

NTA-HELIOS

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Objectives



Increase of the intensity of the extracted current and the average charge state of ion

$$I \propto \frac{n_e}{\tau_i}$$

$$\langle q \rangle \propto n_e \tau_i$$

Simulations about the ECR-heating mechanism for modern ECRIS

Data analysis about FTE

Completion of particle dynamics modelling through numerical simulations

Data analysis about the variation of EEDF shape under different conditions of magnetic field (changes in mirror ratio and longitudinal profile)

Data analysis about the OXB conversion mechanism with the WEGA Stellarator of Max Planck Institute of Greifswald

Design of a Plasma Trap

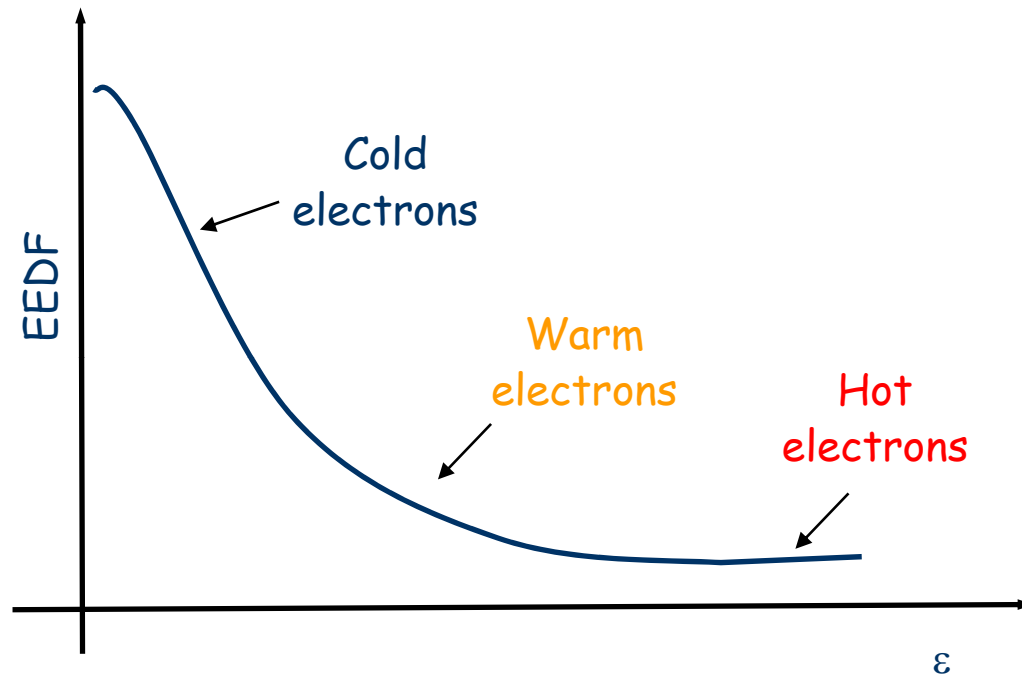


1. different modes take to different **heating rates**;
2. Density non-uniformity can make shorter the **ion lifetime τ_i** and the **plasma energy content is depressed**, although the density n_e remains about unchanged.

To be confirmed:

tuning of frequency may restore conditions of good axial confinement, removing the hollow shape of extracted beam, and positively affecting the **emittance**.

ECRIS plasmas EEDF



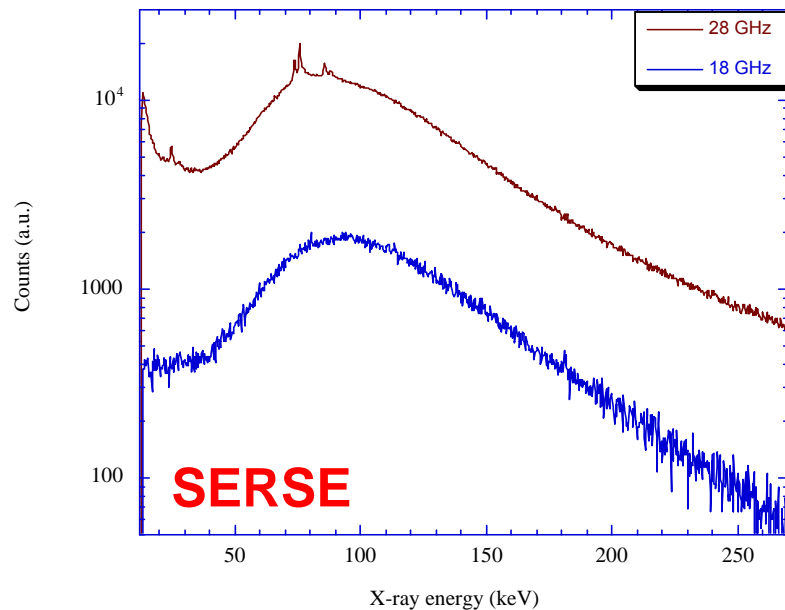
Cold electrons: the energies of most of plasma electrons are in the range 5-50 eV

Warm electrons: energies of a relevant amount of electrons range between 500 and 10000 eV.

Hot electrons: a relatively small fraction of electrons reach energies of several tens or hundreds of keV

Cold electrons contribute to plasma stability and ion confinement, **warm electrons** are of primary importance for ionization up to high charge states, **hot electrons** are detrimental for ECRIS (He boil-off). They do not contribute to ionization as almost collisionless.

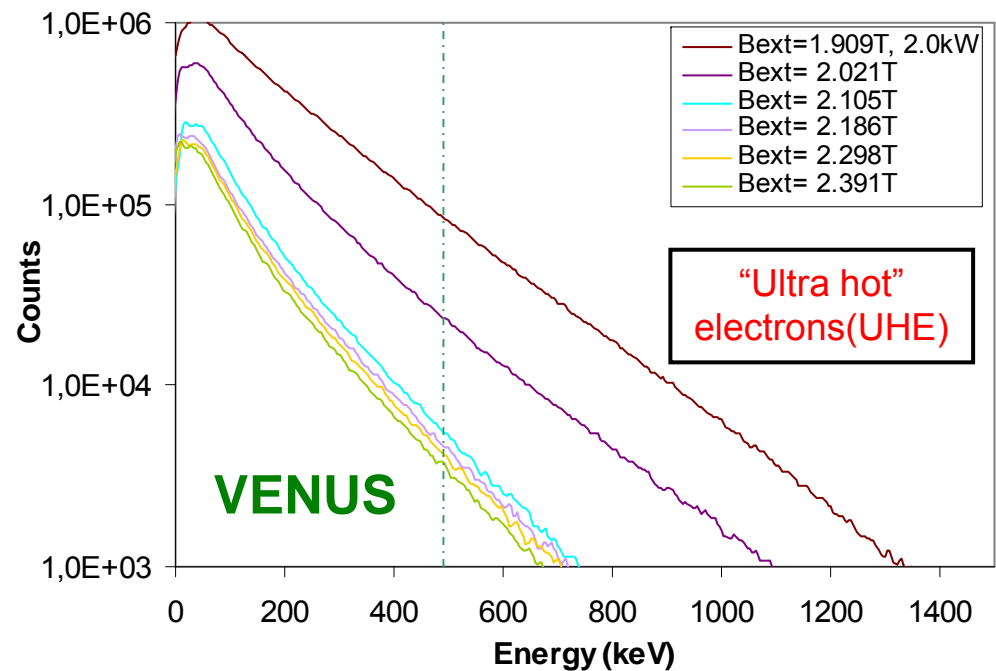
The production of the **UHE** strongly depends
on the **magnetic field gradient**.



