Evaluation of Collisional-Radiative Model for Argon I on the Texas Helimak

Qualifier Seminar by

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Goals

- Understand and test structure of a collisional-radiative model for Ar I.
- Compare predictions of model using the Texas Helimak.

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Emission Spectroscopy

- Passively gain information on state of plasmas
  - Plasma constituents, impurities, ionization states
  - Density
  - Temperature
  - Bulk motion

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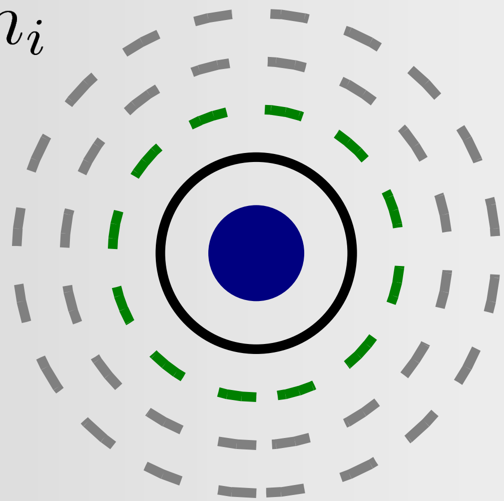
Atomic States as Populations



- Each state is independent population.

$$n_0 = \sum n_i$$

- Spectral line intensity proportional to population density.

$$I_{kj} = A_{kj} n_k$$

Simple Models for Populations

High Density

Collisional Transitions Dominate (detailed balance)

$$\sum_i \langle \sigma_{ki} v \rangle n_e \gg A_k$$

$$\langle \sigma_{ij} v \rangle n_i = \langle \sigma_{ji} v \rangle n_j$$

Thermal Equilibrium

$$\frac{n_i}{n_0} = \frac{g_i}{g_0} e^{-\beta(E_i - E_0)}$$

Low Density

Radiative Transitions Dominate ("coronal" limit)

$$\sum_i \langle \sigma_{ki} v \rangle n_e \ll A_k$$

$$\langle \sigma_{1k} v \rangle n_e n_1 = A_k n_k$$

$$A_k = \sum_i A_{ki}$$

Collisional-Radiative Model

- Medium Density: develop full rate equations.

$$\frac{dn_i}{dt} = R_{gain}(n_{j\neq i}, n_e, T, ...) - R_{loss}(n_i, n_e, T, ...) = 0$$

- Can include many different rate processes.
- Solve system of equations for level population, which then gives line emission.

$$I_{kj} = A_{kj} n_k(n_e, T, ...)$$

- In principle, could be “inverted” for density, temperature, ...

Collisional Processes

- Electron and atomic impact excitation, de-excitation, ionization, and three-body recombination

Example semi-empirical cross-section:

$$\sigma_{ex}(i,j,E) \propto (E/E_{ij}-1)ln(CE/E_{ij})(E/E_{ij})^{-2}$$

- Assume isotropic Maxwellian distribution.

$$\langle \sigma v \rangle = \int d\mathbf{v}\sigma v f(\mathbf{v}) = \sqrt{\frac{2}{\pi}(\frac{m_e}{kT})^3} \int dv \sigma v^3 exp[-m_e v^2/2kT]$$

$$\langle \sigma v \rangle = \frac{2}{m_e^2}\sqrt{\frac{2}{\pi}(\frac{m_e}{kT})^3} \int dE \sigma E exp[-E/kT]$$

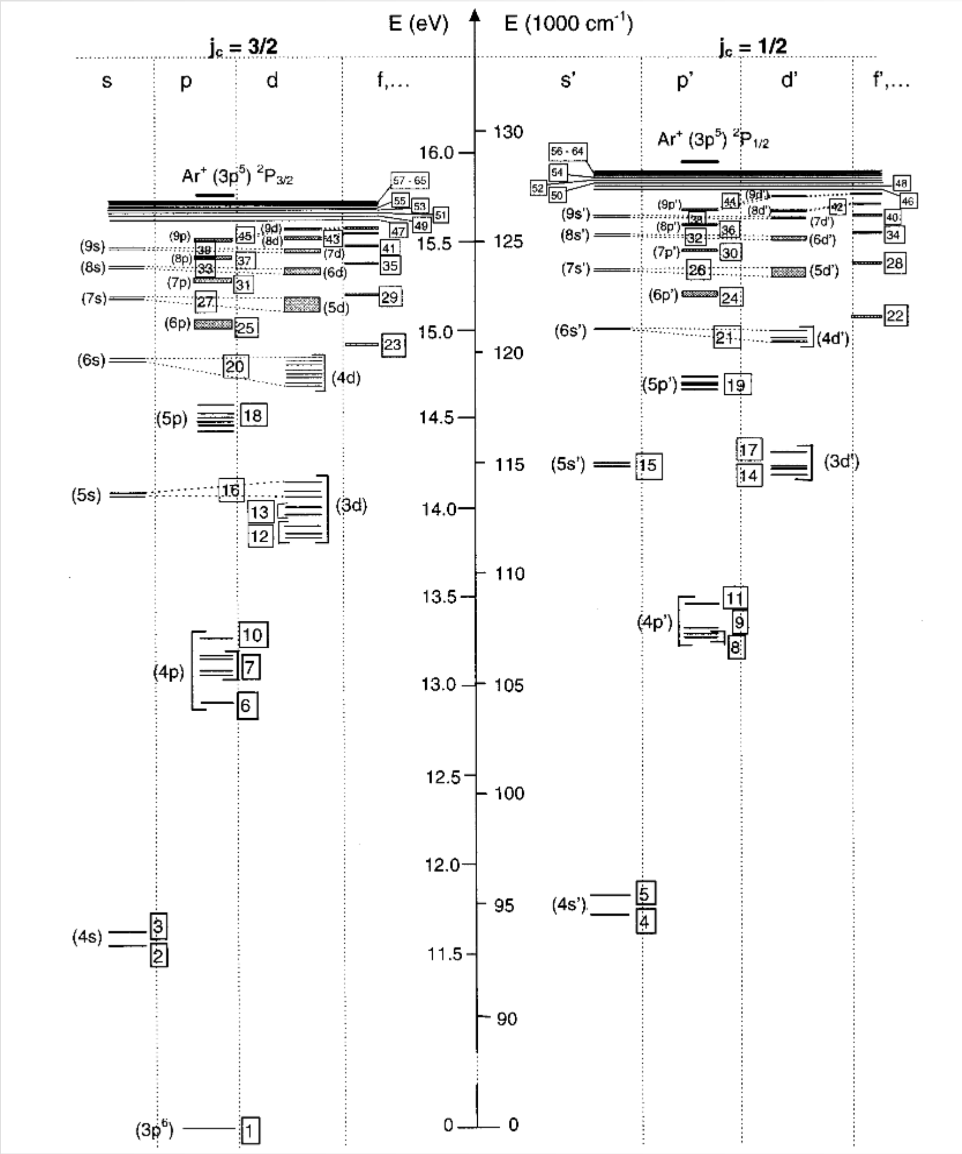
Radiative Processes

- Photo-excitation, photo-ionization, radiative decay, and radiative recombination.
  - Spontaneous emissions: A_{ij}
  - Photo-excitation accounted for by escape factor:

$$A_{k1}^{eff} = \Lambda A_{k1}$$

  - $kR \gg 1$ Optically thick: $\Lambda \rightarrow 0$
  - $kR \ll 1$ Optically thin. $\Lambda \rightarrow 1$

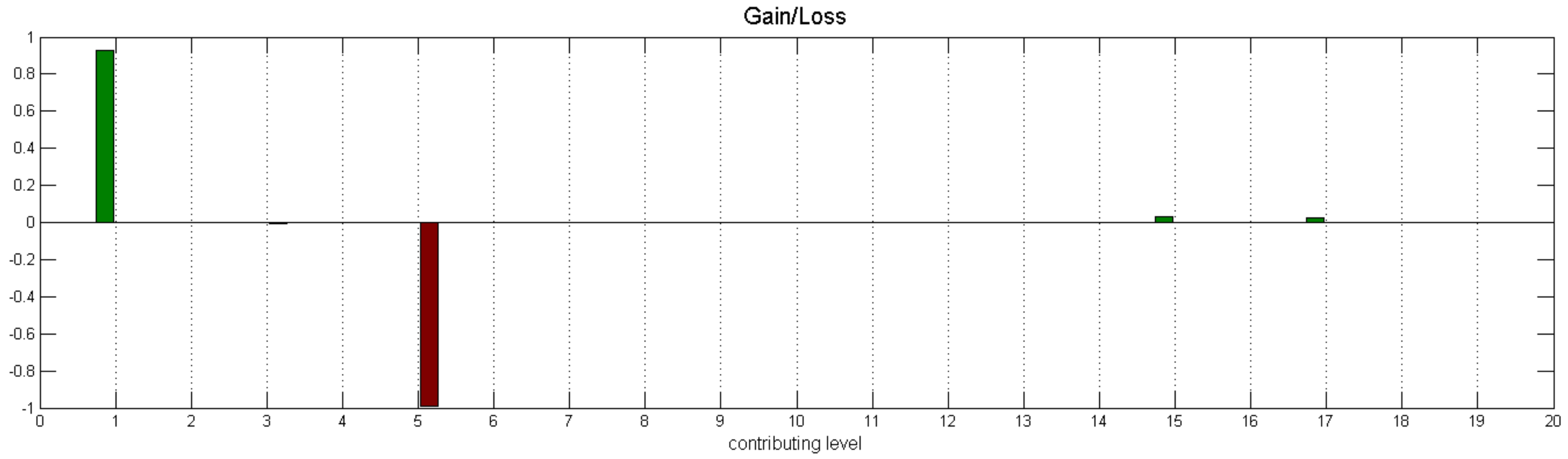
Argon Level Model

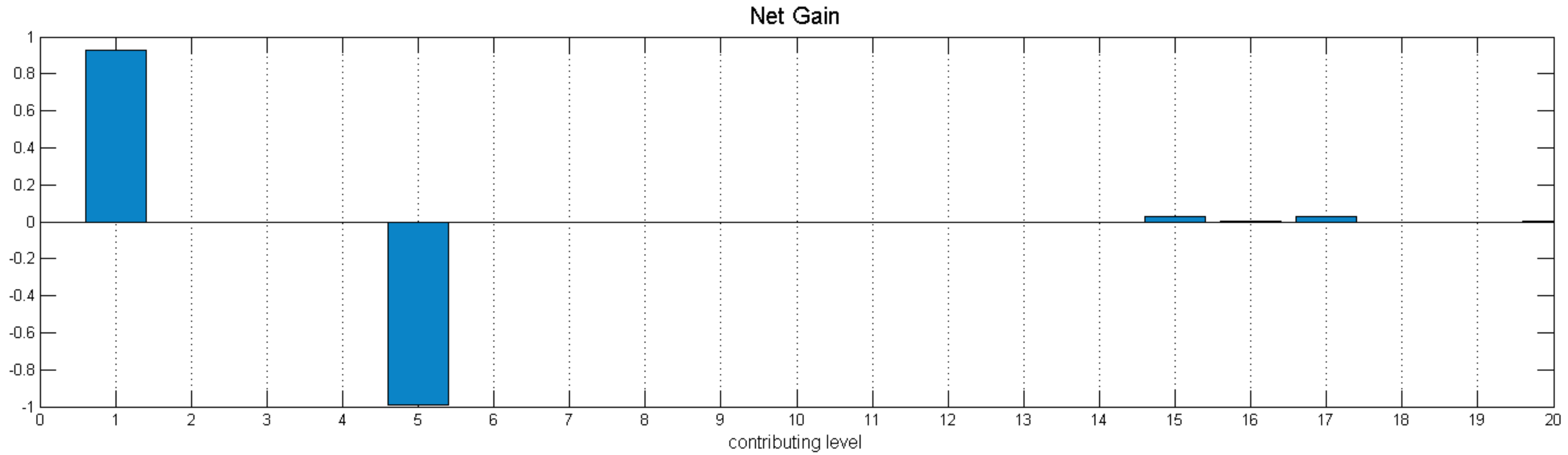


[2]

