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A NOVEL TEMPERATURE MEASUREMENT APPROACH FOR A HIGH PRESSURE DIELECTRIC BARRIER DISCHARGE USING DIODE LASER ABSORPTION SPECTROSCOPY (PREPRINT)

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14. ABSTRACT

A tunable diode laser absorption spectroscopic technique is used to measure both electronically excited state production efficiency and gas temperature rise in a dielectric barrier discharge in argon. The effect of voltage pulse rise time on the power deposition and electronically excited state production efficiency have been measured over a operating pressure range from 100 Torr up to 500 Torr.

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Plasma physics, laser spectroscopy, dielectric barrier discharge

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A Novel Temperature Measurement Approach for a High Pressure DBD Using Diode Laser Spectroscopy

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Columbus, Ohio

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National Research Council
Washington, D.C.

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Objective

To Compare the Effect of Applied Voltage Rise-Time on Argon Metastable Production Efficiency in a High Pressure, Pulse-Excitation DBD

- **<u>Advantages of “Short” Pulse Excitation (dV/dt ≈10 ns)</u>**
  - Short pulse excitation allows “overvolting” operation to achieve a single current strike, high E/n discharge, with only a small increase in average gas temperature (*e.g.*, $\Delta T < 100$ Kelvin).
- **<u>Disadvantages of “Short” Pulse excitation are</u>**
  - External circuitry complexity and cost.
  - Scaling to large electrode areas results in increased dielectric losses and increased parasitic EM effects.
  - Attempting to increase power deposition by increasing the total applied voltage becomes self-limiting since the conduction current competes temporally with a comparatively larger displacement current ($\propto$ dV/dt).[1]
- **<u>The objective of this study is</u>**
  - Determine the extent to which high-pressure DBD operation using a degraded total applied voltage rise time can achieve high E/n operation with a single current strike as well as the subsequent effect on Ar^m production efficiency as compared to the short-pulse case.
  - If the the long-pulse excitation production efficiency is comparable to that of the short pulse, it may be more attractive due to it’s lower external circuit complexity and cost as well as the benefit of physical scalability to large area discharges.

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[1] Bletzinger P. and Ganguly B.N., *J Phys D: Appl Phys* **36** 1550 (2003).

Gas Parameters of Interest

1. **Argon Metastable (Ar^m) Number Densities**[3]
   - Power deposition efficiency (e^- kinetics).
   - Extent to which collisional "quenching" of Ar^m inhibits and promotes excimer formation.

2. **Average Translational Temperature**[1,2]
   - Efficiency of power deposition into electronic states.
   - E/n, governs the rate of excitation/ionization.

- High pressure operation with small temperature rise is important for Ar^*_2 excimer formation and also several other applications

- In this work, pure argon is used for baseline measurements to develop tools for future studies of energy transfer kinetics involving molecular gases.

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[1] J.M. Williamson, P. Bletzinger, B.N. Ganguly, J. Phys. D: Appl. Phys. **37** (2004) 1658-1663. 30% N2/Ar DBD using TDLAS at 772.42 nm.

[3] J.M. Williamson, P. Bletzinger, B.N. Ganguly, *J. Appl. Phys.* **97** 103301 (2005). 30% N2/Ar DBD using DLAS at 772.4 nm.

[2] Leiweke R.J. and Ganguly B.N., *Appl. Phys. Lett.* **88** 131501 (2006). "Neat" argon DBD using TDLAS at 772.42 nm

Optical and Electrical Diagnostics

Measurements are presented for the range 100-500 Torr:

