Characterization of Ionic Winds from Flames and Corona Discharges

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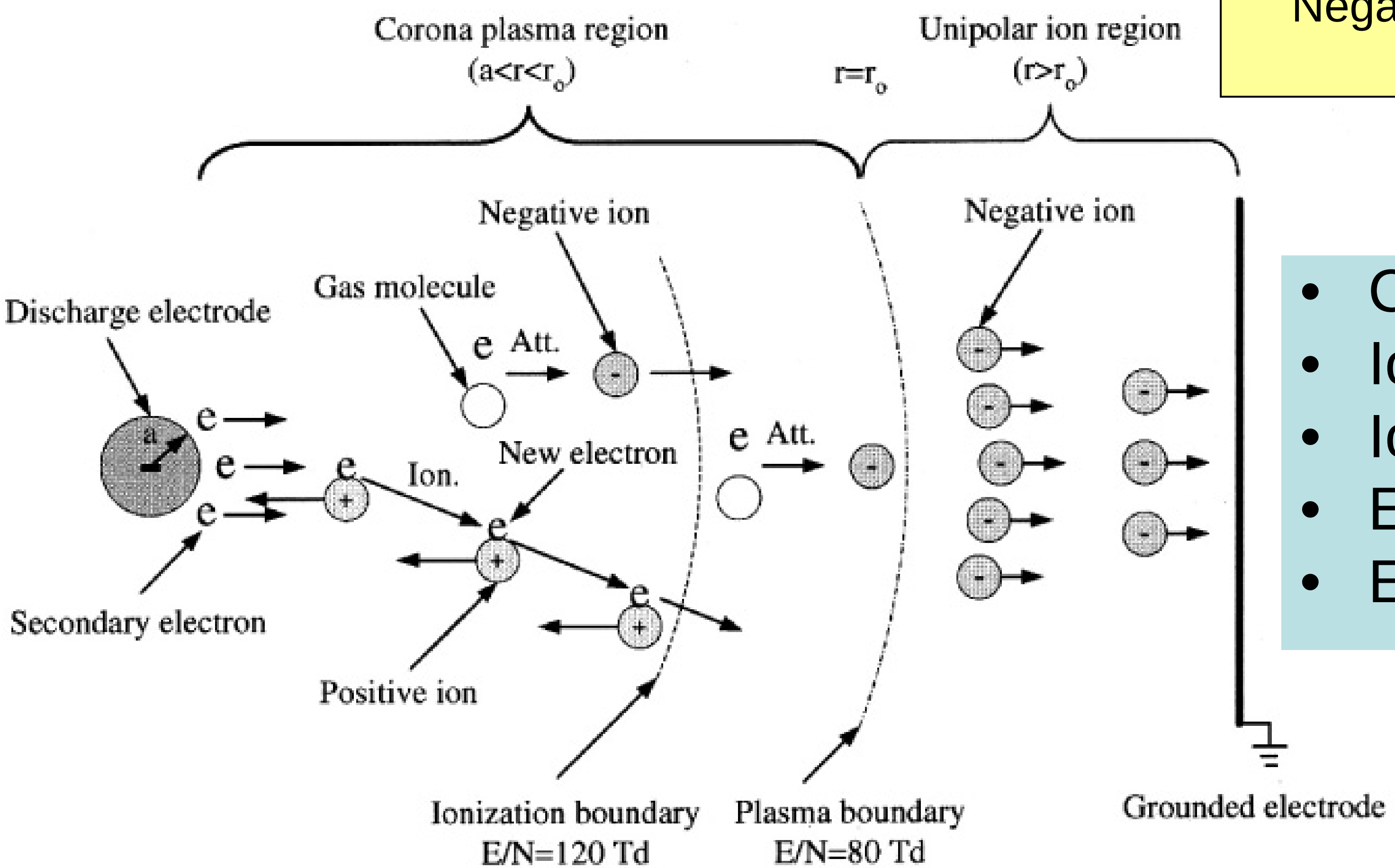
Creating Ionic Wind via Corona

Negative DC Corona Discharge



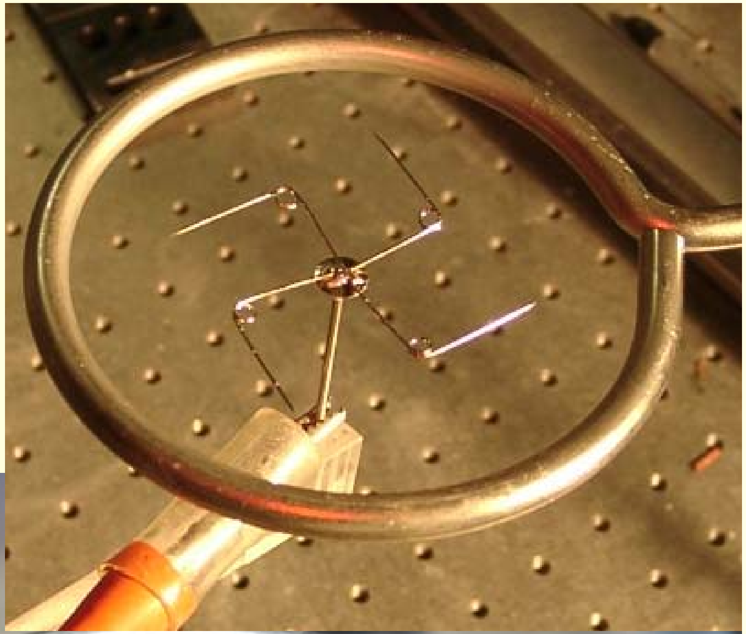
- Chattock wind
- Ion wind
- Ionic wind
- EHD flow
- Electric wind

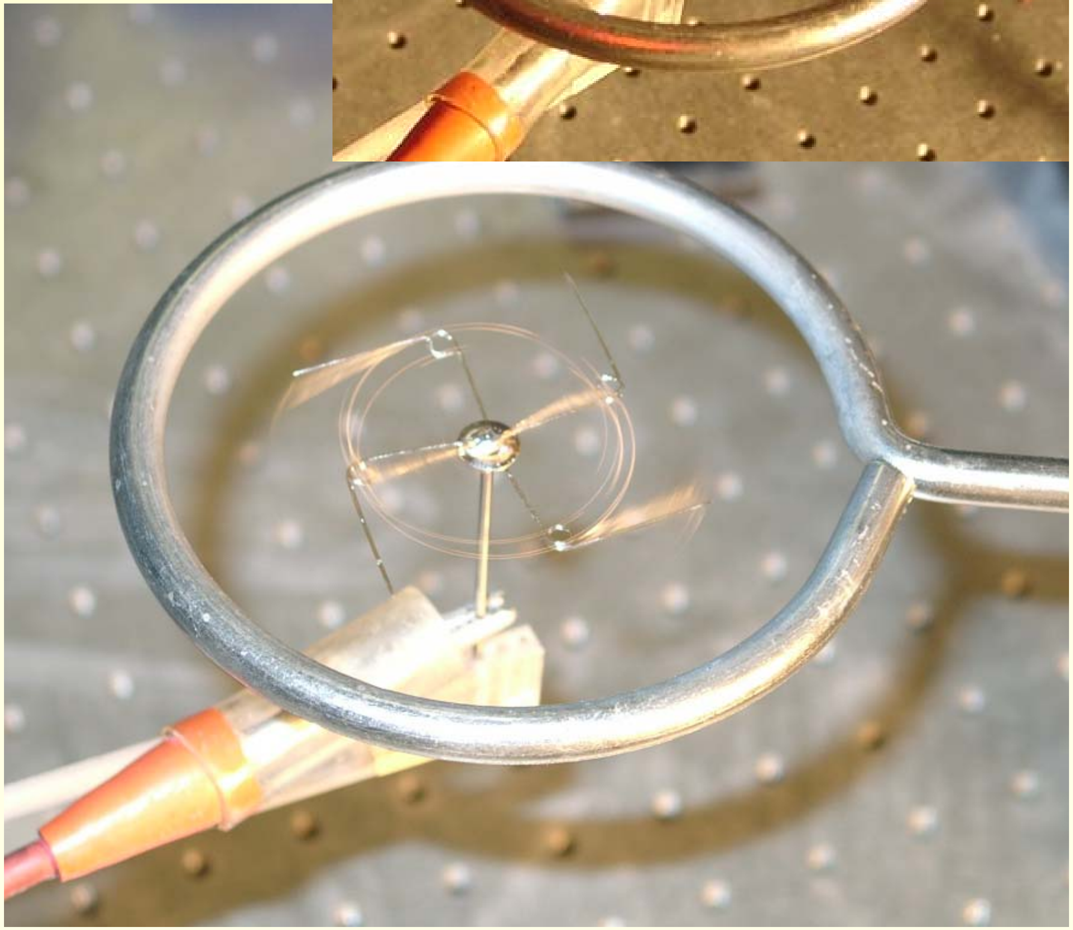
1 Td = 10^{-21} V m^2
E = electric field strength (V/m)
N = neutral density – ($1/m^3$)

Drawing not to scale – from Chen and Davidson, *Plasma Chemistry and Plasma Processing*, Vol. 23, No. 1, March 2003.

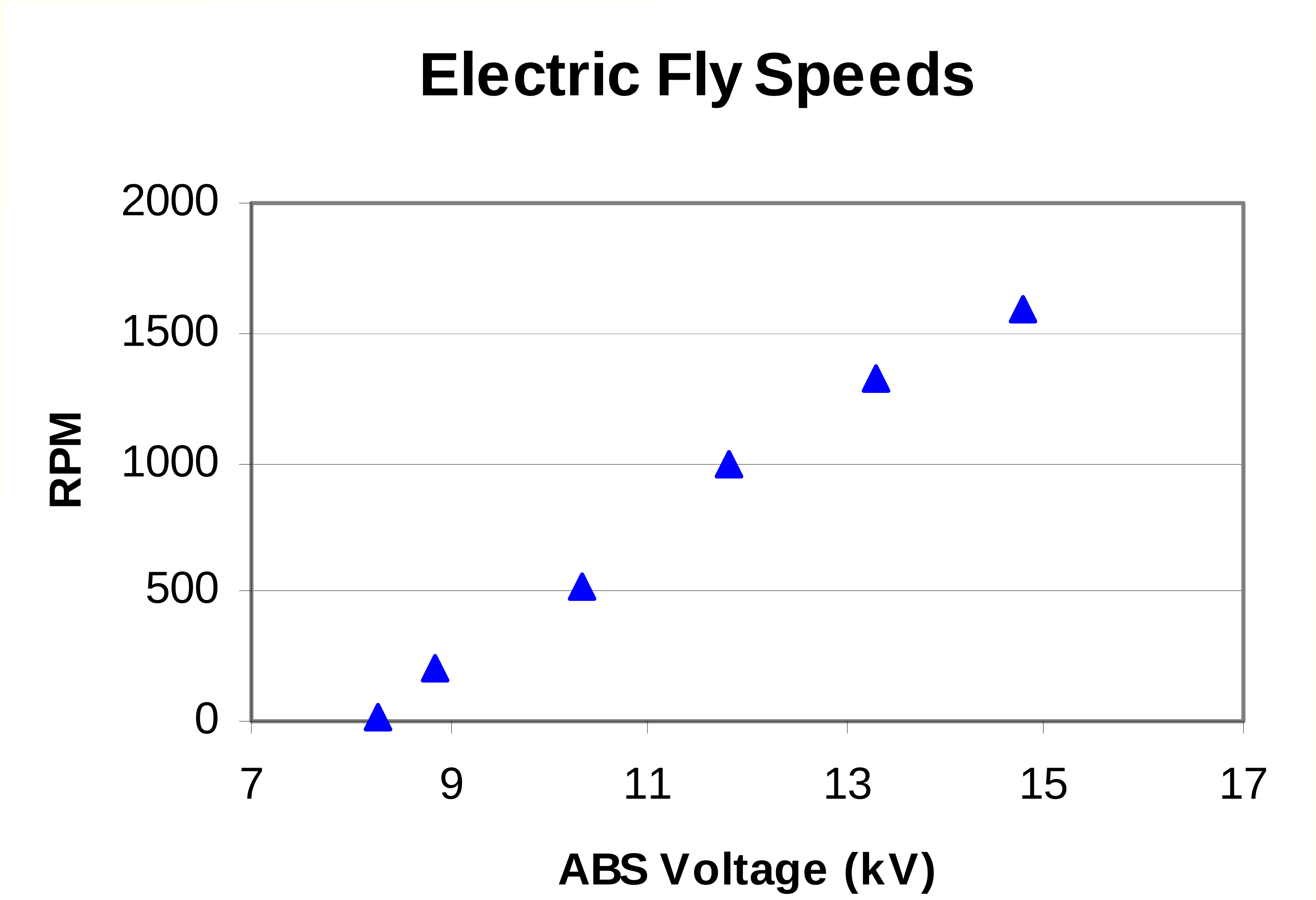
Ion Winds and The Electric Fly

- Wilson (1750) built spinning pinwheel
- Cavallo (1777) claims similar-charged air repels points
  - does not work in vacuum
- Electric fly used to discuss ion wind theory: Michael Faraday (1838), James Clerk Maxwell (1873), among others
- Most recently discussed by Leonard Loeb in *Electrical Coronas* (1965)
- Electric fly motion can be observed before any wind motion
  - spins at voltages well below breakdown





