Experimental evidences of trapped E.M. waves in an axis-symmetric magnetic trap

G. Castro[1], R. Miracoli[2], G. Torrisi[1] L. Celona[1], O. Leonardi[1], D. Mascali[1], and S. Gammino[1]

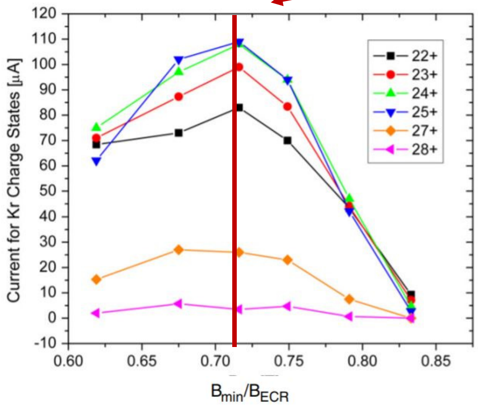
[1]INFN-LNS, Catania – Italy

[2]ESS-Bilbao, Zamudio, Spain

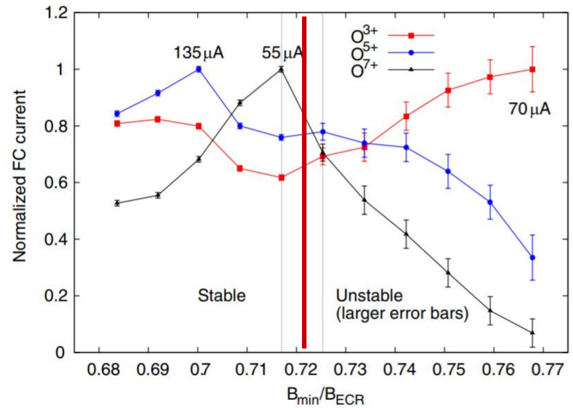
24[rd] International Workshop on ECR ion sources – MSU (USA) - September 28-30

Motivations

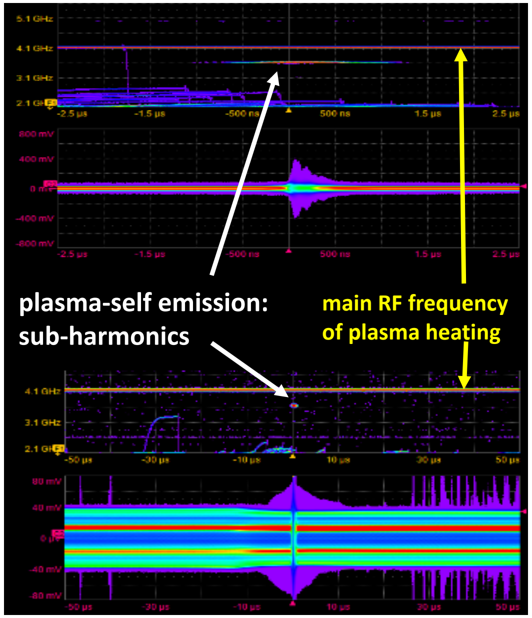
Instability threshold



Gammino et al., PPST 18 (2009) 045016



Tarvainen et al., PSST 23 (2014) 025020



Above a particular B_{min}/ B_{ECR} ratio ~0.7-0.75, Resonant interaction between E.M field and electrons can lead to **cyclotron instability** ---> detrimental to plasma confinement and extracted currents of highly charged ions

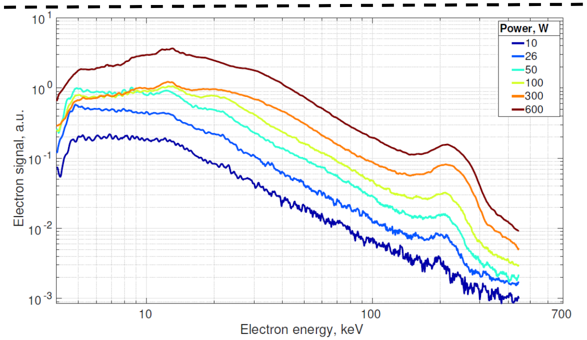
Motivations

$$\frac{dE_\mu}{dt} \approx (\Gamma - \Delta) E_\mu$$

$$\Gamma_x \propto \omega_{ce} \frac{N_{e,hot}}{N_{e,cold}}$$

$$\Delta_x \propto \frac{\omega}{\omega_{ce}} \nu_e + \frac{v_g |\ln R|}{L}$$

Amplification of EM wave whitin the plasma is a key factor to generate kinetic instabilities



Cavity mode excitation by the volumetric cyclotron emission hypothesized to explain hump generation in plasma EEDF.
Izotov et al., On the role of rf-scattering in the electron losses from minimum-B ECR plasmas, Arxiv
.

- Two-Close Frequency Heating (**TCFH** $\Delta f < 1$ GHz) can positively affect plasma stability and improve source performances; (Naselli et al., PSST 28 (2019) 085021), Racz et al., 2018 *JINST* **13** C12012

Motivations

- Modification of few Tens of MHz of the injection frequency can modifies beam shape – beam emittance and Charge State Distribution (**Frequency Tuning Effect- FTE**);
- Two-Frequency Heating (**TFH**, $\Delta f \sim$1-5 GHz, improves the production of higher charge state;
- Electron Bernstein Waves production for overdense plasmas generation ---> Proton sources;
- Etc. etc.

Microwave-to-plasma coupling is crucial in determining beam characteristics:

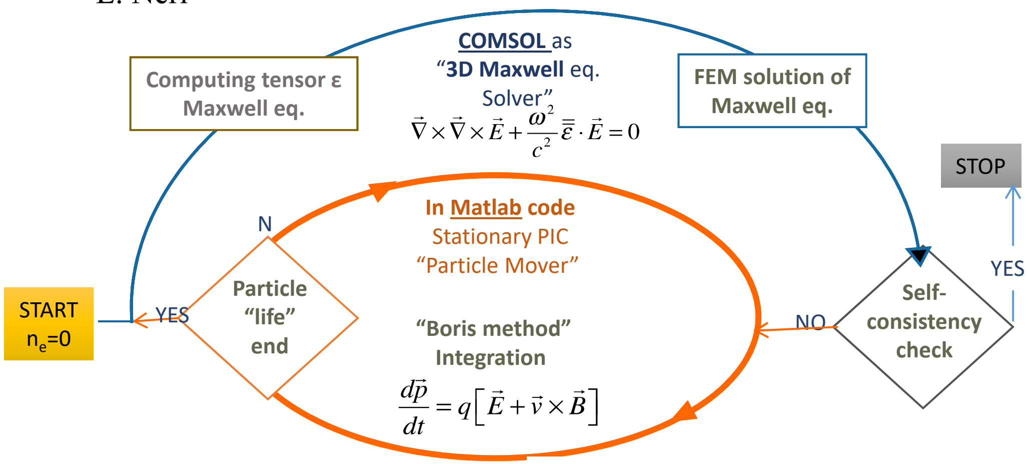
Simulation Approach:
(Development of self-consistent models)

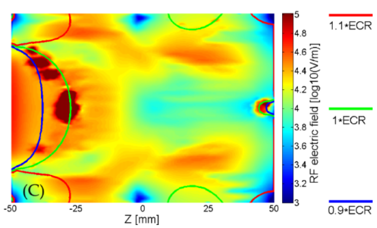
Experimental Approach:
(Direct measurement of RF power and spectrum)

Motivations

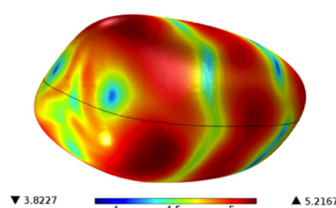
Courtesy of L. Neri

Simulation Approach:
(Development of self-consistent models)



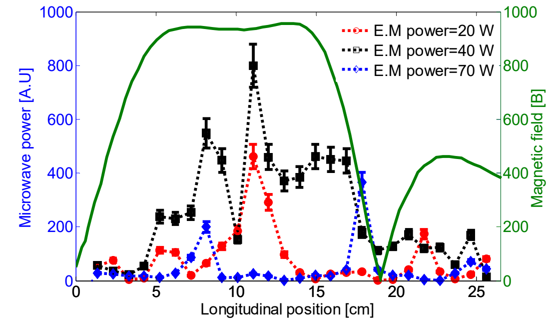


L. Neri et al., RSI, **87** (2016) 02A505;

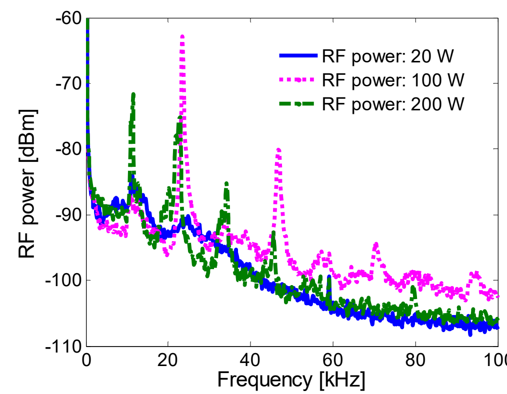


Mascali et al., Eur. Phys. J. D (2015) 69: 27

Experimental Approach:
(Direct measurement of RF power and spectrum)



Modal behaviour: In plasma detection of E.M modes

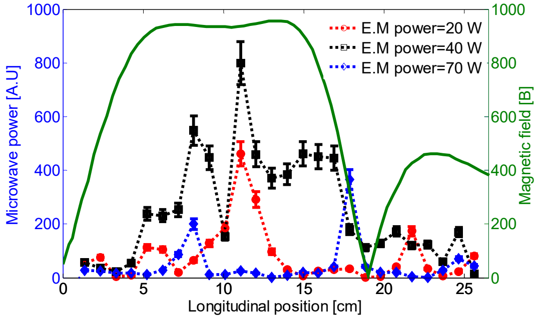


Instability characterization: ES wave generation or emission

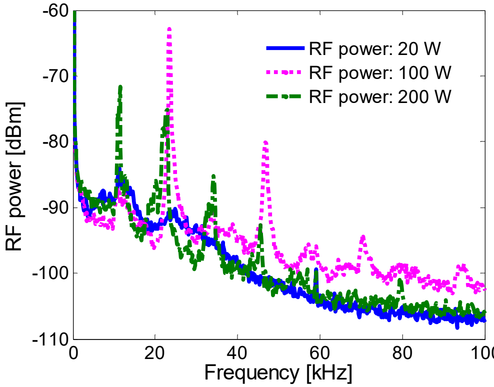
Simulation Benchmark

Motivations

Experimental Approach:
(Direct measurement of RF power and spectrum)



Modal behaviour:
In plasma detection of E.M modes



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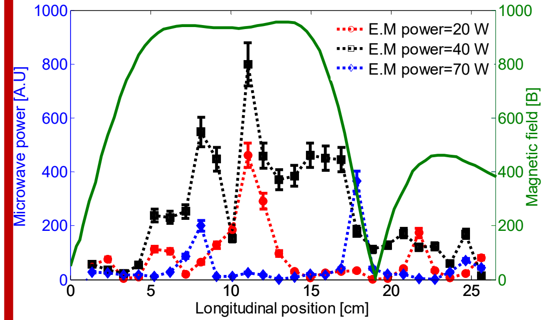

