Production of High Intensity, Highly Charged Ions – II

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Plasma Heating

Modeling electron heating
driven by microwaves

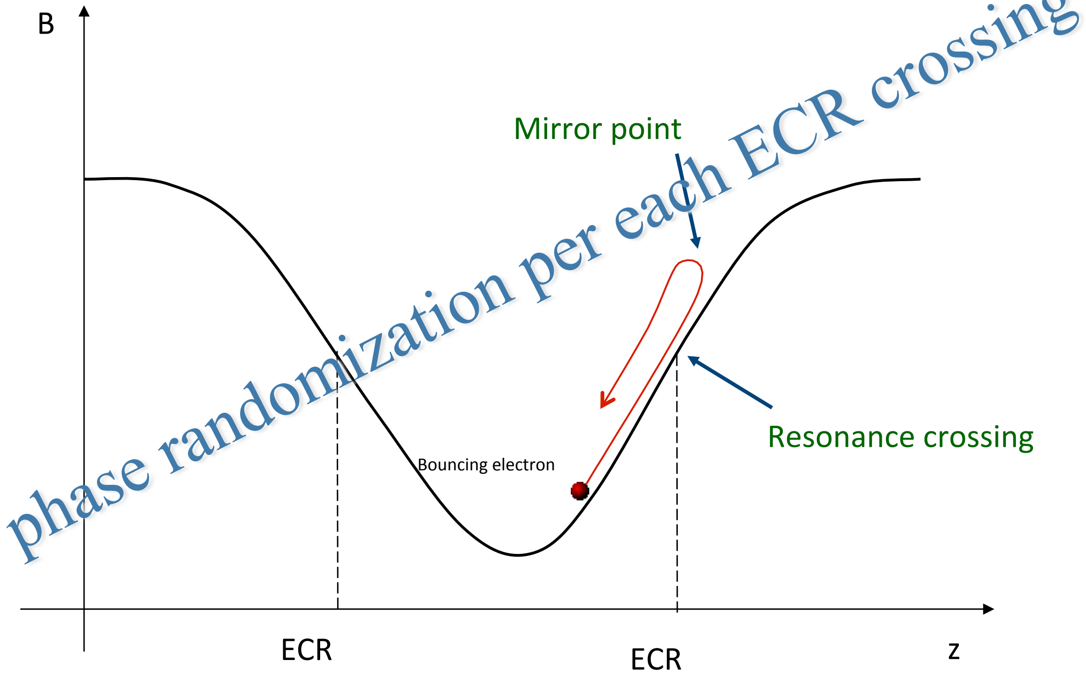
Heating Models

- Single particle approach (SPA): predicts the endpoint energy scaling with L, P_{rf}, E.
- Diffusive approach (DA): in agreement with SPA about boost of heating for long L.
- Importance of turbulence: rarely taken into account, it is at the basis of overbarrier heating in multi-mirror devices.

The Single Particle Approach

M. A. Lieberman and A. J. Lichtenberg, Plasma Phys. 15 125 (1973)

The stochastic heating theory



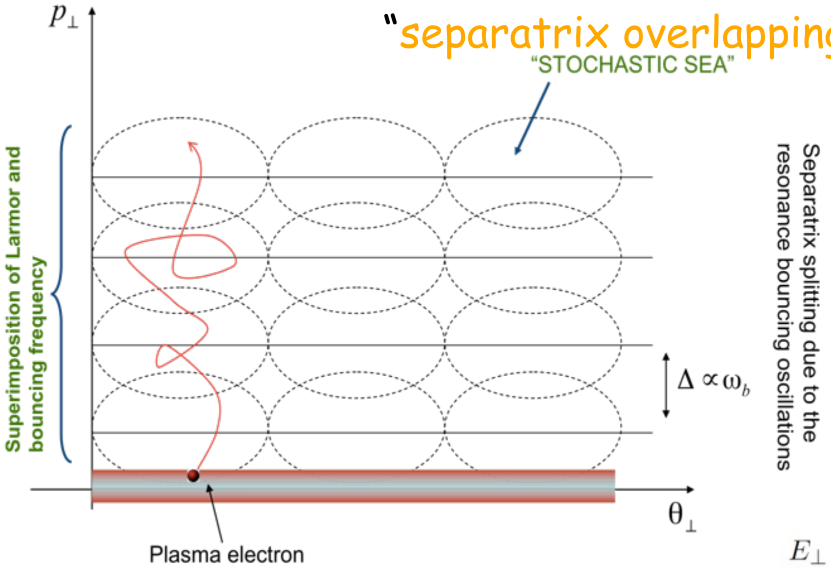
phase randomization per each ECR crossing

Bouncing Frequency: $\boxed{\omega_b}$

The Single Particle Approach

The stochastic heating theory & the "pendulum model"

"separatrix overlapping"



Since the electron rebounces inside the trap:

$$z = z_0 \cos\left(\omega_b t + \psi_0\right)$$

where ω_b is the bouncing frequency

Assuming, in a simplified picture, that the electron interacts with a linearly polarized plane wave:

$$E_\perp\left(t, z, r, \theta\right) = E_{\perp_0} \cos\left(\omega t - kz + \theta_\perp\right)$$

$$\boxed{E(r,\theta,z,t) = E_0 \cos\left[(\omega_{RF} t + \theta_\perp - k z_0 \cos(\omega_b t + \psi_0)\right]}$$

This formula accounts for the composition of the bouncing and cyclotron frequencies, leading to an effective multi-waves interaction

The Single Particle and Diffusive Approach

Trend of the perpendicular velocity for through resonance multi-passing electrons

$$\varepsilon = \varepsilon_i + \Delta\varepsilon + 2\underline{\underline{\cos\left(\phi_0 - \phi_p\right)}}\sqrt{\varepsilon_i \times \Delta\varepsilon}$$

$$\Downarrow$$

STOCHASTIC TERM

For longitudinal B fields like:

$$\begin{cases} \boxed{B = B_{\min}\left(1 + z^2 / L^2\right)} \\ L = \left(\nabla B / B\right)^{-1} \end{cases}$$

$$\boxed{W_b \approx 5W_s = \left[m_e L\left(1 + \frac{l^2}{L^2}\right)\right]^{1/4} l\omega^{1/2}(eE)^{3/4}}$$

Absolute stochastic barrier **(ABS)** (the phase randomization stops)

In order to obtain HCI we need to have a value of ABS large but not so much w.r.t. the ionization energy we aim to have. Therefore SPA already gives information on the ability of the traps you design to reach the goal you aim in term of HCI.

[Lieberman&Lichtenberg, *Plasma Phys.* 15 125 (1973); A. Girard et al. Phys Rev E]

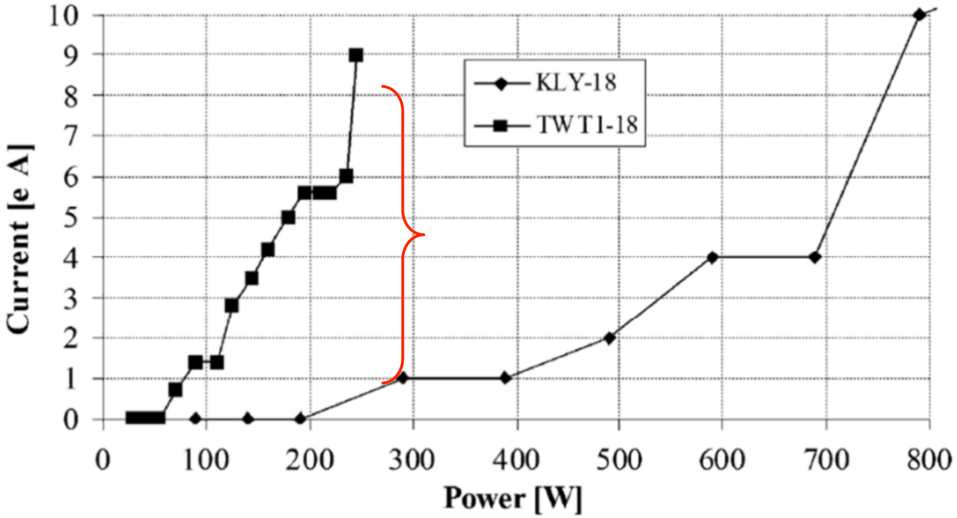
Importance of Modeling

Impact of magnetic field and pumping wave frequency on ion and electron dynamics

FINE TUNING OF ECRIS PARAMETERS (B , f)

How does the pumping wave frequency influence the plasma heating?

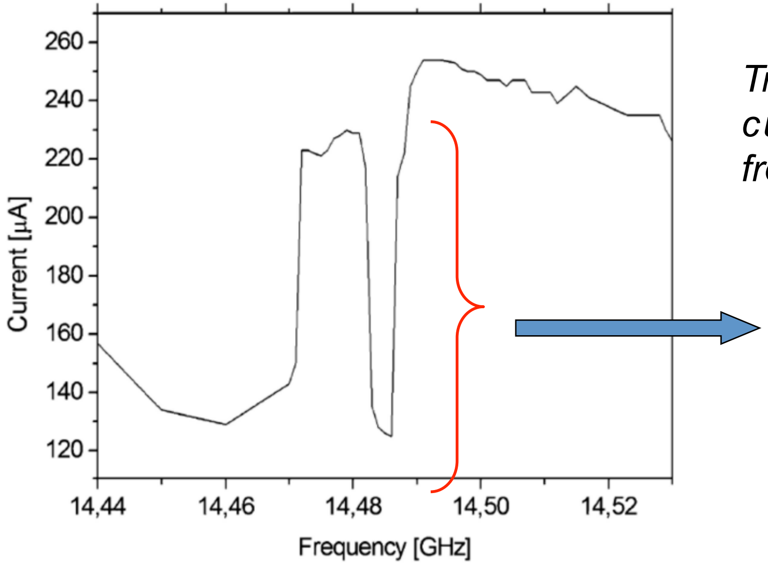
Signs about the importance of the frequency tuning effect came already in 2004 from an experiment carried out on SERSE [A. Galatà, Tesi di Laurea]



Comparison between trends of O^{8+} at 18 *GHz* for klystron (up to 800 W) and TWT1 operating in the same range of frequency.

TWT → BROADBAND GENERATOR?

