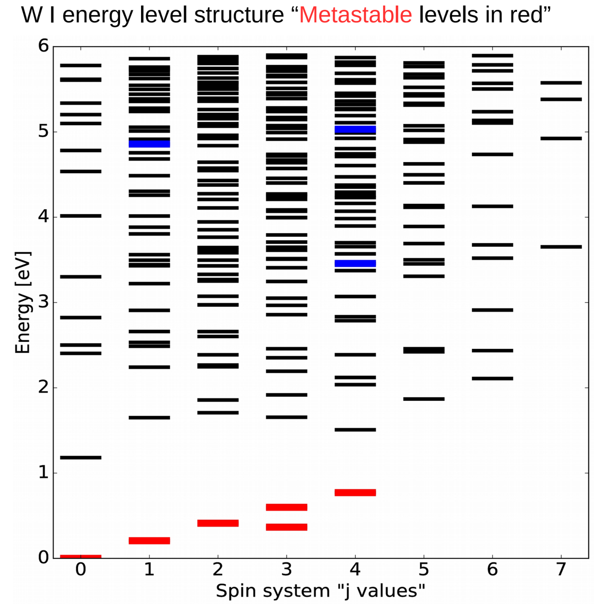
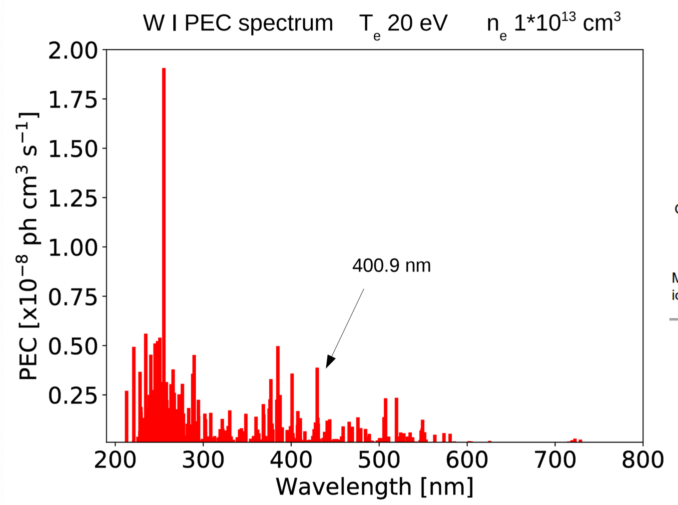
Abstract

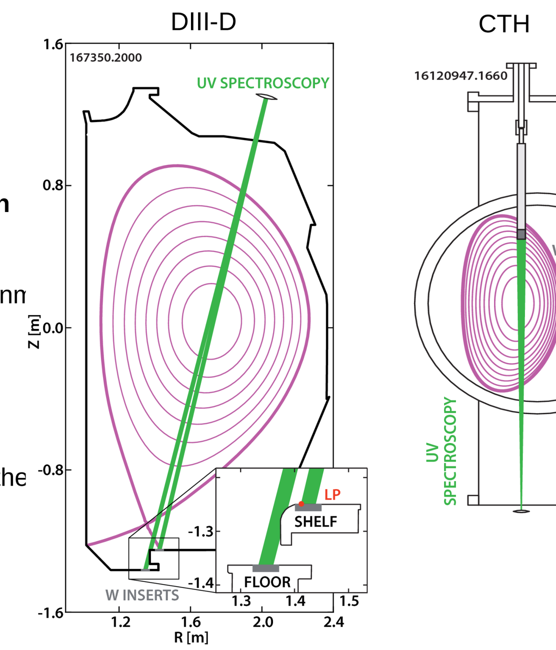
- **High-Z materials are leading candidates for future first wall**
- **Erosion of plasma facing components can significantly impact performance**
    - Erosion can be diagnosed from spectral line emission and the (S/XB) coefficient 'ionizations per photon'
- **Emission from W I is most intense in the UV region**
- **Metastable states can have a large impact on spectral line modeling**
- **A new collisional radiative code has been developed to deal with the challenges of modeling W I spectral lines but can be applied to any impurity atom**





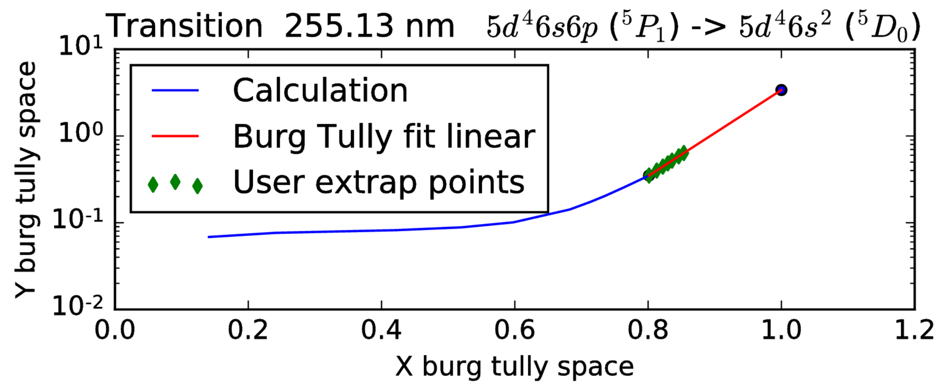
Spectrometer setup

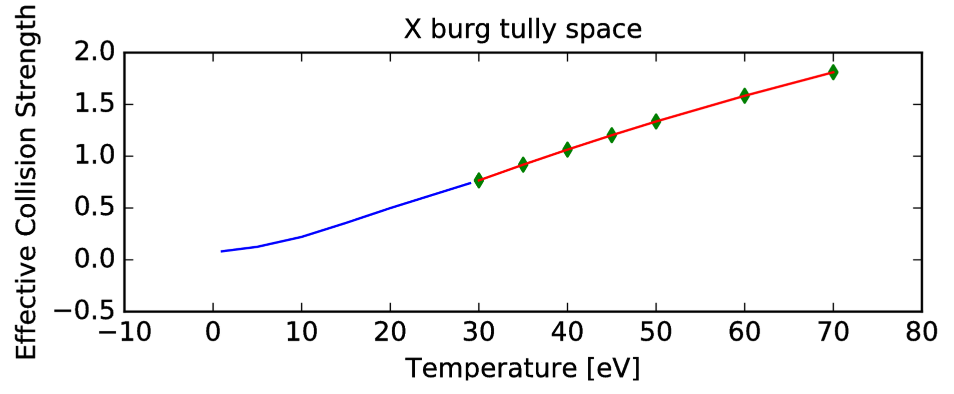
- **Three StellarNet survey spectrometer were installed on DIII-D and CTH**
    - Spectrometers with 200-300, 300-400 and 200-400 nm ranges
    - Integration times of 30 to 2000 ms utilized
- **Two viewing chords used on DIII-D**
    - Spectrometers measured W emission from tiles on the divertor floor & shelf
- **Single viewing chord on CTH**
    - Tungsten introduced into CTH on a movable probe



