Intra-Pulse Rotational Spectroscopy for Pulsed-Nanosecond Discharges

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I. Abstract

- Measured 0-0 transition of the nitrogen second positive system in pulsed-nanosecond discharge (PND)

- Wrote computer program that:
  - Generated corrected spectra from ICCD images based on user input
  - Simulated emissions for a given rotational temperature
  - Conducted an automatic search for the correct rotational temperature of an input spectrum

- Measured the current and voltage characteristics for PND
  - Calculated energy transfer to plasma
  - Estimated ion-pair cost

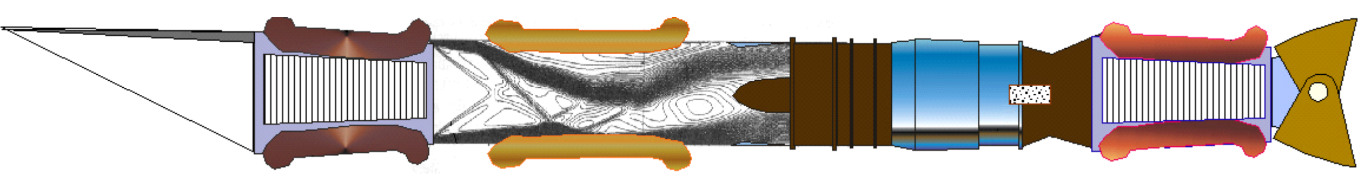


Figure 1 Hypersonic MHD energy bypass engine [1].

II. Motivation

- Large volume, high pressure, uniform plasmas are a challenge.
  - Promising uses in materials processing, aviation, and medicine.
- PNDs fulfill these requirements, but discharge mechanisms are poorly understood.
- Measurements of rotational and gas temperatures provide important validation of modeling efforts and insight on the plasma chemistry.

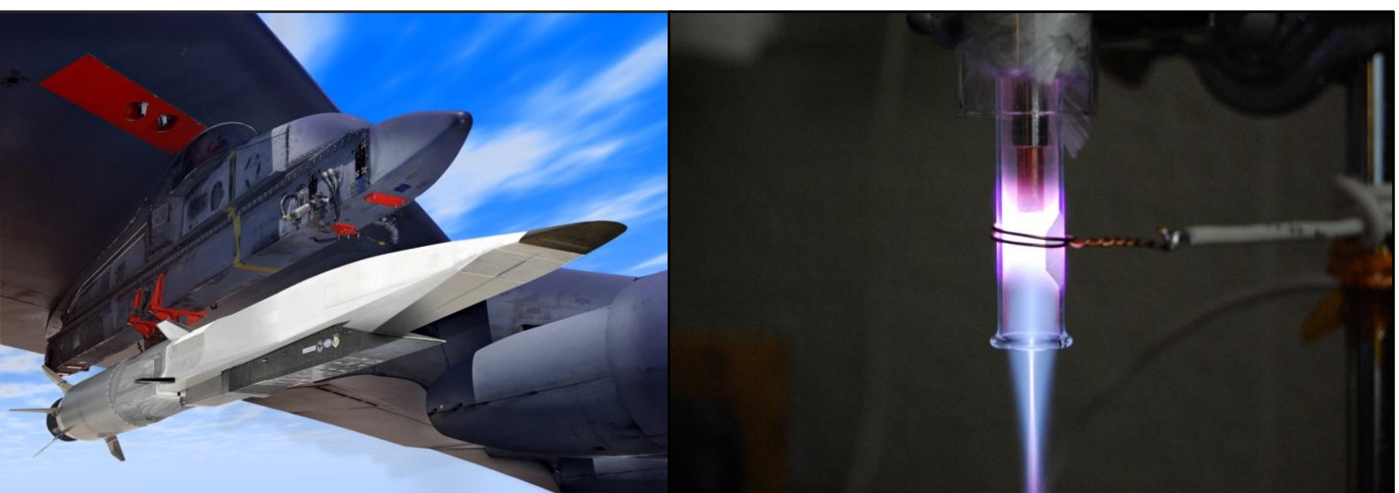


Figure 2 (left) Hypersonic test vehicle, X-43 [2]. (right) PSTL atmospheric pressure plasma jet.