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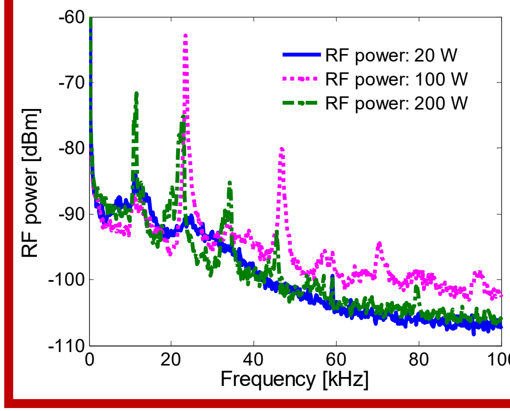
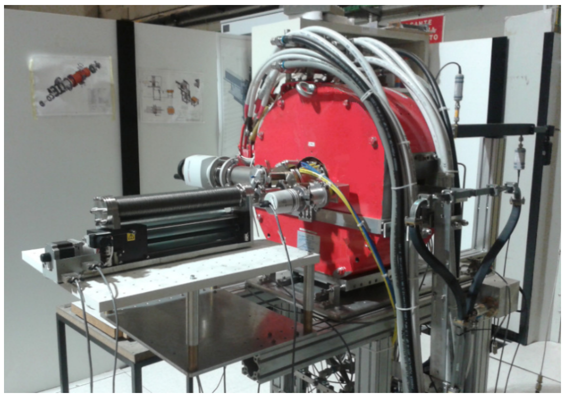


Instability characterization: ES wave generation or emission

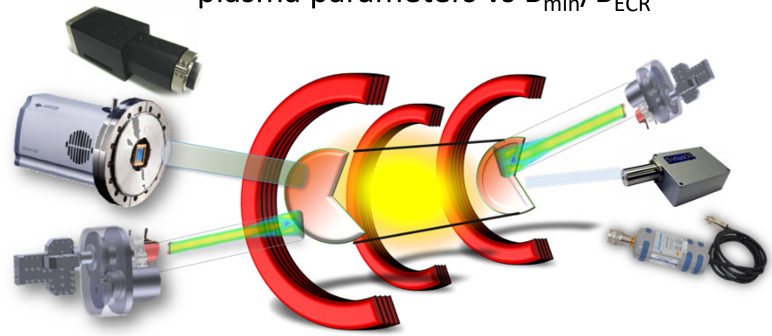
Simulation Benchmark

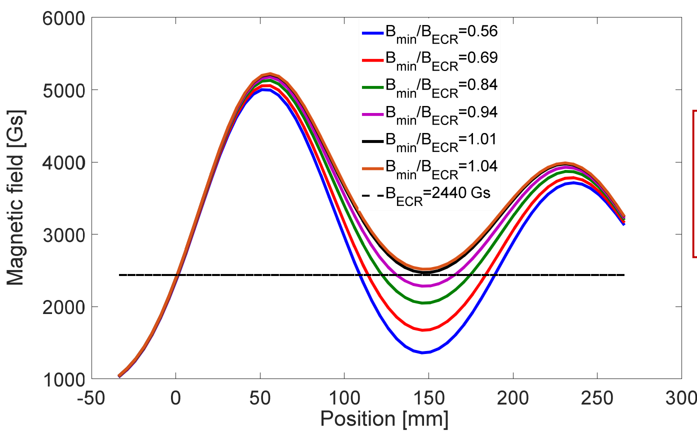
The flexible plasma Trap



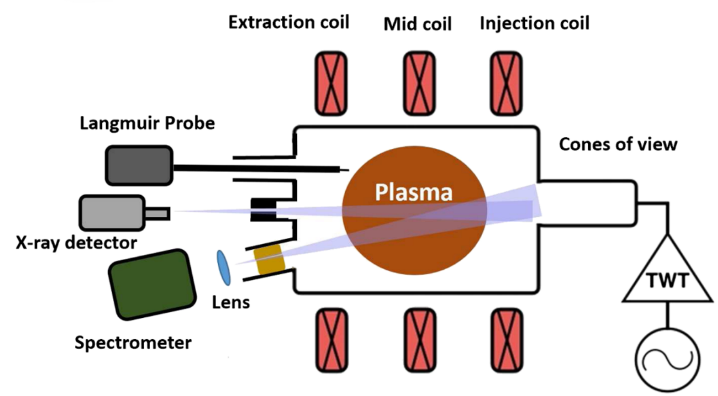
The FPT at the INFN-LNS

Multidiagnostics investigation devoted to characterize plasma parameters vs B_{min}/B_{ECR}



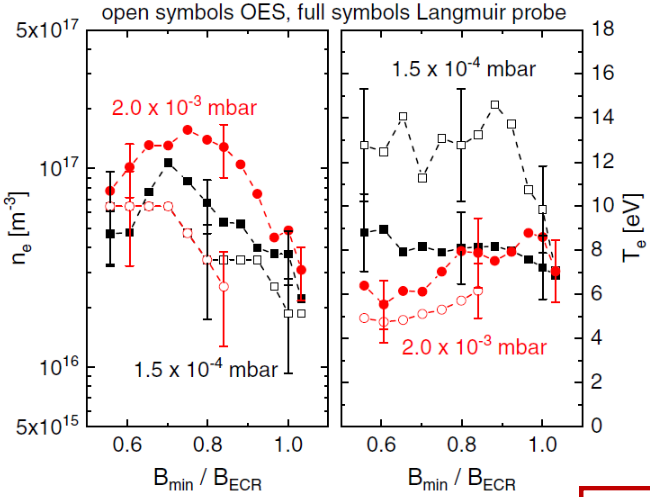


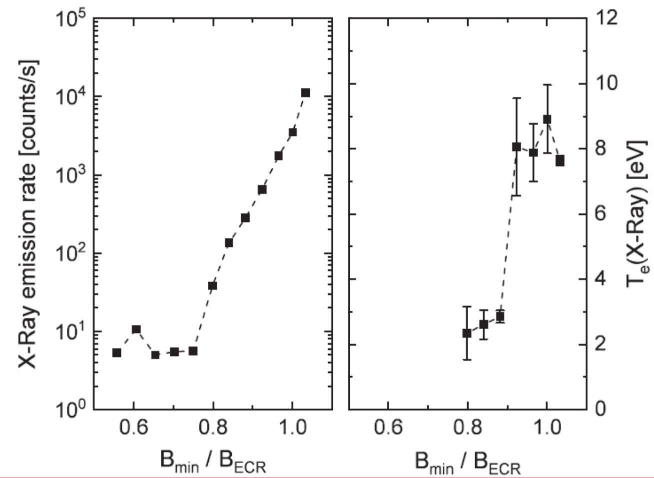
Flexible Magnetic field generated by three solenoids



Experimental results from FPT

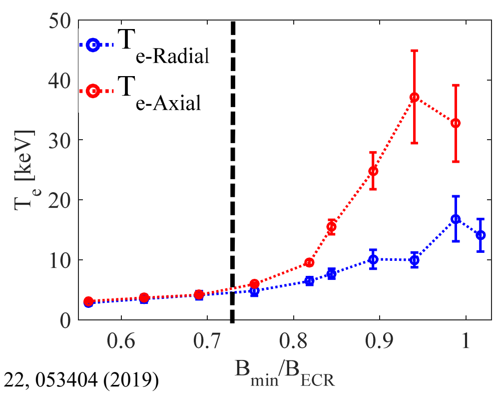
LP + OES diagnostics for cold electrons characterization





Volume X ray diagnostics for Warm- hot electron characterization

Radial and axial X-ray diagnostics for temperature anisotropy



Above critical B_{min}/B_{ECR}:

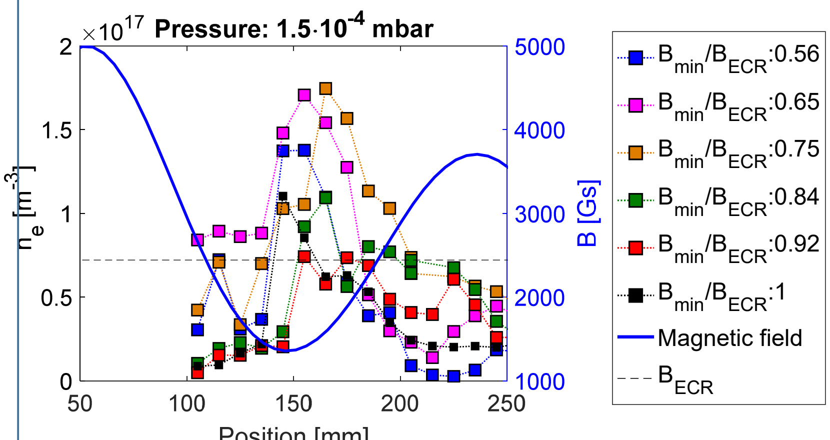
- Energy content is transferred from cold to warm and hot electrons population
  - Anisotropy between radial and axial electron population increases.

How MW field affects or is affected by plasma parameters as B_{min}/B_{ECR} ratio is changed?

G. Castro et al., Phys. Rev. AB 22, 053404 (2019)
Miracoli et al., Jinst 14 (2019) C01016

Search for a correlation between wave intensity and plasma parameters

Langmuir Probe characterization



Measures carried out at constant injected power.

I-V curves analysis: use of **different models** valid in the density range (10^{16}-10^{18} m^{-3})

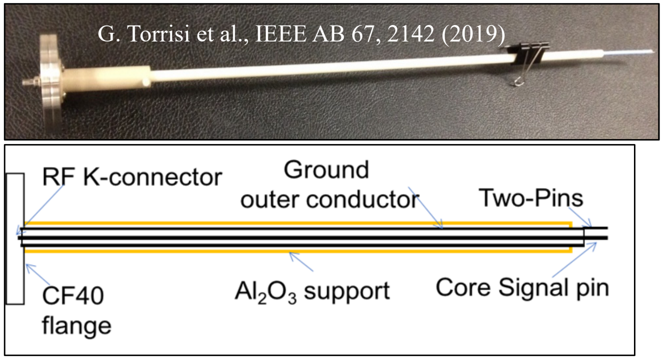
FPM: Floating Potential Method (F. Chen - 2002)

BRL: Bernstein, Reynolds and Lafambroises model

ABR: Allen, Boyd and Reynolds model;

OML: Orbited motion limited

Wave intensity characterization

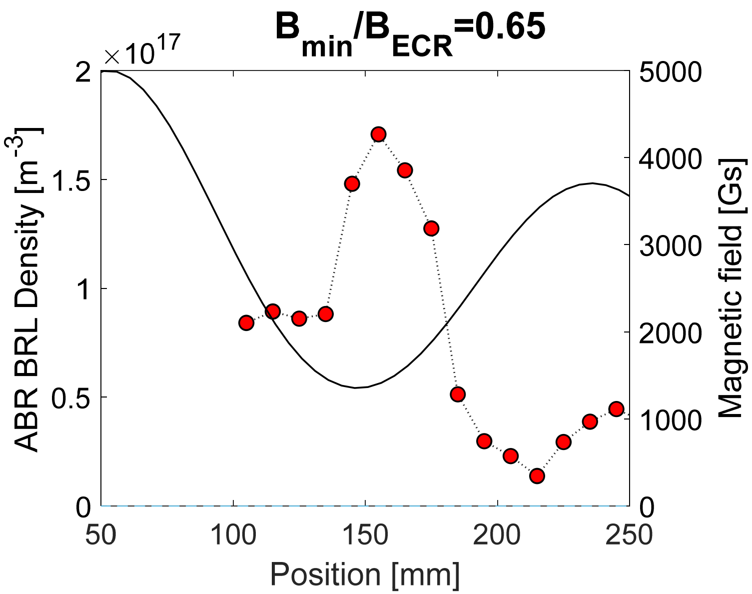


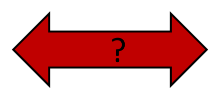
"Customized" Microwave coaxial Cable "Sucoflex 102" DC/40 GHz enclosed in Alumina tube

