The energy distribution of electrons escaping minimum-B ECR plasma in unstable mode

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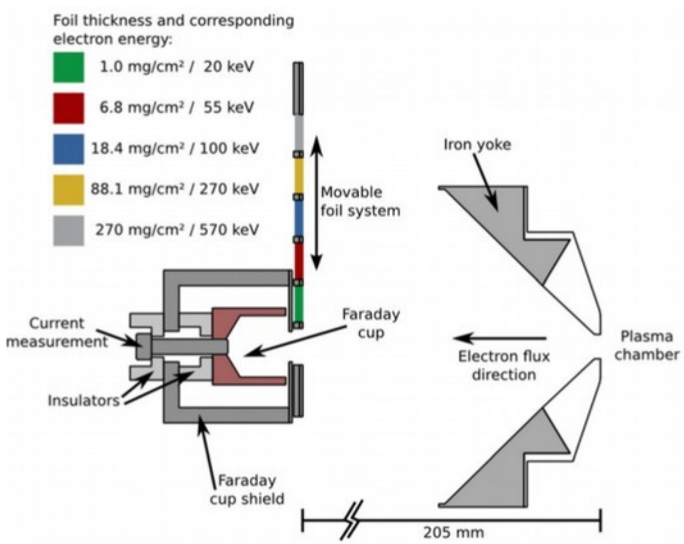
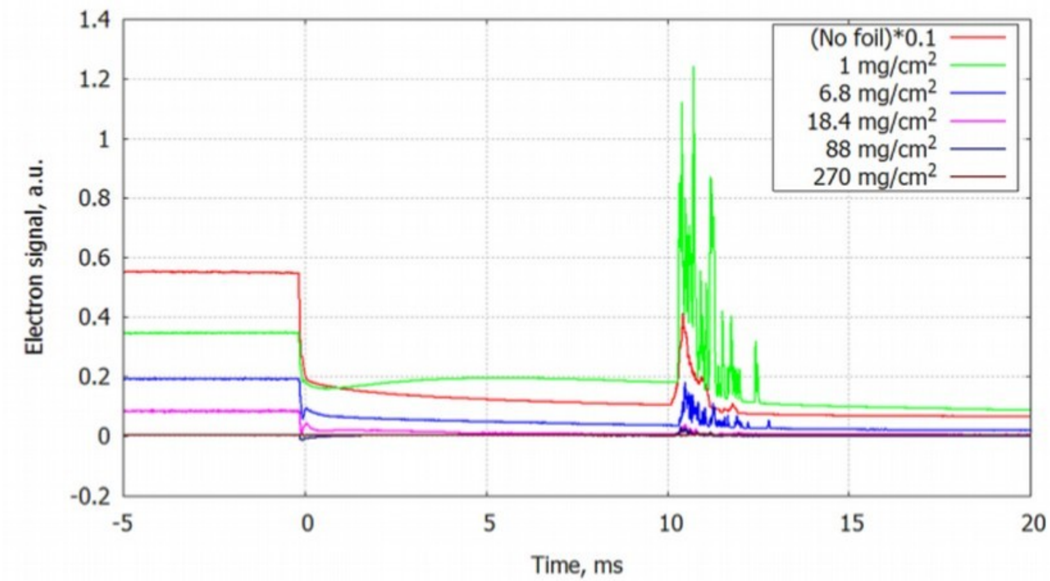
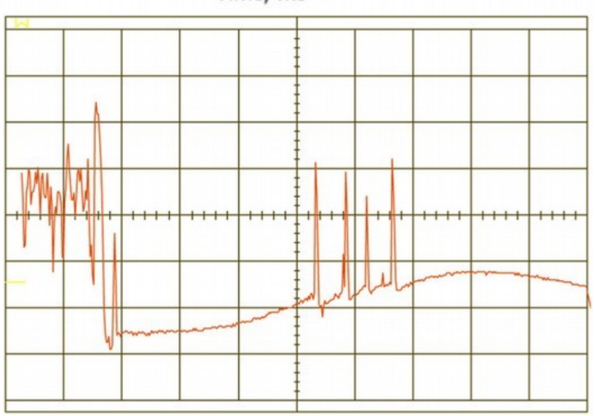
The 23rd International Workshop on ECR ion sources
10-14 September 2018 Catania, Diocesan Museum

Electrons escaping confinement carry important information on plasma dynamics: first attempt at JYFL with aluminum foils as energy filters





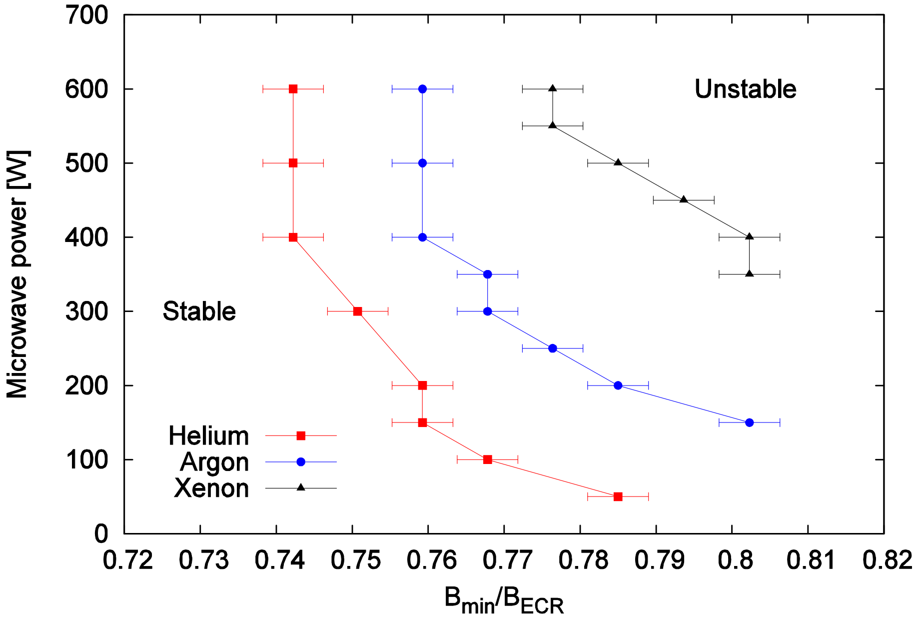
Very similar to what we saw at SMIS-37: kinetic instability



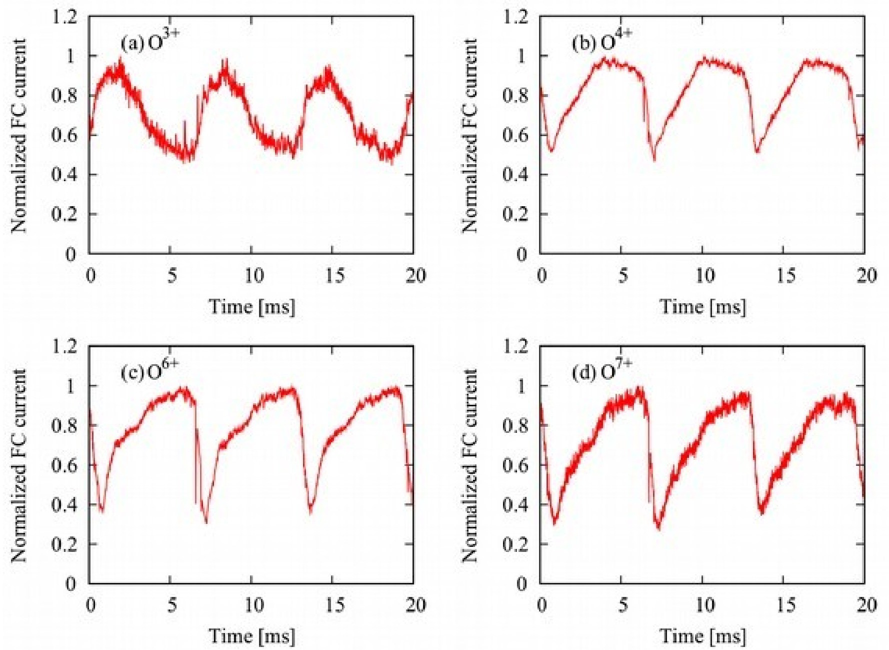
DOI: 10.1063/1.4769260

Min-B plasma may be kinetically unstable

Stable/unstable threshold:
B_{min}/B_{ecr} is the key parameter



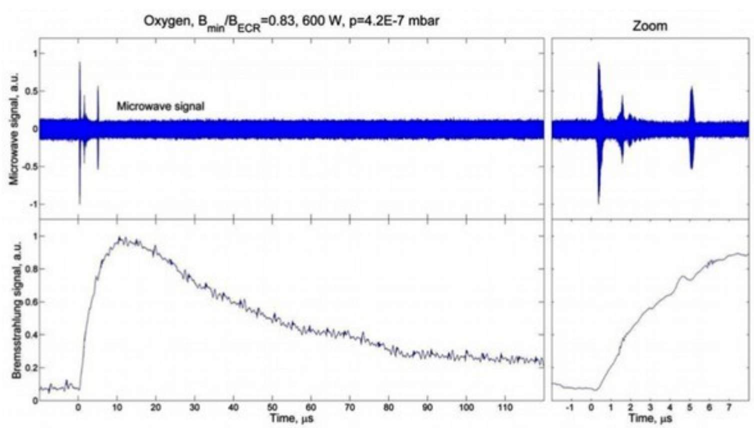
Instabilities dramatically affect high charges production

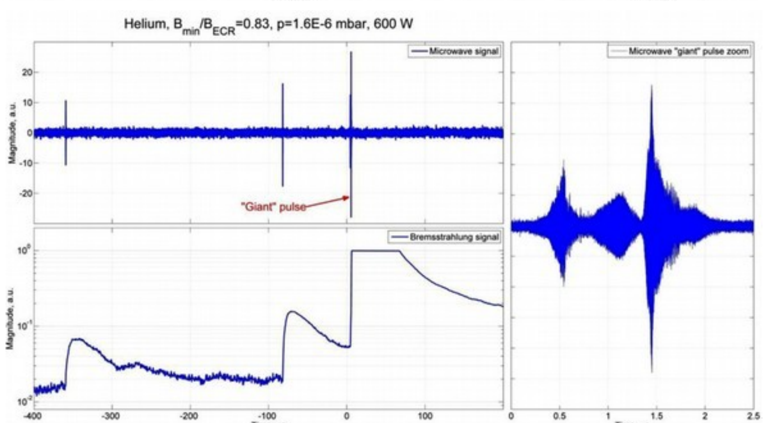


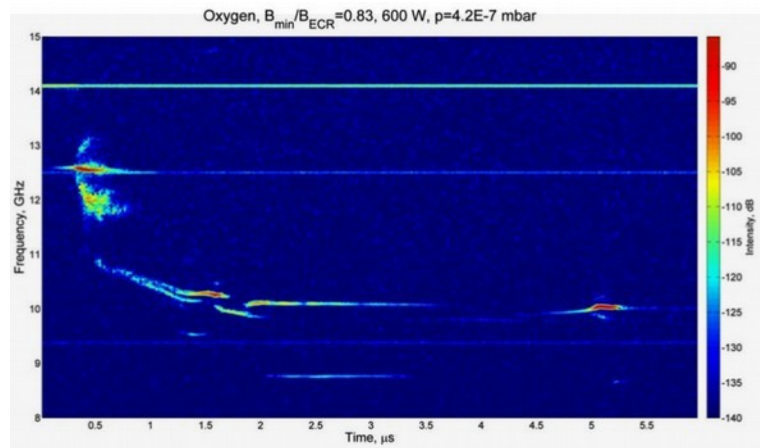
The threshold is roughly on the level of B_{min}/B_{ecr} ~0.75, which is often observed as the point where ECRIS performance drops

