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On the observations of standing waves in cylindrical cavities filled by Microwave Discharge and ECR plasmas

L. Celona, G. Ciavola, S. Gammino, N. Gambino
F. Maimone, D. Mascali, R. Miracoli

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Experimental evidences

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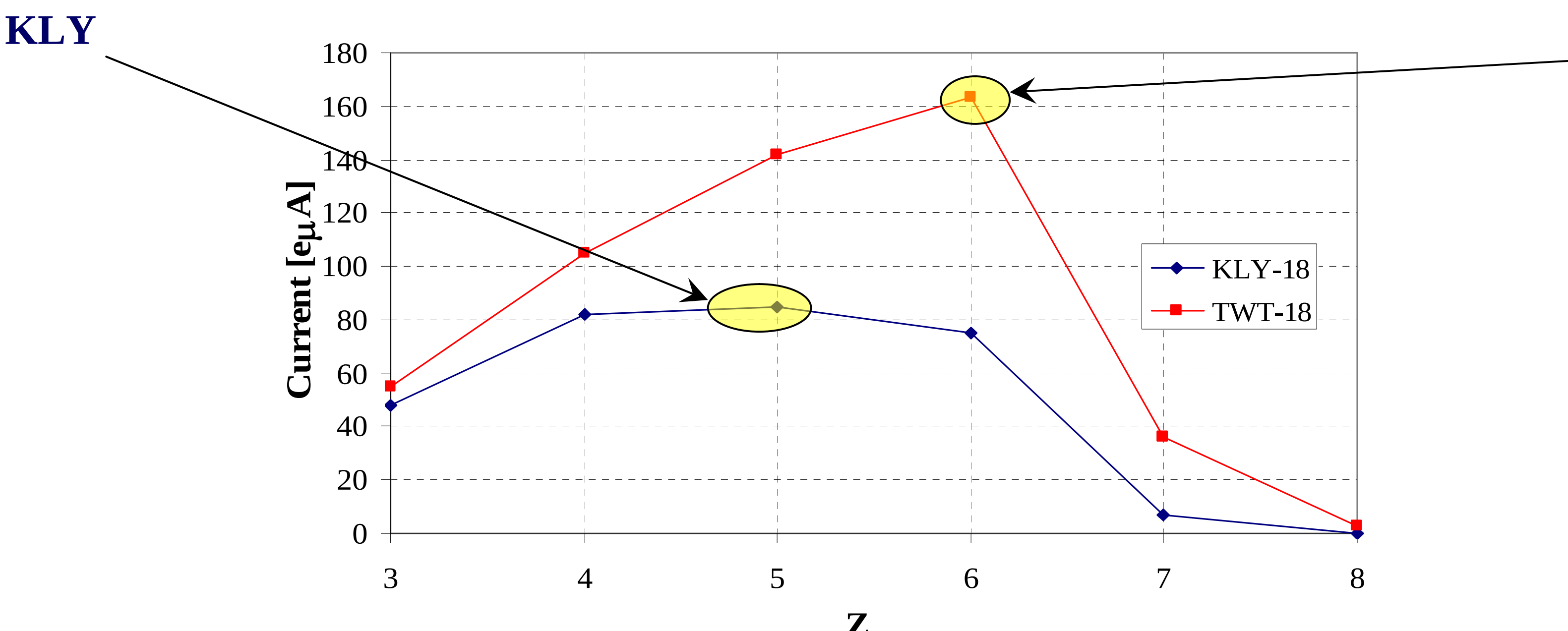
- Preliminary observations in 2001.
- Systematic measurements carried out in fall 2003 and fall 2004.



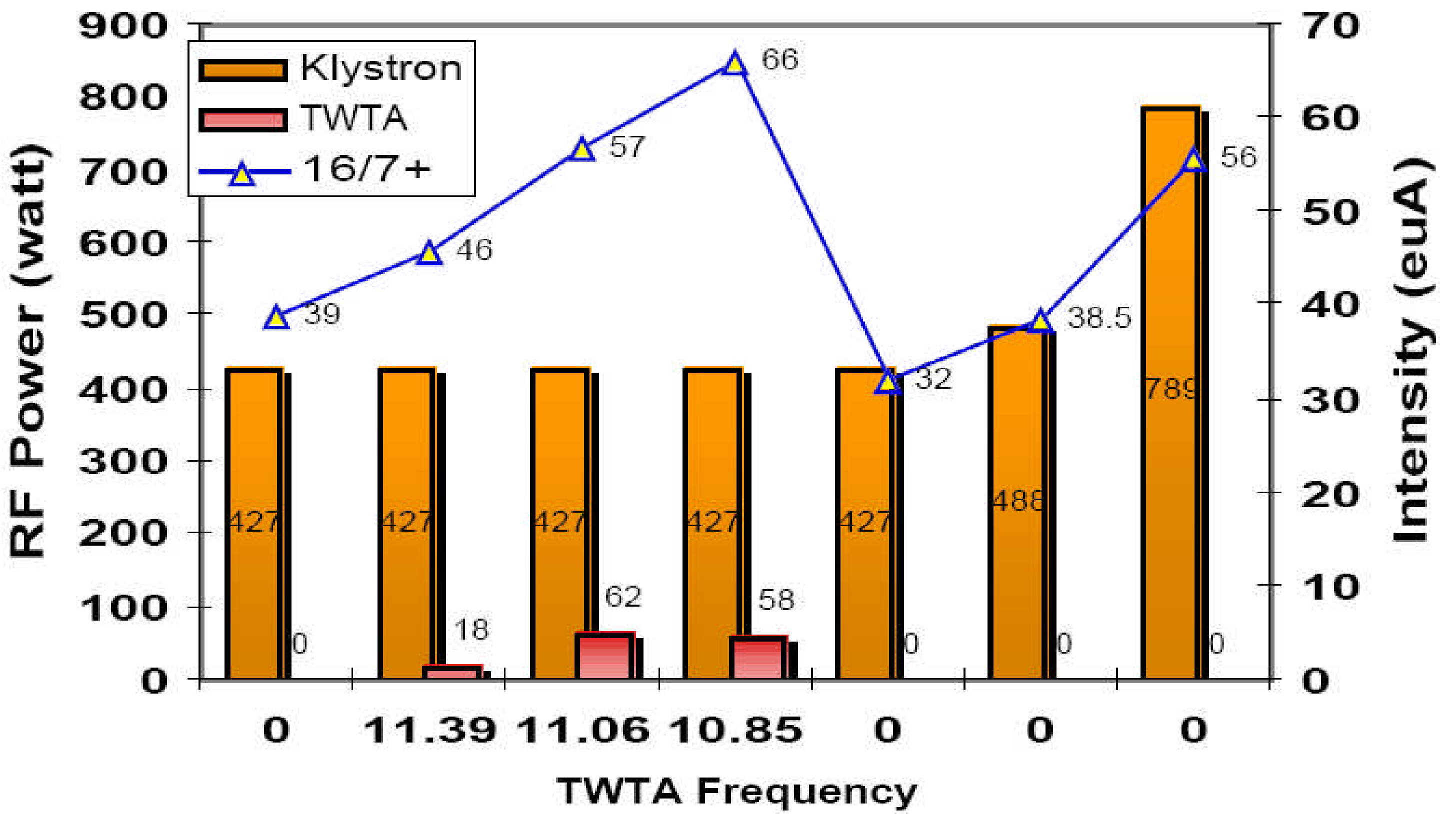
TWTs

Beam	*Gain*
O^{3+}	1.1
O^{4+}	1.3
O^{5+}	1.7
O^{6+}	2.2
O^{7+}	5

CSD of ^{18}O at 18 GHz with Klystron at 200 W and TWT1 at 195W.

S. Gammino et al. – Nuclear Instrument and Methods A - 2002
L.Celona et al. - Proceedings of 16th International Workshop on ECR Ion Sources, ECRIS'04

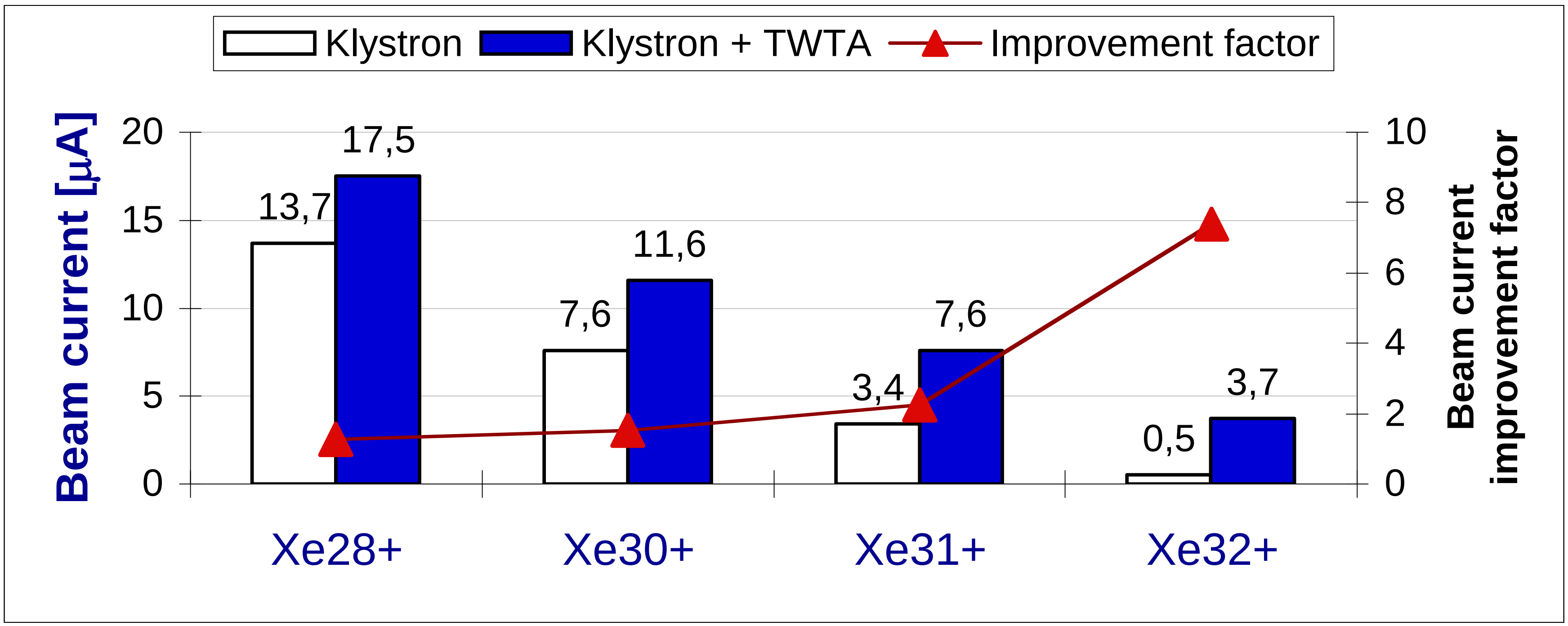
Experimental evidences



Strong improvement of the TFHE efficiency by tuning the second frequency provided by means of a TWT

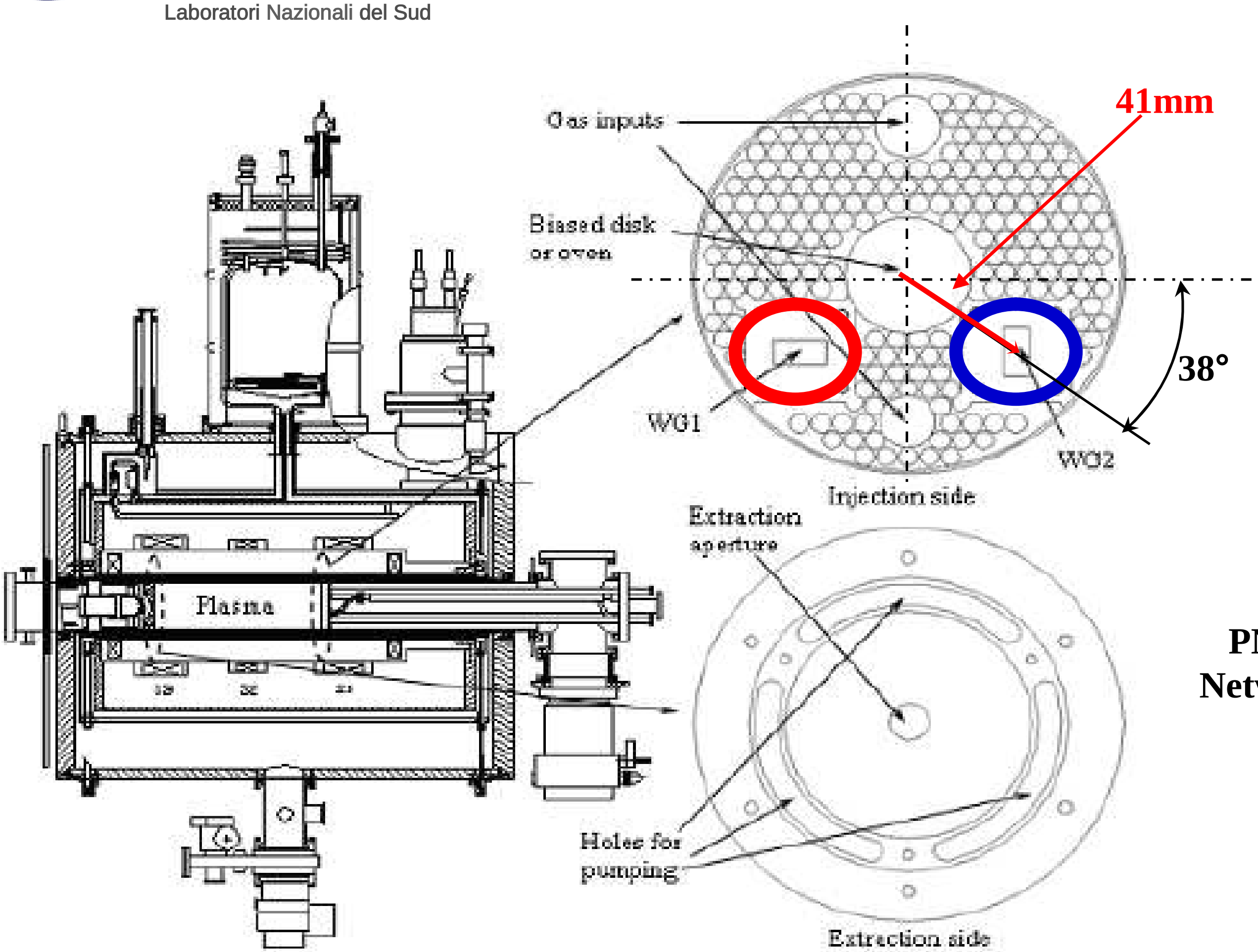
R.C. Vondrasek et al. - Proceedings of 15th International Workshop on ECR Ion Sources, ECRIS'02

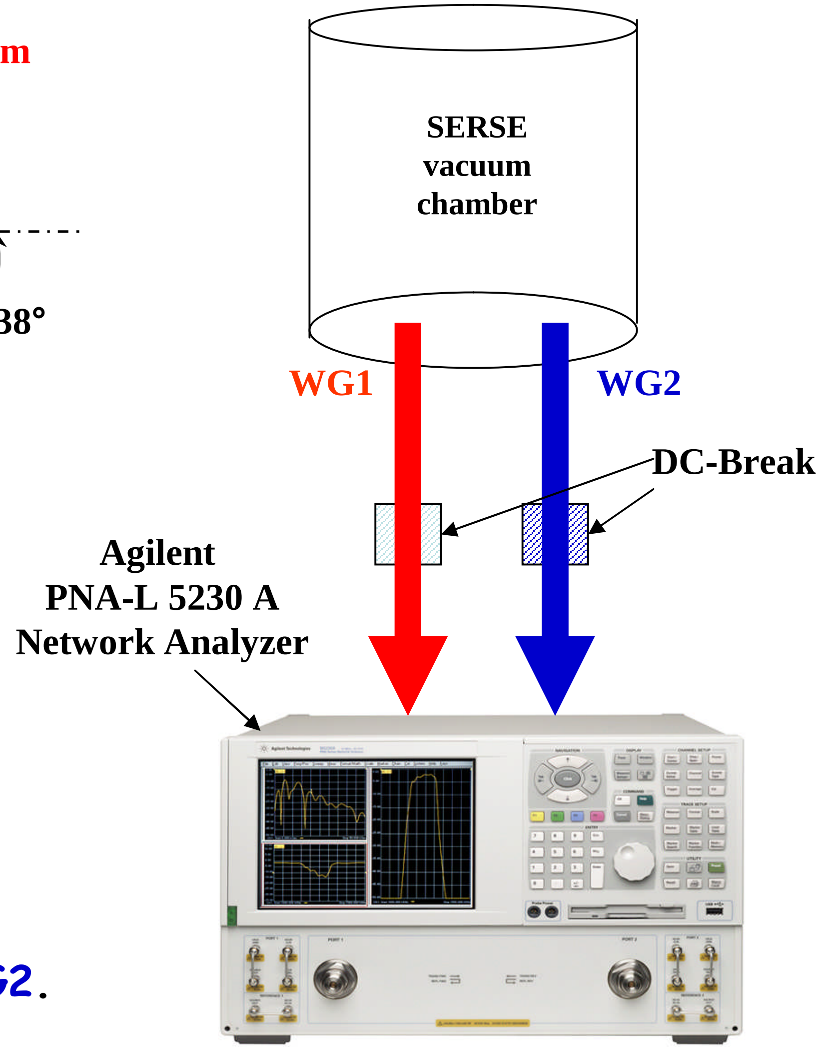
Experimental evidences



H. Koivisto – Kick off meeting ISIBHI, January 2005, Grenoble

SERSE measurements





Two different ports for the MW injection: WG1, WG2.

