Electron Dynamics in Radio Frequency Magnetron Argon Discharges

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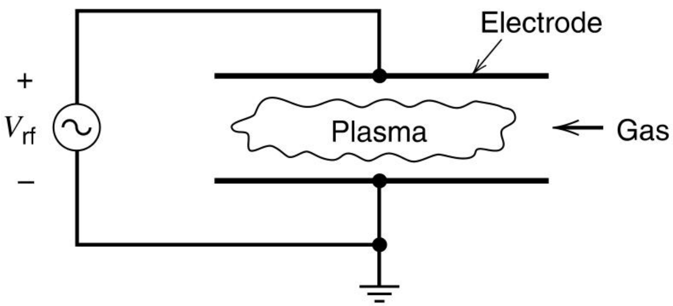
Outline

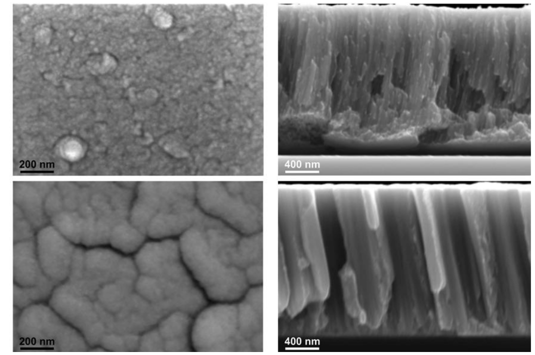
- Background of redio frequency magnetron sputtering
- Modeling and simulation
- Results and discussion
  - Fundamental plasma parameters
  - Electron current densities
  - Electron power absorption
  - Ionization dynamics
- Conclusion

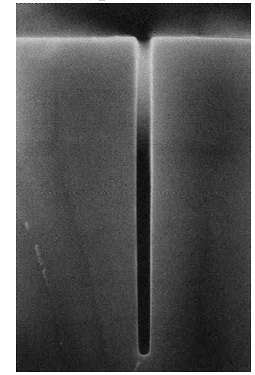
Bocong Zheng, Yangyang Fu, Keliang Wang, Thomas Schuelke, Qi Hua Fan, *Electron dynamics in radio freqeuncy magnetron sputtering argon discharges with a dielectric target*, **Plasma Sources Science and Technology** 30, 035019 (2021).

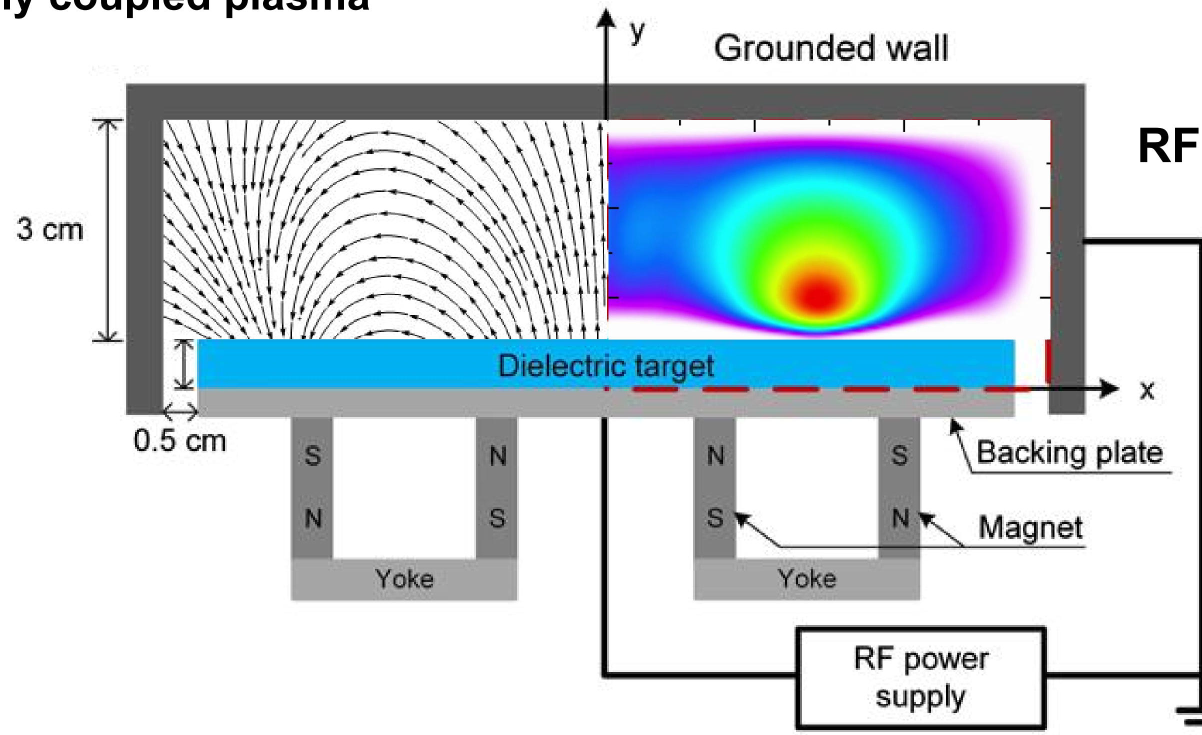
Radio Frequency Magnetron Sputtering (RFMS)