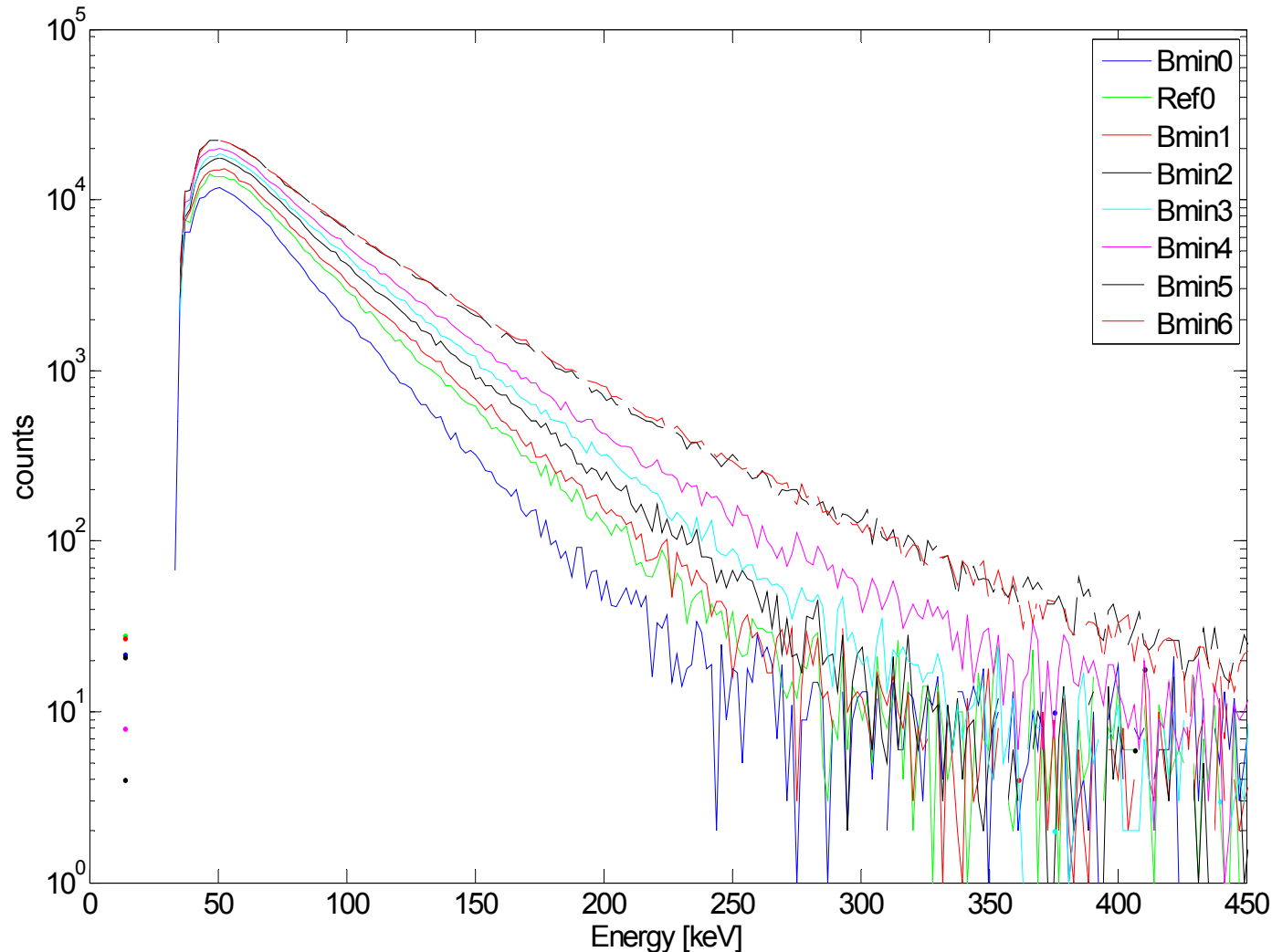
High energy EEDF tails were
already observed at INFN-
LNS in 2000 for **SERSE**
source @ 28 GHz

Energy Barrier according to
Liebermann and Lichtenberg
model for VENUS:

$$W_b = 500 \text{ keV}$$

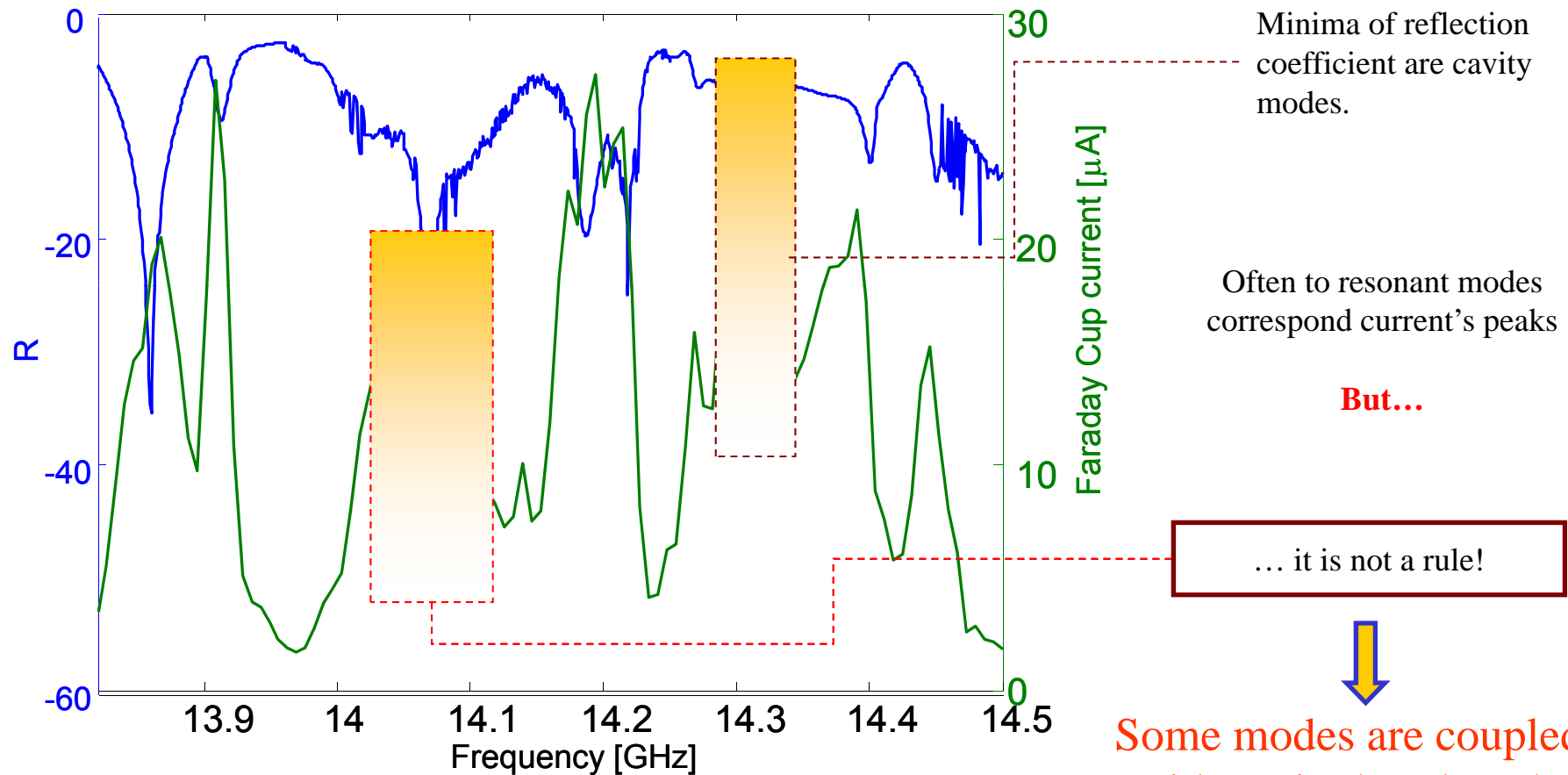


Hot electron component



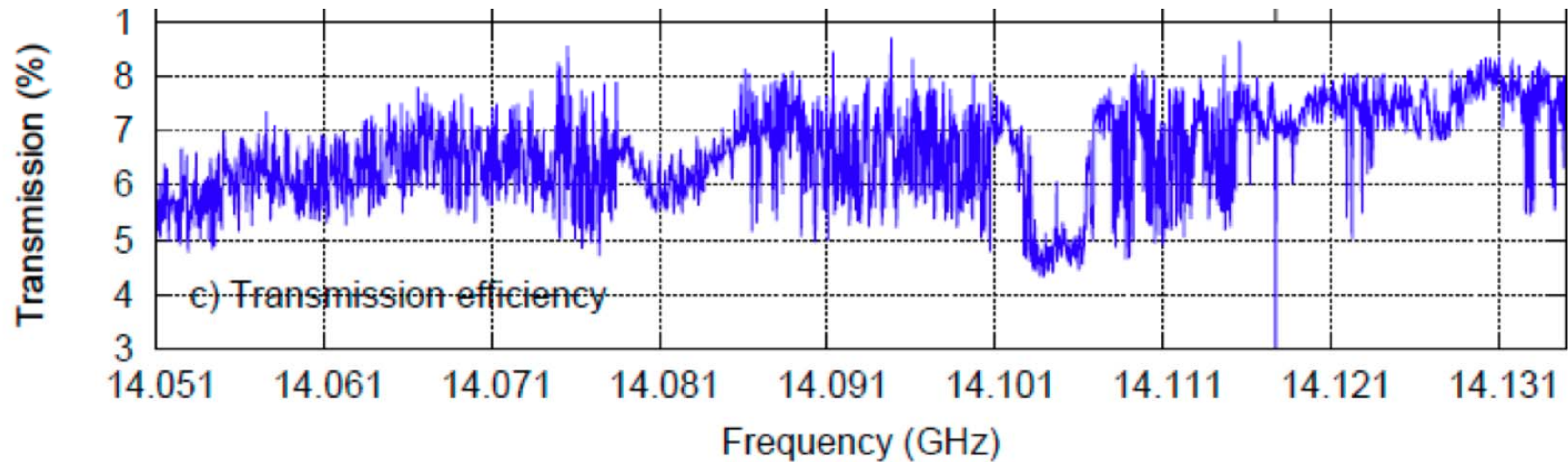
The damping of high energy electrons with an appropriate gradient of the magnetic field in the ECRIS plasma trap was studied during the tests carried out at the Michigan State University.

Relationship between modes and current's peaks: the experiment at CNAO



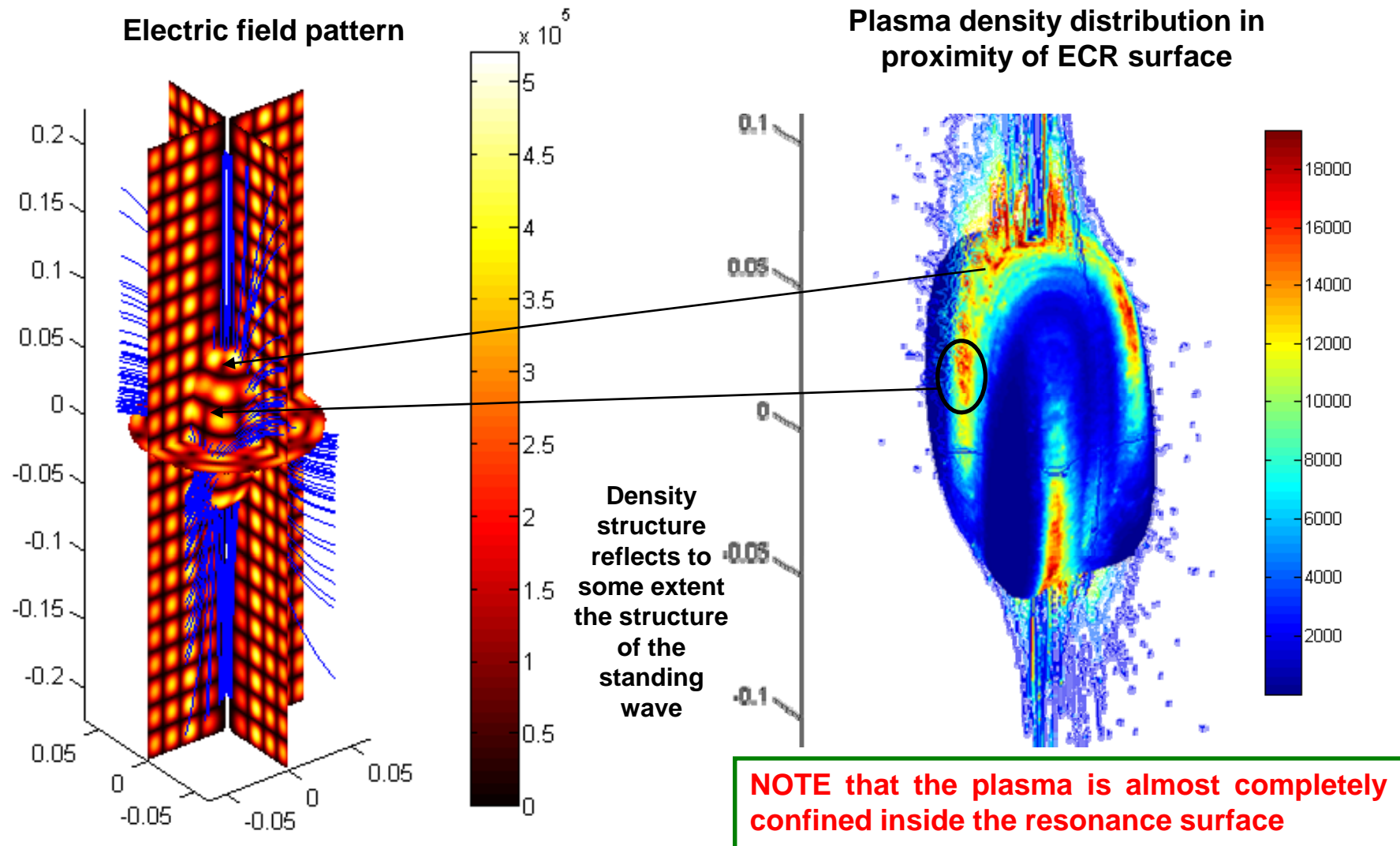
comparison between extracted current and reflection coefficient at different frequencies (test on the **CNAO ECRIS**)

Some modes are coupled with cavity but they do not match properly to the plasma!!!



