IOPS, Thursday, February 25, 2021

Electron power absorption dynamics in magnetized capacitively coupled radio frequency oxygen discharges

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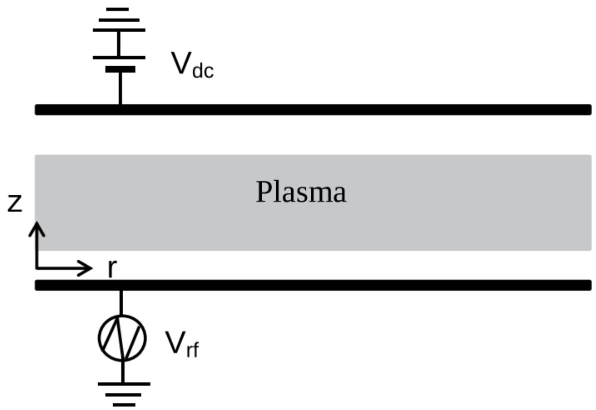
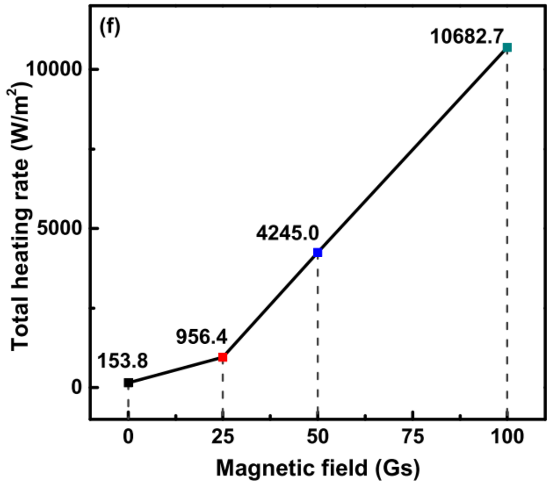
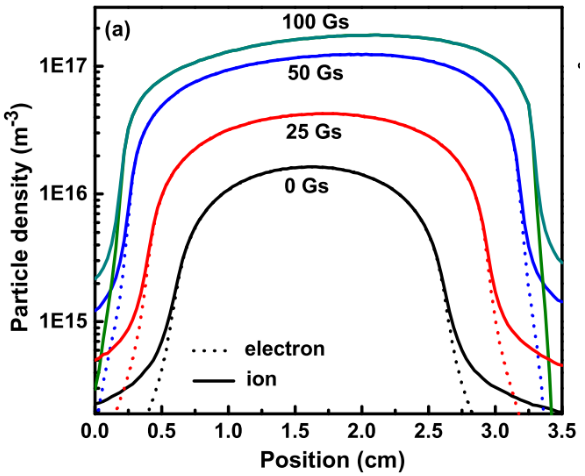
OUTLINE

- Background & Motivation
- Description of PIC simulation
- Influence of a magnetic field on plasma properties
- Influence of a magnetic field on electron heating
- Electric field reversal and analytical analysis
- Conclusions