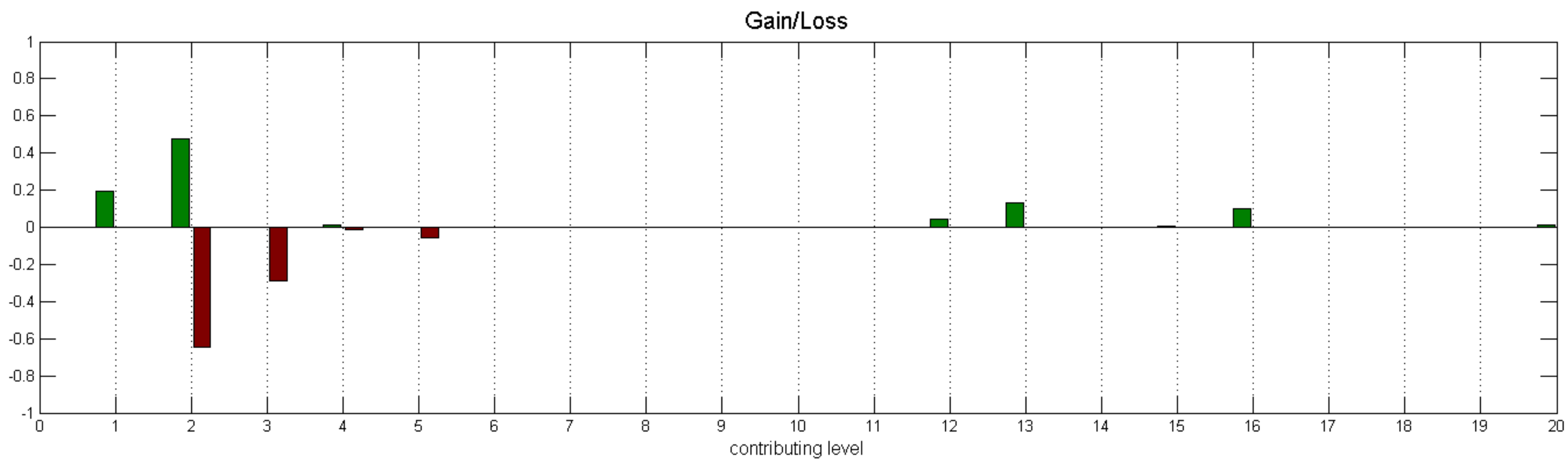
- Complex level structure.
- Levels of similar energy are grouped together to simplify model. Is this valid?
- Can higher levels be removed? Compare results to models which do not include them.
- Level population solution depends on plasma parameters: neutral density, ion density, and electron temperature and density.

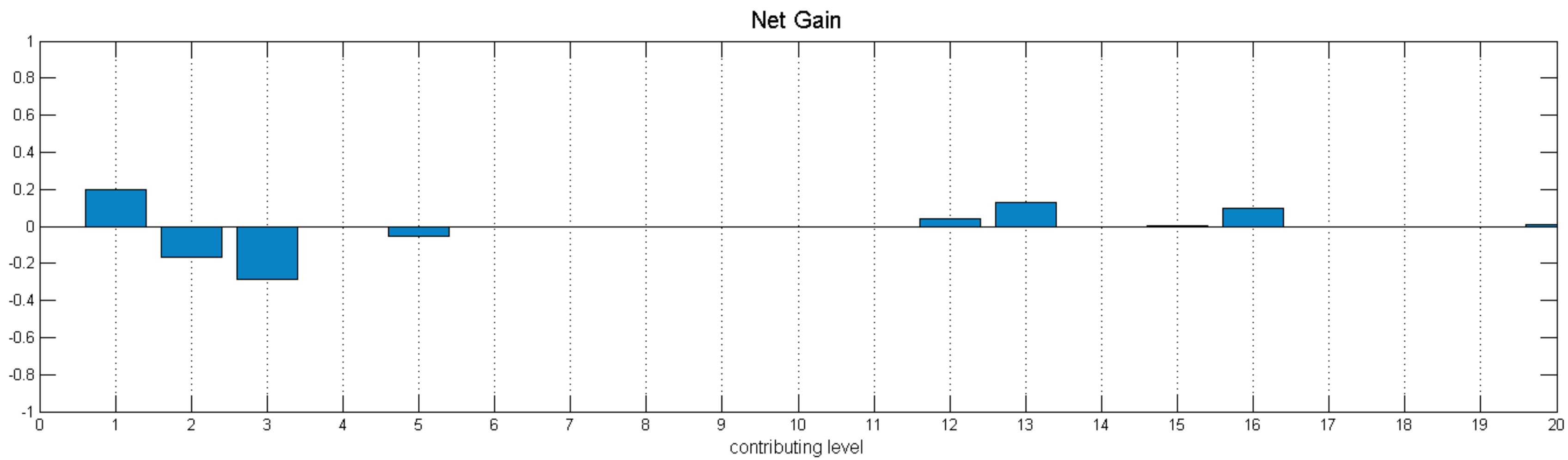
Level 11 Populating





Level 7 Populating





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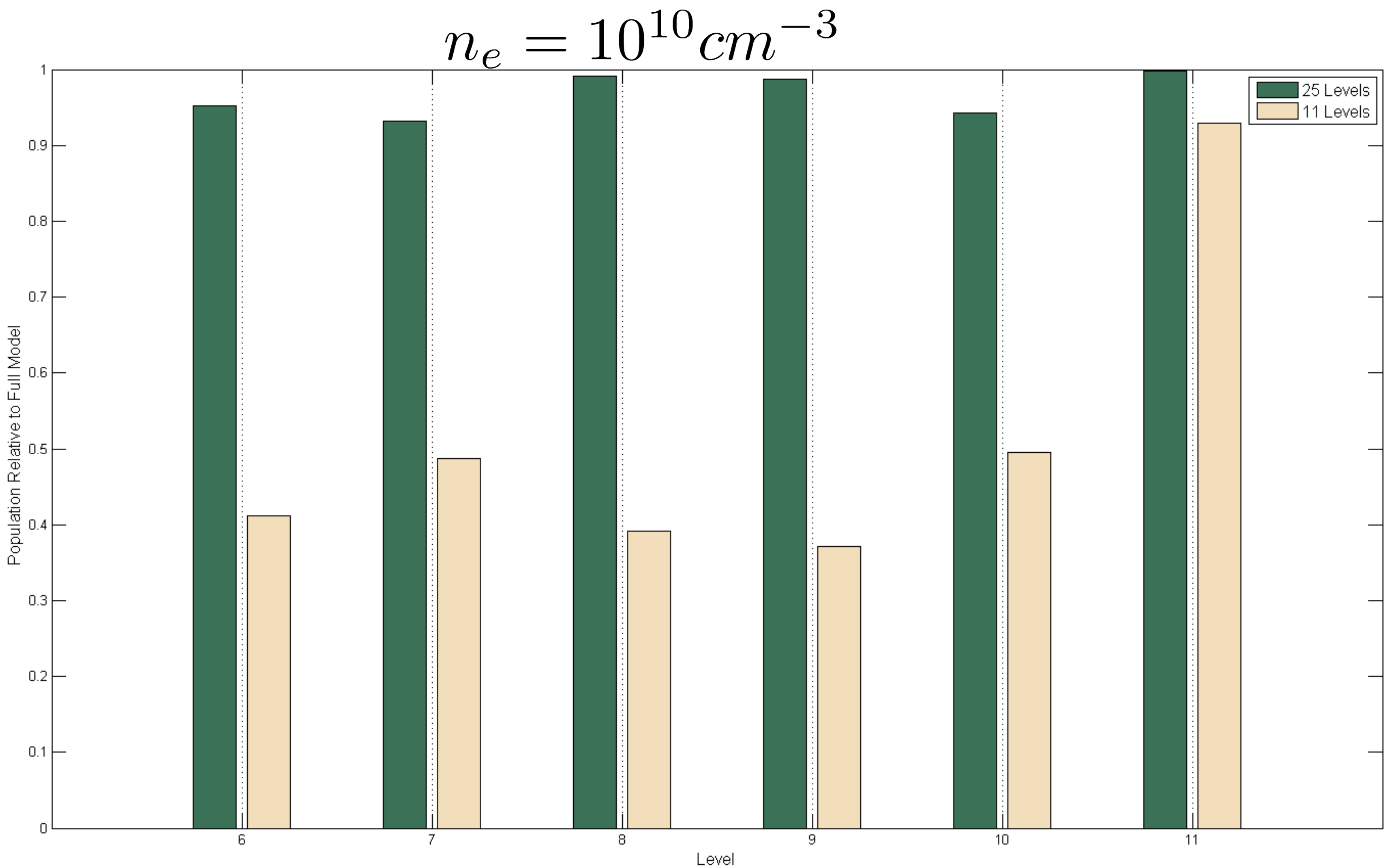
Removing Higher Levels



(makes a difference in absolute, and relative, populations)

