INNOVATIVE SCHEMES OF PLASMA HEATING FOR FUTURE MULTIPLY-CHARGED IONS SOURCES: MODELING AND EXPERIMENTAL INVESTIGATION

G. Castro[1], D. Mascali[1], G. Torrisi[1], L. Celona[1], O. Leonardi[1], M. Mazzaglia[1,2], D. Nicolosi[1], R. Reitano[1,2], G. Sorbello[1,3], C. Altana[1], F. P. Romano[1,4] and S. Gammino[1]

[1]LNS-INFN, Catania, Italy
[2]Università degli studi di Catania, dipartimento di Fisica, Catania, Italy
[3]Università degli studi di Catania, DIEEI, Catania, Italy
[4]CNR-IBAM, dipartimento di Fisica, Catania, Italy

Outline

- **Motivations:**
  - Overcoming the actual limitation of ECRIS

- **Introduction:**
  - The Electron Bernstein waves (generation and absorption)

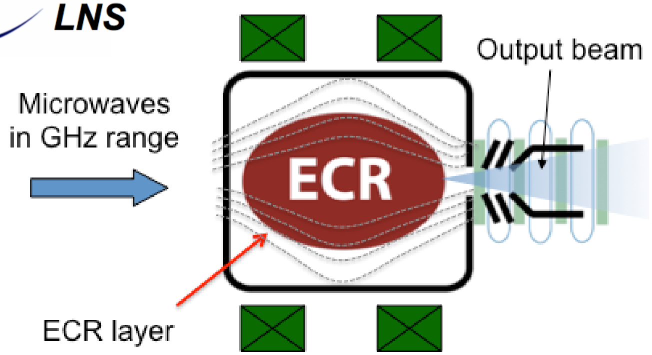
- **Experimental apparatus:**
  - The plasma reactor;
  - The diagnostics;

- **Experimental evidences:**
  - Overcome of the density cutoff (LP and interferometric techniques);
  - Ancillaries phenomena;

- **New perspectives at INFN-LNS:**
  - The FPT and launcher;

- **Conclusions**

Overcoming the actual limit of ECRIS



$\omega_p^2 < \omega^2$ → $n_e < \frac{\epsilon_0 m_e}{e^2}\omega^2 = n_{cutoff}$

Beam characteristics

$\langle q \rangle \propto n_e$

$I \propto n_e$

ECRIS STD MODEL

$n_e \propto \omega_{RF}^2$ → ***INTRINSIC Density limitation***

1. **Higher Frequency Generators to increase the plasma density**;
2. **Higher Magnetic Fields to make longer the ions confining time**;

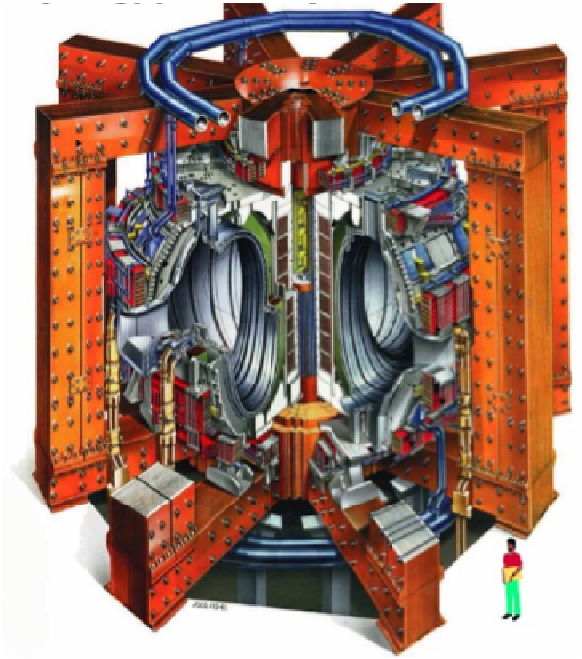
Brute force cannot be anymore used because of technological reasons (magnets, hot electrons generations, plasma overheating, cooling, …)

→ Optimization of wave to plasma coupling

→ Alternative heating schemes

A look in the word of the fusion plasmas

Jet tokamak for nuclear fusion (energy production)



Also in the field of fusion, higher and higher density plasmas are required to satisfy the **Lawson criterion**;

Overdense plasmas have been generated by using ElectronStatic waves, and, in particular, Electron Bernstain Waves, instead of EM waves;

10 times overdense plasma have been generated at Greiswald (Ge) stellarator by using EBW heating

Y. Y. Podoba *et al.*, *Physical Review Letters* 98, 255003, 2007.

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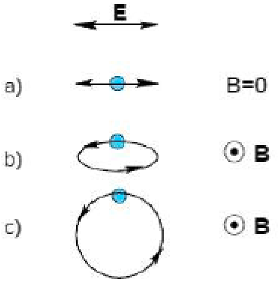
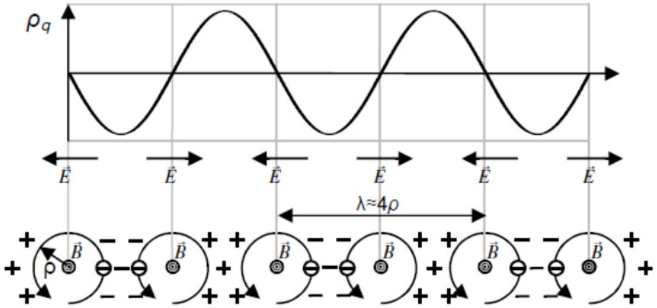
Bernstein waves

EBW consists in phase bunching of electrons in a magnetized plasma.

They generalized Langmuir waves

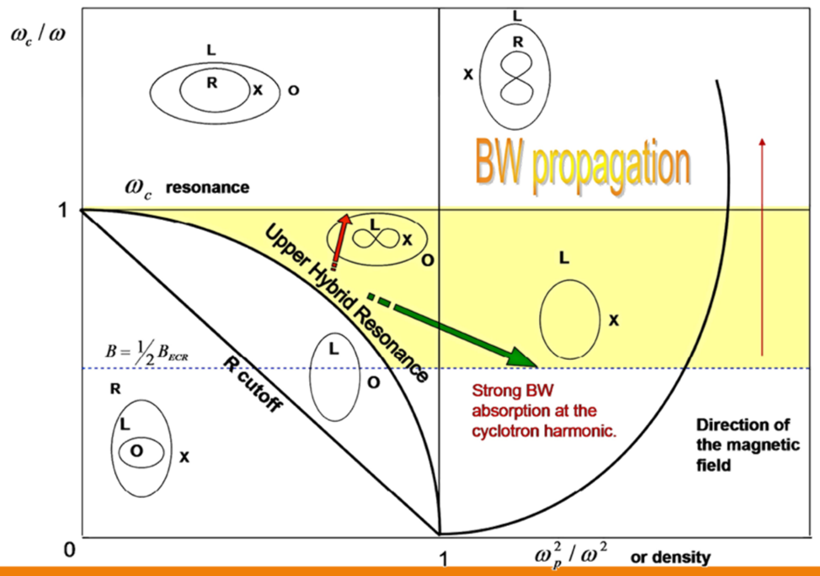




No Density cutoff

Resonance at cyclotron harmonics

Excited at UHR by X-waves


The BW propagation region

From EM waves to EBW

1. High field side launch

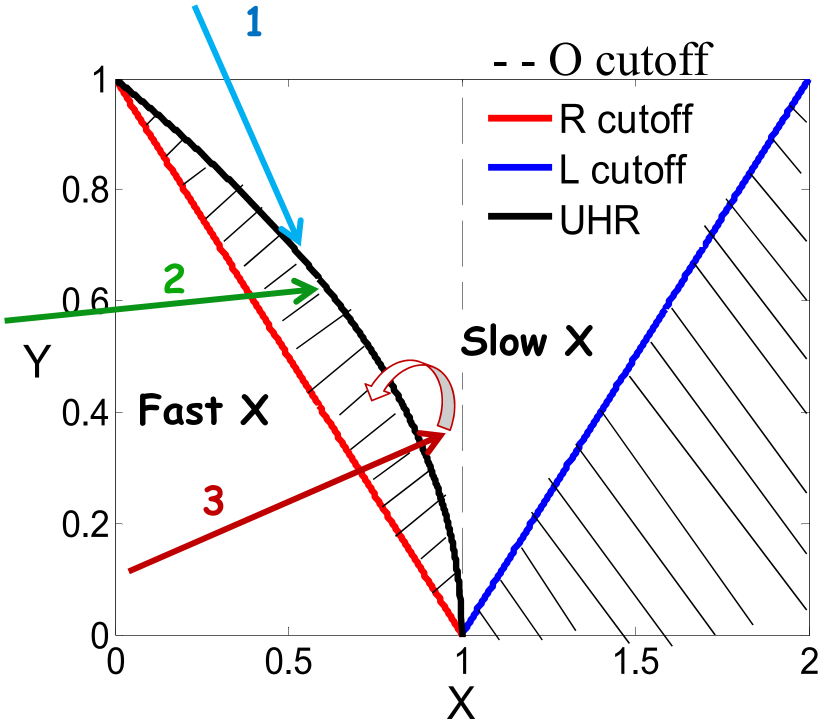
S-X wave is launched from high magnetic field to UHR

2. Direct FX-B conversion

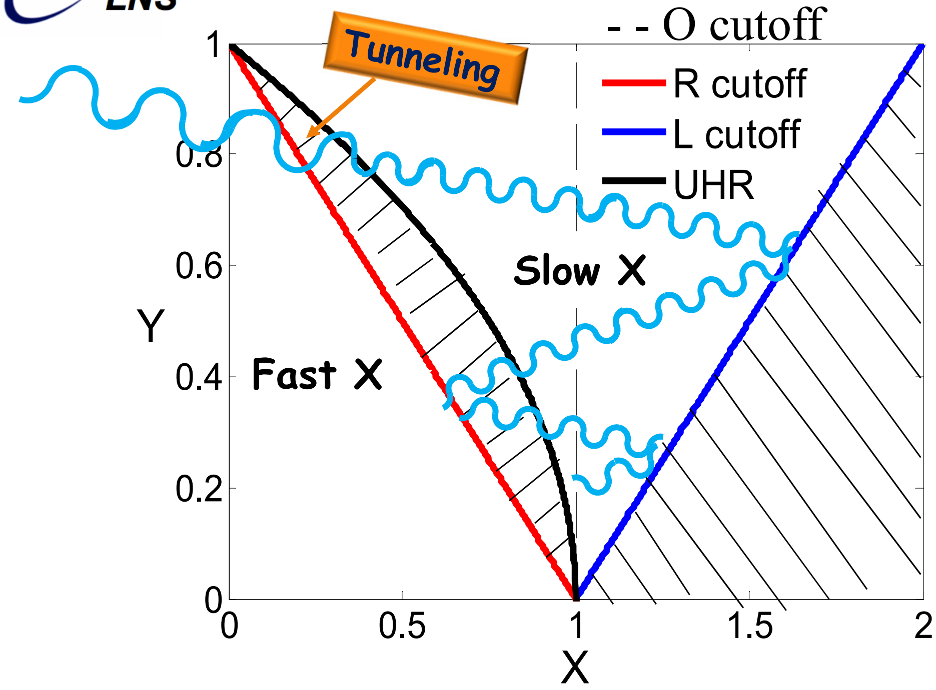
F-X tunnels trough R cutoff and reaches UHR

3. O-SX-B conversion

An O wave is launched. O-SX conversion at O cutoff, S-X reach UHR



Direct FX-B conversion



Conversion factor from FX to B wave:

$$C_{FX-B} = 4e^{-\pi\eta}(1 - e^{-\pi\eta})\cos\left(\frac{\phi}{2} + \theta\right)$$

$\eta=294|BL_n|^{UHR}$ $\qquad$ $L_n = \frac{n_e}{\partial n_e / \partial x}$

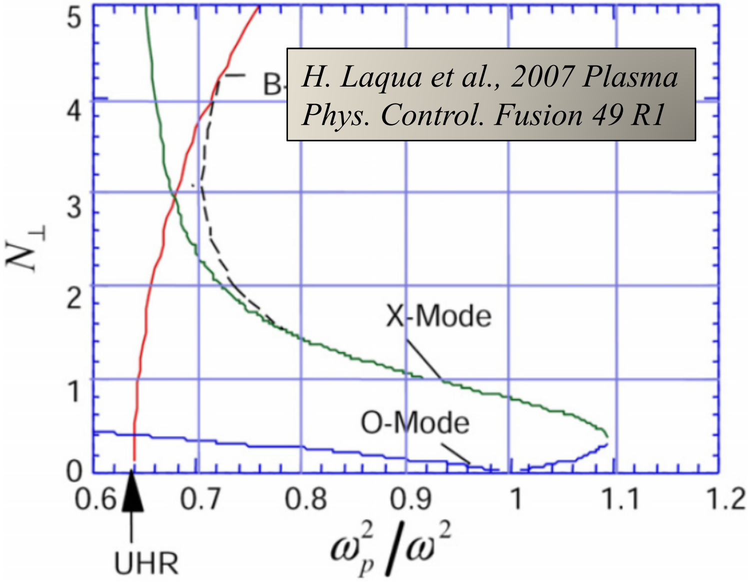
$|C_{FX-B}|=1$ when $\eta \approx 0.22$; $\quad L_n \approx \frac{0.75}{B}$**[mm]**