I. BACKGROUND



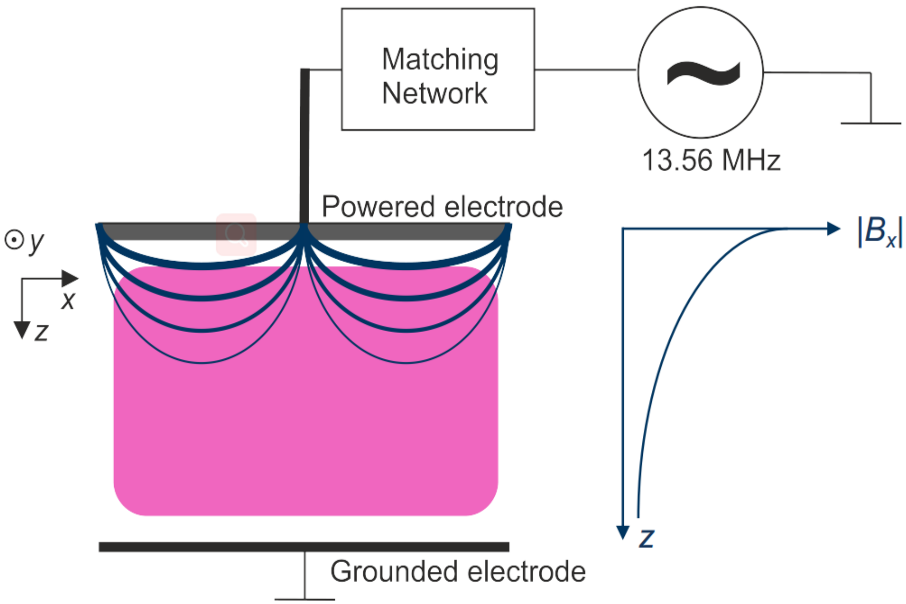


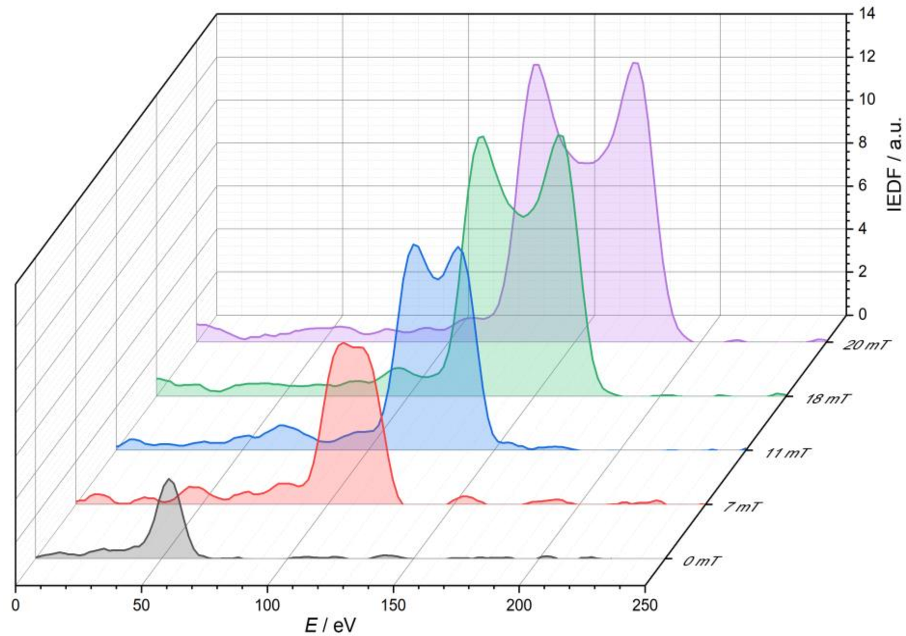


- For the application of CCP discharges, appropriate and controllable plasma properties are required. Magnetized CCPs show good performance in improving plasma properties, especially the plasma density.

Shali Yang et al. Physics of Plasmas 24, 033504 (2017)

I. BACKGROUND

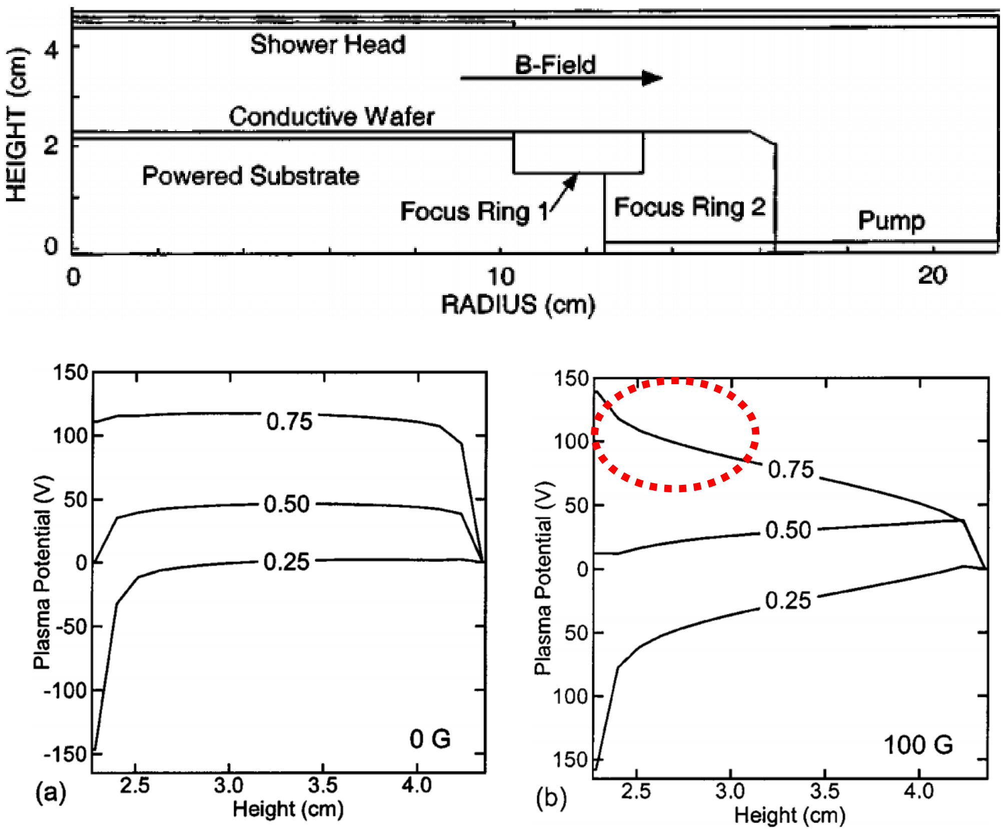


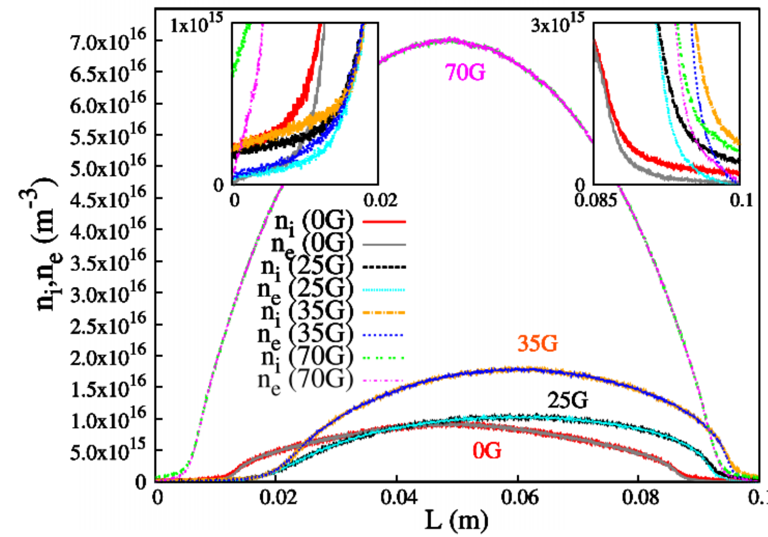


- Magnetically asymmetric effect (MAE) can produce controllable asymmetry in the discharge.
- Mean ion energy increases at the grounded electrode due to the DC self-bias.
- Bimodal shape for higher magnetic fields due to higher densities and a decreased sheath width.

