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# Confinement of highly energetic electron beams in low pressure capacitive discharges

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**The effect of the driving frequency on the confinement of beam electrons and plasma density in low pressure capacitive discharges, PSST published, 2015:**
The dynamics of beams of highly energetic electron play a major role in low pressure capacitively coupled radio frequency discharges. These energetic electrons are accelerated by the modulated plasma sheaths and can reach the opposing sheath without any collisions. Furthermore, they are very important to sustain the plasma because their energy is much higher than the ionization threshold of the neutral gas. The question which arises is: what is the confinement quality at the boundary of the discharge? It is observed that with a certain combination of driving frequency, gap size and pressure, the electron beams can hit the opposing sheath during the sheath collapse. In that case, the beam electrons can overcome the sheath potential and are lost (completely, including their energy) at the electrode. In this work, a frequency variation is investigated by means of Particle-In-Cell simulations. Additionally, the confinement quality is discussed with an analytical model.

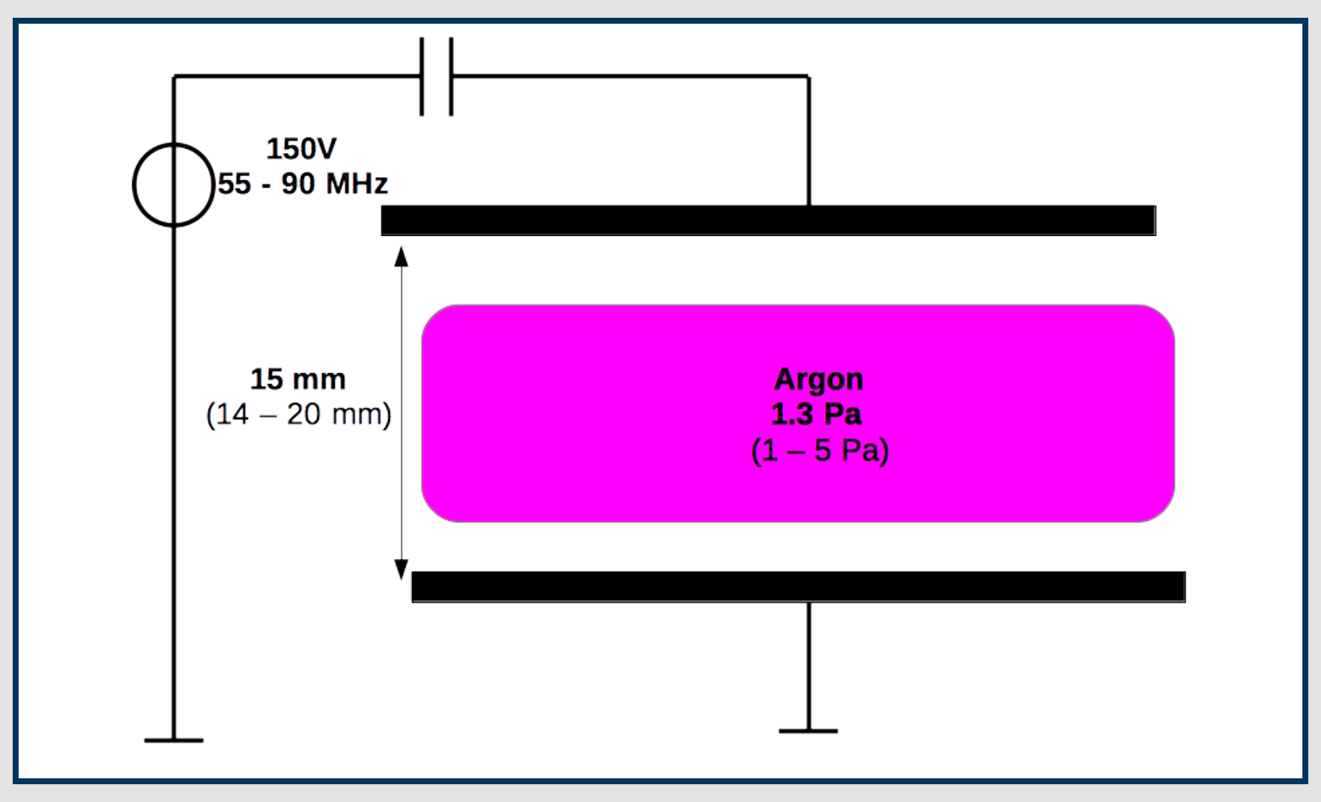
## Simulation and Power Balance Model

**Simulation Model**

- 1d3v Particle-In-Cell code (benchmarked [1])
- three electron-neutral and two ion-neutral collisions [2]

