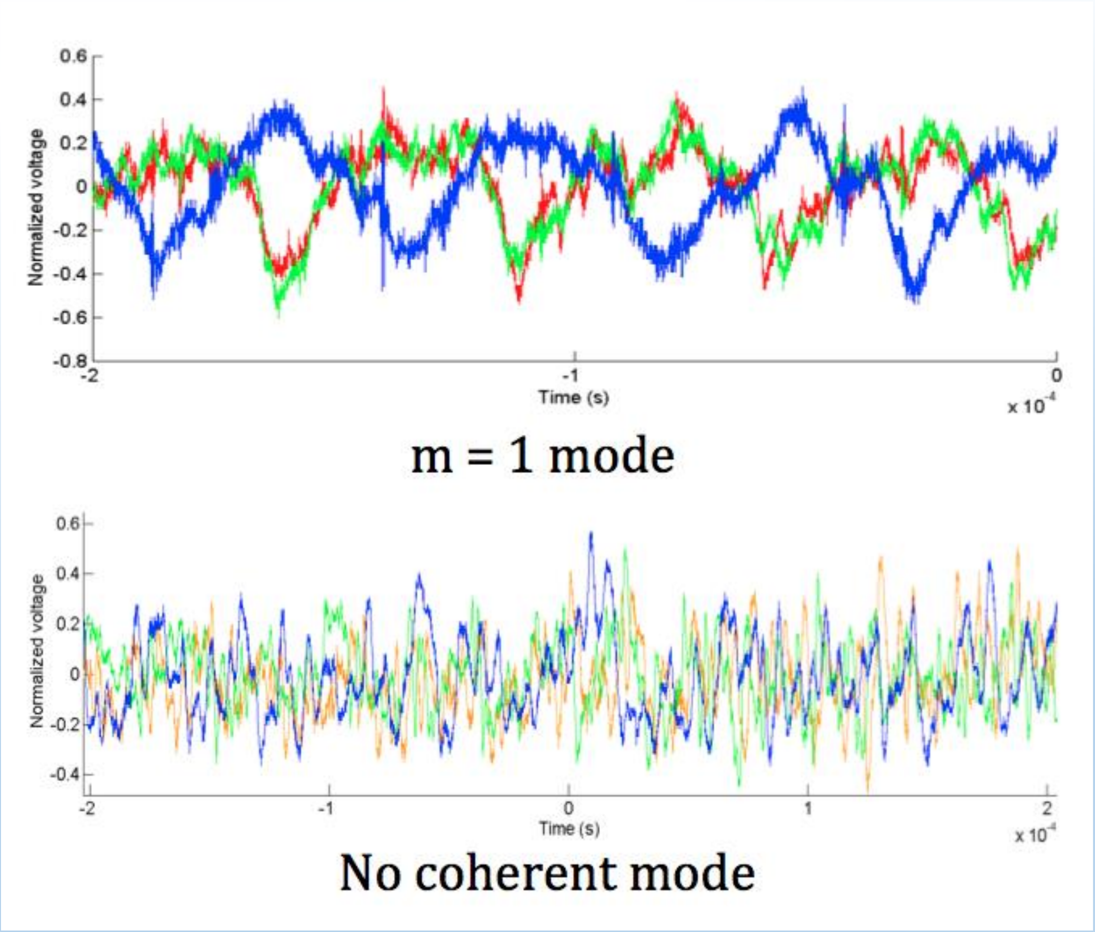
- Addition of a second ionizing source, without primary electrons.

Thank you for your attention

Low frequency instabilities : looking for symetries…

→Flute regular modes
→No symetry for « turbulent » plasma



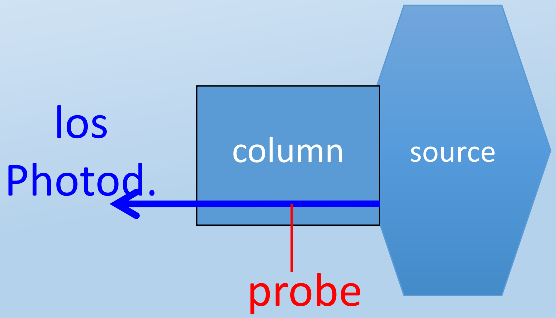


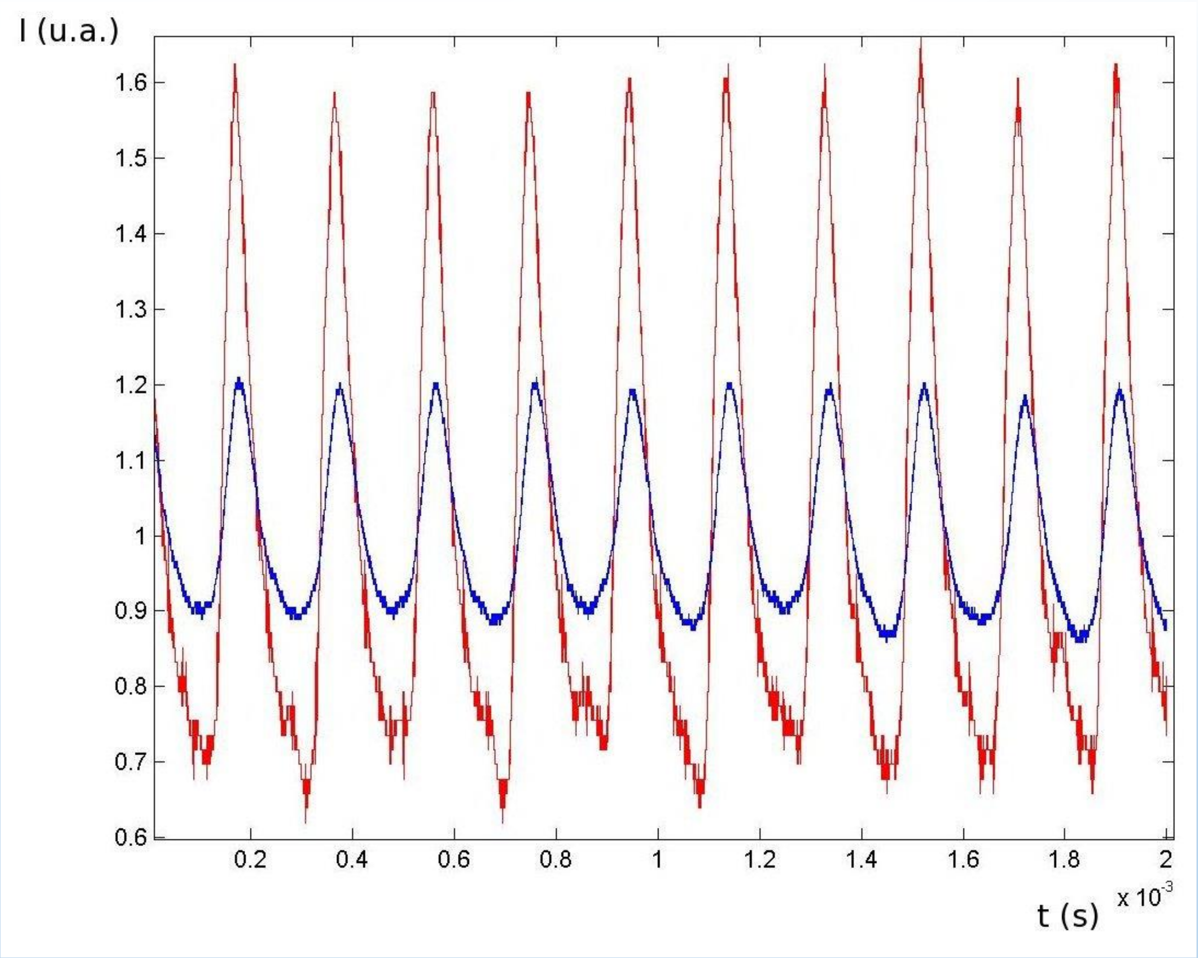
Low frequency instabilities : possible optical measurements…

→Strong correlation between probe and photo-diode signals

- : probe polarized at $V > V_{plasma}$

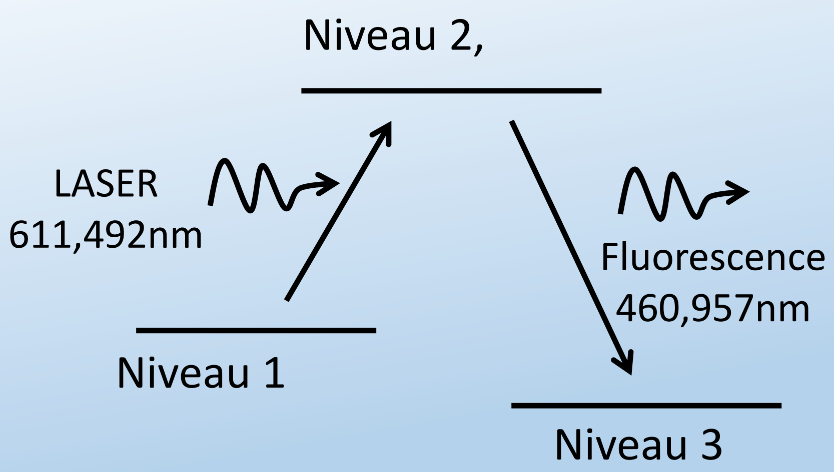
- : photo-diode (collimated los)





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.

