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Sorting Category: 5.1.1.2 (Experimental)

Carbon Sources and Fluxes in the DIII-D Divertor[1]

R.C. ISLER, Oak Ridge National Laboratory, N.H. BROOKS, W.P. WEST, General Atomics, D.G. WHYTE, University of California, San Diego — Carbon production in the DIII–D divertor has been investigated from spectra of C I atoms and of CD and C_2 molecular bands. The CD bands, which provide a signature for chemical sputtering, are not observed frequently and tend to appear far out in the scrape-off layer near the first wall. C_2 also appears rarely; it is believed to be produced by sublimation of carbon from localized hot spots and not to constitute a large divertor carbon source. Nevertheless, effective C I temperatures vary from 0.5 to 2.0 eV, and the lower end of this range is more consistent with a molecular source, even though the upper end could be indicative of physical sputtering. Calculated influxes of the different ionization stages of carbon indicate that at least 95% of the carbon produced at the plates is retained in the divertor. This result will be correlated with direct measurements of the parallel flows of carbon ions.

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☐ Prefer Oral Session
☒ Prefer Poster Session

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Special instructions: DIII-D Poster Session 2, immediately following DG Whyte

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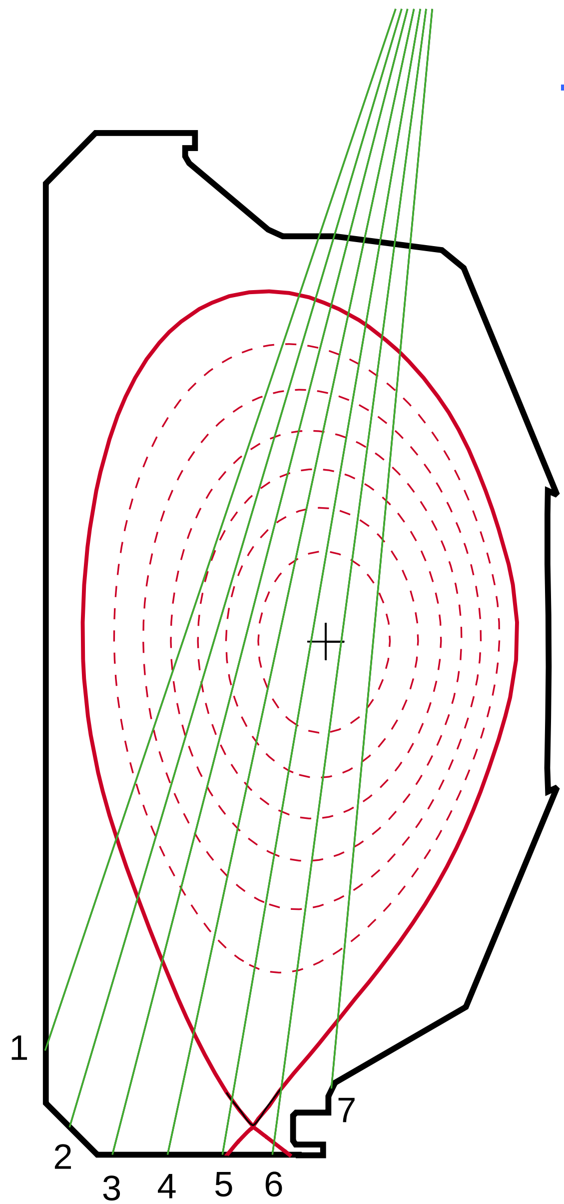
Motivation for Carbon Source Studies

- Carbon is the major impurity in DIII-D.
- We would like to understand the sources, production mechanisms, and transport in an effort to minimize the impurity content of the core plasma.
- The initial efforts have concentrated on spectroscopic studies of carbon produced in the divertor.

Spectroscopic Analysis

- Fluxes of C I - C IV diffusing in the upstream direction are evaluated using a simplistic model in order to determine influxes and shielding efficiency.
- Effective C I temperatures are obtained to gain insight into sources.
- Band spectra are analyzed to see if molecules play a role in carbon production.
- Parallel carbon ion flows in the divertor are determined to assess the role of convection in transport and shielding.

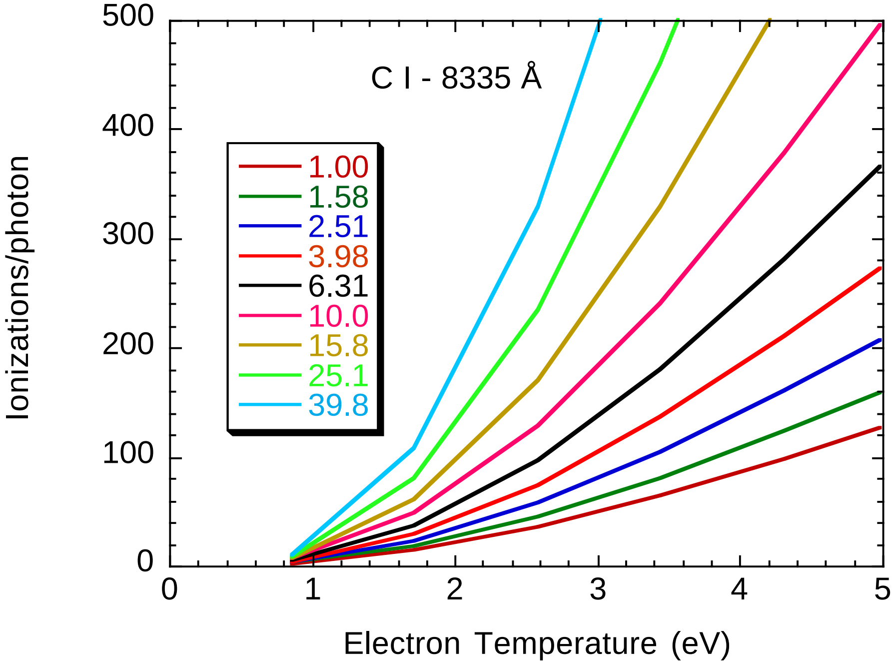
Visible Spectrometer Views into the Lower Divertor



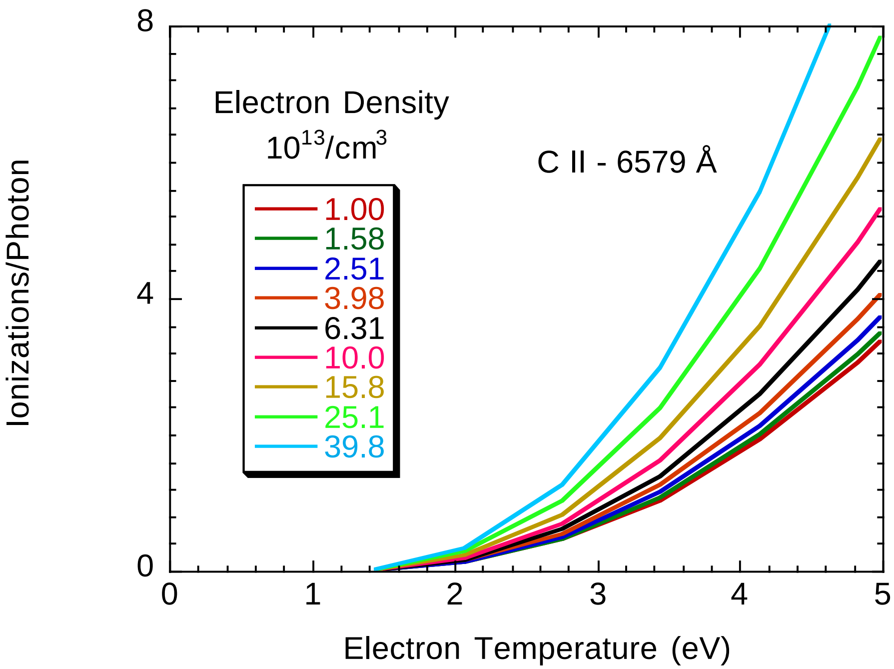
- Fluxes of low charge stages of carbon from the divertor floor to the core plasma are obtained by the combining measured spectral line intensities from the vertical views with calculated ionization/photon ratios.

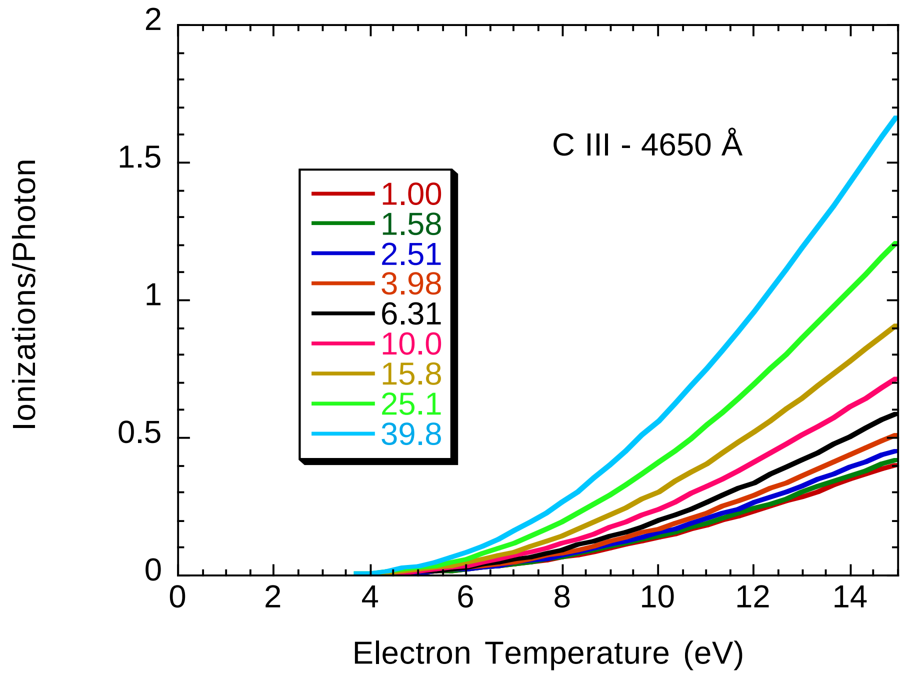
$$\Gamma = I\ S(T)/X(T)\ B$$

- Electron temperatures are assumed to be the same as the measured ion temperatures.



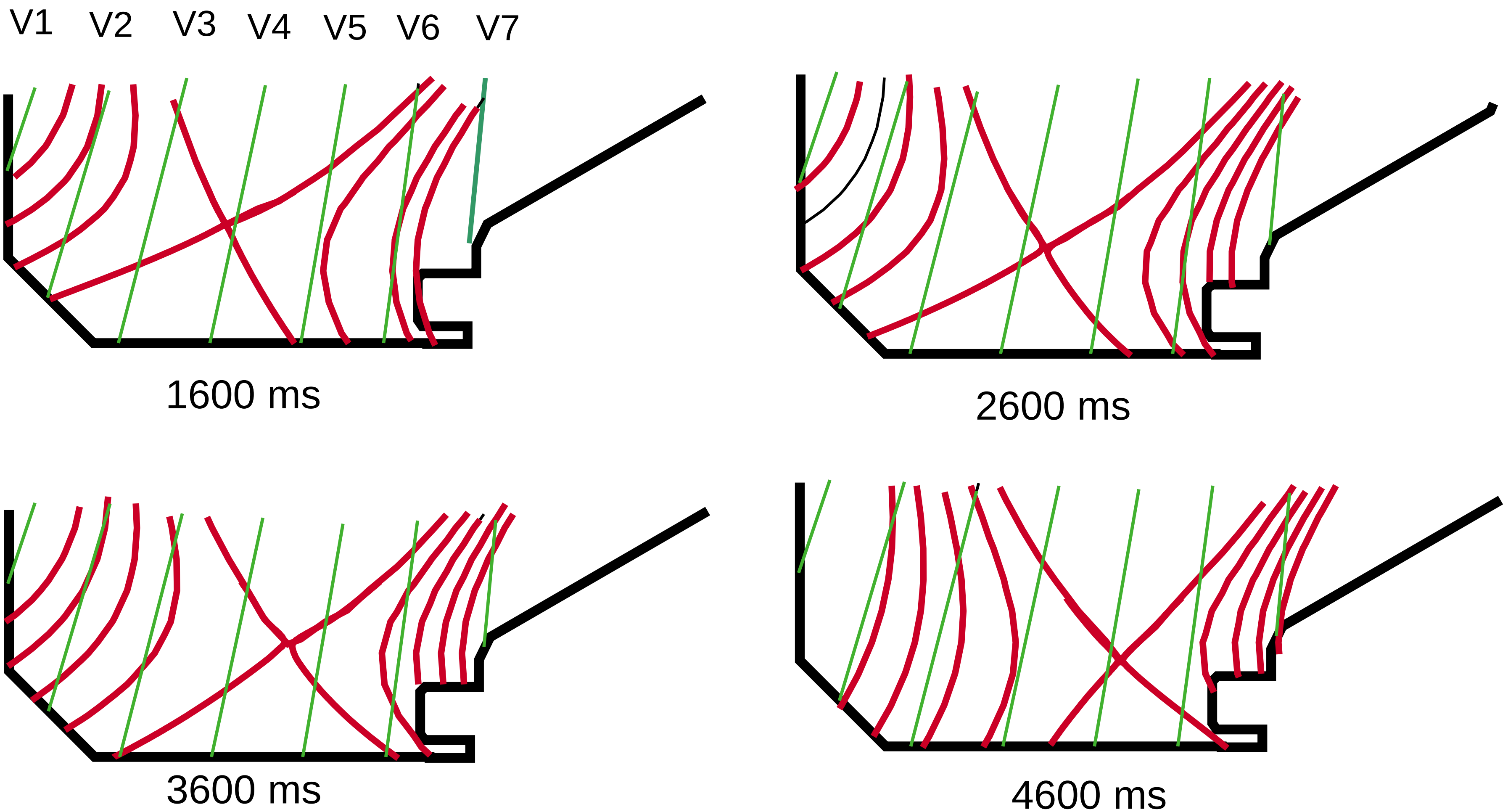
Ionizations/photon for readily observed lines of the low charge states of carbon





Attached Plasmas

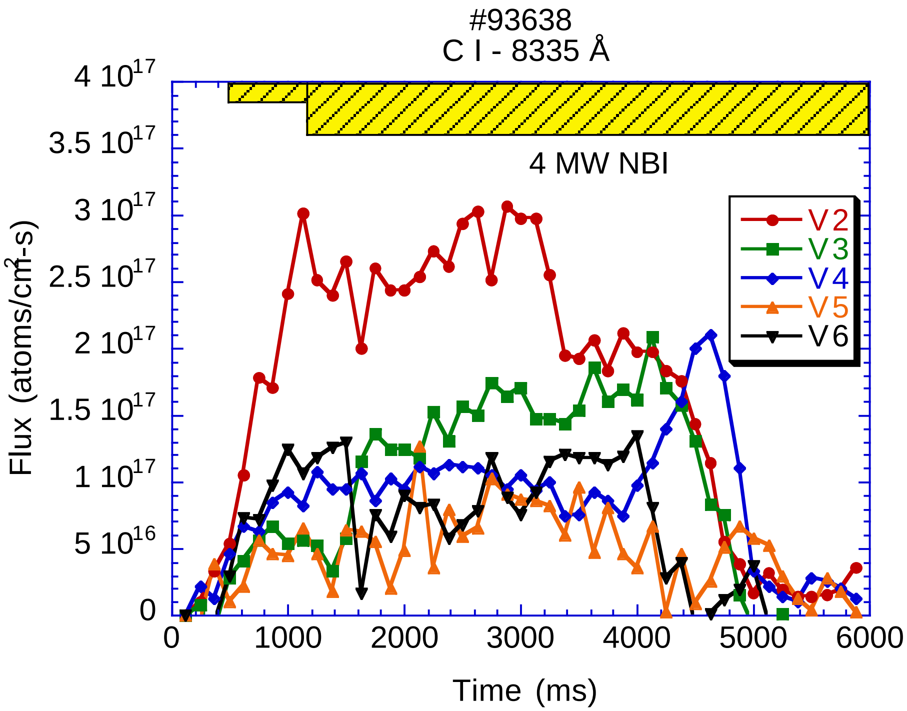
The divertor was adjusted to four different magnetic configurations during a single discharge