ColRadPy: Collisional Radiative Modeling in Python

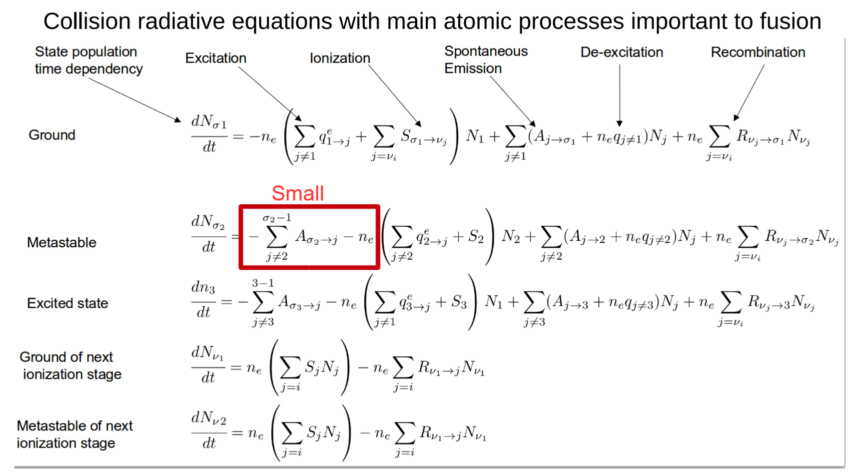
- **Radiating ions in plasma provide potential for both plasma diagnostics and plasma modeling**
- **Collisional radiative theory provides a powerful tool for modeling of low and moderately dense plasmas (not ICF densities)**
    - Includes all of the significant atomic processes for plasmas (excitation,ionization…..)
- **A new python program is presented that solves the collisional radiative (CR) and ionization balance problems**
- **ColRadPy can produce data for import to plasma transport codes and data for spectral diagnostics**
- **A number of other collisional radiative codes exist including ADAS, CHIANTI, atomdb [1-3]**
    - **The purpose of ColRadPy is to provide a convenient python model that can be incorporated into other python codes**
- **ColRadPy has been compared to ADAS to confirm the validity of the code**





ColRadPy: Collisional Radiative Modeling in Python

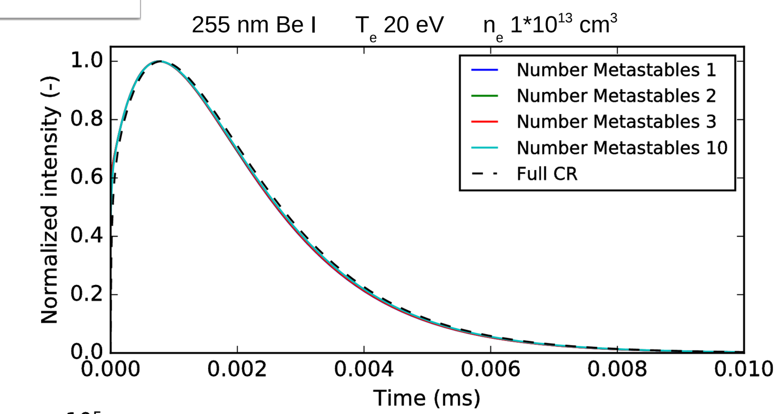
- **ColRadPy is capable of solving the standard CR system of equations as well as the time dependent system**
    - Allows for the impact metastable states to be studied
    - Major populating mechanisms for fusion plasma implemented into CR equations
        - Development to add more functionality is ongoing
    - Time dependent CR solution, ionization balance, error bar propagation for atomic data

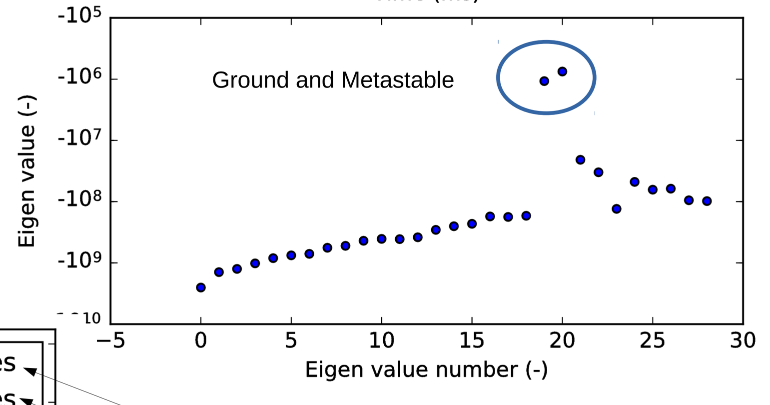


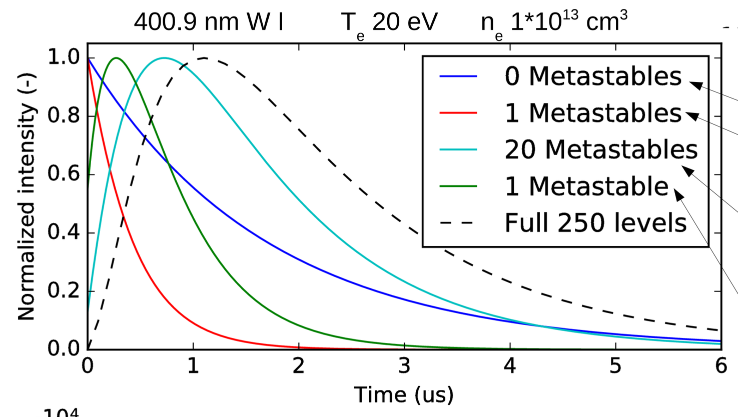
Collision radiative equations in Matrix form after quasistatic approximation

