Nonequilibrium Microwave and DC Discharges in Atmospheric Pressure Air

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Motivation

- Nonequilibrium atmospheric pressure air plasmas are of interest in a variety of applications such as electromagnetic wave shielding and bio-decontamination.

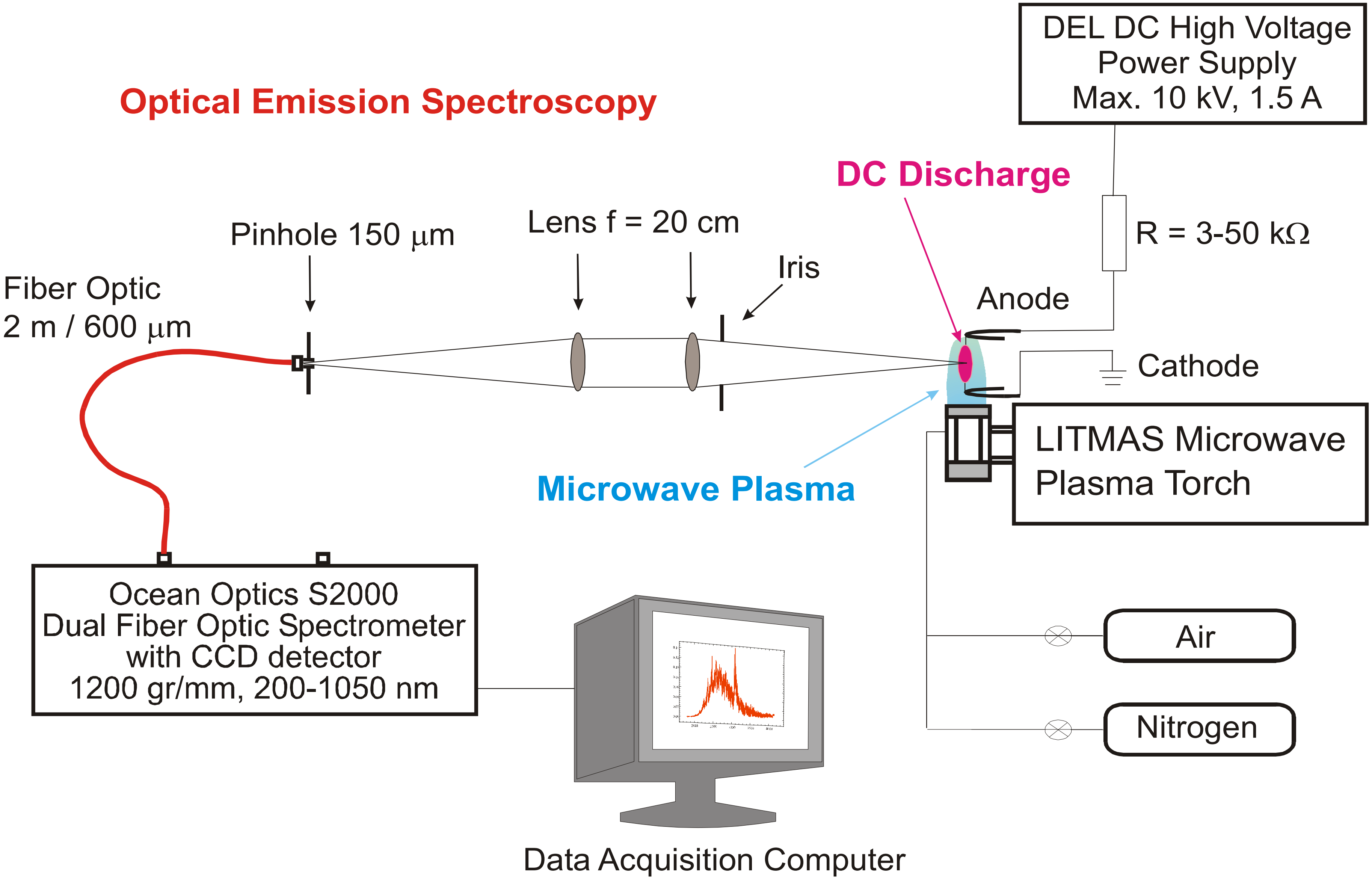
- Large volumes, relatively low temperatures ($\leq$ 2000 K) and high electron number densities ($n_e \geq 10^{12}$ cm^{-3}) are desired.