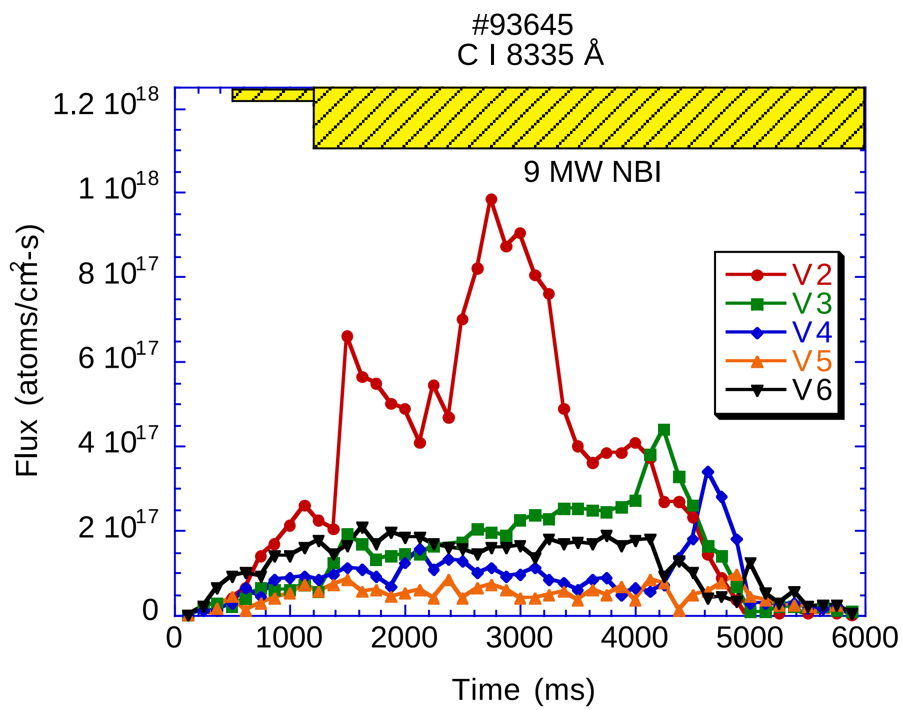


Divertor C I influxes in attached plasmas

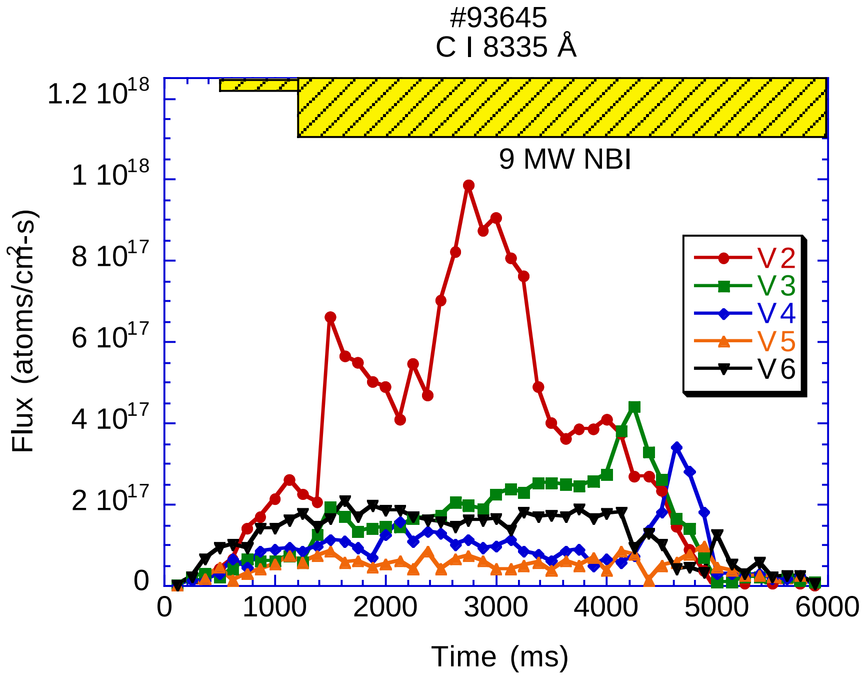
•Carbon production is strongest in the inner leg

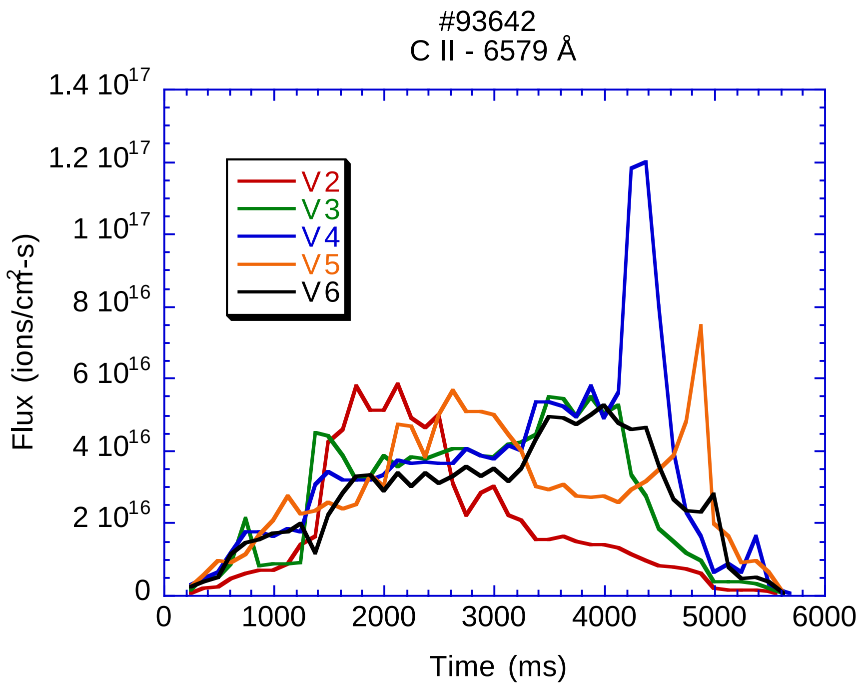
• Somewhat surprisingly, the peak production does not appear to be at the strike point.