**Power Balance Model** [3]

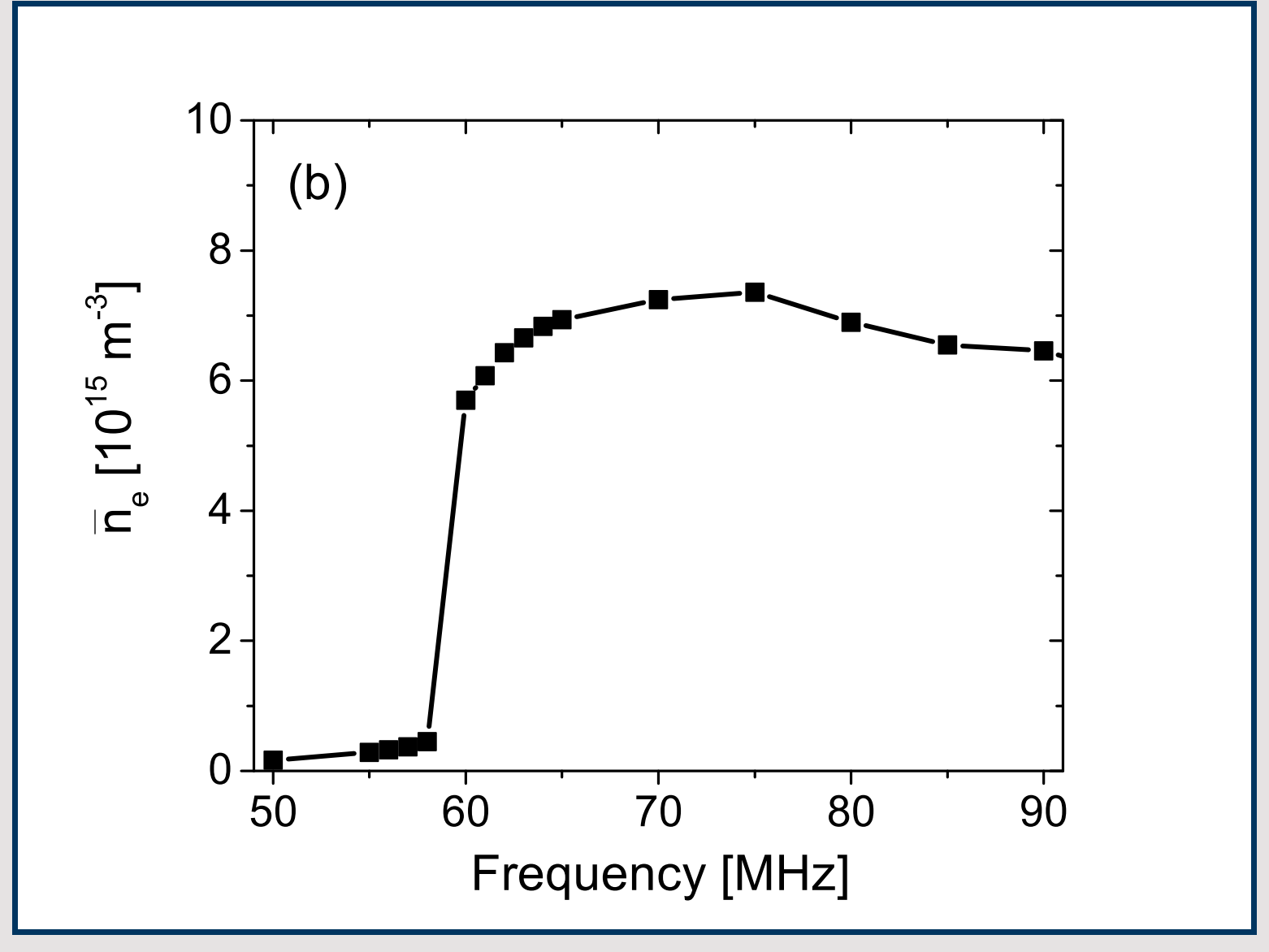
- $S_{\mathrm{abs}} = 2en_{\mathrm{i,el}}u_{\mathrm{i,el}}(\varepsilon_{\mathrm{c}} + \varepsilon_{\mathrm{e}}) \Longrightarrow n_{\mathrm{i,el}} = \frac{S_{\mathrm{abs}}}{2eu_{\mathrm{i,el}}(\varepsilon_{\mathrm{c}}+\varepsilon_{\mathrm{e}})}$
- $S_{\mathrm{abs}}$: total power absorbed by the electrons per area
- $u_{\mathrm{i,el}}$: ion velocity at the electrodes
- $\varepsilon_{\mathrm{c}}$: collisional energy loss per electron-ion pair created
- $\varepsilon_{\mathrm{e}}$: the average energy per electron lost at the electrodes
- $n_{\mathrm{i,el}}$: ion density at the electrodes