FX-B conversion optimized for
steep density gradient,
low magnetic field and **low frequency**:

Jones B et al 2003 Phys. Rev. Lett ***90*** *165001* [*FX-B conversion in tokamak*]

Chattopadhyay P K et al., 2002 Phys. Plasma ***9*** *752–5* [*FX-B conversion in reversed pinch*]

O-SX-B conversion



H. Laqua et al., 2007 Plasma Phys. Control. Fusion 49 R1

Conversion factor from O to SX wave:

$$T(N_{\|}, N_y) = \exp\left\{-\pi k_0 L_n \sqrt{\frac{Y}{2}}\left[2(1+Y)(N_{\|,\mathrm{opt}} - N_{\|})^2 + N_y^2\right]\right\}$$

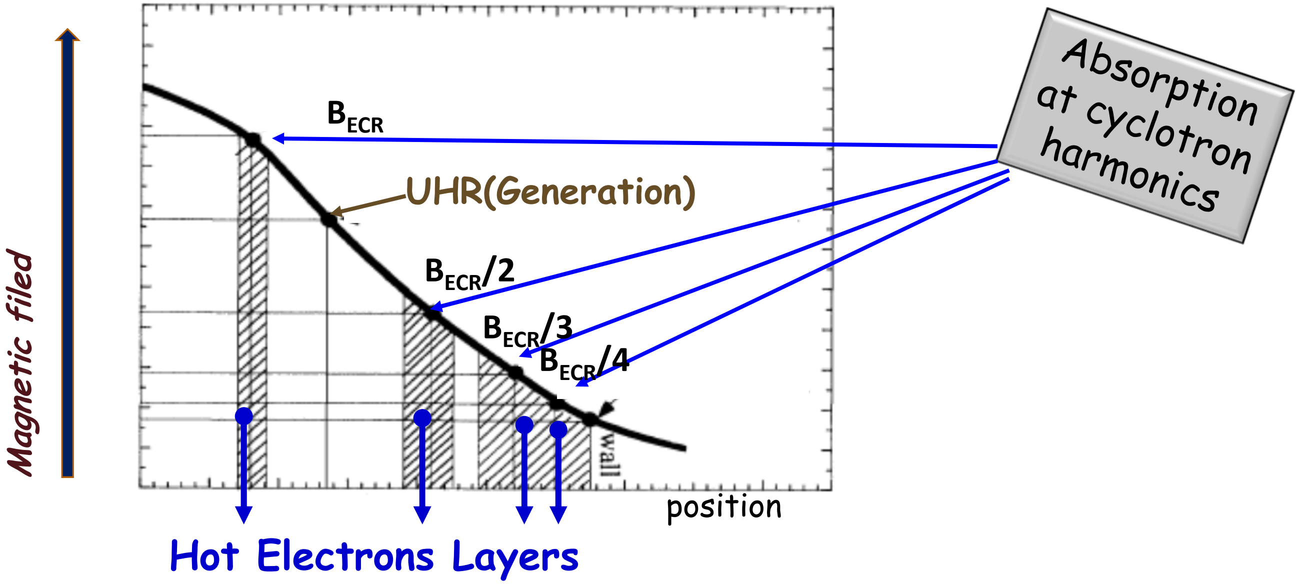
O-SX-B conversion optimized for **flat density profile and $\vartheta_{launch.} = \vartheta_{opt.}$**

$$\sin^2\theta_{\mathrm{opt}} = N_{\|,\mathrm{opt}}^2 = \frac{Y}{1+Y} \qquad L_n \approx \frac{50-1000}{f\ [GHz]}\ [\mathrm{mm}]$$

Optimal launching angle and higher frequency required

Y. Y. Podoba, et al., Physical Review Letters 98 (2007) 255003. [*O-SX-B conversion in stellarator*]

Absorption of Bernstein waves



Absorption at cyclotron harmonics

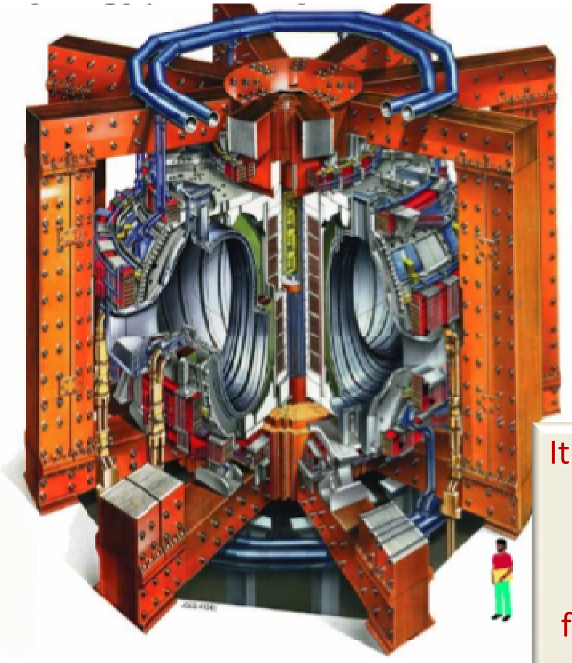
Hot Electrons Layers

High energy electrons → **X ray emission**

Non linear behaviour

The main challange: "downsizing"

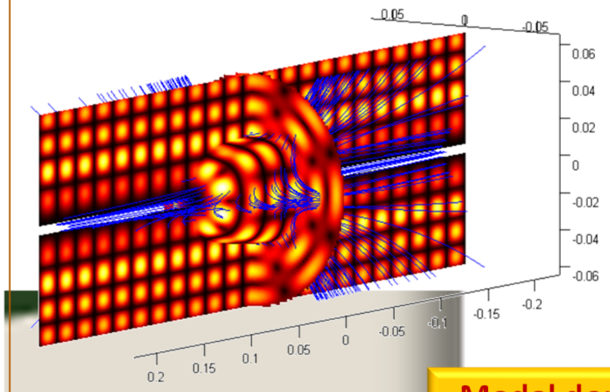
Jet tokamak for nuclear fusion (energy production)



$\lambda << L$

It is possible to lauch E.M waves with optimized angles (optical approximation) for increase EM-to EBW conversion

ECR Ion Source: extremely compact plasma machine



$\lambda \approx L$

Modal dominated cavity. Wave Lauching is not possible («untill now»)

Self-tuning needed to allows EBW heating

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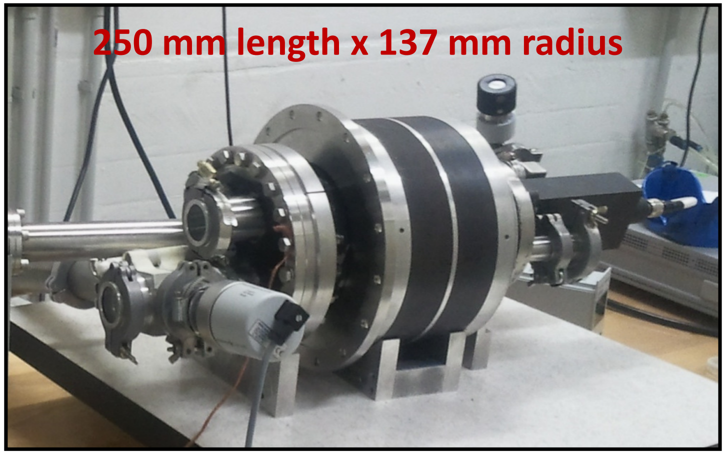
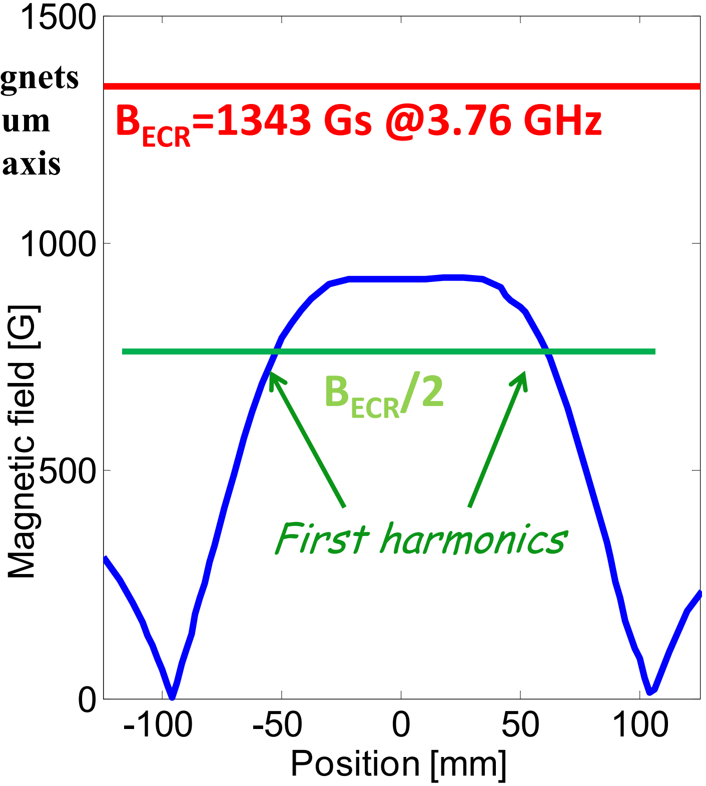
Set-up for EBW plasma generation



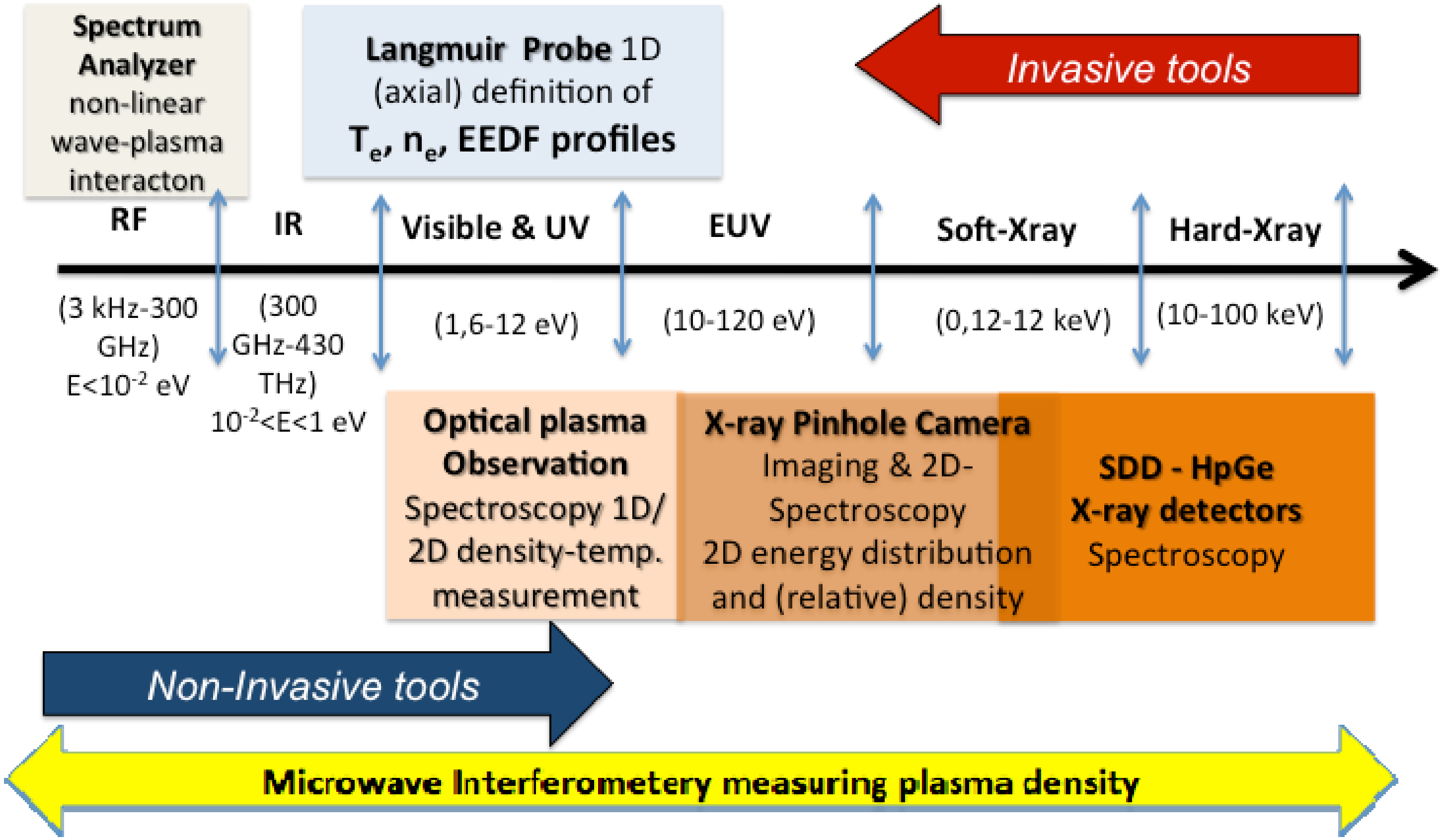
The permanent magnets produce a maximum field of ~0.1 T on axis