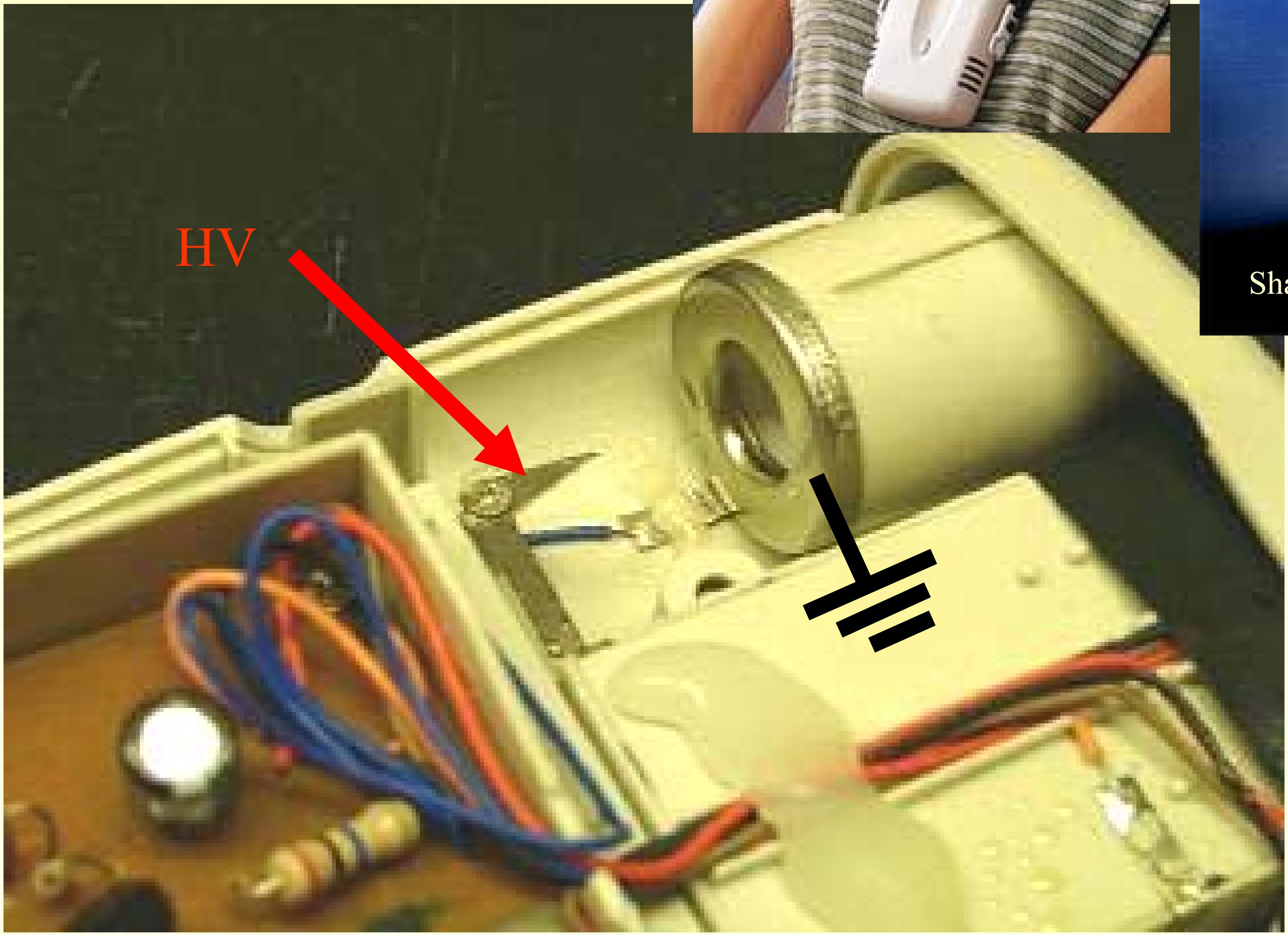
Rotational Speed Linear with Voltage



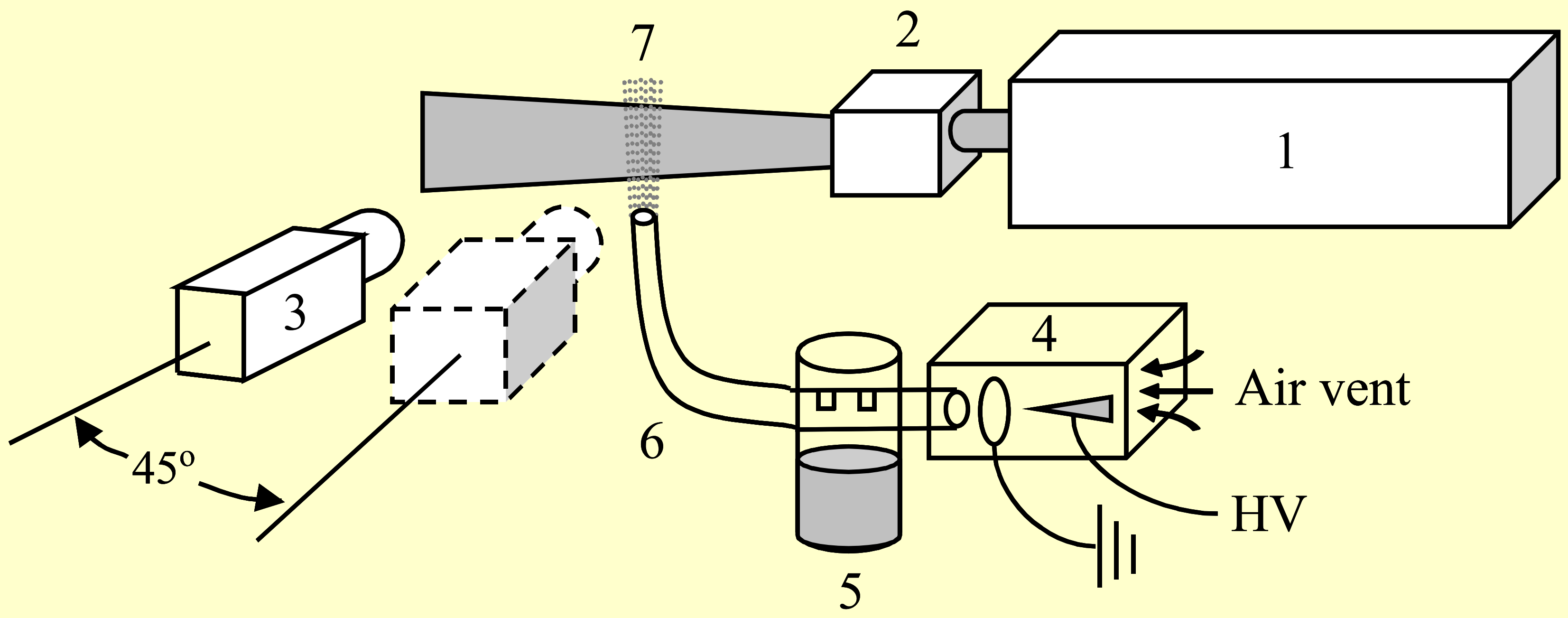
Applications of Ionic Winds

- Coronas
  - – Ionic Breeze – fan and particle removal
  - – Air delivery without moving parts
  - – Electrostatic precipitator enhancement
  - – Heat transfer and evaporation
  - – Plasma actuators
- Flames
  - – Dynamic flame control
  - – Heat direction in microgravity
  - – Earth-based microbuoyancy

Ionic Wind Applications



PIV Experiment

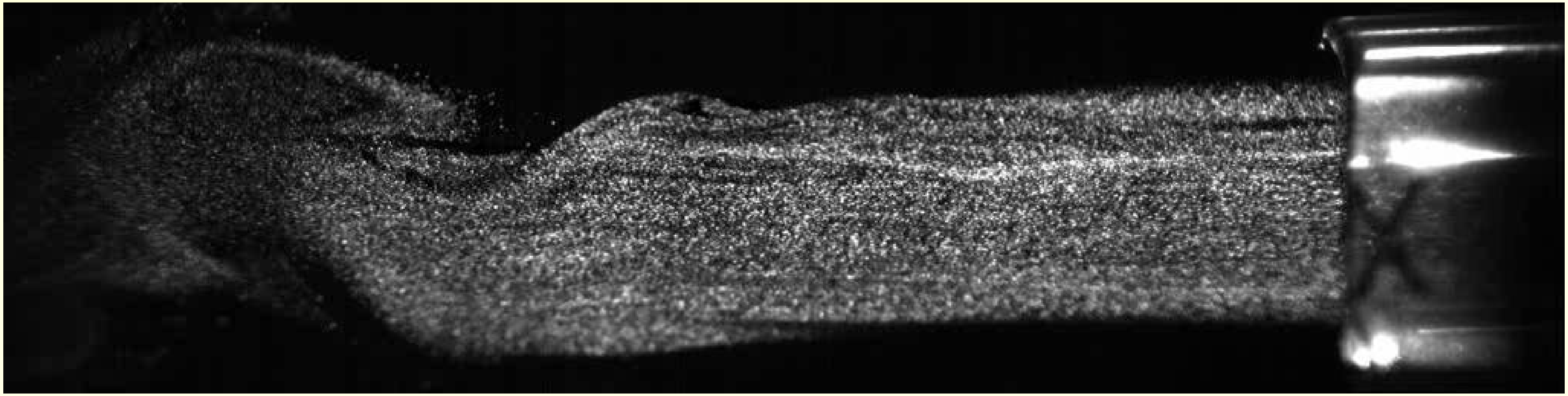


1 Laser
2 Sheet optics
3 Camera
4 Ion wind generator
5 Mist canister
6 Rubber tubing
7 Mist-seeded airflow

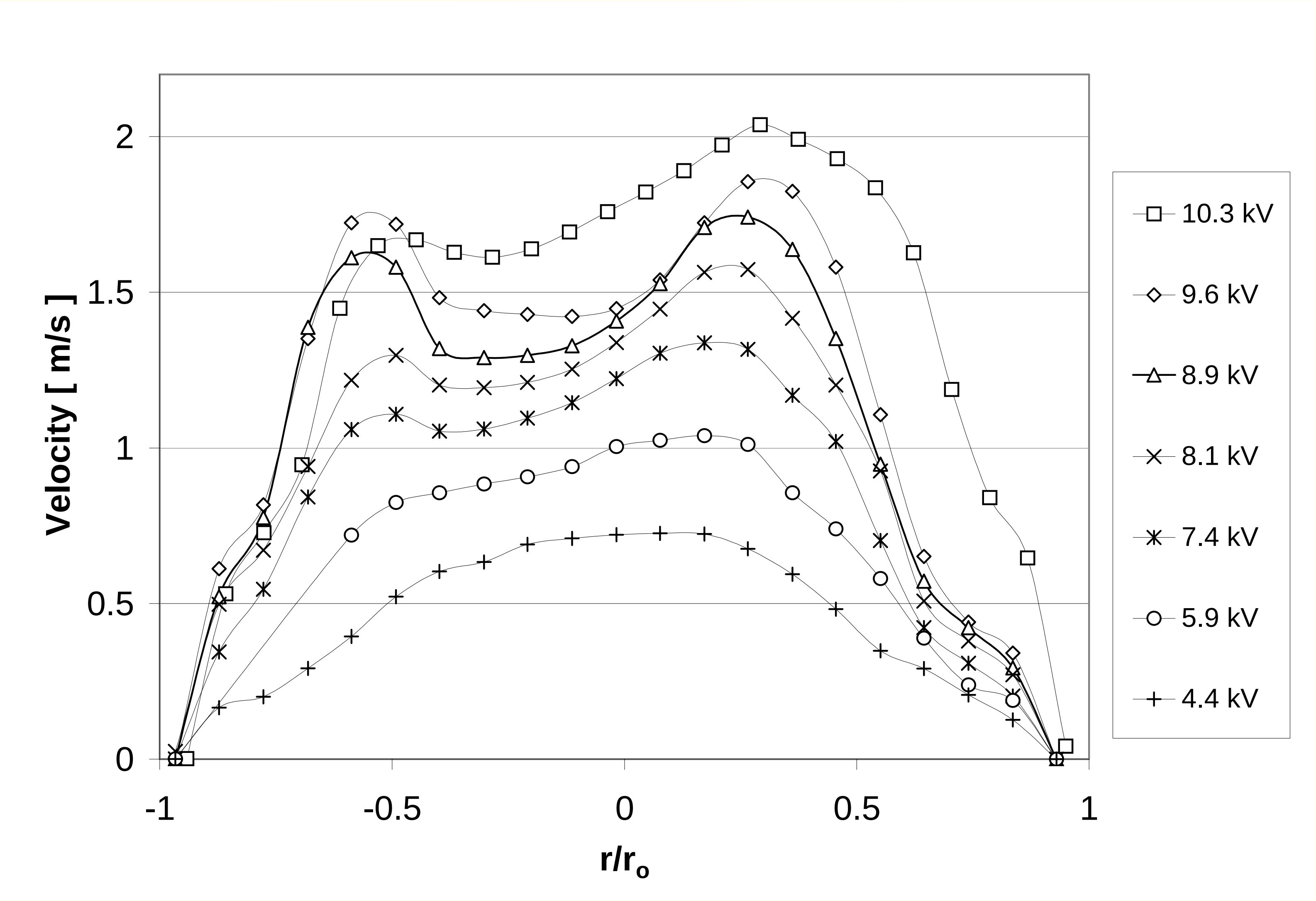
- Copper Vapor laser sync'd to 2kHz camera captured high-speed video
- Camera shifted 45º forward of perpendicular to maximize intensity
- Personal Air Purifier electrodes powered by variable -HV power supply
- Water/glycerin mist traced air flow (seeded downstream of electrodes)

High-speed video

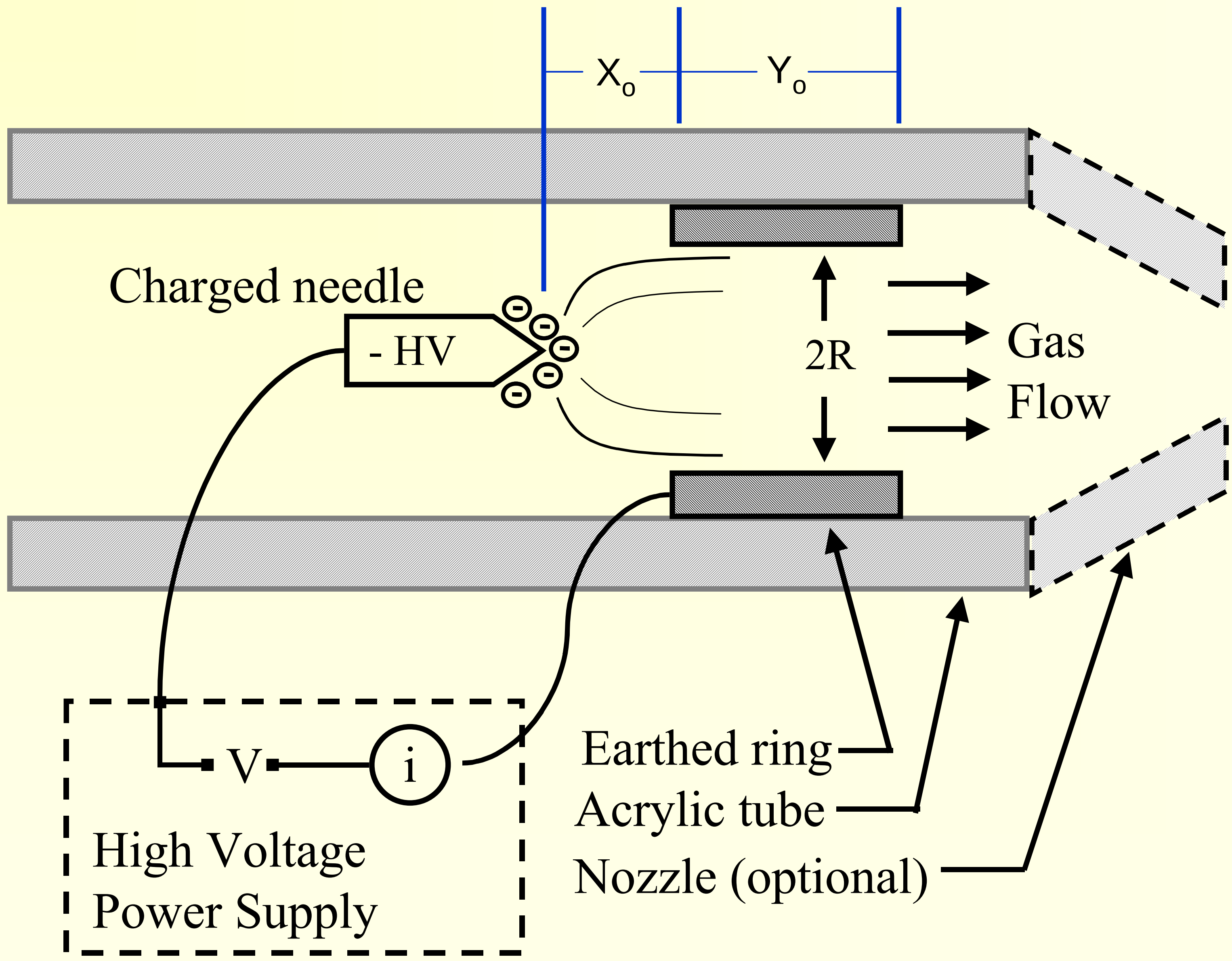
- HV=-10.3 kV (max before breakdown) shown for subtle nozzle (ID = 9.5 mm)
- Actual orientation: directly upwards
- Capture rate: 1,825 frames per second
  - Real time elapsed during 500 images: 1/4 seconds
- Viewing rate: 25 frames per second
  - Total time to view 500 images: 20 seconds