Approach

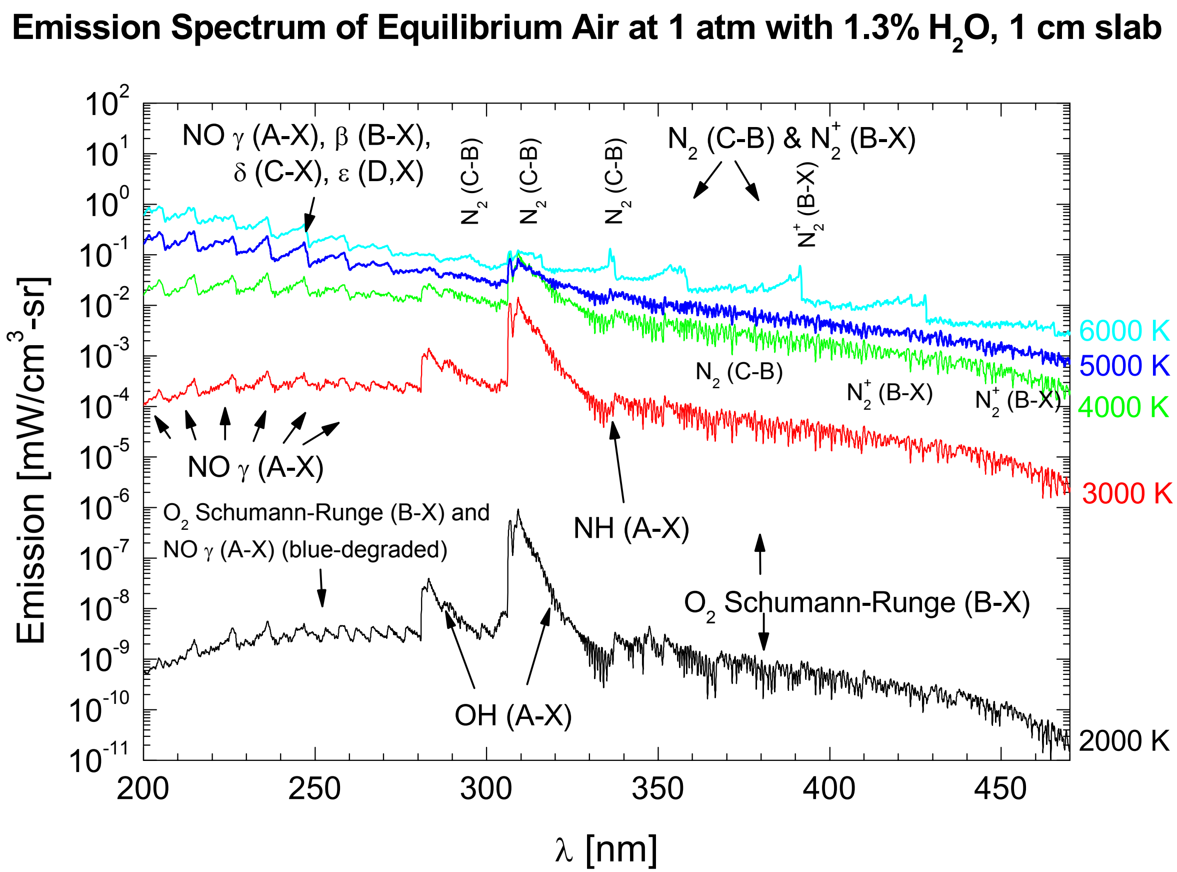
- Microwave torch air plasmas
- DC discharge air plasmas