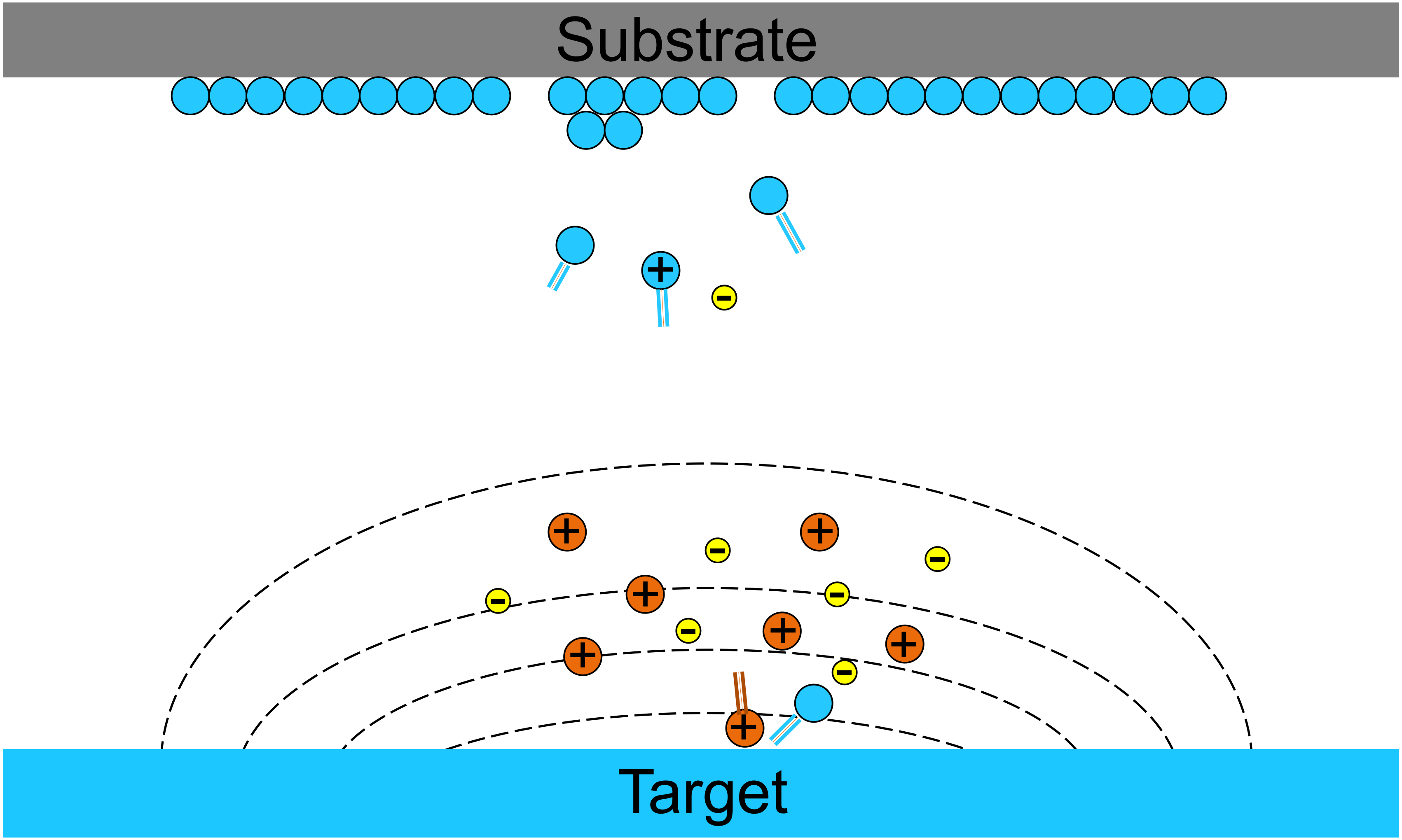
Capacitively coupled plasma





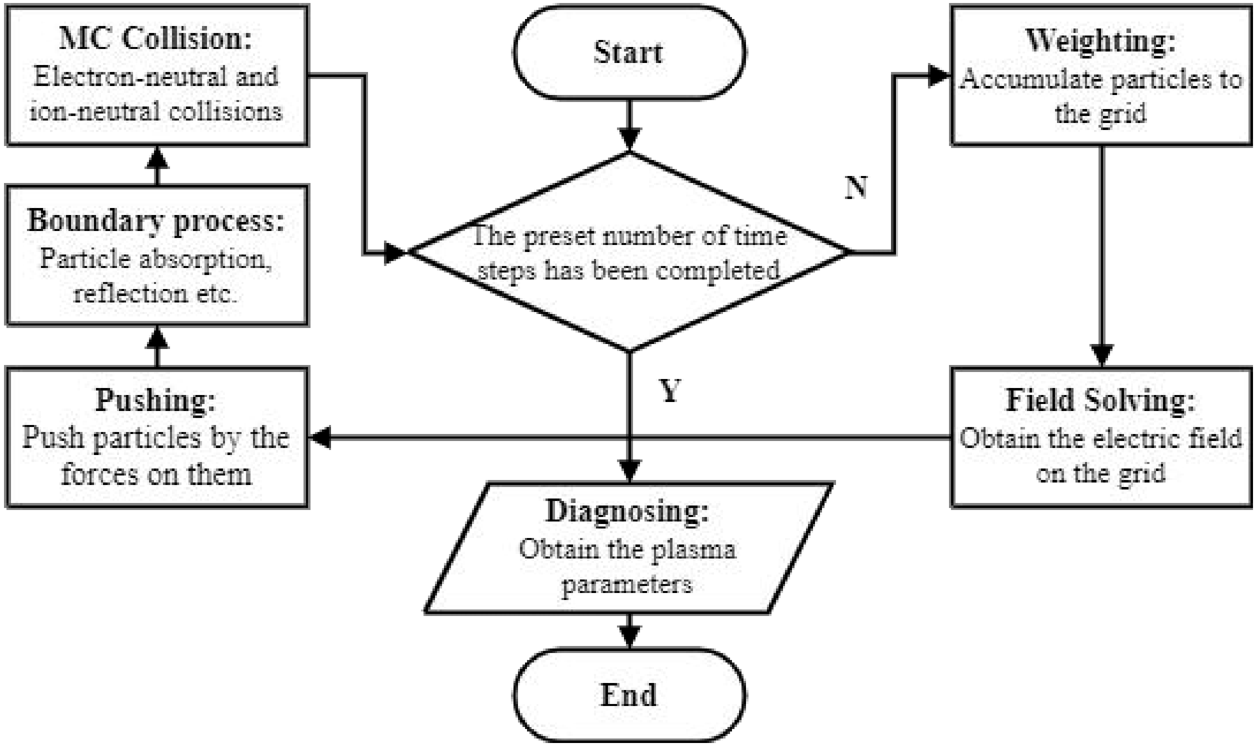


RFMS



Further reference:
J T Gudmundsson, *Physics and technology of magnetron sputtering discharges*, **Plasma Sources Science and Technology** 29, 113001 (2020).

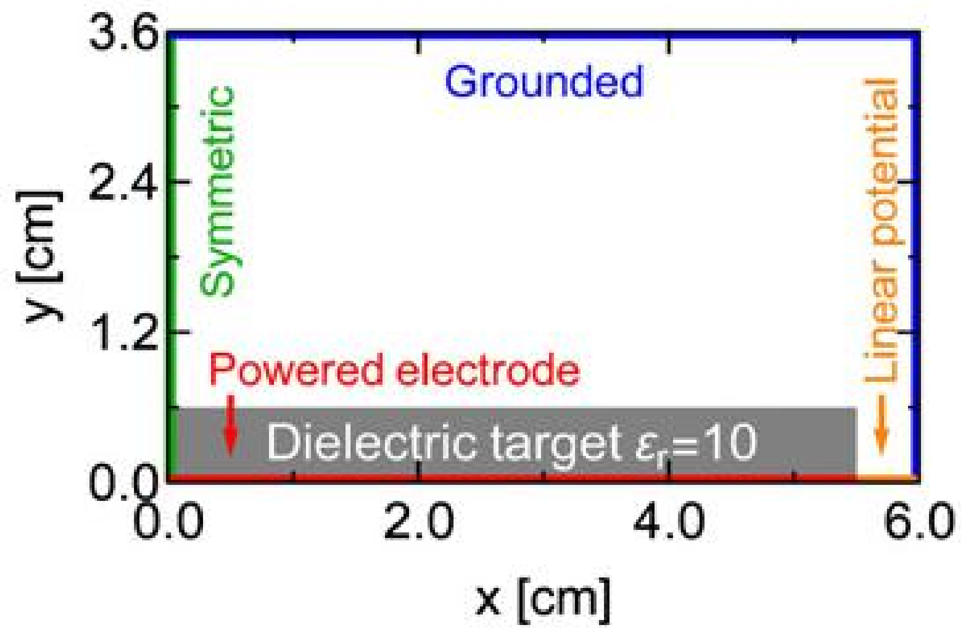
Particle-In-Cell/Monte Carlo Collision (PIC/MCC)



ASTRA code ➡

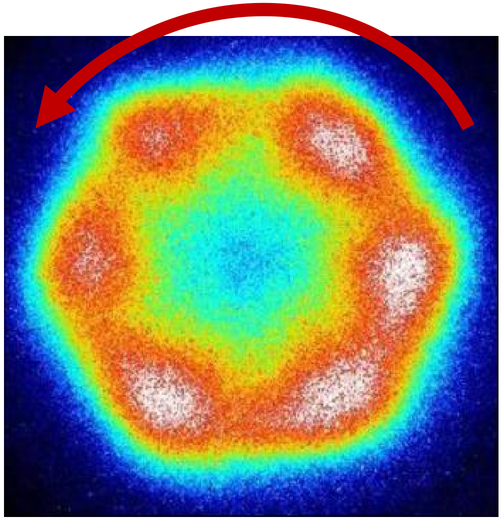
Yangyang Fu†, Huihui Wang, Bocong Zheng†, et al, APL 118, 174101 (2021).
Bocong Zheng et al, PSST 30, 035019 (2021).
Yangyang Fu†, Bocong Zheng† et al, JAP 129(2), 023302 (2021).
Bocong Zheng et al, POP 28, 014504 (2021).
Yangyang Fu†, Bocong Zheng† et al, APL 117, 204101 (2020).
Yangyang Fu†, Bocong Zheng et al, POP 27, 113501 (2020).
Yangyang Fu†, Bocong Zheng et al, PSST 29, 09LT01 (2020).
Bocong Zheng et al, JPD 53, 435201 (2020).
Bocong Zheng et al, PSST 28, 09LT03 (2019).

Simulation region



Parameter	Value
Gas pressure	10 mTorr
Gas temperature	300 K
Voltage amplitude	200 V
Driving frequency	13.56 MHz
SEE coefficient	0
Electron sticking coefficient	0.5

E × B direction



Panjan, JAP 125, 203303 (2019).

