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

atomki DEBRECEN

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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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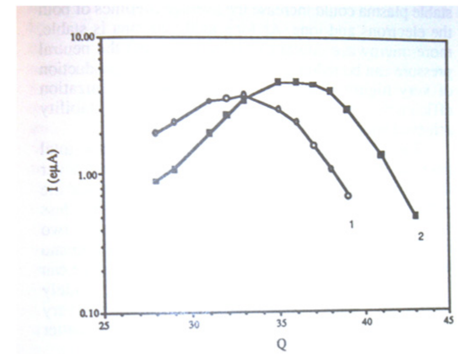
Introduction (TFH)

Two far frequencies (df > 1 GHz)

Z. Q. Xie and C. M. Lyneis, “Improvements on the LBL AECR Source,” in Proc. 12th International Workshop on ECRIS, Tokyo, Japan, April 1995, pp. 24-28

S. Gammino, et. al., “18 GHz upgrading of the superconducting electron cyclotron resonance ion source SERSE,” Rev. Sci. Instrum., vol. 70, no. 9, p. 3577, Sep. 1999

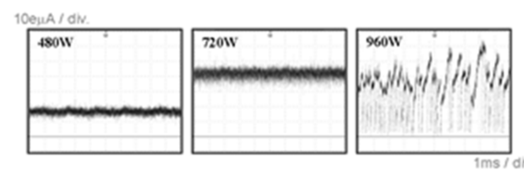


CSD shift

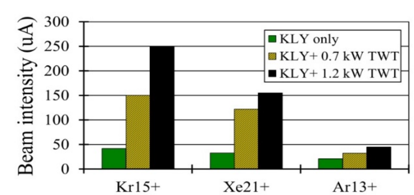
Two close frequencies (df< 1GHz)

A. Kitagawa, et al., “Two-Frequency Heating Technique for Stable ECR Plasma”, *in Proc. 20th International Workshop on ECRIS*, Sydney, Australia, Sep. 2012, pp. 10-12

S. Biri, et al., “Two Frequency heating technique at the 18 GHz NIRS-HEC ECR ion source”, Rev. Sci. Instrum. vol. 85, p. 02A931, Dec. 2013



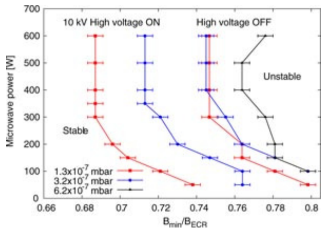
temporal instability at high power



New records with two close frequencies

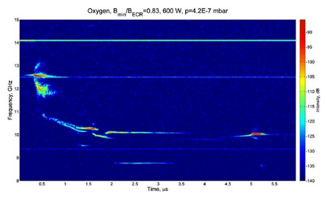
Introduction (Instability)

O. Tarvainen, et al., “Beam current oscillations driven by cyclotron instabilities in a minimum-B electron cyclotron resonance ion source plasma” Plasma Sources Sci. Technol. vol. 23, p. 025020, April 2014



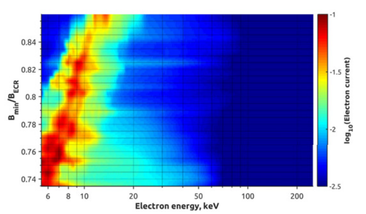
Instability threshold

I. Izotov, et al., “Microwave emission related to cyclotron instabilities in a minimum-B electron cyclotron resonance ion source plasma” *Plasma Sources Sci. Technol*. vol. 24, p. 045017, July 2015



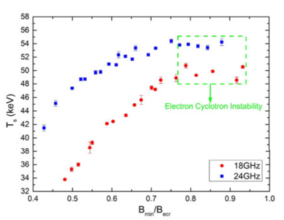
Microwave emission

I. Izotov, et al., Measurement of the energy distribution of electrons escaping minimum-B ECR plasmas
Plasma Sources Sci. Technol. 27 (2018) 025012



EEDF shift of lost electrons

J. B. Li, Effects of magnetic configuration on hot electrons in a minimum-B ECR plasma, Plasma Phys. Control. Fusion 62, 095015 (2020)



Saturation of spectral temp.

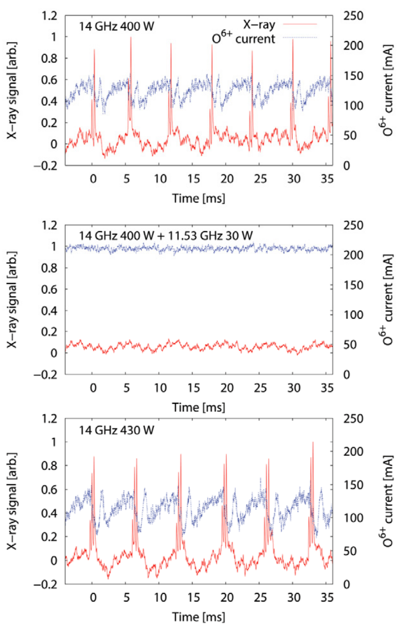
Introduction (Instability and TFH)

Two far frequency heating

V. Skalyga, et al., Suppression of cyclotron instability in Electron Cyclotron Resonance ion sources by two-frequency heating, Physics of Plasmas 22, 083509 (2015)

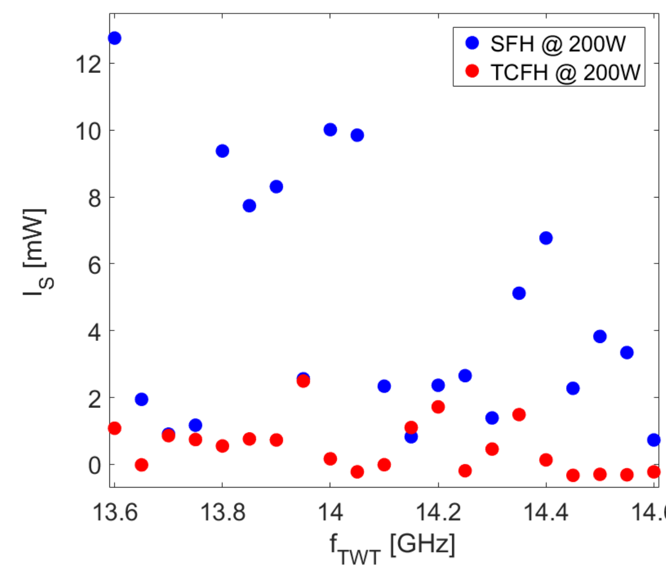
Two close frequency heating (TCFH)

