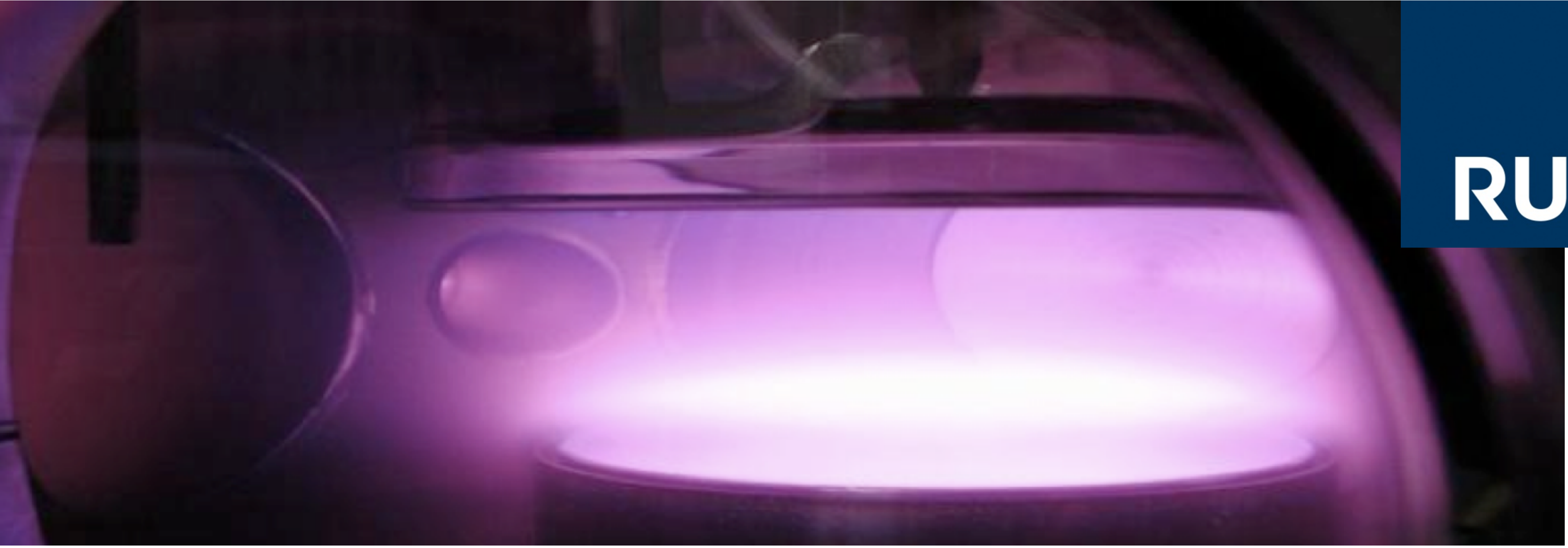


Hysteresis Effects and Confinement of Beam Electrons in Capacitive Discharges

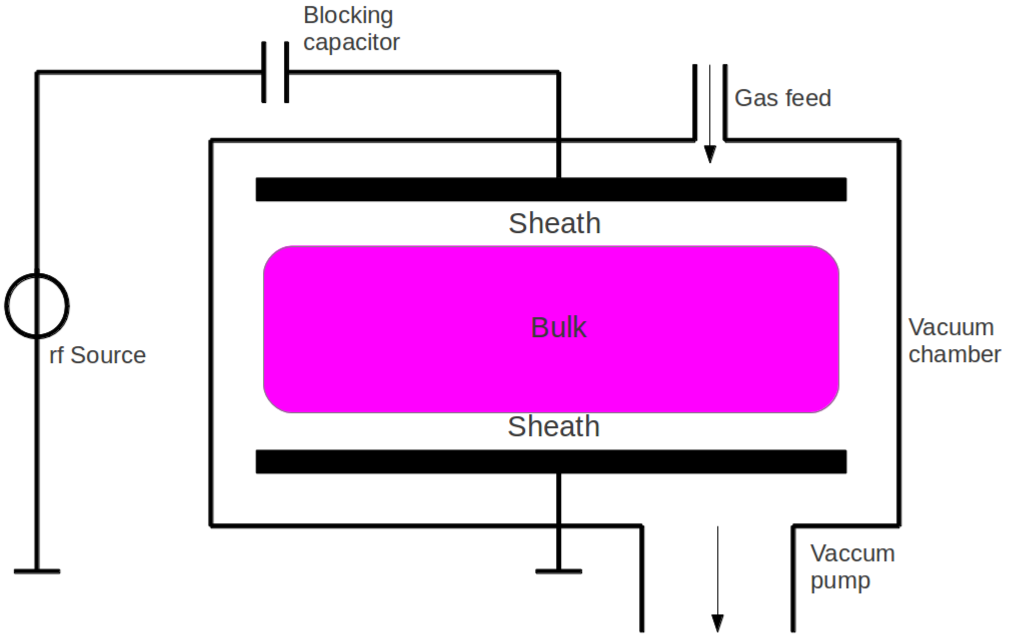
S. Wilczek[1], J. Trieschmann[1], J. Schulze[2], E. Schüngel[2], R. P. Brinkmann[1], A. Derzsi[3], I. Korolov[3], P. Hartmann[3] , Z. Donkó[3], T. Mussenbrock[1]

[1]Ruhr-University Bochum
[2]West Virginia University
[3]Wigner Research Centre for Physics

Outline

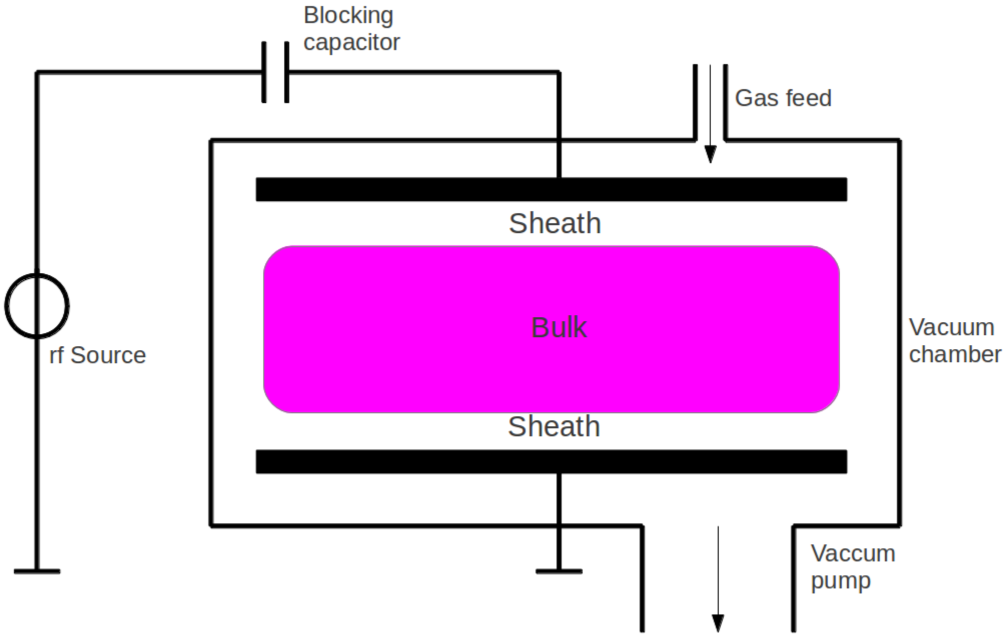
- Motivation: Electron heating and confinement in ccrf discharges
- Electron power balance model
- Particle-In-Cell simulation
- Dynamic and generation of electron beams
- Results: driving frequency variation
- Hysteresis effects
- Conclusion

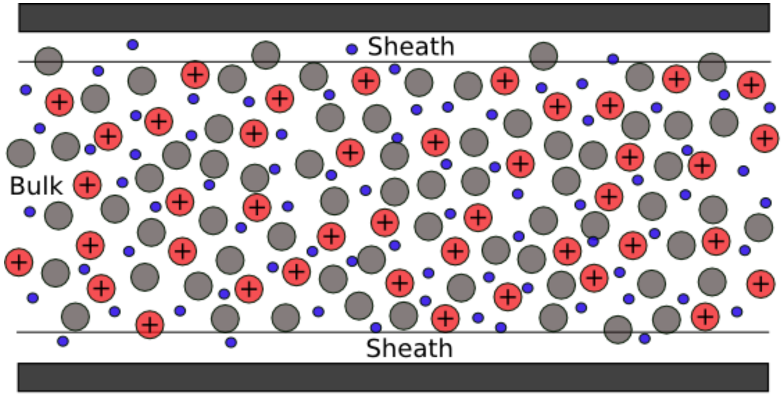
Electron heating in ccrf discharges



- classical capacitively coupled radio frequency discharge
- understand the electron power gain on a nanosecond timescale
- influences the plasma density and the ion flux to the wall
- highly relevant for industrial application

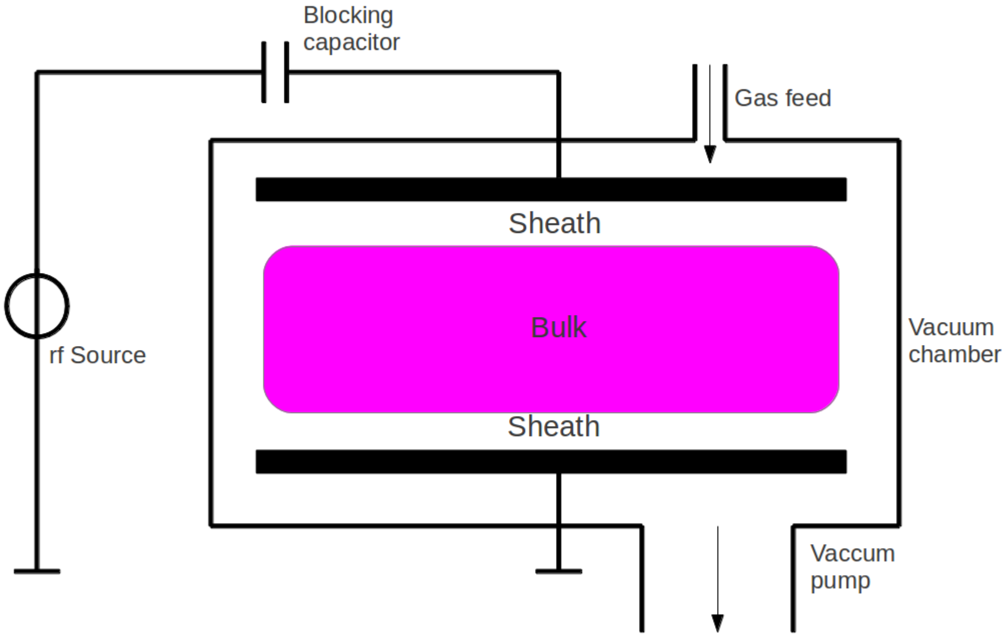
Electron heating in ccrf discharges (high pressure)

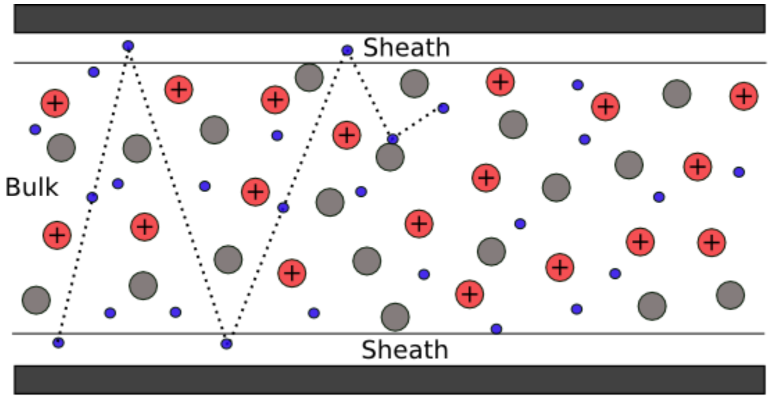




- high pressure regime: p > 10 Pa
- ohmic heating is dominant
- electron-neutral collisions
- electrons can not reach the opposing sheath without collisions ($\lambda_m/L_{gap} \ll 1$)

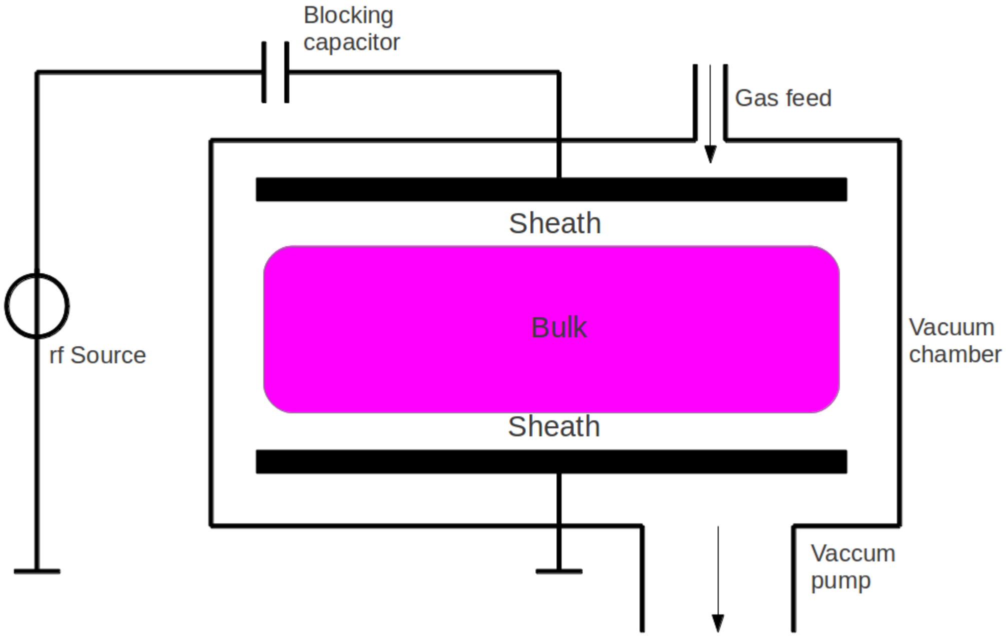
Electron heating in ccrf discharges (low pressure)

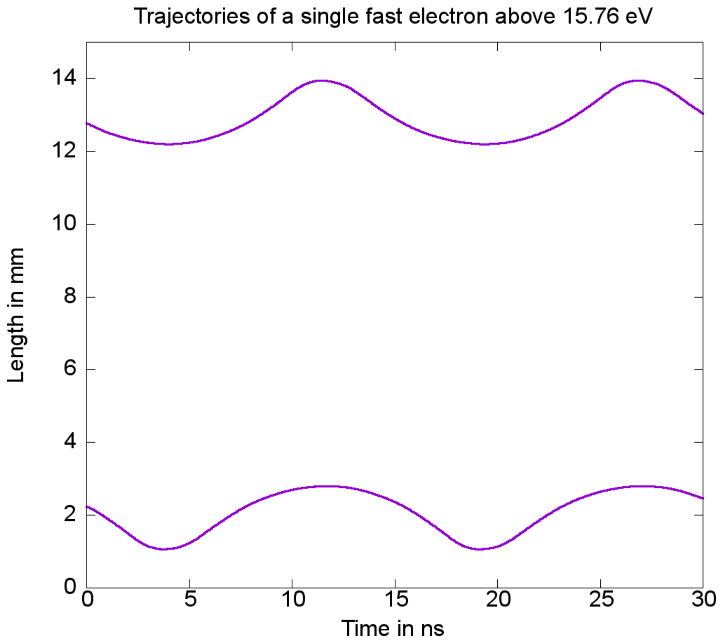




- low pressure regime: $p < 10$ Pa
- stochastic heating is dominant
- electron interaction with the plasma <u>modulated</u> sheath
- impingement phase becomes important ($\lambda_m / L_{gap} > 1$)

Confinement of electrons





- sheath edge[1] modulated by the rf-frequency
- half period shifted at the opposing sheath (symmetric discharge)
- trace electrons by means of 1d3v PIC simulation

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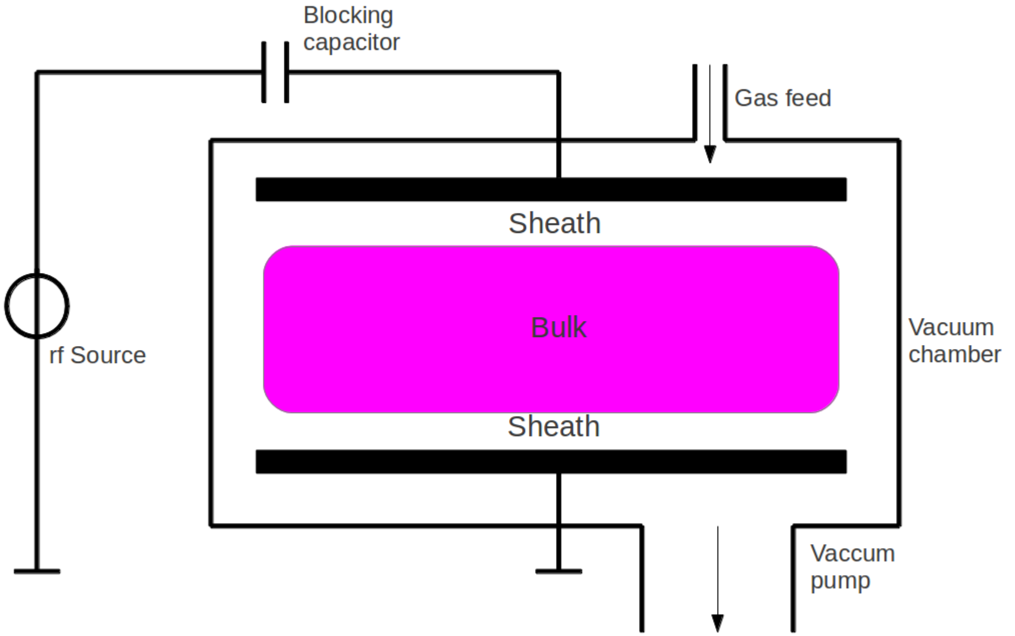
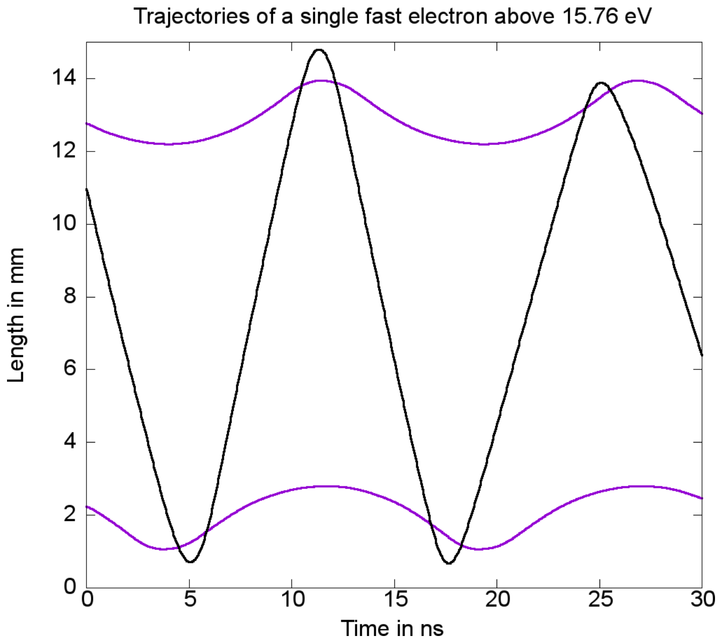
[1] R. P. Brinkmann, J. Appl. Phys. 102, 093302 (2007)

