L'expérience Mistral

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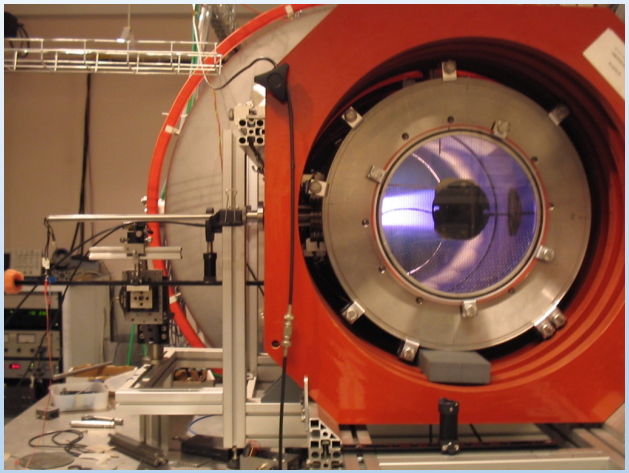
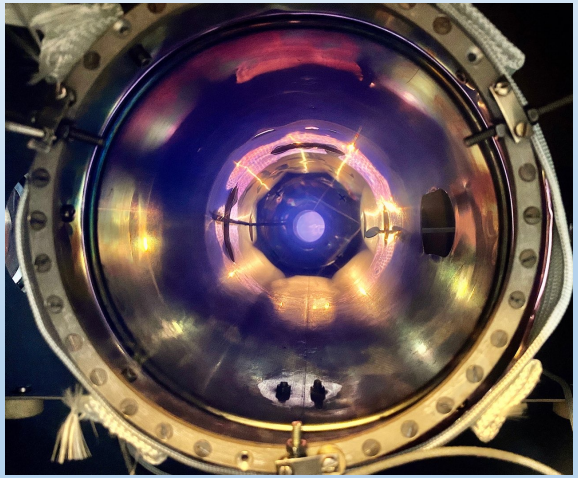




Les décharges multipolaires

Magnetic Multipole Containment of Large Uniform Collisionless Quiescent Plasmas

Rudolf Limpaecher† and K. R. MacKenzie

Department of Physics, University of California, Los Angeles, California 90024

(Received 18 December 1972)

Over 1200 Alnico magnets (1.3 × 1.3 × 4 cm) are used to contain a conventional discharge plasma produced by 1–20 A of emission from 6–48 small filaments at − 60 V. Densities up to 10^{12} ions/cm^3 are produced in argon at 2×10^{-3} Torr. At 5×10^{-6} Torr typical parameters are: 8×10^{10} ions/cm^3; $n_i/n_0 \approx 0.7$; $T_e \approx 5$ eV; $T_i \approx 0.5$ eV; noise $< \delta n/n > \approx 2 \times 10^{-4}$; and $< 1\%$ nonuniformity over a volume 31 cm diam by 69 cm. Uniform dense plasmas of He, D, and H are also produced. The ion containment appears to be both magnetic and electrostatic.

- Murs « magnétiques » avec des aimants permanents diposés autour d'une enceinte afin d'obtenir un grand volume de plasma **basse pression** (<10^{-3} mBar), **non magnétisé** et **calme** pour des études fondamentales.

→ **2 décharges de volumes 1 l et 86 l (38cm x 76 cm)**

→ ***Mistral :*** *utilisation d'une source multipolaire pour créer une colonne de plasma magnétisée.*

Les décharges multipolaires

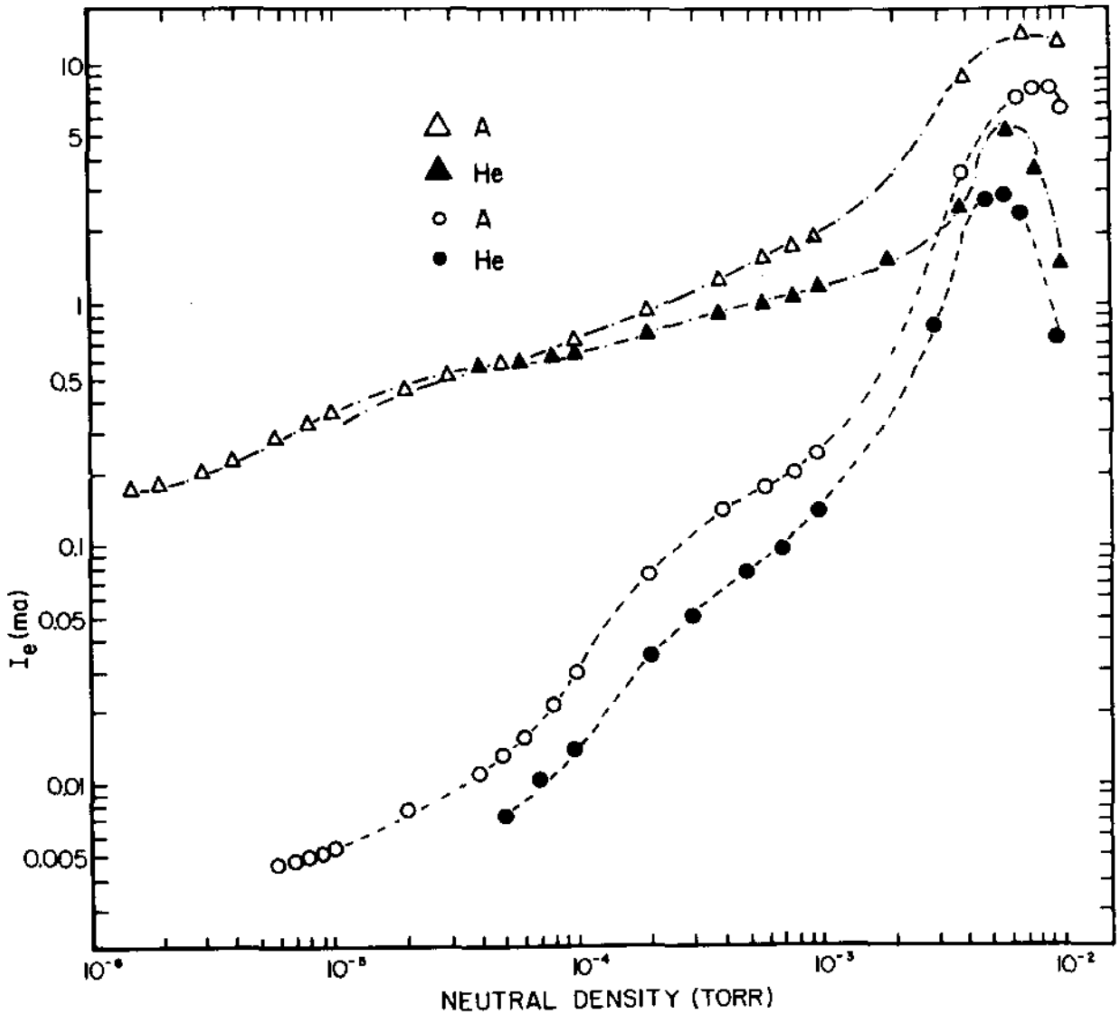
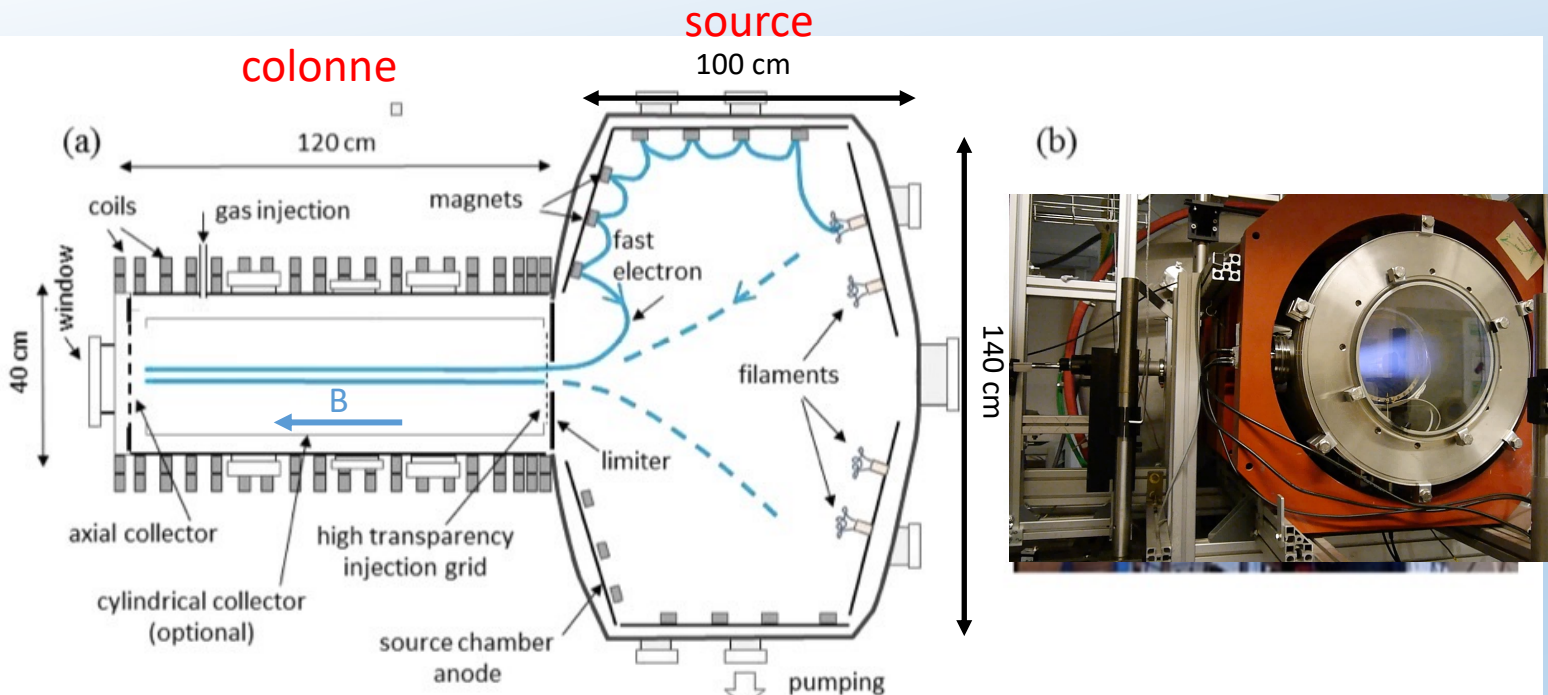


FIG. 2. Plasma density vs pressure for argon and helium in the chambers with magnetic walls (triangles) and nonmagnetic walls (circles).