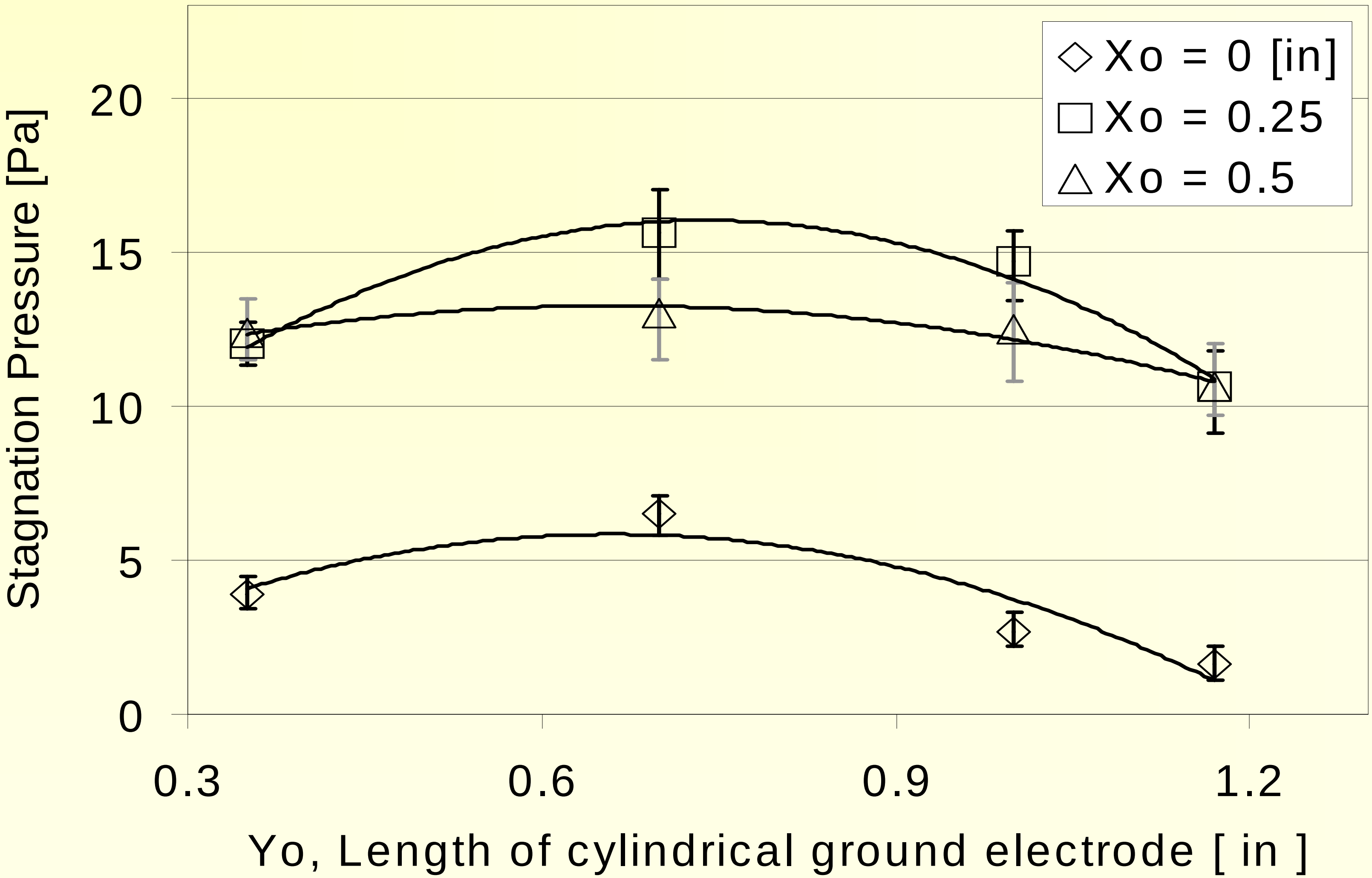
PIV results -- Velocity profile at exit



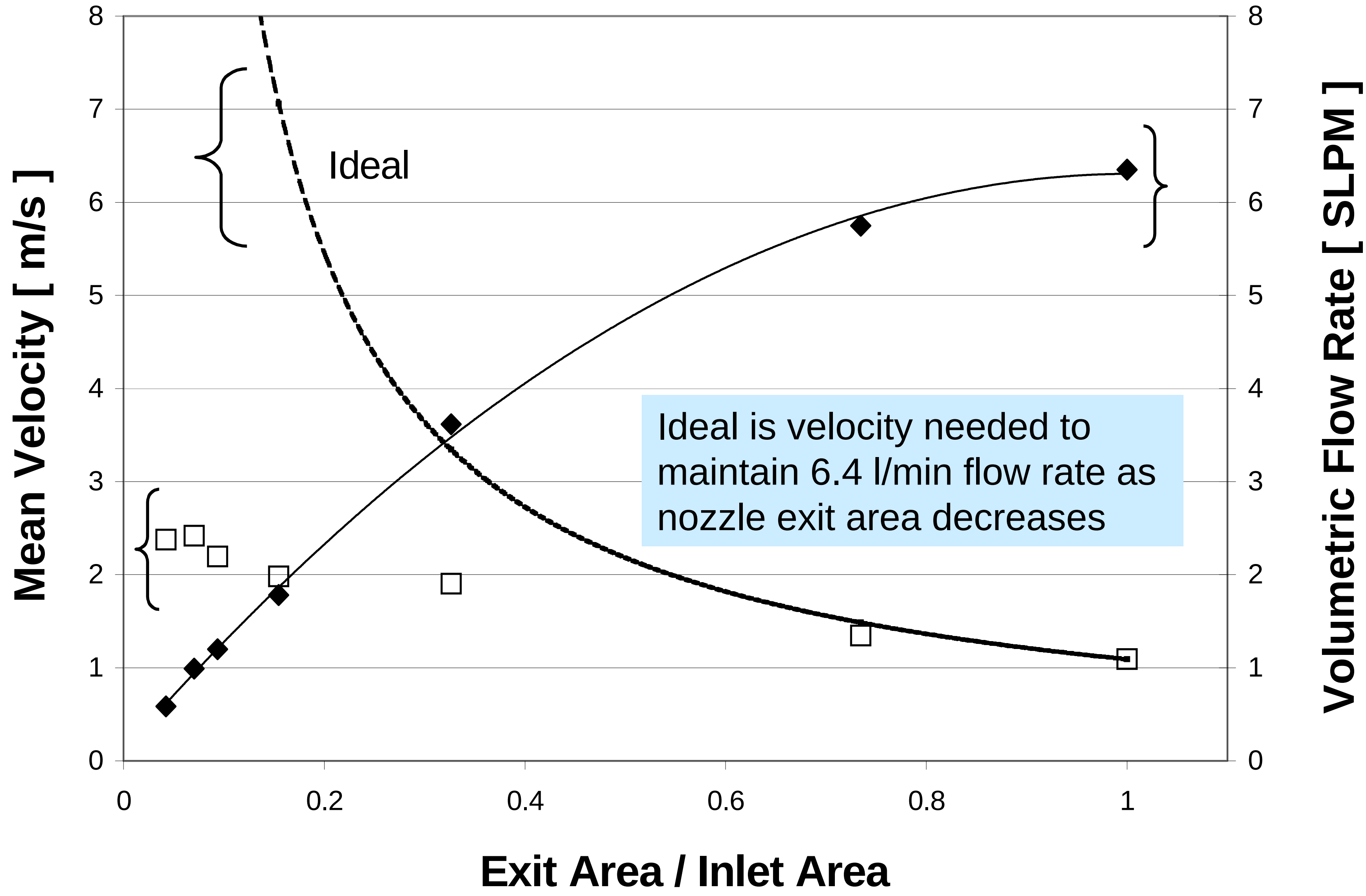
Point-to-Cylinder Ionic Wind



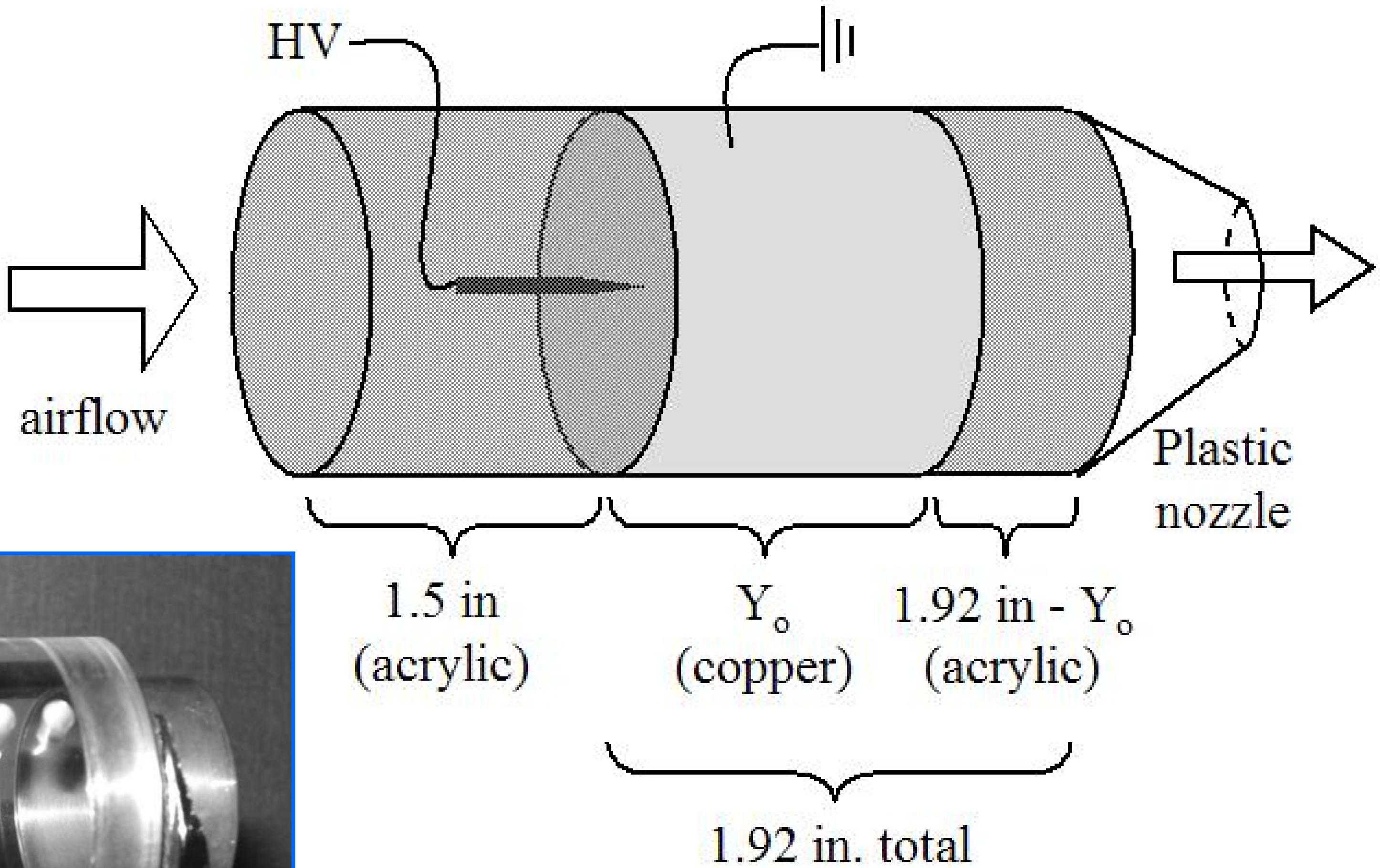
Optimizing the Ion Wind

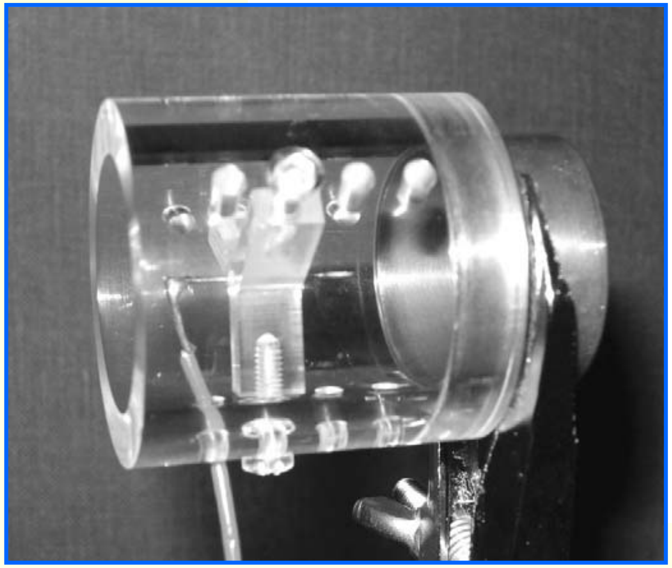


Flow Limit of Single Stage

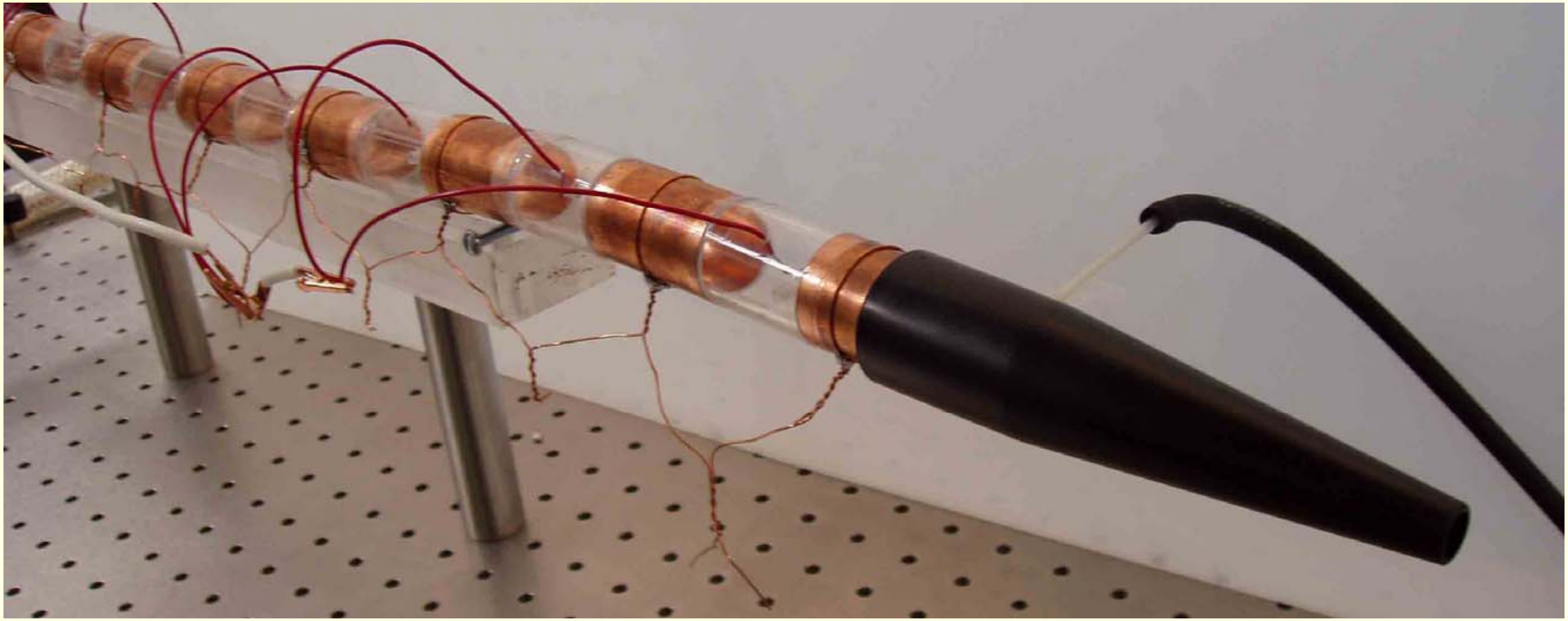


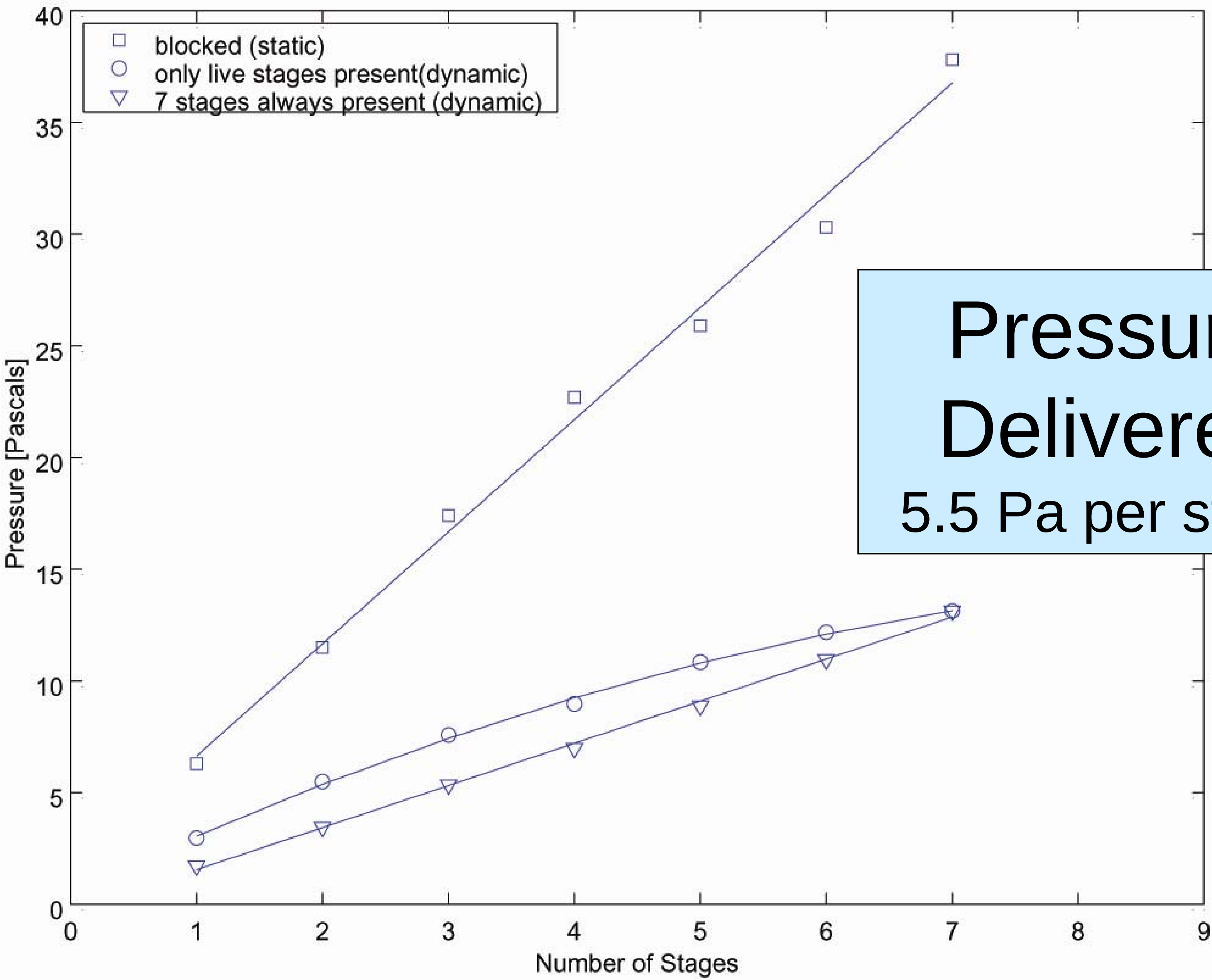
Stacking Stages to Increase Pressure





Multi-Stage Ion Blower

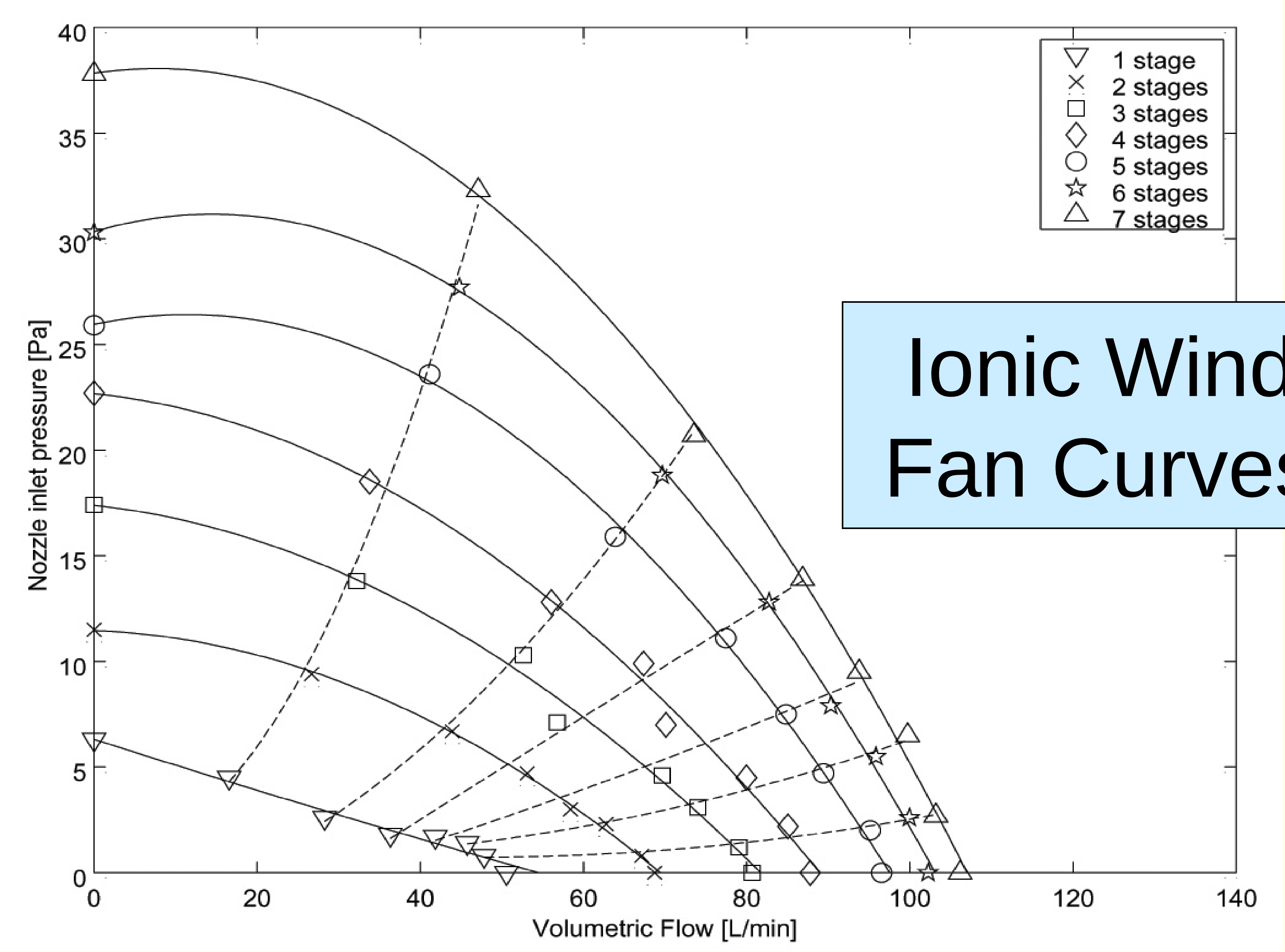




Pressure Delivered

5.5 Pa per stage

Staged System Performance



Ionic Wind
Fan Curves

Future Activities

- Swirl Generator
  - ESP enhancement
- Microscale Gas Delivery
  - Point of application flows
- All Electric Burner
- Modeling