Evidence of Frequency Tuning Effect (FTE) on the SUPERNANOGAN source



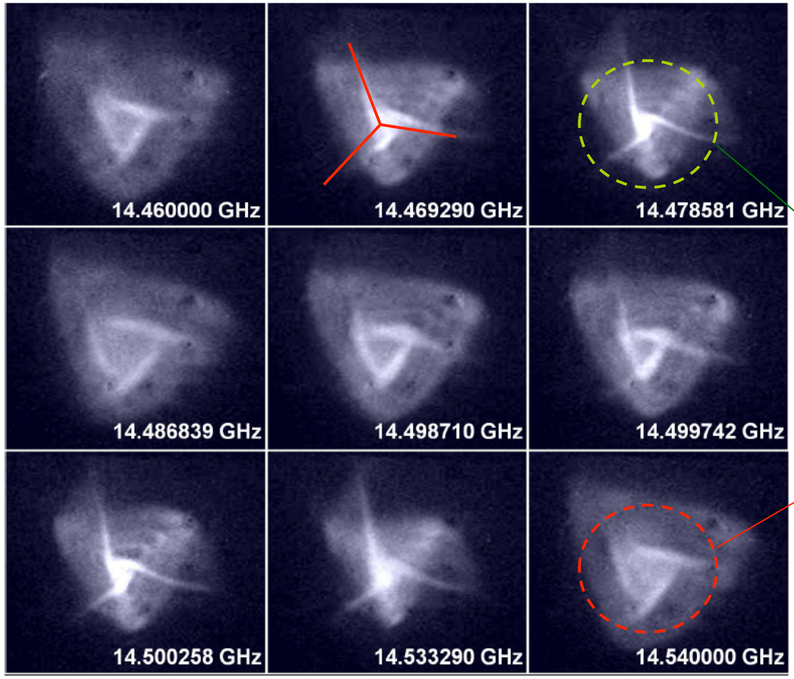
Trend of the analyzed C^{4+} *current versus the RF frequency.*

The extracted current is doubled after a frequency shift of 5 MHz

Transmission of a cyclotron or a RFQ changes significantly when the frequency of the source is slightly changed.

Frequency tuning on the CAPRICE source at GSI

[L. Celona, et al. Observations of the frequency tuning effect in the 14 GHz CAPRICE ion source. *Rev. Sci. Instrum.*, Feb. 2008. vol. 79, no. 2, p. 023 305.]



Frames of the extracted beam for different frequencies

“three cusp” shape of the extracted beam according to the magnetic structure

Well focused and high brightness beam

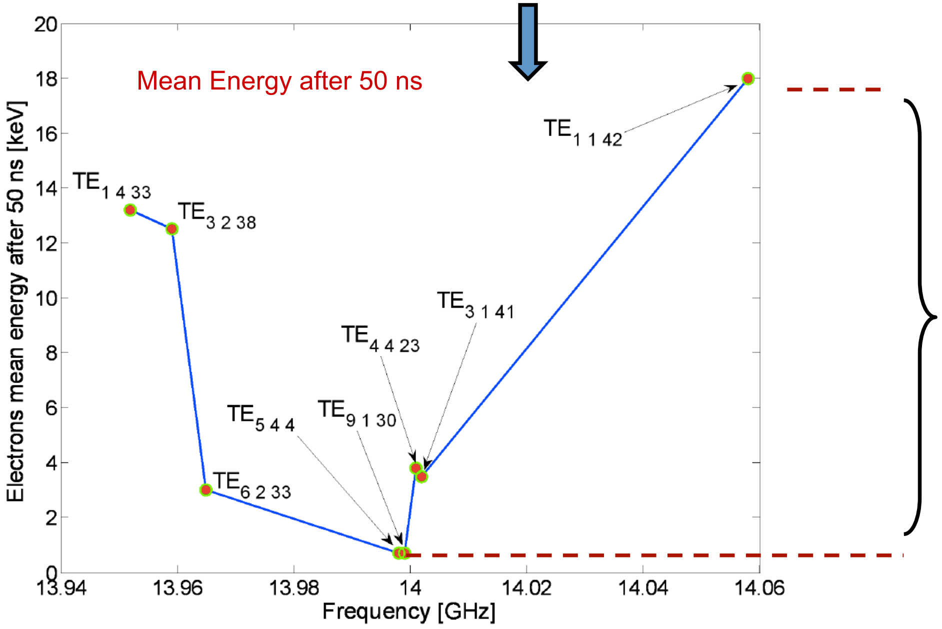
Broadened, low brightness beam

The Frequency Tuning strongly affects also the beam shape and brightness

Fluctuations of electron energy during the frequency tuning

[S. Gammino et al, IEEE Trans. Plasma Sci., 2008]

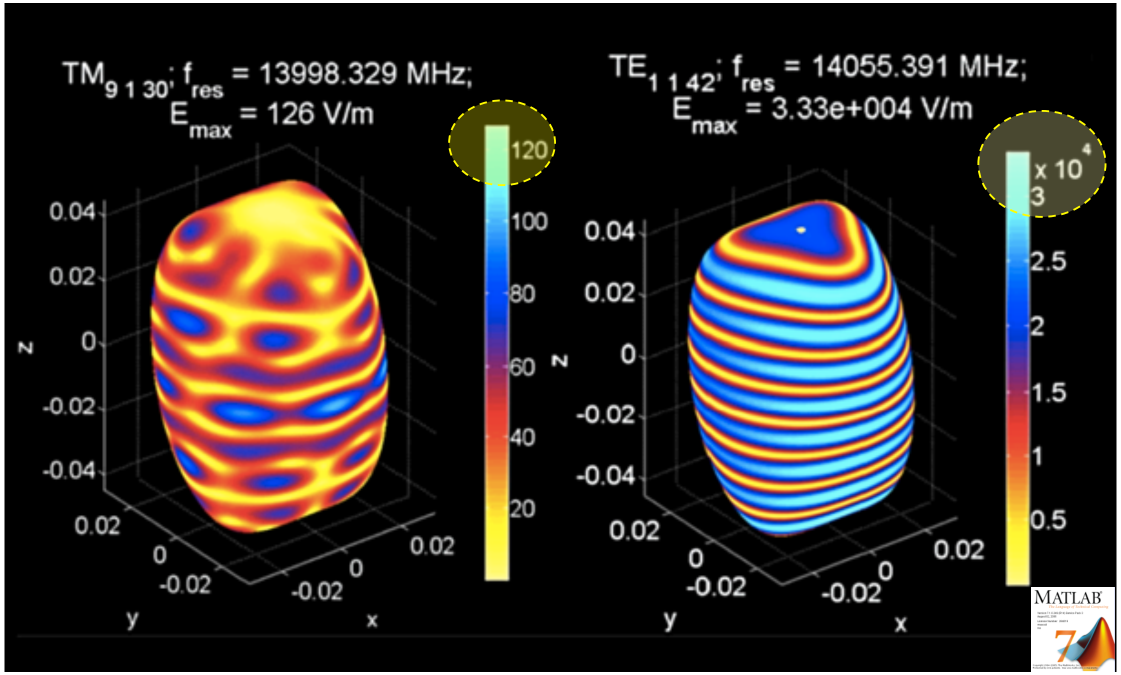
3D collisionless Monte Carlo simulations about ECR-heating of electrons crossing many times the resonance zone in a min-B configuration.



Strong fluctuations of heating rapidity for different excited modes inside the plasma chamber

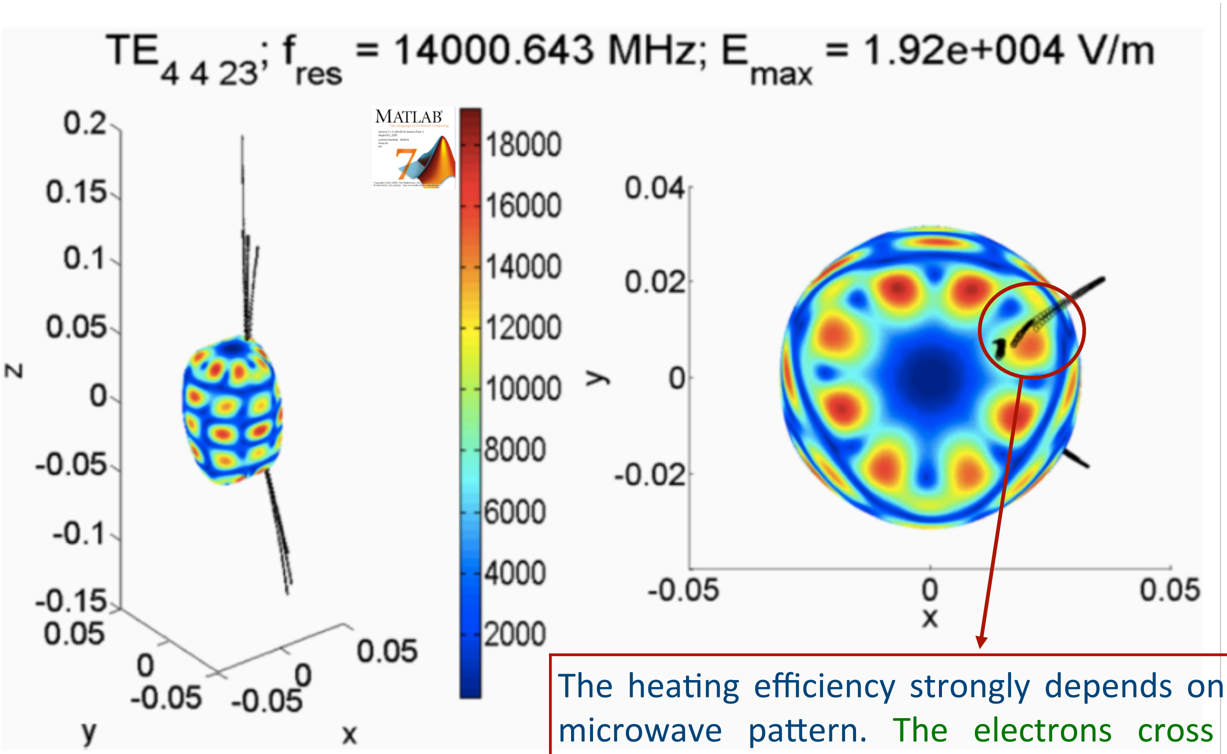
Exciting a mode is not enough: standing wave structure is dominant!

Mode excitation is not enough



Even slight variation of the exciting frequency produce strong changes in the electric field distribution over the resonance surface. The heating depends mainly on the mode pattern!

