Australian National University

NEUTRAL GAS TEMPERATURE MEASUREMENTS OF A RADIO FREQUENCY MICRO-THRUSTER

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SP3 Space Plasma, Power & Propulsion

The Open University

Background

Smaller satellites require smaller propulsion systems

Thrust in the order of μNs to mNs

Electric Propulsion (EP) has high specific impulse (I_{sp})

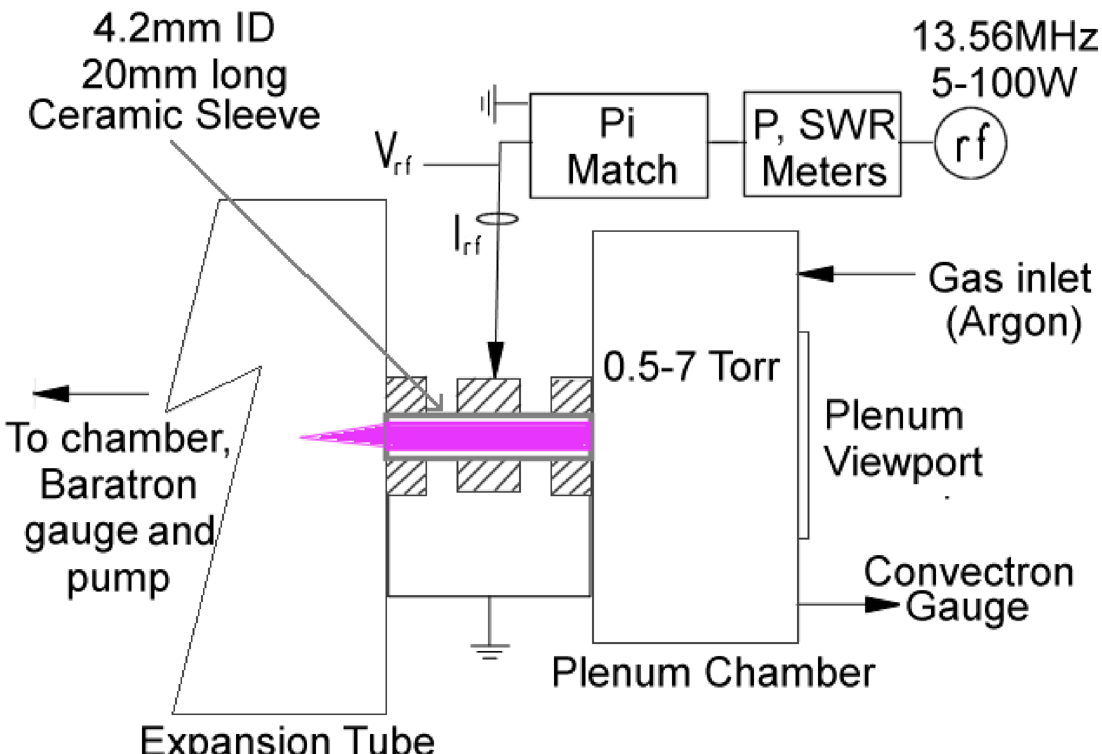
Current EP examples:

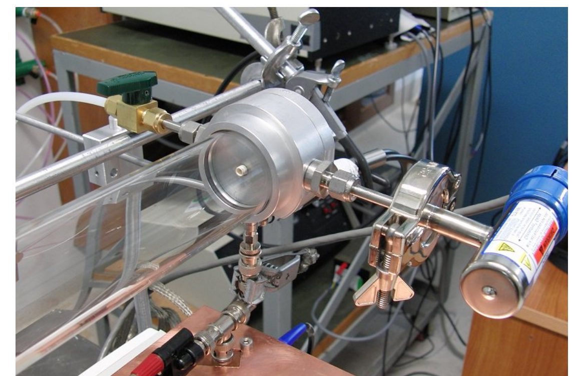
- Hall/gridded ion thruster: Efficiency decreases when scaled down
- Resistojet/Arcjet: Limited lifetimes due to erosion and thermal stress
- Pulsed Plasma Thrusters: Electromagnetic broadband radiation

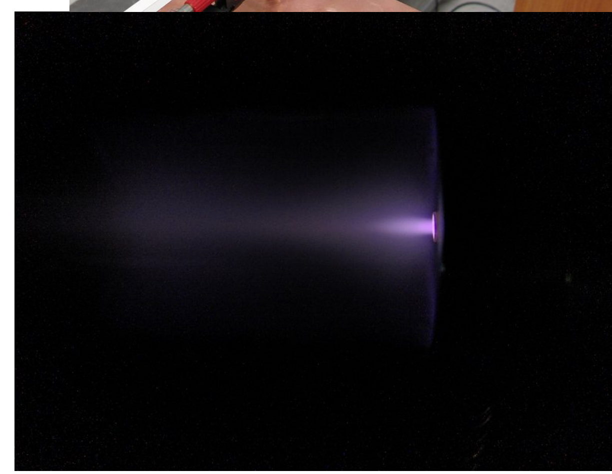
Pocket Rocket

Capacitively coupled radio-frequency (rf) argon discharge

Produces weakly ionised plasma (~1%)







Pocket Rocket Thrust Estimates

Rocket Equation $T = v_{ex} \frac{d\,m_p}{d\,t}$ with $v_{ex} = \left(\frac{8\,k\,T_g}{\pi M}\right)^{\frac{1}{2}}$

Cold Gas Thruster Effect: $\frac{d\,m_p}{dt} = 3\,mg\ s^{-1} \rightarrow T \approx 1\text{mN}$

Power to kinetic energy calculations [1]:

$P_{in} = 10\,W = 10\text{Js}^{-1}$ of KE $\rightarrow v_{ex} = 2600\text{ms}^{-1}$

$v_{ex_z} = \frac{v_{ex}}{3} \approx 860\,ms^{-1} \rightarrow T_g = 1430\text{K}$ and $T \approx 2.6\text{mN}$

Langmuir Probe experiment (10W, 1.5Torr) [1]:

Electron temperature $T_e = 3\text{eV}$

Estimates $T_g = 3200\text{K} \rightarrow v_{ex_z} = 1290\,ms^{-1} \rightarrow$ and $T \approx 3.8\text{mN}$

[1] C Charles and R.W Boswell Plasma Sources Sci. Technol. 21(2012)

Pocket Rocket Thrust Estimates

Particle Balance:

$T_e = 2\text{eV}$ gives $T_g \approx 300\text{K} \rightarrow T = 1\text{mN}$

$T_e = 2.5\text{eV}$ gives $T_g \approx 1430\text{K} \rightarrow T = 2.6\text{mN}$

Neutral gas heating occurring?

Ion neutral collisions $\lambda_{mfp} = 45\mu m$ at 1.5 Torr

~92 collisions across 4.2mm discharge diameter

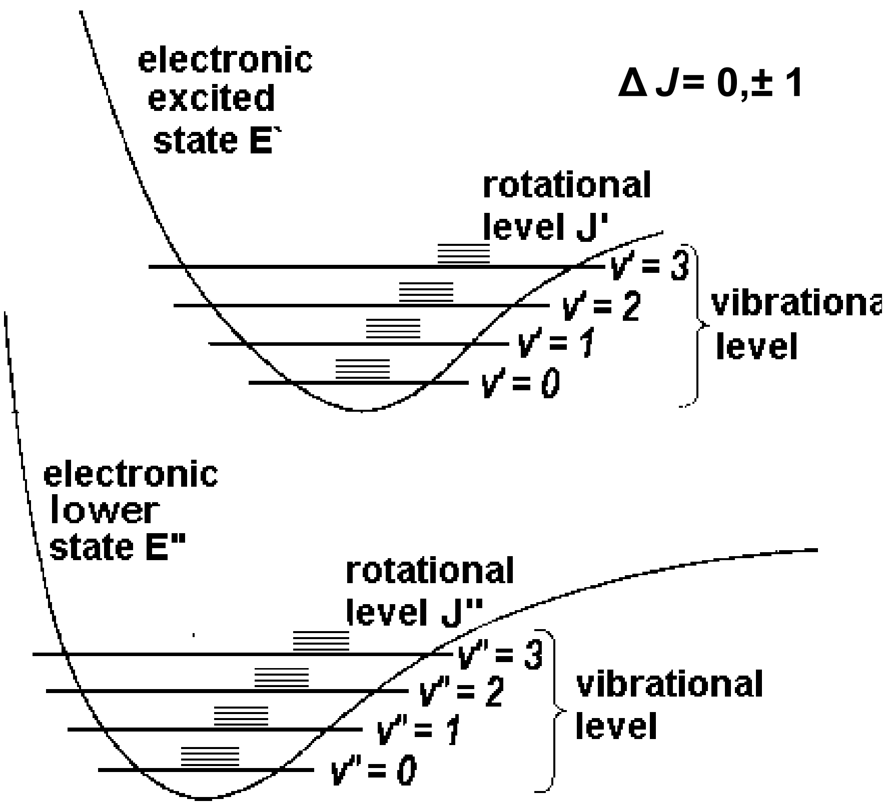
~46 ion–neutral charge exchange collisions