III. Molecular Spectra

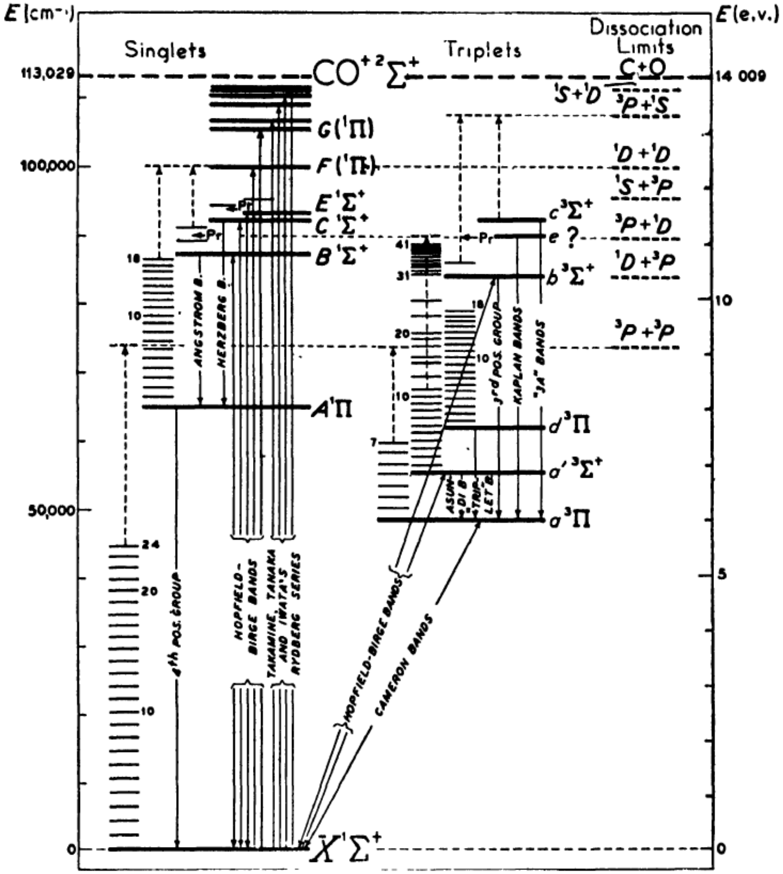


Figure 3 Energy level diagram of the nitrogen molecule as illustrated by Herzberg [3].

- Many degrees of freedom in comparison to atoms
  - Electric, vibrational, rotational
- Vibrational and rotational transitions occur in mid-infrared
- Coupled to electronic transitions yield manifolds or bands
- Band shapes reflect rotation energy distribution

IV. Second Positive System

- Transition from $C^3\Pi_u$ -> $B^3\Pi_g$
  - Initial state populated from $X^1\Sigma_u$
- Assumed that rotational energy distribution is preserved in excitation
- Features three branches: P, Q and R
- Commonly used for estimation of neutral gas temperature [4]