- ***sensitive to the short wavelength*** of longitudinal waves near the resonance layer
- ***polarization sensitive, the electrostatic radial component***
- **small enough to have the desired spatial resolution**

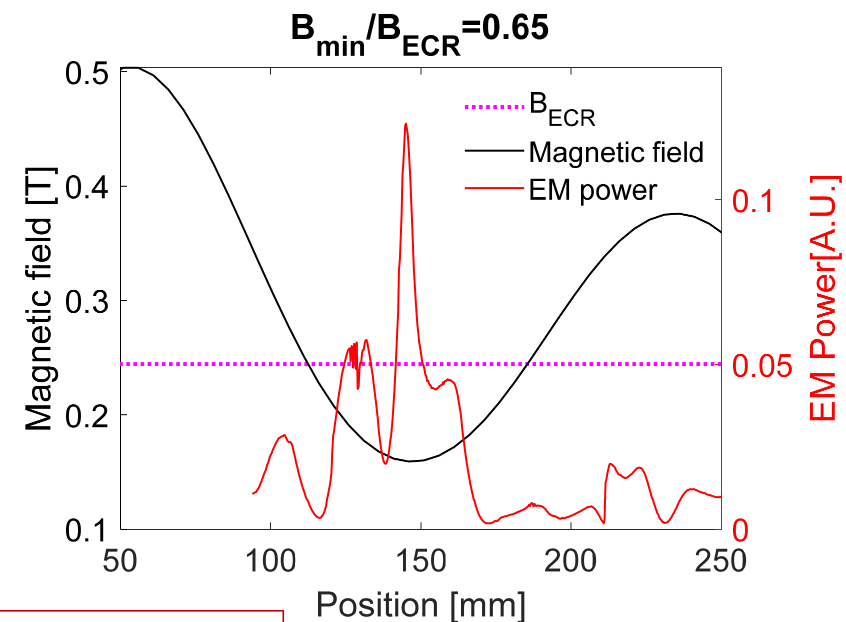
Search for a correlation between wave intensity and plasma parameters

Langmuir Probe characterization





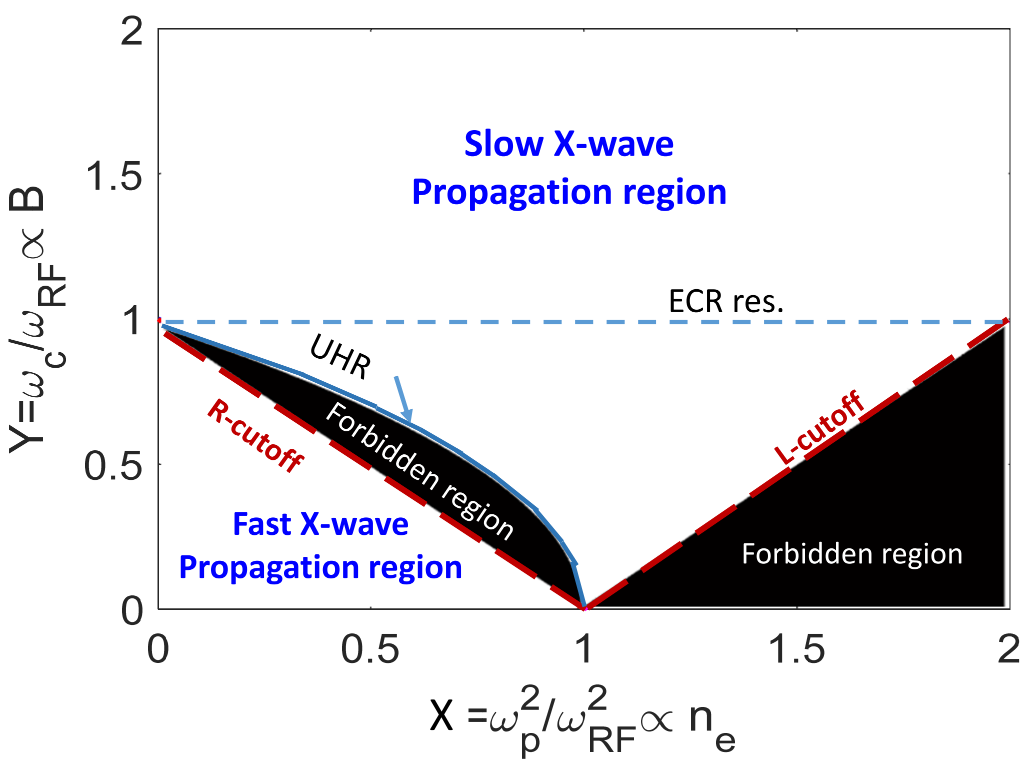
Wave intensity characterization



FPT operated in the following conditions:
Pressures: $1.5 \cdot 10^{-4}$ mbar; $2 \cdot 10^{-3}$ mbar
Fr: 6.8 GHz, B_{min}/B_{ECR}: 0.6 to 1

The Clemmow-Mullaly-Allis (CMA) Diagram

Collisionless approximation



Normalized plasma parameter:

$$X = \frac{\omega_p^2}{\omega_{RF}^2} \propto n_e \qquad Y = \frac{\omega_c}{\omega_{RF}} \propto B$$

$$\omega_c = \frac{eB}{m_e} \qquad \omega_p = \sqrt{\frac{e^2 n_e}{m_e \varepsilon_0}}$$

Extraordinary wave propagation in plasma constrained by:

R Cut-off: Y=1-X

L Cut-off: Y=X-1

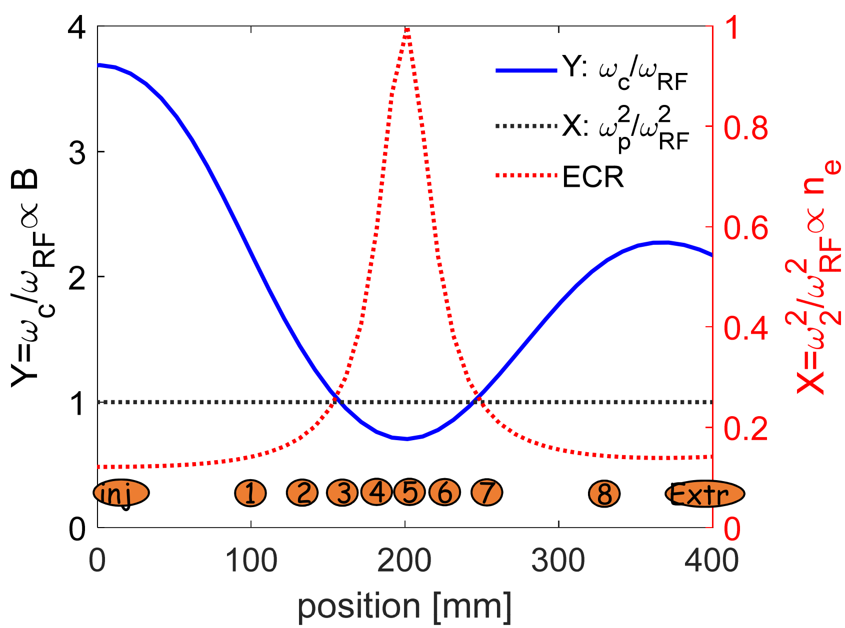
UHR: $Y = \sqrt{1-X}$ $\quad \vec{k} \perp \vec{B}$

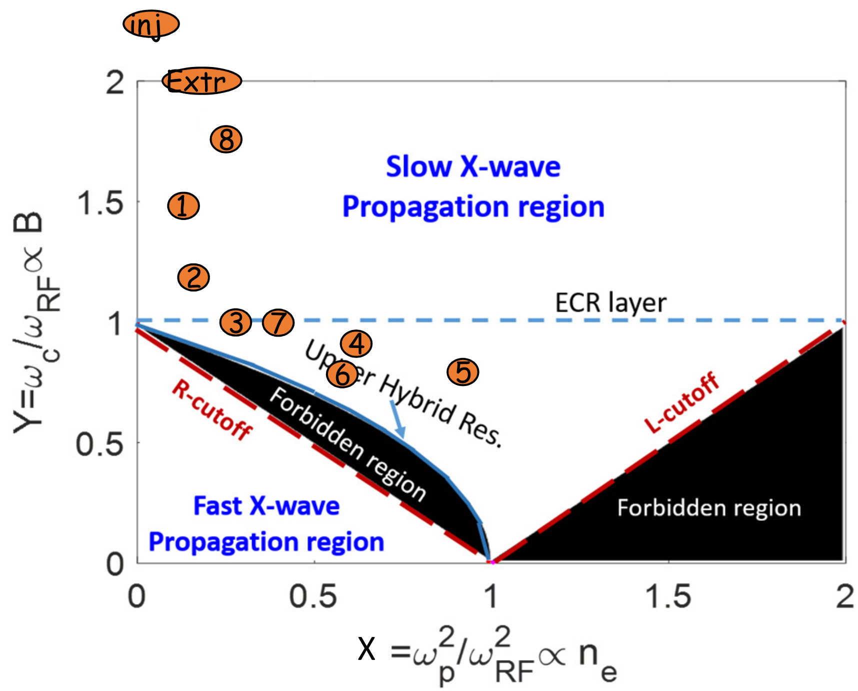
General UHR: $Y = \sqrt{\frac{X-1}{X\cos^2\theta - 1}}$