Direct thrust measurements ideal

-engineering challenges prevent at this time

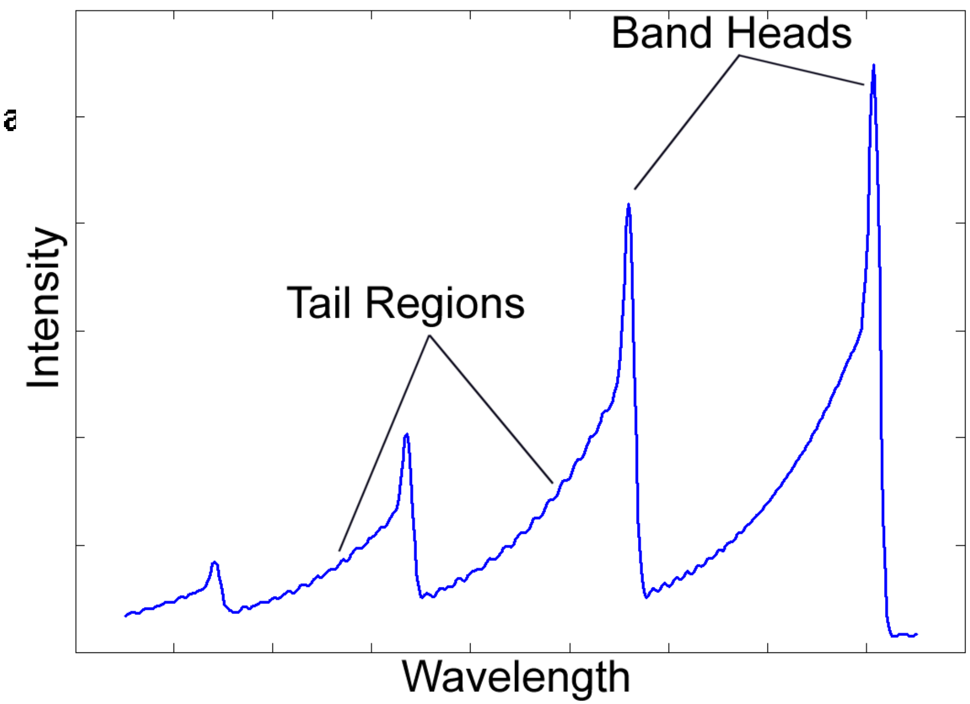
Rovibrational Spectroscopy

Electronic transition (E',v',J') → (E",v",J")



Adapted from http://www.pci.tu-bs.de

Find T_r and T_v from band spectrum shape then $T_r \approx T_g$



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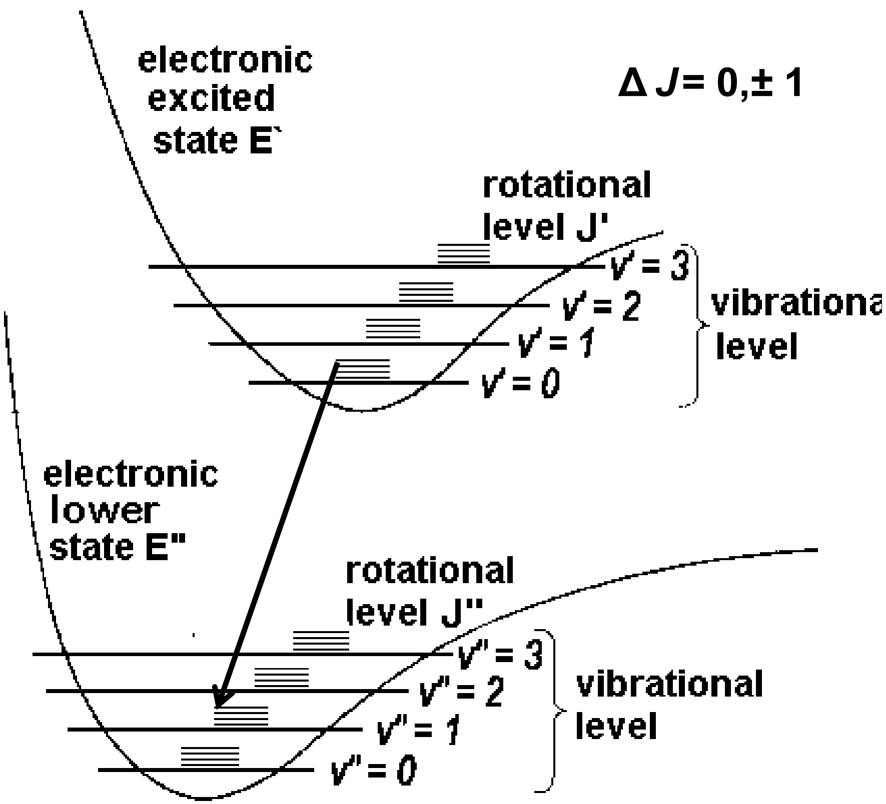

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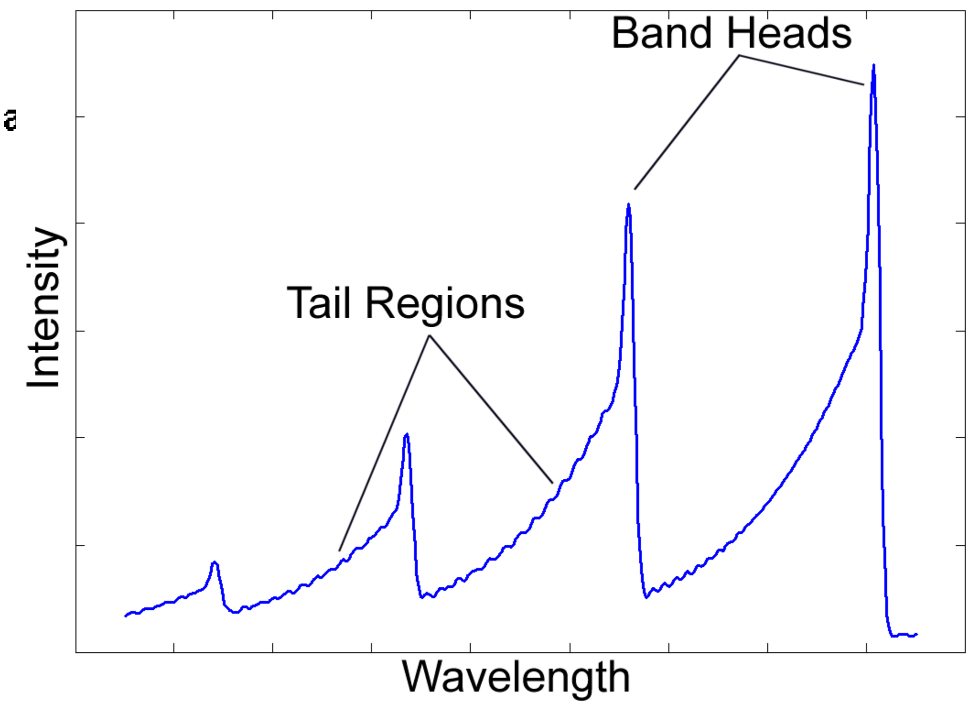

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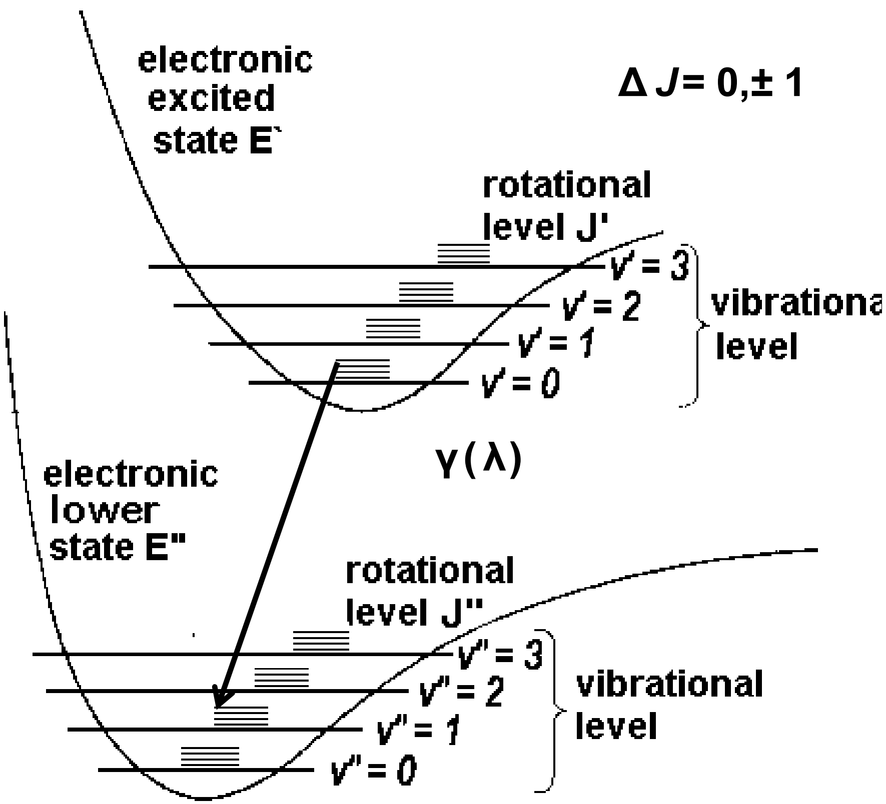