Confinement of electrons





- electron interaction at the rf-modulated boundary sheaths ($\lambda_m/L_{gap} \approx 3$)
- decelerated by hitting the collapsing phase
- gain energy by hitting the expanding phase
- lost at the wall (especially during sheath minimum) <u>critical confinement</u>

Electron power balance model[2]

$$\boxed{S_{\text{abs}} = 2en_{\text{s}}u_{\text{b}}(\varepsilon_{\text{c}} + \varepsilon_{\text{e}})}$$

- S_{abs}: total power absorbed by the electrons per area: $\langle E \cdot J_e \rangle_{t,x}$
- e: elementary charge
- ε_{c}: collisional energy loss per electron-ion pair created
- ε_{e}: the average energy per electron lost at the electrodes
- u_{b}:Bohm velocity
- n_{s}: plasma density at the Bohm point

$$\Longrightarrow \boxed{n_{\text{s}} = \frac{S_{\text{abs}}}{2eu_{\text{b}}(\varepsilon_{\text{c}}+\varepsilon_{\text{e}})}}$$

- $S_{\text{abs}} \sim \omega_{RF}^2$
- $n_{\text{s}} \sim \omega_{RF}^2$
- Correct? What happens if the confinement becomes critical? ($\lambda_m/L_{gap} > 1$)

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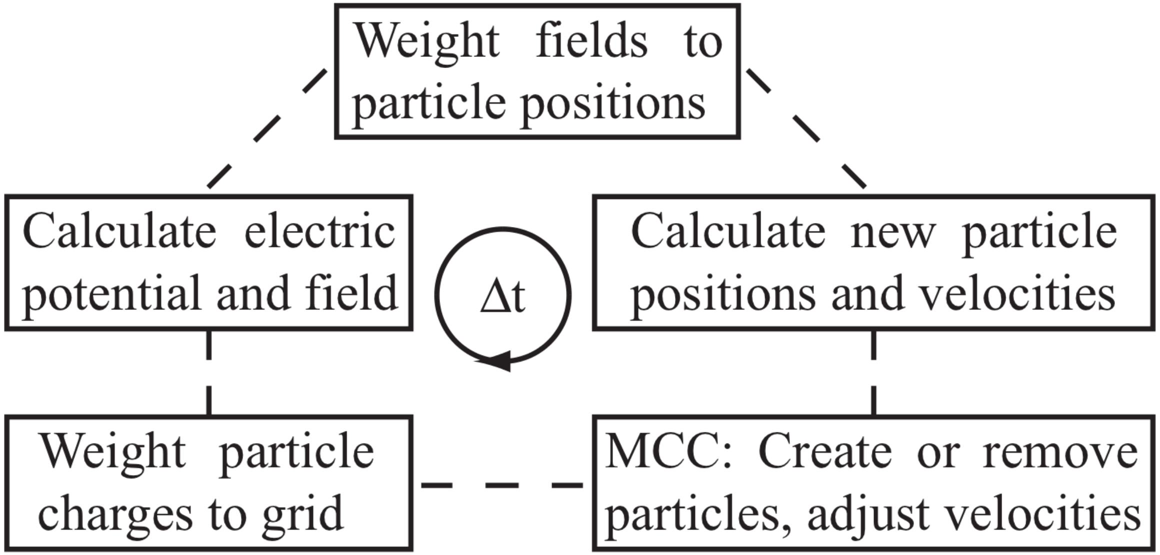
[2] M. A. Liebermann and A. J. Lichtenberg, Principles of Plasma Discharges and Materials Processing (2005)

PIC/MCC Simulation

- 1d3v Particle-In-Cell code (Mussenbrock, Donkó)
- benchmarked against different PIC implementations[3]
- no reflection of particles at the electrodes and no secondary electrons
- argon chemistry, 3 electron-neutral (elastic, excitation, ionization) and 2 ion-neutral (isotropic and backward elastic scattering) collisions


Weight fields to particle positions

Calculate new particle positions and velocities

MCC: Create or remove particles, adjust velocities

Weight particle charges to grid

Calculate electric potential and field

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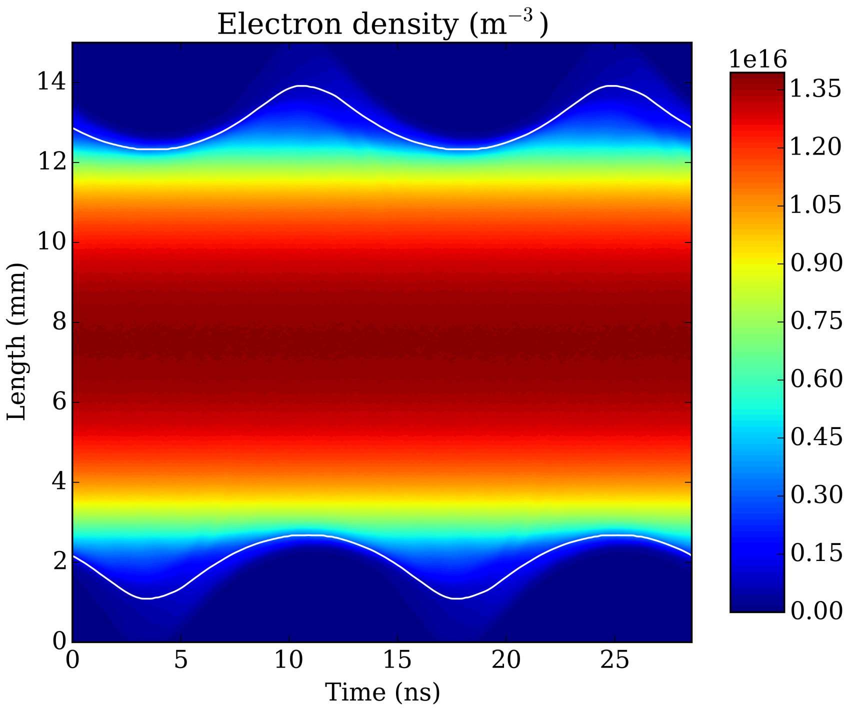
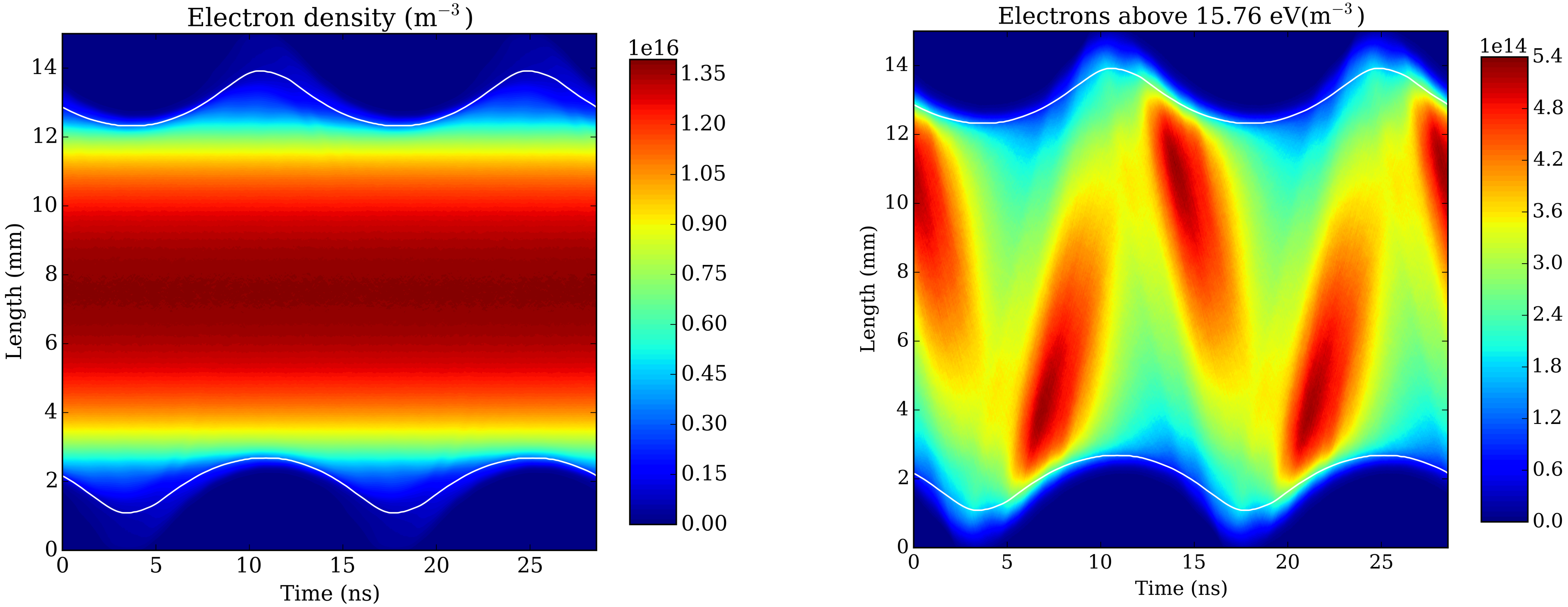
[3] M.M. Turner et. al, Phys. Plasmas 20, 013507 (2013)

Spatio-temporal distribution of the electron density



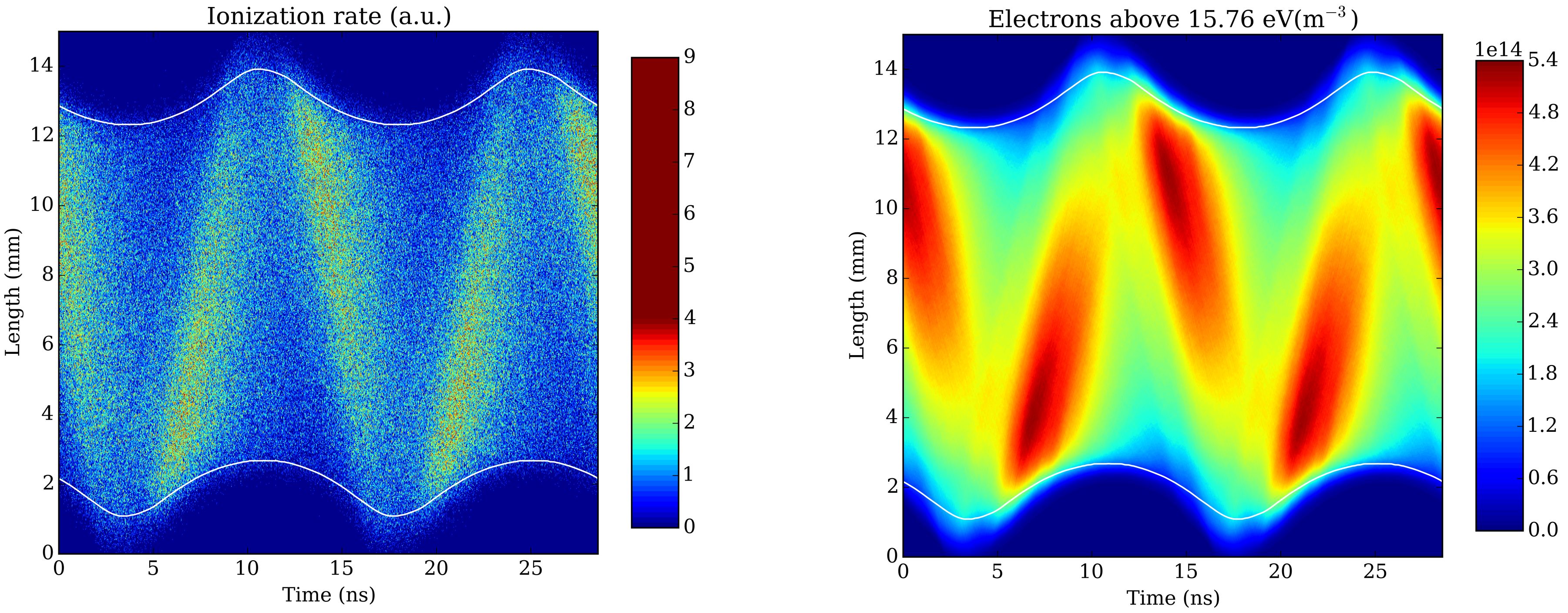
- homogeneous electron density in the plasma bulk
- electrons modulated in the plasma sheath
- which electrons are important for the confinement and for the ionization?

Spatio-temporal distribution of fast electrons (ε > 15.76 eV)



- extract all electrons above 15.76 eV (ionization threshold of argon)
- sheath expansion accelerates energetic electrons
- directed acceleration $\Longrightarrow$ beam-character
- not mono-energetic beam formation!

Spatio-temporal distribution of the ionization rate



- responsible for the ionization process (sustain the plasma)
- influences the plasma density as well as the EEPF
- experimental measurement with PROES[4]

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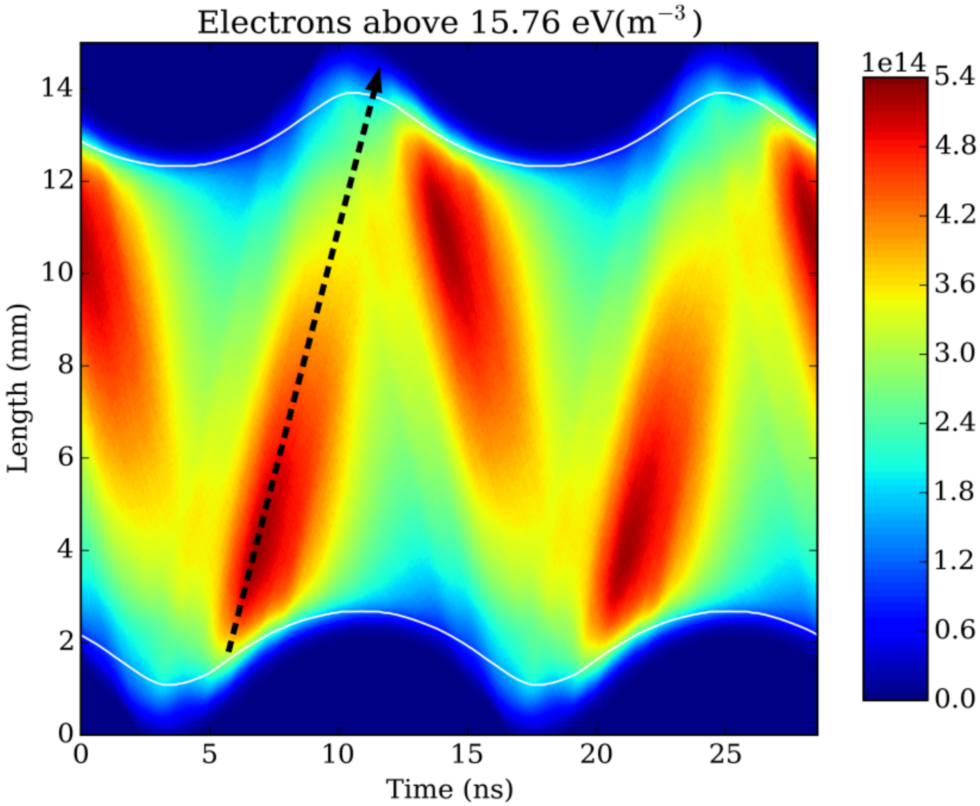
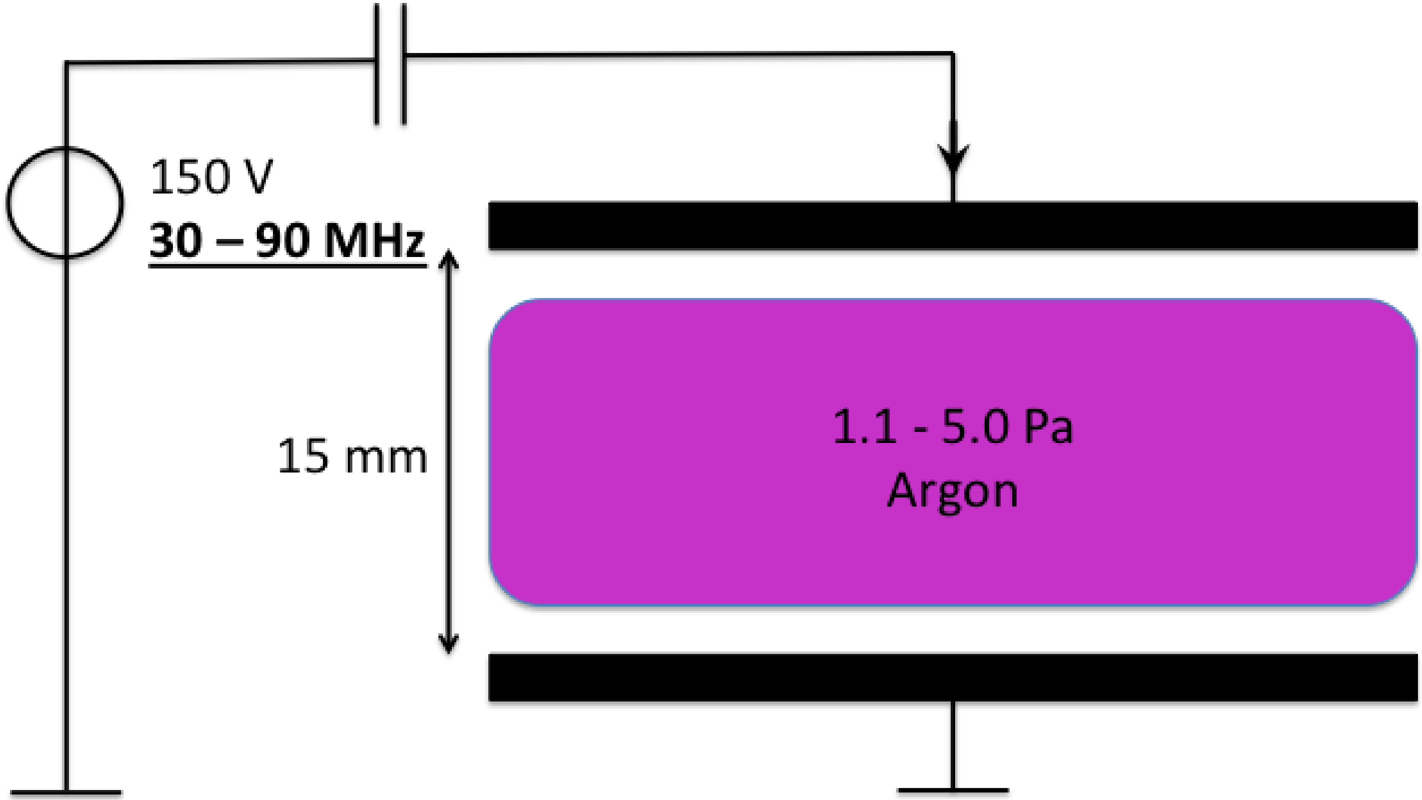
[4] J. Schulze et al., J. Phys. D: Appl. Phys. 41, 042003 (2008)