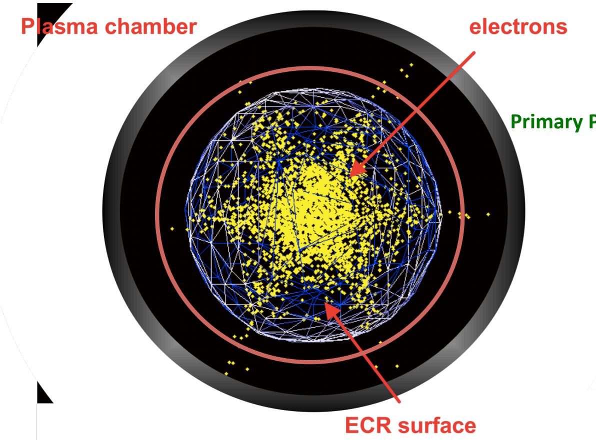
Explanation of frequency tuning effect

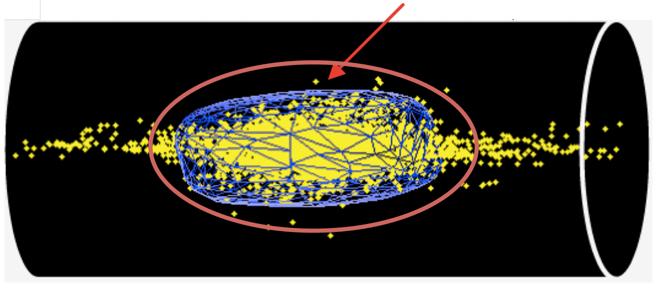


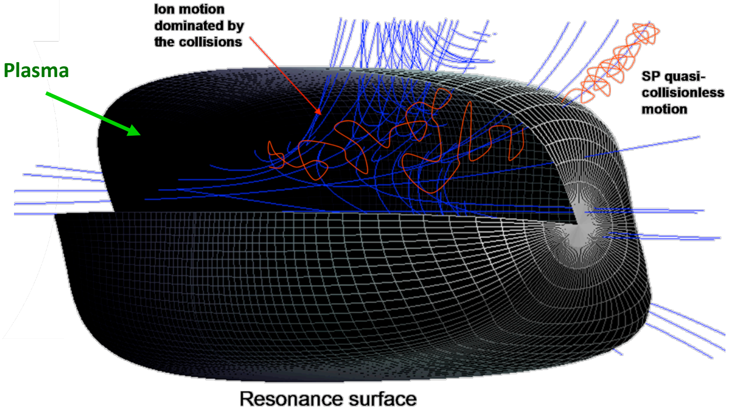
The heating efficiency strongly depends on the microwave pattern. The electrons cross the resonance surface in particular regions according to the field lines structure.

Simulations' Results for Single Frequency Heating

Plug-in & ECR plug Effect



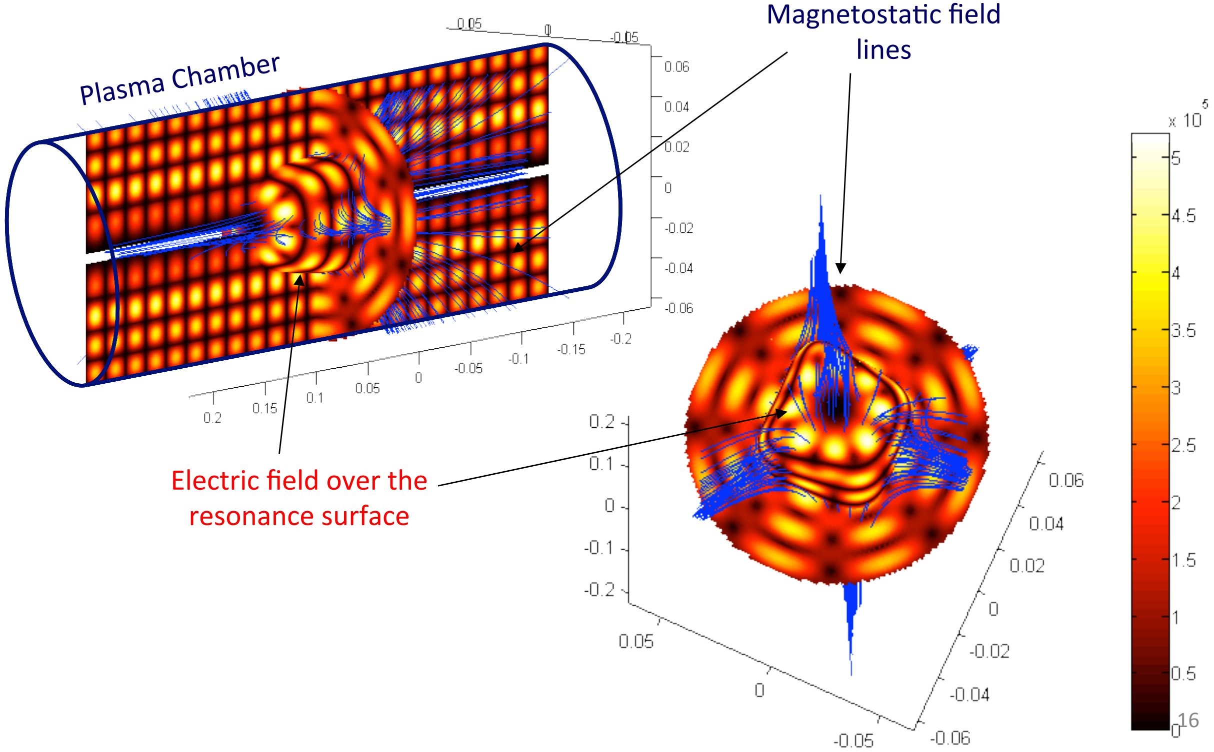




The Plasma can be divided into two regions: PRIMARY (inside the ECR volume) & SECONDARY plasma

Modeling of electron and ion dynamics with Monte-Carlo calculations

Inner "empty-cavity" electric field distribution for the $TE_{4\,4\,23}$ mode close to 14 GHz



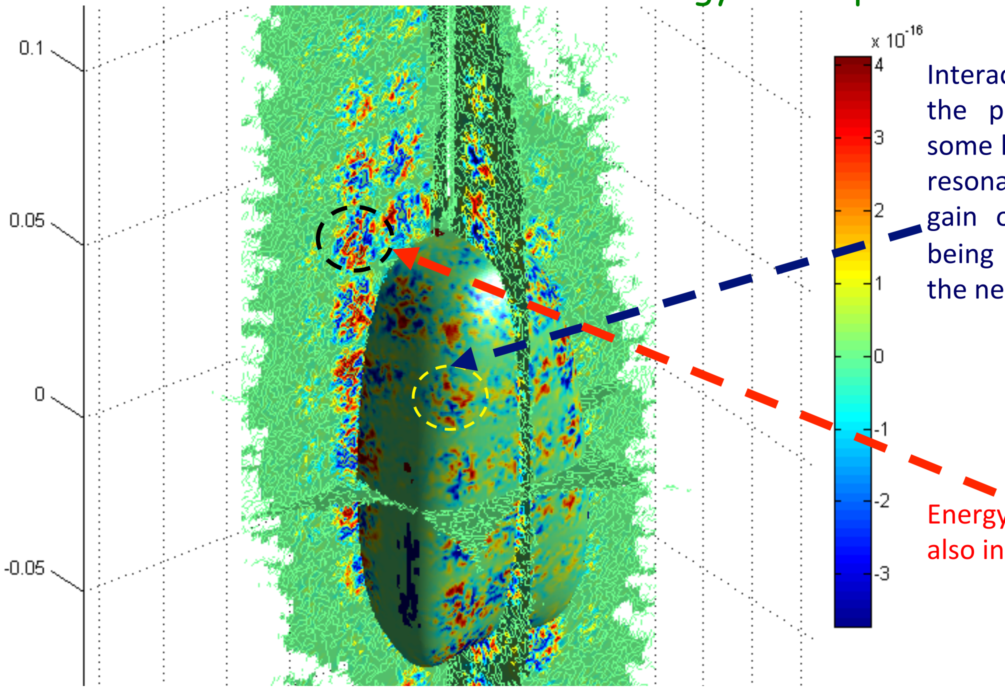
Plasma Chamber

Magnetostatic field lines

Electric field over the resonance surface

Modeling of electron and ion dynamics with Monte-Carlo calculations

[D. Mascali et al., Oral presentation at 19th ECRIS Workshop, Grenoble, 2010]



Localization of electrons energy absorption during 5 μs

Interaction of the wave with the plasma takes place in some localized areas over the resonance surface. Particles gain or loss energy locally, being positive for electrons the net balance.

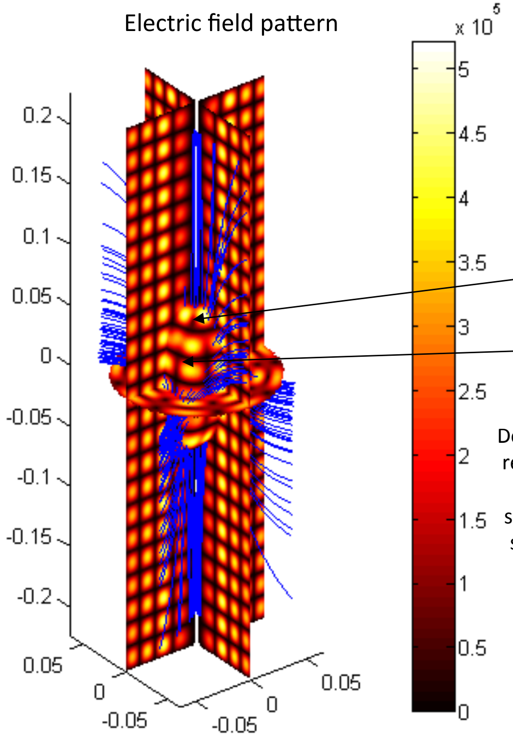
Energy exchange takes place also in off-resonance regions.