M Oberberg et al 2018 Plasma Sources Sci. Technol. 27 105018

I. BACKGROUND

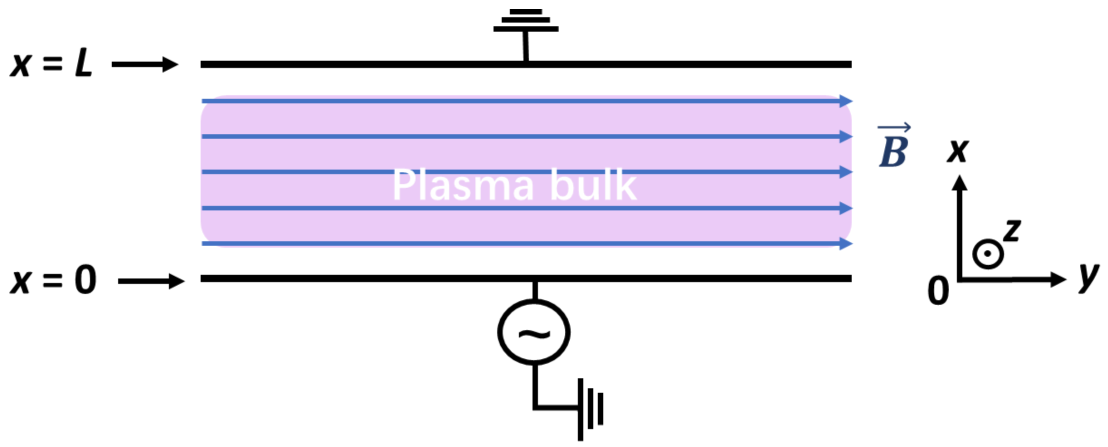




- Without magnetic field, the bulk plasma potential is always positive with respect to surfaces, while the electric field in the powered sheath is reversed during sheath collapse in the presence of a B field.
- The ion density becomes asymmetric with increasing the strength of the magnetic field.

Mark J.Kushner, Journal of Applied Physics 94, 1436 (2003)
Sharma S et al. Physics of Plasmas 25, 080704 (2018)

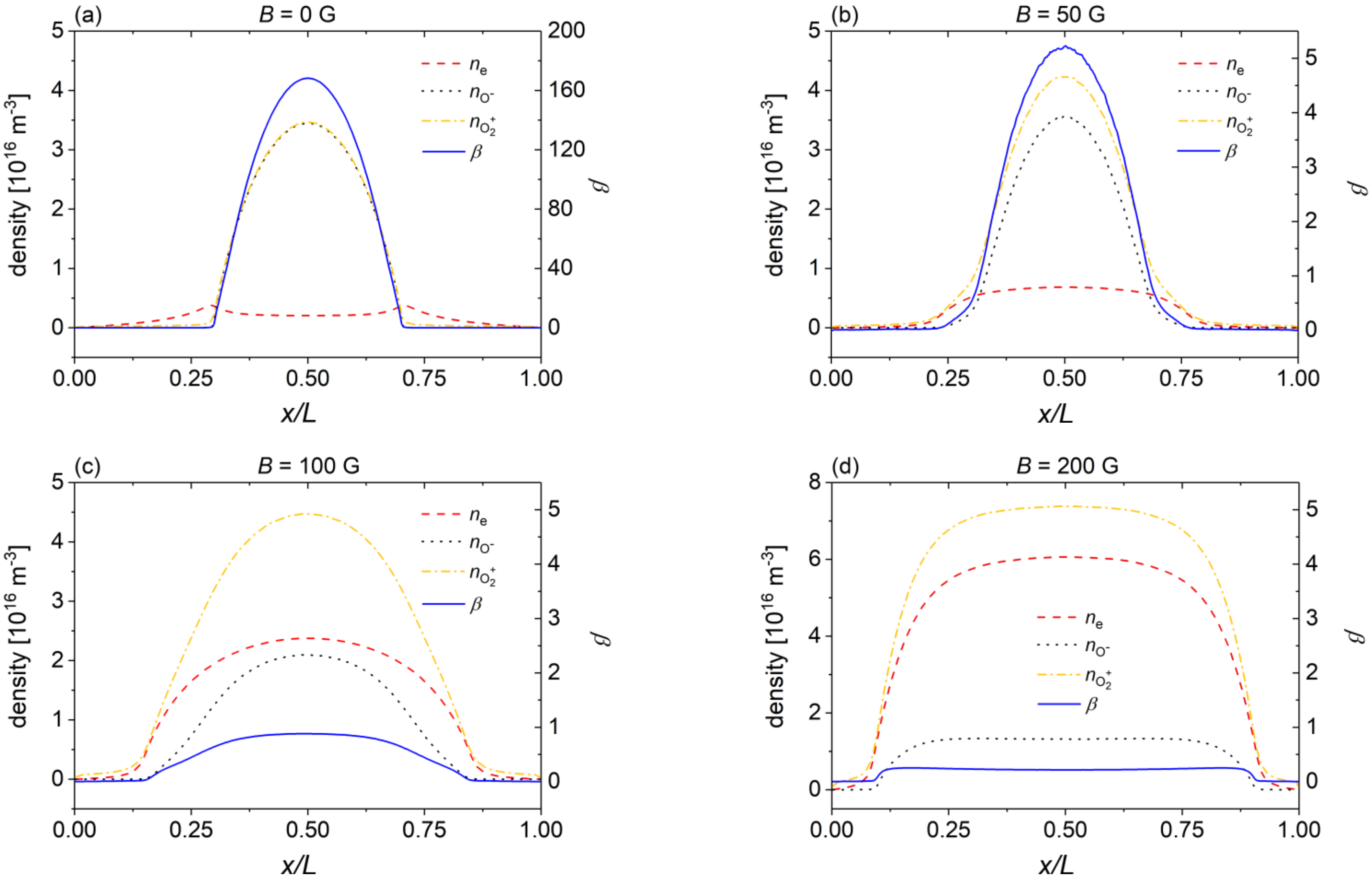
II. 1D3V PIC SIMULATION



- Electrode gap: L = 2.5 cm
- Gas pressure: p = 100 mTorr
- Driving voltage: $V(t) = V_0 cos(2\pi ft)$
- Driving frequency: f = 13.56 MHz
- Voltage amplitude: V_0 = 300 V
- SEE coefficient: 0

- Traced particles: O^-, O_2^+, e^-
- Neutral particles considered: O_2, $O_2(a^1\Delta_g)$
- Time step: 5 x 10^{-12} ~ 1.6 x 10^{-11} s
- Grid size: 2.5 x 10^{-5} ~ 6 x 10^{-5} m

III. INFLUENCE OF MAGNETIC FIELD ON PLASMA PROPERTIES



- The electron density and O_2^+ density increase with the magnetic field, the O^- density decreases at the discharge center as a function of the magnetic field. The electronegativity is greatly reduced.
- The plasma spread to a larger scope due to the reduced sheath width.

