Thermal Mode Nonequilibrium in Gas Dynamic and Plasma Flows

by

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Outline

- What is thermal mode nonequilibrium?
  Emphasis on high density, collision-dominated flows,
  cold molecular plasmas

- Environments
  i) Cool Electric Discharge Plasmas
    - Self-Sustained vs. Preionized
  ii) Optically Pumped Plasmas
    - Excitation of Vibrational States
    - Kinetics and Energy Transfer Studies
  iii) Gas Dynamic Flows
    - Supersonic Expansions of High Enthalpy Gases
    - Strong Shock Waves

- Applications
  i) Plasma Wind Tunnels
  ii) Gas Lasers
  iii) Chemistry: Isotope Separation

- Summary: Where do we go with this?

What is thermal mode equilibrium?

$n_i/g_i \sim \exp(-E_i/kT)$,

$N = \sum n_i$, and $E = \sum n_i E_i$

If we know the energy levels, E_i, and the gas temperature, T, we can calculate the whole ideal gas thermodynamic table:

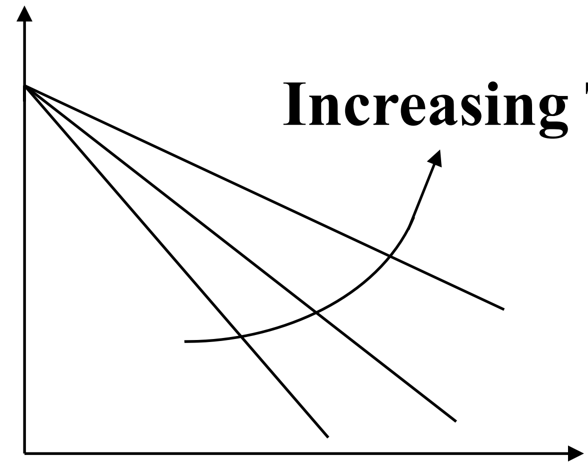


Table 1 Air at Low Pressures (for One Pound)

T	t	h	p_r	u	v_r	ϕ
1000	540.3	240.98	12.298	172.43	30.12	.75042
1001		241.23	12.343	172.61	30.04	.75067
1002		241.48	12.388	172.79	29.96	.75092
1003		241.73	12.433	172.97	29.88	.75117
1004		241.98	12.478	173.15	29.81	.75142

What is thermal mode nonequilibrium?

Thermal nonequilibrium exists whenever:

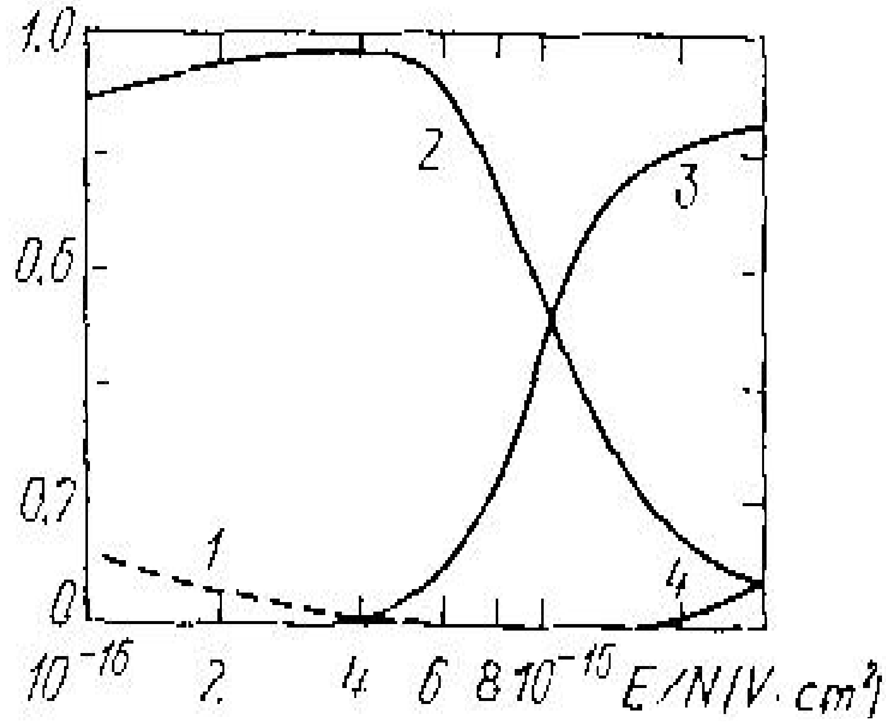
- **The populations, n_i/N, of one or more modes are distributed according to the Boltzmann law, *but* the temperature, T, of at least one mode differs from that of the others.**

OR

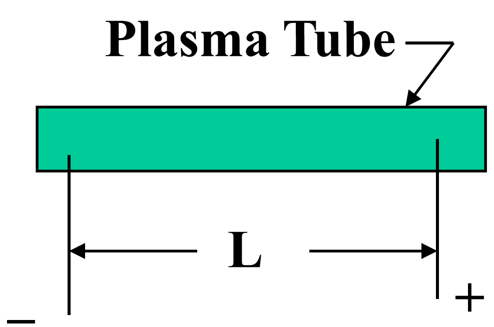
- **The populations, n_i/N, of one or more modes are *not* distributed according to the Boltzmann law.**

Fraction of Power into each Mode, as a function of E/N. E/N is approximately proportional to the mean energy of the free electrons.

1. **Rotational mode**
2. **Vibrational mode**
3. **Electronic mode**
4. **Ionization**



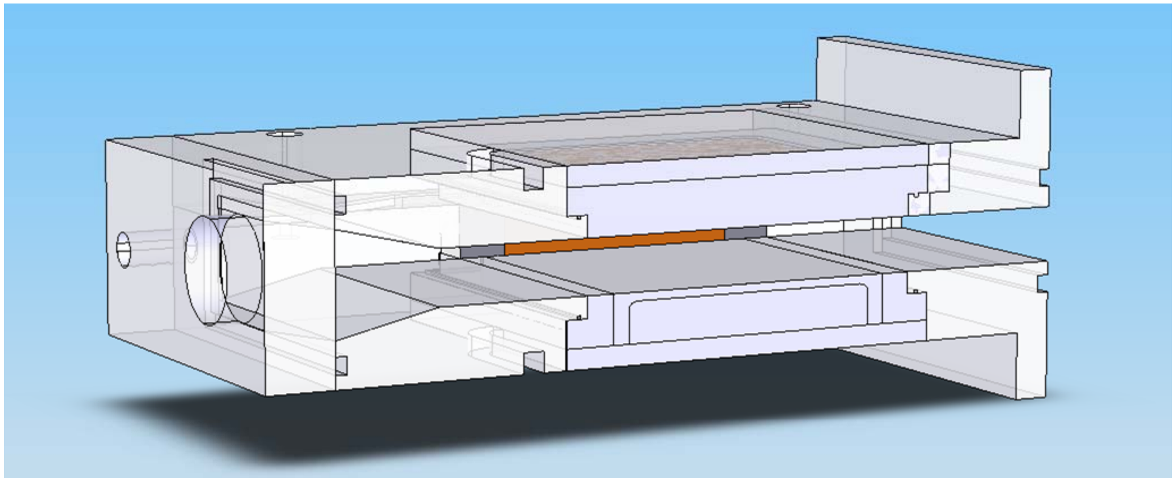
Ratio of Electric Field, E, to total number density of molecules, N



Electric Field = Voltage/Electrode Separation

E = V/L

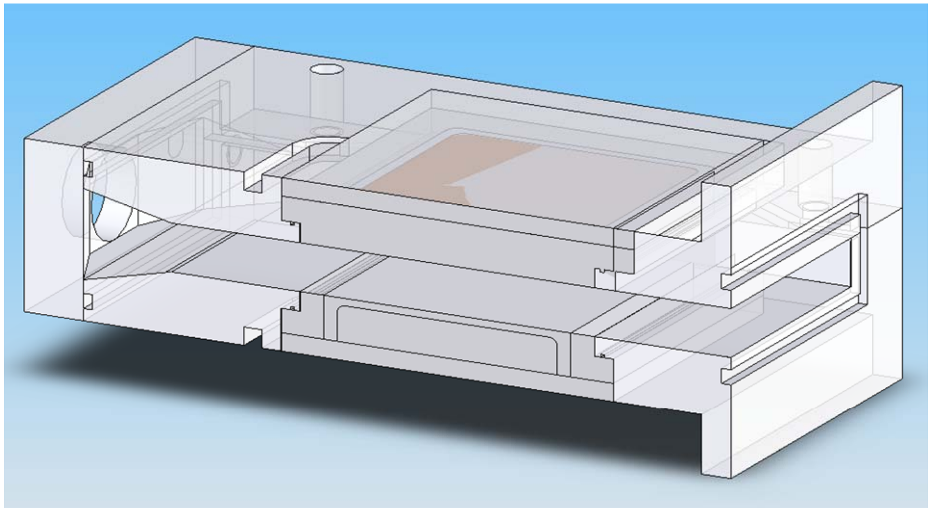
Environments: Preionized Electrical Glow Discharge Short Pulse HV Ionizer, D.C. Sustainer - Geometry



Pulser electrodes in top and bottom walls

DC electrodes in side walls

Flow direction left to right



Dimensions: 1 cm x 5 cm, 10 cm long

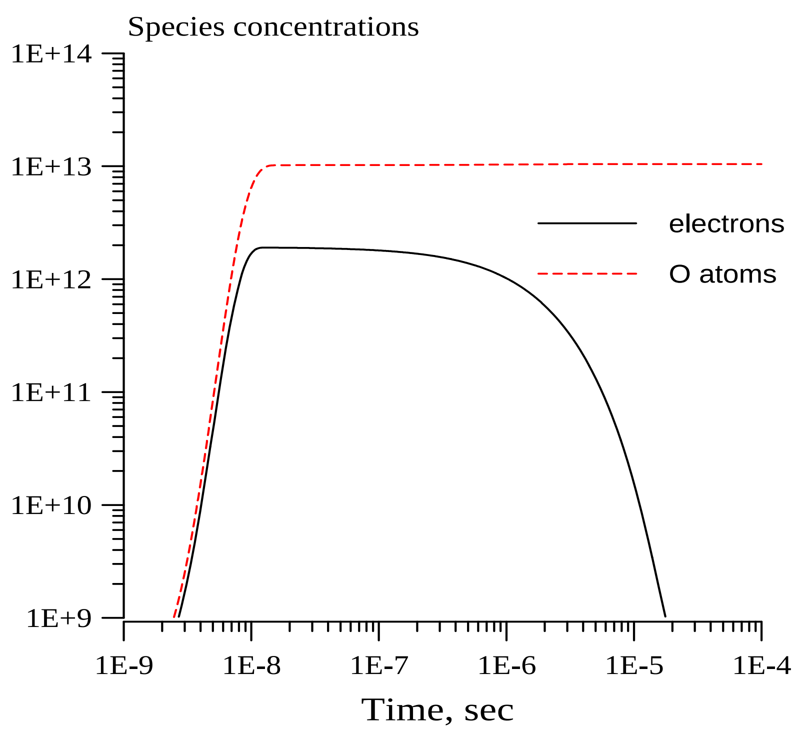
Mach number: M~0.2

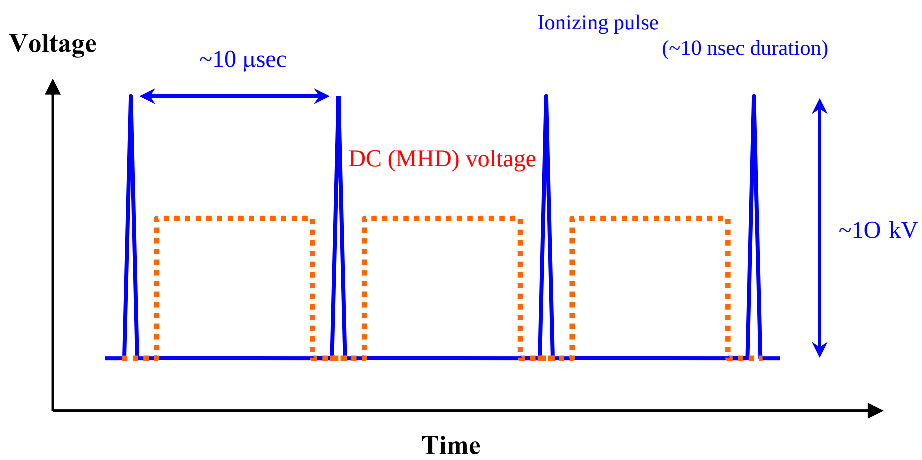
Discharge pressure: up to 160 torr

(O_2-He, O_2-Ar)

Mass flow rate: up to 12 g/sec

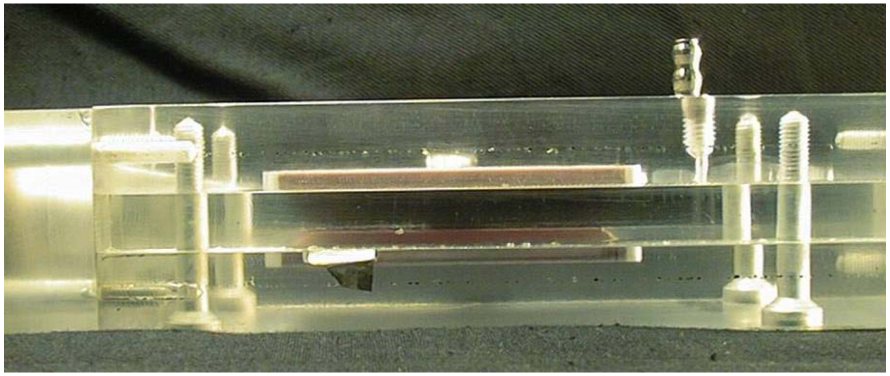
Environments: Preionized Electrical Glow Discharge
Short Pulse HV Ionizer, D.C. Sustainer -Performance

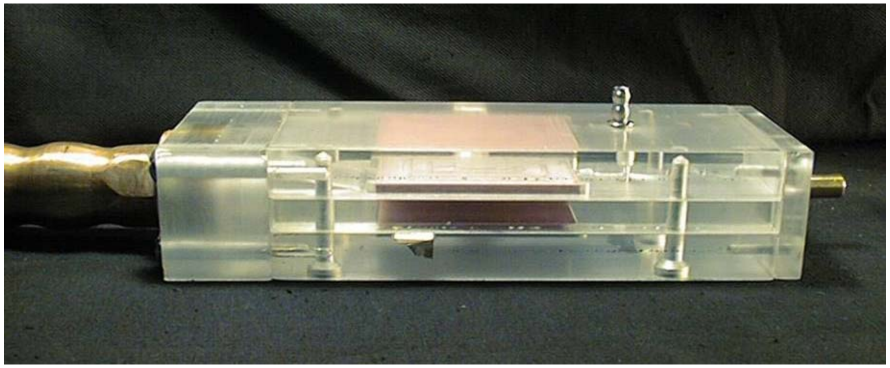


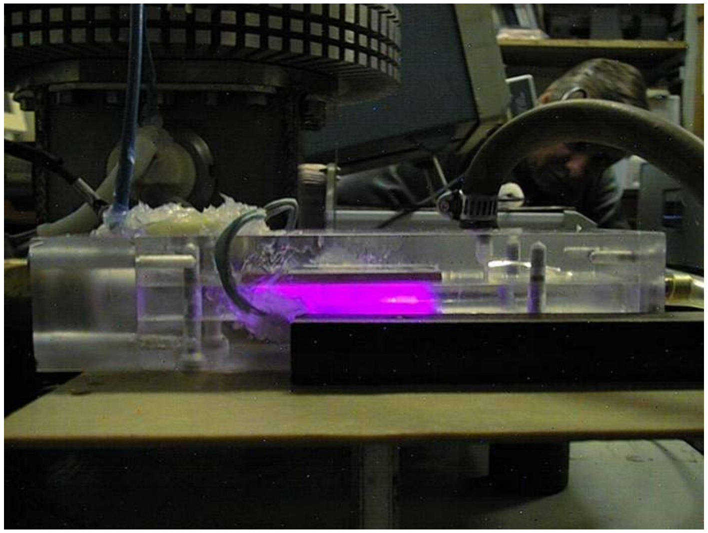


On the left, species concentrations after the ionizing pulse, on the right, schematic of the pulsed and d.c. discharge operation. P=0.1 atm, T=300 K, E/N_{max}=350 Td, E_{max}=8.5 kV/cm, τ_{pulse}=10 nsec

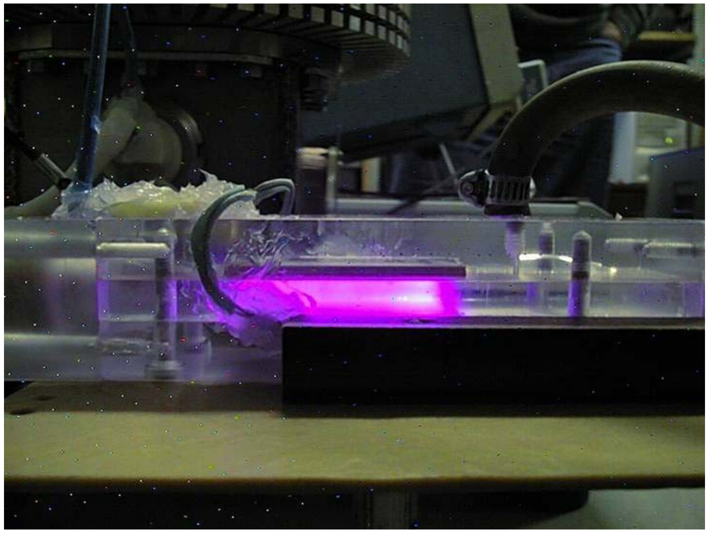
Environments: Preionized Electrical Glow Discharge
Short Pulse HV Ionizer, D.C. Sustainer -Photos