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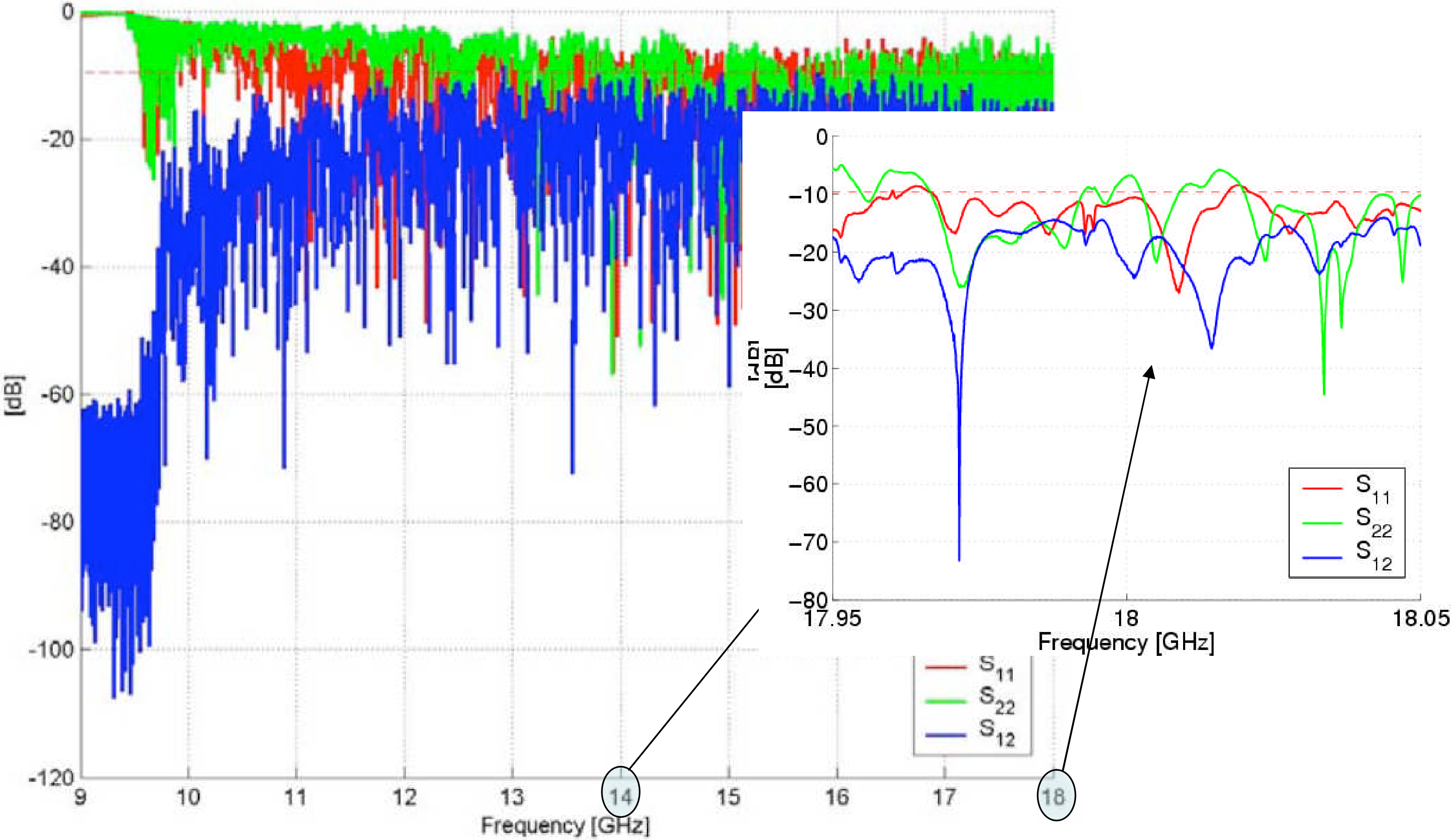
SERSE S-parameters (9-18 GHz) in vacuum



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L. Celona et al. – High Energy Physics and Nuclear Physics, 2007, 31 (S1), 147.

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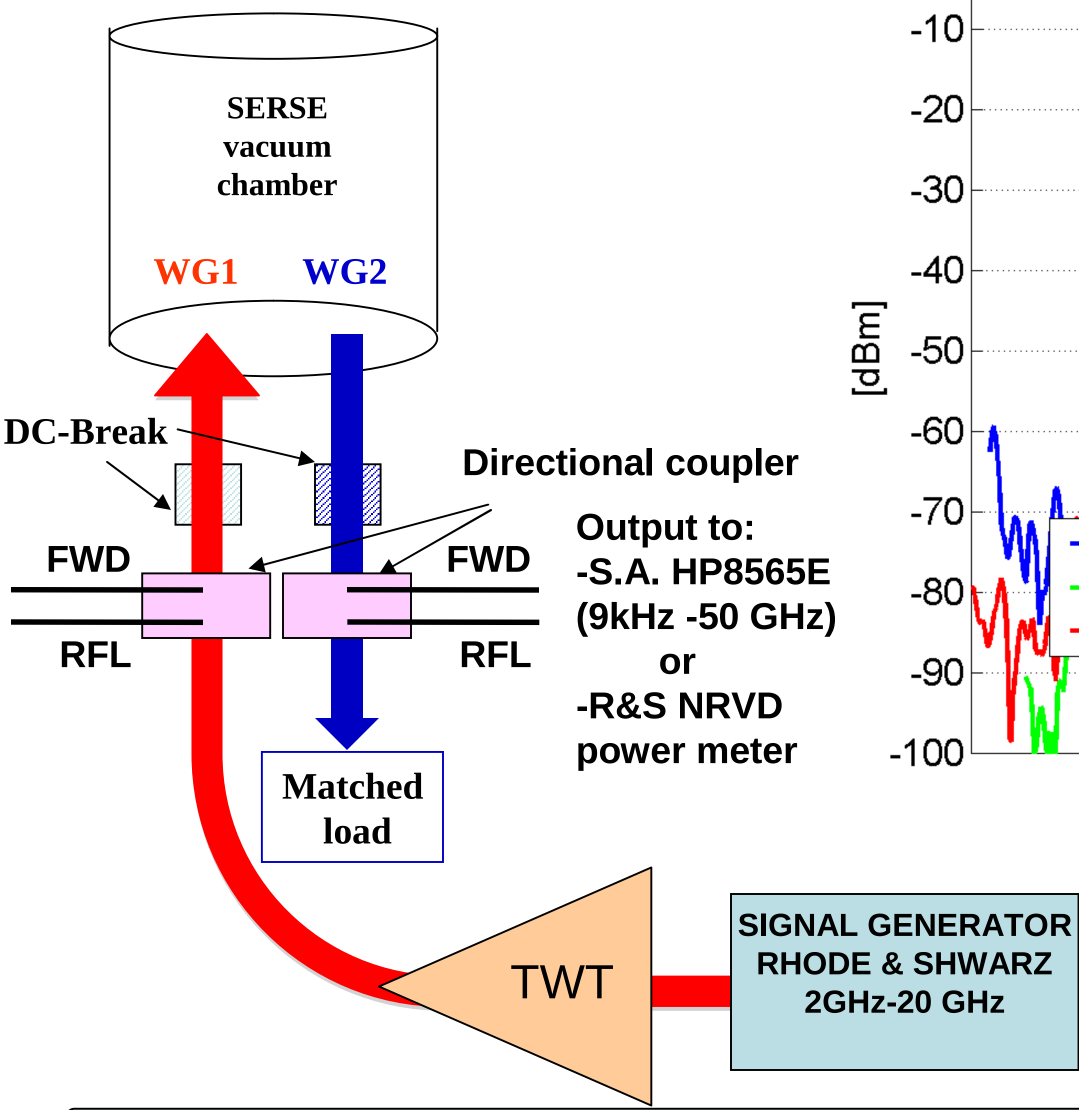
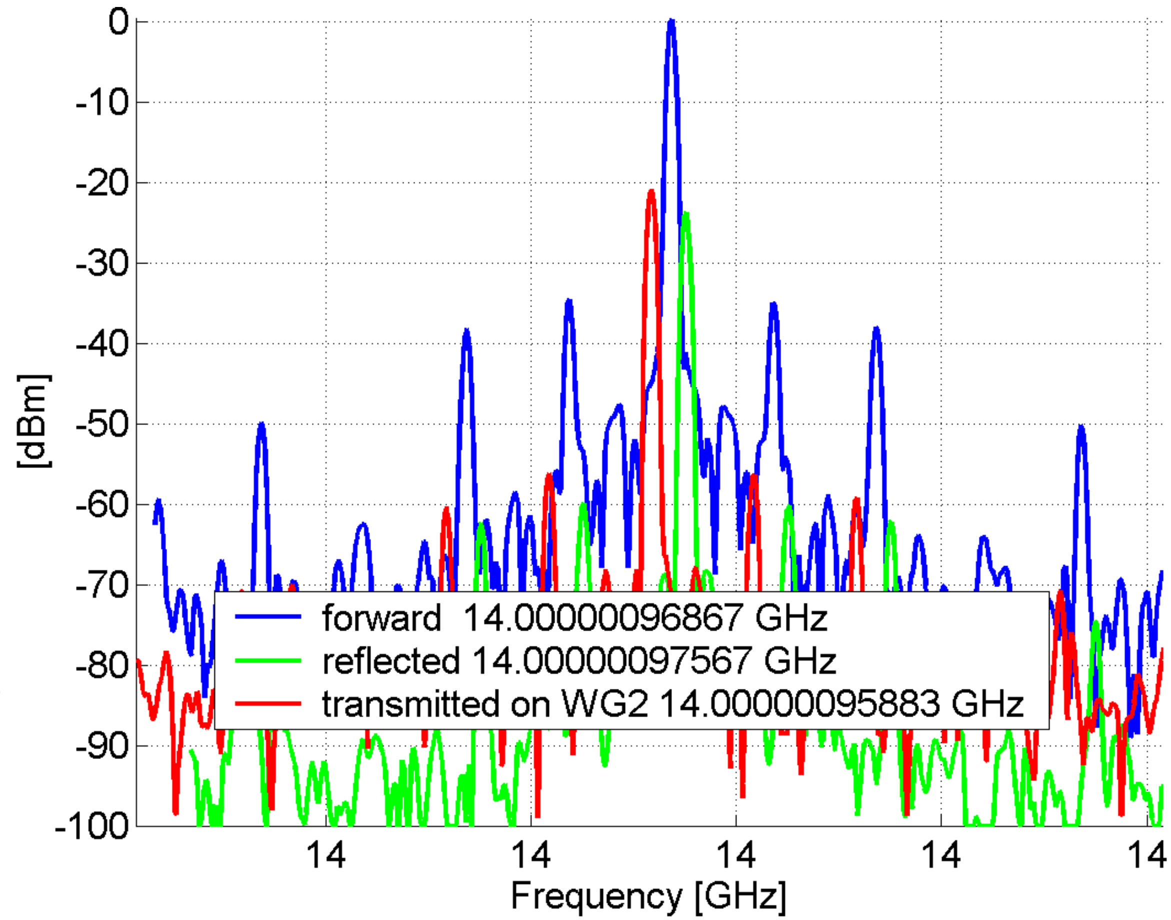
SERSE measurements with plasma





- Poor directivity of D.C. cannot permitted S_{11} and S_{22} measurement.
- We are using as a probe WG2 not a coaxial connector!

Experimental evidences

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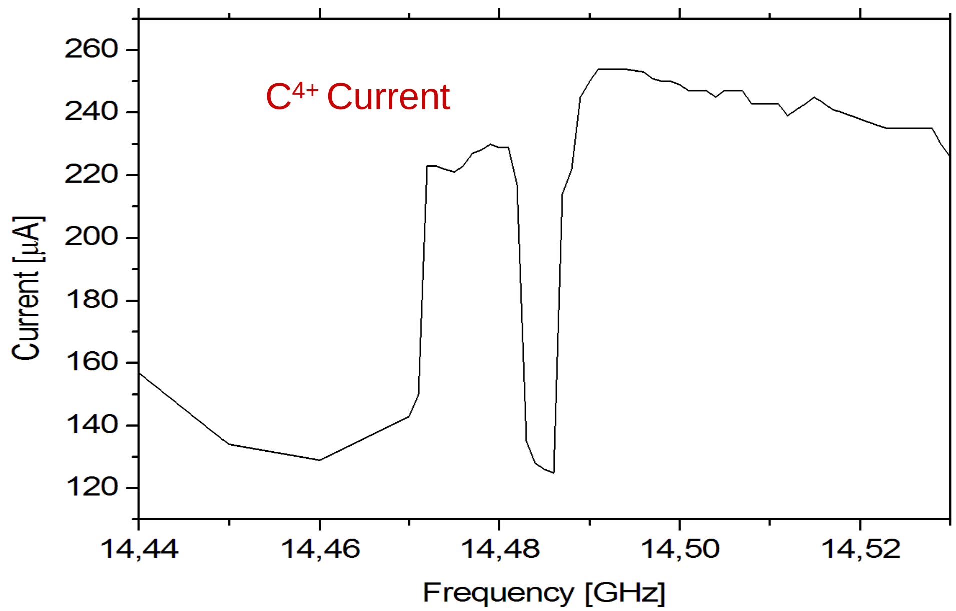
Measurements on the CNAO SUPERNANOGAN ECR Ion Source showed a clear dependence of the C^{4+} extracted current from the microwave frequency.



S. Gammino. - High Energy Physics and Nuclear Physics, 2007, 31 (S1), 137.

Explanation of experimental results

A field modal distribuion is preserved inside the chamber even in presence of plasma.
The electromagnetic field distribution changes by varying the frequency and it causes a better or worse power transfer, due to the ECR phenomenon, between EM wave and plasma.

The community was not convinced….

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Frequency tuning effect

2006- 2007 A set of measurements with the CAPRICE ion source at the GSI test bench has been carried out to investigate its behaviour in terms of <u>intensity</u> and <u>shape</u> of the extracted beam when the microwaves generating the plasma sweep in a narrow range of frequency (±40 MHz) around the klystron centre frequency (14.5 GHz).

Remarkable variations have been observed confirming that a frequency dependent electromagnetic distribution is preserved even in presence of plasma inside the source.

L. Celona, G. Ciavola, F. Consoli, S. Gammino, F. Maimone, D. Mascali, P. Spädtke, K. Tinschert, R. Lang, J. Mäder, J.Roßbach, S. Barbarino, R.S. Catalano, Rev. Sci. Instrum., 79, 023305 (2008).