E. Naselli, et al., Impact of two-close-frequency heating on ECR ion source plasma radio emission and stability Plasma Sources Sci. Technol. 28 (2019) 085021



Termination of
beam current oscillation

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



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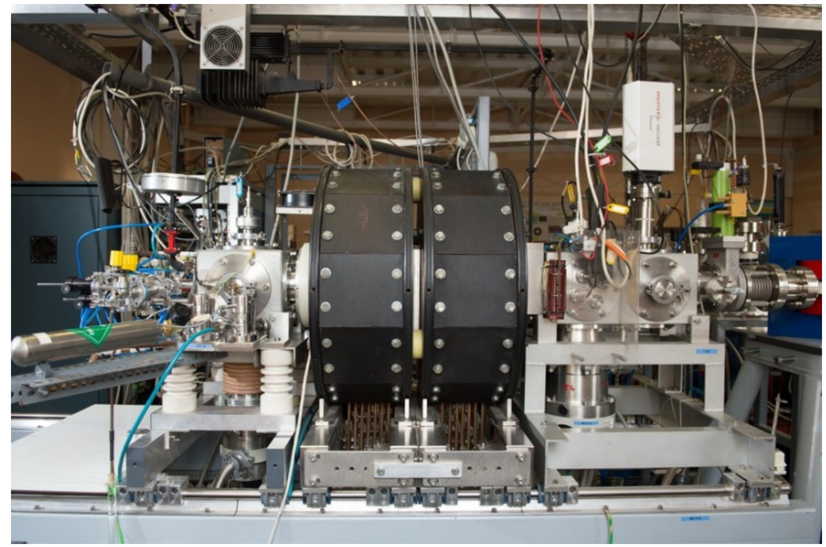
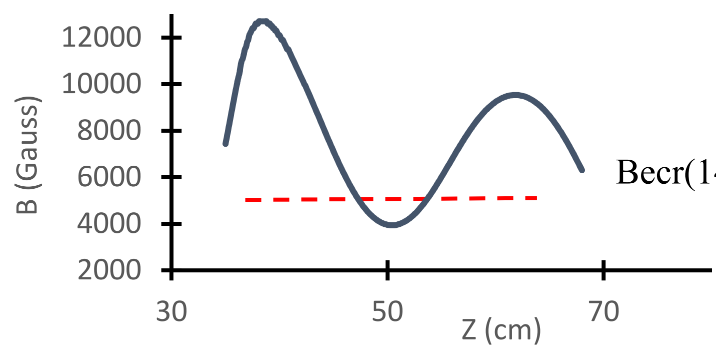
Experimental setup