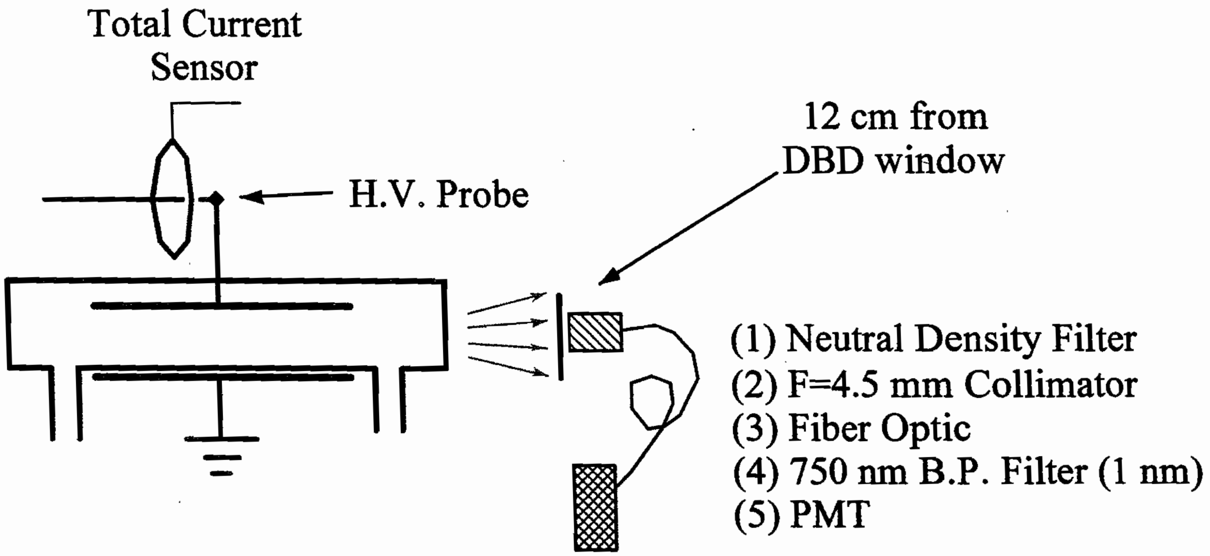
- Power deposition is used to infer the total Ar^m production efficiency

- Quenching corrected emission at 750 nm, used for
  1. A temporal bound on conduction current pulse behavior
  2. Infer pressure scaling of excitation rates.

- Average gas temperature obtained using *two novel* diagnostic techniques to
  1. Infer the extent to which power is coupled into atomic electronic states rather than thermal heating by electron-heavy particle elastic scattering collisions.
  2. Estimate the PMT signal quenching correction factor.

- TDLAS is used to measure both $1s_5$ and $1s_3$ argon metastable (Ar^m) populations.

Electrical and Optical Measurements



(1) Neutral Density Filter
(2) F=4.5 mm Collimator
(3) Fiber Optic
(4) 750 nm B.P. Filter (1 nm)
(5) PMT

DBD Broadband Optical Emission

Current Sensor:

- ≈2 ns rise time
- 1000× H.V. Probe: ≈ 4 ns rise time, 75 MHz b.w. at -3 dB
- Used for electrical power deposition estimates

750 nm Emission:

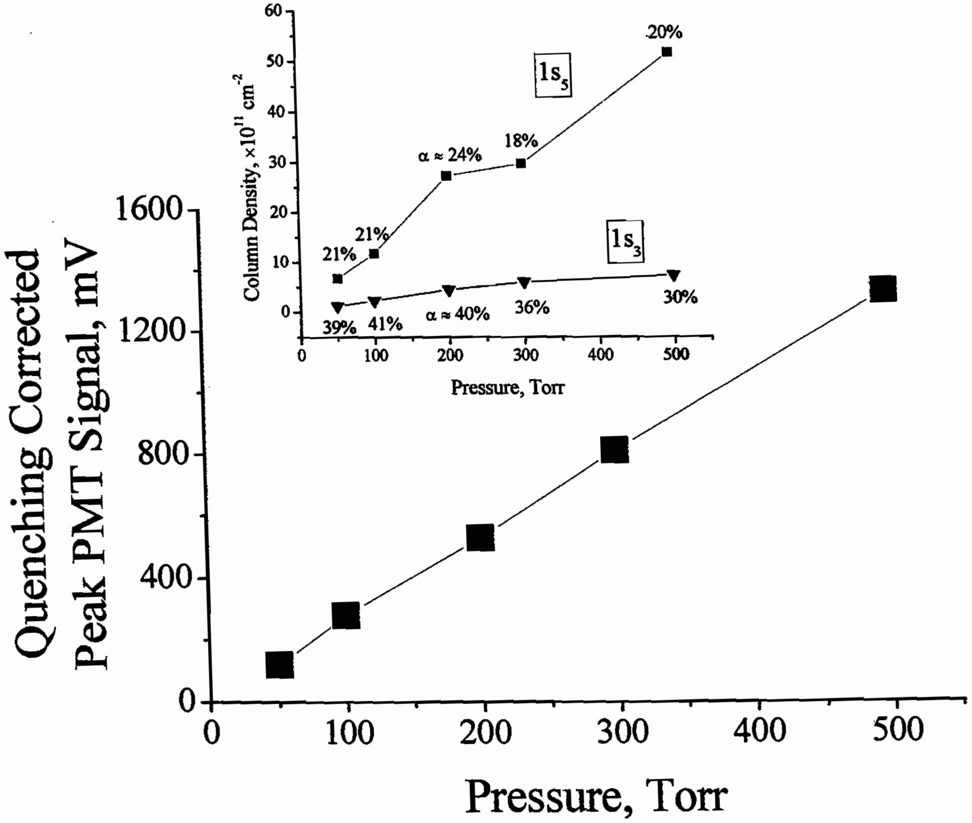
- Quench-corrected 750 and 751 nm emission is *volume averaged*
- Permits estimates of the $2p_1$, $2p_5$ level excitation rates
- Time-integrated emission scales with peak Ar^m column densities