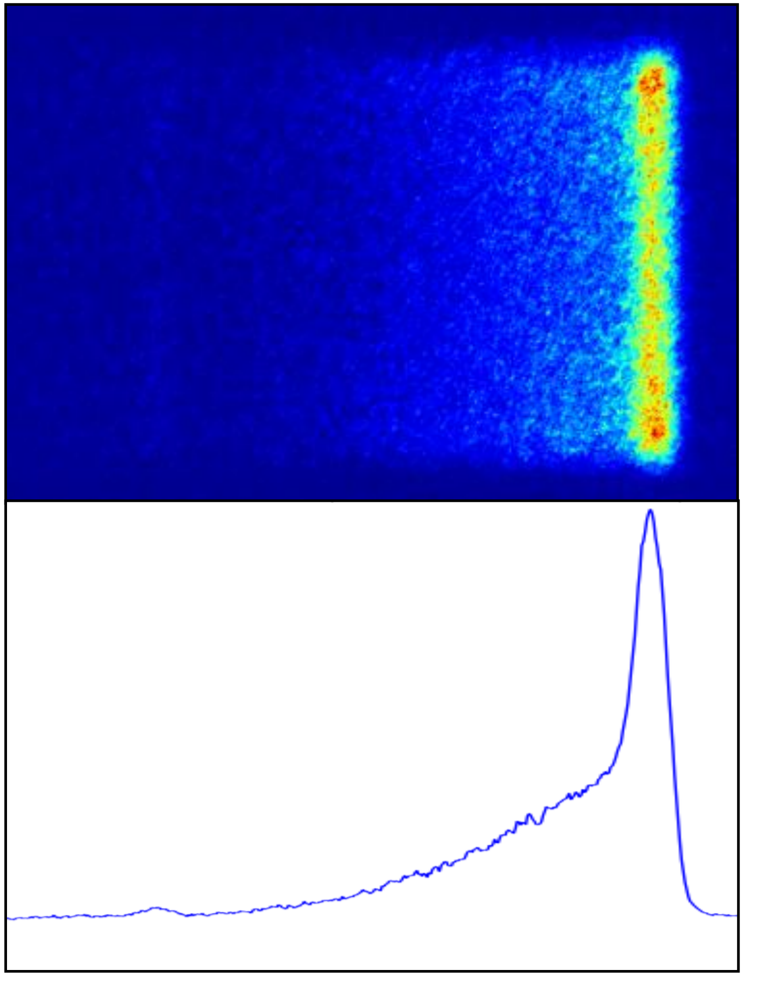


Figure 4 (top) ICCD image of nitrogen's second positive system. (bottom) Collapsed version of spectra, processed for background.

V. Previous Work

- High resolution (FWHM 0.05 nm) spectroscopy of first negative system in nitrogen [5]
- Required long acquisition times, > 30 minutes
- Time-averaged rotational temperature of 900 K

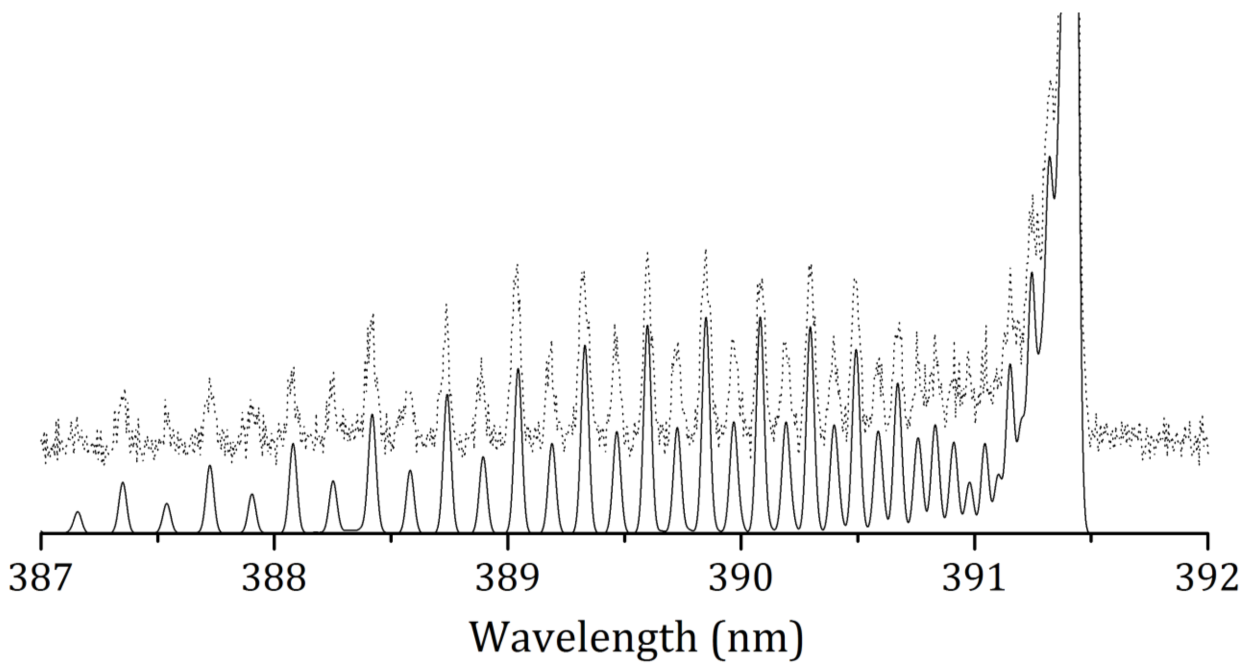


Figure 5 Previous measurements of nitrogen's first negative system using a photomultiplier tube [5].