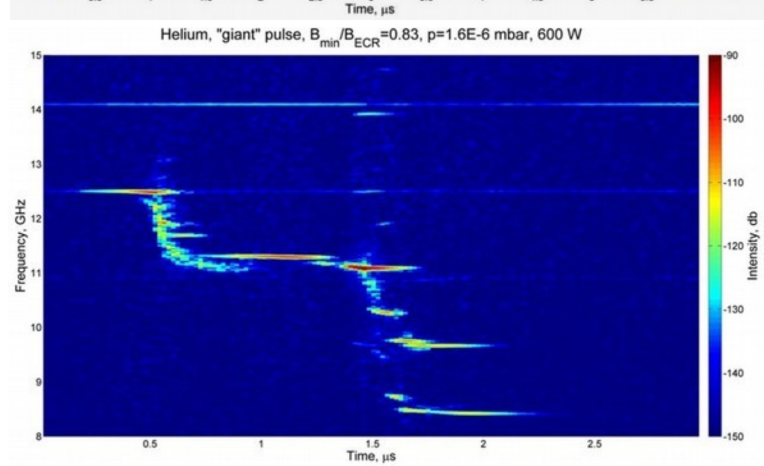
DOI: 10.1088/0963-0252/23/2/025020

And it emits a lot of x-ray and microwave power including radiation at frequencies below min-B, which implies interaction with electrons with energies > 100 keV









DOI: 10.1088/0963-0252/24/4/045017

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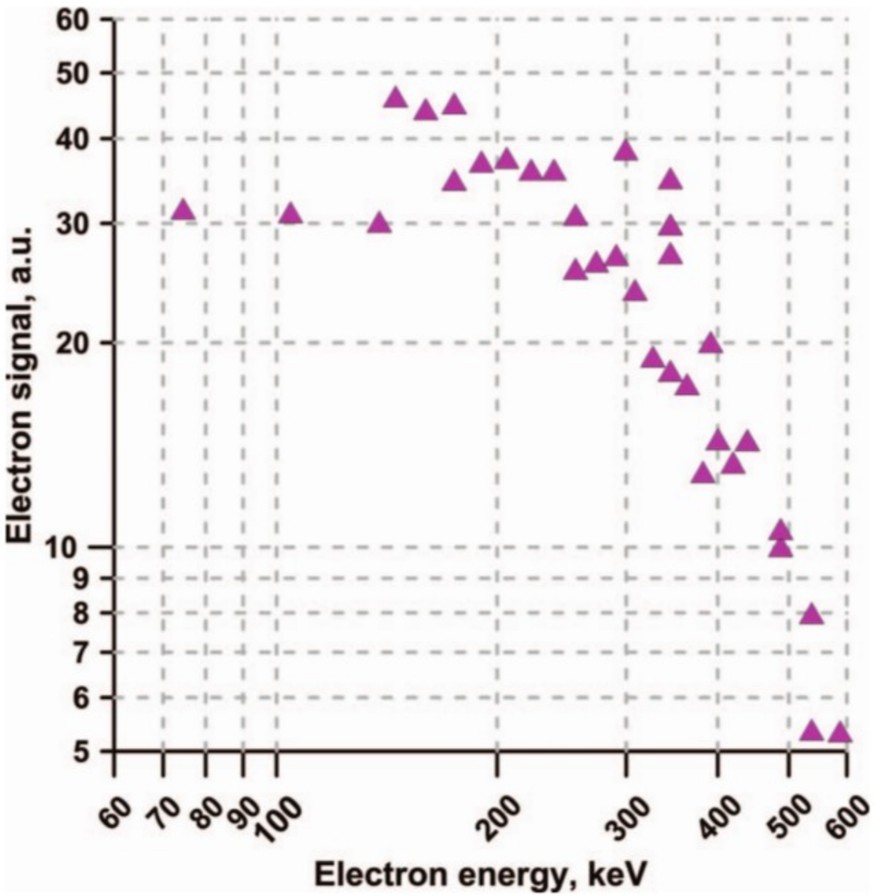
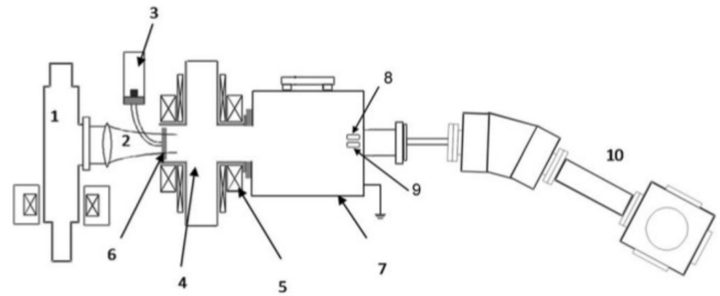
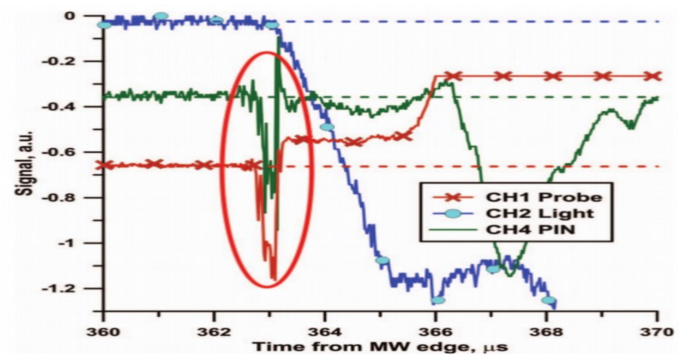
University of Jyväskylä

First attempt (2011) with magneto-static energy spectrometer at SMIS-37 gasdynamic ECRIS

ICIS`11, Giardini Naxos, Italy





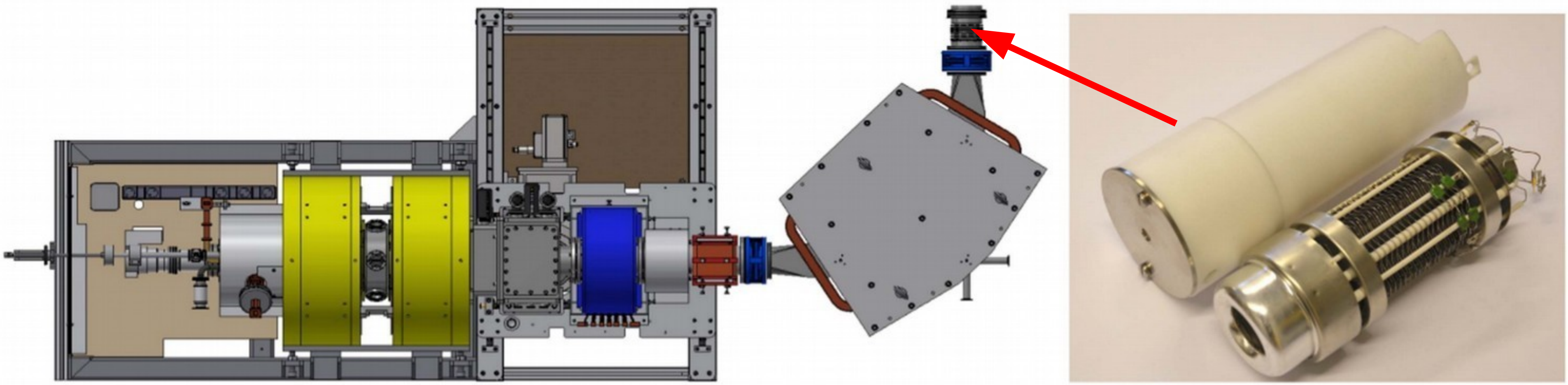


Though the average electron energy in plasma is ~50 eV, we observed 600 keV electrons leaving the trap. That was an expected result as similar energies were observed at OGRA-4 baseball trap in 1991 at Kurchatov FRC.

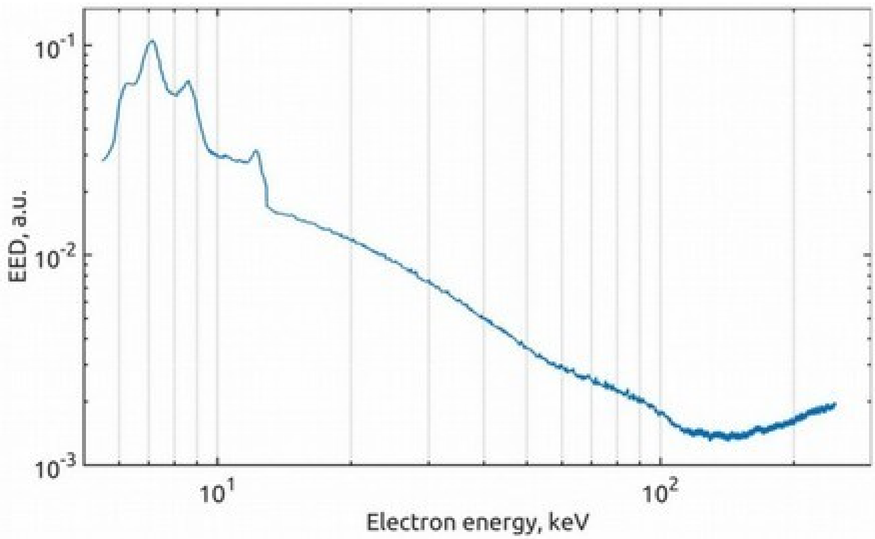
DOI: 10.1063/1.3673012

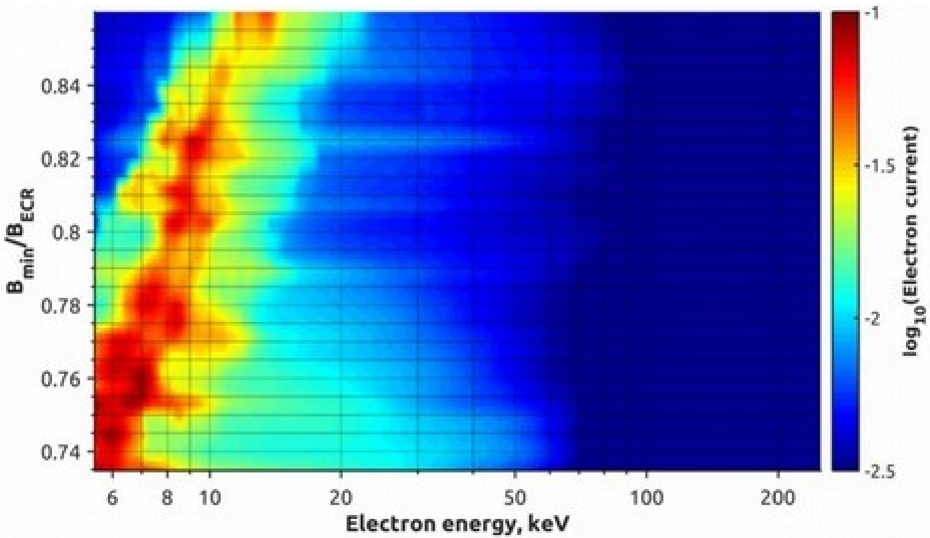
Measurements implemented at JYFL

DOI: 10.1088/1361-6595/aaac14
PSST 2018



JYFL 14 GHz ECRIS Beamline Dipole magnet Secondary electron amplifier





Improved scheme of the experiment

- Measuring principle is the same: scanning through bending magnetic field with high current/temporal resolution
- Very high collimation >1000
- Precise analog current source (**forget modern digital power supplies**)
- Scanning algorithm improved
- Data processing and analyzing “software” improved
- High-gain low-drift pre-amplifier for pulsed measurements
- High gain low-noise current amplifier for «CW» measurements
- Dynamic range of electron signal is more than **60 dB!** Simultaneous measurement of background signal and bursts in unstable mode is very challenging. Large amount of data should be accumulated.