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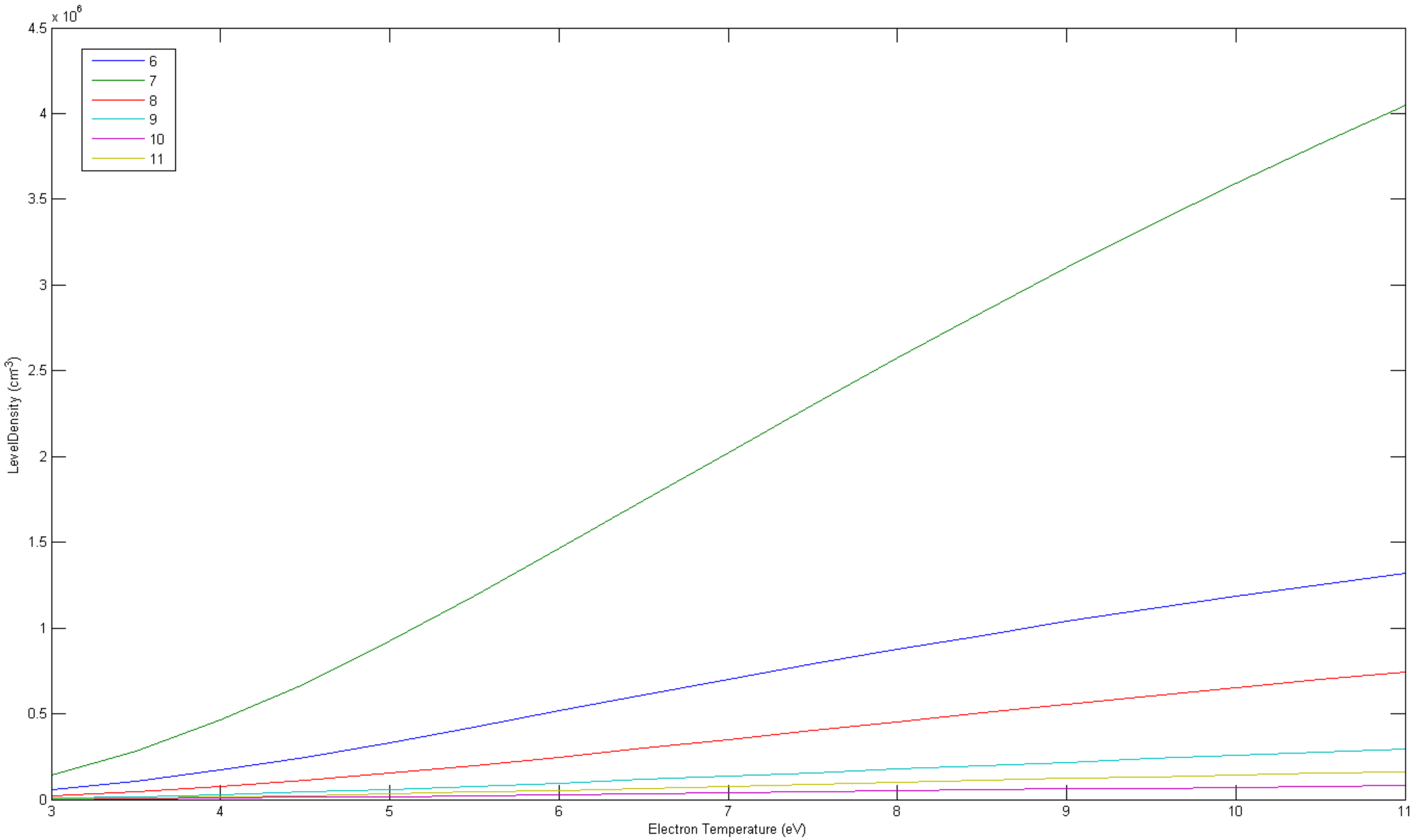
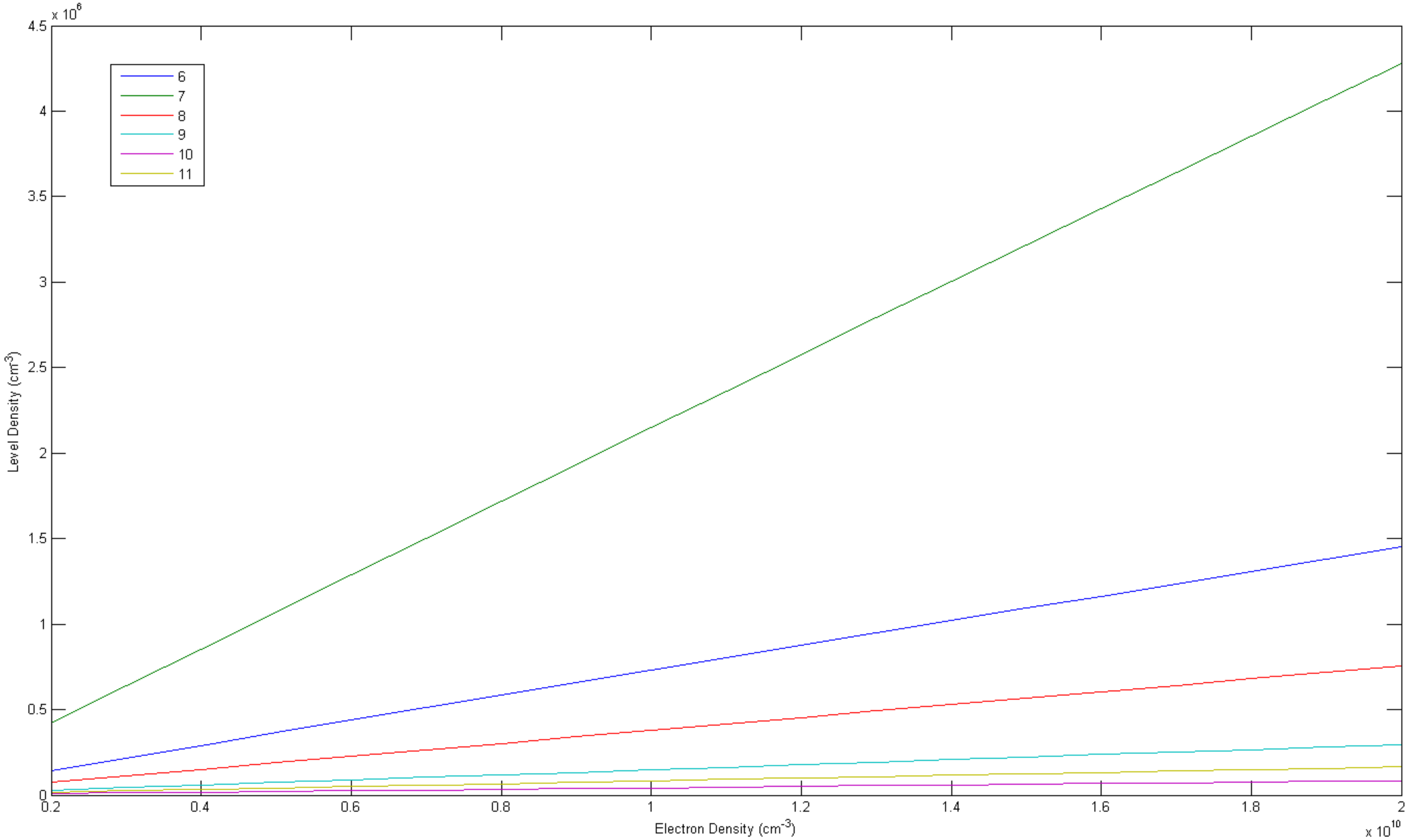
T_e Dependency



n_e Dependency



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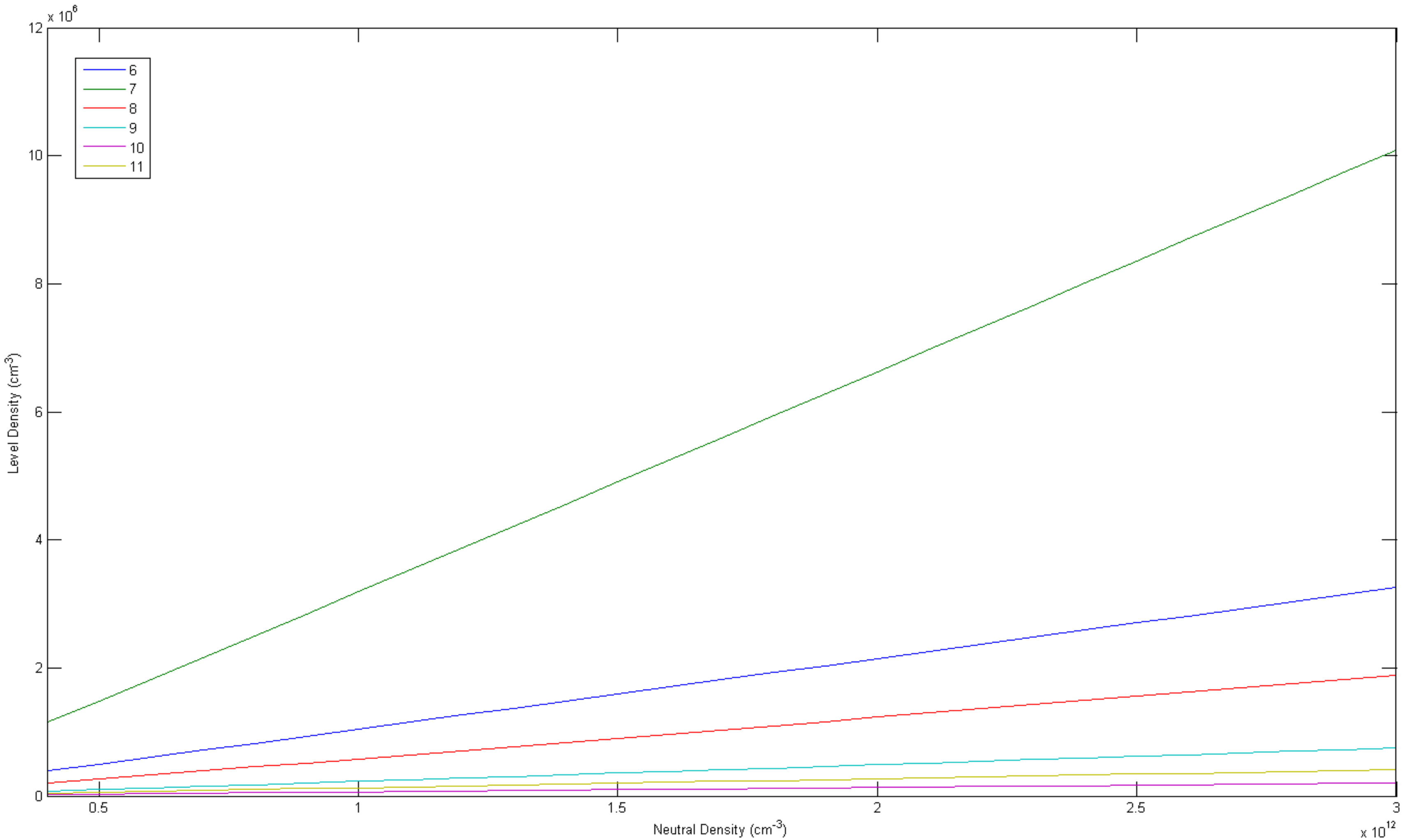
N_0 Dependency