L'expérience MISTRAL

- Créée en 2000 par Th. Pierre et G. Leclert déclinaison de la machine **MIRABELLE** (G. Leclert, IJL, Nancy).
- **But** : étude des instabilités d'une colonne de plasma magnétisée.
- 2 parties :
  - **Source** = décharge multipolaire de grand volume → faisceau d'électrons primaires ionisants.
  - **Colonne** = zone d'étude d'une colonne de plasma magnétisée.



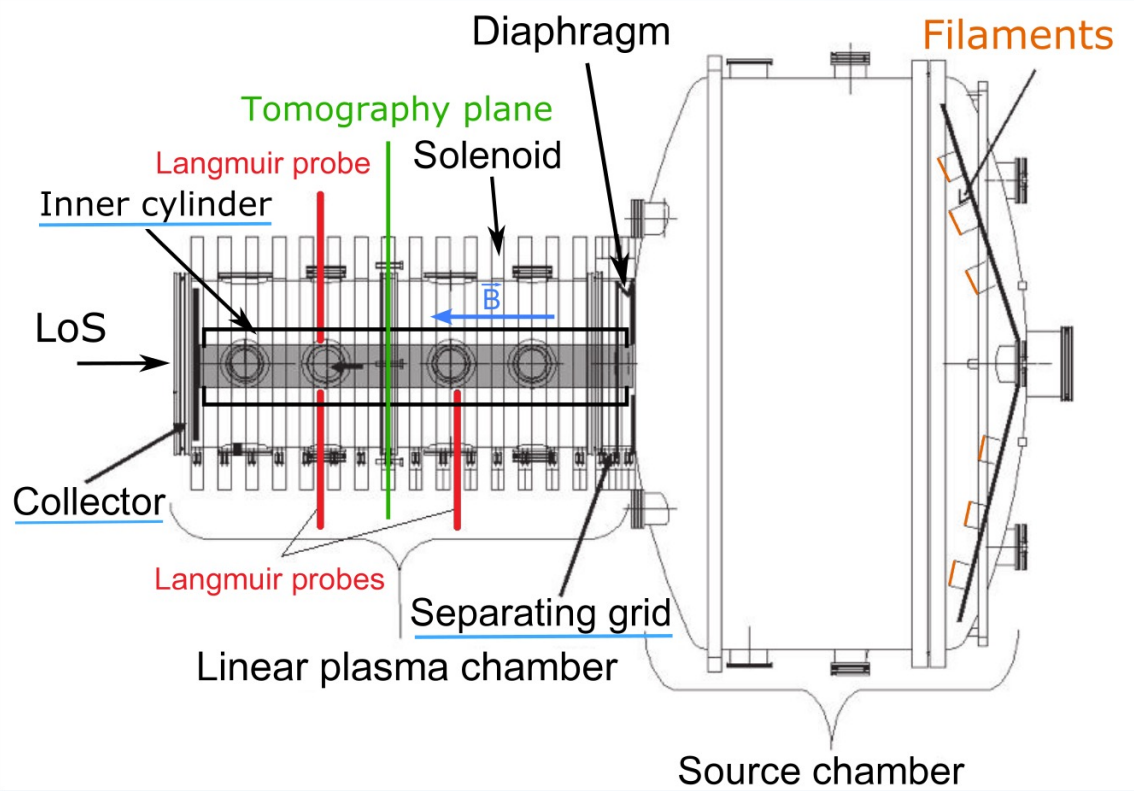
L'expérience MISTRAL

- $r_{limiter} = r_{plasma} = 40$ mm
- $P_{vide} = 1E^{-6}$ mBar.
- 5.10^{-5} mbar < P < 10^{-2} mbar
- $B_{solenoid}$ < 30 mT
- Gaz : He, Ne, Ar, Kr, Xe

- 1 eV < T_e < 5 eV
- 10^{14} m^{-3} < N_e < 10^{17} m^{-3}
- $T_{Ar\ neutral}$ = 300 K
- $T_{Ar\ ion}$ = 1100 K
- N_{ep}/N_e = 3 %

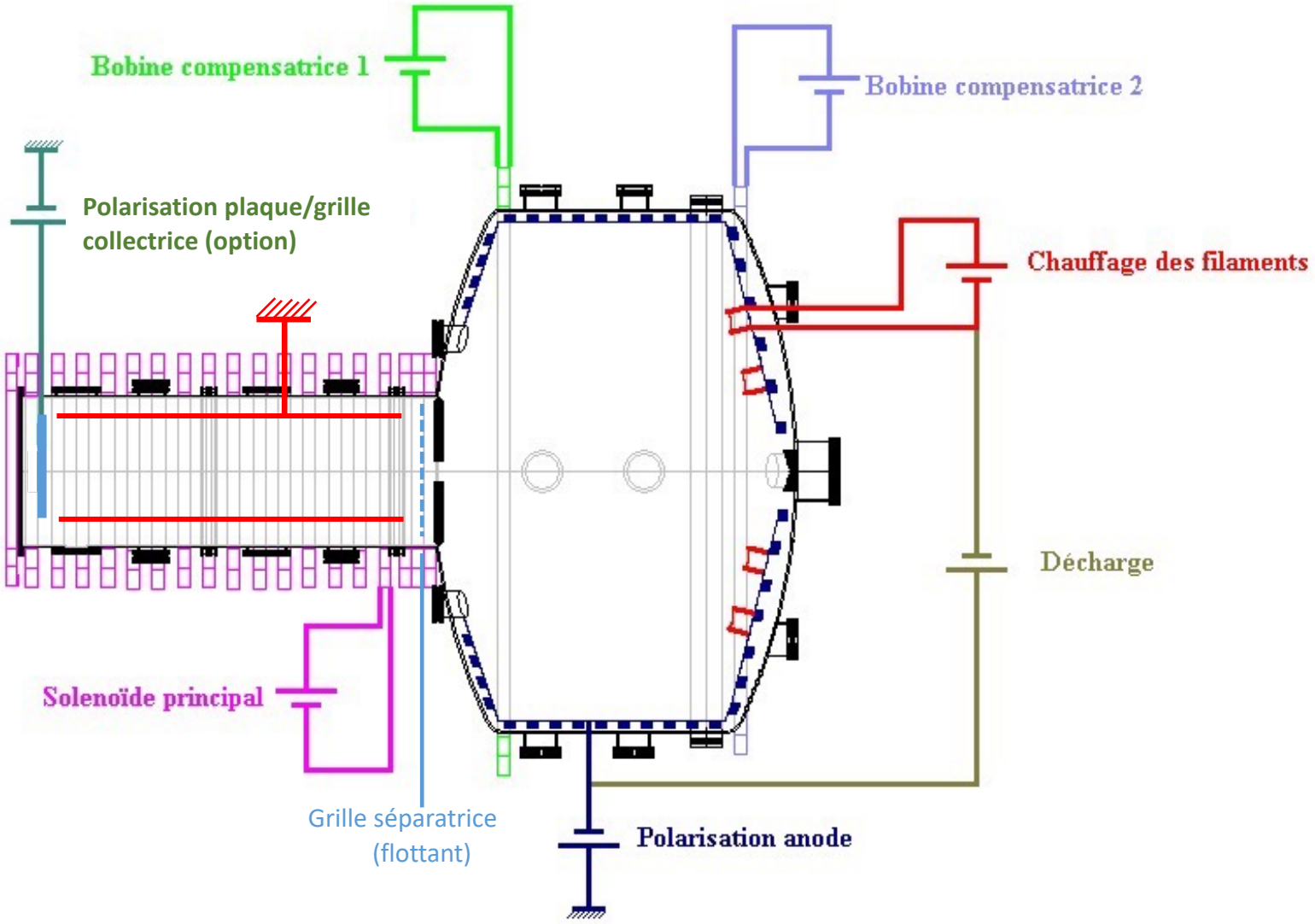
- ν_{ci} = 1 kHz (1.5E-4mBar Ar ; 160 G)