These devices typically work at 2.45 GHz for proton generation (ECR @ 875 Gs), Plasma reactor has been operated at 3.76 GHz to focus on EBWs

No ECR possible

Plasma diagnostics methods



Spectrum Analyzer non-linear wave-plasma interacton

Langmuir Probe 1D (axial) definition of **T_e, n_e, EEDF profiles**

Invasive tools

RF

(3 kHz-300 GHz)

$E<10^{-2}$ eV

IR

(300 GHz-430 THz)

$10^{-2}<E<1$ eV

Visible & UV

(1,6-12 eV)

EUV

(10-120 eV)

Soft-Xray

(0,12-12 keV)

Hard-Xray

(10-100 keV)

Optical plasma Observation

Spectroscopy 1D/ 2D density-temp. measurement

X-ray Pinhole Camera

Imaging & 2D-Spectroscopy

2D energy distribution and (relative) density

SDD - HpGe

X-ray detectors

Spectroscopy

Non-Invasive tools

Microwave Interferometery measuring plasma density

Plasma diagnostics tools

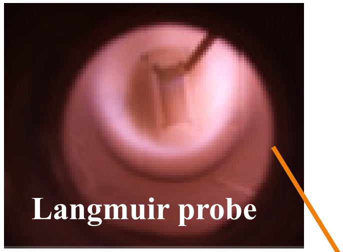
Interferometer

Spectrum analyzer

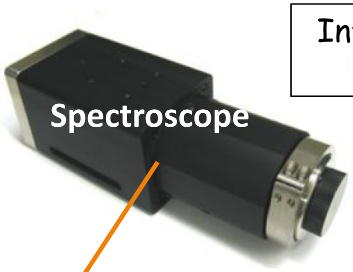
Information about ion waves and **ion heating**

X ray detectors

X ray imaging CCD camera



Langmuir probe



Spectroscope

Information about total electron density and electron density distribution

Information about expected Current, emittance, and brillance

Information about **Electron Energy Distribution Function** and 2D X-ray distribution.

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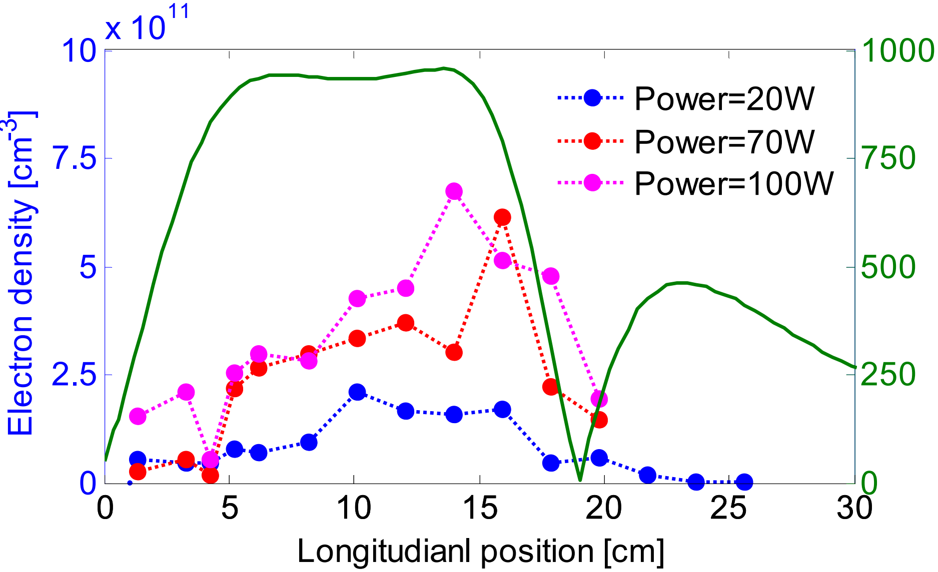
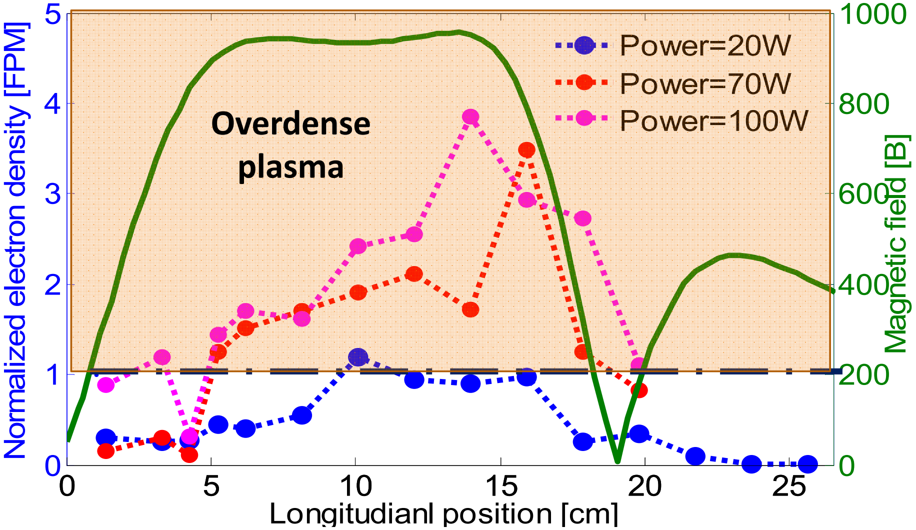
Results from LP measurements-1

Nitrogen gas @1.5$\cdot$10^{-4} mbar
3.76 GHz MicroWave frequency

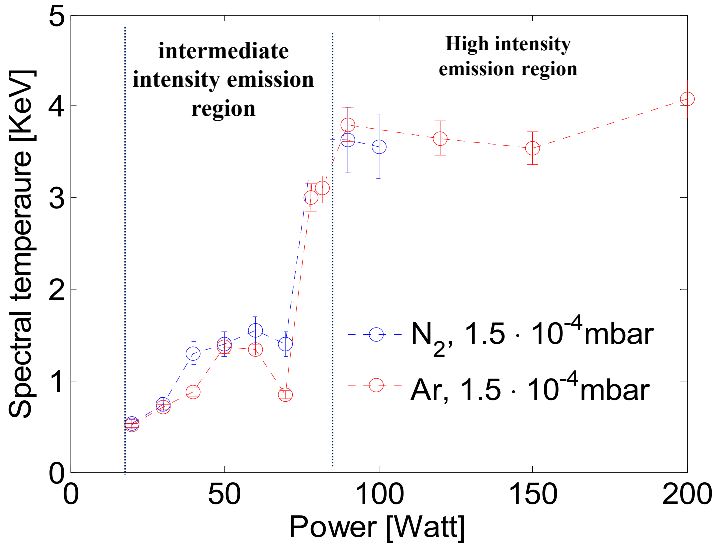


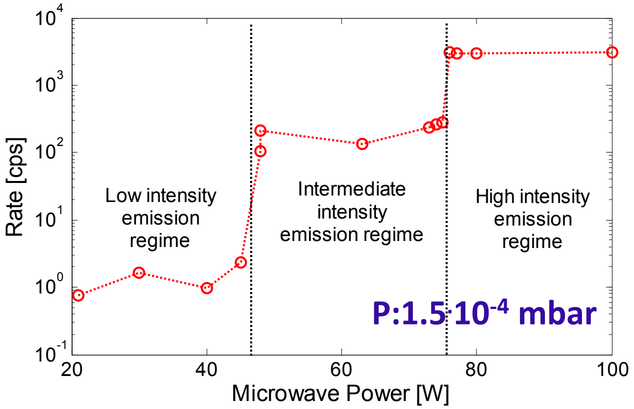
Density cut-off @3.76 GHz = 1.75 $\cdot 10^{11}$ cm^{-3}

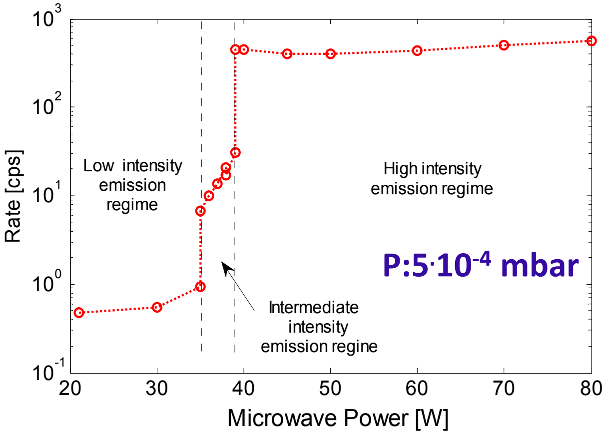


different models validated in **high density** (10^{10}-10^{12} cm^{-3}) **magnetized plasmas (RF)**

X ray measurements from SDD





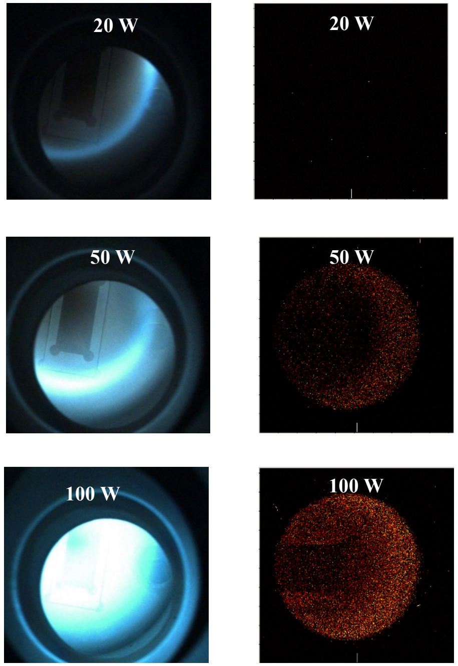


- Spectral temperature increases from ≈1 to 4 keV with MW power;
- Three emission regimes indentified, depending on power and pressure;

From optical to X ray inspection

R. Racz talk: MODO01 for more information

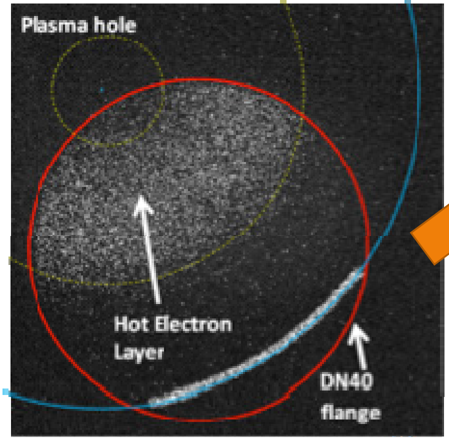
Imaging in optical and X-ray domain

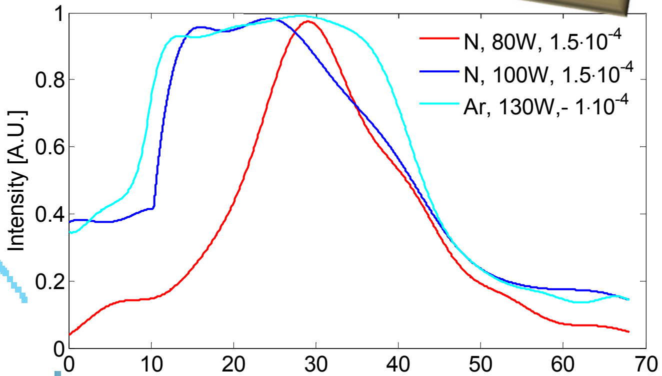


Transversal reconstruction of the plasma structure in X-ray domain (1-30 keV).