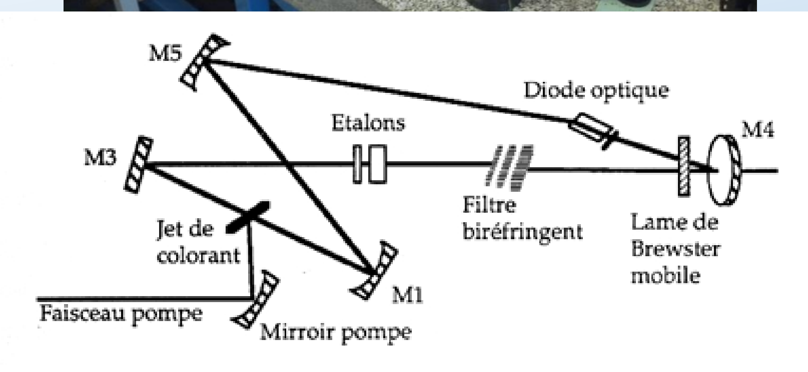


Level 1 to level 2 transition condition:
Laser frequency = transition 1-2 frequency

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

LIF instruments

Dye Laser



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

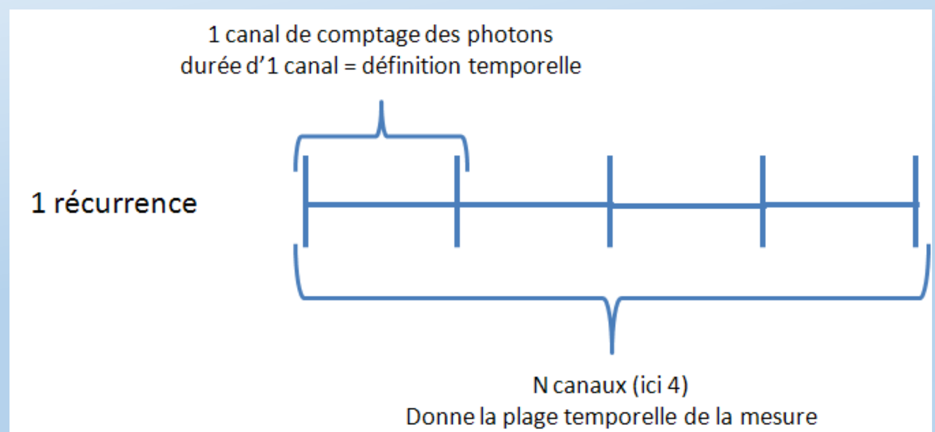
Multi-Channel Scaler (MCS)

The MCS allows to:

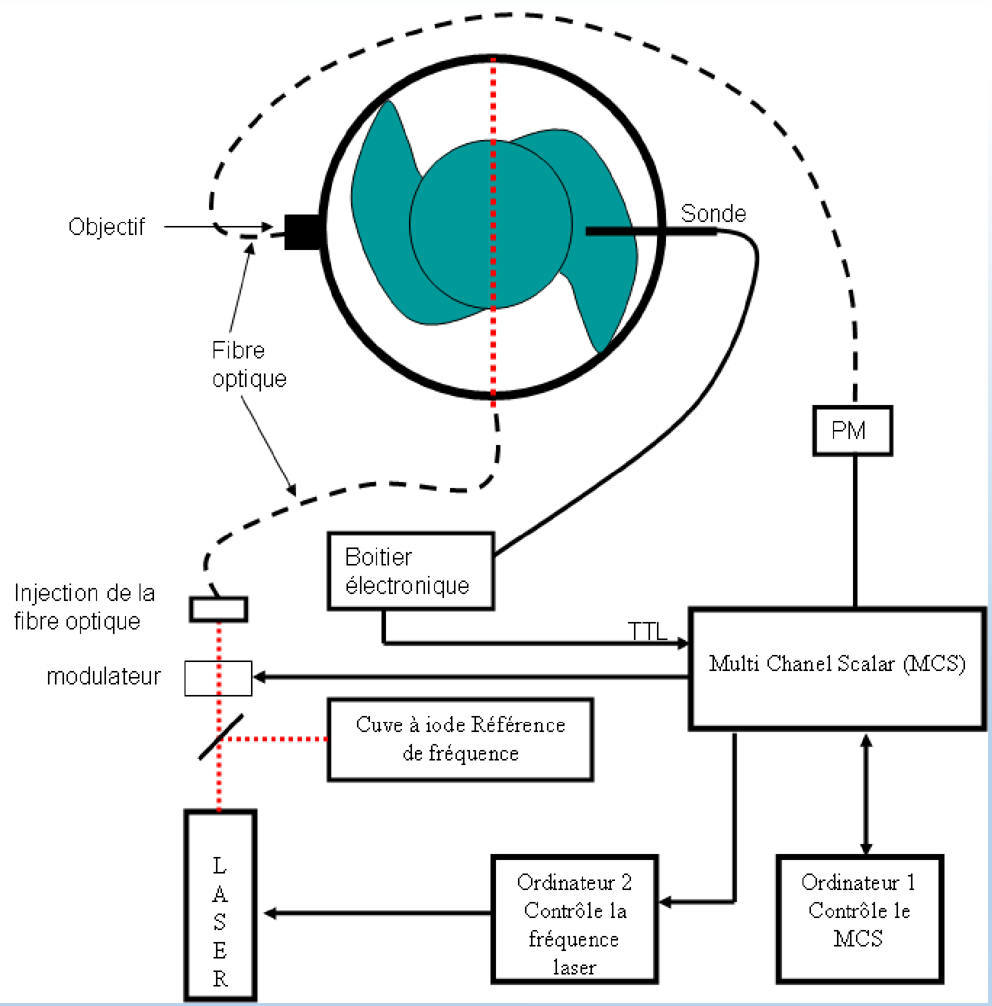
- ➢ Count photons (detected by a photomultiplier).
- ➢ Add temporal resolution to measurement.

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).



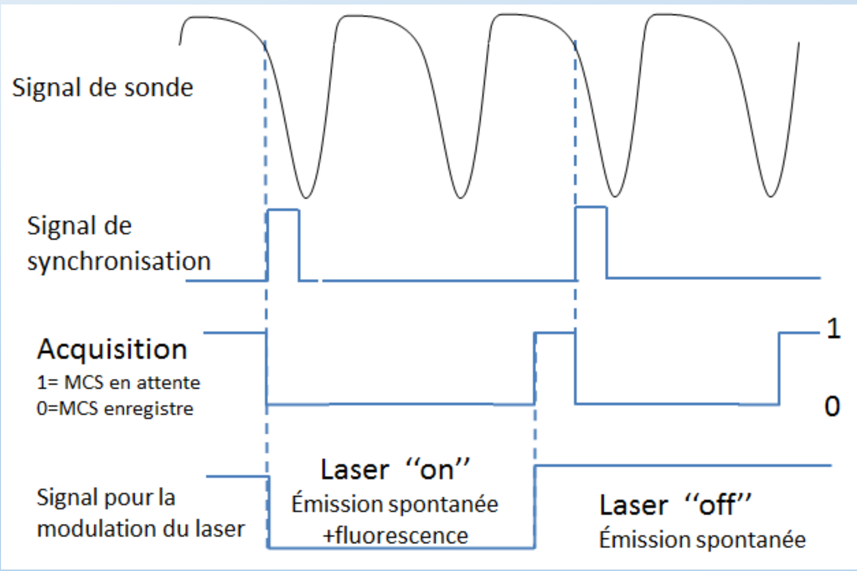
LIF on MISTRAL experiment



- 2 Measurements:
  - laser on
  - laser off

Allows to substract background signal (spontaneous emission)

•Synchronization with perturbation to keep temporal definition during recurrences.