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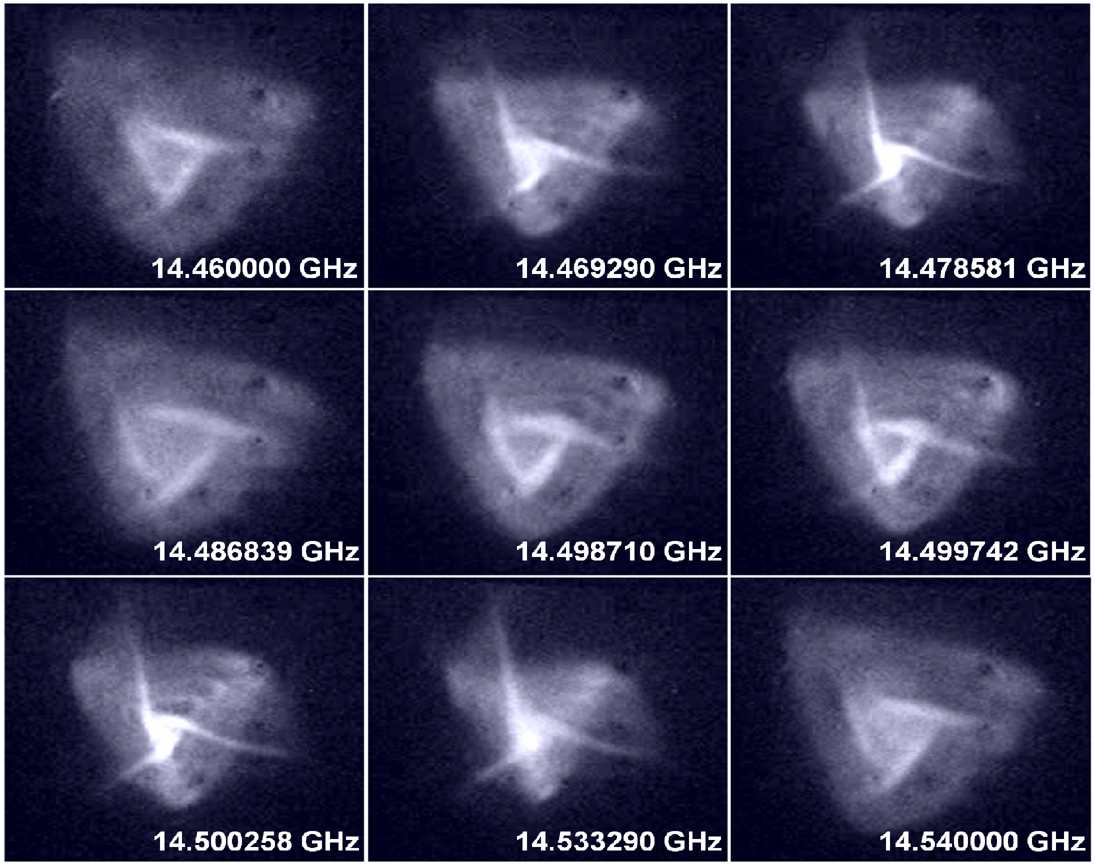
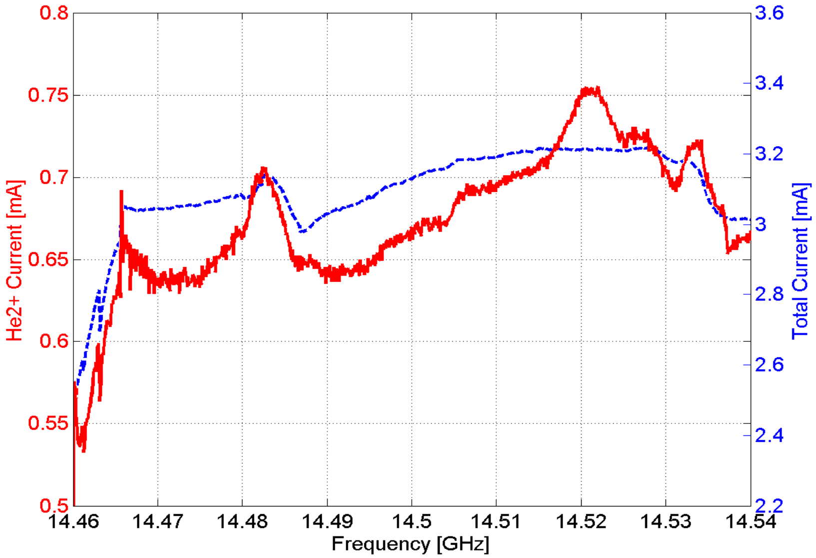
Evolution of the beam shape and of the beam current with the frequency



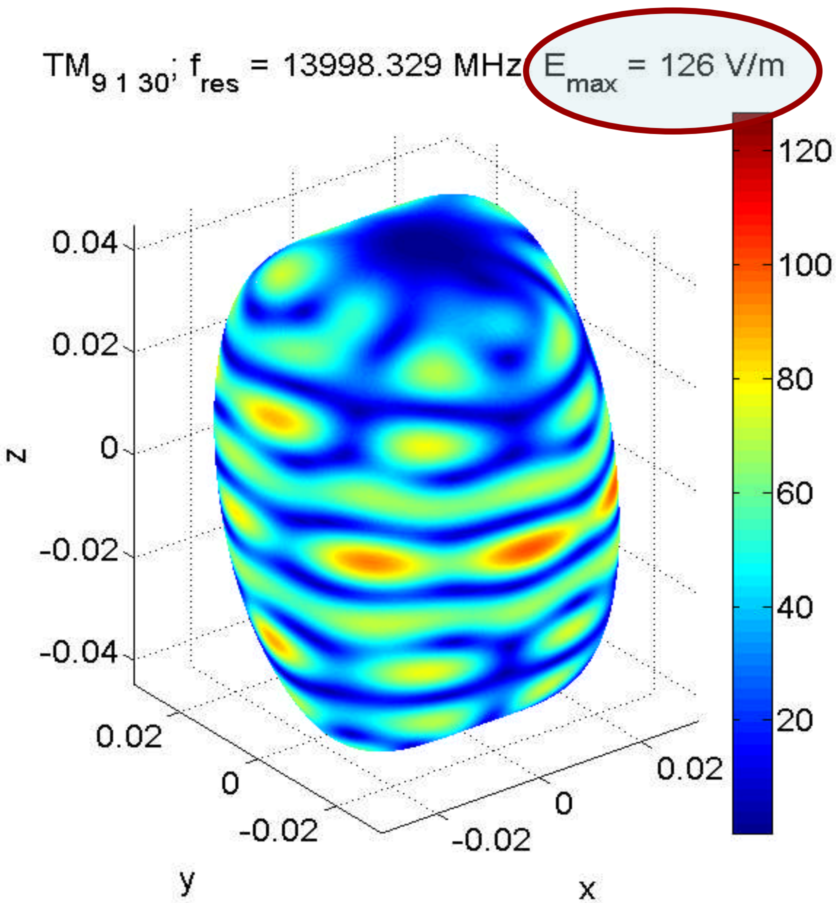


Microwave power = 500 W
Sweeping time = 150 sec
P_{inj}= 4.3 10^{-6} mbar

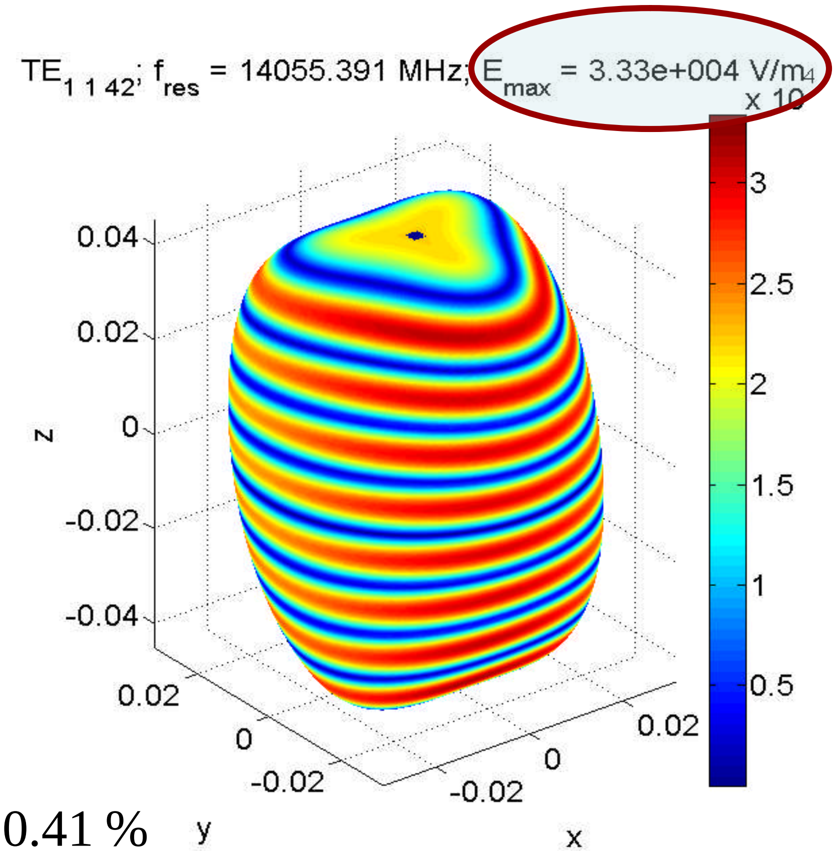
VT1 viewer (around 25 cm far from the extraction electrode)

L. Celona, G. Ciavola, F. Consoli, S. Gammino, F. Maimone, D. Mascali, P. Spaätke, K. Tinschert, R. Lang, J. Mäder, J.Roßbach, S. Barbarino, R.S. Catalano, Rev. Sci. Instrum., 79, 023305 (2008).

WHY???
Electromagnetic field distribution!!!



$$\frac{\Delta f_{res}}{f_{res}}[\%] = 0.41\ \%$$



F. Consoli, L. Celona, G. Ciavola, S. Gammino, F. Maimone, S. Barbarino, R.S. Catalano, D. Mascali, Rev. Sci. Instrum., 79, 02A308 (2008).

S. Gammino, G. Ciavola, L. Celona, F. Maimone, D. Mascali , IEEE Transaction on Plasma Science, Vol.36, No.4, 2008, 1522.

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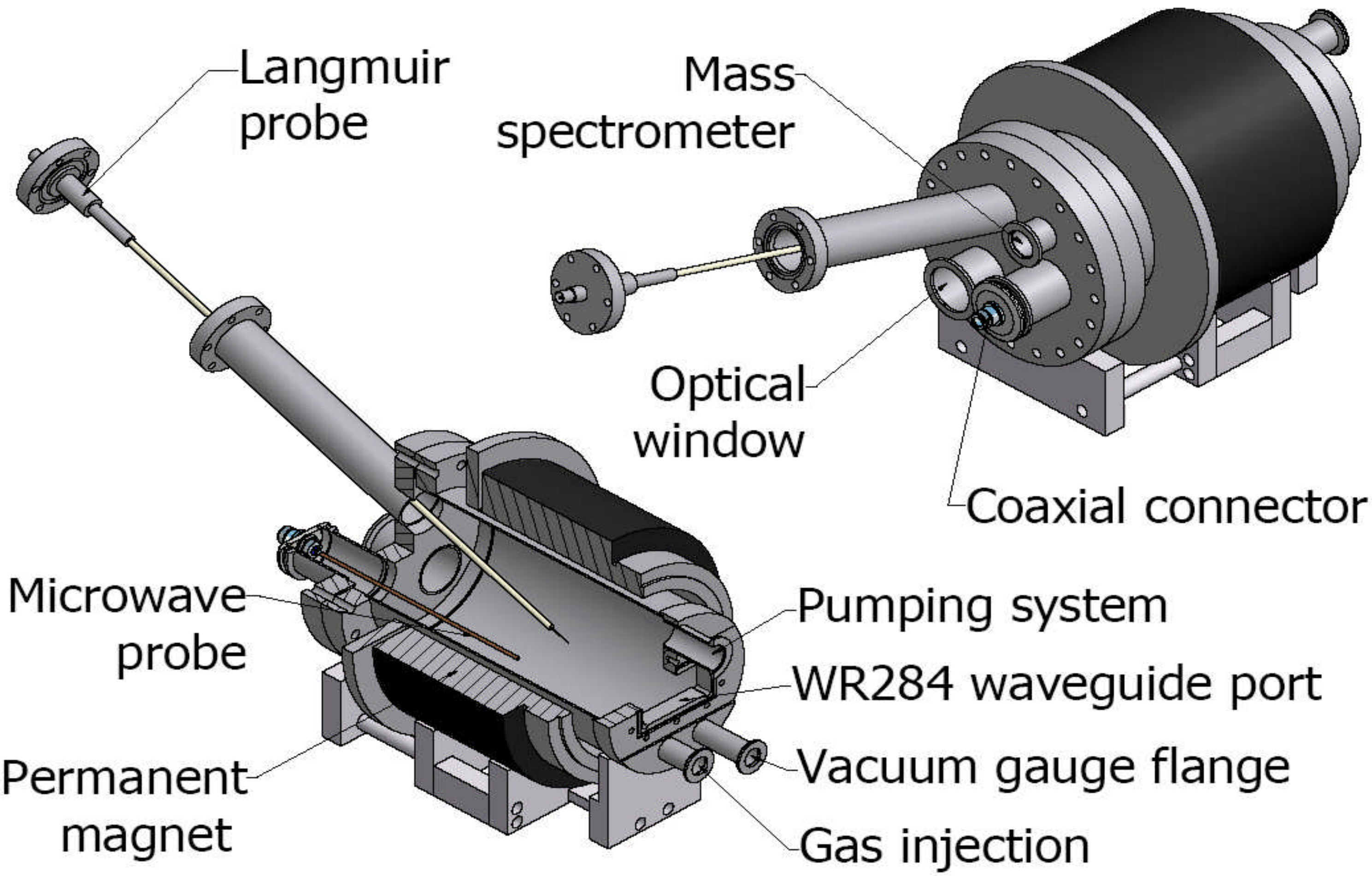
The plasma reactor



Resonant frequency in vacuum

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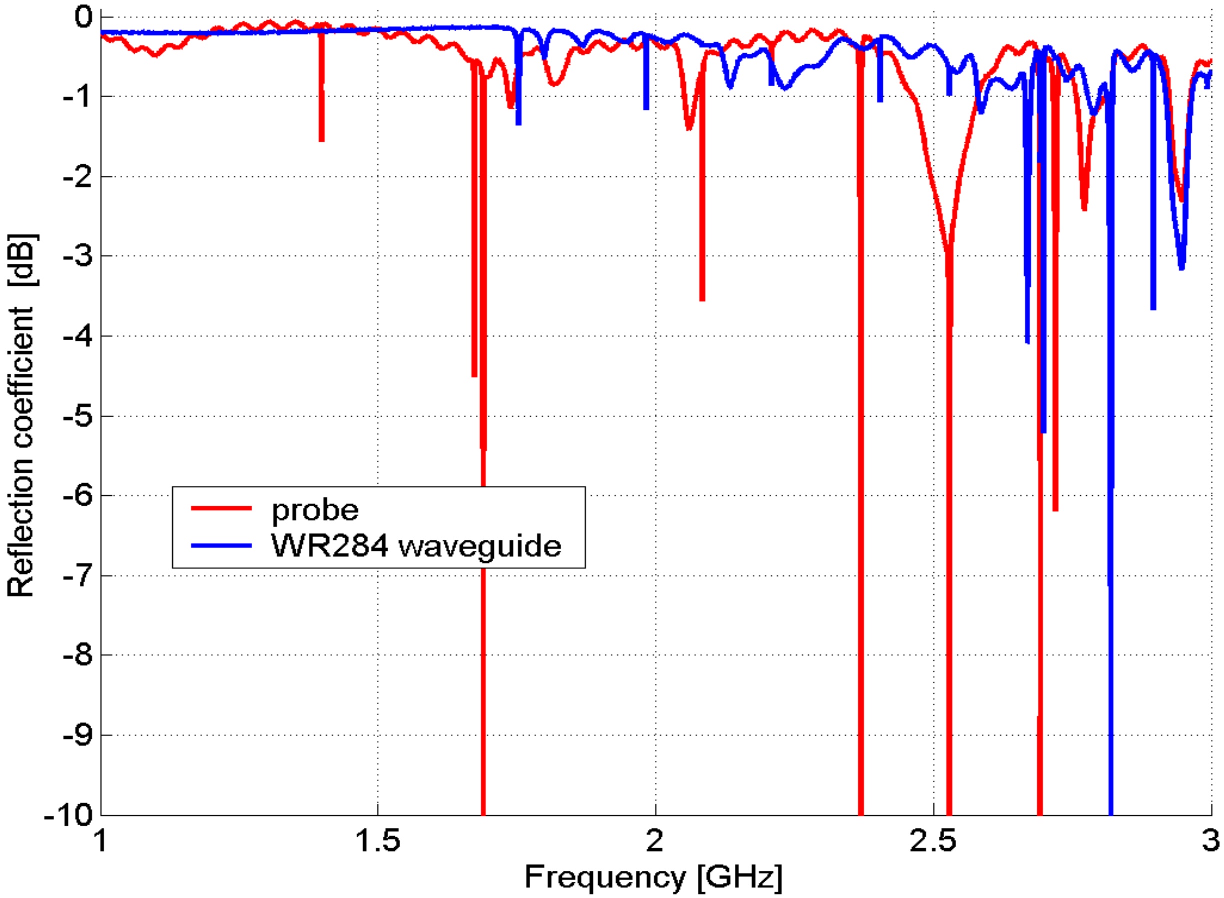

	Mode	Calculated res. Freq. [GHz]	Measured Res. Freq. probe GHz	Measured Res. Freq. WR284 [GHz]
1	TE_{111}	1.39896	1.3978	
2	TM_{010}	1.67507	1.6731	
3	TE_{112}	1.70123	1.6897	
4	TM_{011}	1.76585		1.7534
5	TM_{012}	2.01378		1.9822
6	TE_{113}	2.11092	2.0838	
7	TE_{211}	2.19960	2.2091	2.2089
8	TM_{013}	2.37005	2.3687	
9	TE_{212}	2.40320		2.4033
10	TE_{114}	2.57732	2.5288	2.5287
11	TM_{110}	2.66896	2.6925	2.6925
12	TE_{213}	2.70872	2.6975	2.6975
13	TE_{011}	2.72685	2.7198	
14	TM_{111}			
15	TM_{014}	2.79351	2.8191	2.8191
16	TE_{012}	2.89358	2.8956	2.8956
17	TM_{112}			

Simplified model of the cavity:

$$f_{nml}^{TM\,mode} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{p_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2}$$

$$f_{nml}^{TE\,mode} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{p'_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2}$$