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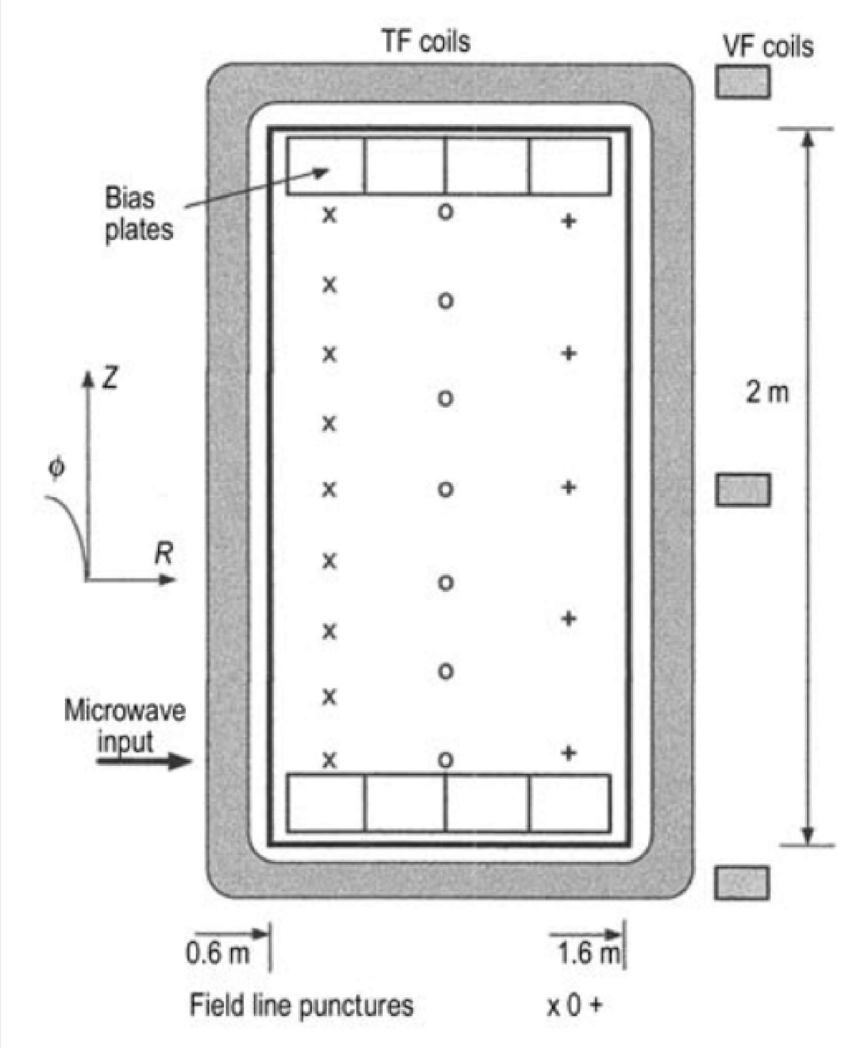
Texas Helimak



[3]

- ECRH: 6kW @ 2.45GHz
- Uniformity in vertical direction.
- Variations in radial direction.

- Measurement of electron temperature and density via Langmuir probes at top and bottom.

Parameters

$$T_e \approx 10eV$$

$$n \leq 1 \times 10^{17} m^{-3}$$

$$B = 0.05 - 0.13T$$

$$\langle R \rangle = 1.1m$$

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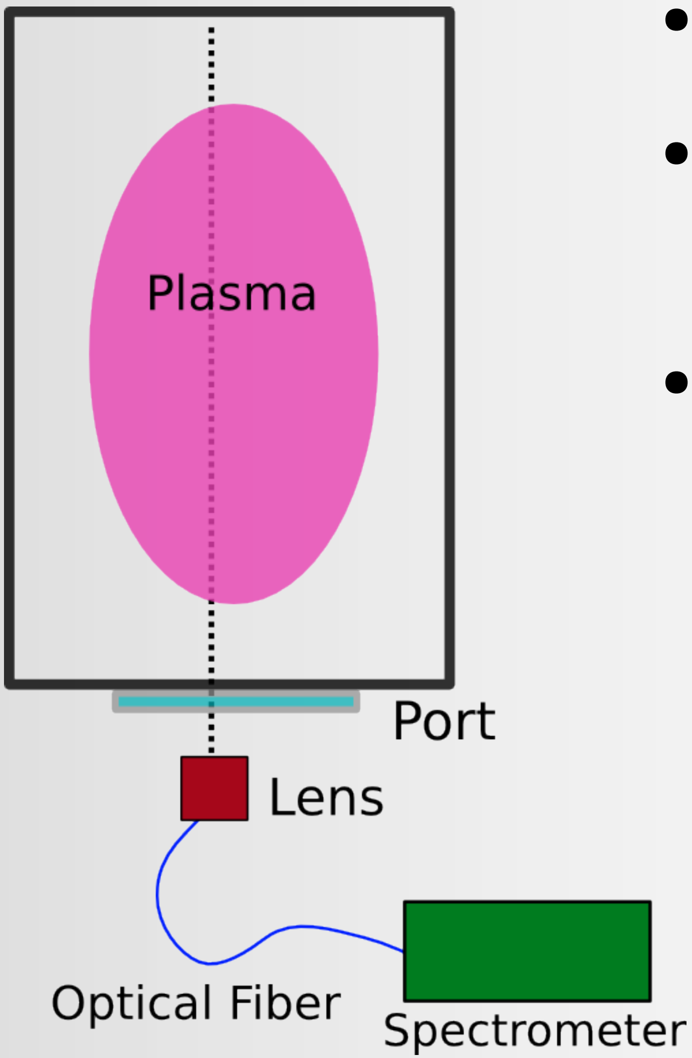
External Photo

Internal Photo

Measurement Method



- One radial position per shot.
- Calibration for view-port, lens, fiber, and spectrometer.
- Assume uniformity of plasma

$$N_{counts} = \Delta t \Delta \lambda K_{cal} L_{rad}$$

$$K_{cal} = \frac{N_{counts}}{\Delta t \Delta \lambda L_{rad}}$$

$$L_{rad} = \frac{hc}{\lambda} \int dl \epsilon$$

$$\epsilon_{ki} = \frac{1}{4\pi} f(\lambda) A_{ki} n_k$$

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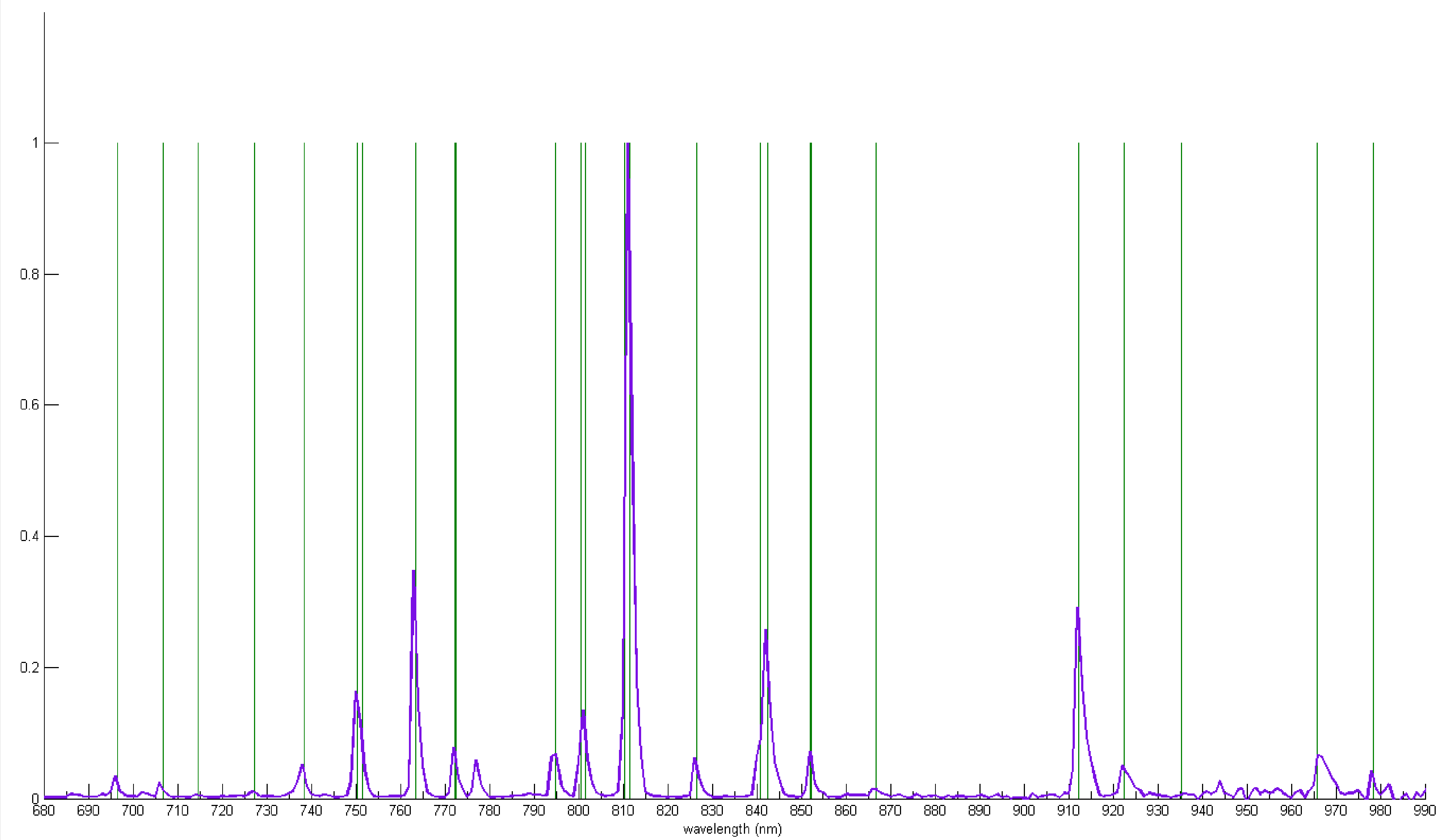
Argon Plasma Spectrum



Measured Lines

	$\lambda(nm)$	Upper Level	Model	$\lambda(nm)$	Upper Level	Model
	696.54	$^2P_{1/2}4p[1/2]_1$	9	800.616	$^2P_{3/2}4p[3/2]_2$	7
	706.72	$^2P_{1/2}4p[3/2]_2$	8	801.479	$^2P_{3/2}4p[5/2]_2$	7
	714.70	$^2P_{1/2}4p[3/2]_1$	8	810.369	$^2P_{3/2}4p[3/2]_1$	7
	727.29	$^2P_{1/2}4p[1/2]_1$	9	811.531	$^2P_{3/2}4p[5/2]_3$	7
	738.398	$^2P_{1/2}4p[3/2]_2$	8	826.452	$^2P_{1/2}4p[1/2]_1$	9
overlap	750.387	$^2P_{1/2}4p[1/2]_0$	11	840.821	$^2P_{1/2}4p[3/2]_2$	8
	751.465	$^2P_{3/2}4p[1/2]_0$	10	842.465	$^2P_{3/2}4p[5/2]_2$	7
	763.51	$^2P_{3/2}4p[3/2]_2$	7	852.144	$^2P_{1/2}4p[3/2]_2$	8
	772.376	$^2P_{3/2}4p[3/2]_1$	7	866.79	$^2P_{3/2}4p[3/2]_1$	7
	772.421	$^2P_{1/2}4p[1/2]_1$	9	912.3	$^2P_{3/2}4p[1/2]_1$	6
	794.818	$^2P_{1/2}4p[3/2]_1$	8	922.45	$^2P_{3/2}4p[3/2]_2$	7

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Measured Lines (cont.)