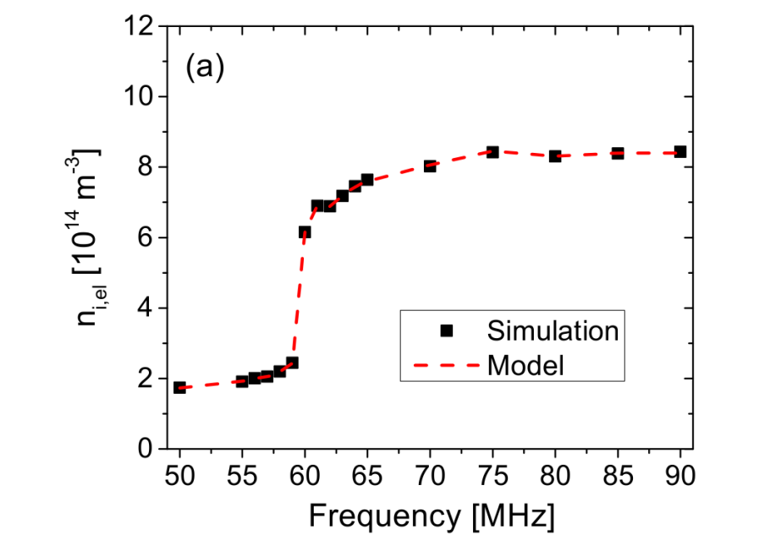
## Frequency Variation

- classical models predict a quadratic dependence of the plasma density on the driving frequency
- considering a collisionless and non-local regime: $\lambda_m/d_{gap} > 1$
- step-like increase of the plasma density by a factor of 13
- occurs between 59 and 60 MHz
- transition from a low density resonant heating mode to the classical $\alpha$-mode
- input parameters of the power balance model are taken from the simulation as a function of the driving frequency
- the power balance model is helpful to understand the physical origin of this abrupt mode transition