→ ions faiblement magnétisés

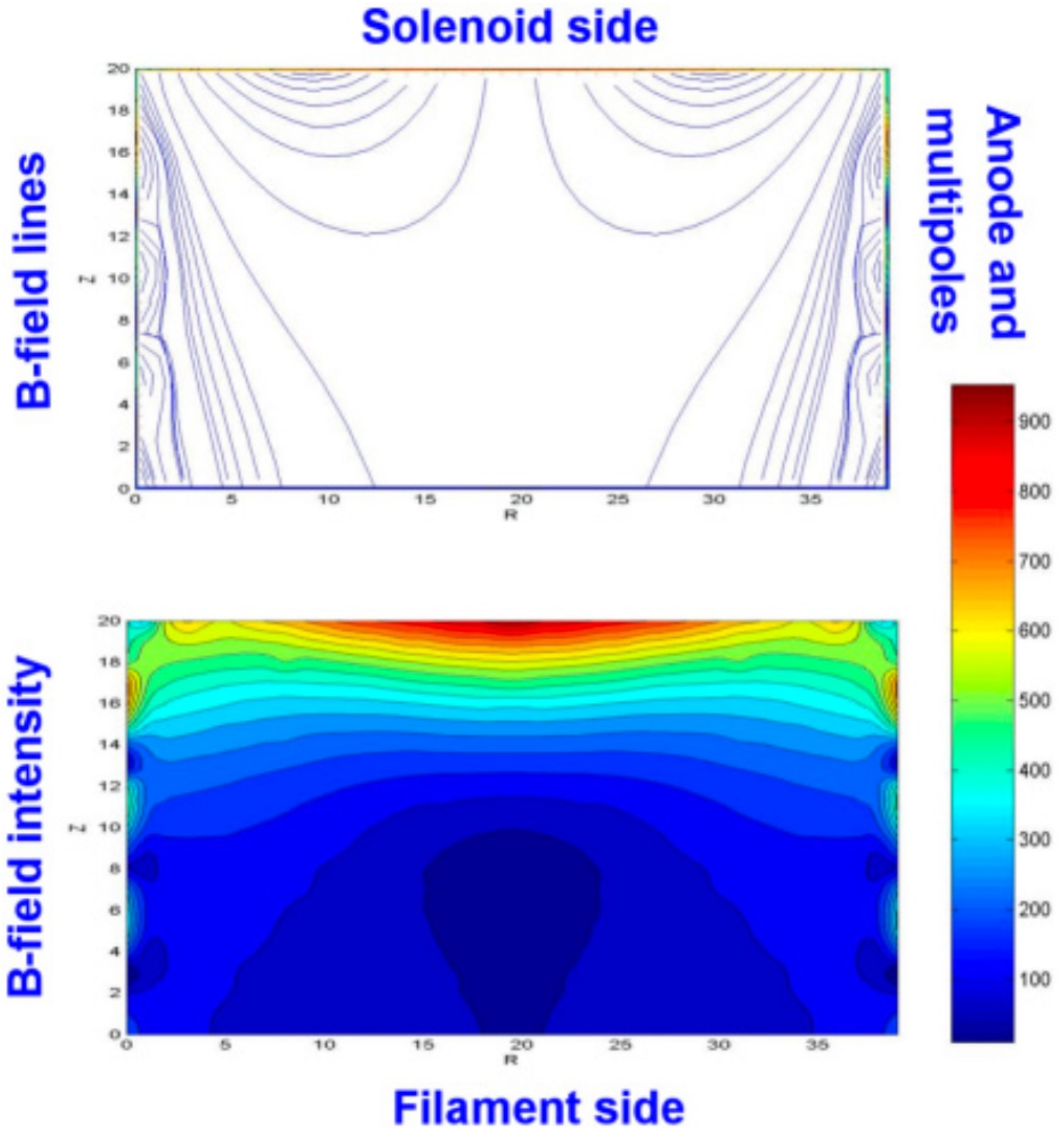


Chambre source de Mistral

Chambre source de Mistral



Configuration magnétique de la source



- **Bobine compensatrice 1** (côté solénoïde) : montée en opposition / Bsolénoïde.

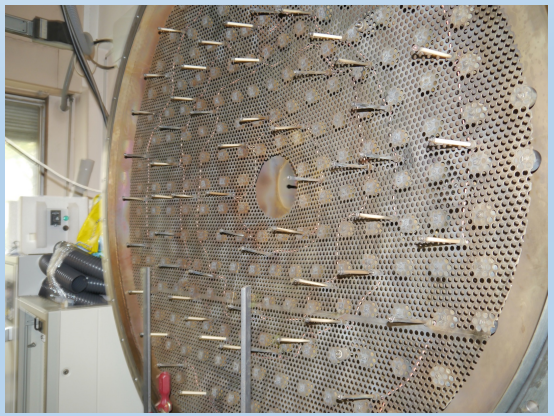
→ Limiter $B_{solénoide}$ dans la source.

→ $I_{typique}$: 110 A (pour I_{Sol} = 160 A)

- **Bobine compensatrice 2 (**côté filaments)

→ création d'un « cusp » pour isotropisation des é.p.

→ $I_{typique}$: 40 A (pour I_{Sol} = 160 A)

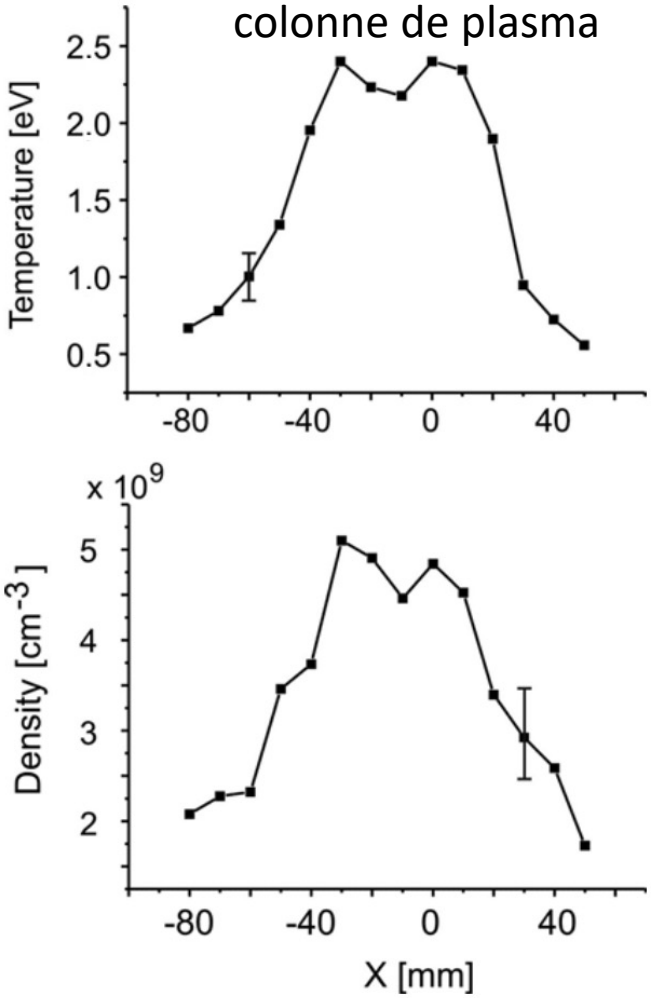


Barni et al., New J. Phys. 2005

Rôle des électrons primaires dans Mistral

Distribution radiale de n_e, T_e et rôle des é.p.

colonne de plasma



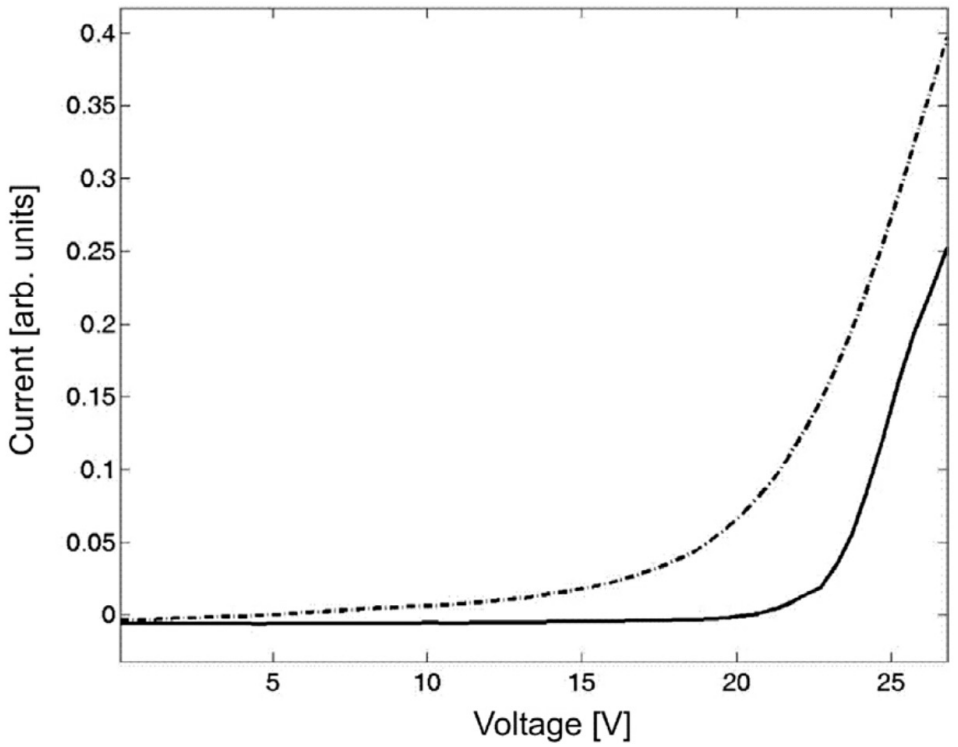
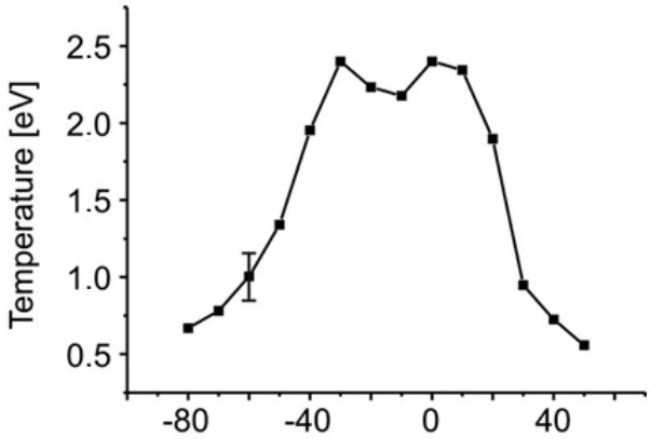
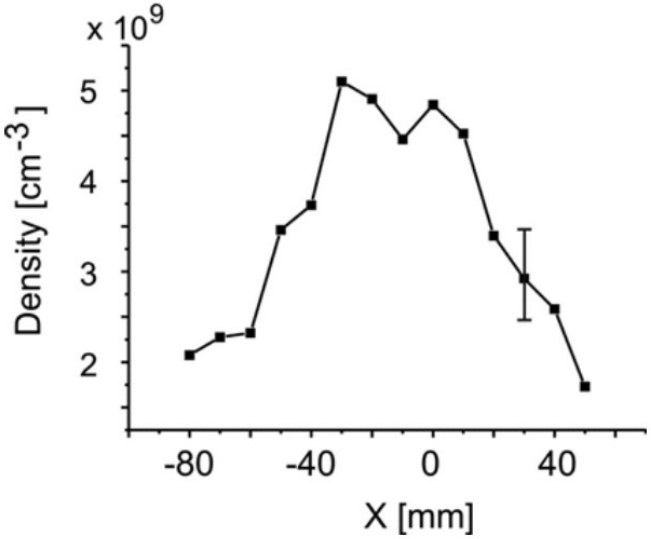


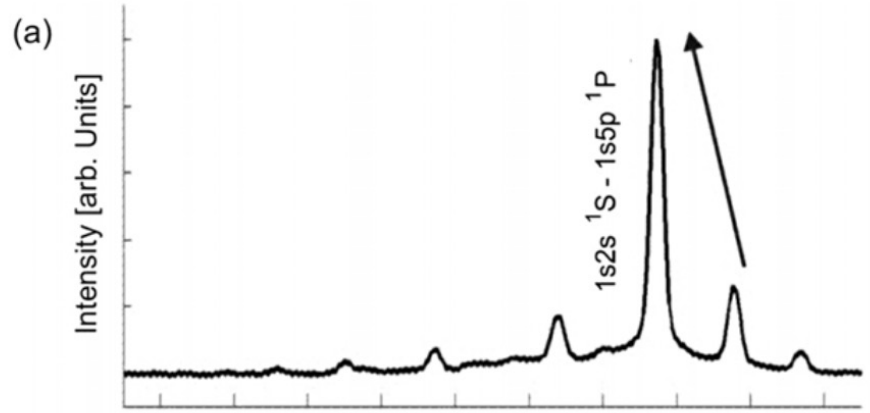
Figure 2. Langmuir probe characteristics with primary electrons (first experimental configuration: dashed-dotted line) and without primary electrons (second experimental configuration: solid line): The slope of the left part of the dashed-dotted curve (ionic saturation region) is increased, indicating a hot electron fraction.