$\lambda(nm)$	Upper Level	Model
935.42	$^2P_{3/2}4p[3/2]_1$	7
965.78	$^2P_{3/2}4p[1/2]_1$	6
978.45	$^2P_{3/2}4p[5/2]_2$	7

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Measure and Fit to Level Density

- Intensity proportional to level density.

$$I_{ki} = \frac{g_{lk} A_{ki} n_l}{\sum g_{lk}} \longrightarrow n_l = \frac{(\sum g_{lk}) I_{ki}}{g_{lk} A_{ki}}$$

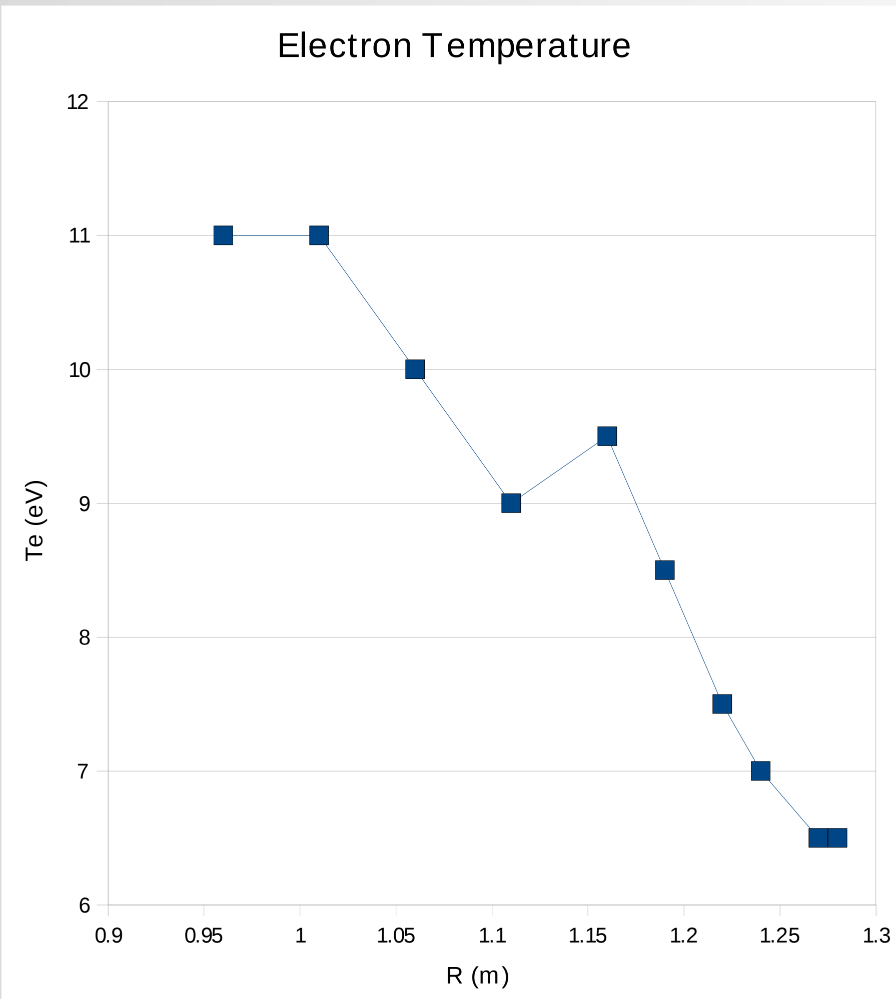
- Average values from all independent lines.

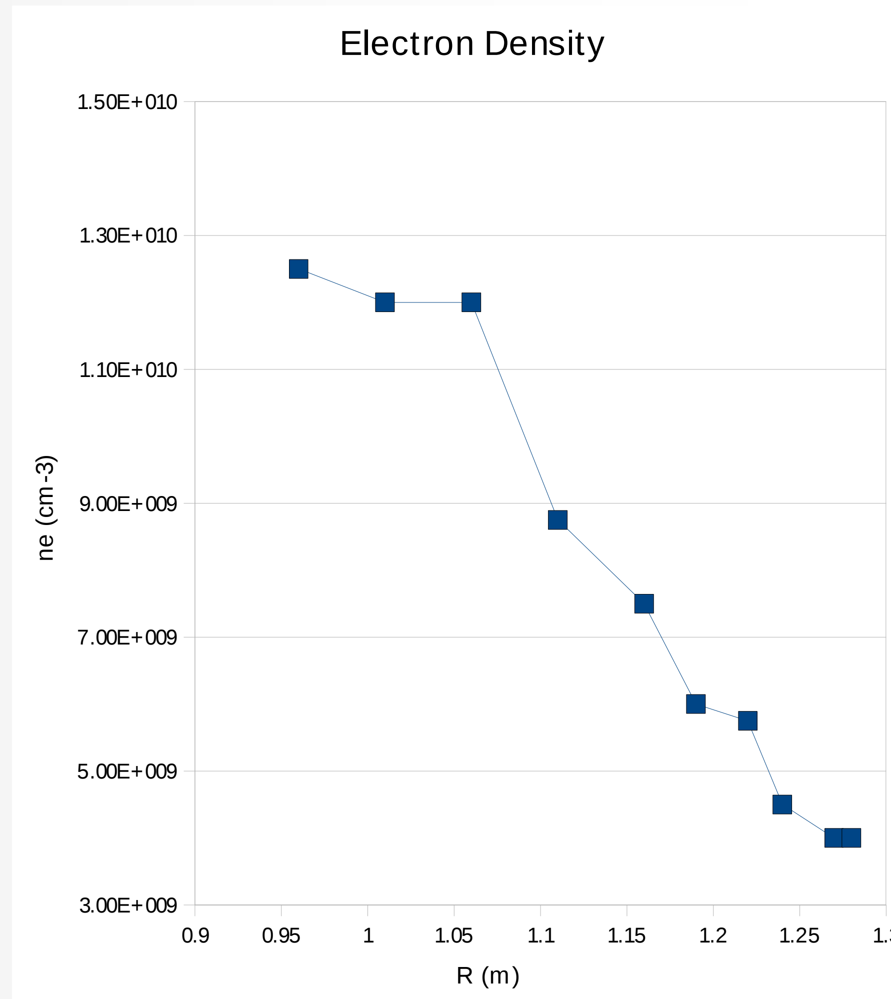
$$\bar{n_l} = \frac{\sum n_l}{N}$$

- Neutral density as free parameter: T_e, n_e fixed at each position.

Temperature & Density Est.

(at radial positions where spectra were taken)