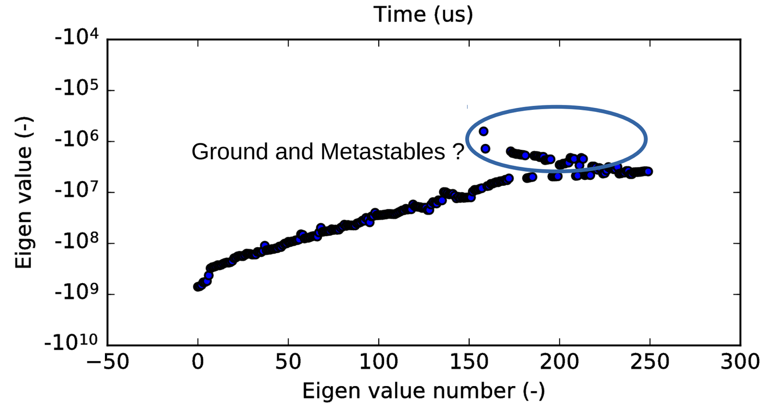
$$\begin{bmatrix}N_3\\N_4\\\dots\\N_n\end{bmatrix} = \begin{bmatrix}C_{33}&C_{34}&\dots&C_{3n}\\C_{43}&C_{44}&\dots&C_{4n}\\\dots&\dots&\dots&\dots\\C_{n3}&C_{n4}&\dots&C_{nn}\end{bmatrix}^{-1}\begin{bmatrix}-C_{31}N_{\sigma_1}-C_{32}N_{\sigma_2}-R_3N_{\nu_1}-R_3N_{\nu_2}\\-C_{41}N_{\sigma_1}-C_{42}N_{\sigma_2}-R_4N_{\nu_1}-R_4N_{\nu_2}\\\dots\\-C_{n1}N_{\sigma_1}-C_{n2}N_{\sigma_2}-R_nN_{\nu_1}-R_nN_{\nu_2}\end{bmatrix}$$

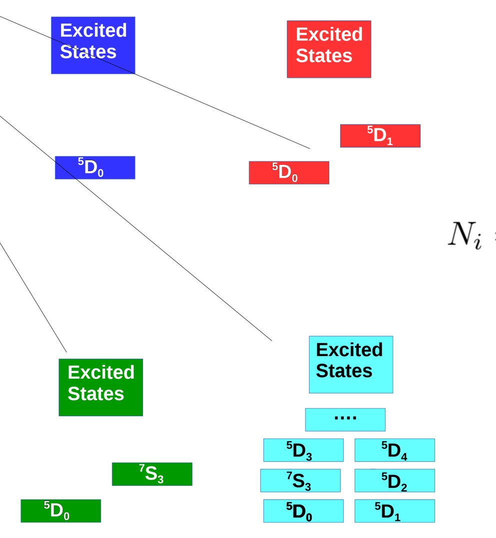
- **Low-Z materials like Be can be modeled correctly with few metastable states**
- **High-Z materials like W need many metastable states**
    - Transport codes will likely not be able to handle all the metastable states required
        - Make smart choices on which levels are metastables
        - Maybe possible to bundle levels together and maintain important physics







