Alternative plasma heating schemes within the classical ECR-heating scenario

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Multi-frequency heating,
Broadband heating,
Phase relationship
1. Frequency tuning *(Gammino’s talk)*
2. Two Frequency Heating
3. Two Closed Frequency Heating
4. “Flat B Field” heating
5. “Broadband” heating

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**STRONG INCREASE OF THE HEATING RAPIDITY**

![Production of high energy electrons](image)

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**The TWO Frequency Heating effect: a long history**

1994 – First evidence of the TFH at LNBL, California

[Z. Q. Xie and C. M. Lyneis. Improvements on the LBL AECR Source. *in Proc. 12th Int. Workshop ECR Ion Sources, Tokyo, Japan, 1995.*]

CSD peak from 33+ to 36+ for $^{238}\text{U}$, current increased by a factor 2-4 for CS>35+

2002 – Observation of TFH on the SERSE source at INFN-LNS; first evidence of the importance of TWT also in case of TFH


3 eμA of Sn29+ were produced with two KLY (1.4 +1.0 kW) @ 14.5 and 18 GHz. The same current with TWT 8-18 GHz @ 200 W

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2001 – TFH on the SERSE source at INFN-LNS; first evidence of the importance of TWT also in case of TFH


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neither the relationship between the two frequencies nor the respective power was univocally determined.
Simulations’ Results for Single Frequency Heating

Plug-in & ECR plug Effect

The e.m. field allows to confine up to 40% of electrons that otherwise go away from the plasma.

Simulations’ Results for SFH

Power Saturation Effects

The electron energy tends to saturate for higher powers.

Heating process more difficult for higher powers:
- ECR zone crossing time is strongly reduced at higher energies
- Strongly confined electrons don’t reach again the ECR zone

The Power saturation value seems to depend on:

\[ E: \text{Electric Field at the resonance point.} \]
\[ \nabla B: \text{Magnetostatic Field Gradient} \]

STRONG GRADIENTS limit the maximum achievable energy per time unit, thus reducing the ECRIS potentiality.
Improvement of the electron heating
The possibility of Two Frequency Heating - TFH

Strong ECR plug effect and plug-in
Energy and “recovering mechanism” saturation with the RF power

plasma heating with two electromagnetic waves instead of one, by using two medium or low powers

possibility to optimize the plasma heating by efficiently transferring the electromagnetic energy

Electrons passing just one time across the resonance have a high probability to be strongly accelerated (the acceleration affects the perpendicular component of the velocity). Hence they are expelled by the loss cone and recovered by the electromagnetic field.
Simulations of the Two Frequency Heating

<table>
<thead>
<tr>
<th>Power Setting</th>
<th>Confined Fraction (%)</th>
<th>Mean Electron Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(14 + 18)GHz, (1000 + 300)W</td>
<td>38.2</td>
<td>1.9589</td>
</tr>
<tr>
<td>18 GHz, 2000 W</td>
<td>35.2</td>
<td>1.2612</td>
</tr>
<tr>
<td>18 GHz, 1000 W</td>
<td>19.2</td>
<td>1.0141</td>
</tr>
<tr>
<td>14 GHz, 300 W</td>
<td>12.9</td>
<td>1.5509</td>
</tr>
</tbody>
</table>

1. Strong increase of the confined fraction in the case of TFH;
2. Strong increase of the mean electron energy;
3. TFH @ 1300 W more efficient than Single Frequency Heating (SFH) @ 2000W;
4. Electron Energy for @ 300 W – 14GHz higher than @ 2000 W – 18 GHz.


The “idea” of the Two Close Frequency Heating Effect

Two contiguous resonance surfaces ensure a sort of “electron surfing” on the two heating frequencies if the phase relationship is proper

\[ \Delta \omega \equiv 1.4 \left( \frac{2k_z q}{m} \right) \left( \frac{c}{\omega} \right) \left( \frac{eE}{mc \omega} \right)^2 \left( \frac{eE}{m} \frac{\Delta B}{\Delta z} \frac{1}{B_{ECR}} \right)^3 \]

Frequency correlation

Phase dependence on microwaves power

\[ \Delta \phi \equiv \left( \frac{\pi}{2} - \text{const} \cdot \frac{\phi}{P} \right) \]