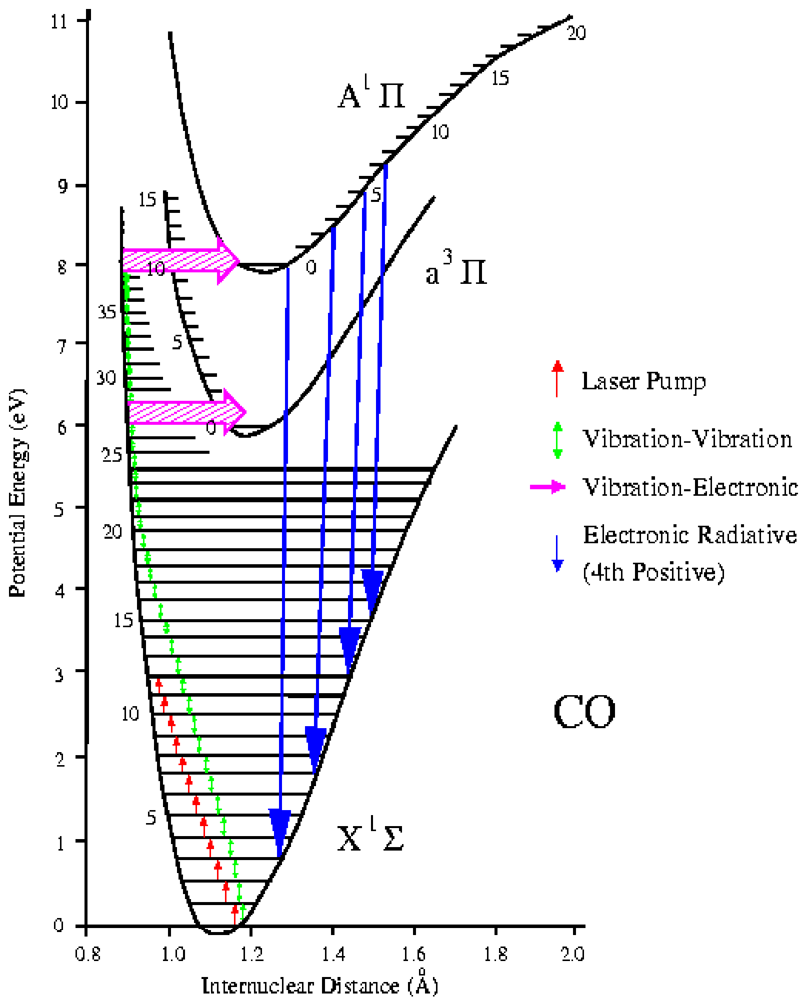
P=300 torr, 10 kHz

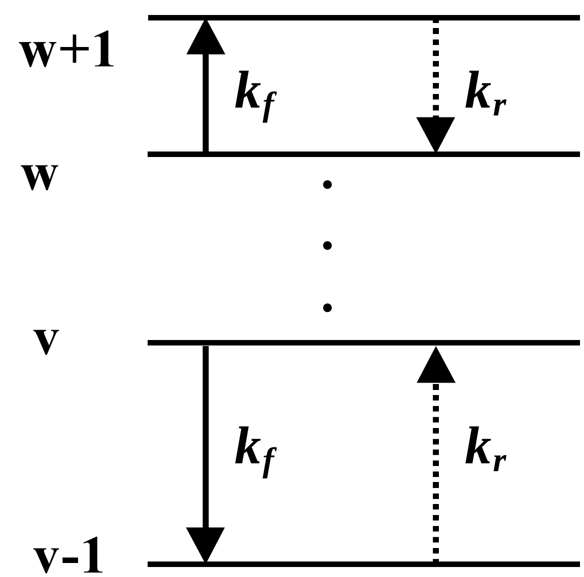


P=500 torr, 10 kHz

Environments: Optical Pumping – Excitation of Vibrational Mode by CO Laser Radiation. Vibration-Vibration (V-V) Exchange

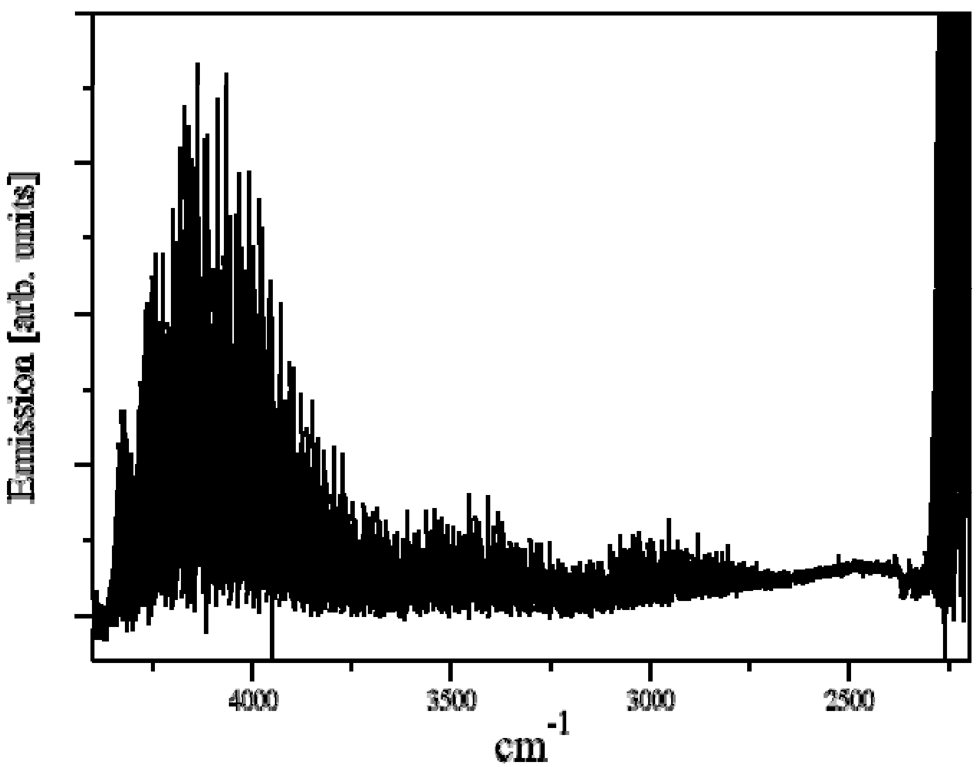
$$\frac{k_k}{k_r} = \exp\left(\frac{\Delta E_{v,v-1} - \Delta E_{w+1,w}}{T}\right) > 1$$

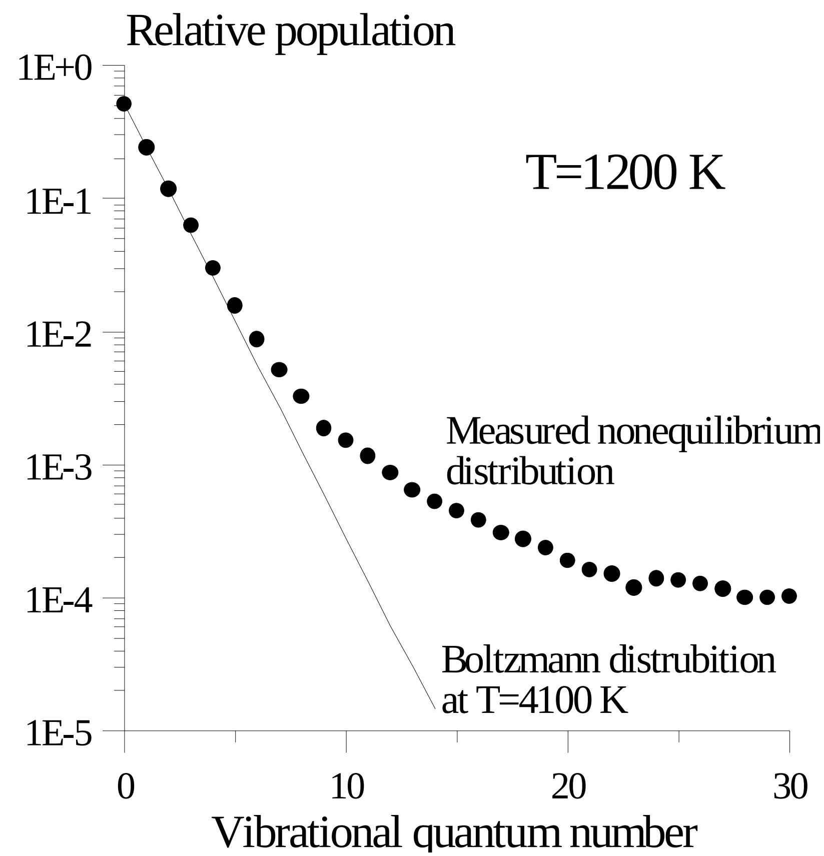




CO(v)+CO(w) → CO(v-1)+CO(w+1)

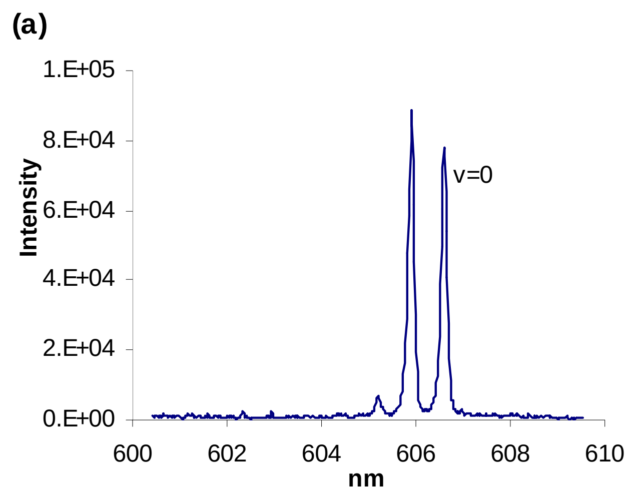
Environments: Optical Pumping – Excitation of Vibrational Mode by CO Laser Radiation. Measurement of Vibrational State Populations – Vibrational Distribution Function

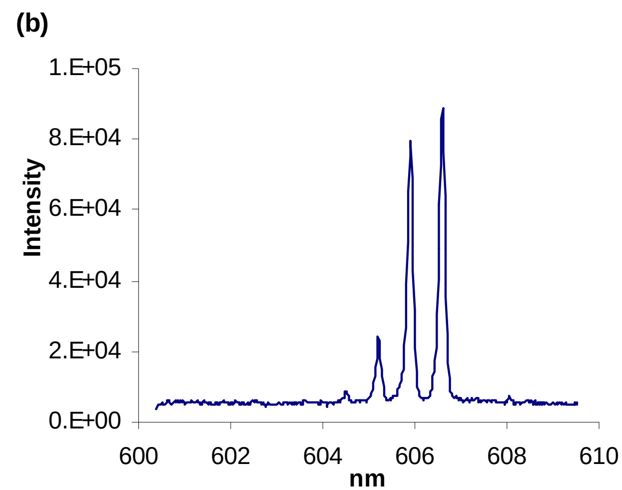


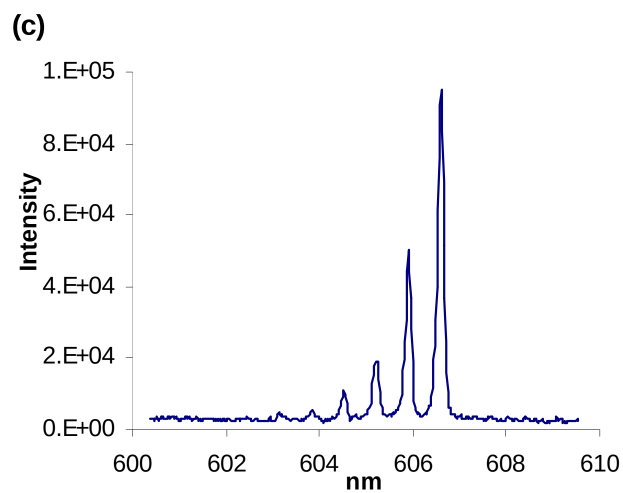


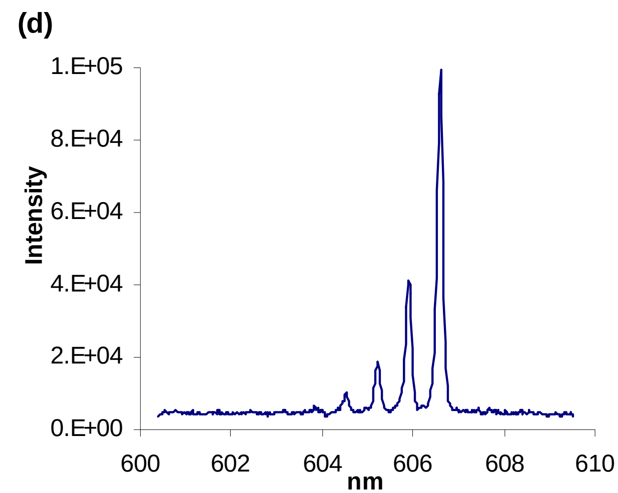
Environments: Optical Pumping of Nitrogen Vibration by Raman Absorption – Excitation of High Vibrational States by V-V Energy Exchange

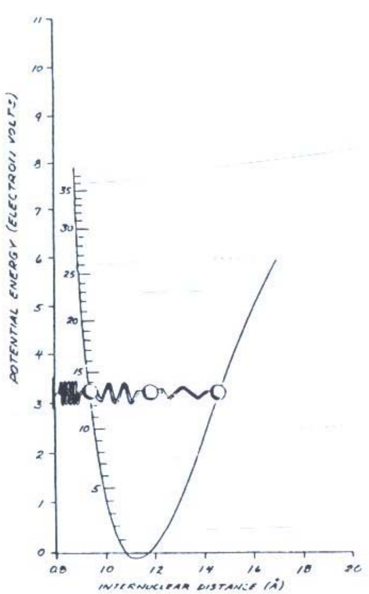
Each peak is from a successive vibrational state, v, ground state signal on the right. The time delay between the pump and probe pulse is (a) 150 ns, (b) 1 ms, (c) 5 ms, (d) 10 ms.





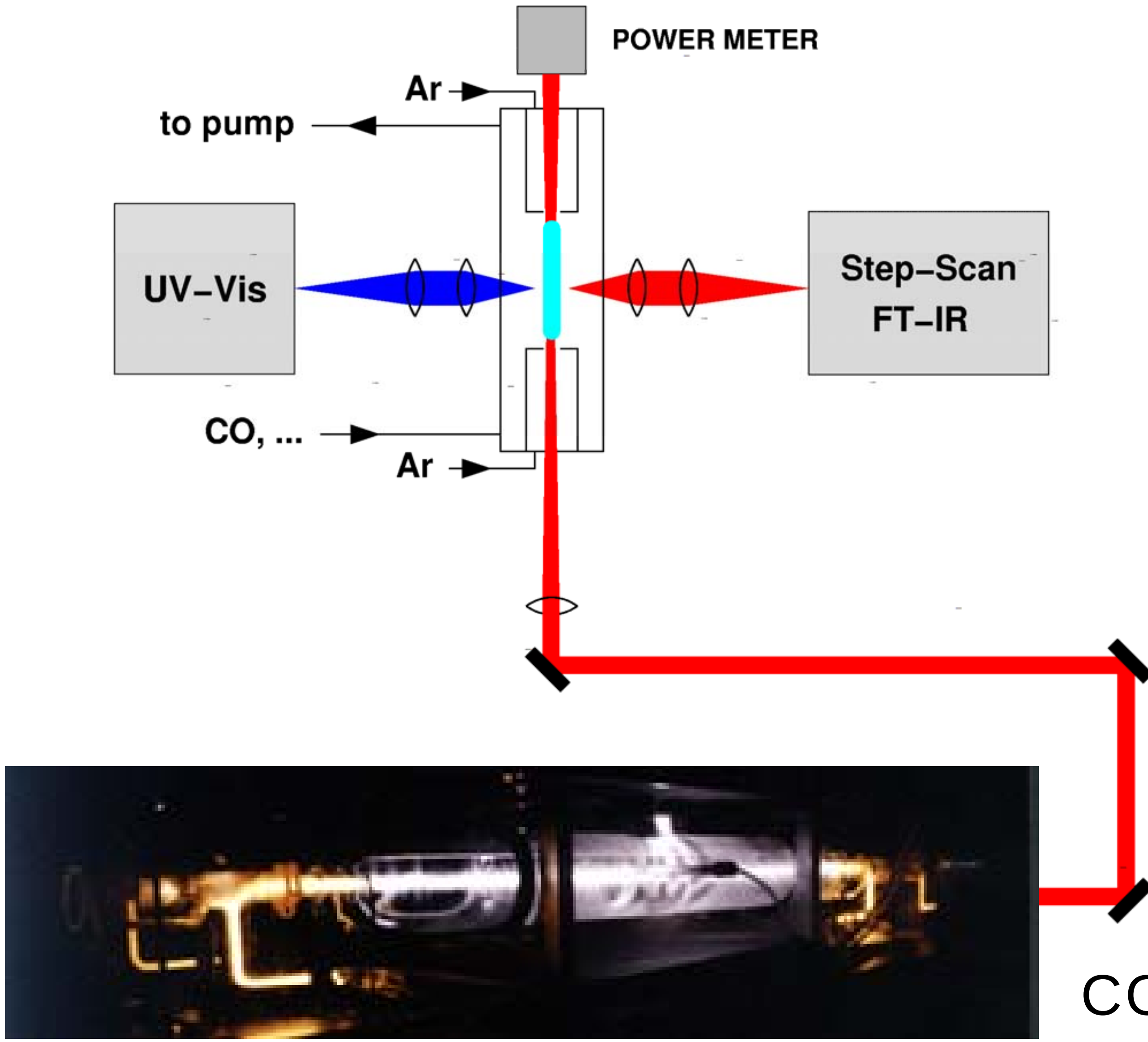






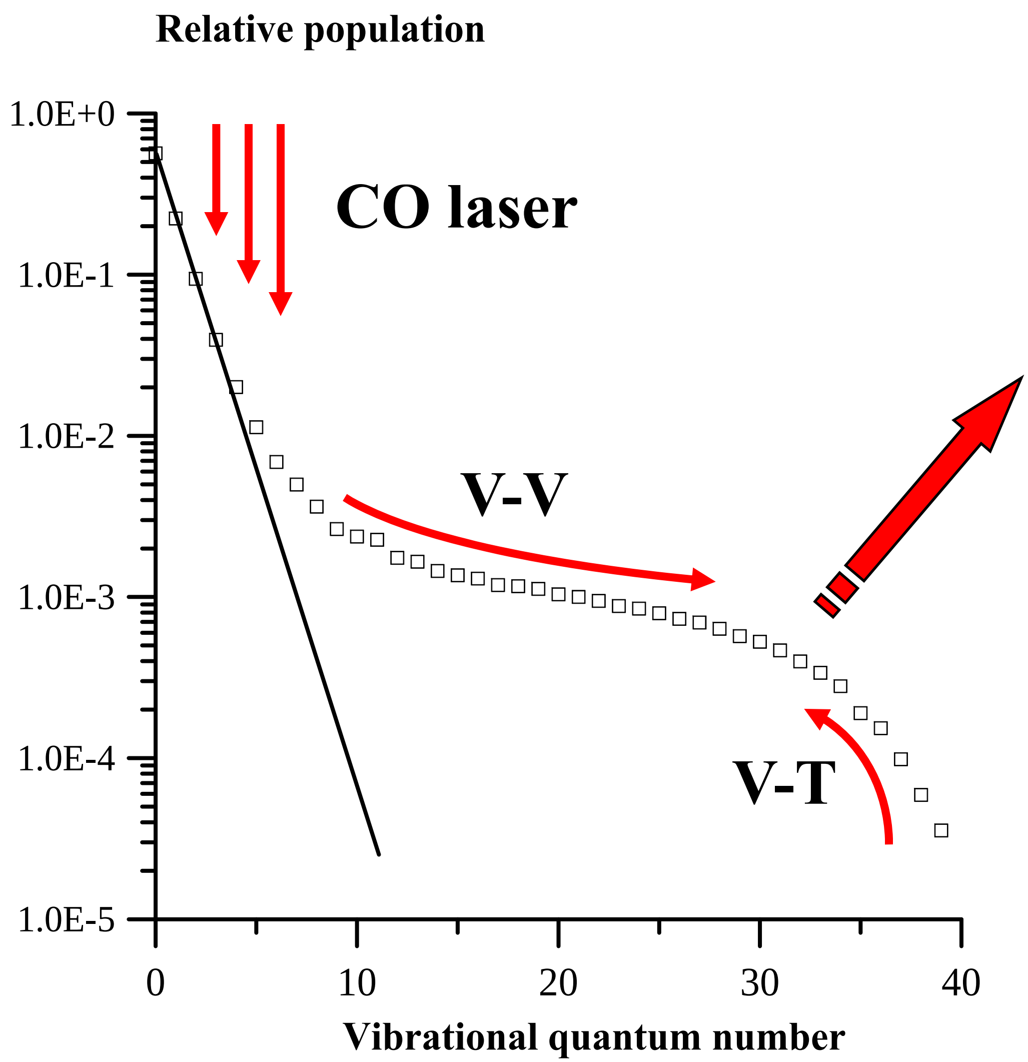
Optically Pumped Plasmas: Kinetics Studies