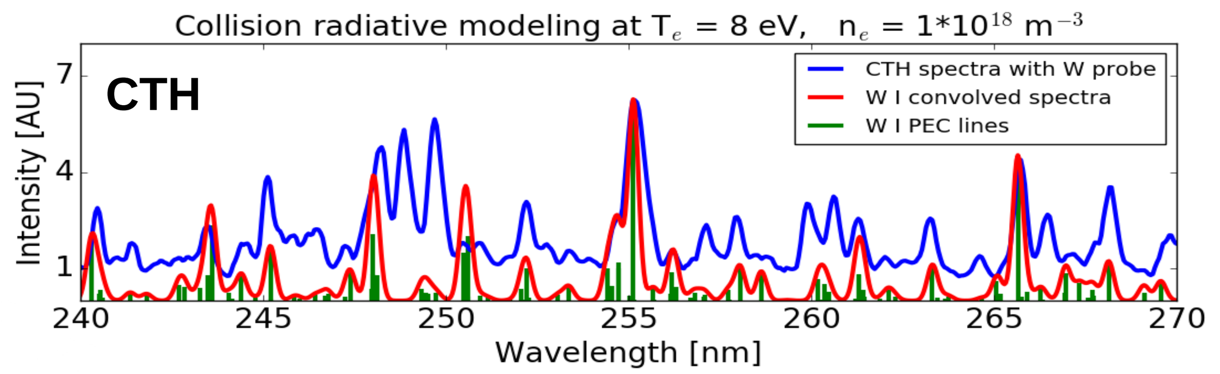


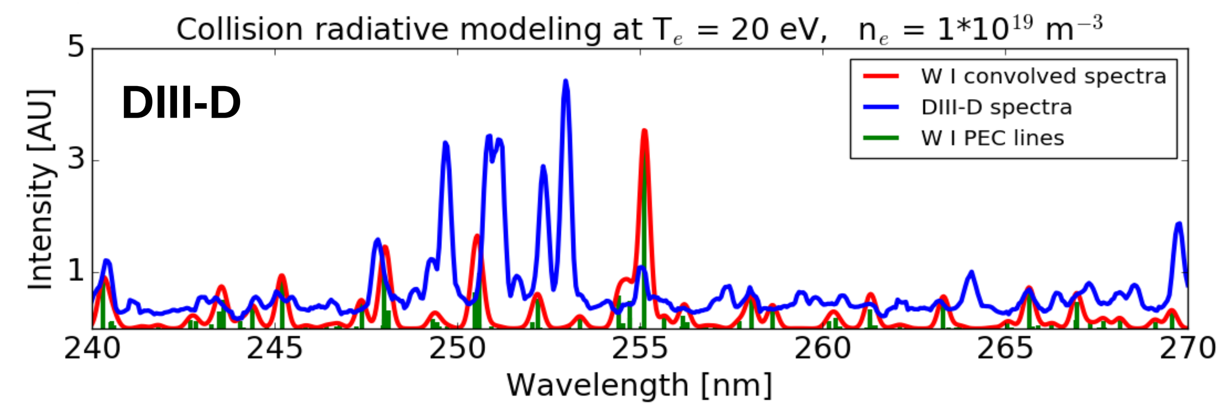


$$N_i = \sum_\sigma -N_\sigma \sum_j C'^{-1}_{ij} C_{j\sigma}$$

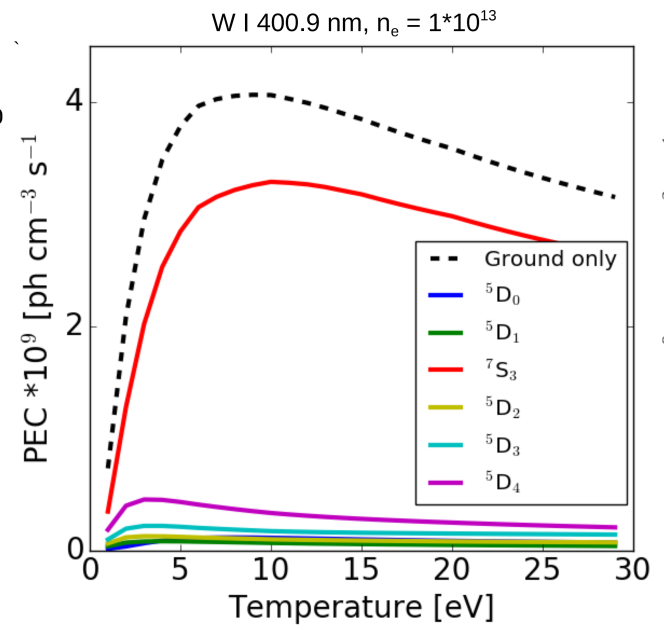
- **UV spectrometers in rough agreement with MDS spectrometer**
- **Calibration below 350 nm could not be obtained due to spectrometer light levels**
- **Upgraded spectrometer being considered to view the large promising lines in the UV**

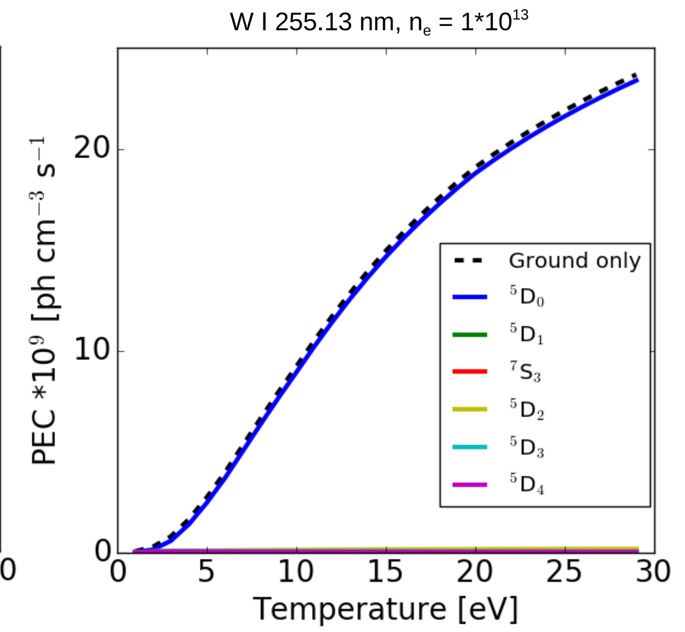
Experimental modeling of W I spectral lines and erosion



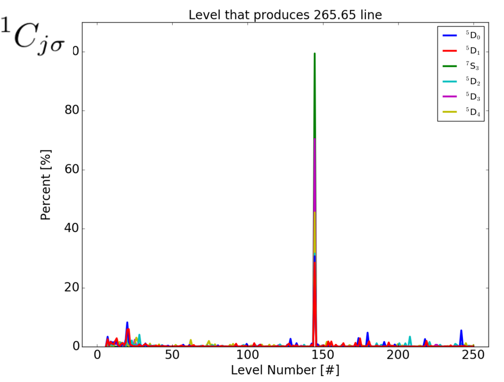


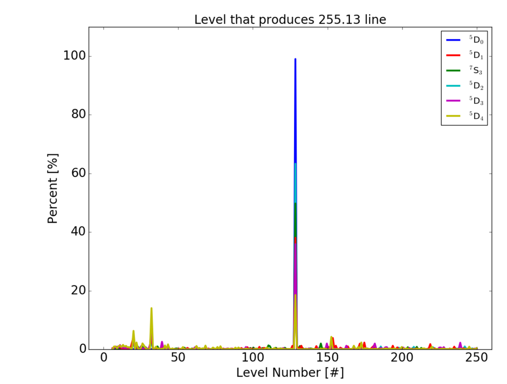
- **New R-Matrix W I excitation calculation completed see Stuart Loch's poster UP11.00034**
- **Photon emissivity coefficients show good agreement with CTH W I spectra**
- **Predicted spectra agreement not as good for DIII-D spectra**
    - Disagreement due to un-modeled metastable states?