Goal of this work

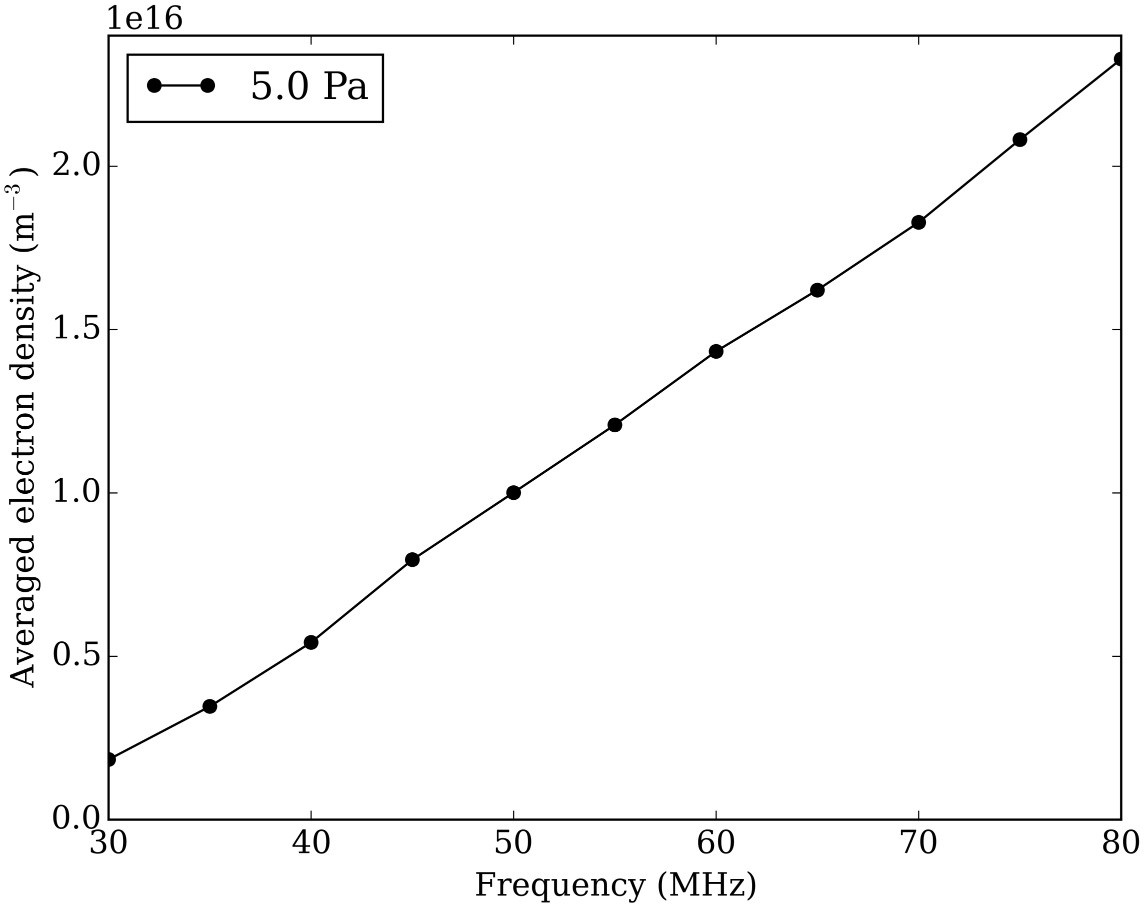
- investigation of the electron confinement at the opposing sheath ($\lambda_m/L_{gap} > 1$)
- study the frequency dependence on the plasma density for non-local regime
- still quadratic dependence? ($n_e \sim \omega_{RF}^2$)



Frequency variation

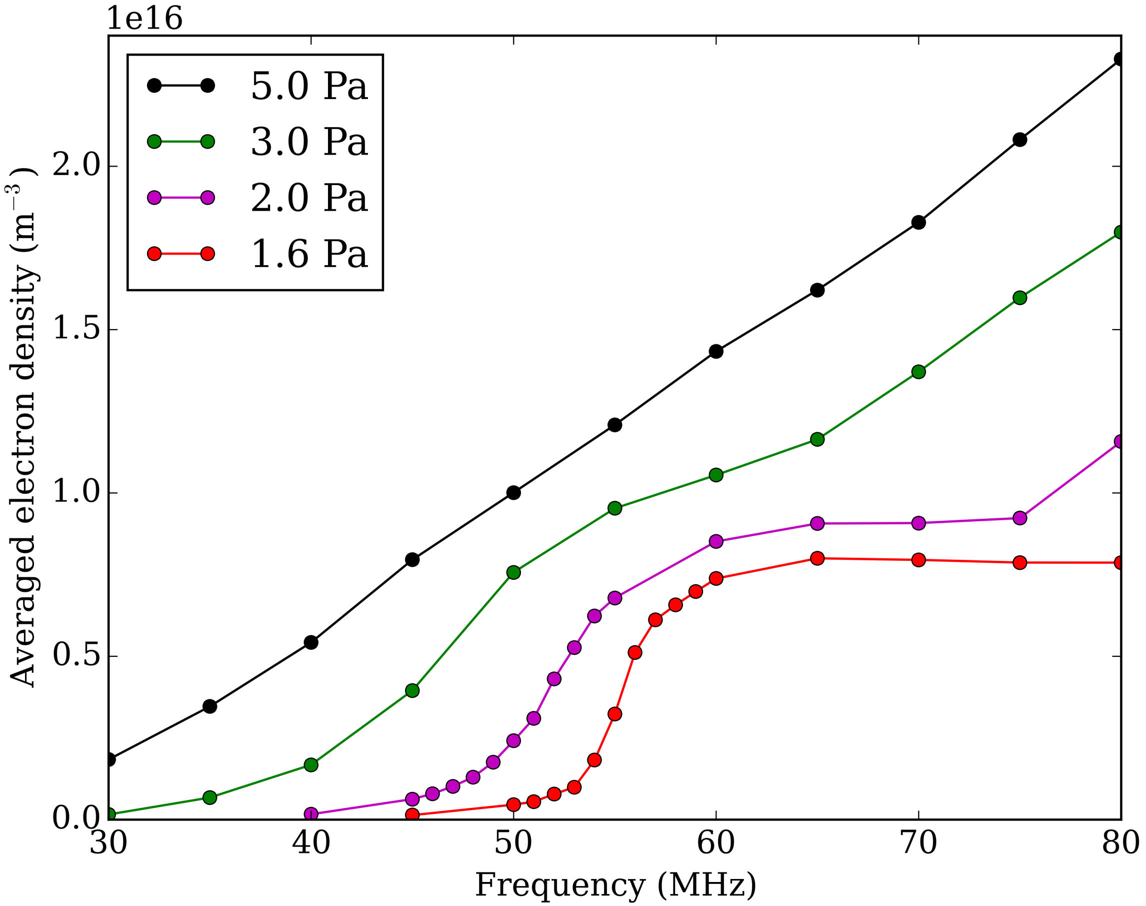


Frequency variation (different pressures)



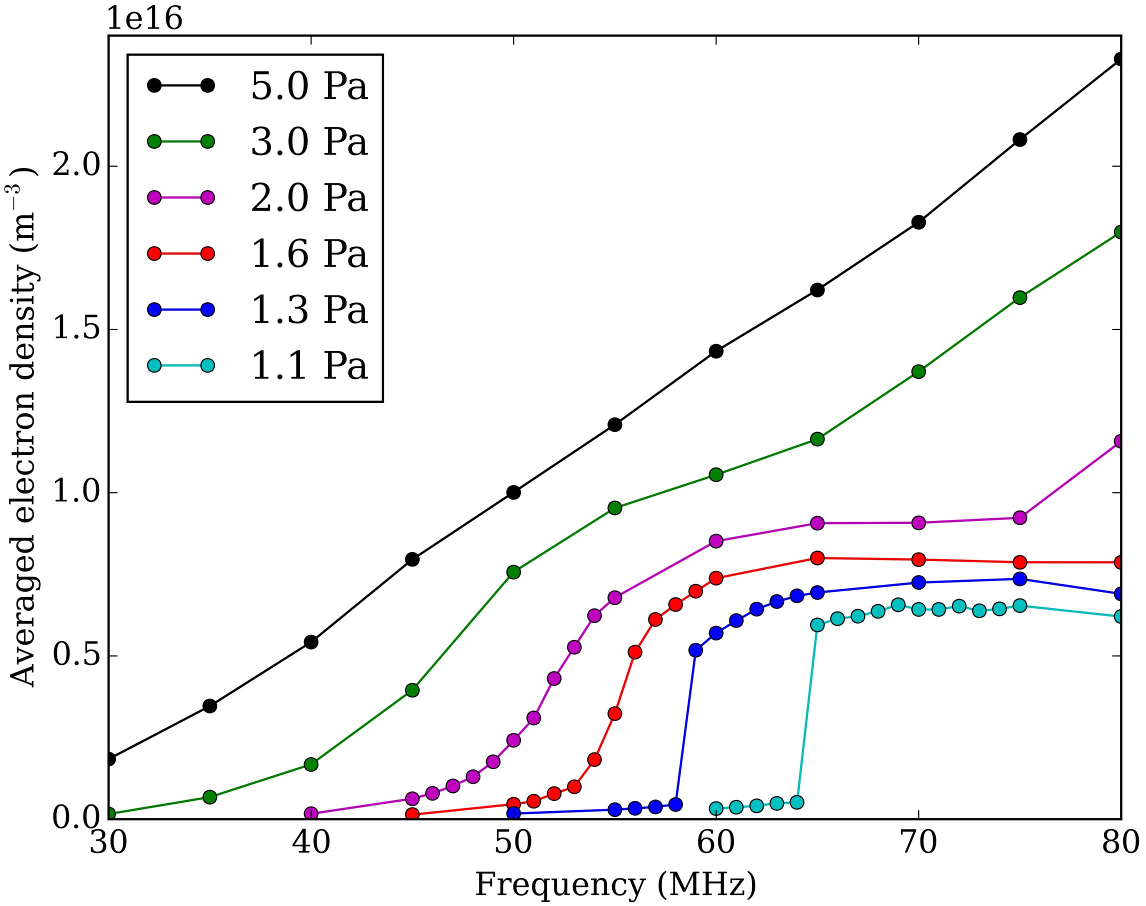
- $\frac{\lambda_m}{L_{gap}} < 1$ interaction with the oppsing sheath is not important
- quadratic trend of the electron density over the driving frequency $(n_e \sim \omega_{RF}^2)$

Frequency variation (different pressures)



- $\frac{\lambda_m}{L_{gap}} \geq 1$ interaction with the opposing sheath becomes important
- density over frequency becomes non-quadratic

Frequency variation (different pressures)



- $\frac{\lambda_m}{L_{gap}} > 2$ beam interaction is significant
- abrupt mode-transition[5] (step-like increase (factor of 13))

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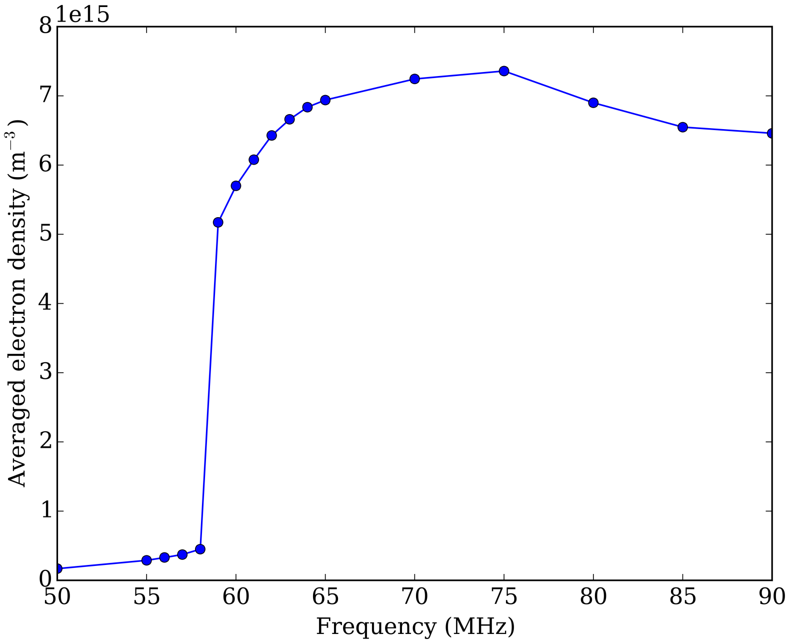
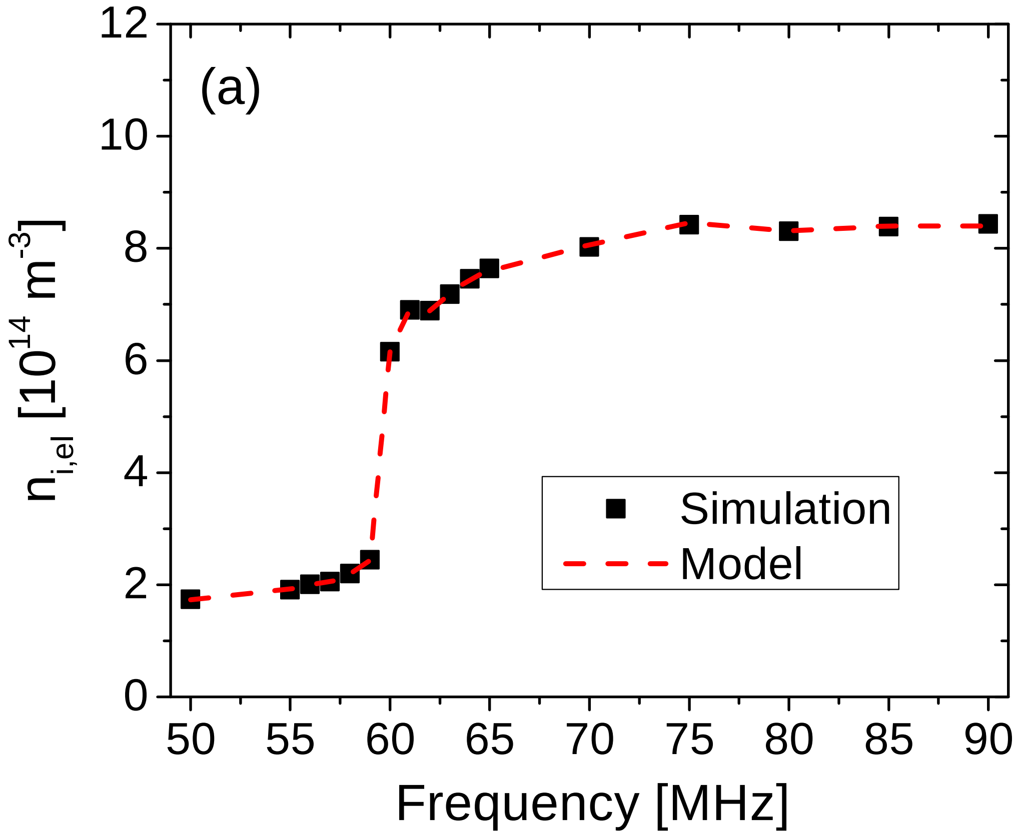
[5] S. Wilczek et. al, Plasma Sources Sci. Technol. 24, 024002 (2015)