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



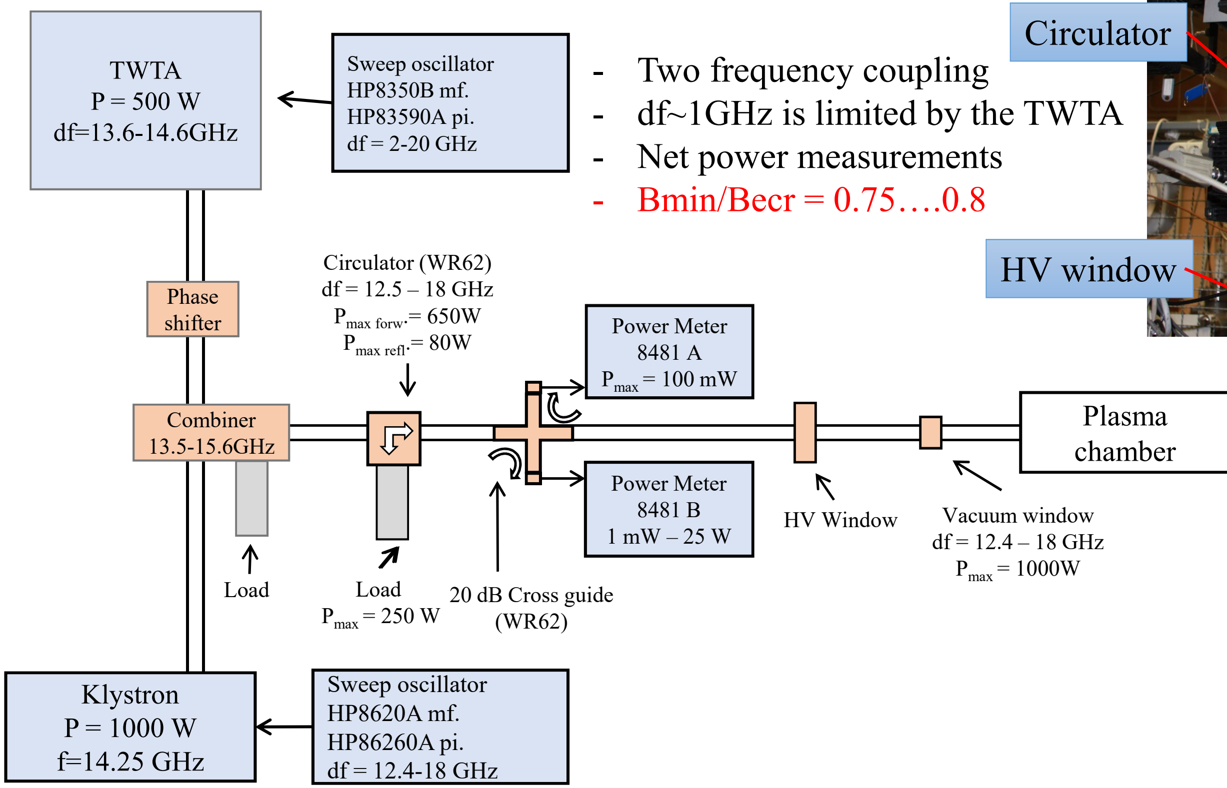


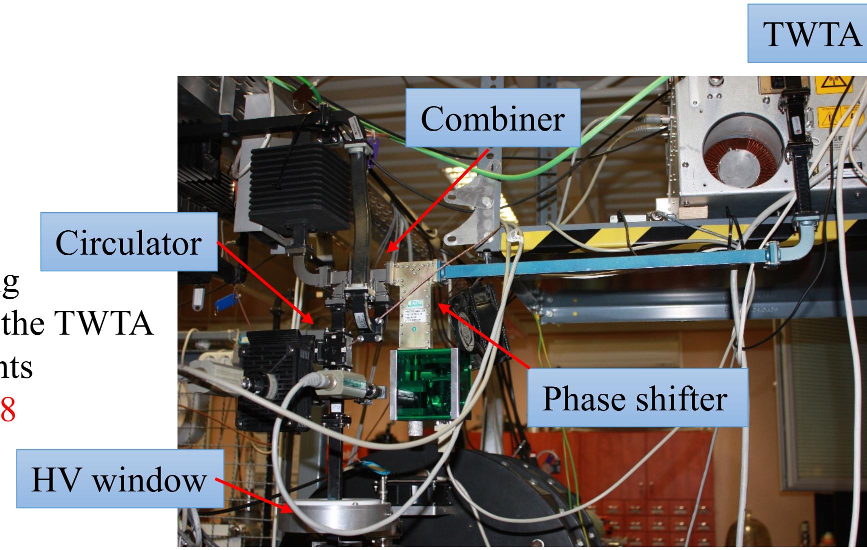
Becr(14.25GHz)=0.51T

$$\frac{B_{min}}{B_{ecr}} \sim 0.76$$

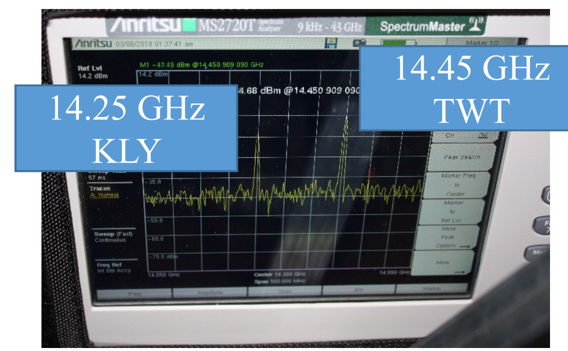
Experimental setup (coupling of TCF)

- Two frequency coupling
- df~1GHz is limited by the TWTA
- Net power measurements
- Bmin/Becr = 0.75….0.8

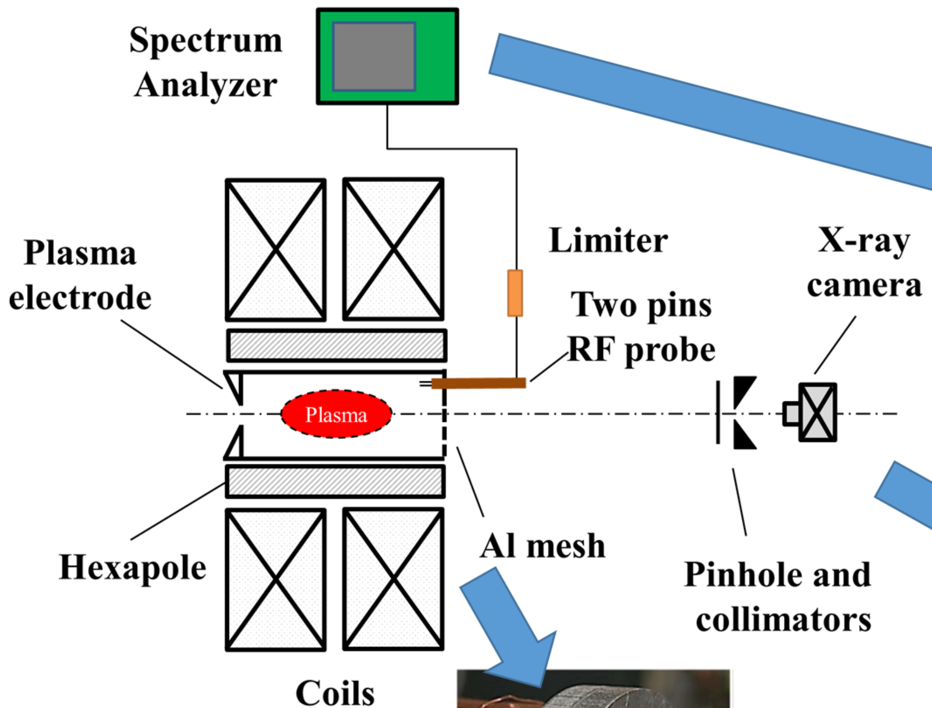


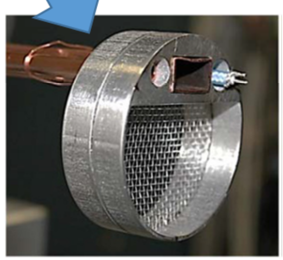


Direct frq. measurements by Spectrum Analyzer



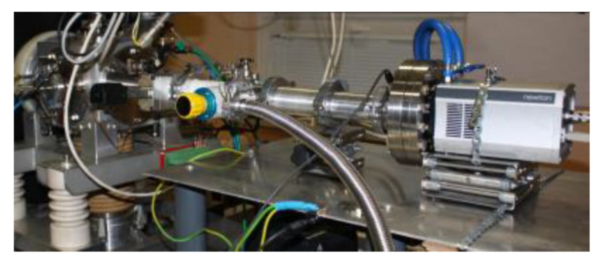
Experimental setup (diagnostics tools)