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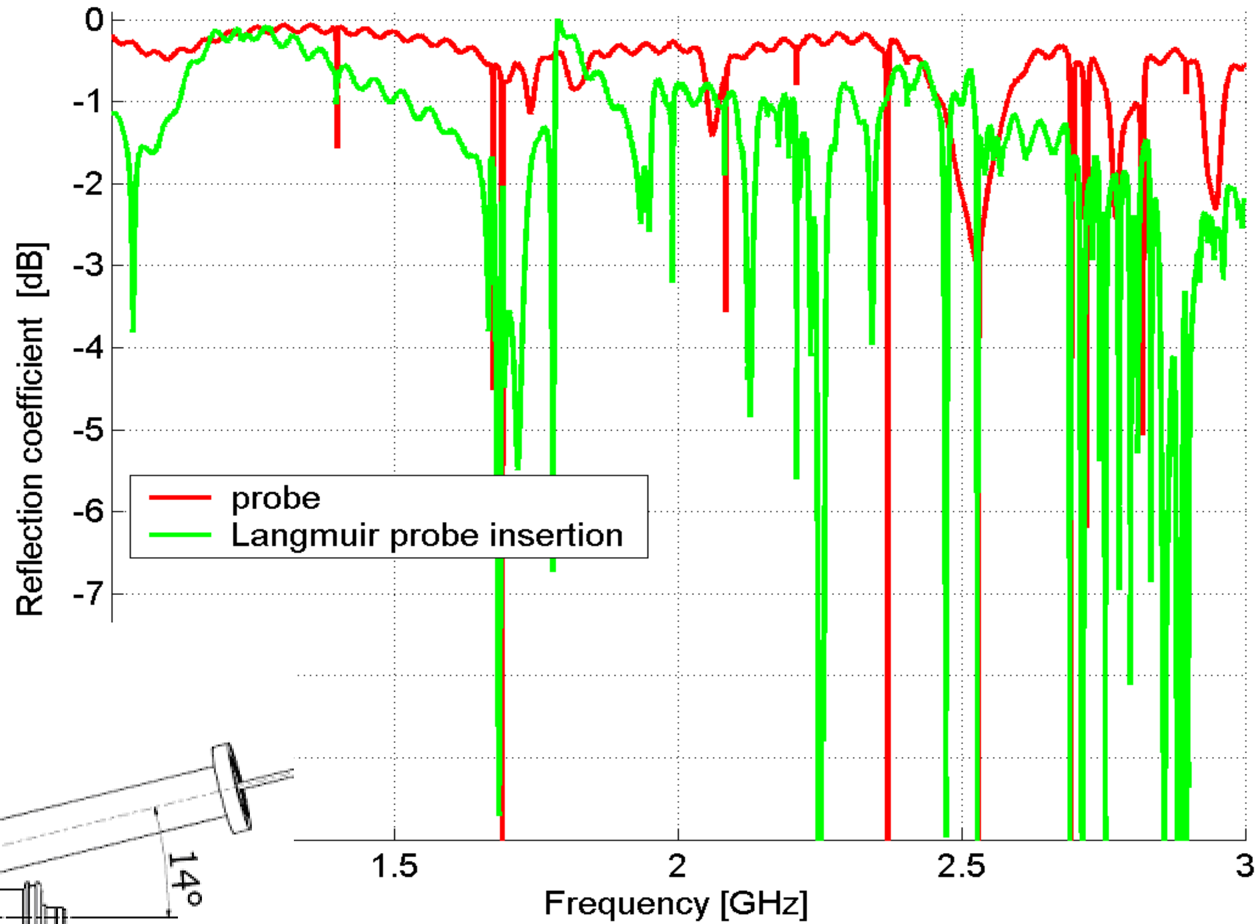
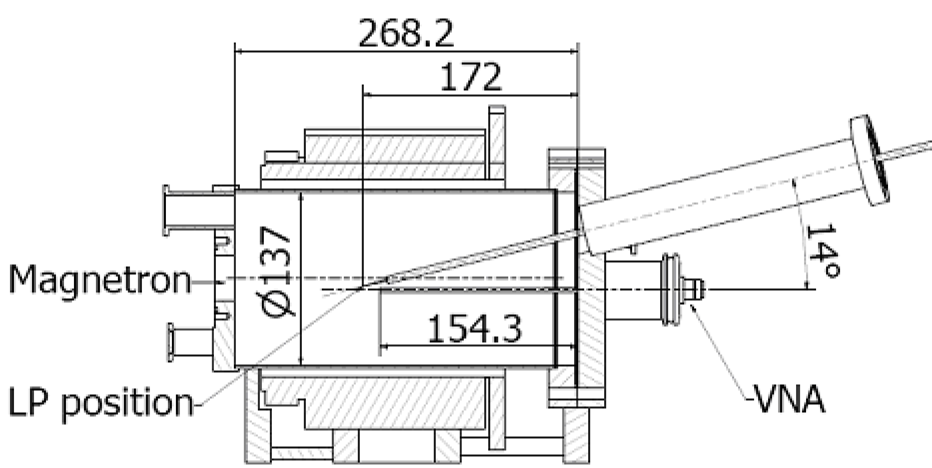
Effect of Langmuir probe insertion@ z=172 mm

- Perturbations!

- Some modes has similar resonant frequencies, however we cannot argue if they are TE or TM modes. But…





S_{11} with plasma and LP @ z=172 mm

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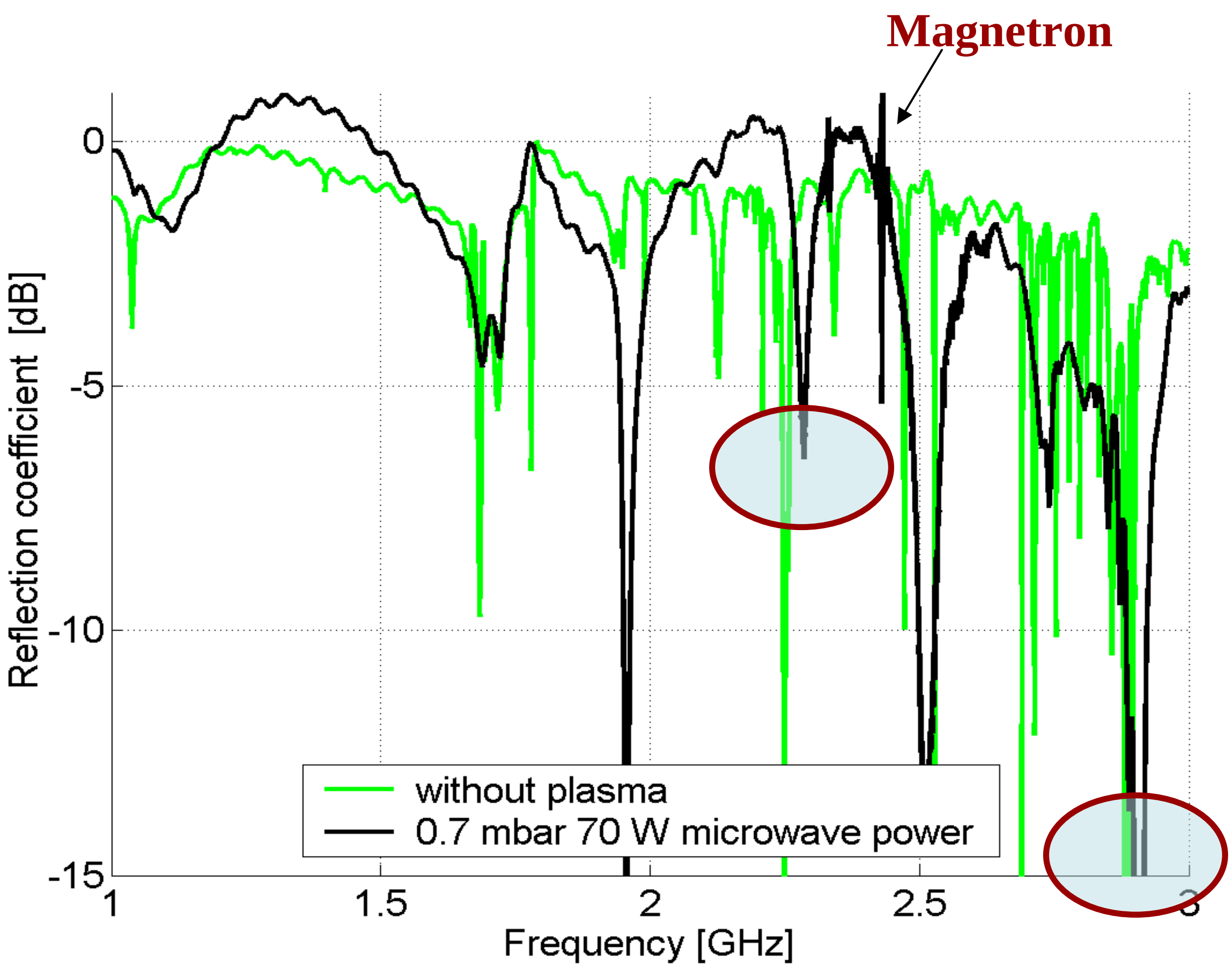
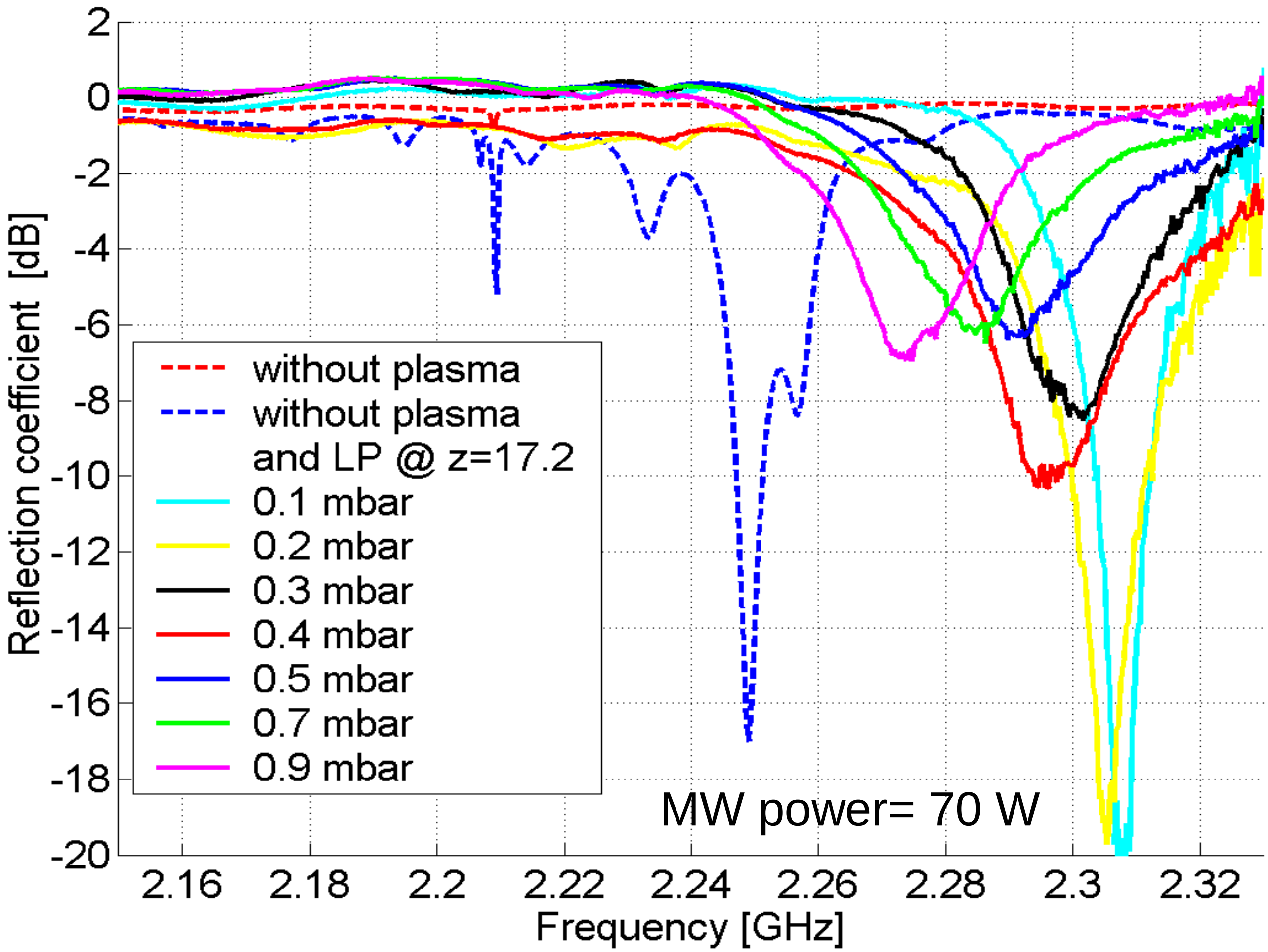


- *A clear modal structure is present when the plasma is created.*
- ***Attention**: The analysis do not permit to affirm which modes are excited.*
  This is another story…

Langmuir probe measurement
N_e=5.98·10^15 at/m^3
for:
MW power= 70 W
Gas pressure= 0.7 mbar

Frequency variation with the gas of the mode around 2.3 GHz.



- *The resonance shifts to higher frequencies decreasing the gas pressure.*
- *From the LP measurement and by supposing the cavity filled by homogeneous plasma it is possible to calculate the frequency shift.*

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Calculation of frequency shift

	Mode	Calculated res. Freq. air [GHz]	Calculated Res. Freq plasma (ne=5.98*10^15) [GHz]	Measured Res. Freq. probe [GHz]	Measured Res. Freq. WR284 [GHz]
1	TE_{111}	1.39896	1.45878	1.3978	
2	TM_{010}	1.67507	1.74669	1.6731	
3	TE_{112}	1.70123	1.77397	1.6897	
4	TM_{011}	1.76585	1.84136		1.7534
5	TM_{012}	2.01378	2.09989		1.9822
6	TE_{113}	2.11092	2.20119	2.0838	
7	TE_{211}	2.19960	2.29366	2.2091	2.2089
8	TM_{013}	2.37005	2.47139	2.3687	
9	TE_{212}	2.40320	2.50596		2.4033
10	TE_{114}	2.57732	2.68752	2.5288	2.5287
11	TM_{110}	2.66896	2.78308	2.6925	2.6925
12	TE_{213}	2.70872	2.82455	2.6975	2.6975
13	TE_{011}	2.72685	2.84345	2.7198	
14	TM_{111}				
15	TM_{014}	2.79351	2.91296	2.8191	2.8191
16	TE_{012}	2.89358	3.01730	2.8956	2.8956
17	TM_{112}				

The electron density measured with the Langmuir probe positioned at 17.2 cm inside the plasma chamber at 0.7 mbar gas pressure and 70 microwave power was about 5.98*10^15/m^3

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} \longrightarrow \varepsilon_r = \left(1 - \frac{\omega_p^2}{\omega^2}\right)$$

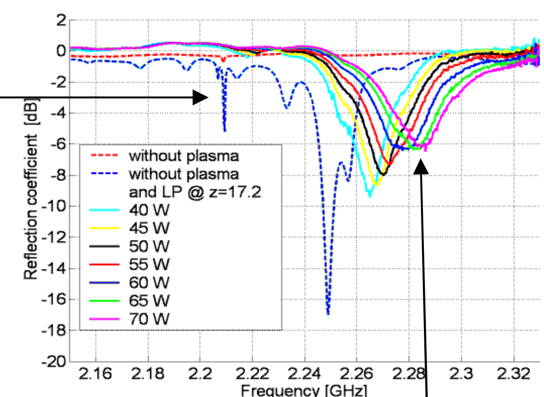
The modes that exists inside a cylindrical cavity will shift to higher frequencies if the electrical perimittivity of the medium that fill it becomes smaller

$$f_{nml}^{TE\,mode} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}}\sqrt{\left(\frac{p'_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2}$$

$$f_{nml}^{TM\,mode} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}}\sqrt{\left(\frac{p_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2}$$

$$\Rightarrow \frac{f_{vacuum}}{f_{plasma}} = \sqrt{\varepsilon_r}$$

The mode TE_{211} should shift to a frequency about 90 Mhz higher according with the reflection coefficient measurement



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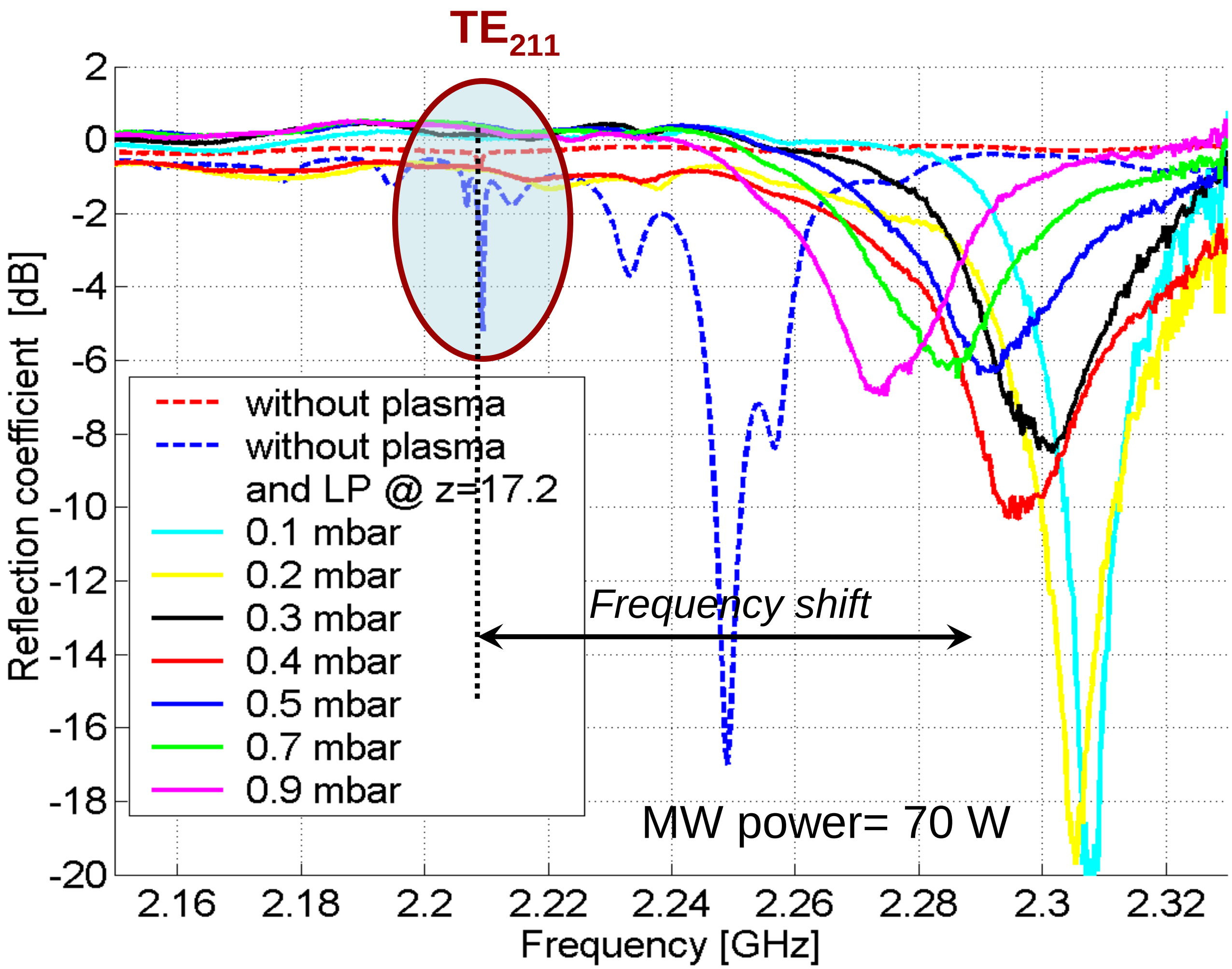
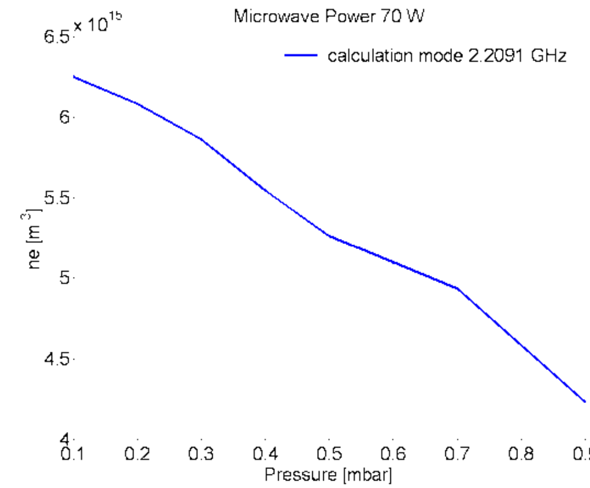
Frequency variation with the gas of the mode around 2.3 GHz.