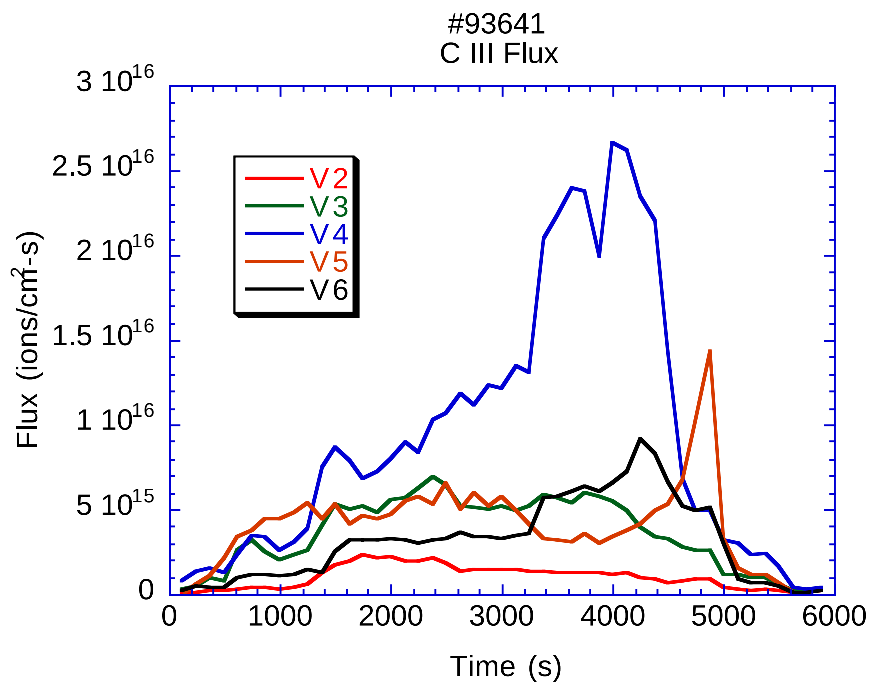




Fluxes of low stages of carbon in attached plasmas

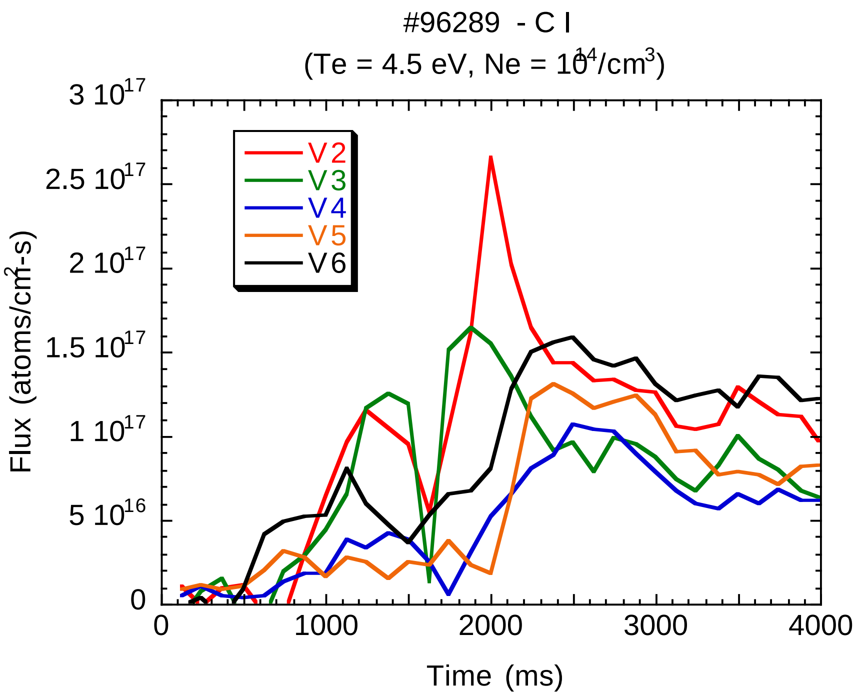




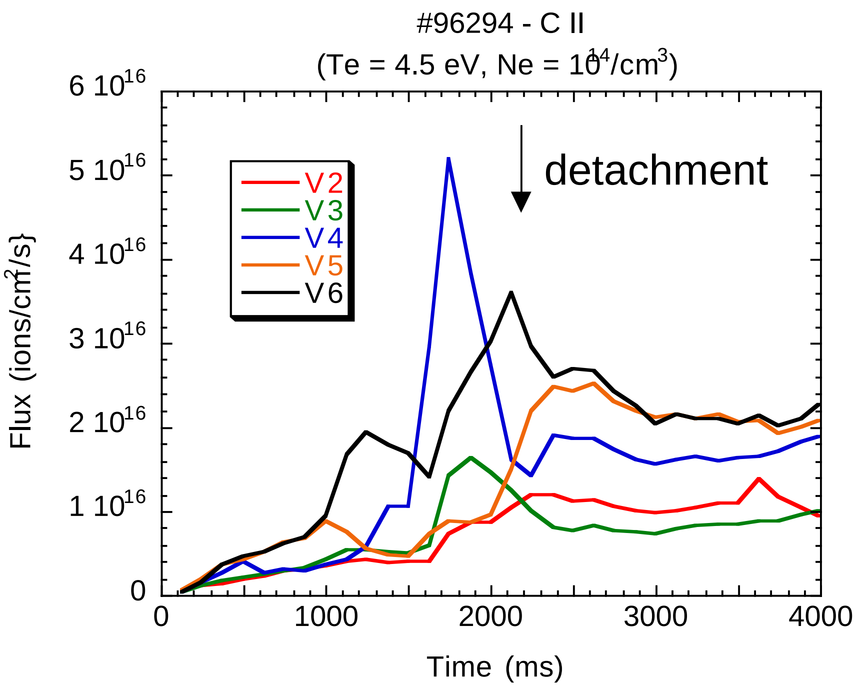


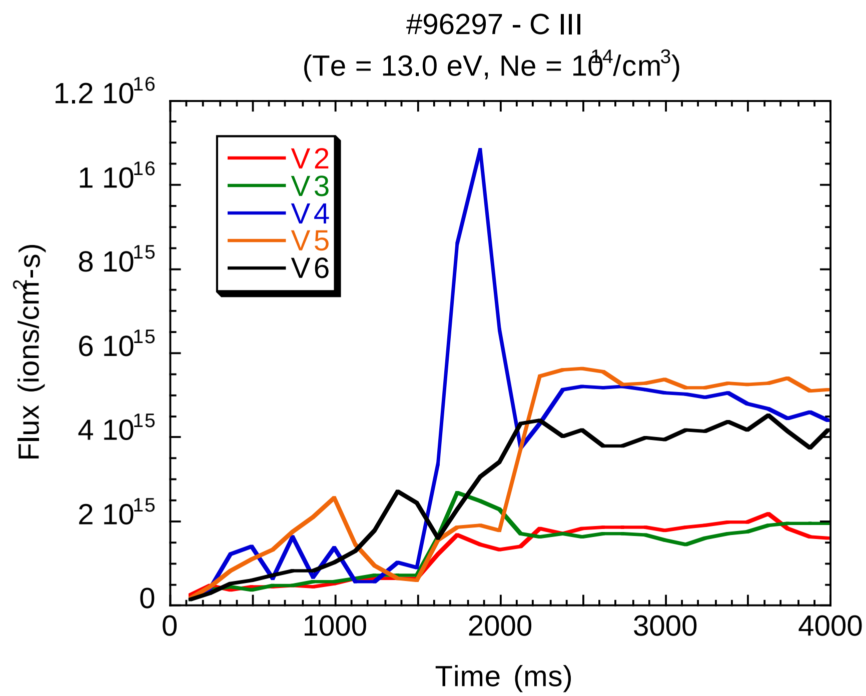
Detached Plasmas

Influxes for C I, C II, and C III



- Apparent influxes decrease with increasing ionization stage

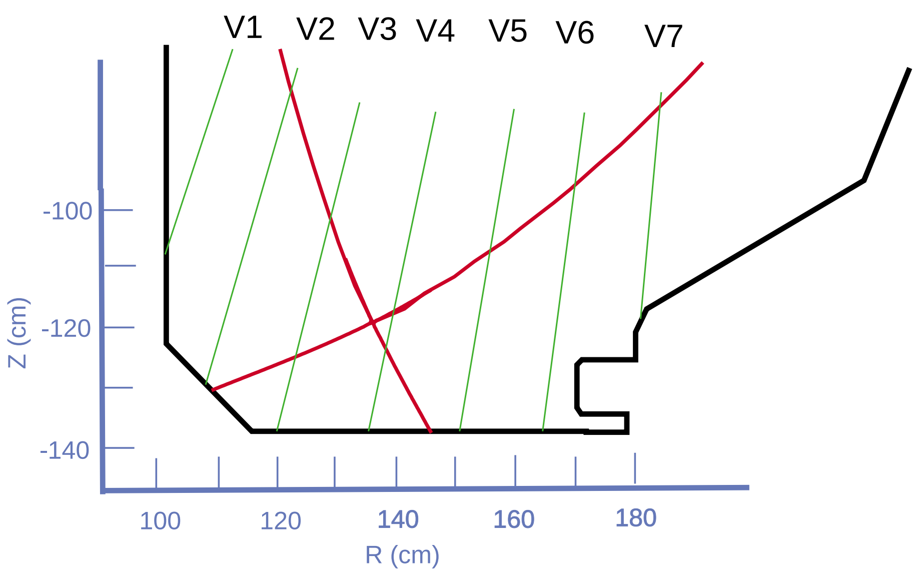


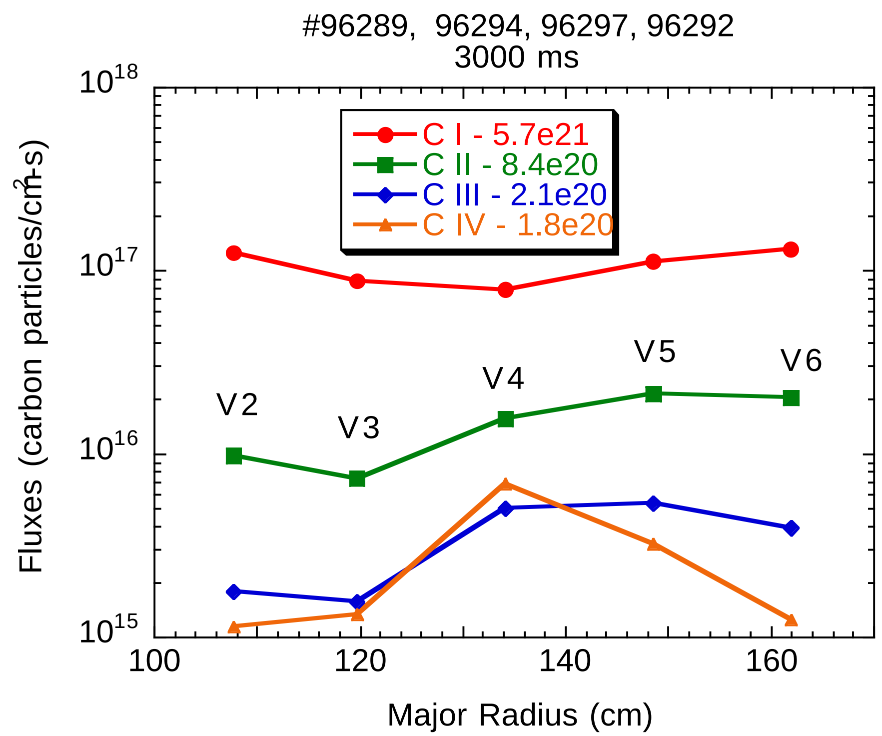


Fluxes of C I - C IV

•Neutral carbon is produced all along the inner divertor leg. The radiation is only slightly peaked at the inner strike point.

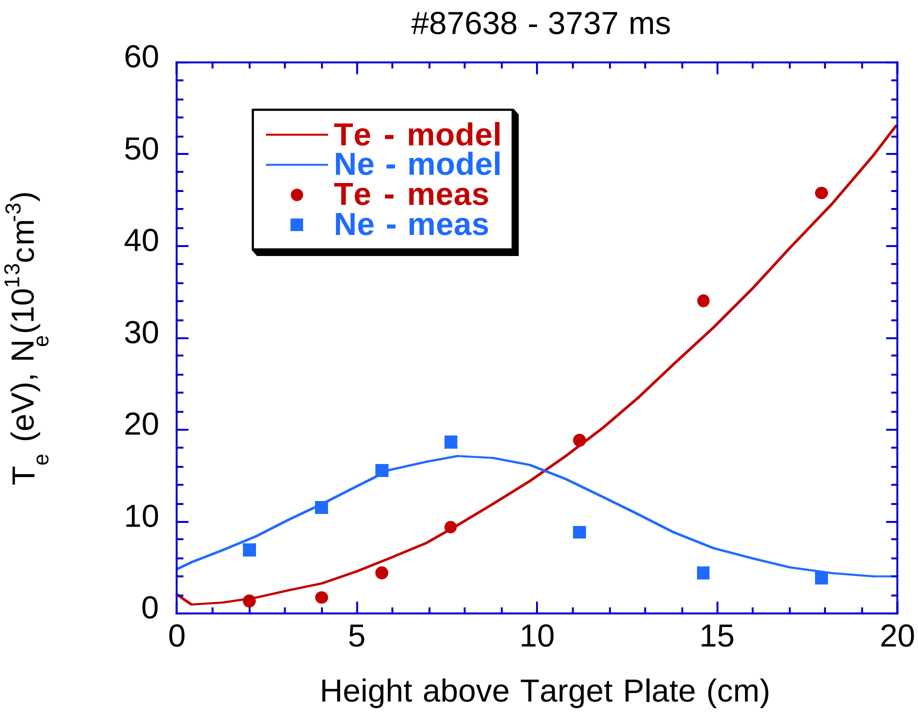
•The calculated fluxes decrease strongly as a function of ionization stage. Indications are that at least 96% of the carbon produced in the divertor flows back to the target.

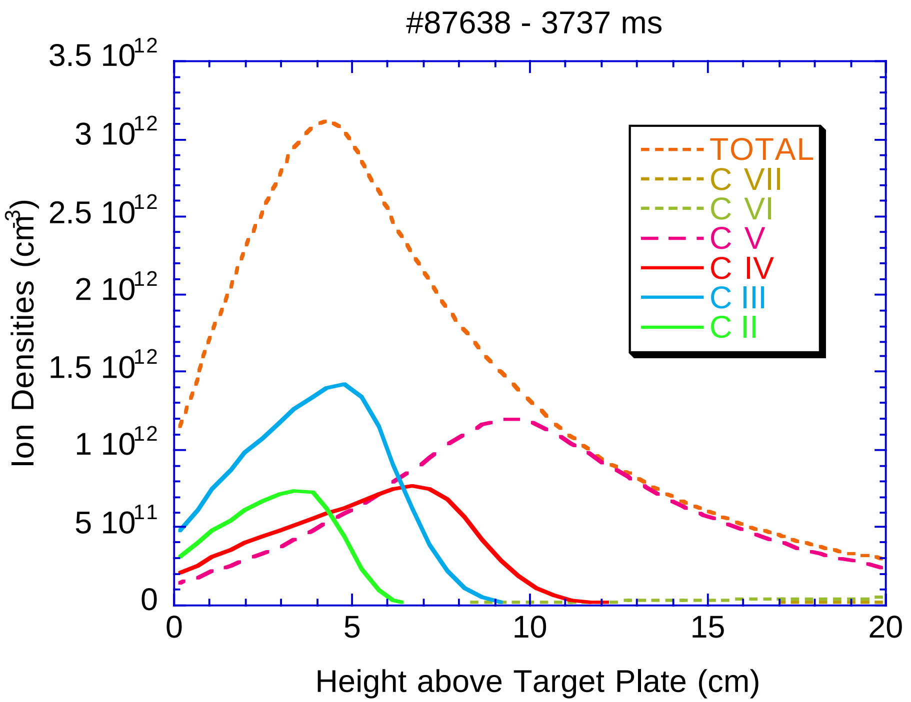




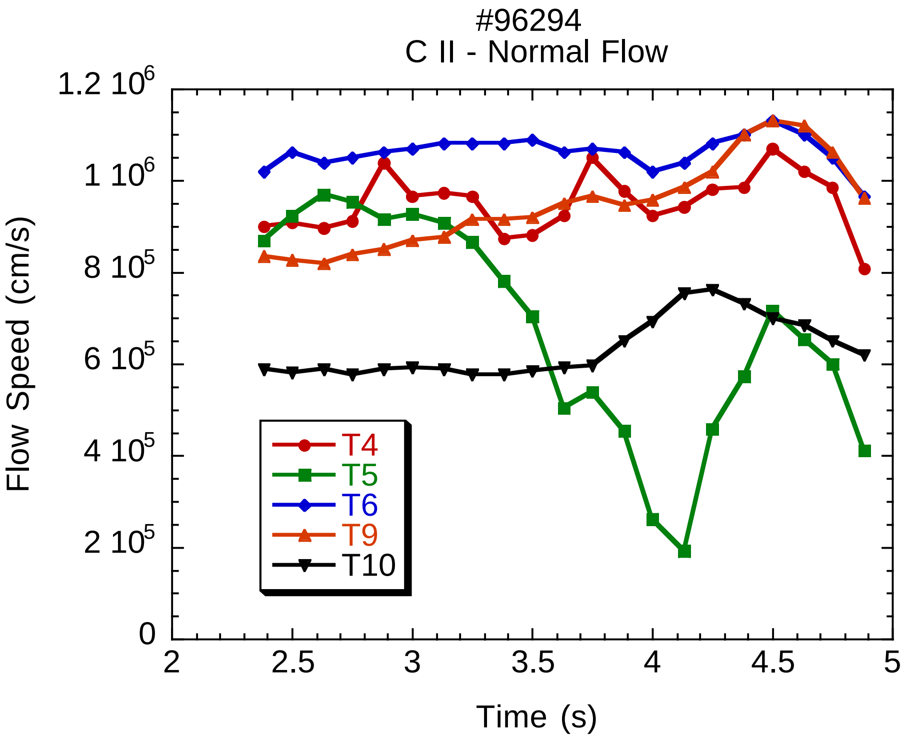
Transport Modeling

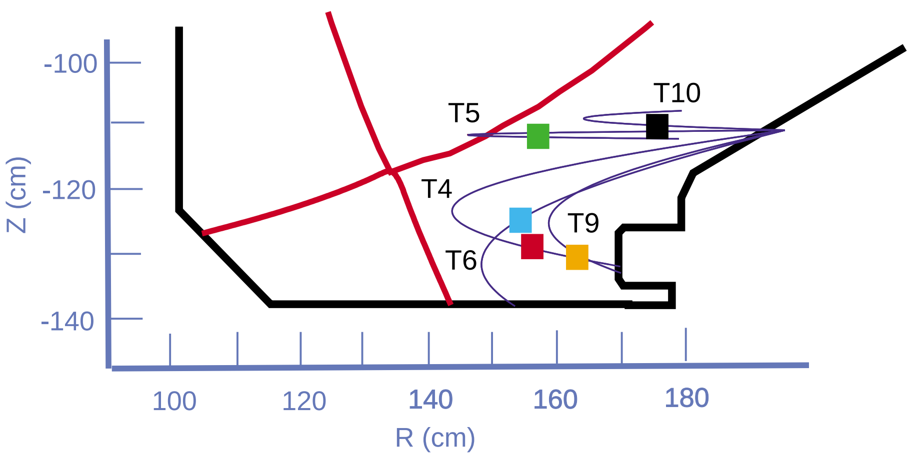
- "Naïve" transport modeling with both diffusion and convection has previously shown that strong convection toward the target limits the upstream density of carbon.





C II PARALLEL FLOWS TOWARD THE STRIKE PLATE





Comparison of Ionization Times and Flow Times to Strike Plate for C II

$\tau_{ion} = 1.3 \times 10^{-4}$ s   at 4.5 eV and $10^{14}/cm^3$

View	Lparallel (cm)	τparallel (s)
T4	219	2.2×10^{-4}
T6	84	7.6×10^{-5}
T9	158	2.0×10^{-4}
T5	1235	1.4×10^{-3}
T10	531	8.9×10^{-4}

Because of rapid parallel convection to the target, it is expected that the C II flux which diffuses upward toward the core is much less than the C I influx.

Summary of fluxes, flows and source locations

- Simple estimates of carbon fluxes indicate that about 95% of impurities produced in the divertor are shielded from the core. This is similar to UEDGE results.
- Measured convective flow velocities are consistent with the shielding observations.

- The primary source location appears to be inside the inner strike point in attached plasmas!
- The source seems to be almost uniform across the target in detached plasmas!
- Both these results are surprising.

Production Mechanisms

- The possible production mechanisms are usually believed to be:
  - † physical sputtering
  - † chemical sputtering
  - † sublimation or radiation enchanced sublimation
- In order to examine the active mechanisms in DIII-D, we have conducted spectroscopic studies of C I, C II, C III, C IV, CD, and C_2.

Expected Signatures for Various Production Mechanisms

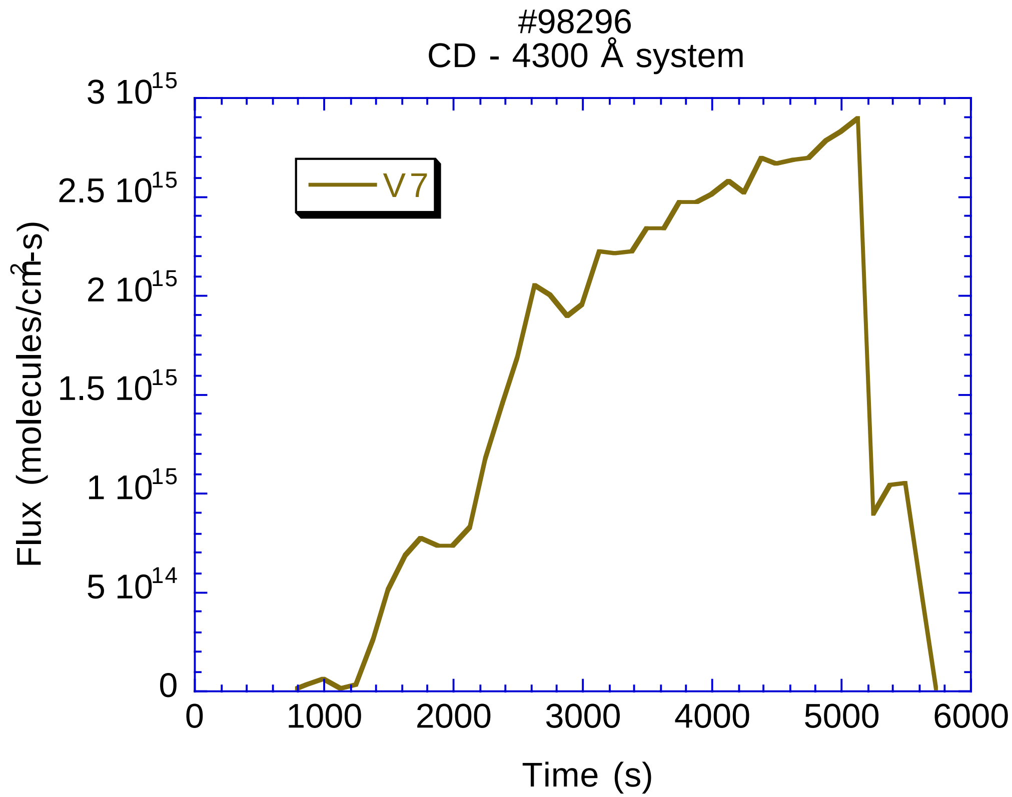
- C I atoms generated by physical sputtering should have effective temperatures > 0.8 eV.
- Chemical sputtering involves the production of CD_4. This process is usually detected from excitation of the CD 4300Å band system. C I atoms subsequently produced should have effective temperatures of 0.3 - 0.8 eV.
- Sublimation produces C, C_2, and C_3 in equal amounts. RES principally produces C atoms. Effective C I temperatures should be equal to the carbon tile temperatures, i.e. < 0.3eV