Evident improvements of the transmission in **LINAC** and in **CYCLOTRONS** by means of FTE have been observed at CNAO, INFN-LNS, INFN-LNL, JYFL, MSU, HIT, etc.

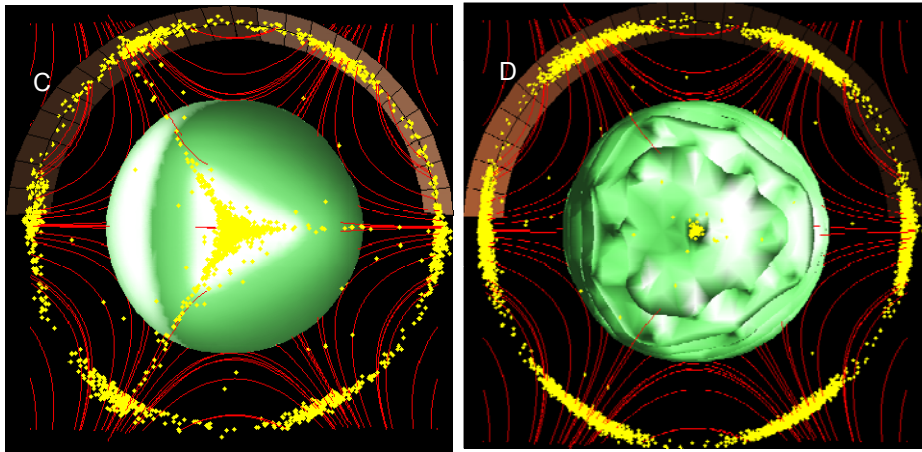
The pattern of the electromagnetic field influences
also the plasma density distribution



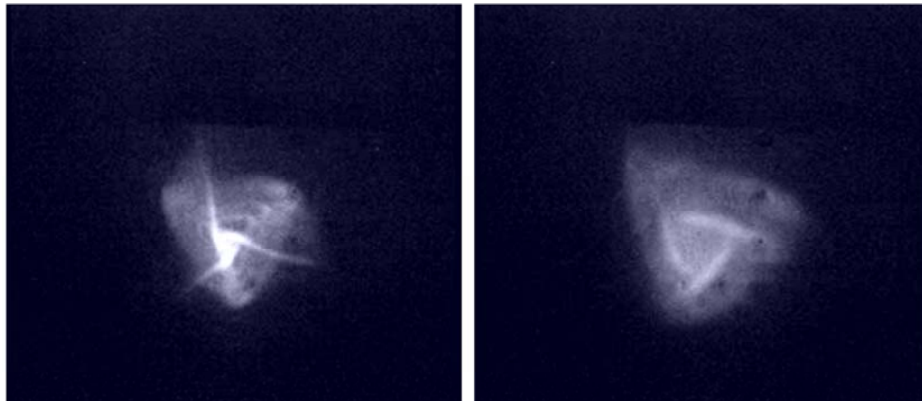
Ion Dynamics and Beam Formation



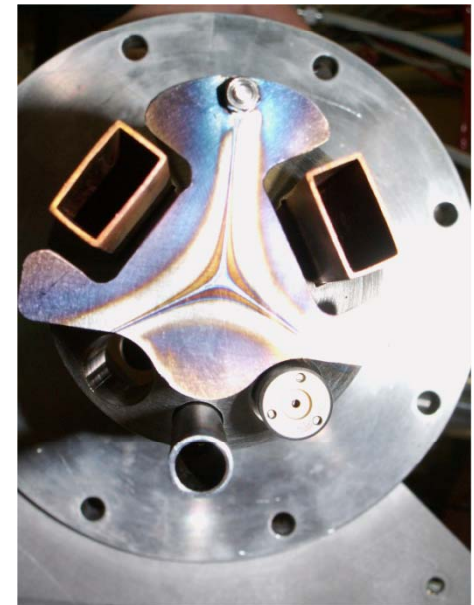
The plasma dynamics heavily affects the beam emittance



The influence of the ion dynamics on the plasma star shape at the extraction side is confirmed also experimentally.



Lateral ion losses are confirmed also by observation of depositions in case of gold plasmas.



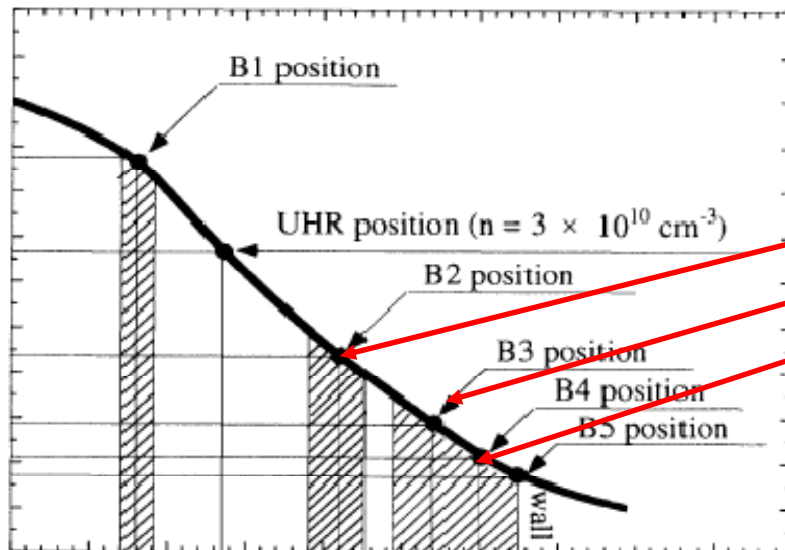
In case of low scattering the ions “remember” the structure of the magnetic field (its shape is preserved in the extracted beam and is enhanced by “corrugations” of the plasma volume).