θ angle between $\vec{k}$ and $\vec{B}$

$X > 1$ overdense plasma

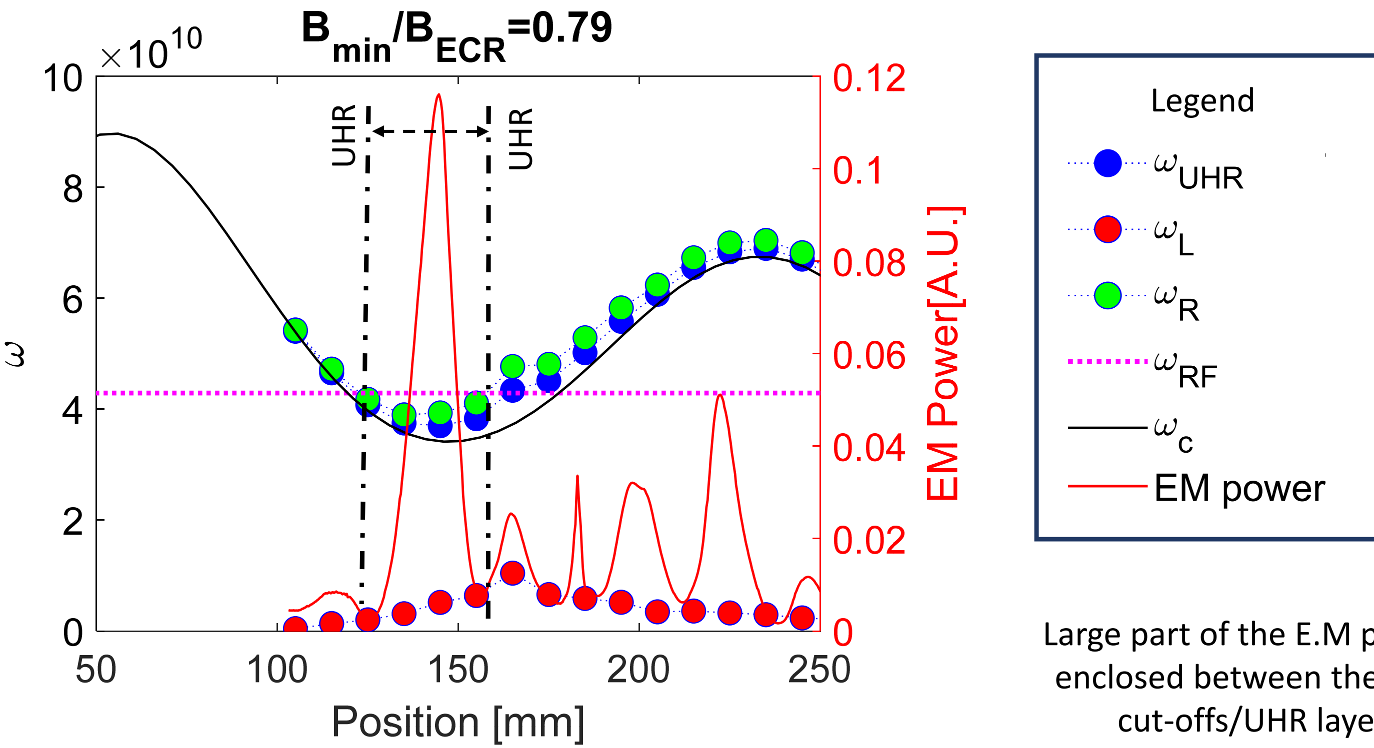
Data Analysis by CMA diagram





For each position of the LP, plasma parameters have been evaluated and placed on the CMA diagram

Experimental results vs LP position

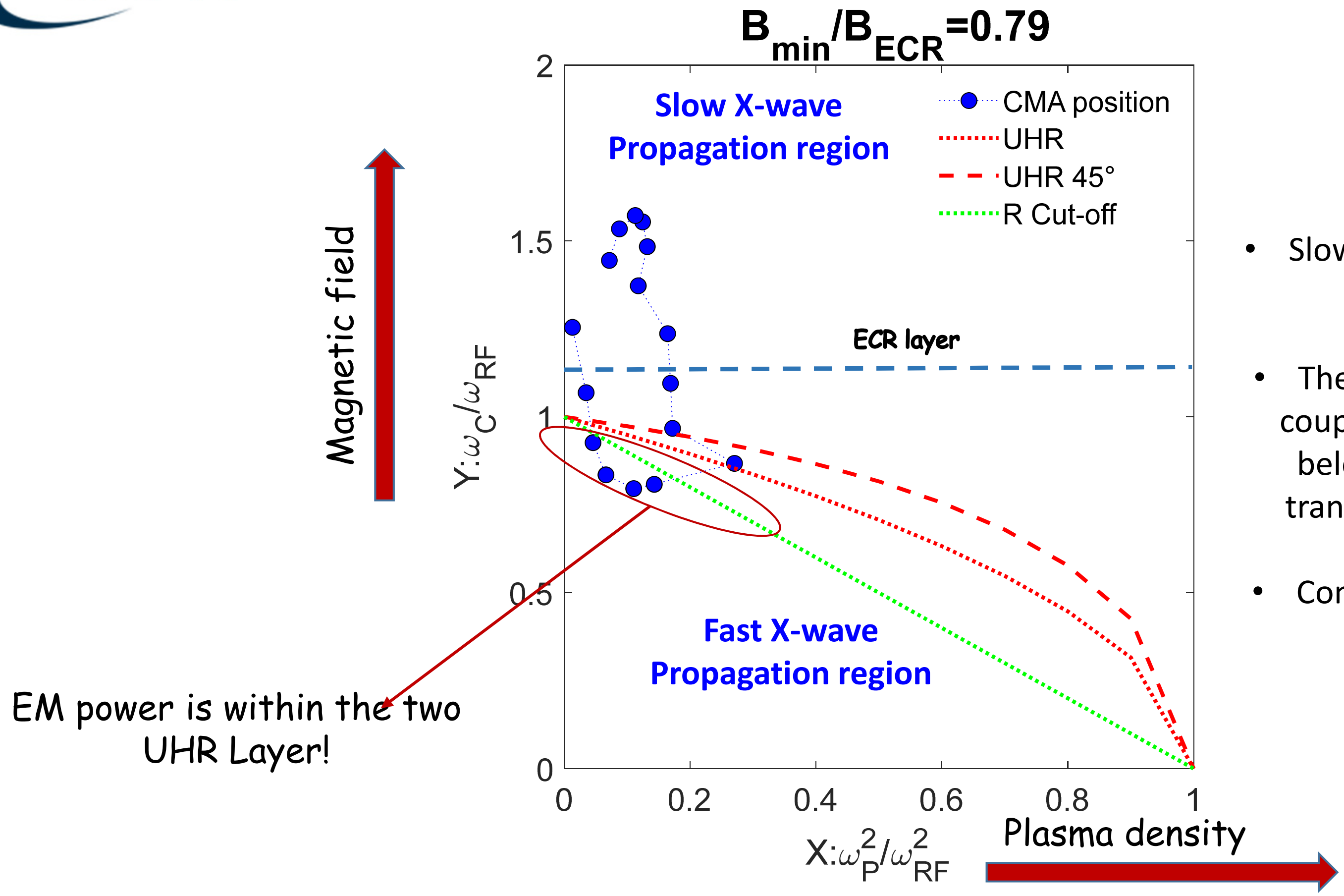


Large part of the E.M power is enclosed between the two R cut-offs/UHR layers,

$$\omega_{UHR} = \sqrt{\omega_p^2 + \omega_c^2}$$

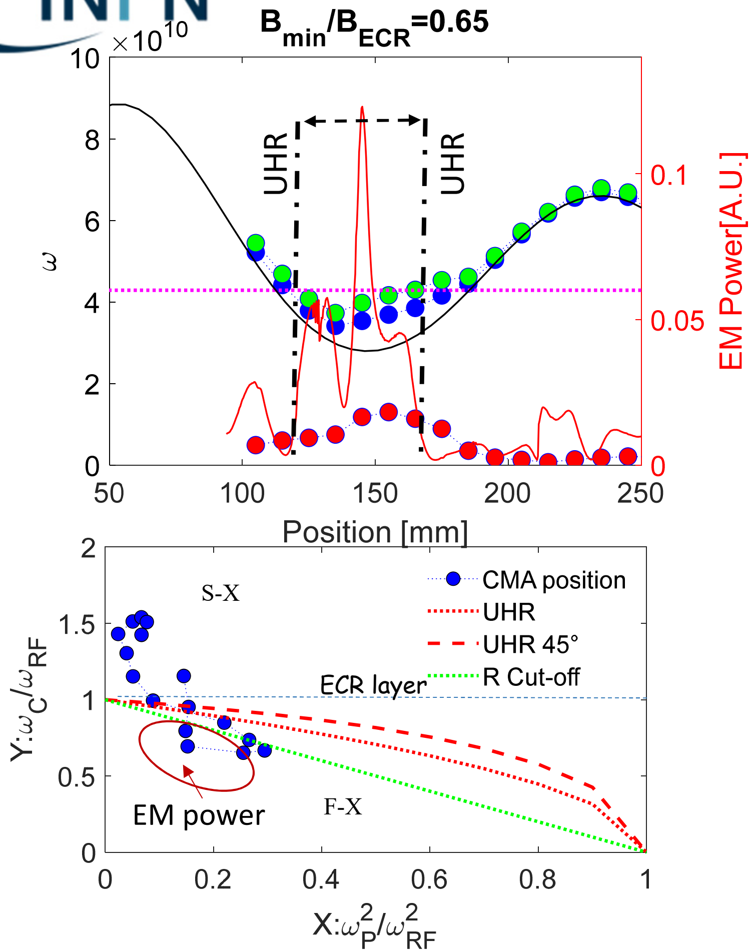
$$\omega_{R,L} = \frac{1}{2}\left(\sqrt{4\omega_p^2 + \omega_c^2} \pm \omega_c\right)$$

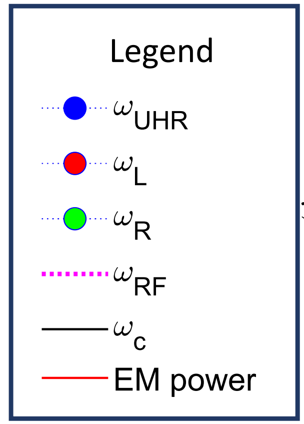
Experimental results – CMA diagram

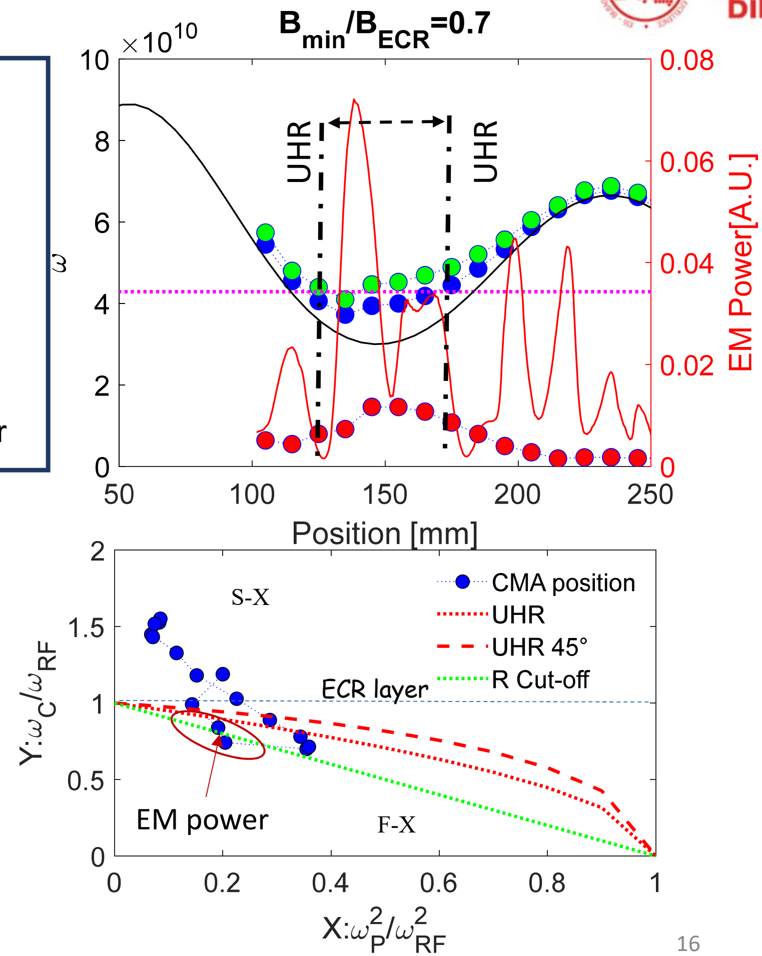


- Slow to Fast - X wave transition
- The largest part of E.M power coupled with plasma is enclosed below the R-cutoff region and transported by the Fast X wave;
- Conditions for wave trapping?

