Measurements and Simulations of the Energy Distribution of Electrons Lost from the Minimum B-field

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High energy is needed for high charges production

>100 keV is the optimum “Te” for i.e. Xe54+ production.

“Te” is a wrong term for an ECRIS with a ~collision-less confinement.

A knowledge on EEDF inside the plasma is the key for tuning the CSD and confinement.

PIC simulation might be the right path to follow, though we need to benchmark it somehow.
Are there such “hot” electrons? Yes.

Measuring of x-ray bremsstrahlung gives an upper limit of electron energy inside the trap and an estimate of a characteristic energy.

Does it give one an information on the EEDF itself? No.
First attempts to measure energy of electrons escaping the confinement

Main results:
1. There are kinetic instabilities.
2. Electron energy may reach several hundreds of keV (direct measurement) - matches bremsstrahlung well.
3. Electron flux drops immediately when microwaves are switched off.

DOI: 10.1063/1.4769260
First LEED measurement, SMIS37, 2011

Is there any way to measure the (lost) electrons energy distribution (LEED)?

LEED

Electron energy, keV

Electron signal, a.u.

Signal, a.u.

Time from MW edge, μs

DOI: 10.1063/1.3673012
Measurement principle

JYFL 14 GHz ECRIS  |  Beamline  |  Dipole magnet  |  Secondary electron amplifier

SEA

Electron flux  \( \vec{B} \)
LEED as a function of power (2018)
LEED as a function of power (new)
LEED as a function of oxygen pressure
LEED as a function of the magnetic field
Hump energy
Hump energy

Lost electrons energy hump

Electron energy, keV

B_min

Hump energy
Pulsed heating experiment

- Slow building up of the LEED
- Fast drop at the trailing edge
- High energy electrons are confined well in between the pulses
Heating pulse cut-off

2018.01.31/2; \( \frac{B_{\text{min}}}{B_{\text{ECR}}} = 0.735 \) (500 A); 400 W; \( 3.5 \cdot 10^{-7} \) mbar \( \text{O}_2^+ \)

Electron energy, keV

Total losses (a.u., log scale)

\( \mu \text{W cut-off} \)

Time, ms

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LEED build-up and decay

- Energies >10 keV and the hump is developing slowly (~50 ms)
- Hump disappears within 1.5 ms after the trailing edge of uw
- Afterglow instability throws out plenty of charge
- Low energy expelled faster

Ivan Izotov, IAP 15/35 18th International Conference on Ion Sources, Lanzhou, China. September 2, 2019
NAM-ECRIS PIC simulations: lost electrons

Despite the coincidence (?) of the hump, the dependencies of its energy on parameters are not predicted well -> something is not taken into account.
NAM-ECRIS PIC simulations: confined electrons
A technique to estimate the real EEDF?

Experiment: the integral over time of all electrons detected after the microwaves have been turned off.

This technique might be effective yet qualitative method of confined EEDF estimation!
The LEED in unstable plasma

2018.01.26/scan5
400 W; $B_{\text{min}}/B_{\text{ECR}} = 0.842$ (560 A); 3.5E-7 O₂

µW emission (a.u.)

Electron energy, keV

$10^2$

$10^1$

Time, µs

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Unstable plasma

2018.01.26/scan5
400 W; $B_{\text{min}}/B_{\text{ECR}}=0.842$ (560 A); $3.5\times10^{-7}$ O$_2$

$\mu$W emission (a. u.)

Average energy, keV

Total losses (a.u., log scale)

Electron energy, keV

10$^1$ - 10$^2$

Time, $\mu$s

-4 - 5
Unstable plasma

![Graph showing unstable plasma with different energy distributions and labels: 
- $<E> = 186$ keV
- $<E> = 234$ keV
- $<E> = 173$ keV
- $<E> = 208$ keV]
Effects of power modulation on LEED and stability
Power modulation: transition to CW mode

More details on CW mode: PRL 120, 155001 (2018)

DOI: 10.1103/PhysRevLett.120.155001

1. No hump
2. LEED similar to external 2-freq heating

More details on CW mode: PRL 120, 155001 (2018)

DOI: 10.1103/PhysRevLett.120.155001
CW mode may be of practical interest
LEED in two-frequency stabilization

Klystron CW unstable plasma is stabilized by pulsed TWTA radiation. **555A**, 14 GHz 300W + 12.7 GHz 150W 2 s on / 5 s off.
LEED in two-frequency stabilization: no “cold” ECR

Klystron CW unstable plasma is stabilized by pulsed TWTA radiation. 570A, 14 GHz 250W + 11.56 GHz 100W 2 s on / 5 s off. No ECR
LEED in two-frequency heating mode: no "cold" ECR

14GHz/100W + 11.56GHz/100W, 0.5s/0.5s, 570 A (R=0.86/1.04)
Lost electrons energy hump

TE21 mode → 3.814 GHz
Conclusion

✔ LEED measurements give an important insight on ECRIS plasma.

✔ PIC modeling is essential, LEED measurements are needed to benchmark it.

✔ Existence of the second frequency may explain many observed effects (theory is under development – almost ready)!

✔ We ask you to perform the experiments with different sources in terms of size/frequency/power/flexibility!
谢谢你的关注

Thank you for your attention!