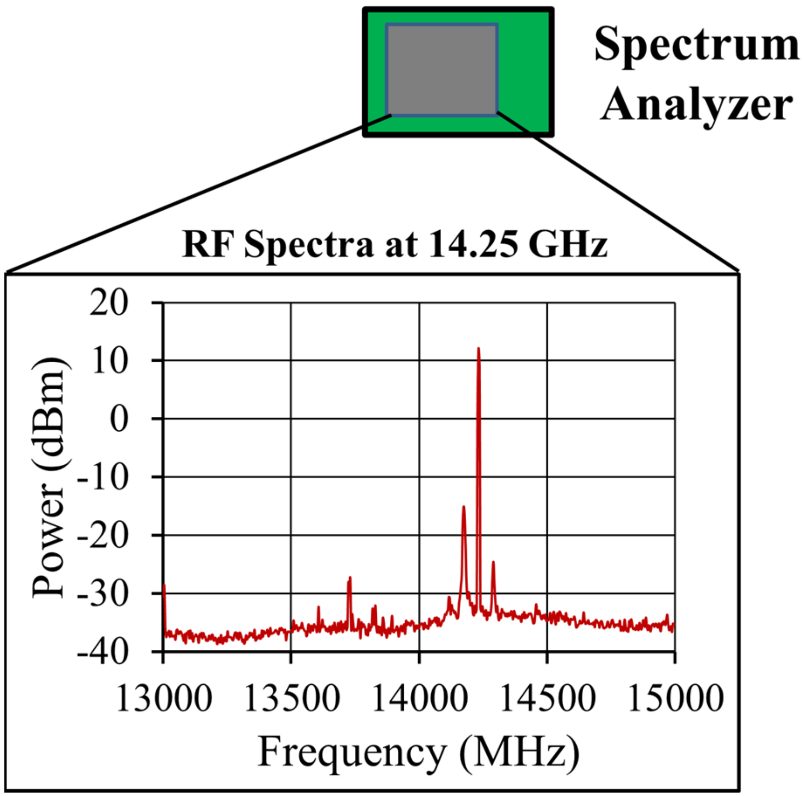


Spectrum Analyzer

X-ray camera coupled to pinhole



Data from spectrum analyzer



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

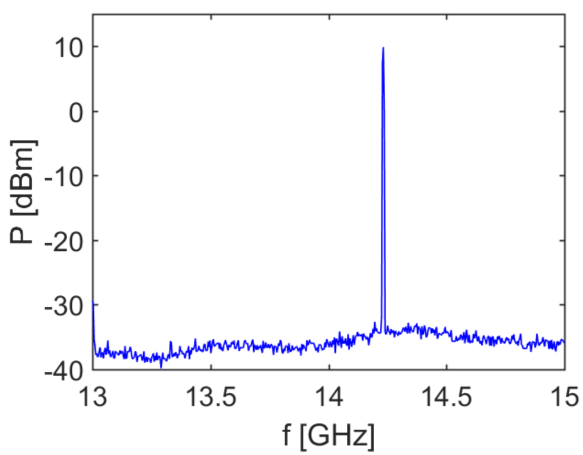
E Naselli[1,2], D Mascali[1], M Mazzaglia[1], S Biri[3], R Rácz[3], J Pálinkás[3], Z Perduk[3], A Galatá[4], G Castro[1], L Celona[1], S Gammino[1] and G Torrisi[1]

Spectral properties of the RF

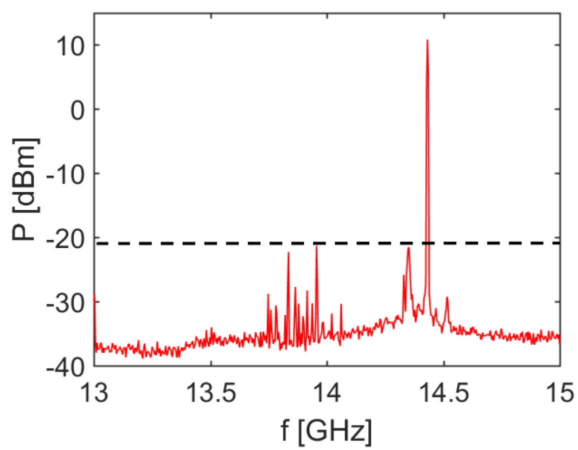
Quantitative estimation on the strength of the instability

Data from spectrum analyzer

Stable plasma



Unstable plasma

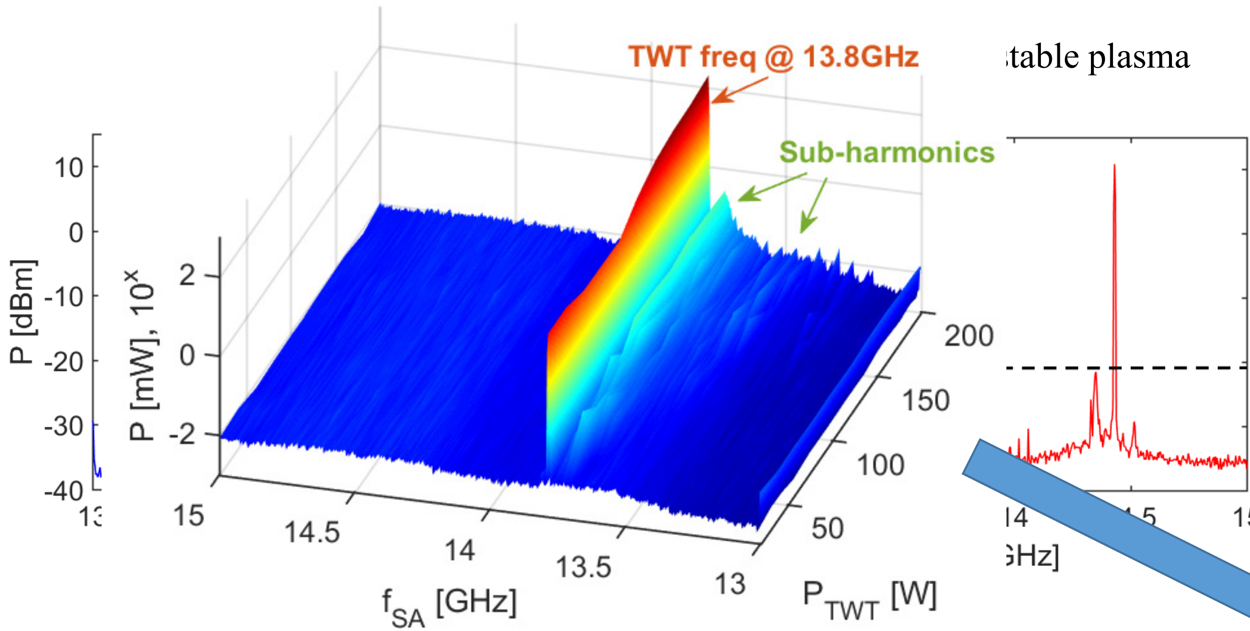


Instability strength (Is):

- Total power emission toward the probe (except the main peak)
- Number of the subharmonics

$$I_{\mathrm{S}} = \left(\int_{13\mathrm{GHz}}^{15\mathrm{GHz}} \frac{\mathrm{d}P(f)}{\mathrm{d}f} \mathrm{d}f - P_{\mathrm{mp}} \right) (1 + w(N_{\mathrm{sub}} - 1))$$

Data from spectrum analyzer



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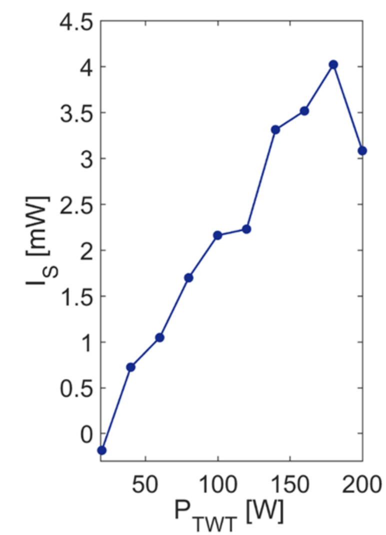