Experimental Setup for CO Plasma



CO laser

Optically Pumped Plasmas: Kinetics Studies
Energy Transfer and Kinetics Processes in a CO Plasma



2 Torr CO, 100 Torr Ar,
CO laser power 10 W c.w.

Ionization:

CO(v)+CO(w) $\rightarrow$ $(CO)_2^+ + e^-$

V-E:

$CO(X^1\Sigma, v\sim40)+M \rightarrow CO(A^1\Pi)+M$

Chem. Reactions:

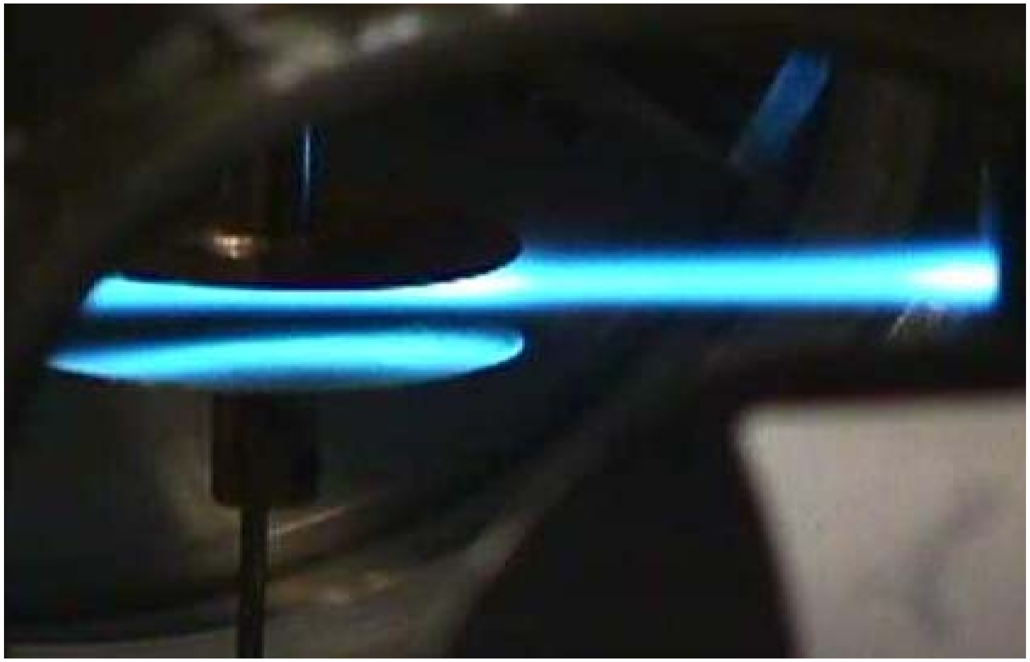
CO(v)+CO(w) $\rightarrow CO_2+C$

T = 600 K

T_v = 3300 K

Optically Pumped Plasmas: Kinetics Studies

Optically Pumped CO Plasma Photo



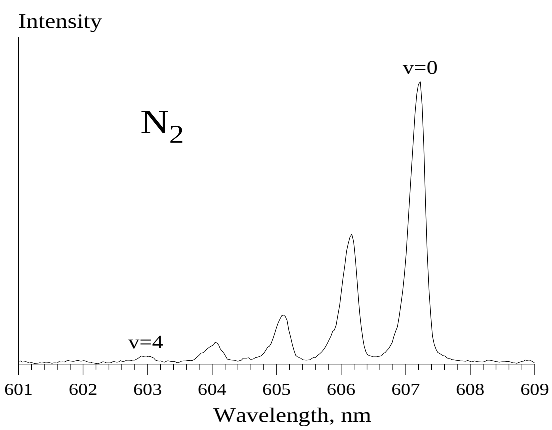
Optically Pumped Plasmas: Kinetics Studies

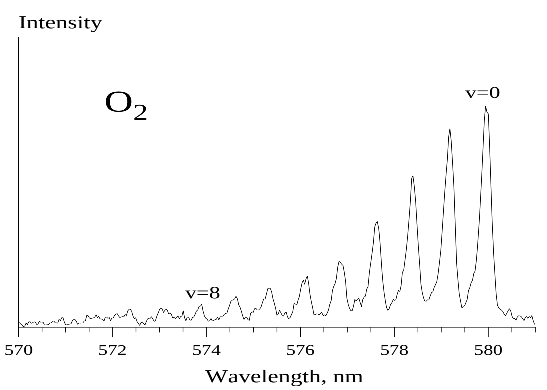
Steady –State Vibrational Excitation of a Flowing Dry Air Mixture

The Ohio State University

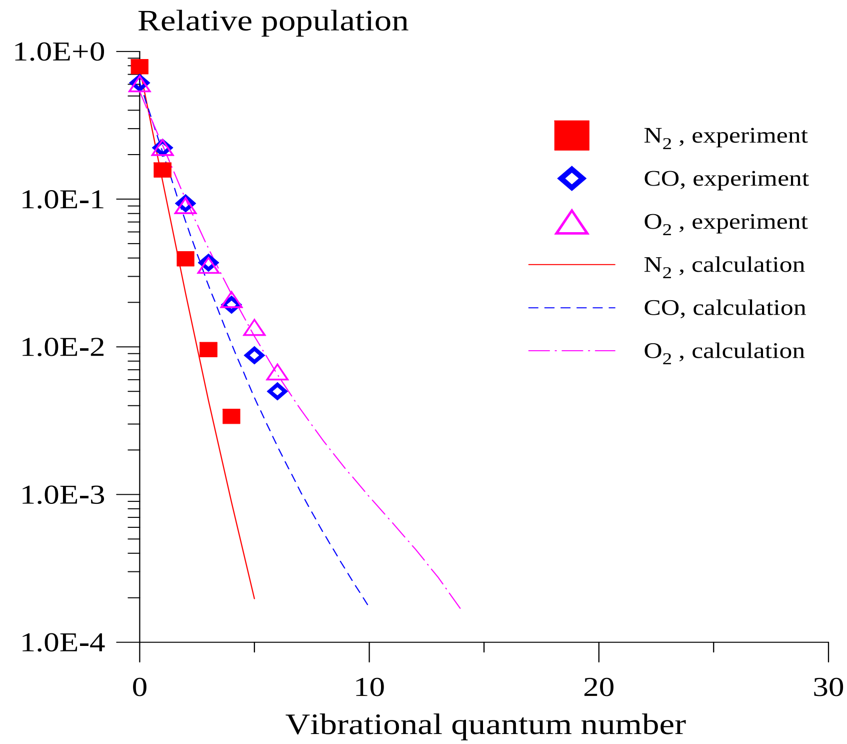
Nonequilibrium Thermodynamics Laboratories

Vibrational energy level populations for an optically pumped air plasma. If energy were equilibrated, temperature of vibrational modes would be ~ 2000K. Measured as kinetic temperature is only 500 K. Extreme nonequilibrium is created in a steady state, atmospheric pressure, molecular gas plasma. Gas mixture is CO/N2/O2=5/75/20, P=1 atm. Pump laser power is 10 W.





Raman Spectra

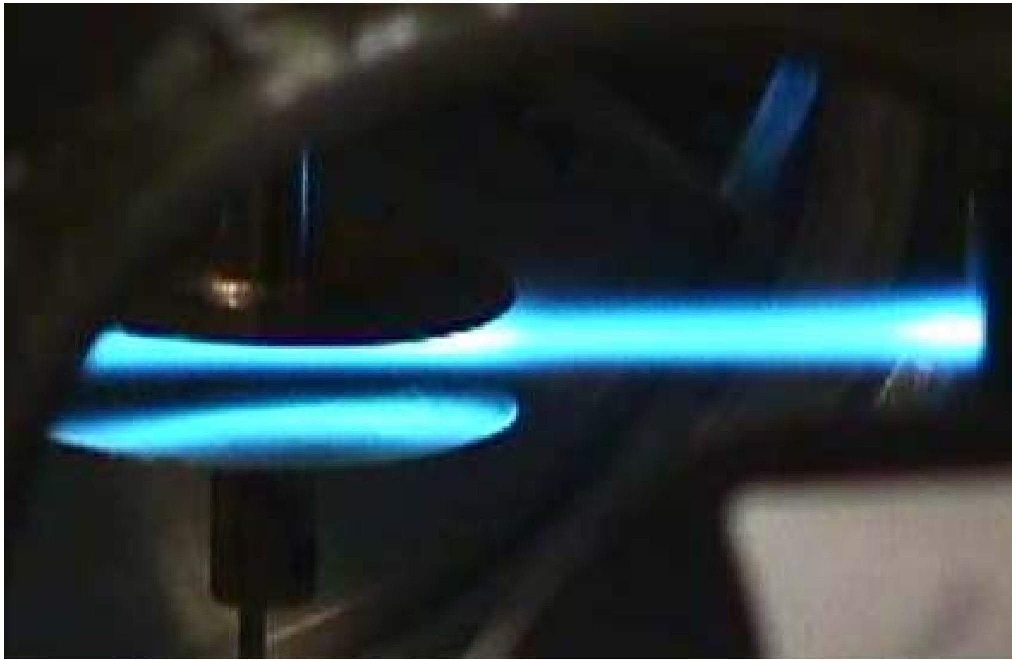


Experimental Vibrational State Populations Inferred from Raman Spectra. Calculated State Populations from Master Equation Kinetic Model

Associative Ionization in Optically Pumped Plasmas I

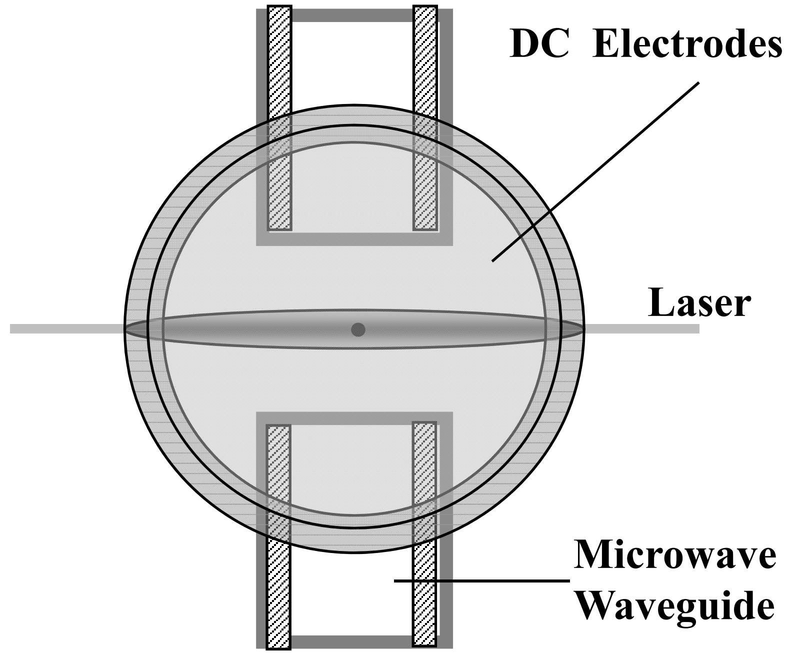
$CO(v) + CO(w) \rightarrow (CO)_2^+ + e^-$, $E_v + E_w > E_{ion}$

Thomson discharge



Electron production rate:
$k_{ion} \sim 10^{-13}$ cm^3/s

Microwave absorption

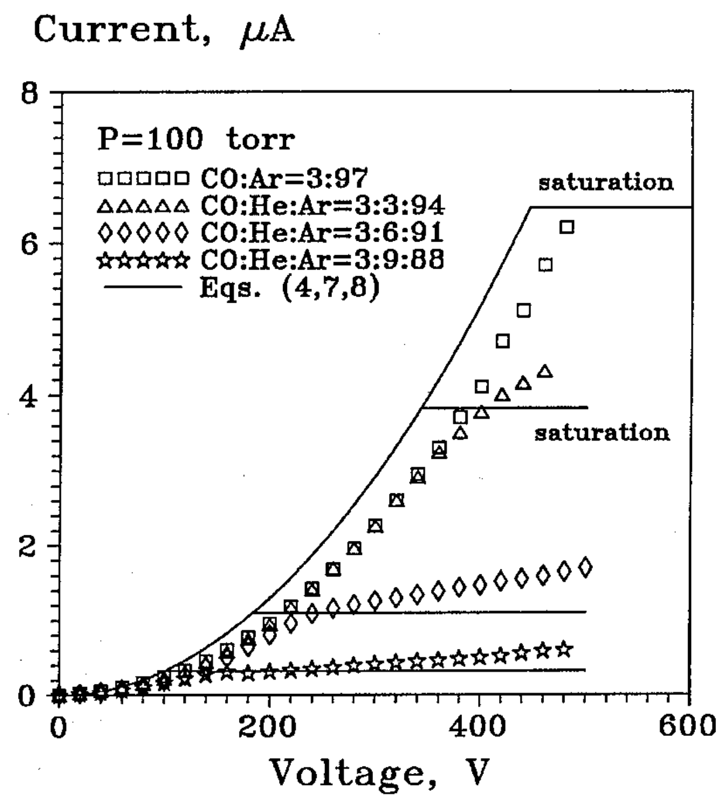


Electron density:
$n_e \cong 10^{11}$ cm^{-3}

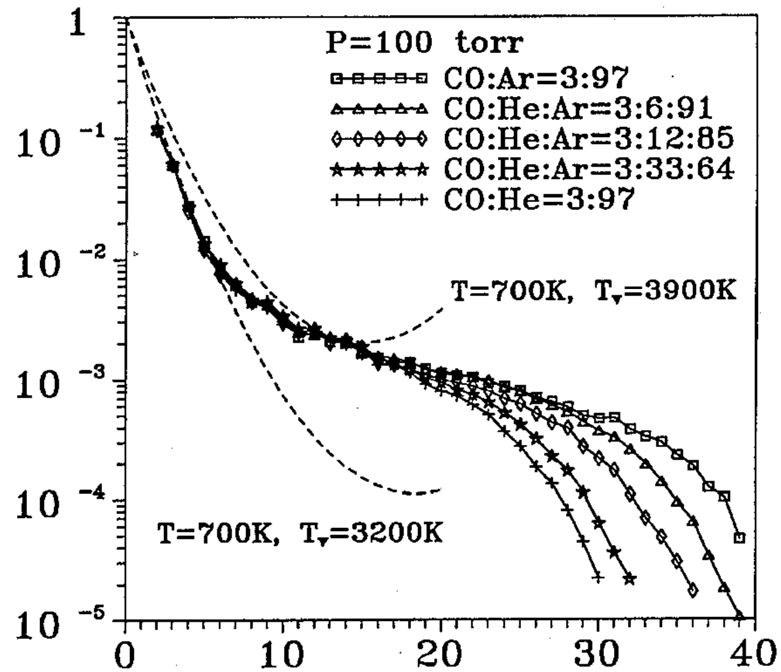
Optically Pumped Plasmas: Kinetics Studies

Associative Ionization in Optically Pumped Plasmas II

$CO(v) + CO(w) \rightarrow (CO)_2^+ + e^-$, $E_v + E_w > E_{ion}$



Current-voltage characteristics of the DC Thomson discharge at different helium partial pressures



Vibrational distribution functions of carbon monoxide at different helium partial pressures

Optically Pumped Plasmas: Kinetics Studies
Coupling of Vibrational Populations with Free Electrons

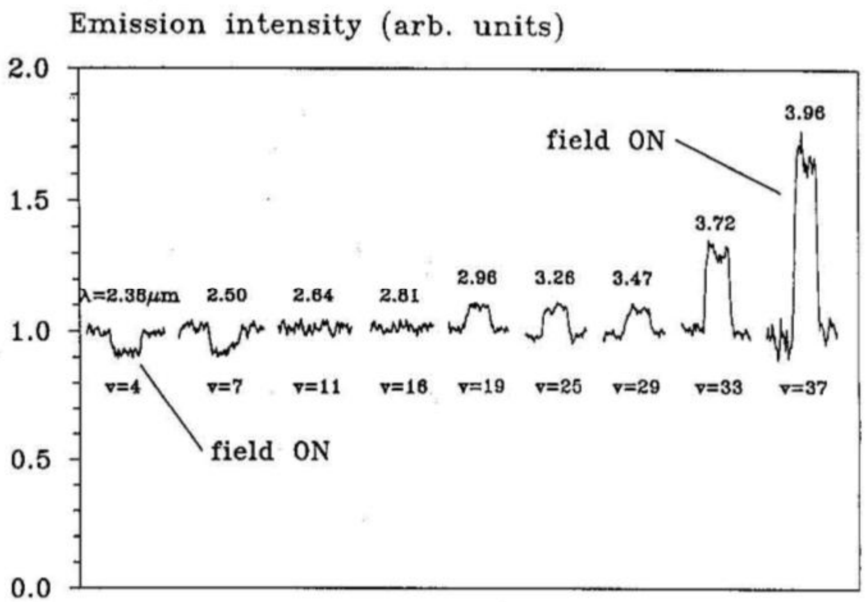


Fig. 11. Electric field influence on different CO vibrational level populations.