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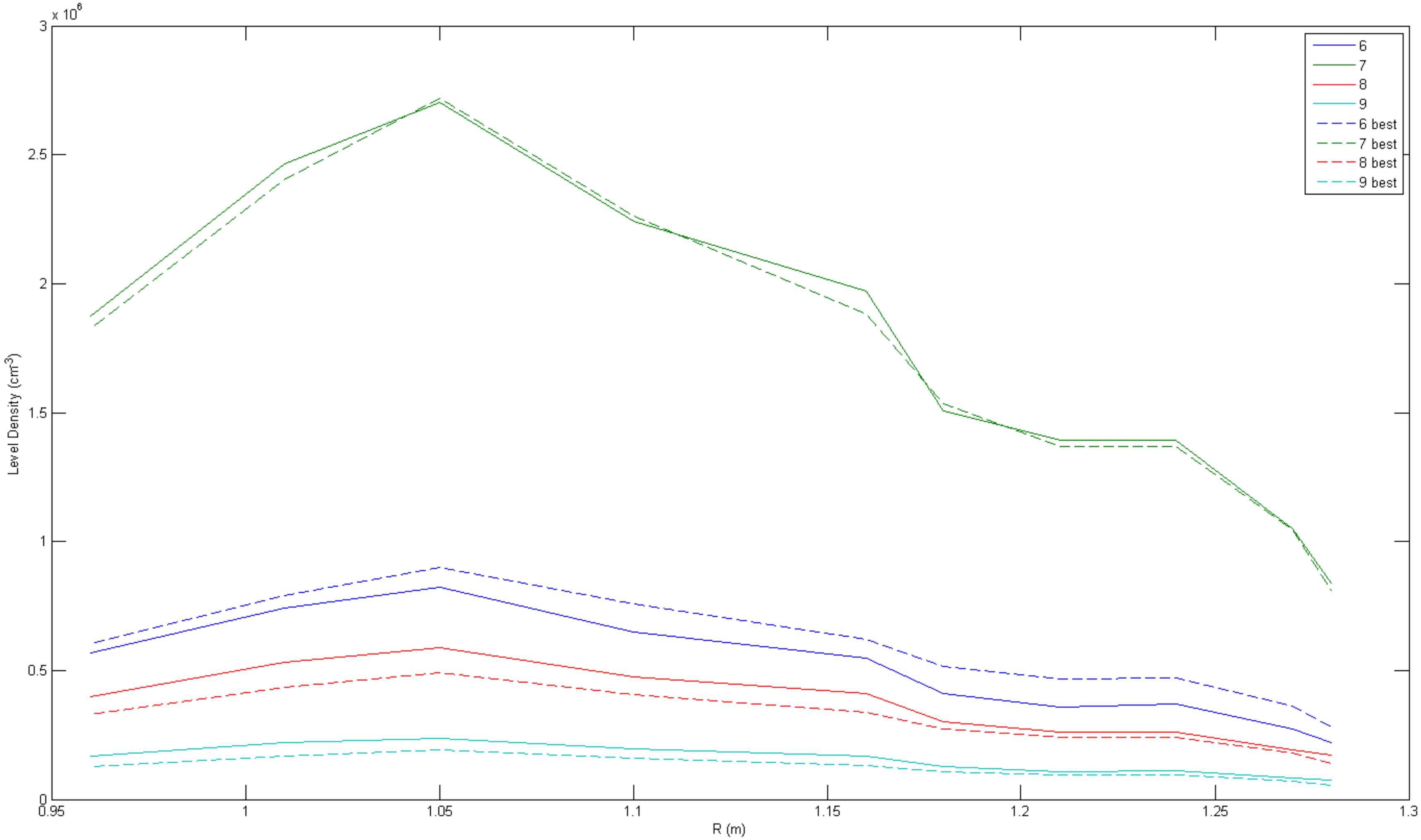
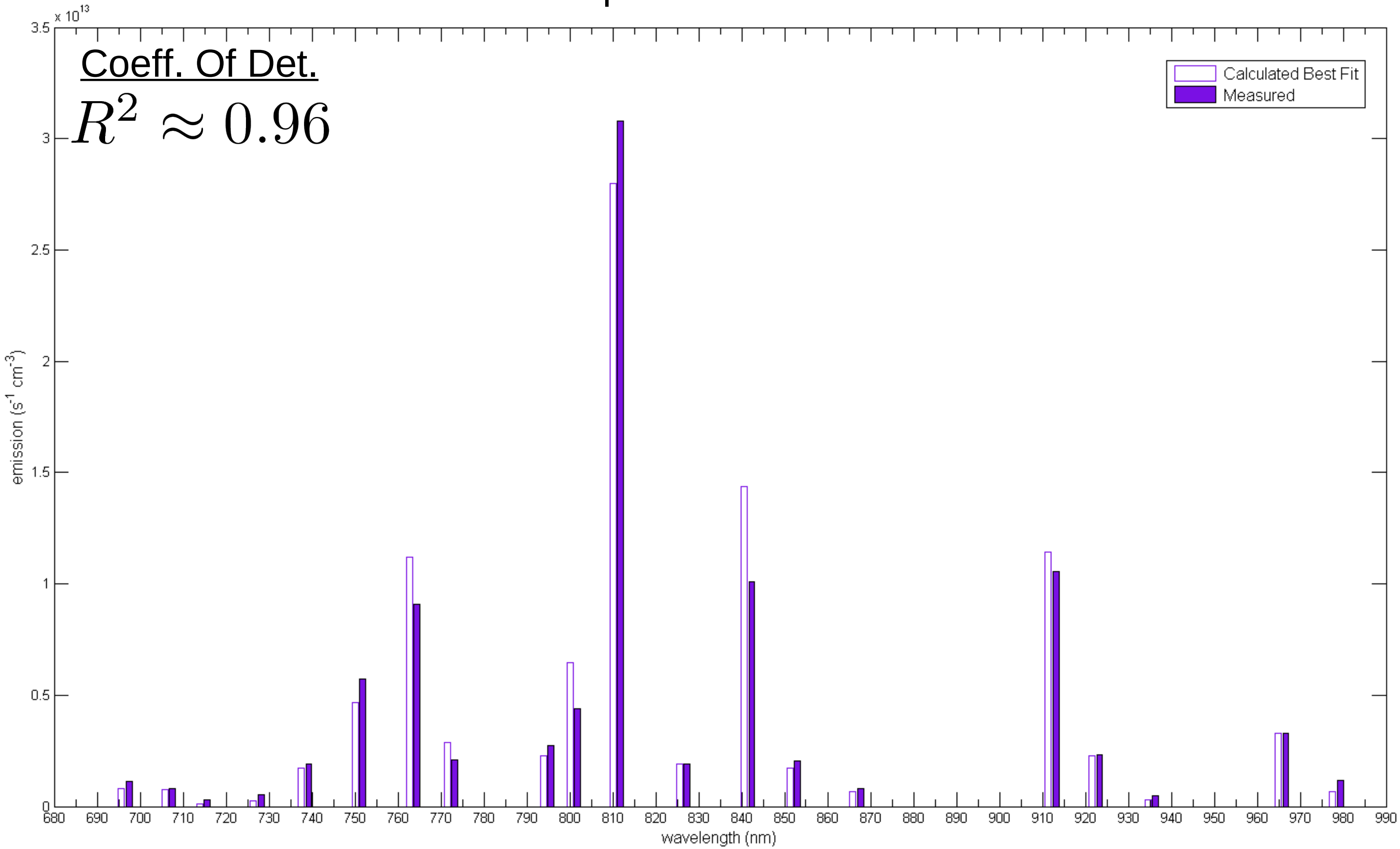
Level Densities

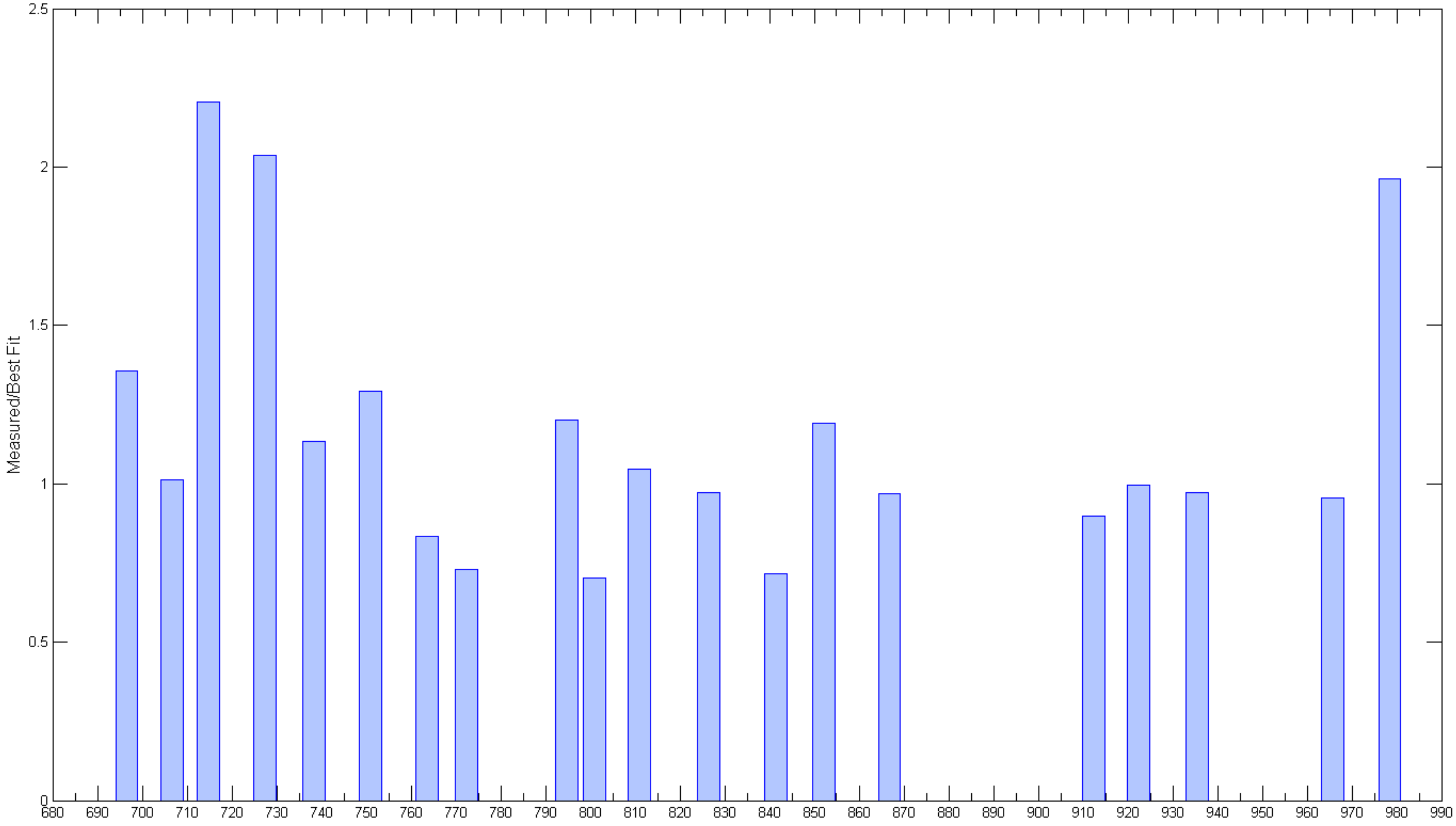


Comparison of Lines

Radial position R = 0.96m



Measured Versus Best Fit



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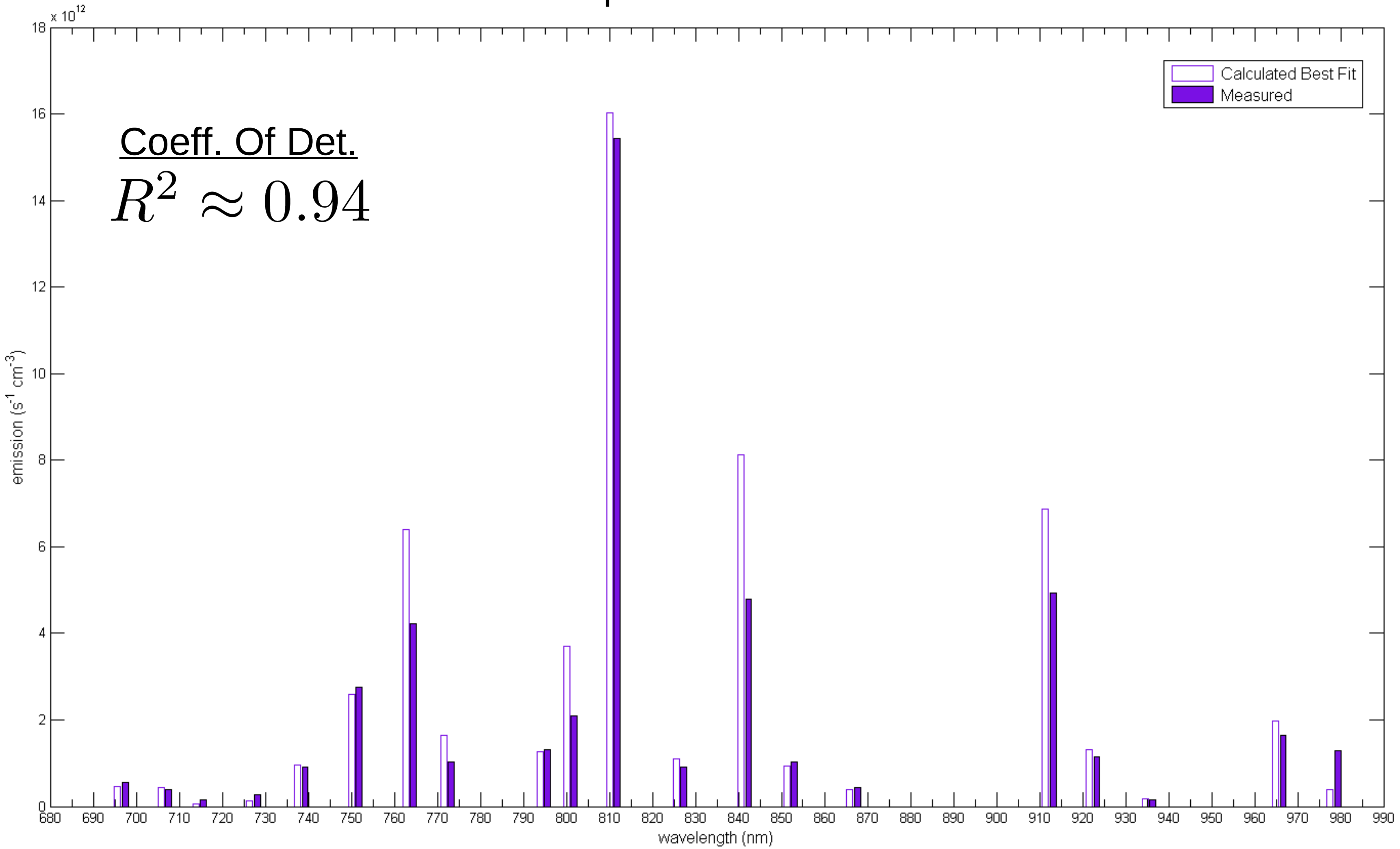
Comparison of Lines (cont.)