- Study DC discharges in microwave preheated air

Experimental Setup



Optical Emission Spectroscopy of Air Plasmas



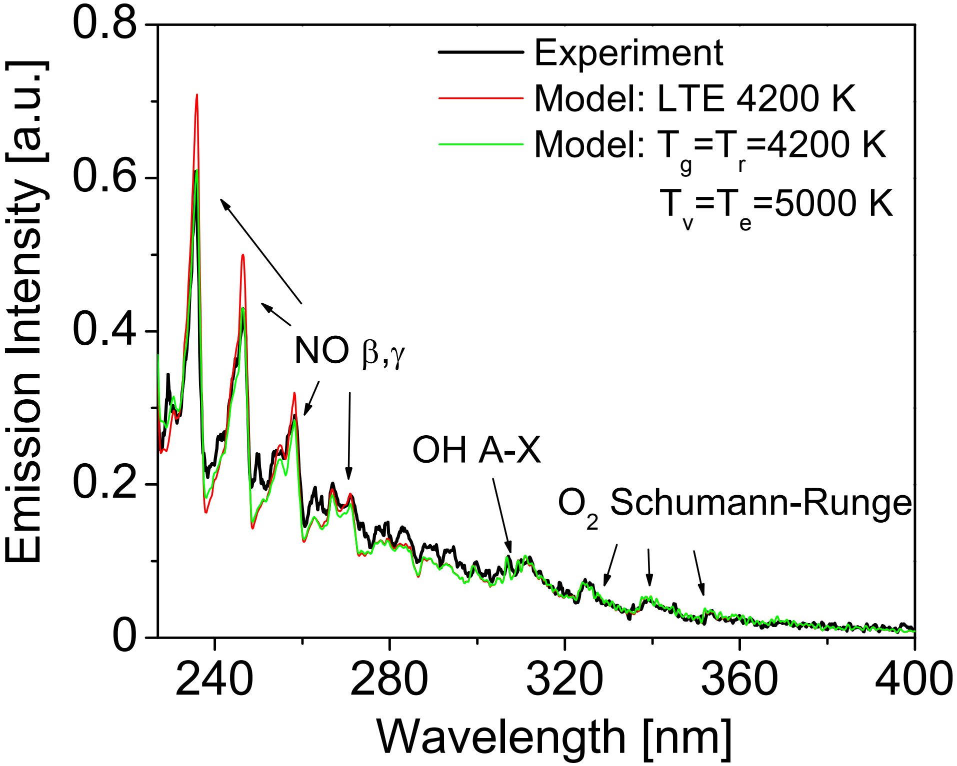
- LTE Air: Absolute emission intensity depends on the temperature
- N_2 (C-B) 2nd positive, N_2 (B-A) 1st positive, N_2^+ (B-X) 1st negative systems:
  - T > 6000 K in LTE air
  - Commonly observed in nonequilibrium discharges

Microwave Air Plasma

1) Low Flow Rate, High Temperature Case

Air Flow Rate: 9 SLPM
MW Power: 1.5 kW
Energy Density: 10,000 J/l
Flow Velocity: ~27 m/s

