Plasma modulation in a high-intensity acoustic standing wave field

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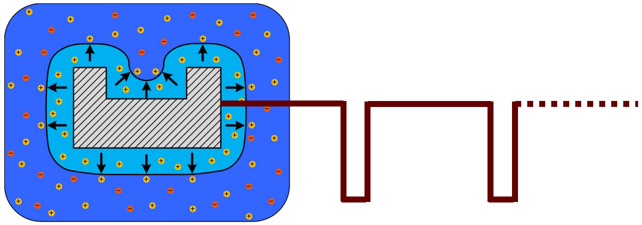
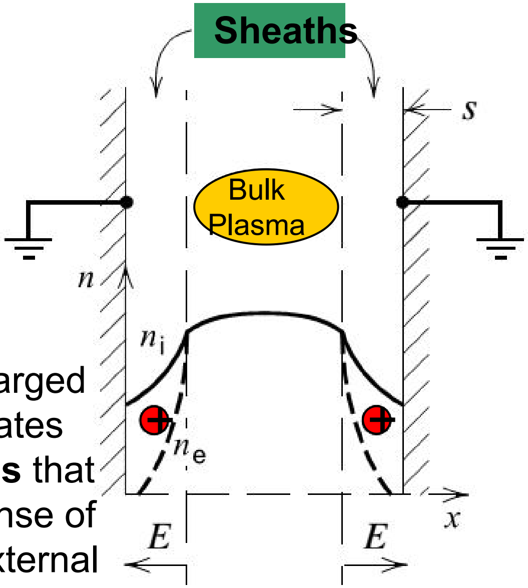
Introduction

- Distributions of plasma species
  - determined by the discharge characteristics and are stable over time
- Plasma modulation
  - Scientifically interesting and practically attractive
- Pulsed plasmas
  - Enhanced plasma uniformity
  - Controllable ion energy
  - Improved plasma density
  - Increased deposition and etching rate
- Plasma modulation by external ***E*** is limitec



Collective behavior of plasmas

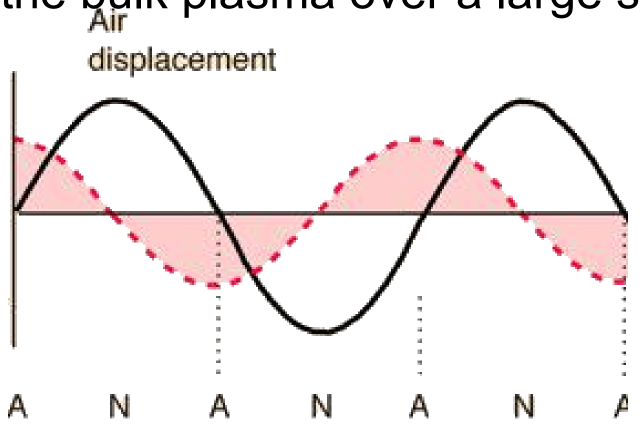


Movement of charged particles generates **local net charges** that restrict the response of plasmas to the external ***E***

Bulk plasma remains nearly unaffected

Introduction

- Effective way to modulate bulk plasmas?
- Plasmas can be used to control the neutral flows
  - Corona/SDBD
  - the generated flows can influence the spatial distribution of the chemical species generated from the discharge, $v_{max} < 10$ m/s.
  - Small v_{max}: can very much affect the long-lived species, but have little effect on the short-lived excited species
- Generate a strong neutral flow in the plasma
  - Modulate ions and reactive species in the bulk plasma over a large scale
  - Acoustic standing wave field
  - The acoustic pressure and particle velocity in the acoustic field can create strong neutral flows as well as friction forces to the plasma species
  - Strong modulation effect