### The “new idea” of the Two Close Frequency Heating Effect: the simulation results

<table>
<thead>
<tr>
<th>$\Delta \theta$ [$^\circ$]</th>
<th>Confined Fraction</th>
<th>$E_{\text{final}}$ [keV]</th>
<th>$\Delta E/E$ [%]</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>0.916</td>
<td>4351</td>
<td>2.9</td>
</tr>
<tr>
<td>45</td>
<td>0.918</td>
<td>4815</td>
<td>13.9</td>
</tr>
<tr>
<td>80</td>
<td>0.907</td>
<td>4848</td>
<td>14.7</td>
</tr>
<tr>
<td>90</td>
<td>0.903</td>
<td>5045</td>
<td>19.3</td>
</tr>
<tr>
<td>100</td>
<td>0.894</td>
<td>4562</td>
<td>7.9</td>
</tr>
<tr>
<td>135</td>
<td>0.907</td>
<td>4383</td>
<td>3.7</td>
</tr>
<tr>
<td>180</td>
<td>0.920</td>
<td>4810</td>
<td>13.8</td>
</tr>
<tr>
<td>225</td>
<td>0.903</td>
<td>4703</td>
<td>11.2</td>
</tr>
<tr>
<td>270</td>
<td>0.908</td>
<td>5000</td>
<td>18.2</td>
</tr>
<tr>
<td>315</td>
<td>0.907</td>
<td>4934</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Energy increase for TCFH (500+500 W) with respect to SFH @ 1000 W.

Final Energy increases up to 30% in Three Close Frequency Heating.

Possibility to exploit wave-electron energy transfer by means of the Multi Frequency Heating.

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### Plasmas driven by Electrostatic Waves

Mode conversion and non-linear plasma heating in compact-size devices
The dispersion relation for the X wave is:
\[
\frac{c^2 k^2}{\omega^2} = \frac{c^2}{v_\phi^2} = 1 - \frac{\omega_{pe}^2}{\omega^2} \frac{\omega^2 - \omega_{uh}^2}{2}
\]

with:
\[
\omega_{uh} = \omega_{pe} + \omega_{ce}
\]
Upper hybrid frequency
\[
\omega_{pe} = (n_e e^2 / m_e e_0)^{1/2}
\]
Plasma frequency

X waves are partially reflected and partially tunnel the R and L cutoffs
\[
\omega_L = \frac{1}{2} \left( \omega_{ce} + \sqrt{\left(\omega_{ce}^2 + 4\omega_{pe}^2\right)^2} \right),
\omega_R = \frac{1}{2} \left( -\omega_{ce} + \sqrt{\left(\omega_{ce}^2 + 4\omega_{pe}^2\right)^2} \right)
\]

If the UHR layer is embedded by to cutoffs then the X wave rebounce between them and adopts a standing wave behaviour.

At the UHR most of the X wave electric field is directed longitudinally to the wave vector \( k \), thus exciting electrostatic wave oscillations.

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

Assuming that the electromagnetic wave has an even small, but still non negligible, \( k \) component oriented perpendicularly to the B field (oriented along the z axis), we can calculate the electric field of the X wave at the UHR.

It can be shown from the Maxwell equations that:
\[
[\omega^2 - \omega_h^2] E_x + \frac{\omega_{pe} \omega_{ce}}{\omega} E_y = 0
\]
which at the UHR, where: \( \omega = \omega_{uh} \) becomes:
\[
E_y = 0 \Rightarrow \vec{E} = E_x \hat{x}
\]
Since we assumed \( B \) directed along \( z \), and the \( k \) vector of our interest as: \( \vec{k} = k_x \hat{x} \)

the wave becomes purely electrostatic, and since it propagates perpendicularly to the magnetic field it takes the name of Bernstein electrostatic plasma wave

\[
C = C_{\text{max}} \cos^2 \left( \frac{\phi}{2} + \theta \right), \\
C_{\text{max}} = 4e^{-\pi \eta} (1 - e^{-\pi \eta}) \\
L_B \gg L_n \\
\eta \approx \frac{\omega_c L_n}{c \alpha} \left[ \sqrt{1 + \alpha^2} - 1 \right]^{1/2}
\]
with \( \alpha = \left( \frac{\omega_p}{\omega_c} \right)_{\text{UHR}} \)

Phase term modulated by \( C_{\text{max}} \)
Plasma Heating at B<B_{ECR}: generation and absorption of BW

The X wavelength approaches the BW wavelength at the UHR, and a forward and backward propagating BW is generated.

The BW dispersion relation predicts a resonance at the harmonics of Electron Cyclotron frequency, and a wave cutoff at UHR.