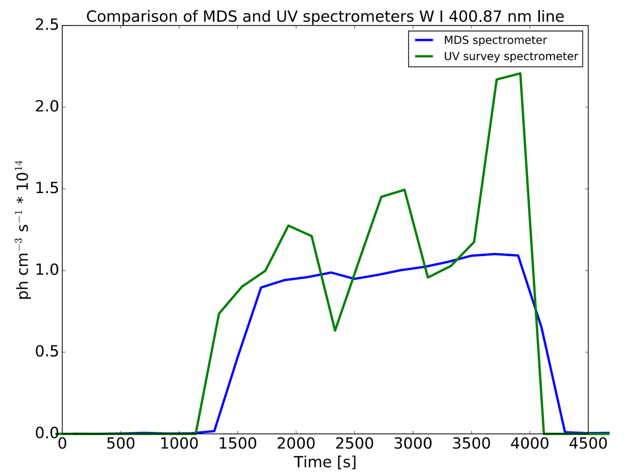


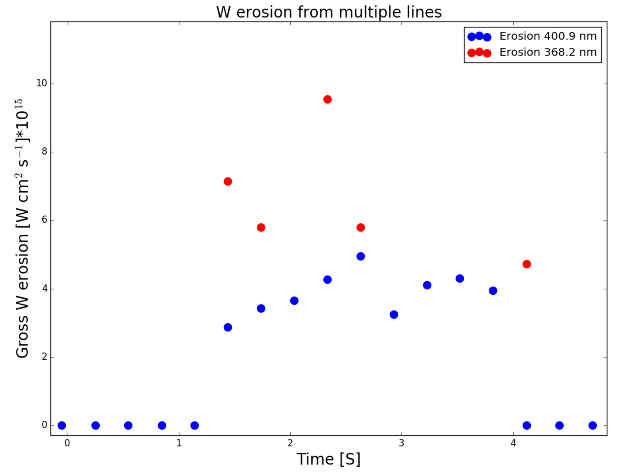


- **Populating mechanism can be determined from collisional radiative theory**
    - Important transitions can be identified and optimized around in atomic calculations
- **Strong W I lines are populated directly from the six lowest metastable states**



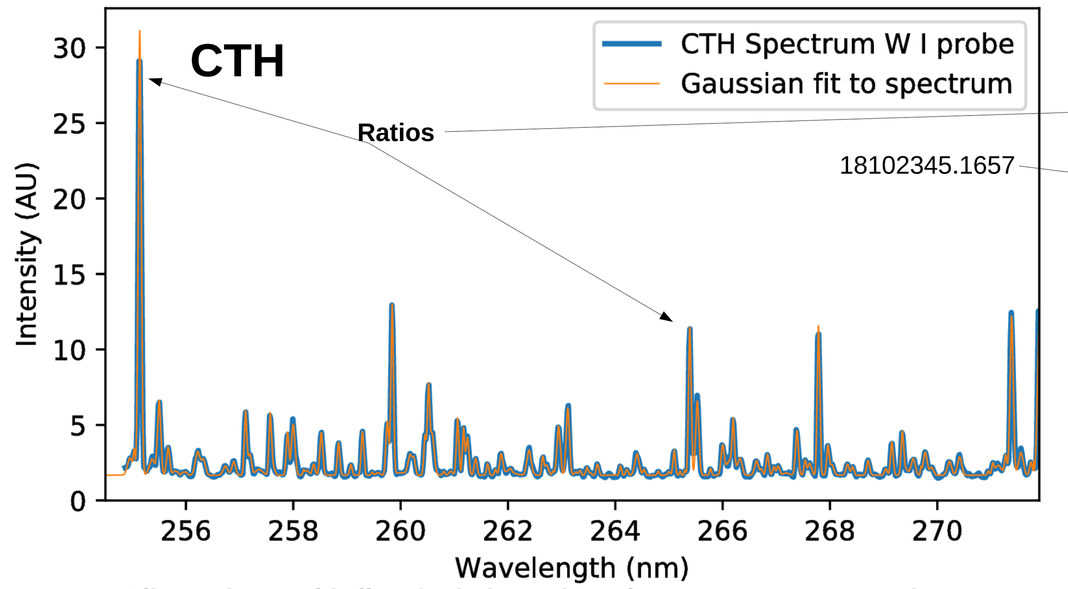


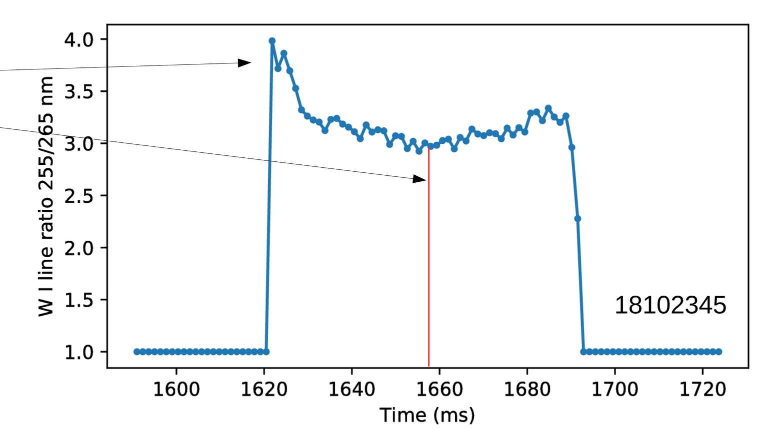




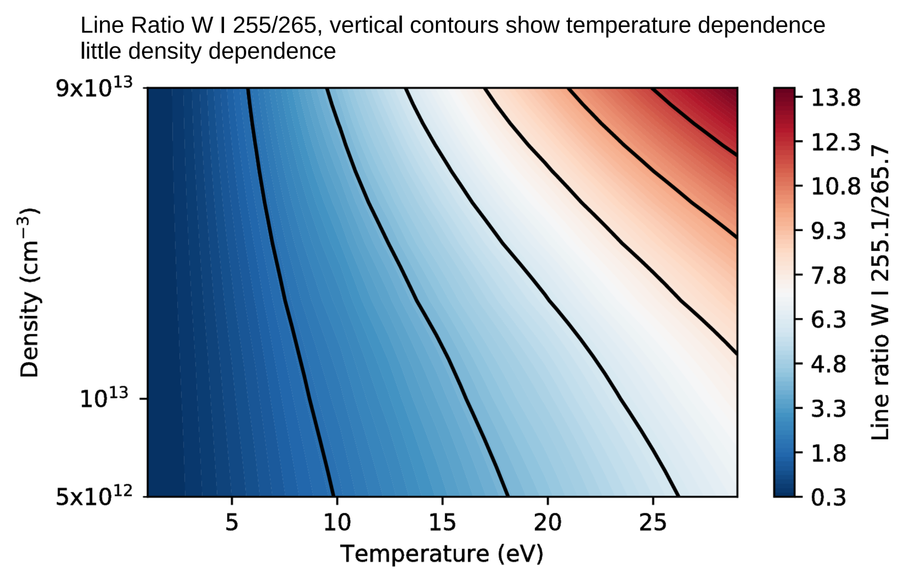
Experimental modeling of W I spectral lines and erosion