VI. Line Shifts

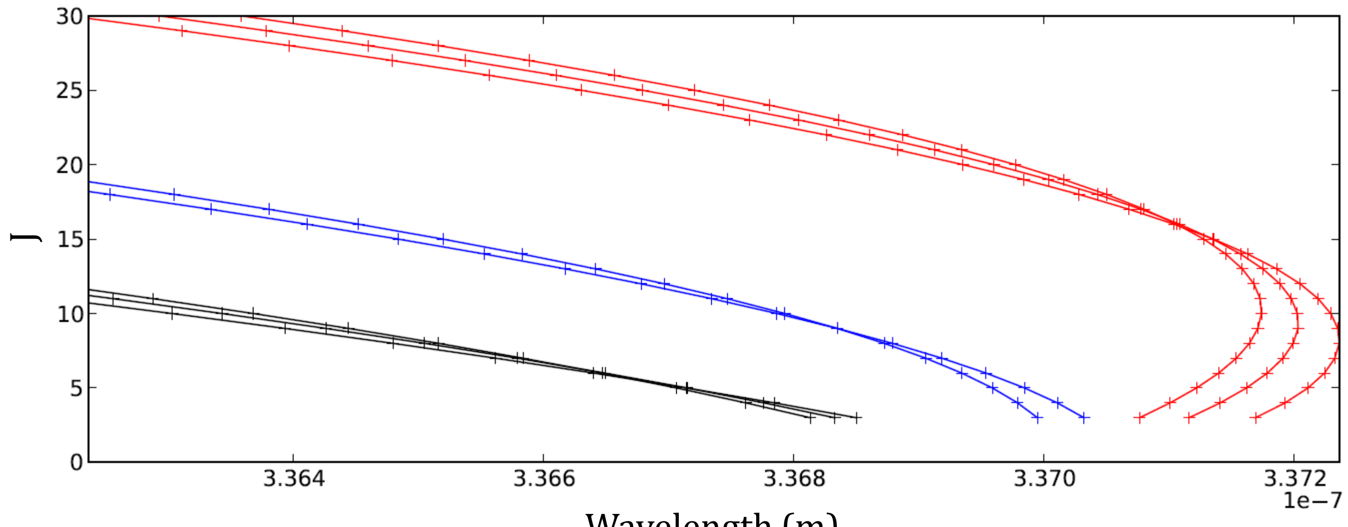


Figure 6 Fortrate diagram of the second positive system of nitrogen.

- Term values obtained from semi-empirical formula, first suggested by Budó [6] and later Herzberg,

$$F_{0;J} = B_v\left[J(J+1) - \sqrt{Z_1} - 2Z_2\right] - D_v\left(J - \tfrac{1}{2}\right)^4 \qquad Z_1 = Y_v(Y_v - 4) + \tfrac{4}{3} + 4J(J+1)$$

$$F_{1;J} = B_v\left[J(J+1) + 4Z_2\right] - D_v\left(J + \tfrac{1}{2}\right)^4 \qquad Z_2 = \frac{1}{3Z_1}\left[Y_v(Y_v - 1) - \tfrac{4}{9} - 2J(J+1)\right]$$

$$F_{2;J} = B_v\left[J(J+1) + \sqrt{Z_1} - 2Z_2\right] - D_v\left(J + \tfrac{3}{2}\right)^4$$

- Represent spin coupling, transition from Hund's case (a) to (b)

- Updated constants obtained from Laher and Gilmore [7]

VII. Intensities

- Intensity distribution determined from input temperature
- Boltzmann distribution assumed for population of states
- Honl-London factors used to scale individual branches [3]