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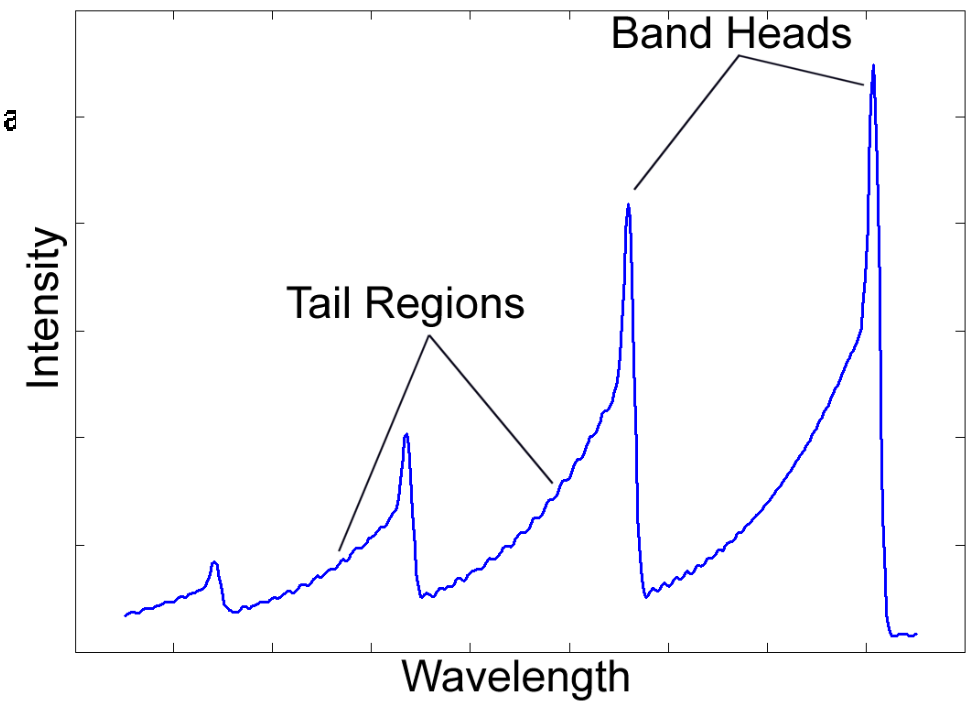

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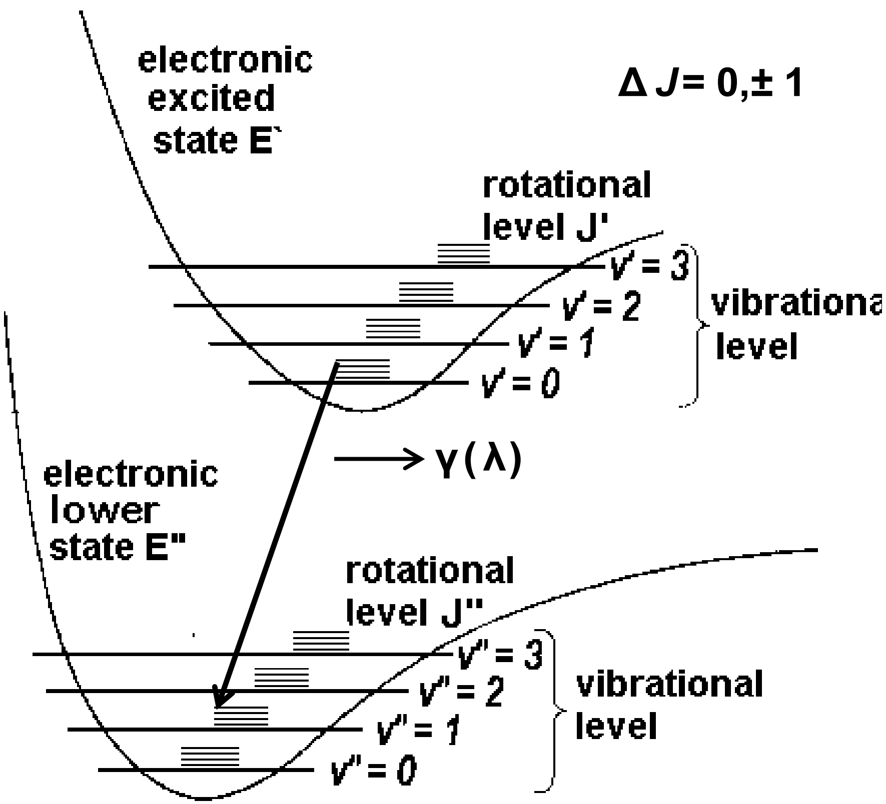

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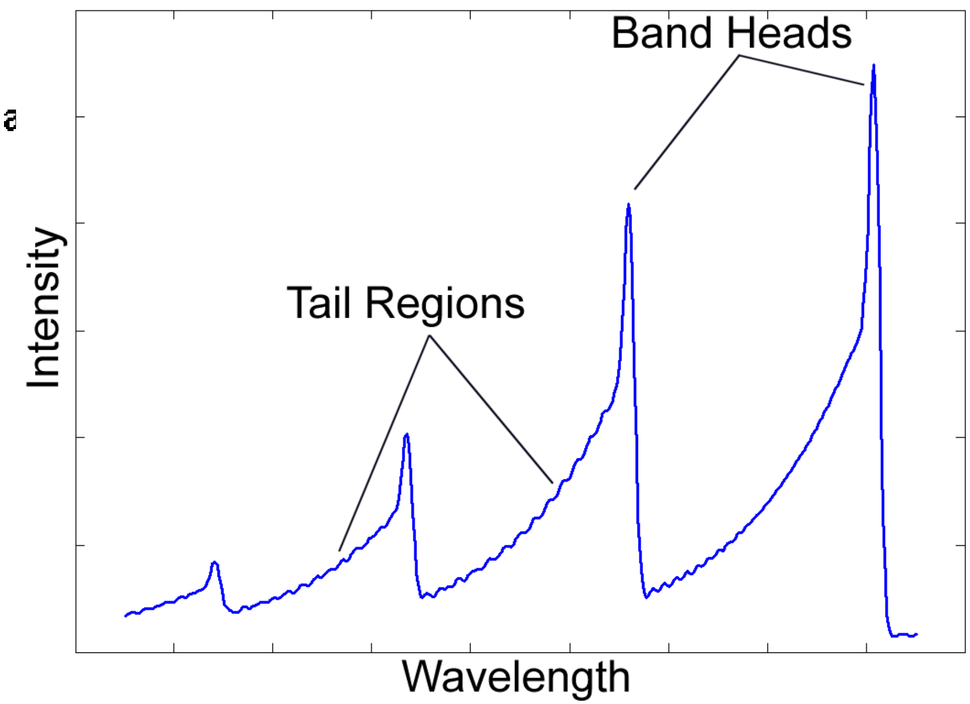
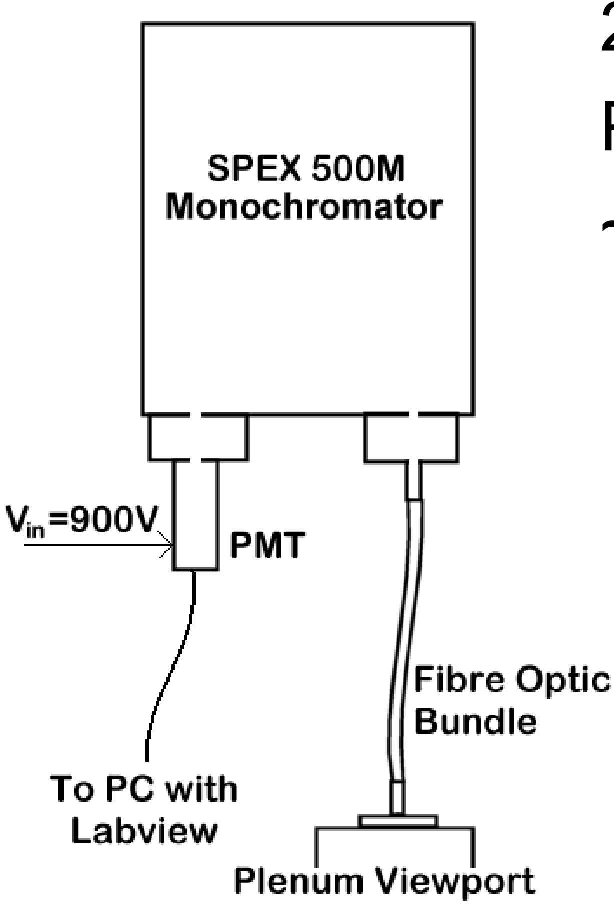


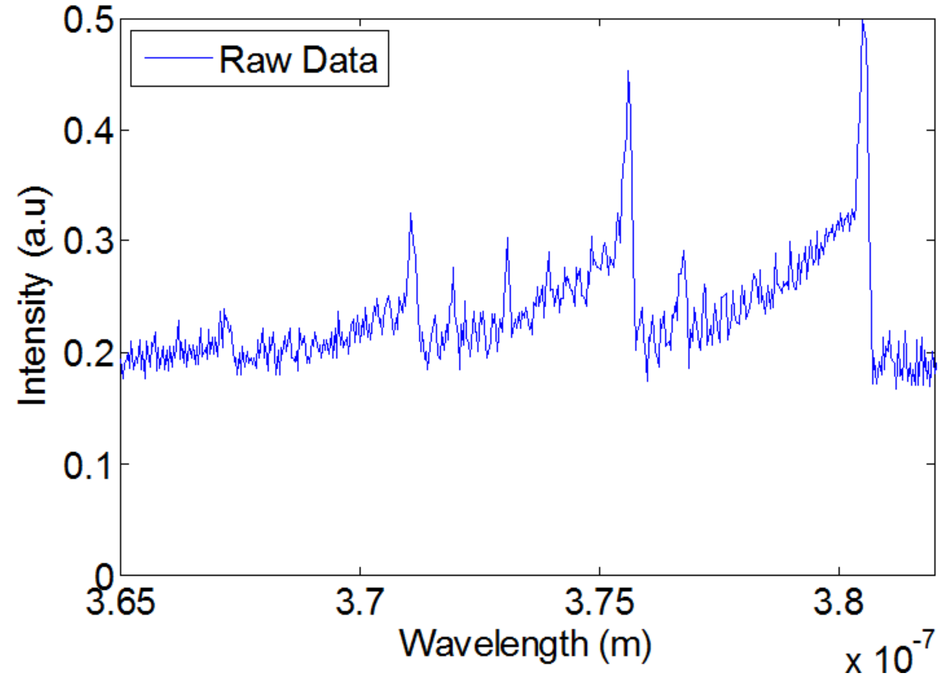
Experimental Setup



2nd positive N_2 system

Power: 5-40W, Pressure: 0.5-4Torr

~10% N_2 (too high, ideal <5%)