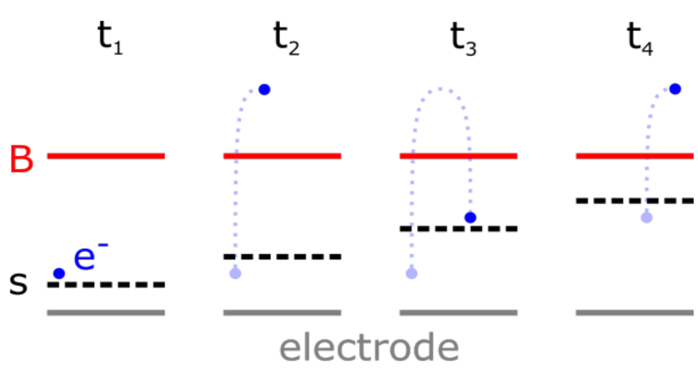
III. INFLUENCE OF MAGNETIC FIELD ON PLASMA PROPERTIES

Reasons for the enhanced electron density:

1. Increased electron-sheath interaction time.

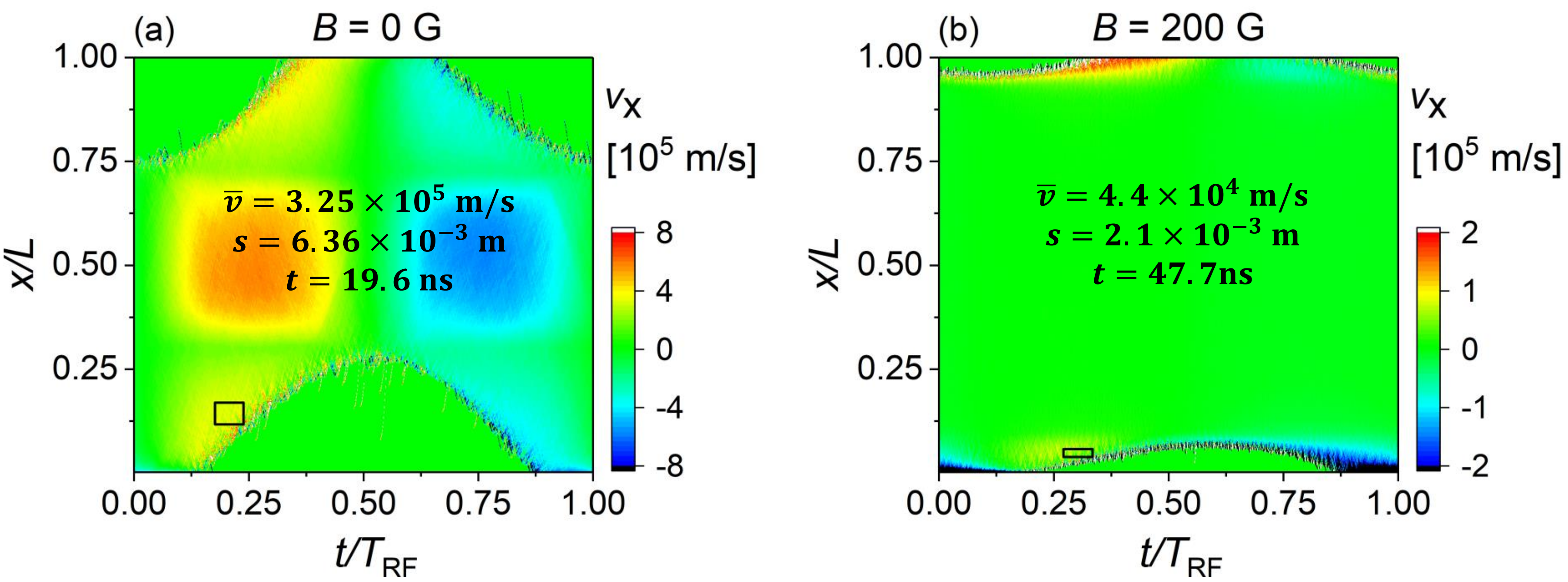
B = 0: 'Classical' a-mode: Electron acceleration is comparable to a racket hitting a tennis ball.

B > 0: Electrons are kicked by the expanding sheath, but are accelerated back towards the sheath by the Lorentz force: Rubber-band racket.



vs.