Radial position R = 1.27m



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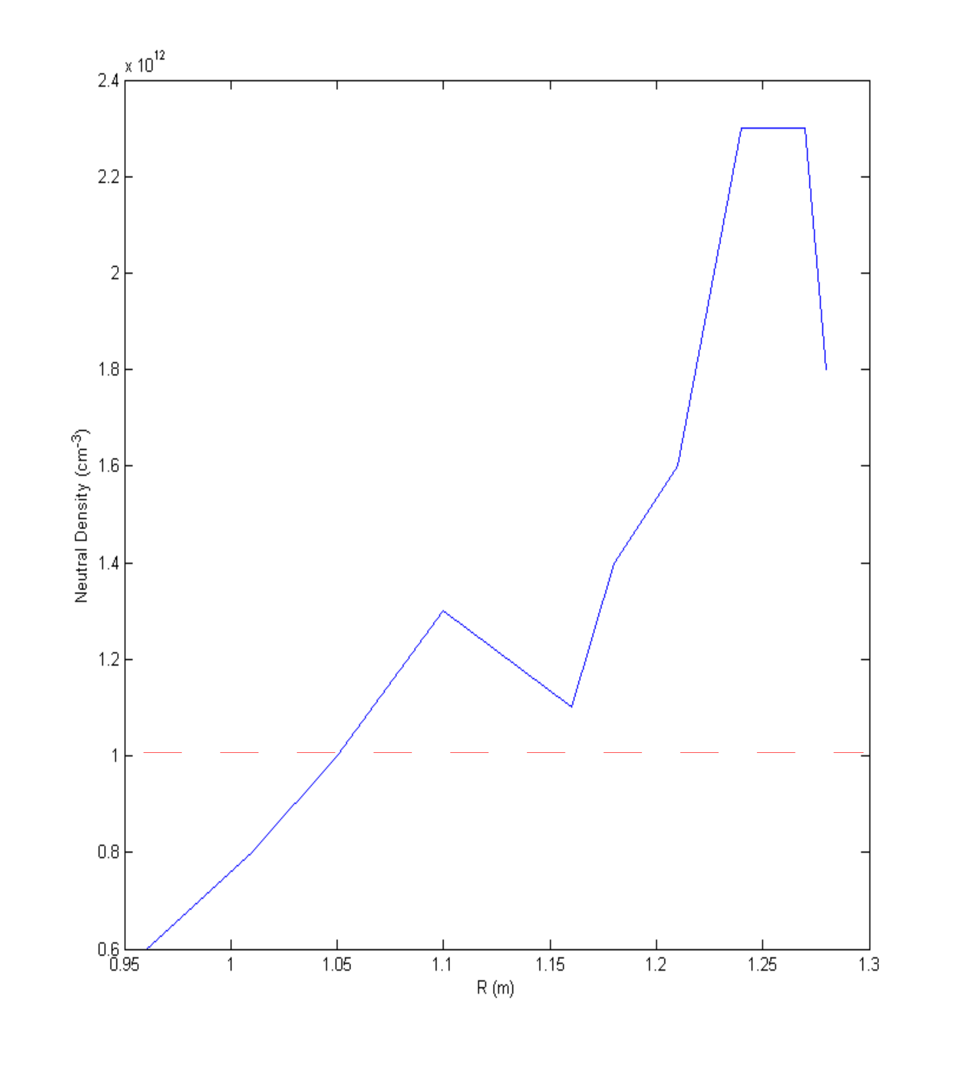
Neutral Density Best Fit



- Fill Pressure:

$$P = 3 \times 10^{-5} Torr$$

$$T = 300K$$

$$n_0 = 0.97 \times 10^{12} cm^{-3}$$

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Fitting to Measure n_e and T_e

- Absolute level densities depend on n0, ne, and Te nearly linearly.
- Must depend on relative intensities to remove ambiguities.
  - Only 6 independent levels for all measured lines.
  - Choose lines to represent levels.

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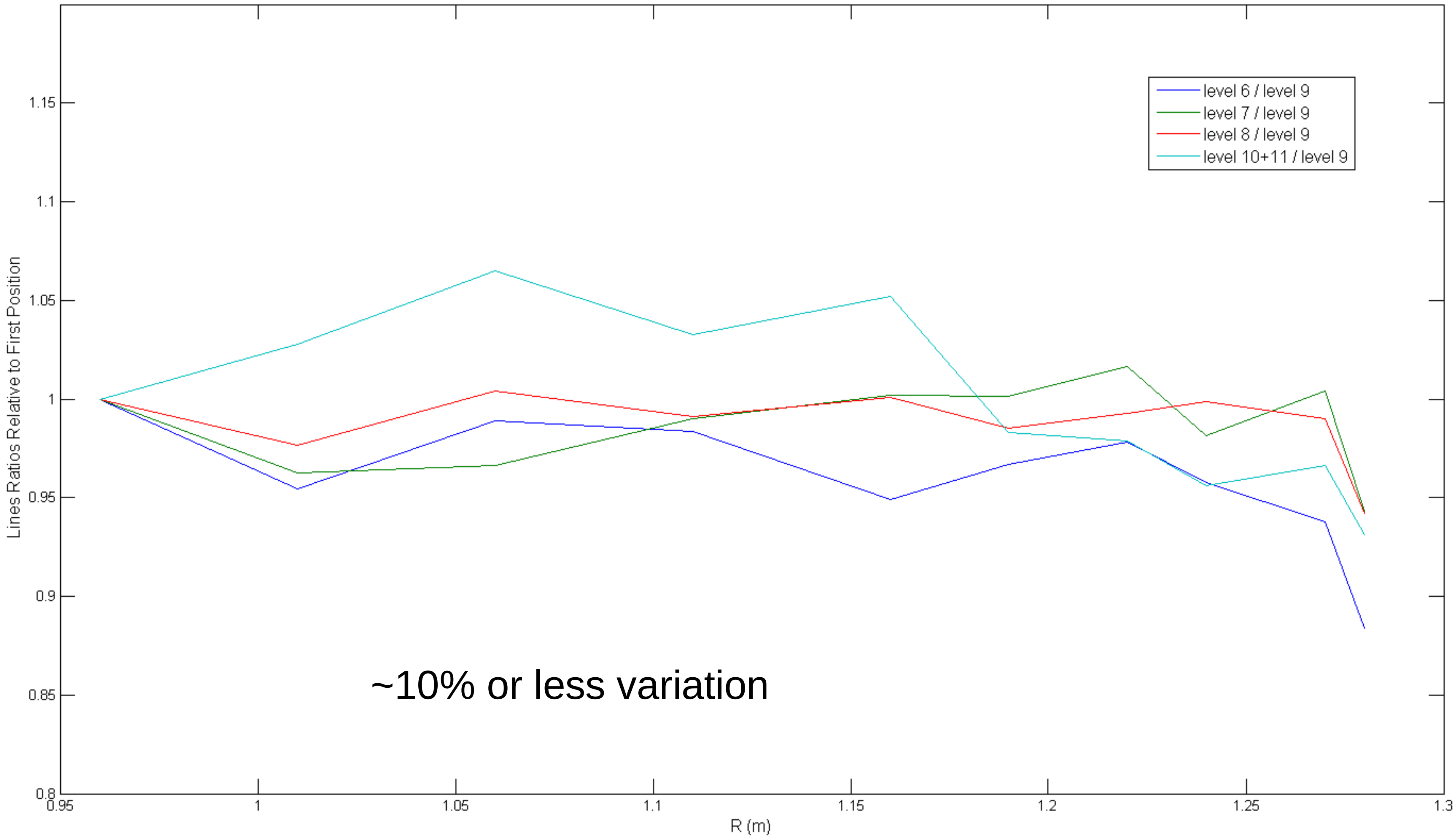
Est. Level Population Ratios



Testing Level Groupings

- Level 7 and 8 in model consists of several non-degenerate physical levels.
- Line intensities determined by statistical weight:

$$I_{ki} = \frac{g_k A_{ki} n_l}{\sum g_k} \longrightarrow \frac{I_{ki}}{I_{mn}} = \frac{g_k A_{ki}}{g_m A_{mn}}$$

- All lines should predict the same level density.
- Line ratios should be fixed, and not depend on plasma parameters.