- ✓ **Energy resolution < 500 eV**
- ✓ **Time resolution ~ 10 ns — 100 us**

EEDF processing

$$F(\varepsilon,t)=\frac{1}{N(t)}\int_{E_{min}}^{E_{max}}\varepsilon\cdot f_a(S(B,t))\cdot d\varepsilon - distribution\,function$$

$$N(t)=\int_{E_{min}}^{E_{max}} f_a(S(B,t))\cdot d\varepsilon - total\,number\,of\,\,particles$$

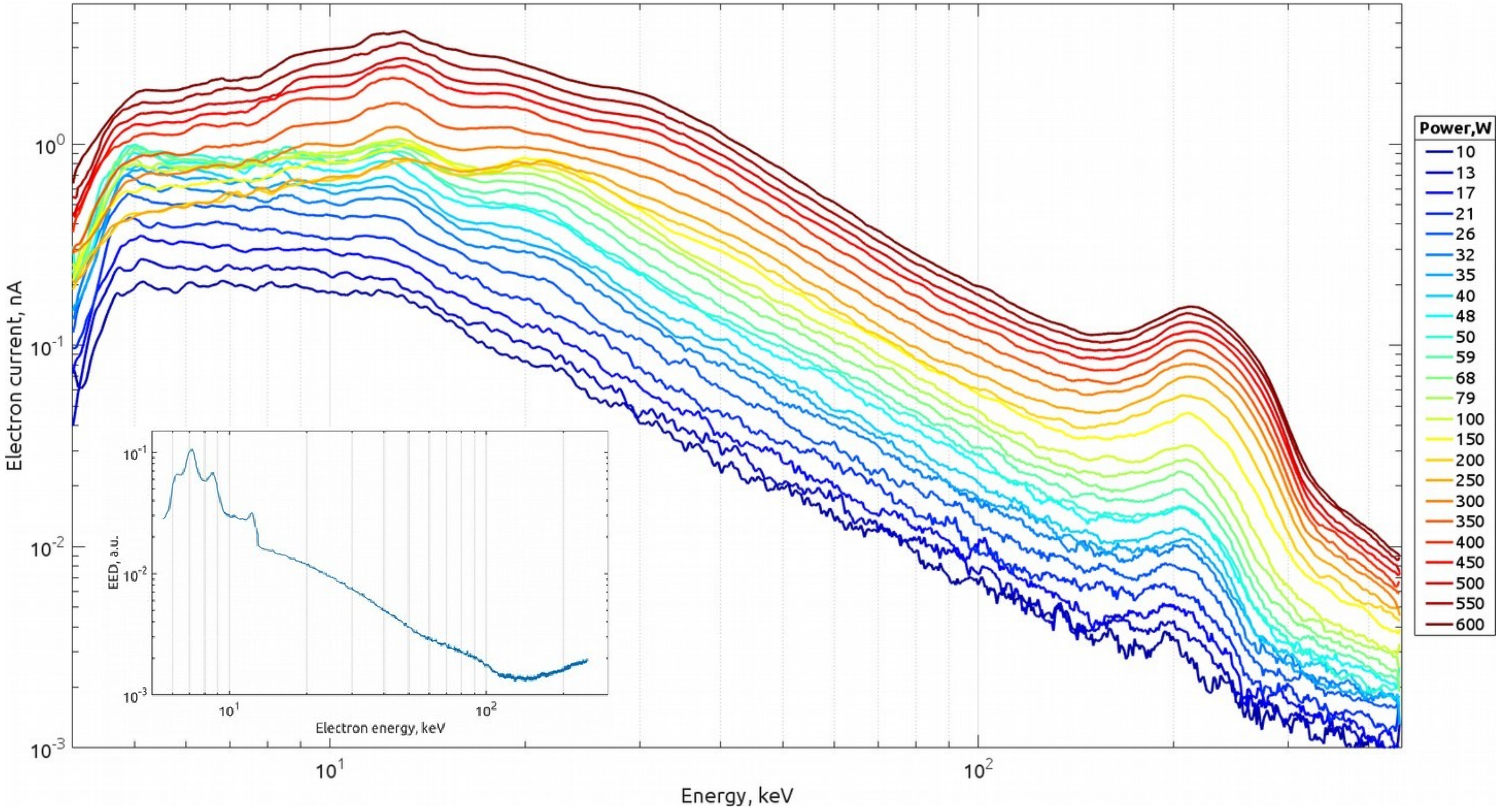
B — magnetic field in the bending magnet;
t — time
ε — electron energy

S(B,t) — recorded electron signal

f_a — apparatus response function, which takes into account:

- dependence of electron transport efficiency through the apparatus on the energy (IBSimu);
- secondary electrons amplifier response function (datasheet);
- secondary electrons yield from amplifier cathode (published data)
- electrons back-scattering

Power sweep in stable plasma, O_2 (3.5E-7), B_{min}/B_{ecr} = 0.76



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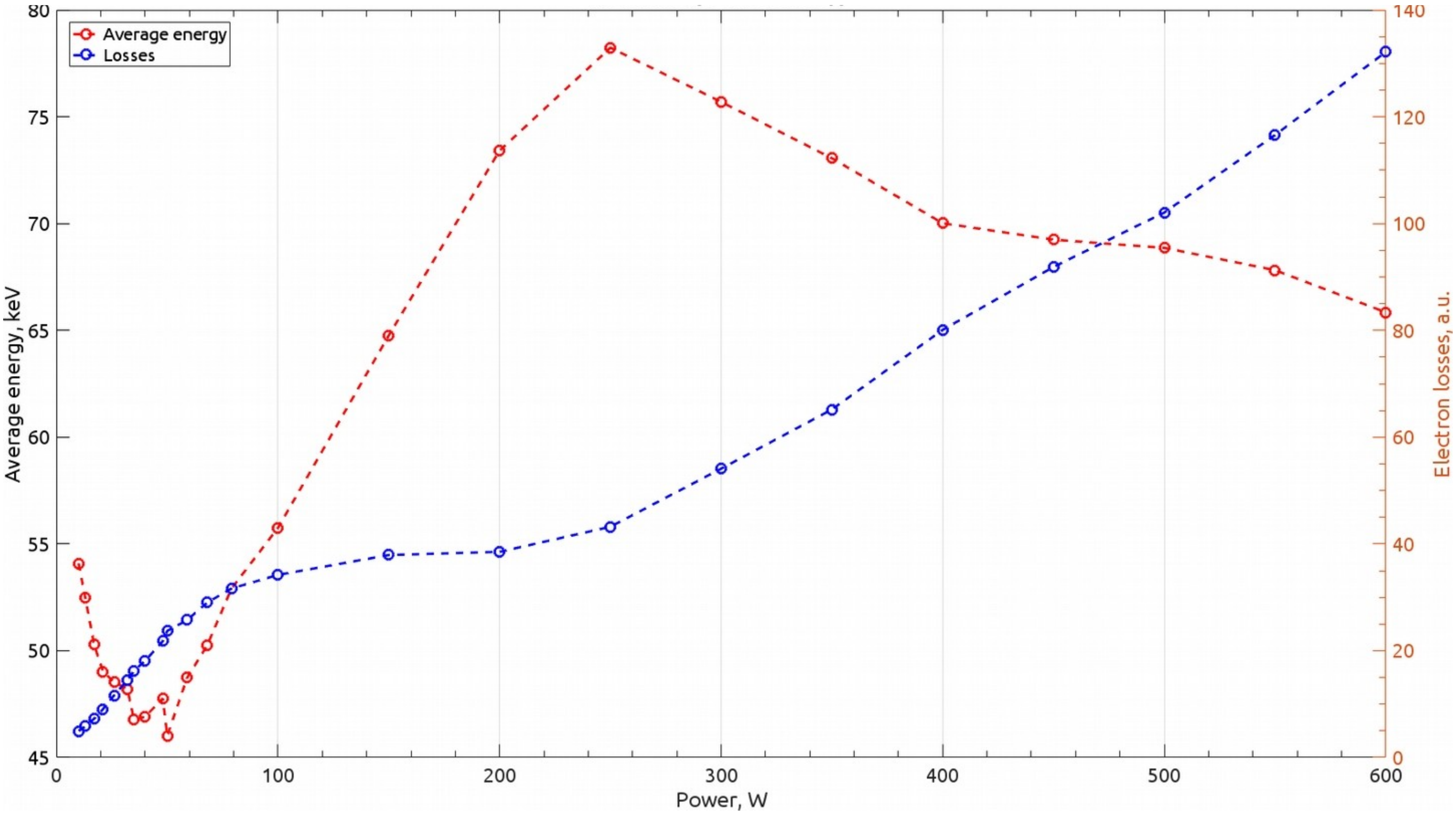
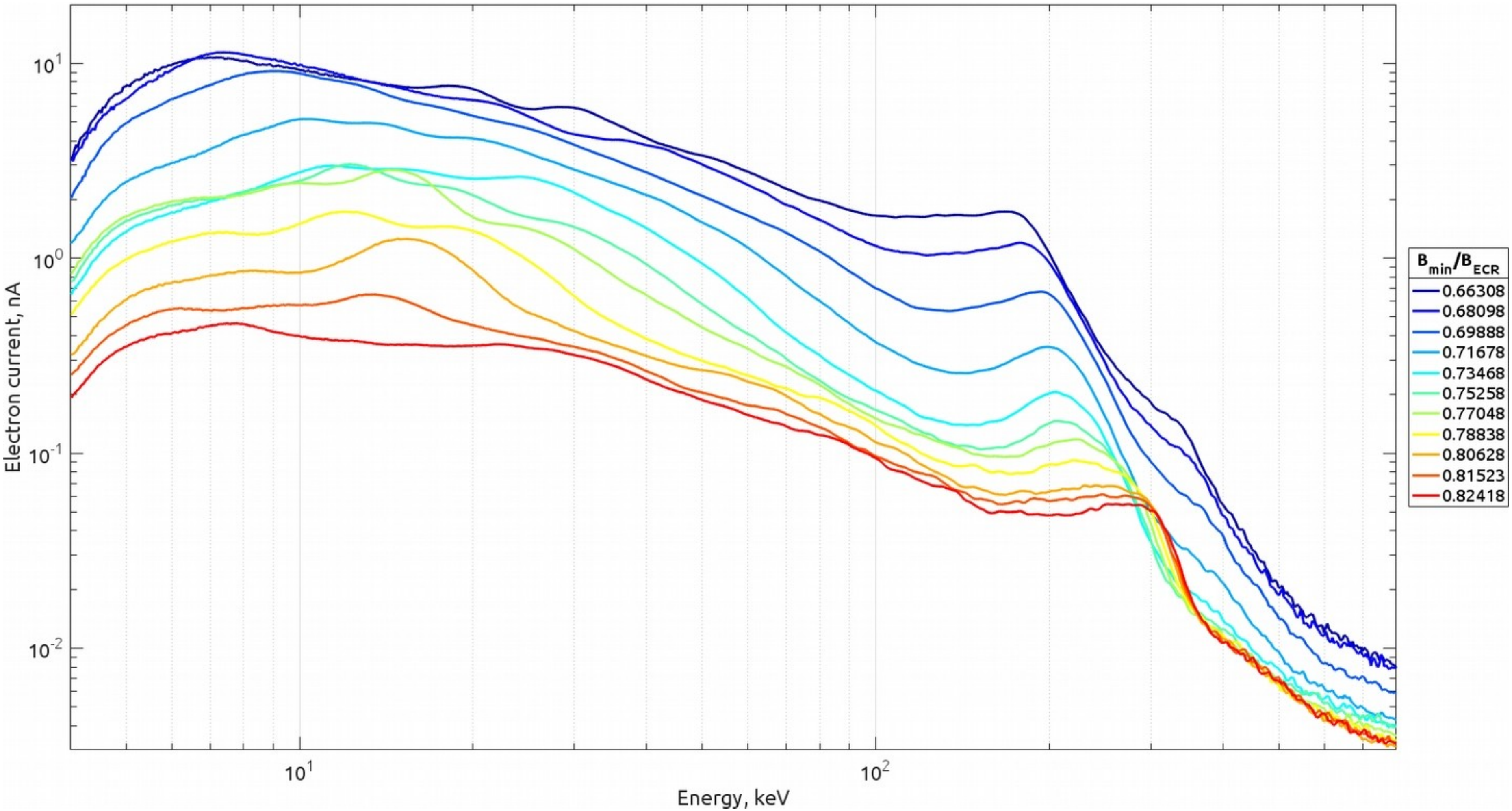