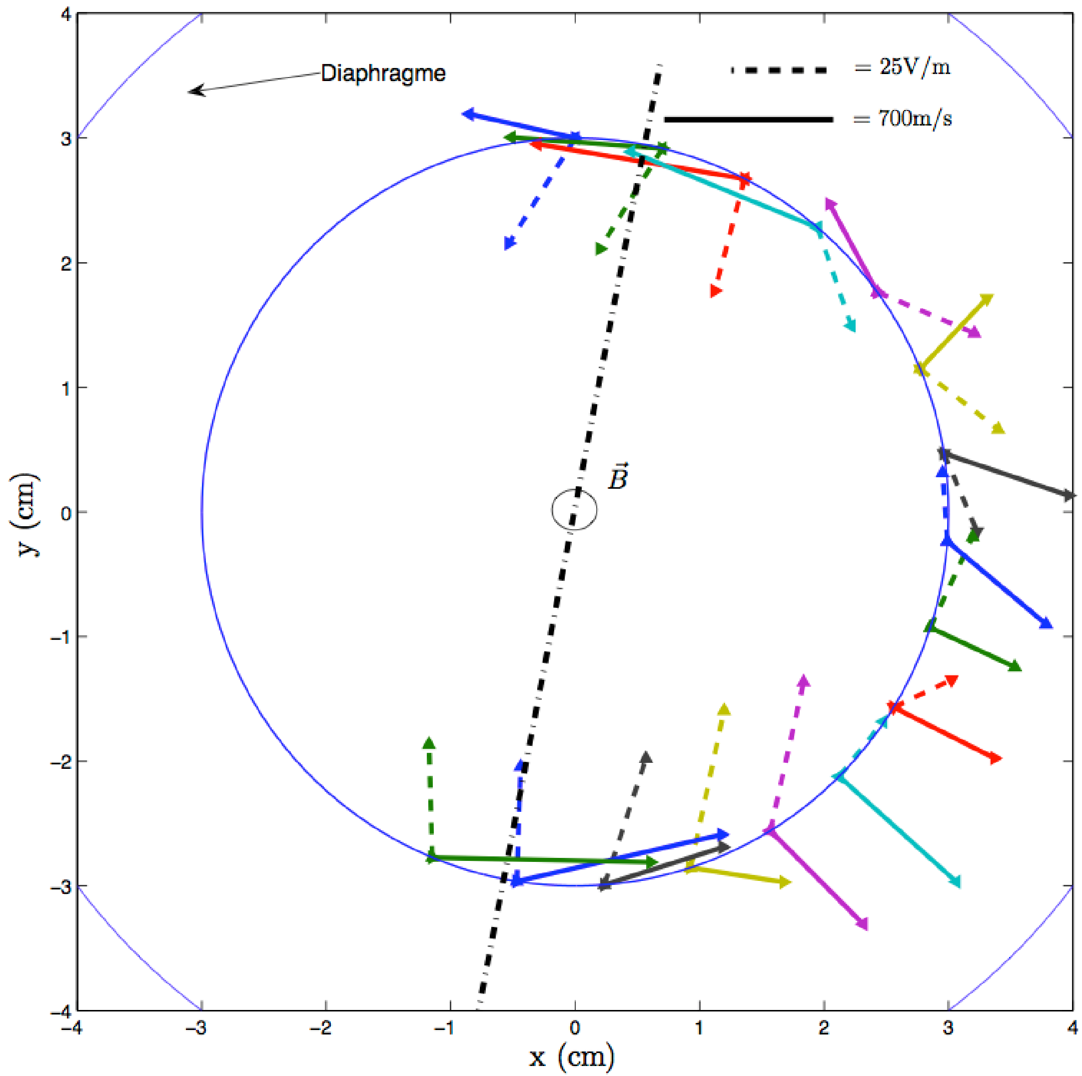


LIF measurements in Mistral : m=2 mode

- : 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]



Tomographic study of magnetized plasma column instabilities (MISTRAL)

→ ***P. David*** *PhD thesis*

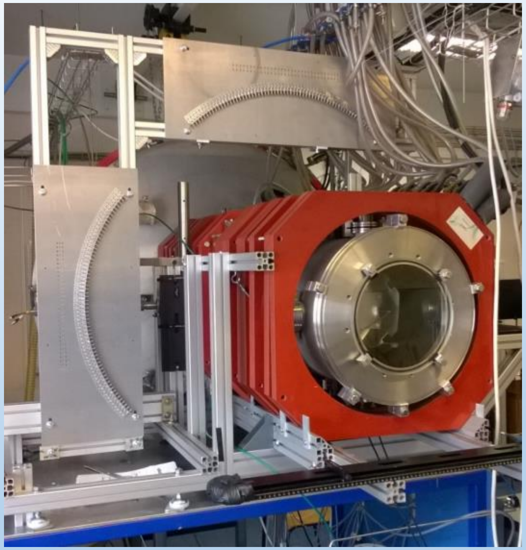
→Advantages :

- 2D spatial structure of regular modes without any hypothesis
- non intrusive

→« Turbulent » modes study

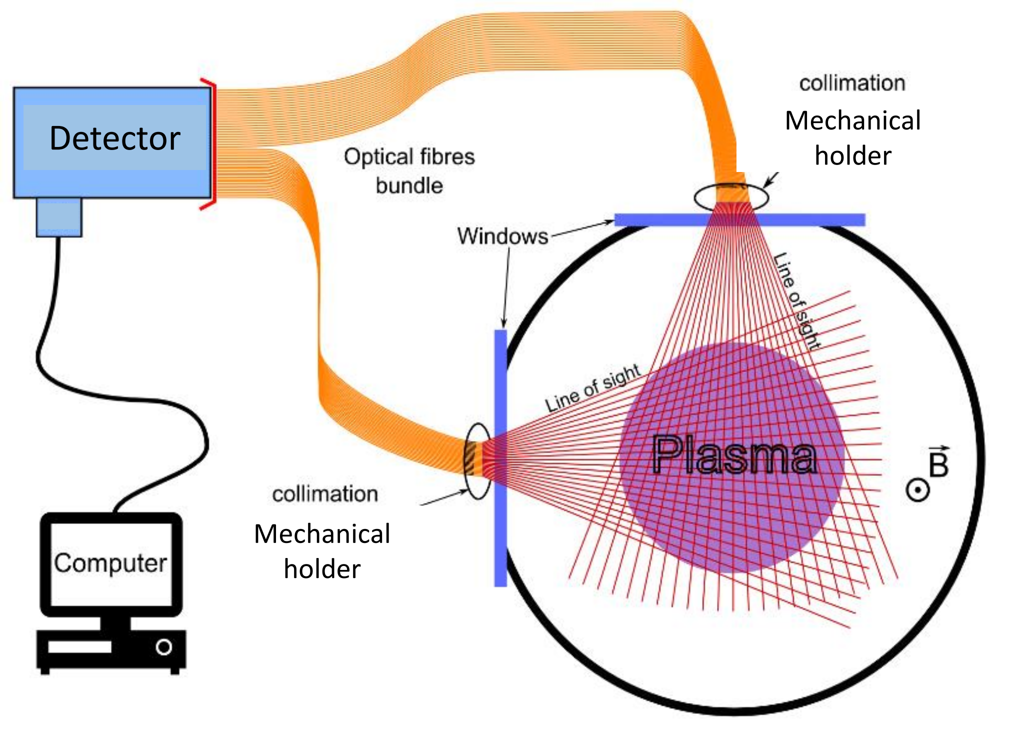
→Possible « one shot » acquisition

→2x64 channels, ν_{acq} = 1 MHz



Tomography : experimental set-up

→ Instantaneous measurements, or on reproducible phenomenons : spatial structure study of regular modes.



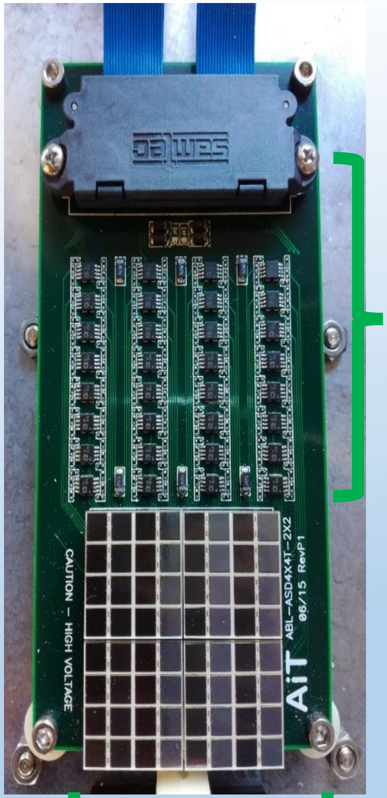
Experimental set-up: captors matrix

Captors :

- 2 x 64 bundle fibres Ø100 µm x 5 m
- 128 x SiPM detectors bar
  - Gain (> 10^6, PDE > 30%) with weak voltages/PMTs (~ 20 to 40 V)
  - Fast response time : <100 ps
  - ν_{acq} max. = 1 MHz

Limitations :