Frequency variation: 15 mm, 1.3 Pa, 150 V



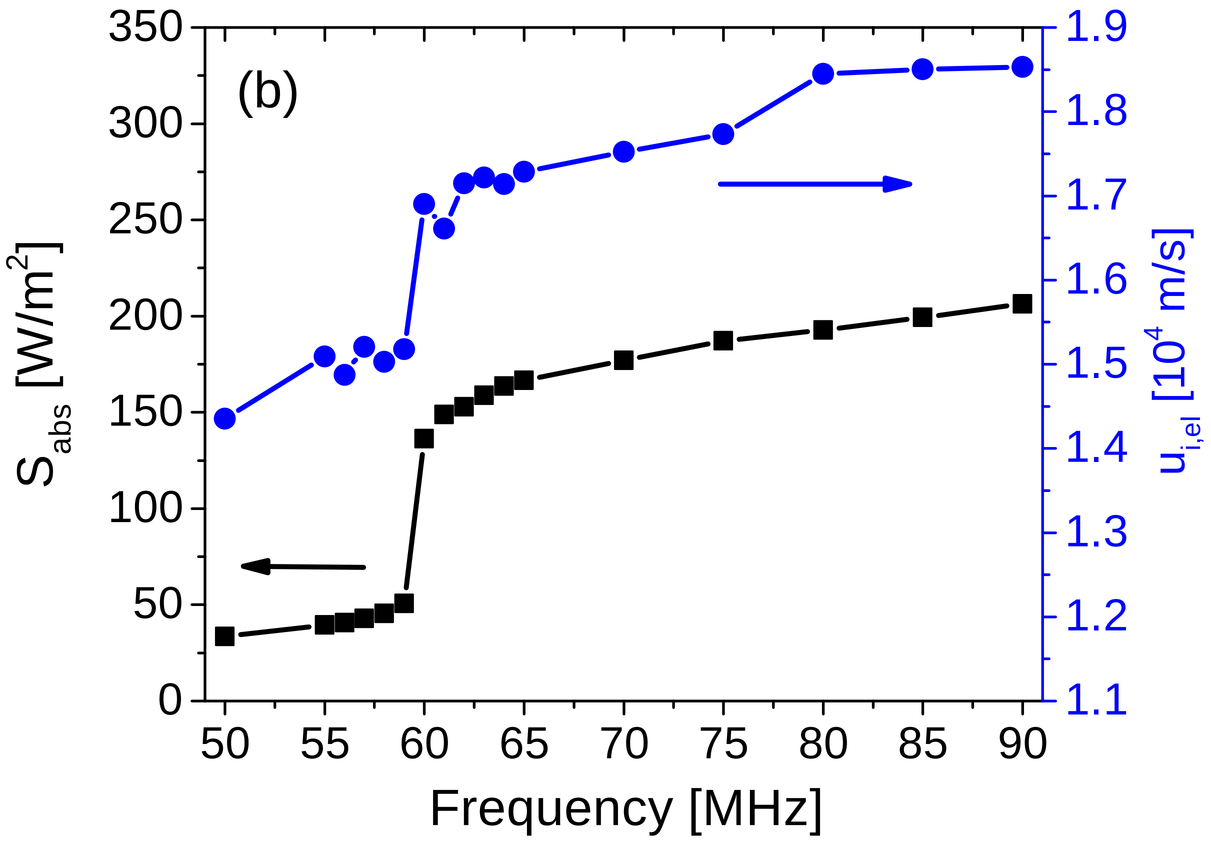
- power balance model in order to find the physical origin of the step-like increase
- $n_\mathrm{s} = \frac{S_\mathrm{abs}}{2eu_\mathrm{b}(\varepsilon_\mathrm{c}+\varepsilon_\mathrm{e})} \Longrightarrow n_\mathrm{i,el} = \frac{S_\mathrm{abs}}{2eu_\mathrm{i,el}(\varepsilon_\mathrm{c}+\varepsilon_\mathrm{e})}$
- flux conservation: $u_\mathrm{b} n_\mathrm{s} = u_\mathrm{i,el} n_\mathrm{i,el}$ (ion density and velocity at the electrode)
- $n_\mathrm{i,el}$: density from the simulation
- $n_\mathrm{i,el}(S_\mathrm{abs}, u_\mathrm{i,el}, \varepsilon_\mathrm{c}, \varepsilon_\mathrm{e})$: input parameters from simulation

Simulation vs. model



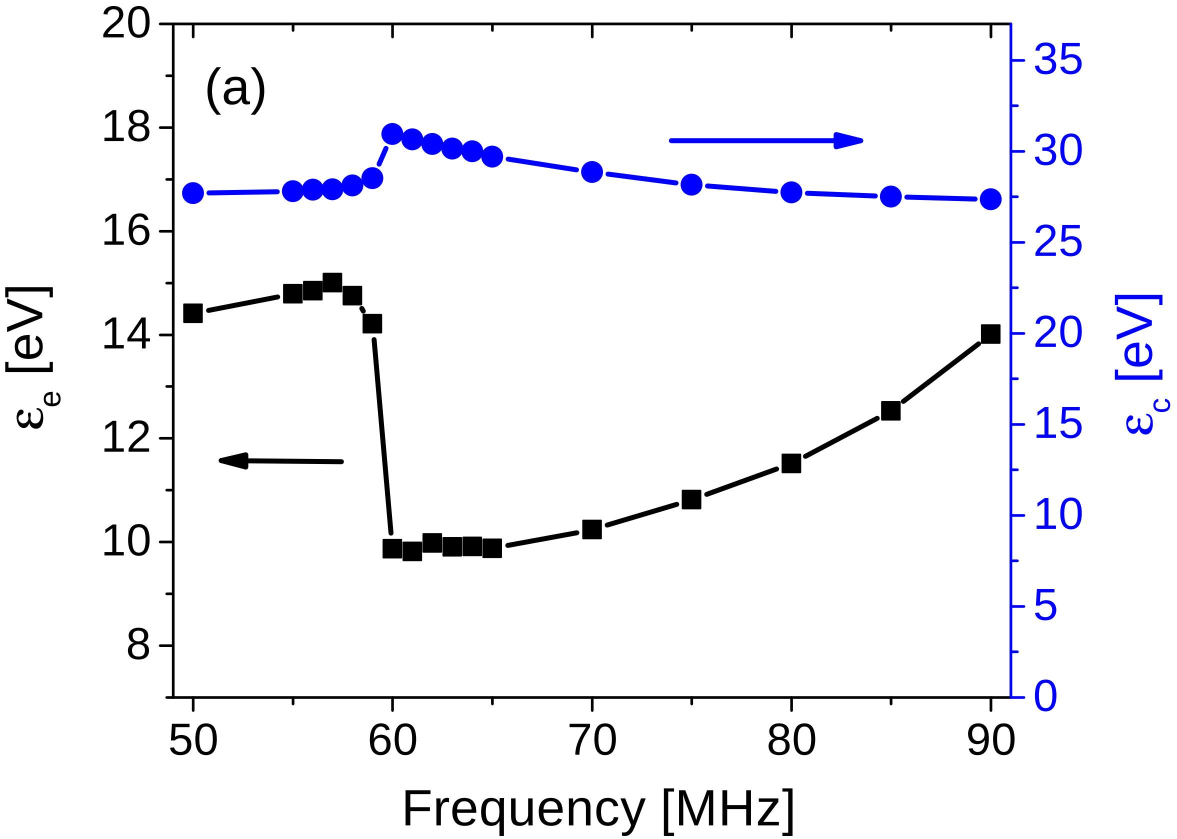
- based on $n_{\mathrm{i,el}} = \frac{S_{\mathrm{abs}}}{2eu_{\mathrm{i,el}}(\varepsilon_{\mathrm{c}}+\varepsilon_{\mathrm{e}})}$, model reproduced the ion density perfectly
- investigate input parameters (S_{abs}, $u_{\mathrm{i,el}}$, ε_{c}, ε_{e})
- high and low density mode

Simulation vs. model



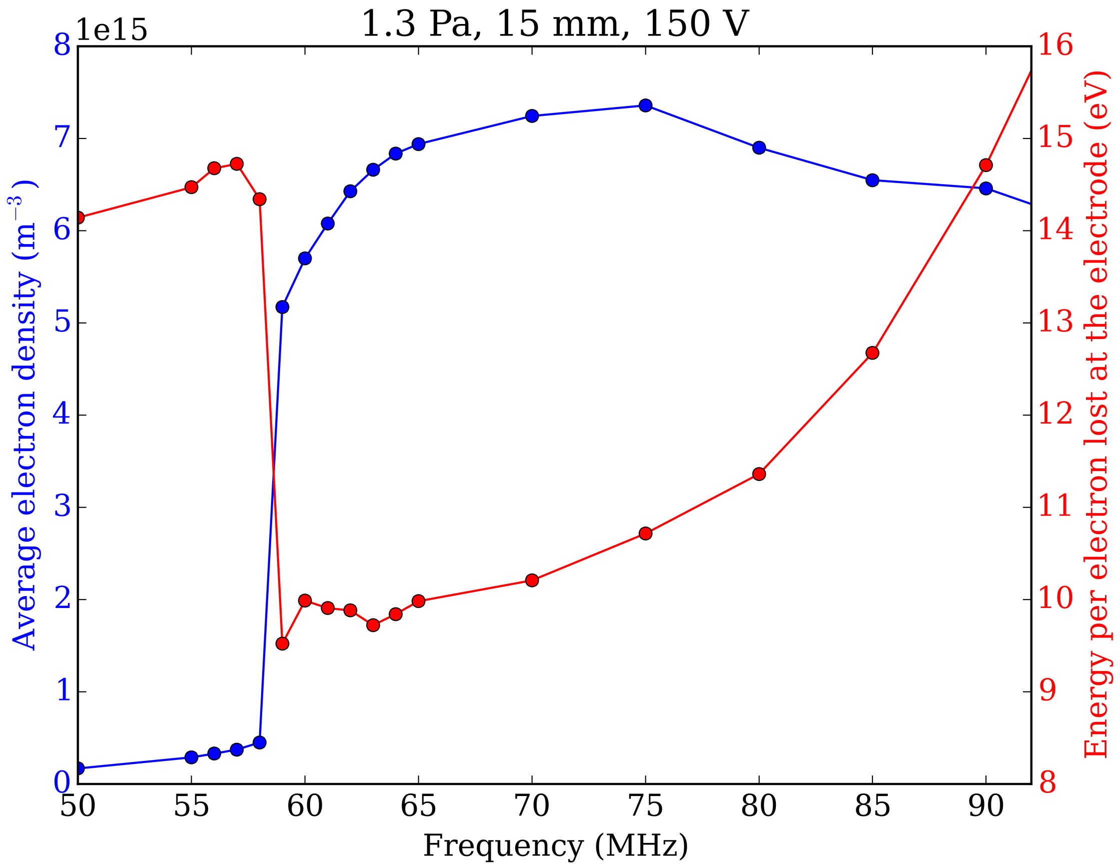
- $n_{\mathrm{i,el}} = \frac{S_{\mathrm{abs}}}{2eu_{\mathrm{i,el}}(\varepsilon_{\mathrm{c}}+\varepsilon_{\mathrm{e}})}$
- ion velocity increases by about 50%, can not lead to increase the density
- total power increases by 3.6, electrons absorb much more power

Simulation vs. model



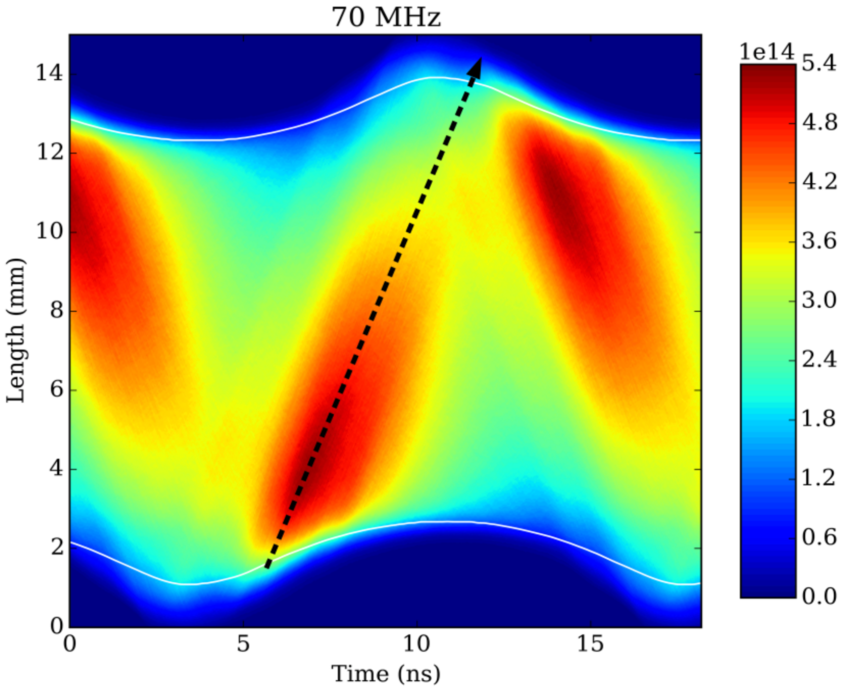
- $n_{i,el} = \frac{S_{abs}}{2eu_{i,el}(\varepsilon_c+\varepsilon_e)}$
- ε_c small increase of 2 eV, can not leas to increase the density
- ε_e significant decrease of 5 eV, drastic enhancement of confinement

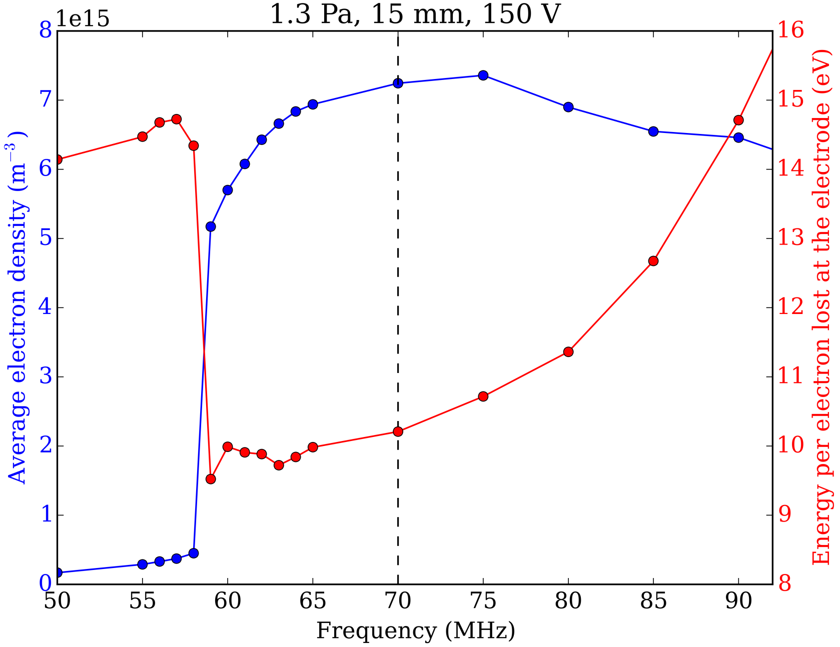
Confinement of beam electrons



- energy per electron lost at the electrode (ε_e) significant factor
- electron power absorption (S_{abs}) significant factor
- compare two cases in detail (70 and 55 MHz)

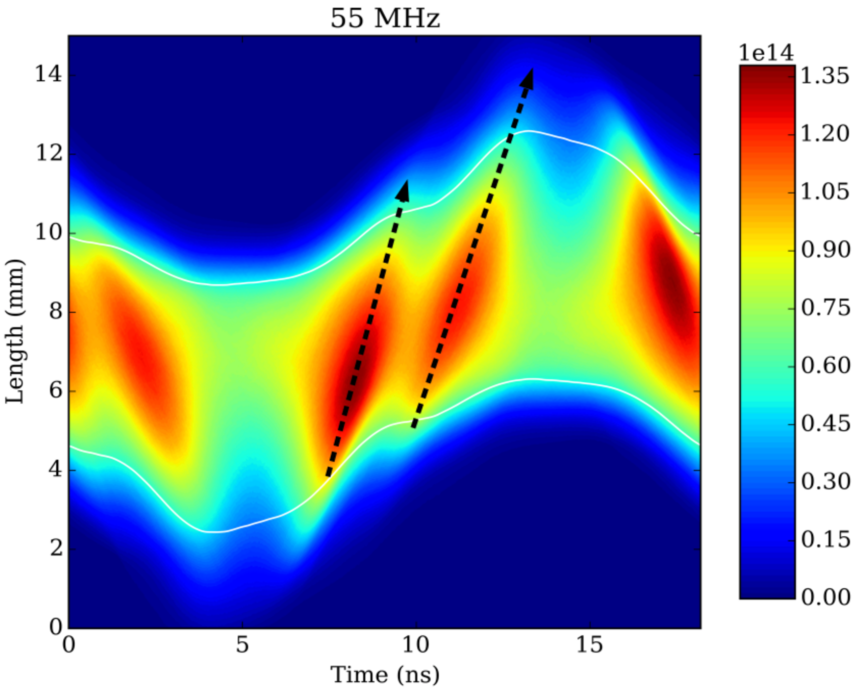
Confinement of beam electrons (ε > 15.76 eV): 70 MHz

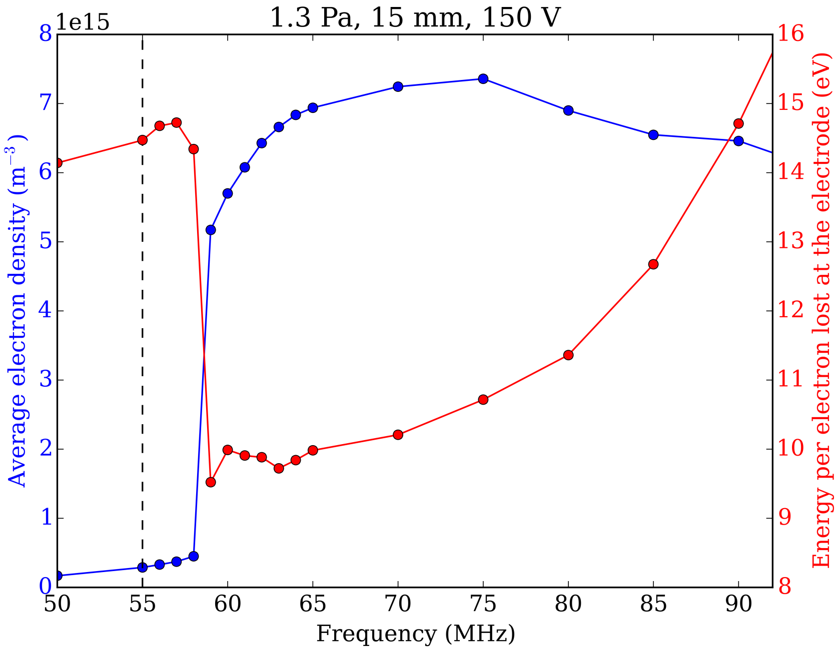




- most of the electron beams reach the beginning of the expanding phase
- good confinement as well as reflection for these electrons
- enhanced power absorption $E \cdot J_e$

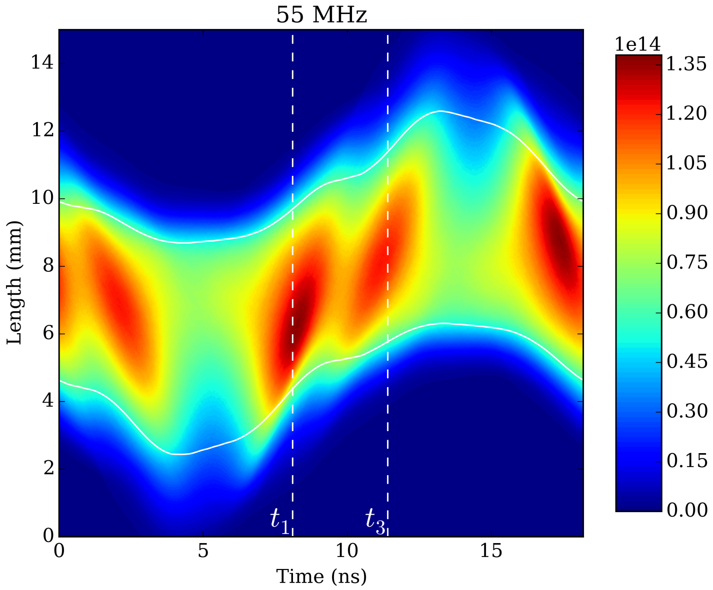
Confinement of beam electrons (ε > 15.76 eV): 55 MHz