Applications of Ionic Winds

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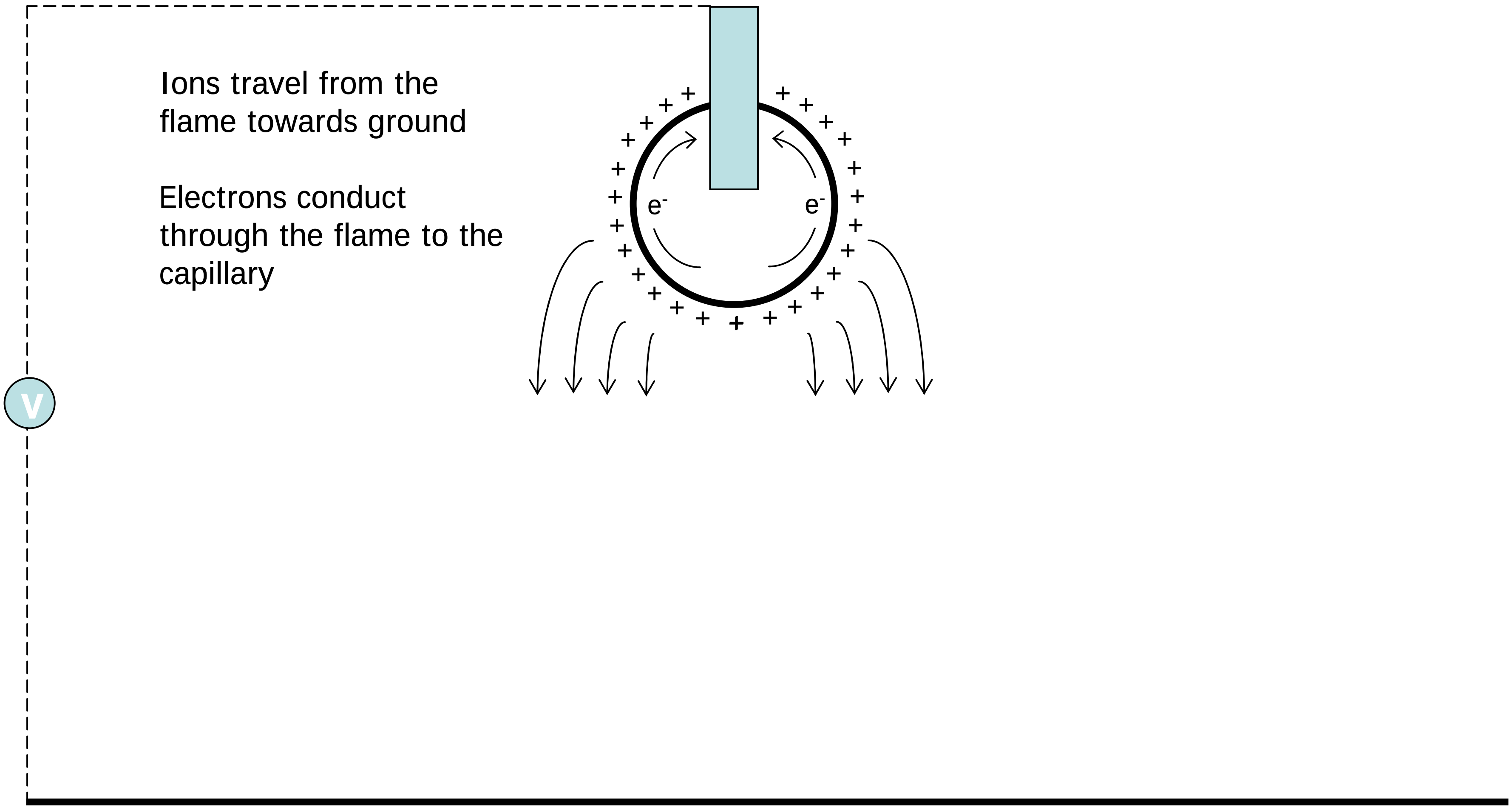
Flame Derived Ion Wind



Force and Velocity from Ion Wind

- *K* is mobility of the charge carrier -- 1 $cm^2/s/V$
- *g* is gravitational acceleration; ρ is the density
- *x* is the distance over which the field acts
- *j* is current density – flame: 1 $\mu A/cm^2$

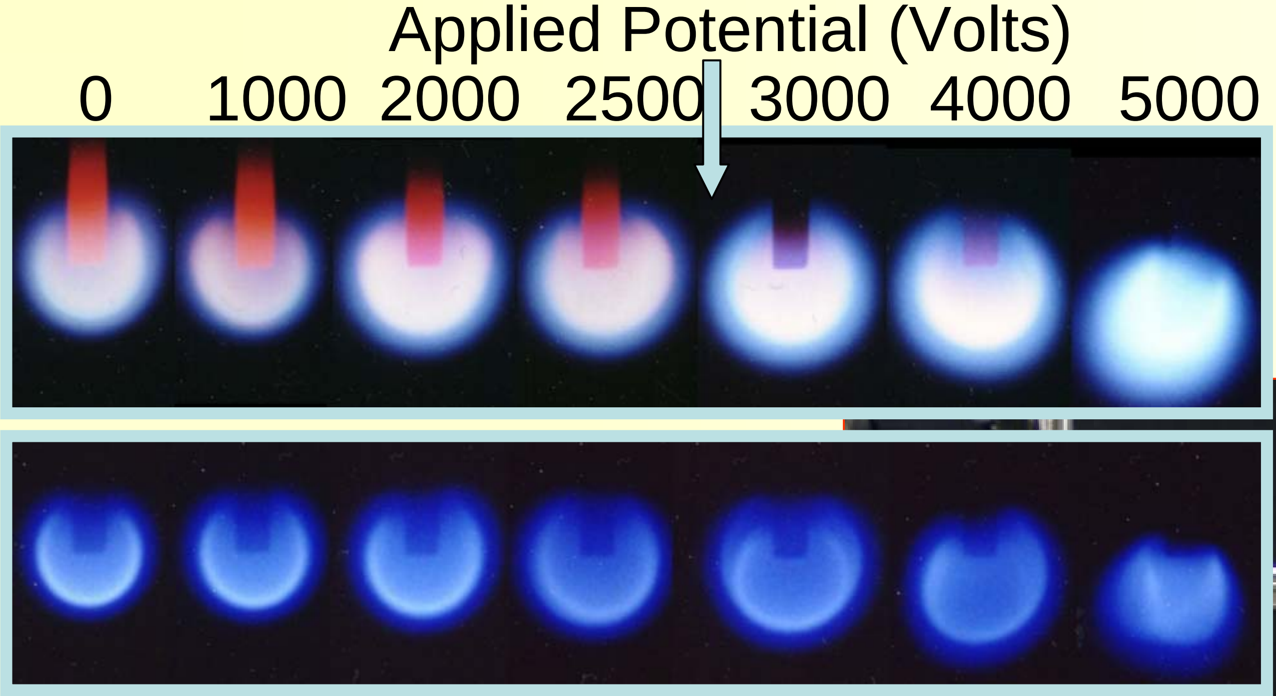
$$\frac{F_e}{F_b} = \frac{j}{K\rho g}$$

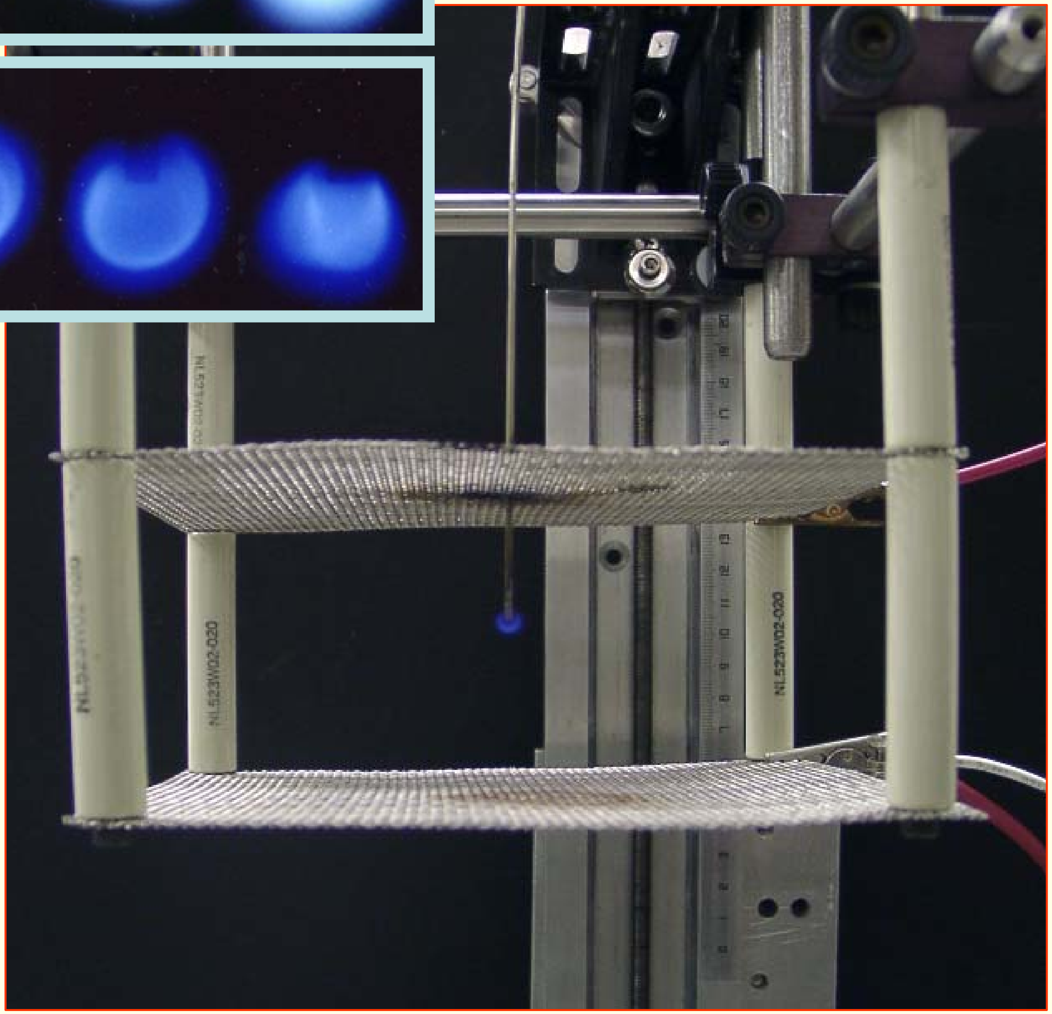
$$v_e = \sqrt{\frac{j}{\rho K} x}$$

Order of 1-2

Order of 1 m/s
over 1 cm distance

Effect on Small Diffusion Flame



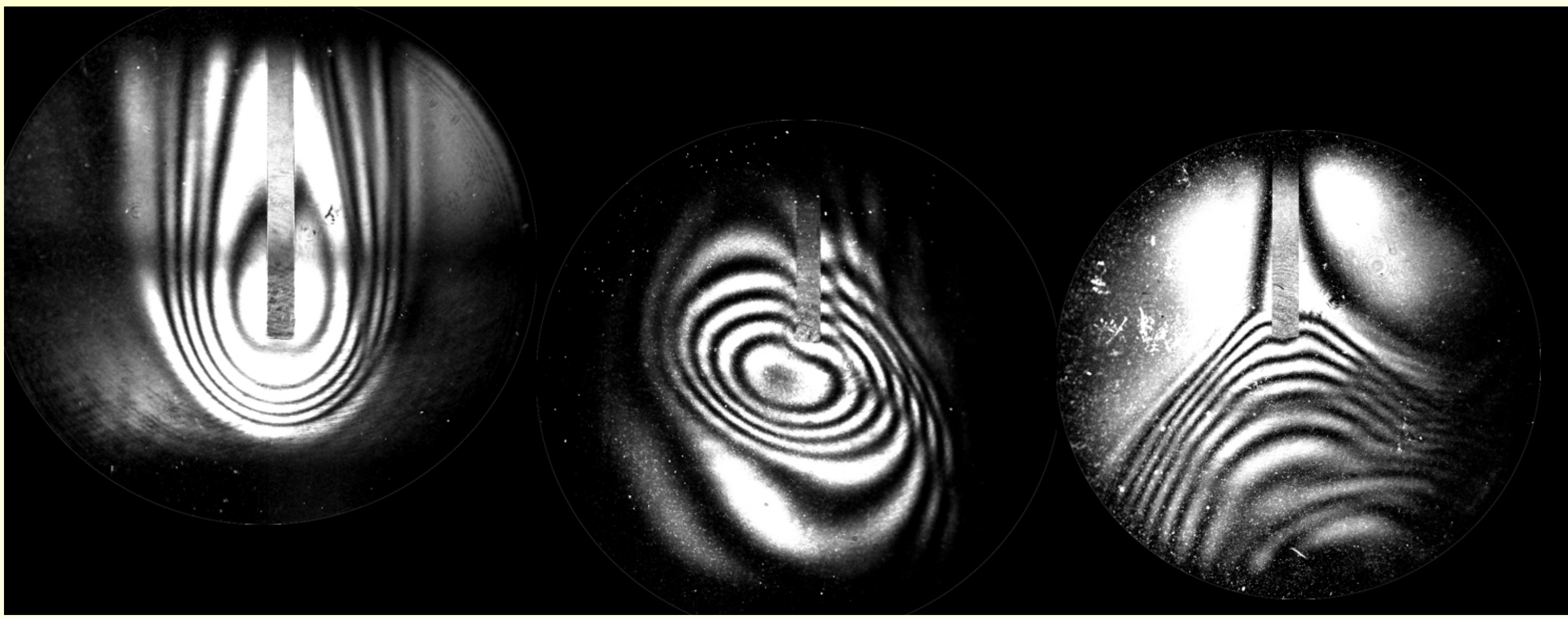


Methane fuel flowrate: 9 cc/min
Capillary diameter: 1.7 mm
Electrode Spacing: 7 cm