Oscillation frequency in E × B direction of several hundred kHz << RF

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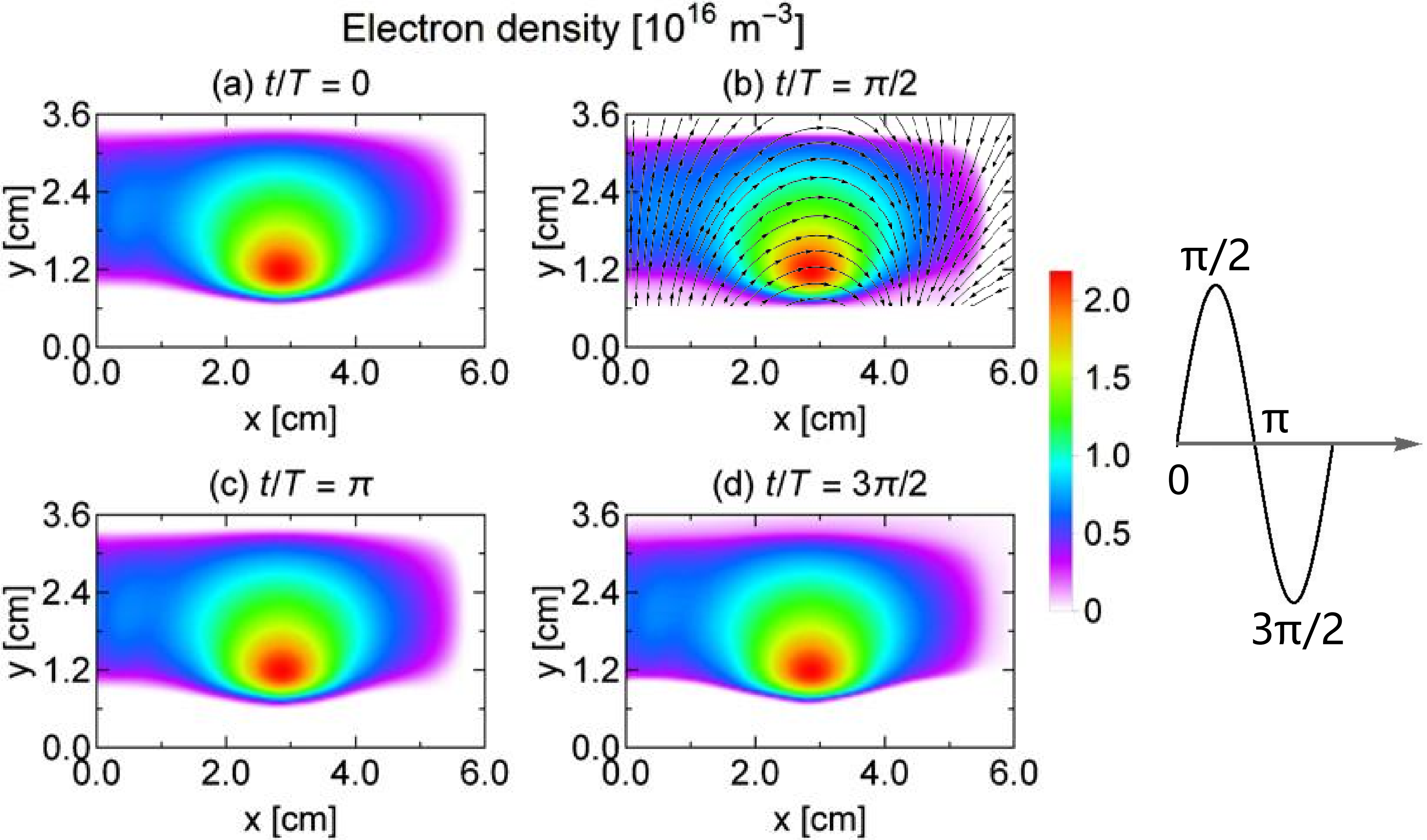
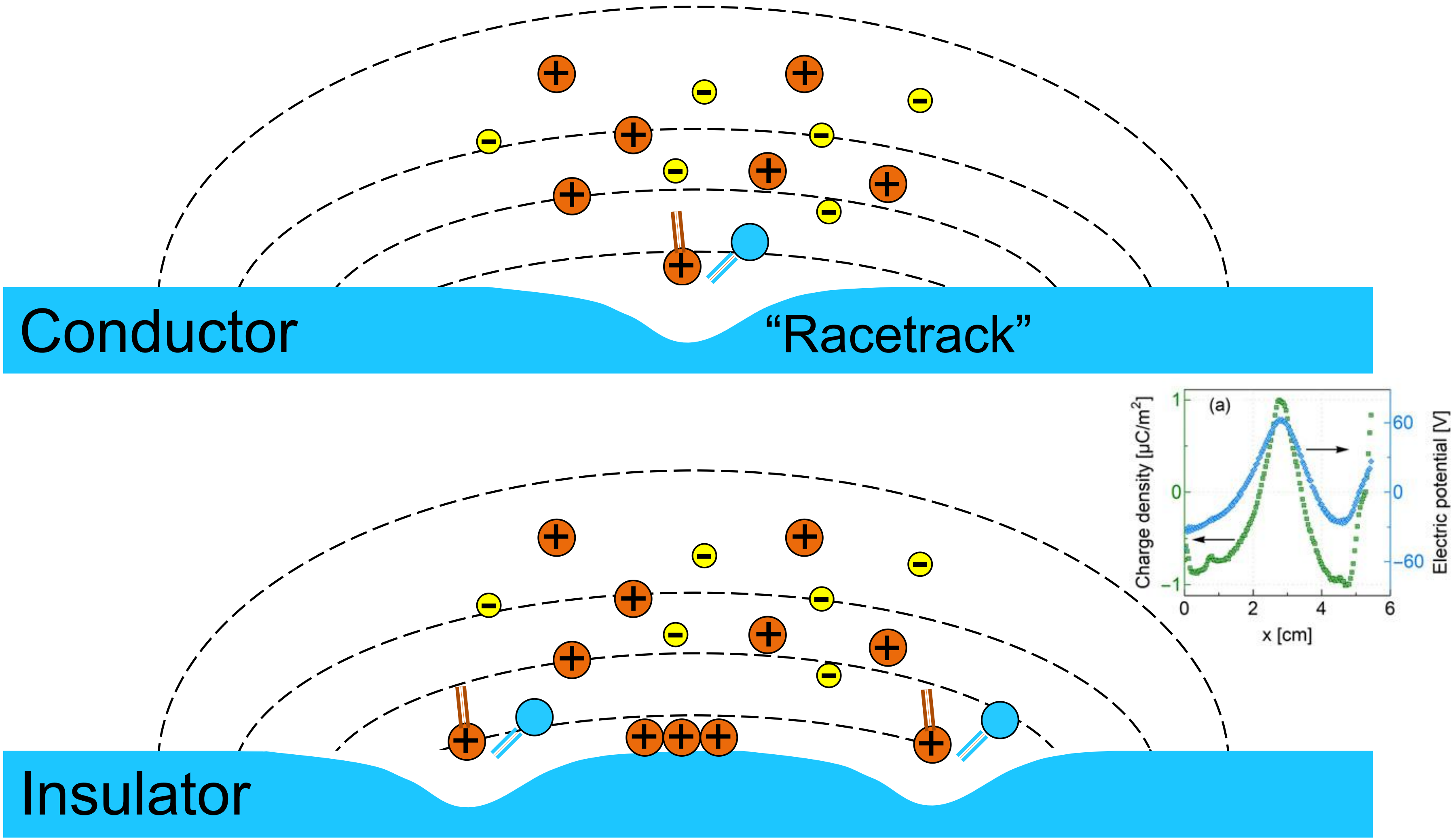
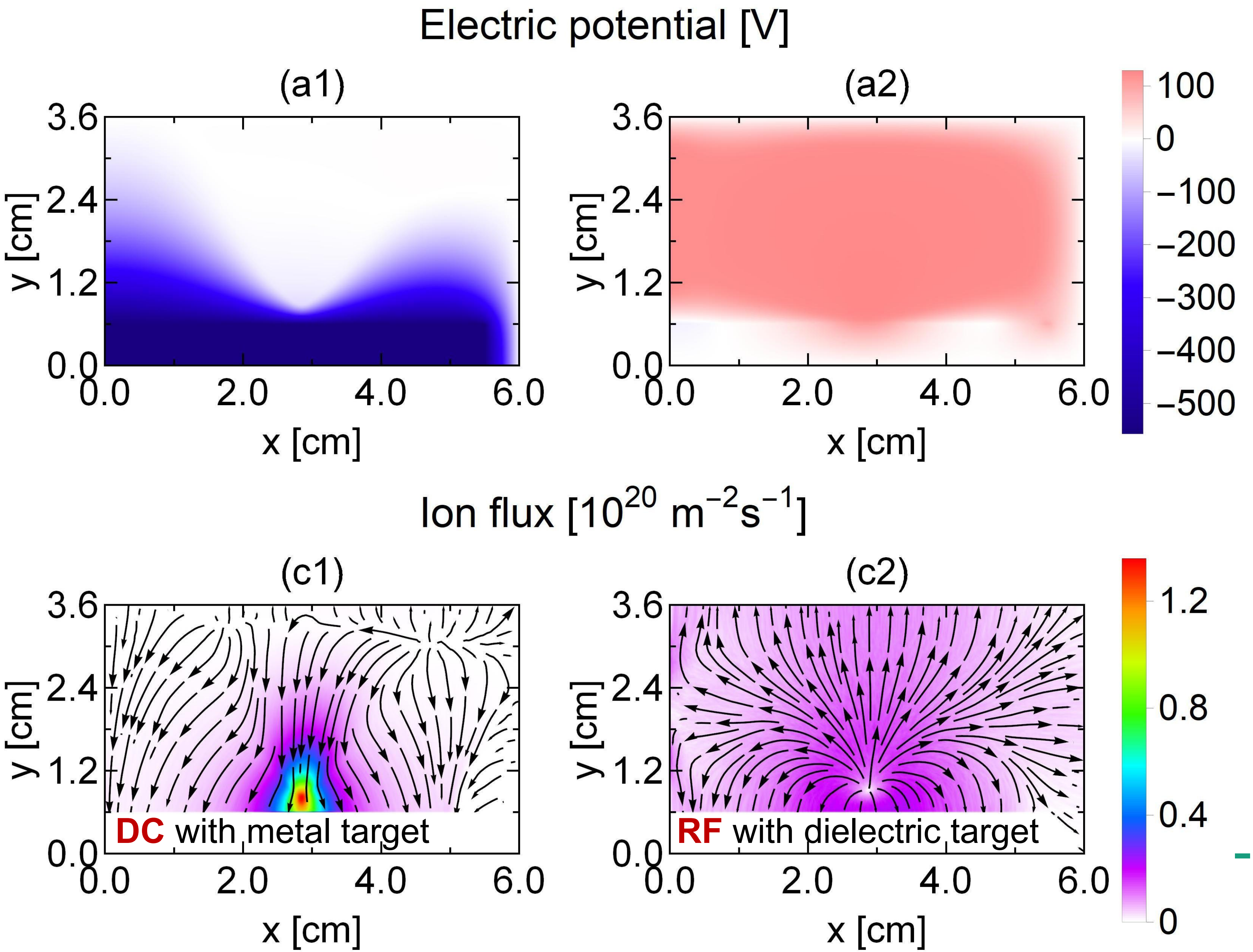
Electron density