From the calculations of frequency shift we have a rough estimaton of plasma density.

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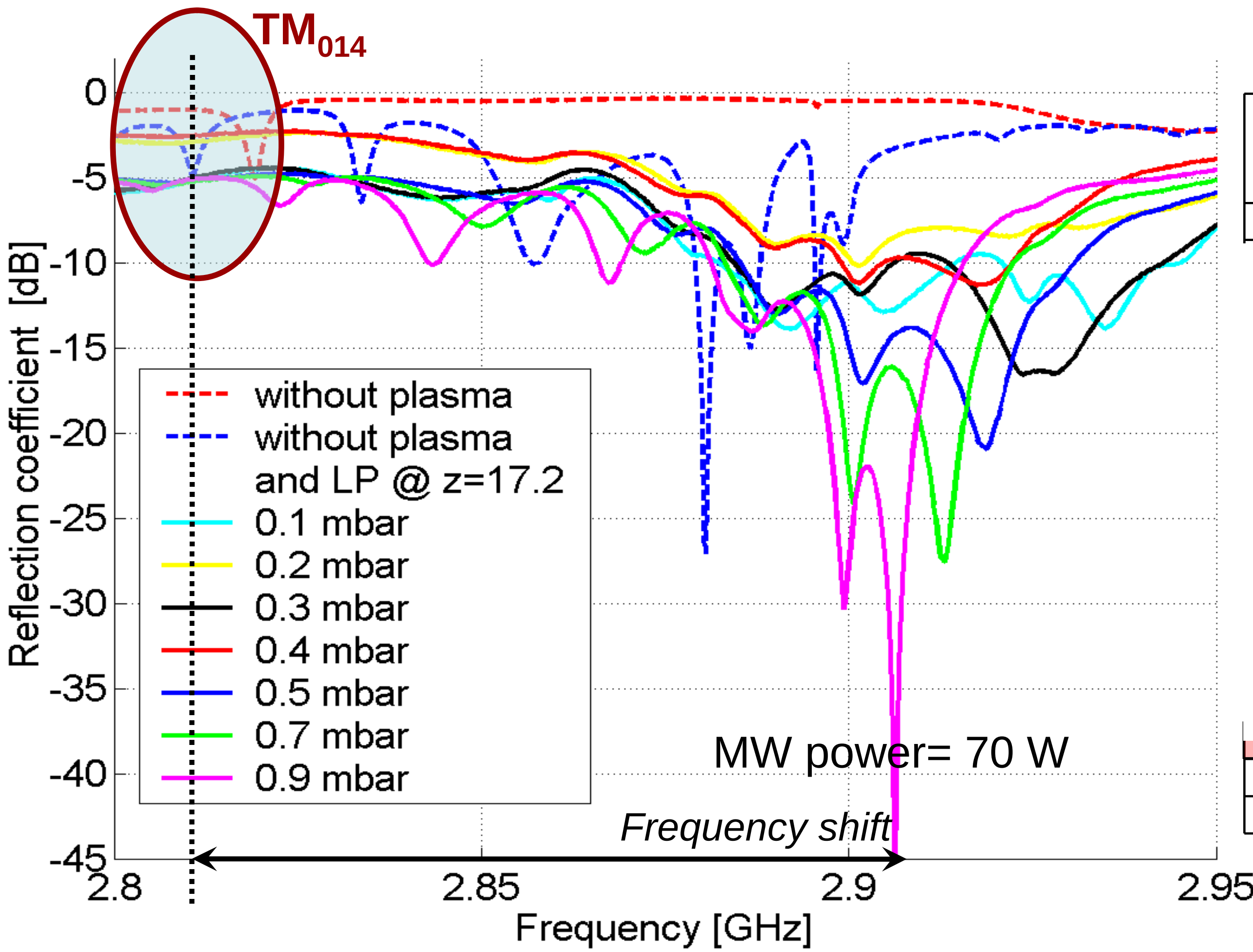
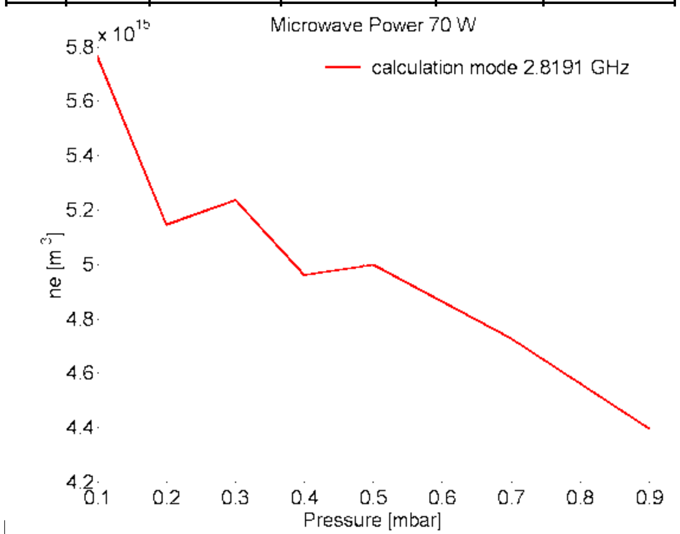
Frequency variation with the gas of the mode around 2.9 GHz.



	Mode	Calculated res. Freq. air [GHz]	Calculated Res. Freq plasma (ne=5.98*10^{15}) [GHz]	Measured Res. Freq. probe [GHz]	Measured Res. Freq. WR284 [GHz]
1	TE$_{111}$	1.39896	1.45878	1.3978	
[illegible]	TM$_{014}$	[illegible]	[illegible]	[illegible]	[illegible]
16	TE$_{012}$	2.89358	3.01730	2.8956	2.8956
17	TM$_{112}$				



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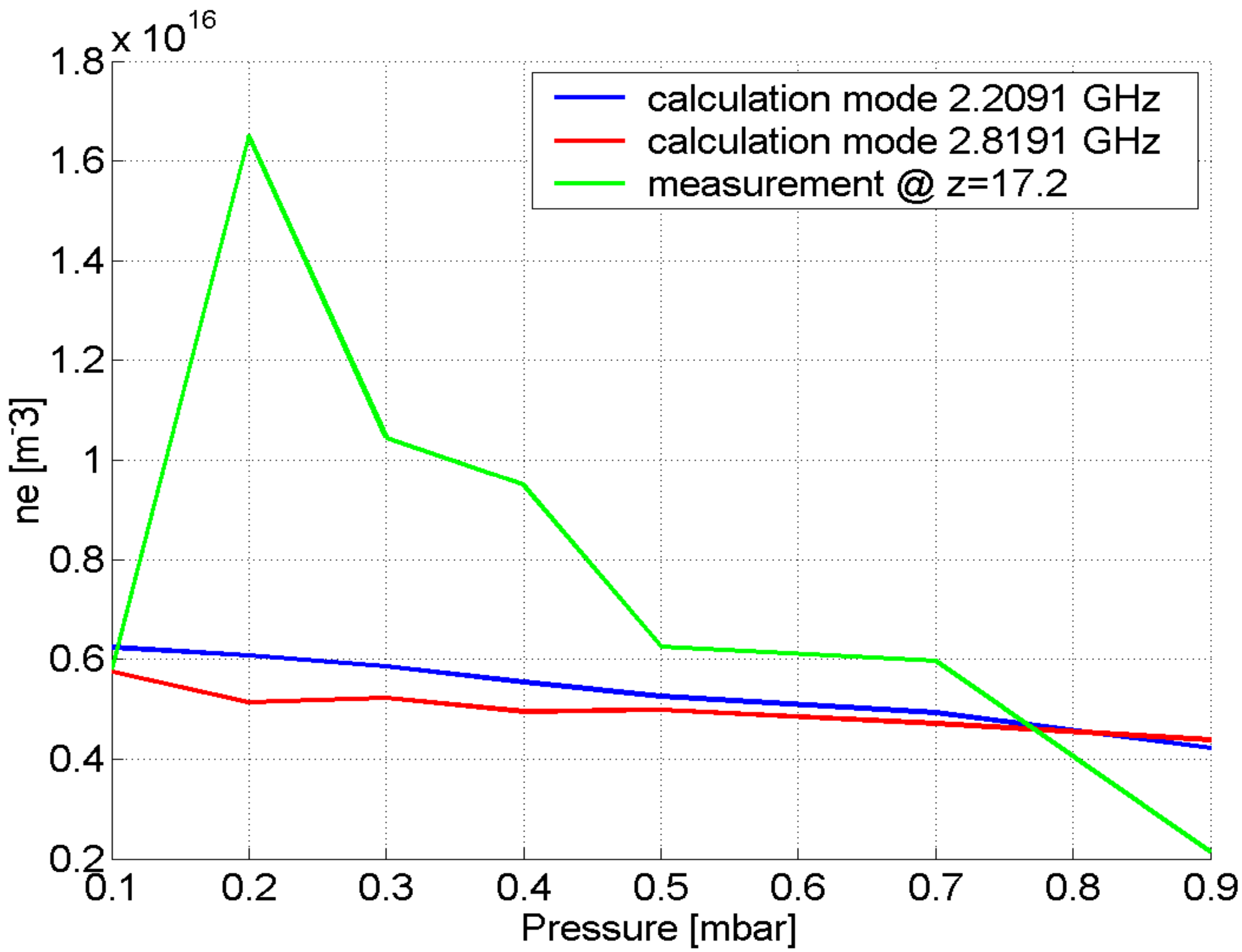
Comparison between calculations and measurements with the Langmuir probe



Frequency variation with the power of the mode around 2.2 GHz.

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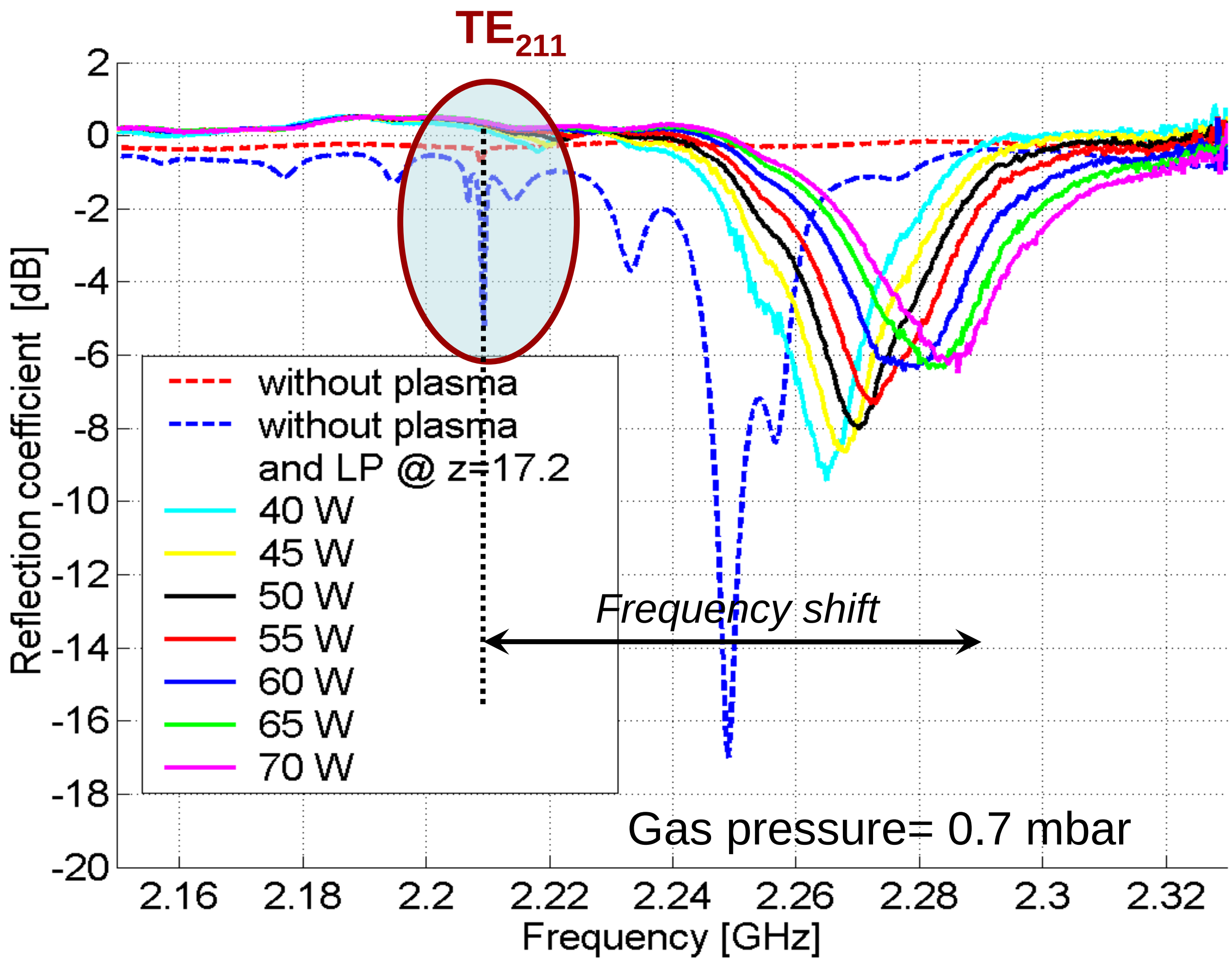
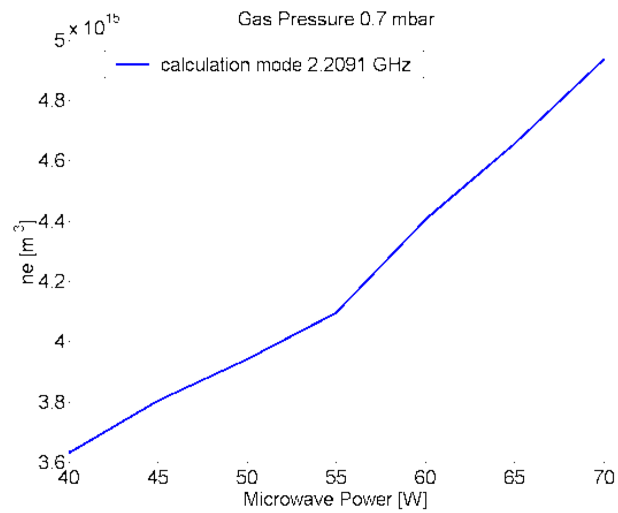
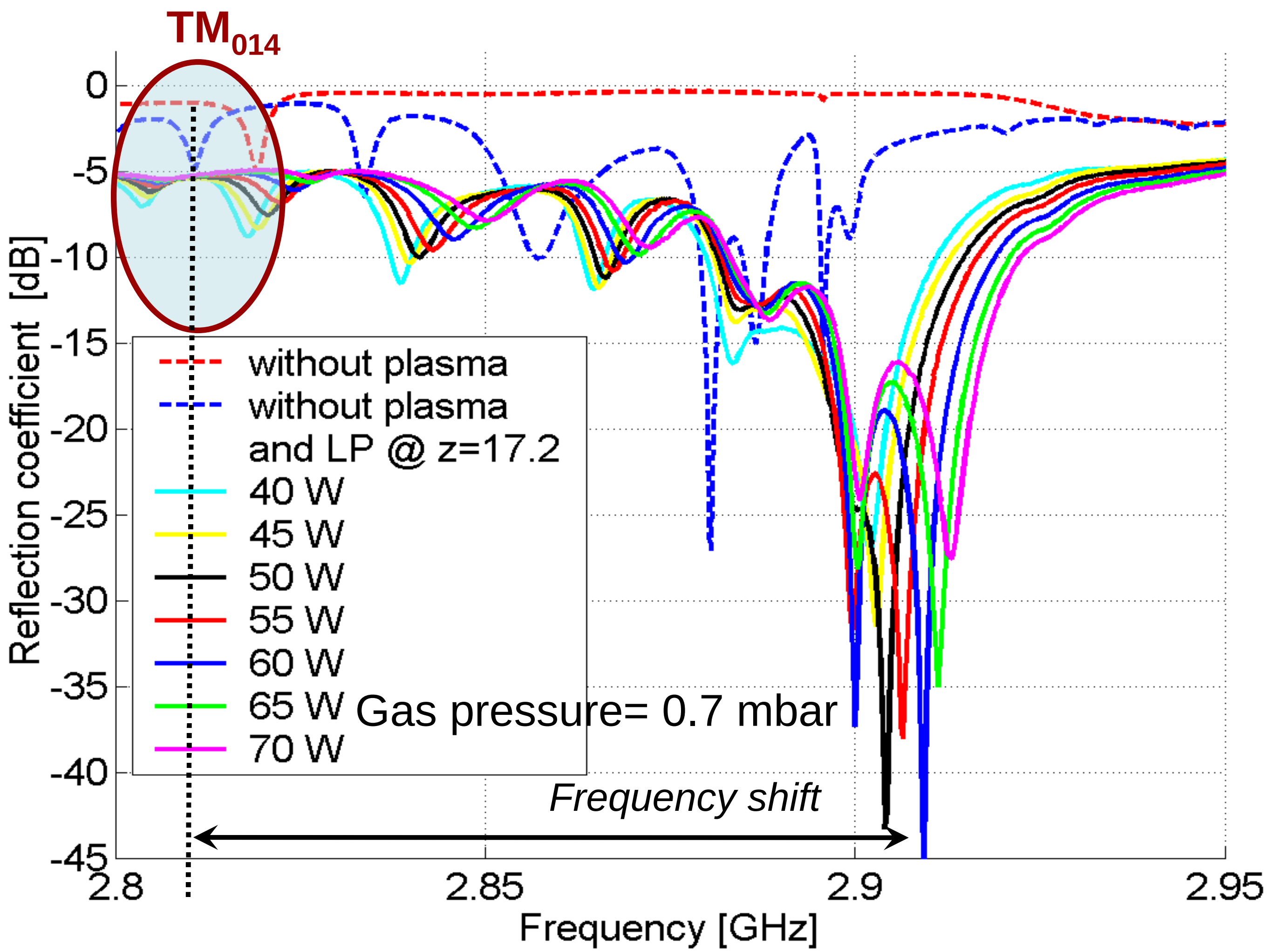