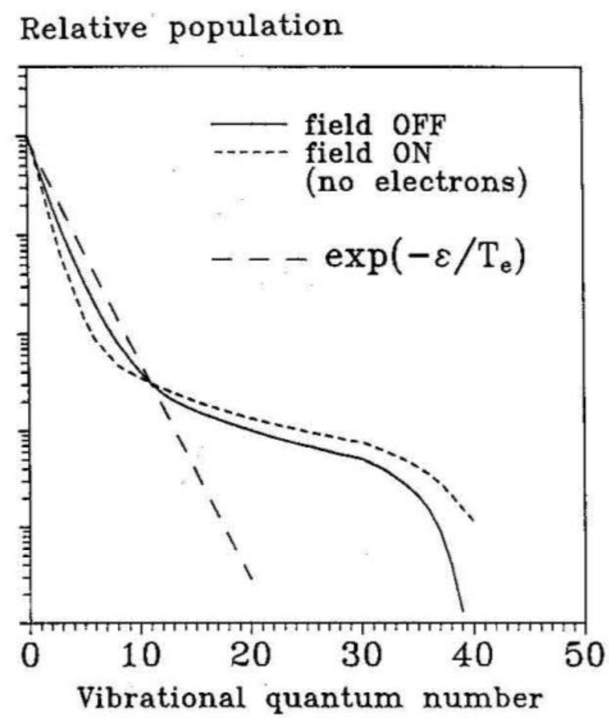
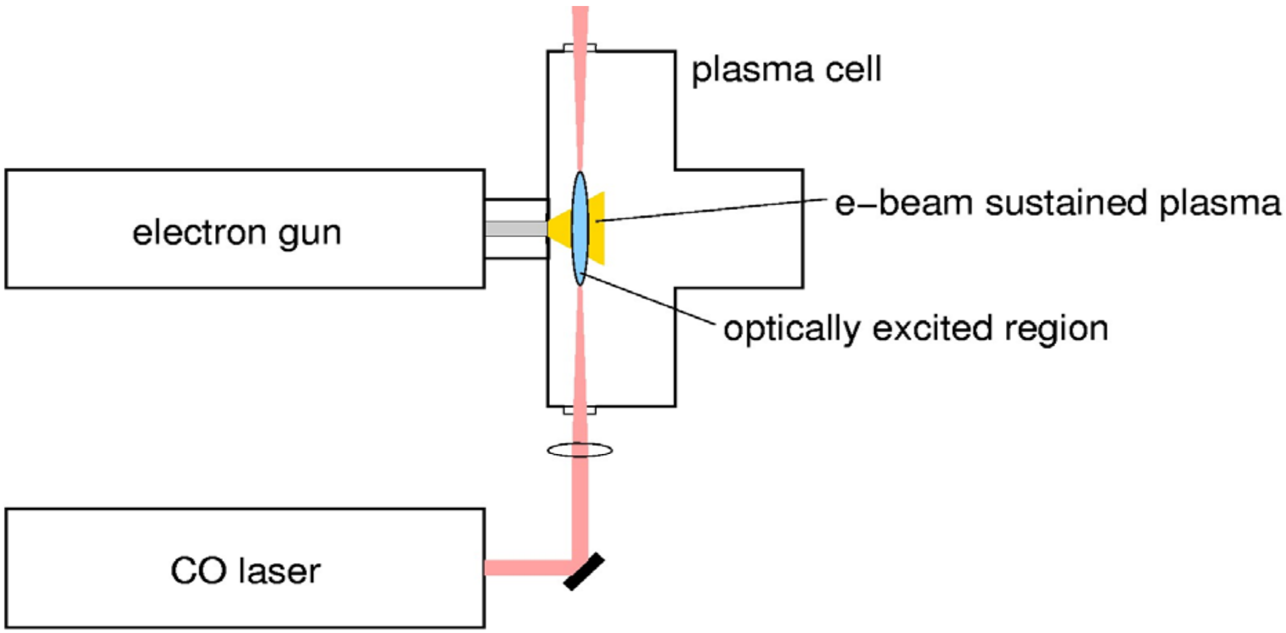
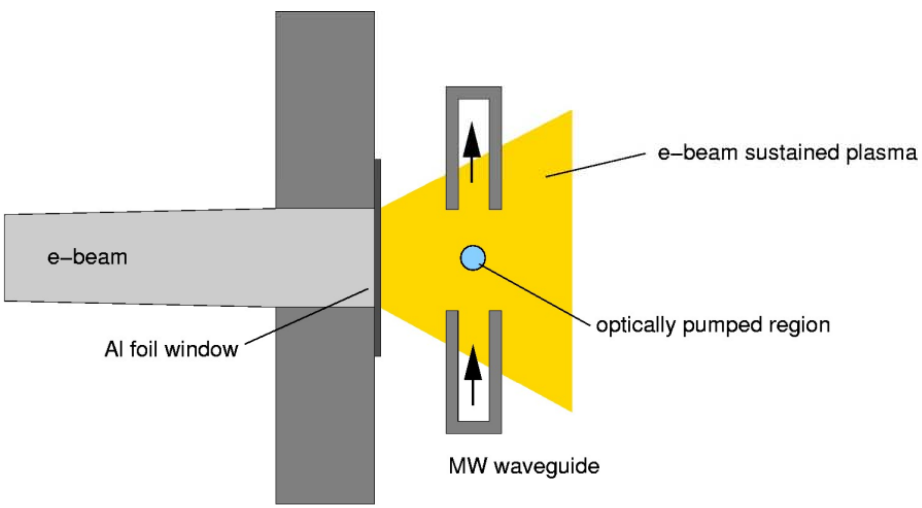


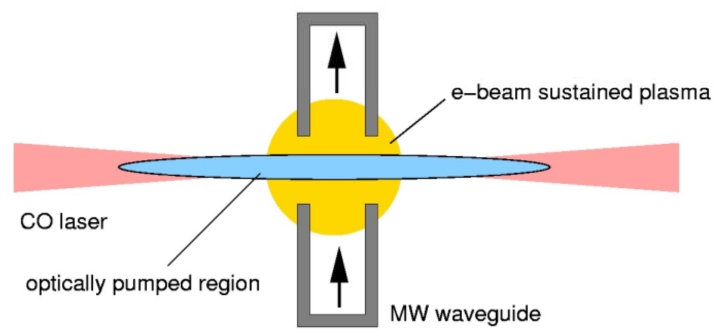
Fig. 12. Qualitative demonstration of the V→e→V–ΔV effect (strongly exaggerated). ϵ: electron energy; T_e: electron temperature.

Optically Pumped Plasmas: Kinetics Studies

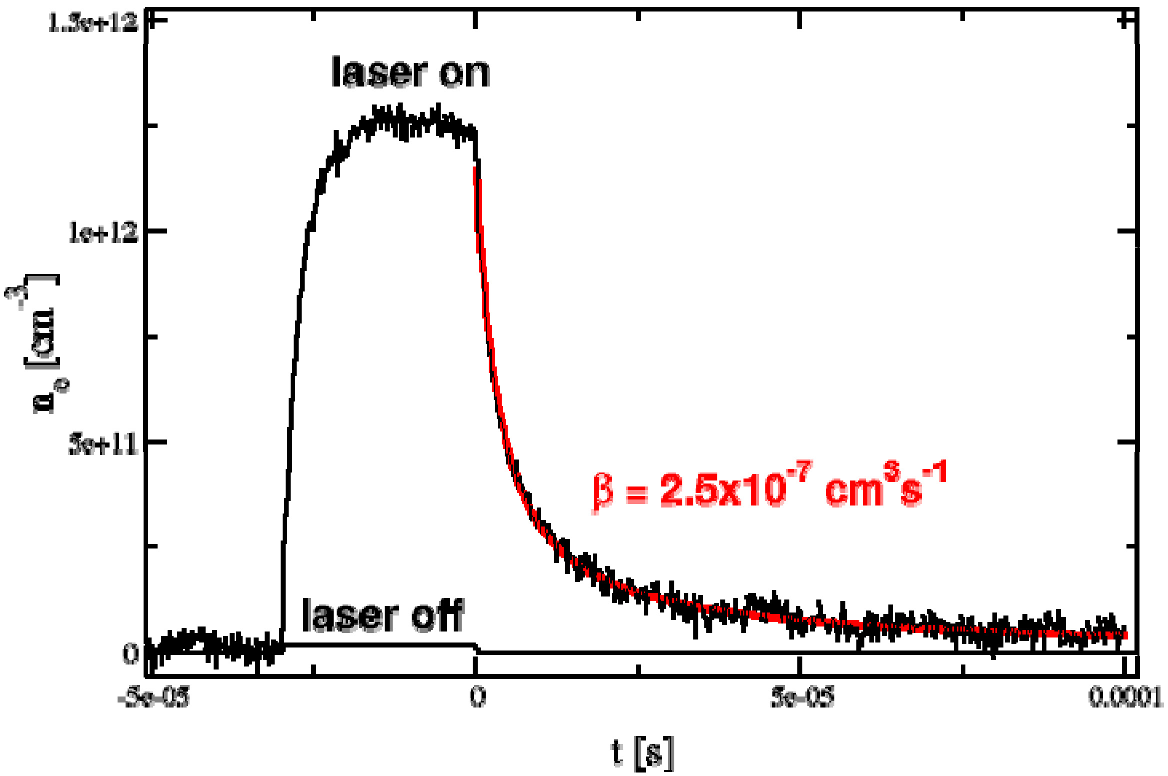
Measurements of Electron Density Decay (by microwave attn) for E-beam Created Plasma – Experimental Schematic







Measurements of Electron Density Decay (by microwave attn) for E-beam Created Plasma – Inhibition of Electron Loss Processes in Cold Air



Plasma Power Consumption at 10^{13} Electrons/cm^3 in 1 Atm, 560 K Air:

Electron-Ion Recombination

$\beta = 2.5\times10^{-7}$ cm^{3}sec^{-1}

Nonequilibrium: 56 W cm^{-3}

Equilibrium: 450 W cm^{-3}

Electron Attachment to O_2

$k_{eff} = 2.3\times10^{-33}$ cm^{6}sec^{-1}

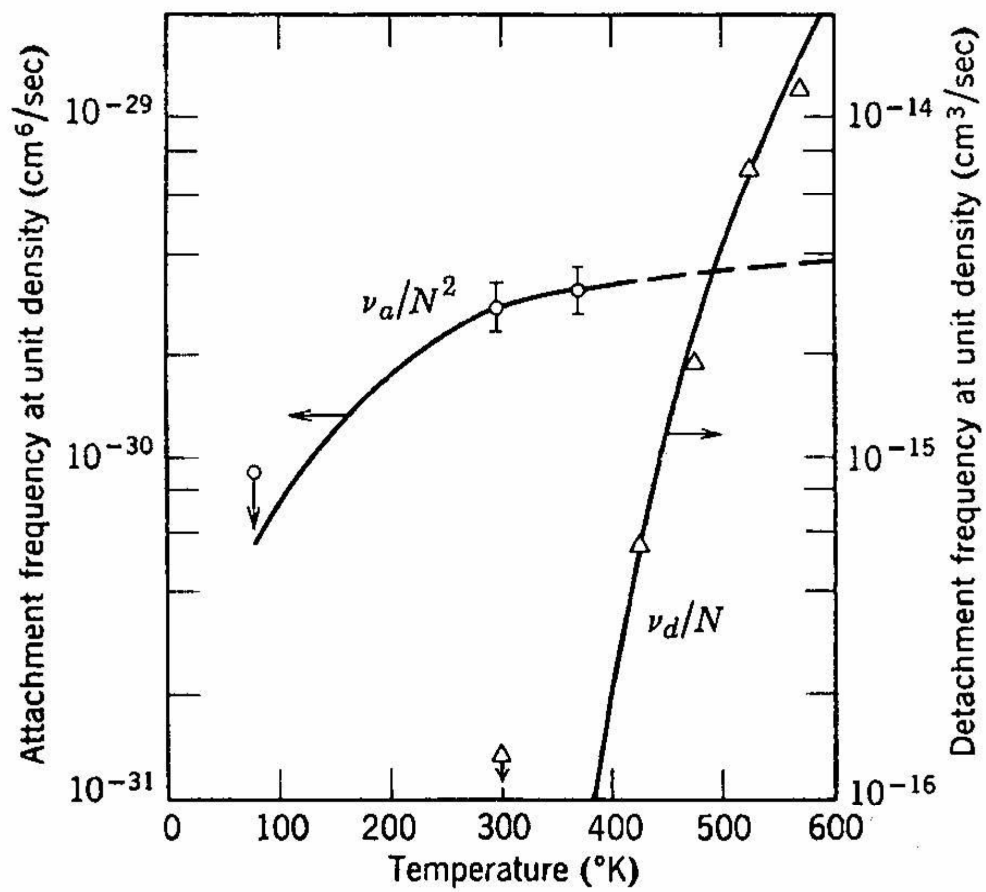
Nonequilibrium: 1.2 W cm^{-3}

Equilibrium: 1.4 kW cm^{-3}

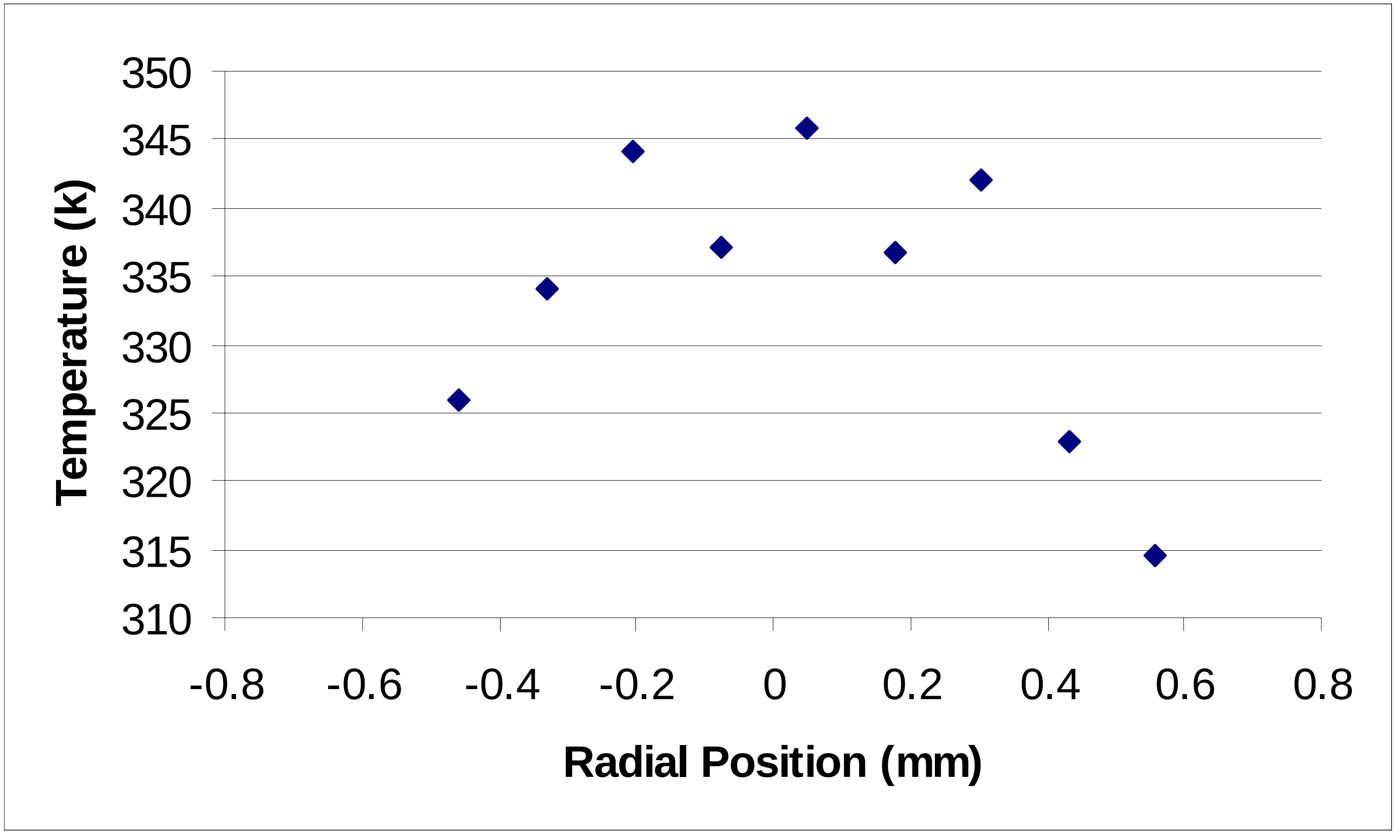
Attachment is weakly dependent upon heavy species temperature whereas detachment is highly dependent

$$O_2 + e^- + M \Leftrightarrow O_2^- + M$$

O_2 Electron Affinity ~0.43 eV
(~Two Vibrational Quanta)



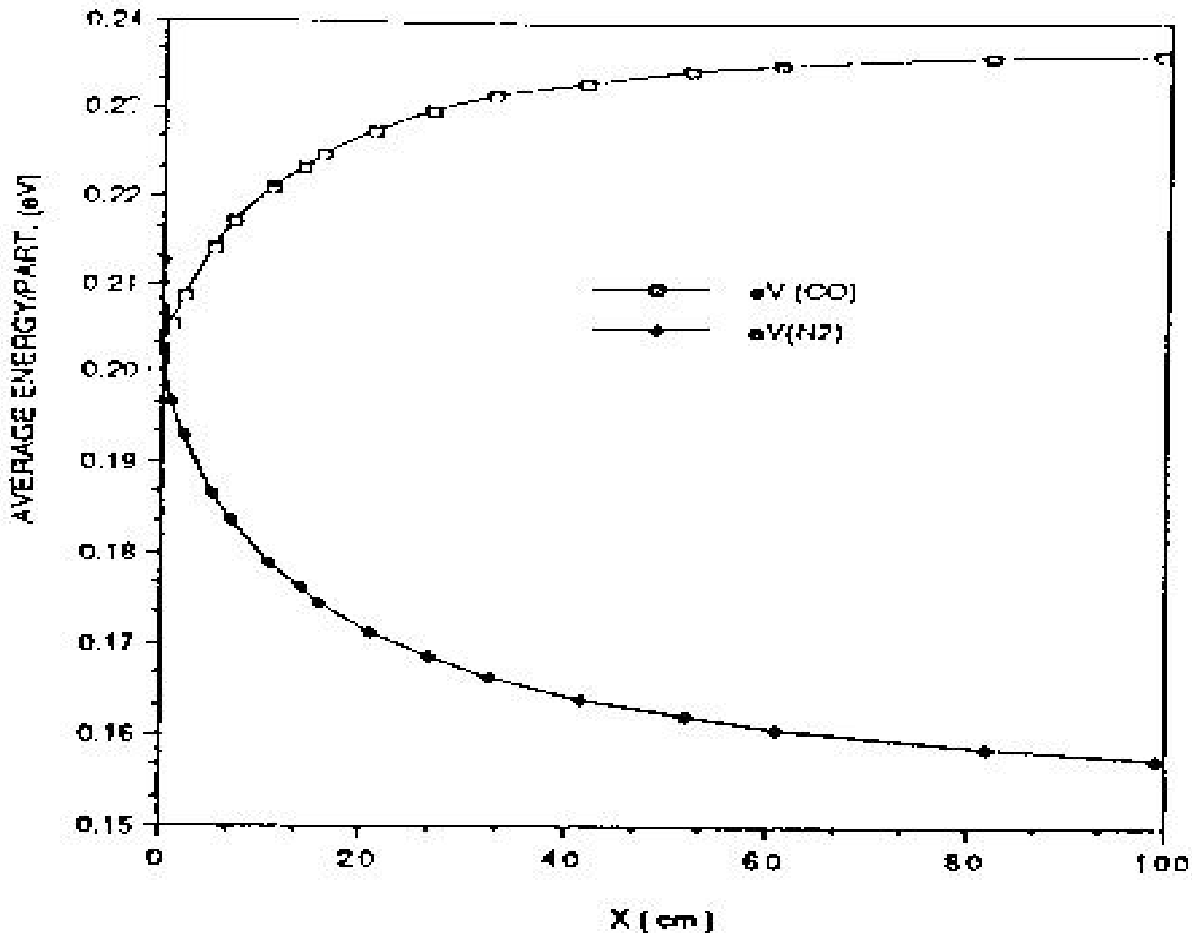
200/18/35 $N_2/CO/O_2$ – Optically Pumped
(Diameter of Vibrationally Excited Region ~ 1 mm)