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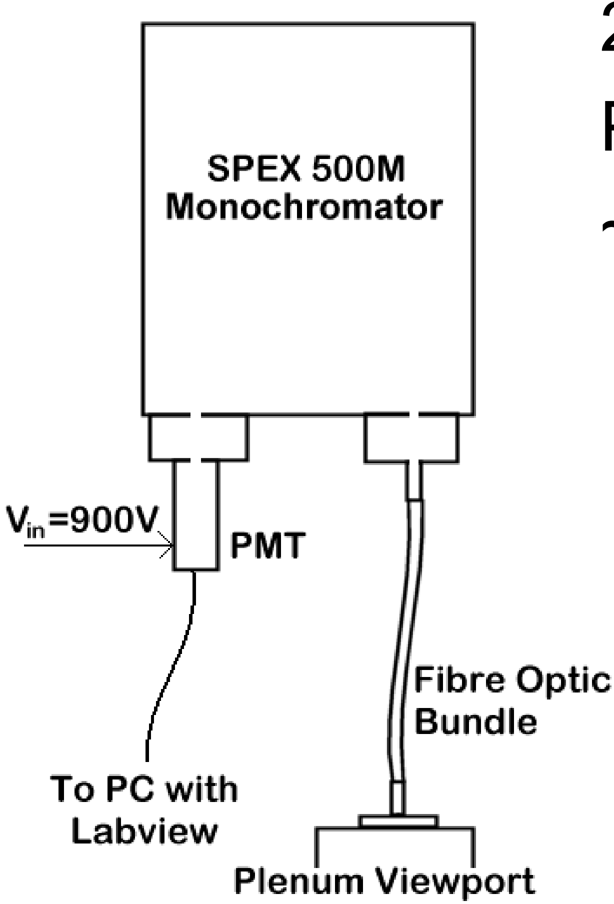

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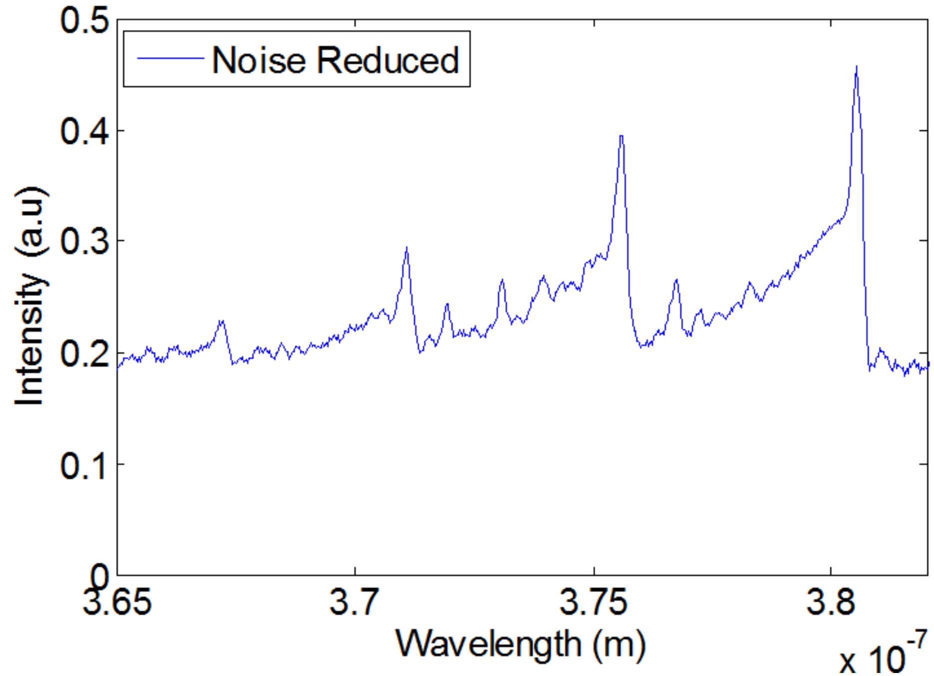

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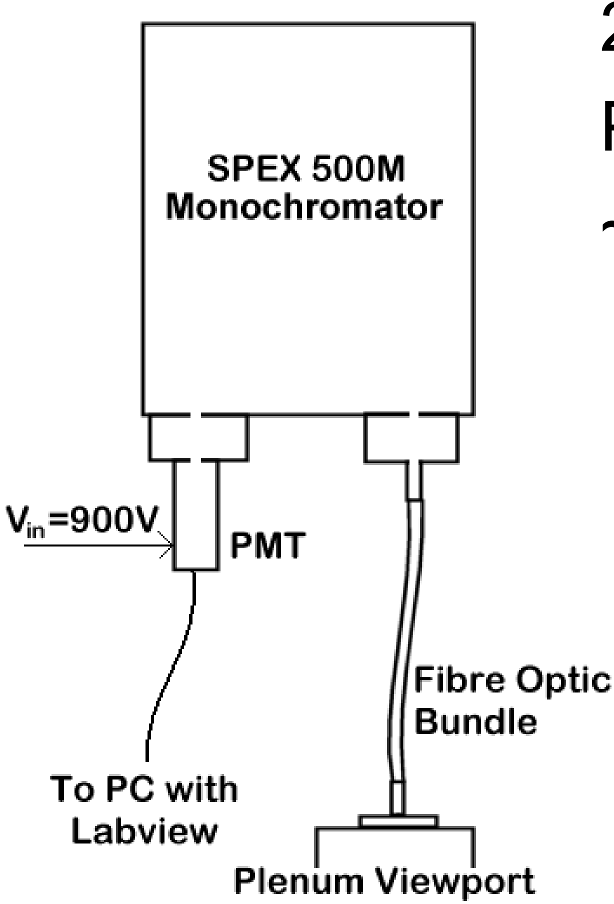

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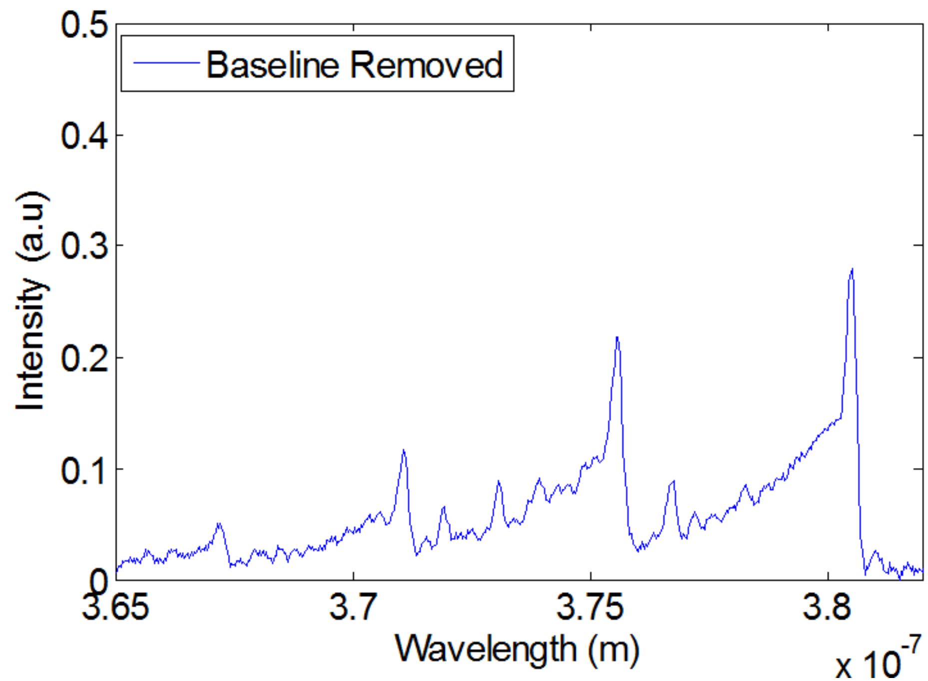