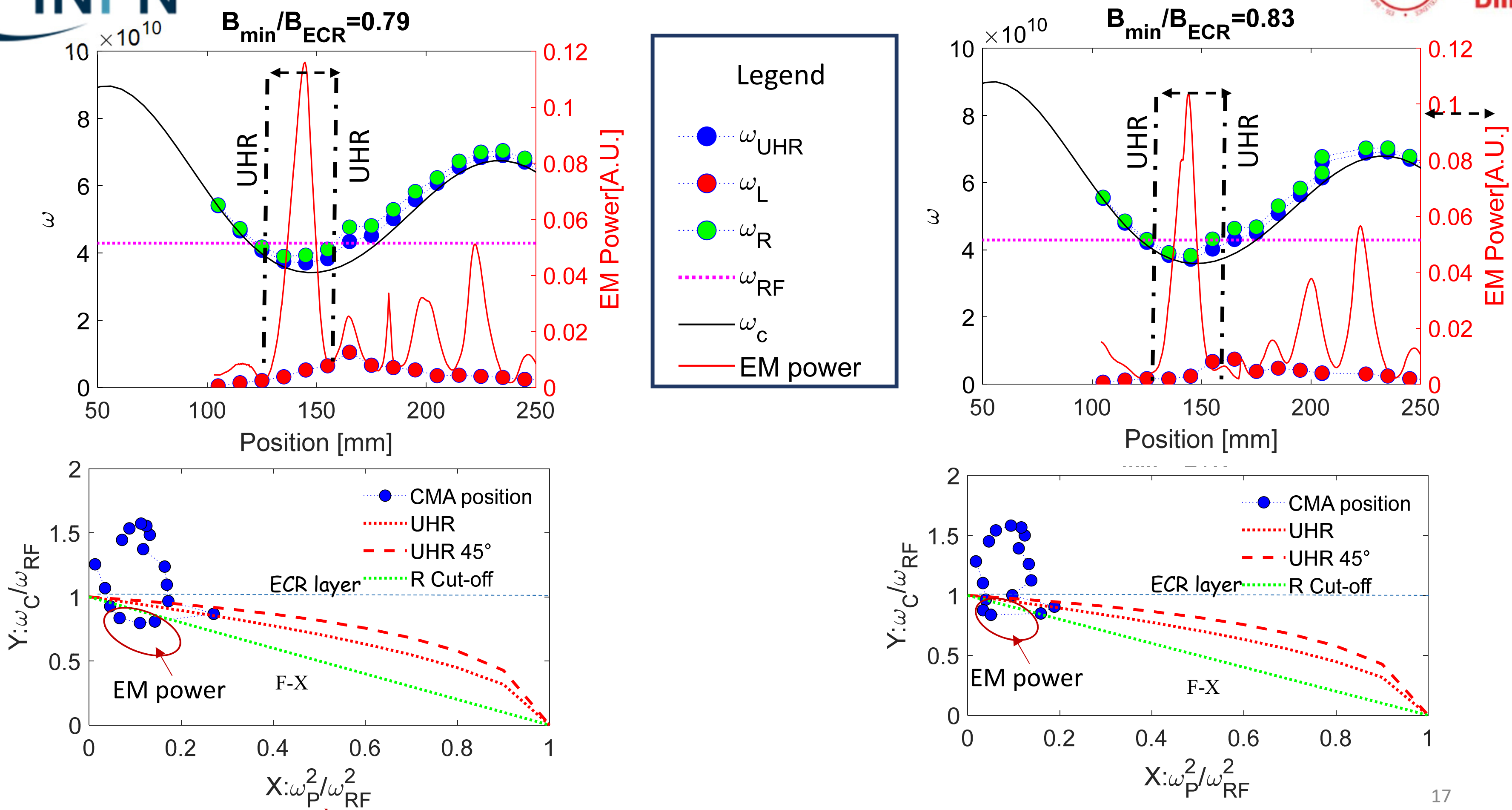
Experimental results







Experimental results



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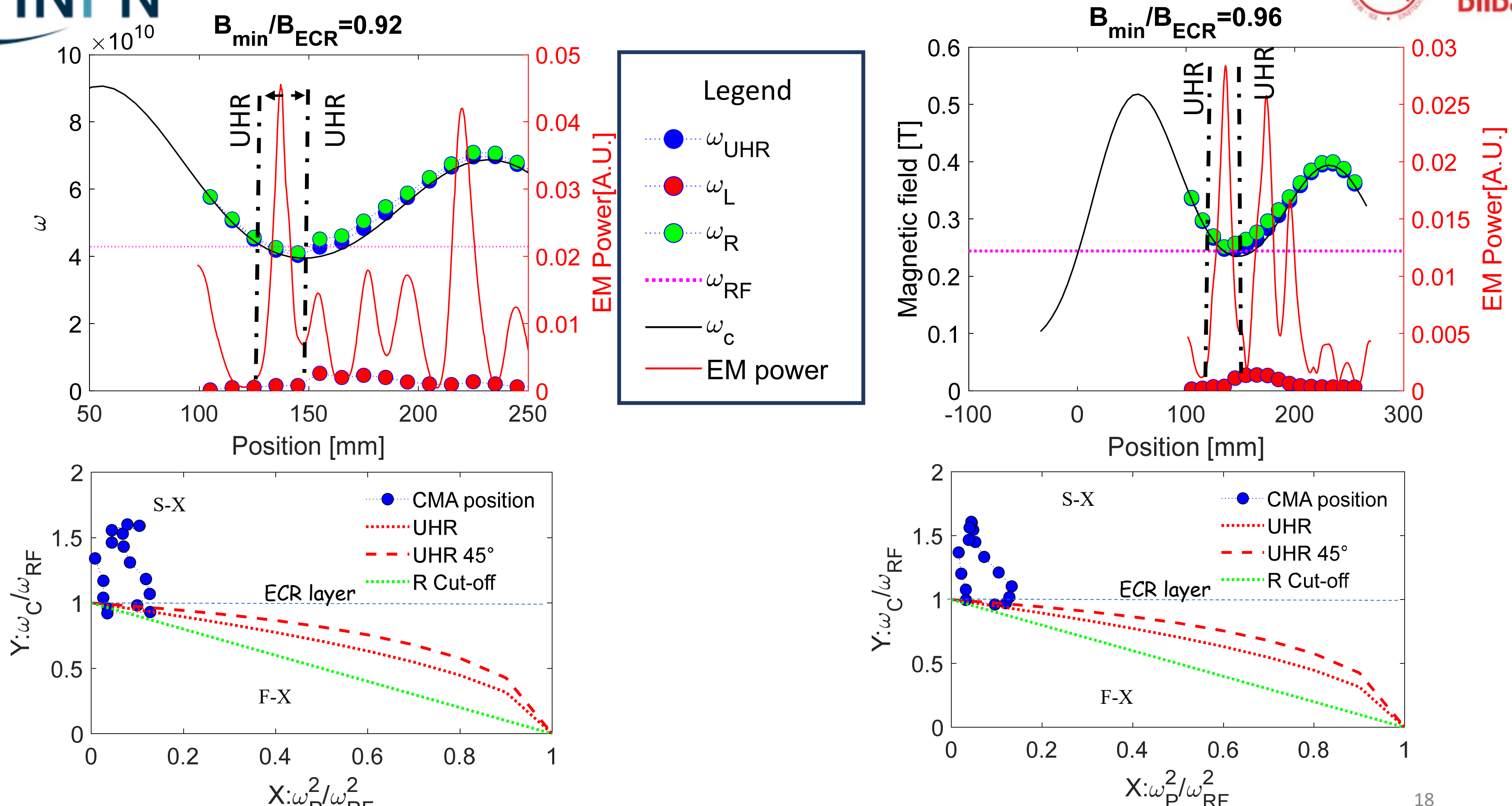
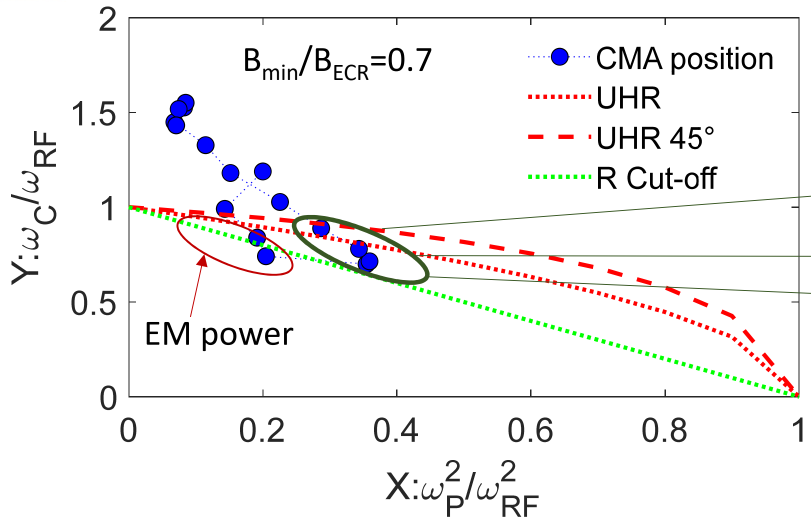
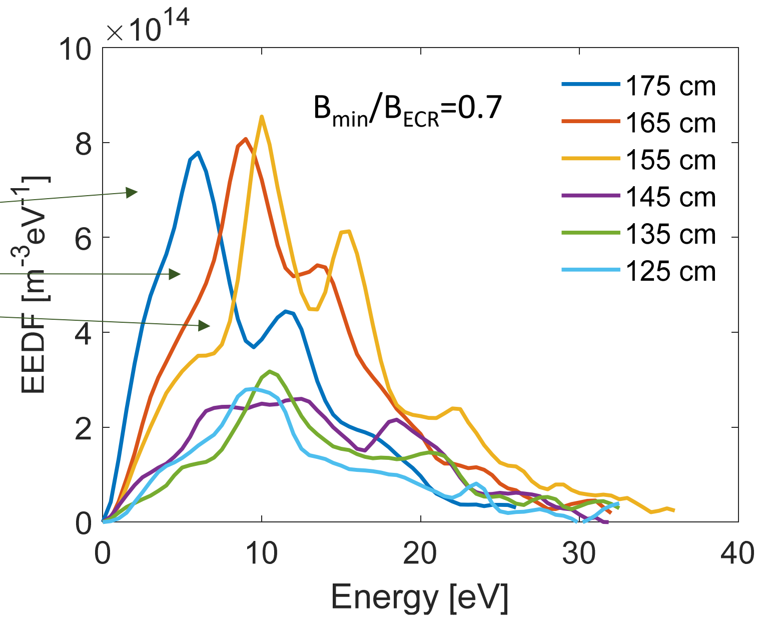