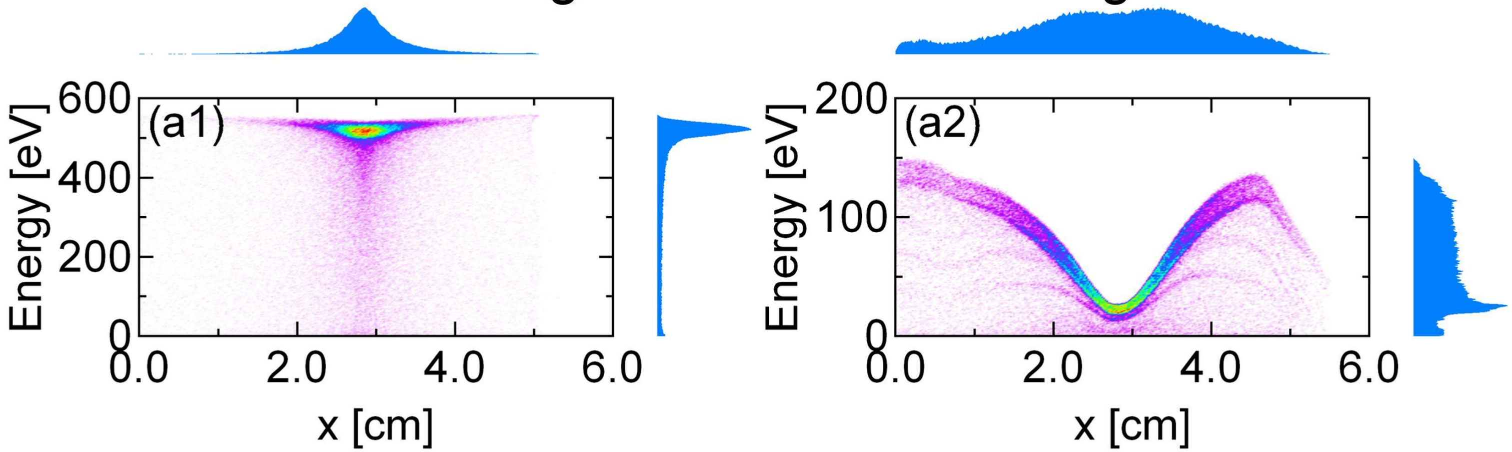
Abnormal etching profile



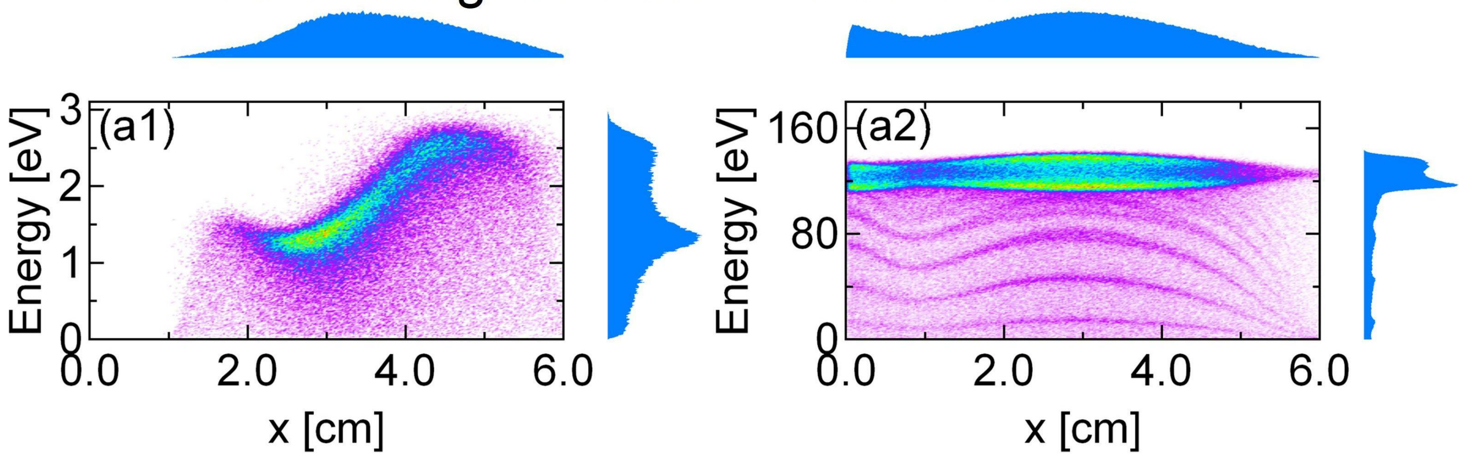

Electric potential [V]
(a1)
(a2)
y [cm]
x [cm]
3.6
2.4
1.2
0.0
2.0
4.0
6.0
100
0
−100
−200
−300
−400
−500
Ion flux [10^20 m^−2s^−1]
(c1)
(c2)
DC with metal target
RF with dielectric target
1.2
0.8
0.4
0