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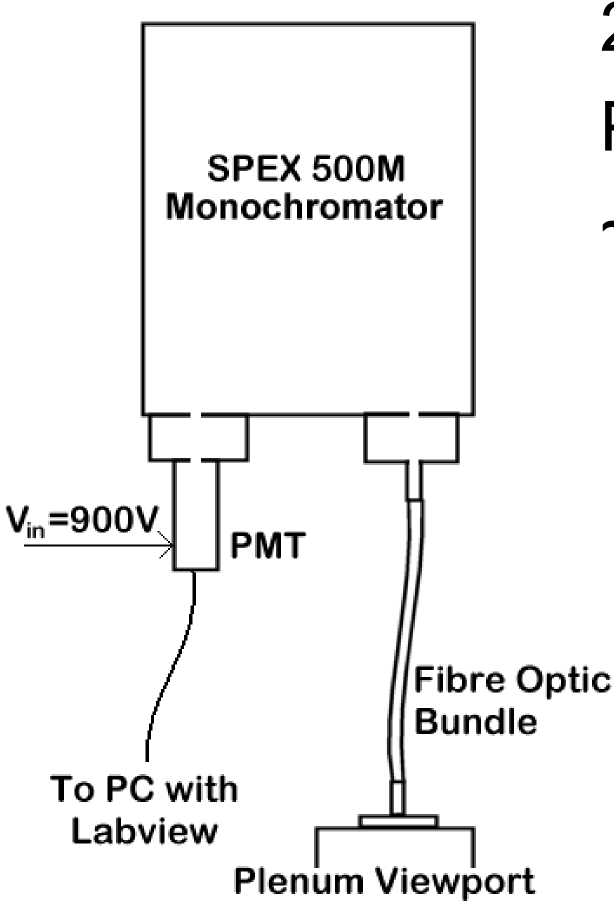

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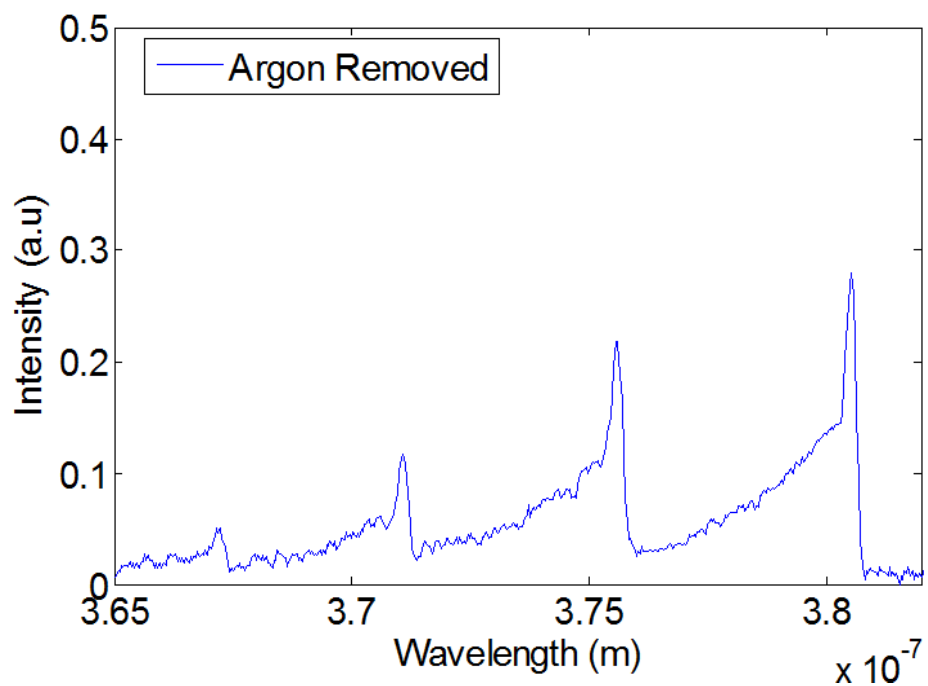
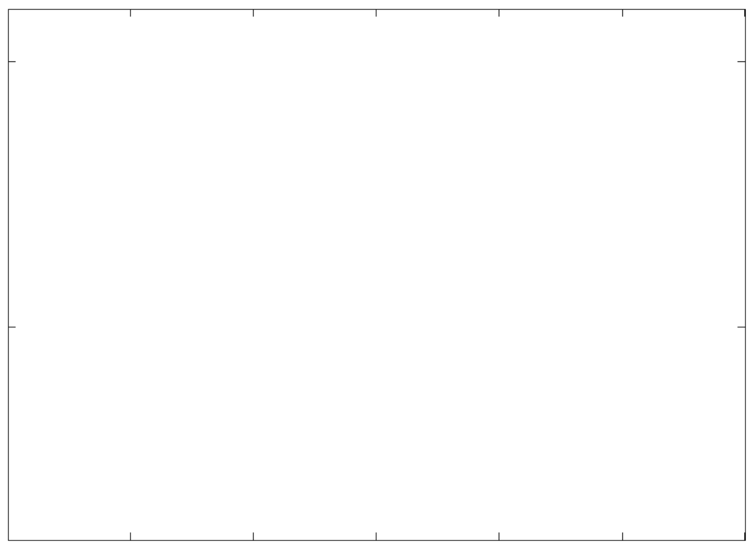


Simulated Spectrum

1) Wavelengths $\lambda = \left\{ n_a \sum_{pq} Y^{c}_{pq} \left(v' + \frac{1}{2}\right)^{p} [J'(J'+1)]^{q} - Y^{B}_{pq} \left(v'' + \frac{1}{2}\right)^{p} [J''(J''+1)]^{q} \right\}^{-1}$

2) Intensity $I = \frac{D}{\lambda^4} q_{v',v''} \exp\left[\frac{-E_{v'}}{kT_v}\right] S_{J',J''} \exp\left[\frac{-E_{J'}}{kT_r}\right]$

3) Line broadening function $g(\Delta\lambda) = \frac{a - (2\Delta\lambda/W)^2}{a + (a-2)(2\Delta\lambda/W)^2}$



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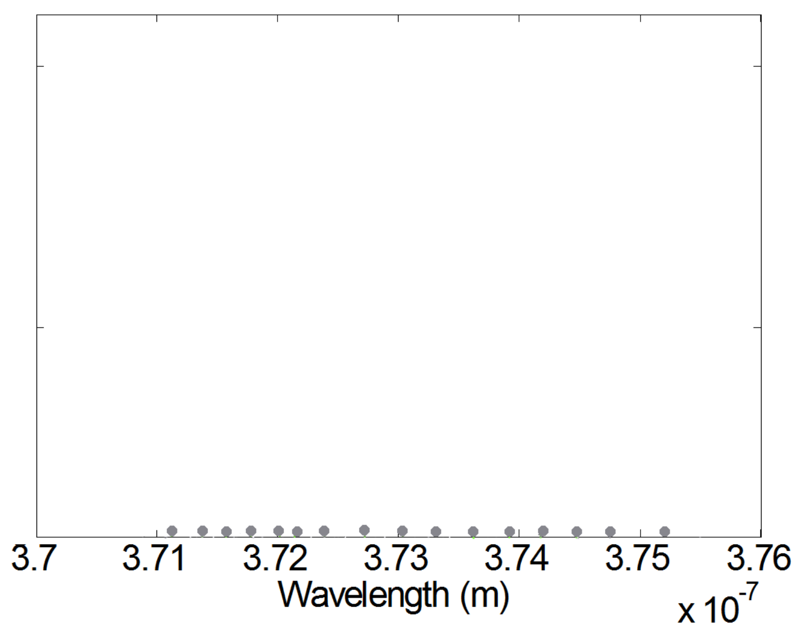

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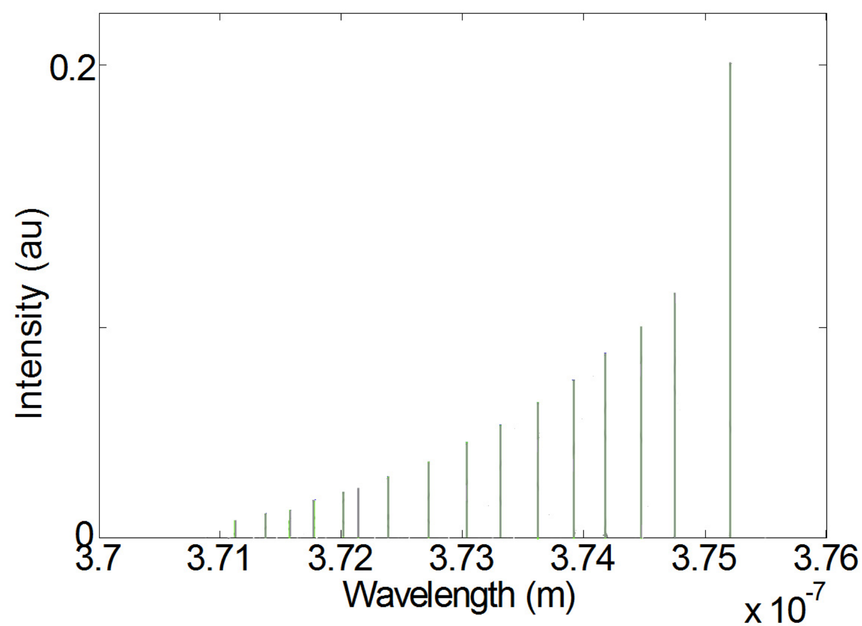