The Electron Energy Distribution Function



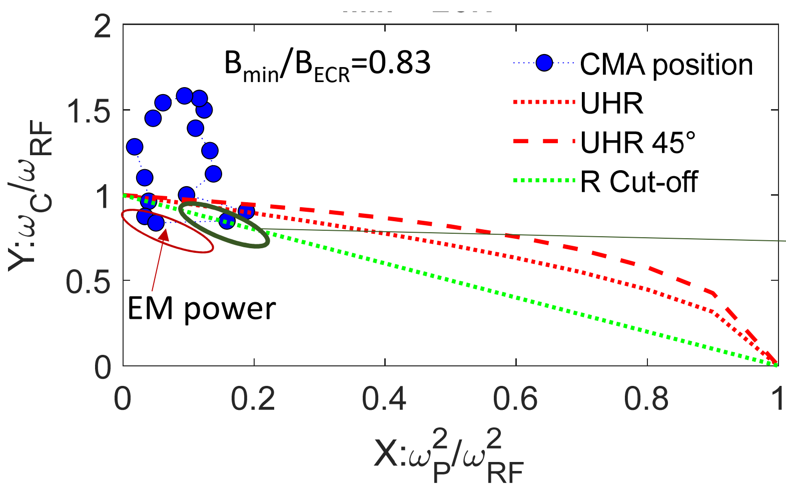


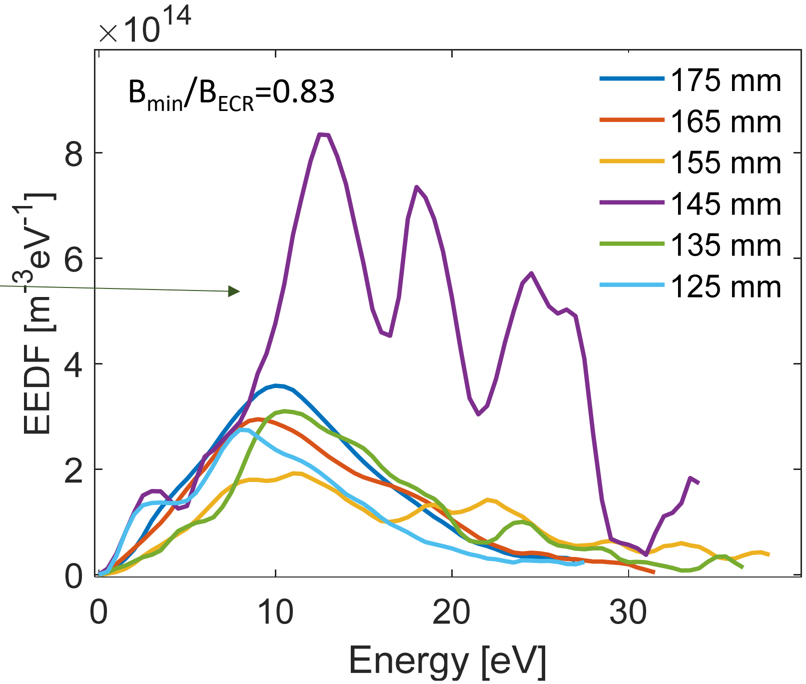
Analysis shows a double peaked EEDF in all measurements carried out close to UHR

EEDF distorsion is generated by two electron population in relative motion:
Coupling to ES waves?

$$f(\nu) = A_1(T_{e1,}\nu)e^{-\frac{m\nu^2}{2kT_{e1}}} + A_2(T_{e2,}\nu)e^{-\frac{m(\nu-\nu_0)^2}{2kT_{e1}}}$$

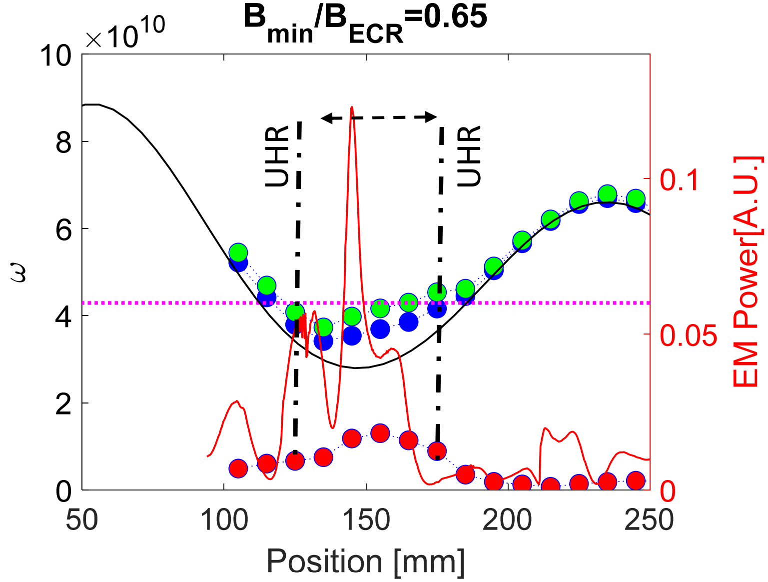
The Electron Energy Distribution Function

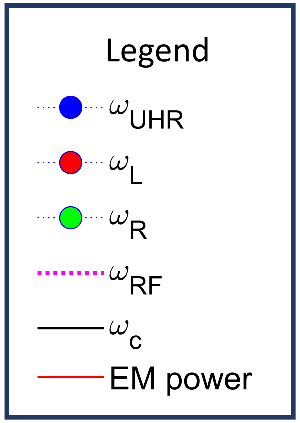


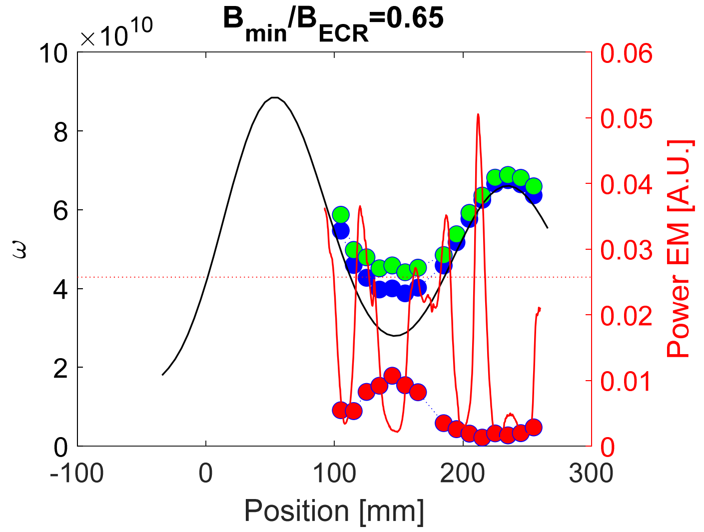


EEDF distorsion has been measured for any value of B_{min}/B_{ECR} close to UHR layer

Experimental results – the role of pressure



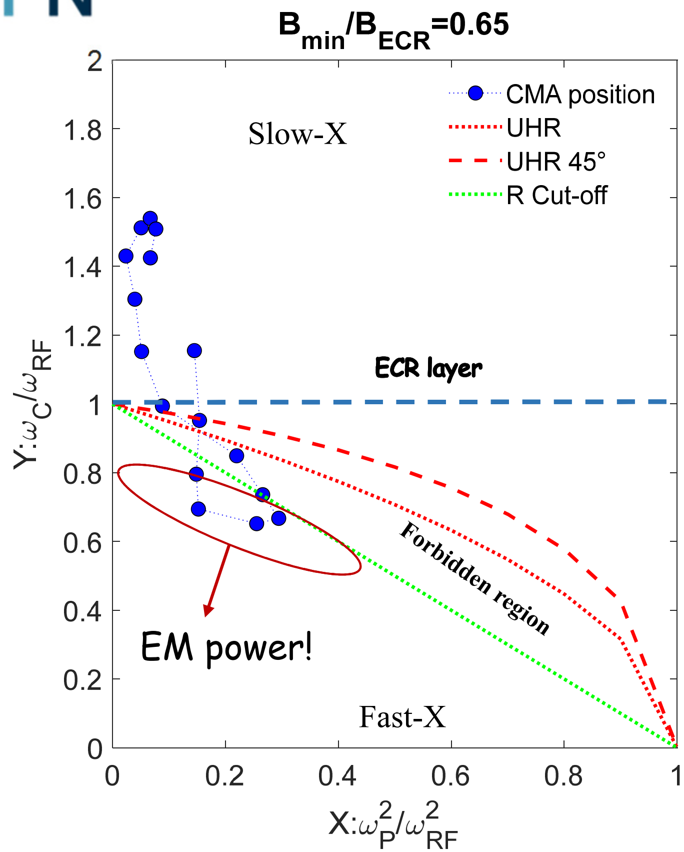




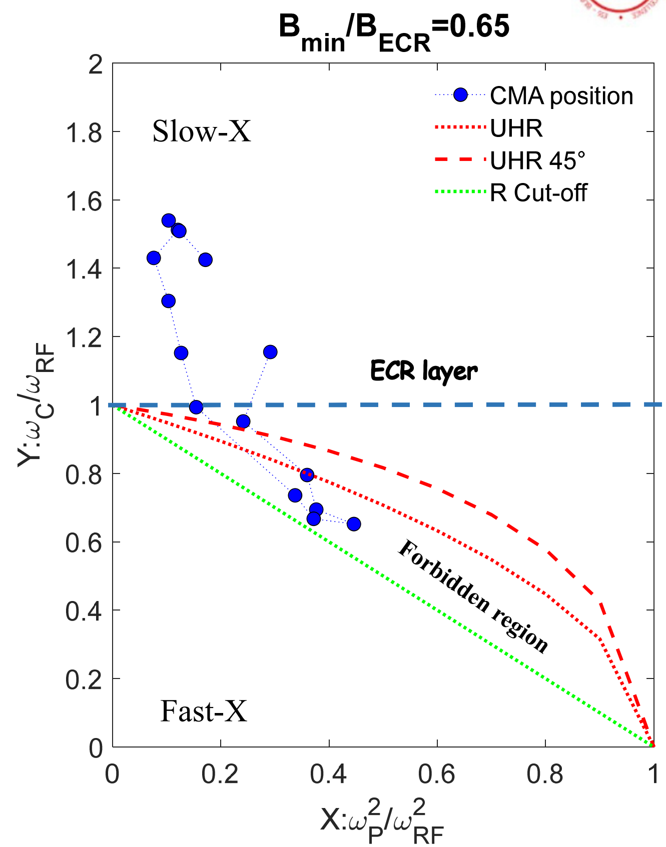
Pressure: $1.5 \cdot 10^{-4}$ mbar → Pressure: $2 \cdot 10^{-3}$ mbar

Increase of pressure apparently avoid EM power densification within the plasma core