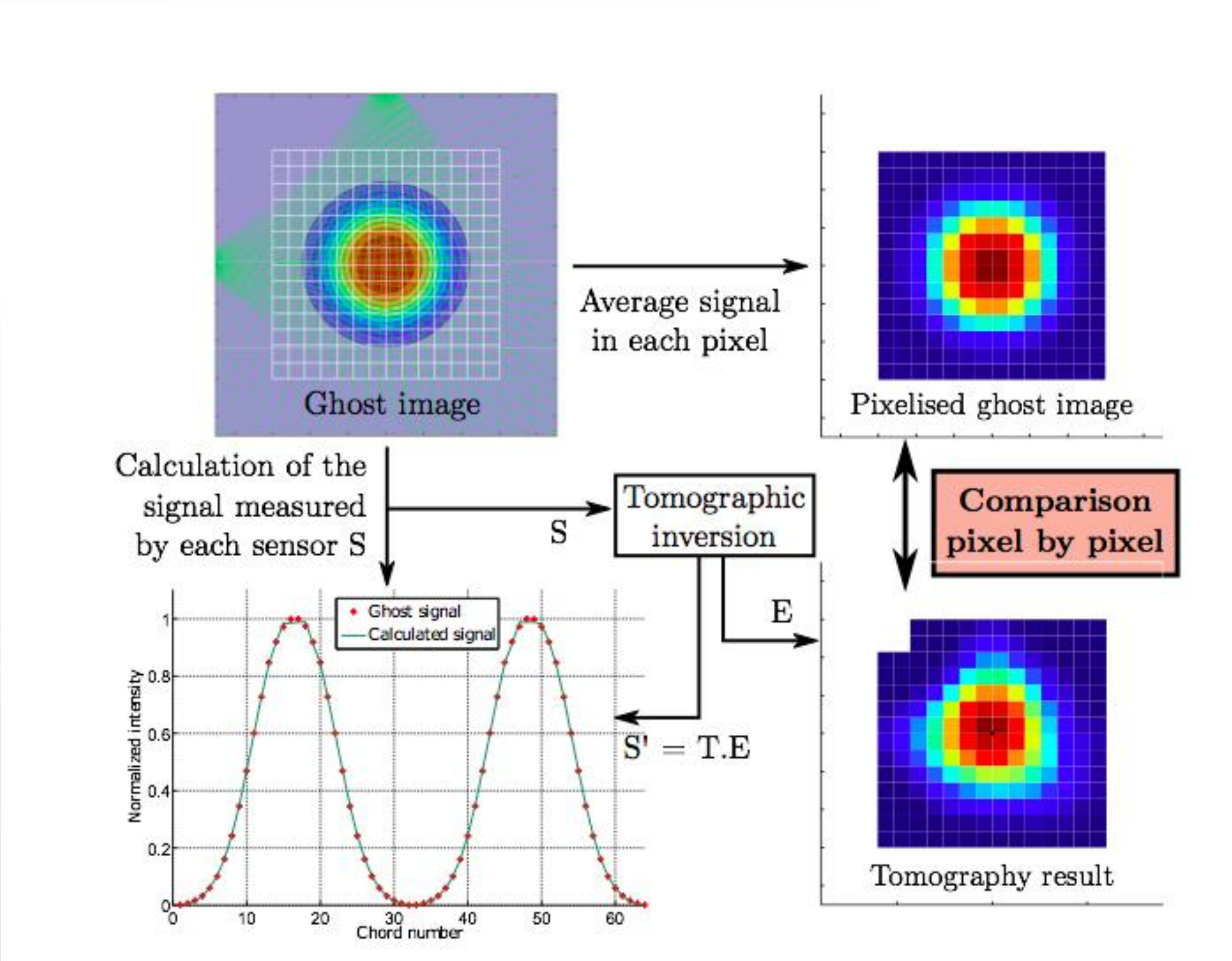
- No spectral resolution
- Important noise: “fake“ signals (after pulse/cross talk)



Amplification stage

8x8 matrix detector

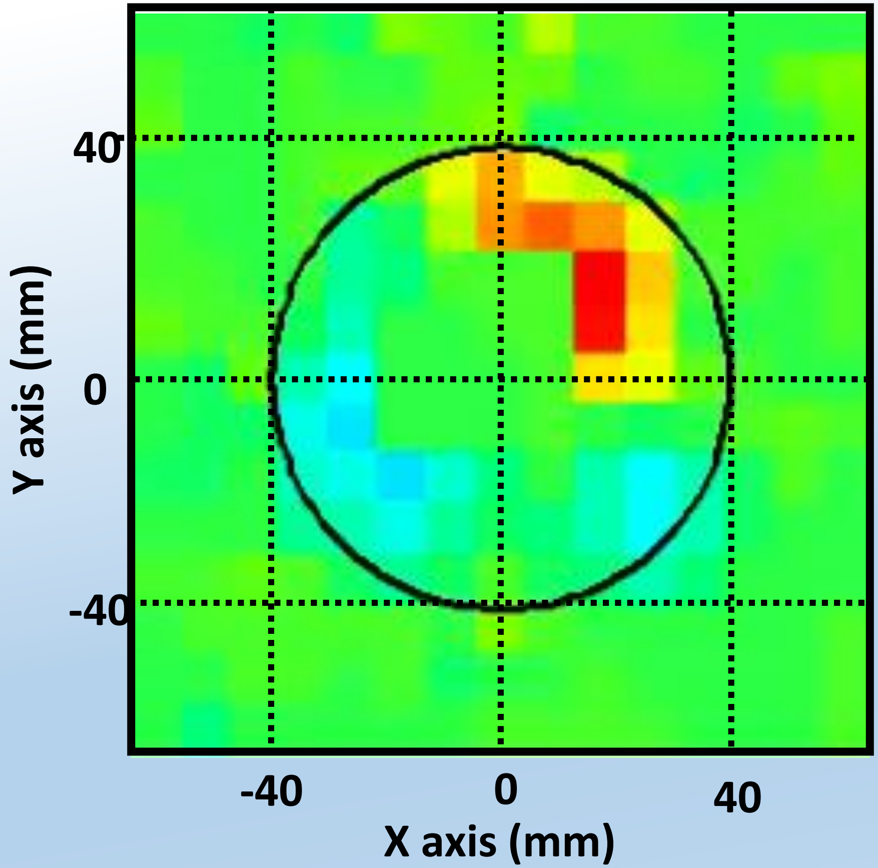
Tomography : validation of inversion code



First tomographic results …

- →Spatial structures of regular modes
- →Weak perturbation by probe
- → Radial profile more peaked: primary electrons
- →V_p and n_e : $\pi/2$ phase delay

Local emissivity of an m=1 flute mode



[P. David POP 2016]

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 :

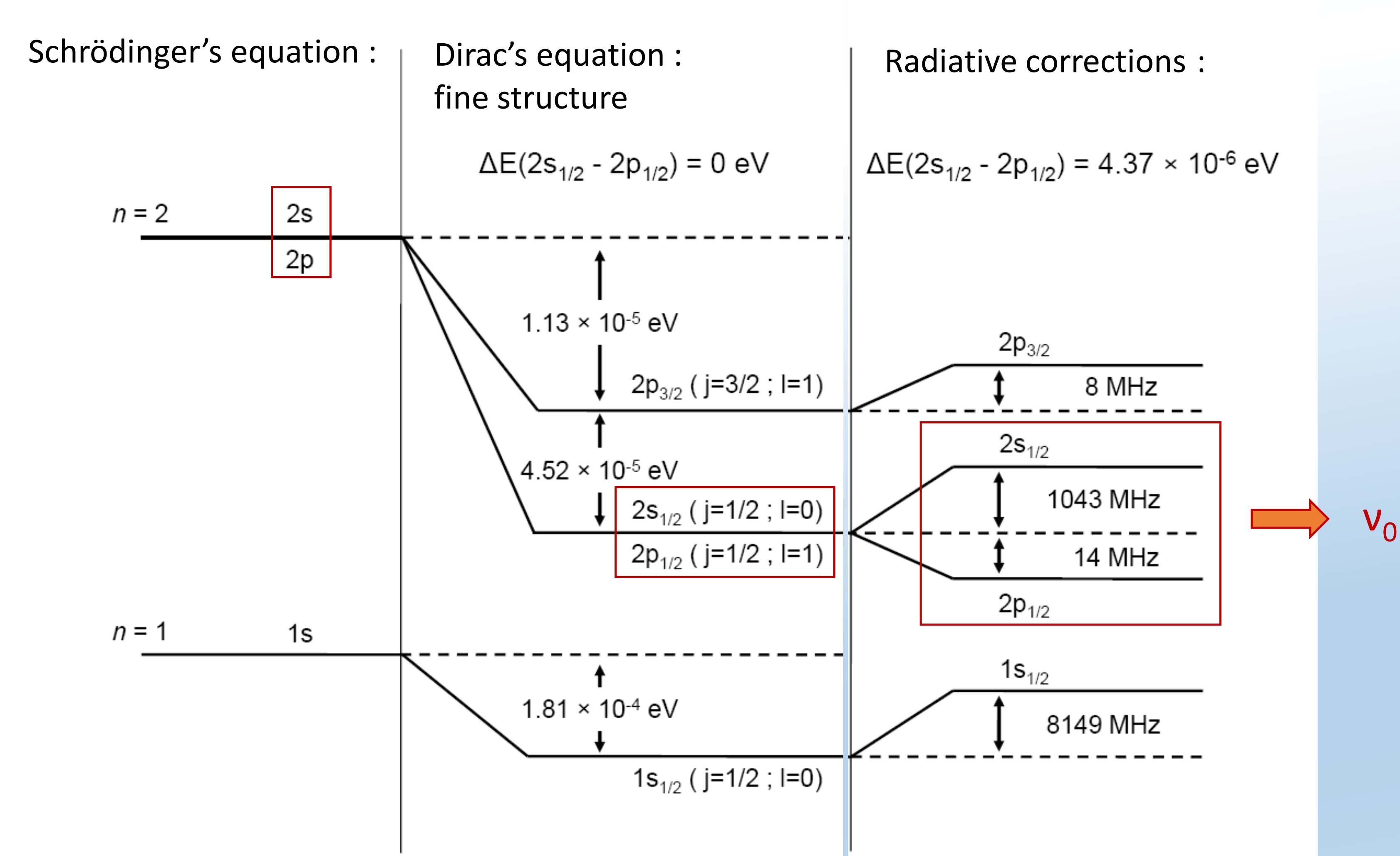
- Measurement of local electric field in Mistral
- Measurement of electric field in front of ICRF IShTAR (Ion cyclotron Sheath Test Arrangement) antenna