Off resonance interaction between wave and electrons may be linked to ultra-hot electrons…

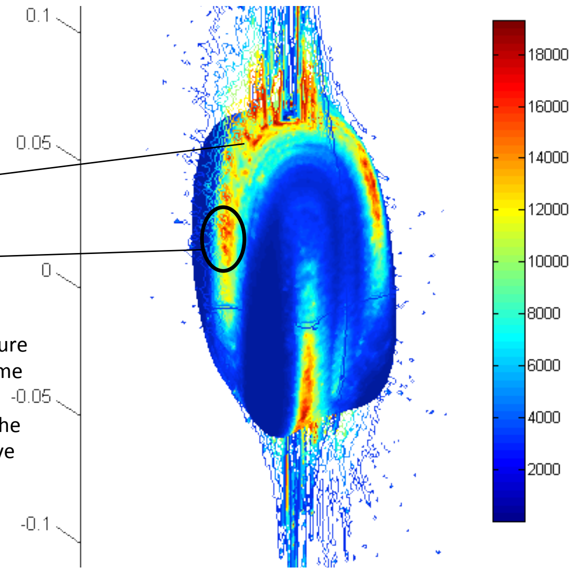
Modeling of electron and ion dynamics with Monte-Carlo calculations

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

Electric field pattern



Plasma density distribution in proximity of ECR surface

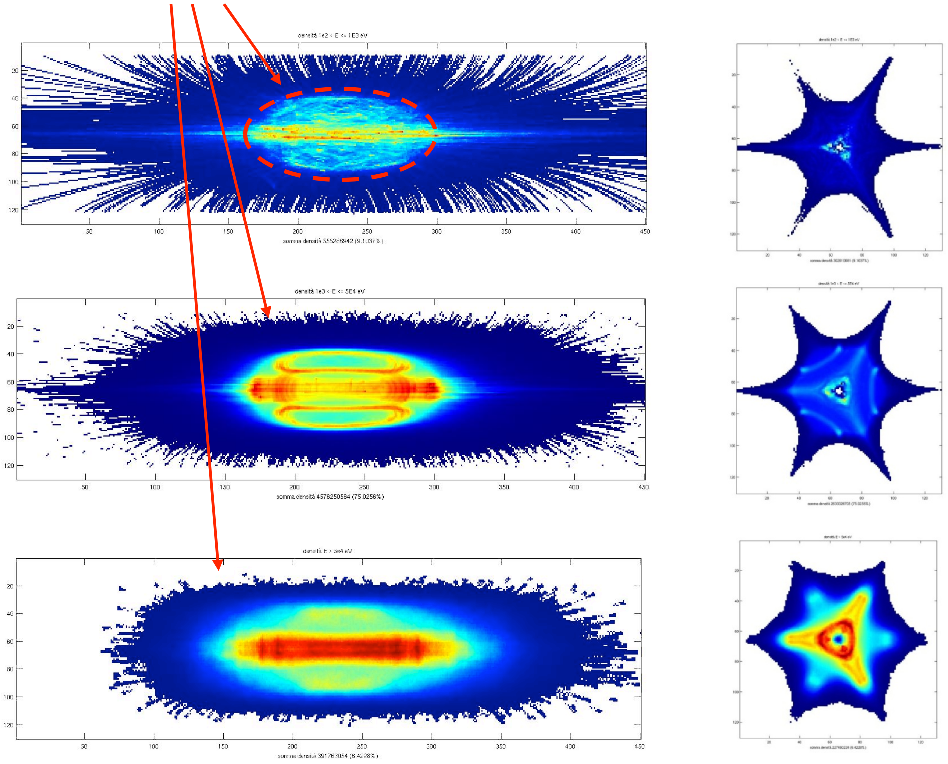


Density structure reflects to some extent the structure of the standing wave

NOTE that the plasma is almost completely confined inside the resonance surface

SIMULATED 3D STRUCTURE OF THE PLASMA

Simulations based on a 3D Monte-Carlo collisional approach reveal that the plasma almost totally accumulates inside the ECR surface (PLASMOID GENERATION).



0.001<E<1 keV

1<E<50 keV

E>50 keV

[D. Mascali, K. Wiesemann, L. Celona, S. Gammino and G. Ciavola, in preparation for Phys. Rev. E]

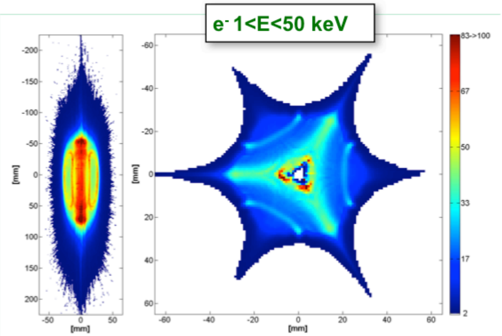
Consequences

The RF heating of the plasma gives a footprint which is useful also for the beam emittance.

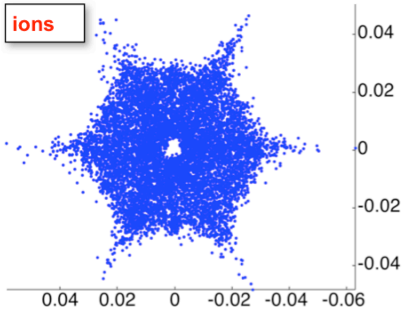
The presence of more electrons takes more HCI in the meniscus around the axis, hence to a beam with low emittance.

Hypothesis about overbarrier electrons production

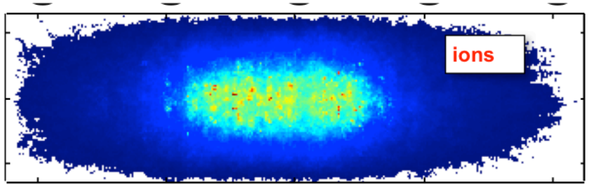
Ions initial position can be extracted where high energy electrons are placed. Net ion-electron density determines fluctuations in plasma quasi-neutrality

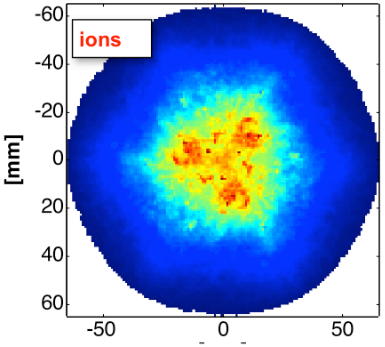


Electrons distribution fixes regions of ion generation



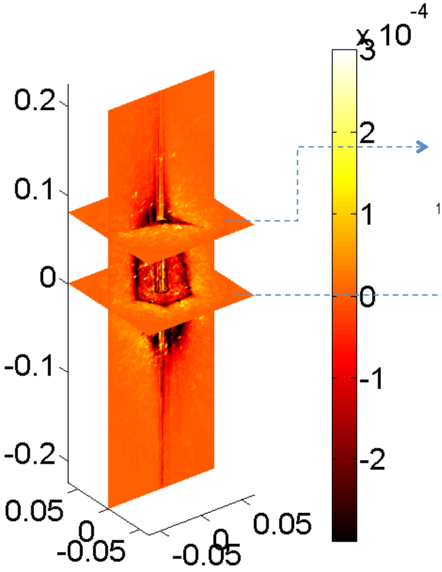
Ions were simulated asuniquely subjected to collisions and eventually to the magnetic field

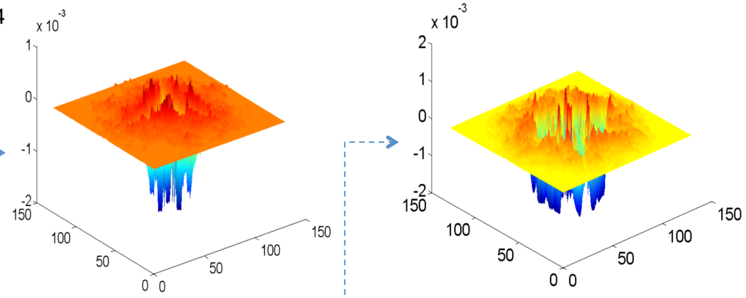




[D. Mascali, K. Wiesemann, L. Celona, S. Gammino and G. Ciavola, *in preparation for Phys. Rev. E*]

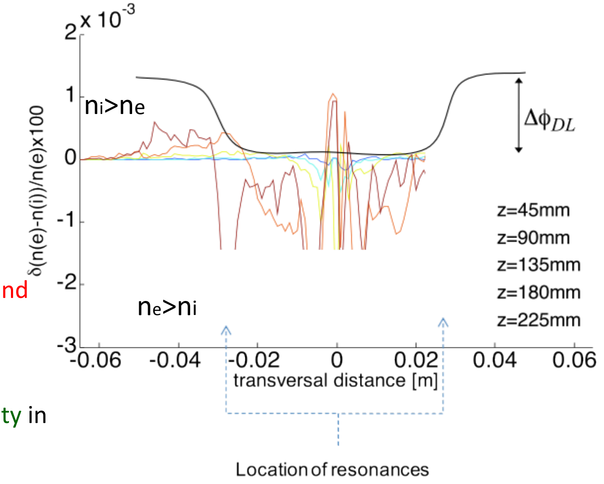
The DL formation at the plasmoid edge



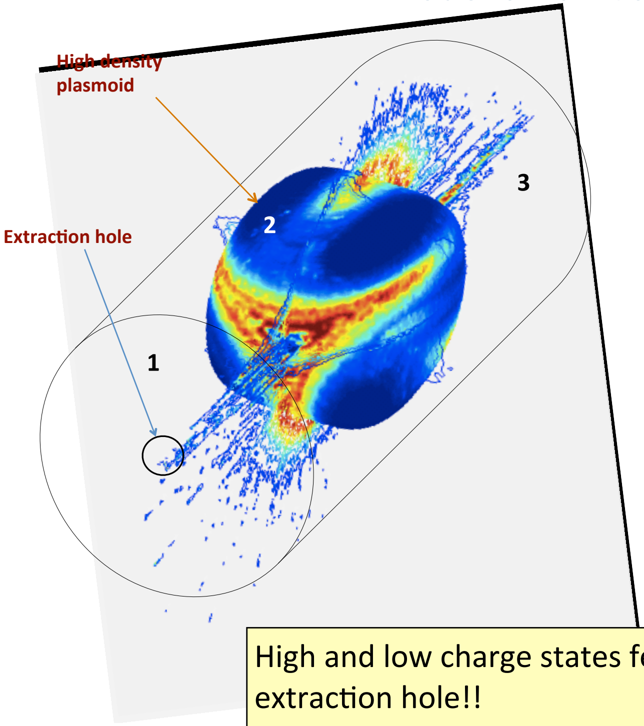


Electrons are retained by the RF plug effect, while ions tend to diffuse across ECR layer due to their larger inertia and collisionality.

