Characteristics of Atmospheric-pressure Microgap Glow discharge Excited by Microwave Aiming at VUV Light Source

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Outline

• Microwave-excited microgap discharge: $cw$, high-pressure, high-density, non-thermal plasma

• Electron temperature and density measurements by laser Thomson scattering

• Gas temperature characteristics
  • OES measurements
  • Fluid dynamic simulation for heat transport

• Preliminary VUV emission measurements

• Summary
A comparison

Discharge pumped excimer laser

Discharge in a microgap

Pulsed

$\Delta t \sim 100\text{ns}$

$p \sim 1 \text{ atm}$

$n_e \sim 10^{15} \text{ cm}^{-3}$

$\varepsilon \sim 1 \text{ MW cm}^{-3}$

$T_g << T_e$

$\sim 1 \text{ cm}$

1/100

(in linear dimension)

$\sim 100\mu m$

$CW$ plasma production with similar parameters?
Concept of high-pressure microgap discharge

- Non-equilibrium plasma
  \[ \frac{(d / \pi)^2}{D} < \frac{1}{n_e \sigma_m v_e / m_e} \]

  Diffusion lifetime  Heating time

- Rapid gas replacement
  \[ \tau = \frac{w}{v_{flow}} \]
  \[ v_{flow} = 100 \text{ m/s} \]
  \[ d = 100 \text{ µm} \]
  \[ \tau = 1 \text{ µs} \]

- Stable discharge
- High power-density deposition
DC or RF excitation leads to discharge constriction

DC

200µm

DC or RF(13.56MHz)

Microwave
Microwave power transfer to the microgap

- Microwave (2.45 GHz)
- Waveguide
- Microwave (2.45 GHz)
- Copper electrode
- Microgap
- Heat conduction
- Copper block (2 cm thick)
- Strip-line structure
- $\lambda/4$
- Gas flow
Microgap discharge in air (100 W)
High-spatial-resolution Thomson scattering measurement

YAG laser

Plasma
High-spatial-resolution Thomson scattering measurement

YAG 2ω 532 nm

0.5mm aperture

3000 mm

f=150 mm doublet lens

Microgap plasma

Electrode

2 mm

YAG 2ω 532 nm

Entrance slit

Triple Grating Spectrograph

532 nm

10^{-6}

ICCD camera

PC

Entrance slit

High-spatial-resolution Thomson scattering measurement

Microgap plasma

Electrode

2 mm

YAG 2ω 532 nm

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High-spatial-resolution Thomson scattering measurement

Microgap plasma

Electrode

2 mm

YAG 2ω 532 nm

Entrance slit

Triple Grating Spectrograph

532 nm

10^{-6}

ICCD camera

PC
Fitting of the observed Thomson/Raman spectra

air 1atm, no gas flow, microwave power 100W
Spatial distribution of $n_e$ and $T_e$ for air discharge

- Air 1 atm,
- No gas flow,
- Microwave power 100W

Electrode 2 mm
Comparison between air and He/N$_2$ (5%) discharges

Thomson spectra at the plasma center

Discharge without chamber (1 atm)
Microwave power 100W

$T_g \approx 2500K$ for air
$T_g \approx 1200K$ for He/N$_2$
(from Raman)
Electron density and temperature for different plasmas

<table>
<thead>
<tr>
<th>Plasma Type</th>
<th>Density</th>
<th>Temperature</th>
<th>Other Parameter</th>
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</thead>
<tbody>
<tr>
<td>Type 1</td>
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<td>Type 2</td>
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<td>Type 3</td>
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Preliminary VUV emission measurements

Spectra

Ar: 1 atm
Microwave power: 3.5W

Xe: 1.5 atm
Microwave power: 1W

Power dependence (without gas flow)

He/Ar(20%), 2.5 atm
Ar (420.1 nm)

He/Xe(10%), 2.5 atm
Xe (823.2 nm)
Gas Temperature study

* OES measurements
* Fluid dynamic simulation of heat transport
Power dependence of the gas temperature
(derived from $N_2 \; C^3\Pi_u - B^3\Pi_g$ optical emission)

Weak dependence of $T_g$ on $P_{\mu\text{wave}}$

air 1atm, no gas flow
Flow-rate dependence of the gas temperature

Open-air setup
1 atm
microwave power 100W
Temperature structure in the microgap discharge