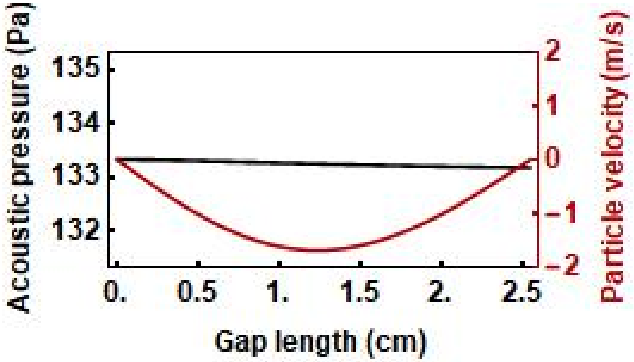
Model description

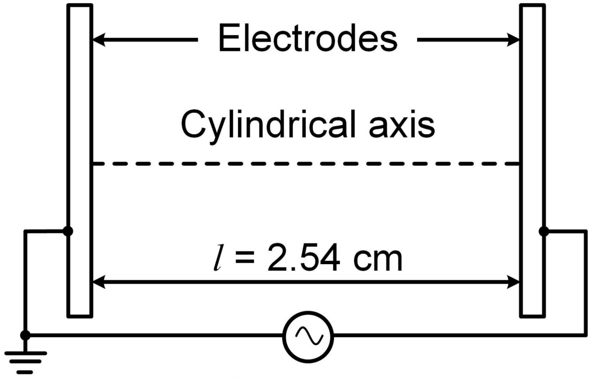
- One-dimensional CCP discharges
- Working gas Ar of 1 Torr

$$
\begin{aligned}
c^2\frac{\partial^2\varphi}{\partial x^2}-\frac{\partial^2\varphi}{\partial t^2}+\delta\frac{\partial^3\varphi}{\partial x^2\partial t}&=\frac{da}{dt}x+a\frac{\partial\varphi}{\partial x}\\
&\quad+(\gamma-1)ax\frac{\partial^2\varphi}{\partial x^2}+2\frac{\partial\varphi}{\partial x}\frac{\partial^2\varphi}{\partial x\partial t}+(\gamma-1)\frac{\partial\varphi}{\partial t}\frac{\partial^2\varphi}{\partial x^2}\\
&\quad+\frac{\gamma+1}{2}\left(\frac{\partial\varphi}{\partial x}\right)^2\frac{\partial^2\varphi}{\partial x^2},\\
p=p_0\left(1-\frac{\gamma-1}{c^2}\left[\frac{\partial\varphi}{\partial t}+\frac{1}{2}\left(\frac{\partial\varphi}{\partial x}\right)^2+ax-\delta\frac{\partial^2\varphi}{\partial x^2}\right]\right)^{\gamma/(\gamma-1)}\\
u_{\mathrm{n}}=\frac{\partial\varphi}{\partial x},
\end{aligned}
$$

The acoustic pressure *p* and the particle velocity u_{n} are one-way coupled to the plasma discharge model

$$
\begin{aligned}
&\frac{\partial n_{\mathrm{e}}}{\partial t}+\nabla\cdot(-\mu_{\mathrm{e}}En_{\mathrm{e}}-\nabla(D_{\mathrm{e}}n_{\mathrm{e}}))+\boxed{(u_{\mathrm{n}}\cdot\nabla)\,n_{\mathrm{e}}+n_{\mathrm{e}}\nabla\cdot u_{\mathrm{n}}}=R_{\mathrm{e}}\\
&\frac{\partial}{\partial t}\left(\frac{3}{2}n_{\mathrm{e}}T_{\mathrm{e}}\right)+\nabla\cdot\left(\frac{5}{2}T_{\mathrm{e}}\Gamma_{\mathrm{e}}-\frac{5}{2}n_{\mathrm{e}}D_{\mathrm{e}}\nabla T_{\mathrm{e}}\boxed{+\frac{3}{2}n_{\mathrm{e}}T_{\mathrm{e}}u_{\mathrm{n}}}\right)+E\cdot\Gamma_{\mathrm{e}}=Q\\
&\frac{\partial n_{\alpha}}{\partial t}+\nabla\cdot(\Gamma_{\alpha}\boxed{+n_{\alpha}u_{\mathrm{n}})}=R_{\alpha}\\
&\nabla^2\phi=\frac{e}{\epsilon_0}(n_{\mathrm{i}}-n_{\mathrm{e}})
\end{aligned}
$$