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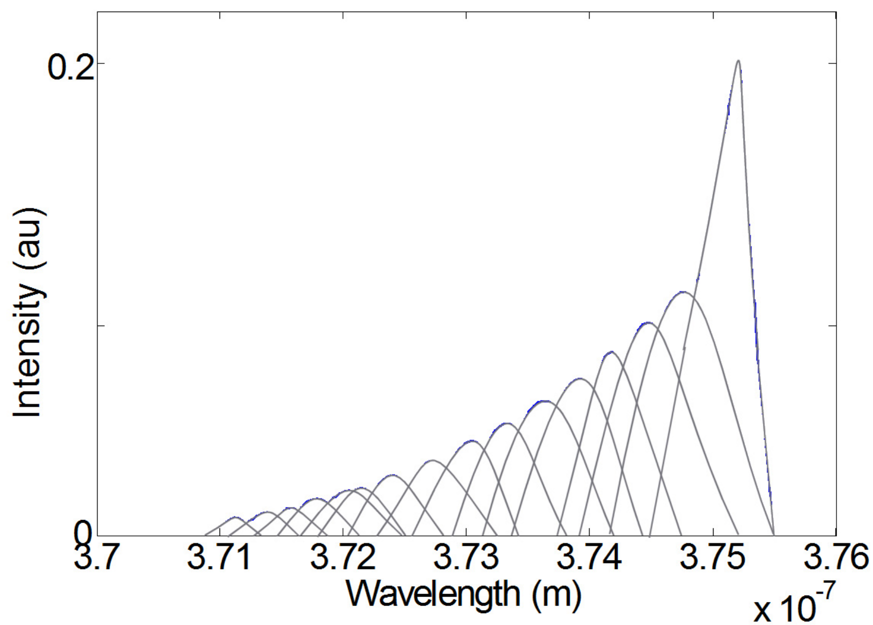

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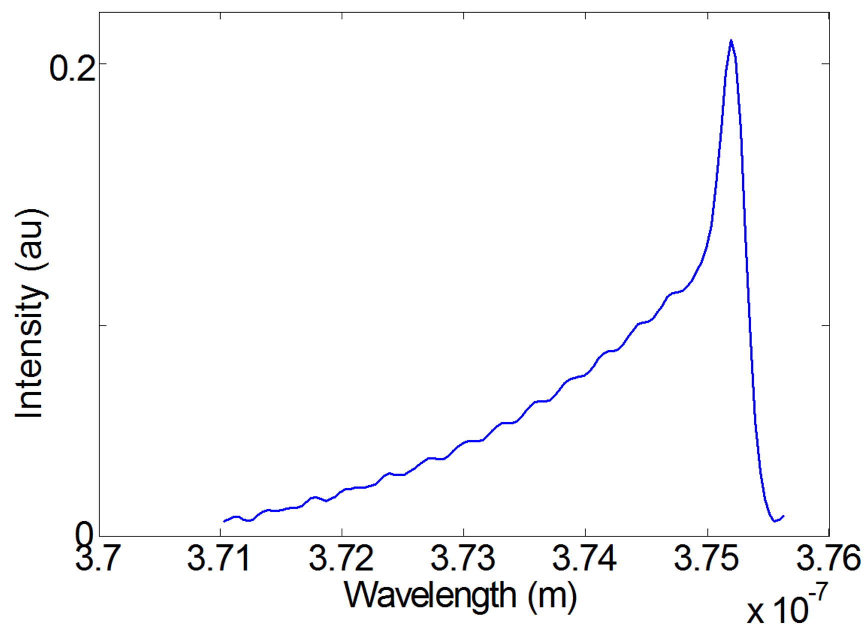
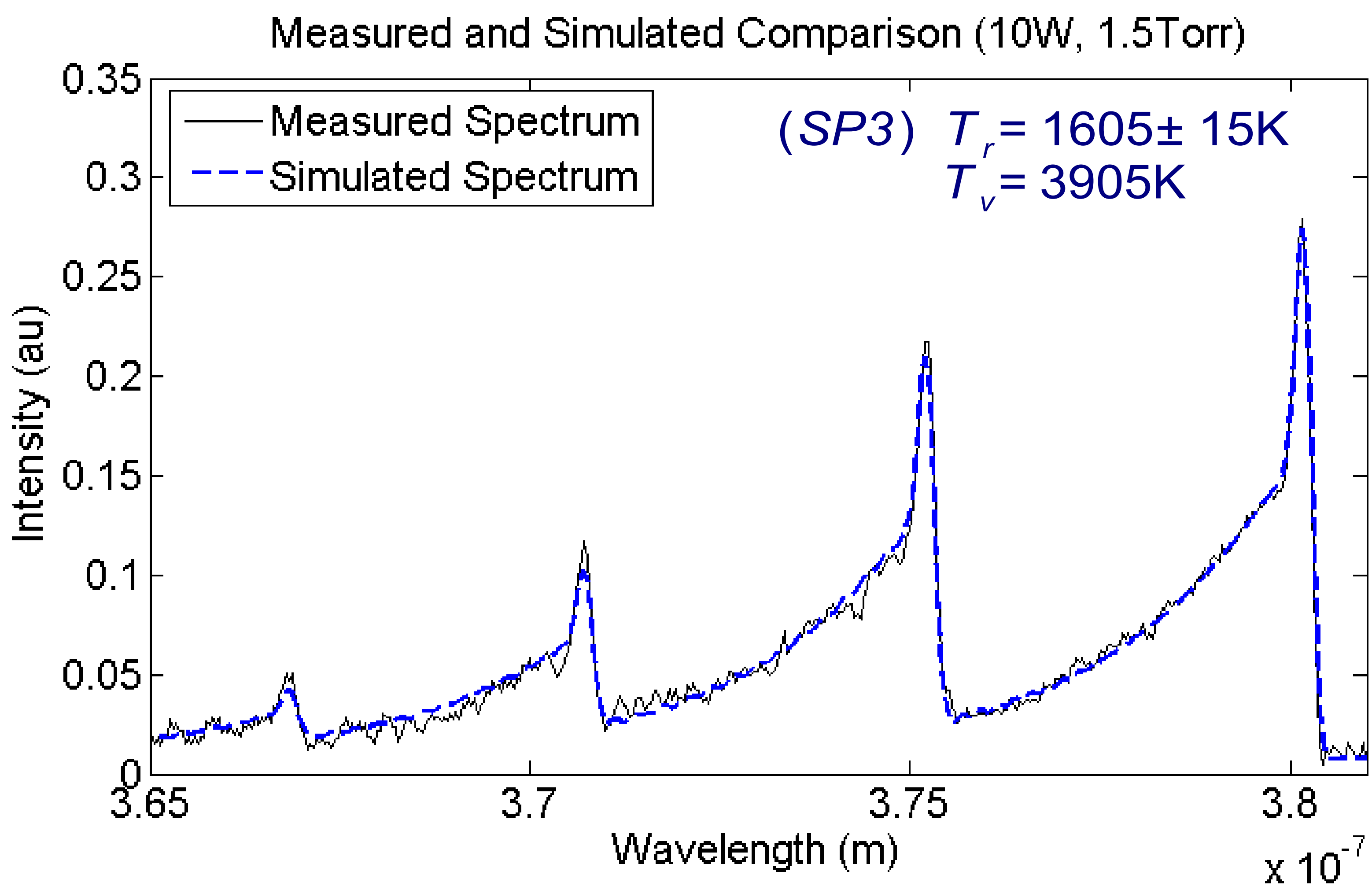
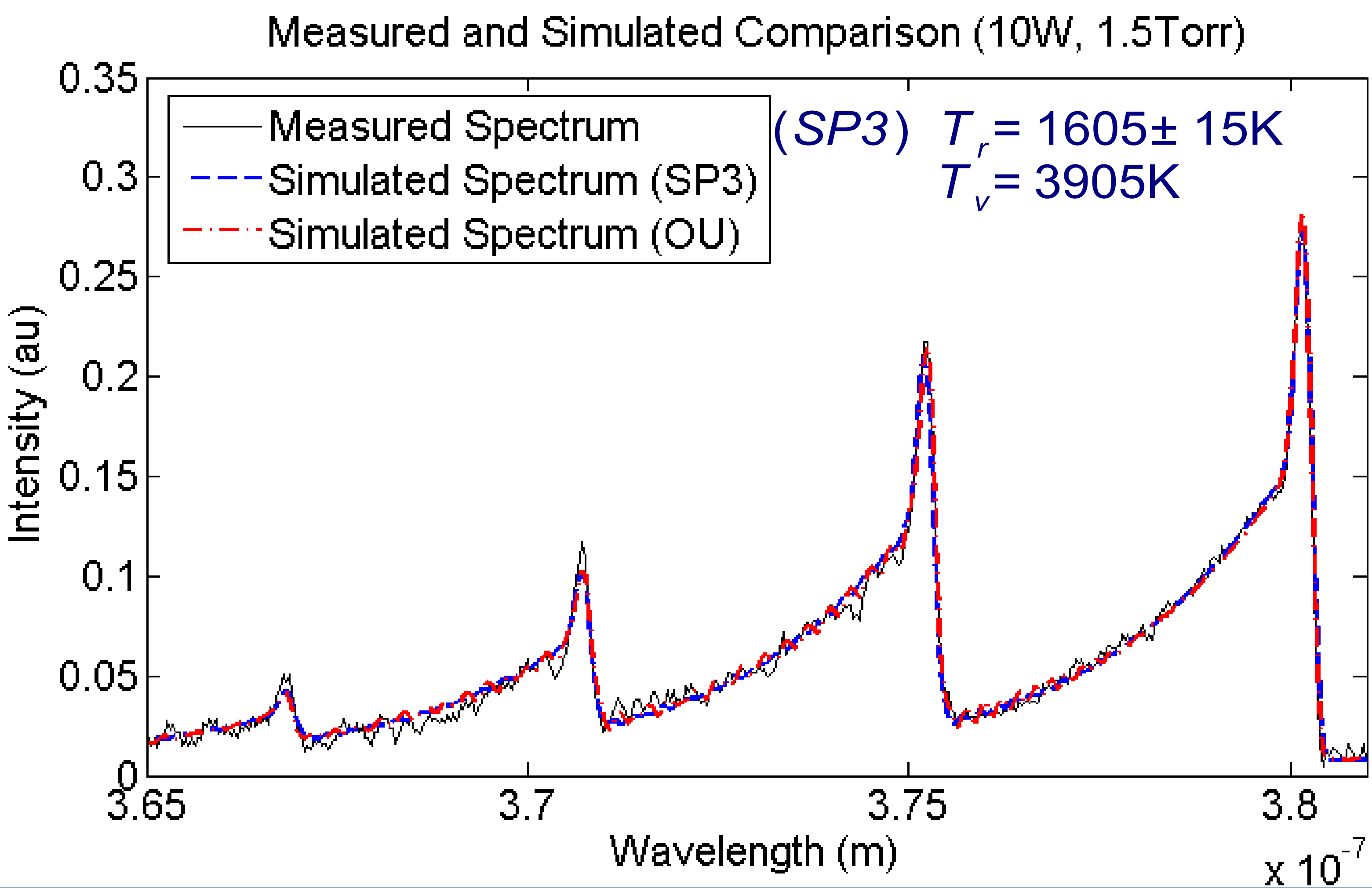