Scaling of Ar^m Populations with Quenching Corrected $2p_{1,5}$ 750 nm Emission

Previous work[7] using <u>short-pulse excitation</u> suggested that the <u>peak</u> quench-corrected[6] PMT signal scales with Ar^m column densities

- ⇒ Mean e^- energy is high enough that the e^- impact excitation rates are similar for both Ar^m and $2p_5$,$2p_1$ levels across our pressure-voltage range

- ⇒ The temporal variation of the emission may be used, *in situ*, with current waveform to optimize Ar^m production efficiency as a function of pressure and total applied voltage by adjusting the breakdown time delay



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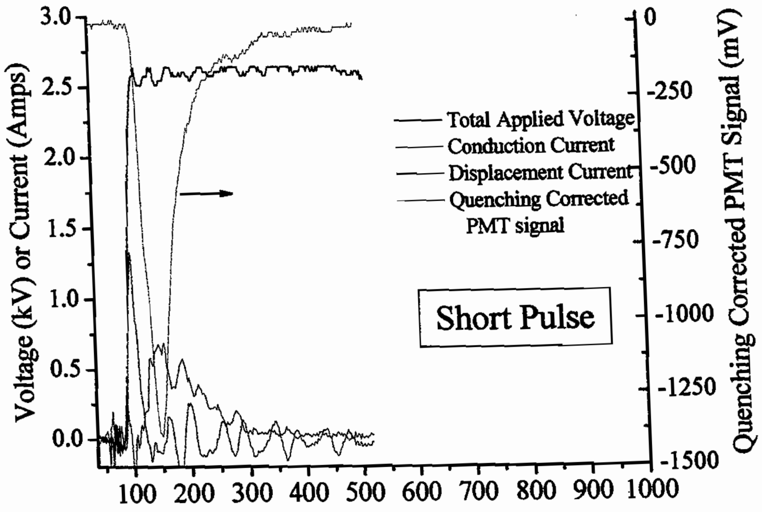
[6] Sadeghi N., Setser D.W., Francis A., Czarnetzki U., and Döbele H.F., *J Chem Phys* **115** (7), 3144 (2001).

[7] Leiweke R.J., Ganguly, B.N., 58th Gaseous Electronics Conference, October 15-18, San Jose, CA (2005).

Applied Voltage Pulse Shaping Results
(300 Torr)

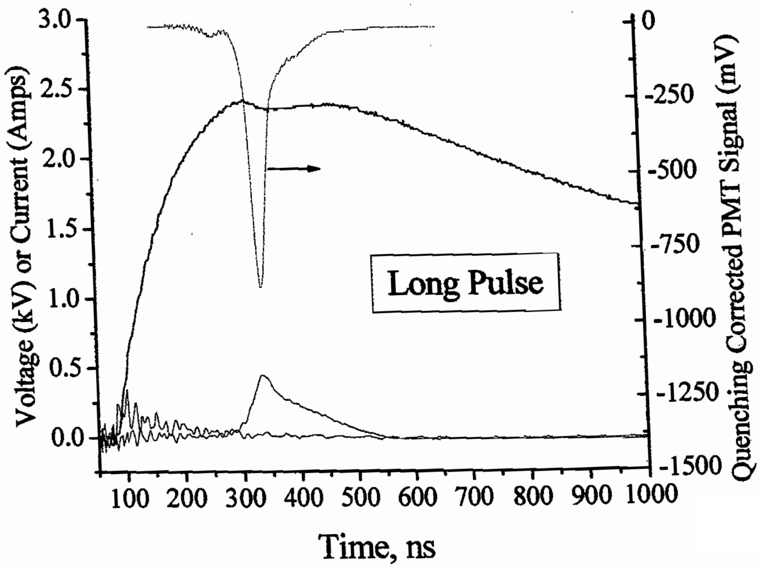
“Short Pulse”: ≈10 ns Total Applied Voltage Rise Time:

- Displacement current (green) is 2x larger than the conduction current and competes temporally with conduction current (blue) with 700 mA peak.
- Peak quenching-corrected PMT signal is ≈1.5x larger than “long-pulse” case.