Gas Dynamic Flows: Vibrational mode nonequilibrium in a supersonic nozzle expansion

Average energy per molecule in electron Volts.
(0.1 eV = 1,161 ^{o}K)

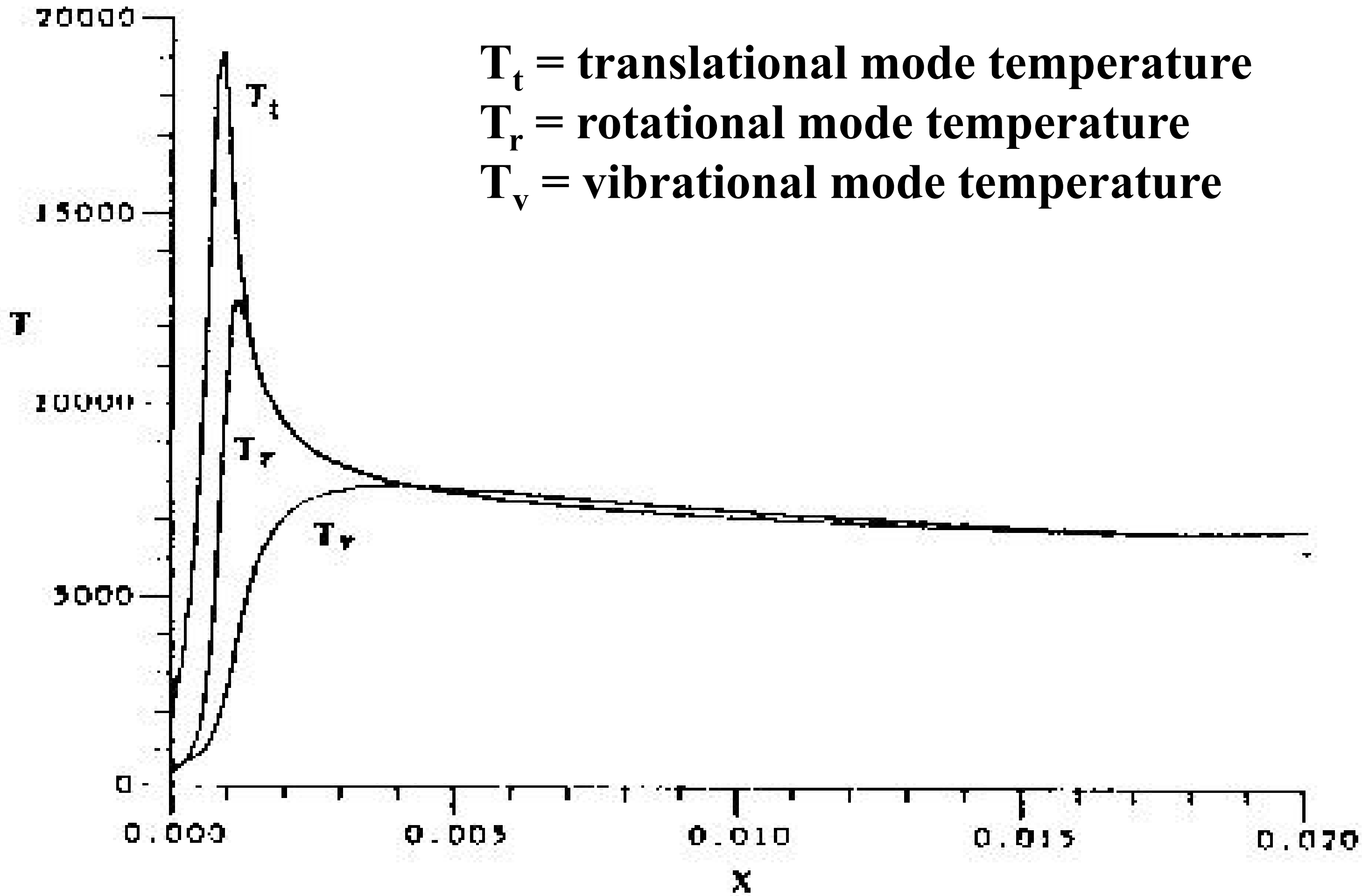
Expansion of a gas mixture of 20% CO, 20% N_2, 60% Ar,
Stagnation Pressure = 100 atm.
Stagnation Temperature = 2,000 ^{o}K.
15 ^{o} Half Angle Nozzle,
Expands to M = 10 at 100 cm downstream of throat



Distance from nozzle throat, in centimeters

Gas Dynamic Flows: Thermal mode nonequilibrium behind a hypersonic shock wave

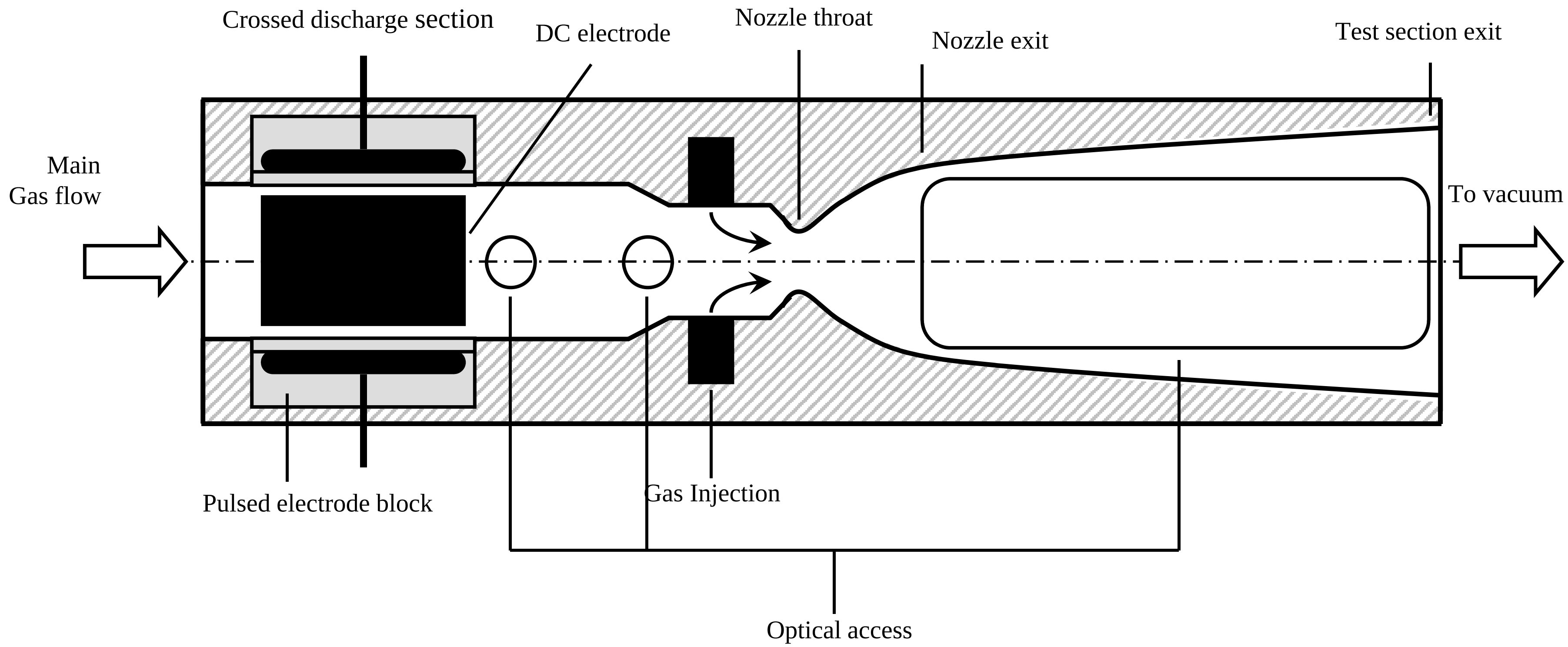
Mode Temperature Degrees K



T_t = translational mode temperature
T_r = rotational mode temperature
T_v = vibrational mode temperature

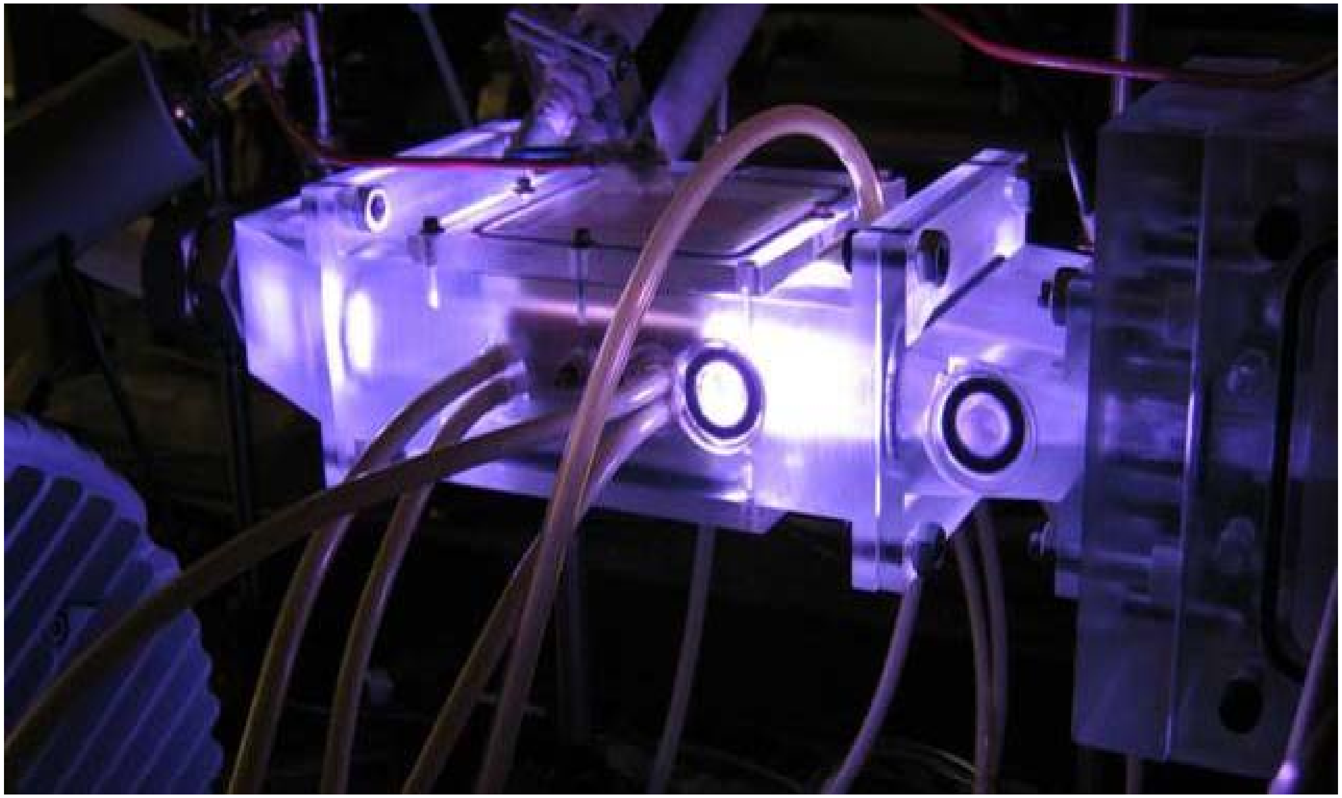
Distance behind shock front, in meters

Plasma Wind Tunnels: A supersonic tunnel with energy loading of selected internal states in the plenum



Schematic of the wind tunnel discharge section / nozzle / test section assembly

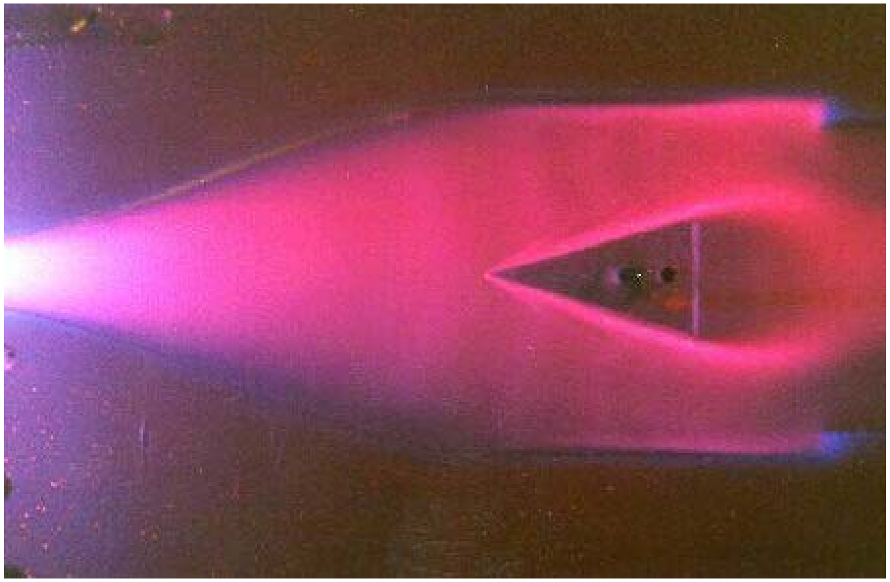
Plasma Wind Tunnels: A supersonic tunnel with energy loading of selected internal states – photo of plenum in operation

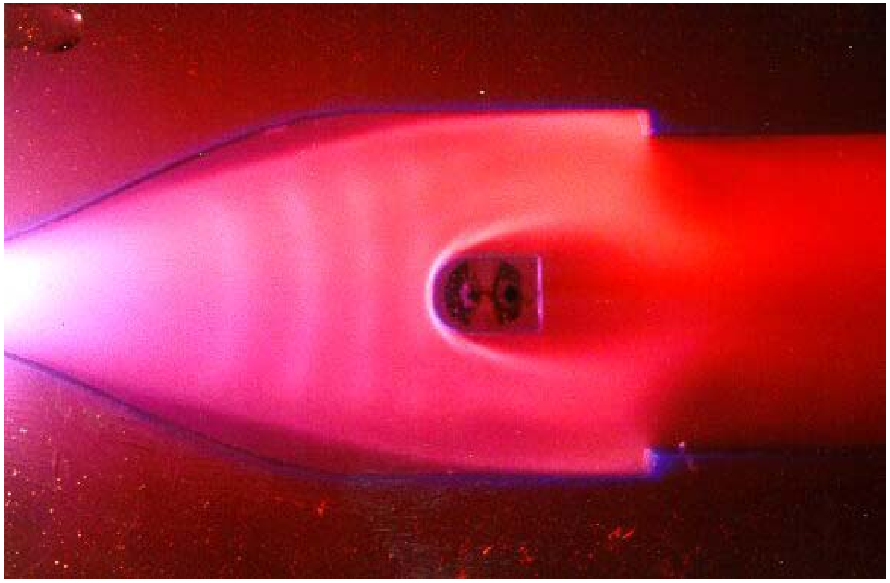


Photograph of a discharge in the nozzle plenum. Dimensions 4x4x10 cm.
A uniform, cold gas fills the plenum;
O_2/He mixture shown, similar uniformity for air; P_0 to 1 atm.

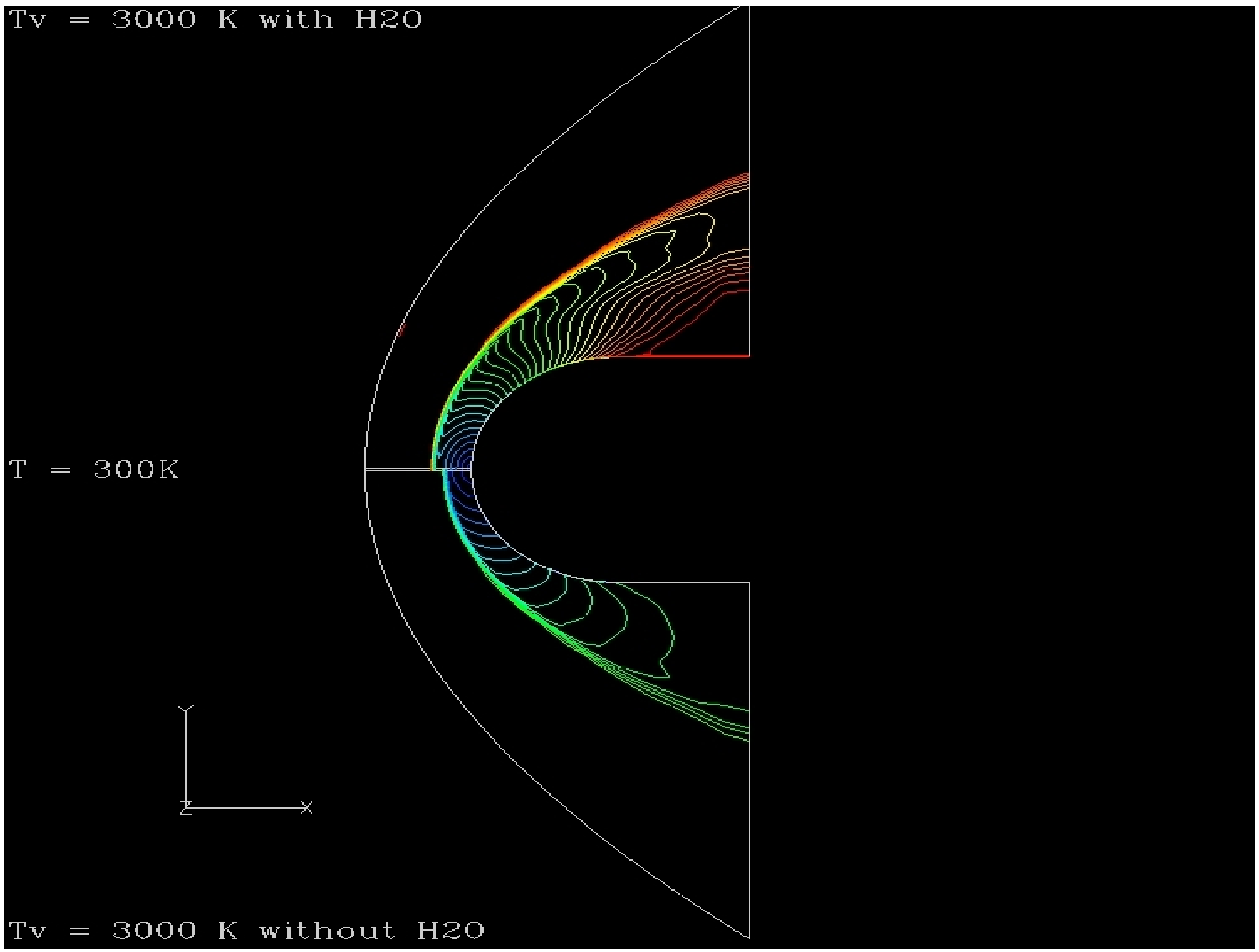
Plasma Wind Tunnels: A supersonic tunnel with energy loading of selected internal states – objects in a 2-D, M = 3 test section