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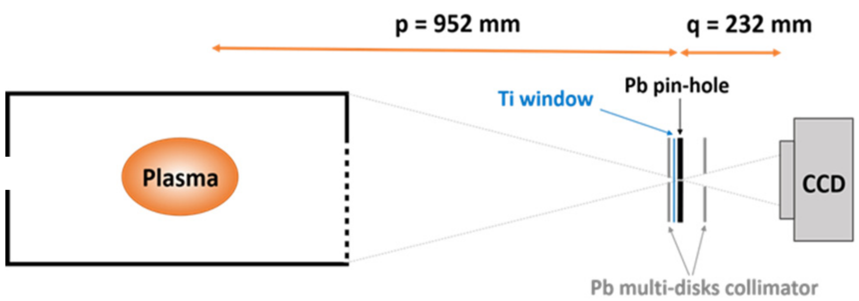
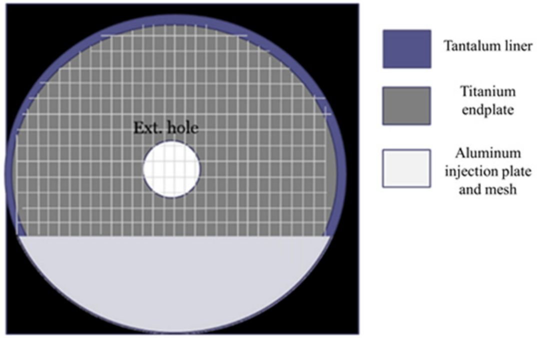
Higher power – stronger instability

Data from X-ray pinhole camera



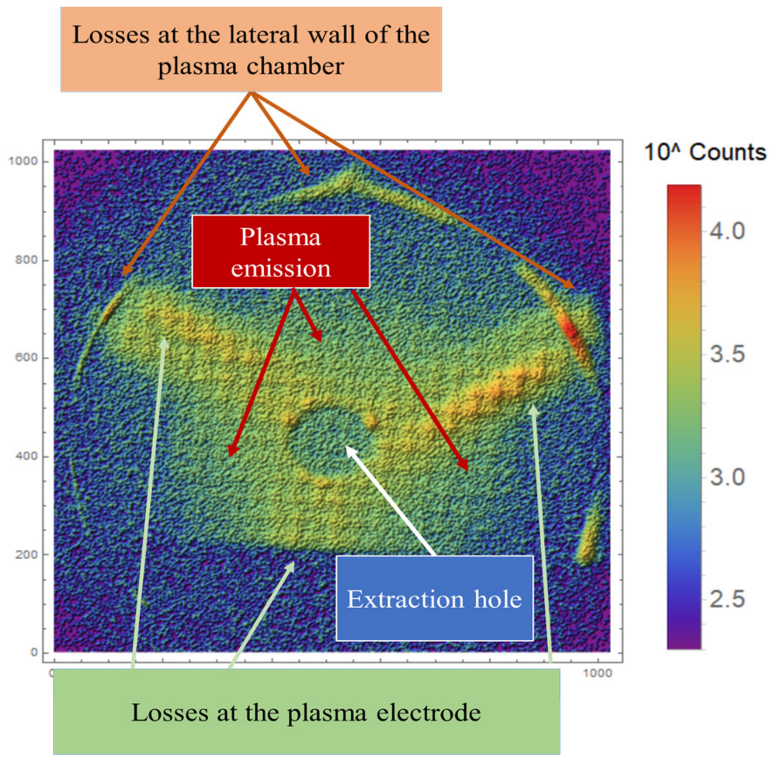
Injection plate



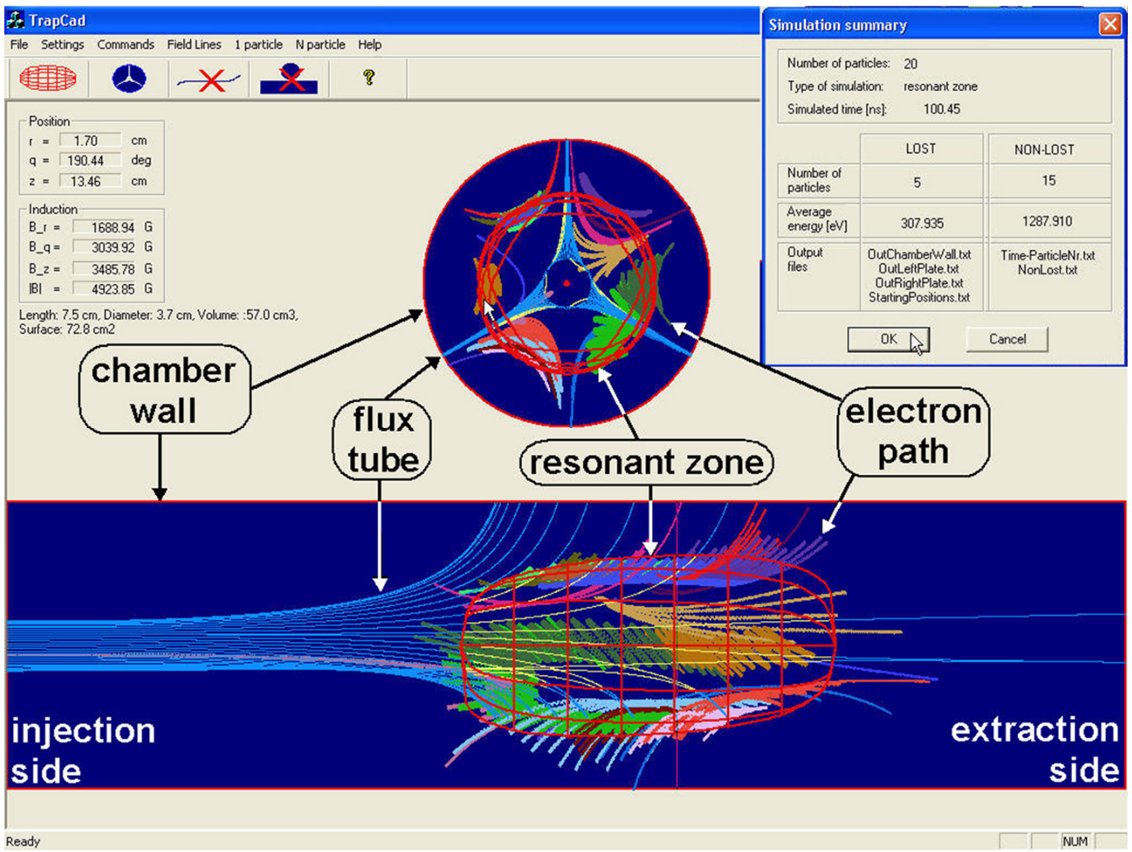
Magnification : 0.244
Multi disks collimator
High resolution: 1024*1024
Energy range: 500 eV – 20 keV