Plasma chamber

X ray imaging evidences that the pumping power is deposited in the annulus where the energetic electrons are generated

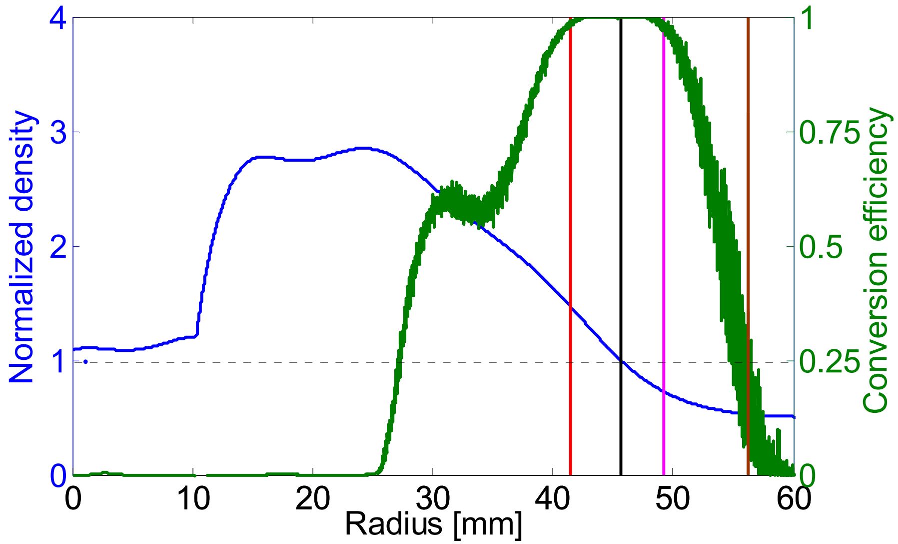




Radial density reconstruction

Radial profile and FX-B conversion

The knowledge of the radial profile allows us to calculate the absolute value of the conversion factor FX-B



Density gradient assumes the value which maximizes FX-B conversion

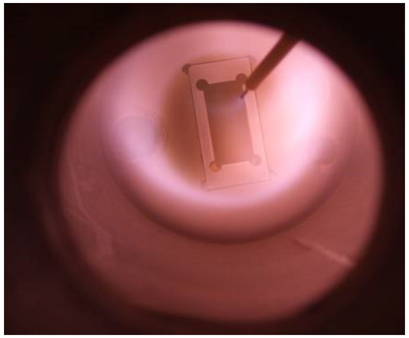
$$\eta = 294|BL_n|^{UHR}$$

$$|C_{FX-B}| = 4e^{-\pi\eta}(1 - e^{-\pi\eta})$$

Radial gradient is the optimal one to allow FX-B conversion

FX-B conversion is the best candidate to explain the generation of **overdense plasma** in the plasma reactor

From LP diagnostics to interferometry



LP diagnostics

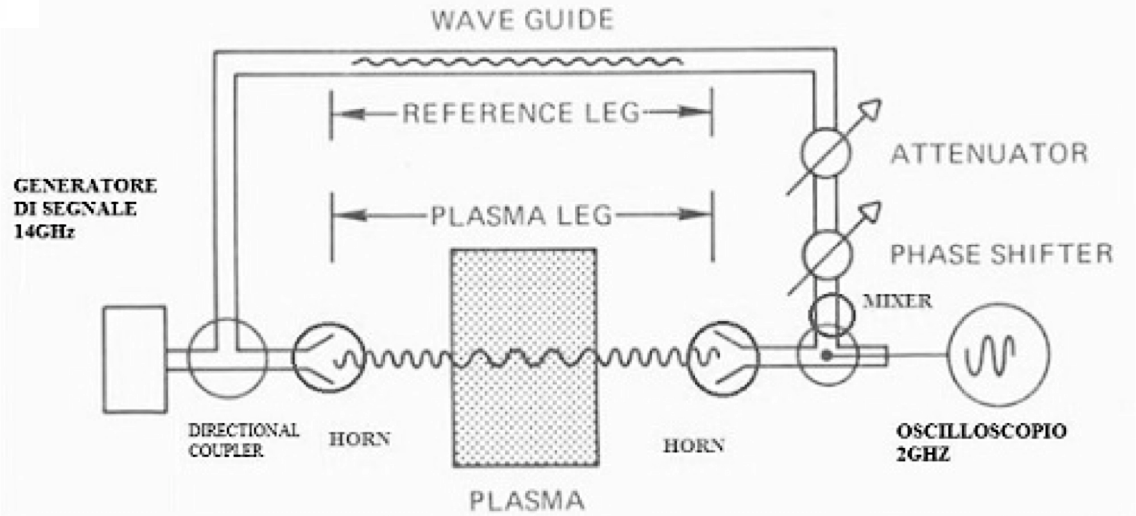
i) Local plasma parameters measurement ✓
ii) the density measurement is “model-dependent”;
iii) LP undergoes to plasma damage when density overcomes 10^{12} cm^{-3};
iv) LP perturbs the plasma chamber, in particular by an electromagnetic point of view.
v) Only cold electron population is characterized 👎

Interferometry

i) Allows whole plasma density probing;
ii) Non-invasive diagnostics; ✓
iii) Well-known technique;
iv) Probing wavelength $\lambda \sim L\ (plasma\ chamber\ dimension)$

→ Modal behaviour of the probing wave 👎

Classical interferometry for plasmas



Classical Scheme of Interferometer

$$\Delta\varphi = \frac{\omega}{c}\left[1-\left(1-\frac{{\omega_p}^2}{\omega^2}\right)^{\frac{1}{2}}\right]L$$

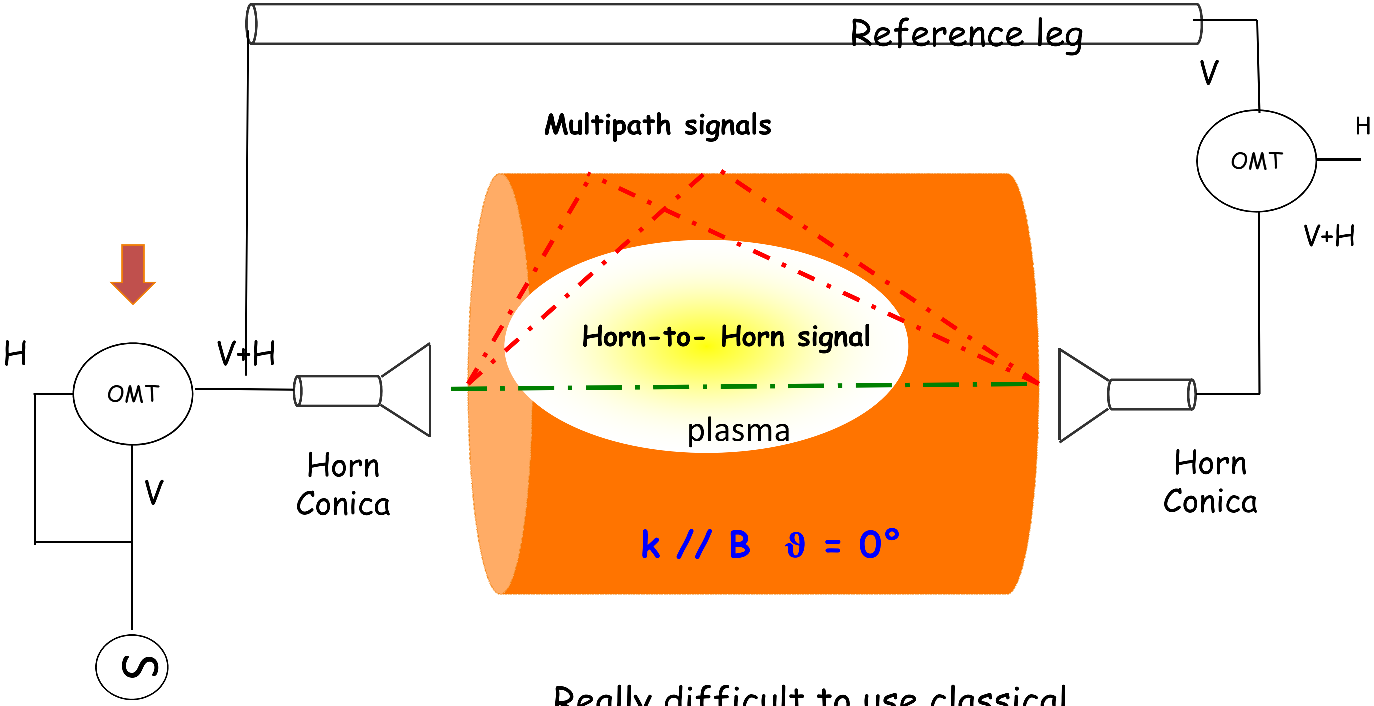
In plasmas the phase variation depends on the "**natural plasma frequency**"

$$ {\omega_p}^2 = \frac{4\pi \boxed{n} e^2}{m\varepsilon_0}$$

The plasma frequency depends on **the density**

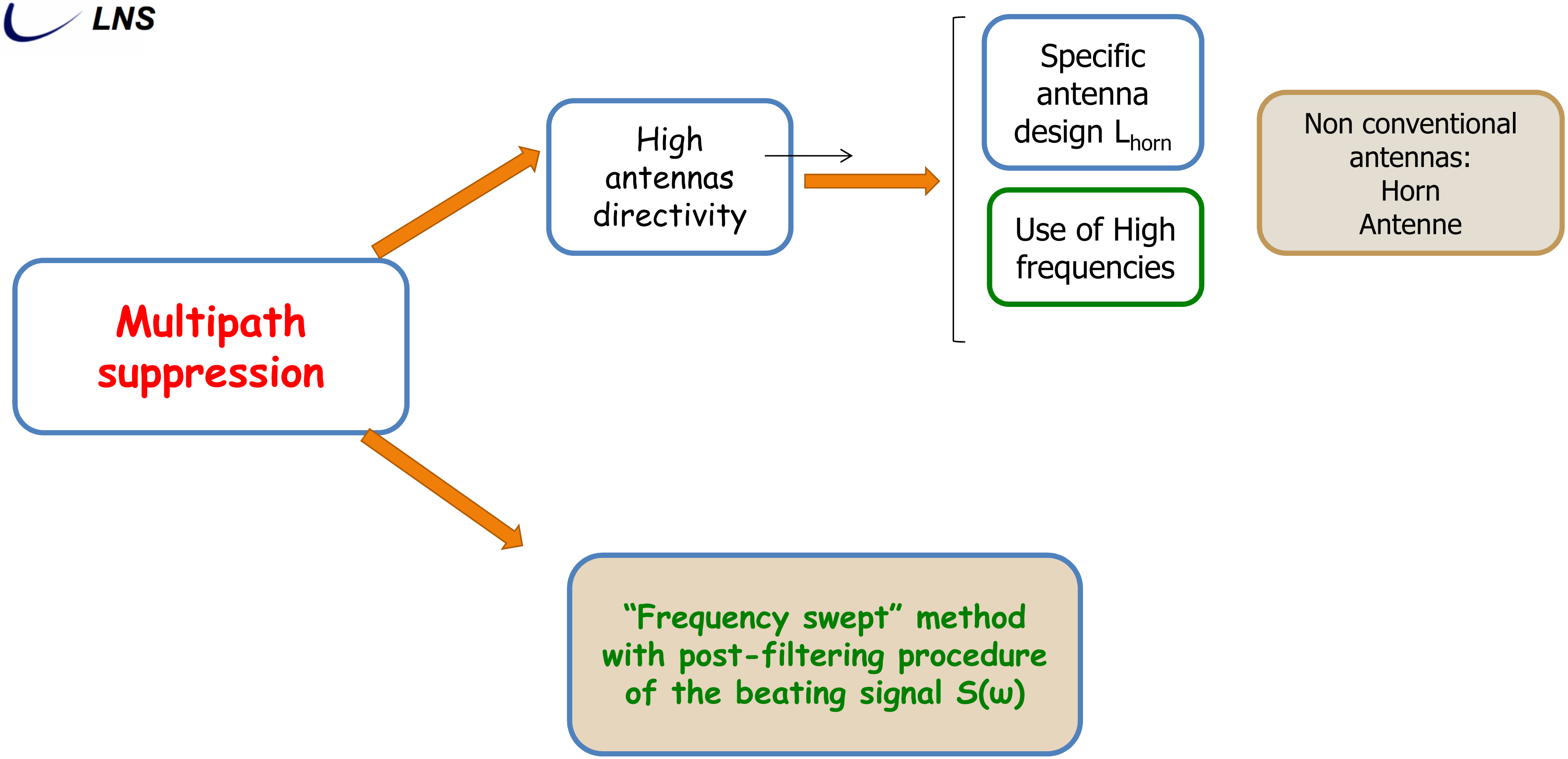
Microwave interferometry measures plasma density through a measurement of phase shift.