“Long Pulse”: ≈150 ns Total Applied Voltage Rise Time

- Displacement current is smaller than the conduction current and leads by ≈100 ns.
- Quenching-corrected PMT signal and current waveforms suggest a <u>*single-strike*</u> discharge.
- Discharge occurs at lower total applied voltage (2.3 kV) than the short-pulse case (2.6 kV) and the conduction current is 400 mA.



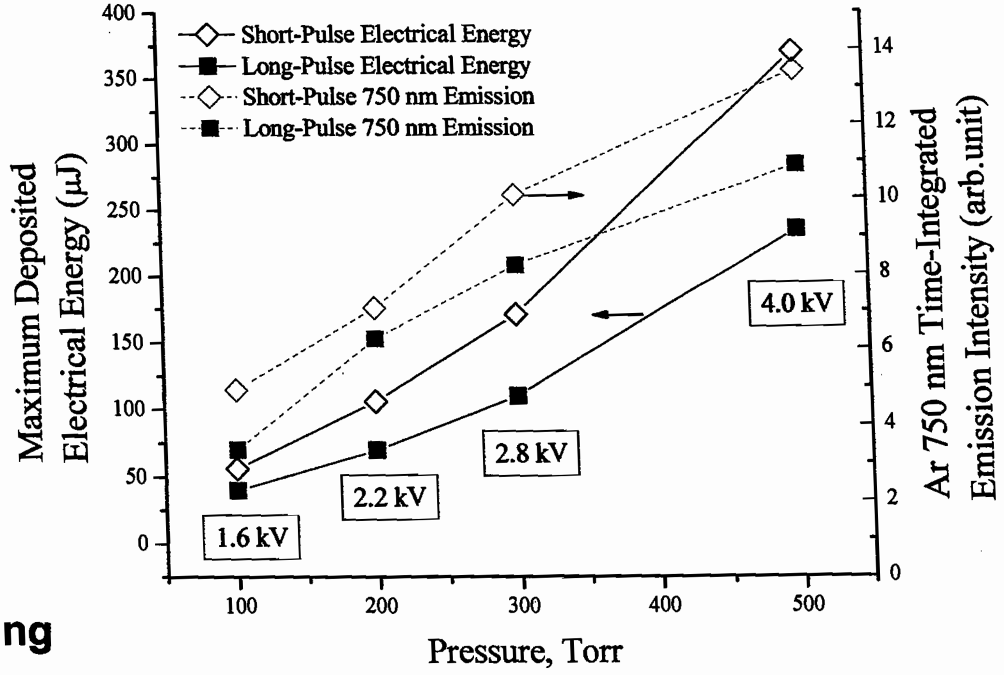
Pressure Scaling of DBD Operation

- Long-pulse pressure scaling is similar to that of the Short-pulse.
- Lower Ar^m production, inferred by the relative PMT signals indicates that the Long-Pulse is less efficient than the Short-Pulse.

$$E_{deposit} \leq \int I_{cond} V_{applied} dt$$

$$S_{PMT}^{total} = \int S_{PMT}(t)dt$$

⇒These results suggest that the Long-Pulse discharge occurs with a single-strike but at *lower* E/n than the Short-Pulse, but not to the extent of an AC DBD (which exhibits multiple current strikes at much lower E/n).

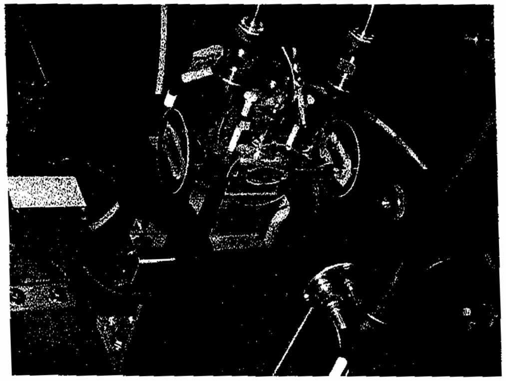


⇒Temperature and absolute Ar^m column density measurements will aid in confirming the extent of e^- elastic scattering (thermal heating) and Ar^m production efficiency.