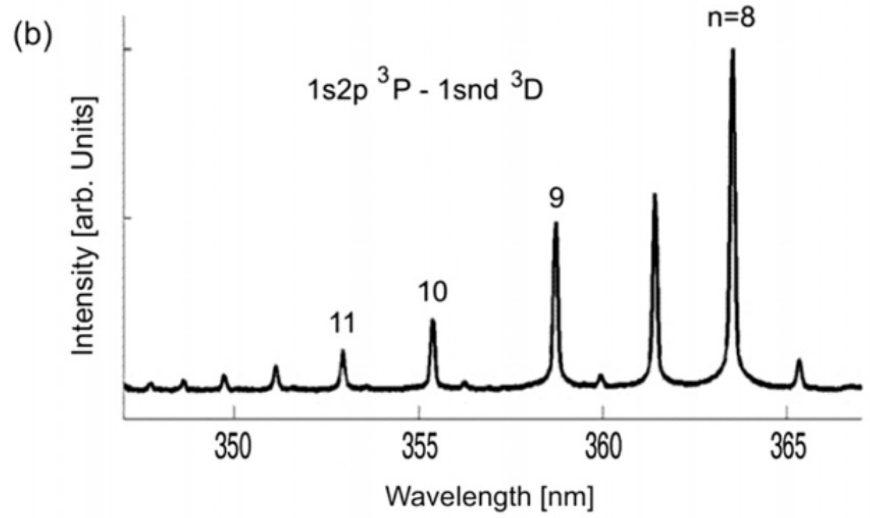
Escarguel et al. PPCF 2007

Distribution radiale de n_e, T_e et rôle des é.p.









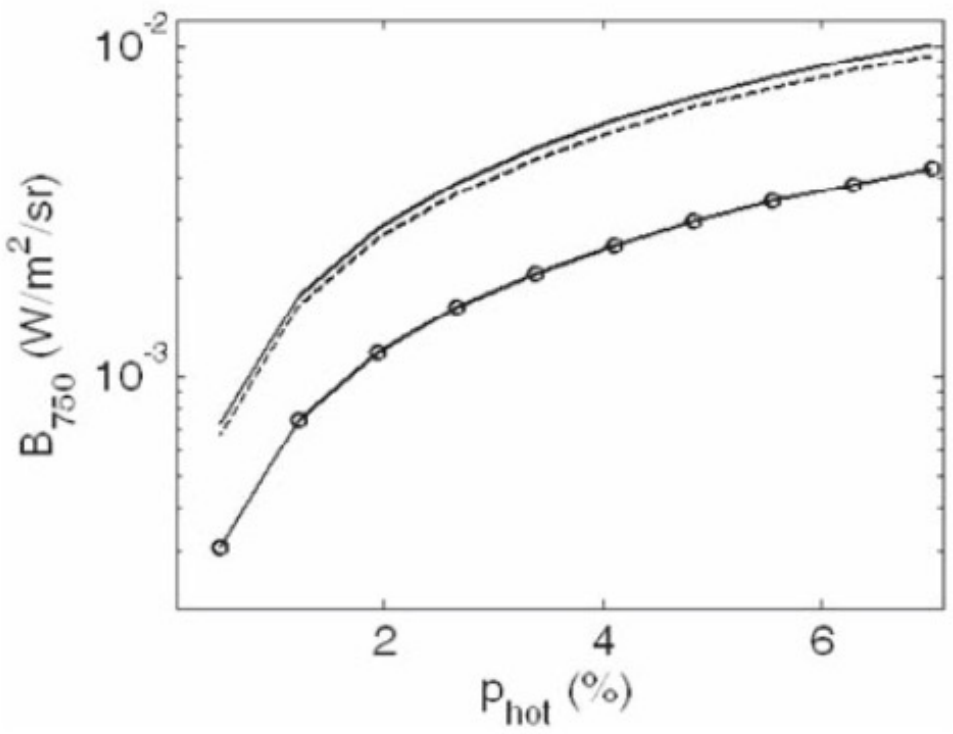
Escarguel et al. PPCF 2007

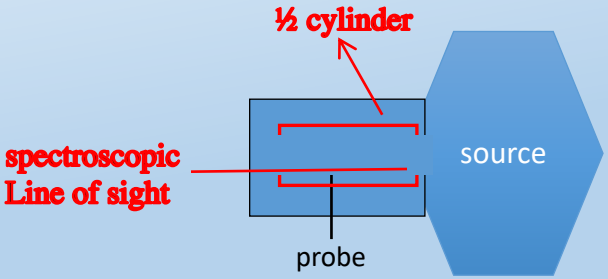
Role of primary electrons (p.e.) in the plasma column dynamics

- $\mathbf{p_{hot}}$ = percentage of p. e.
- **Visible emission spectroscopy:**

Corona equilibrium for calculation of ArI(750 nm) brightness

→ Shows the presence of a few percents of p.e. in the shadow of the limiteur.





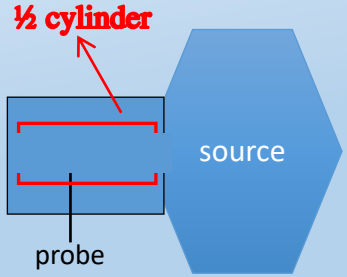
[Escarguel EPJD 2010]

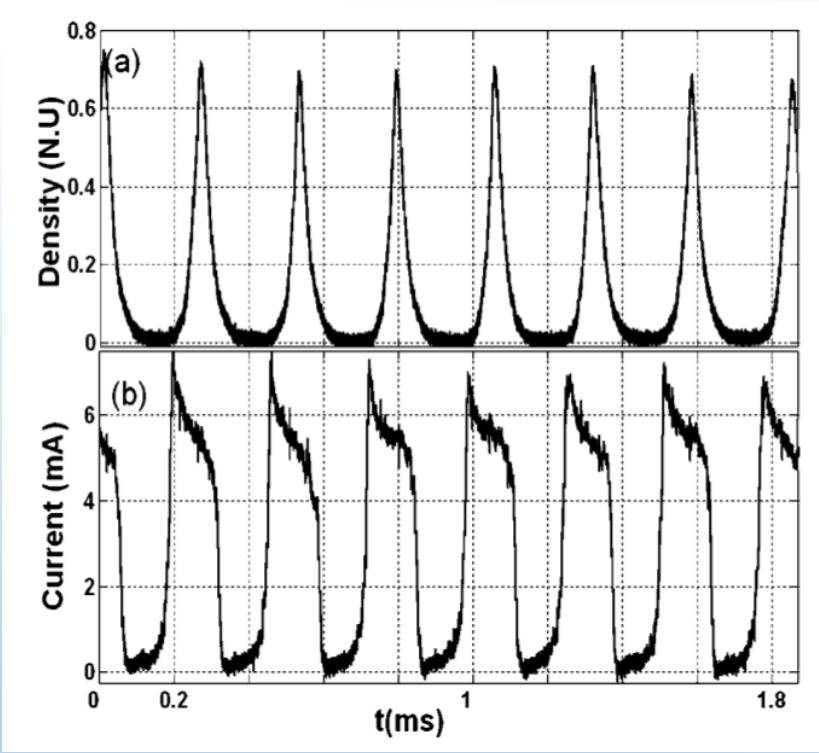
Instabilités non linéaires en rotation autour d'une colonne de plasma

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)





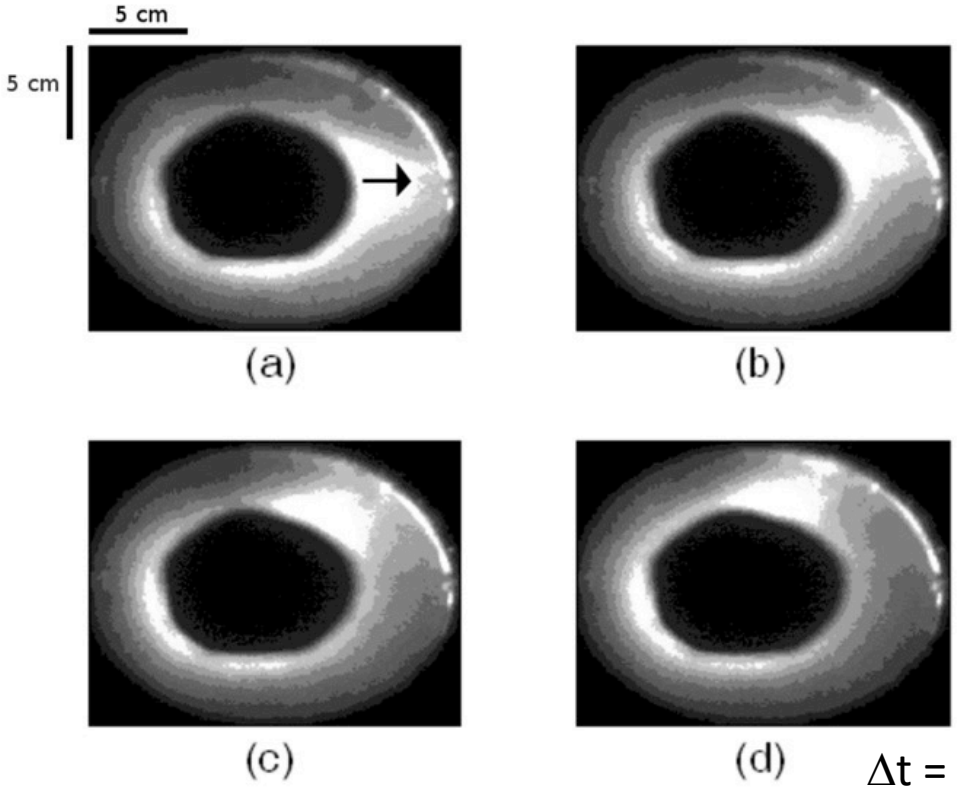
[Jaeger POP 2009]