Criticality: multi-paths introduce spurious signals in small devices



Really difficult to use classical microwave interferometry

Design challenges



Multipath suppression

High antennas directivity

Specific antenna design L_{horn}

Use of High frequencies

Non conventional antennas:
Horn
Antenne

"Frequency swept" method with post-filtering procedure of the beating signal S(ω)

Design of a “frequency swept” interferometer

The method is based on the frequency shift of the beating signal given by the superposition of the reference leg plus the plasma leg waves.

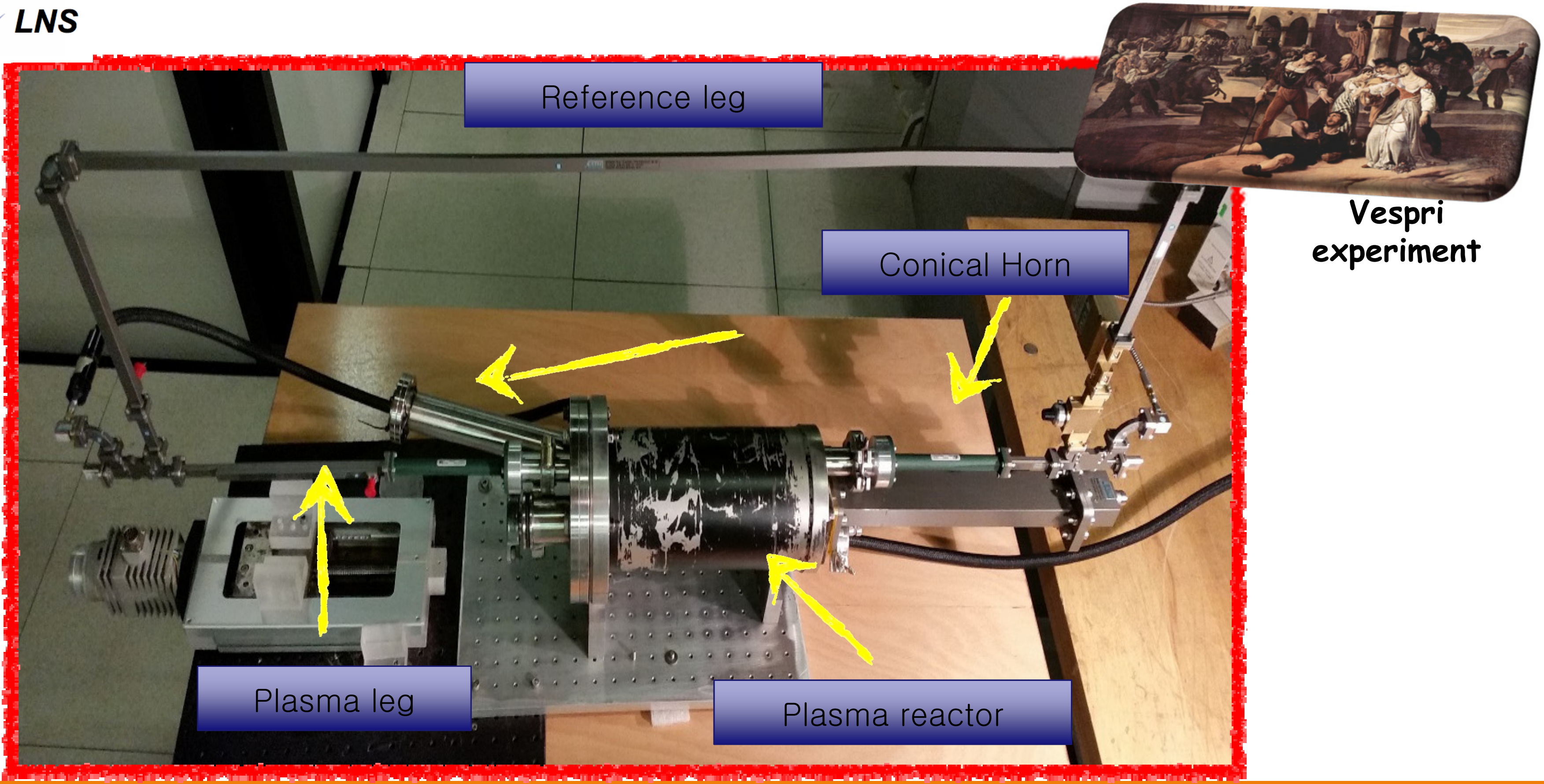
The beating frequency can be fixed as long as the ramp relation “freq. vs. time” is chosen in the following way:

$$\omega_{B_0} = \frac{\partial \omega}{\partial t}\left(\Delta L \frac{\partial k_g}{\partial \omega} + \frac{2a}{c} \right) = \text{constant}$$

$$S(\omega) \propto 2A^2 \cos^2\left\{ \left[\Delta L \sqrt{\omega^2 - \omega_c^2} + \int_{-a}^{a} \sqrt{\omega^2 - \omega_p^2(l)}\, dl \right] \Big/ 2c \right\}$$

The presence of plasma (accounted by the plasma frequency w_p) only shifts the beating frequency, while multipath introduce spurious components in the spectrum

Experimental setup @ INFN-LNS

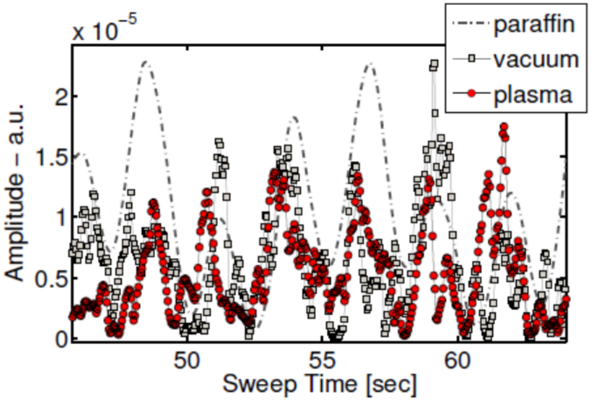


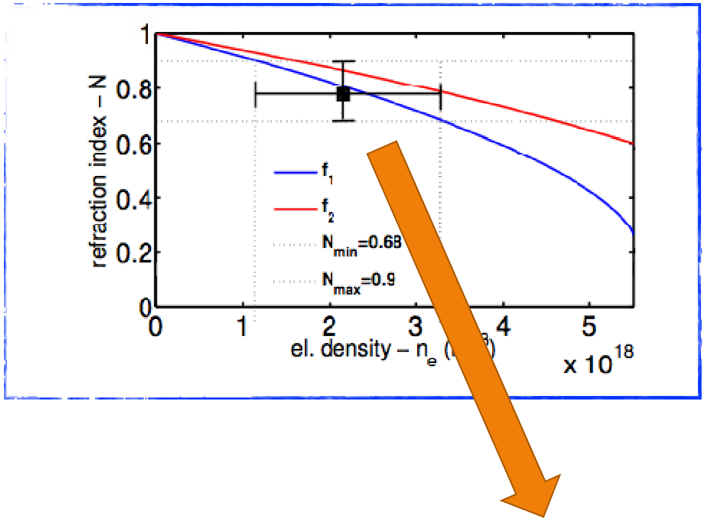
Vespri experiment

Interferometry in ECRIS:

the measurement by Freq. Sweep method

Courtesy of G. Torrisi





Medium	P_{RF} [W]	$\omega_{beat}\ [rad/s]$	Refr. Index N
Empty cavity	0	$2\pi * 0.397$	1
Bulk paraffin	0	$2\pi * 0.380$	1.43
Plasma	150	$2\pi * 0.407$	0.792 ±0.11

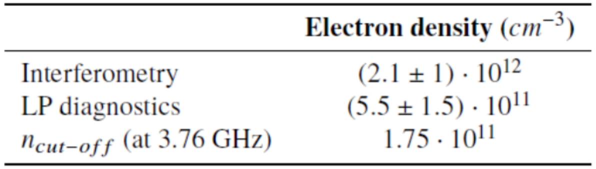
By literature $N_{paraffin}$=1.45

Interferometric method:
$n_e = (2 \pm 1) \cdot 10^{12}$ cm^{-3}

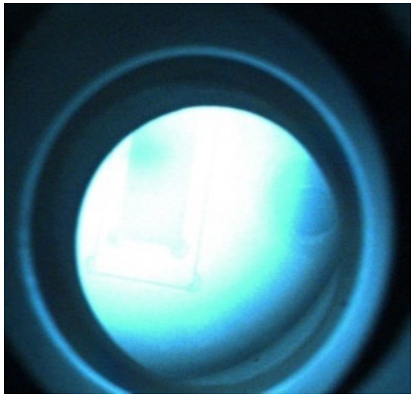
Remarks of density measurements on plasma reactor

Overdense plasma generated by means of FX-B conversion:

- **4 times overdense** according to LP diagnostics
- **10 times overdense** according to interferometry



	Electron density (cm^{-3})
Interferometry	$(2.1 \pm 1) \cdot 10^{12}$
LP diagnostics	$(5.5 \pm 1.5) \cdot 10^{11}$
$n_{cut-off}$ (at 3.76 GHz)	$1.75 \cdot 10^{11}$



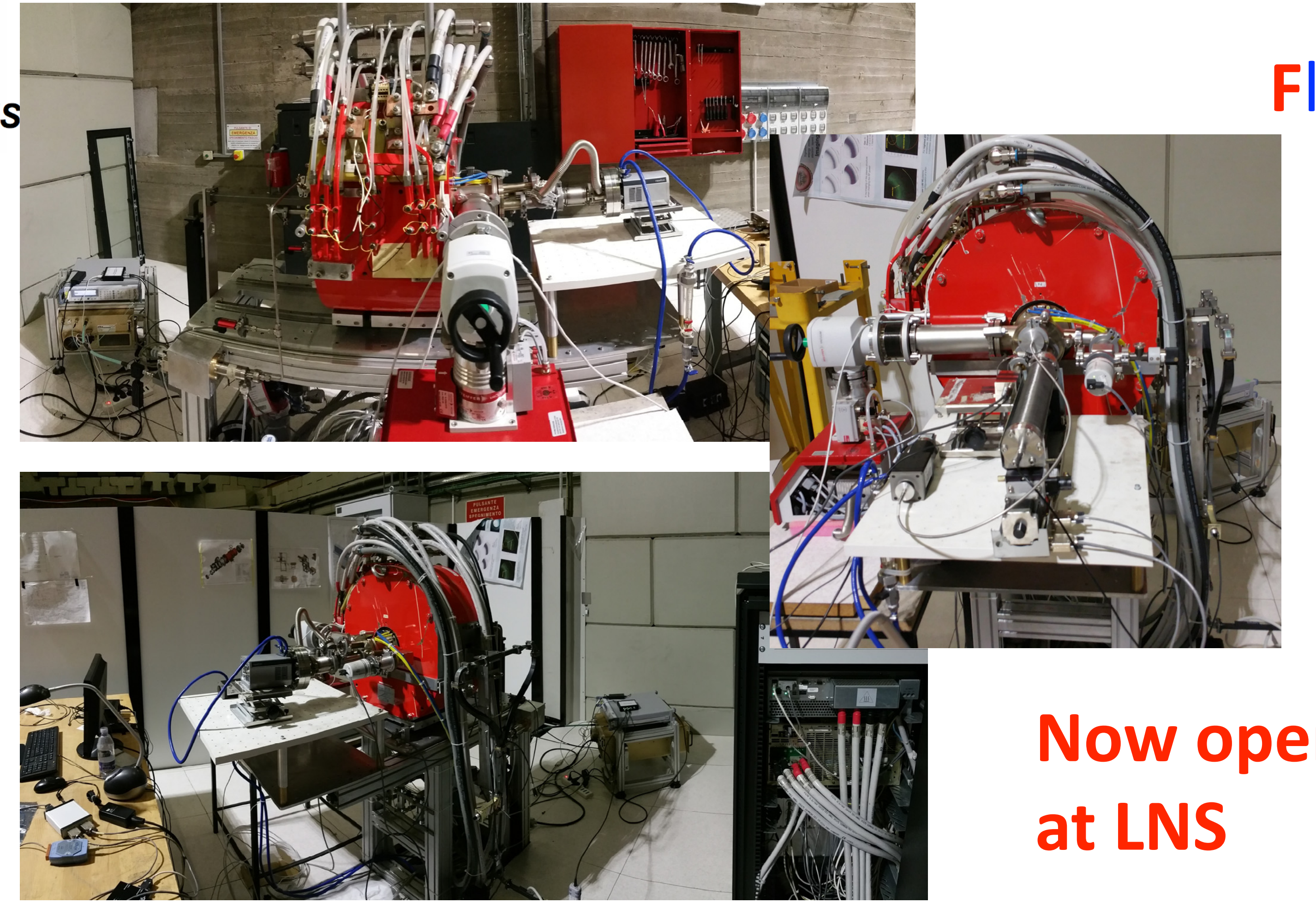
This result has been obtained in a small plasma reactor:

- **No chance to modify magnetic field;**
- **No chance to launch the wave with wanted angles (cavity mode dominated system);**
- **Modal dependent conversion: Fine frequency tuning needed to couple X-mode to EBW;**

We want to move from a cavity modes dominated system towards a microwave orientend system:

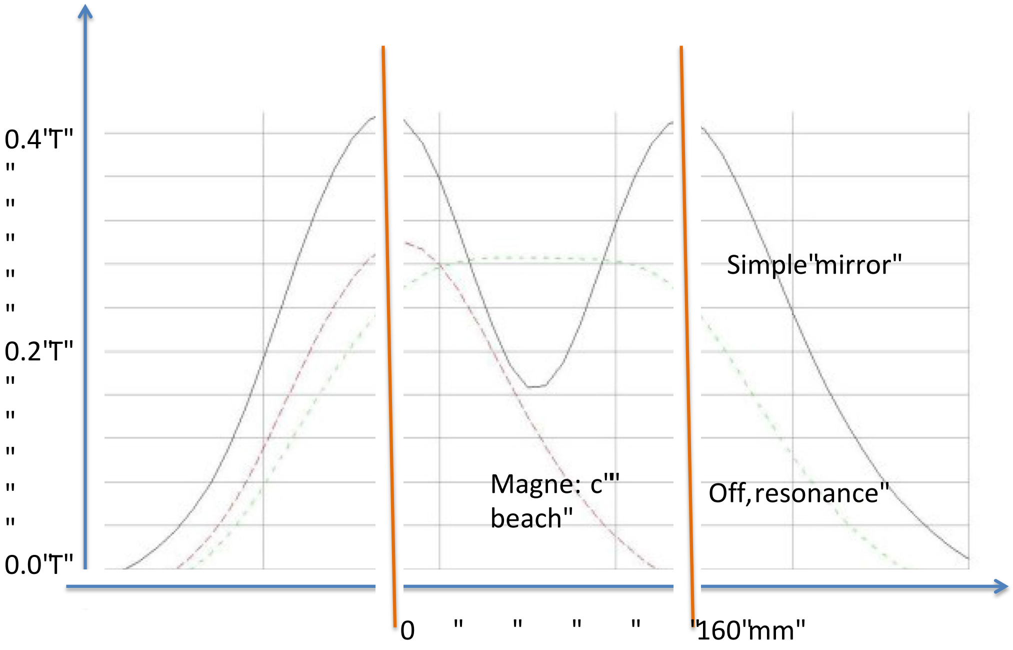
The New Flexible Plasma Trap and launcher at INFN-LNS

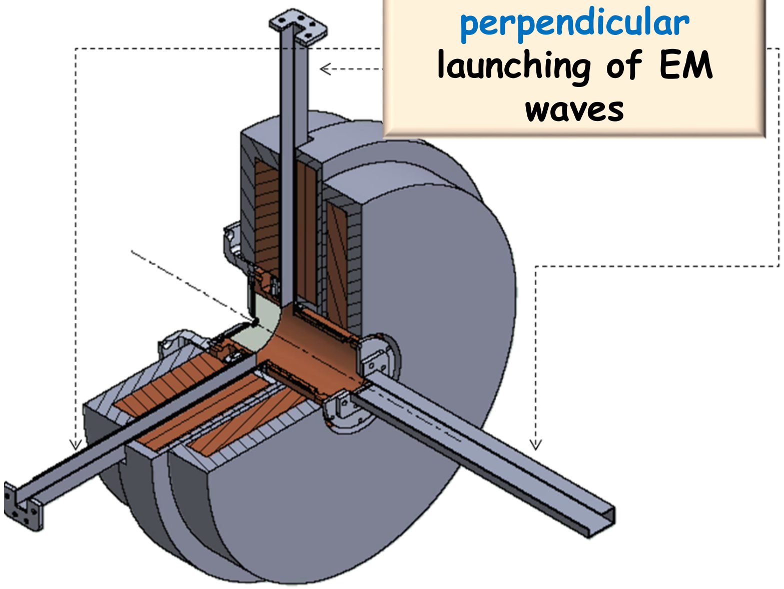
Flexible Plasma Trap



Now operating at LNS

The FPT magnetic field and the microwave injections



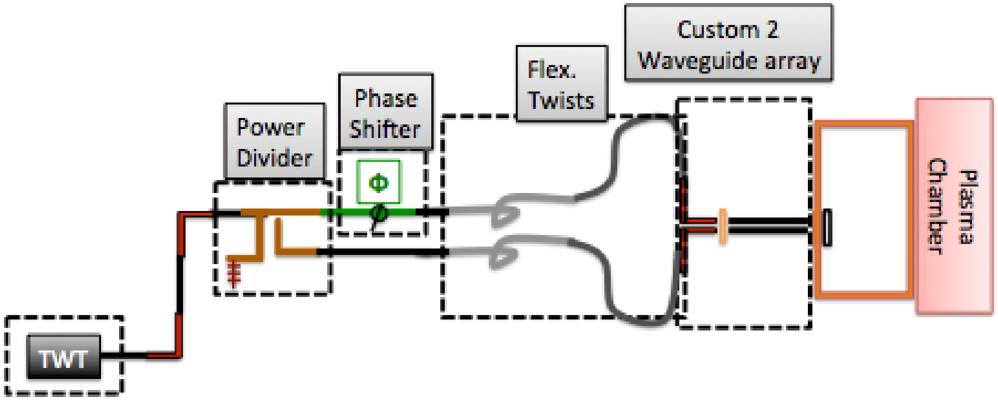


Parallaler and perpendicular launching of EM waves

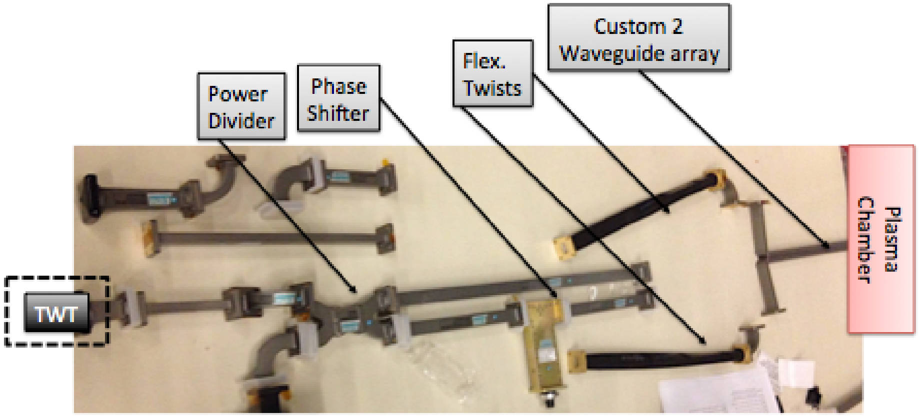
The launcher: mechanical Implementation at INFN-LNS

Phased waveguide array of two elements

microwave launcher: proposed setup

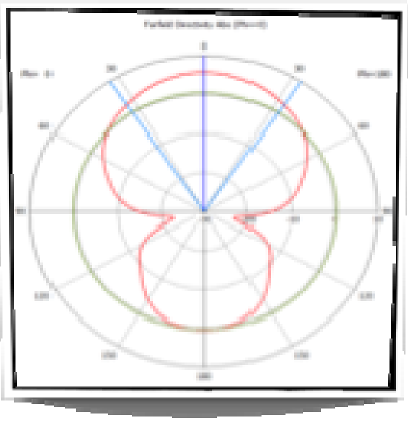


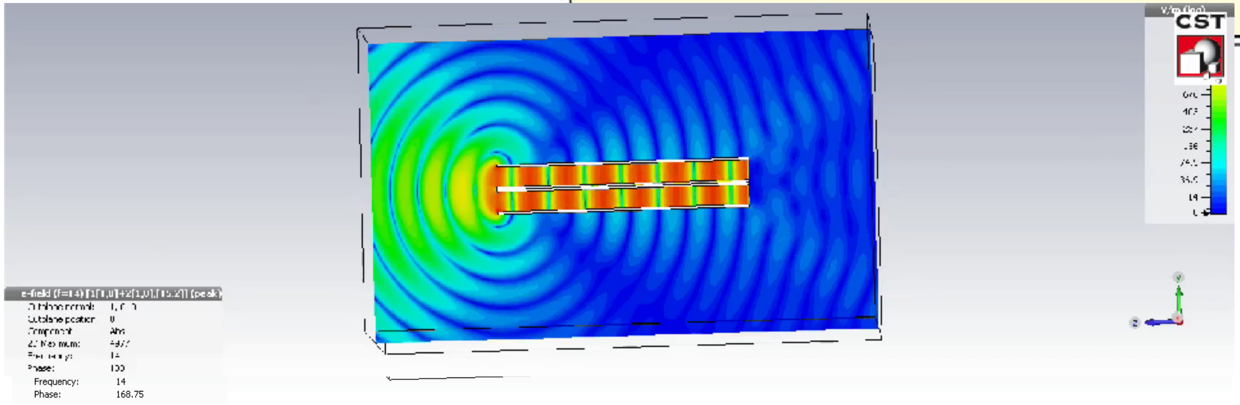
- TWT ampl. 13.75-14.5 GHz
- Power divider
- Phase shifters
- flexible waveguides



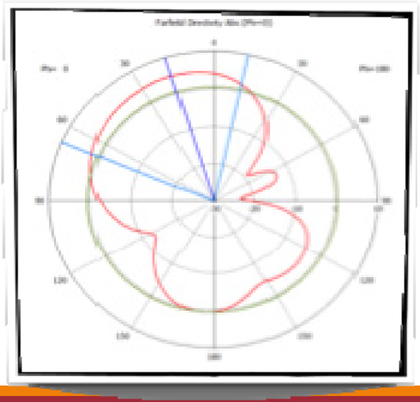
“Microwave-absorption-oriented” design

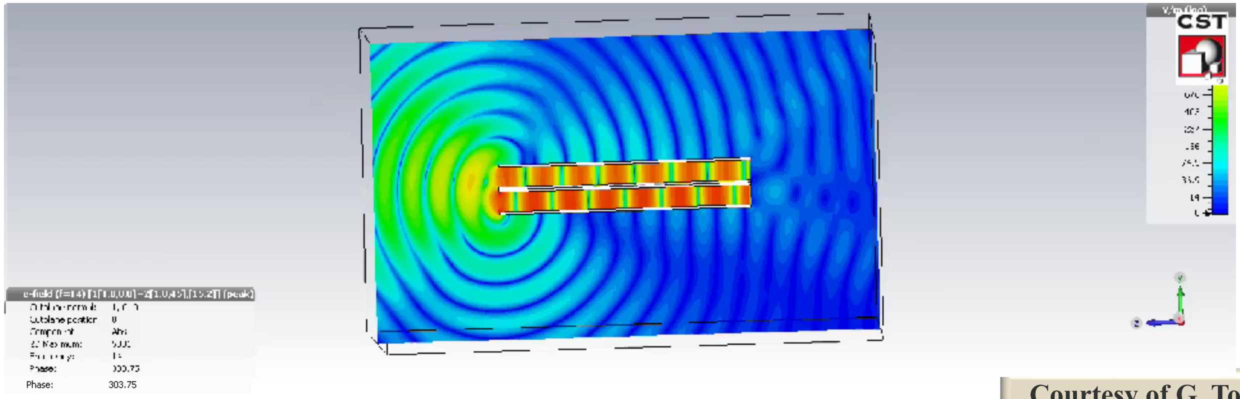
Launcher by “two-waveguides-array”: lobe tilt by phase shift for otimizing oblique coupling of O-modes -->