The Ohio State University Nonequilibrium Thermodynamics Laboratories



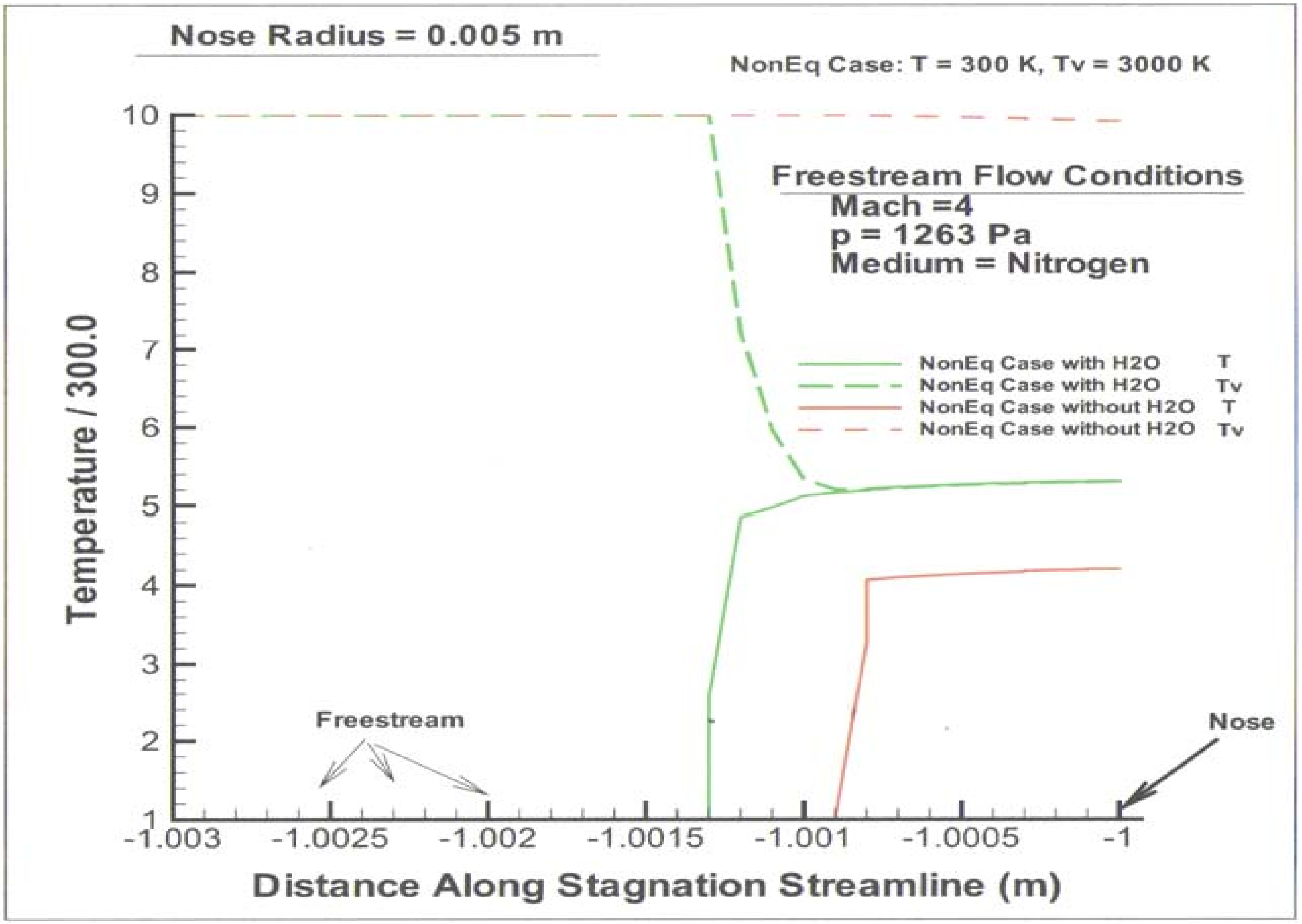


Plasma Wind Tunnels: Calculated M =4 Flow over a 0.5 cm Dia semicylinder. Vibrationally Excited N_2 Expanding from 1 atm.



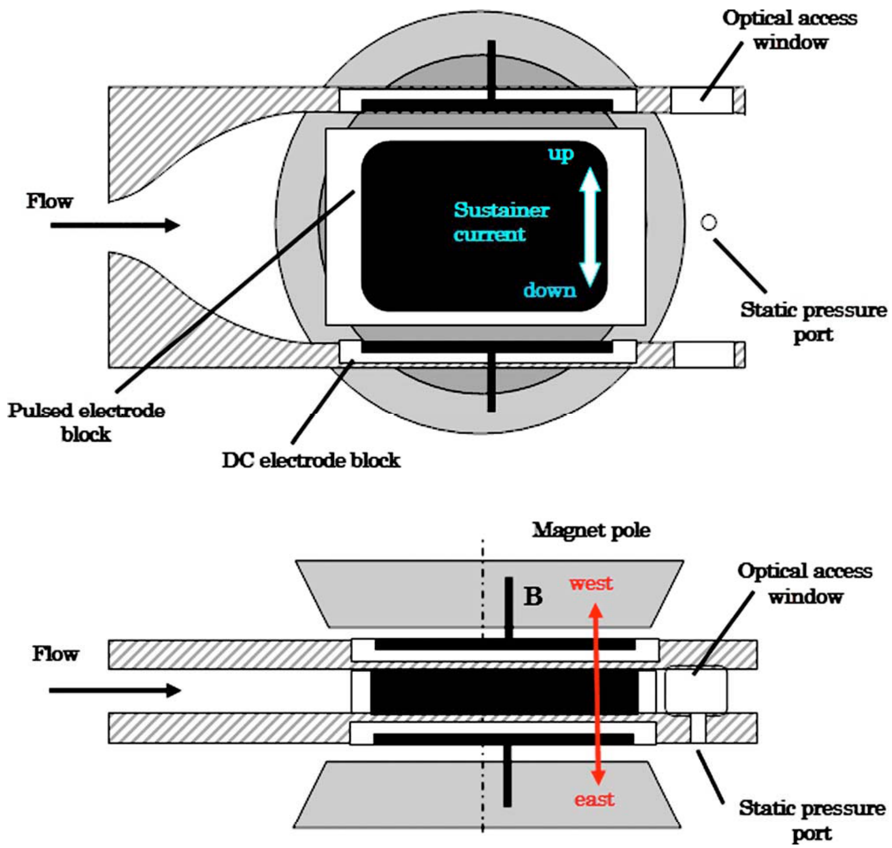
From E. Josuyla, AFRL

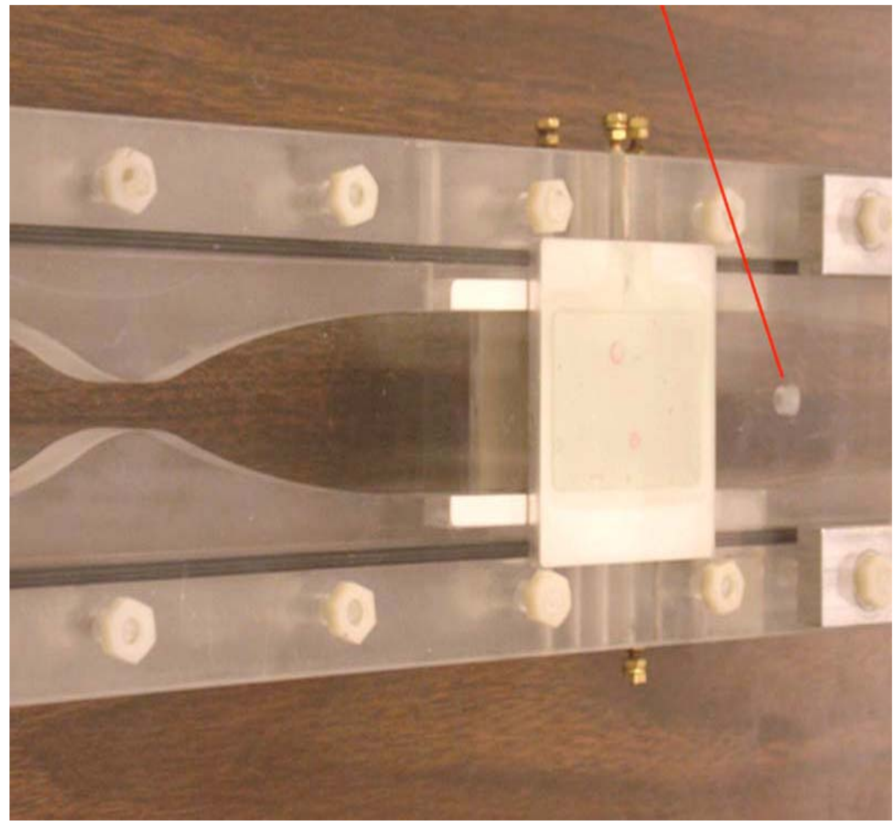
Plasma Wind Tunnels: Calculated M =4 Flow over a 0.5 cm Dia semicylinder. Vibrationally Excited N_2 Expanding from 1 atm.



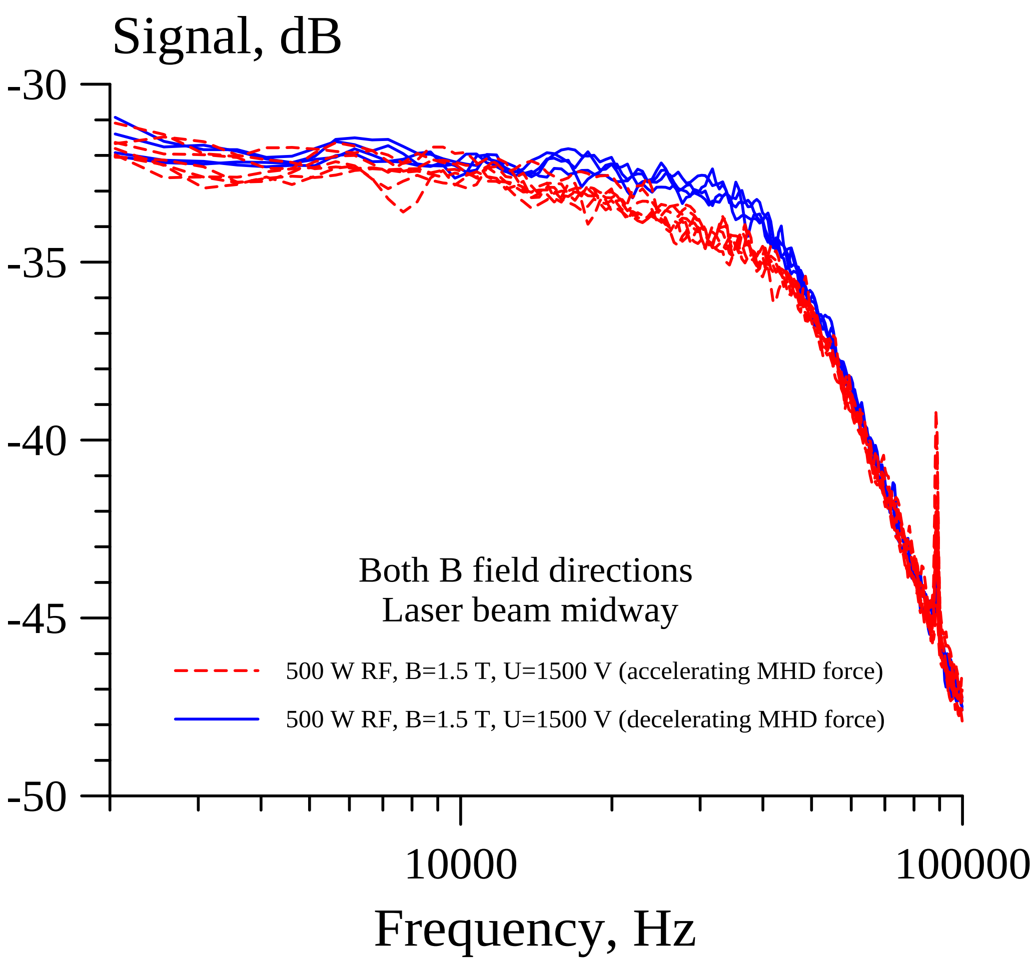
From E. Josuyla, AFRL

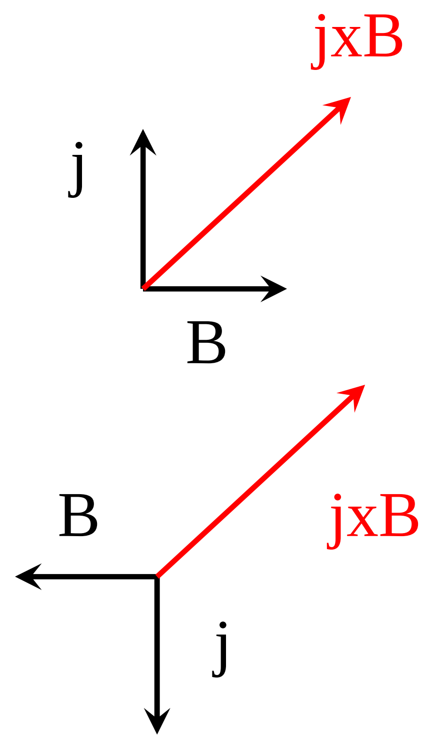
Plasma Wind Tunnels: An M = 4 MHD Tunnel, with transverse pre-ionized discharge and a 2 Tesla Field in test section





Plasma Wind Tunnels: An M = 4 MHD Tunnel. Lorentz force effect on turbulent boundary layer density fluctuation spectra

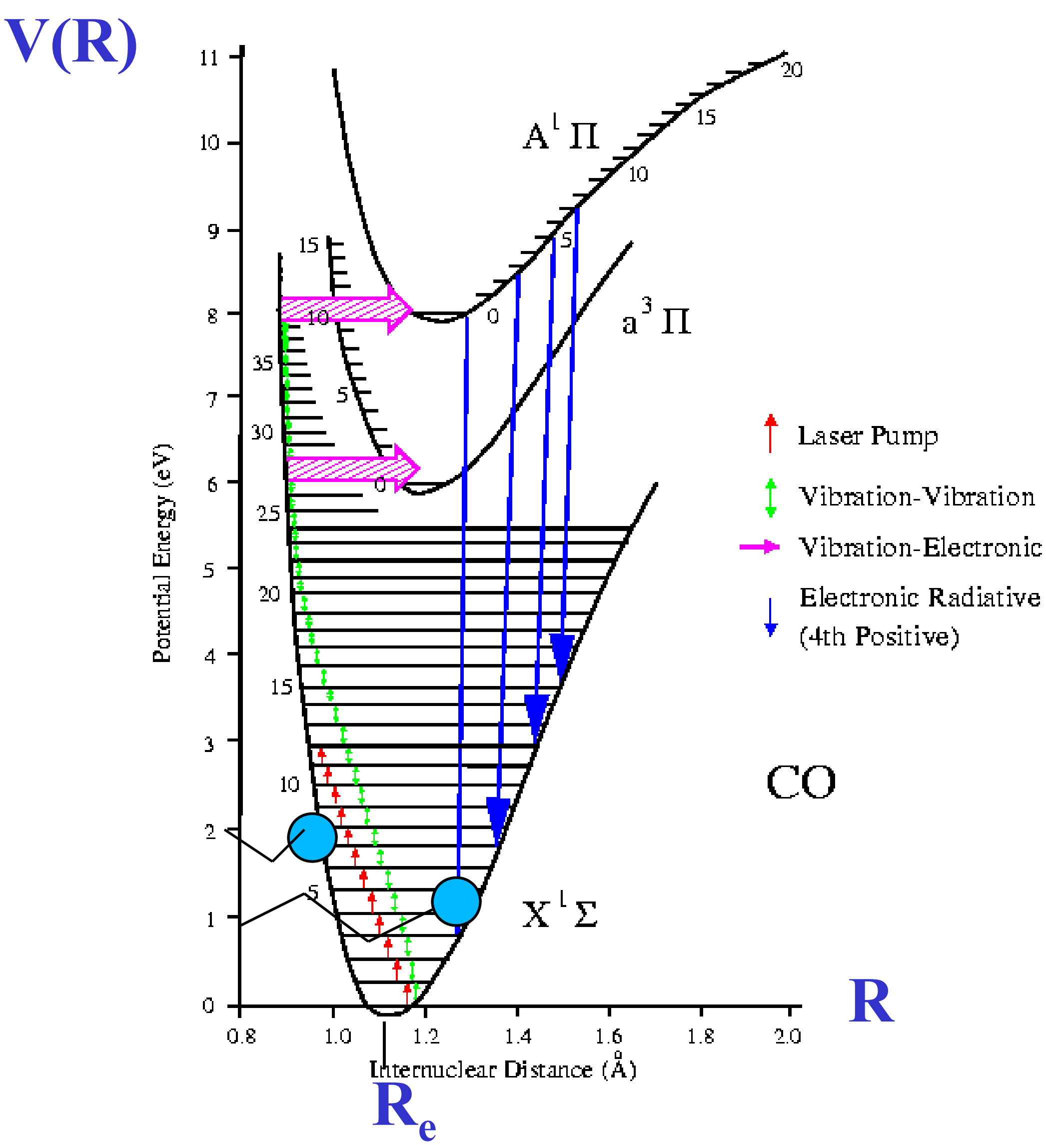


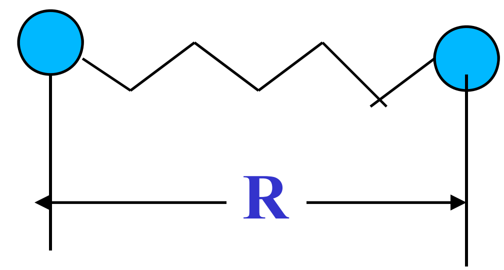


Nitrogen, M=3, P0=1/3 atm

Both accelerating and decelerating Lorentz force are created for two possible combinations of B and E fields, as shown