Conditions

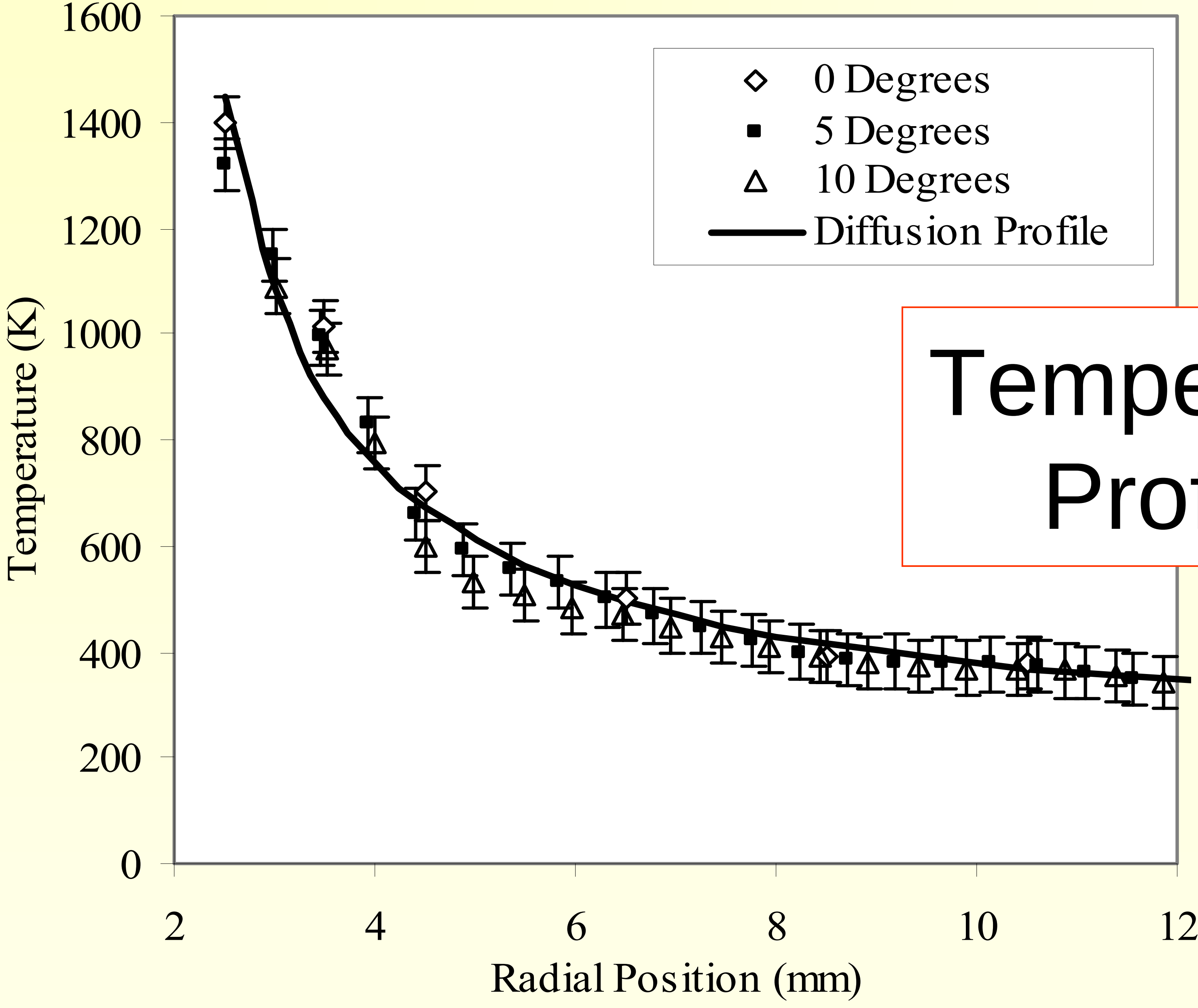
1. Naturally Buoyant – 0 Volts
2. Microbuoyant – 2880 Volts
3. Negatively buoyant – 4300 Volts

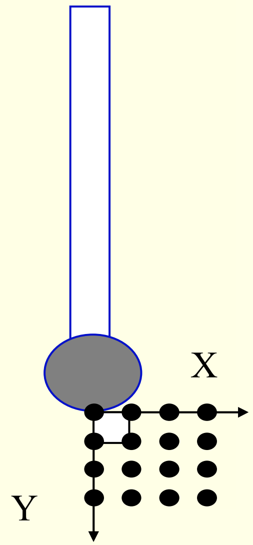
Double Exposure Holographic Interferometry Images (setup #1)



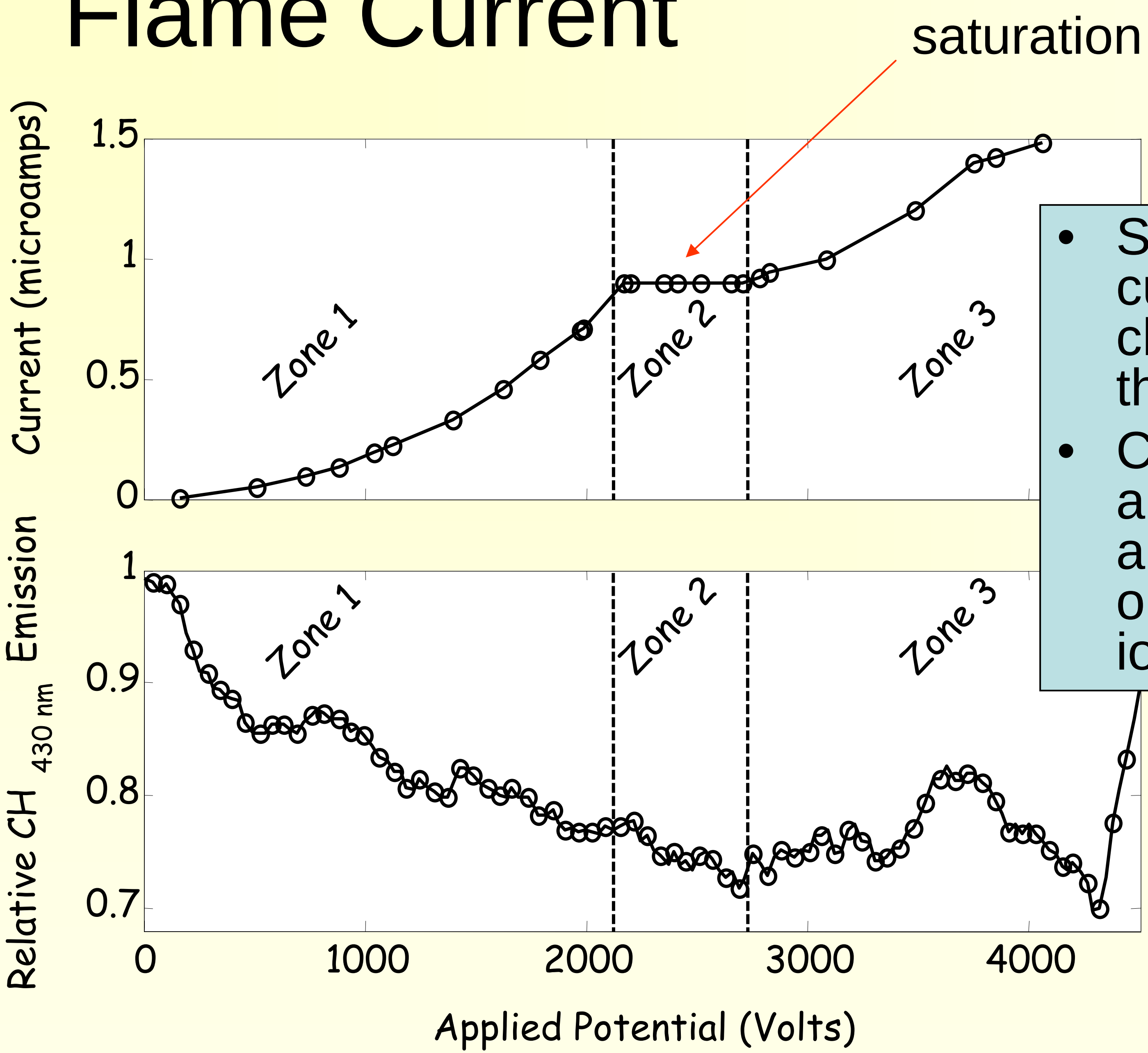
0 Volts **2242 Volts** **2765 Volts**

Temperature Profiles



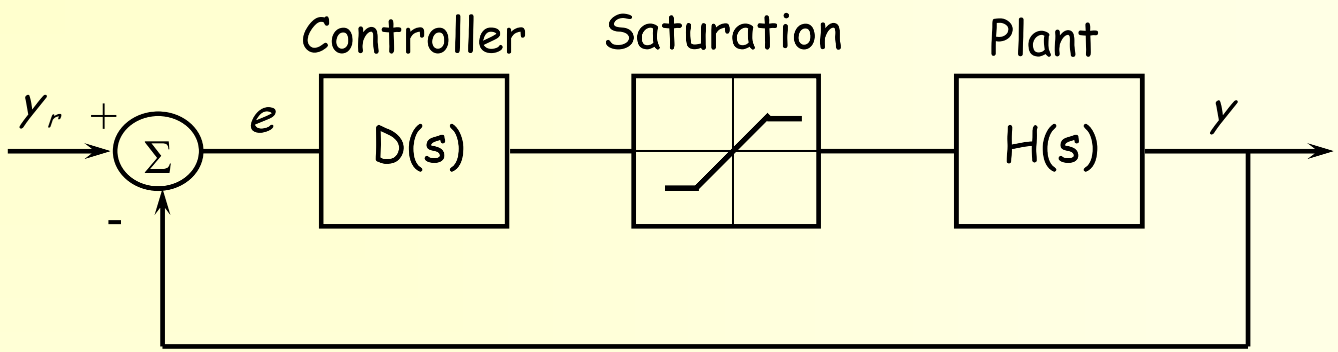


Flame Current

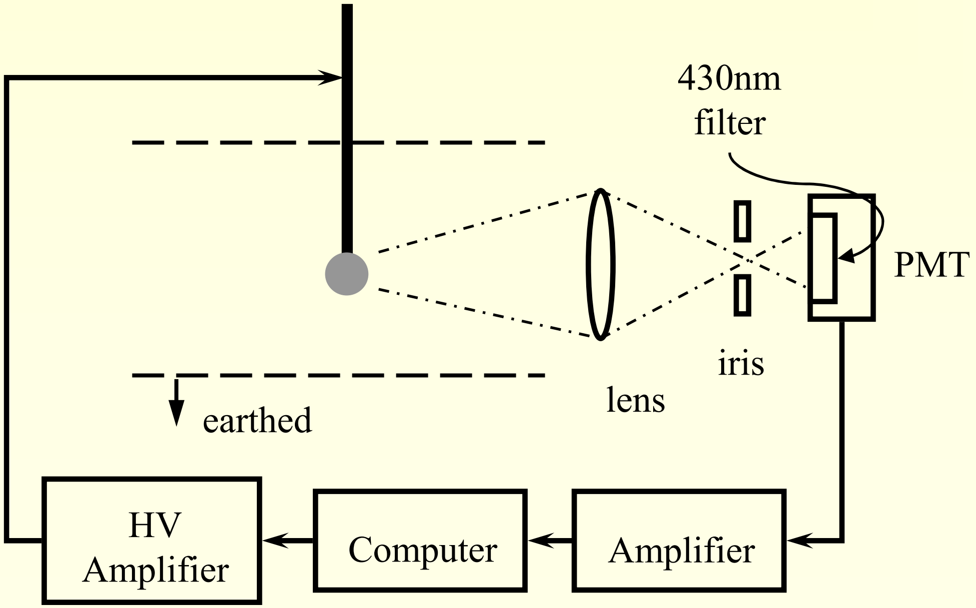


- Saturation current can be characteristic of the flame
- Current provides a detection and/or decision opportunity (e.g., ion probe)

Toward Feedback Control

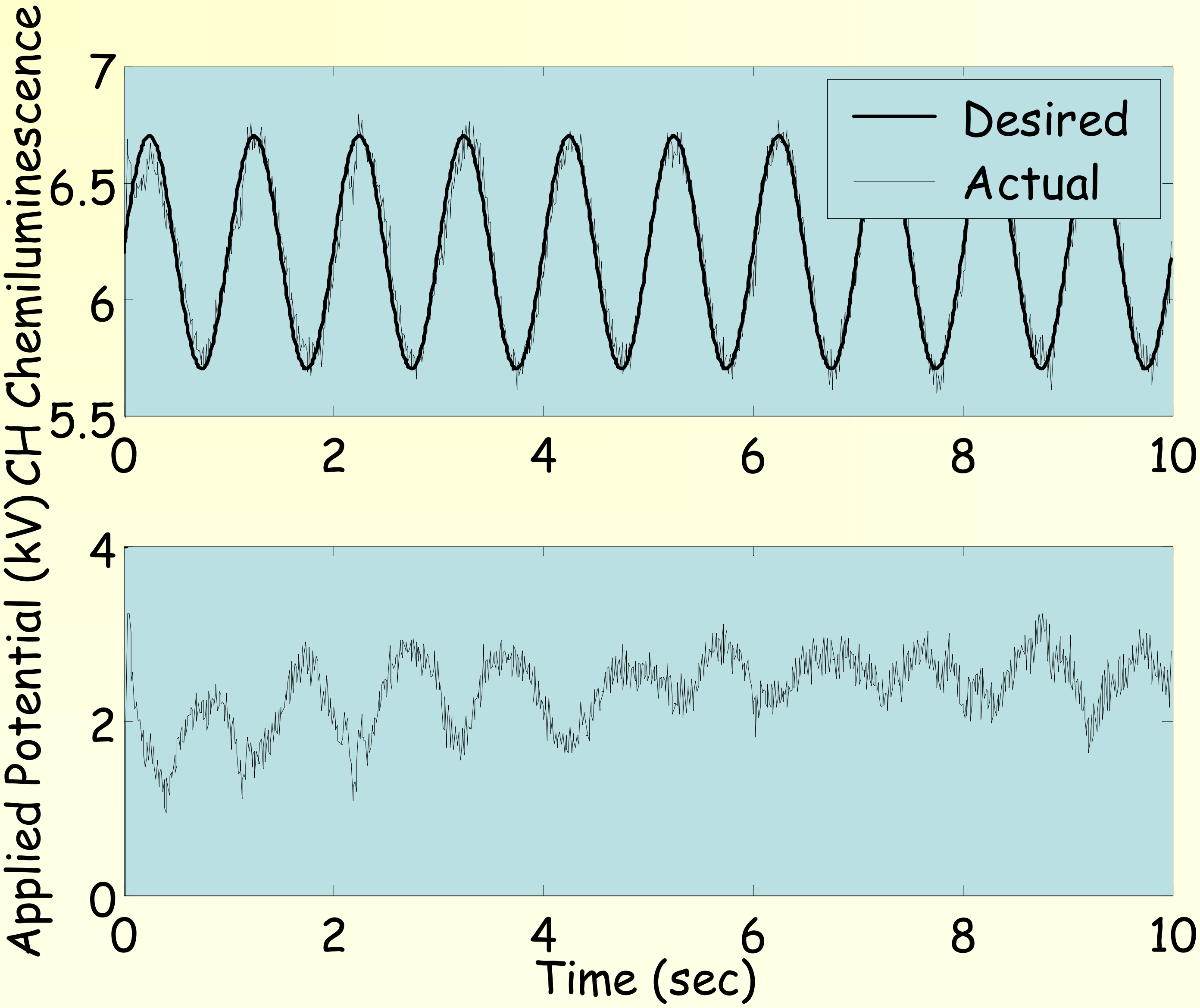


*what do we measure for feedback? CH**



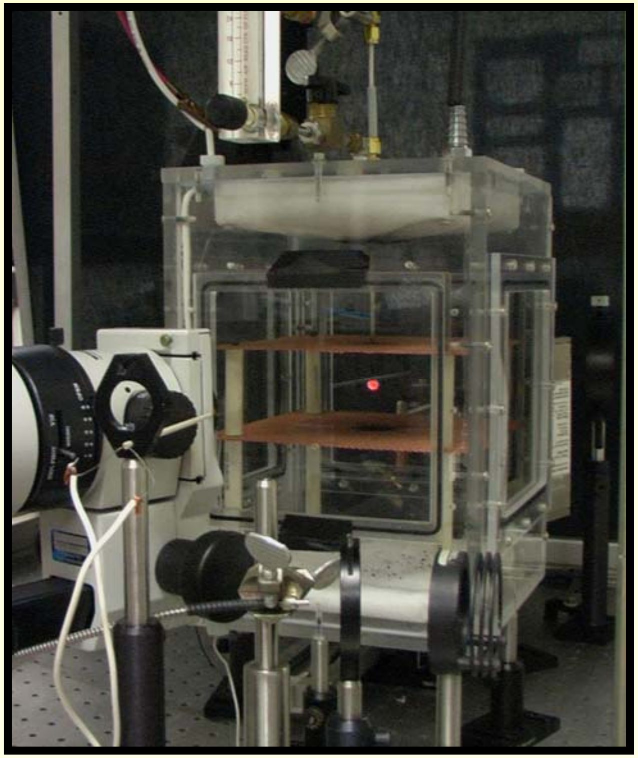
- commonly accepted that CH* is a “good” measure of the global heat release in a flame
  - CH* emission is linearly related to the fuel flow rate
  - the electronically excited states are confined to a thin region of the primary flame surface