Frequency: 14
Phase: 168.75





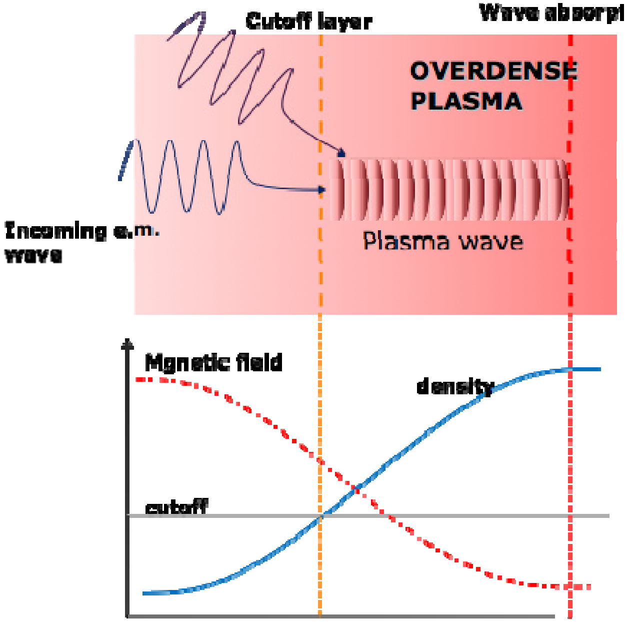
Phase: 303.75

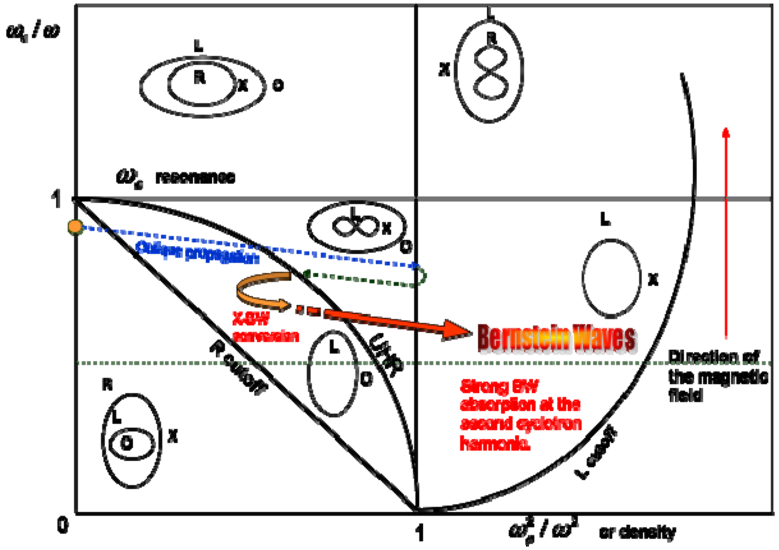
Courtesy of G. Torrisi

“Microwave-absorption-oriented” design

1) Primary plasma generated at 7 GHz by ECR.

2) A secundary plasma generated by perpendicular launching at 14 GHz





Oblique launching allow a more efficient matching of the incoming microwave radiation with the self-oscillations of the magnetized plasma

Conclusions

- **New schemes of plasma heating can allows to overcome ECRIS density limitation:**
- At infn-lns, an overdense plasma has been generated in a small plasma reactor. Density was ~**5 times overdense** according to LP**,**~ **10 times overdense** according to interferometry;

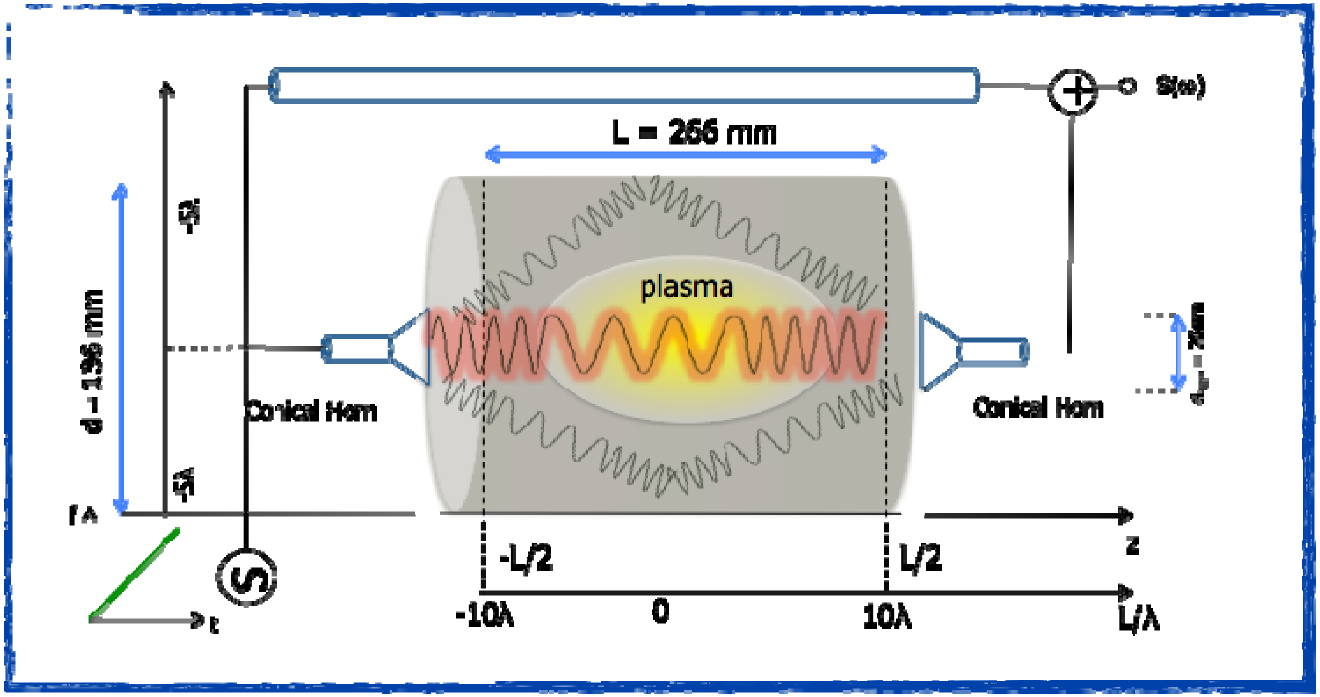
- **Characteristic signatures of Berstein waves generation and absorption was found:**
- Non linear plasma behaviour (different plasma regimes identified), overdense generation and ion noise; FX-B conversion is the candidate to explain bernstein generation;

- **The development of new diagnostics tools represents a fundamental task for the comprehension of the plasa behaviour. A set of diagnostic tool has been installed INFN-LNS** (spectroscope, interferometer, X-ray detector and X-ray pin.hole camera,….). They form an unique diagnostics set for the plasma characterization in different temperature and density ranges; **Information about expected current – emittance and brillance**

- **A Microwave-absorption-oriented design** is been developing at INFN. The new FPT consist of three coils, three microwave injections (1 parallel, 2 orthogunal). A new launcher will launch microwave with desired angles within the plasma chamber;

Thank you
for your attention

Probing the plasma density in all the energy domains

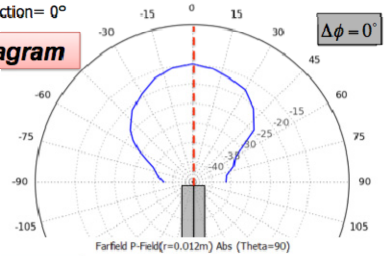


Drawbecks

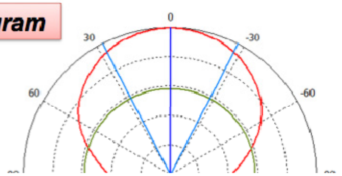
- **Limited ECRIS access probing port**
- **Multi-paths introduce spurious signals**

Main lobe direction= 0°

Measured diagram

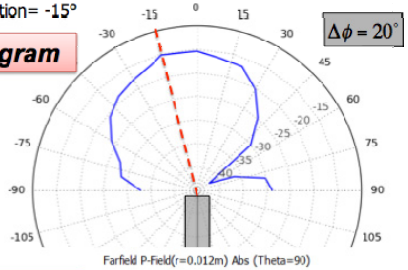


Simulated diagram

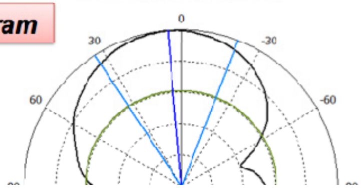


Main lobe direction= -15°

Measured diagram

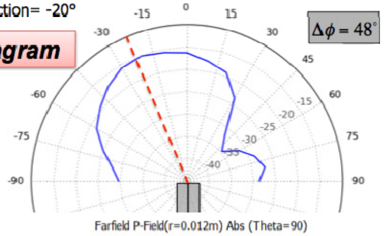


Simulated diagram

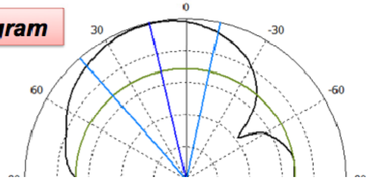


Main lobe direction= -20°

Measured diagram

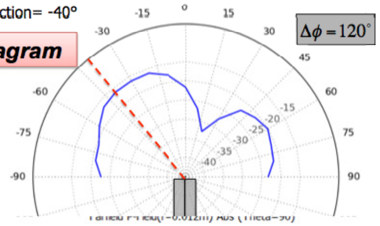


Simulated diagram

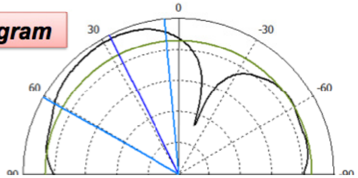


Main lobe direction= -40°

Measured diagram



Simulated diagram

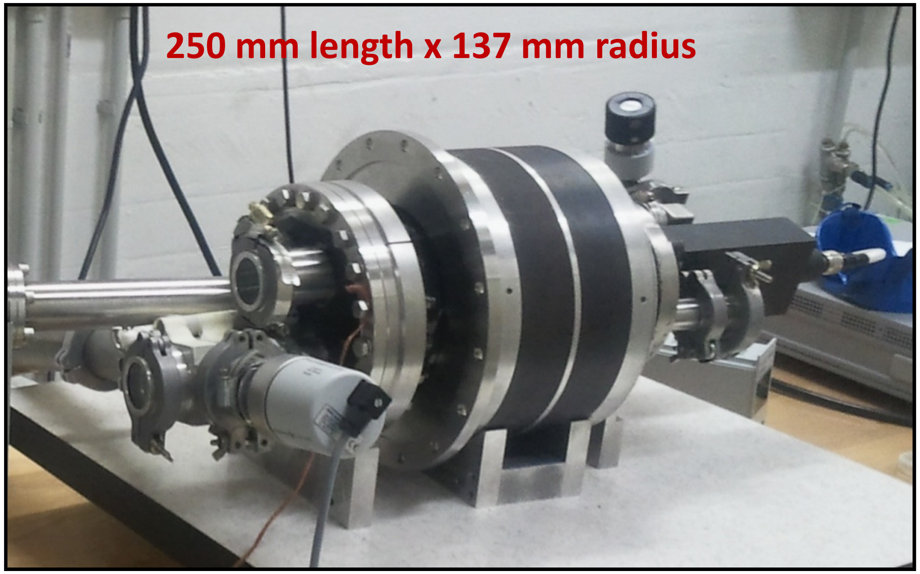


Set-up for EBW plasma generation

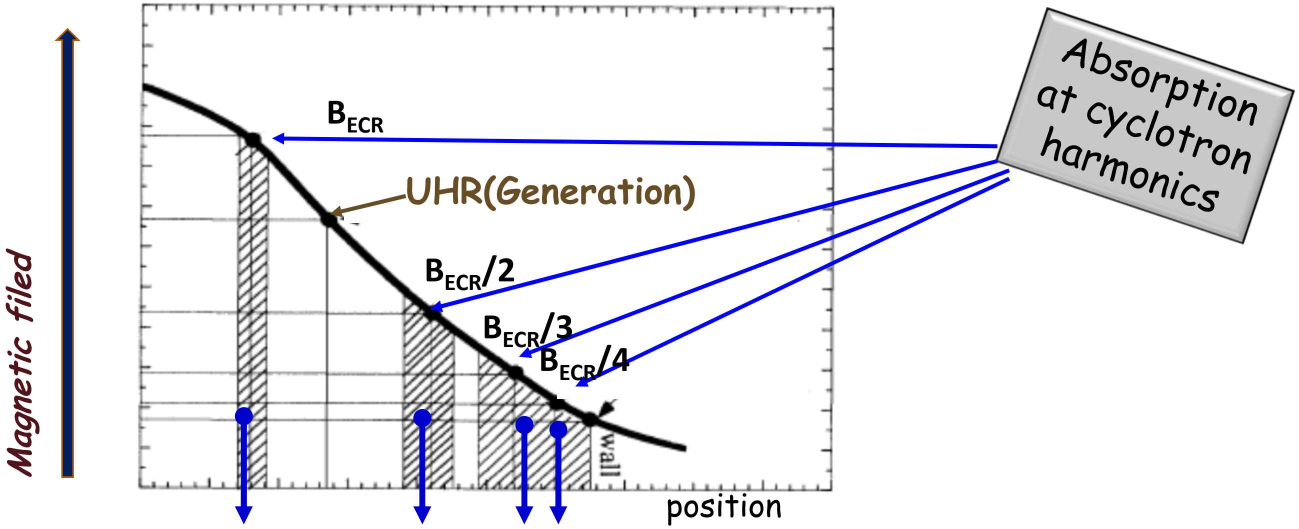
For the first time EBWs have been studied in a compact plasma based ion source:

The Plasma reactor

Limitations:
EM field is cavity mode dominated;
EM field and plasma must self-organize;
No direct control from external;


250 mm length x 137 mm radius

Absorption of Bernstein waves



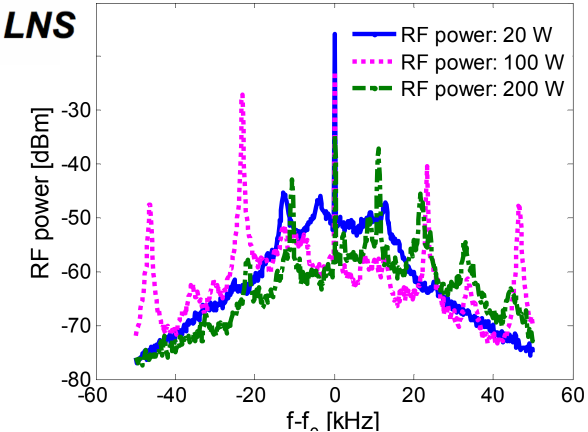
Hot Electrons Layers

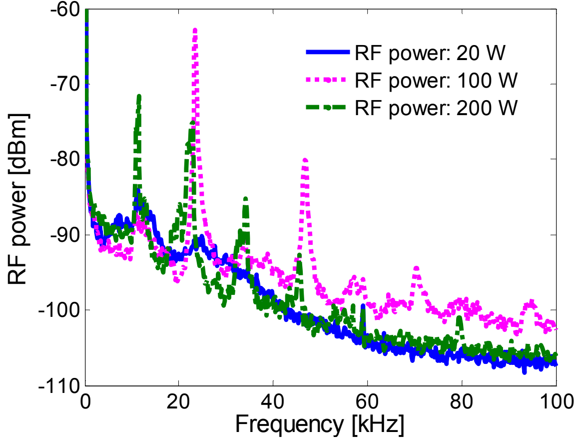
1 No cutoff density → Overdense plasma

2 Non-linear effects →
- Sidebands *around pumping wave*
- Ion waves (*MHz range*)

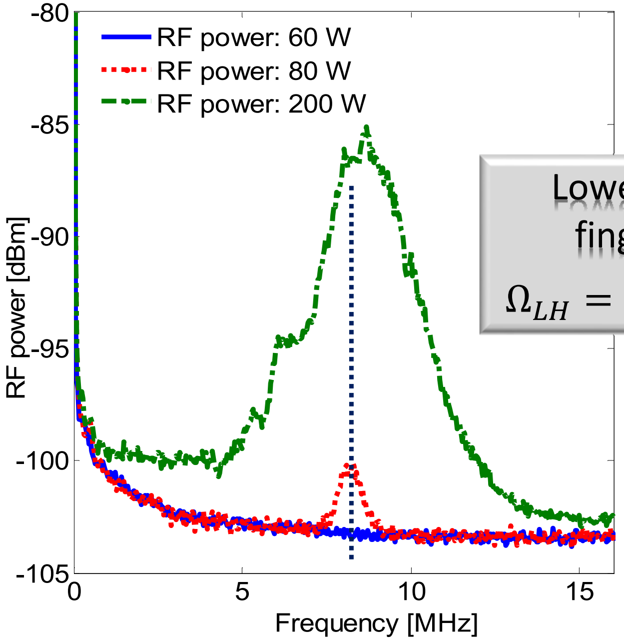
3 High energy electrons → X ray emission

EM spectrum from Spectrum analyzer





Generation of sidebands and ion noise in E.M spectrum over the threshold.

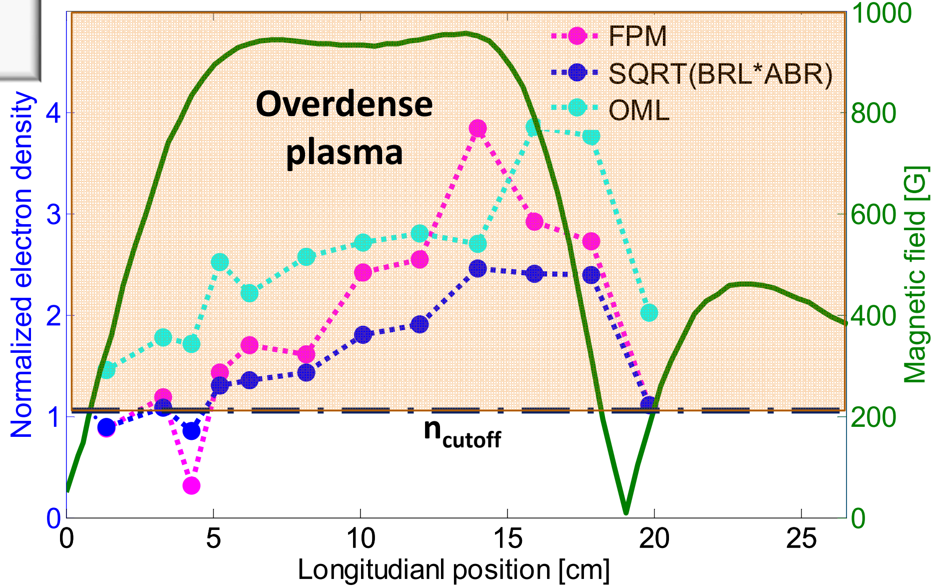


Lower hybrid oscillations: fingerprint of ES decay

$$\Omega_{LH} = \left[\,(\Omega_i\Omega_e)^{-1}+{\Omega_p}^{-2}\right]^{-1/2}$$

Models for LP diagnostics

different models validated in **high density** (10^{10}-10^{12} cm^{-3}) **magnetized plasmas (RF)**



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

BRL: Bernstein, Reynolds and Lafambroises model

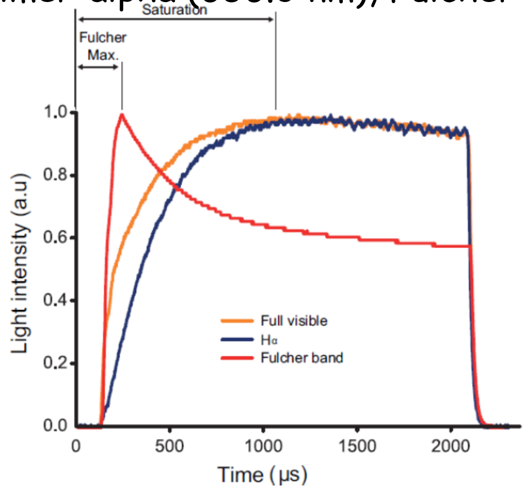
ABR: Allen, Boyd and Reynolds model;

OML: Orbited motion limited

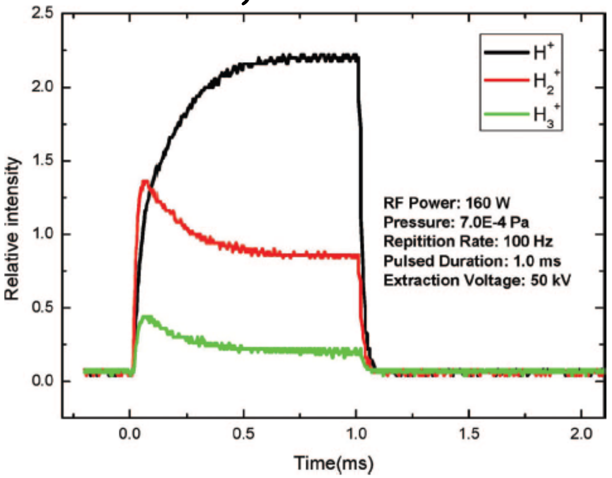
State of art

Correspondence between balmer alpha and fulcher band trend and H and H_2^+ trend was found by literature

Balmer-alpha (656.3 nm), Fulcher band (around 600 nm)



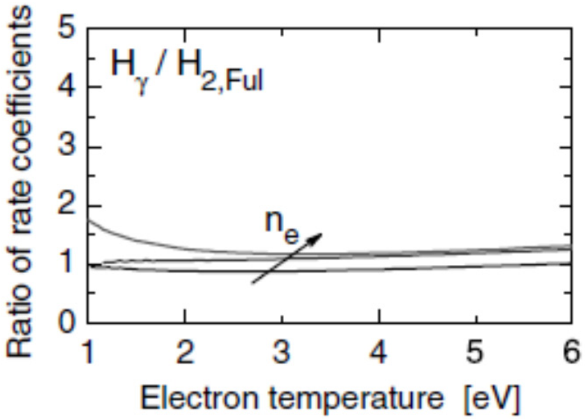
Cortazar et al Nucl. Instrum. and Methods A 781 (2015) 50–56

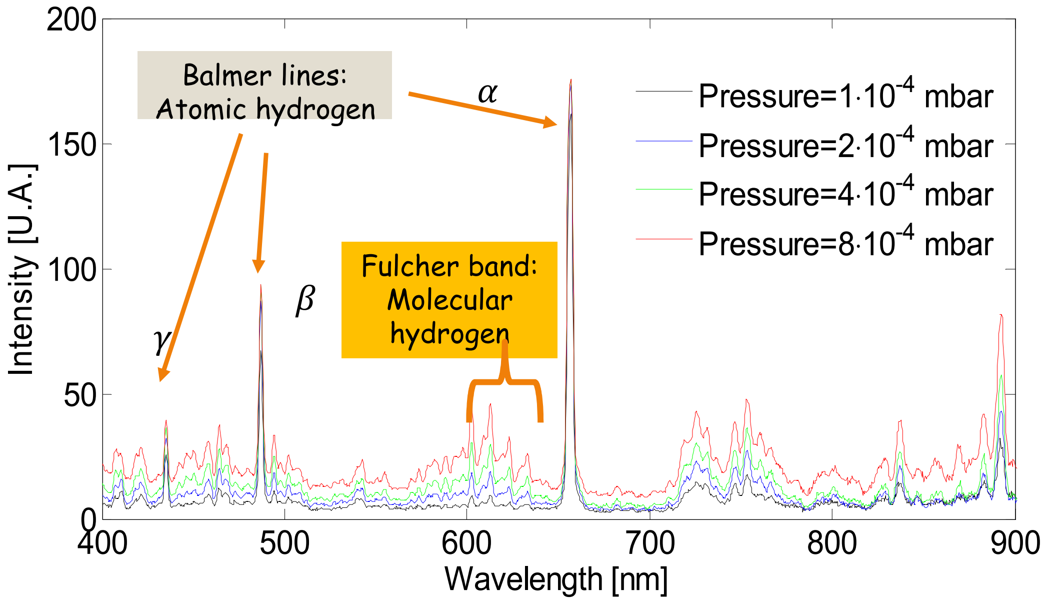


Y. Xu et al. Rev. of Scie. Instrum. **85**, 02A943 (2014);

Room for improvements

Spectroscopic studies suggest that the ratio between H_γ and $H_{2\,ful}$ allows to obtain the ratio between the H and H_2 population, in turn, connected to the proton fraction.




Balmer lines: Atomic hydrogen

Fulcher band: Molecular hydrogen

Courtesy of U. Fantz

Preliminary results from the FPT testbench