DC RF

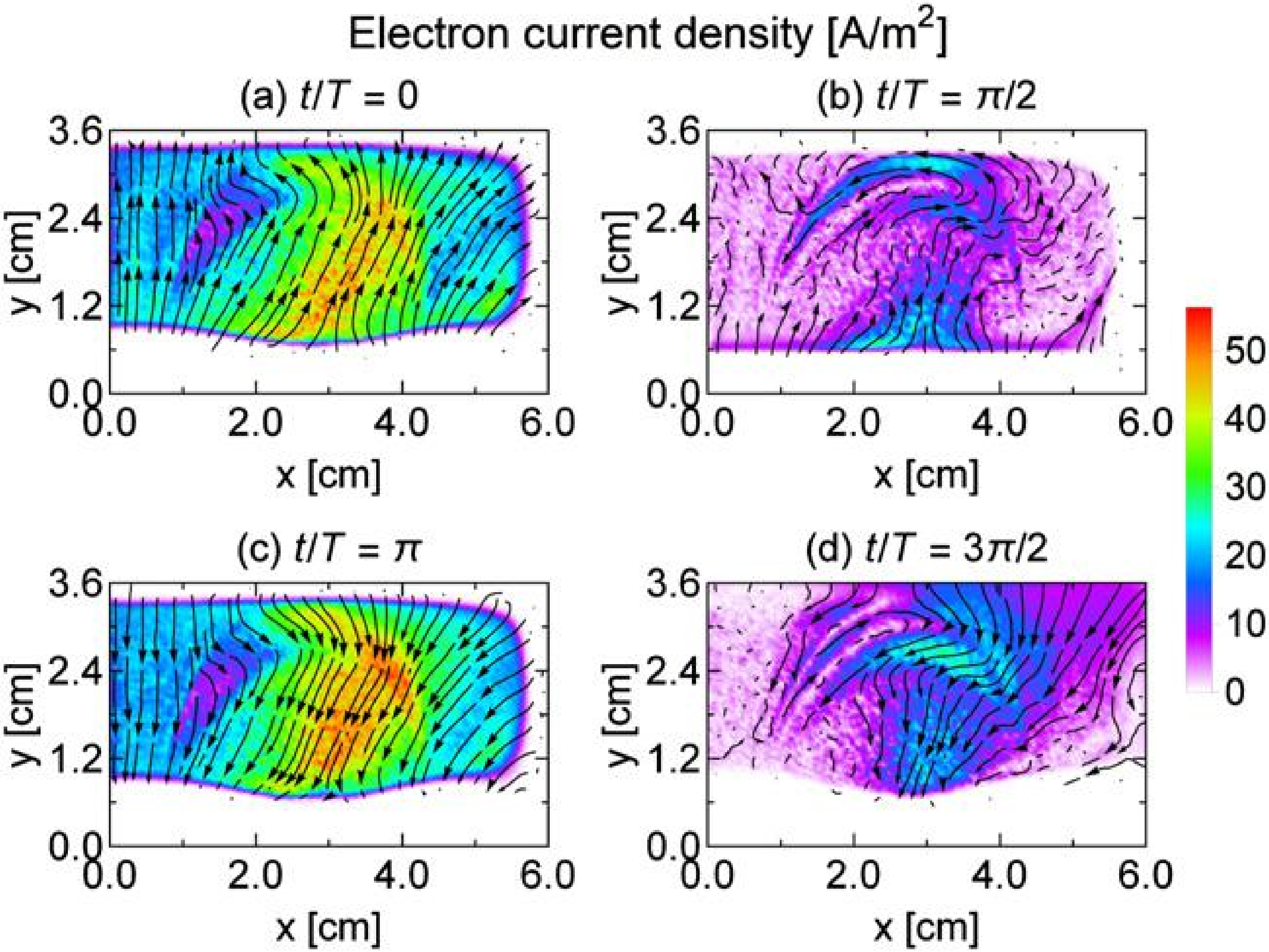
IEDF along the surface of the target

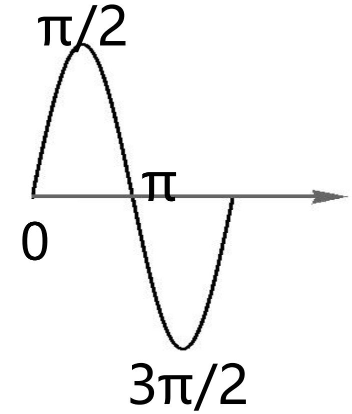


IEDF along the surface of the substrate

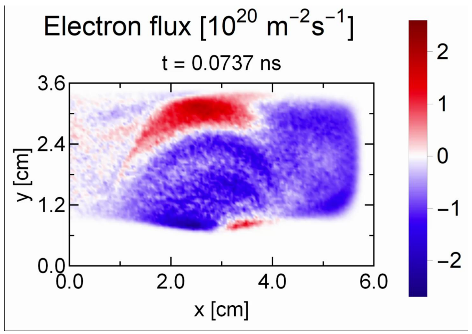


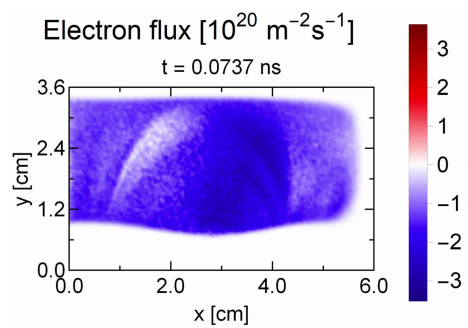
Electron current density





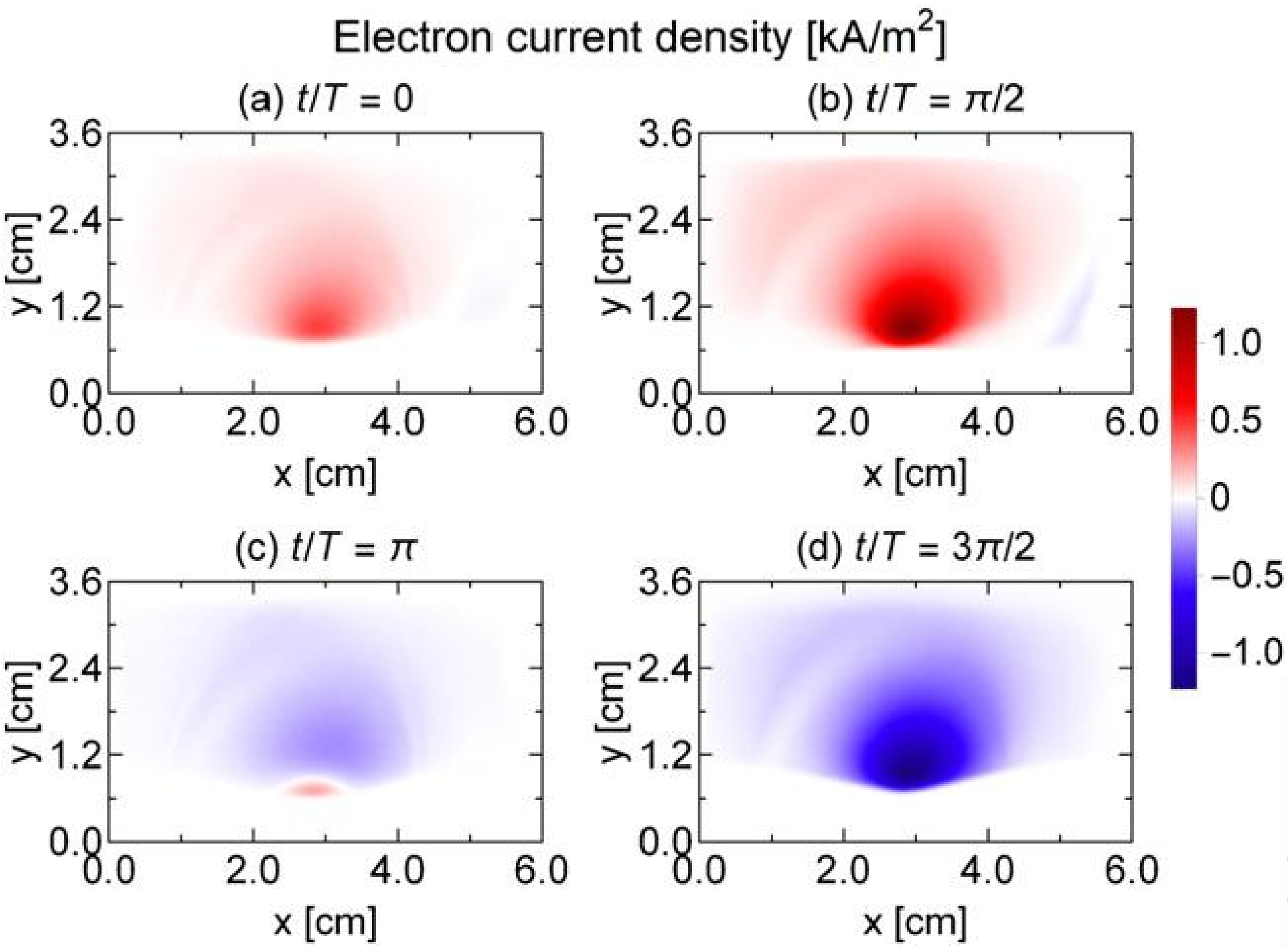
x direction

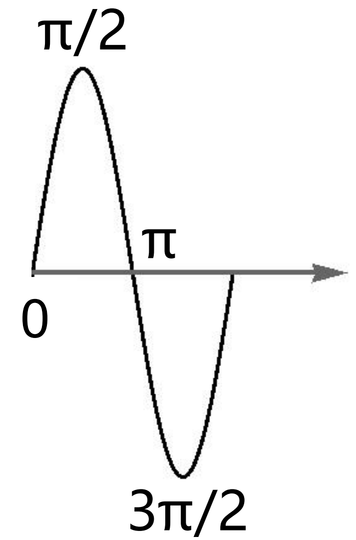


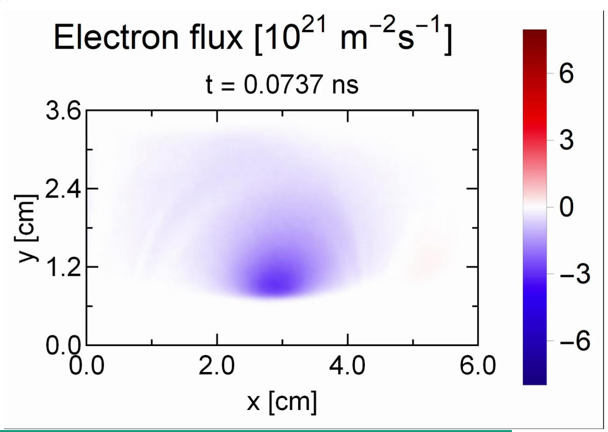


y direction

Azimuthal electron current density







$$m_e n_e \frac{\partial \boldsymbol{u}_e}{\partial t} + m_e (\boldsymbol{\Gamma}_e \cdot \nabla) \boldsymbol{u}_e = -e n_e (\boldsymbol{E} + \boldsymbol{u}_e \times \boldsymbol{B}) - \nabla \cdot \overleftrightarrow{\boldsymbol{\Pi}}_e + \left(\frac{\partial \rho_e}{\partial t}\right)_c$$

$$m_e n_e \frac{\partial \boldsymbol{u}_e}{\partial t} = -e n_e (\boldsymbol{E} + \boldsymbol{u}_e \times \boldsymbol{B}) - m_e \nu_m n_e \boldsymbol{u}_e$$

$$\boldsymbol{u}_e \times \boldsymbol{B} = -\boldsymbol{E} - (\nu_m - i\omega_{RF}) m_e \boldsymbol{u}_e / e$$

$$\epsilon_0 \omega_{pe}^2 \boldsymbol{E} = \overleftrightarrow{\boldsymbol{A}} \boldsymbol{J}_e$$

$$\overleftrightarrow{\boldsymbol{A}} = \begin{bmatrix} \xi & \Omega_z & -\Omega_y \\ -\Omega_z & \xi & \Omega_x \\ \Omega_y & -\Omega_x & \xi \end{bmatrix}$$

$$\xi = \nu_m - i\omega_{RF}$$

$$J_{ez} = \frac{\Omega_x}{\xi} J_{ey} \quad \xrightarrow{\omega_{RF} = 0} \quad \frac{J_{ez}}{J_{ey}} = \frac{e n_e E_y / B_x}{\sigma_y E_y} = \omega_e \tau_{eff}$$

$$\epsilon_0 \omega_p^2 E_y = \left(\xi + \frac{\Omega_x^2}{\xi}\right) J_{ey} \quad \xrightarrow{\Omega_x = 0} \quad J_{ey} = \sigma_p E_y$$

Phase difference of $J_{ez}/J_{ey} \approx 0.28\pi$

Phase difference of $J_{ey}/E_y \approx 0.3\pi$

$$\frac{\Omega_x}{\xi} / \left(\xi + \frac{\Omega_x^2}{\xi}\right) = \frac{2\nu_m \omega_{RF}}{\nu_m^2 - \omega_{RF}^2 + \Omega_x^2} \approx 0.01$$