**Averaged electron density**

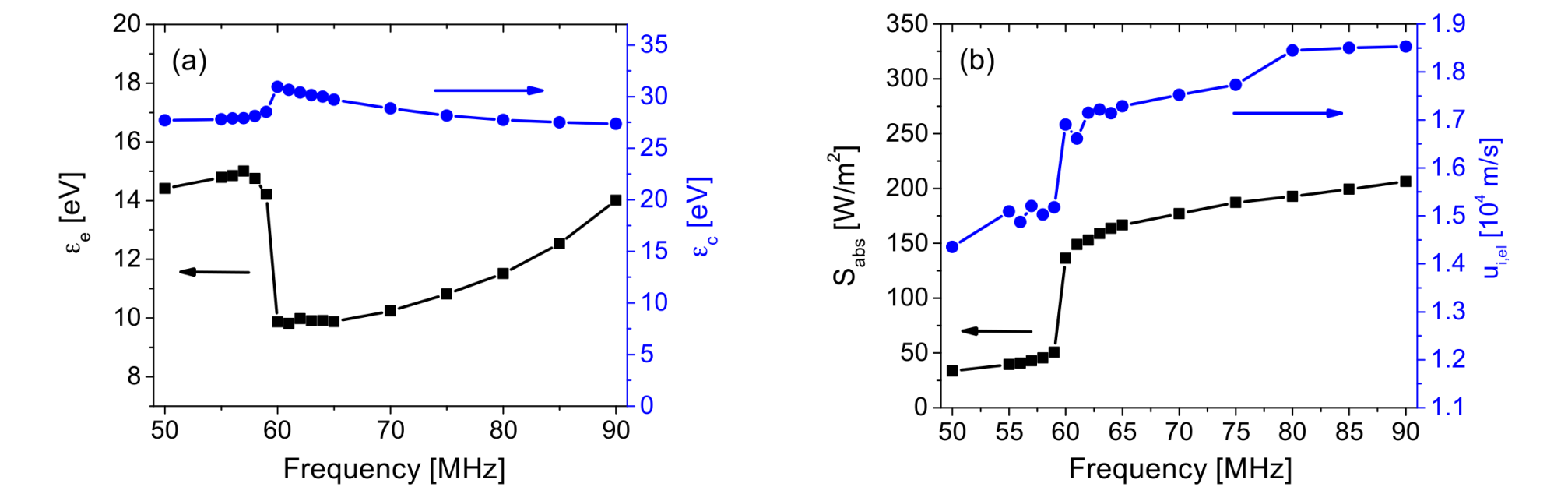


**Model vs. Simulation**
**Ion density at the electrodes**



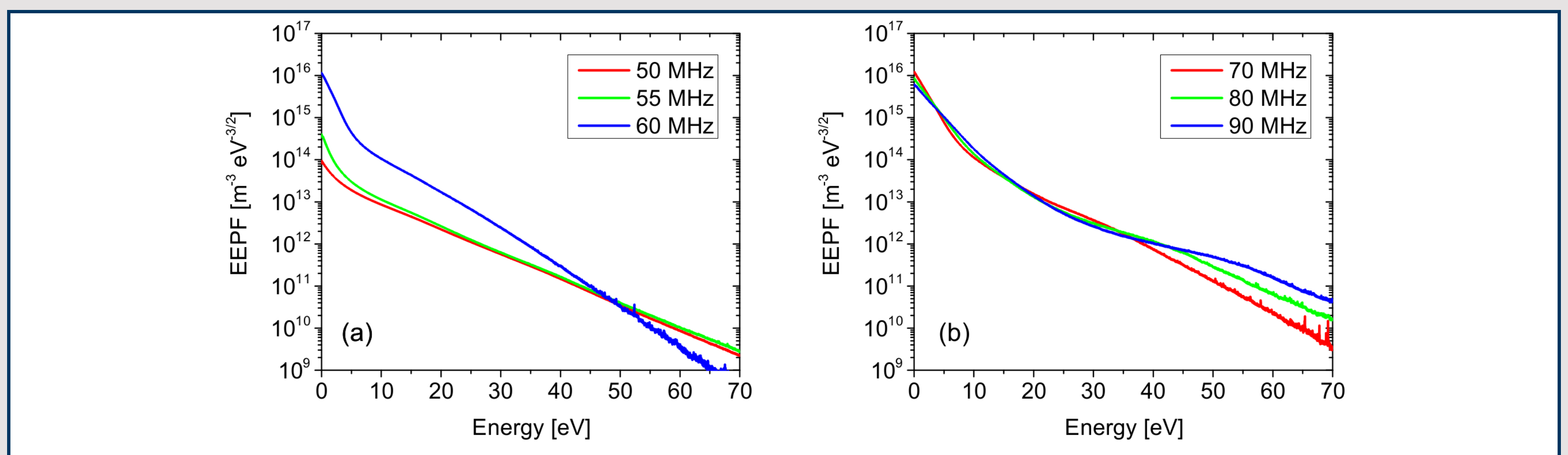
- reproducing the ion density perfectly
- transition is caused by two effects:
- $\Rightarrow$ decrease of $\varepsilon_{\mathrm{e}}$ and increase of $S_{\mathrm{abs}}$