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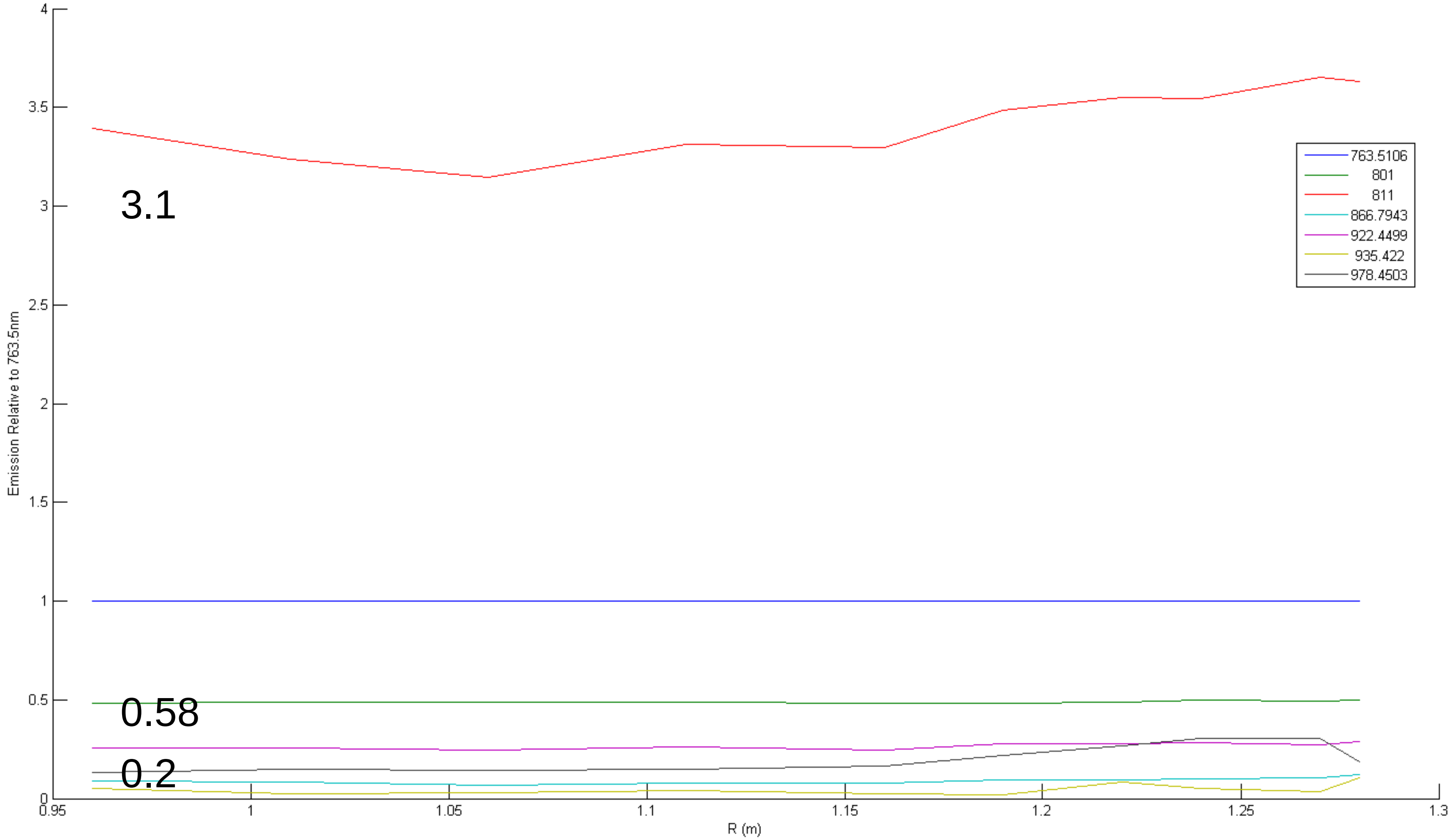
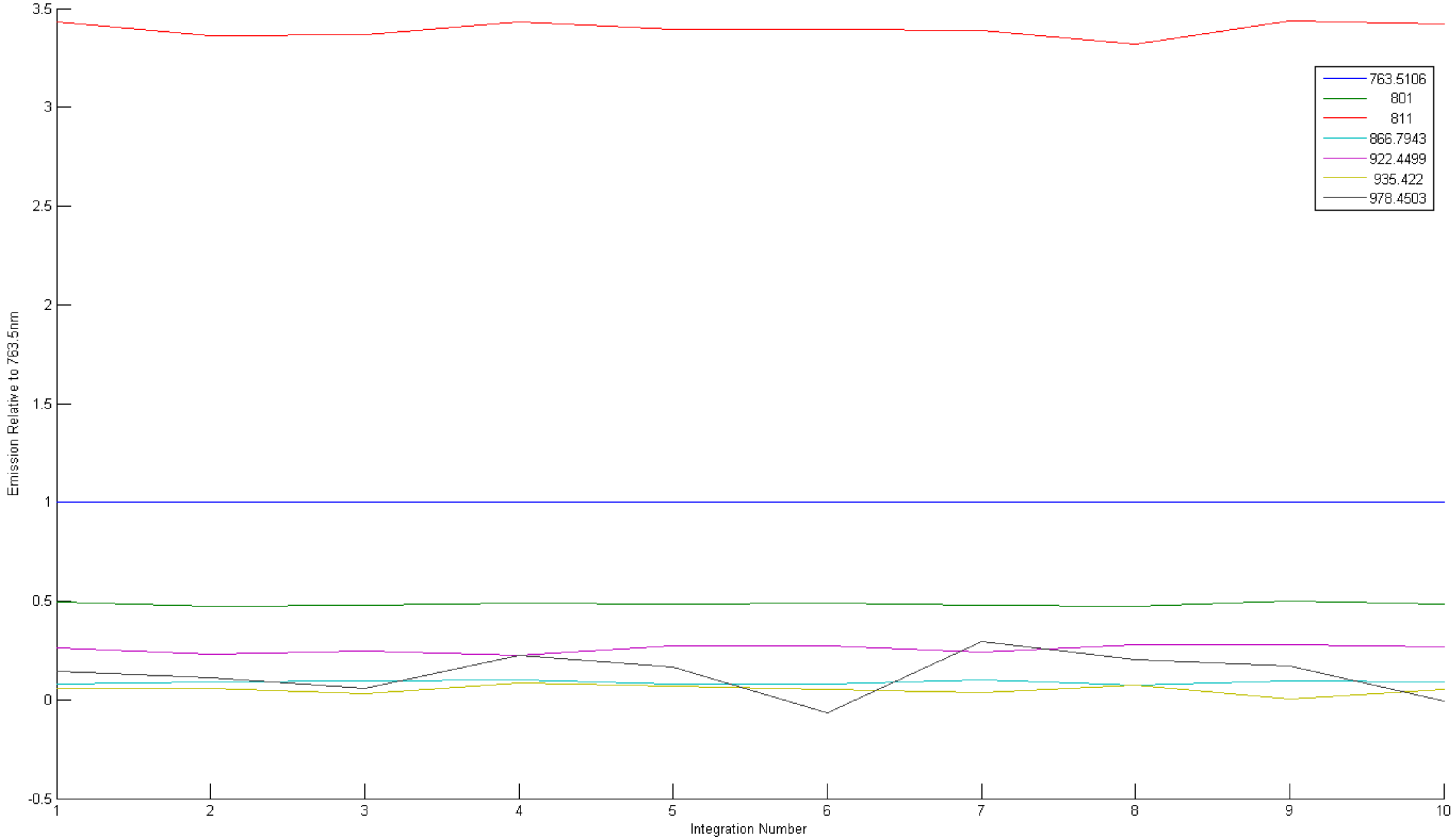
Level 7 Line Ratios

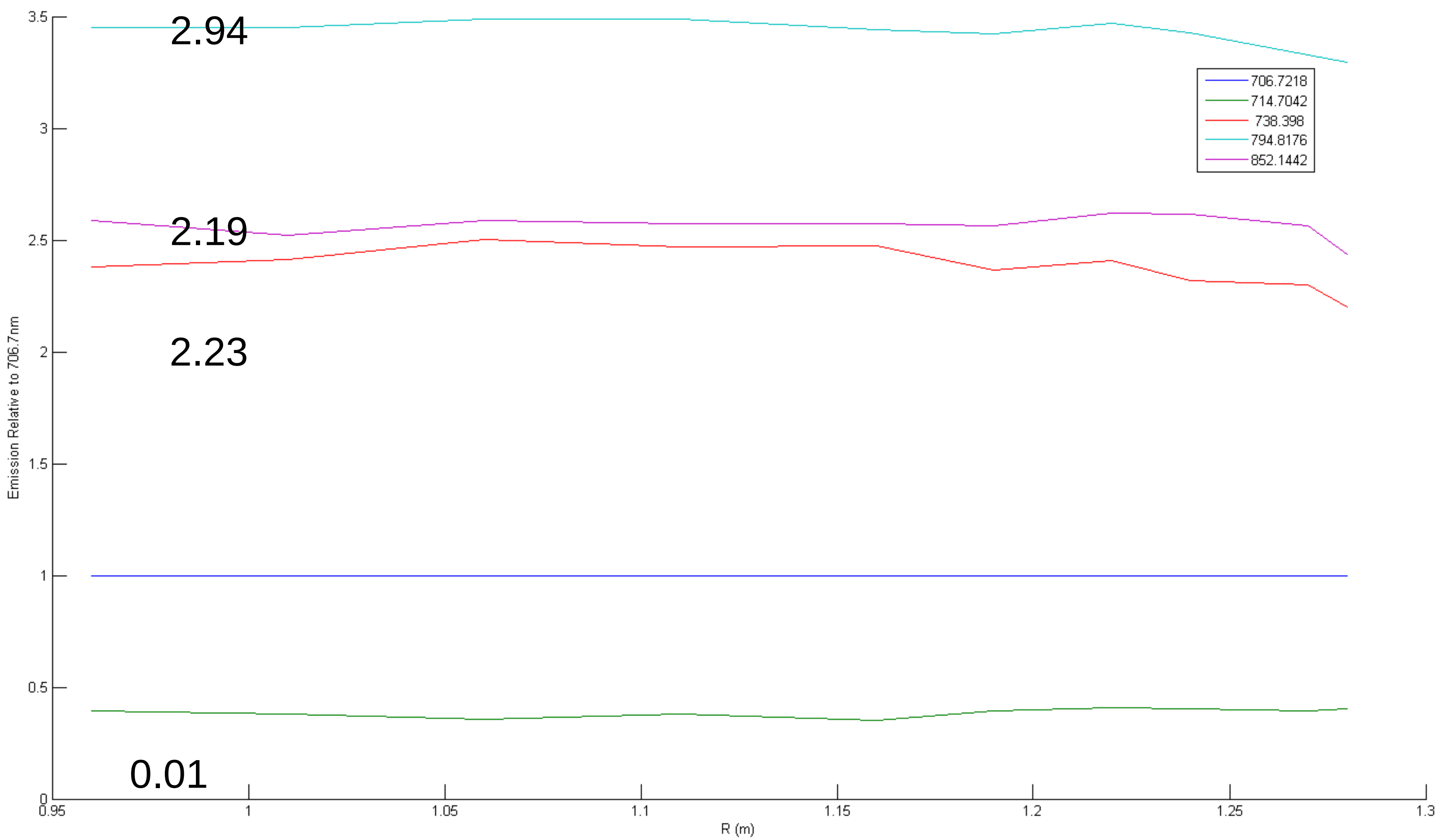


Level 7 Line Ratios (cont)

Radial Position R=0.96m



Level 8 Line Ratios



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Conclusions

- Levels up to level 25 in model are important to predict absolute and relative intensities.
- Produces good fit to measured intensities with some deviations. ($R^2 \approx 0.95$)
- Fitted values show variations of neutral density.
- Fitting to determine electron density or temperature more difficult from the measured lines.
- Grouping of some levels may not be justified.

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References

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[4] H. R. Griem, *Principles of Plasma Spectroscopy* (Cambridge University Press 1997)

[5] E. M Sciamma, Plasma Spectroscopic Diagnostic Tool Using Collisional-Radiative Models and its Application to Different Plasma Discharges For Electron Temperature and Neutral Density Determination, U. Texas Austin Dissertation (2007)

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