ν_m: 10^7 to 10^8; ω_{RF}: 10^7 to 10^8; Ω_x: 10^9 to 10^{10}

Moment analysis of Boltzmann equation

Boltzmann equation

$$\frac{\partial f_e}{\partial t} + \boldsymbol{v} \cdot \nabla f_e - \frac{e}{m_e}(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \cdot \nabla_v f_e = \left.\frac{\partial f_e}{\partial t}\right|_c$$

Momentum conservation equation

$$m_e n_e \frac{\partial \boldsymbol{u}_e}{\partial t} + m_e (\boldsymbol{\Gamma}_e \cdot \nabla) \boldsymbol{u}_e = -e n_e (\boldsymbol{E} + \boldsymbol{u}_e \times \boldsymbol{B}) - \nabla \cdot \overleftrightarrow{\boldsymbol{\Pi}}_e + \left(\frac{\partial \rho_e}{\partial t}\right)_c$$

Electron power density

$$P_e(x, y, t) = \boldsymbol{J}_e \cdot \boldsymbol{E} = J_{ex} E_x + J_{ey} E_y \qquad \boldsymbol{J}_e = -e n_e \boldsymbol{u}_e$$

$$P_{acc} = m_e n_e \sum_i u_{ei} \frac{\partial u_{ei}}{\partial t},$$

$$P_e = P_{acc} + P_{in} + P_{press} + P_{Ohmic}$$

collisionless ($P_{acc} + P_{in} + P_{press}$) collisional ($P_{Ohmic}$)

$$P_{in} = m_e \sum_i u_{ei} \left(\Gamma_{ex} \frac{\partial u_{ei}}{\partial x} + \Gamma_{ey} \frac{\partial u_{ei}}{\partial y}\right),$$

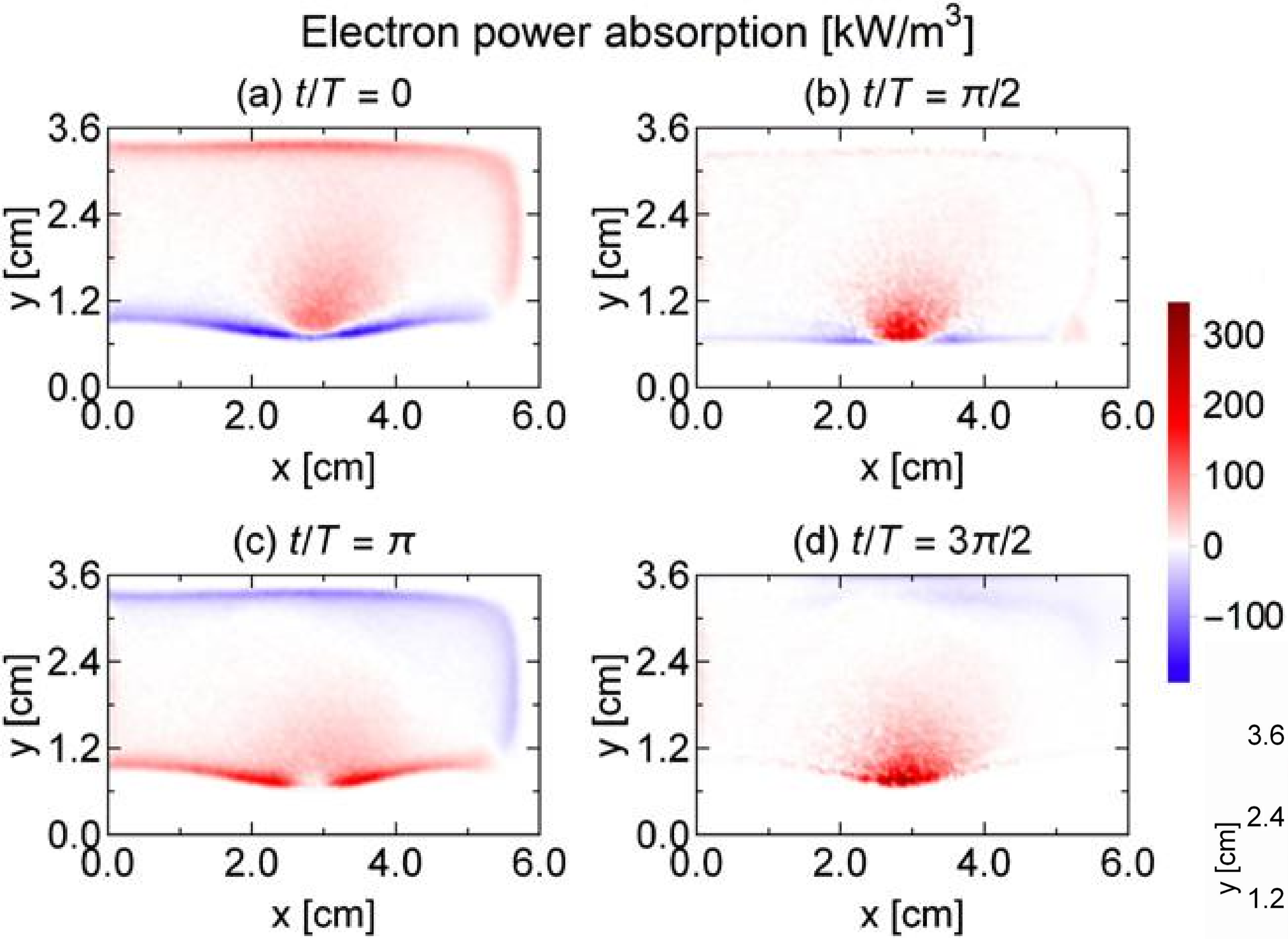
$$P_{press} = \sum_i u_{ei} \left(\frac{\partial \Pi_{exi}}{\partial x} + \frac{\partial \Pi_{eyi}}{\partial y}\right),$$

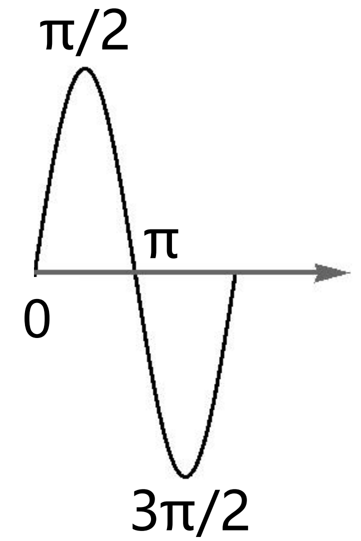
$$P_{Ohmic} = -\sum_i u_{ei} \left(\frac{\partial \rho_{ei}}{\partial t}\right)_c,$$

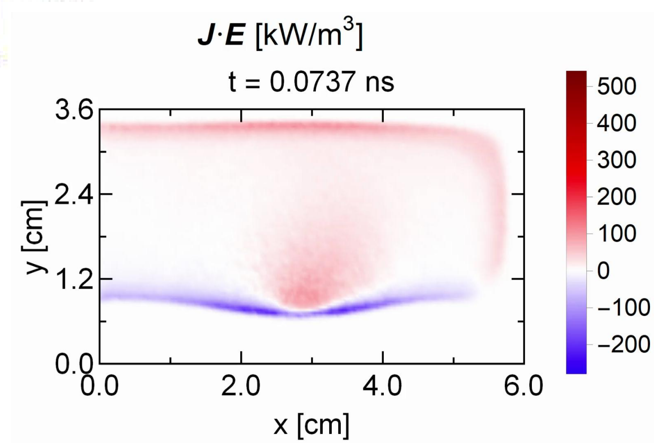
Further reference:

S. Wilczek, J. Schulze, R. P. Brinkmann, Z. Donkó, J. Trieschmann, T. Mussenbrock, *Electron dynamics in low pressure capacitively coupled radio frequency discharges*, **Journal of Applied Physics 127**, 181101 (2020).