- *The resonance shifts to higher frequencies increasing the microwave power.*
- *From the LP measurement and by supposing the cavity filled by homogeneous plasma it is possible to calculate the frequency shift.*

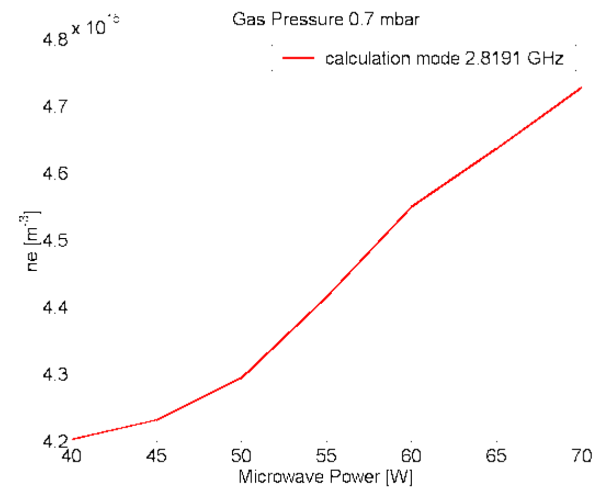


Frequency variation with the power of the mode around 2.9 GHz.

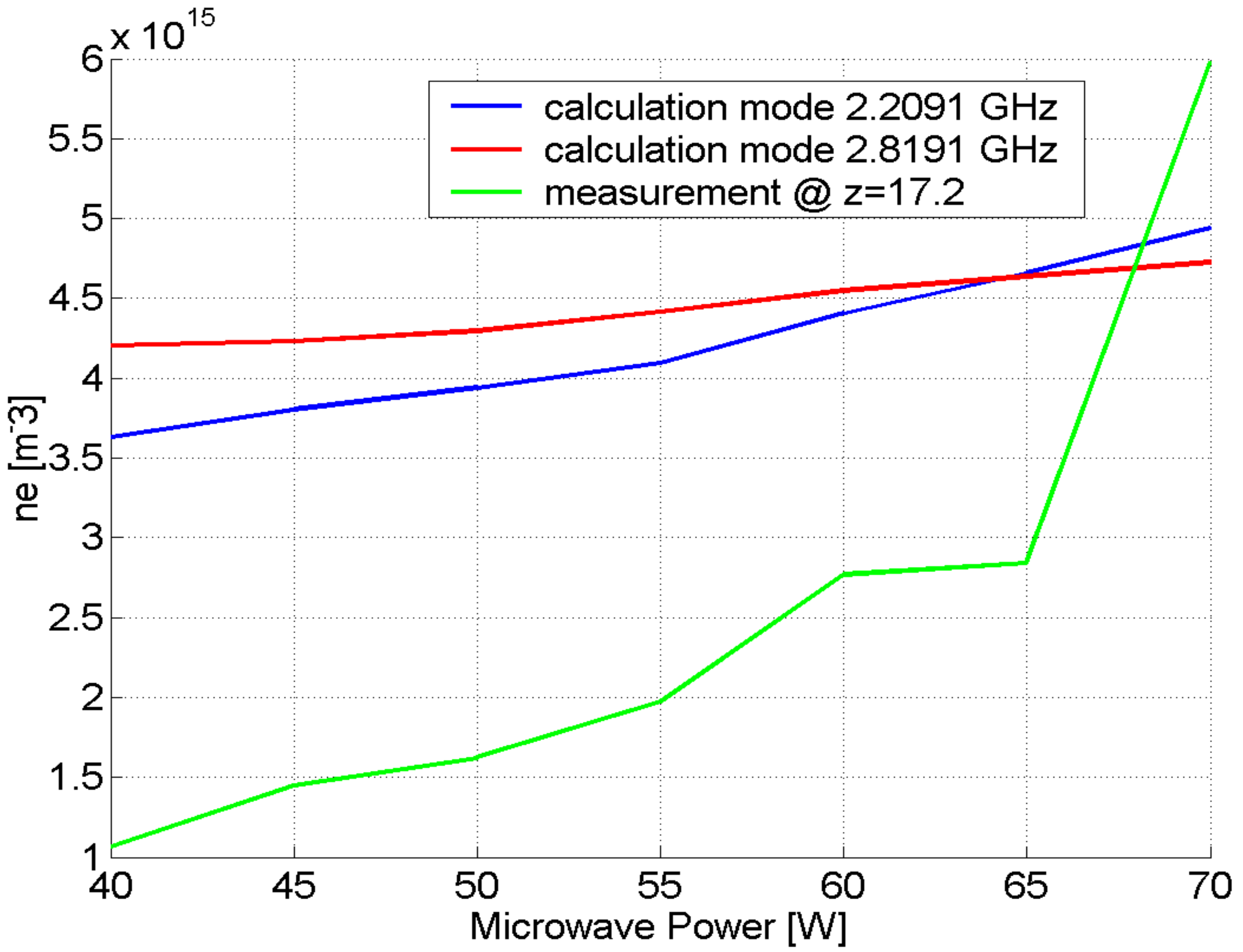


- *The resonance shifts to higher frequencies increasing the microwave power.*

- *From the LP measurement and by supposing the cavity filled by homogeneous plasma it is possible to calculate the frequency shift.*



Comparison between calculations and measurements with the Langmuir probe

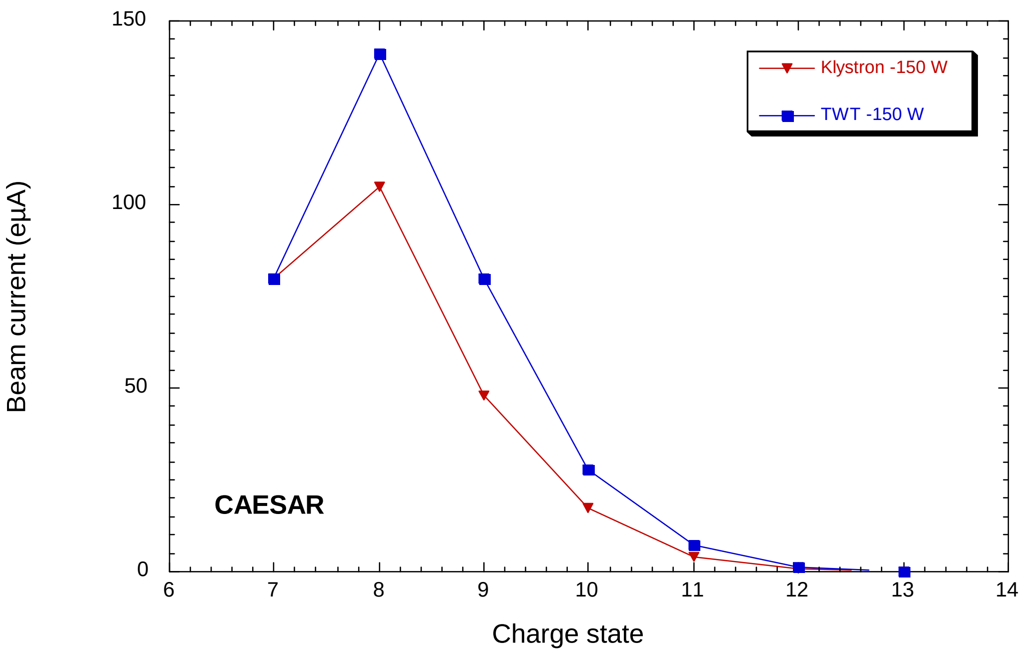


Final remarks

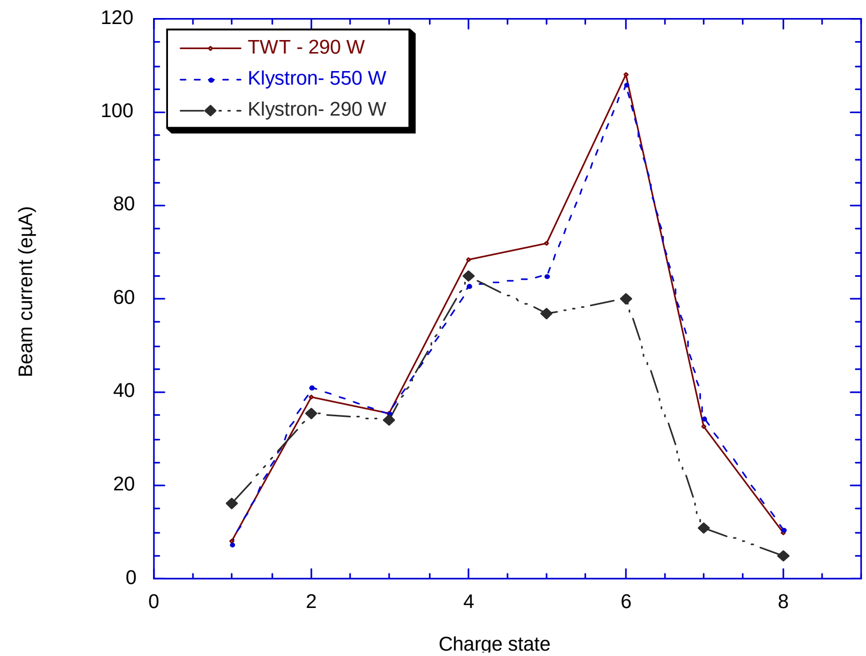
- An electromagnetic modal structure has been observed inside the plasma chamber even in presence of plasma.
- The frequency tuning effect can be explained as a change of the electromagnetic field distibution on the ECR surface. This change affects not only the current produced by the ion source, but also the process of ion beam formation as shown from many hours of video collected at GSI…
- The measurement of the frequency shift gives a rough evaluation of the plasma density.
- Calculations have been reliable for 2.45 GHz.
- Measurement on high performance ECRIS to further investigate the prevuious observations have been planned.

TWT vs. Kly: the first data

- Preliminary results published in 2002 (ECRIS2002, NIMA).



Measured current for the highest charge states of Argon obtained by the source CAESAR at 150 W.



Comparison of the currents for the different charge states of Oxygen obtained by the source SERSE at 290 W and 550 Watt (with the klystron) and at 290 W (with the TWT).

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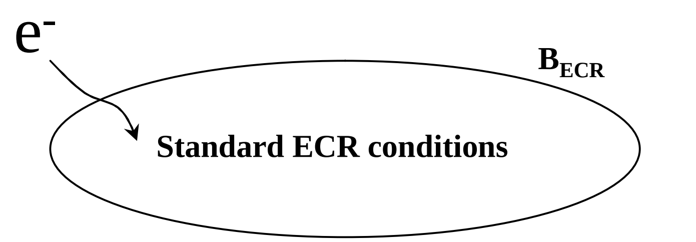
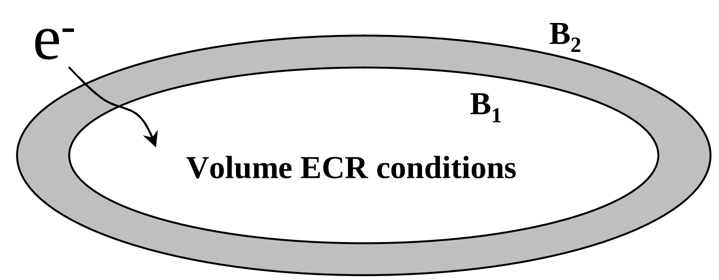
Why?
Speculation on ECR condition

$$B = B_{ECR} = \frac{2\pi\, m_e}{|q_e|}\upsilon_{EM}$$



When TWT is used VOLUME EFFECT takes place?

$$\begin{cases} B_1 = \dfrac{2\pi m_e}{|q_e|}(\upsilon_{EM} - \Delta\upsilon) \\ B_2 = \dfrac{2\pi m_e}{|q_e|}(\upsilon_{EM} + \Delta\upsilon) \end{cases}$$



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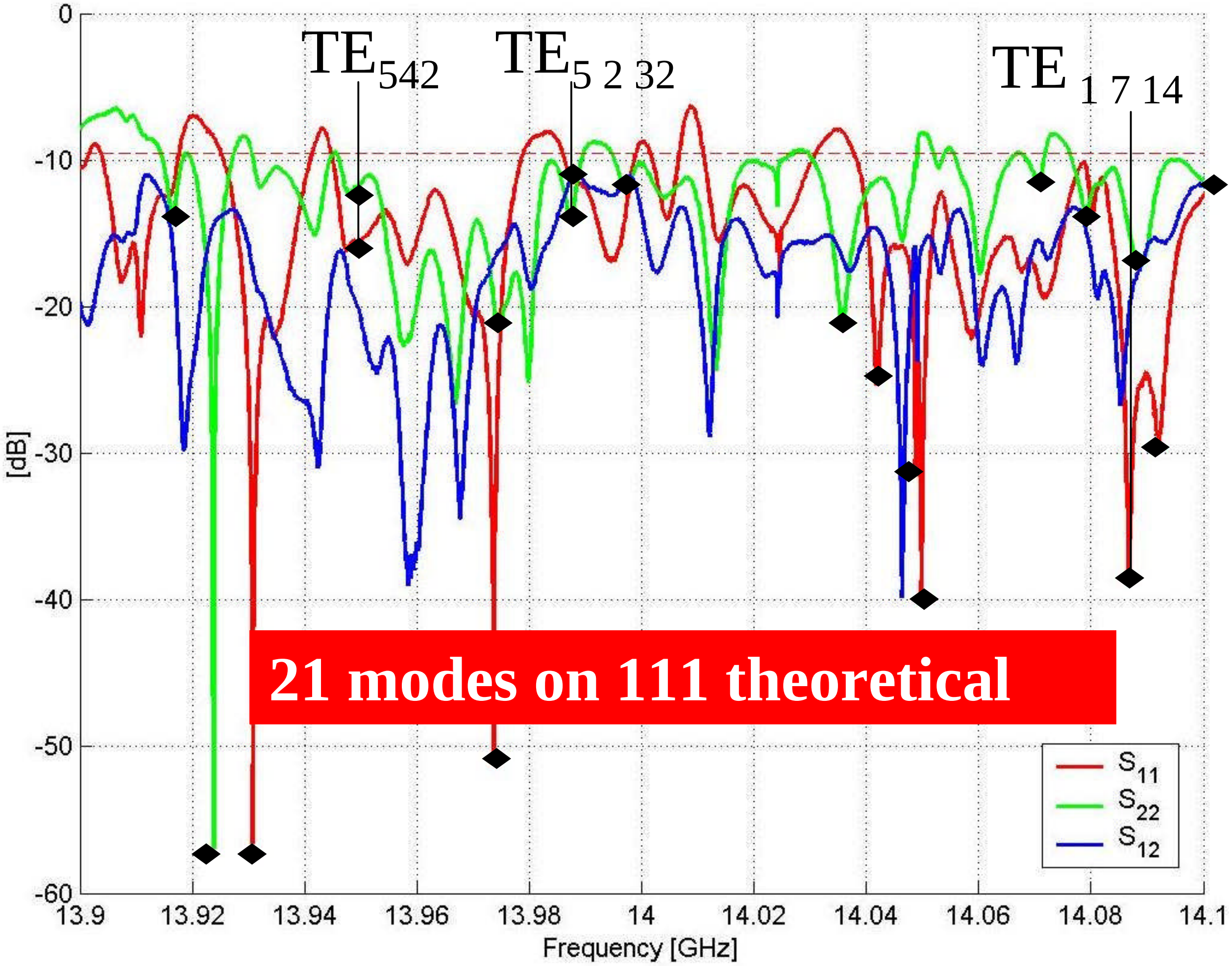
SERSE S-parameters (13.9-14.1 GHz) in vacuum