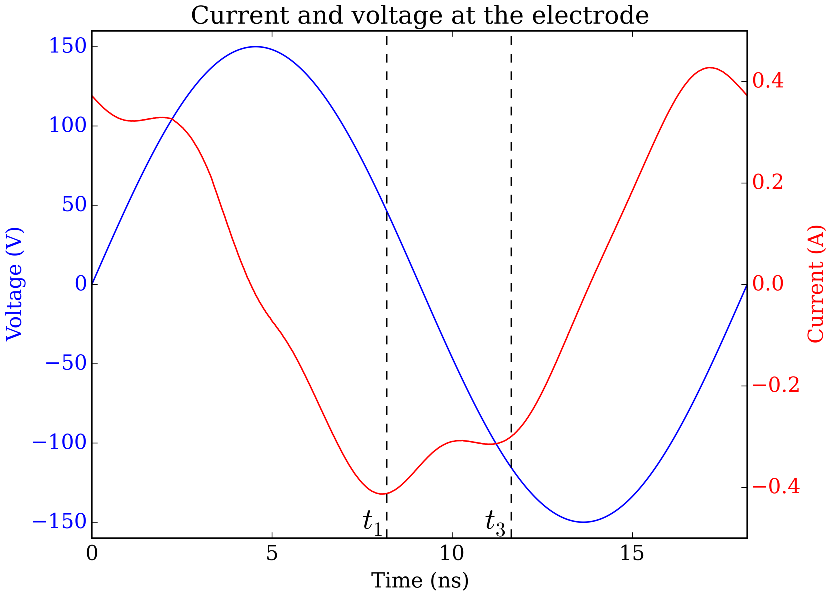




- decreasing the driving frequency $\Longrightarrow$ impingement phase is shifted to the sheath minimum
- abrupt increase of the energy lost (bad confinement) and decrease of the density
- electron beam formation splits up into two beams
- large plasma sheaths and small plasma bulk leads to small ionization regions

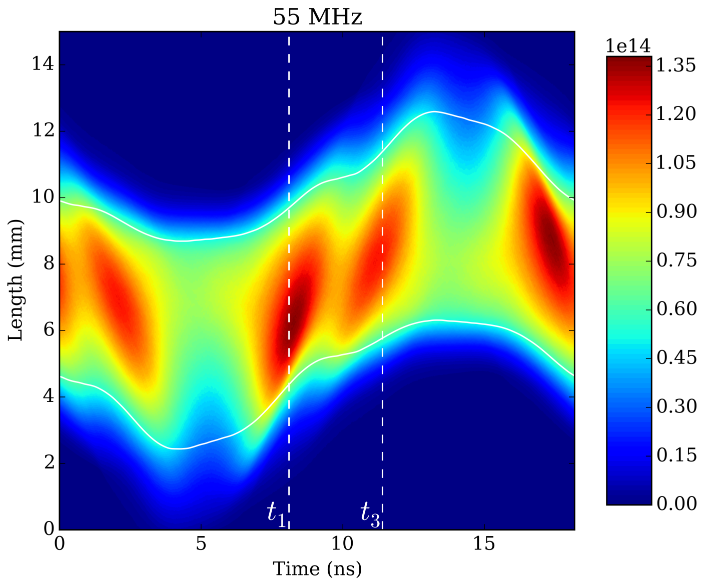
Beam formation: 55 MHz

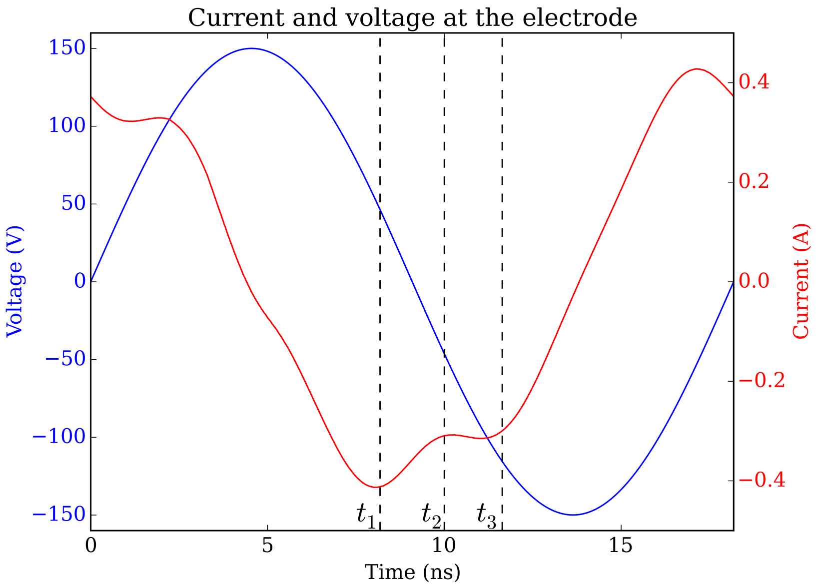


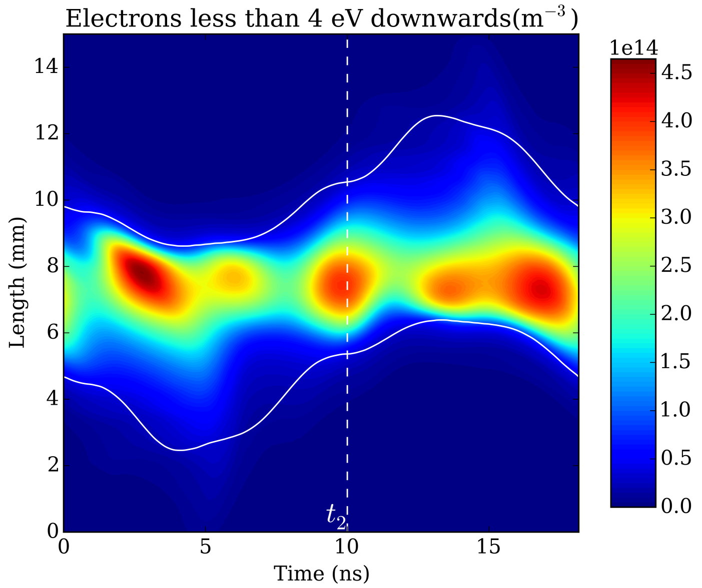


- electron beam formation is connected to the harmonic oscillation of the rf current at the electrode (excitation of plasma series resonance)
- both electron beams represent the two current minima (t_1 and t_3)
- what is the generation of the second electron beam?

Cold bulk vs. hot beam electrons[6]







- first electron beam excites bulk electrons
- cold bulk electrons are attracted back to the sheath due to electric fields generated by the first beam (**timescale:** $1/\omega_{pe}$)
- lead to the generation of the second electron beam

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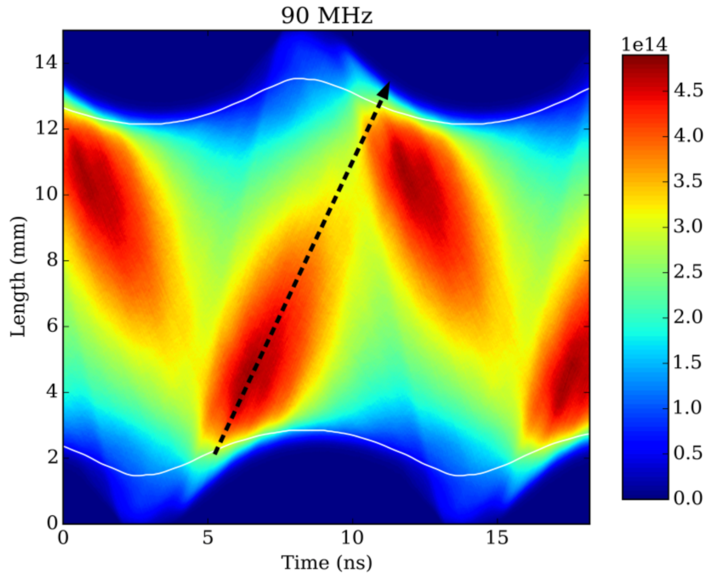
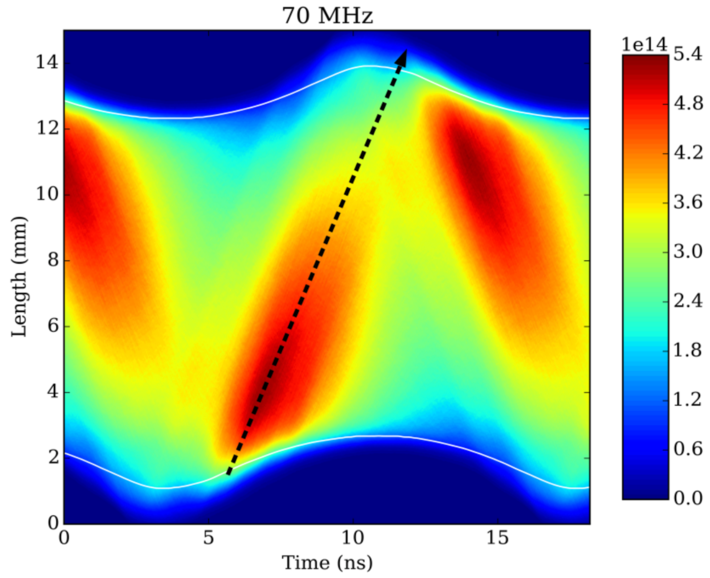
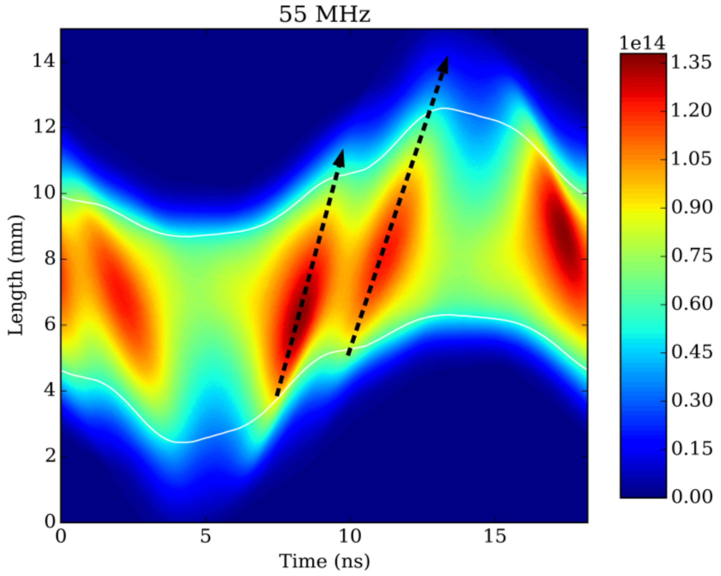
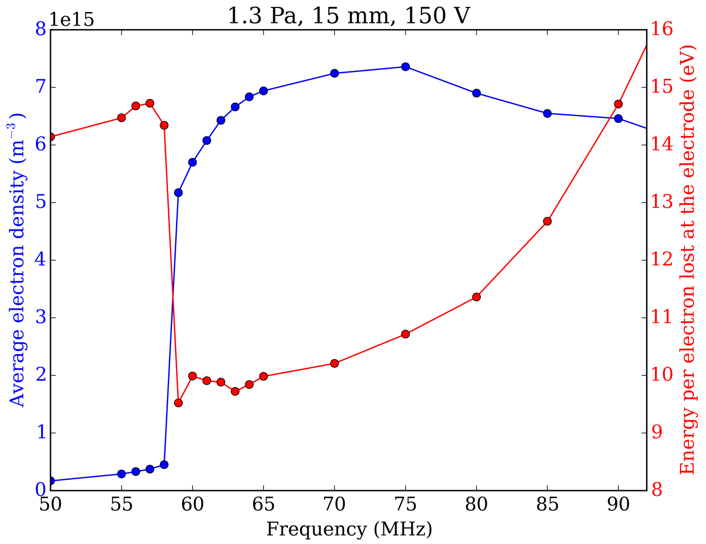
[6] Wilczek et al., Phys. Plasmas. 23, 063514 (2016)

Summary impingement phase

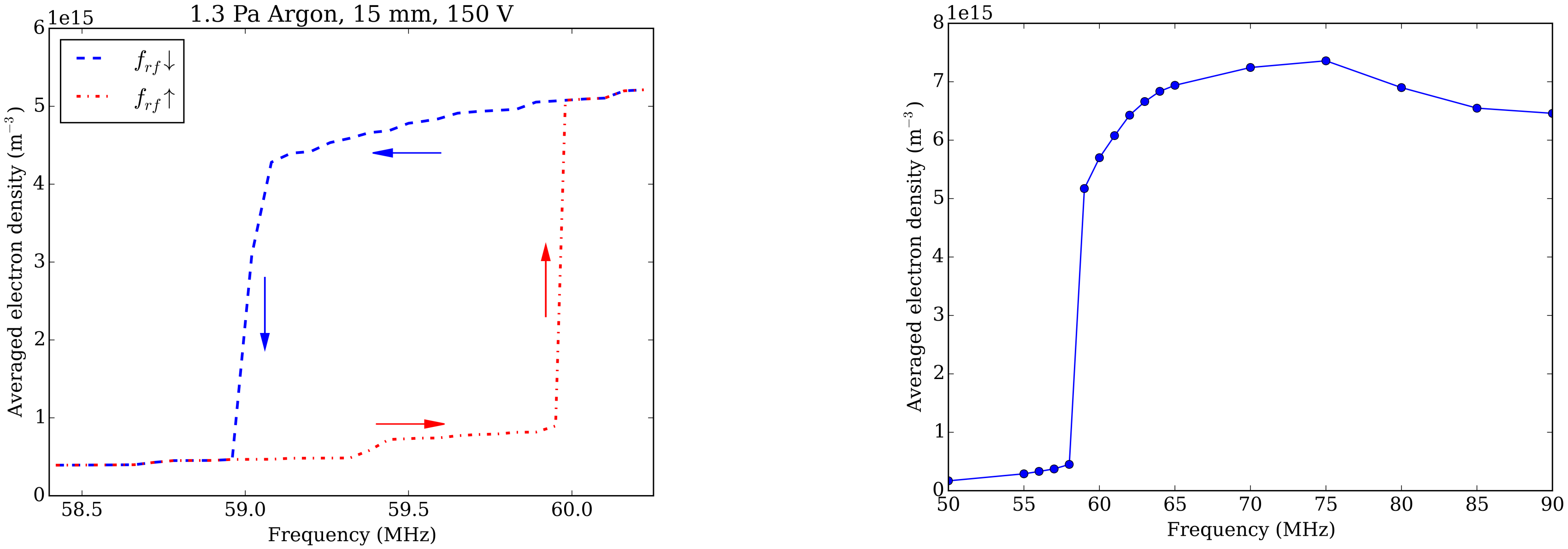






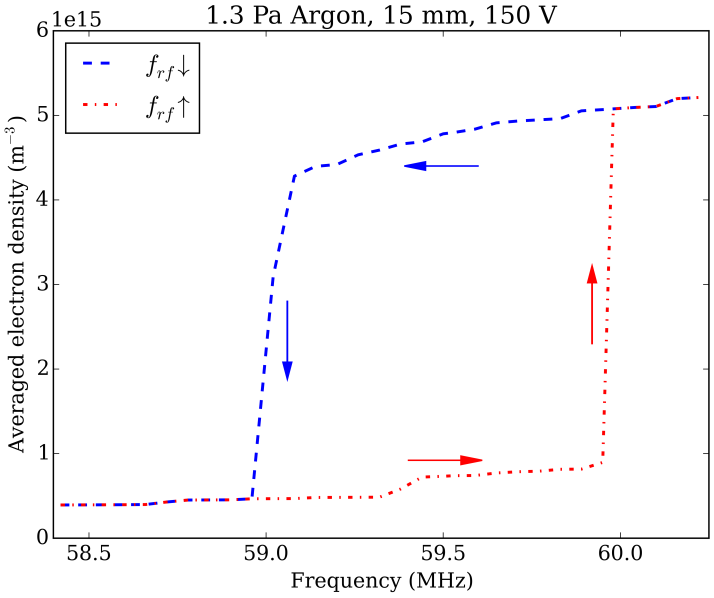


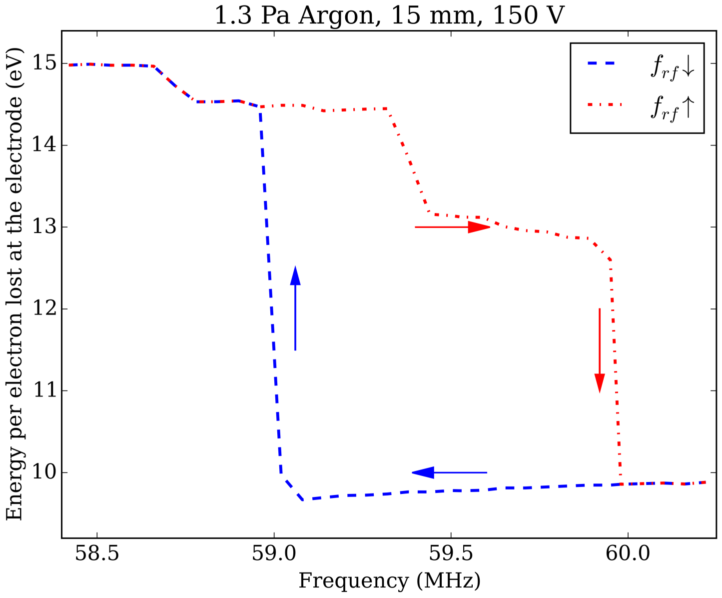
Hysteresis



- 0.03 MHz frequency resolution, increasing and decreasing the frequency by using the results of the converged case before
- 300.000 to 1.000.000 super particles, simulation time > 60.000 rf-cycles