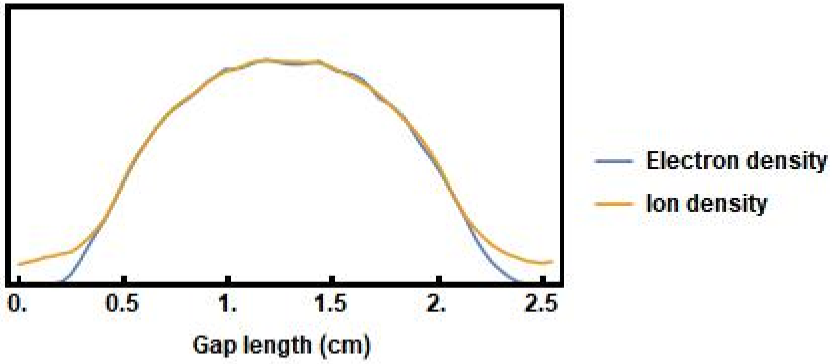


Electrodes

Cylindrical axis

l = 2.54 cm

RF source



Acoustic sta

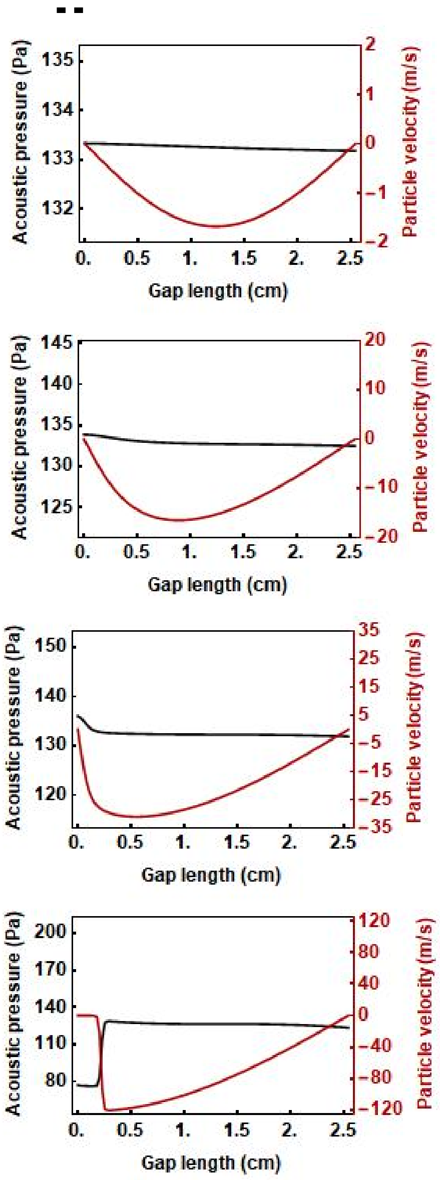
Low-amplitude: acoustic pressure and particle velocity have sinusoidal distributions

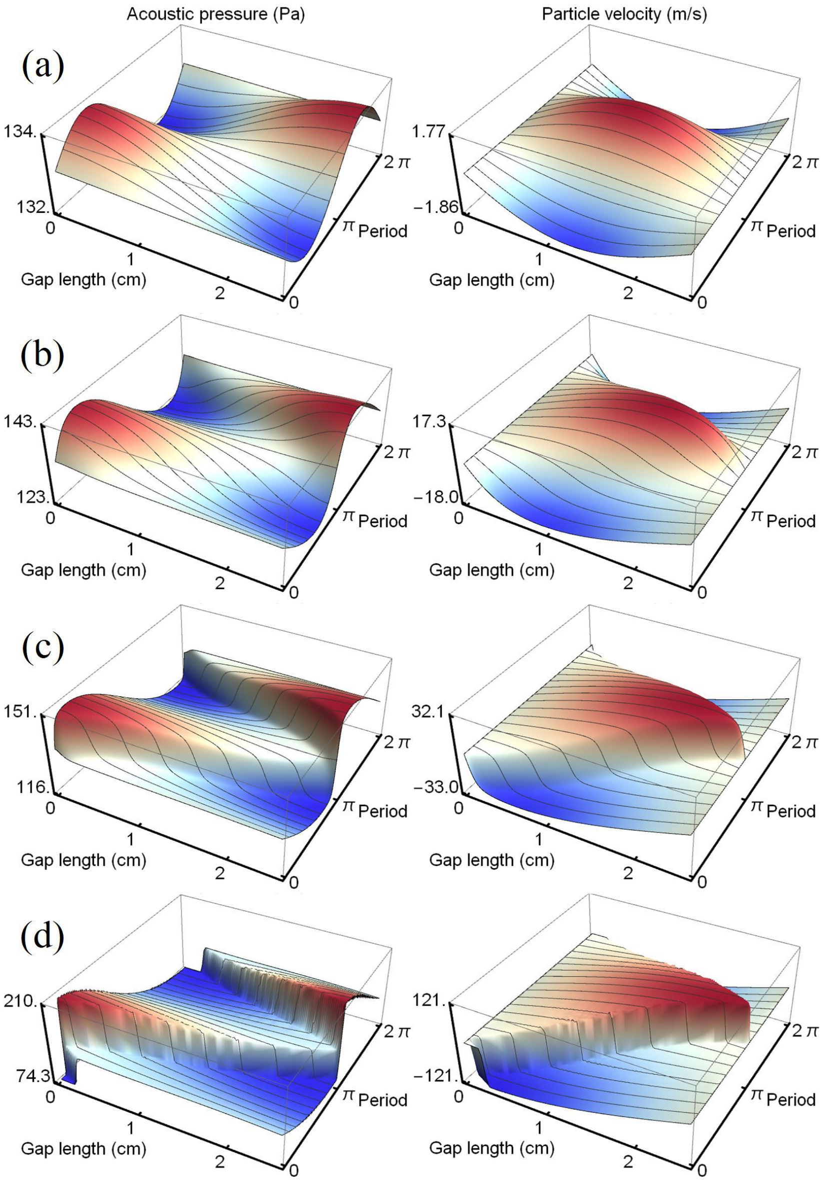
- To achieve the … a angular freque… sc mode
- Acoustic standi… 9 l
- Wave length is