Molecules

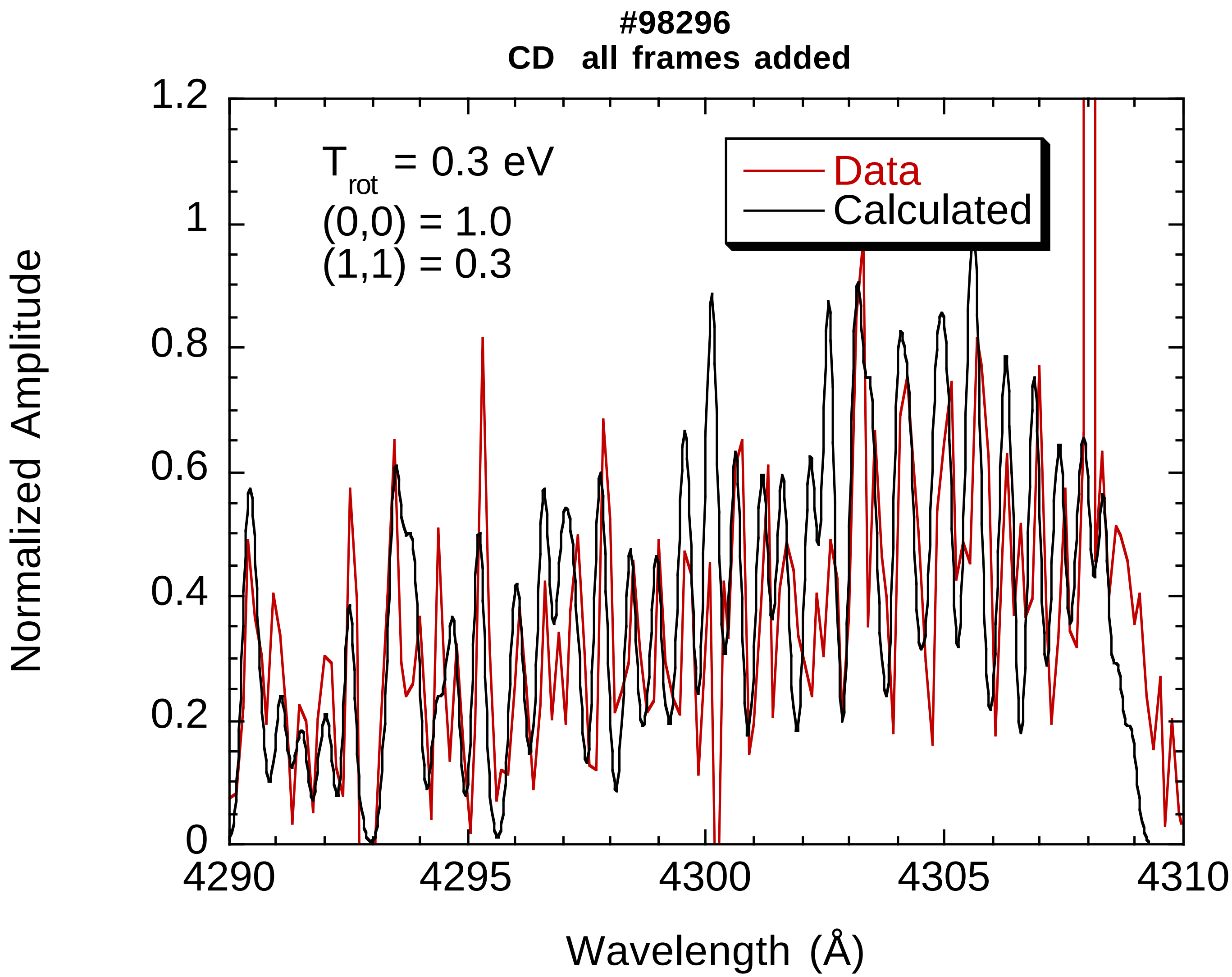
- The chemical sputtering mechanism produces an influx of deuterated methane, which should be detectable through excitation of the 4300 Å bands of CD. These bands are rarely observable in DIII-D, an indication that chemical sputtering is not important in the divertor.
- Sublimation of the carbon tiles is expected to produce C_2. This molecule is detected through excitation of the Swan bands. In general, they appear only during disruptions, although they sometimes show up weakly during normal operation.

CD_4 influxes appear to be less than 1% of the C I influxes

- In this set of discharges CD was observed only along V7 and T8 which terminate on the guard ring.
- The CD_4 flux is calculated by assuming 100 dissociation events/photon
- The C I influxes along V2 - V6 are all estimated to be in the range 1 - 2.5 X 10^{25} particles/cm^2-s.

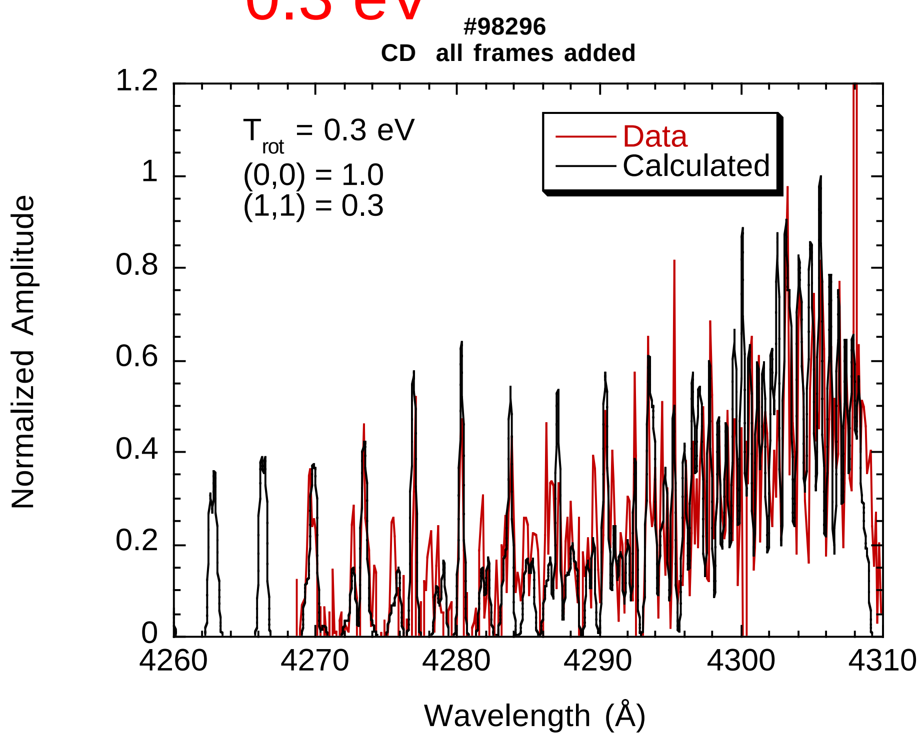


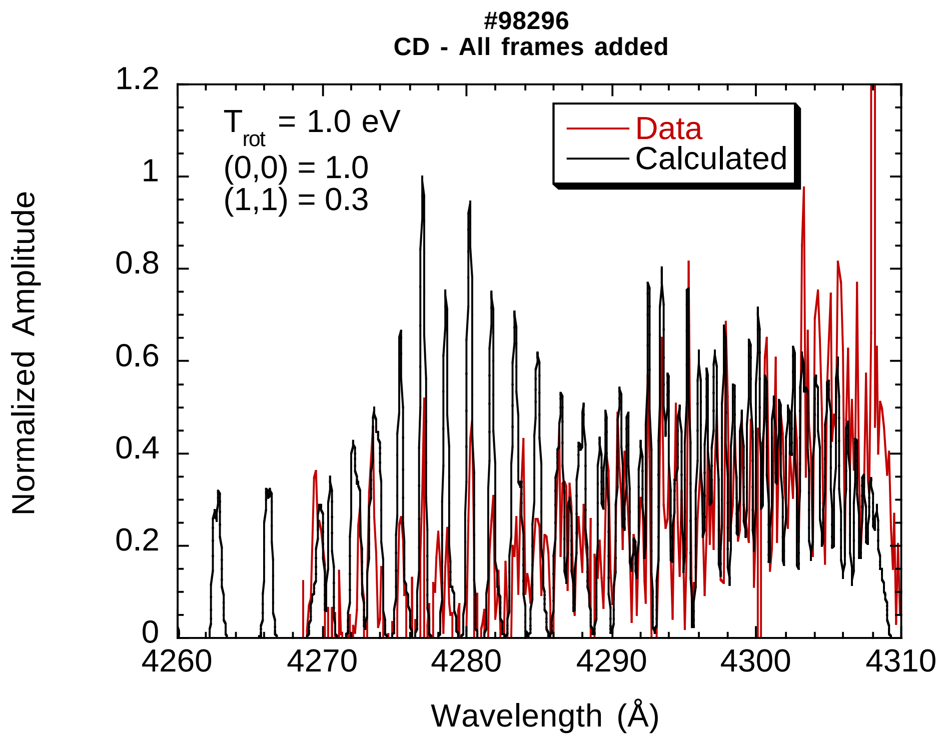
Comparison of CD data and modeled spectra



CD band structure calculations

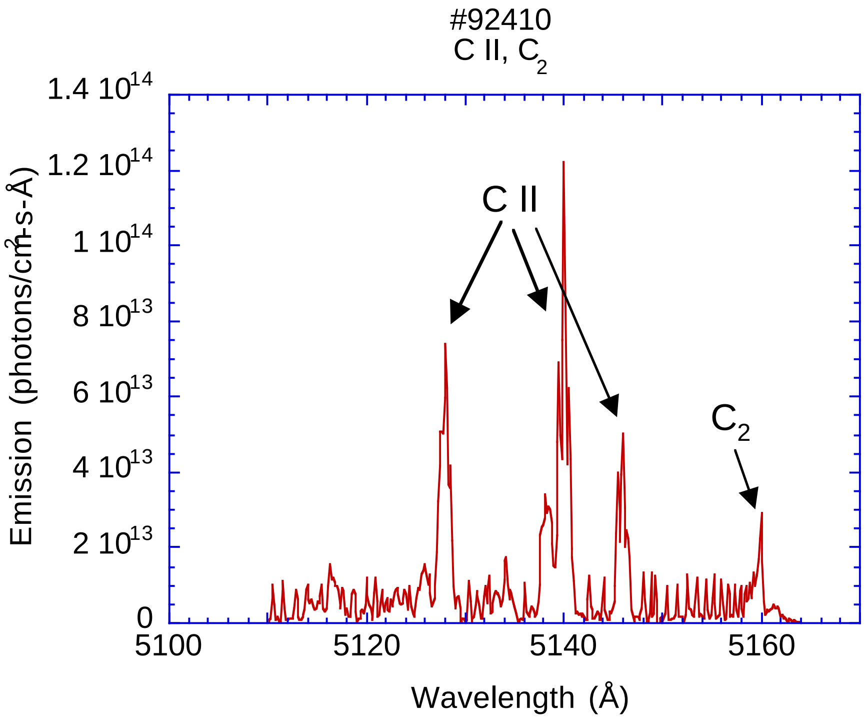
- Detailed features of the experimental data are not well modeled
- The general shape of the bands is best reproduced by a rotational temperature around 0.3 eV

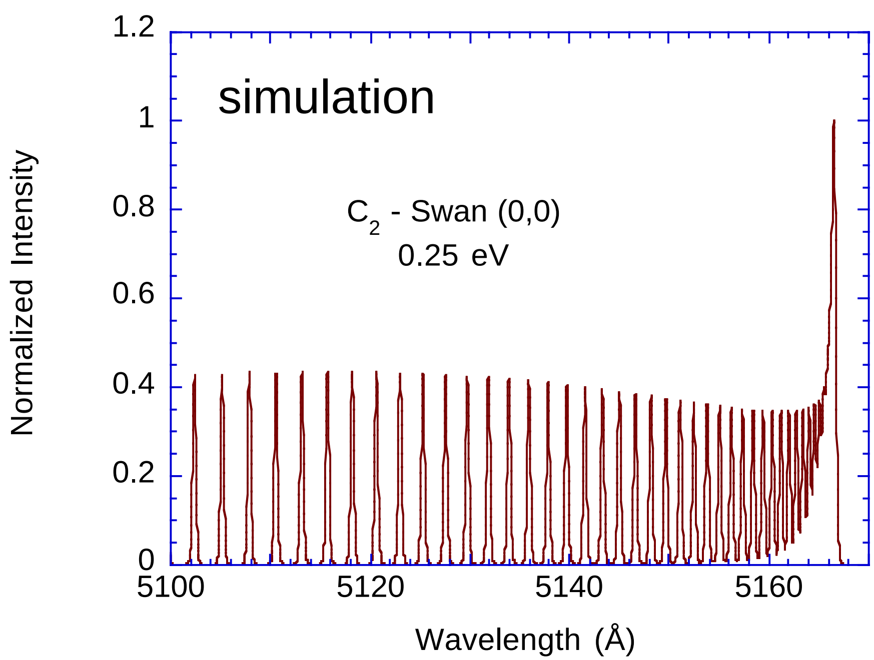


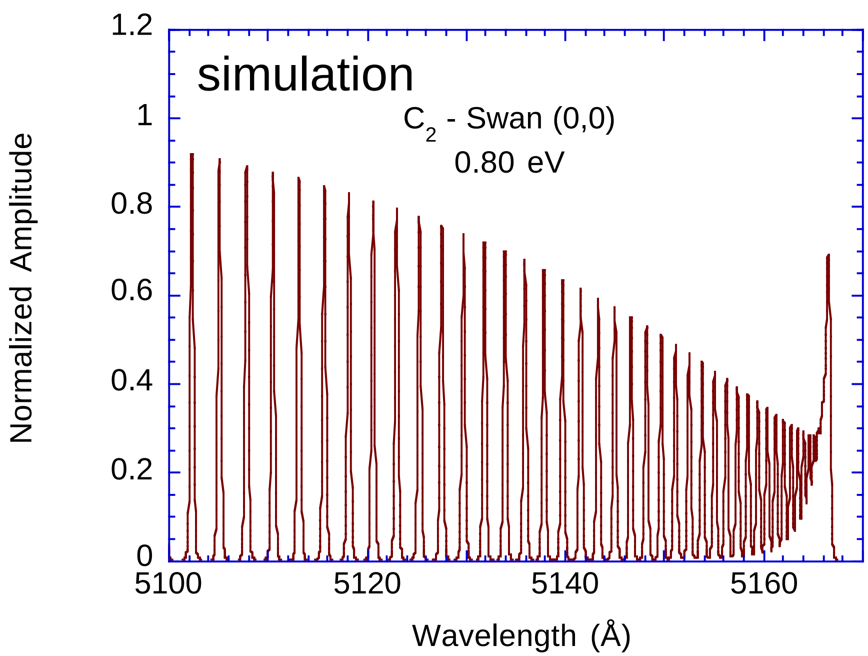


Carbon Molecules

- Carbon molecules are generally observed during disruptions, although they sometimes do appear in the course of a discharge.