- Temperature measured from relative intensity spectral fit

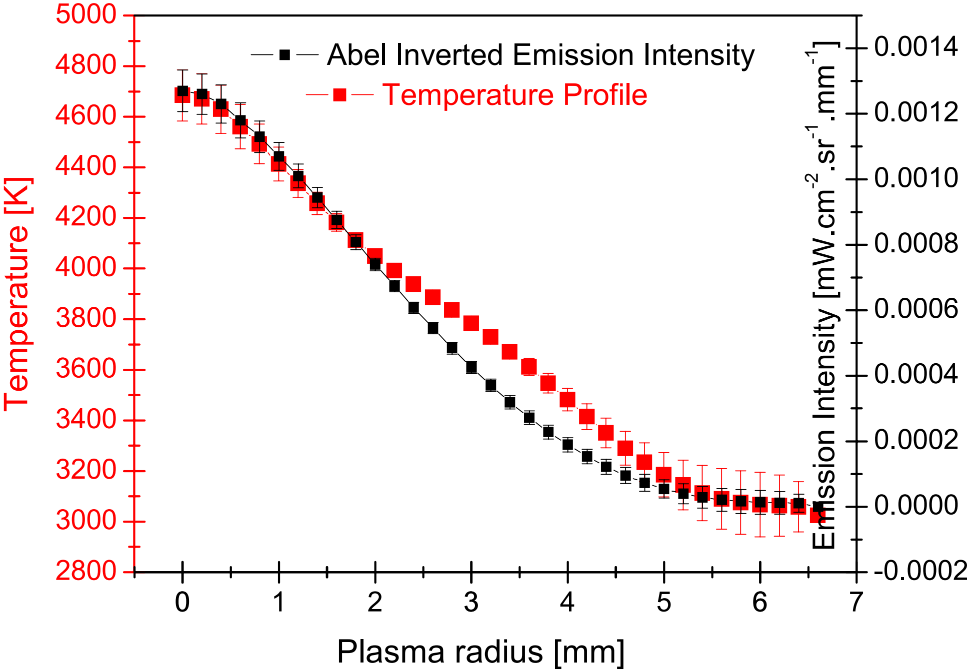


Plasma close to LTE, T_{LTE} ~4200 K

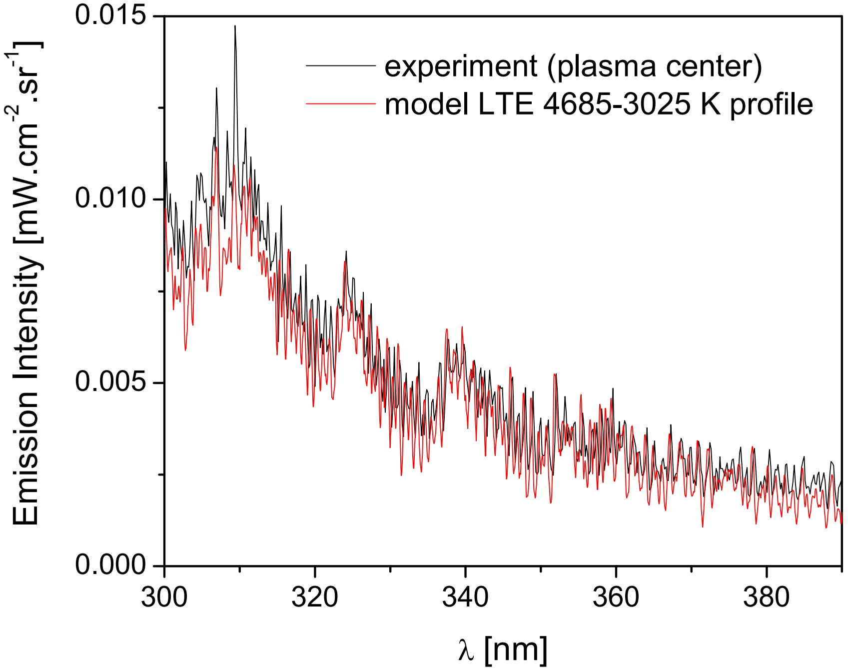
Microwave Air Plasma - Temperature Profile

2) Low Flow Rate, Highest Temperature Case

- Temperature profile measured from absolute intensity O_2 spectra



O_2 Schumann-Runge bands fit:

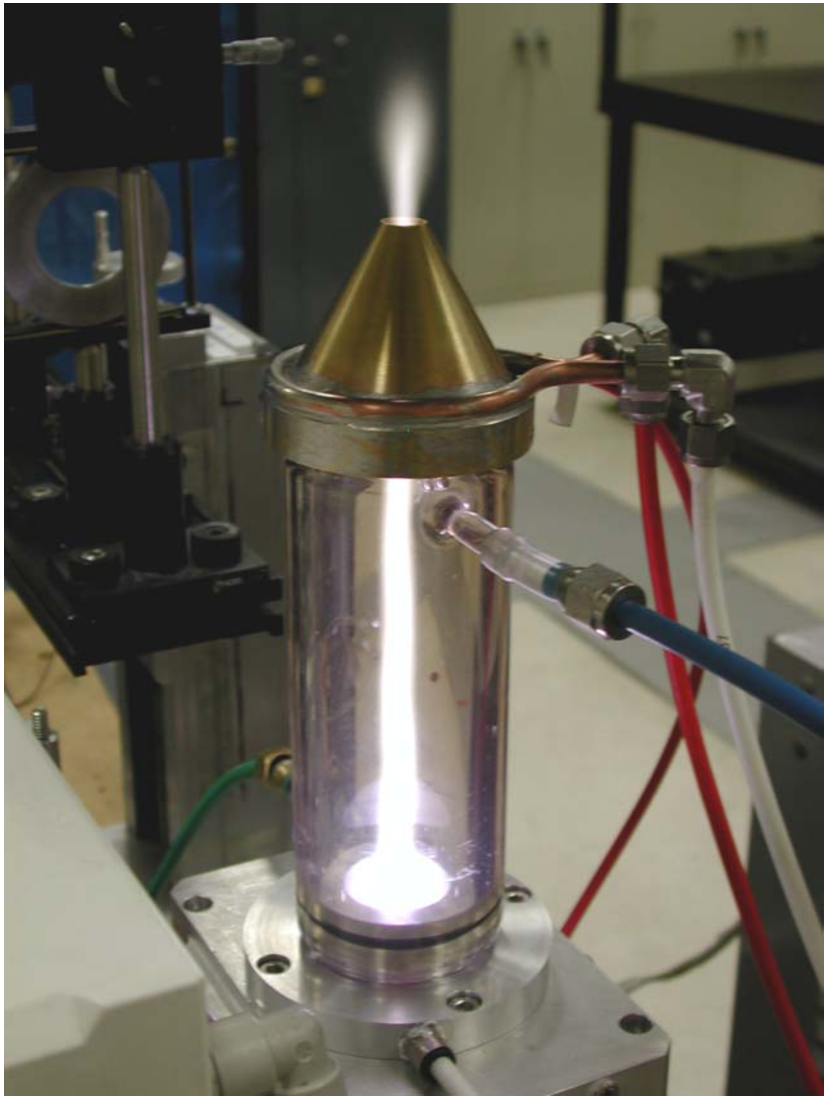


Air Flow Rate: 8 SLPM
MW Power: 1.75 kW
Energy Density: 12,900 J/l
Flow Velocity: ~17 m/s

Plasma close to LTE, T_{LTE} ~4700 K

Microwave Air Plasma

3) High Flow Rate, Low Temperature Case



Air Flow Rate: 110 SLPM
Injected MW Power: 2.1 kW
Energy Density: 1100 J/l
Flowing Velocity: ~120 m/s

Microwave Air Plasma - Temperature

4) High Flow Rate, Lowest Temperature Case

Low Temperature → Low Emission Intensity → No detectable spectrum

Solution: apply Corona Discharge to enhance emission locally

Corona Discharge:

- does not heat gas ($T_{gas} \approx T_{ambient}$, $T_e >> T_{gas}$)
- produces weak but detectable N_2 spectrum (2nd positive system)

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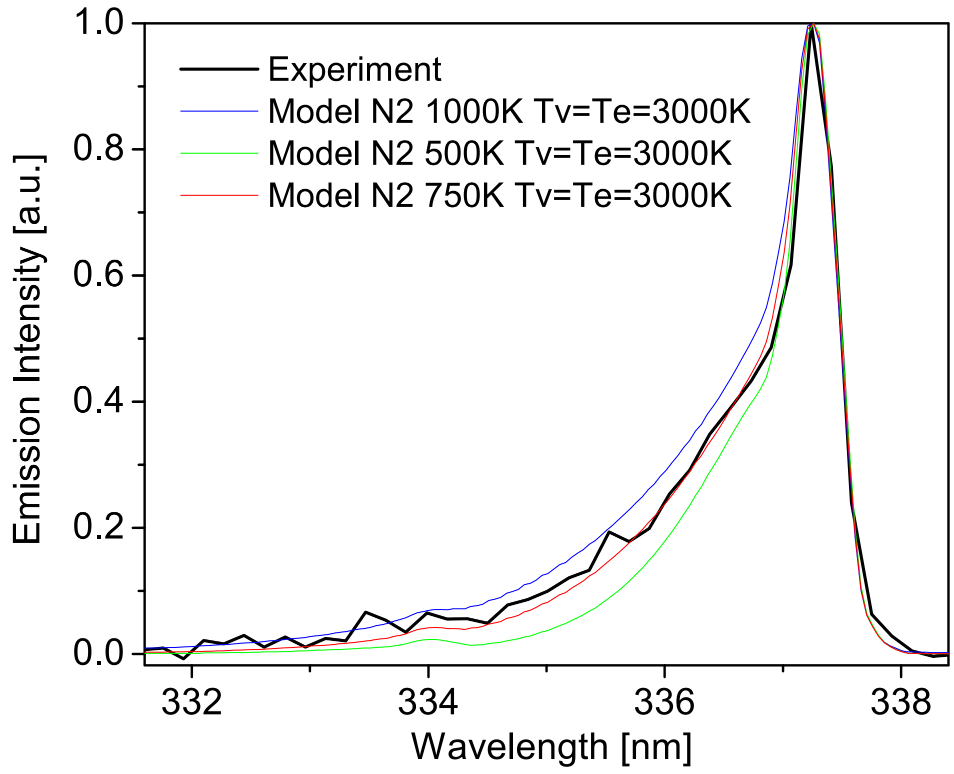
- Temperature measured from relative intensity N_2 C-B spectra