- **Upgraded spectrometer being tested to view the large promising lines in the UV, see David Ennis' poster UP11.00033**
- **Spectrometer able to simultaneously view lines that come from each metastable state**
    - Will allow first W I metastable fraction measurement
- **Tests on CTH have shown improved throughput compared to UV survey spectrometer**

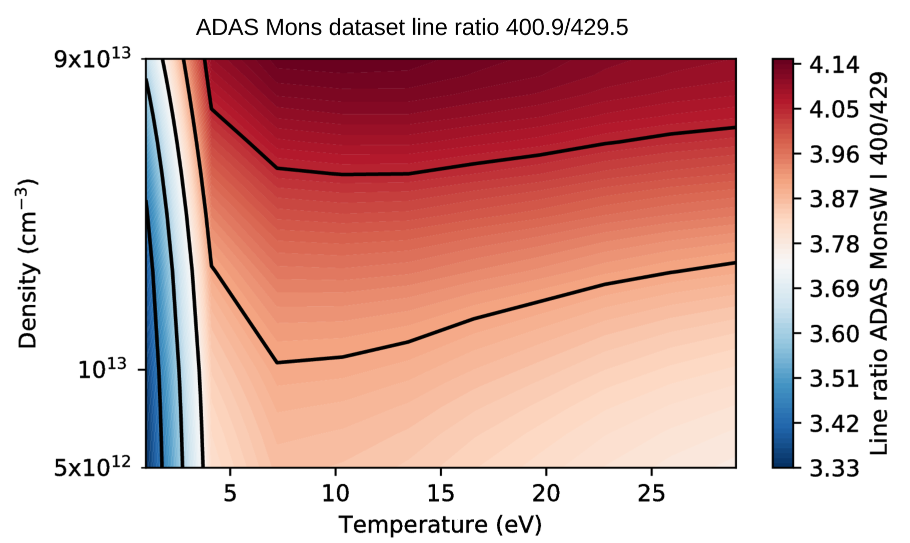


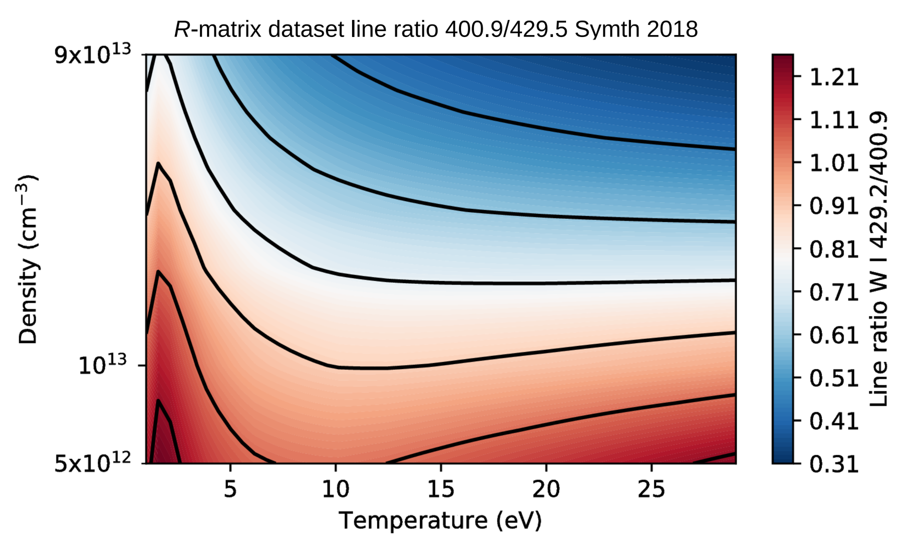


- **W I line ratios could allow for independent electron temperature and density measurements**
    - Contour plots allow optimal line pair diagnostics to be chosen
    - Temperature diagnostics should not have density dependence
    - Density diagnostics should not have temperature dependence

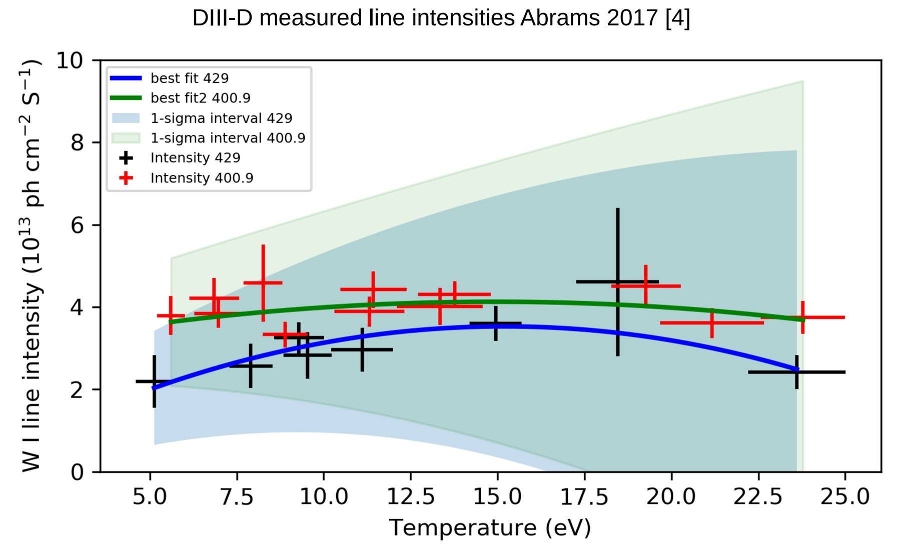


- **New high throughput spectrometer will allow these measurements to be made on DIII-D**
- **Previous work done on DIII-D takes line ratios of 400.9/429.5 nm**
- **While not a temperature sensitive line ratio (see the horizontal contours) the value can be compared against calculations to asses accuracy**