B_{min}/B_{ecr} sweep in stable plasma, P = 400 W



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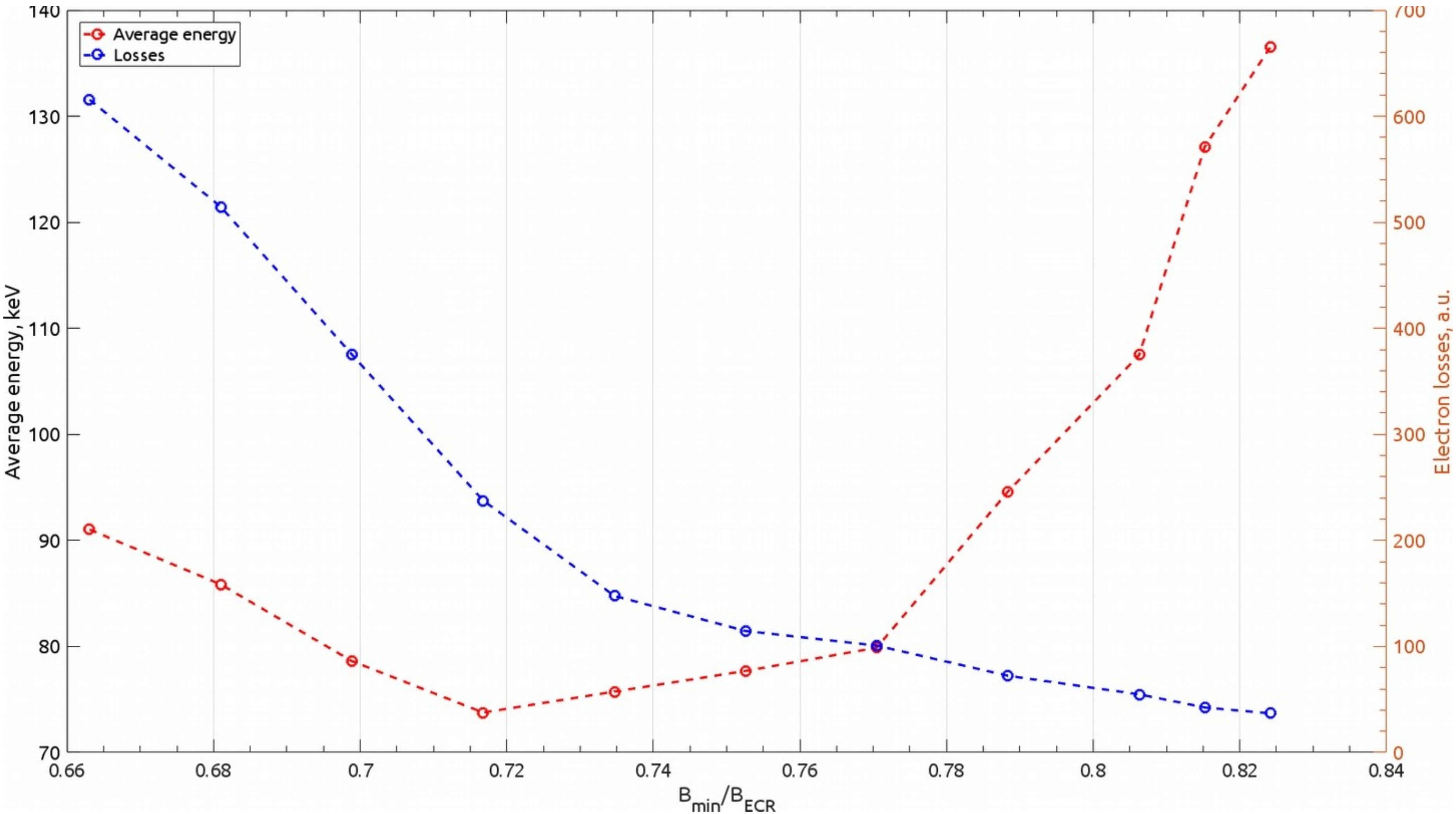
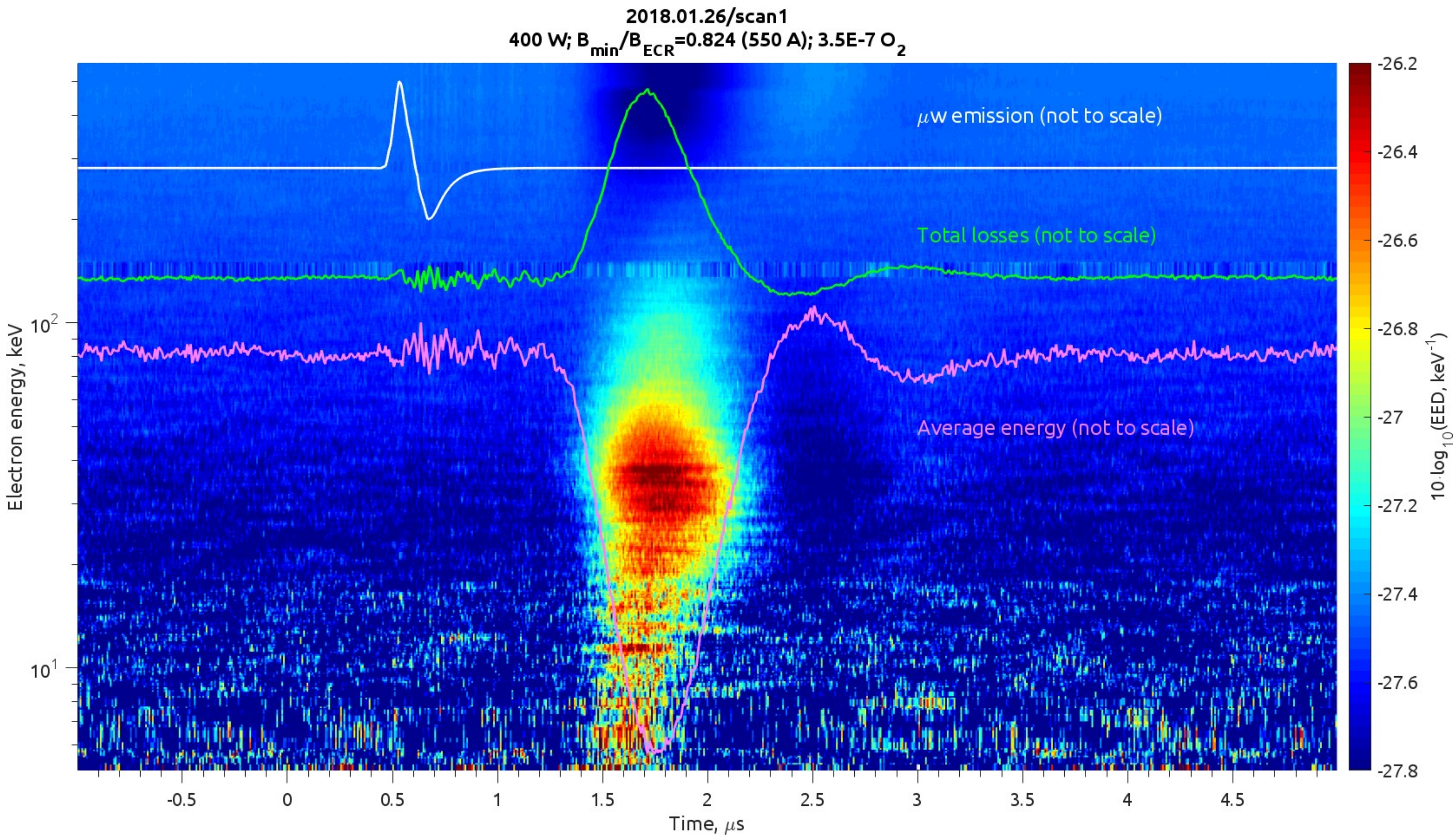
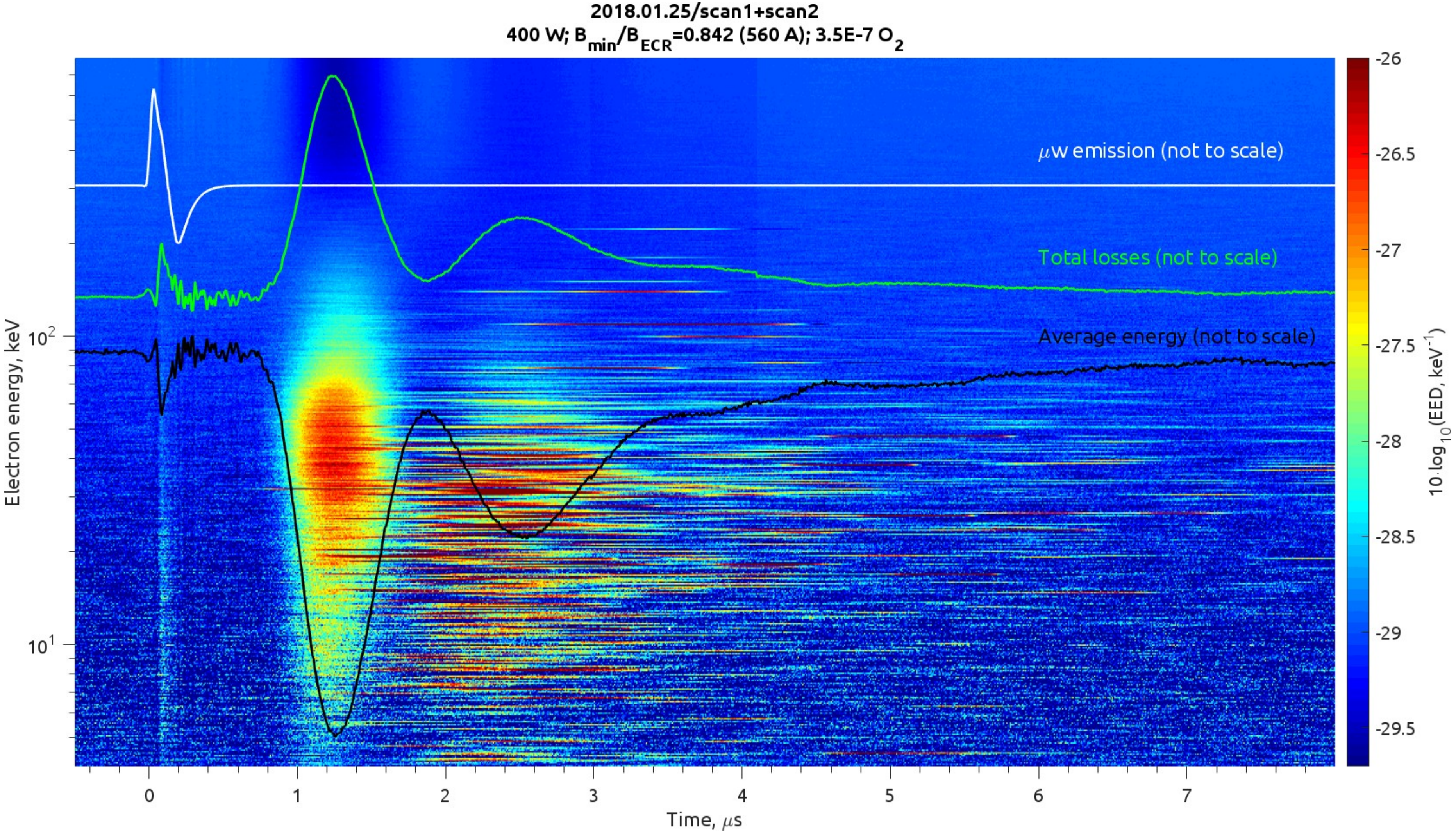