We can measure the energy content
Counts ~ Sum [ni * Ei]

We can see



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

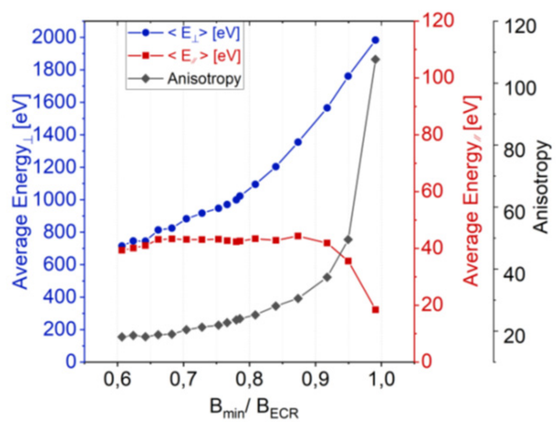
Single frequency runs: f = 18 GHz – 11 GHz → Bmin/Becr= 0.6 – 0.9

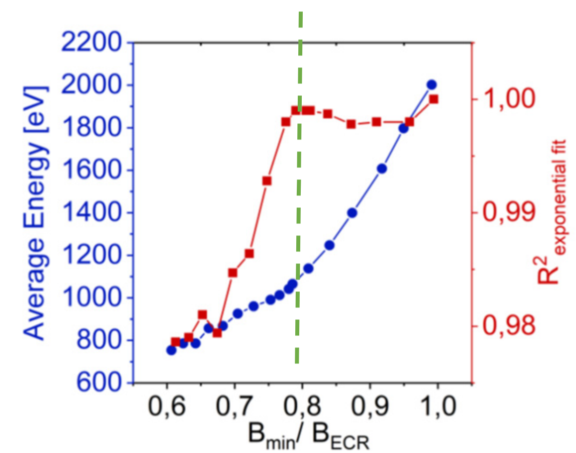
We can obtain the final:

Average Energy (par ∥ $, perp$ ⊥)

Energy distribution

Velocity anisotropy





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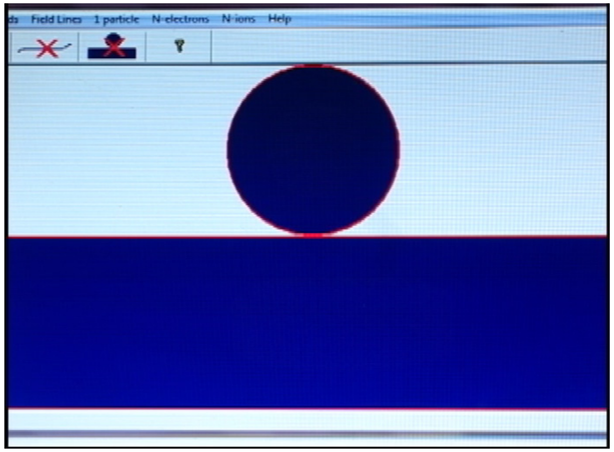

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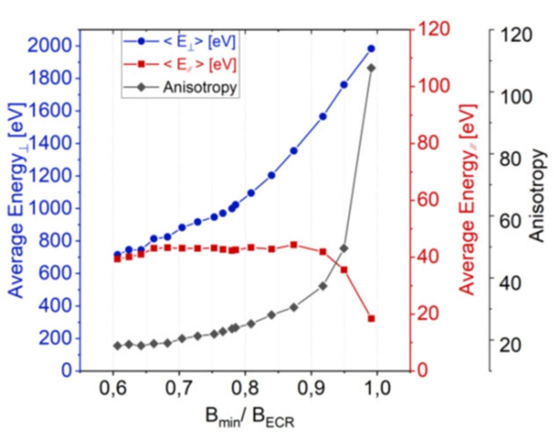