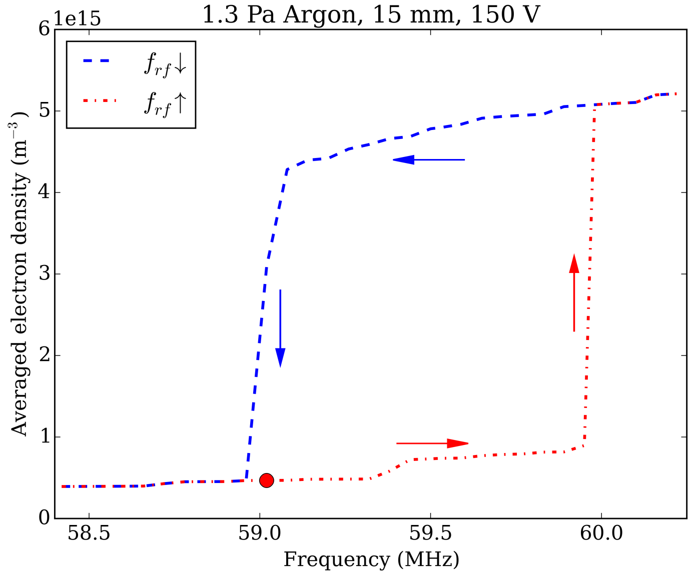
Hysteresis

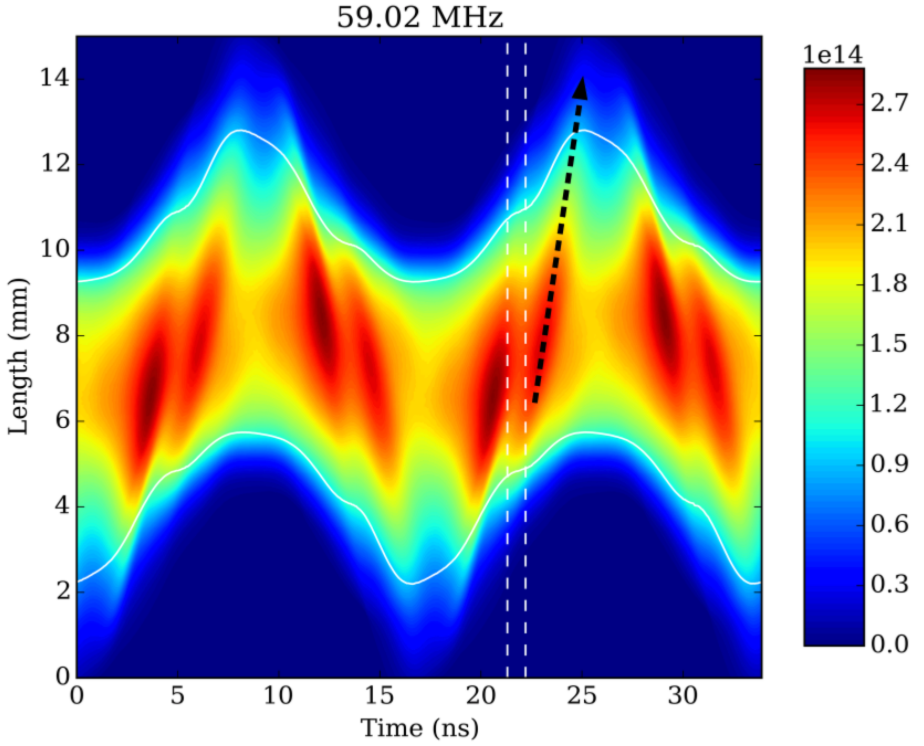


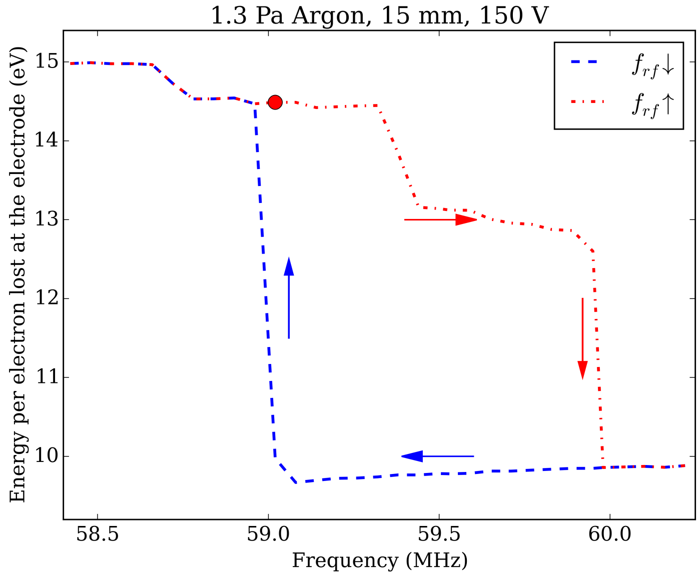


- 0.03 MHz frequency resolution, increasing and decreasing the frequency by using the results of the converged case before
- 300.000 to 1.000.000 super particles, simulation time > 60.000 rf-cycles
- similar behavior for the energy per electron lost at the electrode
- understand the physics of the hysteresis on a nanosecond timescale

Hysteresis upwards (red curve)

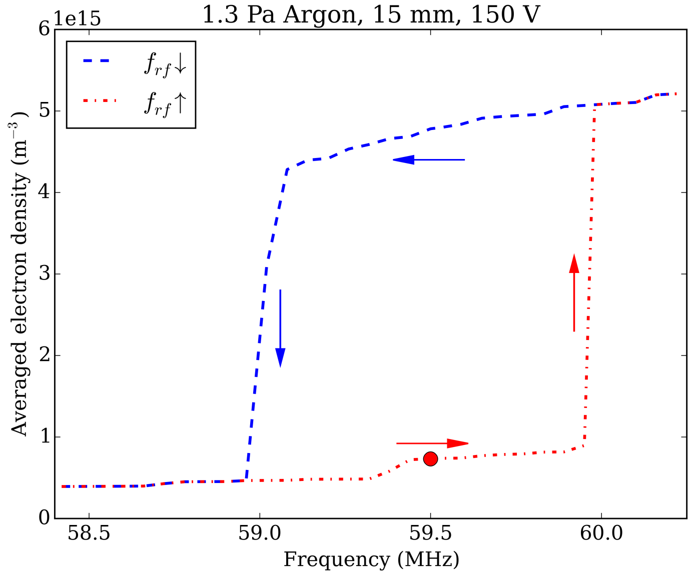


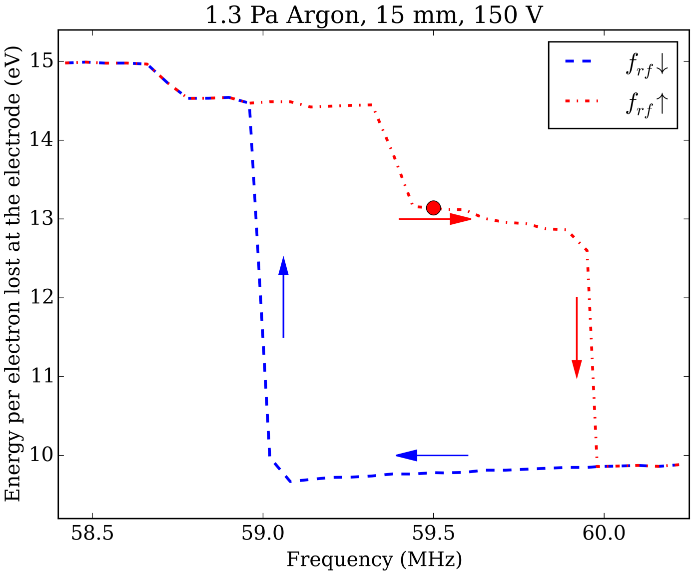


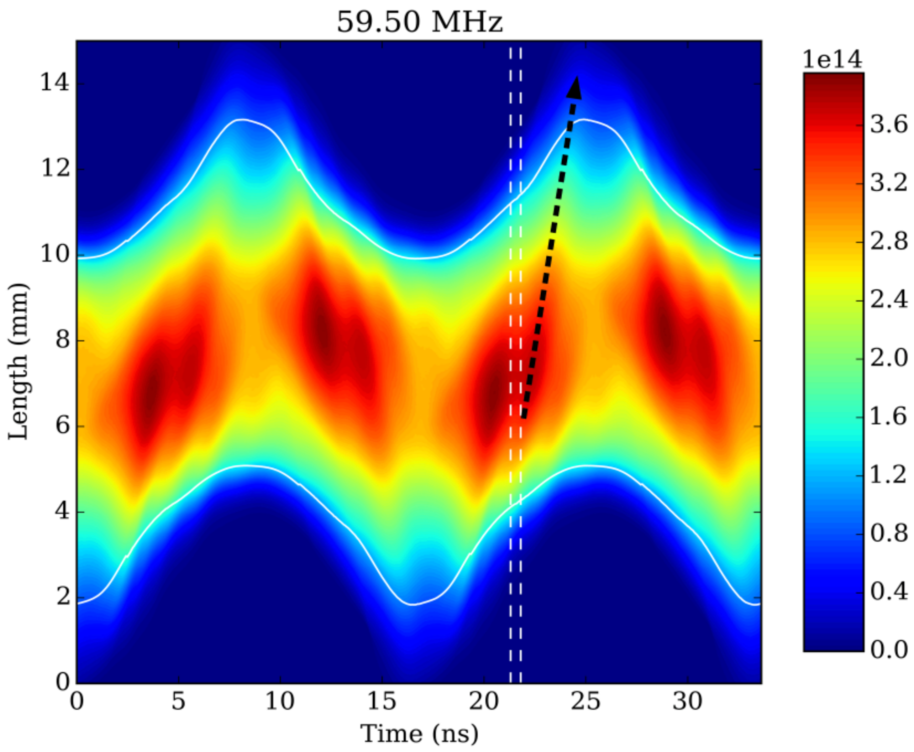


- $n_e \uparrow \Longrightarrow \omega_{pe} \uparrow \Longrightarrow \tau \downarrow \Longrightarrow \Delta t_{beams} \downarrow$
- Δt_{beams} time gap between beams
- Δt_{beams} depending on ω_{pe}
- second beam fully hits the sheath minimum

Hysteresis upwards (red curve)

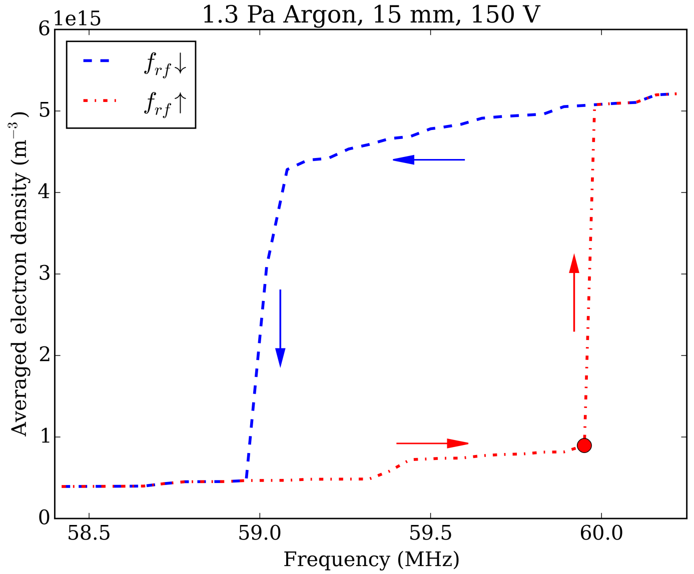


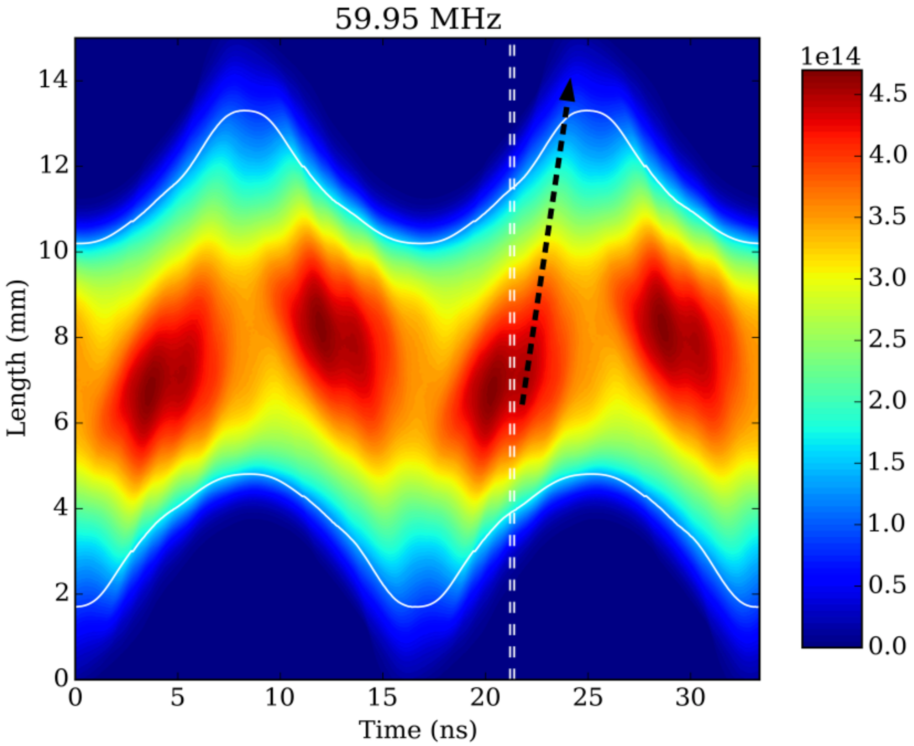


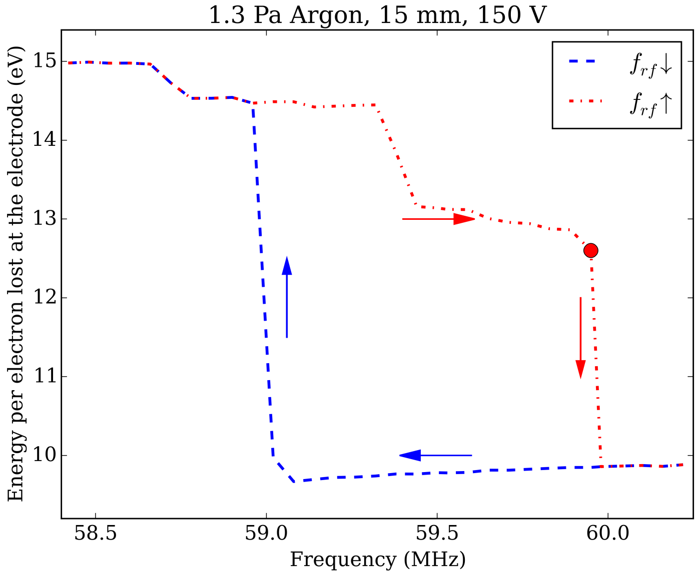


- $n_e \uparrow \Longrightarrow \omega_{pe} \uparrow \Longrightarrow \tau \downarrow \Longrightarrow \Delta t_{beams} \downarrow$
- Δt_{beams} becomes significant shorter
- second beam impingement small shift
- confinement still critical

Hysteresis upwards (red curve)

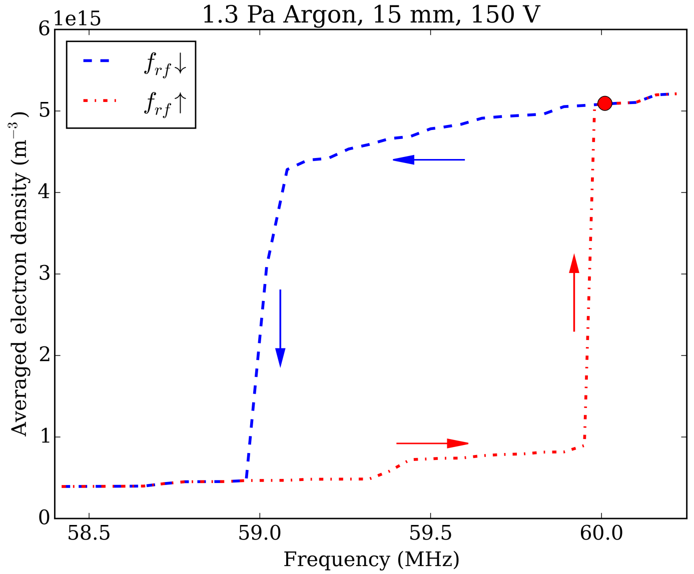


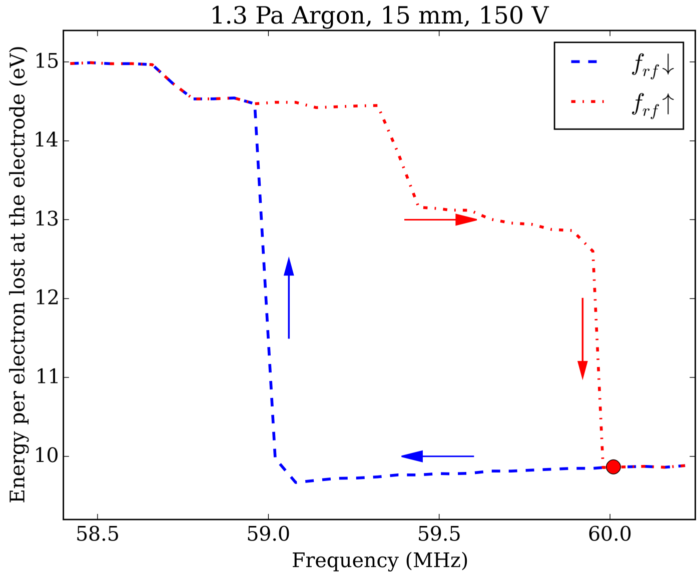


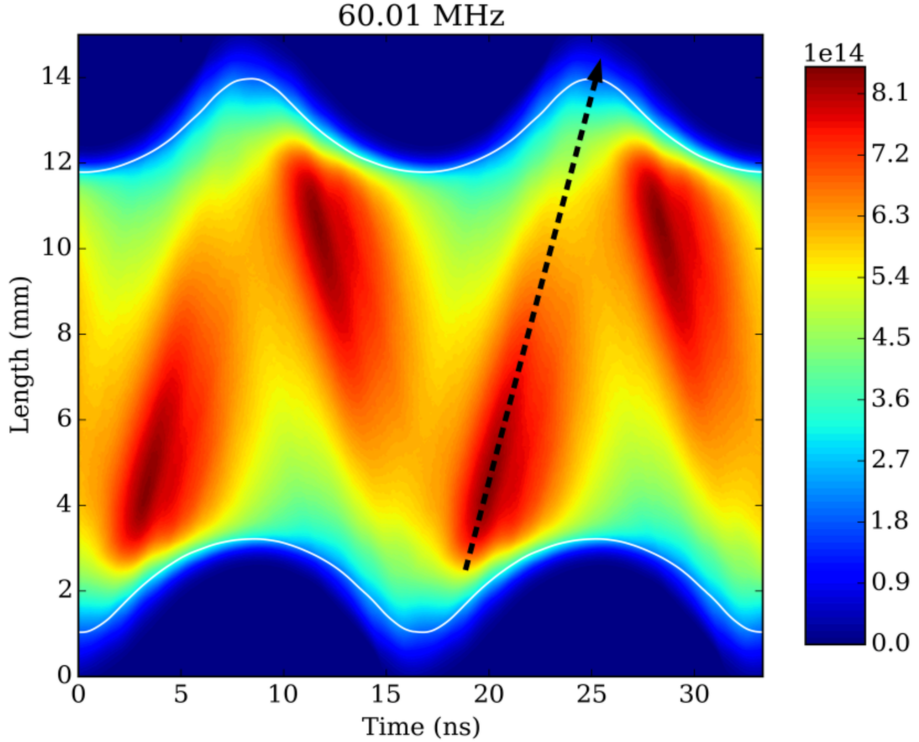


- $n_e \uparrow \Longrightarrow \omega_{pe} \uparrow \Longrightarrow \tau \downarrow \Longrightarrow \Delta t_{beams} \downarrow$
- beams are almost merged
- impingement phase more shifted to collapsing phase