Theory of EM to ES mode conversion: from X to Bernstein Waves



Dispersion relation for EBW

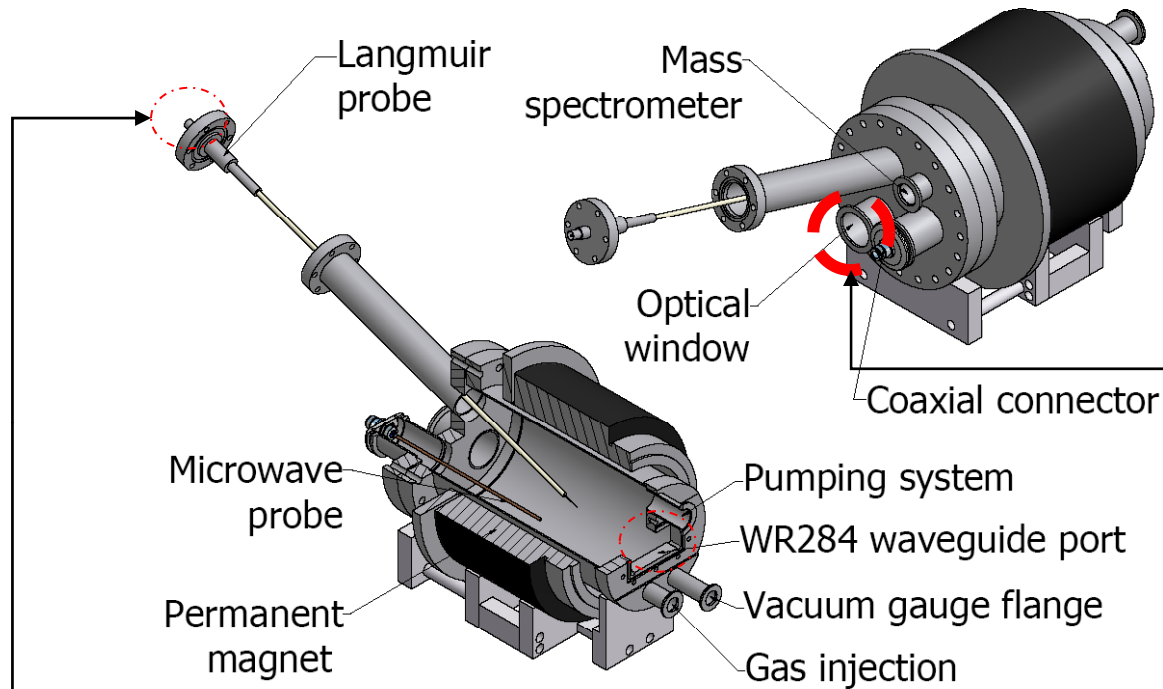
$$1 + \left(\frac{k_B v_{th}}{\omega_p} \right)^2 = e^{-k_B^2 r_L^2 I_0(k^2 r_L^2)} - 2 \left(\frac{\omega}{\omega_c} \right)^2 \sum_q e^{-k_B^2 r_L^2} \frac{I_q(k_B^2 r_L^2)}{q^2 - \left(\frac{\omega^2}{\omega_c^2} \right)}$$



When: $B = \frac{1}{q} \frac{m}{e} \omega_{RF}$ $q=1,2,...,n$

(cyclotron harmonics) this term approaches zero and electron Bernstein waves can be absorbed by the plasma

Experimental Apparatus for conversion detection



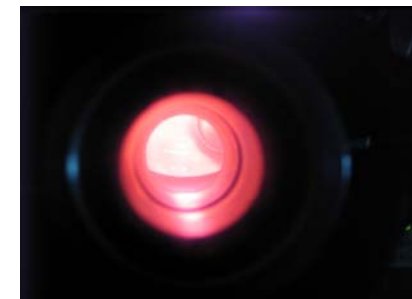
Travelling Wave Tube (TWT)
able to erogate microwaves
from 2.3 to 4.9 GHz



Spectrum analyzer for inner plasma
electromagnetic waves detection

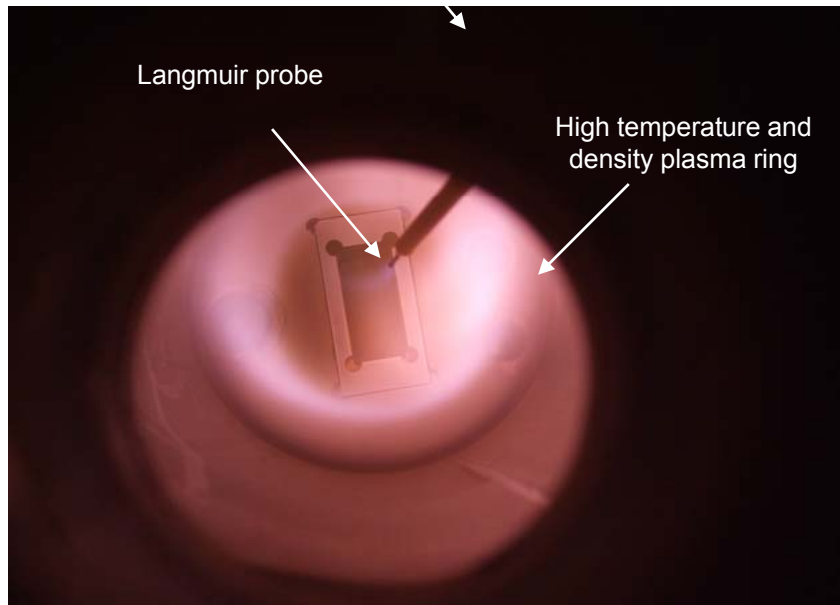


Tungsten probe tip used as
microwave antenna to be
connected to power meter and
Spectrum Analyzer: 4 mm length,
0.15 mm diameter



Optical window for direct
observation of plasma

Additional proofs of X-B mode conversion and plasma heating through BW (July 2010)

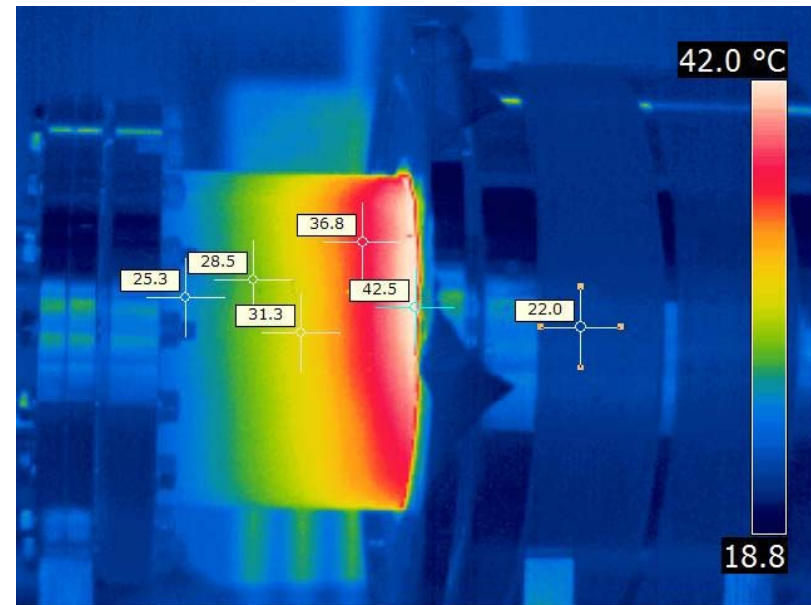


Plasma viewed through the optical window

Where the Bernstein waves are absorbed (at EC harmonic) the **electrons flow rapidly perpendicularly to the magnetic field**.