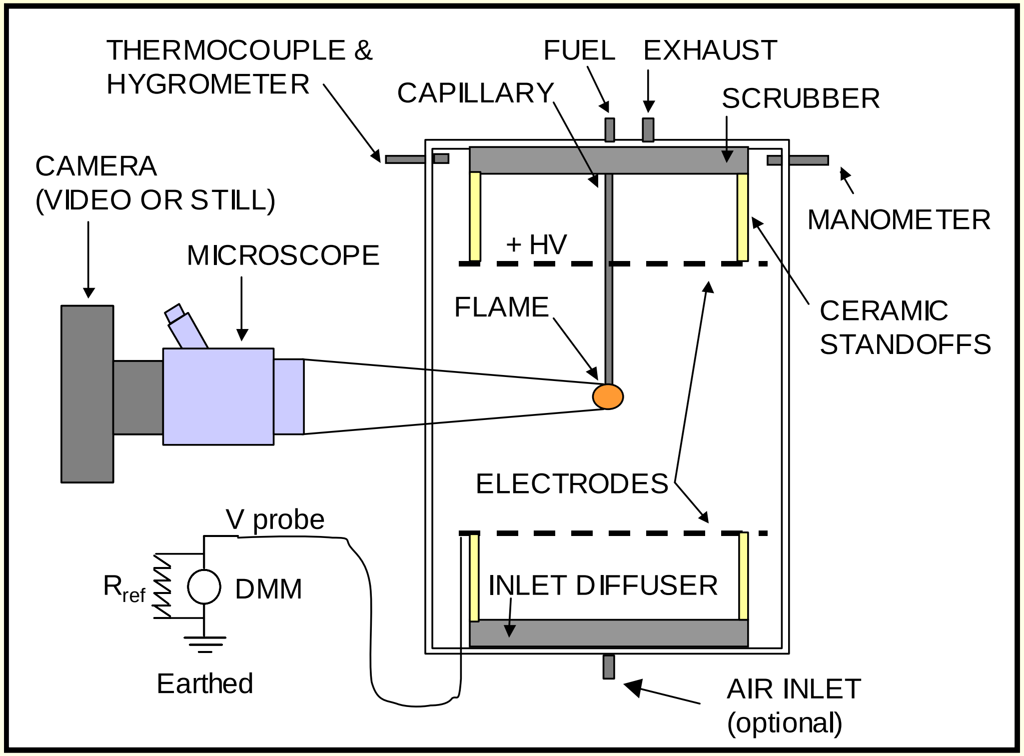
Sine Tracking



Refined Apparatus

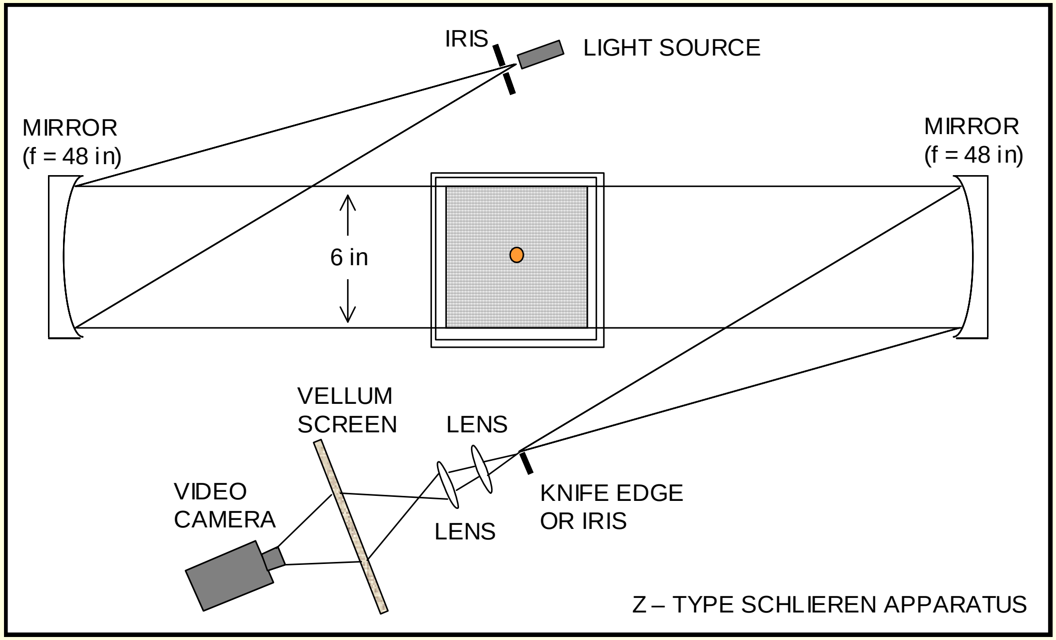
- Acrylic chamber
- Ion current measured at the cathode (ground plane)
- Temperature, pressure, and relative humidity are monitored
- Continuous running via air flushing



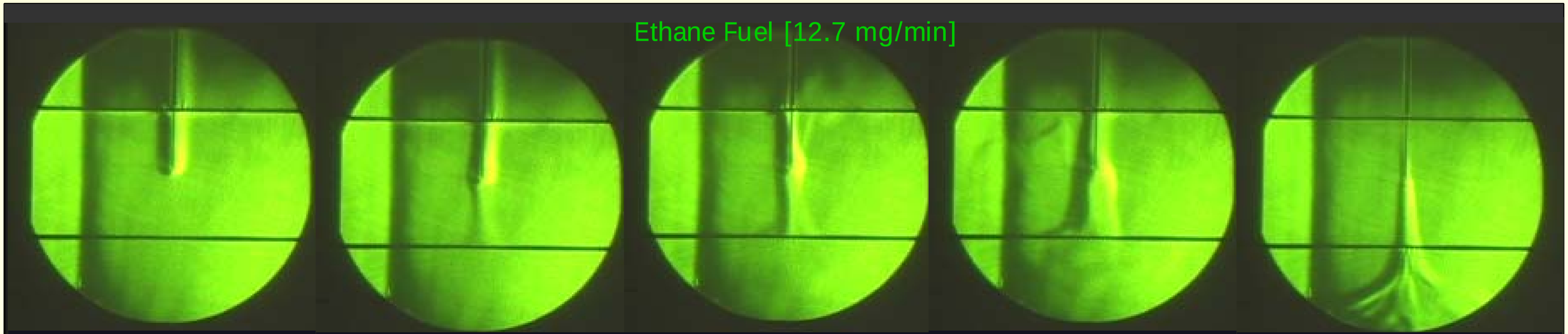


Schlieren Imaging Illustrates Complexity

- Identify buoyancy regimes
- Determine relative electrical characteristics between fuels
- Z-type schlieren apparatus
- Conventional and high speed video



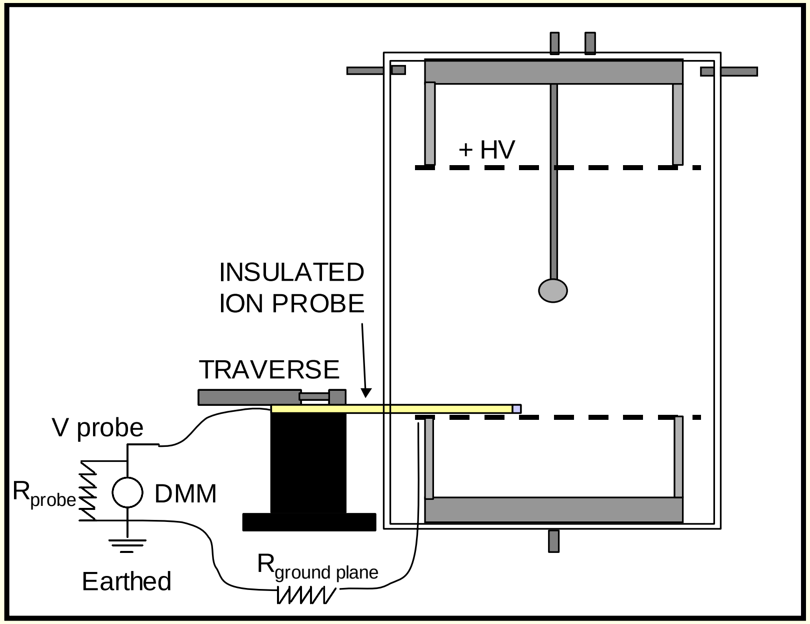
Ethane Fuel [12.7 mg/min]

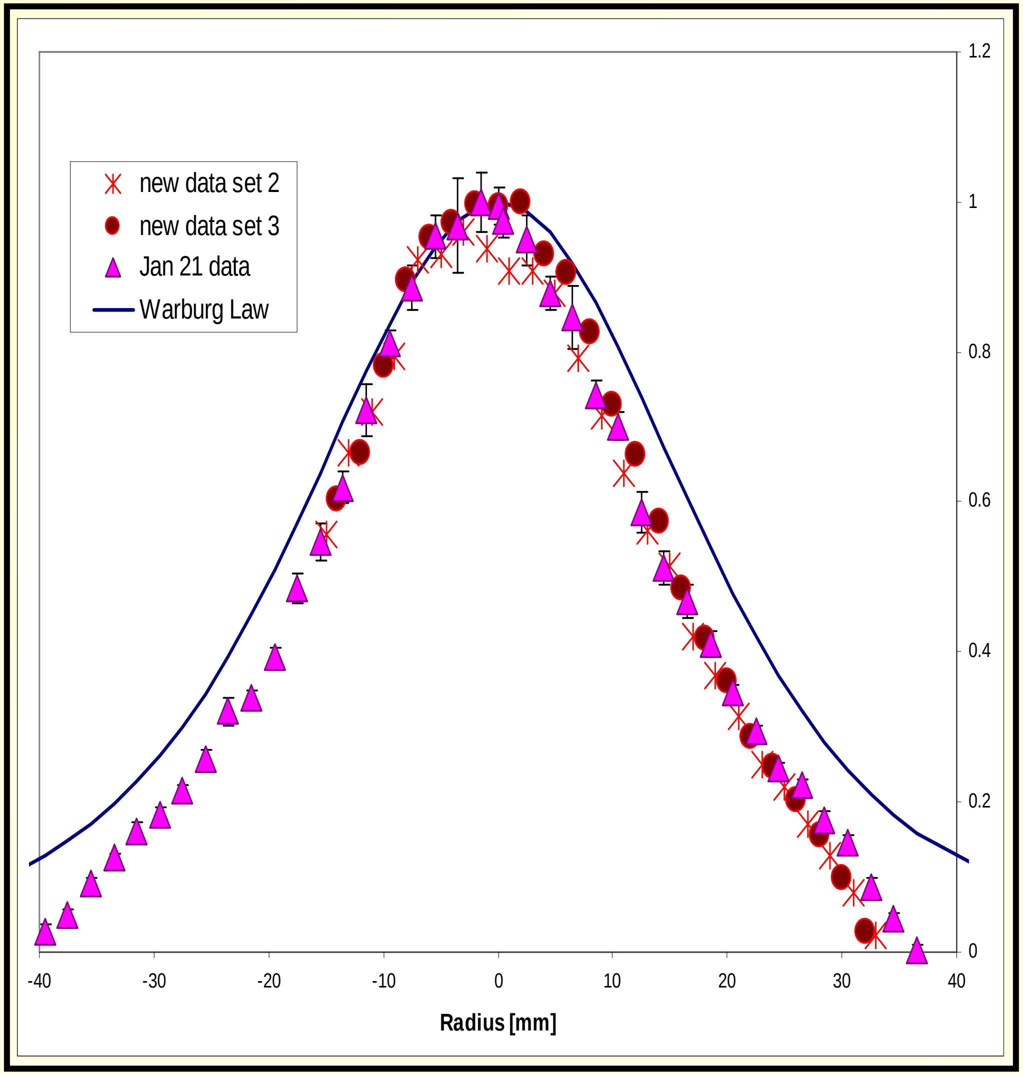


1000 V	2000 V	2400 V	3000 V	5300 V
Buoyant	under balanced	Balanced condition	Partially neg-buoyant	Negatively buoyant
(negligible current)	(subsaturated)	(saturation)	(some 2^{nd}ary ionization)	(much 2^{nd}ary ionization)

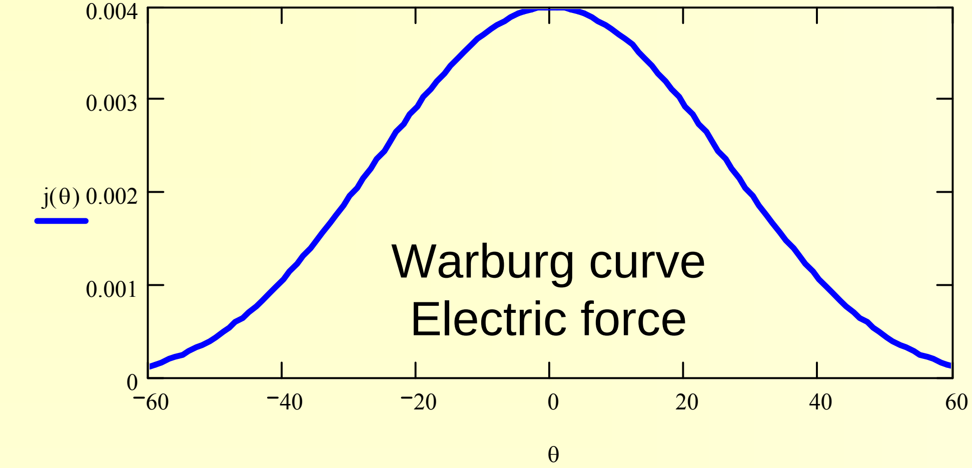
Ion Current Profiles

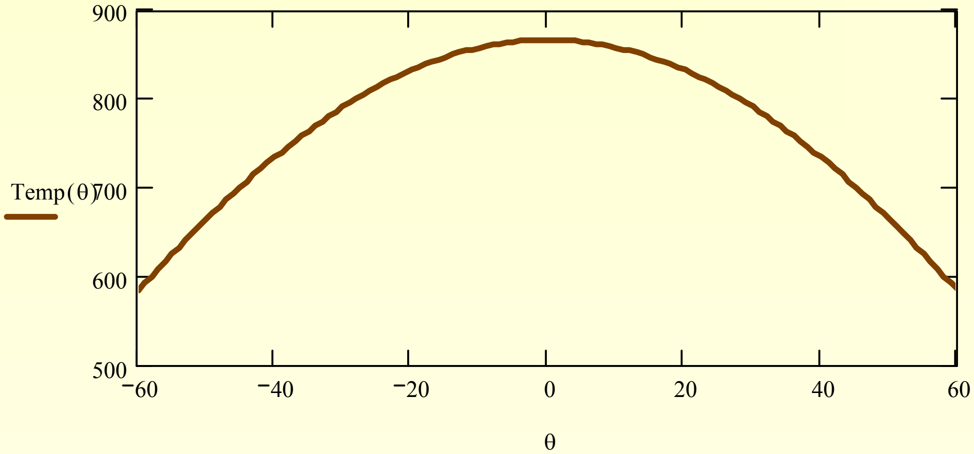
- Point-to-plane distribution (Warburg Law) = $\cos^5\Theta$
- Integrated current provides ion density boundary conditon
- Current distribution for model validation



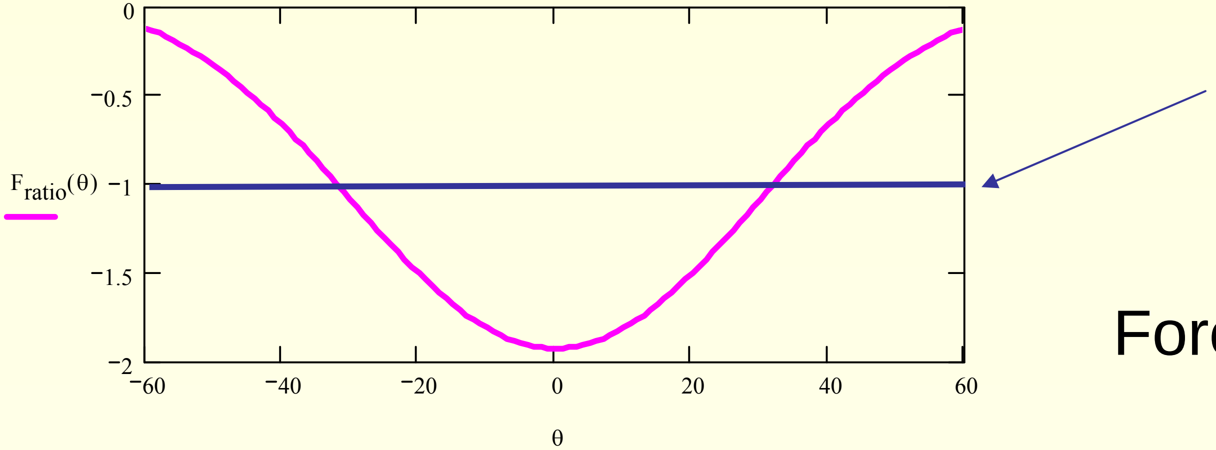


Point to Plane Does not Produce Uniform Balance





Temperature
Inverse of buoyant force



Balance condition

Force ratio – F_e/F_b

Numerical Simulation

Gauss's Law $$\nabla^2 V = \frac{\rho_e}{\varepsilon_o} = \frac{ce}{\varepsilon_o}$$