The DL potential arises radially to preserve quasi-neutrality in high magnetic field side.



Model of Ion Confinement



Because of radial potential dip, ions experience a qV electric field which forces the highly charged ions to accumulate closely to the axis.
The needed time is comparable with time needed to step-by-step ionization.

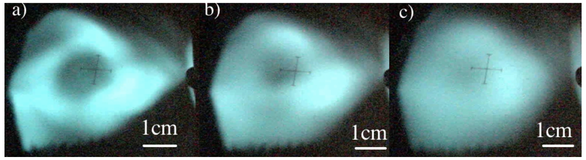
High and low charge states feature different beam shapes at the extraction hole!!

[see G. Machicoane et al., ICIS2007]

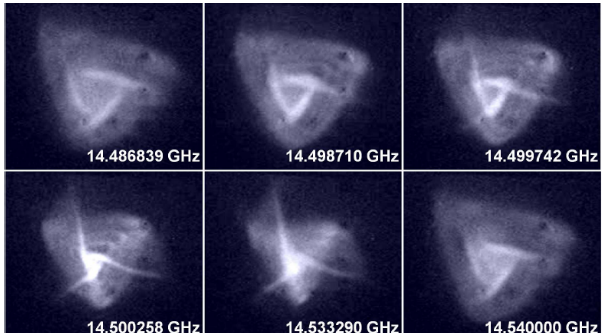
[D. Mascali et al. 19° ECRIS-Workshop, Grenoble 2010]

Huge impact of FTE on ion dynamics and beam formation

Jyvaskyla ECRIS

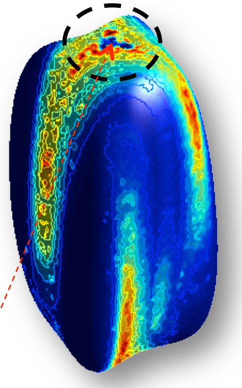


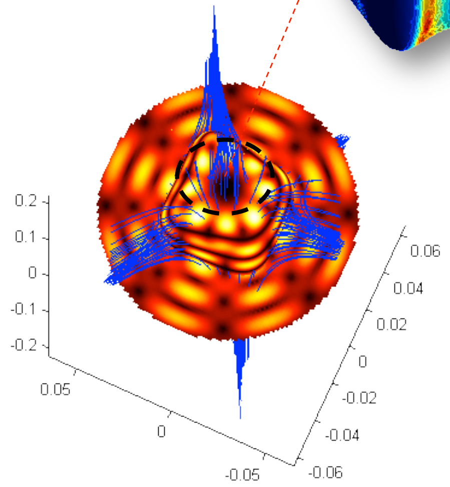
GSI-ECRIS (CAPRICE)



Hollow beam formation is a common feature of most of ECRIS.
Transversal beam shape confirms ions are magnetized in outer plasmoid region

Near axis density depletion takes place because of low EM field.
Most of the resonant modes at f>10GHz exhibit holes in near axis zone



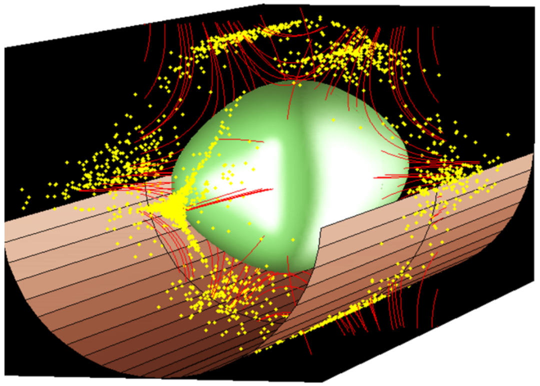


Preliminary results on Ion Dynamics and Beam Formation presented at ICIS 2009

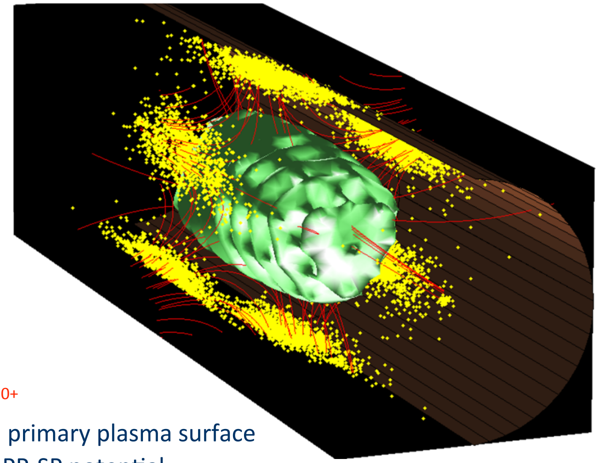
Corrugation of the primary plasma surface:

At first approximation it was assumed to be the same of the electromagnetic field pattern

[D. Mascali et al. Plasma ion dynamics and beam formation in Electron Cyclotron Resonance Ion Sources, Rev. Sci. Instrum.]



Simulated Ar^{10+}
Smooth primary plasma surface
30 V of PP-SP electrostatic potential



Simulated Ar^{10+}
"Corrugated" primary plasma surface
30 V of mean PP-SP potential

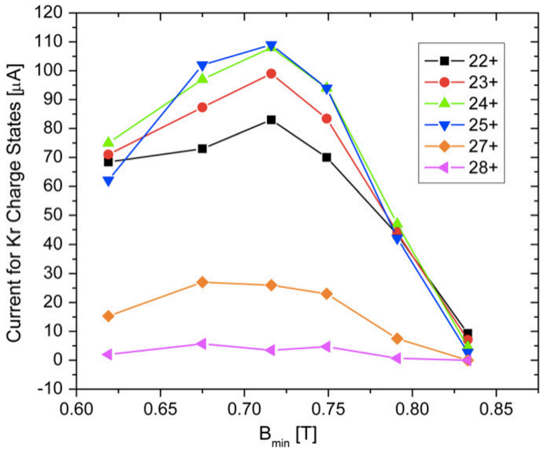
Ion lifetime depends strongly on corrugation, mean value of accelerating potential and inner resonance plasma density. Recent simulations estimate τ_i~0.5-3 ms, according to density fluctuations.

Also the beam formation and handling may take advantage from Frequency Tuning

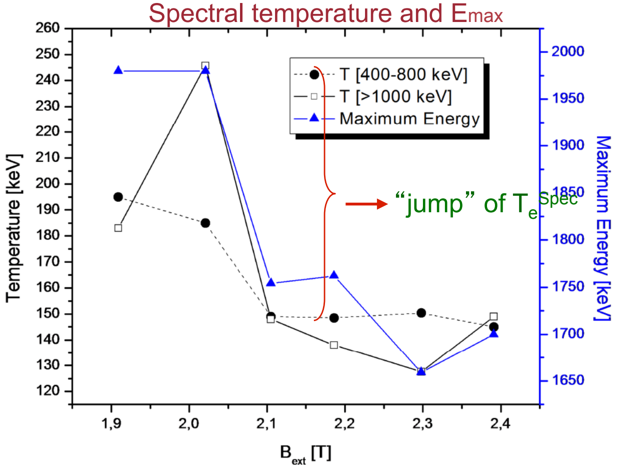
FINE TUNING OF ECRIS PARAMETERS (B , f)

How does the magnetic field profile influence the plasma heating?

Evidence of hot electrons generation for only slight variations of the mirror ratio.



Spectral temperature and E_{max}



→ "jump" of T_e^{Spec}

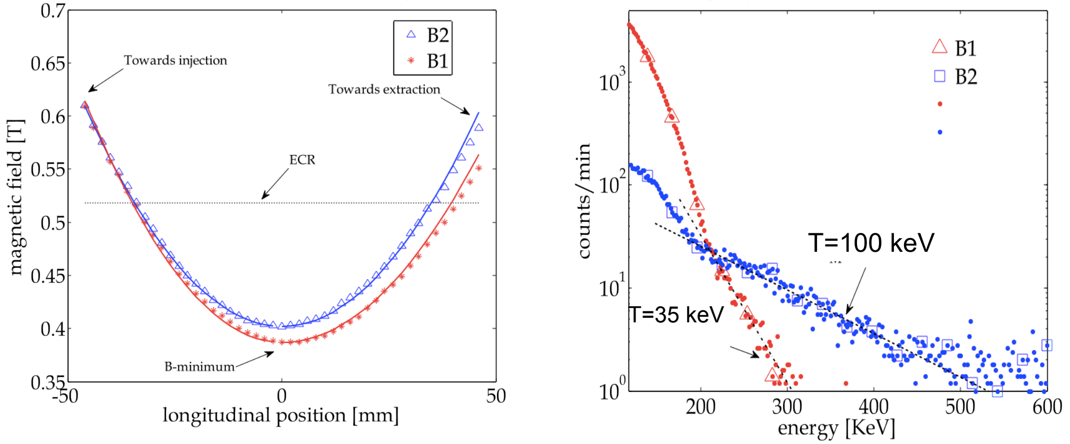
In case of hard-X radiation the charge state distribution is peaked on lower charge states!!

"Gentle" gradients boost the production of very high energy electrons (up to 2 MeV), limiting the exploitation of the ECRIS performances.

[S. Gammino, D. Mascali, L. Celona and G.Ciavola, Plasma Sources Sci. Technol. 18 045016 (2009)]

In some conditions slight variations of L are critical for hard-X rays generation (exp. with CAESAR)

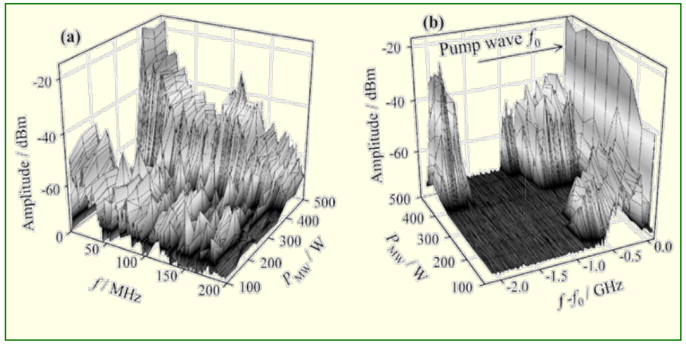
Comparison of the X-ray spectra obtained with slightly different B profiles

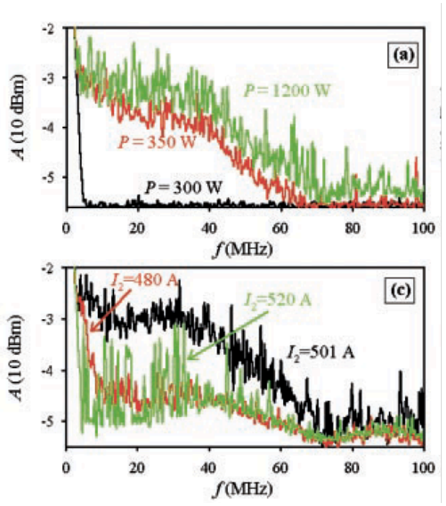


By changing the characteristic length of the mirror trap, L, of just 4mm, we obtained a completely different X-ray spectrum.