Experimental results – the role of pressure

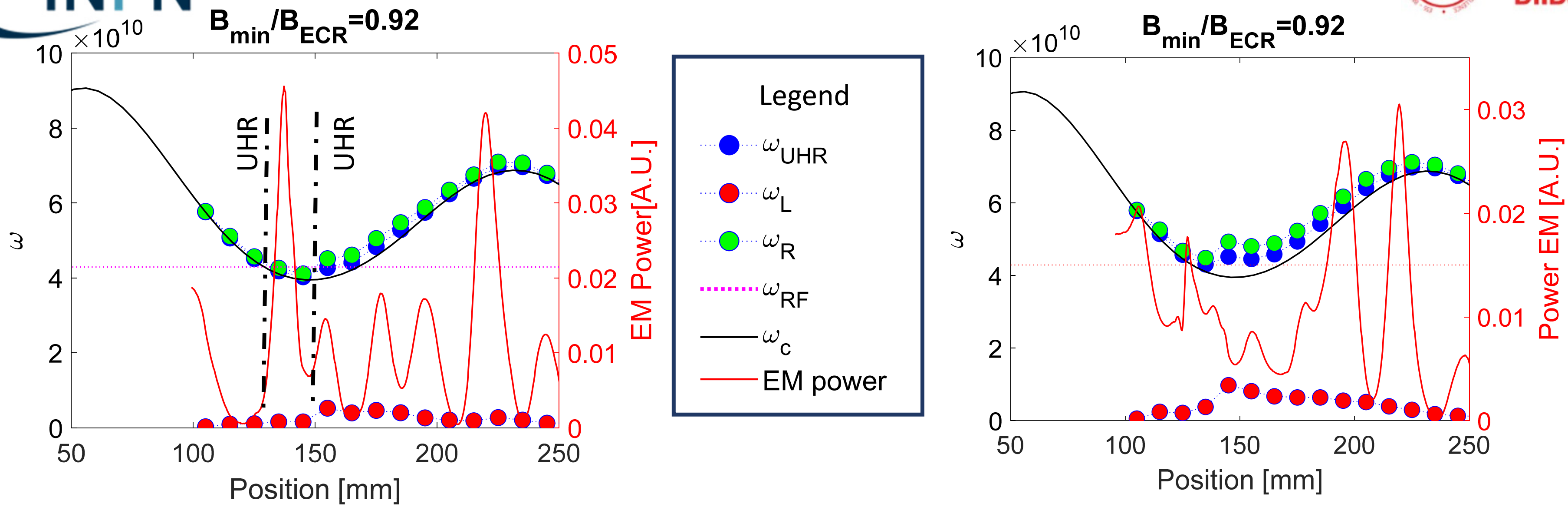


Pressure: 1.5·10^{-4} mbar



Pressure: 2·10^{-3} mbar

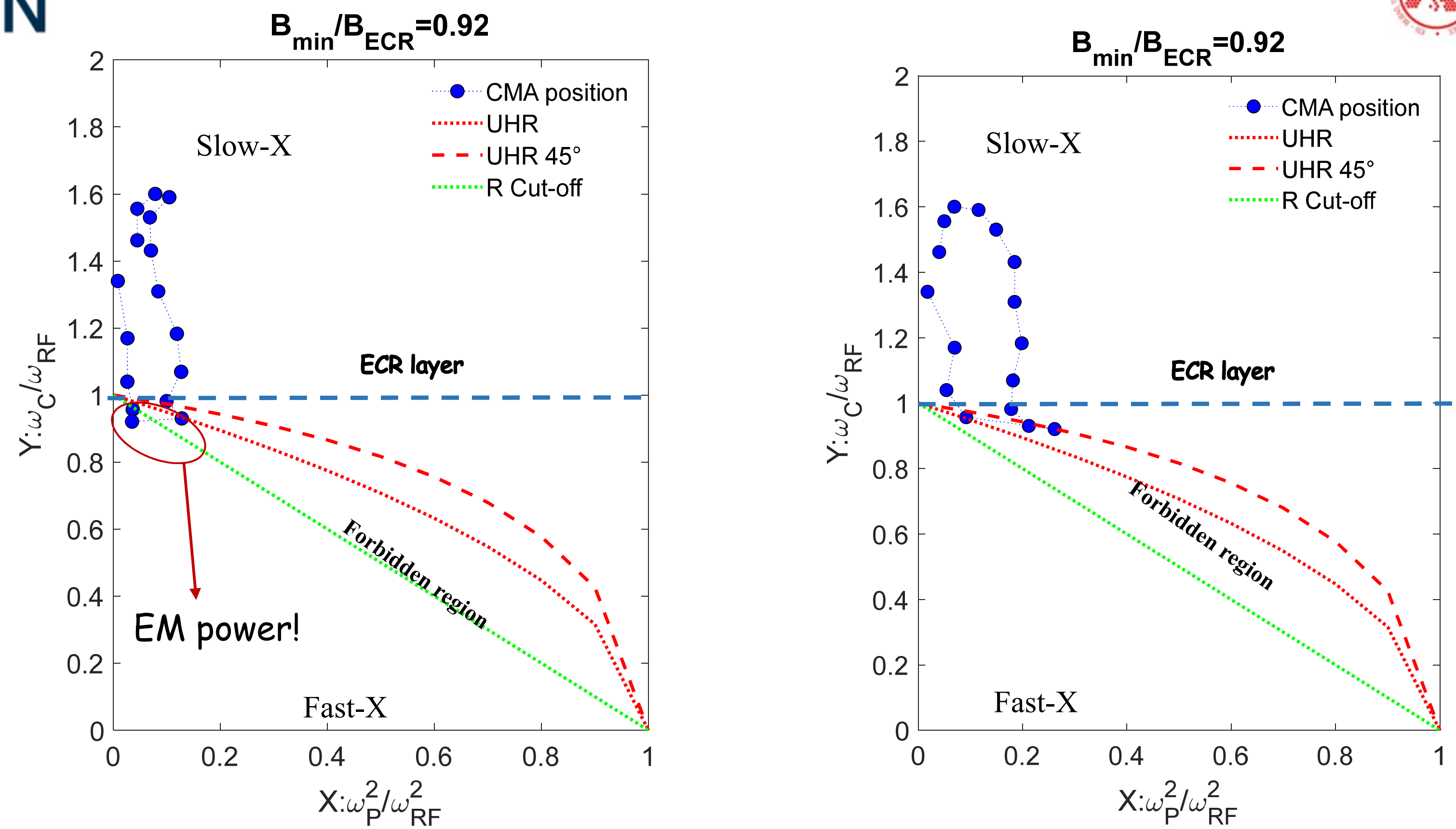
Experimental results



Pressure: $1.5 \cdot 10^{-4}$ mbar → Pressure: $2 \cdot 10^{-3}$ mbar

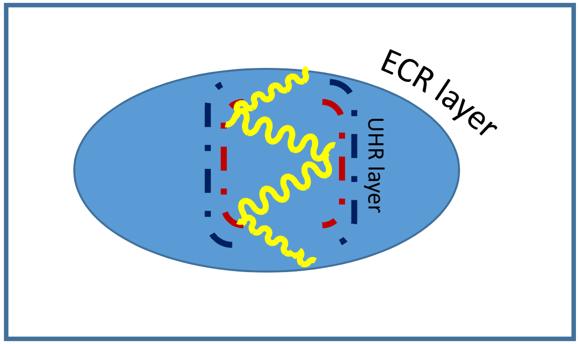
Remotion of EM power from plasma core with pressure is confirmed for any values of B_{min}/B_{ECR}

Experimental results

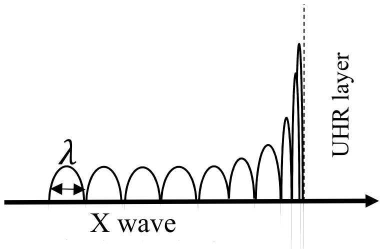


Pressure: $1.5{\cdot}10^{-4}$ mbar → **Pressure: $2{\cdot}10^{-3}$ mbar**

Conclusions



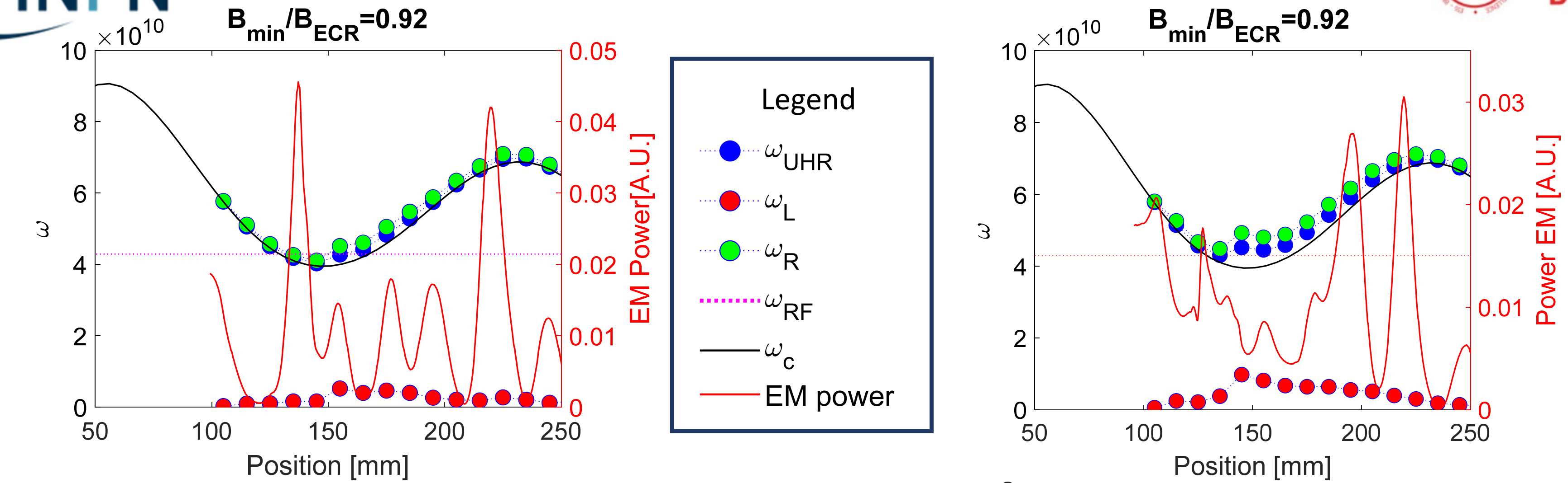
- Evidence of Slow X to Fast X wave transition within plasma core in the FPT.
- Most of the power coupled with the plasma is transported by the Fast – X wave and measured between R cut-off / UHR layers.
- Energy densification within the layers can be interpreted as F-X wave trapping within the R cutoffs/ UHR layers.
  If FX is is not generated, no Energy densification is measured.

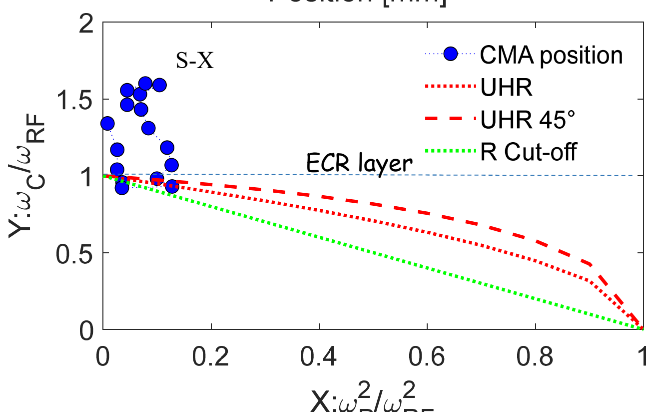


- EM energy densification favoured by the decrease of v_φ to 0 due to UH Resonance → Energy density quick increases approaching the UHR: $\omega_{RF} = \omega_{RF}\sqrt{\varepsilon}$.
- EEDF distorsion at UHR implies an involvement of UHR → coupling between EM waves and ES waves →contribution to kinetic instability (increase of $V_\perp/V_\parallel$)
- Further measurements shall make use of time resolved diagnostics and spectral analysis of the EM power to improve the comprehension of the phenomenon.