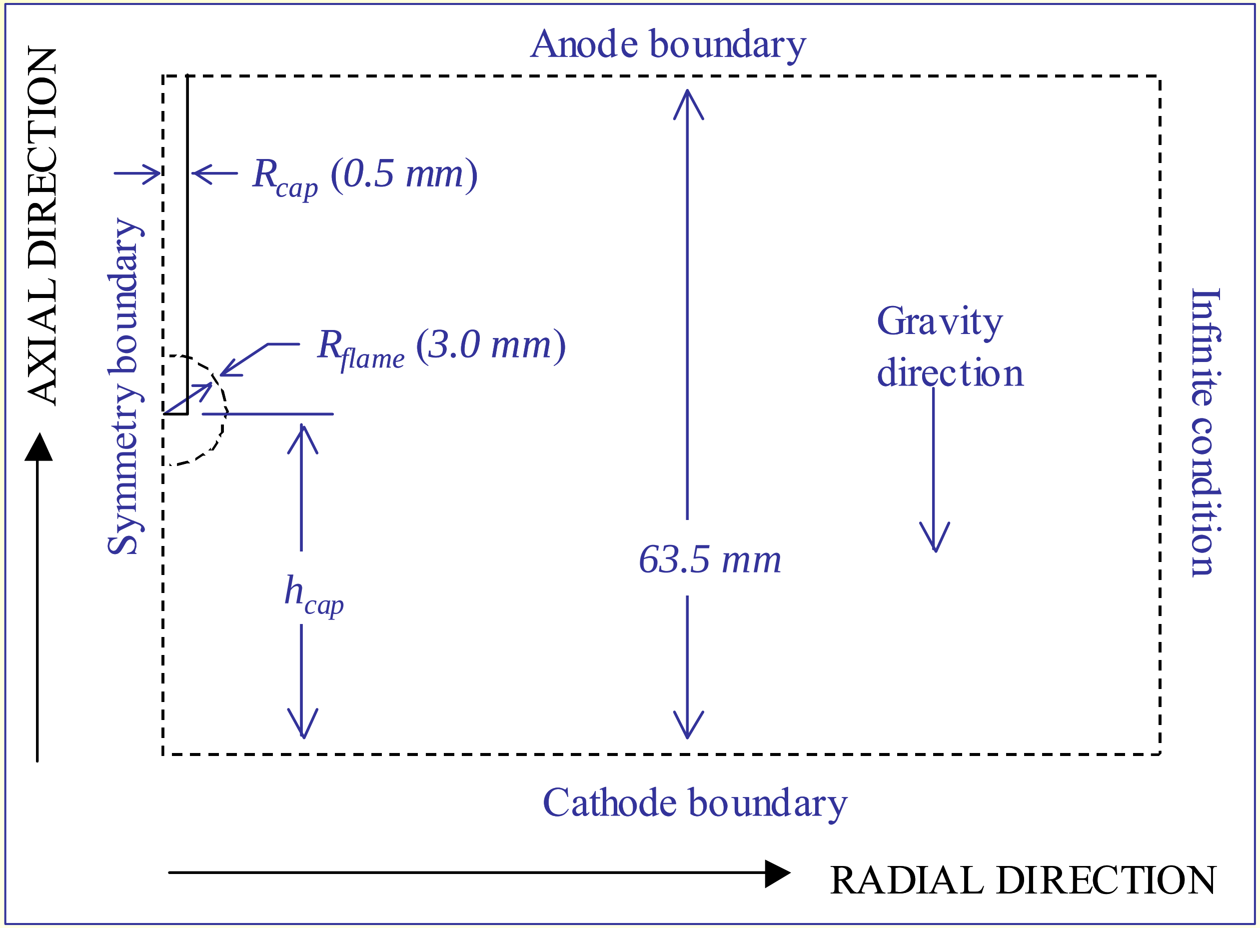
Momentum $$\rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u = -\nabla P + \rho_o g\left(1 - \frac{T_o}{T}\right) + \nabla \cdot (\mu \nabla u) + ce\overline{E}$$

Mass $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$

Energy $$\rho \frac{\partial (c_p T)}{\partial t} + \rho u \cdot \nabla (c_p T) = u \cdot \nabla P + \nabla \cdot (k \nabla T)$$

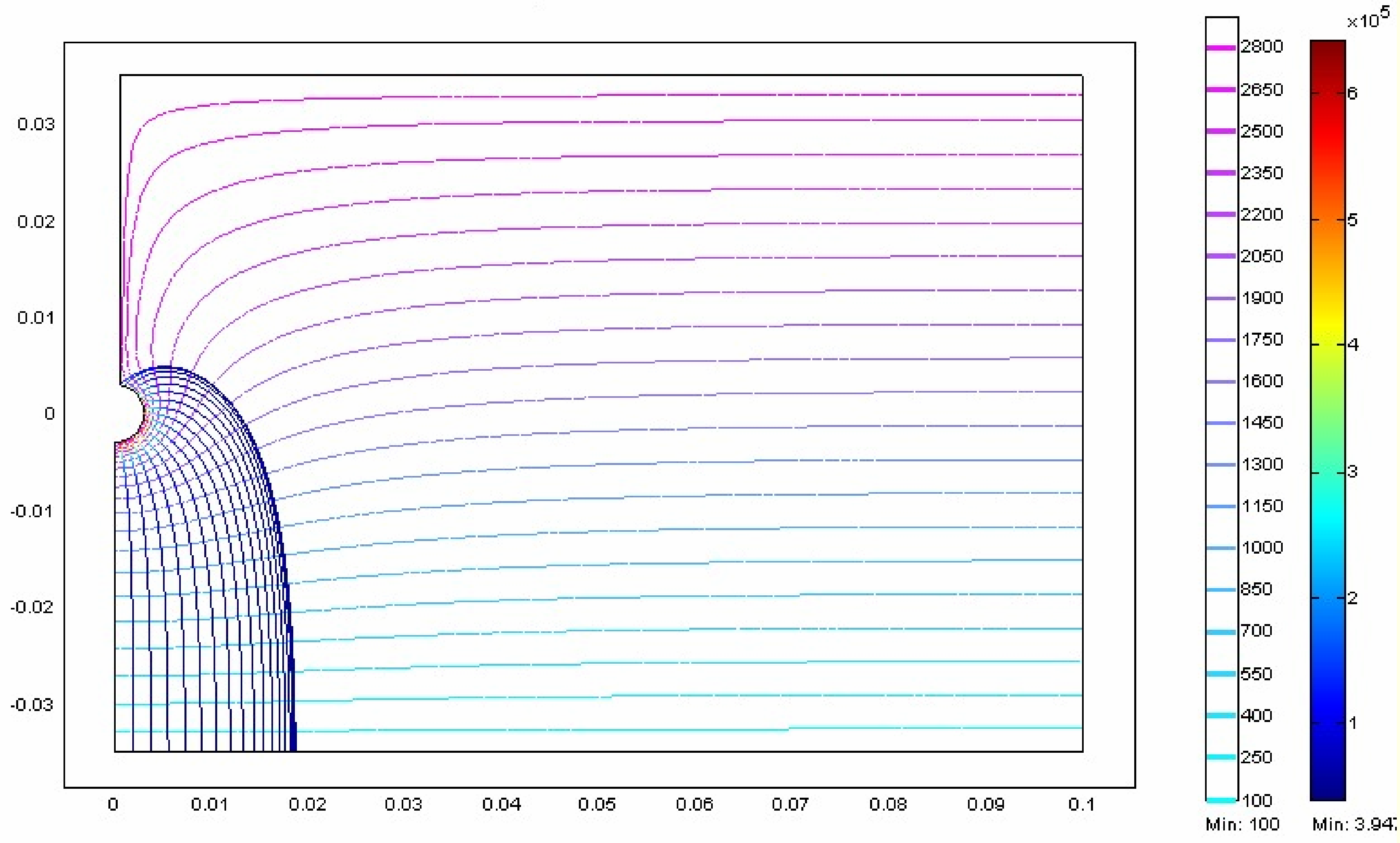
Ion concentration $$\frac{\partial c}{\partial t} + (u \cdot \nabla)c = \nabla \cdot (D \nabla c + ceK_+ \nabla V)$$

Computational Model



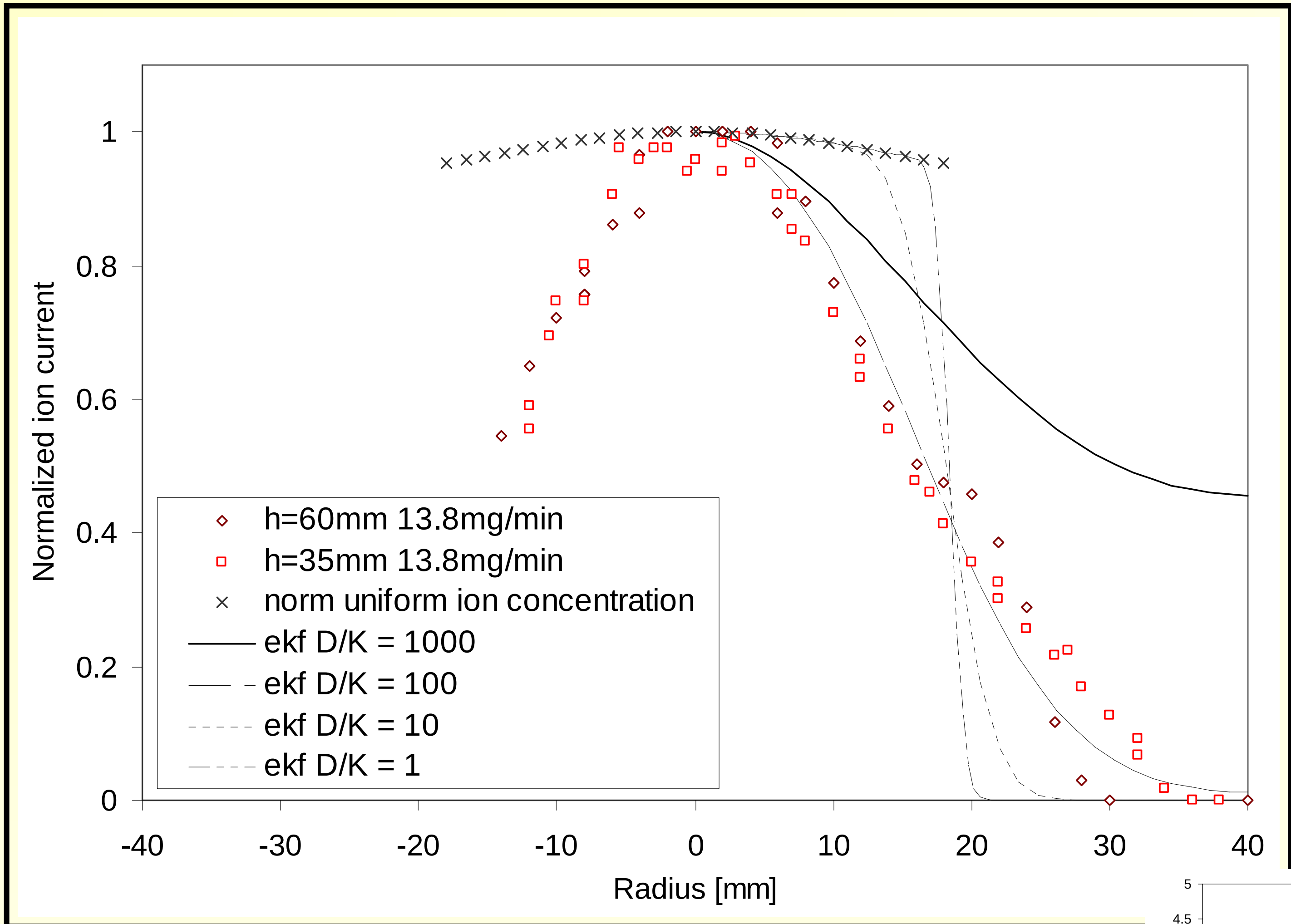
- FEMLAB simulation
- Finite element method
- General equation solver
- Staged solution
    1. Electrokinetic (V, c)
    2. Electrodynamic (V, c)
    3. Hot flow (V, u, v, P, T, c)
- 2-D axisymmetric
- Assumptions
    - Balance condition
    - Isotropic Fickian diffusion
    - Single ion species (positive ions)
    - Temperature is constant within the flame (hot flow)
    - Uniform ion concentration at the flame
    - Ion properties are of H_3O^+

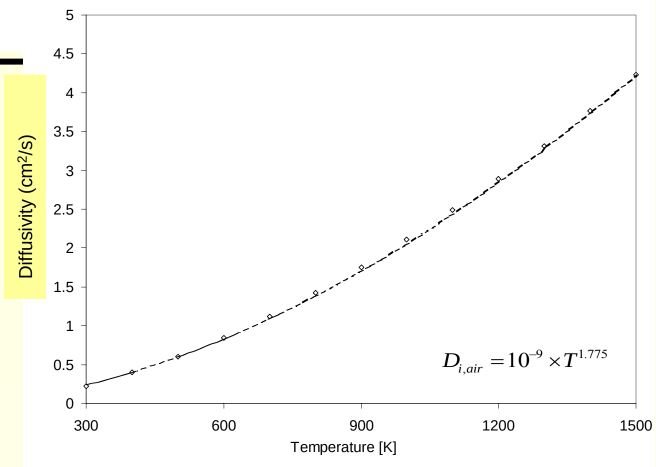
Electrokinetic Potential Field



- Ion motion is decoupled from the field (electrokinetic assumption)
- Flux pathlines illustrate no flux beyond 20 mm away from the centerline

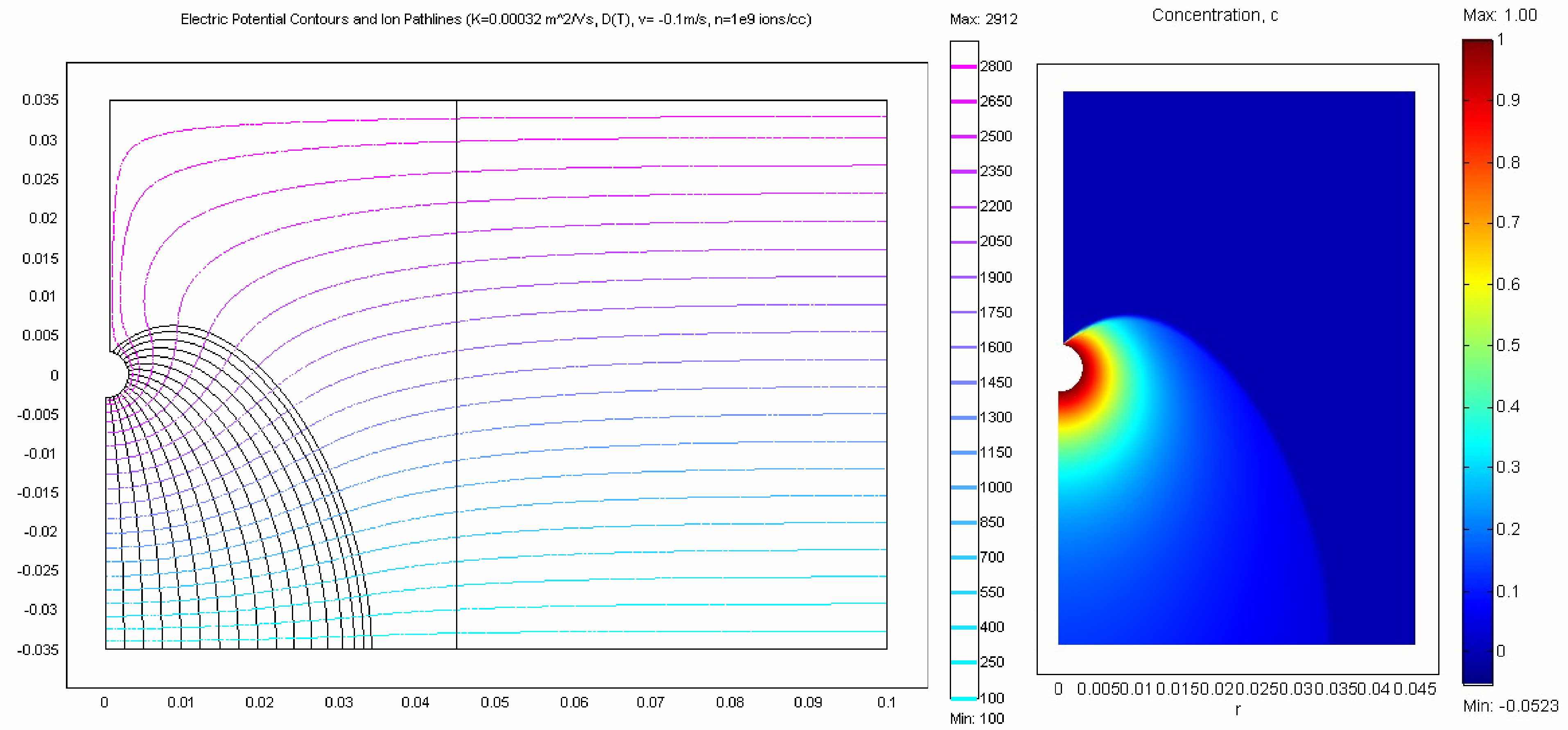
Role of Ion Diffusion





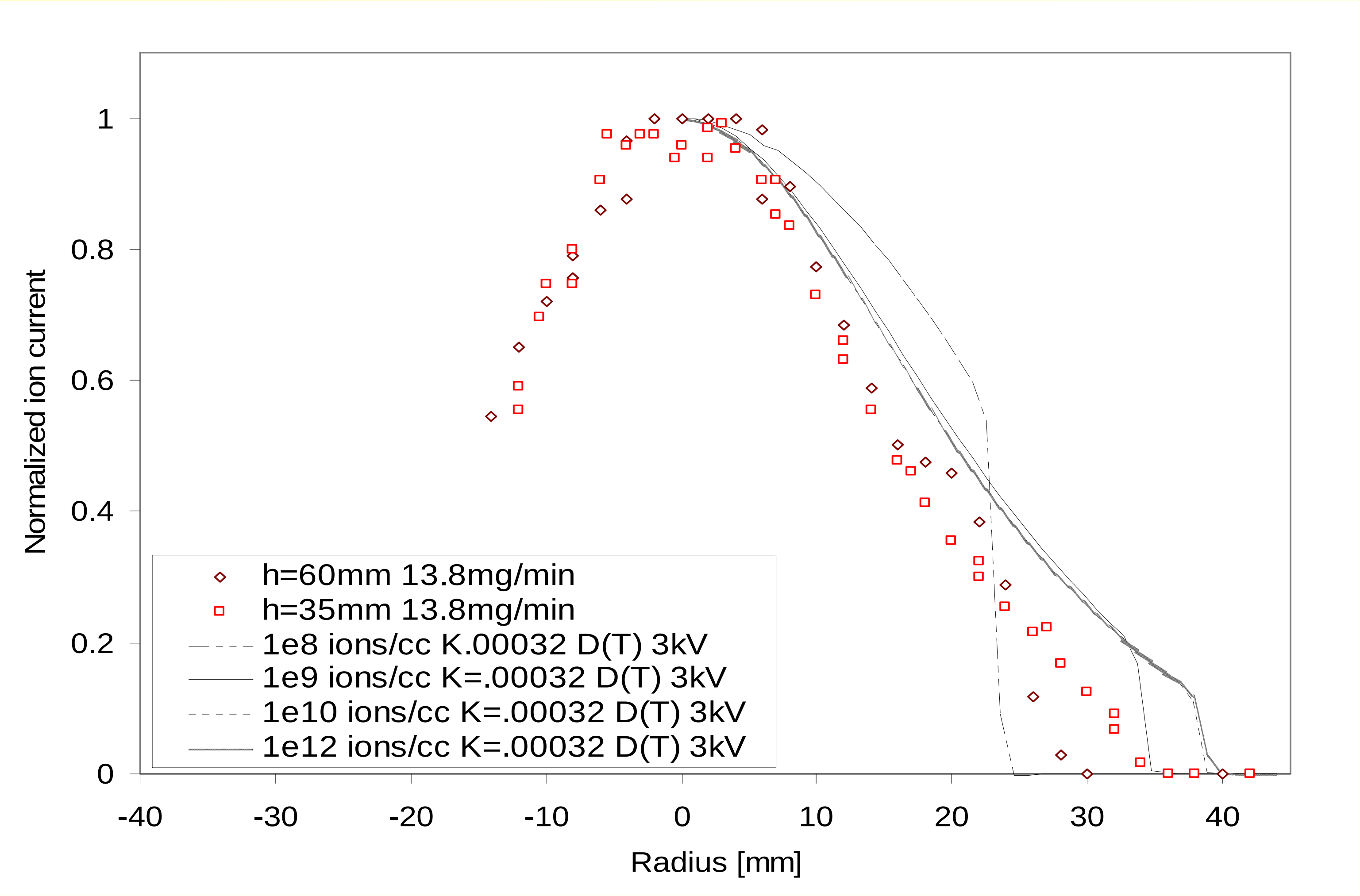
- Diffusivity is varied to match experimental profile
  - D(T) varies by a factor of approx 20 from 300-1500 K
- Results
  - True D/K approximately 1 V
  - Ion drift speed more than 1000 times diffusion velocity
  - Ion diffusion cannot account for measured profile
  - Space charge dispersion is significant