Hysteresis upwards (red curve)

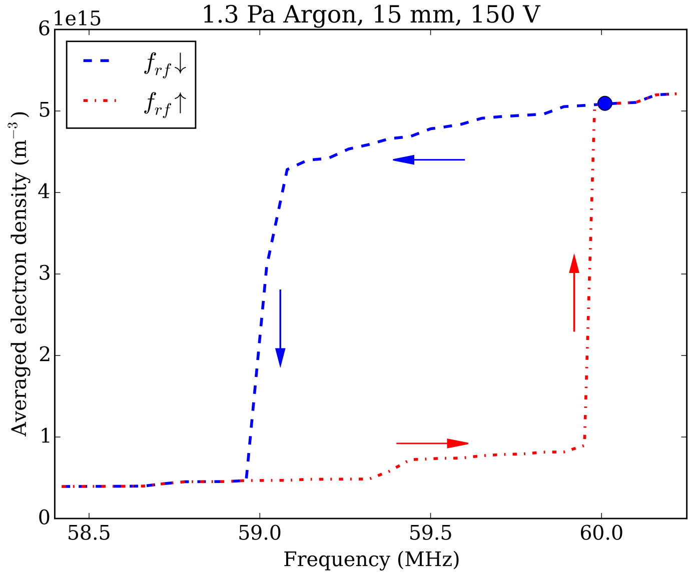


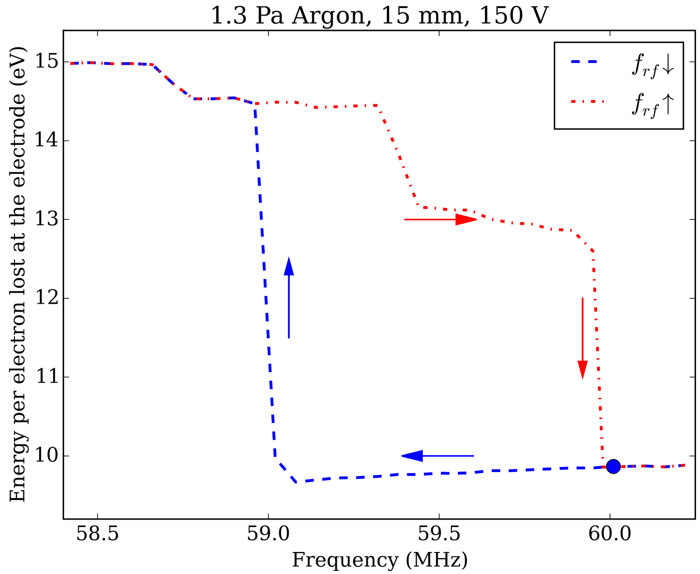


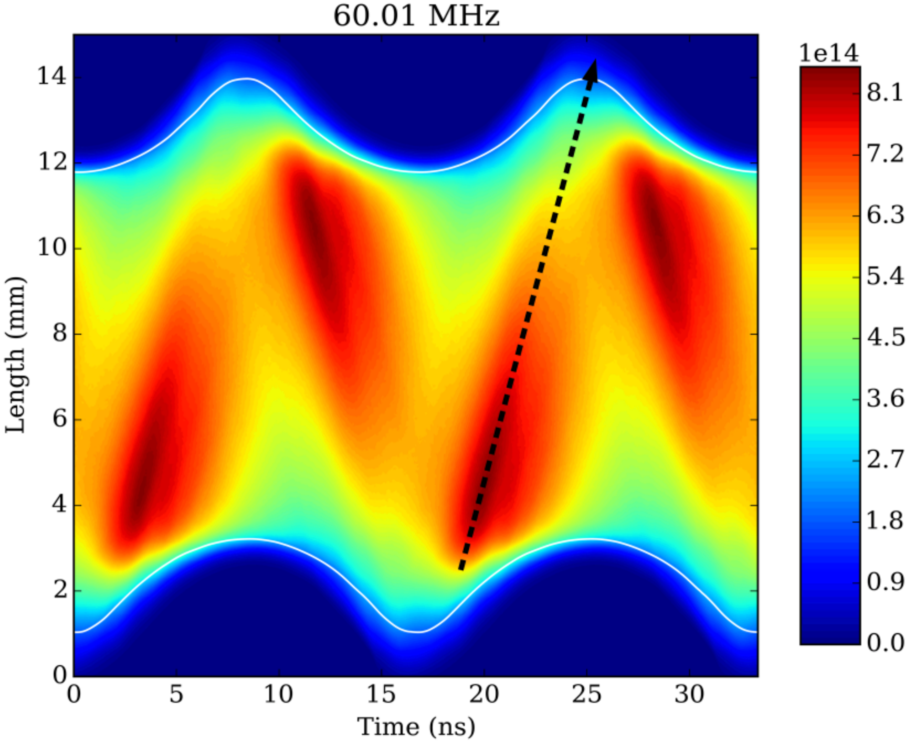


- $n_e \uparrow \Longrightarrow \omega_{pe} \uparrow \Longrightarrow \tau \downarrow \Longrightarrow \Delta t_{beams} \downarrow$
- beam hits the beginning of sheath expansion
- system reaches the high density
- confinement abruptly enhanced

Hysteresis downward (blue curve)

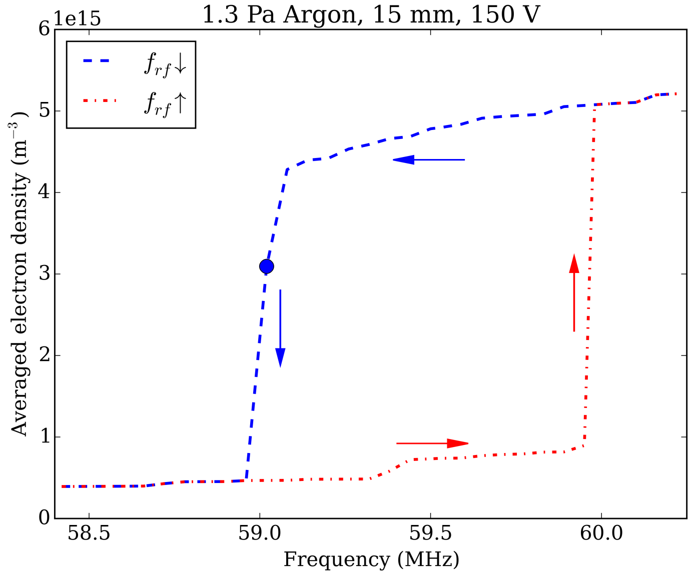


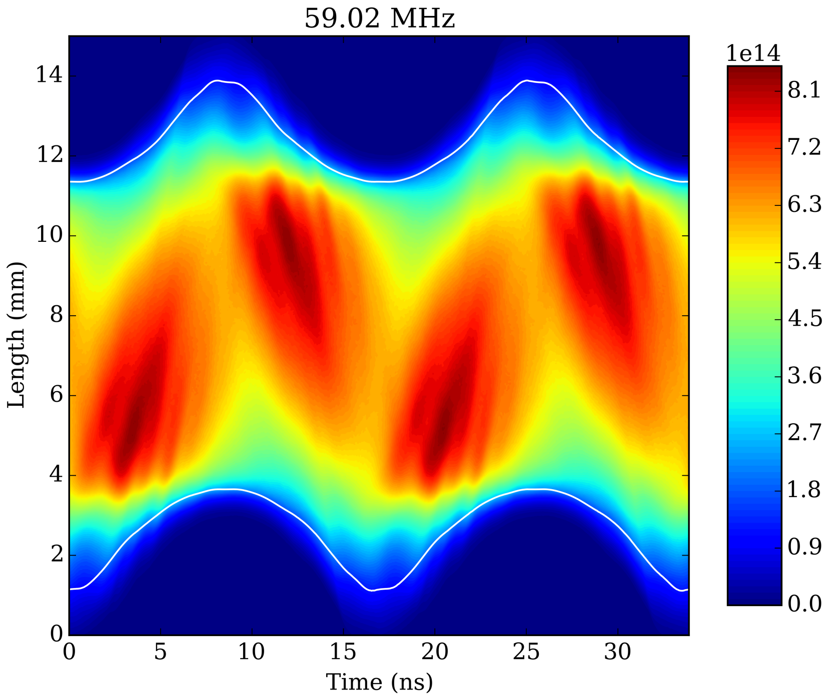


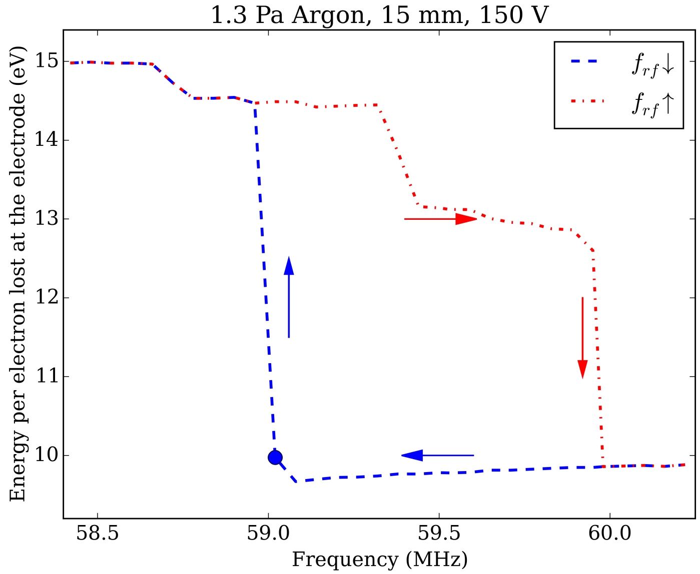


- $n_e \downarrow \Longrightarrow \omega_{pe} \downarrow \Longrightarrow \tau \uparrow \Longrightarrow \Delta t_{beams} \uparrow$
- same effect vice versa
- one beam formation equal to a sum of several beams
- same structure until 59.02 MHz

Hysteresis downward (blue curve)

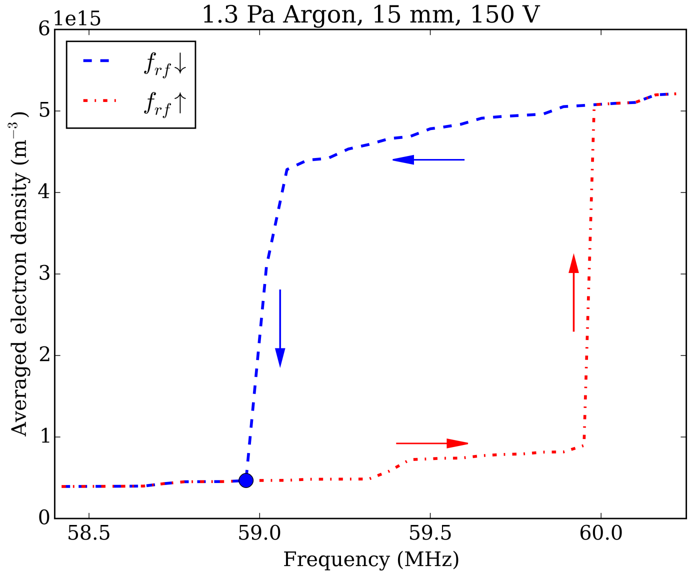


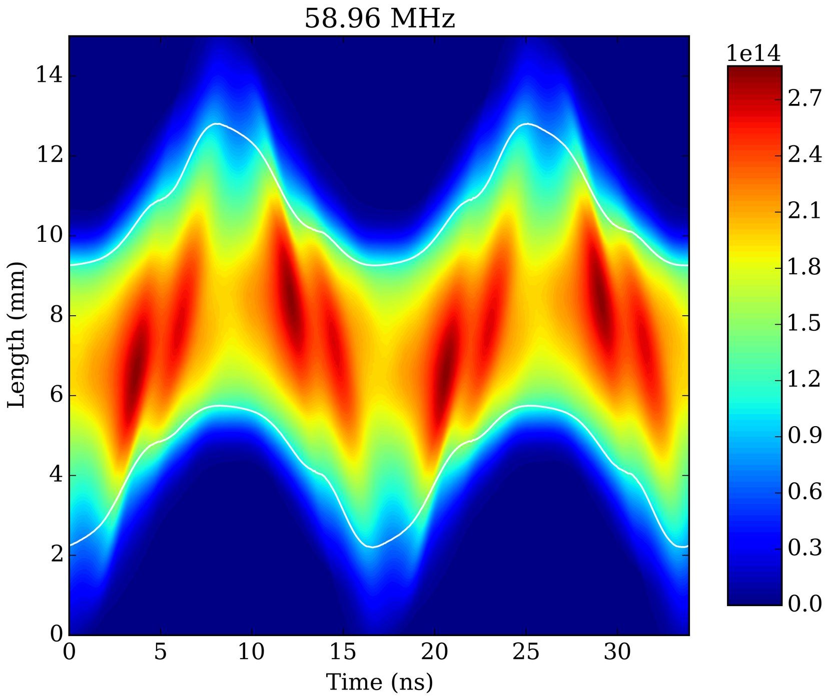


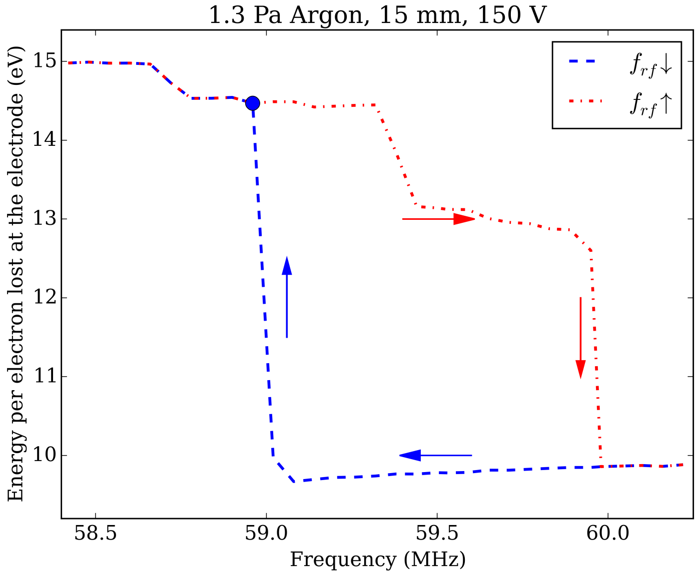


- $n_e \downarrow \Longrightarrow \omega_{pe} \downarrow \Longrightarrow \tau \uparrow \Longrightarrow \Delta t_{beams} \uparrow$
- beam formation tries to split into multi beams
- boundary of the high density mode

Hysteresis downward (blue curve)

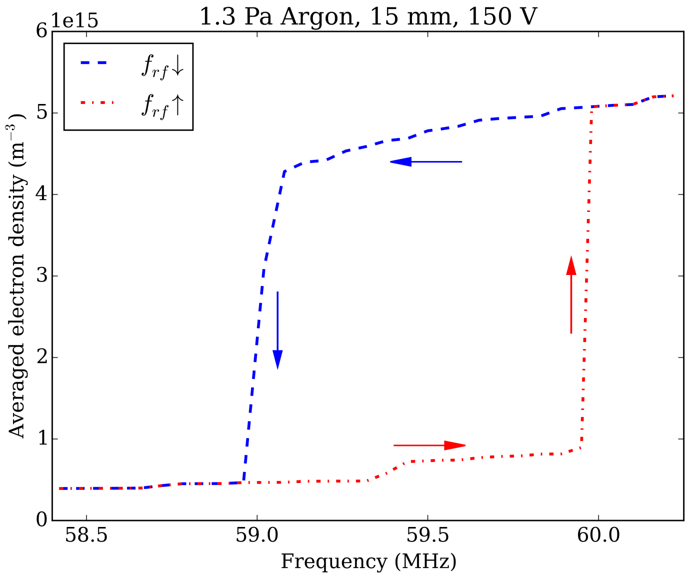


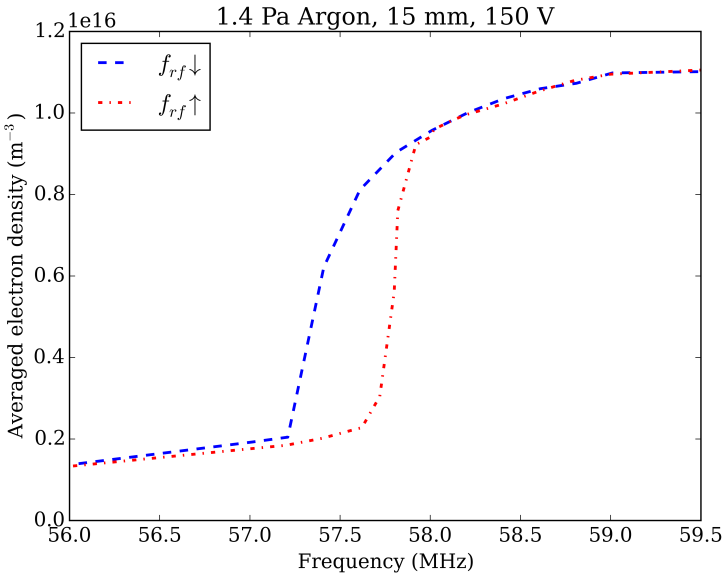


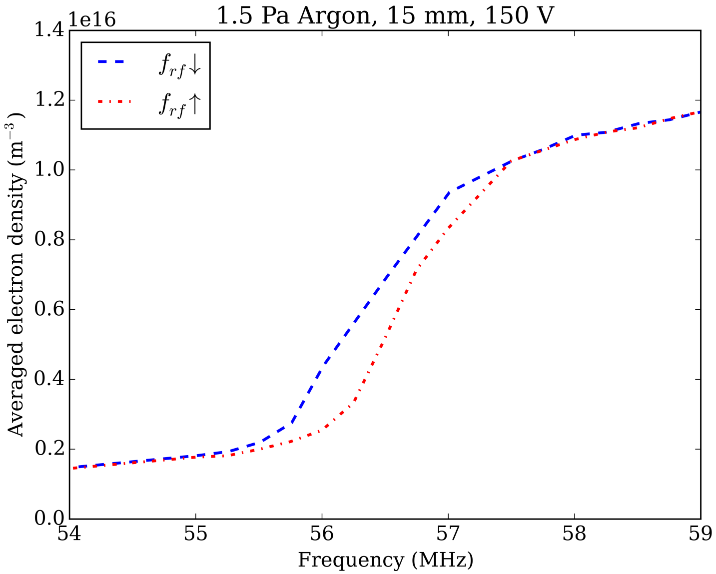


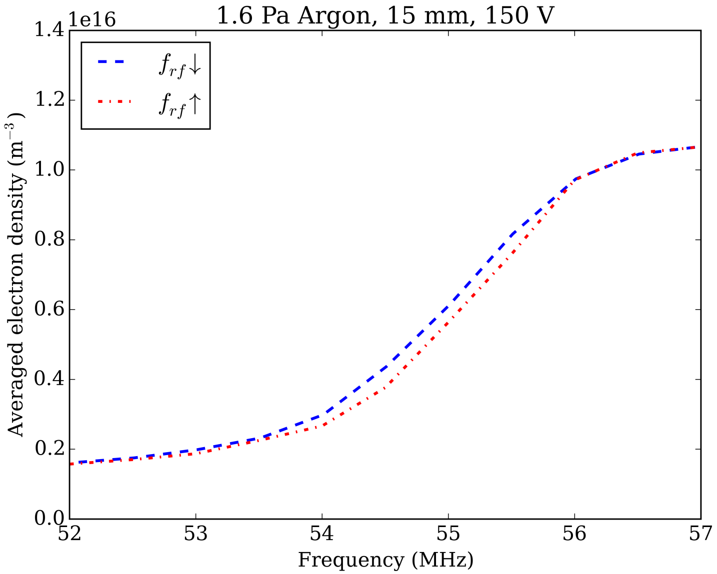
- $n_e \downarrow \Longrightarrow \omega_{pe} \downarrow \Longrightarrow \tau \uparrow \Longrightarrow \Delta t_{beams} \uparrow$
- one of the divided beams fully hits the minimum
- system reacts instantaneously and switches into the low density mode