	L [mm]	l [mm]	W_b [keV]	D_{vv} [a.u.]	T^{spec}[keV]	Ef [keV]
B1	60	30	300	100	35	300
B2	64	34	350	105	100	530

Do turbulences play a role?





Broadening of the pumping wave spectrum due to parametric decay. Noise in the MHz range also appears (IAW, LHW)

A quasi-linear equation for the EEDF can be considered:

$$\begin{cases} \dfrac{\partial f}{\partial t} + \hat{L} D \hat{L} f = 0 \\ D_{turb} = \dfrac{e^2 \varepsilon_{\perp 0} E^2}{m_e} \mathrm{Re} \dfrac{1}{\sqrt{(2q\omega_b)^2 - (\omega - \Omega_\perp + i\gamma)^2}} \end{cases}$$

The spectrum broadening is accompanied by generation of hot electrons. It seems to be critically sensitive to the magnetic field profile (few mT) more than to RF power.

[Ivanov, Wiesemann *IEEE Transaction on Plasma Science*]

In case of turbulent heating induced by mode conversion

The electrostatic modes, generated at the ECR or/and at the UHR, give small kicks to the bouncing electrons, thus providing an additional randomization of the wave-particle phase!!!

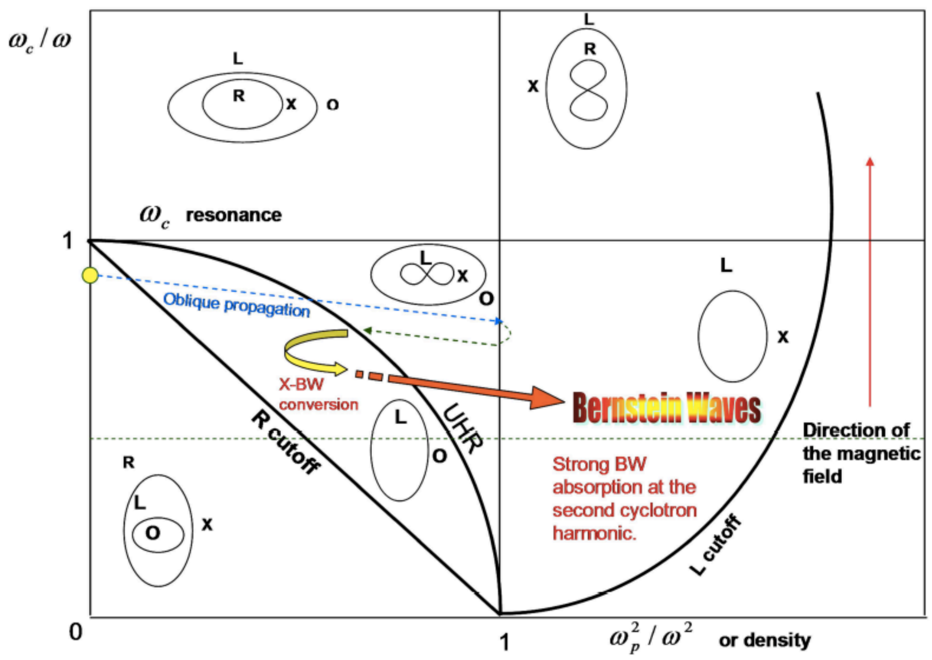
⇓

OVERHEATING AND GENERATION OF SUPRATHERMAL ELECTRONS

Hard X-rays appearently depend on B field detuning

The experiment on the WEGA Stellarator:

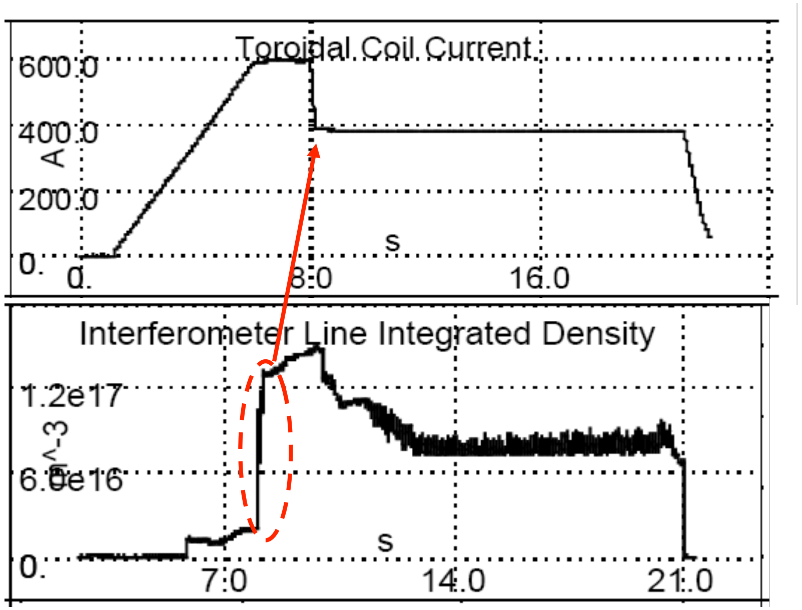
the innovative technique of OXB mode conversion



The BW generation thanks to X-BW conversion at UHR

Trend of the plasma density with respect to the magnetic field

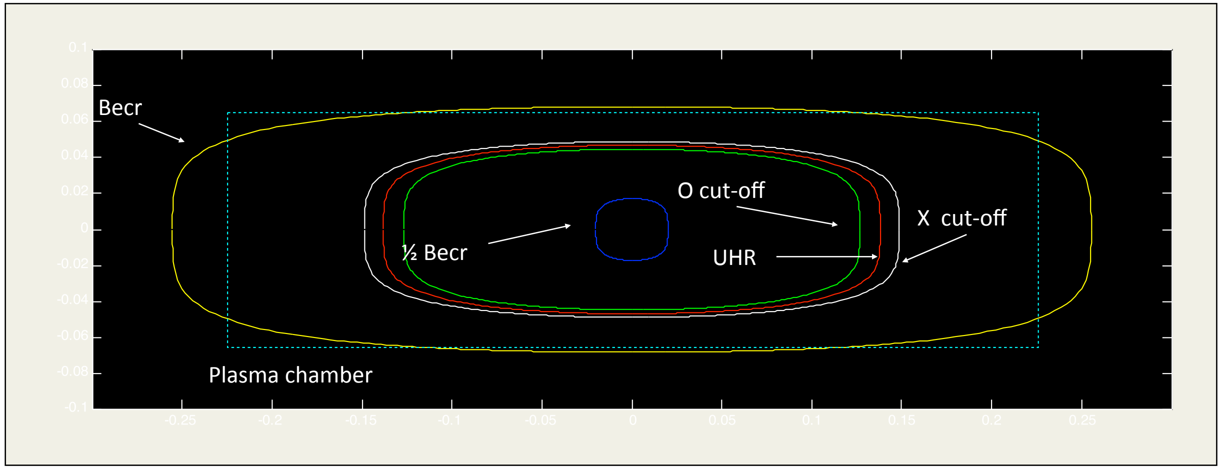
By decreasing the magnetic field below the ECR value the density becomes higher than the cutoff one.



The optimization of the OXB conversion helps to maximize the amount of RF power absorbed centrally, and then to further increase the density.

Central heating and electrostatic waves are mandatory for high density plasmas

The possible application of OXB on ECRIS-like devices



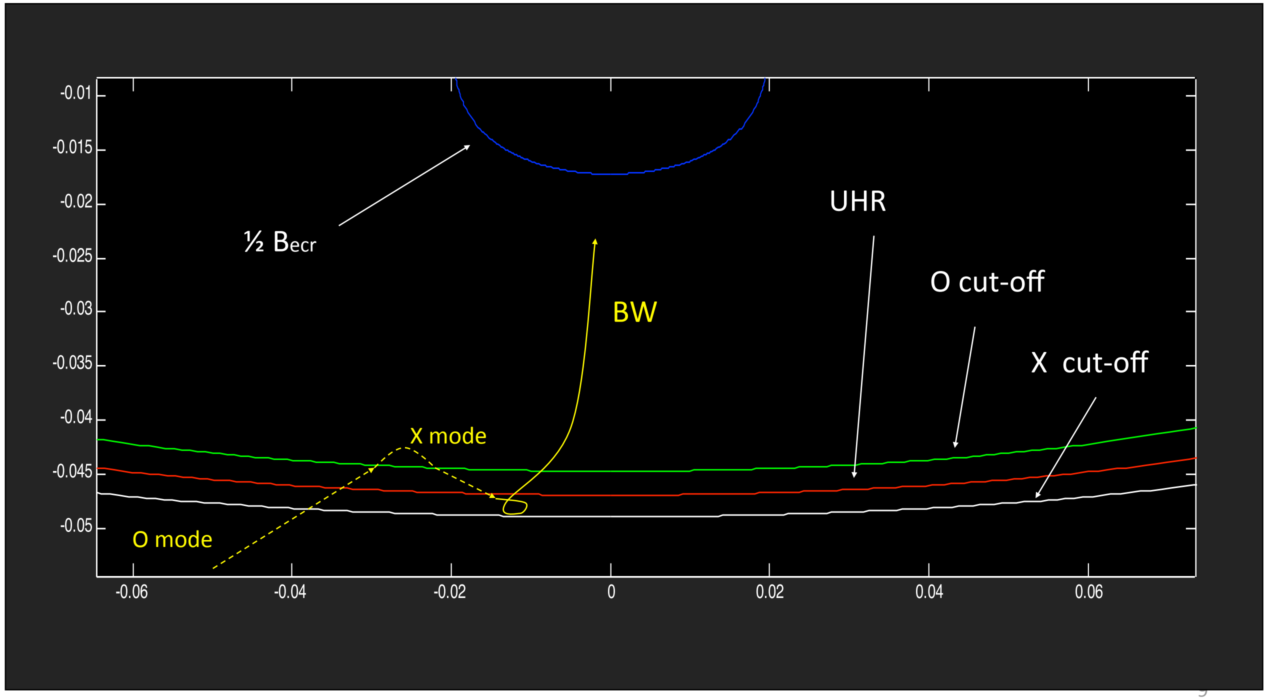
The ECR layer must be placed outside the chamber