~2000K (air), ~1200K (He)

~400K

19K

63K/cm

2 mm

100 µm

100 µm

50 W

Cu electrode

Cu electrode
Heat transport simulation:
Simulation space and boundary conditions

(a) Electrodes

(b) Simulation space

\[ \frac{\partial T_g}{\partial x} = 0 \]
\[ \frac{\partial v}{\partial x} = 0 \]
\[ p = \text{const} \]
\[ T^g = 300 \text{K} \]
\[ v = 0 \]
Heat transport simulation: 
Governing equations

Mass balance
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
\]

Momentum balance
\[
\rho \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + \nabla \left\{ \eta (\nabla \mathbf{v} + [\nabla \mathbf{v}]^T) - \frac{2}{3} \eta (\nabla \cdot \mathbf{v}) \mathbf{I} \right\}
\]

Energy balance
\[
\rho c \frac{\partial T_g}{\partial t} + \mathbf{v} \cdot \nabla T_g = \nabla \cdot (\kappa \nabla T_g) - p \nabla \cdot \mathbf{v} + (\nabla \mathbf{v}) : \left\{ \eta (\nabla \mathbf{v} + [\nabla \mathbf{v}]^T) - \frac{2}{3} \eta (\nabla \cdot \mathbf{v}) \mathbf{I} \right\} + Q
\]

Thermal conduction
Heating / cooling by adiabatic
Compression / expansion
Heating by viscosity
Heat source (plasma)

\[\kappa = a T_g^{0.77}\]
\[\kappa = \frac{5}{2} \cdot \frac{c \eta}{m}\]
\[p = \frac{\rho k T_g}{M}\]
Implication of $n_e = 10^{15}$ cm$^{-3}$

Gas heating by elastic collisions of electrons

$$Q = rac{4}{\sqrt{\pi}} \left( \frac{2m}{M} T_e \right) (\sigma_m v_e) n_e n_g$$

for

$$\begin{aligned}
n_e &= 10^{15} \text{ cm}^{-3} \\
n_g &= 2.7 \times 10^{19} \text{ cm}^{-3} \text{ (1 atm)} \\
\sigma_m &= 10^{-15} \text{ cm}^2 \\
T_e &= 2 \text{ eV} \\
m/M &\text{ for He}
\end{aligned}$$

$Q = 0.45$ MW/cm$^3$
Gas temperature without gas flow

Profile

Dependence on \( Q \) or \( Q_0 \)

He, model (b), \( Q_0=0.5\text{MW/cm}^3 \)

(a) Model \( Q = \text{const.} \)
(b) Model \( Q = Q_0 \rho / \rho_0 \)

Air (Experimental)
Effect of gas flow on the temperature profile C

He, model (b), $Q_0=0.5\text{MW/cm}^3$
Dependence of the gas temperature on the gas flow

Possibly due to admixture of ambient air

He, model (b), $Q_0=0.5\text{MW/cm}^3$
Gas heating and pressure loss

larger $\Delta p$
Unsuitable experimental setup

Direction of VUV observation

Expected gas flow path

more likely gas flow path
Ar₂ intensity vs. gas flow rate and pressure

Ar₂ intensity (arb. units) vs. Flow rate (L/min)
- Power 8W
- Pressure 1 atm

Ar(415nm) intensity (arb. units) vs. Flow rate (L/min)
- Power 8W
- Pressure 1 atm

Ar₂ intensity (arb. units) vs. Pressure (atm)
- Flow rate 1 L/min
- Power 8W
New gas flow scheme
Summary

• Microwave excited microgap plasma
  * Stable cw production of high-pressure, high-density, non-thermal plasma over some length
  * Power deposition level of ~1 MW/cm³
• High-spatial-resolution Thomson scattering measurement
  * Spatial resolution ~25 µm
  * $n_e = 1.8 \times 10^{15}$ cm$^{-3}$ for air discharge at 100 W
• Fluid dynamic simulation for heat transport
  * Importance of local gas density change for gas heating process
  * Need of selfconsistent treatment of plasma and gas dynamics
• To efficiently lower the gas temperature and to obtain efficient VUV excimer emission, the gas flow scheme is very important.

Future work: New gas flow scheme
  Electron temperature control
  Frequency upscaling