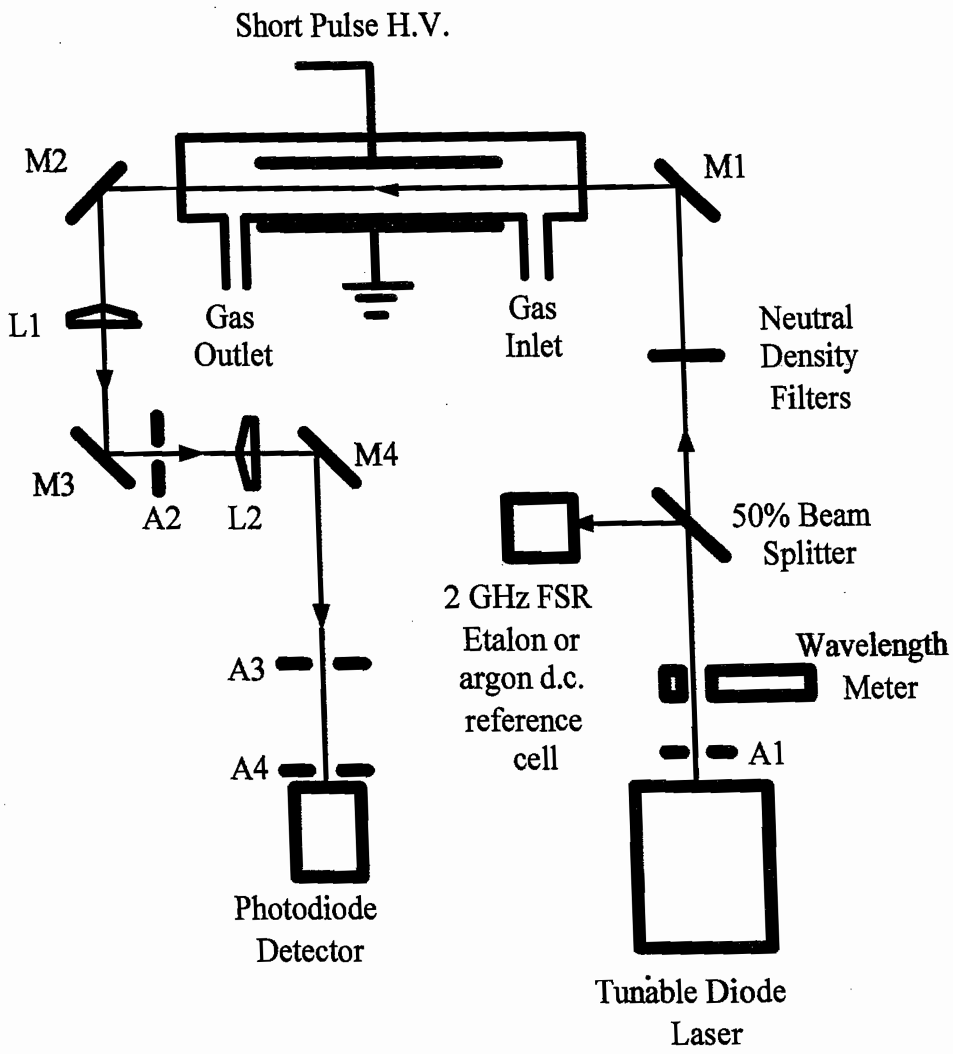
Absorption Measurement Setup

Conditions

- Argon, 25 SCCM
- Pressure = 100 - 500 Torr
- Unipolar, ≈200 ns FWHM total applied voltage pulses
- 5 kHz pulse repetition rate
- Applied voltage and power adjusted to maintain ≈20 % absorption of the $1s_5 \rightarrow 2p_7$ transition