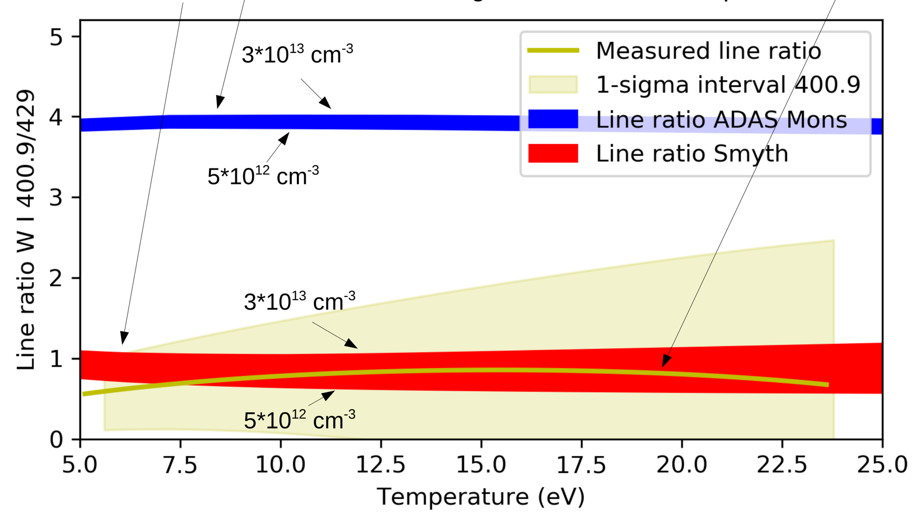


- **Previous ADAS calculations do not agree with experimental results from DIII-D for the 400.9/429 line ratio**
- **New R-Matrix calculation is in better agreement than previous W I datasets for the 400.9/429 nm line ratio**
    - Increases confidence in new calculation



ADAS Mons dataset show disagreement with measured DIII-D spectrum

New R-matrix calculation shows agreement with DIII-D spectrum



W I UV Line Identification

- **Numerous W I lines are identified between the CTH and DIII-D experiments**
    - Erosion can be diagnosed from spectral line emission along with an atomic coefficient representing the 'ionizations per photon' (S/XB)
    - More lines observed in CTH due to the larger solid angle to tungsten sample
    - Large W I lines from CTH also seen in DIII-D
    - Observing lines in both DIII-D and CTH increases confidence that line is from tungsten
- **Probe scan in CTH shows different behavior between W and other base impurities**
    - W I intensities increased dramatically with probe depth
    - W I lines in CTH can be eliminated when the probe is retracted from the plasma
    - Probes made from Mo, Fe and SiC also inserted in plasma allows a "background" spectra with the probe inserted
- **Nineteen new W I lines identified between DIII-D and CTH**
    - The large lines almost all go down to the six lowest metastable states
    - From the atomic data it looks like atoms are excited directly from the metastables, this is consistent with the large lines radiating to the metastables

Regions of large W I spectral density in CTH and DIII-D lines are seen in both devices. High density would allow high resolution spectrometer to measure multiple lines

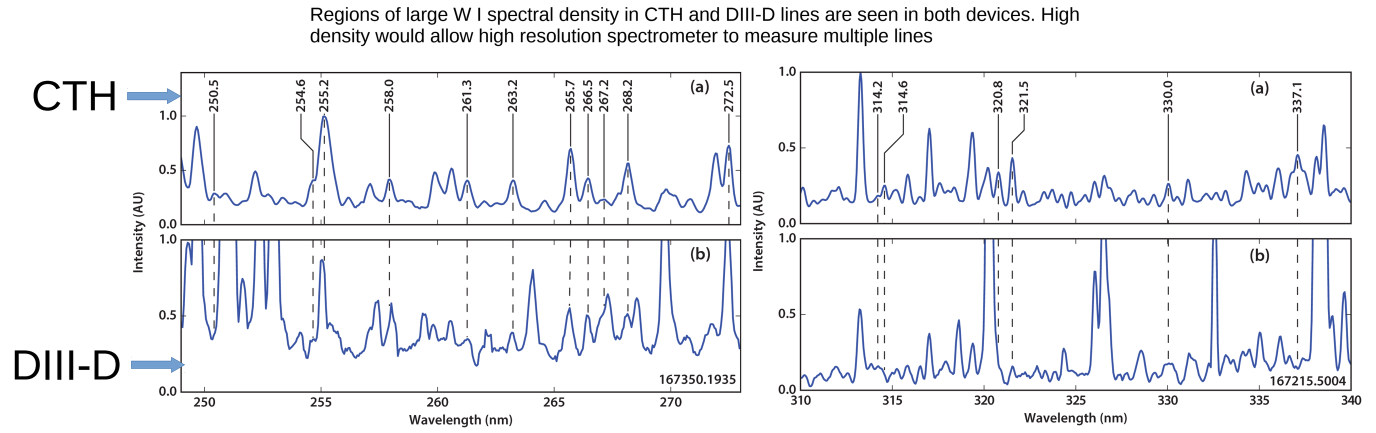
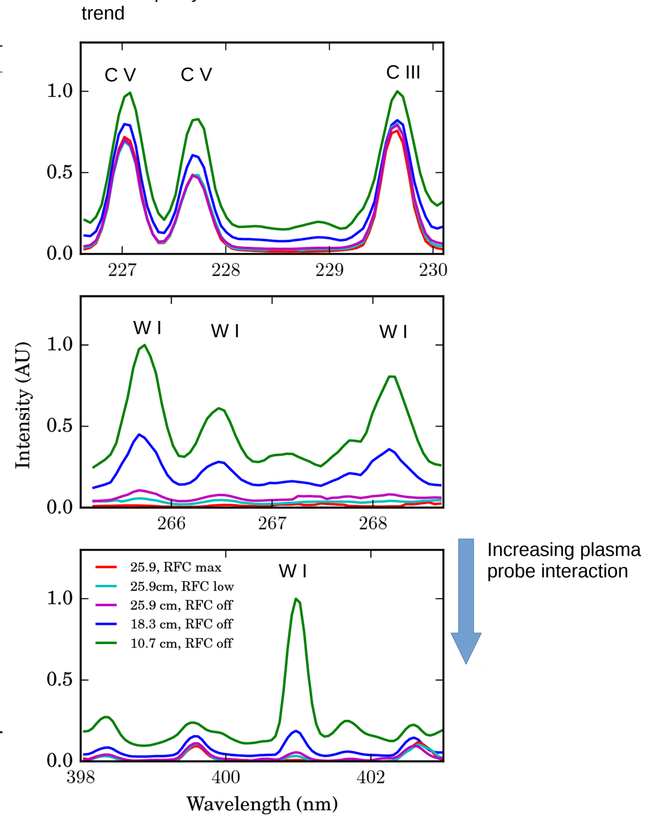