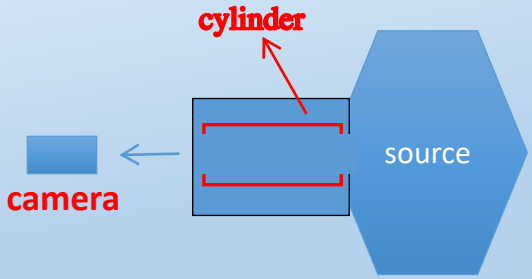
Fast camera results (end view of the plasma)

m=1, 2 regular modes rotating around central plasma column

V_{anode} > 0 : plasma « calme »

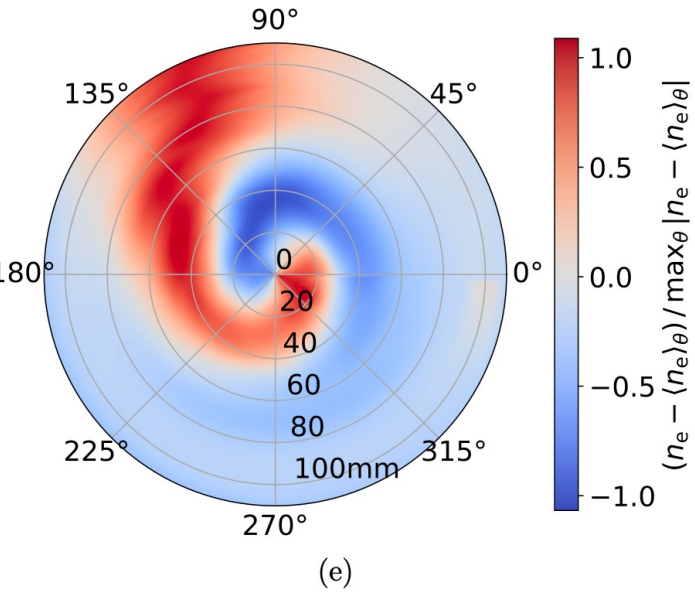
V_{anode} < 0 : plasma instable → modes réguliers en rotation (qques. kHz)





[Escarguel EPJD 2010]

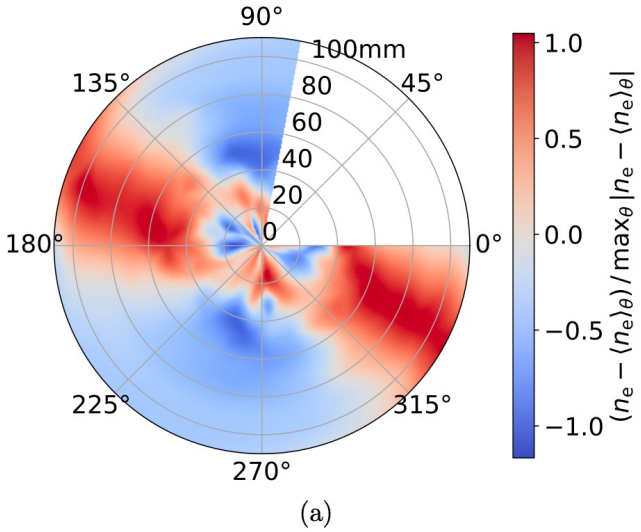
Fast camera results (end view of the plasma)



(e)

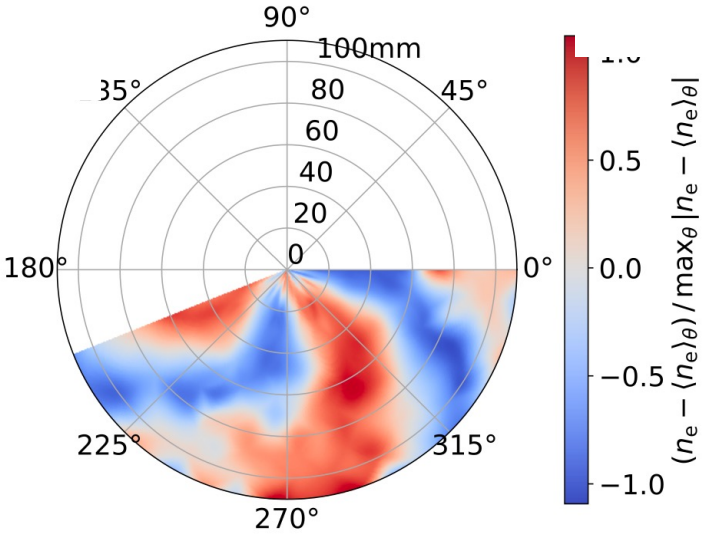
m=1

m=3



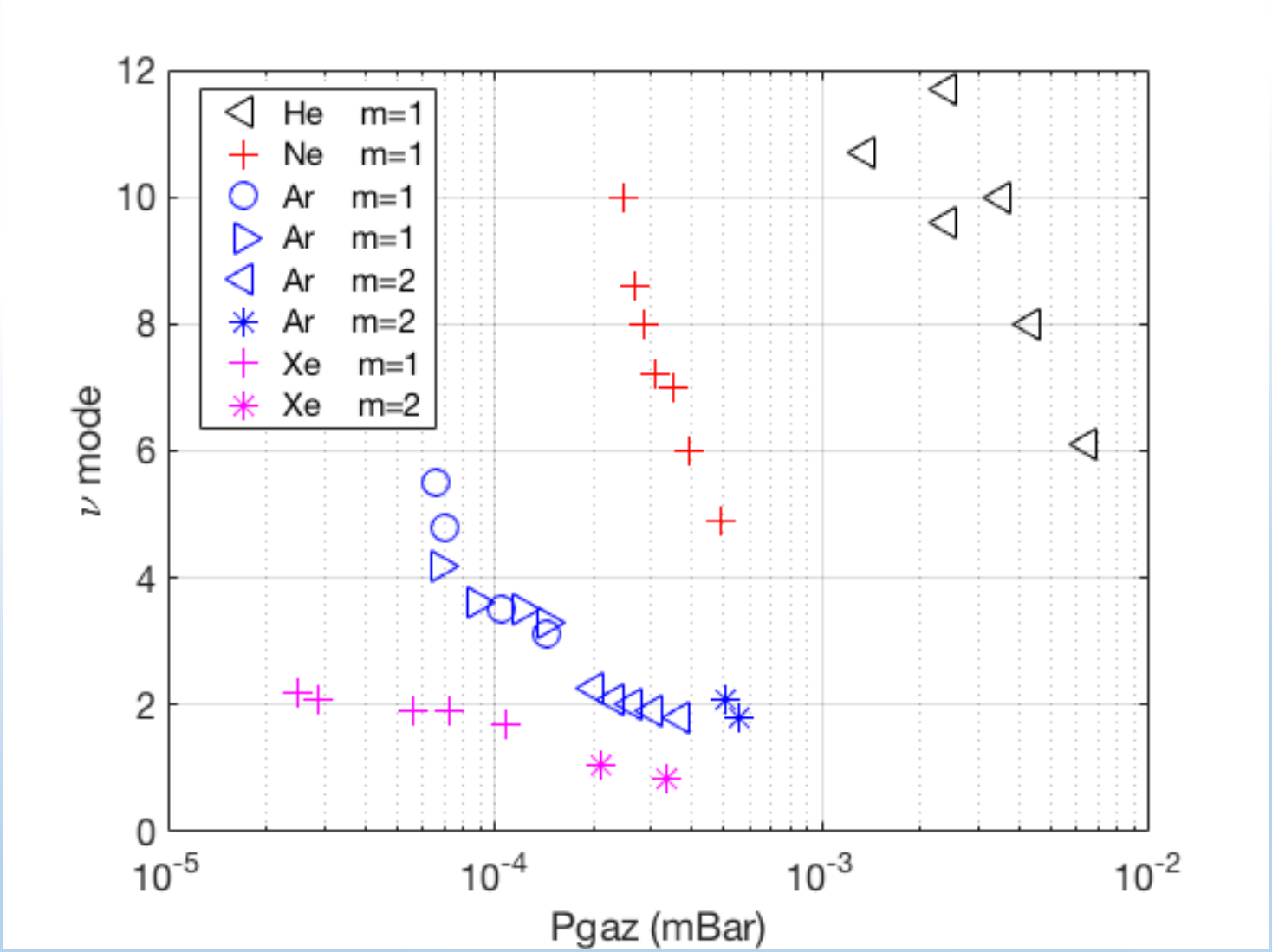
(a)

m=2



(e)

Spoke rotation frequency = f(P)