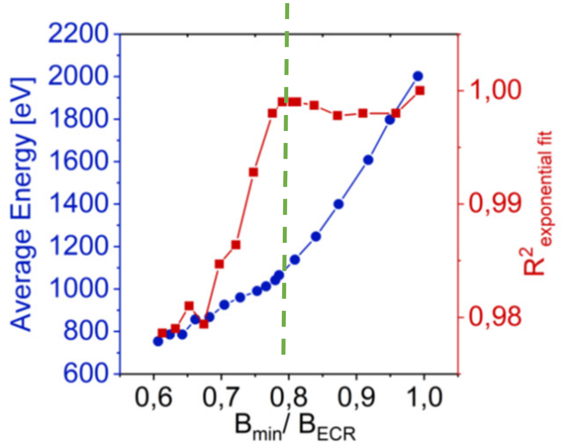

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Experimental results

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, $P_{net} = 200W$

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

Bmin/Becr is changed from 0.75 to 0.8 by changing Becr

RF spectra

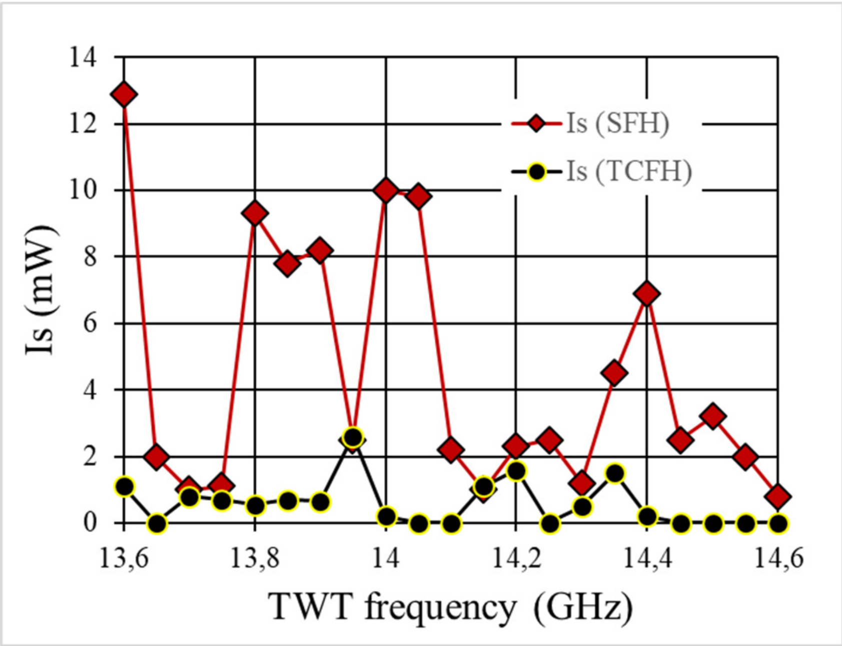
X-ray plasma image

Strength of Instability

Plasma structure

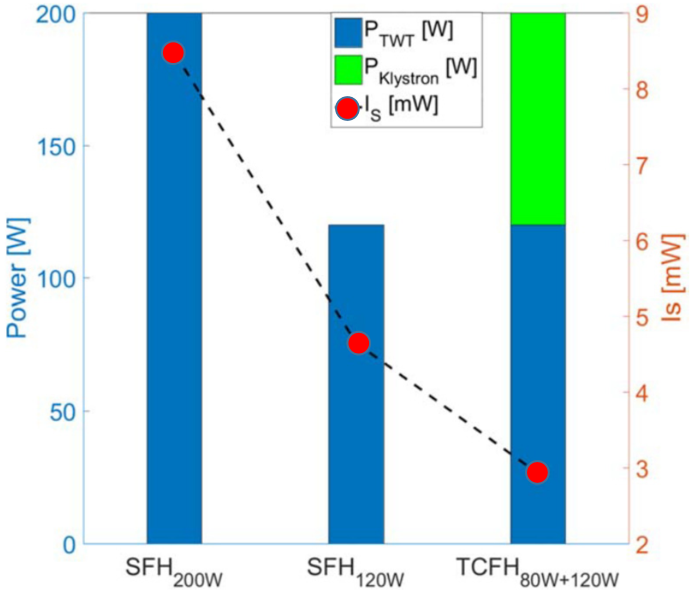
Instability strength vs Bmin/Becr

Definite drop of the Is at TCFH



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

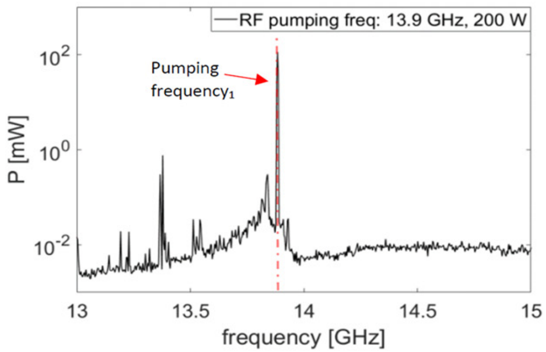
Example 13.9 GHz



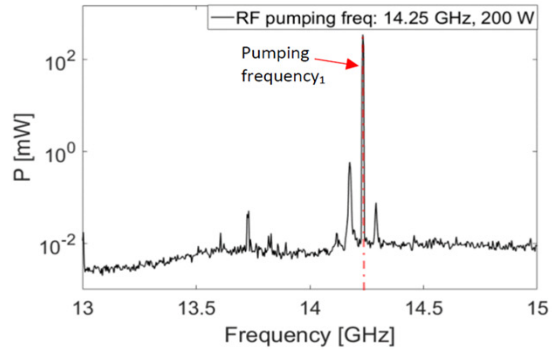
The combination of two frequencies is in this case more stable than a single one, even if the power is increased by almost a factor of two.

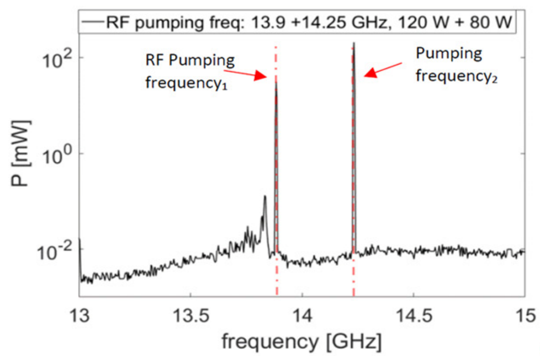
RF spectral changes

SFH: 13.9 GHz



SFH: 14.25 GHz





TFH: 13.9 + 14.25 GHz

Spectral structure of the self-emitted radiation

Single

the emission occurs at frequencies lower than the lowest of the two pumping frequencies

Double

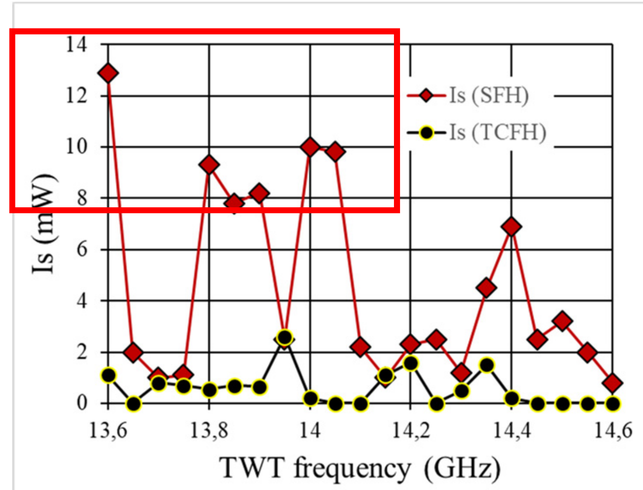
The plasma density distribution is rearranged; becoming denser in the central region (where the B-field is lower)