Table of observed W I lines found in DIII-D and CTH. With first upper level identifications for most lines

Line Observed [nm]	NIST location [nm]	Upper level	Lower level	Confidence
233.30	233.28	$5d^4\,6s\,6p\,(^3I_5)$	$5d^4\,6s^2\,(^5D_4)$	B
	233.29	$5d^4\,6s\,6p\,(^5P_3)$	$5d^4\,6s^2\,(^5D_4)$	B
246.24	246.28			B
243.50	243.60	$5d^4\,6s\,6p\,(^5D_4)$	$5d^4\,6s^2\,(^5D_3)$	B
247.41	247.42	$5d^4\,6s\,6p\,(^5F_4)$	$5d^4\,6s^2\,(^5D_4)$	B
250.54	250.47	$5d^4\,6s\,6p\,([]_2)$	$5d^4\,6s^2\,(^5D_1)$	B
254.61	254.71	$5d^4\,6s\,6p\,(^5F_1)$	$5d^4\,6s^2\,(^5D_2)$	B
255.20	255.13	$5d^4\,6s\,6p\,(^3P_1)$	$5d^4\,6s^2\,(^5D_0)$	A
257.98	258.05	$5d^4\,6s\,6p\,(^5P_1)$	$5d^4\,6s^2\,(^5D_1)$	A
261.30	261.31	$5d^4\,6s\,6p\,(^5F_2)$	$5d^4\,6s^2\,(^5D_2)$	B
265.65	265.65	$5d^5\,6p\,(^7P_4)$	$5d^5\,(^6S)\,6s\,(^7S_3)$	A
266.40	266.28	$([]_2)$	$5d^4\,6s^2\,(^5D_2)$	C
267.09	267.15	$5d^4\,6s\,6p\,(^3F_3)$	$5d^4\,6s^2\,(^5D_3)$	B
268.20	268.14	$5d^4\,6s\,6p\,(^5G_4)$	$5d^5\,(^6S)\,6s\,(^7S_3)$	A
272.50	272.44	$5d^5\,6p\,(^7P_3)$	$5d^5\,(^6S)\,6s\,(^7S_3)$	A
284.82	284.80	$5d^4\,6s\,6p\,(^3D_3)$	$5d^5\,(^6S)\,6s\,(^7S_3)$	B
	294.44	$5d^5\,6p\,(^7P_2)$	$5d^5\,(^6S)\,6s\,(^7S_3)$	A
294.63	294.70	$5d^4\,6s\,6p\,(^5F_3)$	$5d^5\,(^6S)\,6s\,(^7S_3)$	A
	294.74	$5d^4\,6s\,6p\,(^5I_4)$	$5d^4\,6s^2\,(^5D_3)$	A
301.74	301.74	$5d^4\,6s\,6p\,(^5D_4)$	$5d^5\,(^6S)\,6s\,(^7S_3)$	B
314.20	314.14	$5d^4\,6s\,6p\,(^5F_4)$	$5d^4\,6s^2\,(^3H_4)$	B
314.57	314.52	$5d^4\,6s\,6p\,(^3H_5)$	$5d^4\,6s^2\,(^3H_5)$	B
320.79	320.83	$5d^4\,6s\,6p\,(^5F_2)$	$5d^4\,6s^2\,(^5D_2)$	B
321.53	321.56	$5d^4\,6s\,6p\,(^5F_5)$	$5d^4\,6s^2\,(^5D_4)$	A
330.03	330.08	$5d^4\,6s\,6p\,(^5F_4)$	$5d^4\,6s^2\,(^5D_3)$	B
337.09	337.10	$5d^4\,6s\,6p\,(^5F_2)$	$5d^4\,6s^2\,(^5D_3)$	B
361.80	361.75	$5d^4\,6s\,(^6D)\,6p\,(^5P_3)$	$5d^5\,(^6S)\,6s\,(^7S_3)$	A
378.08	378.08	$5d^4\,6s\,(^6D)\,6p\,(^5P_2)$	$5d^5\,(^6S)\,6s\,(^7S_3)$	B
383.54	383.51	$5d^4\,6s\,(^6D)\,6p\,(^5P_2)$	$5d^4\,6s^2\,(^5D_2)$	B
386.82	386.80	$5d^4\,6s\,(^6D)\,6p\,(^7D_4)$	$5d^5\,(^6S)\,6s\,(^7S_3)$	B
400.90	400.88	$5d^4\,6s\,6p\,(^7P_4)$	$5d^5\,(^6S)\,6s\,(^7S_3)$	A

W tipped probe scan in CTH allows W lines to be confidently identified due to significant increase in intensity with probe location. Other impurity lines do not show the same trend



Conclusions

- **A new Collisional radiative code (ColRadPy) has been developed**
    - ColRadPy has been found to be in agreement with ADAS
- **New R-Matrix calculations for W I have been calculated and compared to experiment**
    - Calculation agrees with CTH disagree with DIII-D
    - Agree with DIII-D for some visible lines previously measured (400.9/429 nm ratio)
    - Metastable states play a significant role in spectral modeling for W I
- **New UV spectrometer tested on CTH**
- **Many new UV neutral tungsten lines identified**

[1] H. P. Summers, The ADAS User Manual, version 2.2,http://adas.phys.strath.ac.uk/adas/.
[2]Dere et al. 1997, Landi et al. 2013
[3] Foster AIP Conf Proc 2013
[4] Smyth Phys. Rev. A 2017
[5] Abrams Nucl. Fusion 2017

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