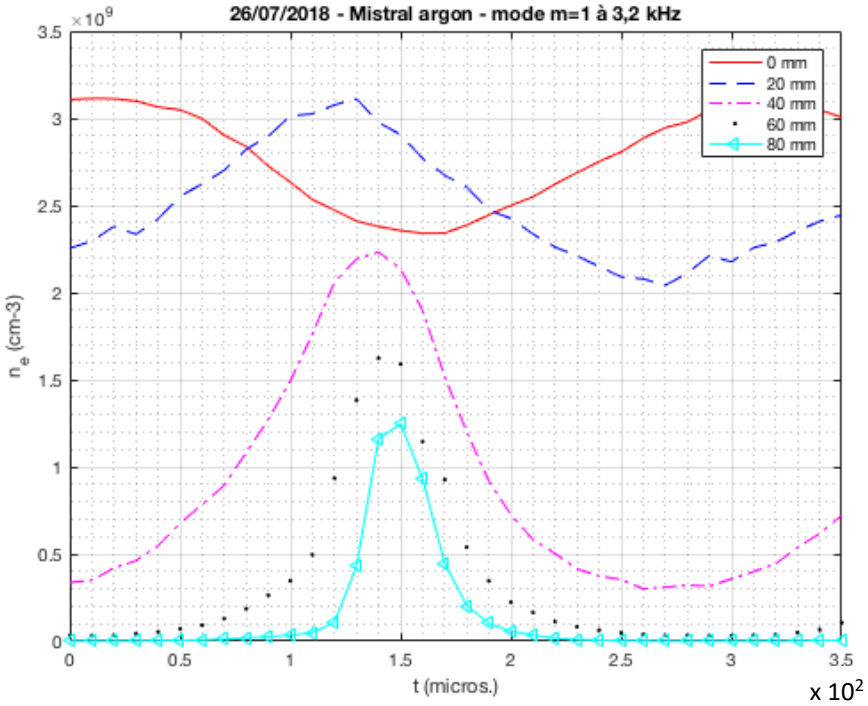
Publication en cours

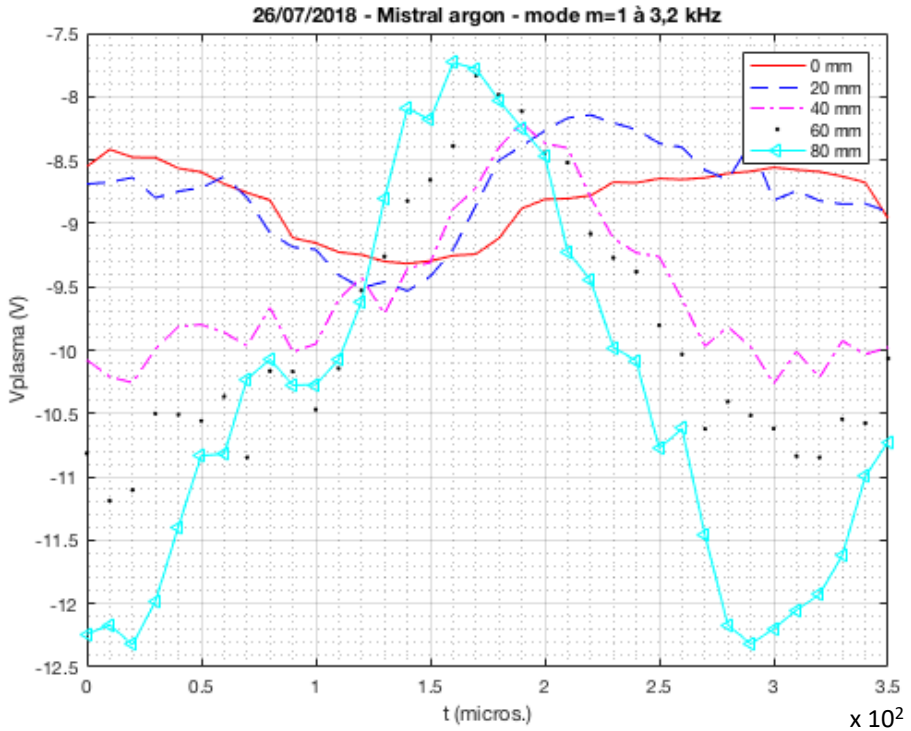
Spatial/time resolved study of a m=1 spoke in argon

- Synchronized Langmuir probe
- 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) ≈ $\pi/2$ in the shadow of the limiteur





m=2 spoke: ArII Laser Induced Fluorescence measurements

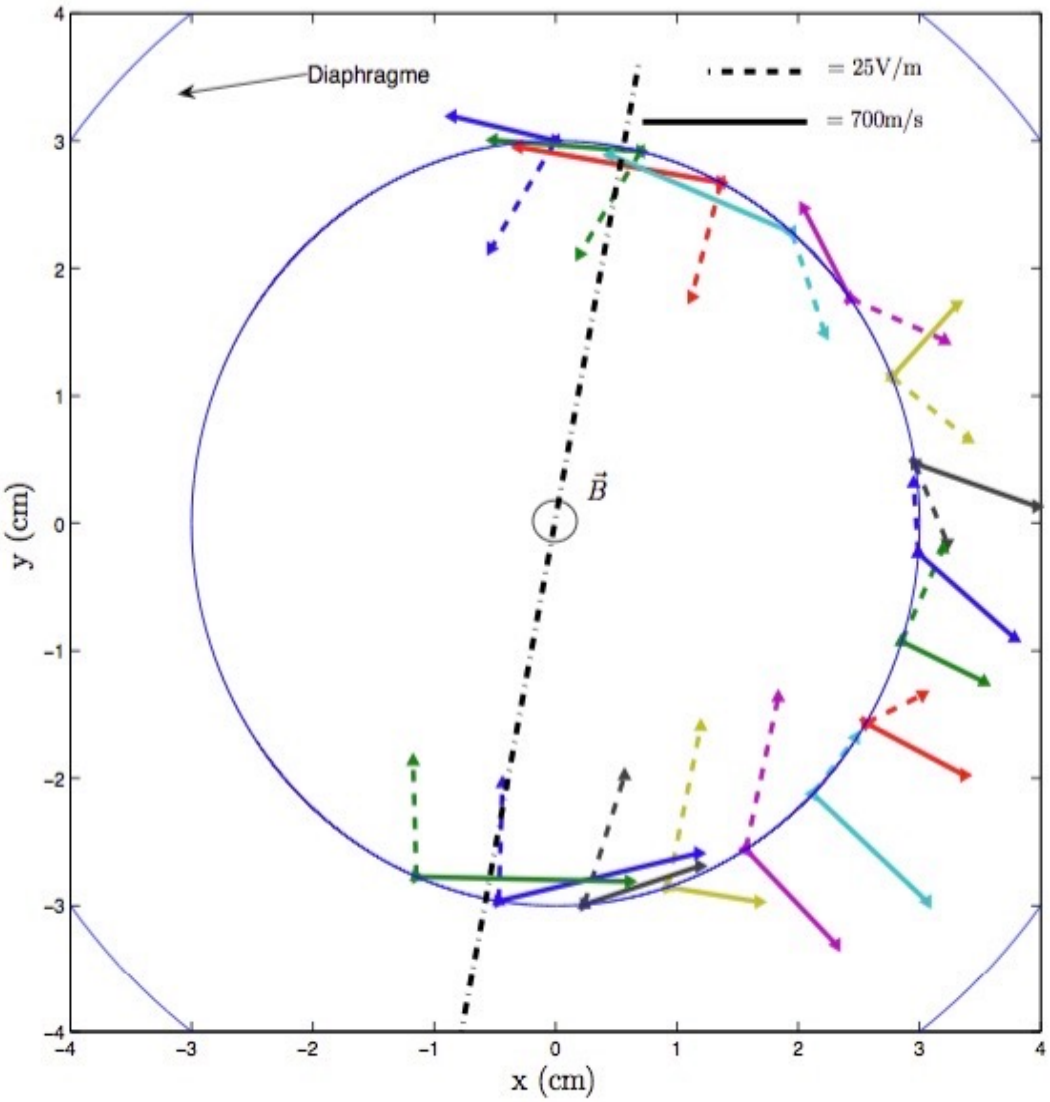
- No surrounding cylinder
- Diaphragm r=5cm
- ν_{spoke}=7.5kHz
- Separating grid = 4V
- Collecting grid = 20V
- P_{Ar}= 2.5.10^{-4}mbar
- B=160G

ArII velocity:

- inside the spoke: azimuthal inward ≠ from v_{spoke}
- outside the spoke: radial
- N_e and v_θ in phase

Electric field:

- inside the spoke: radial
- outside the spoke: azimuthal

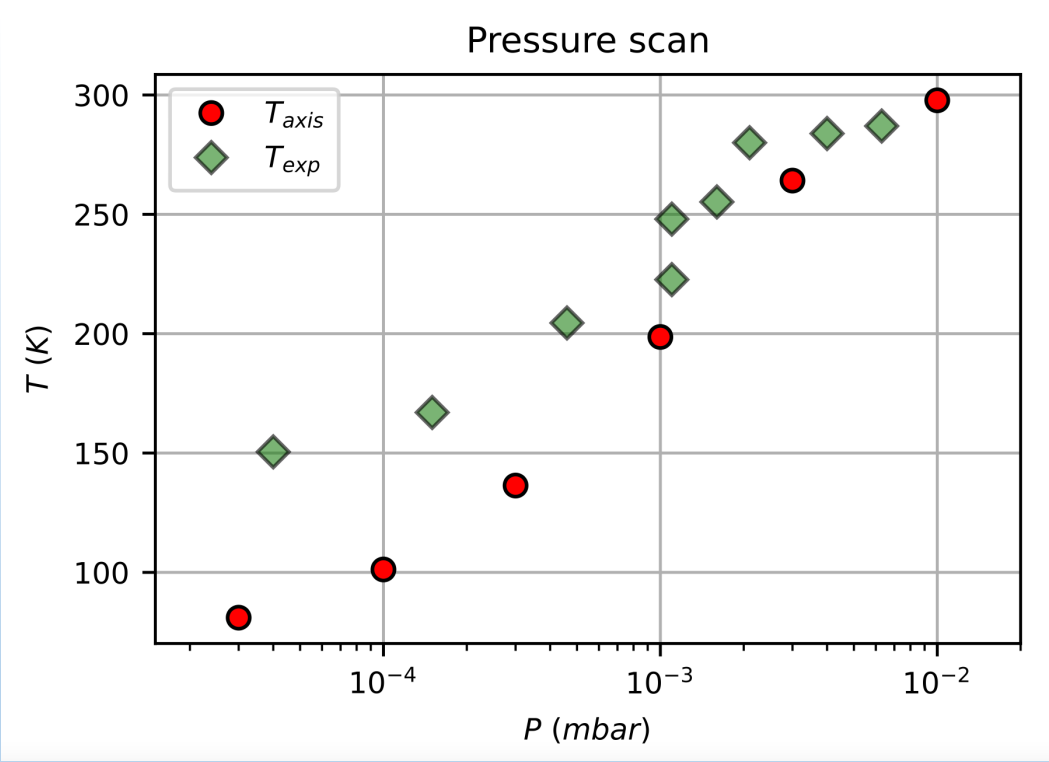


C. Rebont, PRL 2011 ; Claire POP 201

Non localité de la fluorescence induite par laser

Mesures de Fluorescence Induite pas Laser dans un plasma basse pression : attention aux effets non-locaux !