[Cherigier-Kovacic RSI 2015 ; Doveil PPCF 2016]

Lamb shift

- Second property of hydrogenoids :

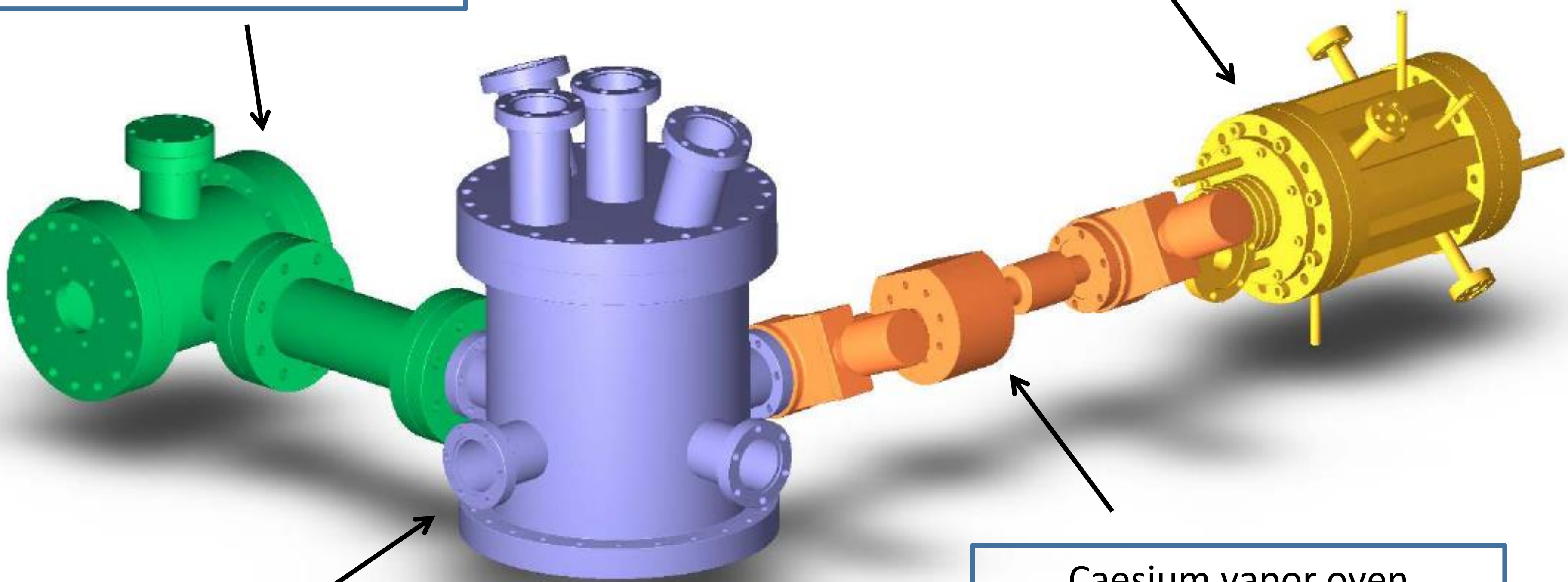
Lamb-shift due to radiative corrections



Schematic view of the EFILE experiment

Collection of Lyman α emission

Plasma source : multipolar device
+
Einzel lenses (extraction)

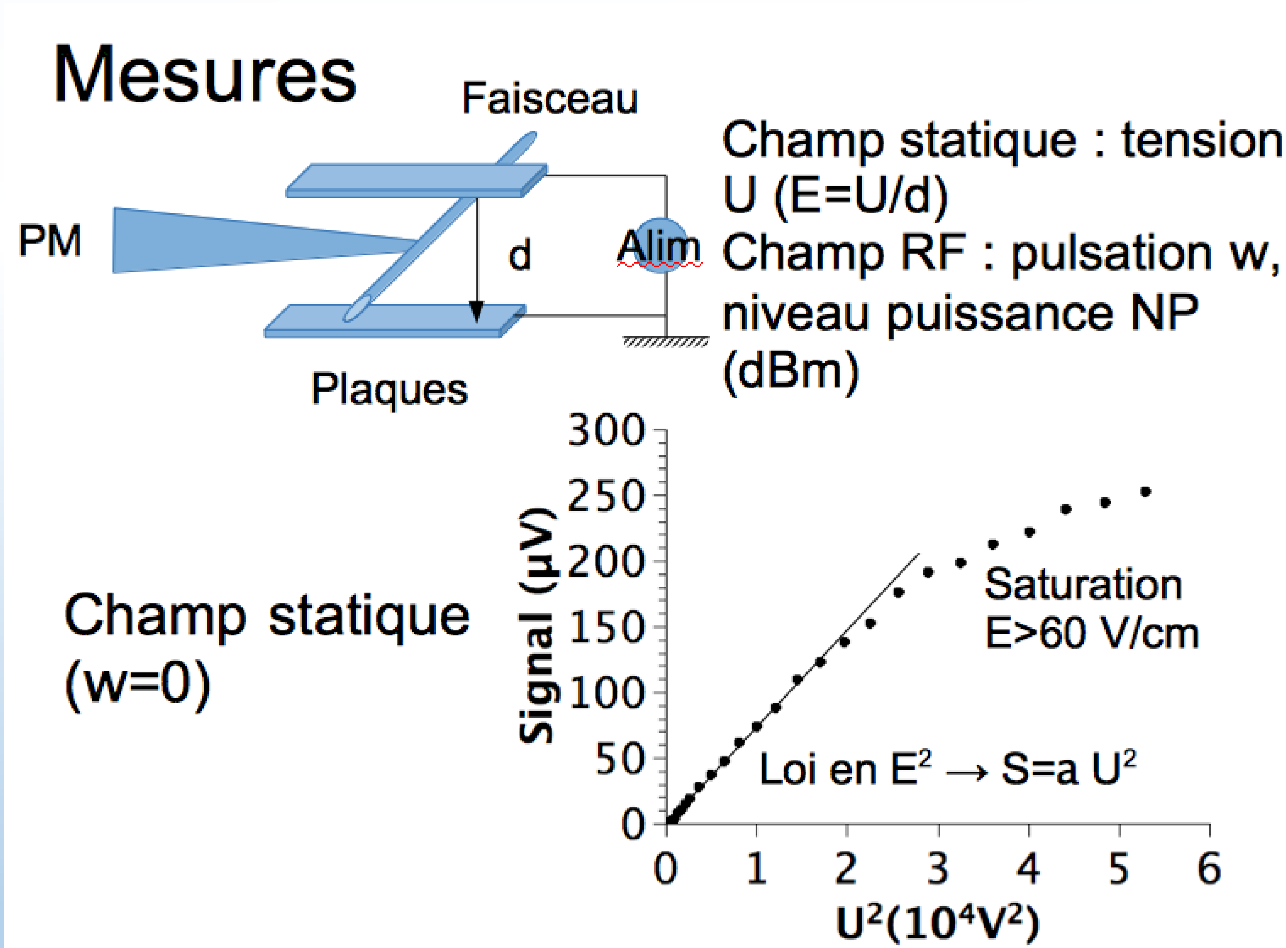


Test chamber: interaction probe beam – electric field + diagnostics* beam / plasma