In order to ensure that the peaked density profile is achieved self consistently the first ECR harmonic must be placed near the center of the chamber

The displacement of the various cutoffs and resonances must be proper to ensure the OXB conversion

The possible application of OXB on ECRIS-like devices

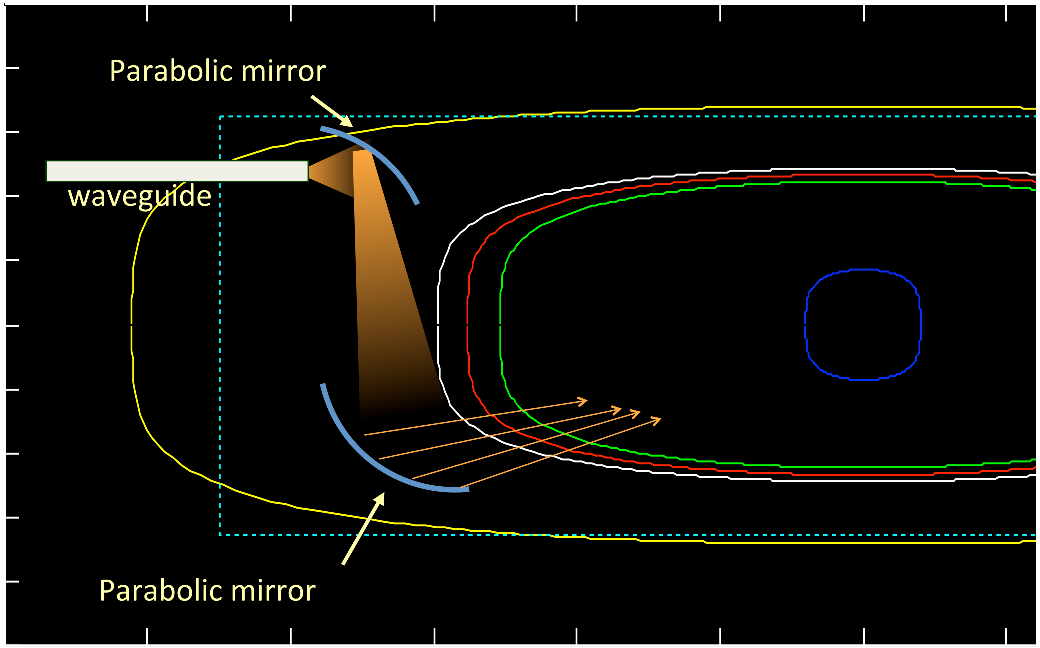
The path of the incoming wave and the nascent wave



The possible microwave injection scheme

2nd scenario

Double mirror system: focused beam



… & PERSPECTIVES

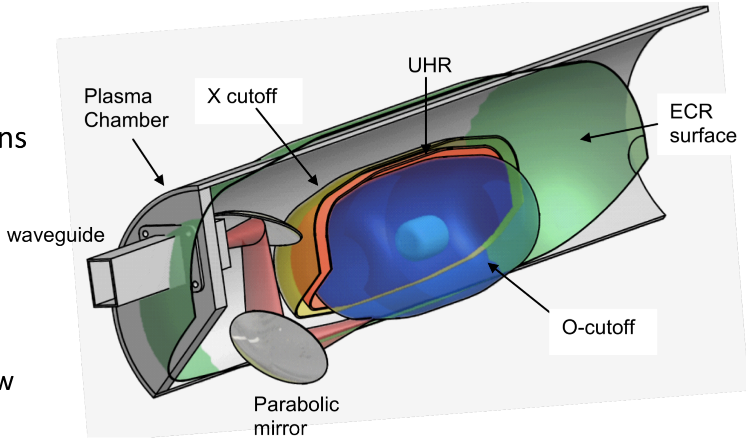
1. How to reduce the amount of hot electrons?

Boosting of stochasticity must be avoided (no UHR, short L, non-axis symmetric B field)!!

2. How to exploit mode conversion through EBW-H avoiding hot electrons production?

Low RF power and different B field profile.

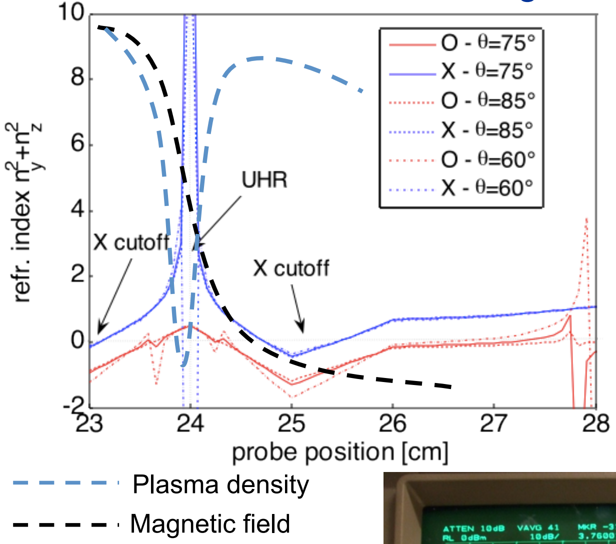
Plasma density boosting for relatively low RF power will permit to overcome ECRIS density limitations



[in collaboration with H. Laqua et al. MPI, Greifswald]

A novel design of the plasma chamber could permit to obtain EM standing waves having maxima in the near axis region (no hollow beams): better beam emittance and brightness.

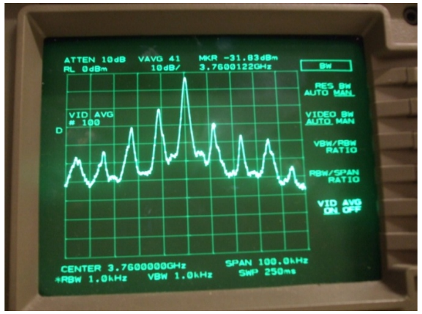
Generation of extremely overdense plasmas through EBW-heating in flat-B-field devices



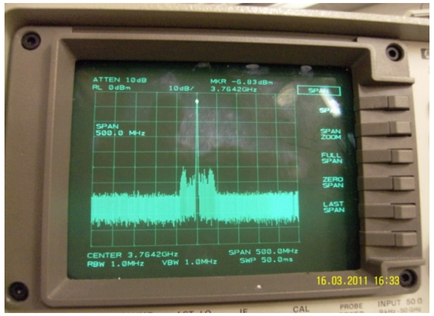
In the 3.76 ± 0.1 GHz, 7 resonant modes exist having r=5, 0< n,ν<2 (60° < θ < 80°).

Displacement of cutoffs and resonances for these modes is compatible with Budden-type mode conversion scenario

Sidebands are the fingerprint of EBW-generation!!



KHz sidebands



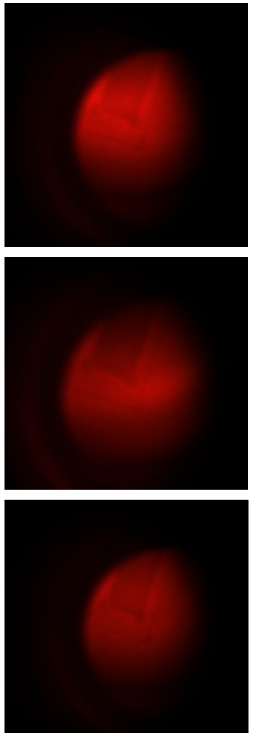
MHz sidebands

[D. Mascali et al. Nuclear Instruments and Methods A, in press]

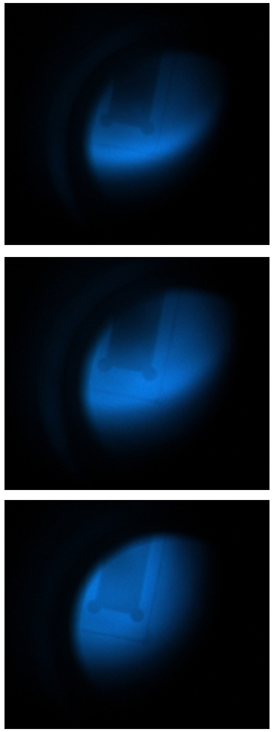
Spontaneous formation of a plasma hole

Rotating plasma and enhancement of ion transport

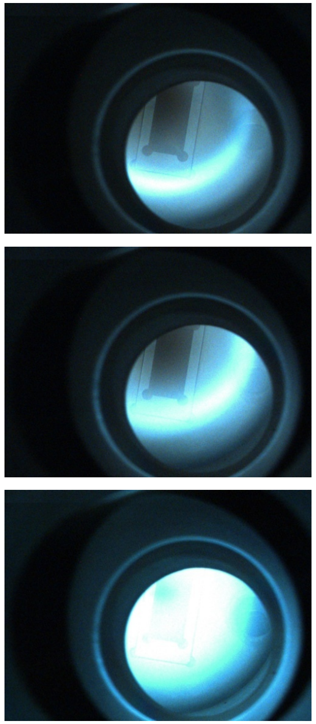
690nm; G= 620; Exp=1/9



470nm; G=620;Exp=1/30



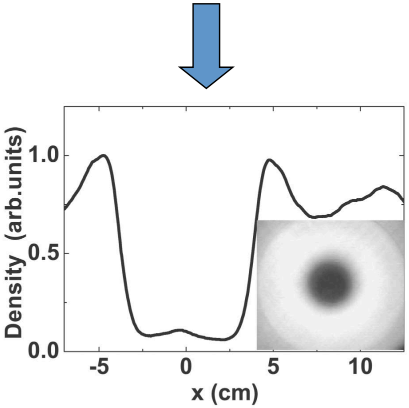
No filters



Neutrals   1+ Ions

Filters reveal that the ions are mostly concentrated around the hole.