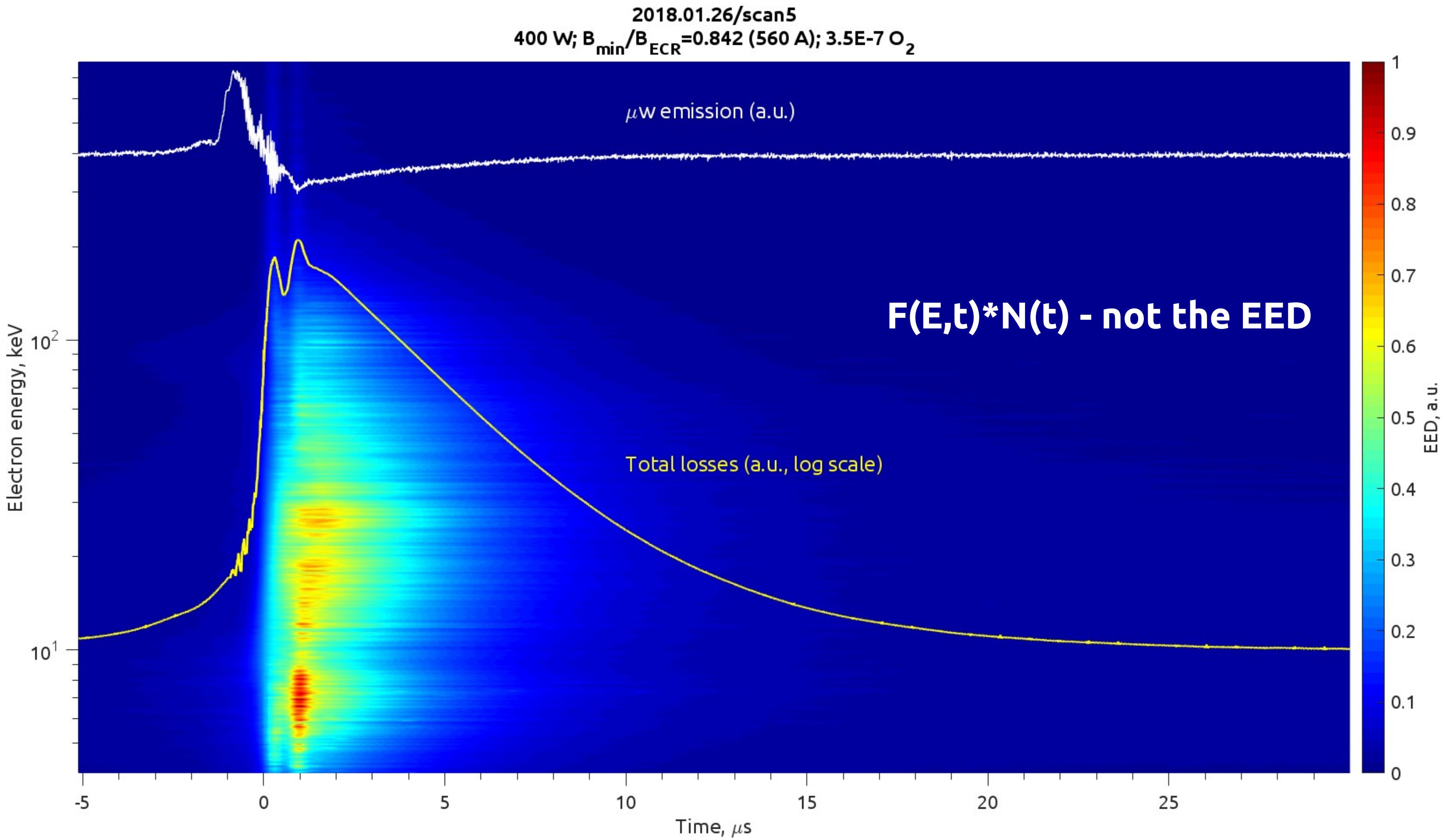
Unstable plasma, P = 400 W, B_{min}/B_{ecr} = 0.824



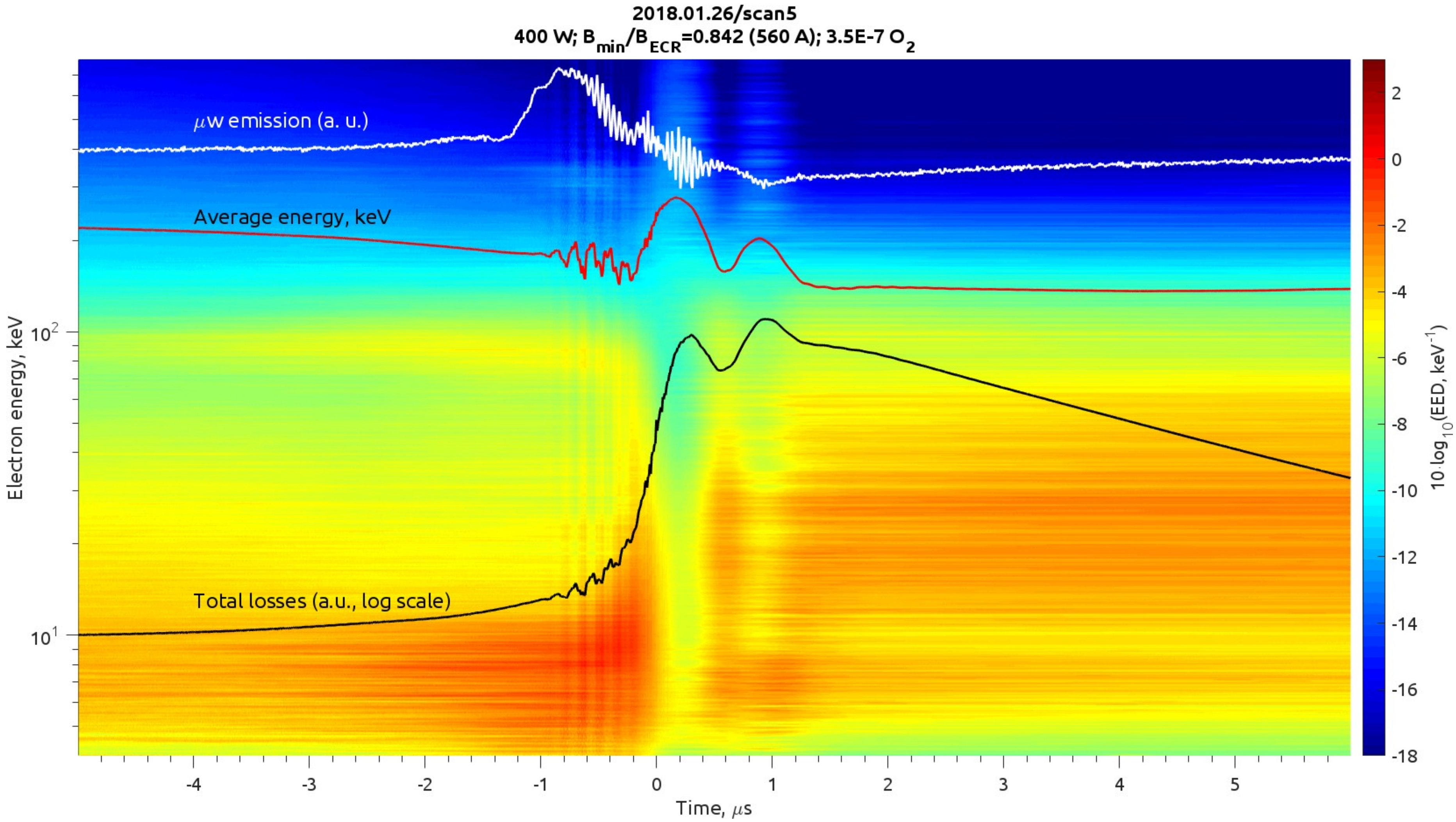
Unstable plasma, P = 400 W, B_{min}/B_{ecr} = 0.842