Increasing the intensity of the acoustic field: nonlinear effect

the wave profiles deviate from the sinusoidal distribution

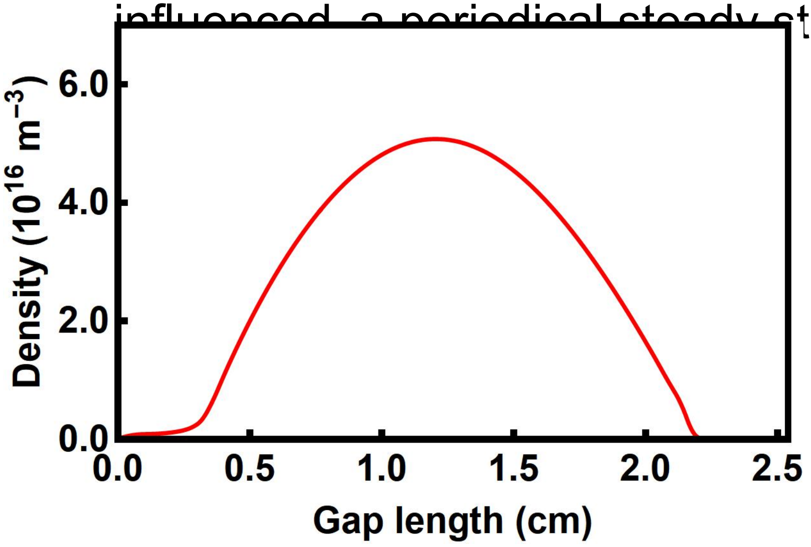
High-amplitude: sawtooth profiles



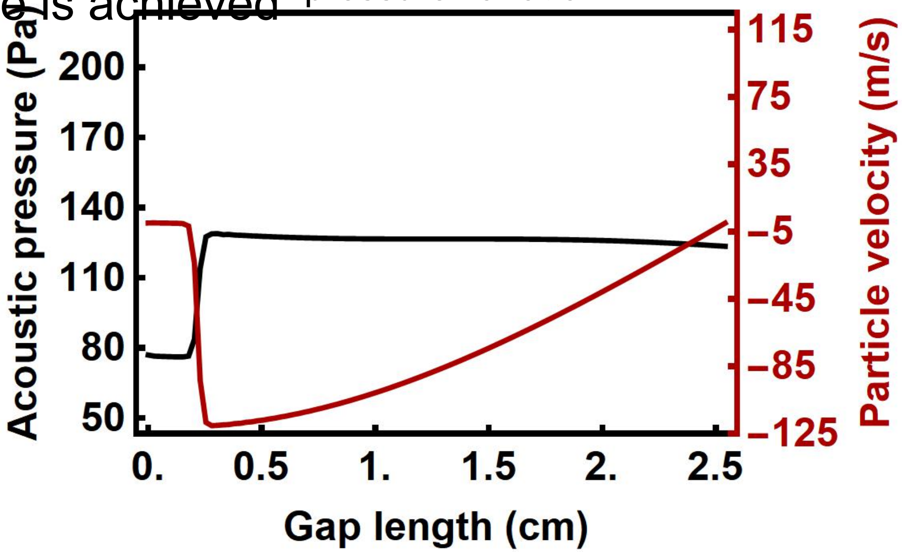


Ion distribution

- Influence of acoustic standing wave on the plasmas
- Without the acoustic standing wave: the Ar$^+$ density profile remains unchanged
- With an acoustic field: the plasma discharge behavior is significantly influenced, a periodical steady-state is achieved