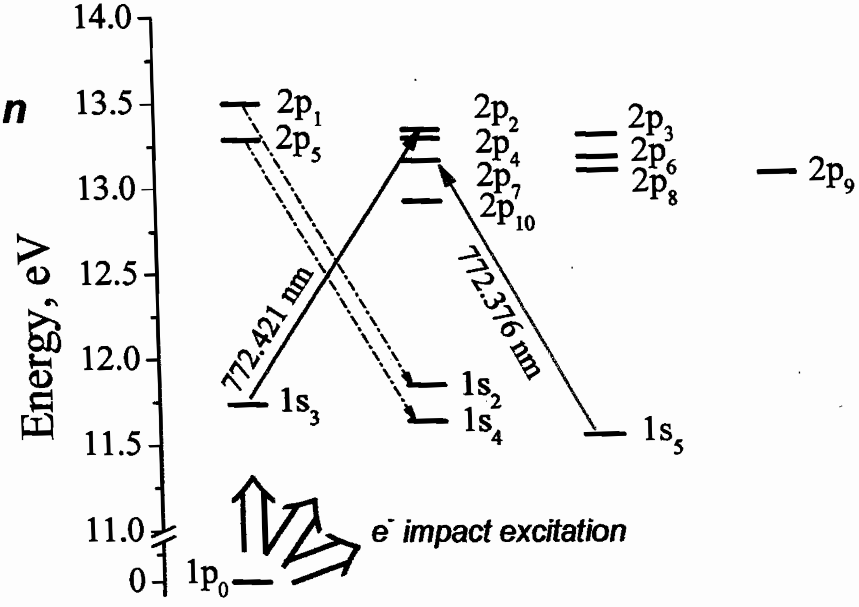
Picture of DBD Layout



TDLAS Approach

- **Ar^m populations can be "large"** *(~10^{11} cm^{-3}),* even in gas mixtures with modest E/n.[1,2]
- **Two Strong transitions ≈22.5 GHz apart[3]**

⇒ ***Both 1s$_3$ and 1s$_5$ column densities can be acquired using a single, ~80 GHz scan***



$2p_2 \rightarrow 1s_3$ at 772.421 nm; A ≈10×10^6 s^{-1}

$2p_7 \rightarrow 1s_5$ at 772.376 nm; A ≈ 5×10^6 s^{-1}

$$\frac{B_{1s_3}}{B_{1s_5}} = \frac{A_{2p_2-1s_3}}{A_{2p_7-1s_5}}\,\frac{g_{2p_2}}{g_{2p_7}}\,\frac{g_{1s_5}}{g_{1s_3}}$$
$$\approx 2\times\frac{3}{3}\times\frac{5}{1}$$
$$= 10$$

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[1] C. Penache, M. Miclea, A. Bräuning-Demian, *et al., Plasma Sources Sci. Technol.* **11** 476-483 (2002). Pure argon.

[2] J.M. Williamson, P. Bletzinger, B.N. Ganguly, *J. Appl. Phys.* **97** 103301 (2005). 30% N$_2$/Ar DBD using DLAS at 772.4 nm.

[3] NIST Atomic Spectra Database v.3.03; http://physics.nist.gov/PhysRefData/

TDLAS Transmission Profiles

- ≈80 GHz, mode-hop free tuning range using 80-200 MHz steps

- Absolute frequency shift is easily measurable above ≈100 Torr

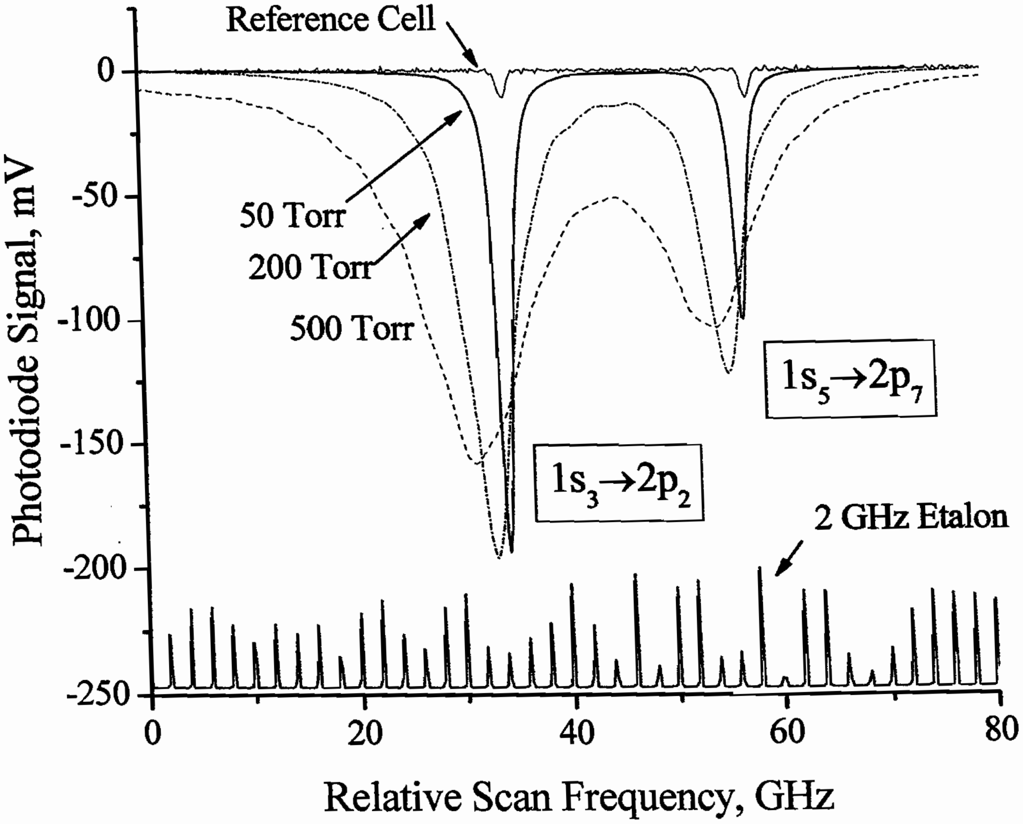
- 100% transmission "baseline" obtained by turning off discharge