Unstable plasma, P = 400 W, B_{min}/B_{ecr} = 0.842, ~0.2M pulses



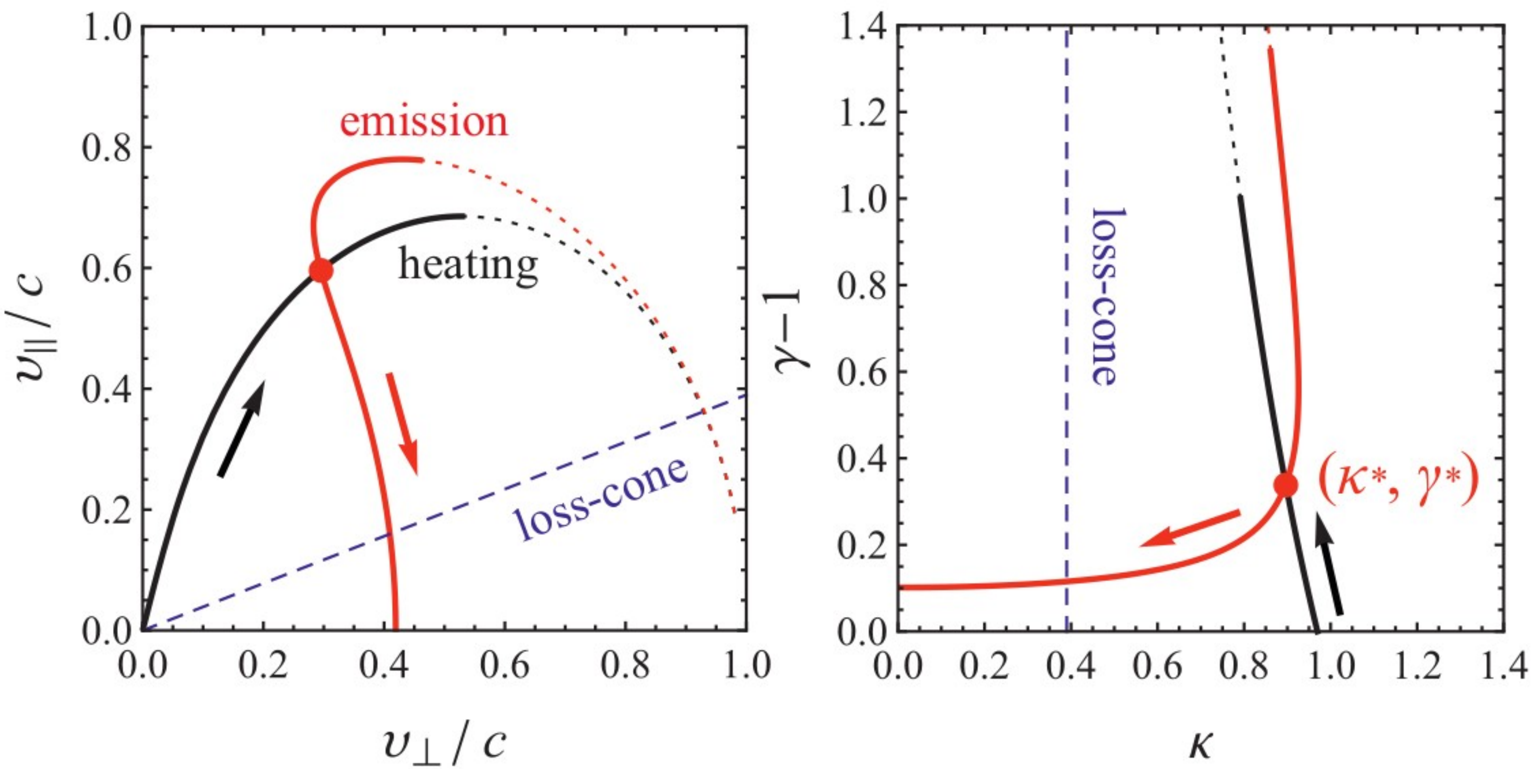
Unstable plasma, P = 400 W, B_{min}/B_{ecr} = 0.842



A. G. Shalashov, E. Gospodchikov, I. V. Izotov, D. A. Mansfeld, V. A. Skalyga, O. Tarvainen
Physical Review Leters 120, 155001 (2018) DOI: 10.1103/PhysRevLett.120.155001

$$\frac{\partial F}{\partial t} = E\frac{\partial}{\partial \kappa}\left(D\frac{\partial F}{\partial \kappa}\right) + J, \quad \frac{\partial E}{\partial t} = E\int_0^\infty \int_{\kappa_c}^1 K\frac{\partial F}{\partial \kappa} d\kappa dv - \nu E$$

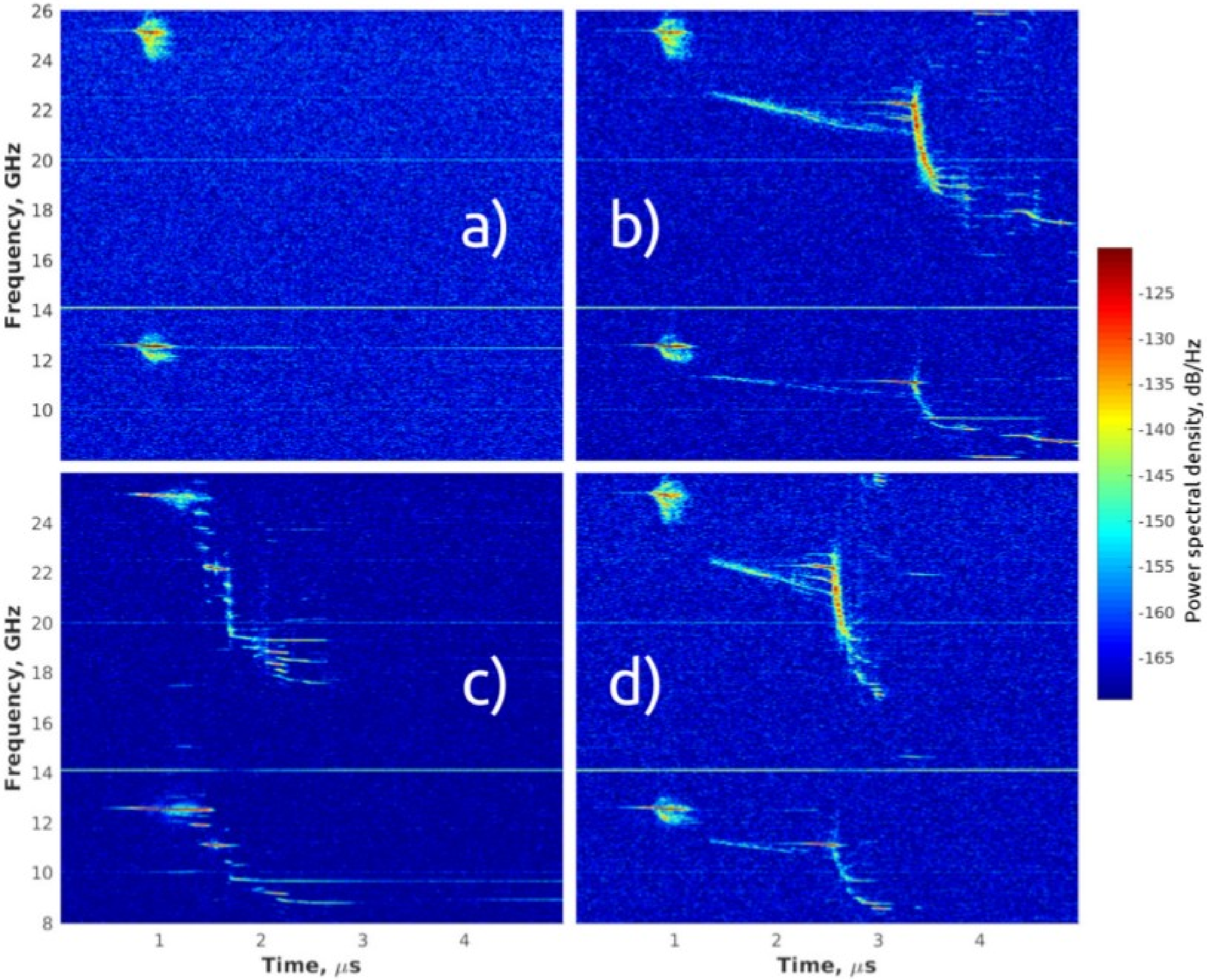
$$\kappa = (v_\perp / v) \times (B_{\min}/B)^{1/2}$$



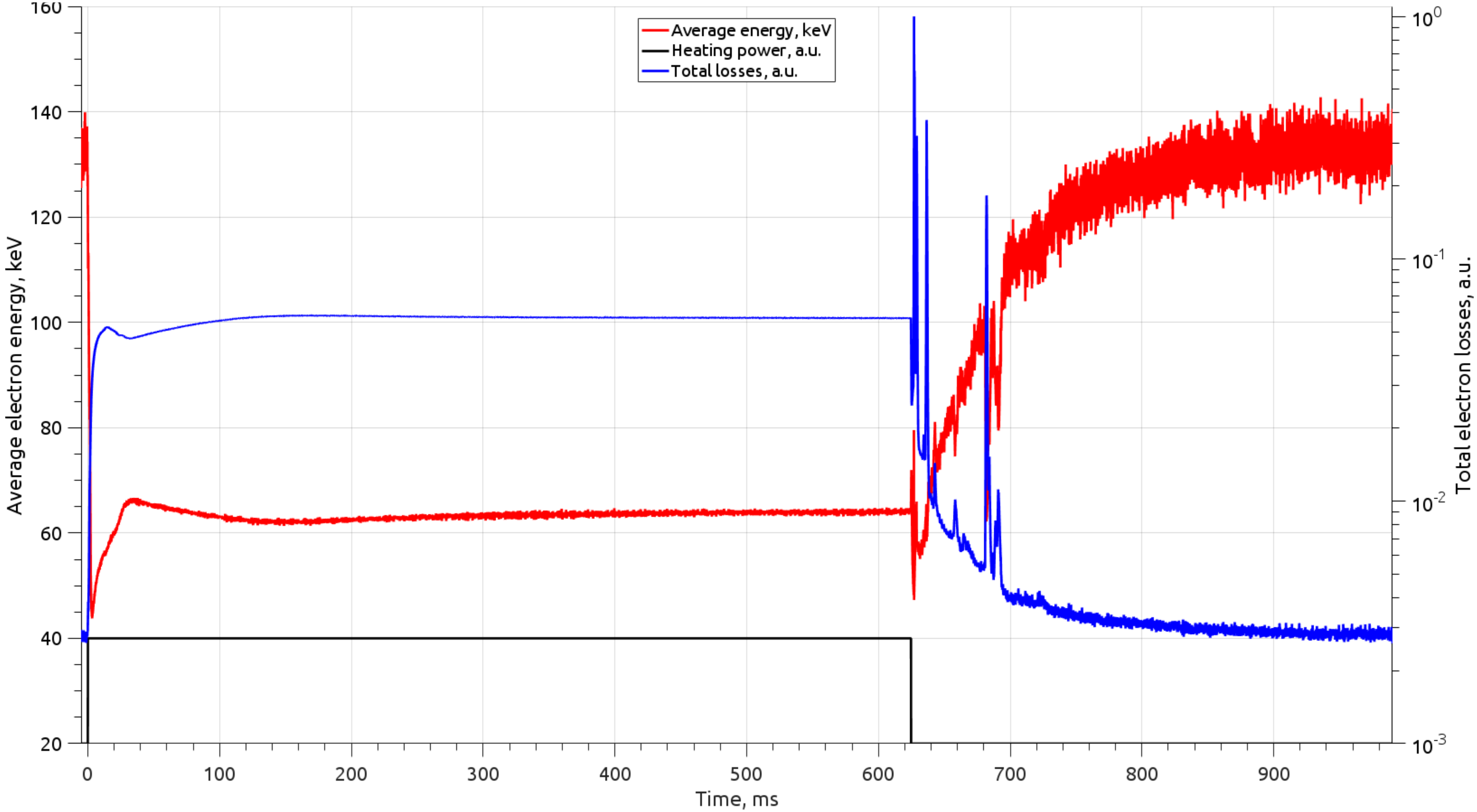
The figure is a courtesy of Alexander Shalashov , IAP RAS
Paper sent to EPL