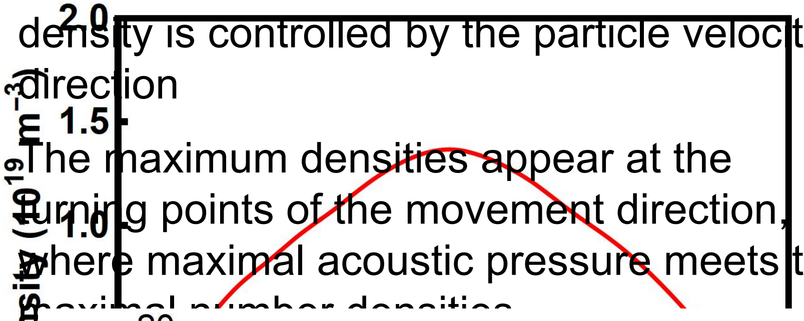
Nonlinear acoustic pressure variation

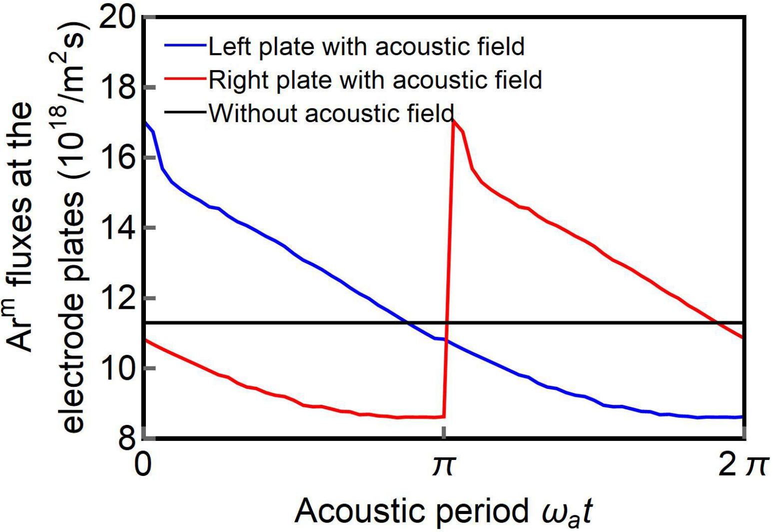


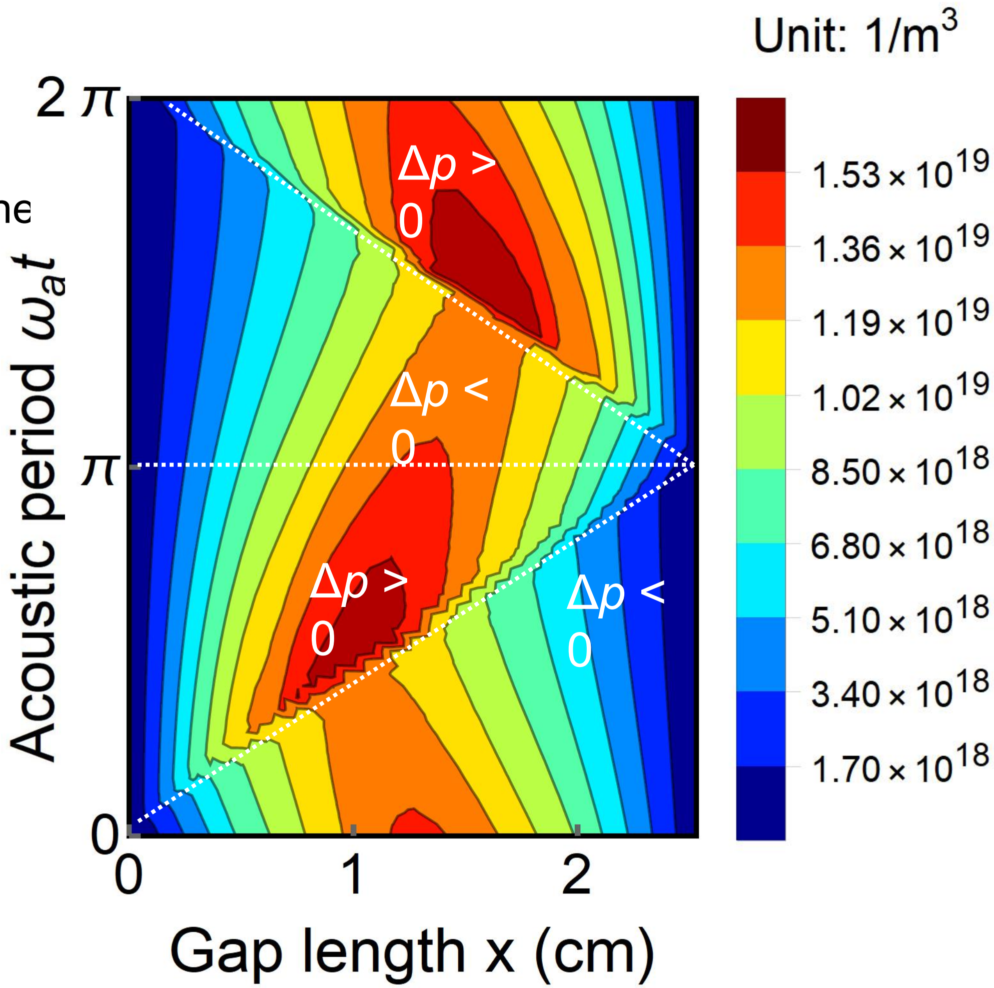
- Plasma modulation effect:
  - primarily attributed to the particle velocity field, which produces a neutral flux friction to the plasma species
  - secondarily to the variation of the neutral gas density, which contributes to a nonuniform ionization rate proportional to the neutral gas density