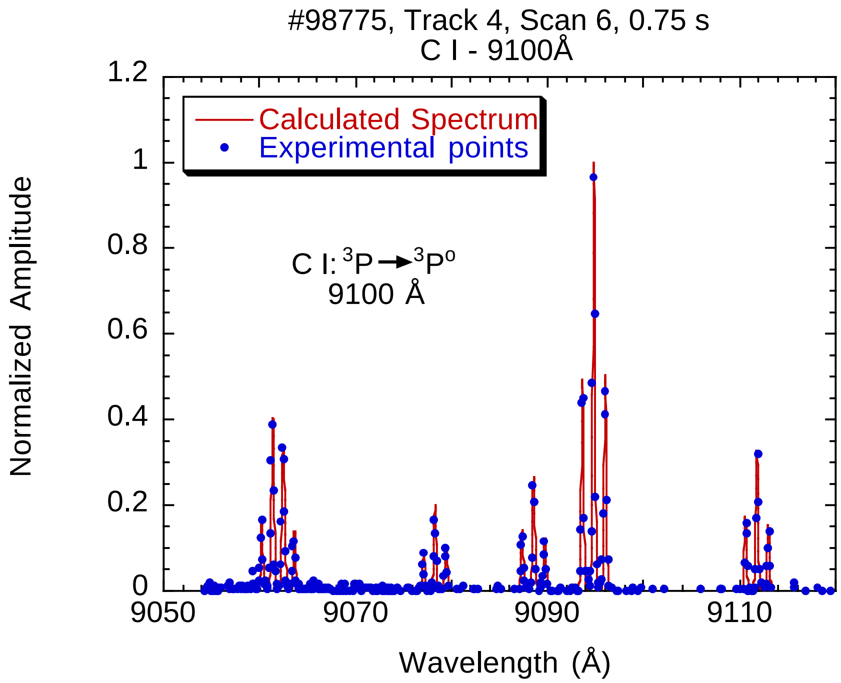


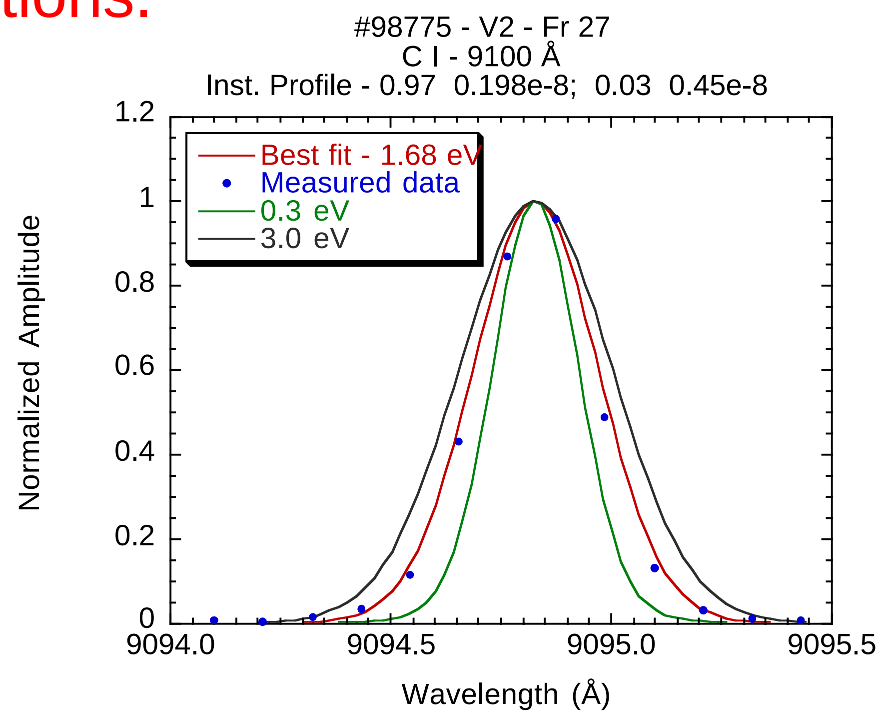
Summary of observations on molecules

- CD is rarely observed. This result appears to preclude chemical sputtering as a major source of carbon in the divertor.
- C_2 bands are strong in the spectrometer views only at times of disruptions, but we cannot rule out sublimation of tiles somewhere in the machine as an important carbon source.
- Rotational temperatures for both molecules are in the neighborhood of 0.3 eV, an indication of little thermalization with the background ions.

Do “effective” C I temperatures indicate production mechanisms ?

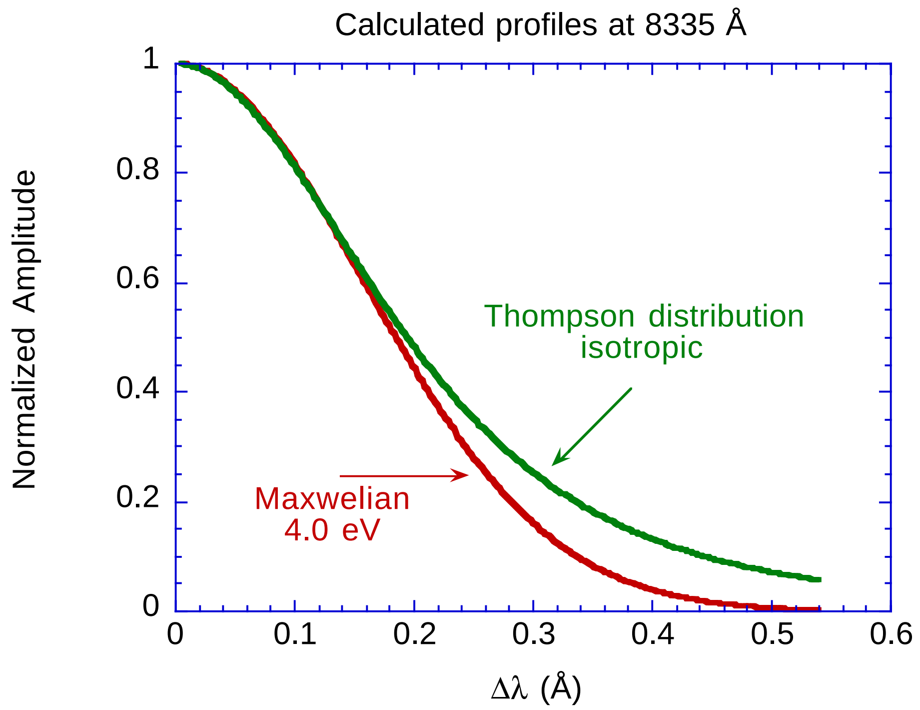
- In principle, C I line profiles need not be symmetric since the distribution in velocity space is generally nonisotropic. However, the profiles do not usually exhibit an obvious asymmetry.
- We define an effective temperature by fitting C I line profiles to Maxwellian distributions.



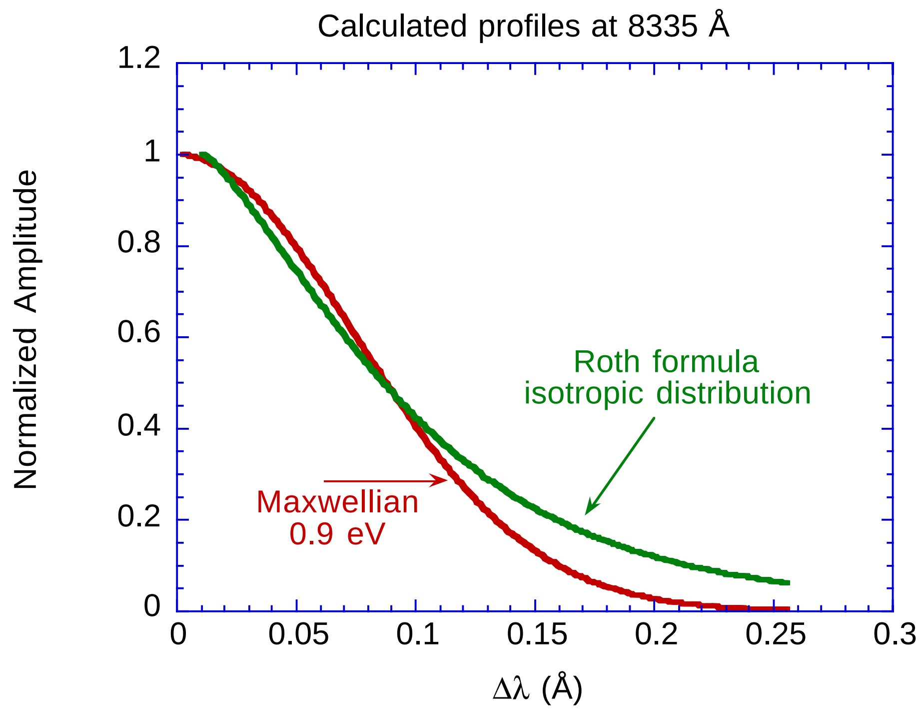


A typical Thompson distribution should produce an effective temperature of several eV. Roth's modified formula predicts an effective temperature near 1 eV.

$$f(E)dE = \frac{E}{(E+U_0)^3}$$

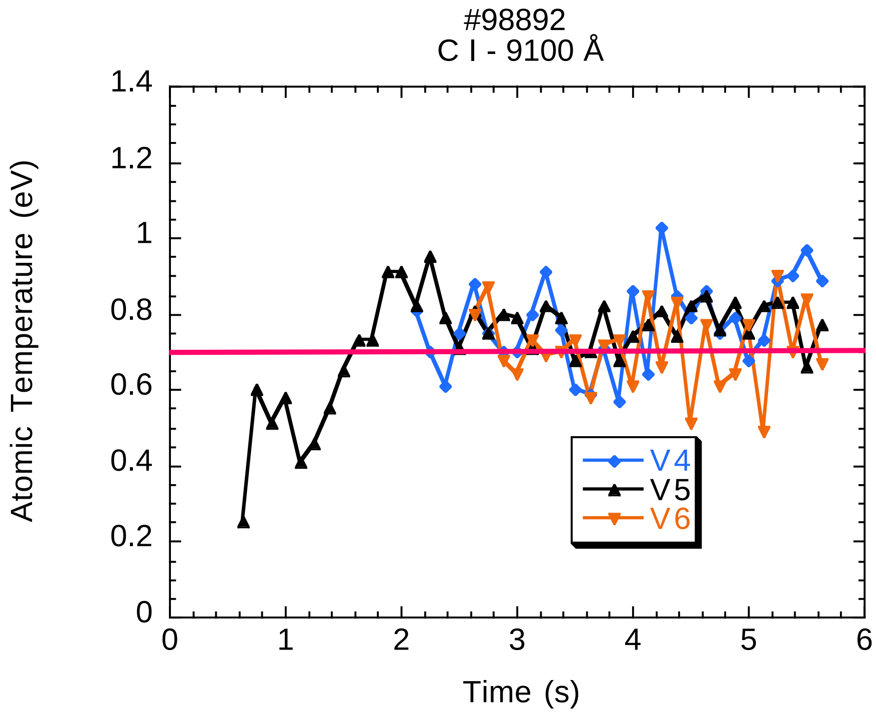


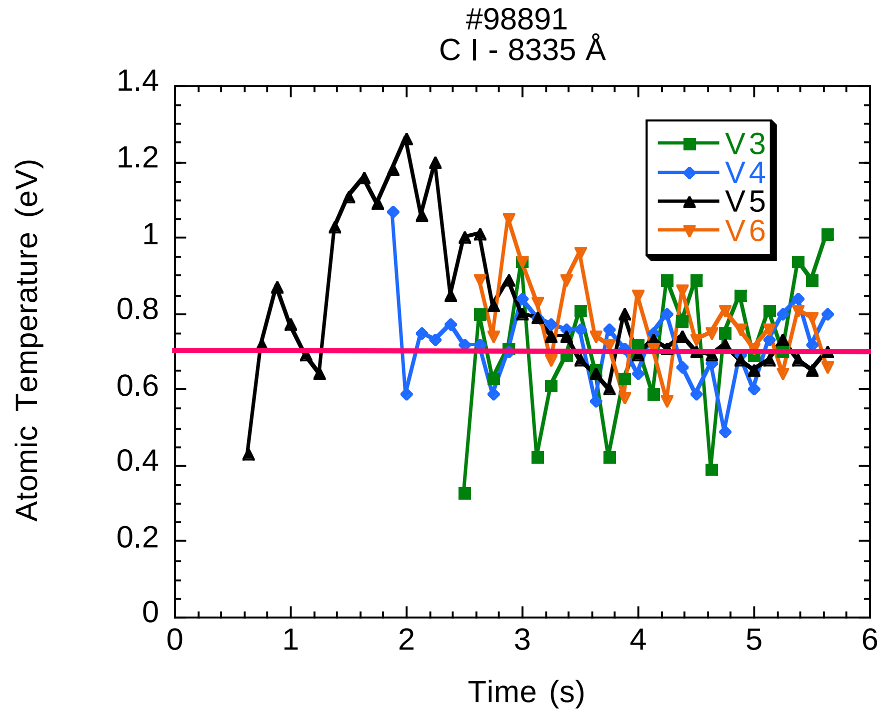
$$f(E)dE = \left[\frac{E}{(E+U_0/3)^4}\right]^{2/3}$$



Effective Temperatures from Singlet and Triplet Lines of C I

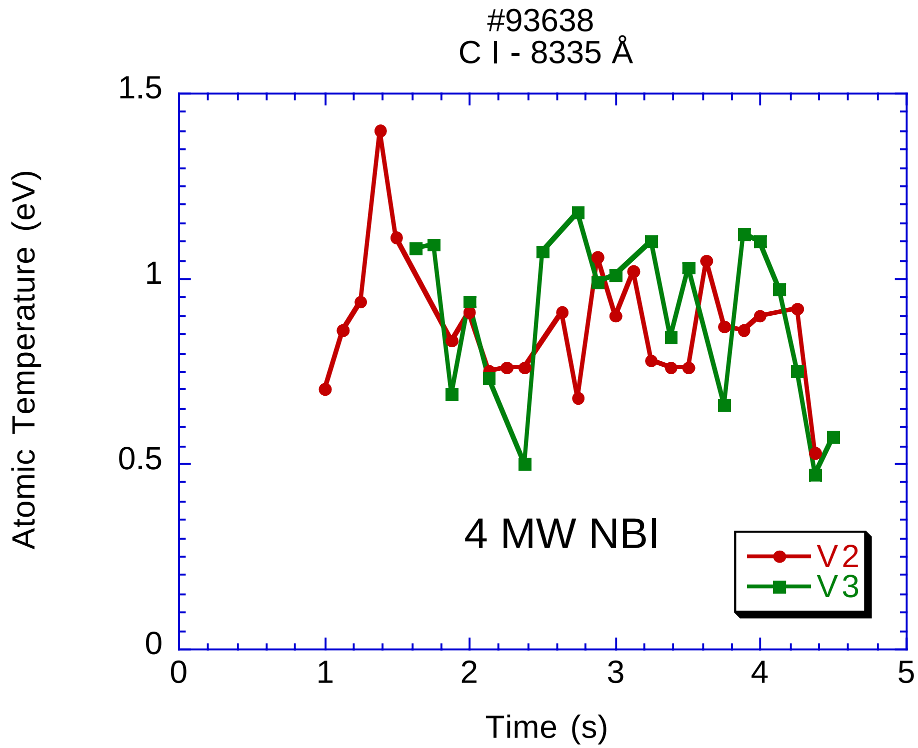
- The instrument function is measured at 7065 Å
- Temperatures measured from singlet and triplet lines of C I are in good agreement. This fact indicates differences of the instrument profile with wavelength are not significant.