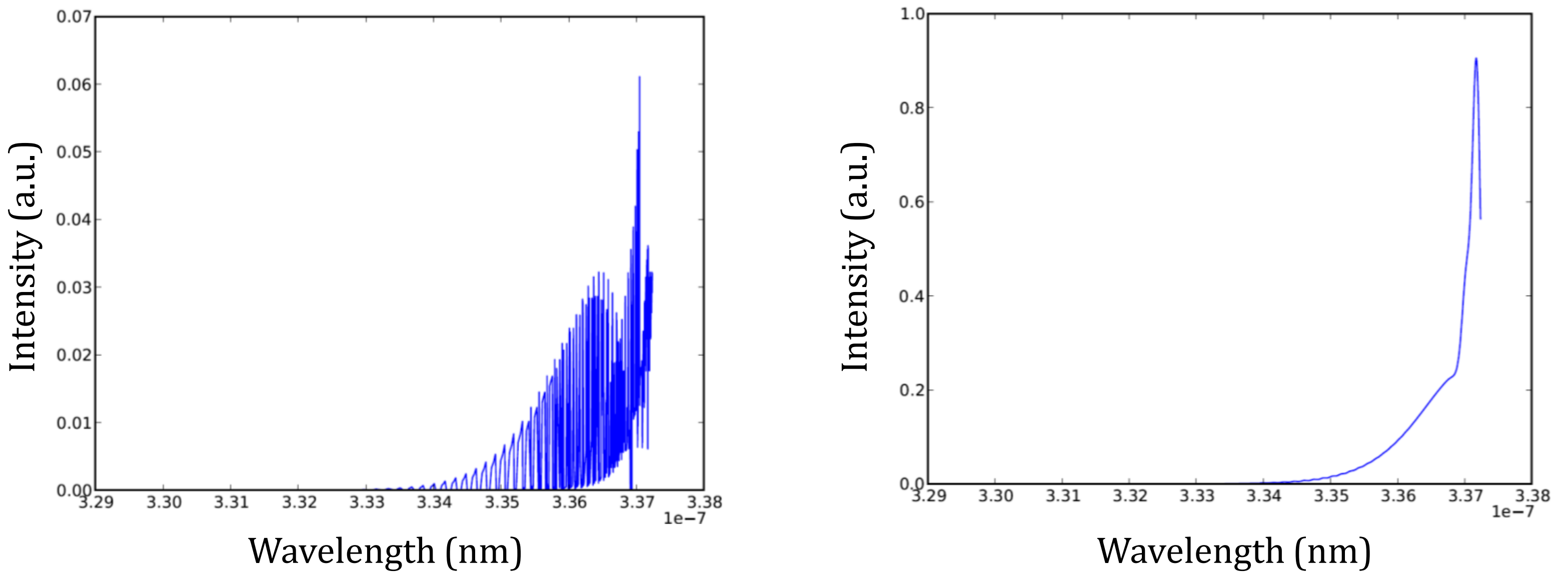
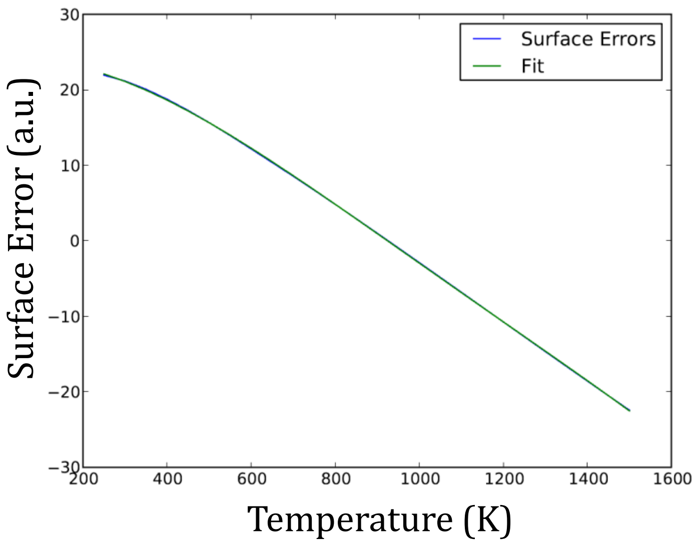


Figure 7 (left) Unbroadened intensities of the 0-0 transition for the second positive system. (right) Spectrum broadened by a Gaussian slit function.