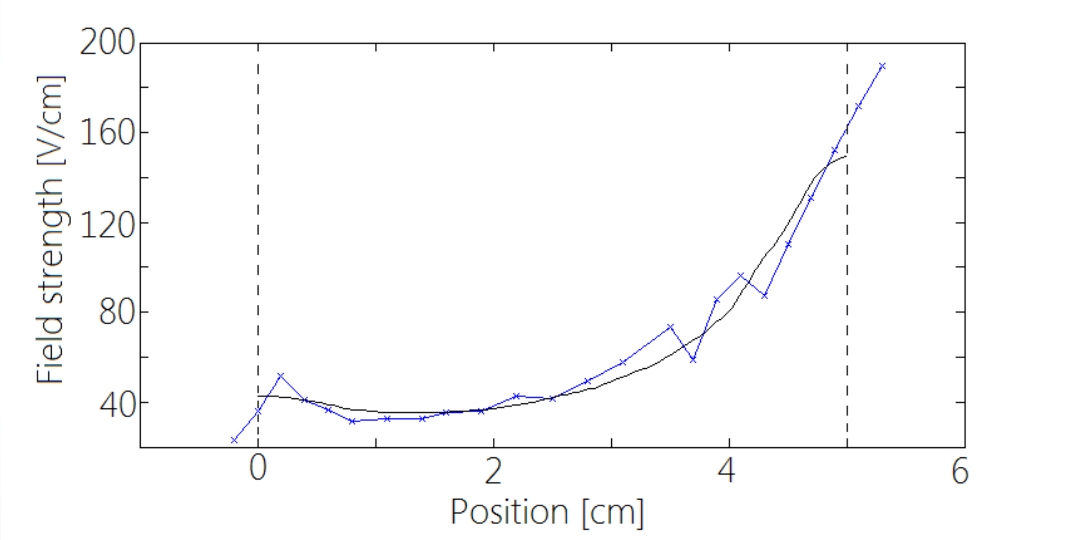
Caesium vapor oven (neutralization)

* mass spectrometer, energy analyzer, Langmuir probes probes

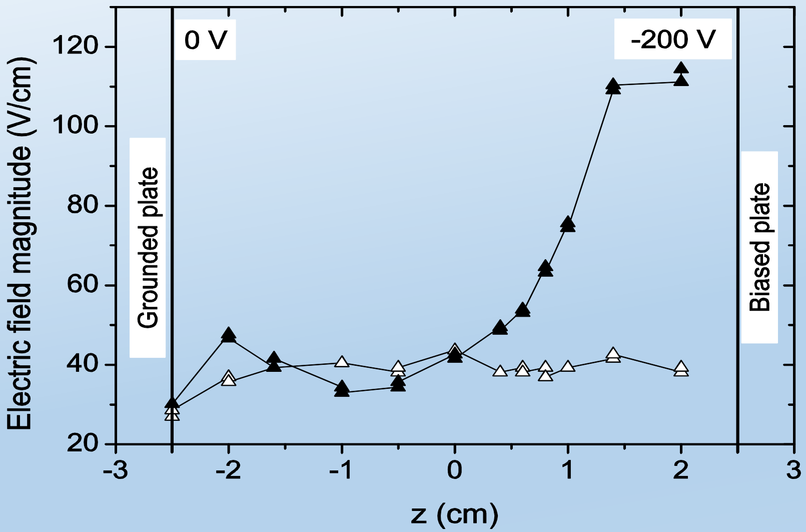
E measurement in the shadow of a limiter : principle



EFILE : results



Diagnostic EFILE in vacuum: comparison with numerical simulation FEM



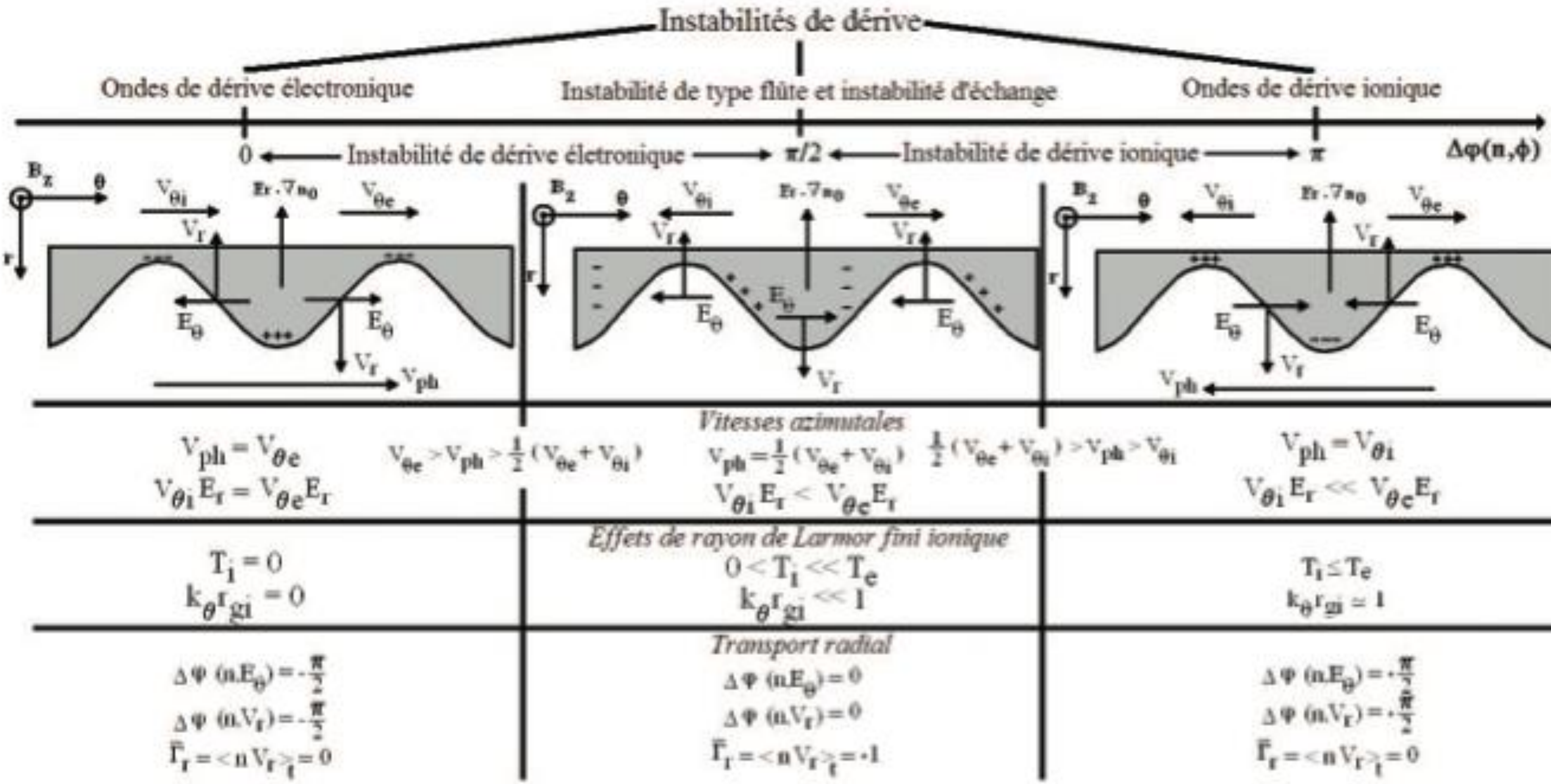
Diagnostic EFILE in plasma

<u>Formation of a plasma sheath:</u>

Electric field profile measured

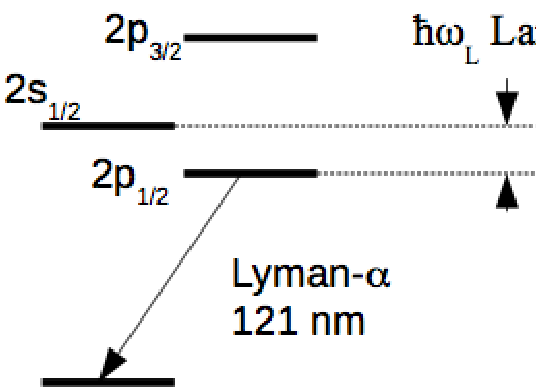
-in vacuum (white triangle)

-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 électronique → 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
$T_i = 0$
$k_\theta r_{gi} = 0$
$0 < T_i \ll T_e$
$k_\theta r_{gi} \ll 1$
$T_i \leq T_e$
$k_\theta r_{gi} \approx 1$
Transport radial
$\Delta\varphi(n,E_\theta) = -\frac{\pi}{2}$
$\Delta\varphi(n,V_r) = -\frac{\pi}{2}$
$\bar{\Gamma}_r = \langle n V_r \rangle_t = 0$
$\Delta\varphi(n,E_\theta) = 0$
$\Delta\varphi(n,V_r) = 0$
$\bar{\Gamma}_r = \langle n V_r \rangle_t = -1$
$\Delta\varphi(n,E_\theta) = +\frac{\pi}{2}$
$\Delta\varphi(n,V_r) = +\frac{\pi}{2}$
$\bar{\Gamma}_r = \langle n V_r \rangle_t = 0$