CO potential

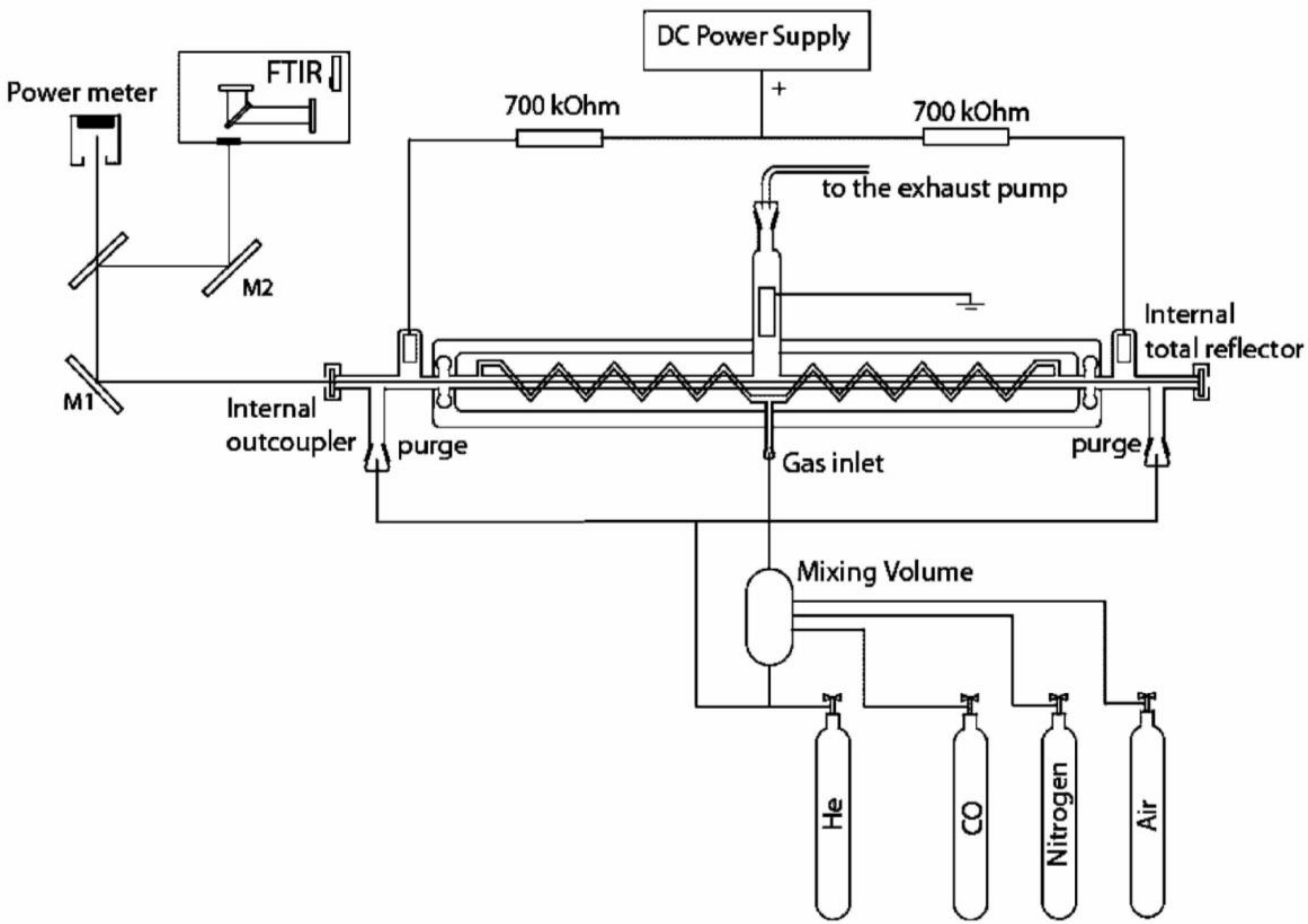




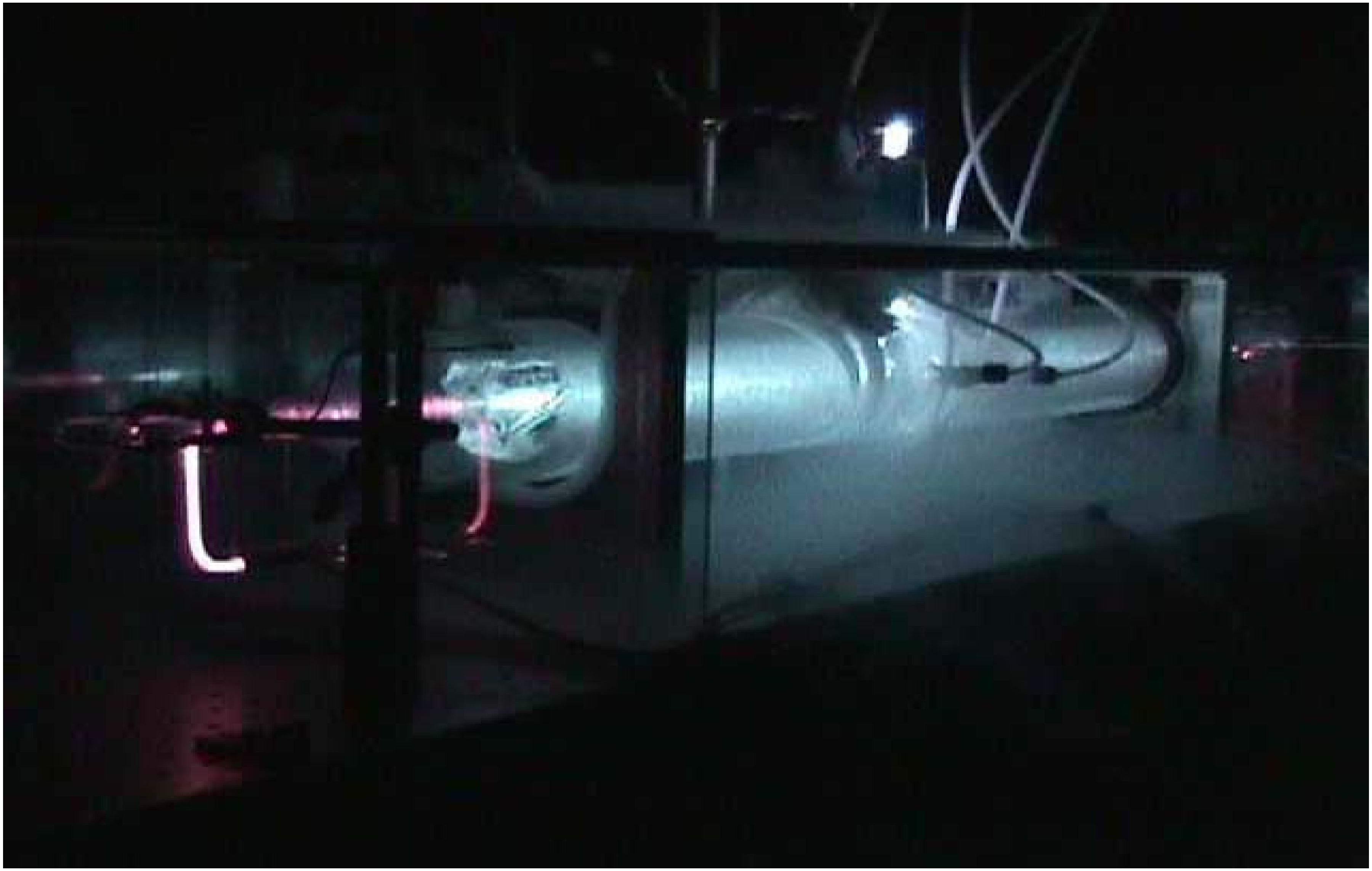
R is the separation of the C and O nuclei. R_e is the equilibrium (nonvibrating) separation.

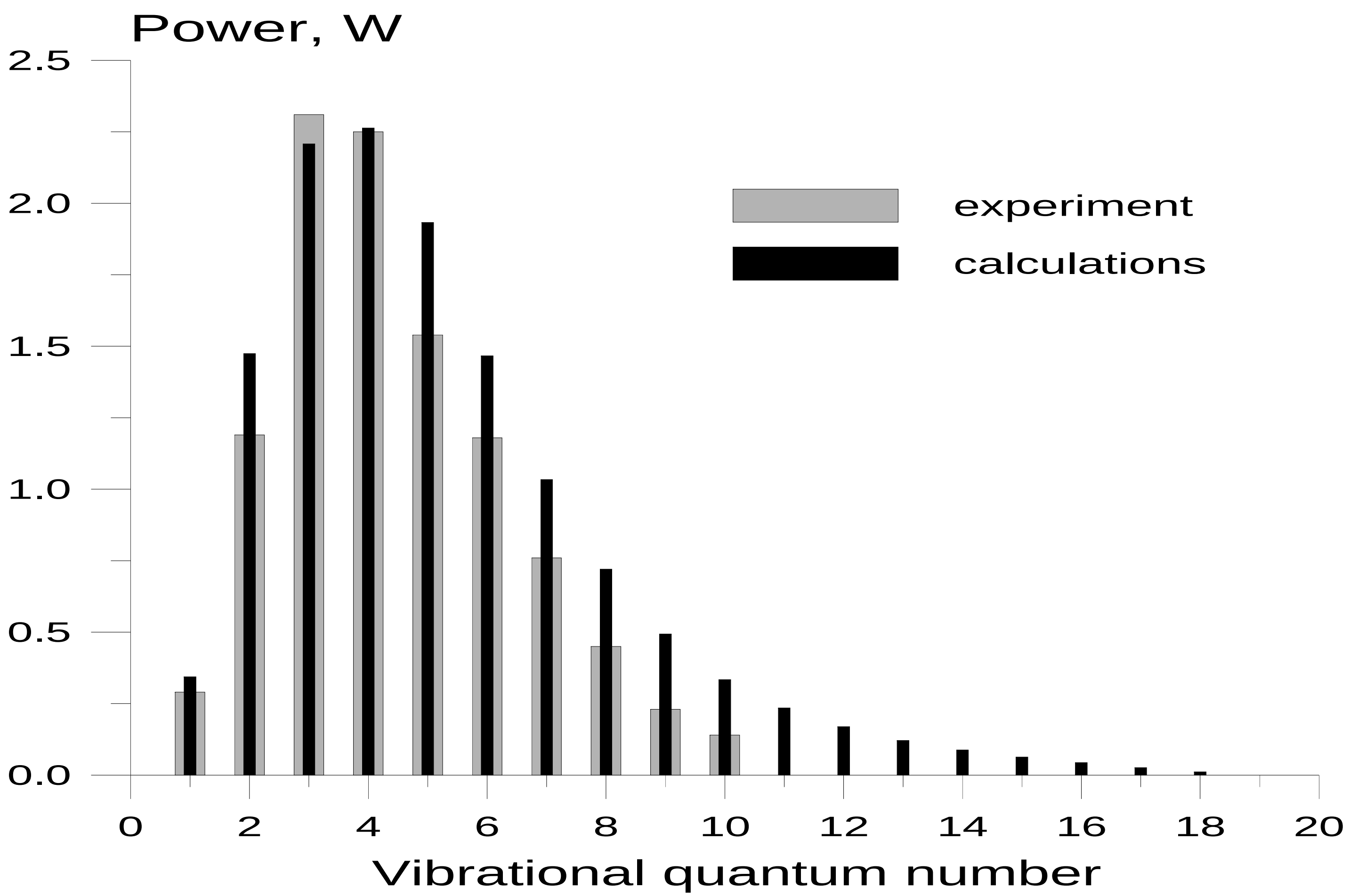
$V(R) = 1/2\ K(R - R_e)^2$ is the potential energy stored in the oscillator

Gas Lasers: Carbon Monoxide Electric Discharge Laser - Schematic

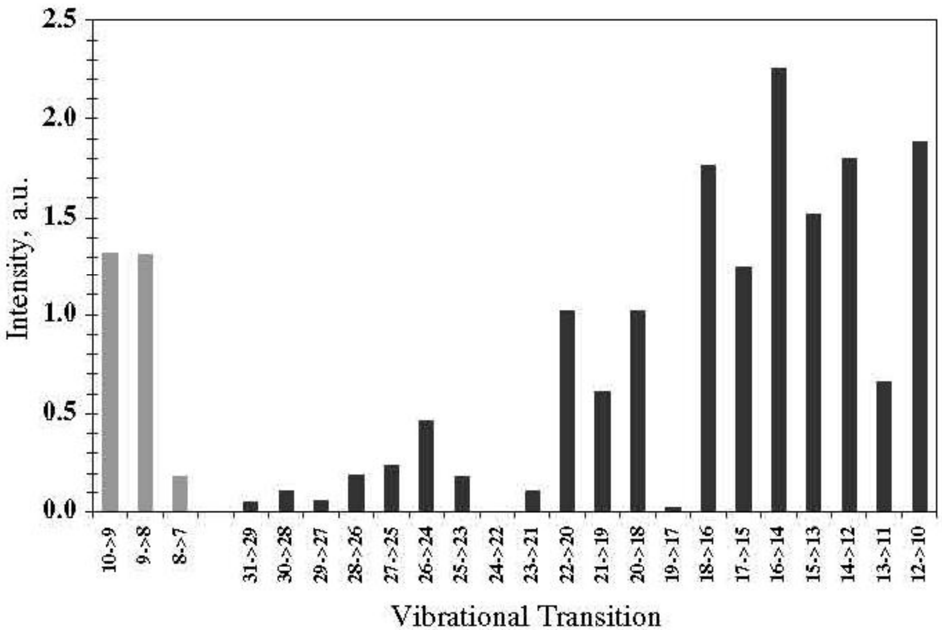


Gas Lasers: Carbon Monoxide Electric Discharge Laser – Photo during operation

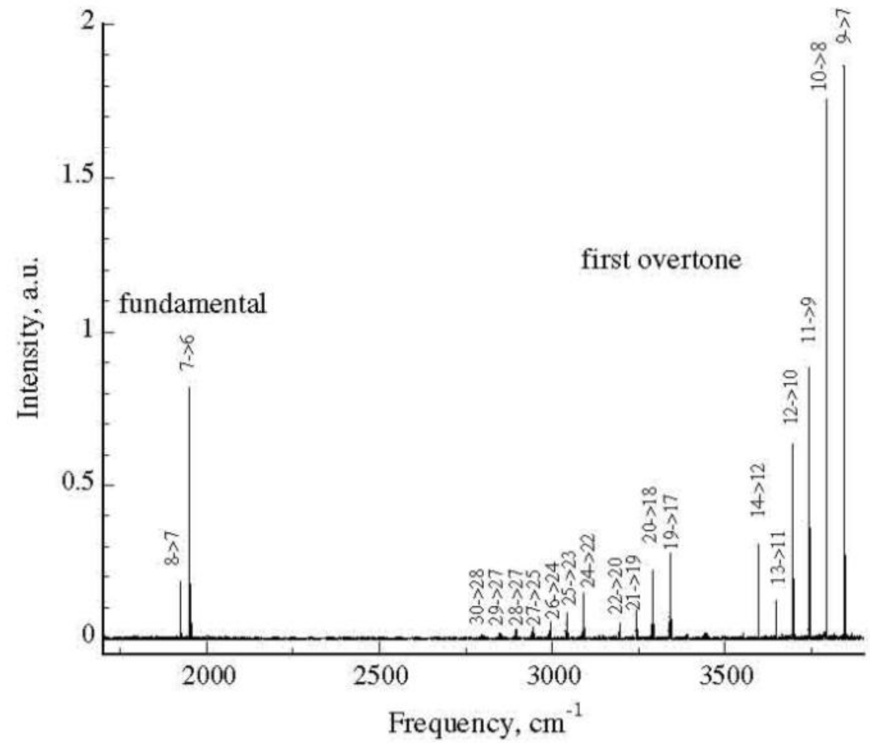



Power, W
2.5
2.0
1.5
1.0
0.5
0.0
experiment
calculations
0
2
4
6
8
10
12
14
16
18
20
Vibrational quantum number

Gas Lasers: Carbon Monoxide Electric Discharge Laer –
Kinetic Modeling of CO Overtone Band Laser,
Comparison with OSU Laser Performance

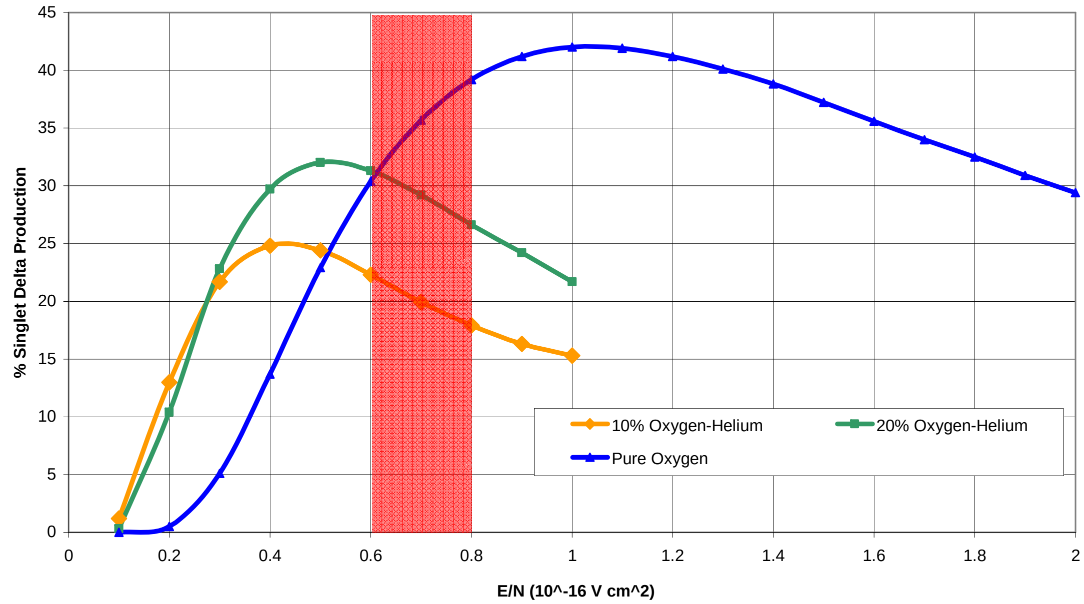


Theoretically Predicted Output Line Intensities

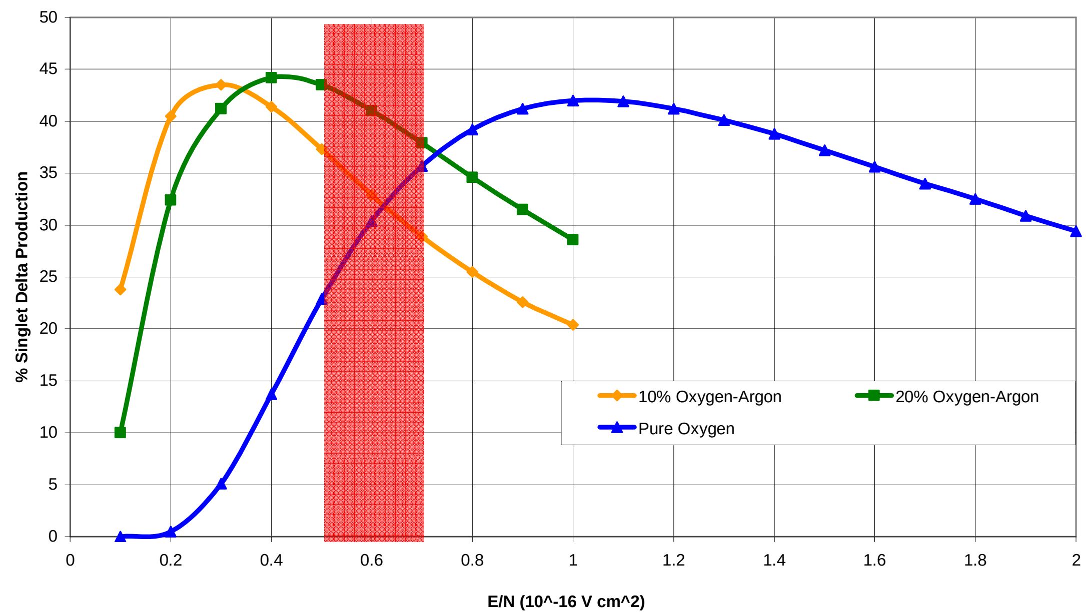


Experimentally Measured Output Line Intensities

Gas Lasers: An Electric Discharge-Excited Oxygen-Iodine Laser (DOIL) – Boltzmann equation solver results: electron energy balance