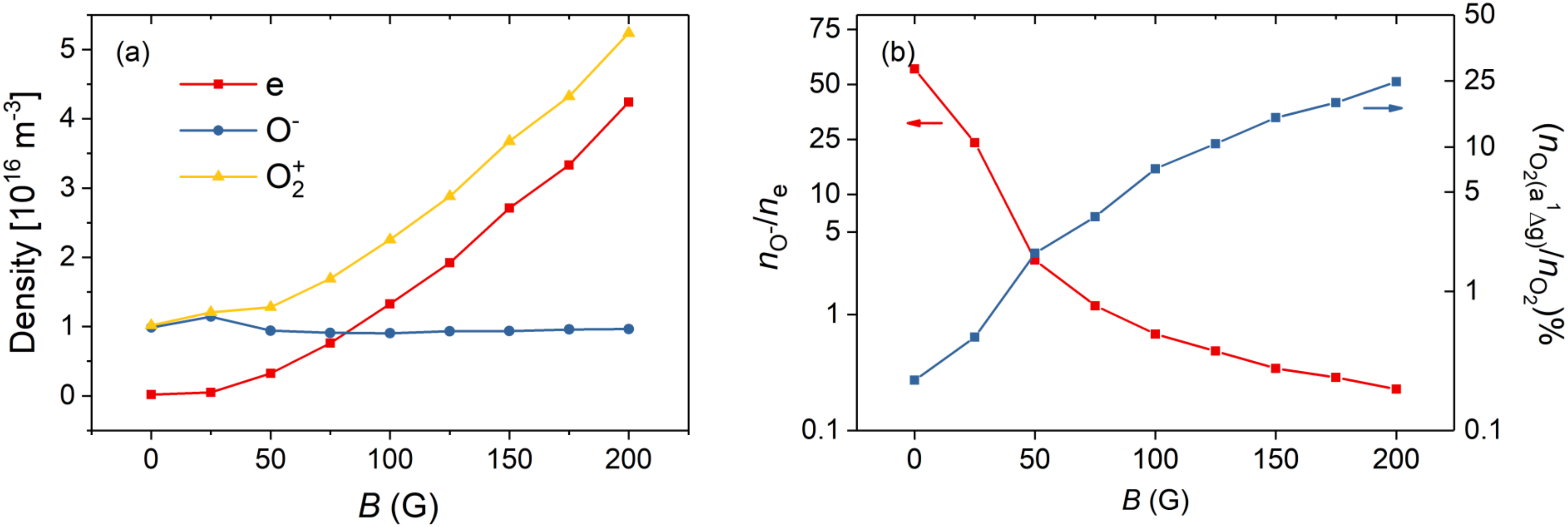
III. INFLUENCE OF MAGNETIC FIELD ON PLASMA PROPERTIES



Reasons for the enhanced electron density:

2. Energetic electrons undergo more collisions before they are lost to the electrodes in the presence of a magnetic confinement compared to the unmagnetized scenario.
3. A strong field reversal is generated during the sheath collapse in the presence of the magnetic field, which greatly enhances the electron power absorption.

III. INFLUENCE OF MAGNETIC FIELD ON PLASMA PROPERTIES



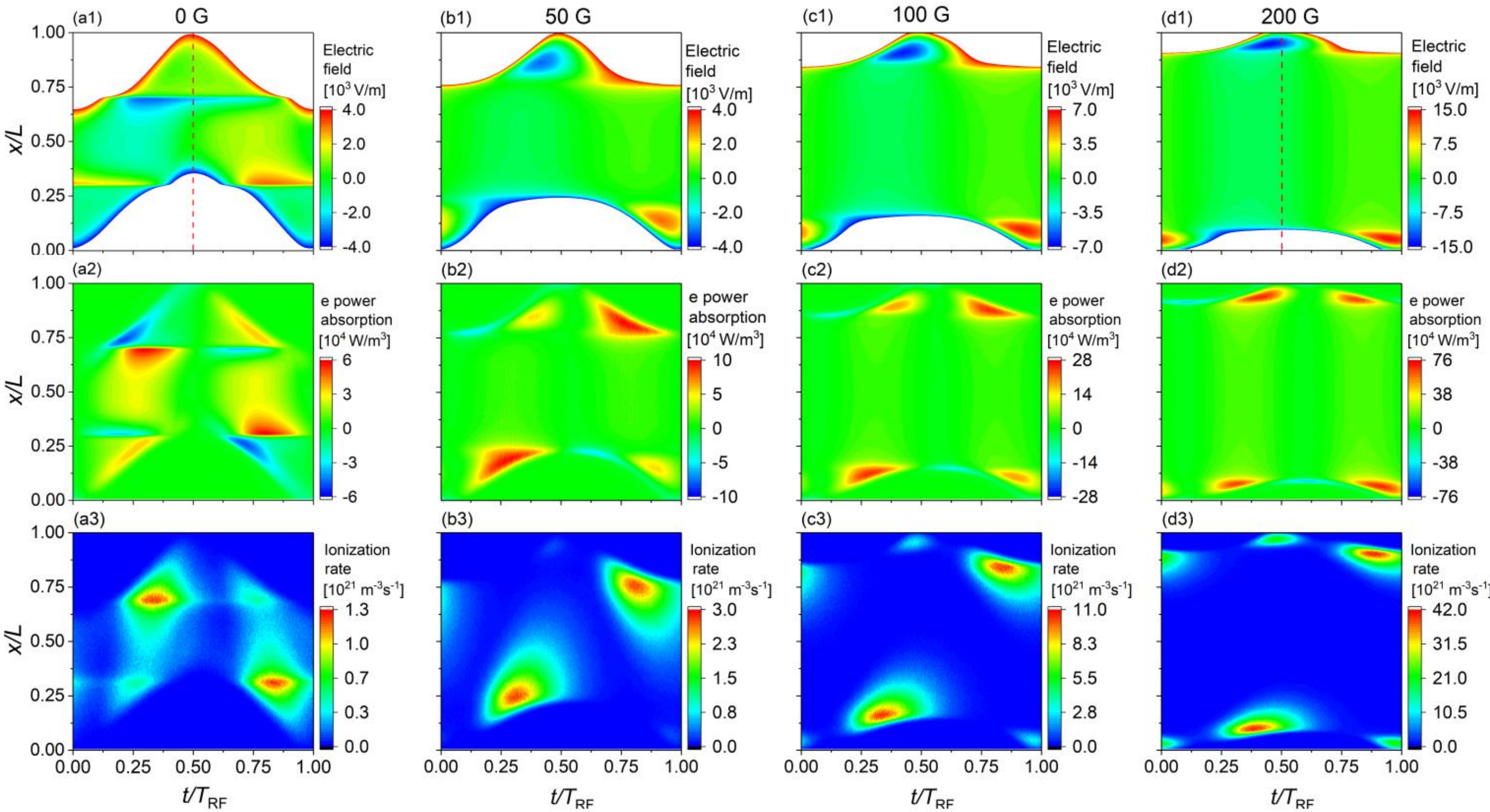
- The space and time averaged O^- density remains approximately constant as a function of the B-field, with the electronegativity decreasing from 58 to 0.23.
- More $O_2(a^1\Delta_g)$ metastables are generated by electron impact excitation at high magnetic fields, which is one of the main reason for the almost unchanged O^- density.