- The $1s_3$,$1s_5$ levels are nearly isoenergetic, so we might expect $n_{1s3}=n_{1s5}$ with 10:1 peak absorptions since

$$\frac{B_{1s_3}}{B_{1s_5}} \approx 10$$

However, we observe 2:1

$\Rightarrow 1s_5$ population > $1s_3$



Column Density Estimation

Beer-Lambert absorption: $\boxed{\tau(\nu) = e^{-n_1 L \sigma_{12}(\nu)}}$

absorption cross-section: $\sigma_{12}(\nu) = \frac{h\nu_{o,a}}{c} B_{12} \int_{-\infty}^{+\infty} \varphi_s(\omega - \nu)\varphi_a(\omega)d\omega$

- Since the laser bandwidth is <100 MHz, source lineshape $\varphi_S \approx$ delta function
- With 2-5% loss in accuracy, the absorption cross-section becomes:

$$\sigma_{12} \approx \frac{h\nu_{o,a}}{c} B_{12}\varphi_a\left(\nu_{o,a} - \nu\right)$$

$$\boxed{n_1 L \approx \frac{-c\ln(1-\alpha)}{h\nu_{o,a}B_{12}\varphi_a(\nu_{o,a})}}$$

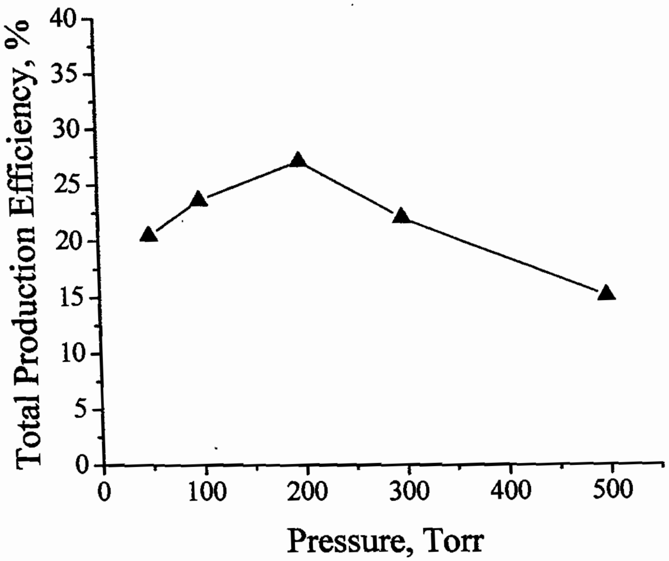
For pressure > 50 Torr, $\varphi_a\left(\nu_{o,a}\right) \approx \frac{0.637}{w_V}$

α = $1 - \tau$
$\nu_{o,a}$ = Absorption center frequency (GHz)
$\varphi_a(\nu_{o,a})$ = Normalized absorber lineshape function evaluated at $\nu_{o,a}$ (GHz^{-1})
w_v = Voigt full-width at half maximum (FWHM) (GHz)

Production Efficiency Estimates

1. Absorption path length = electrode width (L = 1 cm)
2. Ar^m production assumed* to be volume-averaged and uniformly distributed within confines of the electrode geometry (d_{gap}=0.5 cm, w=3 cm)
3. Actual deposited energy < $\int I_{cond} V_{applied}\,dt$ because discharge capacitance < dielectric capacitance ($V_{gap} < V_{total\ applied}$)
4. Power deposition, $\int I_{cond} V_{applied}\,dt$, assumed* to be volume-averaged over the confines of electrode geometry
5. Energy "cost" per metastable ε^m= 16 eV

$$\boxed{\begin{aligned}\eta &\equiv \frac{\text{Total Ar}^m\text{Produced}}{\text{Energy Deposited}}\\ &= \frac{\left(nL_{1s_3} + nL_{1s_5}\right)\varepsilon^m w d_{gap}}{\int I_{cond} V_{applied}\,dt}\end{aligned}}$$



*The emission and absorption measurements performed over this voltage-pressure range suggest that these assumptions are reasonably correct

Production Efficiency Estimates, cont.