Matching


Measured and Simulated Comparison (10W, 1.5Torr)
Measured Spectrum
Simulated Spectrum
(SP3) T_r = 1605± 15K
T_v = 3905K
Intensity (au)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
3.65
3.7
3.75
3.8
Wavelength (m)
x 10^{-7}

Matching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Measured Spectrum
Simulated Spectrum (SP3)
Simulated Spectrum (OU)
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T_v = 3905K
Intensity (au)
Wavelength (m)
x 10^-7
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0.25
0.2
0.15
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0.05
0
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3.7
3.75
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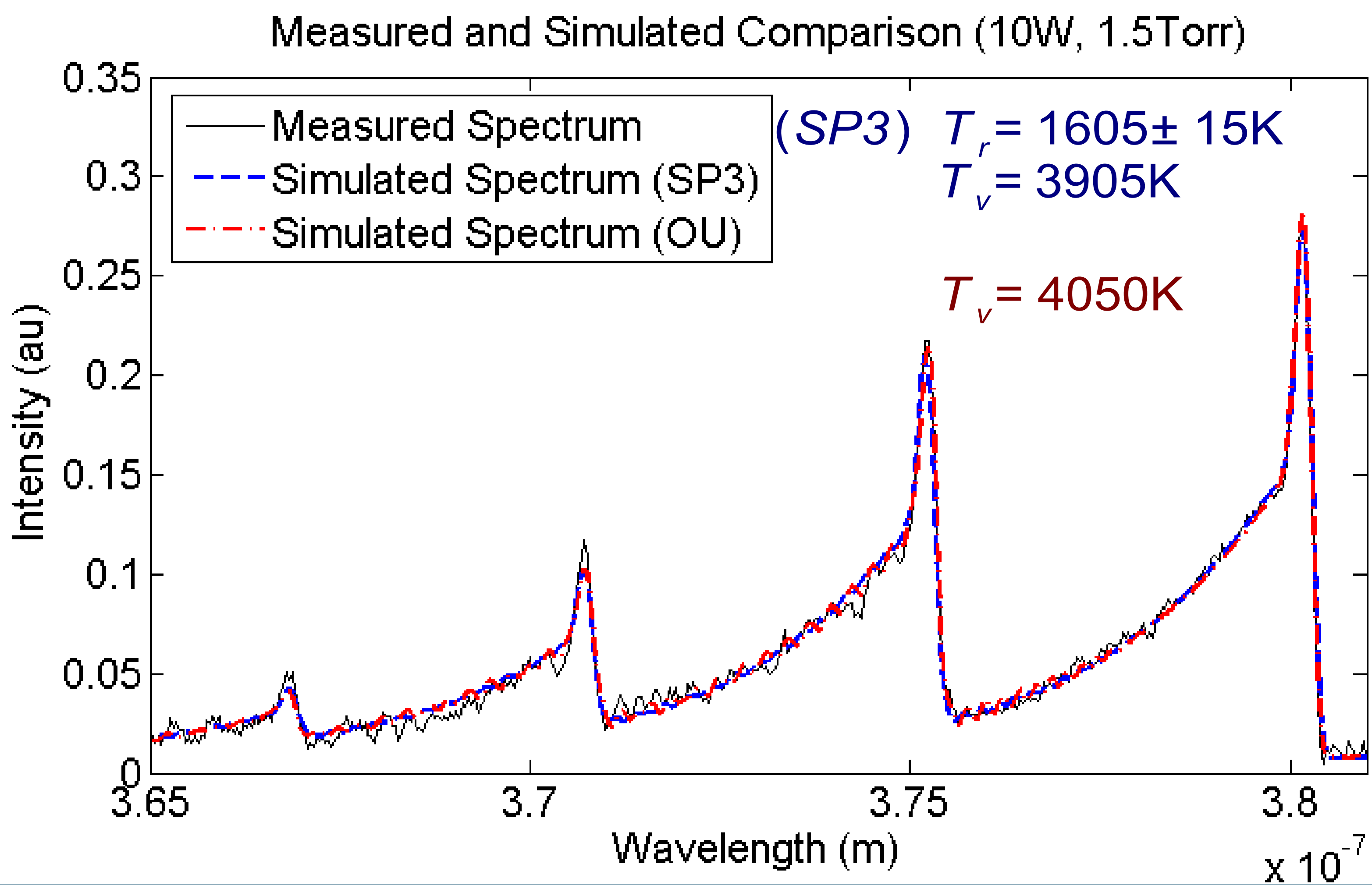
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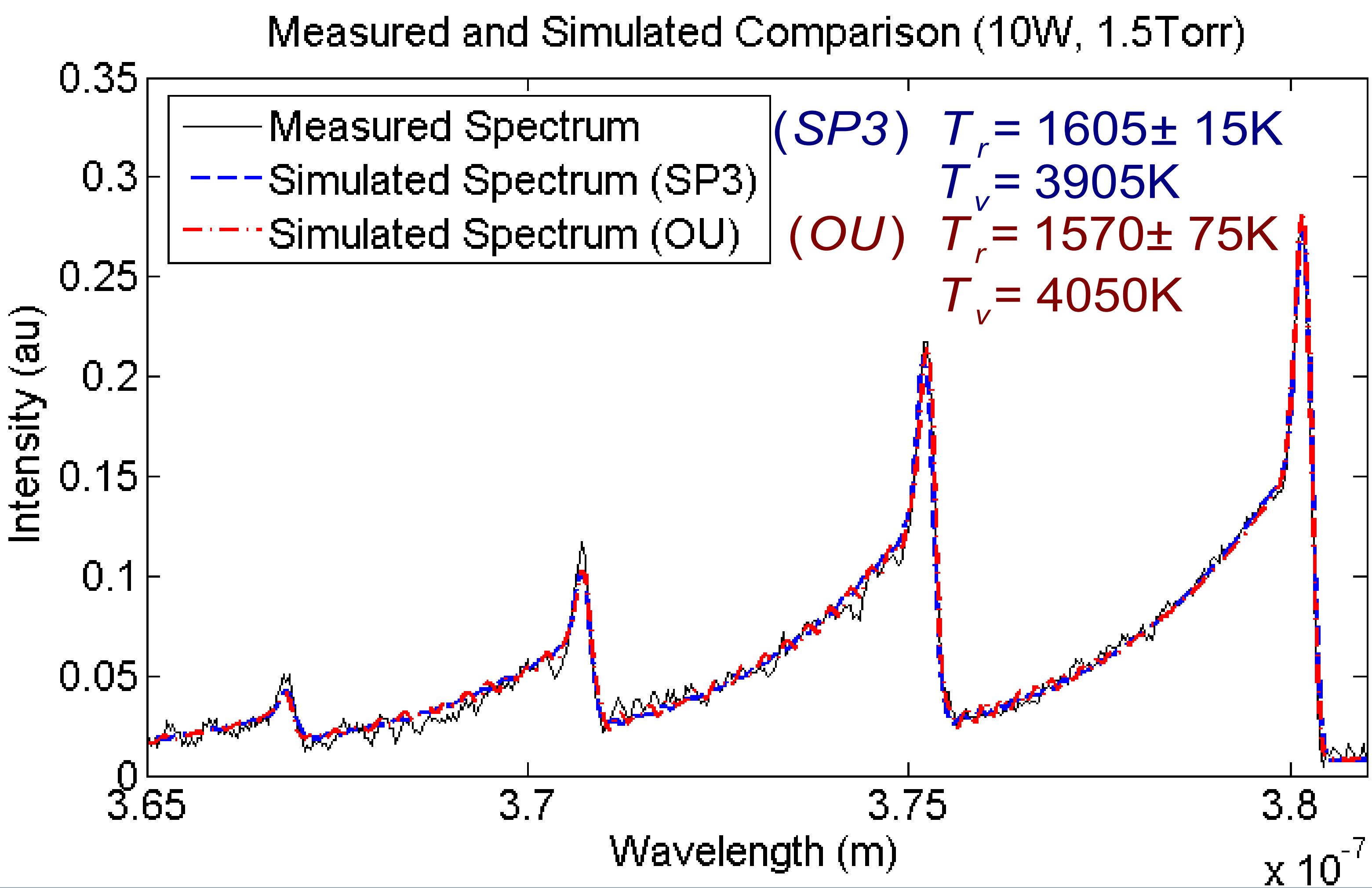
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0.3
0.25
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0.1
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0
3.65
3.7
3.75
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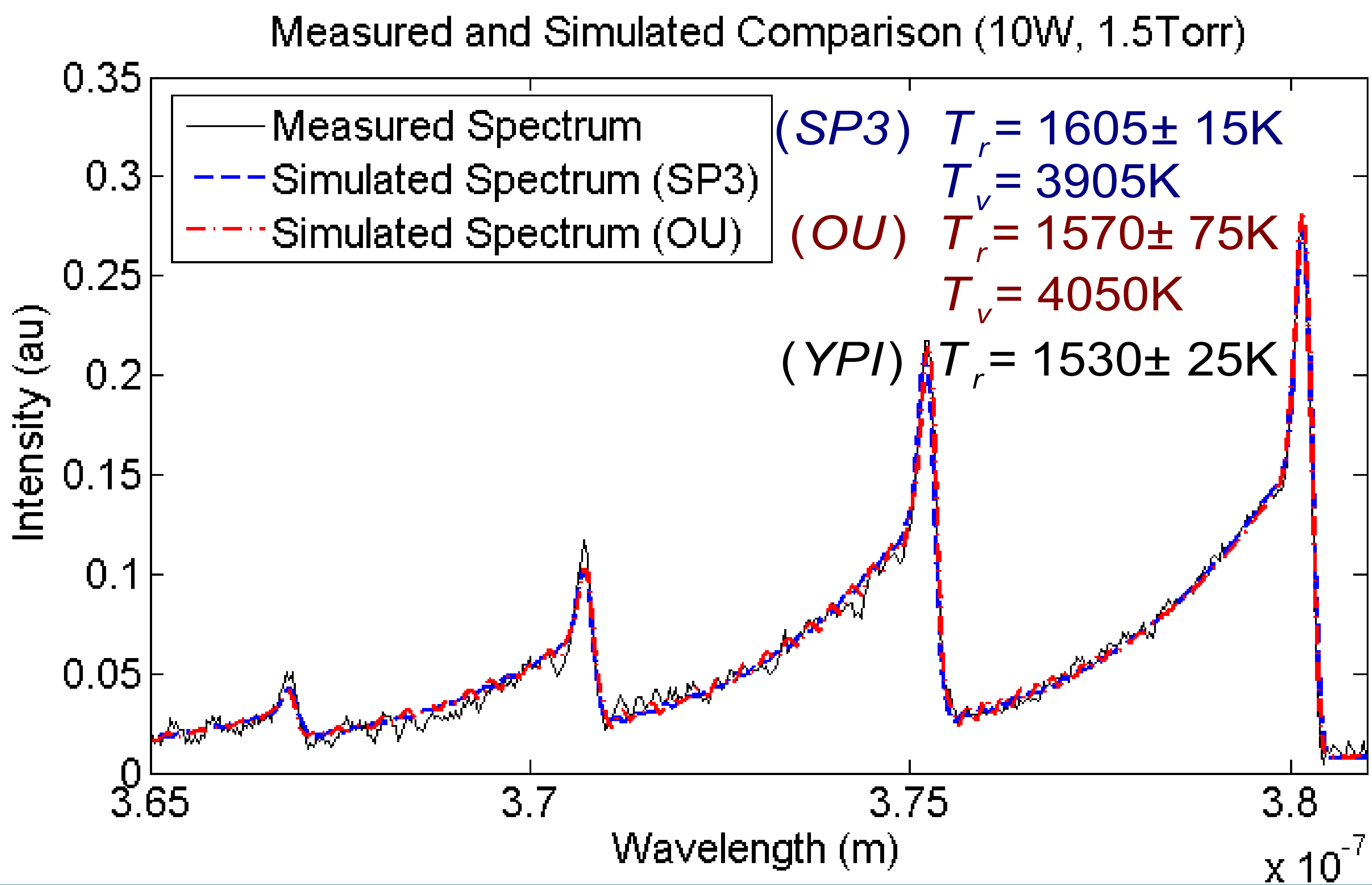
Wavelength (m)
x 10^{-7}