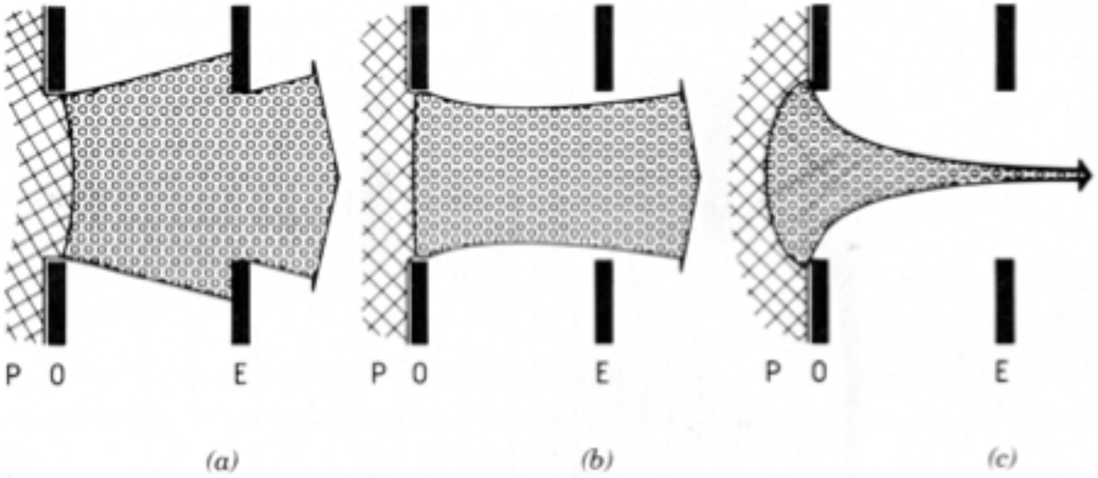
A similar structure was observed by Nagaoka et al. Phys. Rev. Lett. 89, 075001 (2002).



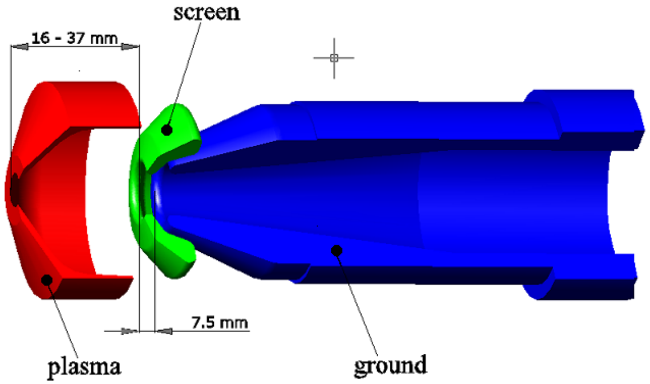
HCI Beam extraction

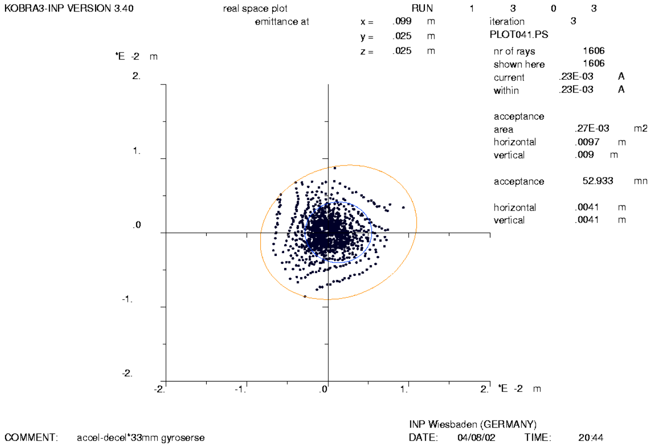
Impact on currents and emittance

Beam extraction

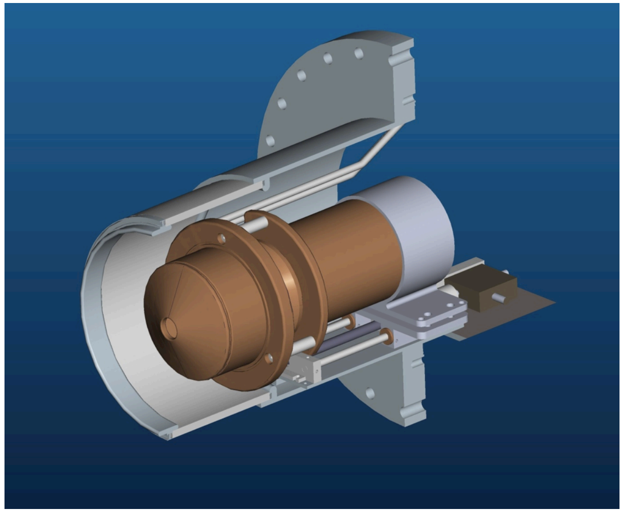


- Accel-decel extraction

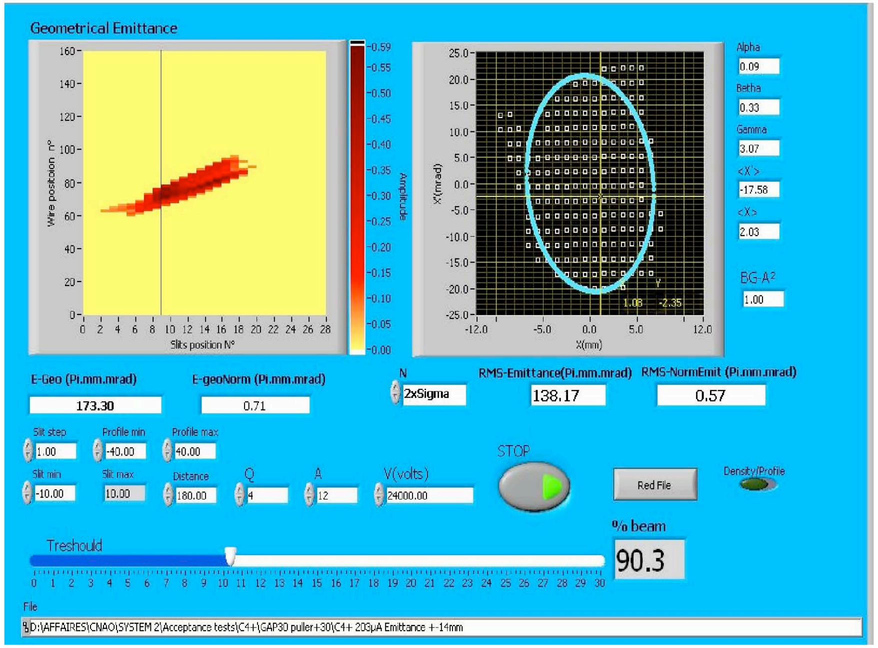



```
KOBRA3-INP VERSION 3.40          real space plot               RUN       1     3     0     3
                                      emittance at    x =  .099  m       iteration       3
                                                      y =  .025  m       PLOT041.PS
                                                      z =  .025  m        nr of rays      1606
                                                                          shown here      1606
                                                                          current     .23E-03   A
                                                                          within      .23E-03   A

                                                                          acceptance
                                                                          area          .27E-03    m2
                                                                          horizontal    .0097   m
                                                                          vertical      .009   m

                                                                          acceptance     52.933    mn

                                                                          horizontal    .0041   m
                                                                          vertical      .0041   m

                                                           INP Wiesbaden (GERMANY)
COMMENT:    accel-decel*33mm gyroserse                     DATE:    04/08/02      TIME:     20:44
```

In ECRIS, the hexapole field influences the structure of the extracted beam in real and phase space



Emittance pattern of an ECRIS beam



Alpha 0.09

Betha 0.33

Gamma 3.07

<X'> -17.58

<X> 2.03

BG-A² 1.00

E-Geo (Pi.mm.mrad) 173.30

E-geoNorm (Pi.mm.mrad) 0.71

N 2xSigma

RMS-Emittance(Pi.mm.mrad) 138.17

RMS-NormEmit (Pi.mm.mrad) 0.57

Slit step 1.00

Profile min -40.00

Profile max 40.00

Slit min -10.00

Slit max 10.00

Distance 180.00

Q 4

A 12

V(volts) 24000.00

Treshould 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

% beam 90.3

File D:\AFFAIRES\CNAO\SYSTEM 2\Acceptance tests\C4+\GAP30 puller+30\C4+ 203µA Emittance +-14mm

Figure 36: 12C^{4+} Emittance with the new gap.

Emittance for a typical C^{4+} beam

A suggestion

The performances of an ECR Ion source for multicharged ions with moderate intensity are not strongly dependent on the beam extraction system.
It is not the case for a high current ECRIS (ref. Chauvin's lecture).

ECR Ion sources for multicharged ions

Nomenclature

ECRIS: classification for "generations"

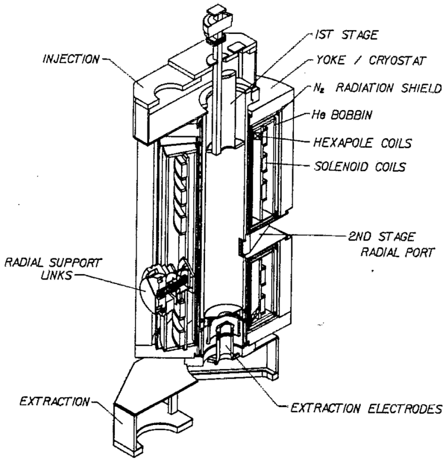
1st generation:
f=6-14 GHz, P=0.5 kW, I<mA, q=6-12 for Ar

→

2nd generation:
f=14-18 GHz, P=1-2 kW, I=1-2 mA, q=8-16 for Ar

→

3rd generation:
f=24-28 GHz, P=5-10 kW, I=20-40 mA, q=14-18 for Ar



SC-ECRIS, MSU-NSCL

SERSE, INFN-LNS

VENUS, LNBL-USA

The future challenges

The future challenges

- Higher charge states required for heavy ions;
- Higher intensities are required for q/m > 0.3;
- Better brightness;
- Improved stability (1% or better);
- Metallic species reproducibility;
- High charge breeding efficiency;
- High absolute ionization efficiency;
- Improvements on magnets and generator technology;
- New heating schemes?

4th generation:

f=56 GHz, P=20 kW, I=100 mA,
q=16-18 for Ar

Large X-ray production, magnets out of technology, excessive costs…?

Thanks for your attention