- Lower Bound Ar^m $\eta \sim 20\%$ for 50-500 Torr and given $V_{\text{total applied}}$

- Peak $\eta \sim 27\%$ at 200 Torr

- Efficiency may be increased at 500 Torr by increasing $V_{\text{total applied}}$

  ⇒ Breakdown time delay decreases so that the discharge operates at a higher E/n[6]

Average Gas Temperature Measurements

Based on ***Lindholm-Foley theory***[9] for van der Waals attractive potentials when no resonance occurs between the absorber & perturber:

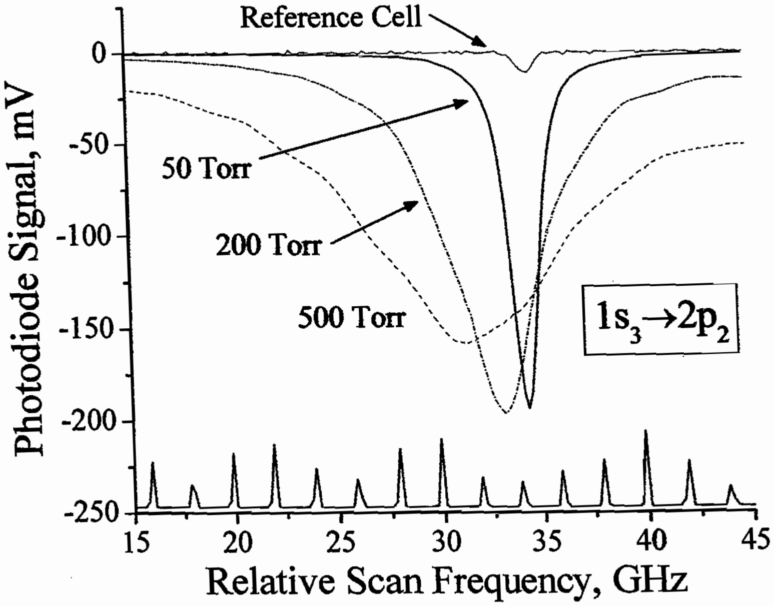
Collision Width Temperature[10]: $T_C = T_o \left[\frac{\Gamma_o p}{w_C} \right]^{\frac{10}{7}}$

Γ_o (MHz/torr) = Broadening coefficient
w_C (MHz) = Collision width (FWHM)

Frequency Shift Temperature[10]: $T_S = T_o \left[\frac{\beta_o p}{\beta} \right]^{\frac{10}{7}}$

β_o (MHz/torr) = Freq. shift coefficient
β (MHz) = Frequency shift

p (torr)	V_{app} (kV)	T_C (K)	T_S (K)
50	1.0	302 ± 35	337 ± 45
100	1.3	279 ± 32	318 ± 55
200	1.9	273 ± 31	321 ± 20
300	2.4	295 ± 32	287 ± 23
500	3.4	291 ± 34	362 ± 30



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[9] Breene R.G., *The Shift and Shape of Spectral Lines* (Pergamon, New York, 1961), pp. 47-51.

[10] Leiweke R.J. and Ganguly B.N., *Appl. Phys. Lett.* **88** 131501 (2006).

Summary & Conclusions

- 750 nm quench corrected emission signal “tracks” Ar^m column densities for both “short” and “long” pulse excitation waveforms.
  - May be used with current waveform to optimize electron kinetics efficiency as a function of pressure and total applied voltage
- Long pulse operation:
  - single-strike operation is maintained
  - Discharge probably operates at a lower E/n, inferred from the deposited energy and quenching corrected PMT signal in the 100-500 Torr range.
- Lower bound estimates of <u>Ar^m production efficiency</u>
  - Short pulse: ~10% for 100-500 Torr
  - Long pulse: ~8% for 100-500 Torr based on PMT signal scaling for Ar^m population and deposited energy
- Average gas temperature, measured using two novel techniques shows
  - Short Pulse $\Delta T<100$ K from 100-500 Torr
  - Long Pulse To be determined with future TDLAS measurements
- Long pulse DBD operation may be attractive alternative to the short pulse due to lower external electrical circuitry cost, complexity, and scalability of the DBD to higher deposited power and physical scalability to larger surface area discharges.