III. INFLUENCE OF MAGNETIC FIELD ON ELECTRON DYNAMICS

E-field

e power absorption rate

Ionization rate



- At B = 0 G, the discharge is strongly electronegative, strong drift and ambipolar fields are generated.
- With the increase of the magnetic field, electron heating mode transits from DA mode to α-mode.
- A strong field reversal is generated, which leads to a strong electron power absorption during the sheath collapse.

III. INFLUENCE OF MAGNETIC FIELD ON ELECTRON DYNAMICS

Electron density

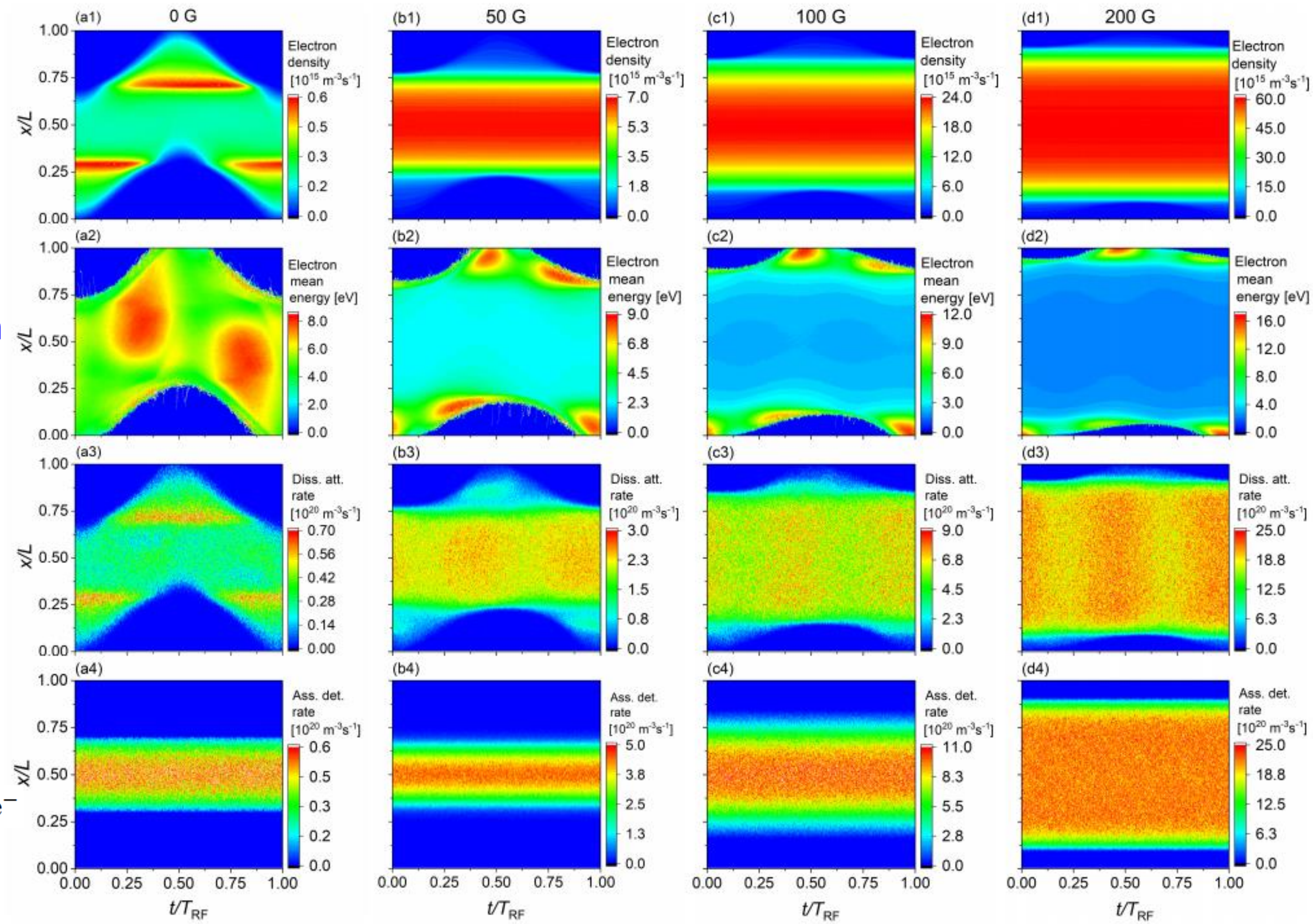
Electron mean energy

Diss. att. rate

$e^- + O_2 \rightarrow O^- + O$

Ass. det rate

$O^- + O_2(a^1\Delta_g) \rightarrow O_3 + e^-$



- The dissociative attachment rate mainly follows the variation of the electron density.
- As a result of the increased O_2(a1Δg) density and the decreased sheath width at high magnetic fields, the associative detachment rate is much higher at large B-fields.