Bursts of microwaves

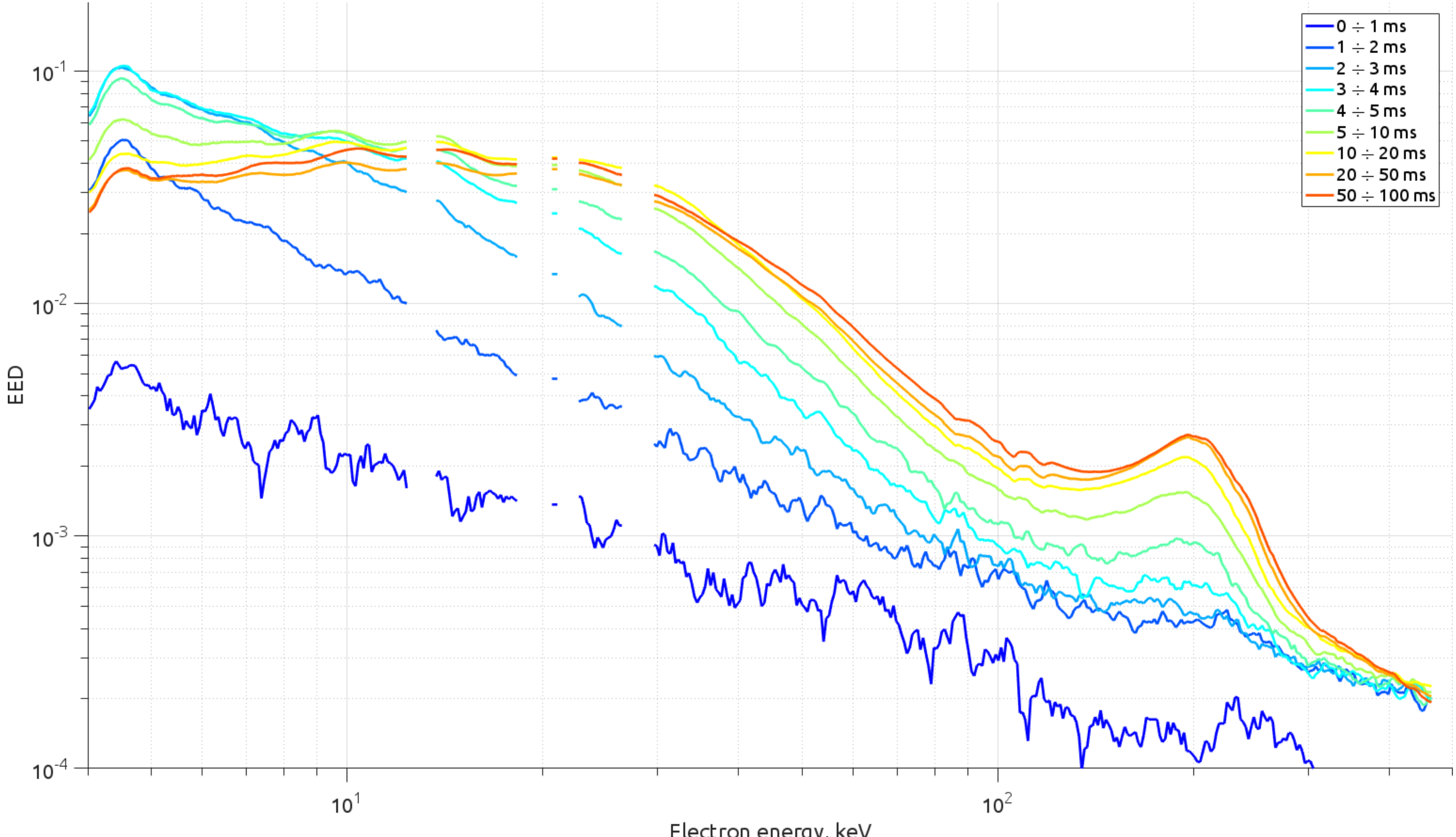
DOI: 10.1063/1.4981387



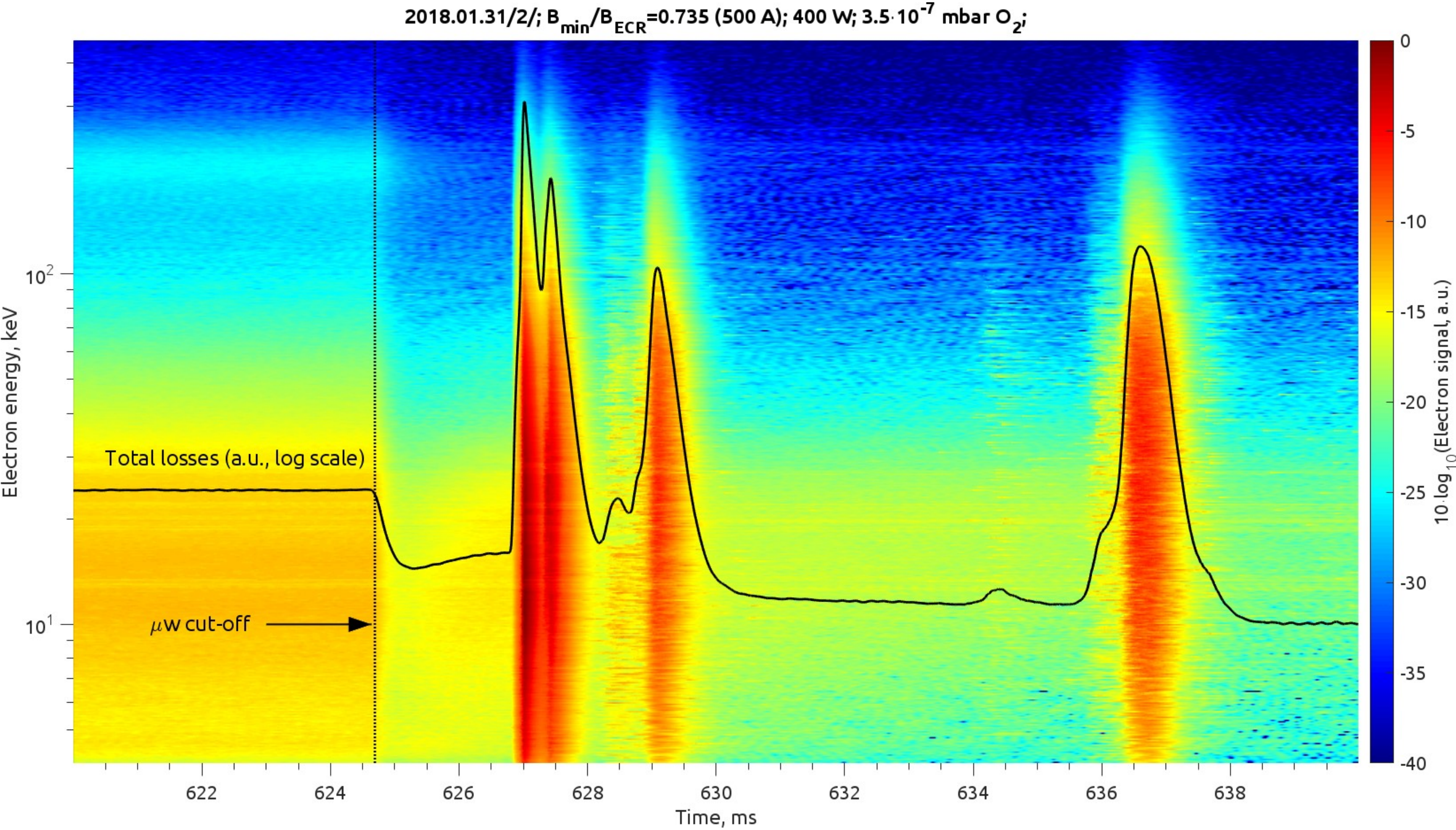
Stable plasma, pulsed P = 260 W, B_{min}/B_{ecr} = 0.735