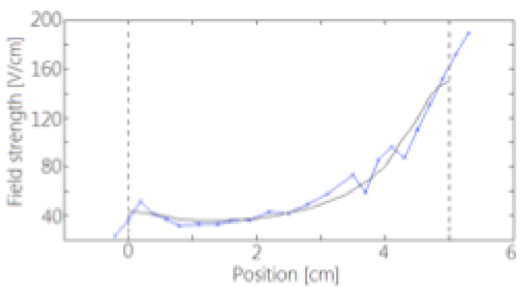
Mesure d'un champ électrique statique ou fluctuant

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

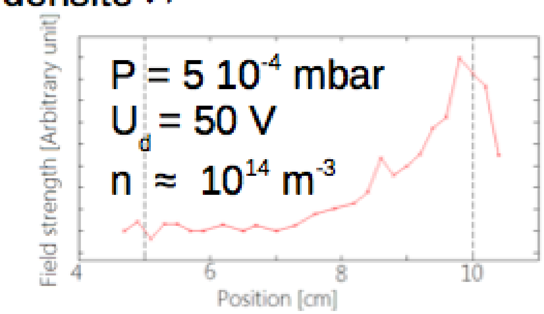


$$\gamma_{2s}^{*}(\omega) = \frac{9e^2 a_0^2 E^2}{h^2} \frac{\gamma_{2p}}{(\omega - \omega_L)^2 + \gamma_{2p}^2/4}$$

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



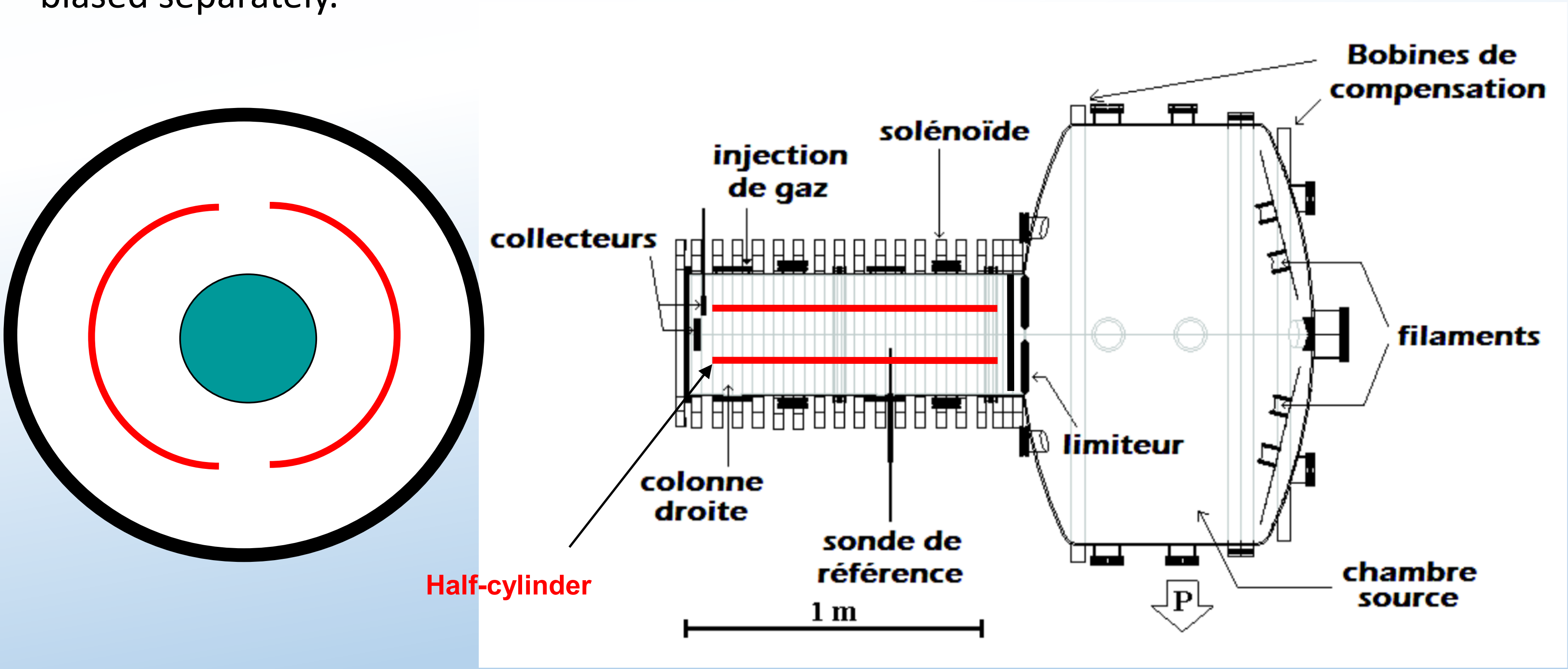
Champ statique dans un plasma : taille gaine ↘ quand densité ↗



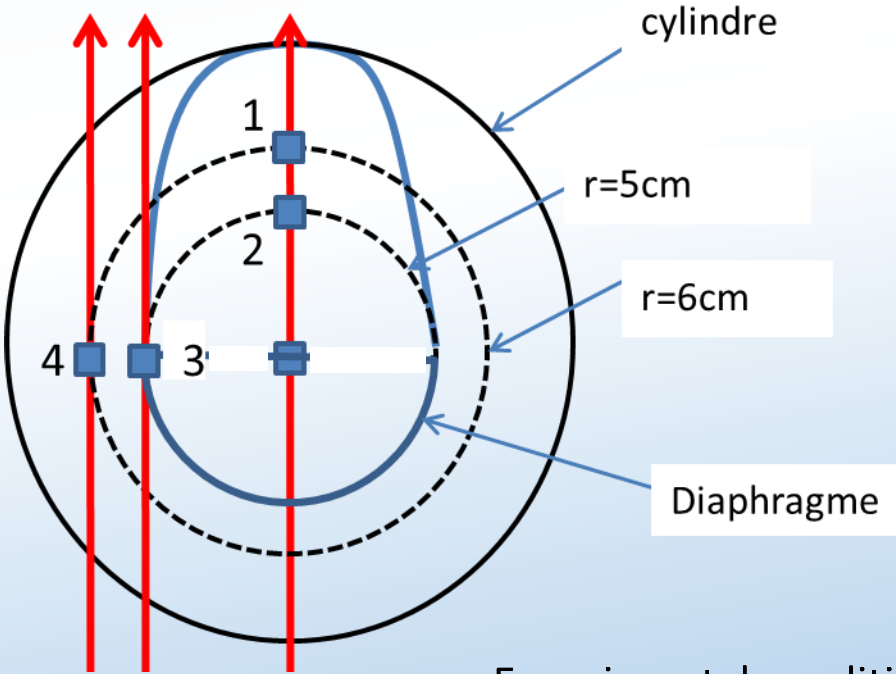
En cours : mesures RF, calibration
Développement : mesures en champ magnétique (MISTRAL)
Projet : mesure champ RF devant antenne ICRF chauffage plasma (Ishtar, Garching)

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
- $\Delta X = 1$ 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:

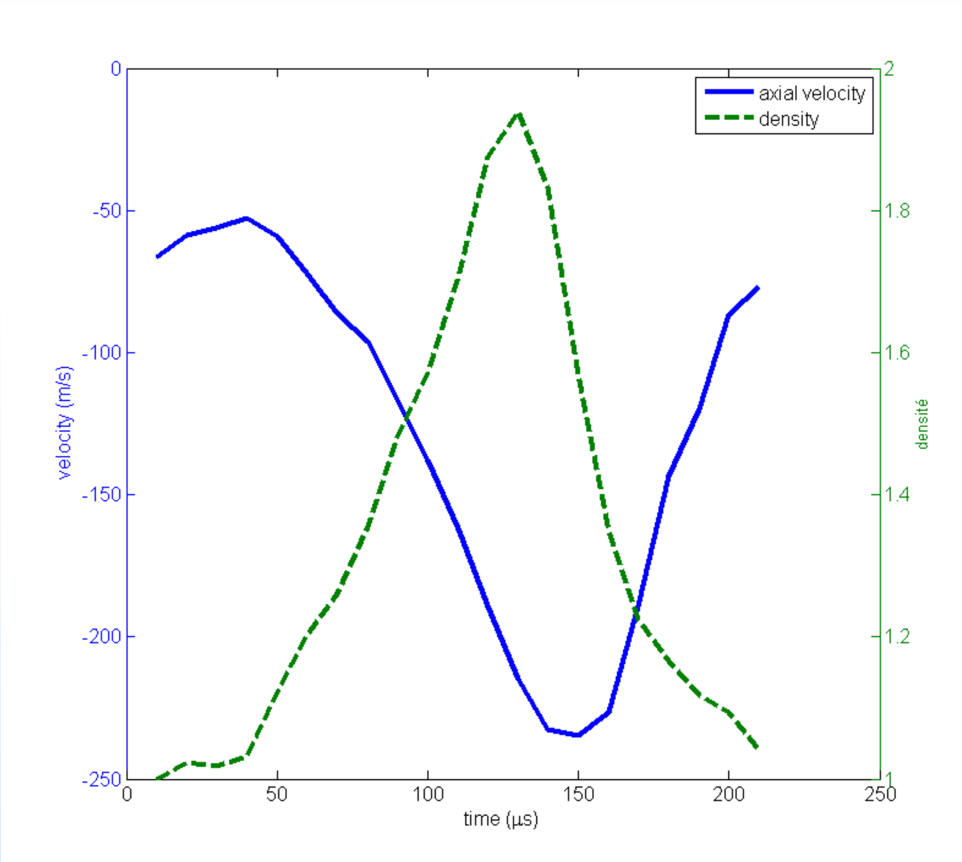
-Grounded half-cylinders

-Floating separatrix and collector (-30 V)