IV. ELECTRIC FIELD REVERSAL & ANALYTICAL ANALYSIS

Momentum balance equation：

$$m\left[\frac{\partial(n\mathbf{u})}{\partial t} + \nabla\cdot(n\mathbf{u}\mathbf{u})\right] = -en(\mathbf{E} + \mathbf{u}\times\mathbf{B}) - \nabla\cdot\mathbf{P} - \mathbf{\Pi}$$

In the *x* direction

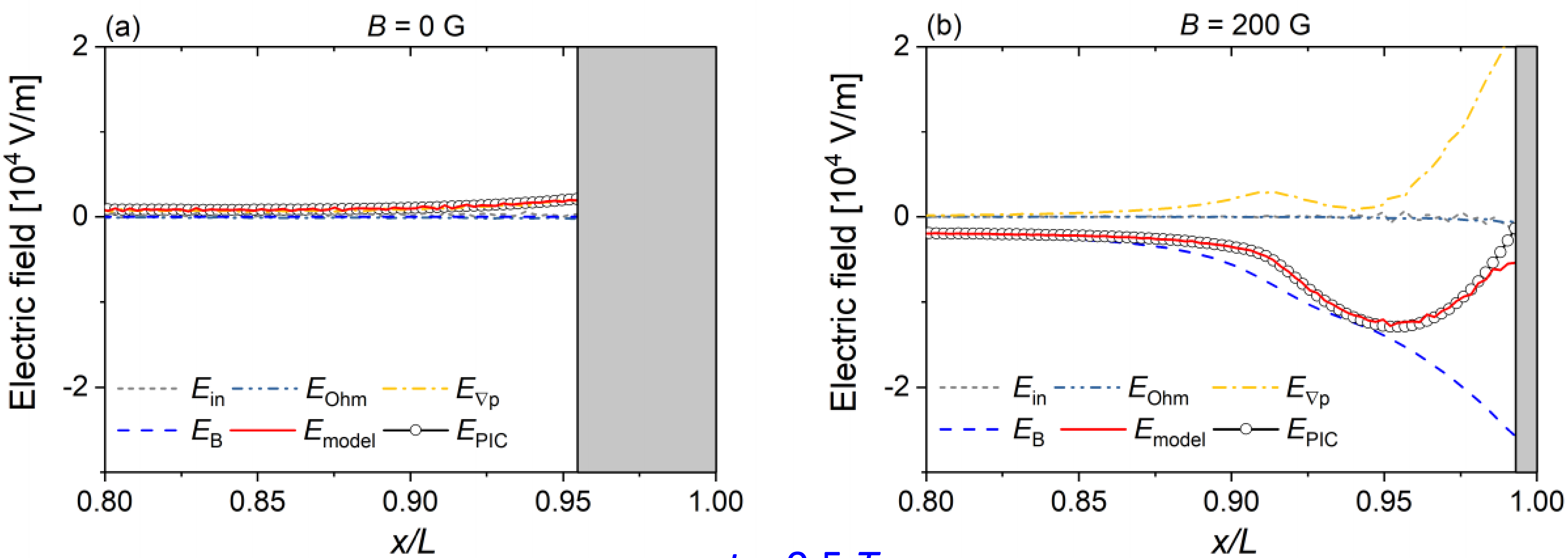
$$m\frac{\partial(nu_{\mathrm{x}})}{\partial t} + m\frac{\partial(nu_{\mathrm{x}}^2)}{\partial x} = -en(E_{\mathrm{x}} - u_{\mathrm{z}}B_{\mathrm{y}}) - \frac{\partial p_{\mathrm{xx}}}{\partial x} - \Pi_{\mathrm{x}}$$

$p_{xx} = nT_{xx}$

$$E_x = -\frac{m}{en}\left(\frac{\partial nu_x}{\partial t} + \frac{\partial n{u_x}^2}{\partial x}\right) - \frac{1}{en}\frac{\partial nT_{xx}}{\partial x} - \frac{\Pi_x}{en} + B_y\, u_z$$