**Parameters from the simulation, used as input for the analytical model**



- the decrease of $\varepsilon_{\mathrm{e}}$ leads to a better confinement of electrons at the electrodes
- electrons dissipate more power via collisions at higher values of $S_{\mathrm{abs}}$
- the spatio-temporal behavior presents a different perspective

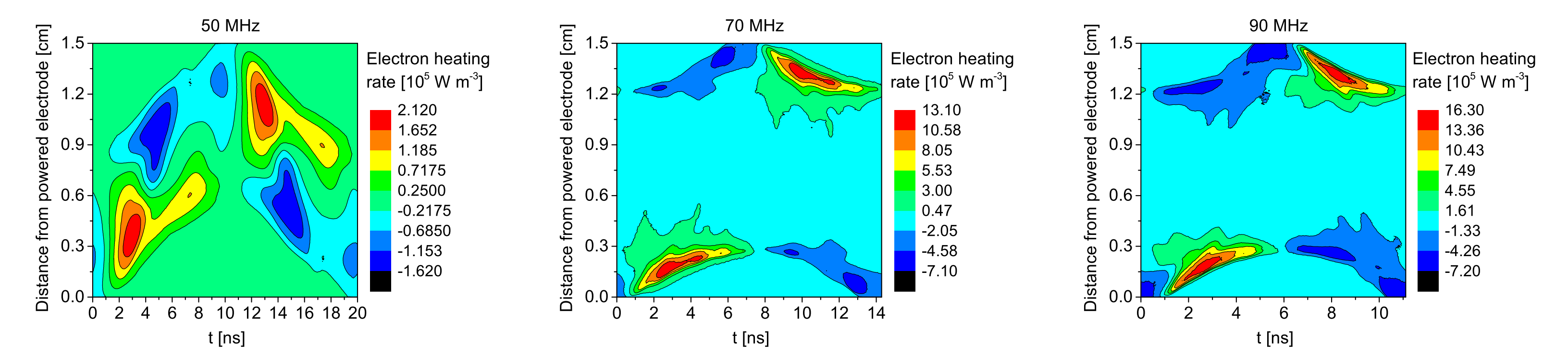
## Electron Energy Probability Function (EEPF)



- electron density is significantly lower at 50 and 55 MHz. However, there are more highly energetic electrons (>50 eV)
- the shape of the EEPF can be controlled by adjusting the frequency (especially the tail of the EEPF)