Hysteresis for higher pressures

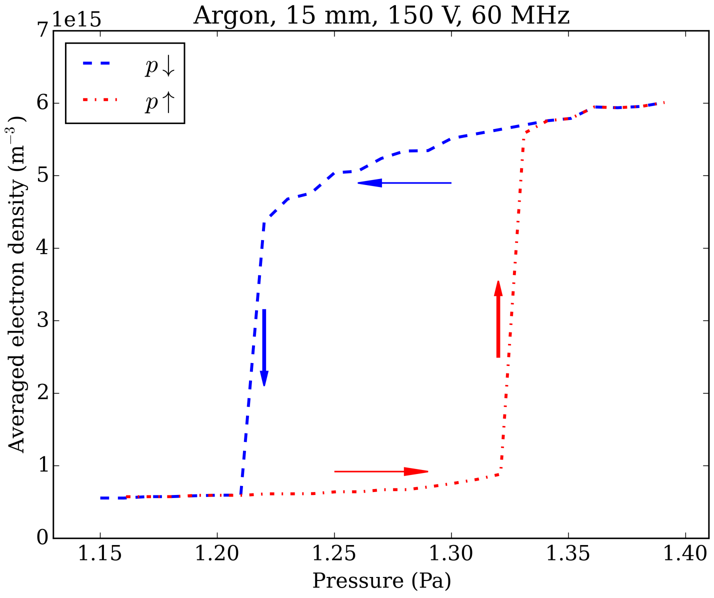


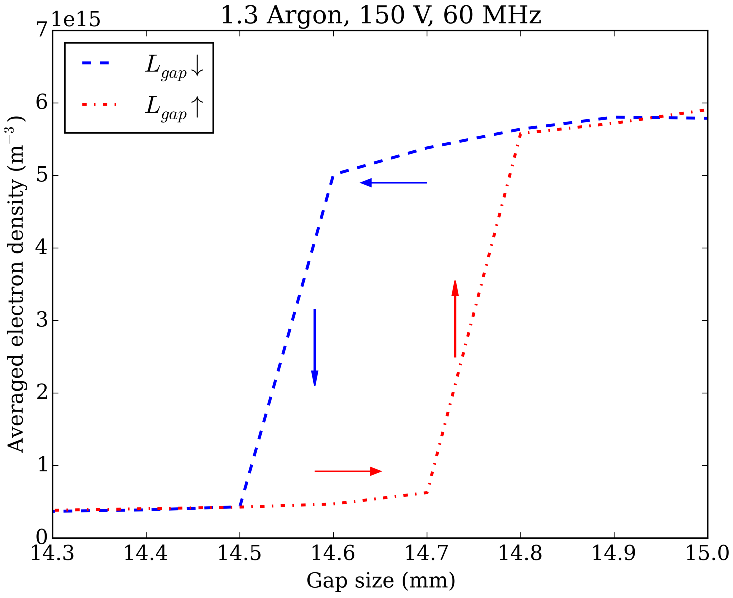




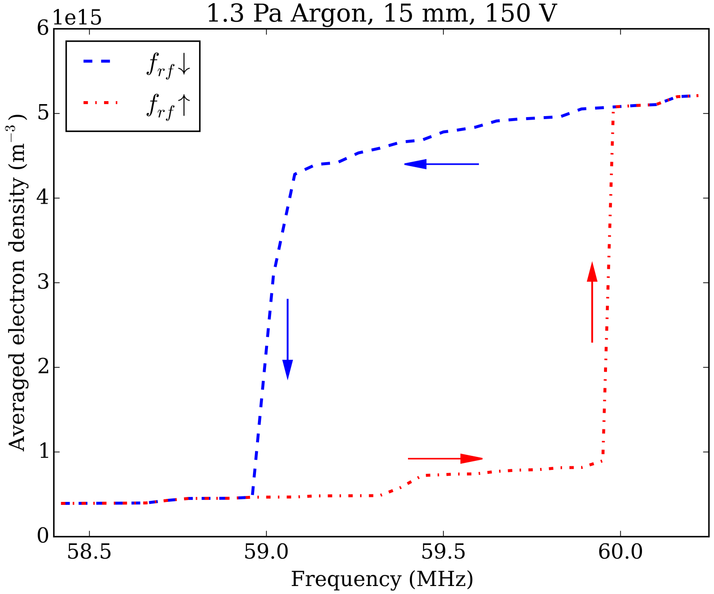


Hysteresis by changing different parameters





- transition between hitting the collapsing and expanding phase (sheath minimum)
- reach two states by increasing and decreasing the parameters
- $\Delta f = 1$ MHz, $\Delta L_{gap} \approx 0.2$ mm, $\Delta p \approx 0.1$ Pa



Conclusion

- critical confinement of energetic electrons for low pressures and small gap sizes ($\lambda_m / L_{gap} > 1$)
- plasma density does not follow a quadratic dependence on the driving frequency
- abrupt mode transition between[7] the expanding and collapsing impingement phase (sheath minimum)
- reach two different modes (high and low density mode)
- in the low density mode the beam formation is divided into two electron beams (interaction between beam and bulk electrons[8])
- hysteresis effect at this transition due to the nonlinearity of the plasma system (inertia of electrons)

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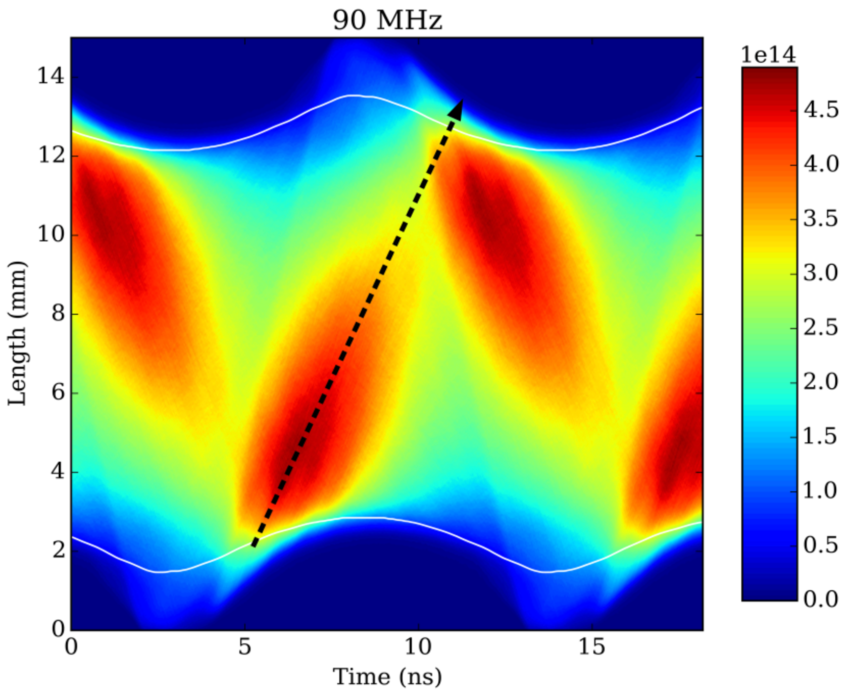
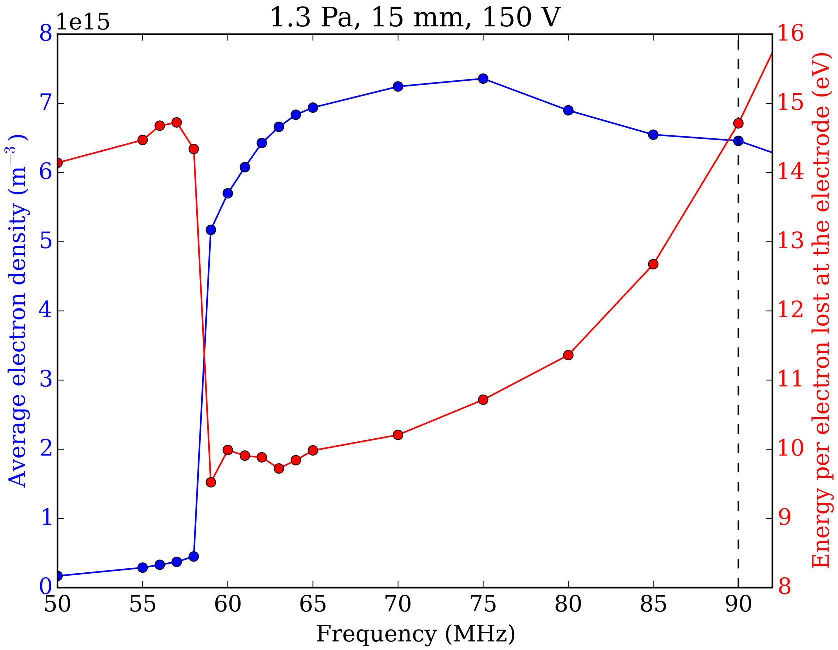
[7] S. Wilczek et. al, Plasma Sources Sci. Technol. 24, 024002 (2015)
[8] S. Wilczek et al., Phys. Plasmas. 23, 063514 (2016)

Confinement of beam electrons (ε > 15.76 eV): 90 MHz





- energetic electrons (ε > 15.76 eV) reach the middle of the expanding sheath
  $\Longrightarrow$ confinement for these electrons is good (responsible for ionization)
  $\Longrightarrow$ enhanced power absorption $E \cdot J_e$
- higher frequencies leads to faster sheath accelerations
  $\Longrightarrow$ more higher energetic electrons ($\varepsilon \gg$ 15.76 eV) are lost

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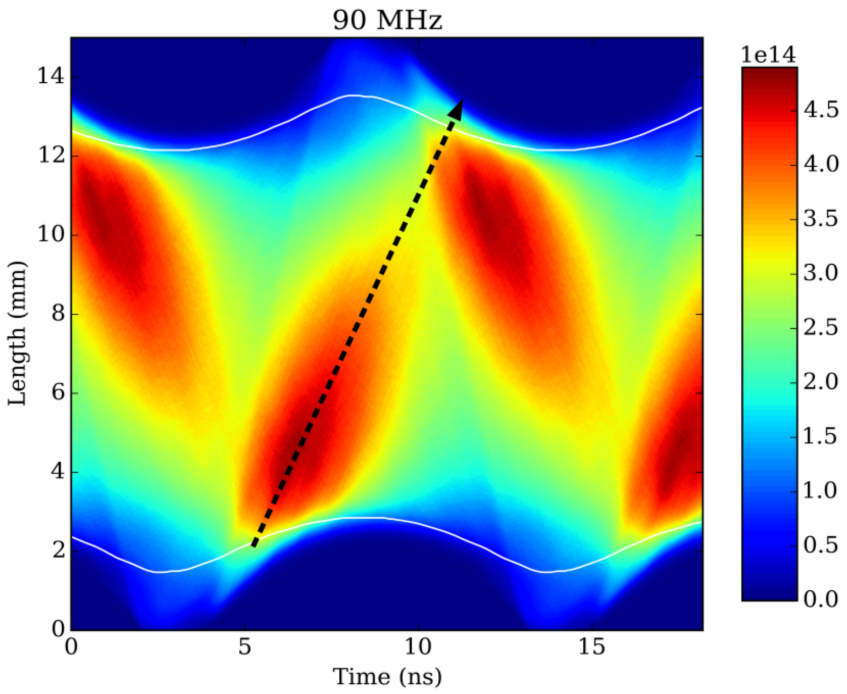

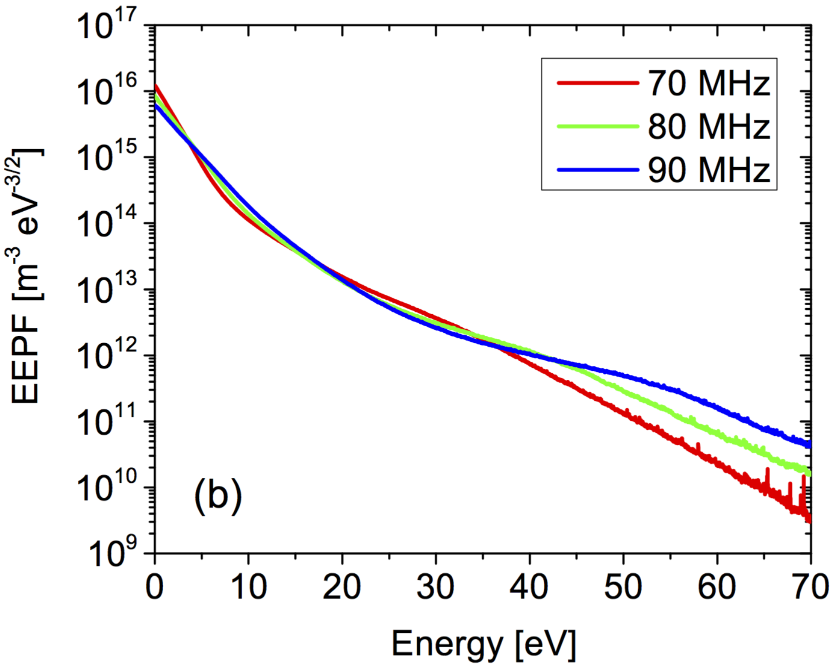

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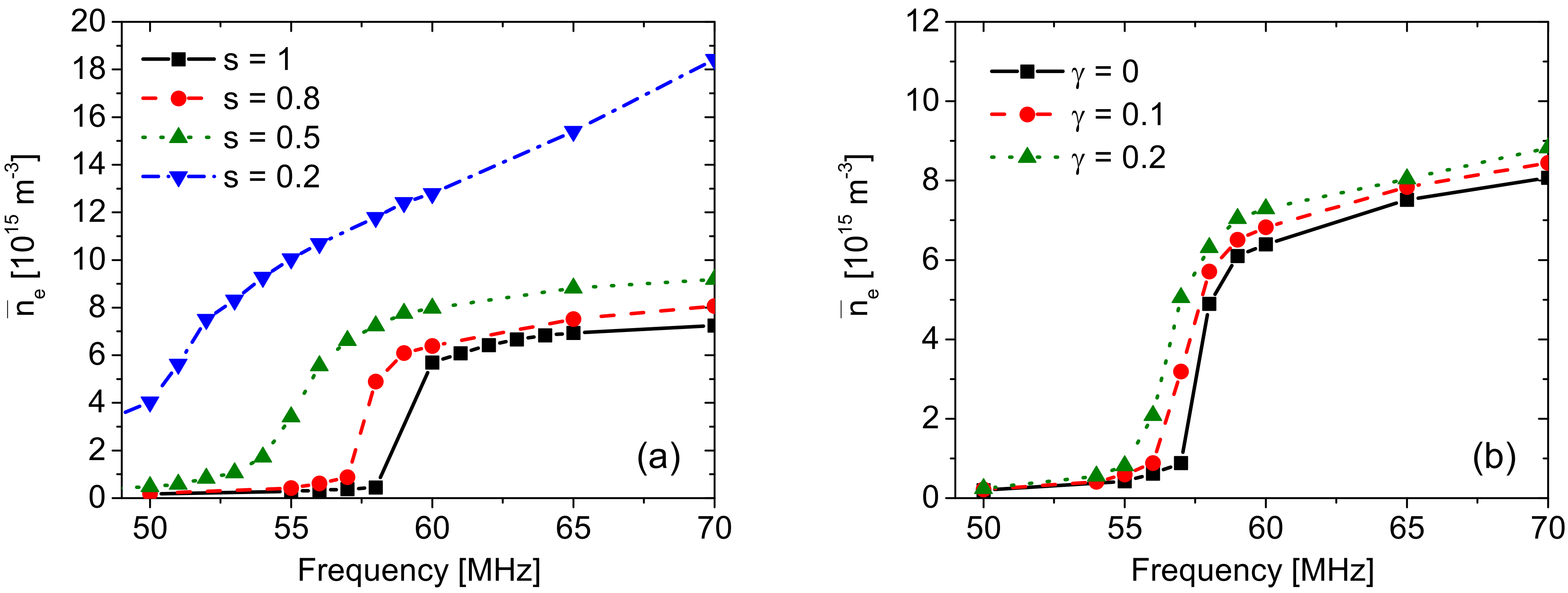
- tail of the EEPF increases, electrons overcome the sheath potential

Sticking and secondary electron coefficient



- 80% reflection influences the transition (but we can decrease the pressure)
- no influence of the secondary electron emission coefficient