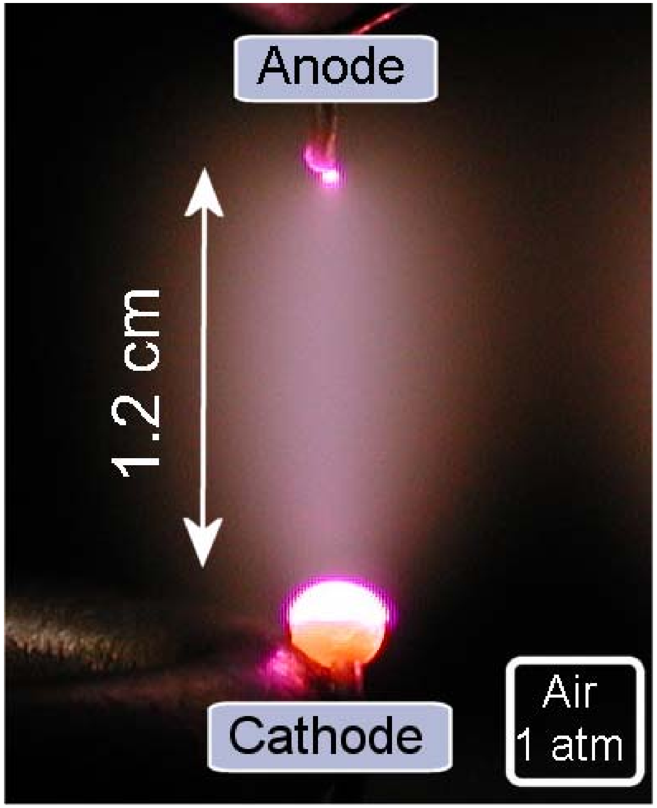
Corona spectrum – N_2 2nd positive system, 0-0 band

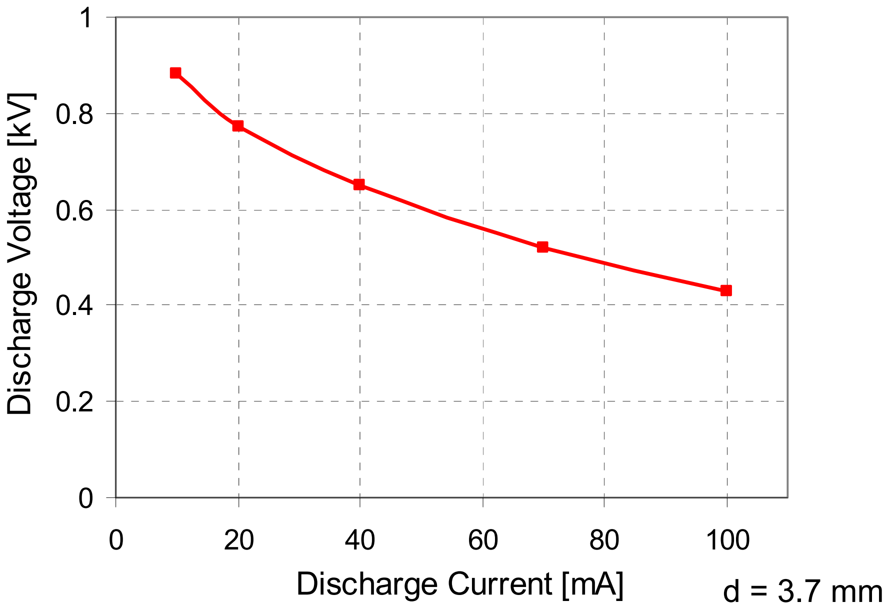


Air Flow Rate: 110 SLPM
Injected MW Power: 1.5 kW
Energy Density: 800 J/l
Flowing Velocity: ~60 m/s