Discharge start-up, P = 260 W, B_{min}/B_{ecr} = 0.735



Trailing edge, P = 260 W, B_{min}/B_{ecr} = 0.735



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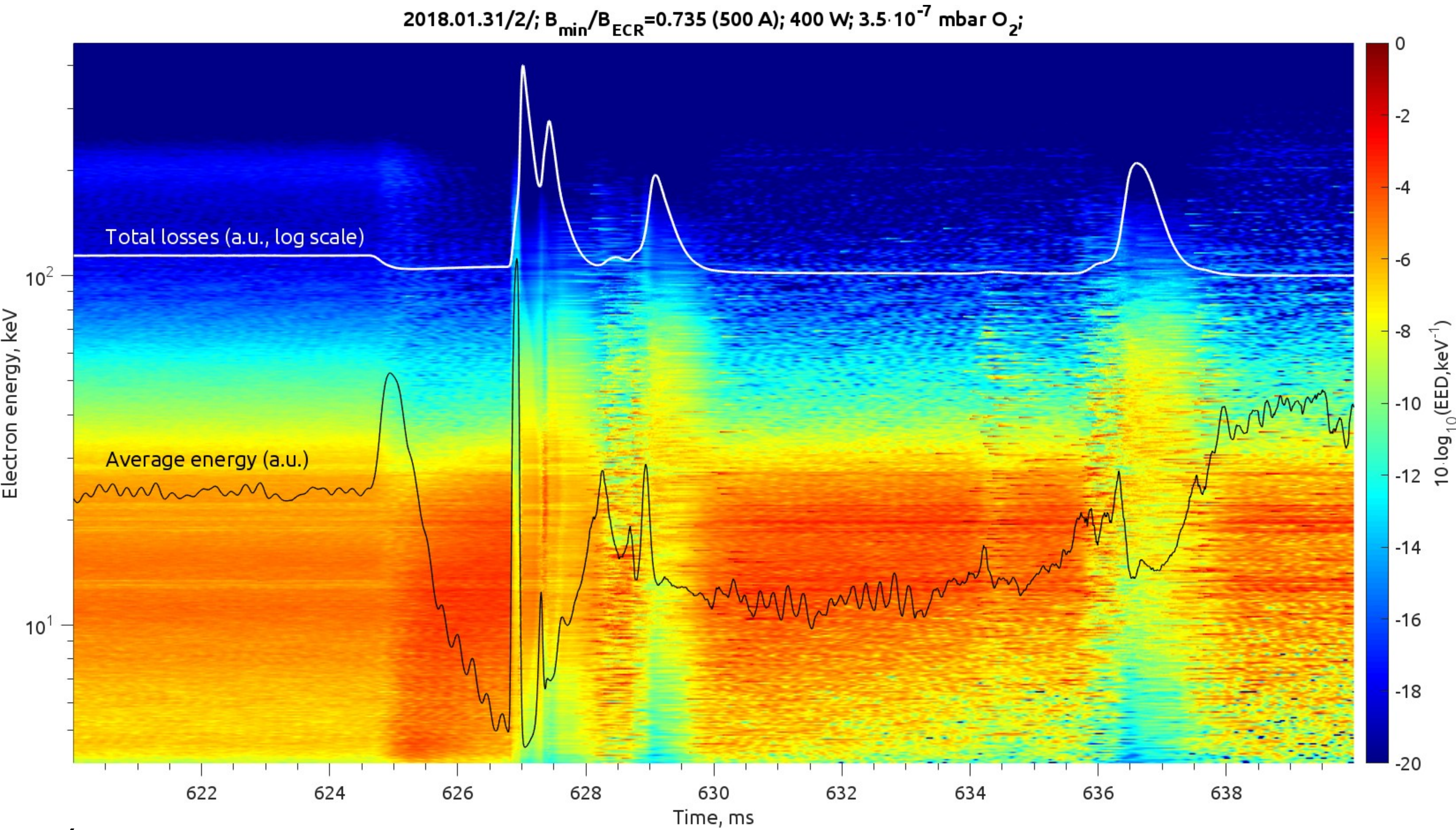

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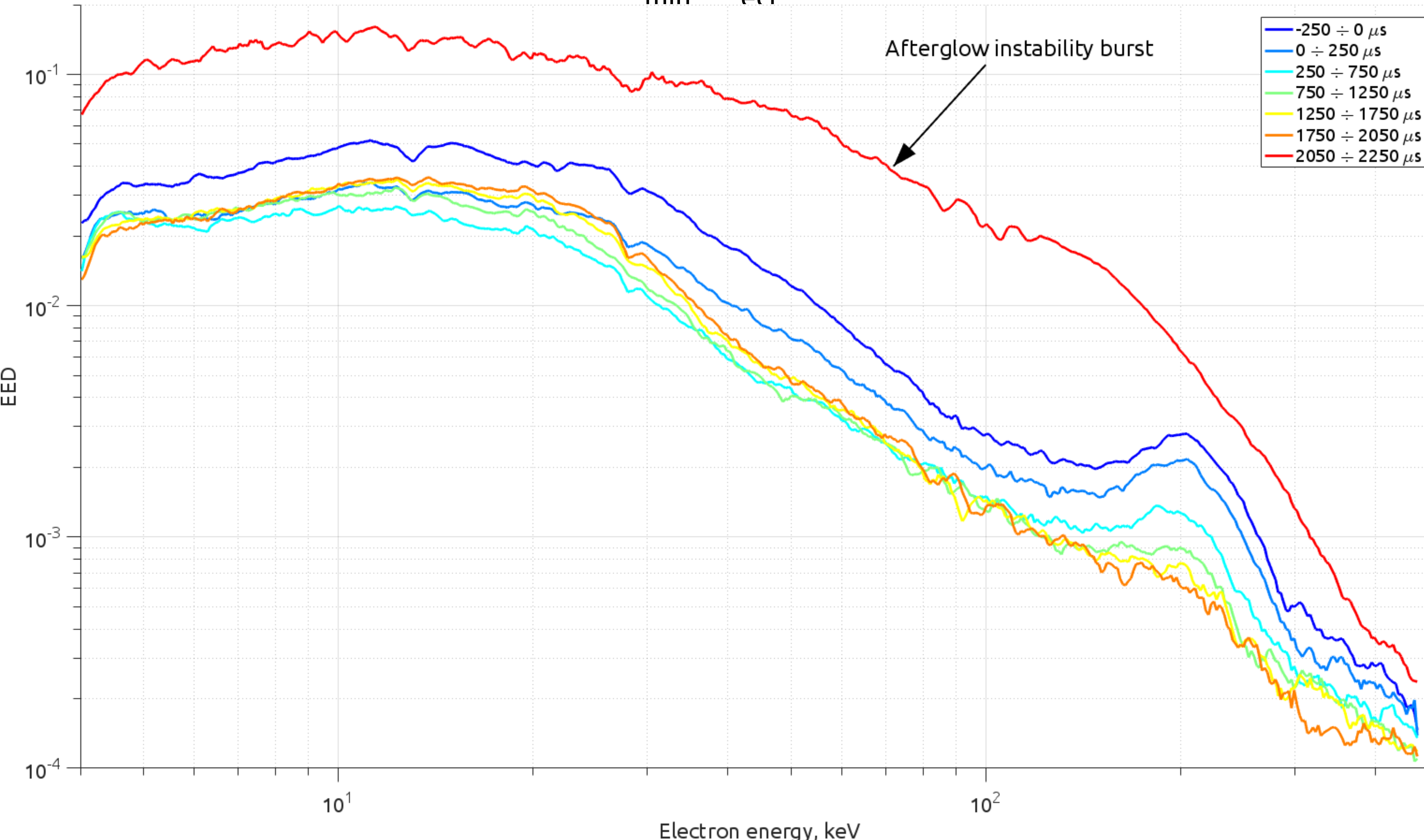

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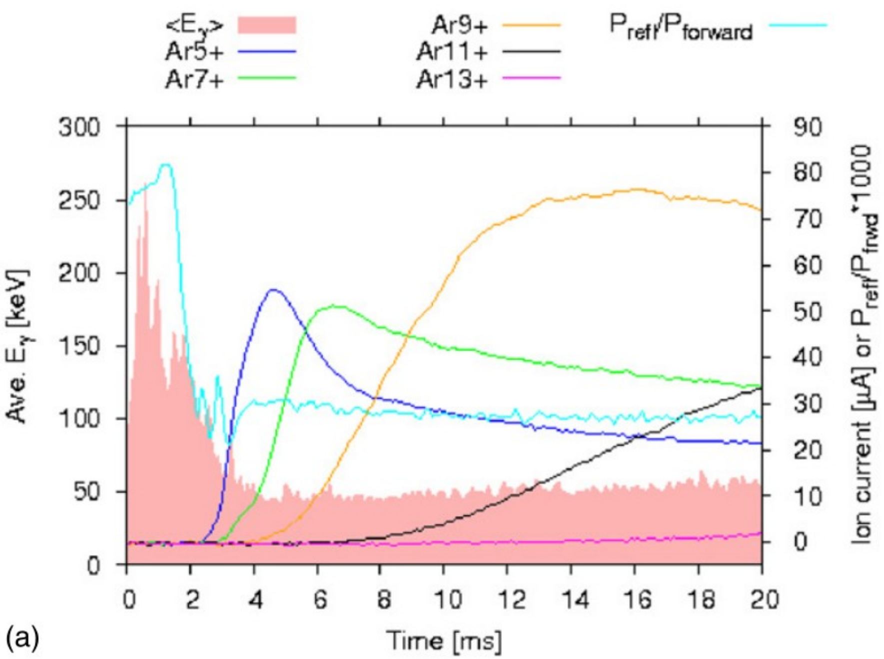

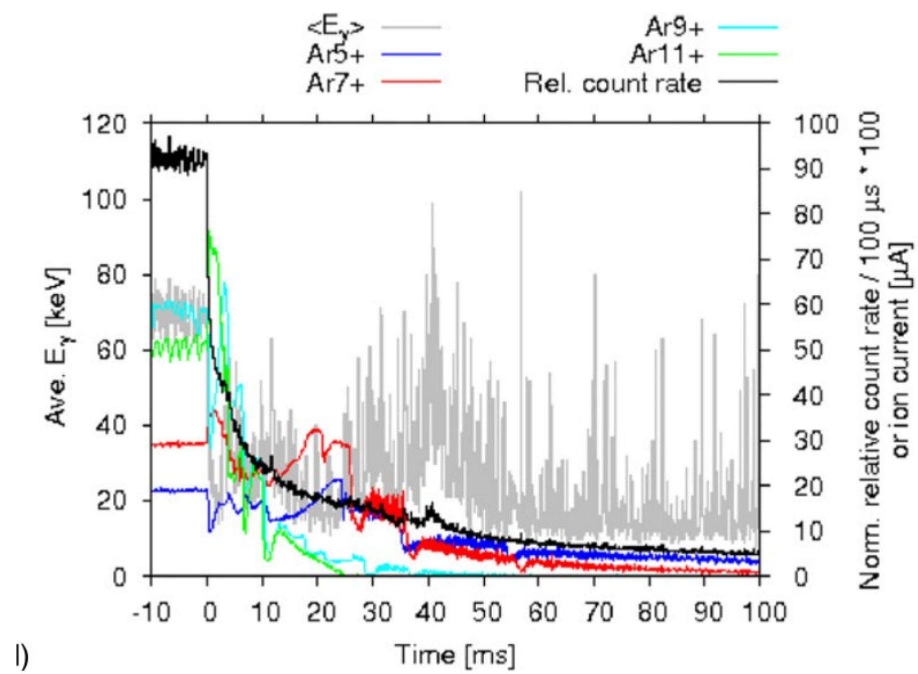

Saturation time of X-ray flux is the same as for electrons. However, preglow effect visible on X-Ray spectra and ion current is much shorter than an overshoot of the average energy of electrons.
In the afterglow relative count rate drops immediately after a trailing edge of the heating pulse, as the flow of electrons does → RF scattering, which is especially efective for ~200 keV electrons?

DOI: 10.1088/0963-0252/20/5/055007

Conclusion

- A simple and robust method of energy spectrometry for electrons escaping ECRIS plasmas has been developed.
- EED of escaped electrons is a powerful diagnostic tool. Though its implementation requires an interruption of a beam line, it gives the real values of electron energies. Bremsstrahlung “temperature” is NOT the average energy of electrons (though may be used as qualitative estimation of heating efficiency and maximum energy of electrons).
- Simultaneous measurements of escaping electrons, x-rays and microwave emission of plasma may be the key to the understanding of a mechanism of kinetic instabilities (theory is under heavy development, exciting results already obtained).
- EED measurement of escaped electrons is able to benchmark existing PIC codes → benchmarked PIC code gives the EEDF ***inside*** the plasma → it might be possible to find an unambiguous correlation between EEDs of escaped and confined electrons.

Thank you!