O_2-He

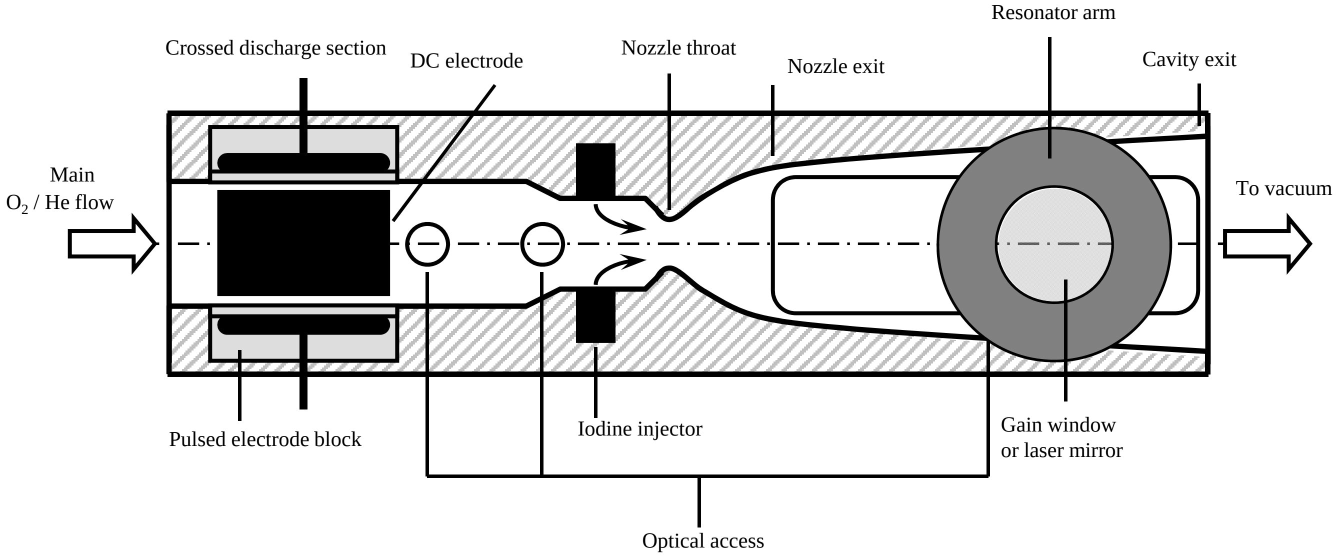


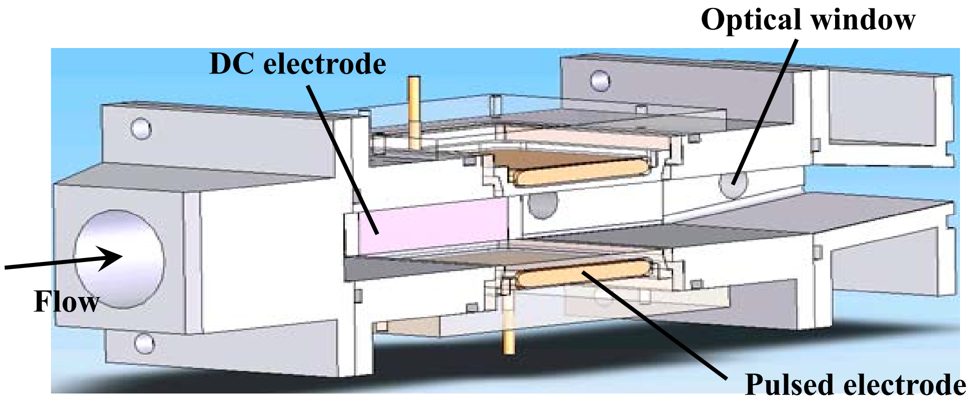
O_2-Ar

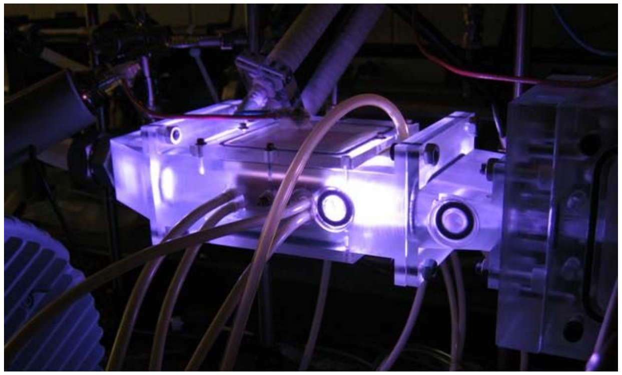
Highest estimated $O_2(^1\Delta)$ yield achieved so far ~10 %

Gas Lasers: An Electric Discharge-Excited Oxygen-Iodine Laser (DOIL)
Schematic of Electric Discharge SDO Generator

Advantages of transverse vs. axial discharge: Large volume, stable at high pressures / powers, rapid convective cooling vs. slow wall cooling. Used in most high power electrically excited lasers.



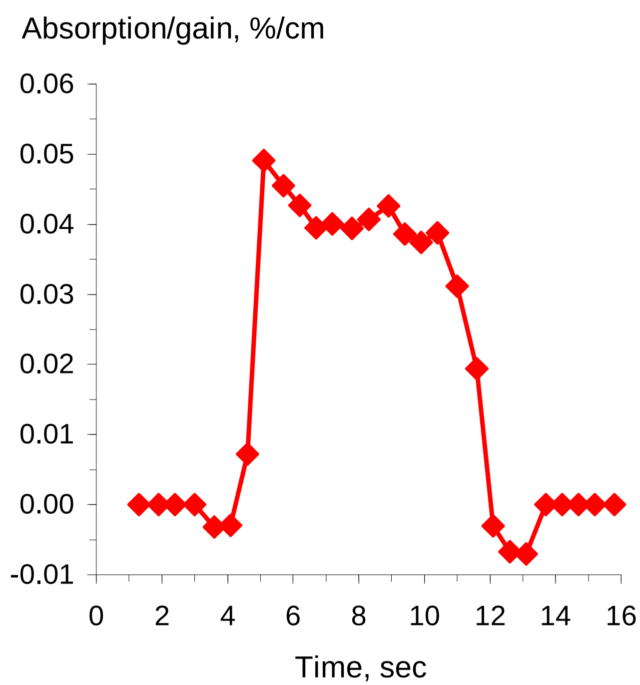


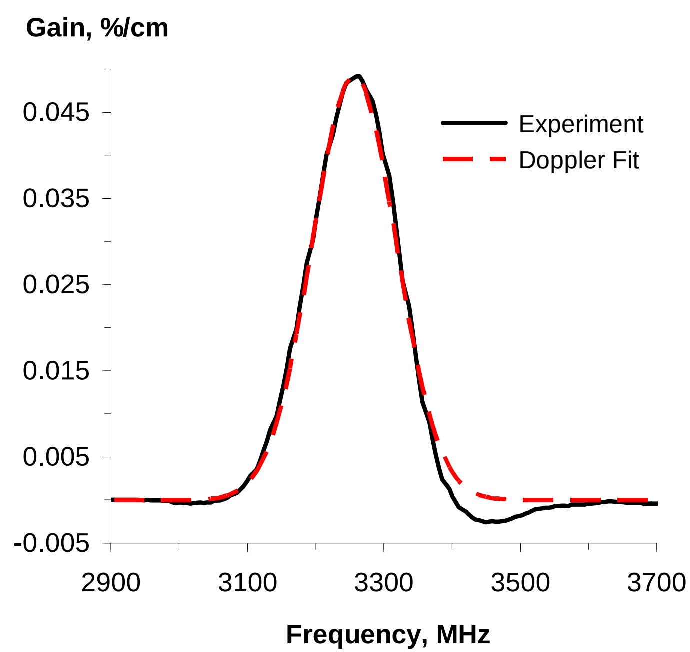


Discharge volume 50 cm^3, pressures up to 460 torr, flow rate up to 0.1 mole/sec (O_2), 1 mole/sec (He)

Gas Lasers: An Electric Discharge-Excited Oxygen-Iodine Laser (DOIL)

Gain at Optimized Conditions: 0.12 %/cm at T=100 K (Currently!)





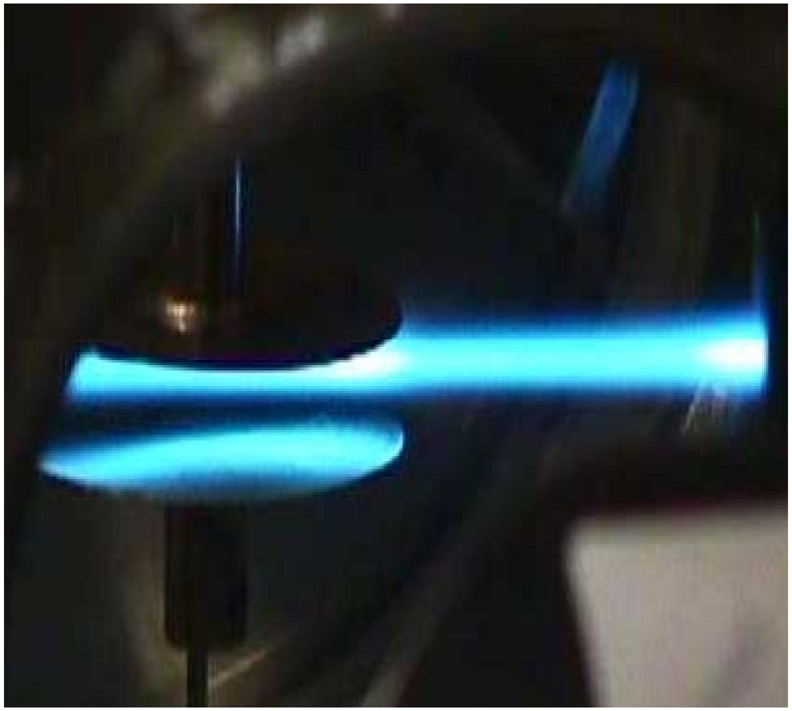
Adding NO: major discharge stabilization factor

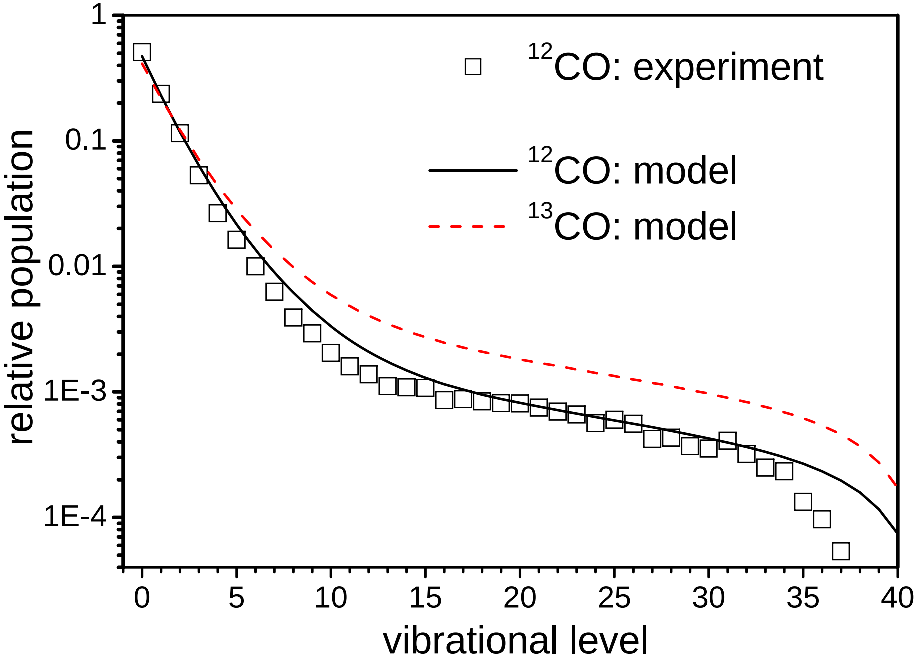
Discharge power increased from 1.9 kW to 2.4 kW

P_0=107 torr, 15% O2 - He flow, NO 0.2 mmole/sec (550 ppm), ν=34 kHz, U_{PS}=3.1 kV, I=1.54 A, discharge power 2.4 kW, I_2 70 µmole/sec (190 ppm).

Gain may be limited by I_2 flow rate

Chemistry: Separation of Heavy Carbon Isotopes I

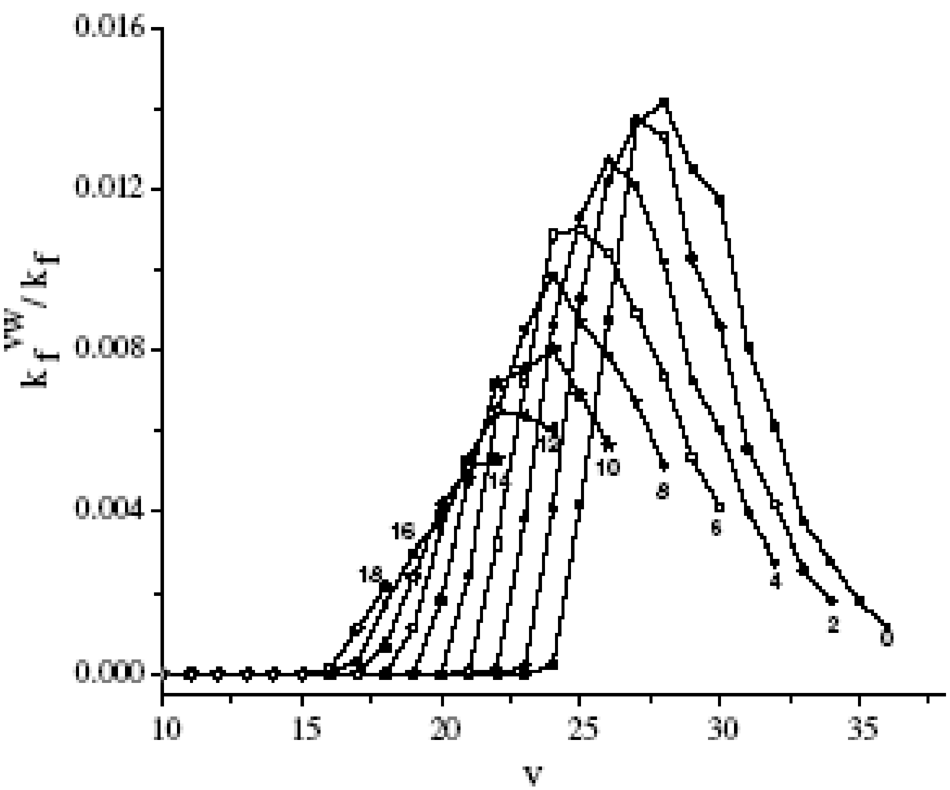


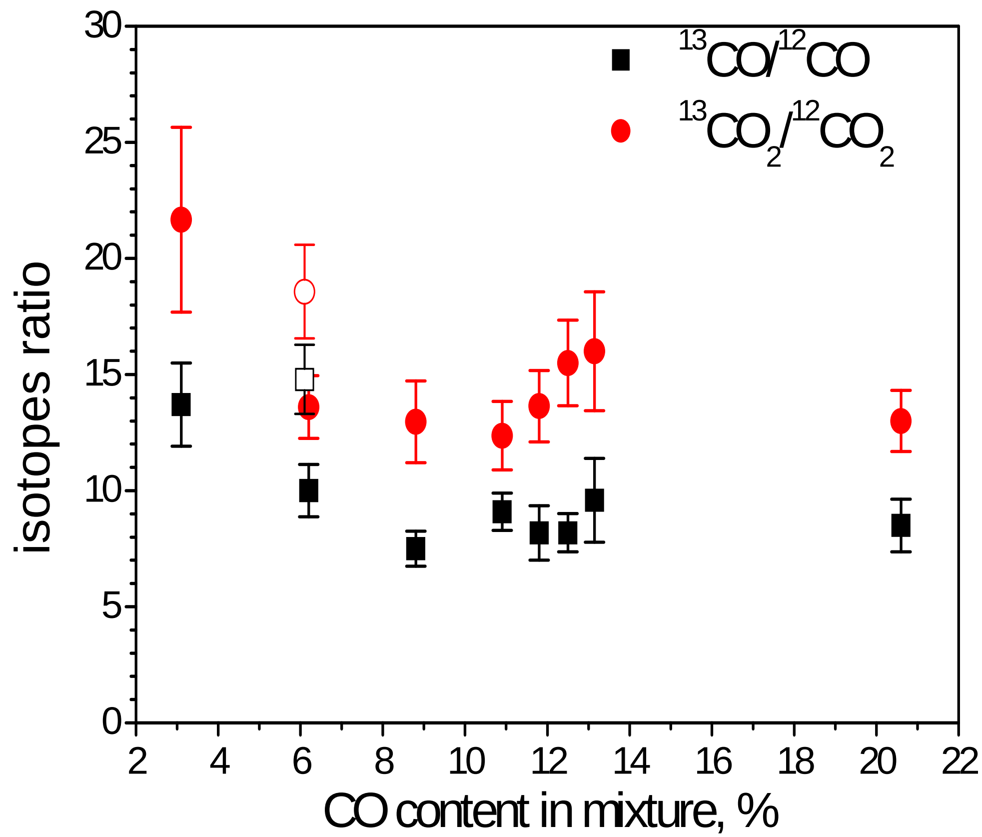


Vibrationally excited CO prepared in cell reacts according to:

CO(v)+CO(w) → CO2 +C

Chemistry: Separation of Heavy Carbon Isotopes II





Summary

What have we learned?

- **Improved methods to sustain extreme mode disequilibrium in gases: High densities, low gas kinetic temperatures, large volumes**
- **New data on mechanisms and rates of some critical energy transfer processes in molecular gases of aerospace interest**
- **Methods for selective excitation of internal energy states**
- **New applications: improved high power c.w. gas lasers, novel chemical syntheses, new aerodynamic control techniques**

Future directions?

- **Special purpose supersonic aerodynamic testing**
- **Modeling code validation**
- **High power c.w lasers and applications: novel refrigeration?**
- **More chemistry: new products**

Thanks!

Support:

USAF:

AFOSR Space Power & Propulsion Program

AFOSR Unsteady Aerodynamics and Hypersonics Program

AFRL Air Vehicles Directorate

AFRL Directed Energy Directorate

NASA Glenn Research Center

NSF

The Michael A. Chaszeyka Gift

Collaborators:

Univ. of Bonn Physics Dept; Heat and Mass Transfer Institute, Belarussian Academy of Physics; Gas Laser Lab, Lebedeev Physical Institute, Moscow Physical Technical Institute

Kind Listeners