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

Mode conversion takes place when the incident EM-X wave encounters the UHR layer, where it is in spatial and temporal resonance with the nascent EB mode.

Dispersion relation for EBW

When: $B = \frac{1}{m} \frac{q}{e} \omega_{RF}$, $q=1,2,...,n$ (cyclotron harmonics) this term approaches zero and electron Bernstein waves can be absorbed by the plasma.
Experimental apparatus for mode conversion detection

- H-Ge X-ray detector
- 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: 4 mm length, 0.15 mm diameter
- Optical window for direct observation of plasma
- Hall probe for measurement of the magnetic field
- Microwave line with insulator
- Pressure gauge
- Microwave probe
- Permanent magnet
- Vacuum gauge flange
- Pumping system
- WR284 waveguide port
- Coaxial connector
- Optical window
- Mass spectrometer
- Langmuir probe
- Optical window for direct observation of plasma

Set-up for X-ray spectroscopy and CCD imaging

Positioning of the CCD for the pass-band filters measurements (plasma imaging).
Experimental apparatus for testing Mode Conversion

1. Electron Density measurements show that the plasma is largely overdense everywhere above 70-80 W of power either at 2.45 and 3.76 GHz!!

Plasma density @ 2.45 and 3.76 GHz measured by ES probe

![Graph showing plasma density at 2.45 GHz and 3.76 GHz](image)

Enhancement of plasma density of one order of magnitude at the 1st harmonic of the cyclotron field!!
1. **Experimental Results @ 2.45 GHz and 3.76 GHz collected with electrostatic probe**

Change of the plasma density shape with the frequency!!!

The plasma density is peaked at the relative 1st harmonic of the two frequencies. The peak position changed with the frequency, confirming that the mode conversion is “frequency sensitive”.

The non parallel component of the k vector with respect to B is in fact provided by the resonator!!

1. **Values up to 10 times the cutoff density have been measured!!!**

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CERN Accelerator School and Slovak University of Technology, Senec, June 2012
L. Celona, Alternative heating schemes

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**X-ray spectra during EM-ES conversion**

1. **Boost of X-ray energy** for low pressures;

2. The plasma exhibits a **threshold-like behavior**: at 1.5E-4 mbar **hot electrons are generated** for \( P_{rf} > 80 \, \text{W} \);

3. In the same RF power domain, a **plasma hole appears** and it is observable in the visible range.
Spontaneous formation of a plasma hole

Rotating plasma and enhancement of ion transport

No filters

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).

CCD imaging during plasma startup at different $P_{RF}$

The formation of the overdense plasma, which takes to strong X-ray emission and electromagnetic spectral broadening, also causes a marked change in plasma shape.

PLASMA HOLE FORMATION

Increasing power
Electromagnetic wave absorption at pp=24 cm is a clear sign of mode conversion

Estimated theoretical trend of the electromagnetic field strength in the area which surrounds pp=24 cm

Unfavorable condition for X-B conversion because of the low power density associated to the EM wave

Electromagnetic wave measurements show that:

1. The EM forms a standing wave inside the resonator although the presence of an absorbing mean like the high density plasma

2. The EM is partially absorbed at pp=24 cm and no other layers of EM to plasma energy transfer are evident

3. The EM-ES conversion at 24 cm is critical because the detected EM power oscillates strongly

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
Details about direct X-B conversion inside the Plasma Reactor

Unfavorable condition for X-B conversion because of the low power density associated to the EM wave

Critical but favorable configuration of plasma density for sustaining the X-B conversion at UHR

Upper Hybrid Resonance

X-L cutoffs

The wave rebounce between the two X-L cutoff being absorbed and converted to BW at UHR

Additional proofs of X-B mode conversion and plasma heating through BW

1. Spectrum analyzer measurements at 24 cm put in evidence the existence of non linear effects typical of X-B conversion, which leads to the formation of sidebands in EM spectrum

2. Sidebands disappear far away from 24 cm position

Δν ≈ 10 kHz
BOOSTING OF EBW-heating to overcome density limitations

Measurements with the Plasma Reactor @ LNS already showed the formation of an overdense plasma in case of UHR active inside the chamber and EBW absorption in higher harmonics of the cyclotron field.

Generation of overdense plasma when $f=3.76$ GHz, with $2\pi/(qB_{\text{max}})/m$

Overdense plasma is generated over a wide plasma chamber volume thanks to BW generation at 3.76 GHz of pumping frequency.

The UHR is accessible through the tunneling of the X cutoff. The wave encounters the UHR and it is there converted.

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