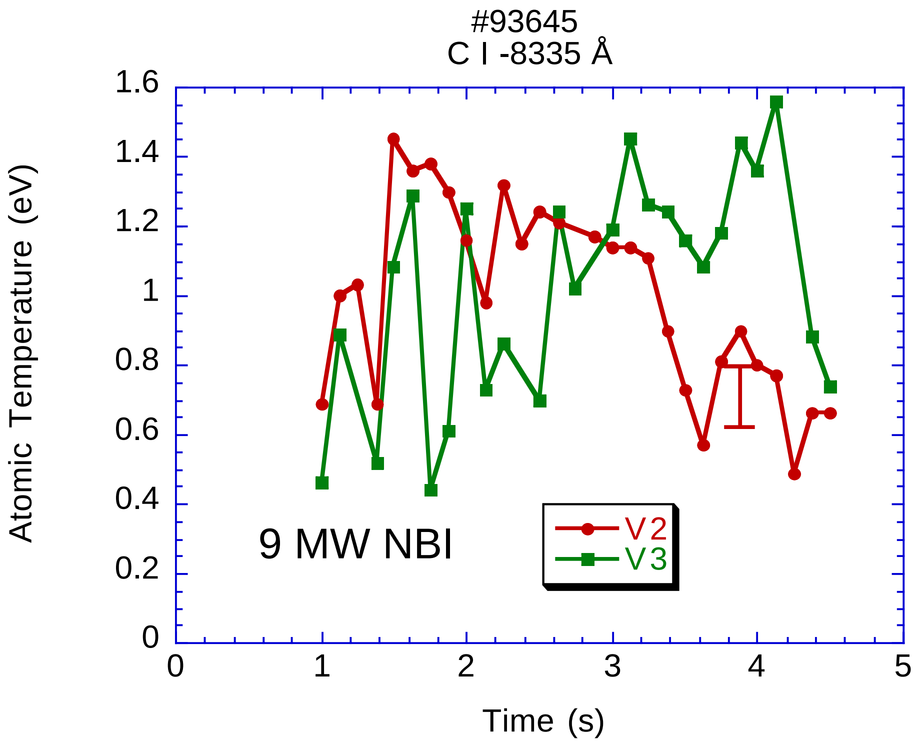




Measured C I Temperatures

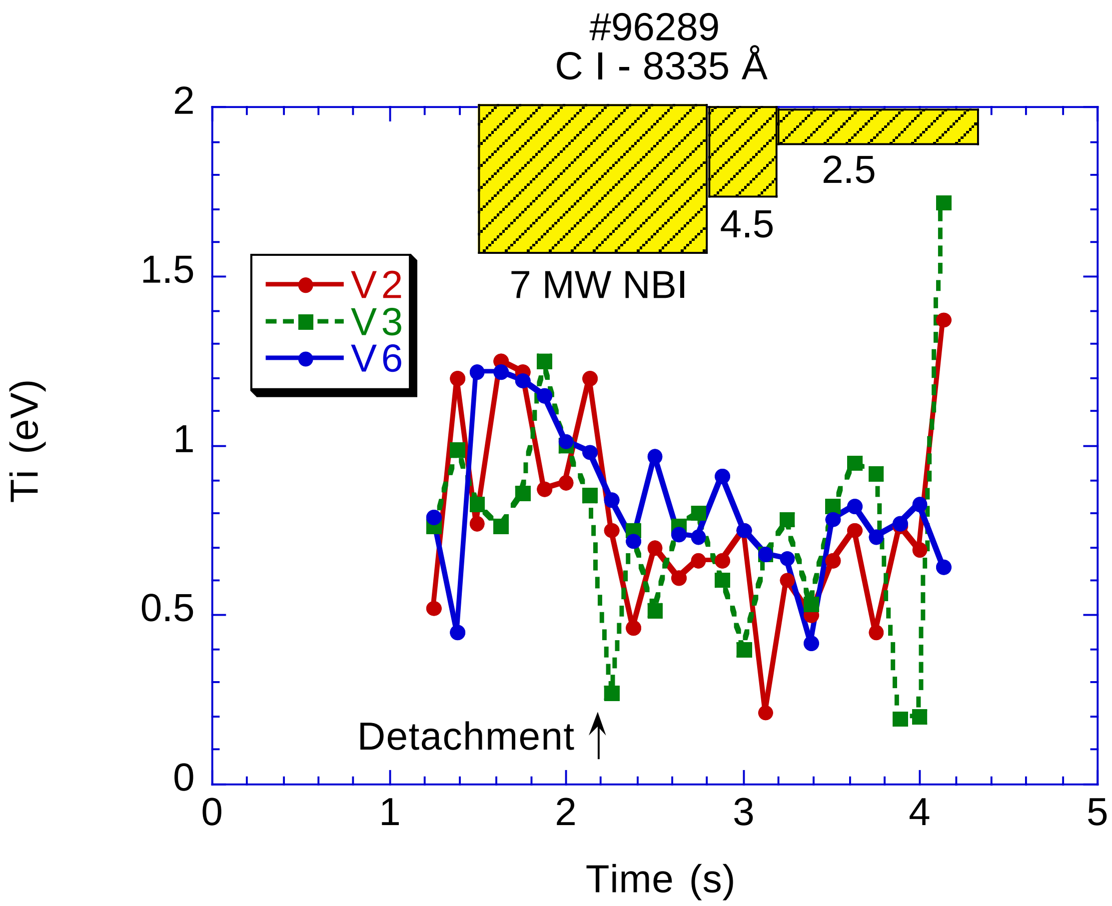
• Effective C I temperatures are often well above 1 eV as might be expected for physical sputtering, however, lower values, down to 0.5 eV, are also typically observed.



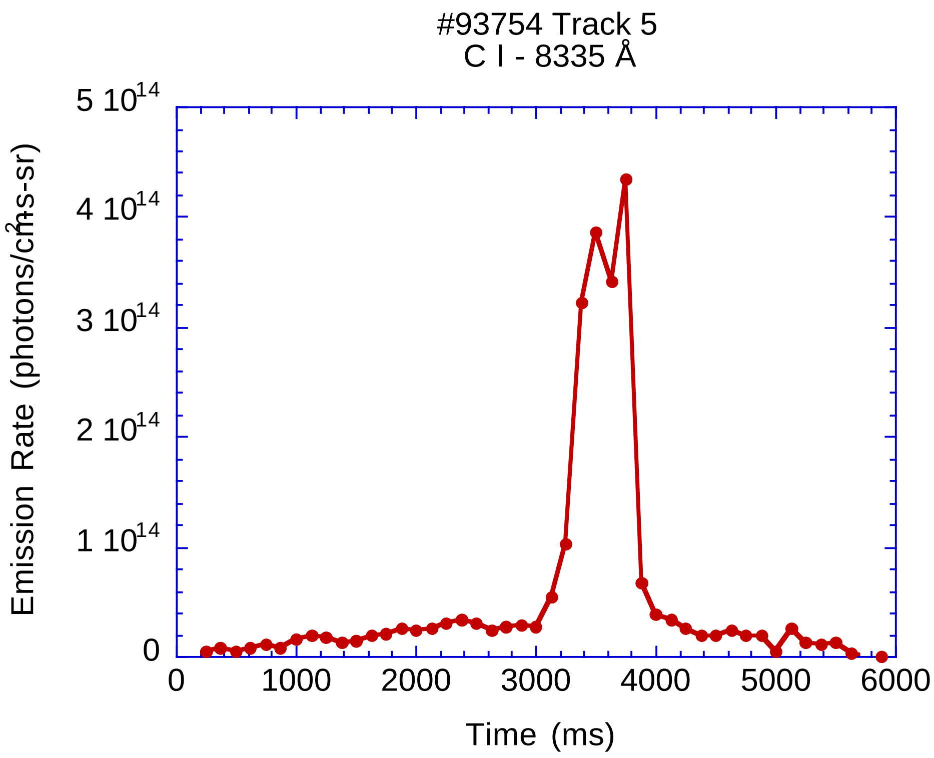


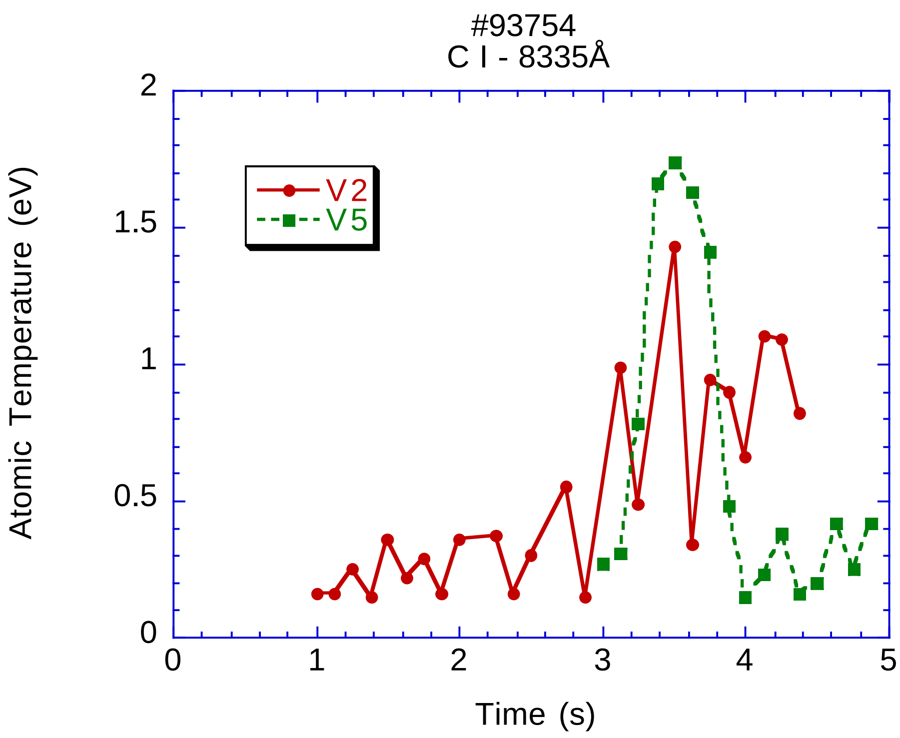
Effective C I temperatures in detached plasmas

- The C I temperature drops following detachment



Effective C I temperatures increase dramatically when outer strike point is swept over inserted DIMES probe





Summary of the use of C I lineshapes for diagnostic purposes

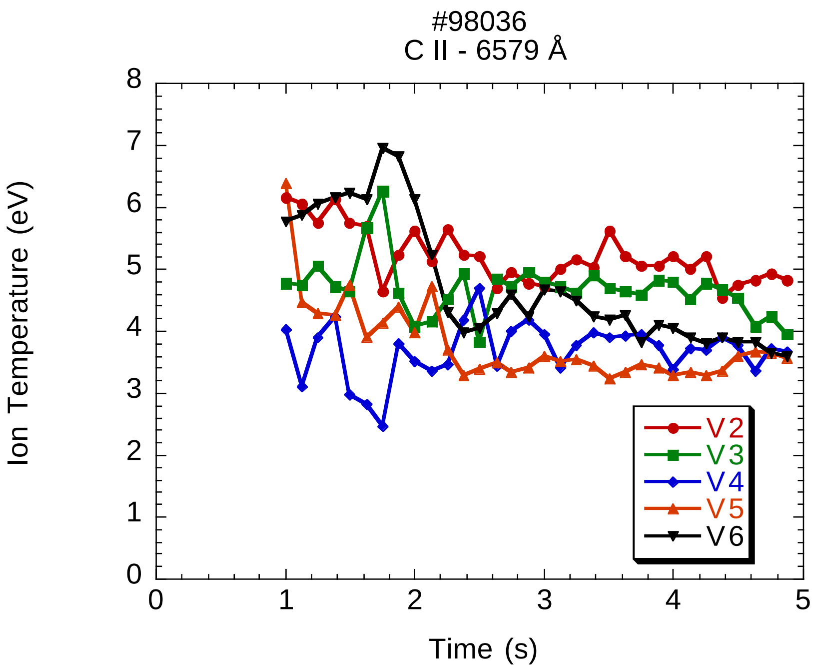
- Measurements of effective C I temperatures do not provide clear evidence of a single, dominant carbon production mechanism.
- Temperatures significantly above 1 eV seem to point to physical sputtering as a source. However, spectral lines from sputtered particles should not appear symmetric unless deuteron/carbon thermalization rates are greater than ionization rates.

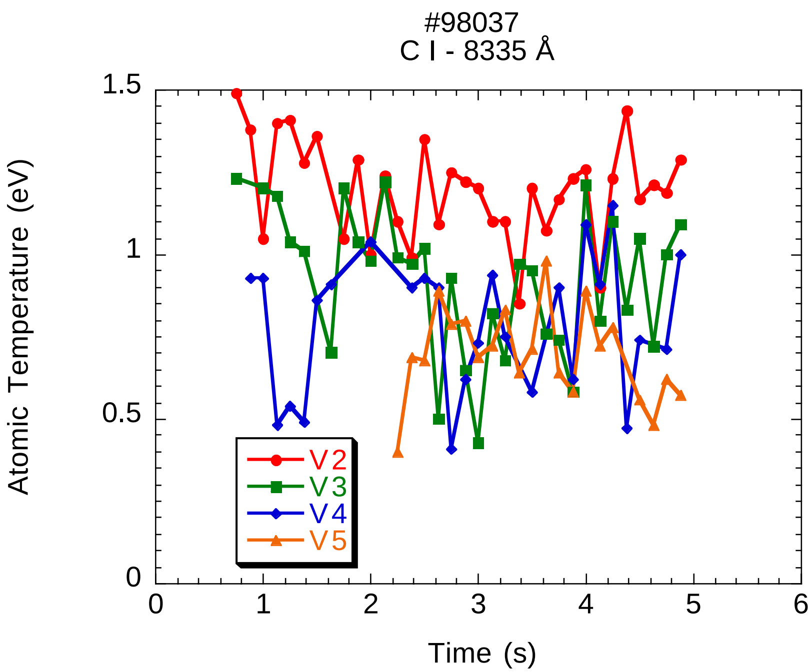
Final Summary

- Less than 5% of the divertor produced carbon gets to the LCFS.
- Chemical sputtering does not appear to be a significant source of divertor carbon. The possibility of RES as a source requires more study.
- Although effective C I temperatures sometimes indicate physical sputtering as the carbon production mechanism, spectral linewidths in general do not provide an unambiguous identification of the release processes.

Inferences concerning carbon sources

- Effective C I temperatures are often in a range that indicates physical sputtering is the dominant production channel.
- However, the apparent symmetry of the lineshapes argues for an isotropic production mechanism such as expected from molecular breakup.
- But CD and C_2 are almost never observed.


#98036
C II - 6579 Å
Ion Temperature (eV)
Time (s)
V2
V3
V4
V5
V6
0
1
2
3
4
5
6
7
8


#98037
C I - 8335 Å
Atomic Temperature (eV)
Time (s)
V2
V3
V4
V5
0
0.5
1
1.5
6

Flux Comparisons between the Inner and Outer Divertor Leg

The mean velocity of a 1 eV carbon atom is 0.4×10^6 cm/s

The ionization rate coefficient at an electron temperature of 6 eV is 0.6×10^{-8} cm^2/s

At an electron density of $10^{14}/cm^3$, the mean free path is 0.67 cm

Therefore, low-temperature atoms from the target plate should penetrate only a short distance upstream

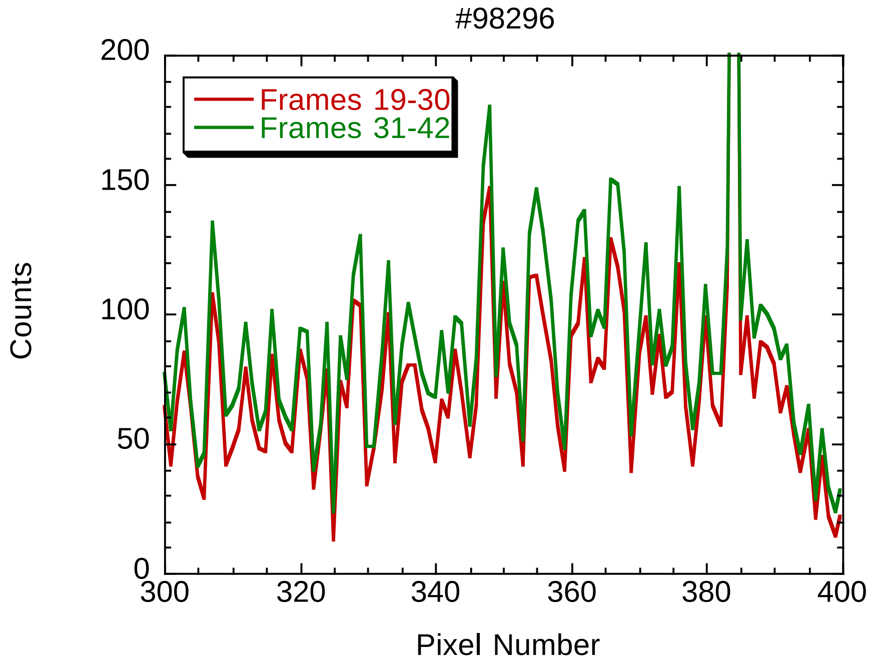
The flux of any ion determined from G = S(T)I/X(T)B is a measured of the intial flux from the source minus the flux that has diffused or been convected back to the wall.