Distribution and flux of excited species

- The movement direction of the maximal density is controlled by the particle velocity direction
- The maximum densities appear at the turning points of the movement direction, where maximal acoustic pressure meets the maximal number densities

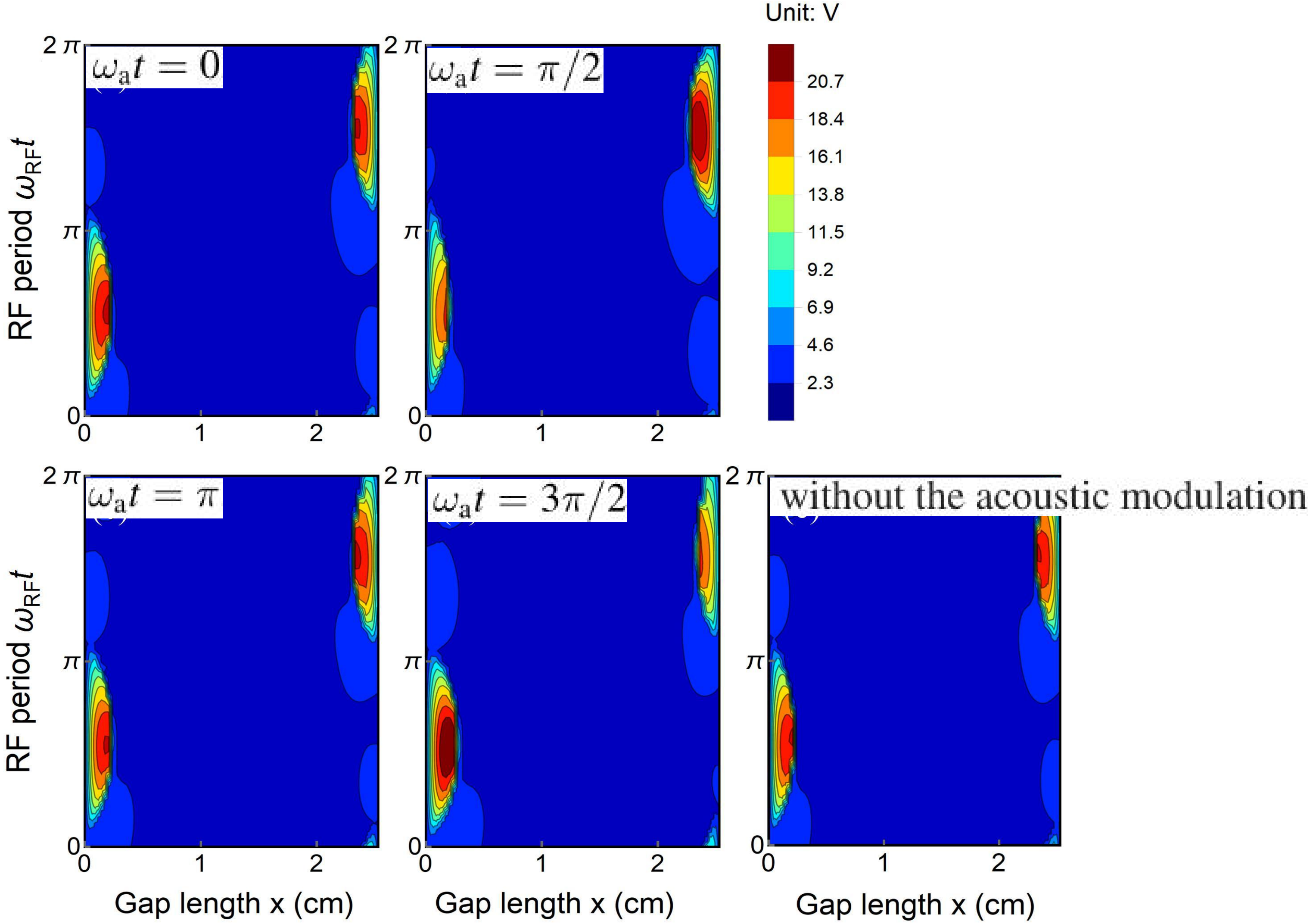






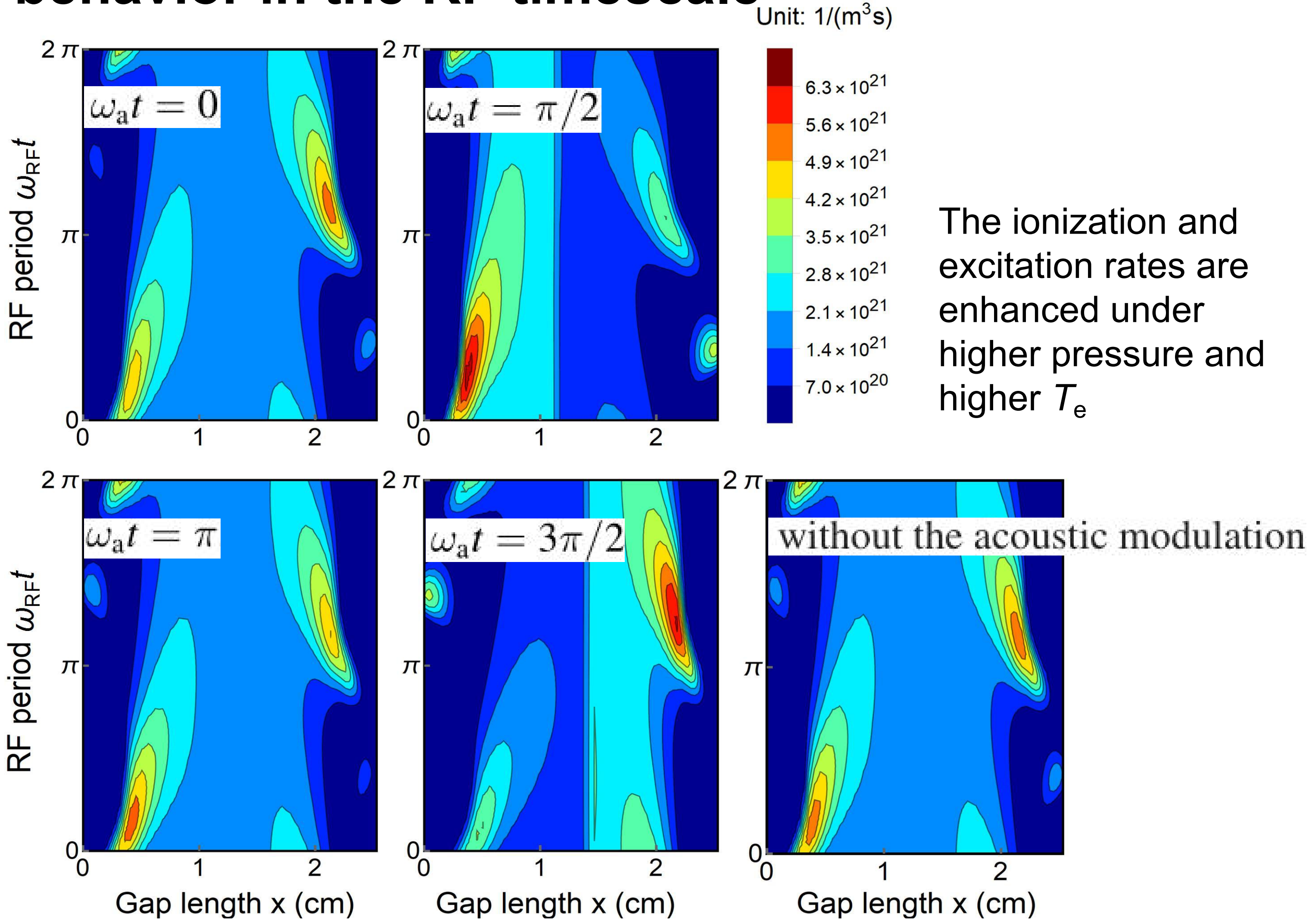
- The flux varies periodically, the peak reaches up to twice of the minimum value