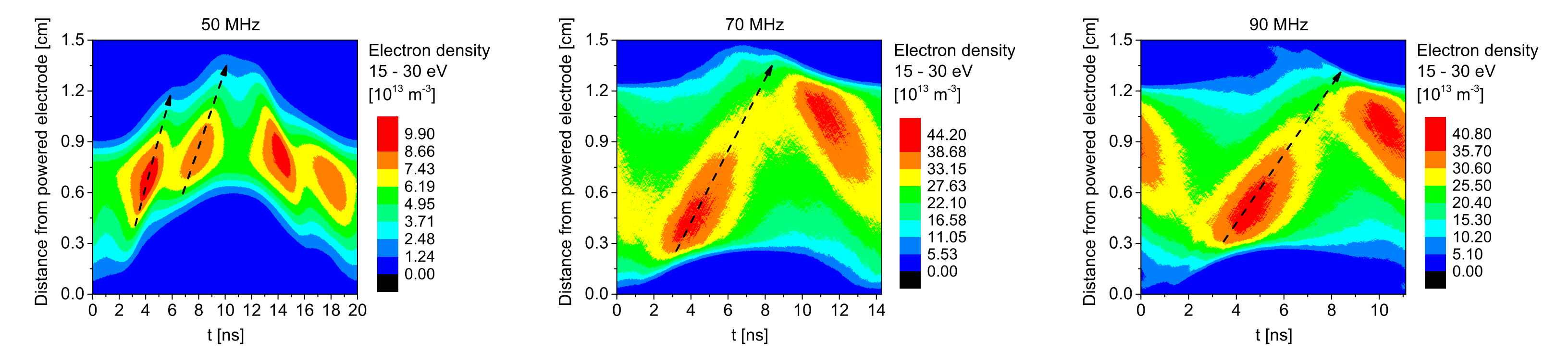
## Spatio-Temporal Results

**Electron heating rate**



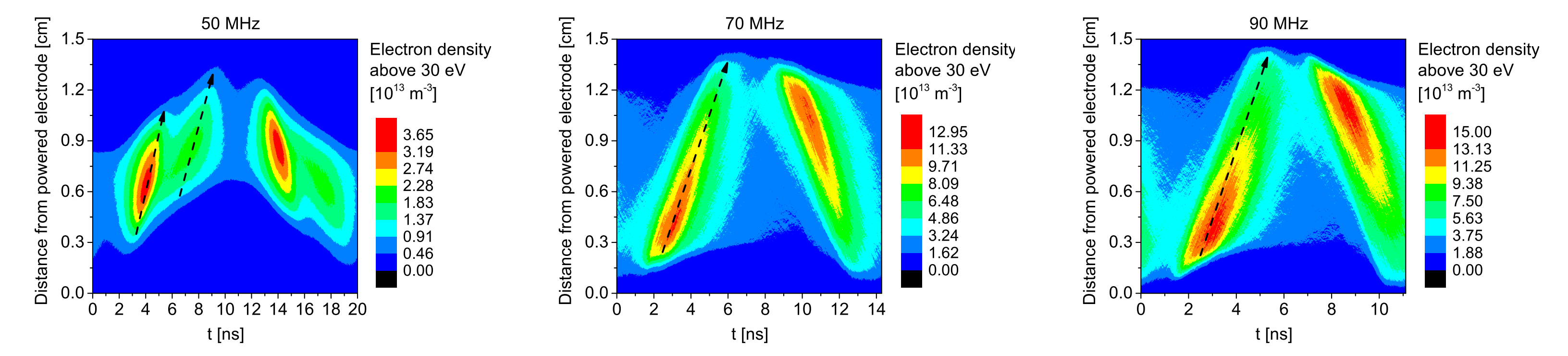
- at low frequencies (50 - 60 MHz) two separated maxima in the electron heating rate are observed
- at higher frequencies smaller plasma sheaths and less cooling is present

**Electron density with energies between 15 and 30 eV**



- in the low density mode, a second beam appears, which hits the opposing sheath during its collapse
- for higher frequencies, electron beams (15 - 30 eV) hit the opposing sheath at different temporal phases

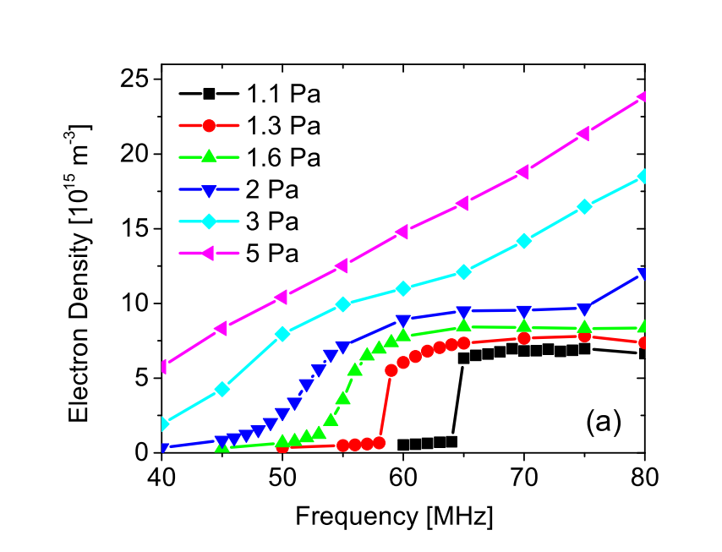
**Electron density with energies above 30 eV**