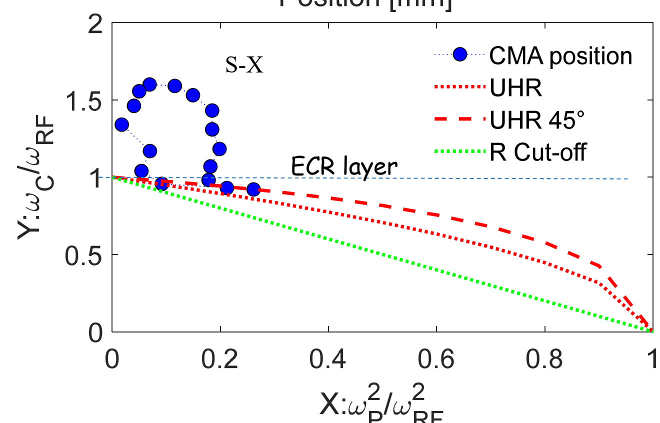
Thank you for your attention

Experimental results – the role of pressure



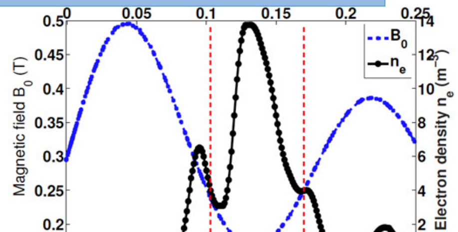


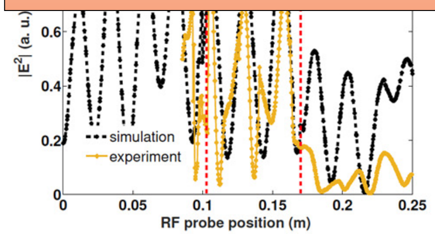
Verified for any value of B_{min}/B_{ECR}



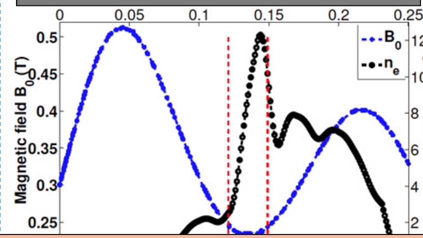
EXPERIMENTAL RESULTS

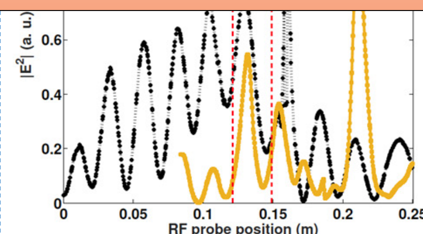
Case 1 --> B_{MIN}/B_{ECR}=0.65



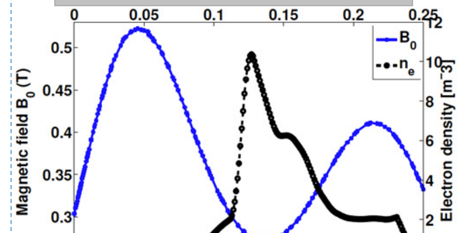


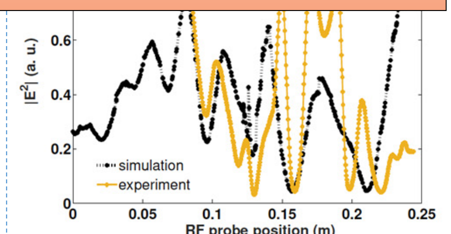
Case 2 --> B_{MIN}/B_{ECR}=0.92





Case 3 --> B_{MIN}/B_{ECR}=1





[G. Torrisi, D. Mascali, G. Sorbello, G. Castro, L. Celona, S. Gammino***;*** ***«****Numerical and Experimental Characterization of RF Waves Propagation in Ion Sources Magnetoplasmas», **IEEE Transactions on Antennas and Propagation***]

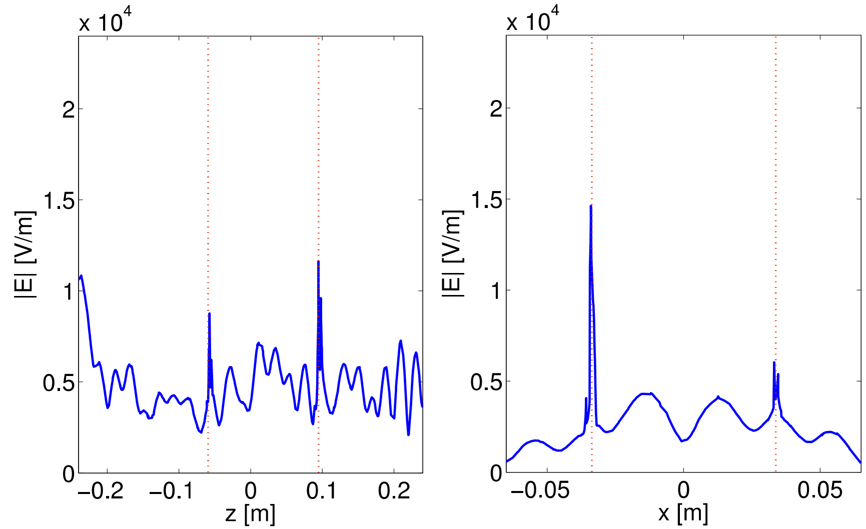
Case 1: w_{ECR}= 70 mm.
The largest plasma volume enclosed by the ECR layers.
There is an **excellent agreement between simulated and measured RF field distribution**

Case 2: w_{ECR}= 30 mm. The plasma volume is smaller.
The agreement between simulated and measured RF field distribution is still evident.

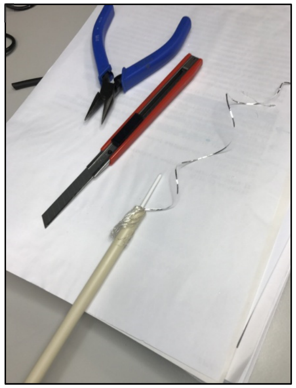
Case 3: $w_{ECR}\rightarrow 0$.
This represents a critical configuration.
General agreement even if locally the two plots deviate somewhere

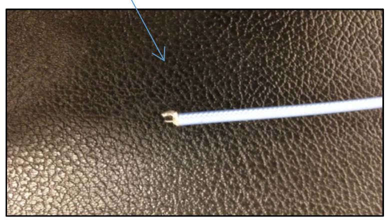
Measurements of wave in plasma: Special probes development

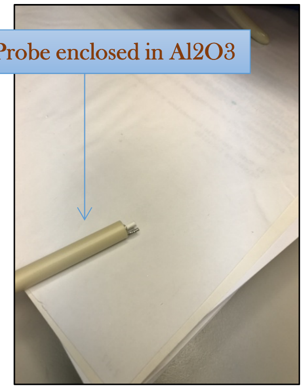
- ***sensitive to the short wavelength*** of longitudinal waves near the resonance layer
- ***polarization sensitive, the electrostatic radial component***
- **small enough to have the desired spatial resolution**

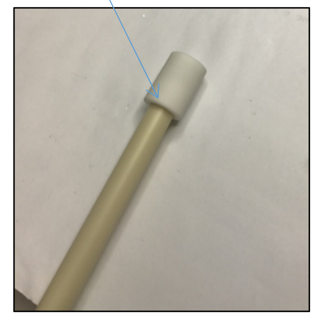


Simulated Electric filed profile along longitudinal z-axis and transversal x-axis of FPT









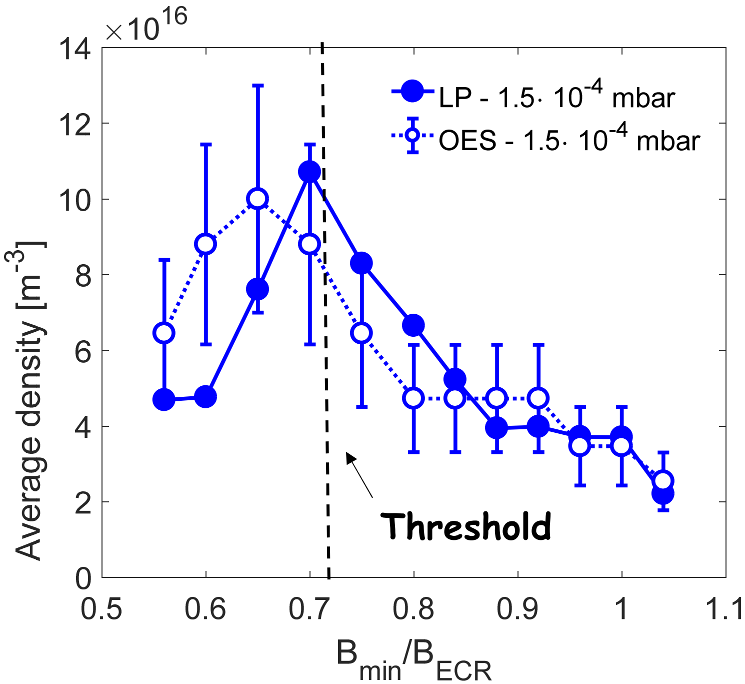
Courtesy of S. Passarello
N. Amato
INFN-LNS mechanical workshop

"Customized" **Microwave Cable "Sucoflex 102©"**

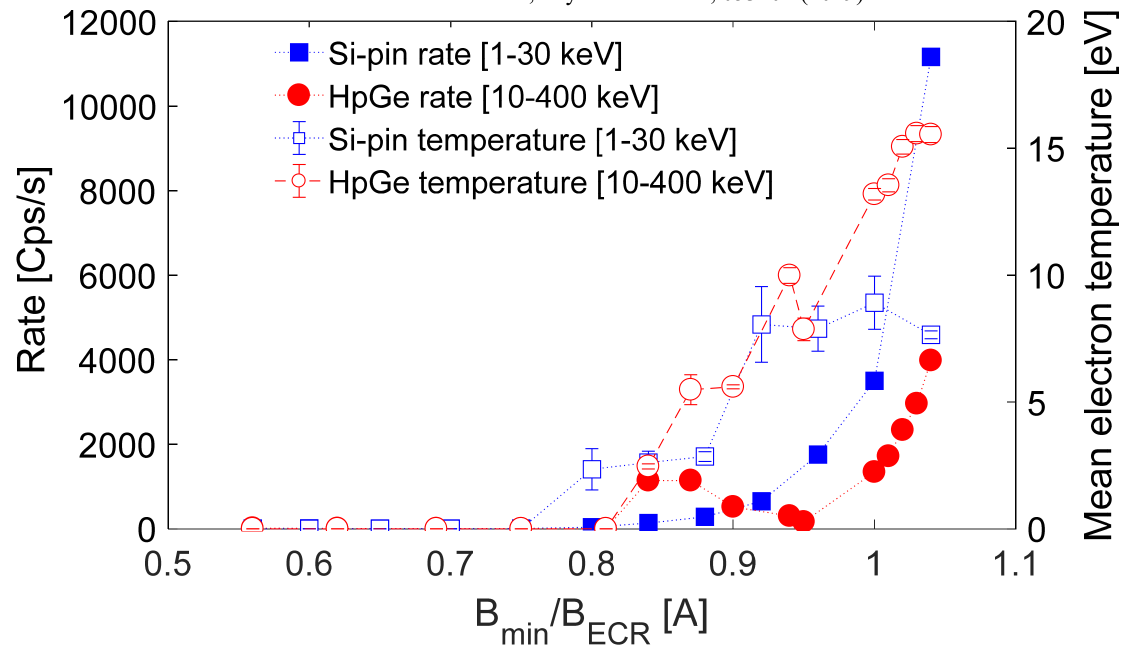
- thermal vacuum DC/40 GHz K-connector 2.9 mm
- ***Outer diameter***: 4 [mm]
- ***Pin length*****:** 3.5 [mm]
- ***Pin distance***: 2 [mm]

Inner Conductor CuAg wire
Dielectric LD_PTFE
Outer Conductor CuAg tape/braid
Jacket FEP

Diagnostics of the electron population in FPT



G. Castro et al., Phys. Rev. AB 22, 053404 (2019)



Cold population diagnostics (LP and OES) and worm/hot population diagnostics evidence a shift of EEDF from low to high energydecrease of the density of cold electrons (1-30 eV) when 0.75 threshold is overcome