Nonequilibrium plasma minimum T_{rot} ~750 K

DC Discharge in Ambient Air





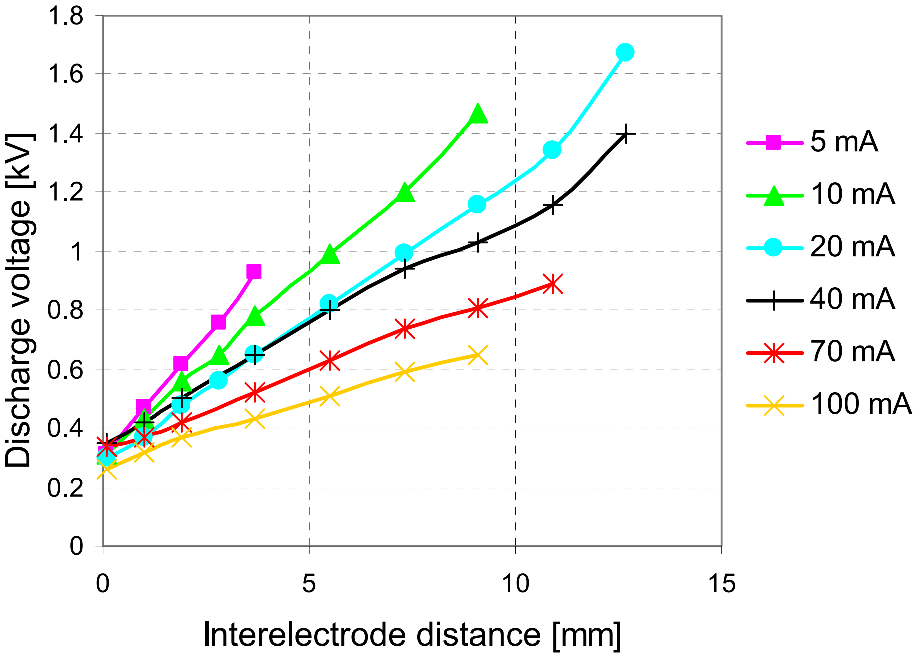
- Current-Voltage Characteristic has a negative slope
- Temperature measured from relative intensity N_2 C-B spectra

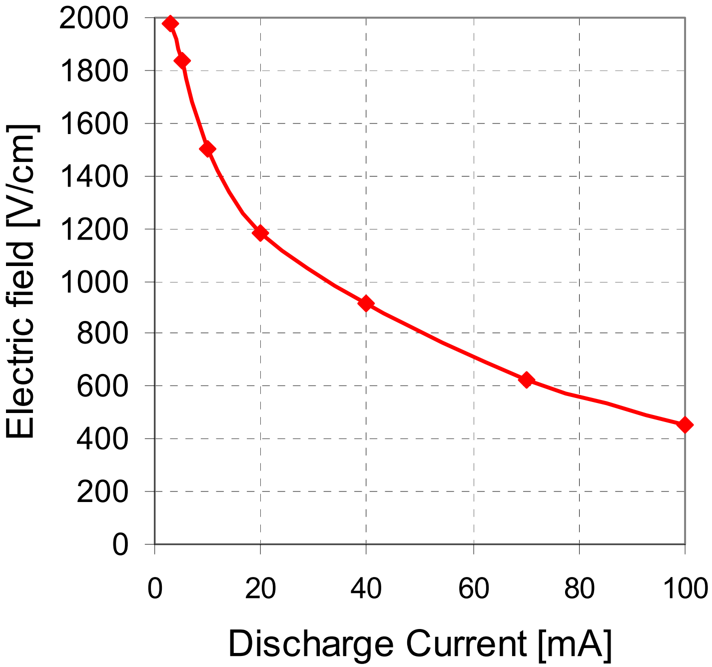
Low gas flow rate
Flow velocity: ~1-10 m/s
Current: 5-100 mA
Interelectrode distance: 0.1-10 cm

Nonequilibrium plasma
T_{rot} ~1500-3000 K T_{vib} ~4000 K

DC Discharge in Ambient Air

Electric field and Electron density



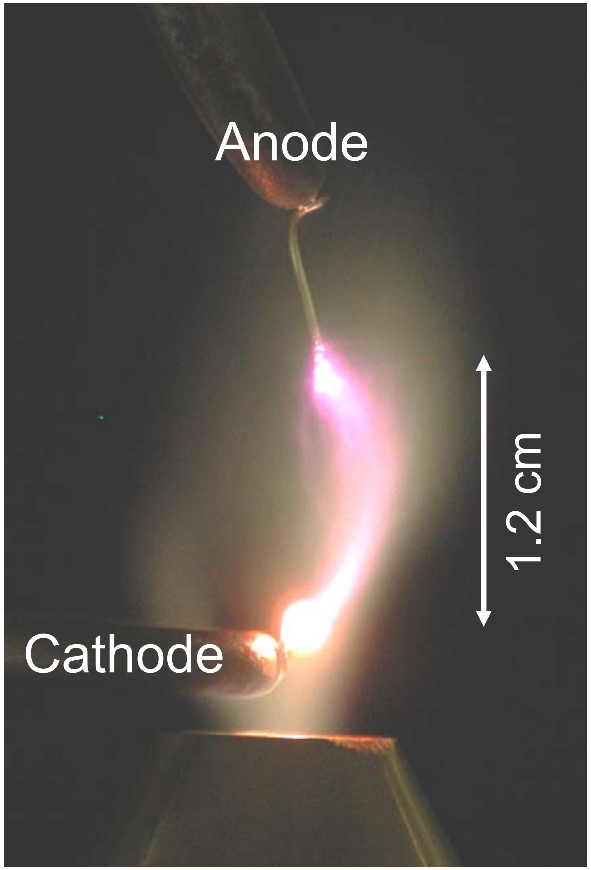


- Electric field in the DC discharge column decreases with increasing current
- Higher I $\rightarrow$ higher T_{gas}, closer to T_e $\rightarrow$ lower gas density $\rightarrow$ lower E