- « High pressure » acquisition : T_{ArI} = ambient T
- T_{ArI} decreases when P decreases: non-local effect of metastable destruction on the walls

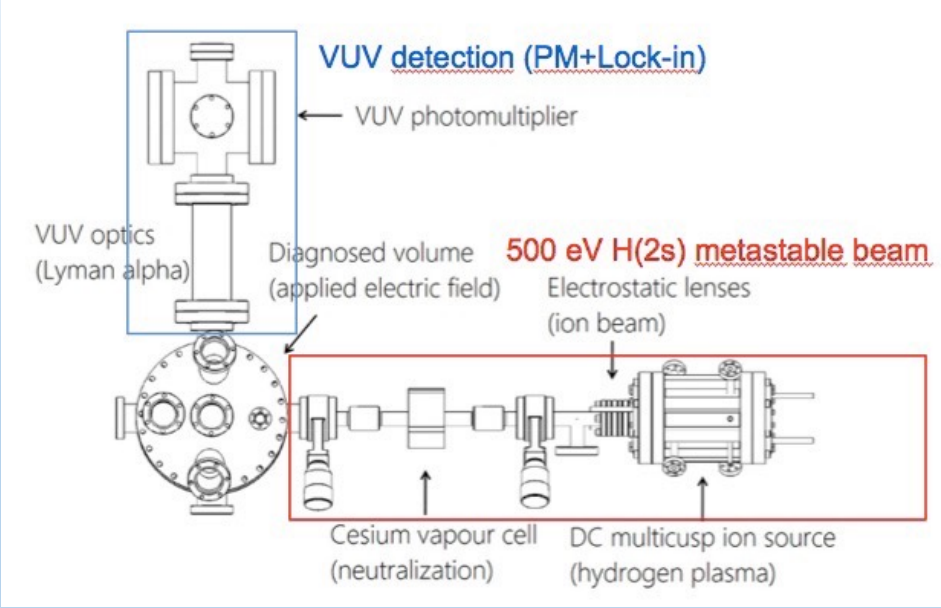


Publication en cours de rédaction

Mistral as a reference experiment for diagnostics development

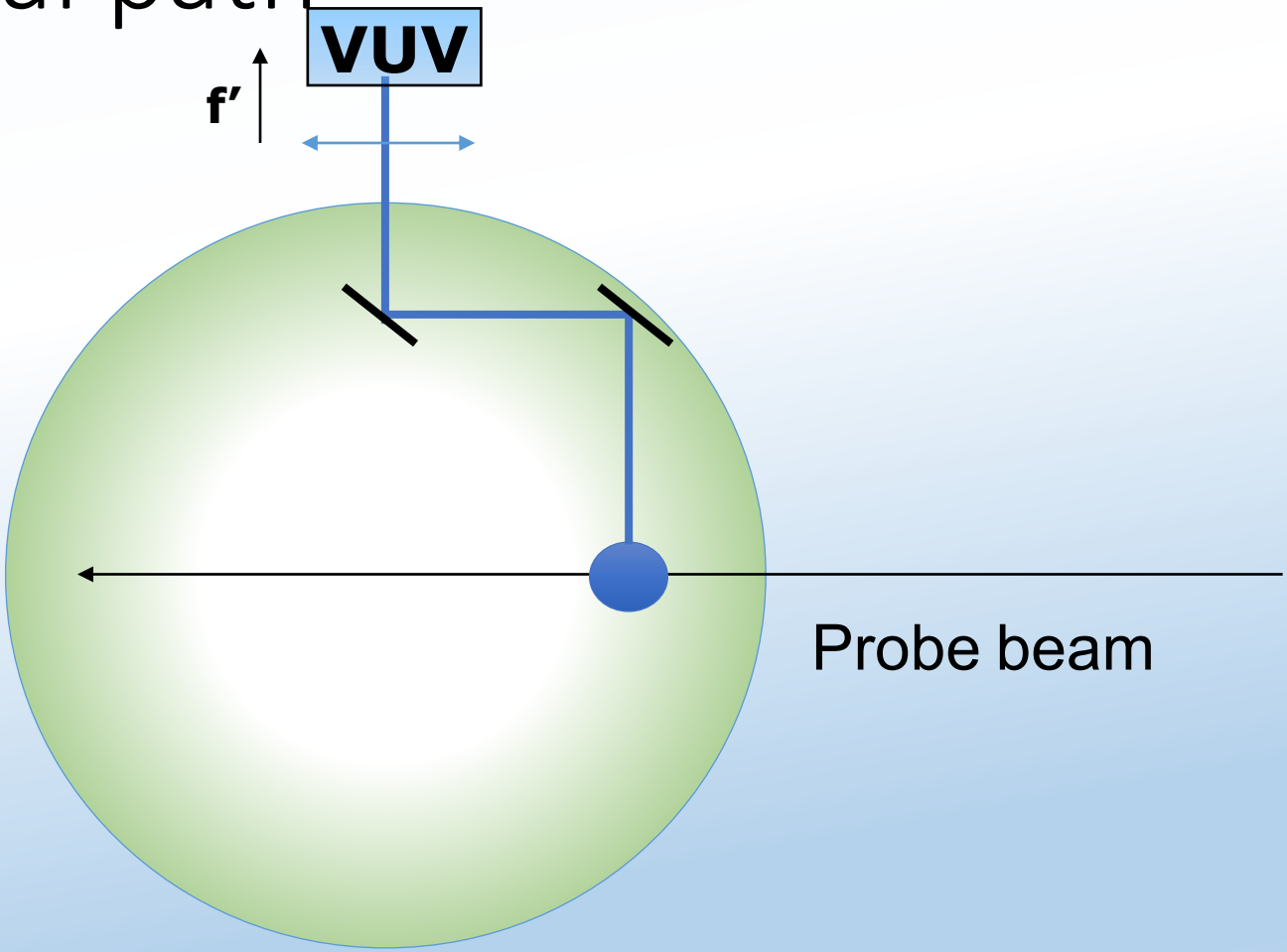
Development of a diagnostic to measure directly The local electric field : EFILE

- Local lectric 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**
- Absolute calibration / damping of metastables by MSE



[Cherigier-Kovacic RSI 2015 ; Doveil PPCF 2016]

4. Optical path



Mirror diameter: 1".
Photomultiplier sensor surface: 8 x 12 mm

Visible tomography

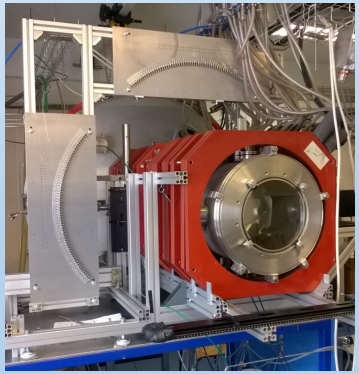
→Advantages :

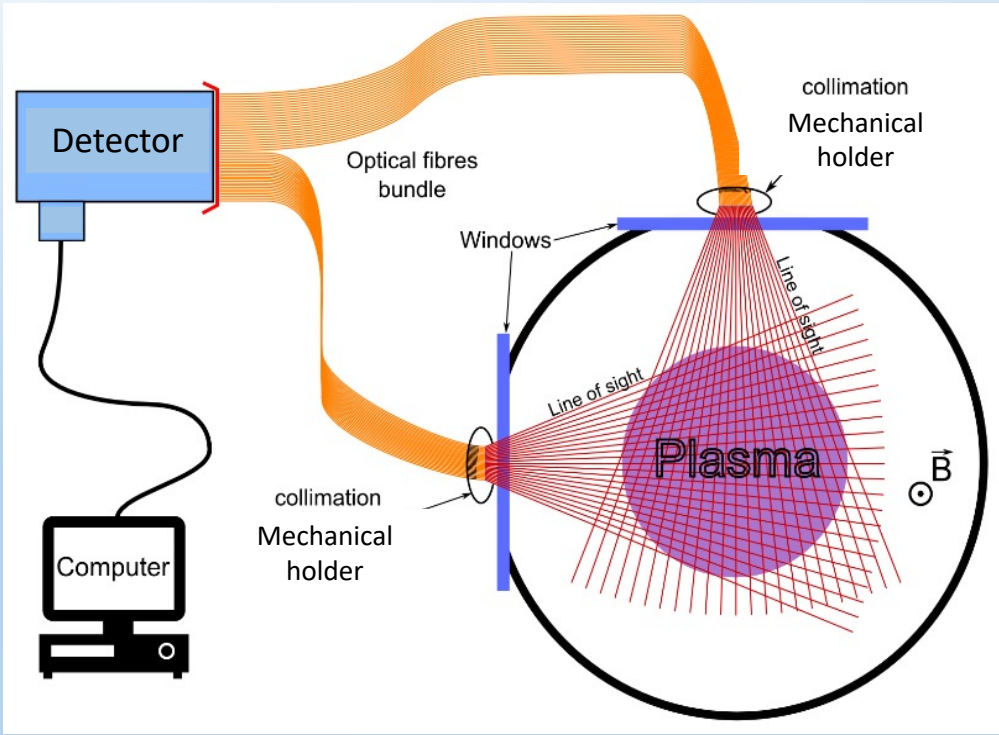
- 2D spatial structure of regular modes without any hypothesis
- non intrusive