The characteristic ionization time for a C II ion at electron temperatures and densities of 6 eV and $10^{14}/cm^3$ is
3.3×10^{-5} s.

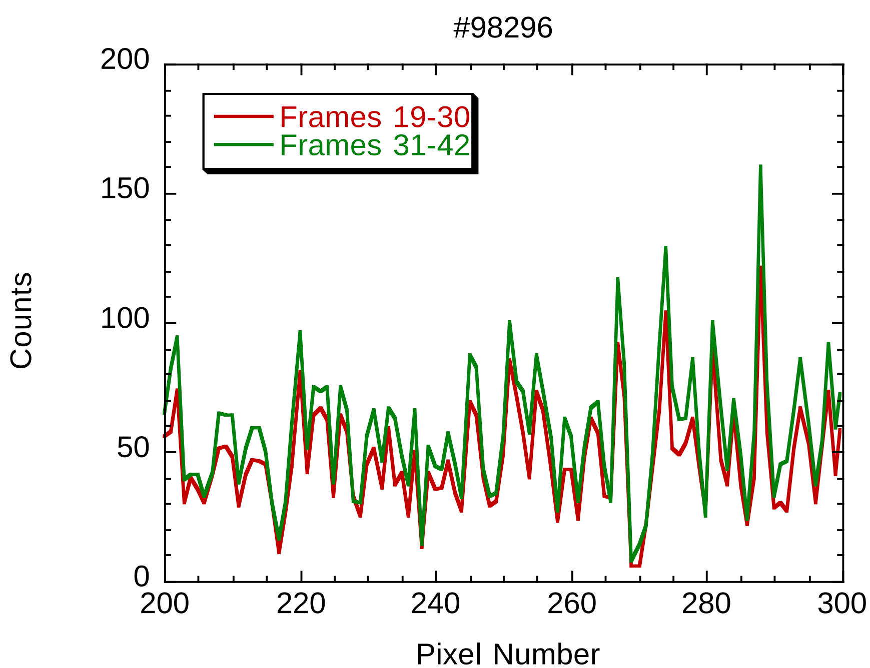
At a typical parallel flow speed of 2×10^6 cm/s a C II ion moves 66 cm in an ionization time.

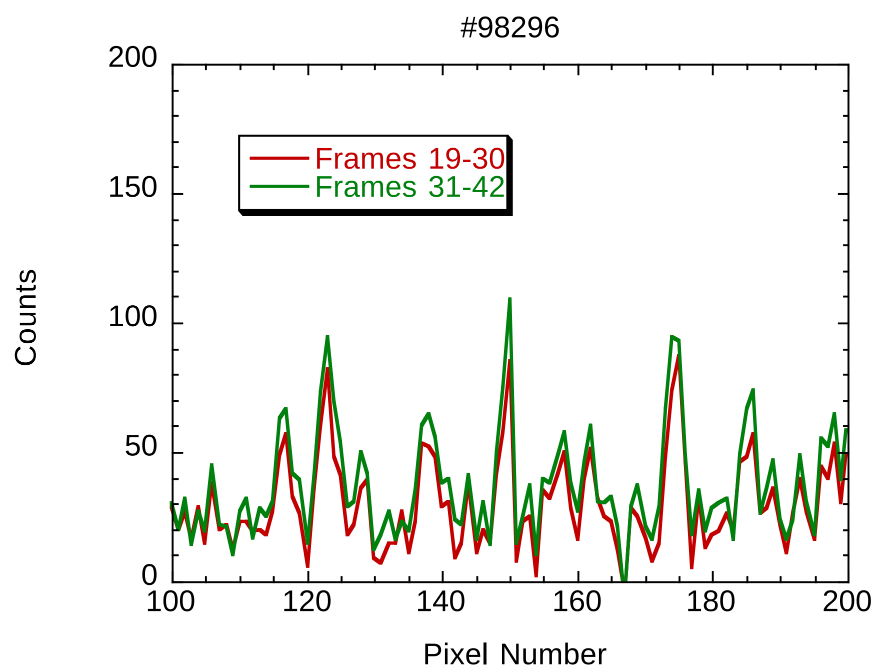
This result, coupled with the short distance 1 eV neutral particles can move before ionization, indicates that a large fraction of C II can flow back to the plate before being ionized to C III.

Spectra from the CD 4300 Å system



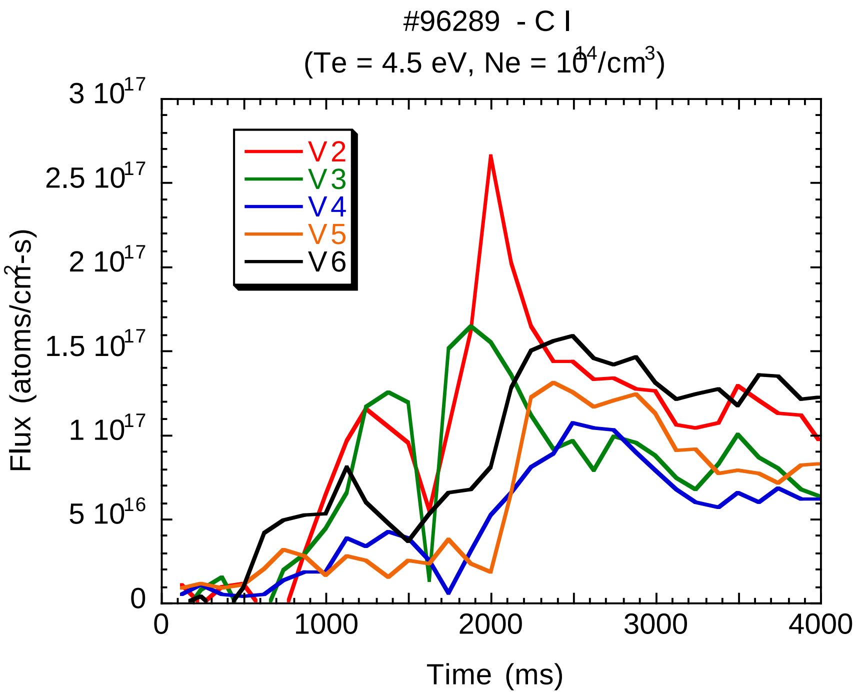
Comparison of measured spectra from two different sets of data shows that most of the detailed structure actually arises from molecular emission and not from noise.

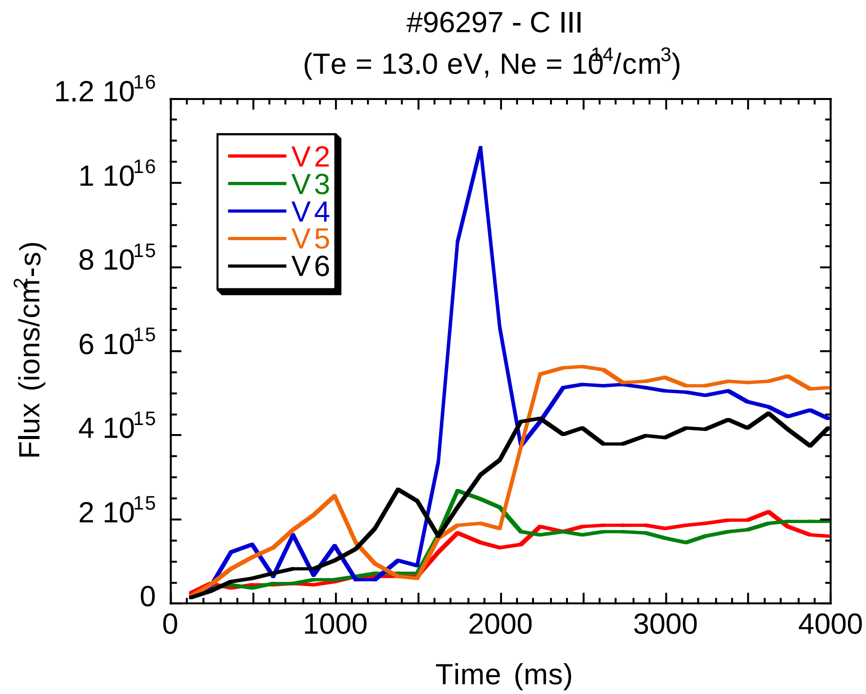


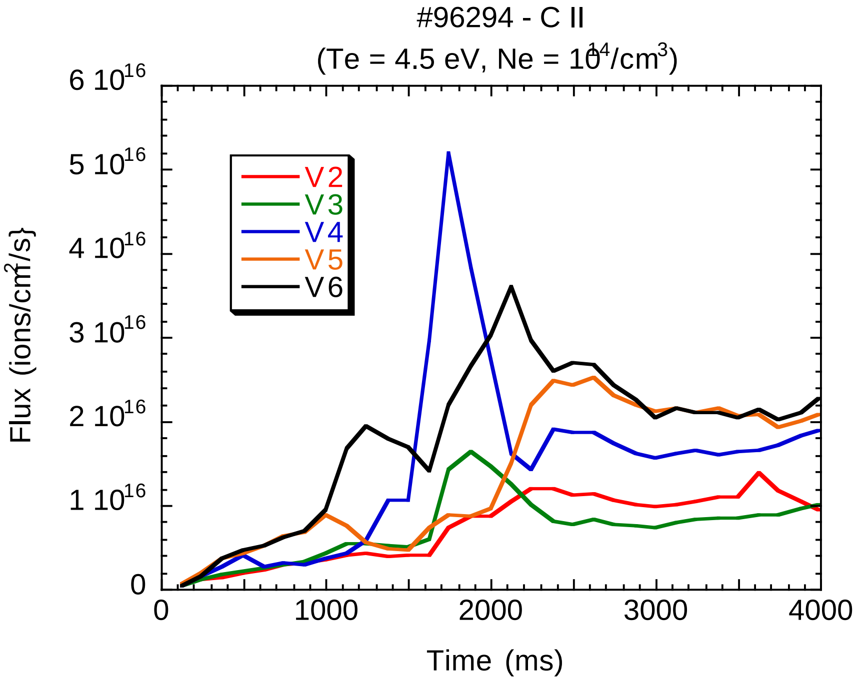


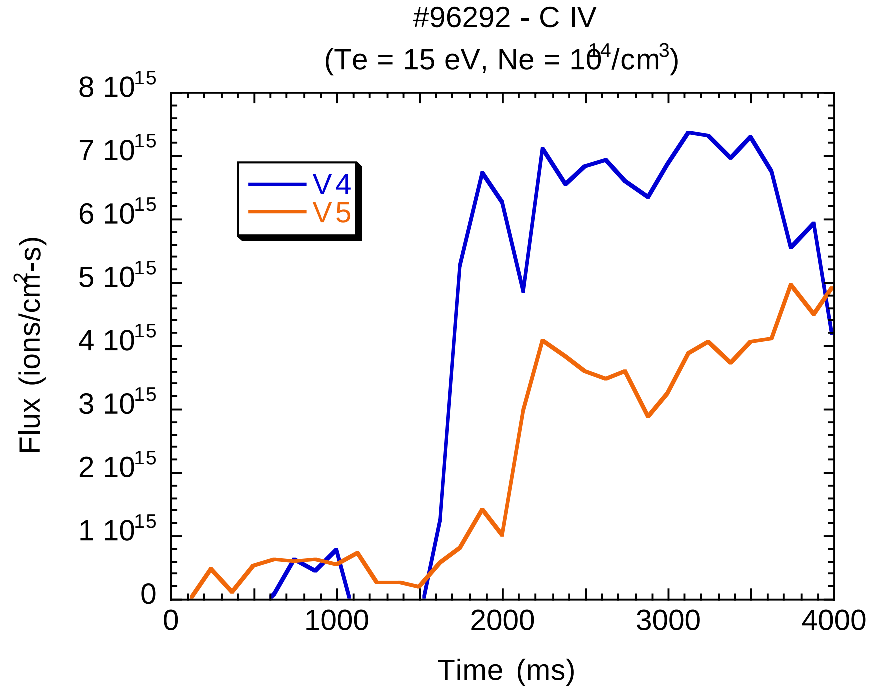
Fluxes from the Inner Divertor Leg

Attached Plasmas


#96289 - C I
(Te = 4.5 eV, Ne = 10^14/cm^3)
Flux (atoms/cm^2-s)
Time (ms)
V2
V3
V4
V5
V6

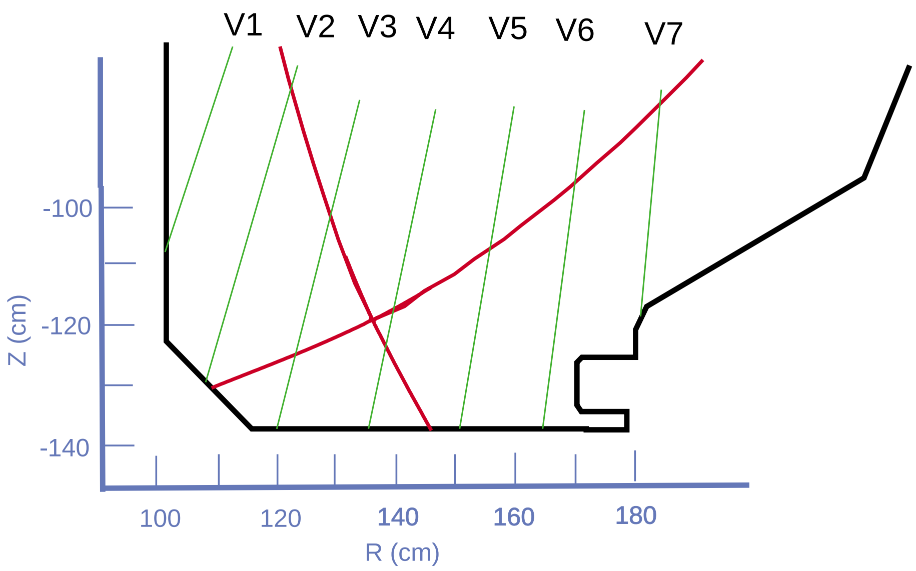

#96297 - C III
(Te = 13.0 eV, Ne = 10^14/cm^3)
Flux (ions/cm^2-s)
Time (ms)
V2
V3
V4
V5
V6

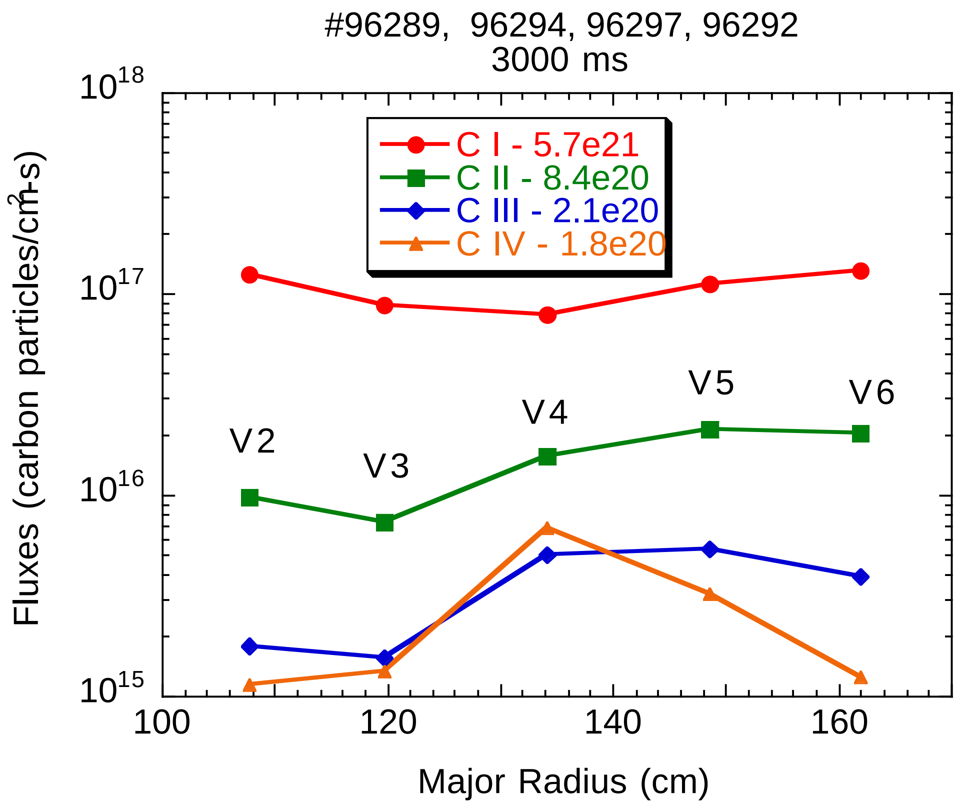

#96294 - C II
(Te = 4.5 eV, Ne = 10^14/cm^3)
Flux (ions/cm^2/s)
Time (ms)
V2
V3
V4
V5
V6


#96292 - C IV
(Te = 15 eV, Ne = 10^14/cm^3)
Flux (ions/cm^2-s)
Time (ms)
V4
V5

Fluxes of C I - C IV

- The mean-free-path for ionizing a carbon atom at an electron density of 4.5 eV and a density of $10^{14}/cm^3$ is 1.3 cm. The C I flux indicates carbon is produced almost uniformly across the strike plate.