VIII. Temperature Matching

- Program searches predefined range for a given interval
- Surface error at each temperature used as measure of match similar to program developed by Chelouah [8]
- Zero crossing of a quintic fit used to determine "correct" temperature



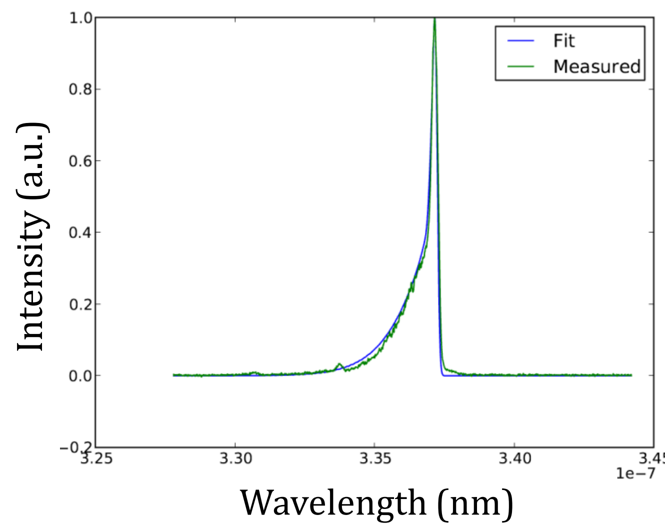


Figure 8 (left) Surface errors for various simulated rotational temperature profiles. (right) Comparison of simulated spectrum to actual spectrum.

IX. Experimental Setup

- Pulses of 8.6 kV_{pp} (FWHM 5 ns) at 20 $\pm$ 0.005 kHz
- 21.3 – 21.5 Torr of air (equivalent to 75,000 ft above sea level)
- Spex 500M monochromator with 2400 g/mm grating (300 nm blaze) coupled to LaVision Picostar HR ICCD

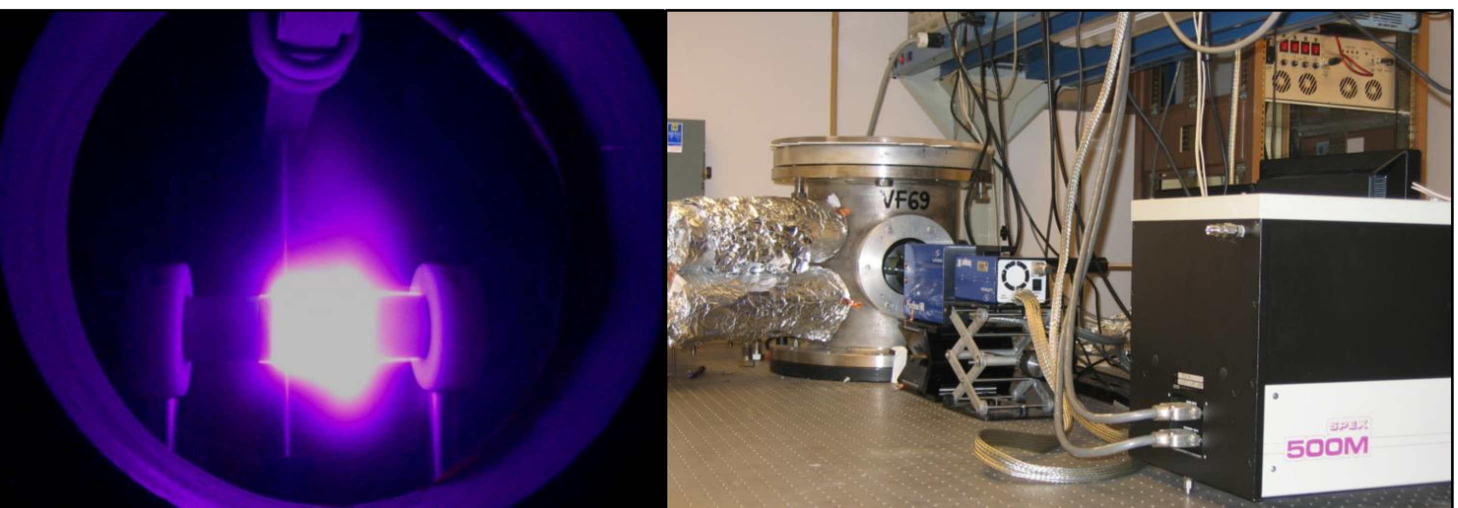


Figure 9 (left) Image of the discharge in operation. (right) Test setup with ICCD, monochromator and vacuum chamber.