Plasma images vs Bmin/Becr

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

&

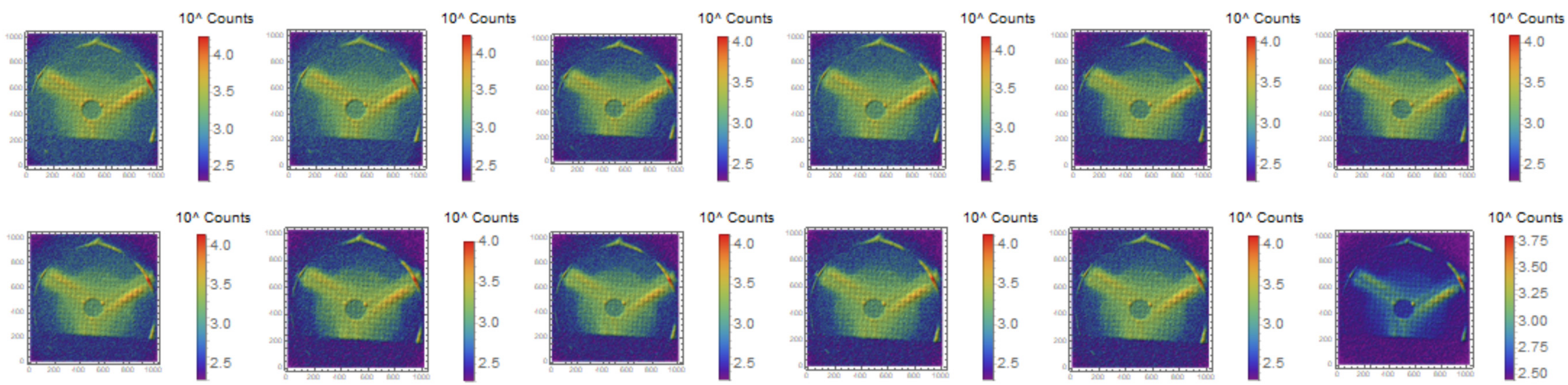
The instability is damped effectively



13.6 GHz | 13.8 GHz | 13.85 GHz | 13.9 GHz | 14 GHz | 14.05 GHz

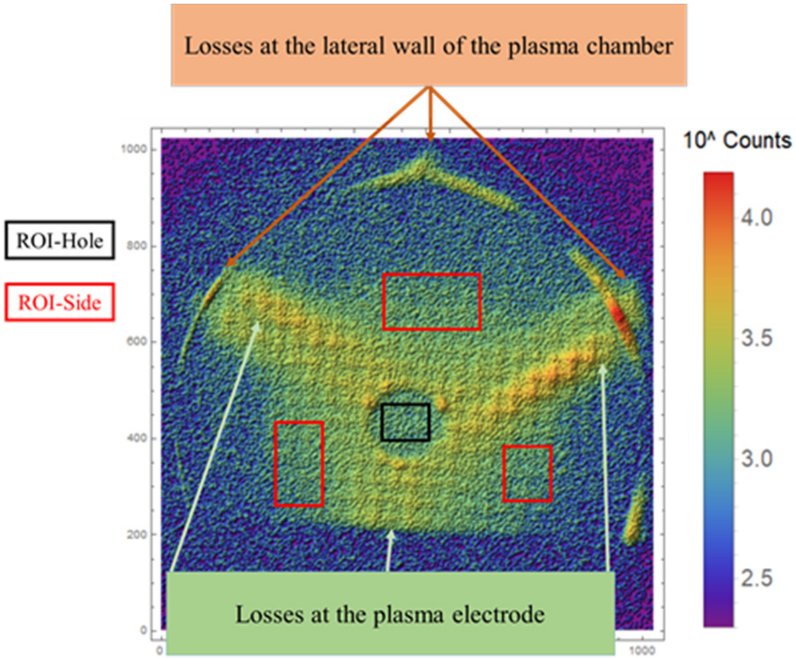
SFH

TCFH

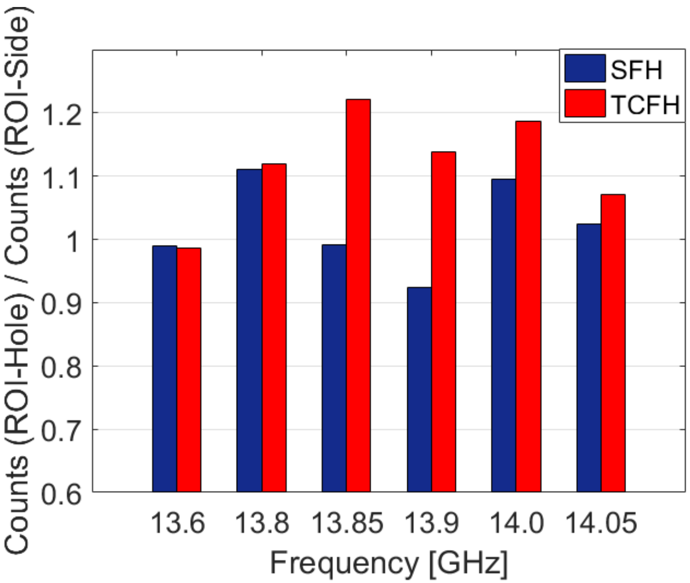


Structural changes

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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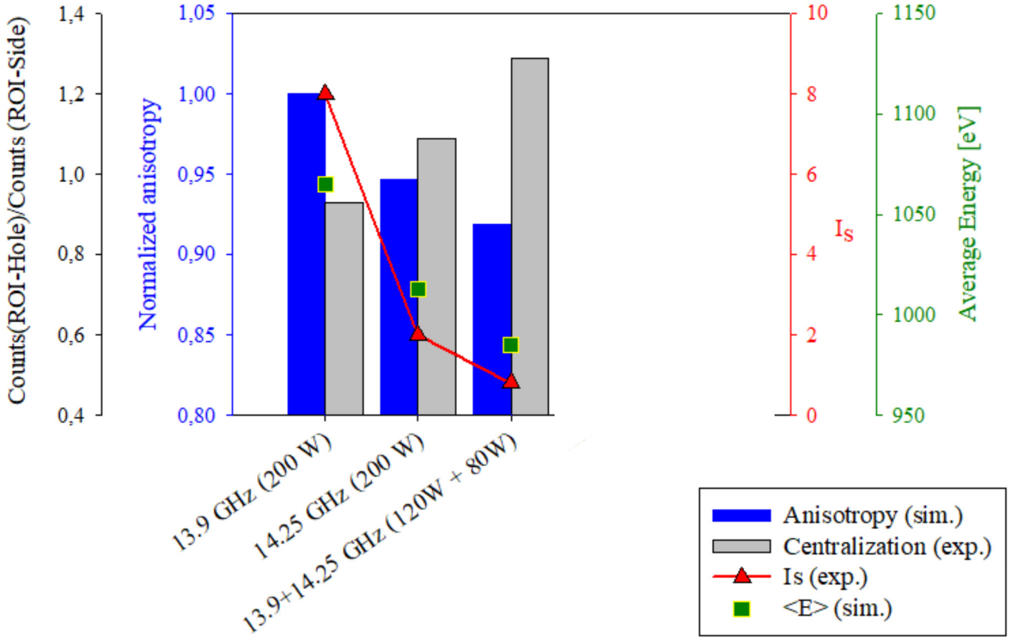
Comparison of experimental results and simulation



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