-P = 9 10^{-4} mbar

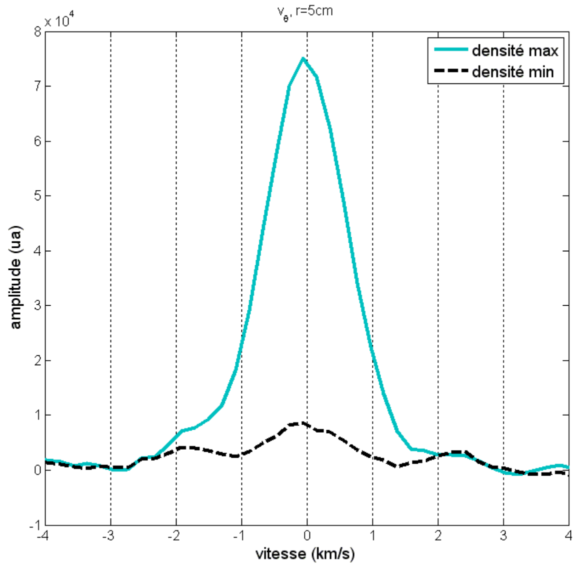
-B = 16 mT

Axial distribution function



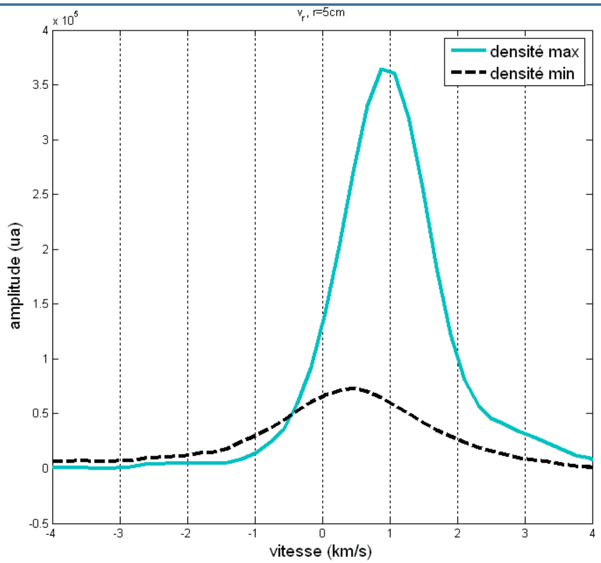
Modulation of mean axial velocity at the same frequency as perturbation
➔ possible drift waves

Results at r=5cm, ionization zone limit



azimuthal

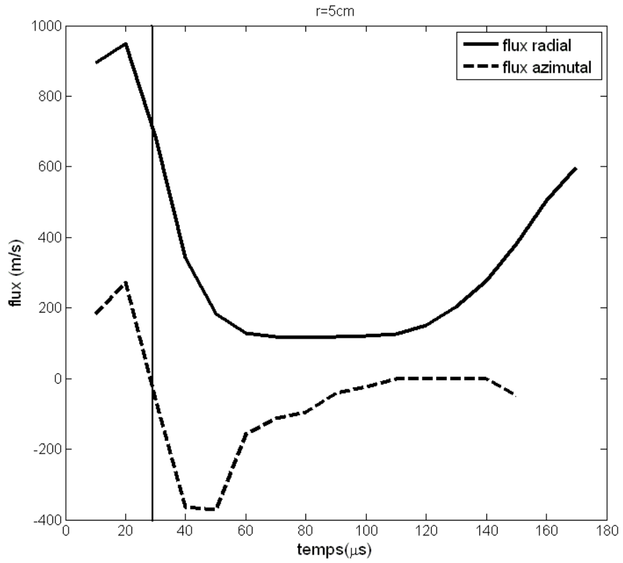
At max and min density ivdf centered at zero velocity.



radial

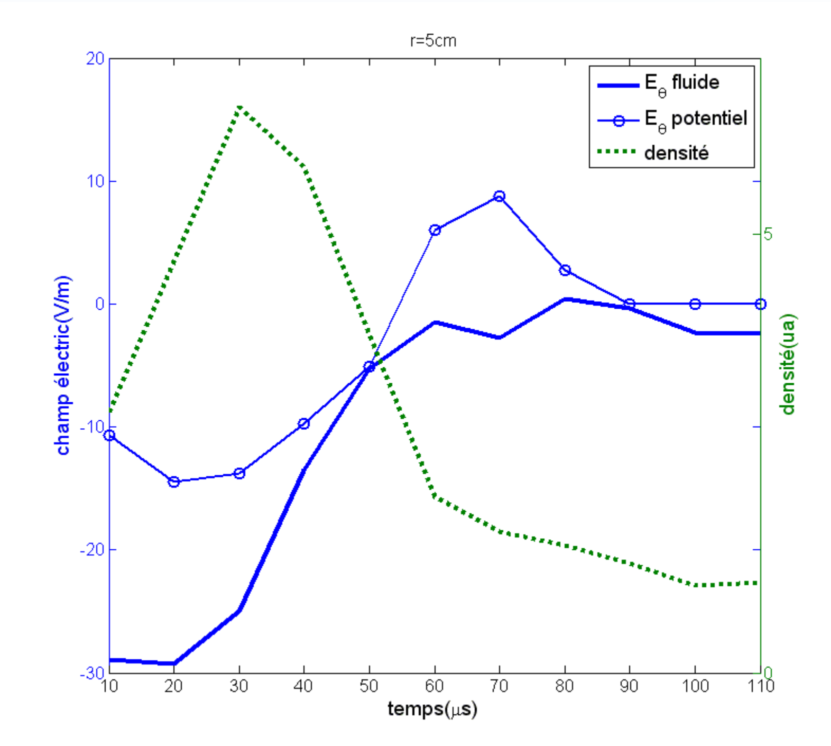
Radial velocity always present.

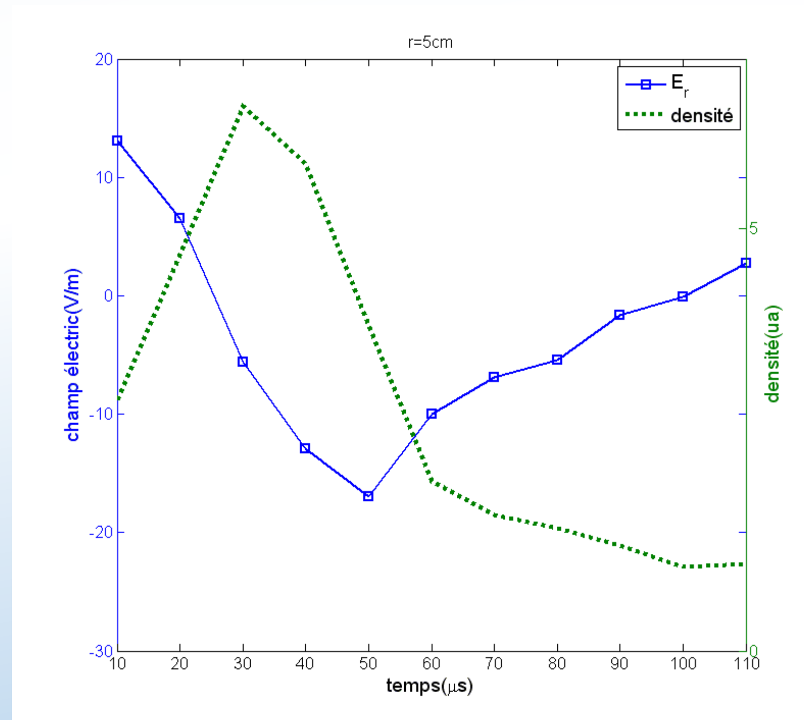
Flux: $\Gamma = n.V$



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.