Plasma behavior in the RF timescale



Variation profiles of the electron temperature at different acoustic-period time

Plasma behavior in the RF timescale

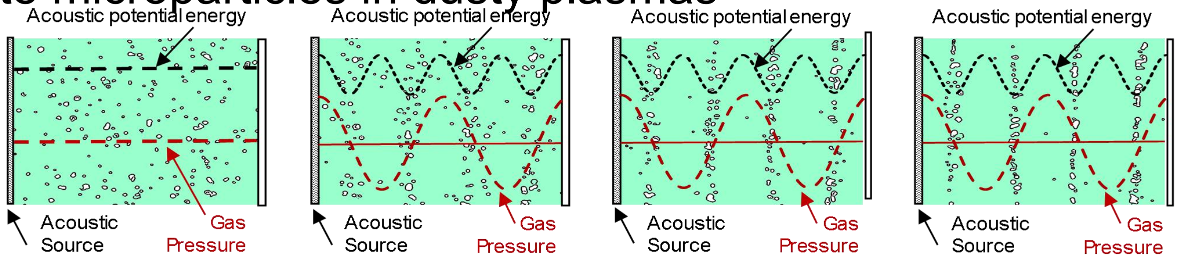


The ionization and excitation rates are enhanced under higher pressure and higher T_e

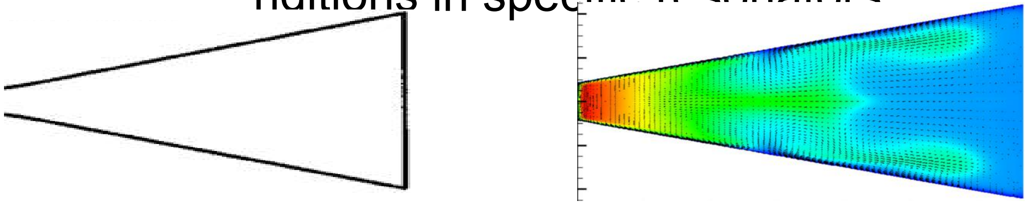
Variation profiles of the excitation rates at different acoustic-period time moments

Potential applications

- Pulsed plasma etching
  - Require large negative ion diffusion flux during pulse-off time
  - Synchronized acoustic standing wave: enhanced negative ion flux
- Enhance plasma chemical reactions
  - Significant fluctuation of neutral gas temperature in a strong acoustic field
  - Temperature-sensitive reactions can be enhanced (e.g., ozone generation)
- Modulate microparticles in dusty plasmas



- Achieve extreme conditions in specific resonators



Conclusions

- **The transient plasma discharge behaviors with an acoustic standing wave field are numerically investigated. The acoustic standing waves have significant influences on the discharge behaviors. By applying an acoustic standing wave, the plasma achieves a periodical steady state**, primarily due to the neutral flux friction to the plasma species and secondarily due to the variation of neutral gas density. With the modulation of the acoustic standing waves, a pulsed excited species flux can be obtained at the electrodes, whose maximum value is up to twice of the minimum value. **The ionization and excitation rate distributions in one RF period are significantly modulated by the acoustic standing waves**, due to the variation of the neutral gas density and the electron temperature.
- The different discharge behaviors obtained with and without the acoustic standing waves indicate an obvious modulation effect. **These preliminary results contribute to the understanding of the mechanism and characteristics of plasma discharges coupled with a high-intensity acoustic standing wave field**, as well as the development of plasma modulation methods by acoustic principles. **These effects have some implications for the ion extraction, the plasma uniformity and the plasma chemical reactions**, which are important for modulating and optimizing the plasmas for plasma etching and plasma enhanced chemical vapor deposition applications.

Thank you
for your
attention