Matching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(YPI) T_r = 1530± 25K
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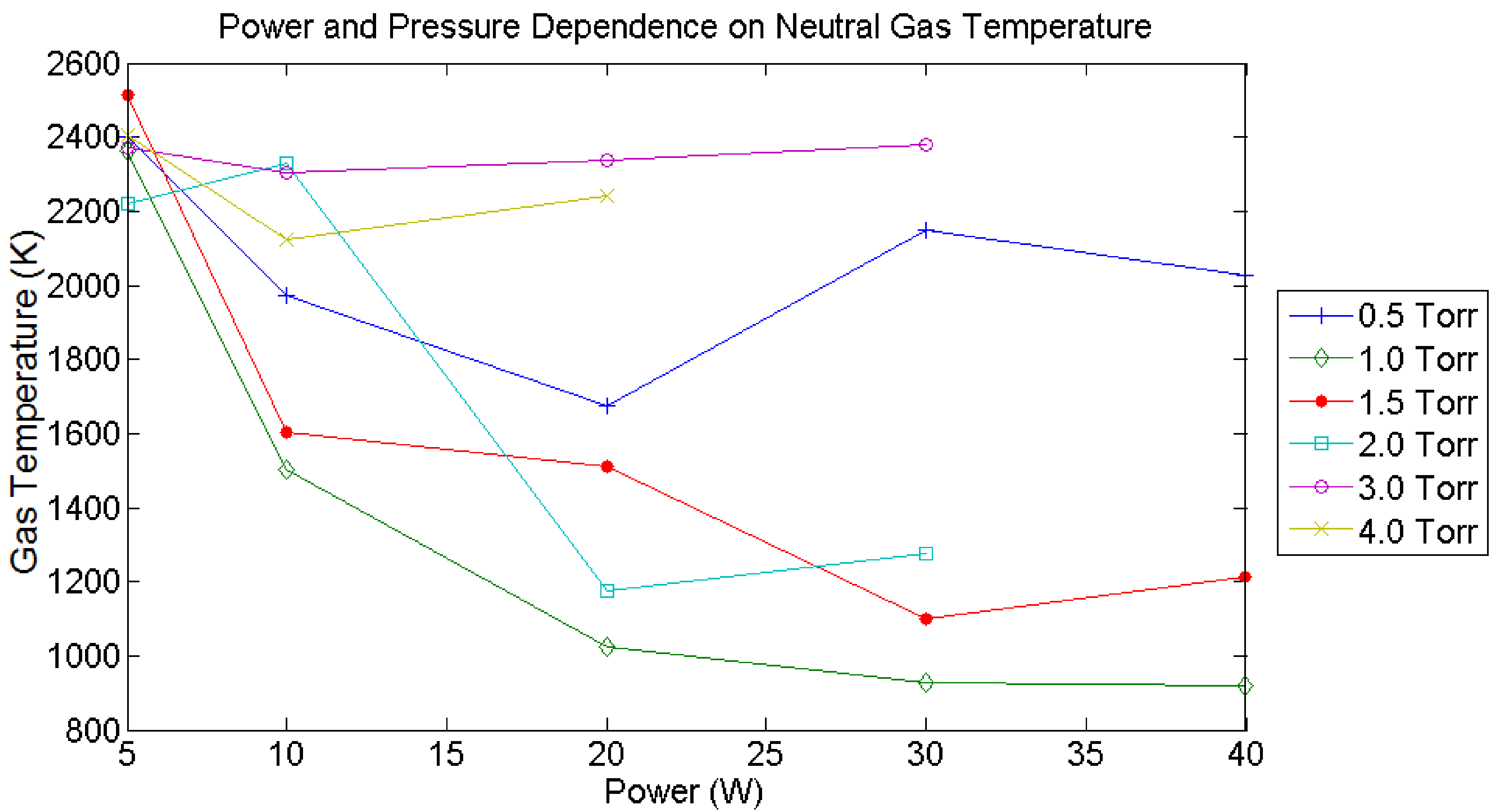
Preliminary Results



Pressure and Power

Bohm velocity $v_B = (\frac{e T_e}{M_i})^{\frac{1}{2}} \approx 2700 \mathrm{ms}^{-1}$

Mean free path $\lambda_{CE} = \frac{1}{n_g \sigma_{CE}}$

Power

- T_e relatively constant → v_B and T_g constant
- Mode change (rotational to vibrational) → T_g decreases

Pressure

- T_e decreases with increasing pressure → v_B and T_g lower
- BUT n_g increases → λ_{CE} decreases → T_g increases

Ceramic heating may also occur

Conclusions

Model for finding T_g has been developed

- Good T_g estimates
- Matches independent code results

Preliminary Results

- Neutral gas heating occurs in PR discharge
- Power and pressure dependence

Future works:

- Refine method to reduce noise issues – CCD array
- If neutral gas heating found work on direct thrust measurements
- Investigate other gases such as CO_2 using same method

Acknowledgements

Aspects of this research made use of software developed by the Inversion Laboratory (ilab). Ilab is part of the Auscope AGOS project - an initiative of the Australian Government funded through the Education Investment Fund.

Kari Niemi from York Plasma Institute for his assistance with a third independent code for checking the data

Peter Alexander from SP3 for being such a wonderful technician