Imaging in X-ray ranges to locally investigate the effect of the two-close frequency heating in ECRIS plasmas

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Outline

• Introduction:
  • Two frequency heating
  • Instability

• Experimental setup
  • Atomki ECRIS
  • Diagnostics tools
  • Simulation tool

• Experimental results

• Comparison: simulation vs. experiment
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Introduction (TFH)

Two far frequencies
(df > 1 GHz)


Two close frequencies
(df < 1 GHz)


Introduction (Instability)


Introduction (Instability and TFH)

Two far frequency heating


Two close frequency heating (TCFH)


Termination of beam current oscillation

Drop of Is (Instability strength) calculated from the RF self emission of the plasma
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Experimental setup

Atomki ECR laboratory

- Permanent magnet hexapole and room temperate coils
- No post acceleration
- Used for atomic physics, material science, ECR plasma physics

14 GHz ECRIS

Becr(14.25GHz) = 0.51T

B_{min} / B_{ecr} \approx 0.76
Experimental setup (coupling of TCF)

- Two frequency coupling
- df~1GHz is limited by the TWTA
- Net power measurements
- $B_{\text{min}}/B_{\text{cr}} = 0.75 \ldots 0.8$

**Sweep oscillator**
- HP8350B mf.
- HP83590A pi.
- $df = 2-20\ \text{GHz}$

**TWTA**
- $P = 500\ \text{W}$
- $df = 13.6-14.6\ \text{GHz}$

**Circulator (WR62)**
- $df = 12.5-18\ \text{GHz}$
- $P_{\text{max \ forw.}} = 650\ \text{W}$
- $P_{\text{max \ refl.}} = 80\ \text{W}$

**Power Meter 8481 A**
- $P_{\text{max}} = 100\ \text{mW}$

**Power Meter 8481 B**
- $1\ \text{mW} - 25\ \text{W}$

**HV Window**
- $df = 12.4-18\ \text{GHz}$
- $P_{\text{max}} = 1000\ \text{W}$

**Klystron**
- $P = 1000\ \text{W}$
- $f = 14.25\ \text{GHz}$

**Combiner**
- $13.5-15.6\ \text{GHz}$

**Phase shifter**
- $20\ \text{dB Cross guide (WR62)}$

**Direct frq. measurements by Spectrum Analyzer**
- $14.45\ \text{GHz}$

**14.25 GHz KLY**

**14.45 GHz TWT**
Experimental setup (diagnostics tools)

- Spectrum Analyzer
- Plasma electrode
- Hexapole
- Coils
- Plasma
- Limiting
- Two pins
- RF probe
- X-ray camera
- Al mesh
- Pinhole and collimators
- X-ray camera coupled to pinhole
- Spectrum Analyzer

Image of experimental setup with labeled components and additional images of diagnostic tools.
Data from spectrum analyzer

Spectrum Analyzer

RF Spectra at 14.25 GHz

![RF Spectra at 14.25 GHz](image)

- Power (dBm)
- Frequency (MHz)

Spectral properties of the RF

Quantitative estimation on the strength of the instability

Impact of two-close-frequency heating on ECR ion source plasma radio emission and stability

E Naselli, D Mascali, M Mazzaglia, S Biri, R Rácz, J Pálinkás, Z Perdik, A Galata, G Castro, L Celona, S Gammino and G Torrisi
Data from spectrum analyzer

Stable plasma

Instability strength ($I_s$):
- Total power emission toward the probe (except the main peak)
- Number of the subharmonics

Higher power – stronger instability

$$I_s = \left( \int_{13\,\text{GHz}}^{15\,\text{GHz}} \frac{dP(f)}{df} \, df - P_{mp} \right) \left( 1 + w (N_{sub} - 1) \right)$$
Data from X-ray pinhole camera

Magnification: 0.244
Multi disks collimator
High resolution: 1024*1024
Energy range: 500 eV – 20 keV

Counts \sim \sum [n_i \cdot E_i]

We can measure the energy content

We can see

Losses at the lateral wall of the plasma chamber

Plasma emission

Extraction hole

Losses at the plasma electrode
Numerical simulation, TrapCAD

- single electron code
- electron–cyclotron-resonance process is calculated
- RF field, plane wave approximation
- realistic magnetic field configuration
- integration of the magnetic field line equation: 4th-order Runge-Kutta method
- Lorentz force integration: time-centered leapfrog scheme
- time-step: 3ps.
Data from TrapCAD

Initial conditions of the simulated electrons:
Number of the simulated electrons: 100,000
Initial position of the plasma electrons: randomly started from the resonant zone
Initial energy of the electrons: both parallel and perpendicular 1- 10 eV
RF power: 200 W
Simulation time: 200 ns

Single frequency runs: f = 18 GHz – 11 GHz \( \rightarrow \) \( B_{\text{min}}/B_{\text{ECR}} = 0.6 – 0.9 \)

We can obtain the final:

Average Energy ( \( \text{par} \parallel, \text{perp} \perp \))

Energy distribution

Velocity anisotropy
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Experimental results

Plasma was optimized for middle charged Ar ion production

Characterization of the source:

**SFH**: frq scan by TWT; 13.6 GHz – 14.6 GHz, df = 50 MHz, \( P_{\text{net}} = 200\, W \)

**TCFH**: frq scan by TWT; 13.6 GHz – 14.6 GHz, df = 50 MHz, \( P_{kly} = 80\, W, P_{TWT} = 120\, W \)

B_{\text{min}}/B_{\text{ecr}} is changed from 0.75 to 0.8 by changing \( B_{\text{ecr}} \)

- RF spectra
- X-ray plasma image
- Strength of Instability
- Plasma structure
Instability strength vs Bmin/Becr

Definite drop of the Is at TCFH

Instability strength as function of the applied frequency in single and in two frequency operation mode.

Example 13.9 GHz

The combination of two frequencies is in this case more stable than a single one, even if the power is increased by almost a factor of two.
RF spectral changes

**Spectral structure of the self-emitted radiation**

- **Single**
  - the emission occurs at frequencies lower than the lowest of the two pumping frequencies

- **Double**
  - The plasma density distribution is rearranged; becoming denser in the central region (where the B-field is lower)
Plasma images vs Bmin/Becr

Selection of those images where the instability is pronounced at single frequency heating &

The instability is damped effectively

- 13.6 GHz
- 13.8 GHz
- 13.85 GHz
- 13.9 GHz
- 14 GHz
- 14.05 GHz

SFH

TCFH
Structural changes

Selection of ROIs
Center and side regions

Centralization parameter

If the instability is effectively damped by the second frequency:

- the plasma is rearranged to be denser in a central region of the plasma
- this observation is in good agreement with the tendency obtained from the RF spectra
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Comparison of experimental results and simulation

Simulation: at same net power, the anisotropy and the average energy decrease at TCFH mode

Experiment: The plasma becomes more centralized and the instability is damped

Based on the good agreement between exp. and sim., two additional simulations were done:

- In TCFH at higher total net powers
- The power for both frequencies was increased in parallel (+10 W +10 W and +20W + 20W)

In principle possible to increase the average energy of the electrons (even above the energy corresponding to 13.9 GHz) and maintain anyway the anisotropy at low level.
Summary

- Effect of the TCFH to the plasma was studied experimentally and by simulation tool

- Instability strength and anisotropy decrease by applying two frequency heating

- Instability is effectively damped → the structure of the plasma changes remarkably: it becomes more centralized

- Sim vs. Exp: TCFH extends the operation conditions (possible usage of higher RF power) vs SFH mode