This flow violates locally the quasineutrality condition and an ambipolar electric field arises. **An $E \times B$ drift generate the plasma rotation around the plasma chamber axis.**

Viscosity accumulates plasma peripherally, like in case of water vortices.



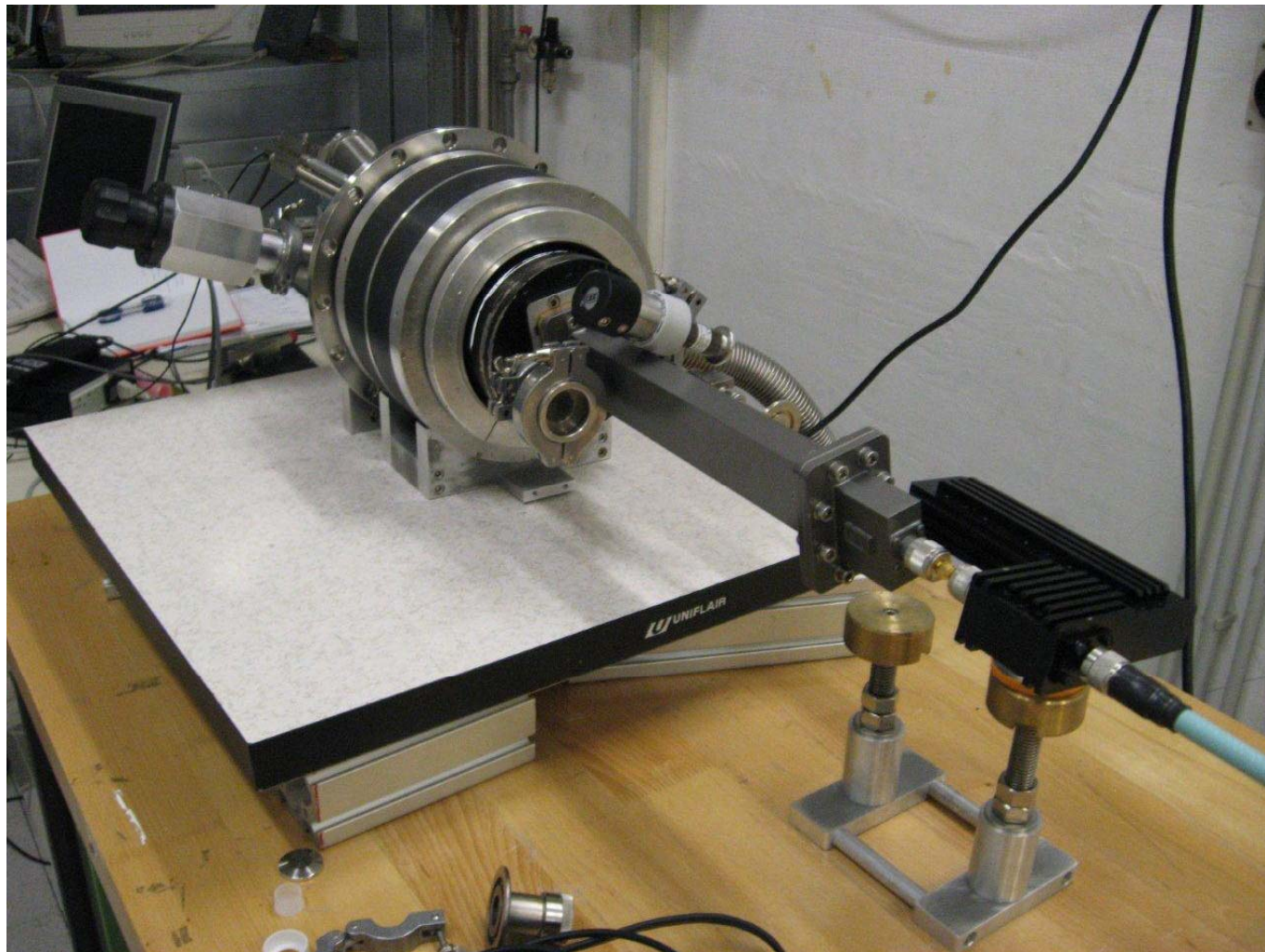
Plasma chamber infrared image

Effects of the **high energy electron ring formation are evident also on the heating of the plasma chamber walls.**

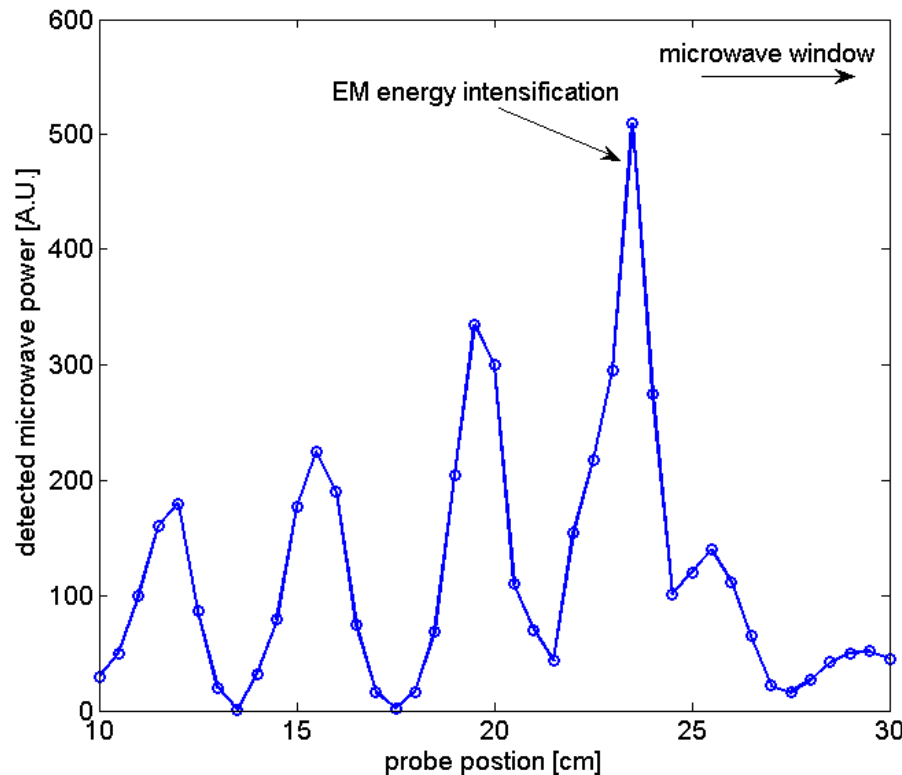
In one hour of continuous operations **the temperature was close to 50 °C**, that is **dangerous for the demagnetization of our magnet**

When the probe tip was left 3-4 minutes at $pp=20$ cm (corresponding to maximum BW absorption) it was almost completely disintegrated by the plasma

Experimental Apparatus for conversion detection (2011)



More sophisticated data analysis on X-B mode conversion at LNS



The measurements of electromagnetic energy distribution confirm the **establishment of standing waves into the plasma chamber**, even in case of extremely high densities (and well above the cutoff).