→« Turbulent » modes study

→Possible « one shot » acquisition

→2x64 channels, ν_{acq} = 1 MHz





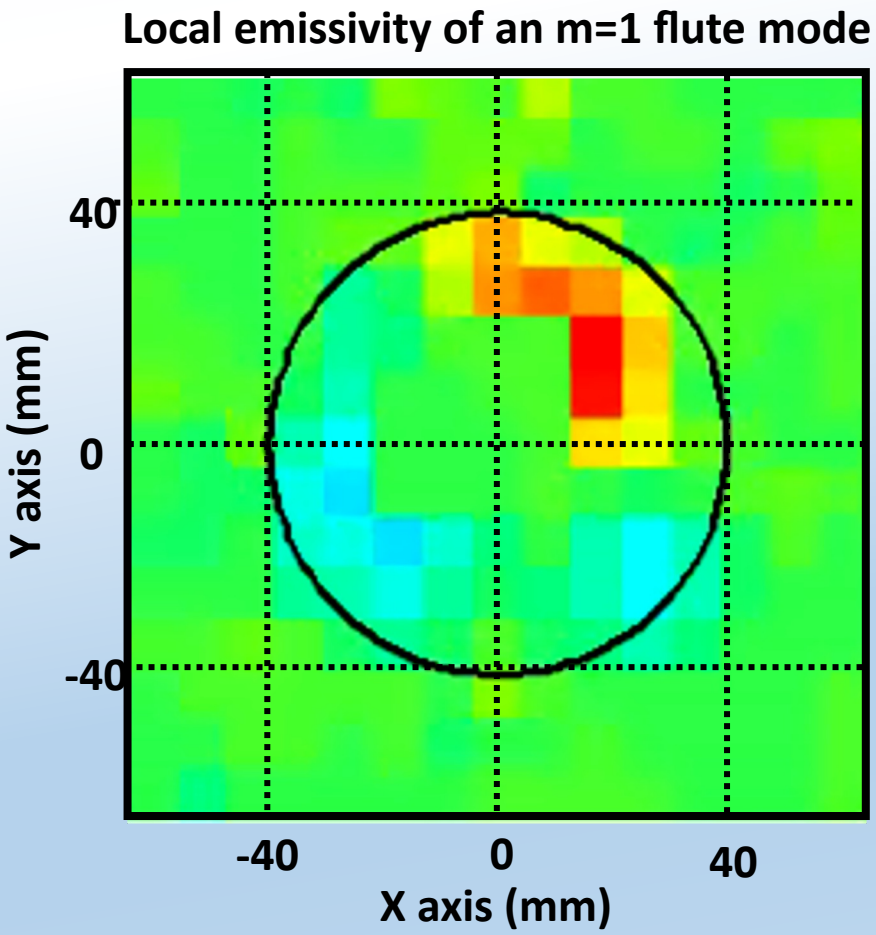
Optical tomography: m=1 rotation

→Spatial structures of regular modes

→Weak perturbation by probe

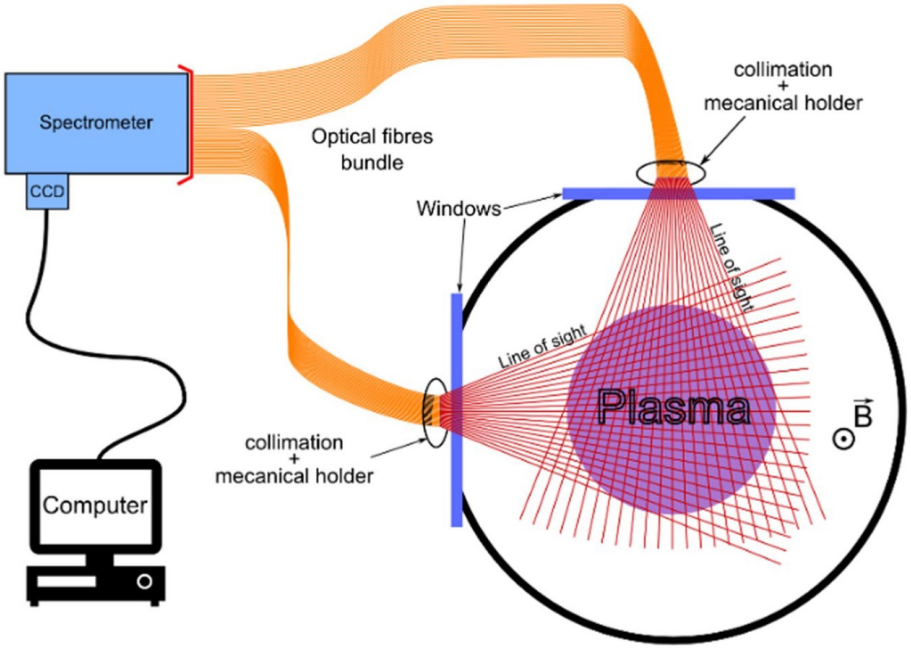
→ Radial profile more peaked: primary electrons

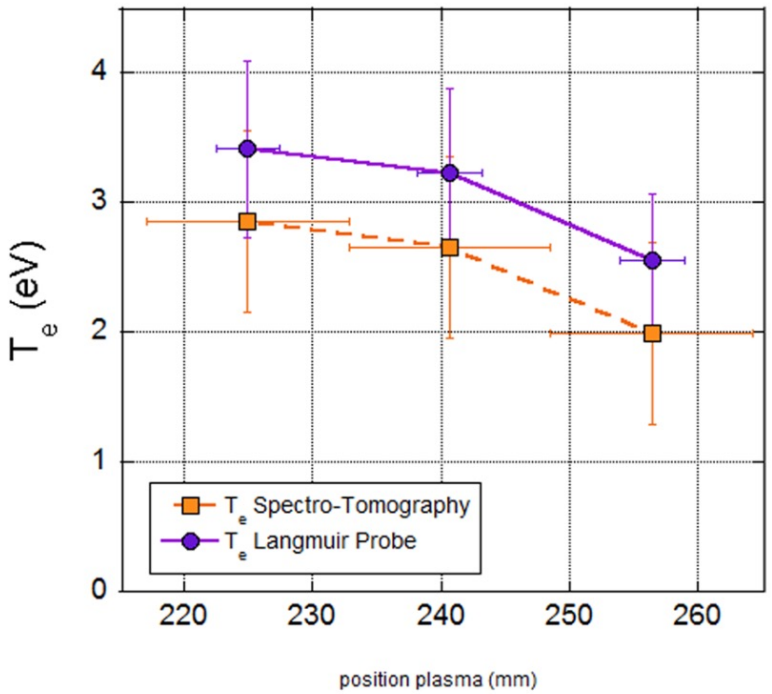
→V_p and n_e : $\pi/2$ phase delay



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

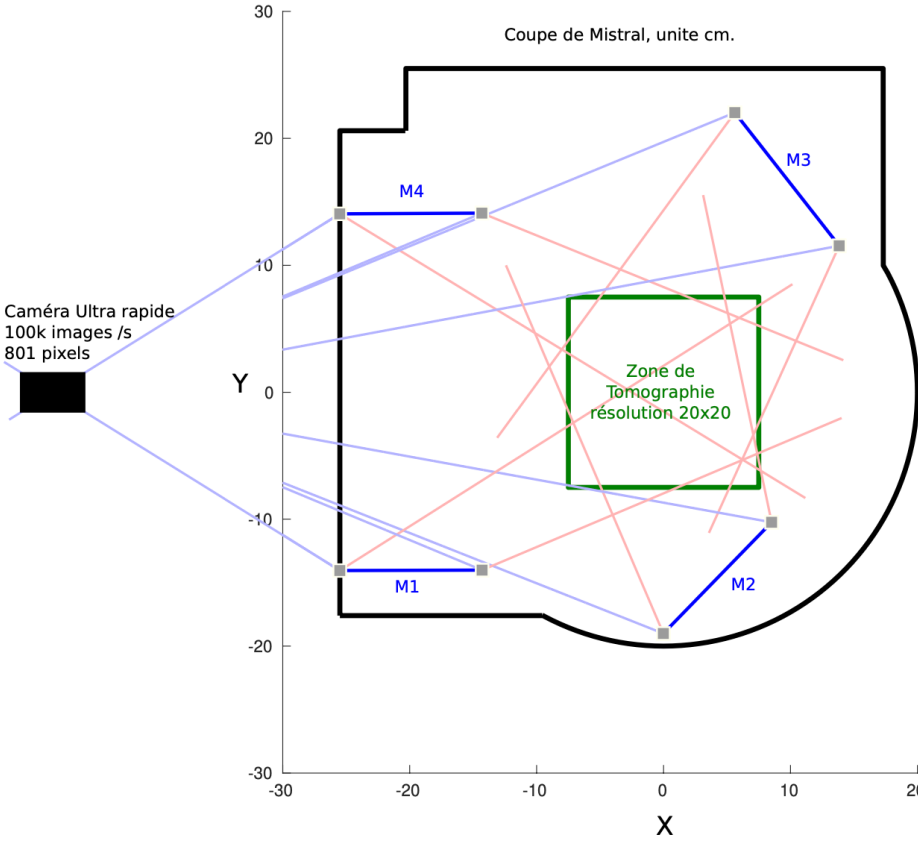
Development of a spectro-tomography diagnostics

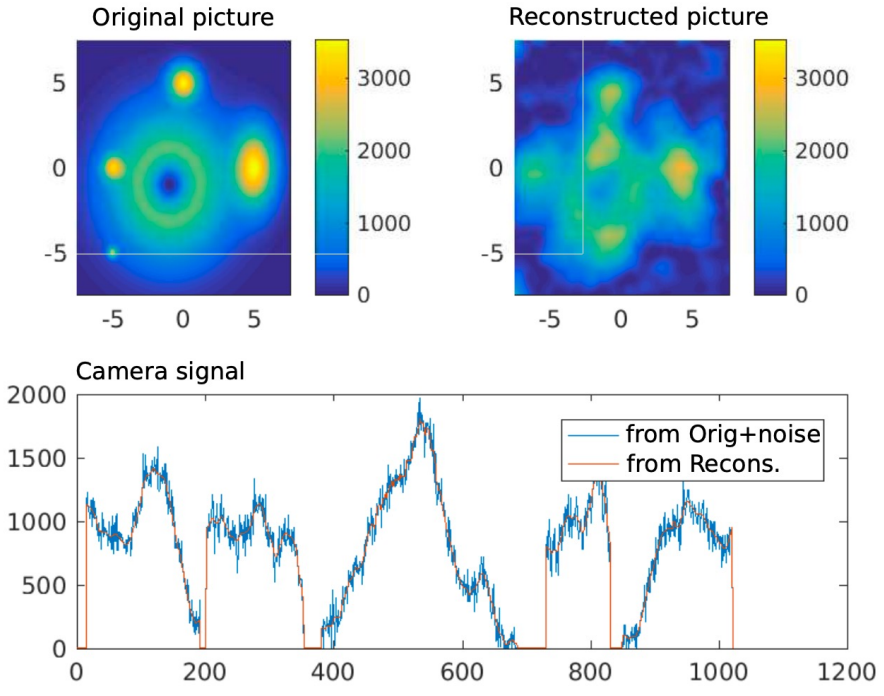




[V. Gonzalez et al. Scientific Reports 2020]

Development of tomography / spectro-tomography diagnostics





L'expérience MISTRAL

Avantages

- Contrôle facile du **diamètre** de la colonne par l'insertion d'un limiteur,
- Colonne de plasma de **grand volume homogène** (radial/axial),
- Source d'ionisation « ***simple*** » : alimentation continue 20 V 150 A.
- Dispositif expérimental « ***sécure*** » : pas de tension > 50 V.
- Fonctionnement **permanent** (limite : chauffage de la paroi de la source)
- **Pas d'onde** ! → Bien pour les diagnostics de sonde !

Inconvénients

- Possibilité de réaliser une version plus petite à voir
- Utilisation d'une petite source transportable de type multipôle ?
- Présence permanente d'un ***faisceau d'électrons primaires*** : E_{ep} = 40 eV, T_{ep} = 16,5 eV
  - À considérer dans l'analyse des carac. de sondes !
  - Rôle important dans le rayonnement du plasma !
  - Ces é.p. jouent un rôle important dans la physique des instabilités observées !

Merci de votre attention