MODE	Resonance Frequency [GHz]	S_{22min} [GHz]
TE$_{1\,6\,13}$	13.91529183950736	13.9164
TM$_{10\,1\,27}$	13.92103796033654	13.9238
TM$_{5\,4\,2}$	13.94834498303971	13.9479
TE$_{0\,2\,39}$ TM$_{1\,2\,39}$	13.97450627904347 13.97450627904347	13.9746
TM$_{5\,2\,32}$	13.98760561229754	13.9874
TM$_{5\,4\,4}$	13.99599288795094	13.9971
TM$_{6\,1\,36}$ TM$_{5\,4\,5}$	14.03559391436303 14.03162263549146	14.0356
TM$_{14\,1\,7}$ TM$_{5\,4\,6}$	14.06818217369672 14.07504762013425	14.0705
TE$_{6\,4\,10}$	14.08055484402864	14.0791
TE$_{17\,1\,4}$	14.08684469003148	14.0894
TM$_{2\,5\,15}$	14.09854853794046	14.0997

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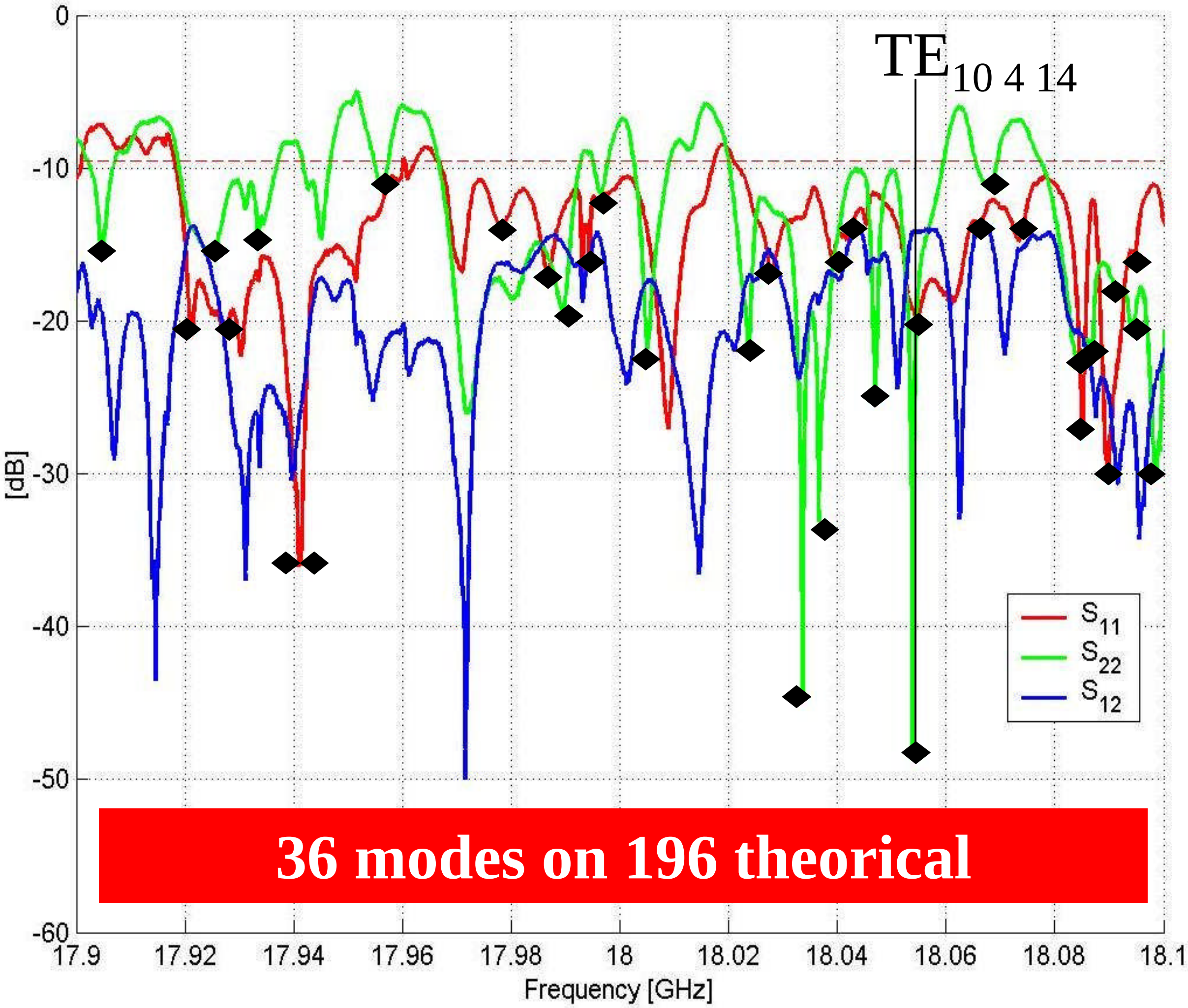
SERSE S-parameters (17.9-18.1 GHz) in vacuum



MODE	Frequency [GHz]	S_{22min} [GHz]
$TM_{0\,8\,3}$	17.90391723129755	17.9045
$TE_{5\,6\,12}$	17.92447606249620	17.9241
$TM_{4\,2\,48}$	17.93360452194094	17.9335
$TM_{15\,1\,31}$	17.94557466589965	17.9451
$TE_{3\,5\,37}$	17.95575383446636	17.9562
$TM_{17\,1\,23}$	17.98882346275034	17.9894
$TM_{14\,2\,18}$	17.99639732301435	17.9966
$TM_{6\,2\,45}$	18.00540526170564	18.0051
$TM_{12\,3\,21}$	18.02390461916021	18.0236
$TE_{3\,7\,10}$	18.03394149734434	18.0336
$TM_{0\,5\,43}$	18.03562535954195	18.0366
$TM_{2\,5\,37}$	18.04728151812772	18.0470
$TE_{10\,4\,14}$	18.05430736661600	18.0537
$TM_{2\,7\,9}$	18.06602936186047	18.0677
$TM_{4\,5\,29}$	18.08425909850669	18.0844
$TE_{11\,2\,38}$ $TM_{5\,2\,47}$	18.08692317950480	18.0869
$TM_{18\,1\,18}$	18.09401675035352	18.0944
$TE_{3\,7\,11}$	18.09842954370864	18.0985

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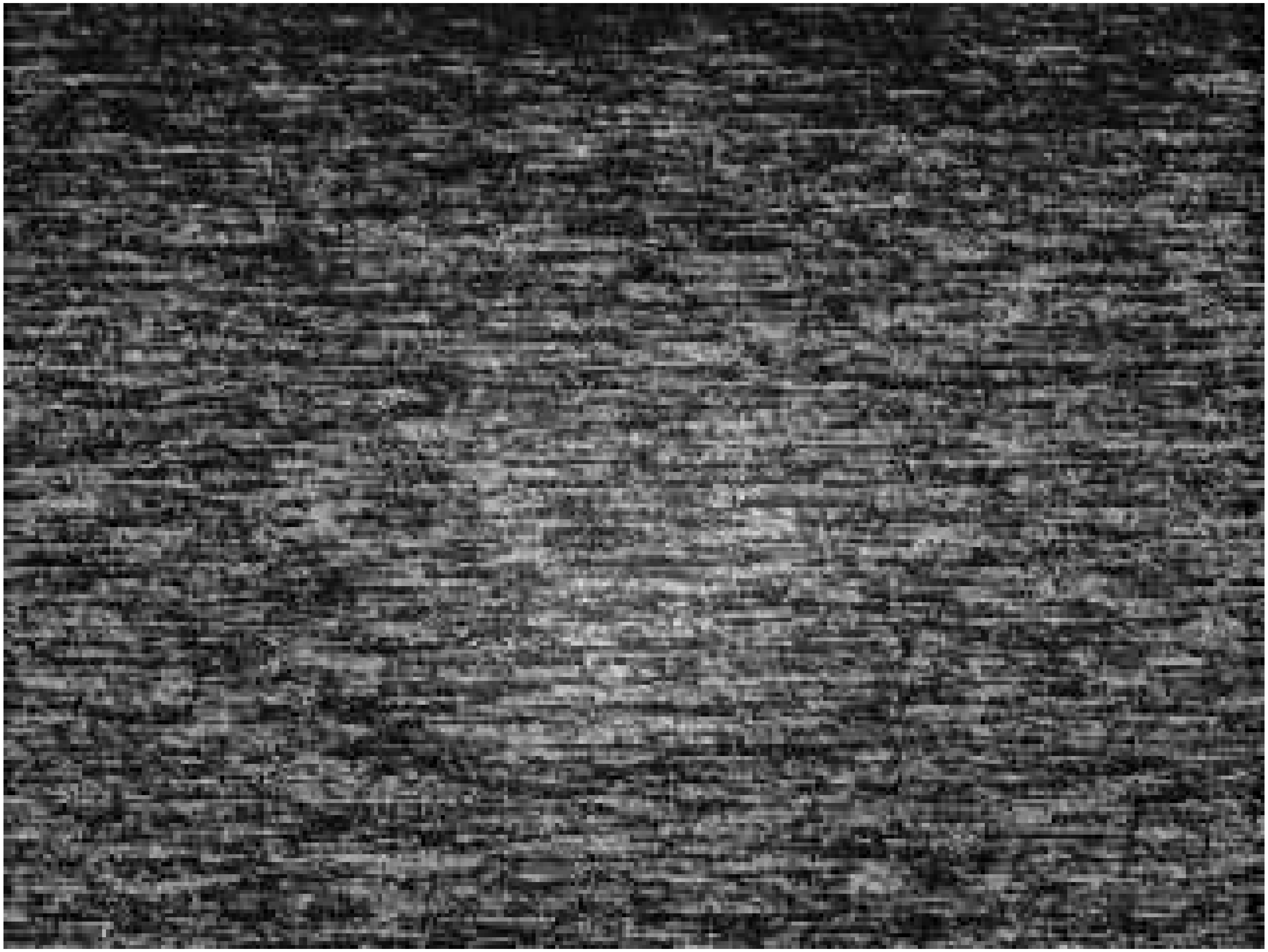
Experimental rsults: video on VT1



He gas

Sweep Time: 15 sec

Freq: 14.5 GHz±40 MHz

Power: 500W

P_{inj}=4.3·10^{-6} mbar

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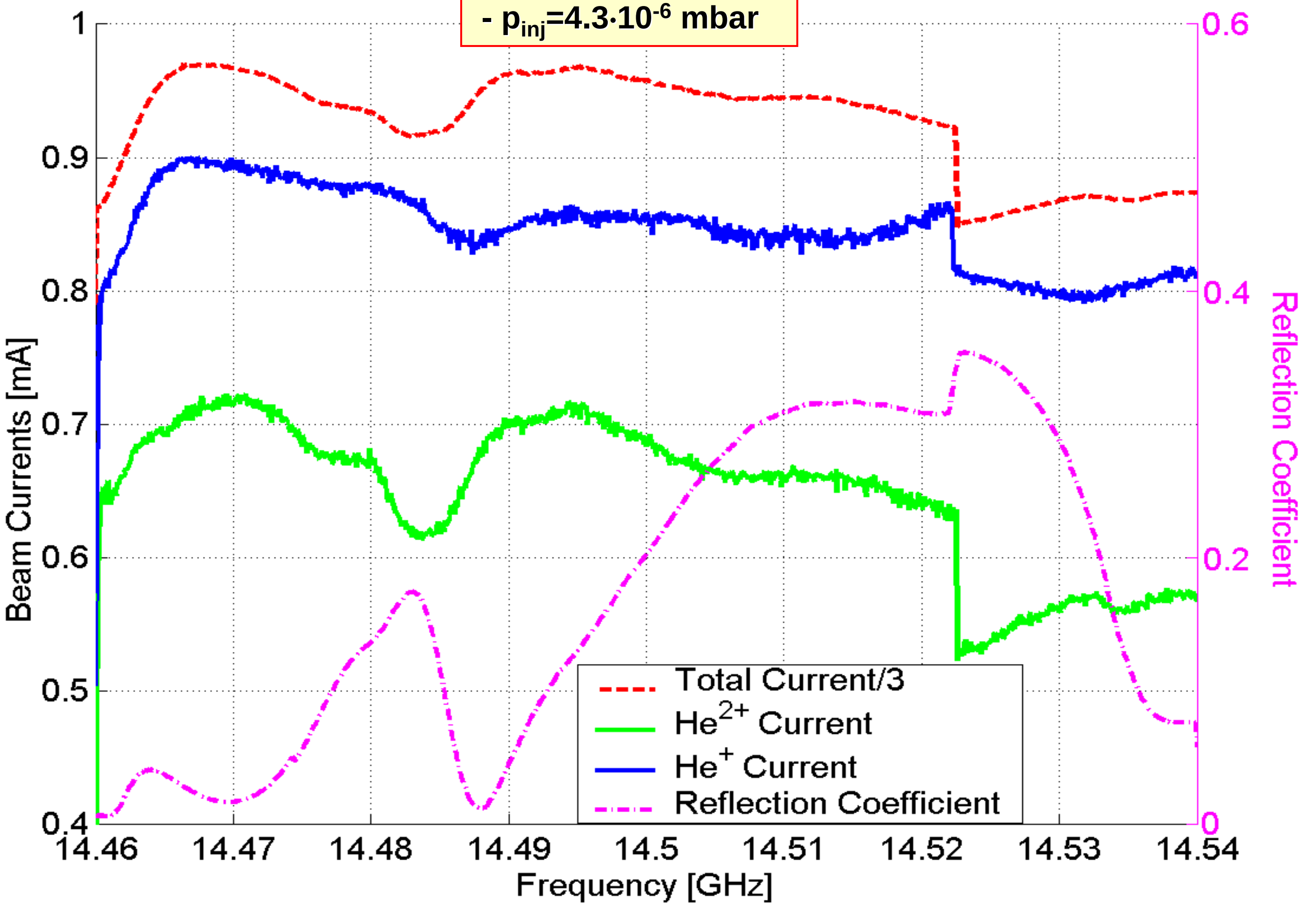
Experimental results: reflection coefficient and beam currents evolution with the frequency

- He Beam
-100 W RF power
- $p_{inj}=4.3 \cdot 10^{-6}$ mbar



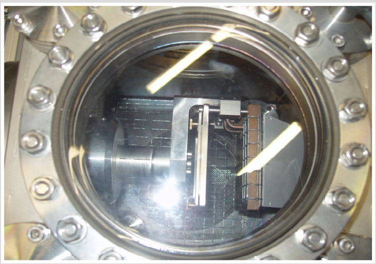
- A rather good agreement can be observed with refl. coef.
- Z_{eq} change with freq. leading to a larger or smaller power into the cavity.
- 14.48-14.5 GHz current increase for a decrease of net power.

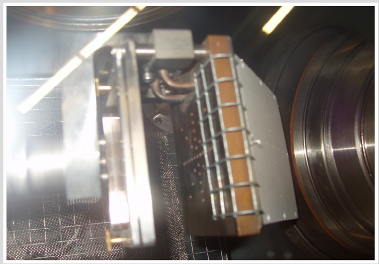
The results are not only due to the anount of power entering but also to the way the EM field is distributed within the cavity and consequently coupled to the plasma here confined.

L. Celona, G. Ciavola, F. Consoli, S. Gammino, F. Maimone, D. Mascali, P. Spaätke, K. Tinschert, R. Lang, J. Mäder, J.Roßbach, S. Barbarino, R.S. Catalano, Rev. Sci. Instrum., 79, 023305 (2008).