- highly energetic beam electrons (> 30 eV) always reach the opposing sheath during its collapse
- the fraction of this highly energetic electrons is only a third of the beam electrons with energies less than 30 eV

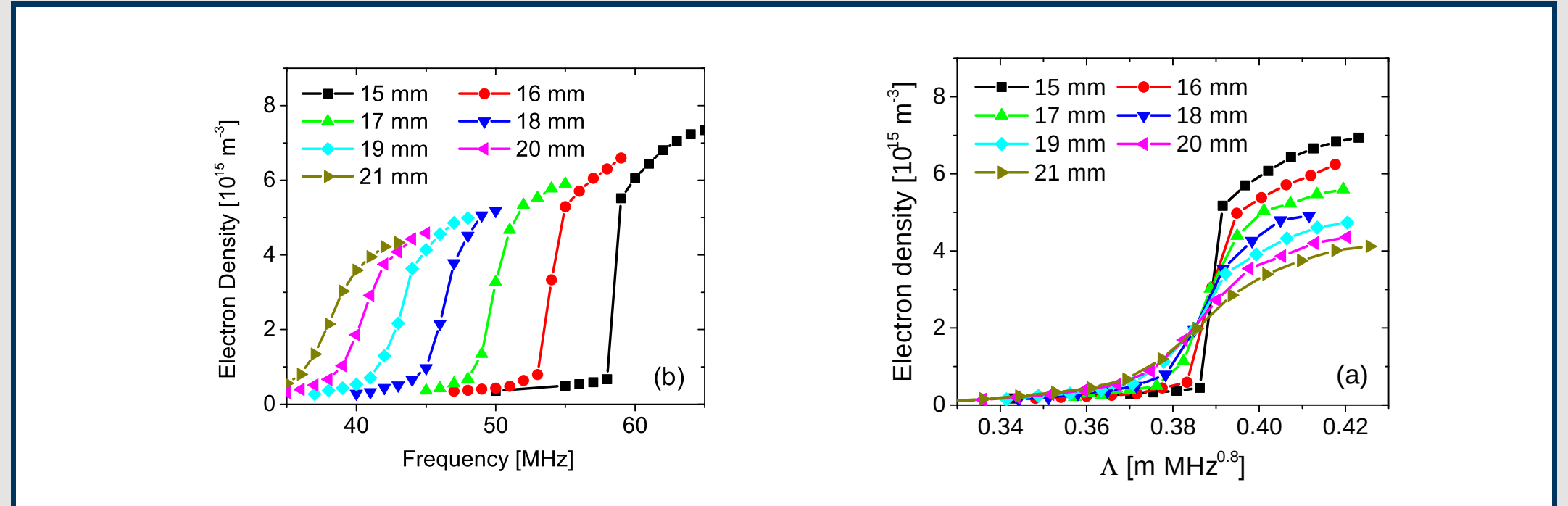
## Parameter Variation

**Pressure dependence**



- $p \uparrow$: transition becomes smoother
- more collisional scattering of electrons
- broader energy distribution of electrons

**Gap size dependence**



- weaker/stronger modulation of the energy lost at the electrodes
- a criterion for the step-like increase at a fixed pressure of 1.3 Pa can be defined
- $d_{gap} \cdot f^{\alpha} \approx \Lambda$, where $\alpha \approx 0.8$, and $\Lambda \approx 0.39$ m MHz$^{0.8}$

**REFERENCES** [1] Turner M M, Derzsi A, Donkó Z, Eremin D, Kelly S J, Lafleur T, and Mussenbrock T 2013 *Physics of Plasmas* **20** 013507; [2] Phelps A V 1994 *J. Appl. Phys.* **76** 747; [3] Lieberman M A and Lichtenberg A J 2005, Principles of Plasma Discharges and Materials Processing, 2nd. ed., Wiley Interscience, NJ: Wiley

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