E_{model} $\quad E_{in}$ $\quad E_{\nabla p}$ $\quad E_{Ohm}$ $\quad E_B$

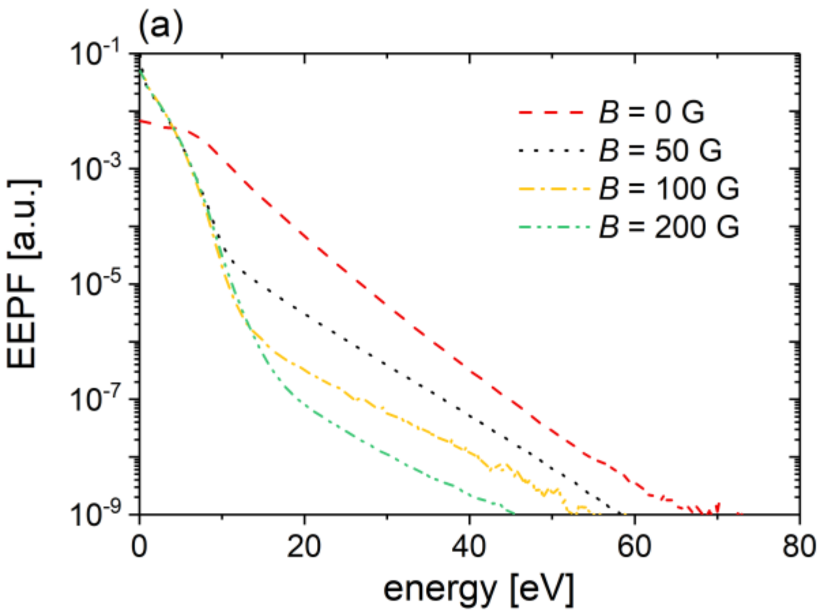
IV. ELECTRIC FIELD REVERSAL & ANALYTICAL ANALYSIS



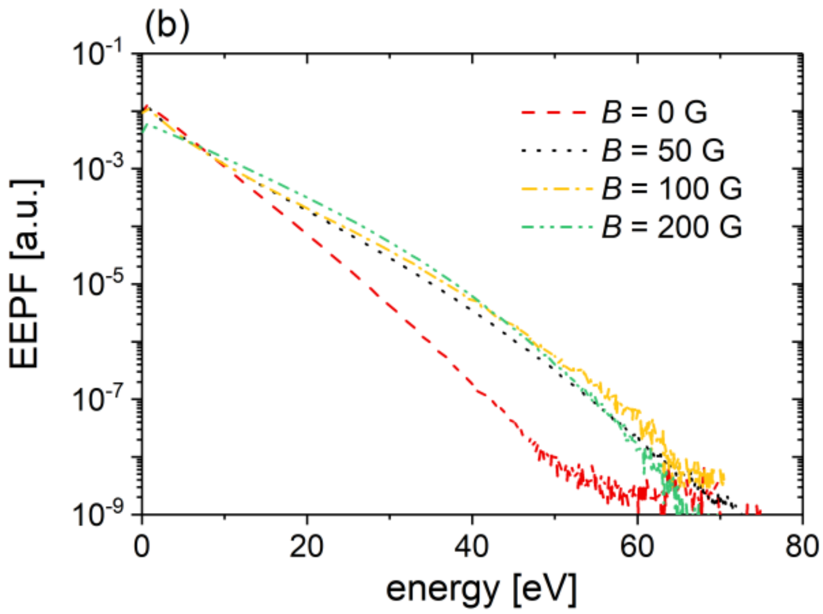
$t = 0.5\ T_{RF}$

- At B = 0 G, no electric field reversal is generated. At B = 200 G, a strong electric field reversal is generated and the negative E_B is the only reason for the generation of the field reversal.
- In order to compensate the high ion flux at each electrode on time average, an electric field reversal must be generated to accelerate electrons towards the electrode.
- Once a small reversed electric field is generated, u_z increases due to the $E \times B$ drift, which in turn further enhances the electric field reversal, until the ion flux can be compensated by the electron flux.

III. INFLUENCE OF MAGNETIC FIELD ON ELECTRON DYNAMICS



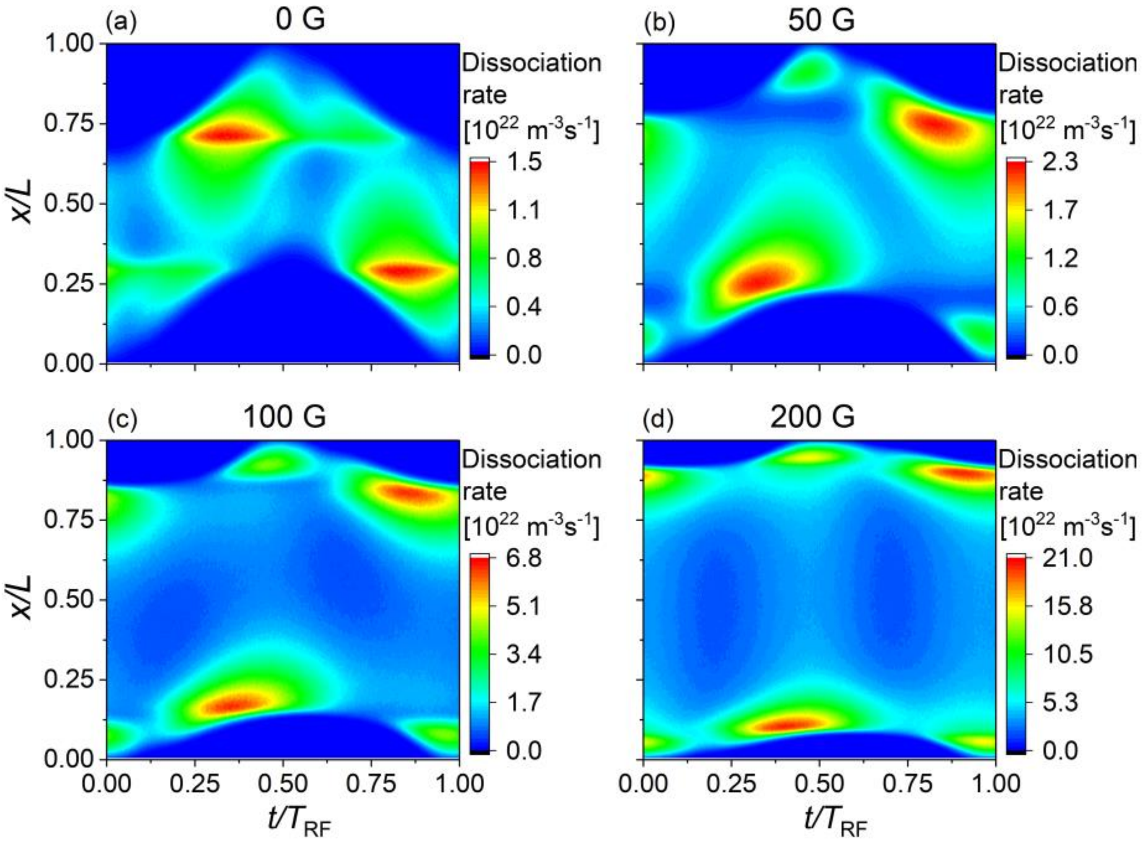
EEDF at the discharge center



EEDF near the expanding sheath

- By increasing the magnetic field, the electron power absorption is attenuated in the discharge center and strong at the sheath edges. This causes the presence of more low energy electrons in the discharge center.
- Due to the extended interaction time of the electrons and the expanding sheath, more electrons are accelerated to relatively high energies compared to the B = 0 G case.

IV. ELECTRIC FIELD REVERSAL & ANALYTICAL ANALYSIS



dissociation rate

- By increasing the magnetic field, the total dissociation rate is enhanced.
- At high B-fields the electric field reversal also enhances the dissociation of oxygen molecules and contributes to the generation of oxygen atoms significantly.

VI. CONCLUSIONS

- The presence of the magnetic field enhances the confinement of electrons, which finally results in increased electron and O_2^+ densities.

- The O^- ion density Is found to remain approximately constant, which is caused by the balance of the both increased dissociative attachment rate and the associative detachment rates as a function of the magnetic field.

- The electronegativity decreases as a function of the magnetic field, which causes an electron power absorption mode transition from the DA-mode to the α-mode.

- A strong electric field reversal is generated with the presence of the B field, which significantly enhances the electron power absorption. By applying a Boltzmann term analysis model, the reversed field is found to be induced by the Lorenz force term.

Thank You For Your Attention !

Dalian University Of Technology

RUB

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