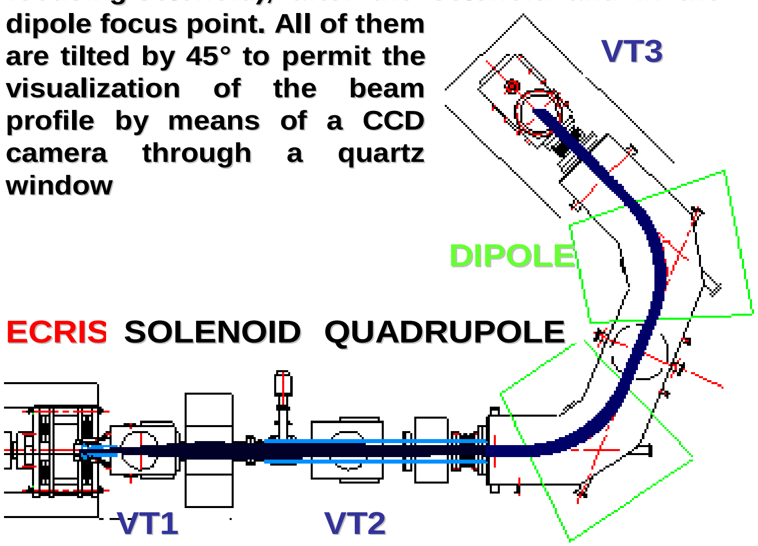
Experimental set-up

BEAM SHAPE MEASUREMENTS BY MEANS OF TARGET VIEWERS

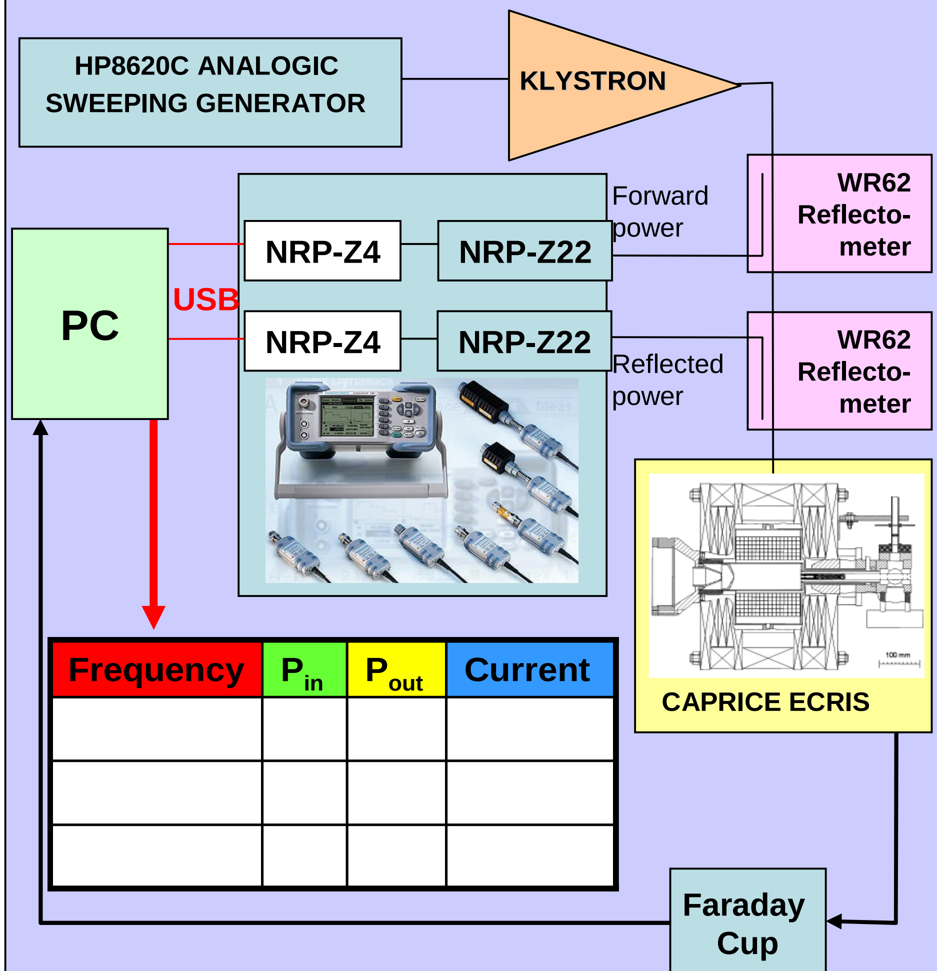




Three viewers (VT1, VT2 and VT3) located respectively: just after the extraction (before the focusing solenoid), after the solenoid and in the dipole focus point. All of them are tilted by 45° to permit the visualization of the beam profile by means of a CCD camera through a quartz window



EXTRACTED CURRENT MEASUREMENTS FOR DIFFERENT OPERATIVE FREQUENCIES



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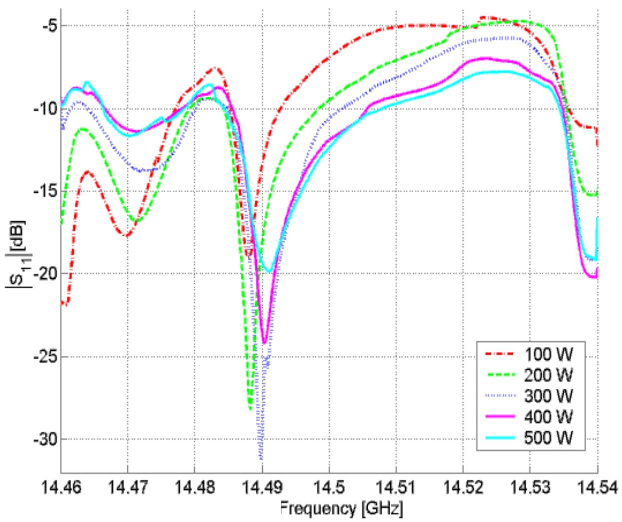
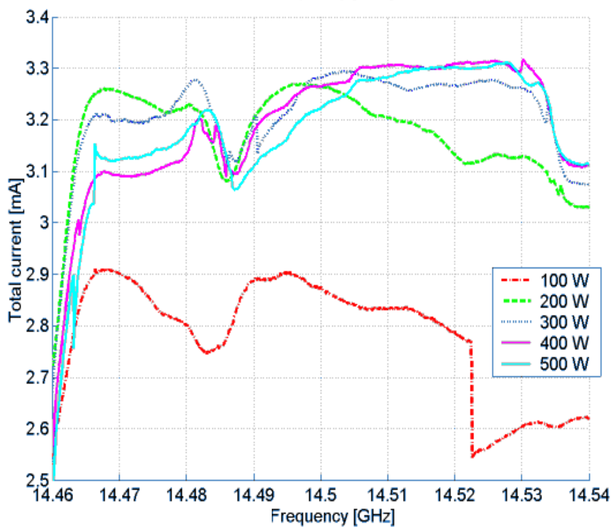
Reflection coefficient and total current extracted from the ion source at different microwave power





The peak around 14.49 GHz shifts in frequency and changes in shape by increasing the power from 100 to 500 W.
This phenomena is due to the change of the plasma parameters (concentration and relative spatial distribution of electrons and ions) which will also cause a change of the "*equivalent (cavity + plasma) impedance*", seen by the input waveguide

The produced currents have a saturation at a power greater than 200 W.

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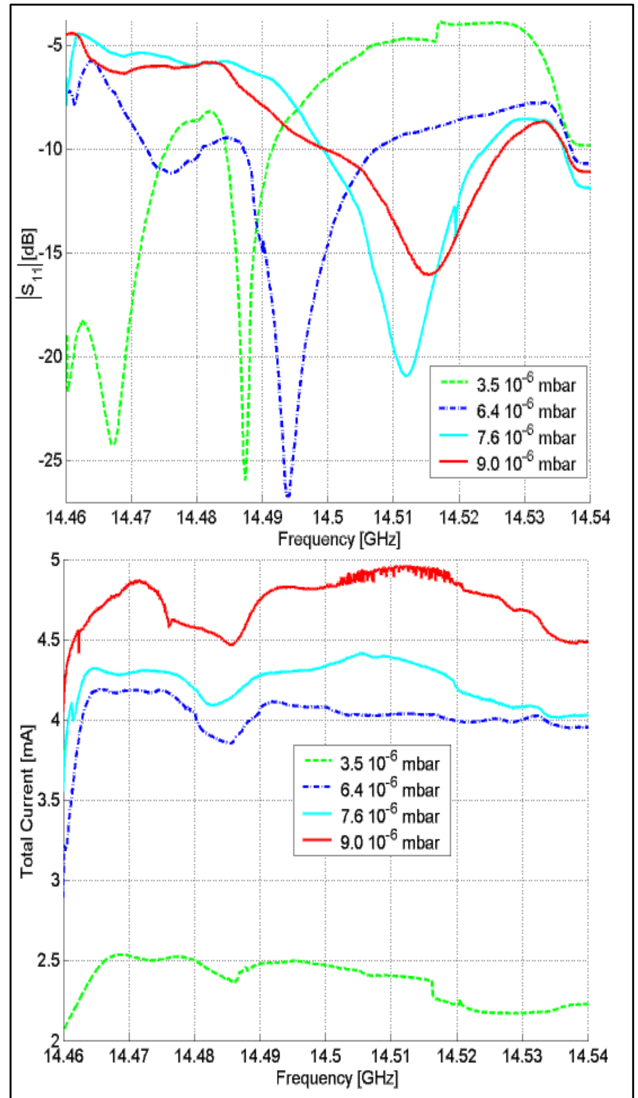
Reflection coefficient and total current extracted from the ion source at different gas pressure

The source behaviour has been also investigated by increasing the pressure in the source plasma chamber from 3.5·10^{-6} mbar to 9.0·10^{-6} mbar with standard magnetic field conditions and at a microwave power of 300 W



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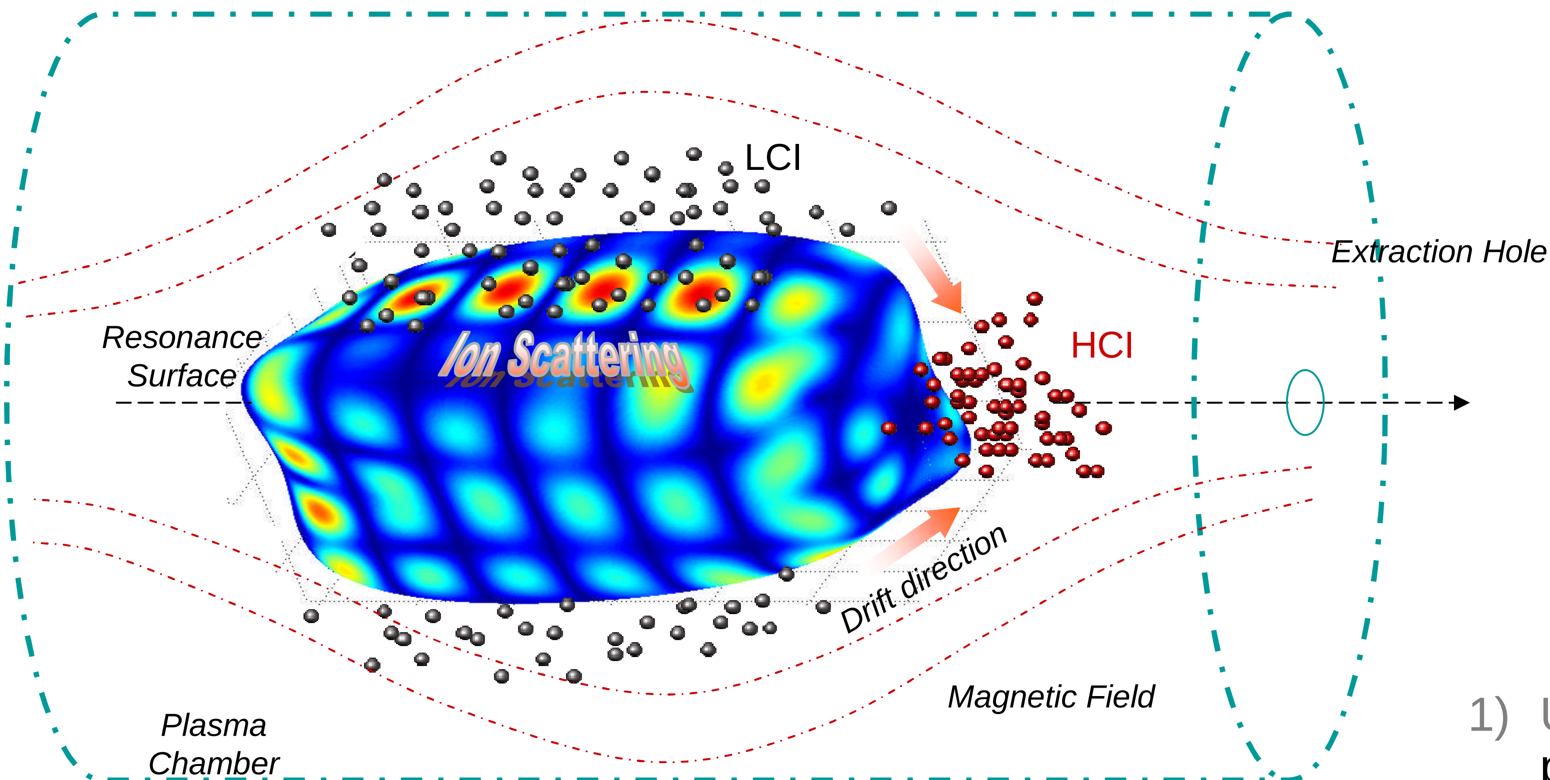
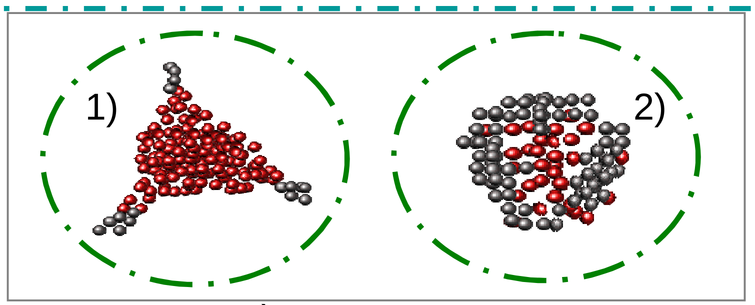
Ion dynamics and ion beam formation





1) 2)

Perturbations of the Primary Plasma Potential (PPP), due to the electric field patterns, strongly influence the beam formation.

1) Uniform E field pattern: ions weakly scattered
2) Structured E field pattern: ions strongly scattered

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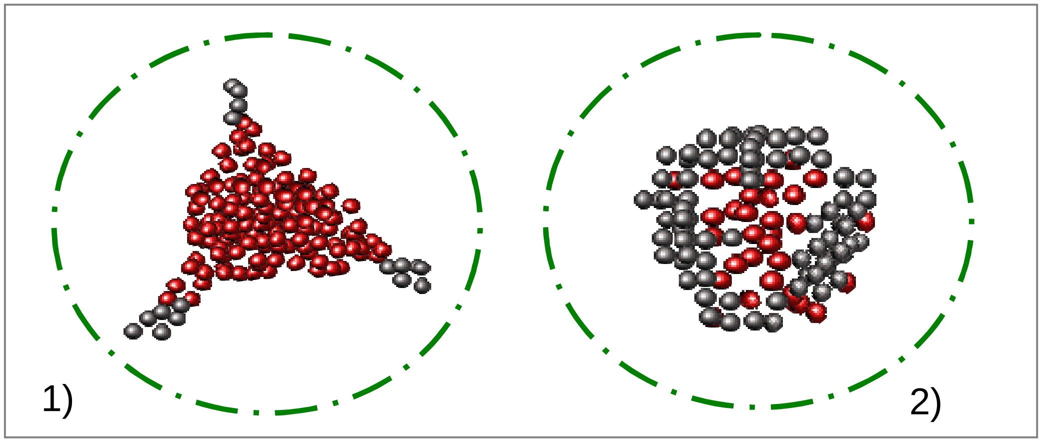
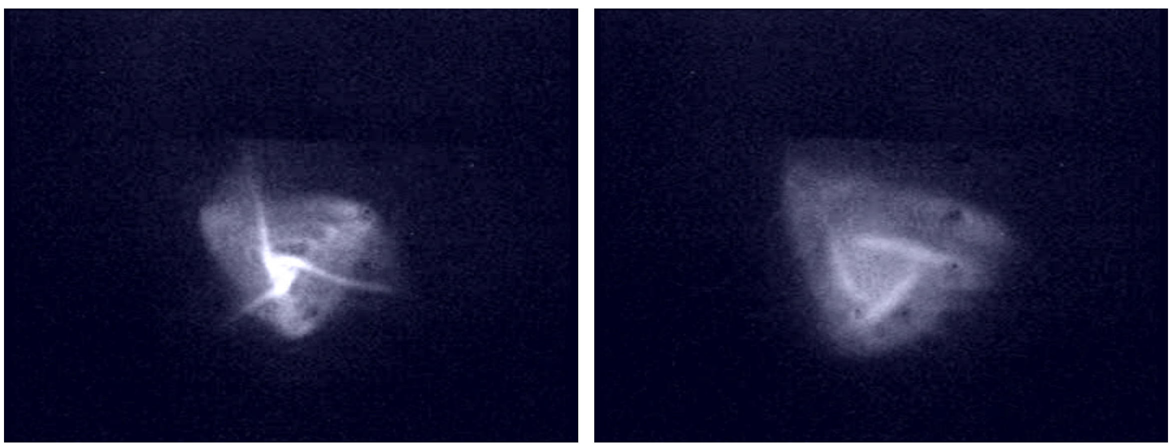
Ion dynamics and ion beam formation





1) Optimal Source performances: Higly Charged ions concentrated in the center of the extracted beam

2) Bad Source performances: ion scattering injects lowly charged ions in the loss cone. The beam periphery is populated by LCI

Also Ion Dynamics may take advantage from Frequency Tuning

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Evolution of S_{11} with plasma

QuickTime™ e un decompressore sono necessari per visualizzare quest'immagine.