T_e and n_e can be related to E and j by Ohm's law and the electron energy equation

I = 10 mA	$j \approx 1.3$ A cm^{-2}	$T_{gas} \approx 2000$ K	$n_e \approx 8\times10^{11}$ cm^{-3}

DC Discharge in Microwave Plasma



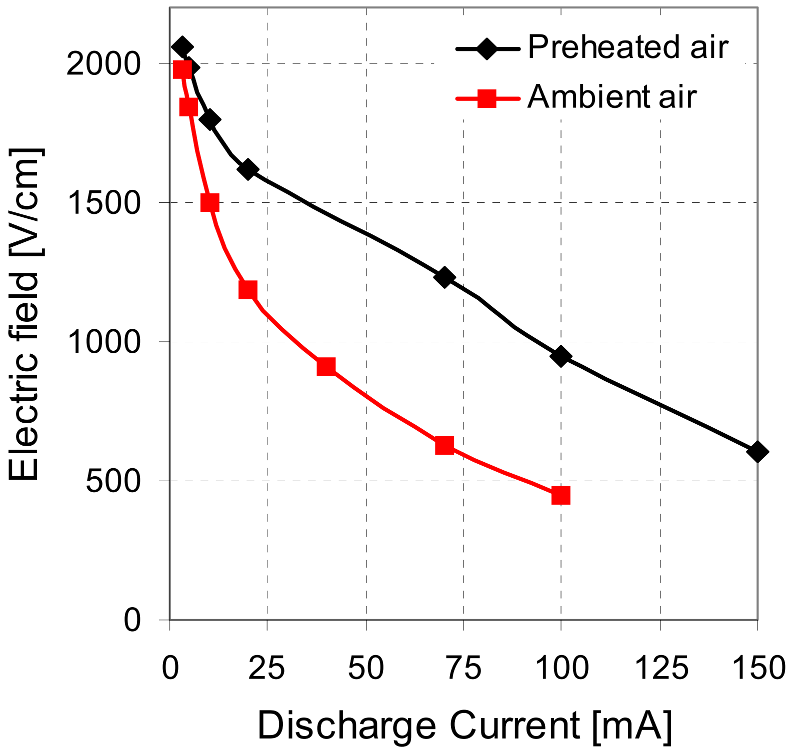
- Microwave plasma enables study of DC discharges in preheated air
- Reduced electron attachment in DC discharge for T_{gas}>1500 K
- Temperature measured from relative intensity N_2 C-B spectra

Wide range of gas flow rate
Flow velocity: ~10-160 m/s
Current: 5-150 mA
Interelectrode distance: 0.1-10 cm

Nonequilibrium plasma
T_{rot} ~1500-3000 K T_{vib} ~4000 K

DC Discharge in Microwave Plasma

Electric field and Electron density



- Electric field in the DC discharge column decreases with increasing current

Higher I

↓

higher T_{gas}, closer to T_e

↓

lower gas density

↓

lower E

- Strong flow of preheated air prevents the discharge to heat up

↓

- Lower T and higher E than in ambient air discharge for a given current

I = 40 mA	$j \approx 3$ A cm^{-2}	$T_{gas} \approx 2000$ K	$n_e \approx 2\times10^{12}$ cm^{-3}

Conclusions

Three approaches to generate air plasmas:

- **Microwave Torch**
  - Nonequilibrium plasmas
  - Near-LTE Plasmas
  - T ~750-4700 K
  - Flow velocities 10-100 m/s

- **DC Discharge**
  - Nonequilibrium plasmas
  - T ~1500-3000K
  - Flow velocities 1-10 m/s
  - T_{gas} depends strongly on I

- **Coupled Microwave and DC Discharge**
  - Nonequilibrium plasmas
  - T ~1000-5000 K, optimum 2000 K
  - Flow velocities 10-160 m/s
  - Enables to decouple T_{gas} from I