Including Space Charge Effects



- Gauss's law is solved including space charge
- Space charge drives ions to travel further from the centerline

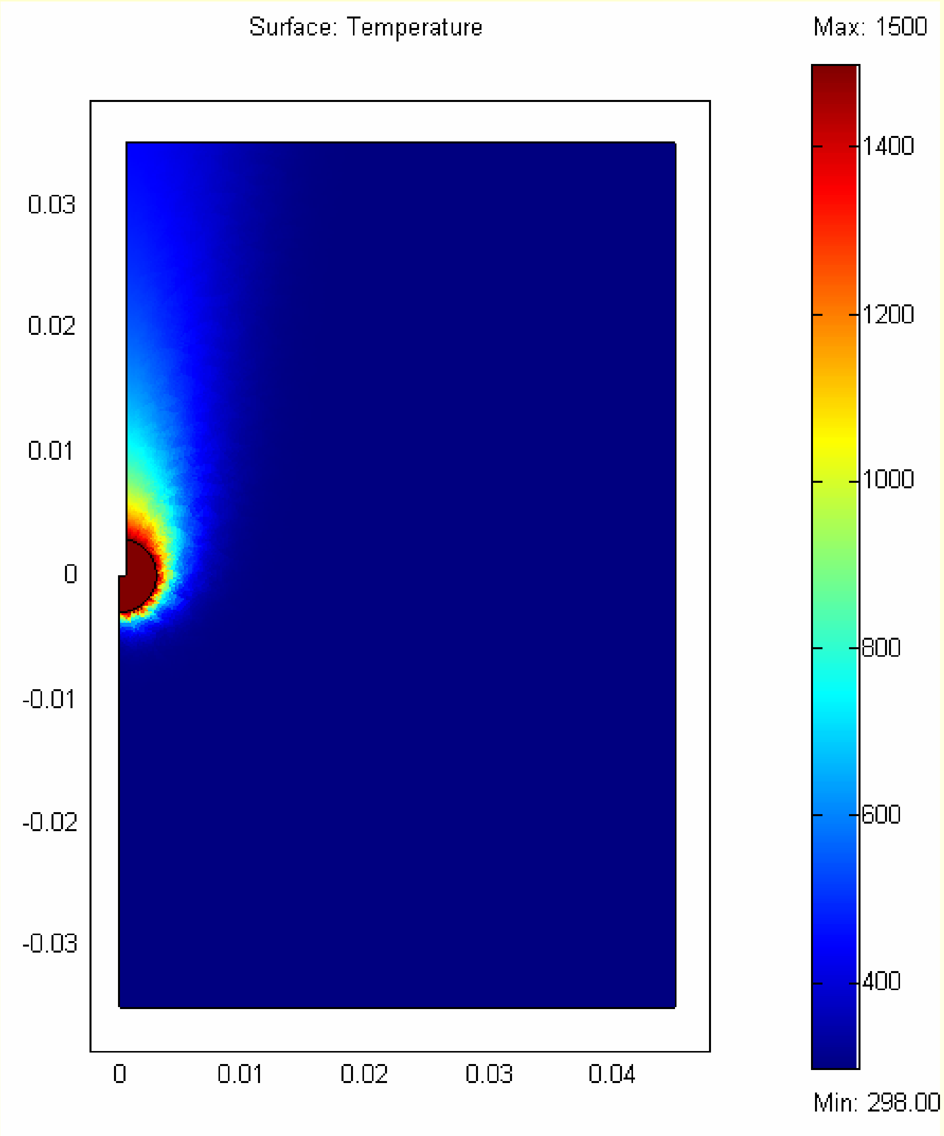
Effect of Ion Concentration

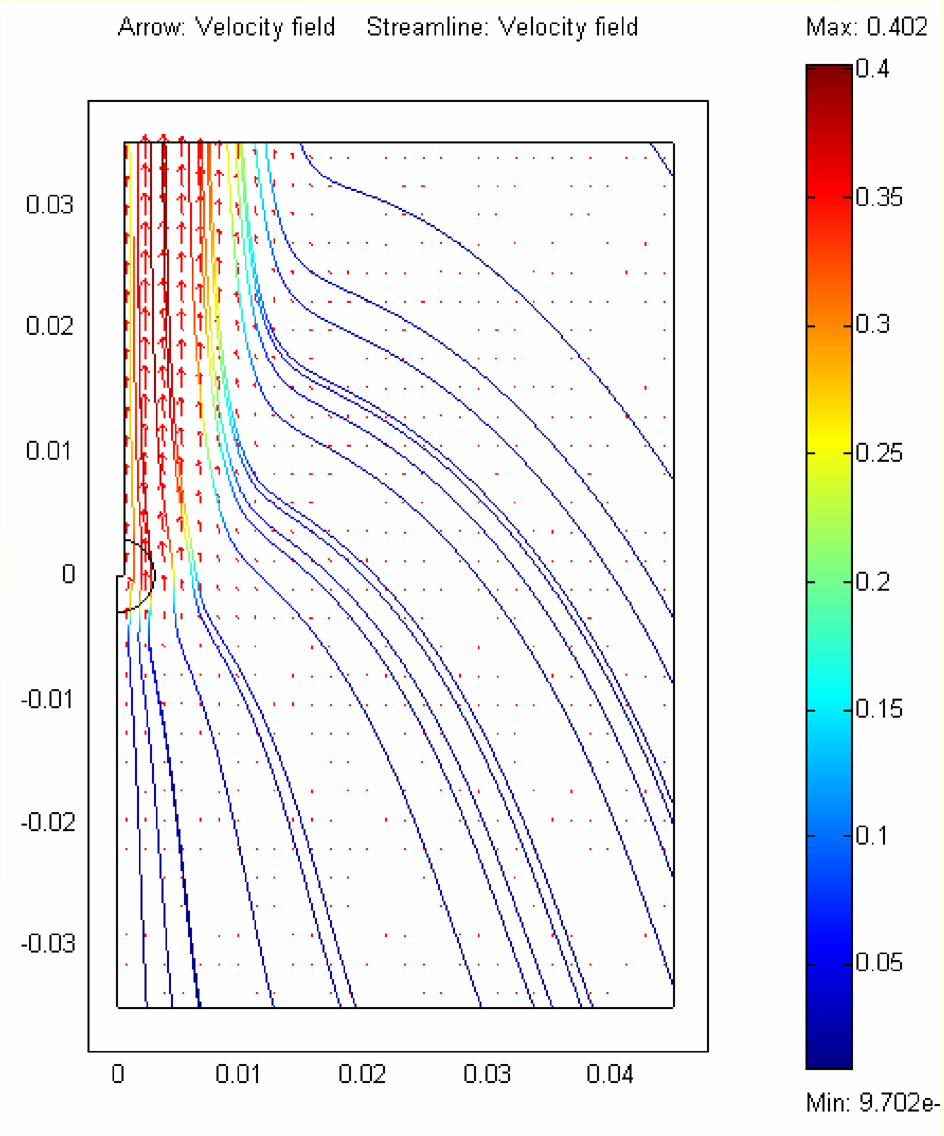


Overall ion concentration in flame is varied

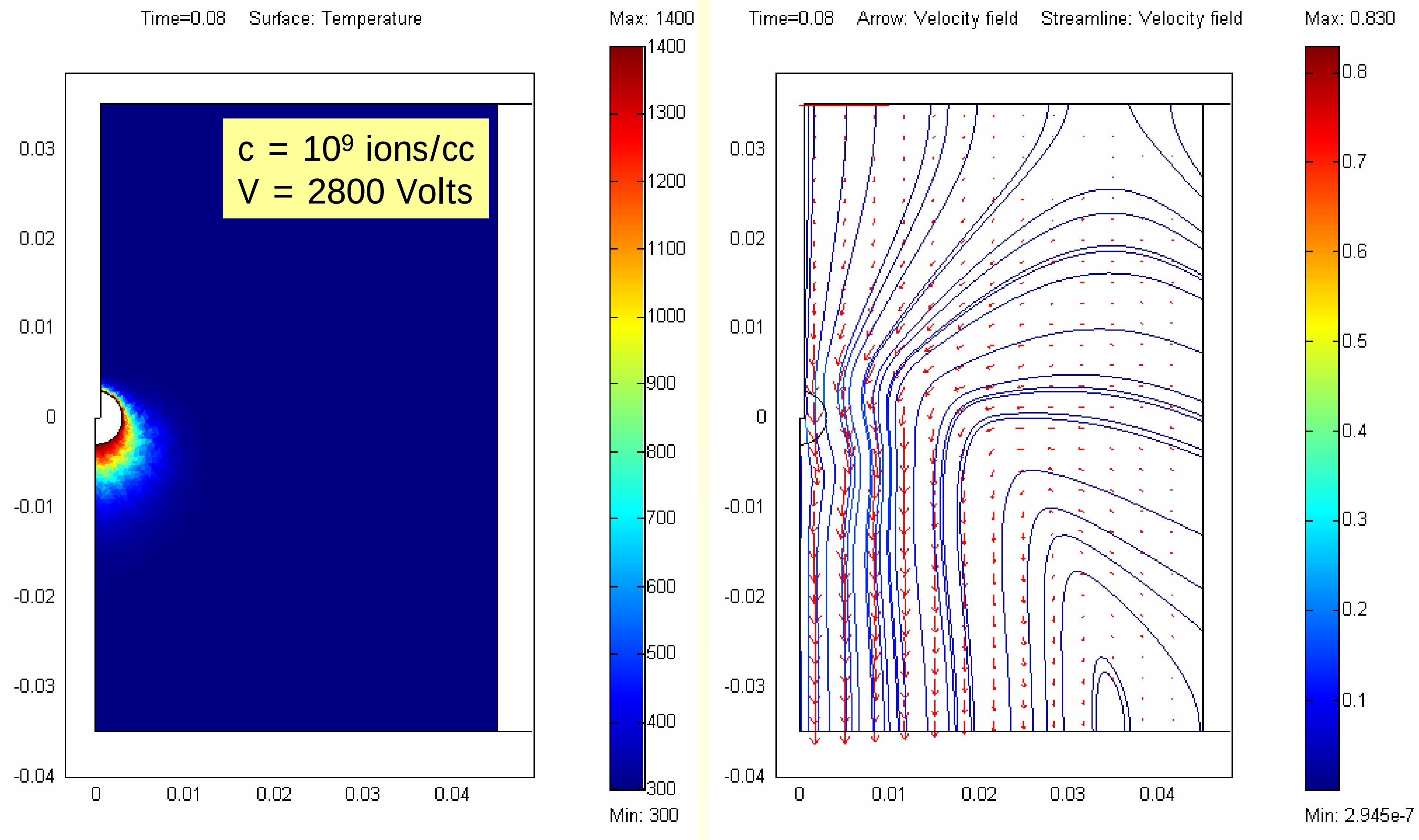
- Lower concentration (10^8 ions/cc) – profile narrows
- Higher concentration (10^{10}-10^{12} ions/cc) – profile broadens

Buoyant Flow Preliminary Results

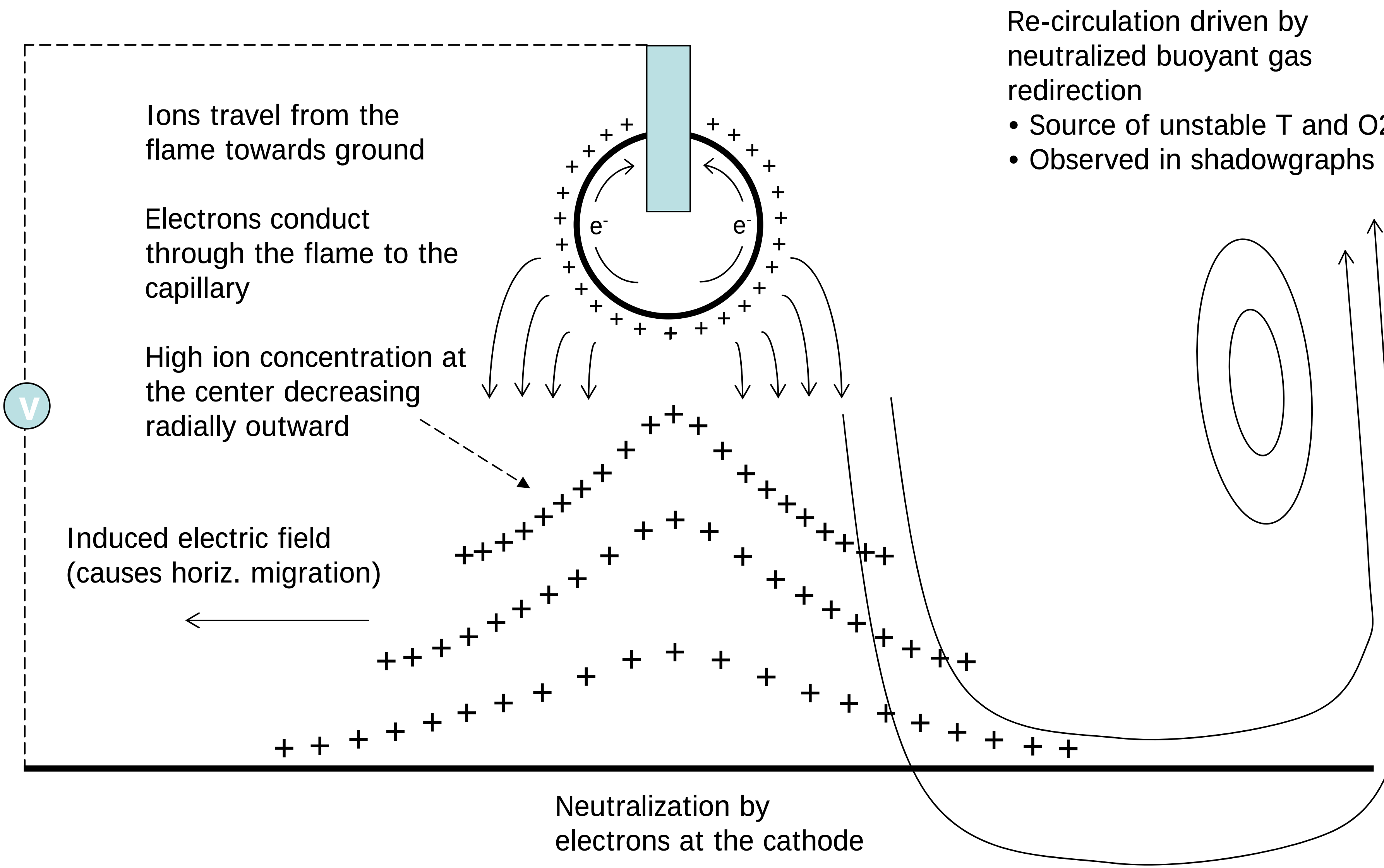




Hot Flow at Balance Preliminary Results



Flame Derived Ion Wind



Final Thoughts

- Ionic winds produce modest flows (a few m/s) with no moving parts
- Positive and negative polarity produces flow in the same direction (allows AC approaches)
- Efficiencies (flow power out/electrical power in) are low but not far worse than standard fans at small sizes
- Flame source ion winds require far less electrical energy (100 times less) than corona winds
- Optimizing ionic wind systems should be possible by modeling systems with various ground plane geometries

Acknowledgments

- Matt Rickard (ionic wind) and Mike Papac (electric flame) – current UCI graduate student researchers
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