X. Intra-Pulse Rotational Temperatures

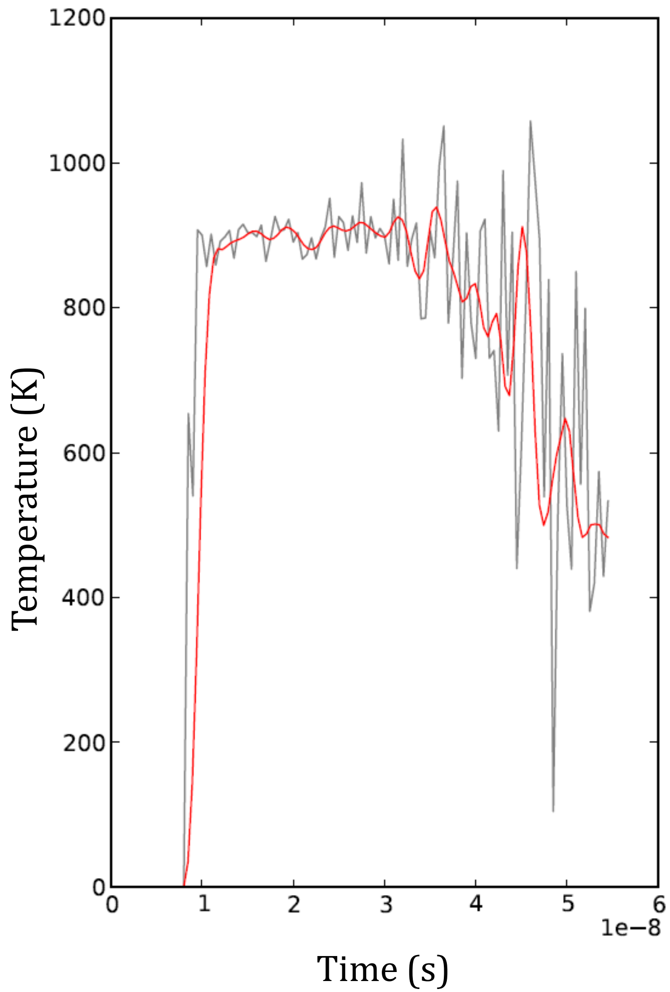
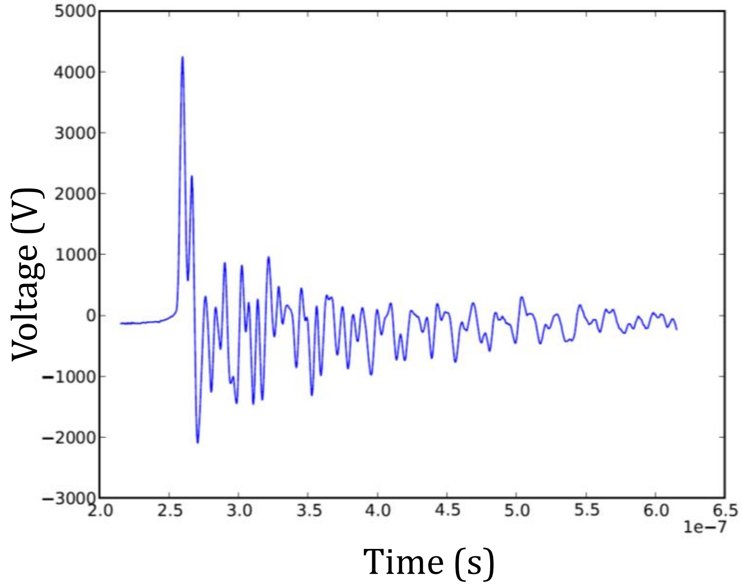


Figure 10 Best match for rotational temperature (gray) and a smoothed curve using a Hanning window (red).