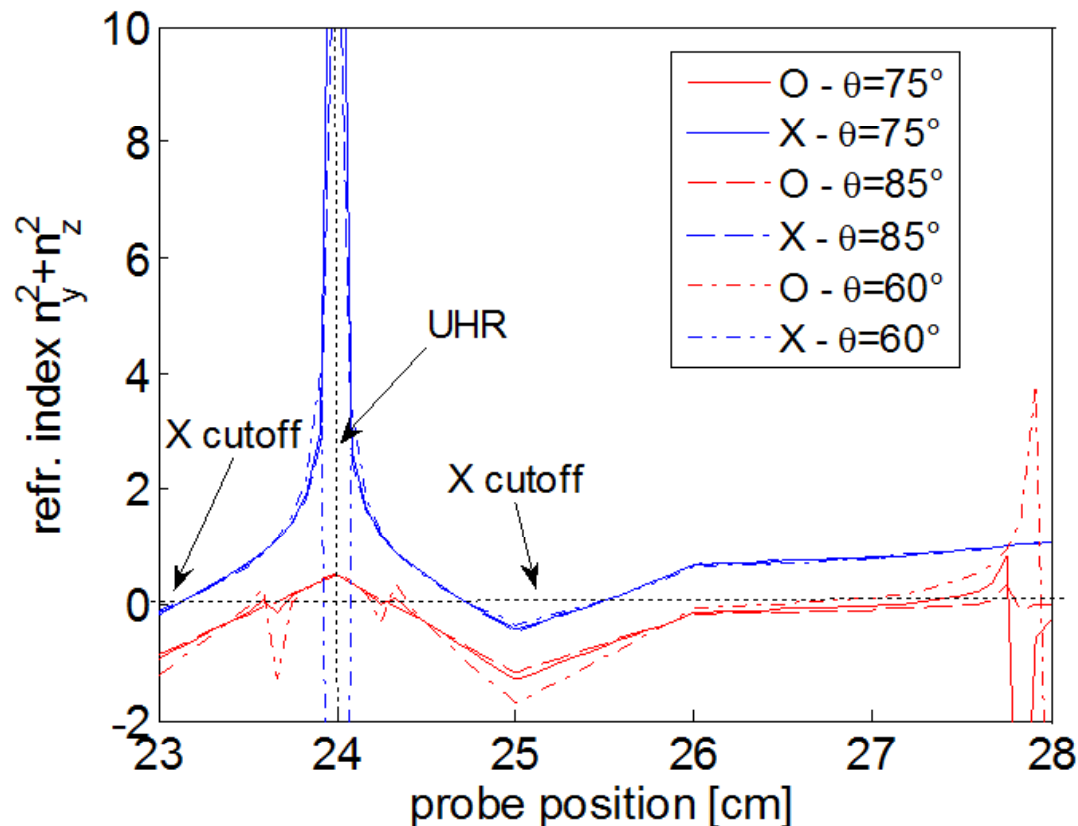
This results is extremely interesting even for ECRIS.

Our hypothesis about the frequency tuning effect is therefore definitively confirmed (up to now only indirect measurements via Network Analyzers were available).

The increase of the detected power is a signal of conversion mechanism occurring at the UHR.

The standing wave nature of the electromagnetic radiation inside the chamber can originate a **perpendicular component of the wave k vector**, thus inducing **conversion even without the perpendicular launching of X wave**.

Detailed calculations of cutoffs and resonances at different angles



Seven modes exist inside the plasma reactor in the range 3.76 ± 0.1 GHz, all of them having $r=5$, $0 < n, \nu < 2$, which corresponds to $60^\circ < \theta < 80^\circ$.

The refractive index can be then calculated accurately according to the magnetic field profile and with the measured density trend (resonances are placed where $n \rightarrow \infty$, cutoffs where $n \rightarrow 0$).

As expected, the UHR is enclosed inside two cutoffs.

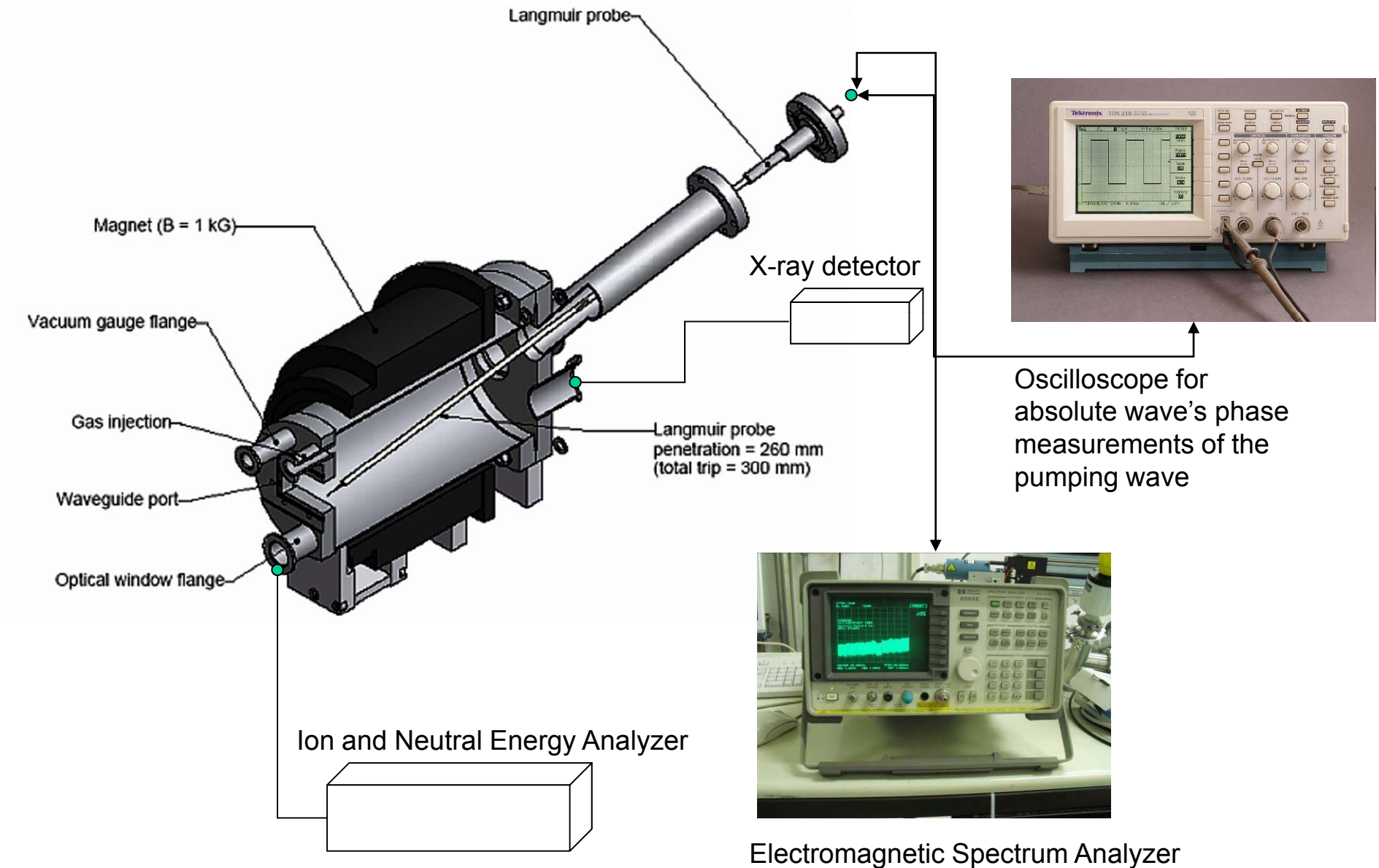
The UHR is accessible only through the tunneling of the X cutoff placed upstream (the incoming wave comes from right in the above figure). The wave encounters the UHR and then the other downstream cutoff and reflects forth and back inside the 'potential well-like structure', thus drastically improving the conversion efficiency.