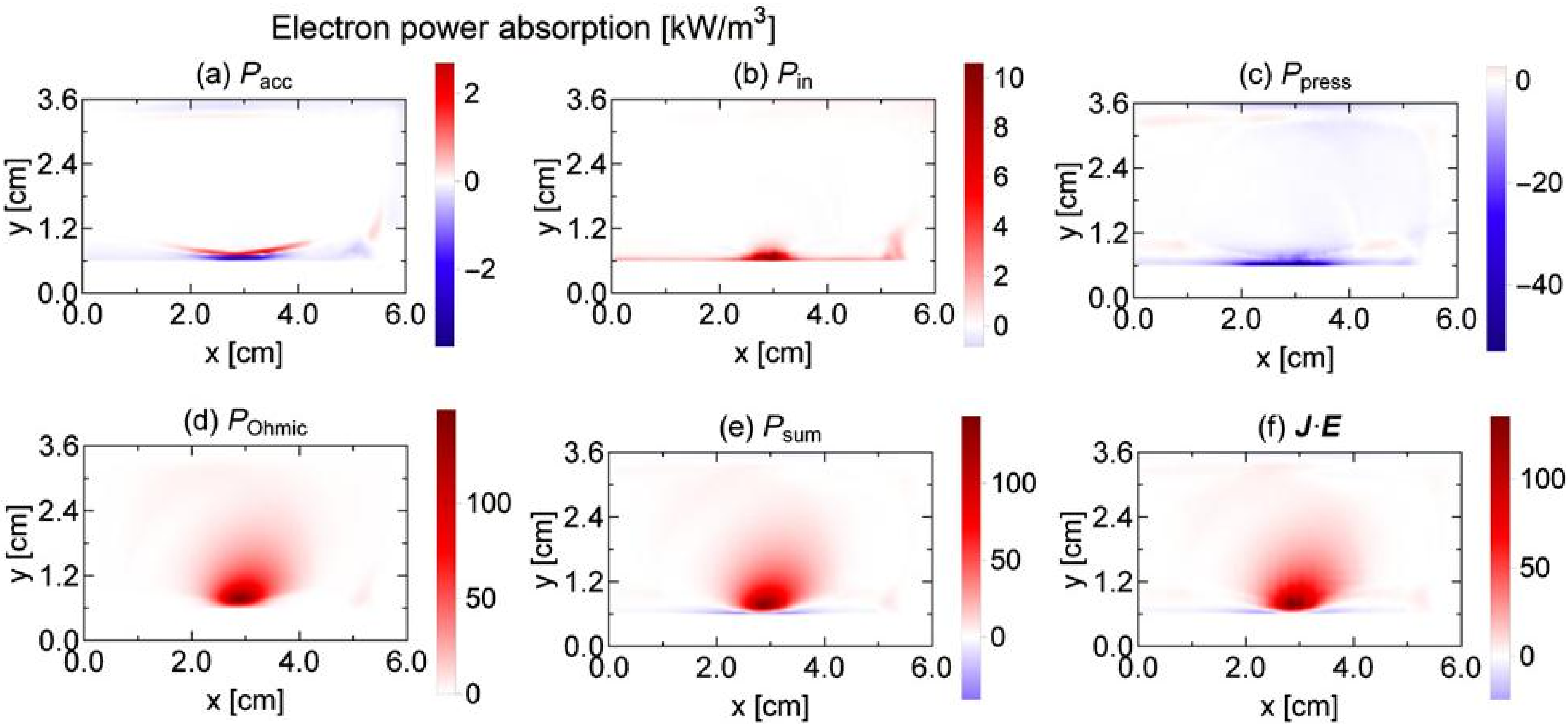
Electron power density





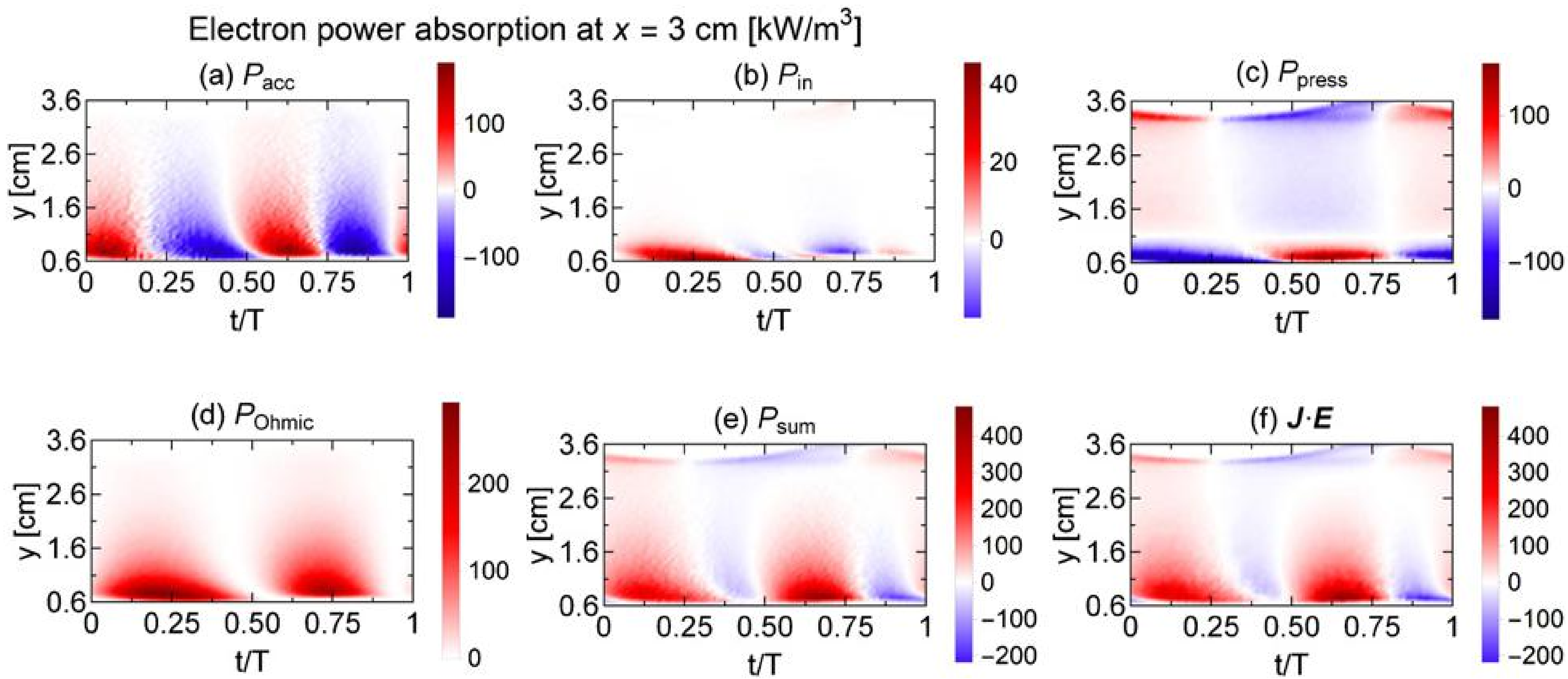


Time-averaged electron power absorption components



Contribution of P_{Ohmic}
in z direaction > 97%

Spatiotemporal electron power absorption components



Minea and Bretagne, *Simple model of power deposited into the plasma bulk of rf planar magnetrons*, **PSST 12**, 97 (2003).

$\boldsymbol{J}_e \cdot \boldsymbol{E}$	Analytical model	PIC simulation
Electric field direction	2%	97.3%
E×B direction	98%	2.1%

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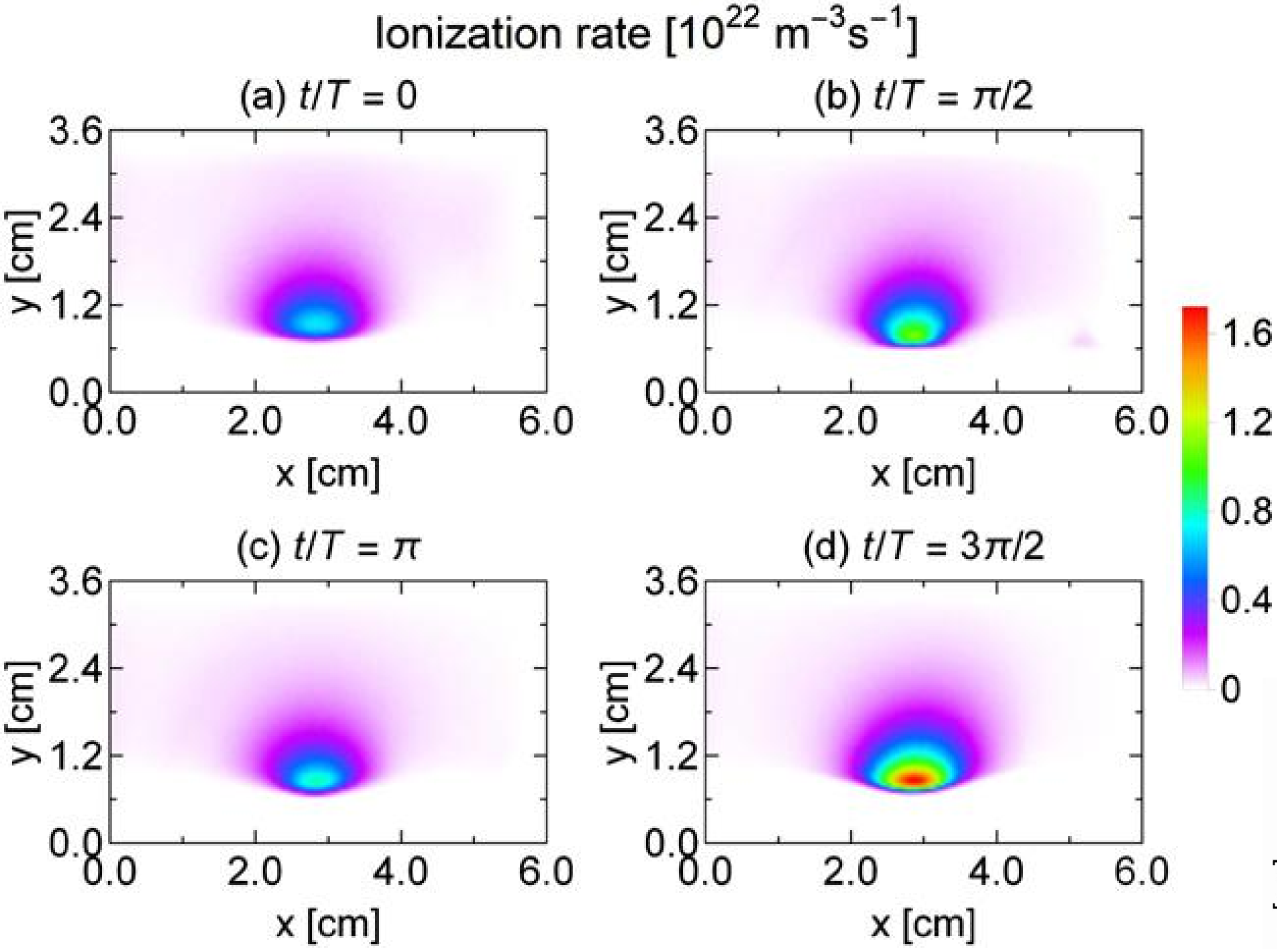
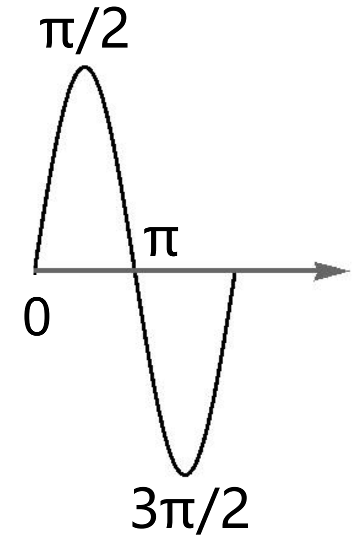
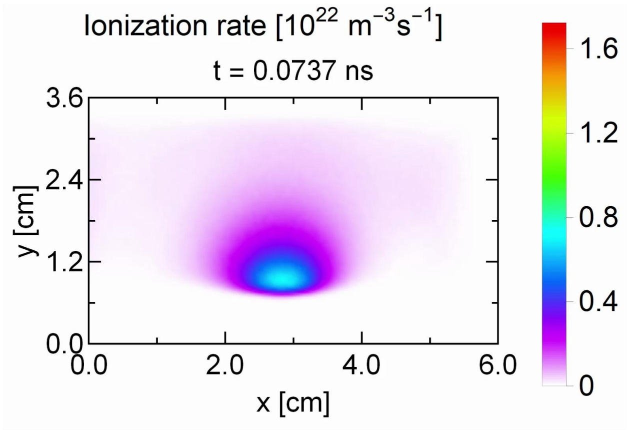
Ionization rate