- Rise in temperature essentially a step function
- Significant uncertainty after 25 ns, mostly due to decreasing signal
- Temperature saturates at approximately 900 K
- Apparent decline in rotational temperature after 35 ns

XI. Current and Voltage



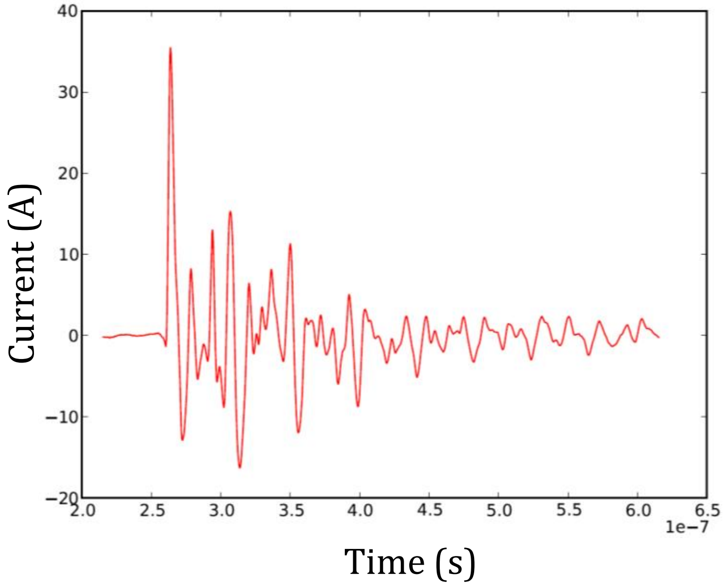


Figure 11 Voltage (left) and current (right) traces of a single pulse.

- Average of 1024 individual pulses
- Significant ringing in transmission lines is evident
- Ringing indicative of a poorly matched load for the pulser

XII. Energy Transfer

- Energy transferred to plasma equal to time integral of the current and voltage multiplied
- Estimated energy transferred per pulse: 0.6 mJ
  - Low amount compared to pulser specifications: 5 – 10 mJ
- Previous measurements of electron density, 2×10^{11} cm^{-3}
  - Ion-pair energy cost of 305 eV
  - Ionization energy of air approximately 34 eV

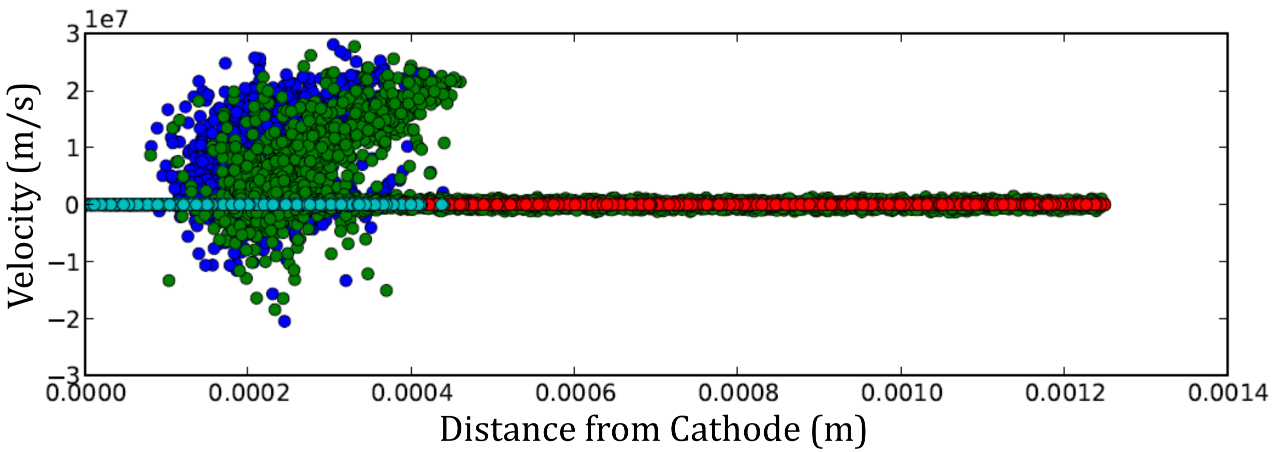


Figure 12 Particle-in-cell simulation of PND in nitrogen showing large collisionality.

XIII. Conclusions

- Verified previous rotational temperature measurements
- Almost immediate rise in rotational temperature
- Measured relatively large energy cost per ion-pair (lower efficiency)
- Created flexible framework for interpretation of rotational spectra

XIV. Future Work

- Improve calibration of spectroscopy system
- Optimize collection optics for spatially resolved measurements
- Adjust monochromator for vibrational spectra
- Expand framework for vibrational temperature matching
- Estimate energy transferred to ro-vibrational states in PNDs
- Determine conditions for most efficient ion-pair production

XV. References

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