What we understood up to now:



- 1- All the physical requirements for mode conversion are satisfied in our plasma;
- 2- It has been demonstrated, for the first time, that standing waves formed in resonant cavities facilitate the mode conversion;
- 3- therefore the X-wave launching system is not strictly required;
- 4- it may be generated conversion somewhere (conditions could be fulfilled only by certain profiles of the magnetic field);
- 5- the plasma trap will help to evaluate the conversion efficiency with parallel launching (in this case the tuning of the frequency is needed, to find the proper angle of k), or with pure perpendicular launching;
- 6- A plasma trap with variable magnetic field is essential to study the phenomenon at different frequencies.

Experiment about mode conversion: phase 2



Experiment about mode conversion: phase 2



- 1- In the phase 2 of the experiment **we will measure the X ray emission with a Silicon-pin detector** placed under vacuum;
- 2- If EBW are accompanied by turbulent heating, **higher energy X-rays should appear**;
- 3- Contemporary to the X-rays, **the ion energy distribution will be measured**: the mode conversion is usually associated to **parametric decay and ion wave generation (ion heating is a clear sign of turbulence)**;
- 4- The X-B conversion is accompanied by the drastic shortening of the pumping wavelength in proximity of the UHR: **the absolute phase of the wave inside the plasma will be measured through Lissajous figures**.

News about ongoing activity

X-rays above 10 keV have been obtained at 30 W only !!!

Their nature is connected with **turbulences** induced by the **parametric decay and modulation instability** (both observed thanks to the spectrum analyzer).

This study is going to complete the campaign of research activities carried out to **discover the nature of very hot electrons in ECRIS plasmas**.

They depend on the reciprocal **displacement of cutoffs and resonances** in the plasma, which in turn is determined by the **magnetic field profile**.

The exact longitudinal profile of the density, in proximity of the resonance, could be crucial (to be investigated **by means of the PlasmaTrap under construction**).

With the Plasma Trap **we will make comparative studies about the pure ECR plasma heating compared with the turbulent heating case induced by the EBW**.

ADDENDUM (not contemplated in the 2011 scope): Ion charge state distribution comparison for two cases with P.T. (Nov-December 2011).

- ✓ S. Gammino, D. Mascali, L. Celona, F. Maimone, G. Ciavola, Plasma Sources Sci. Technol. 18 (2009) 045016
- ✓ V. Toivanen, H. Koivisto, O. Steczkiewicz, L. Celona, O. Tarvainen, T. Ropponen, S. Gammino, G. Ciavola, Rev. Sci. Instr. 81 (2), (2010) 02A319
- ✓ S. Gammino, L. Celona, G. Ciavola, F. Maimone, D. Mascali, Rev. Sci. Instr. 81 (2), (2010)
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- ✓ D. Mascali, L. Neri, S. Gammino, L. Celona, G. Ciavola, N. Gambino, R. Miracoli, S. Chikin, Rev. Sci. Instr. 81 (2), (2010)
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- ✓ H. Koivisto, V. Toivanen, O. Steczkiewicz, O. Tarvainen, T. Ropponen, L. Celona, S. Gammino, G. Ciavola, Eur. Cycl. Prog. Meeting, Groningen (2009)
- ✓ D. Mascali, L. Celona, G. Ciavola, S. Gammino, F. Maimone, Part. Acc. Conf., Vancouver (2009)
- ✓ D. Mascali, Il Nuovo Cimento B, DOI 10.1393/ncb/i2010-10899-9
- ✓ **D. Mascali, S. Gammino, L. Celona, G. Ciavola, L. Neri, G. Castro, R. Miracoli, N. Gambino, Nucl. Instr. & Methods (2011)**
- ✓ D. Mascali, S. Gammino, L. Celona, G. Ciavola, L. Neri, R. Miracoli, F. Maimone, Proc. ECRIS'10
- ✓ V. Toivanen, L. Celona, G. Ciavola, A. Galatà, S. Gammino, P. Jones, H. Koivisto, D. Mascali, P. Peura, T. Ropponen, O. Tarvainen, J. Arje, Proc. ECRIS'10, Grenoble
- ✓ V. Toivanen, V. Aho, J. Kauppinen, H. Koivisto, O. Tarvainen, J. Arje, L. Celona, G. Ciavola, S. Gammino, D. Mascali, A. Galatà, T. Ropponen, Proc. ICCA'10, Lanzhou, China
- ✓ S. Gammino, L. Celona, D. Mascali, G. Ciavola, Proc. ICCA'10, Lanzhou, China
- ✓ S. Gammino, L. Celona, D. Mascali, R. Miracoli, G. Ciavola, F. Maimone, Proc. LINAC'10, Tsukuba, Japan
- ✓ L. Celona, S. Gammino, D. Mascali, G. Ciavola, Proc. HB2010, Morschbach, Switzerland (in preparation for Phys. Rev ST-AB)

3 articoli in preparation (Rev. Sci. Instr, Plasma Sources Sci&Tech, PRL)

Talks

- ✓ L. Celona – Int. Conf. on Ion Sources '09 (invited)
- ✓ S. Gammino – Int. Conf. on Ion Sources '09 (invited)
- ✓ S. Gammino – Congr. Società Italiana di Fisica '09 (invited)
- ✓ D. Mascali – Congr. Società Italiana di Fisica '09
- ✓ G. Castro – Congr. Società Italiana di Fisica '10
- ✓ D. Mascali – Int. Workshop on ECR ion sources '10
- ✓ L. Celona – Int. Conf. on Cyclotrons '10 (invited)
- ✓ S. Gammino – Int. Conf. on LINAC'10
- ✓ **D. Mascali – RF in plasmas '11 (invited)**

Evidenza del decadimento parametrico in plasmi overdense di ns. interesse e damping di turbolenze	31-07-2011
Costruzione di un misuratore di emittanza	30-09-2011
Studio delle caratteristiche del plasma in operazioni in EBW mode	31-10-2011
Applicazione dei risultati alle esigenze del Front-End di ESS	31-12-2011

Plasma trap construction

Some delay on order (for administrative reasons) so delayed construction times, we hope to have it in July 2011. The experience with the PM reactor will make faster the achievement of goals.

Emittance measurements device

Some delay on order (because of change of requirements for computer controls) so delayed construction times, we hope to have it in September-October 2011.