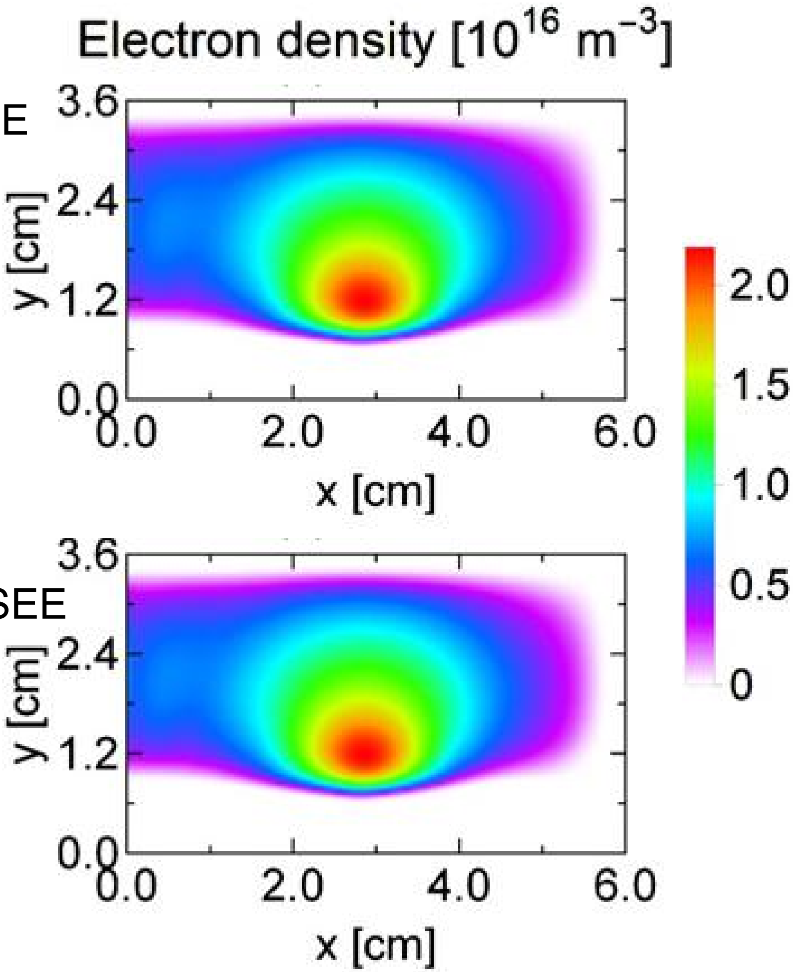


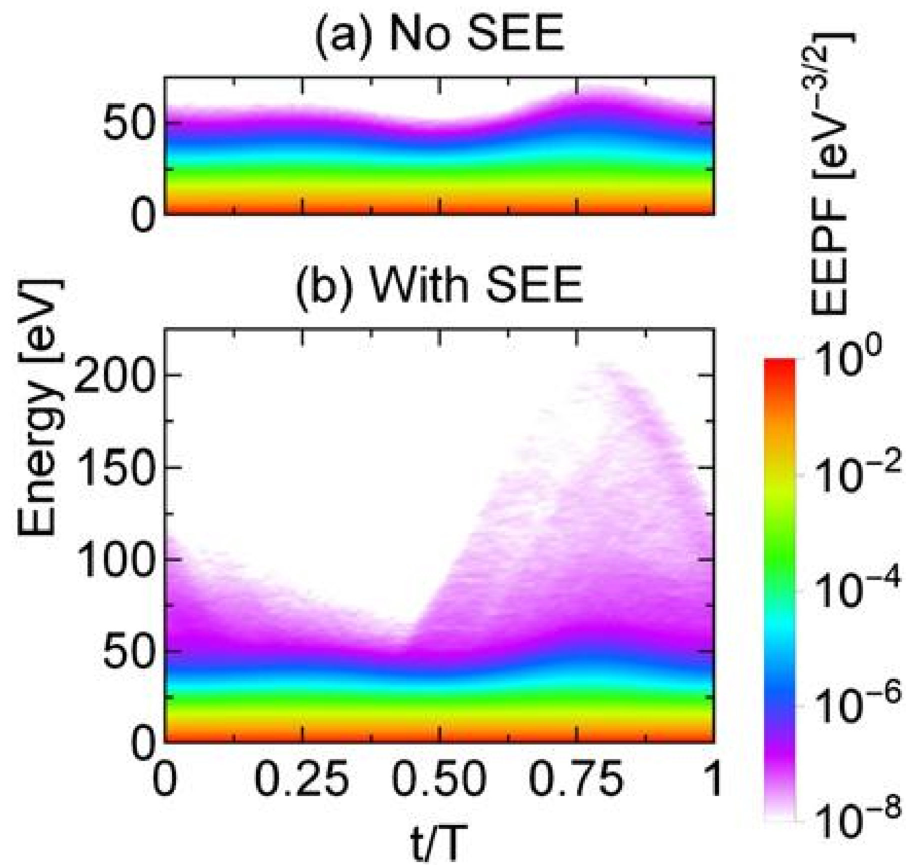


Influence of secondary electron emission

No SEE

With SEE





$$\gamma_{\mathrm{i}}(\varepsilon) = \frac{0.006\varepsilon}{1 + (\varepsilon/10)} + \frac{1.05 \times 10^{-4}(\varepsilon - 80)^{1.2}}{(1 + \varepsilon/8000)^{1.5}}.$$

Conclusion

- The electron dynamics in a typical electropositive RFMS discharge is studied via a fully kinetic, 2d3v PIC/MCC electrostatic simulation.
- A spatially dependent charging is observed on the dielectric target surface, resulting in spatially dependent ion energy distribution along the target surface, which in turn may cause an abnormal erosion profile, that the intensively etched region on a metallic target can be the least eroded on a dielectric target.
- The phase difference and amplitude ratio between electron current densities in different directions are primarily determined by the electron cyclotron angular frequency, the electron momentum transfer collision frequency, and the RF source frequency.
- The dominant electron power absorption mechanism on time- and space-average is the Ohmic power absorption, mostly contributed from the $E \times B$ direction.
- The electron power absorption can be primarily decoupled into the positive power absorption in the bulk plasma region due to collisional dynamics, and the negative power absorption near the target surface due to pressure-induced effects.
- The power absorption and dissipation of electrons in the bulk plasma region are approximately synchronized in time and space, suggesting a suppression of the nonlocal electron motion in magnetron discharges.
- The contribution of secondary electrons is negligible under typical RFMS discharge conditions investigated here.