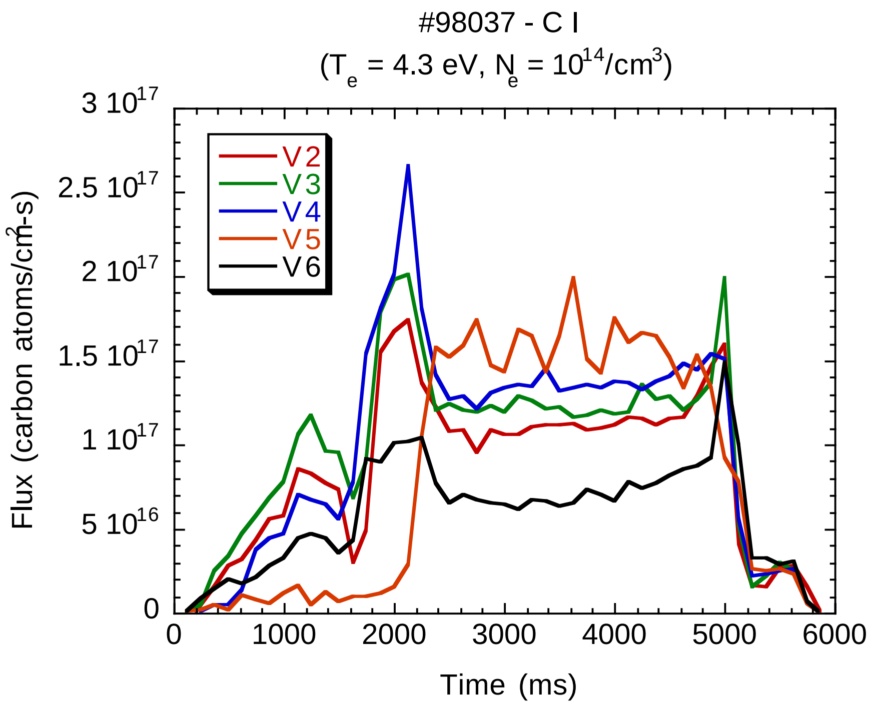


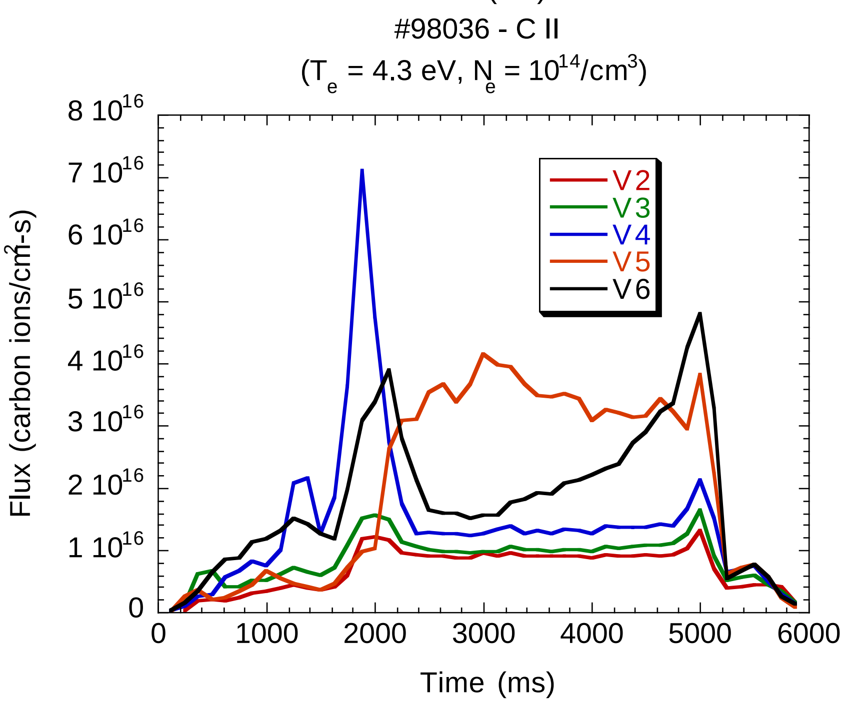


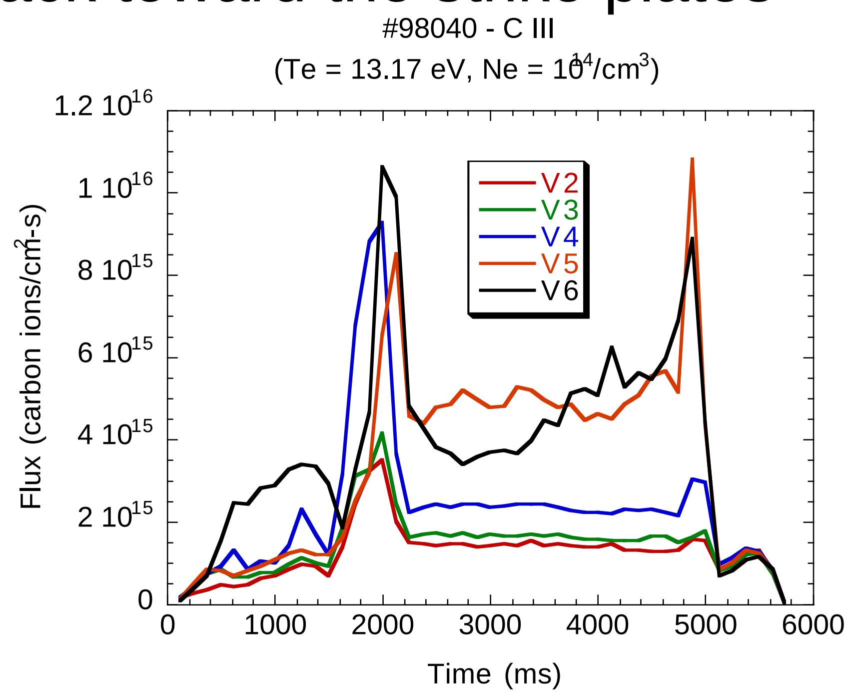
Detached Plasmas

Influxes for C I, C II, and C III

- The decrease in flux toward the core plasma with increasing ionization indicates most of the carbon produced in the divertor flows back toward the strike plates



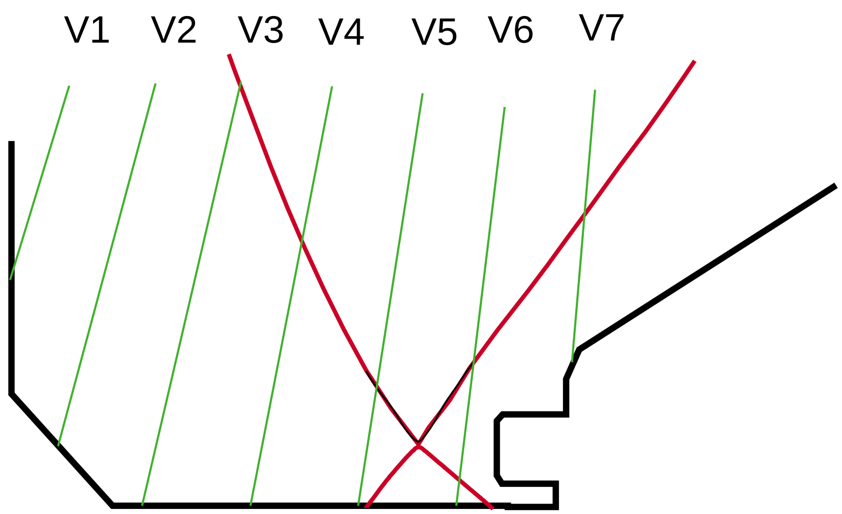


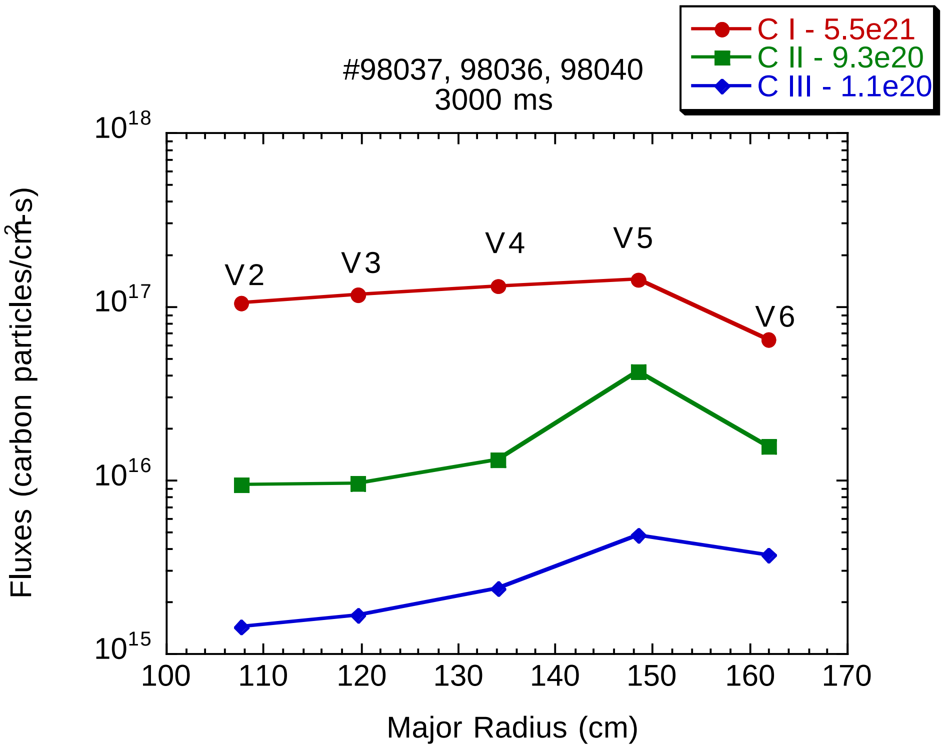


Carbon Fluxes

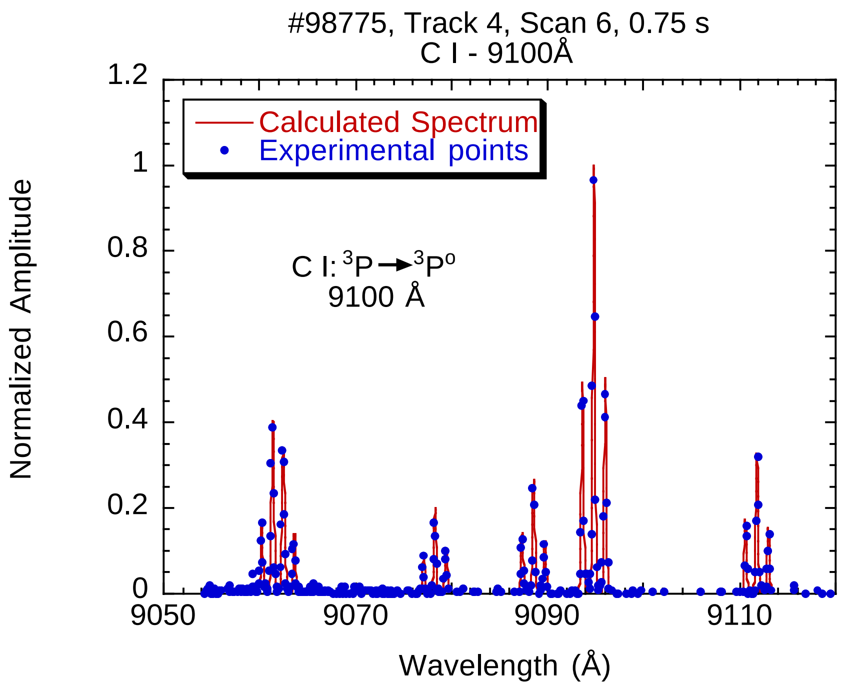
•Neutral carbon is produced all along the inner divertor leg. The radiation is only slightly peaked at the inner strike point.

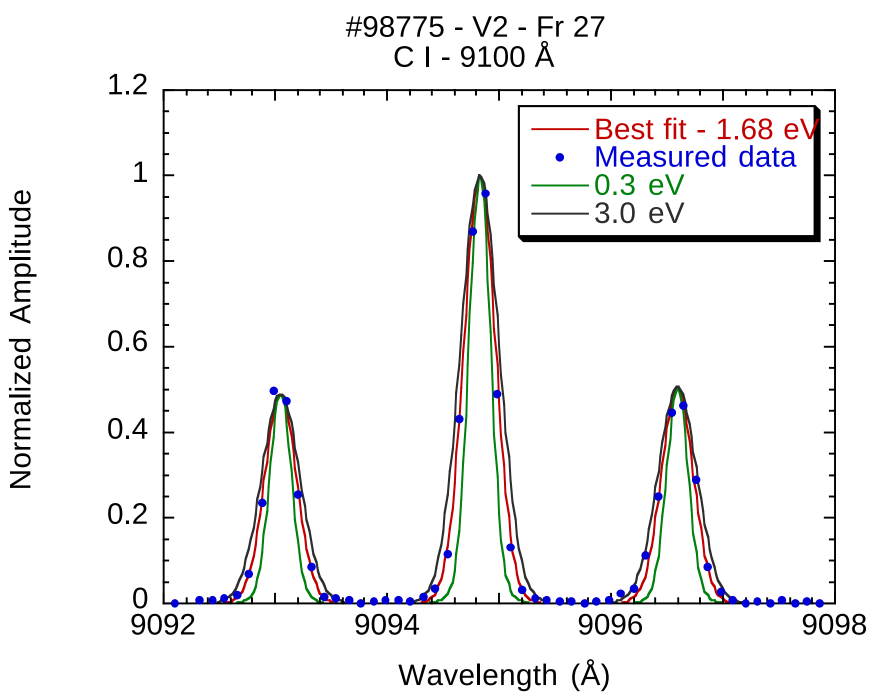
•The calculated fluxes decrease strongly as a function of ionization stage. This result indicates that at least 98% of the carbon produced in the divertor flows back to the target plates.

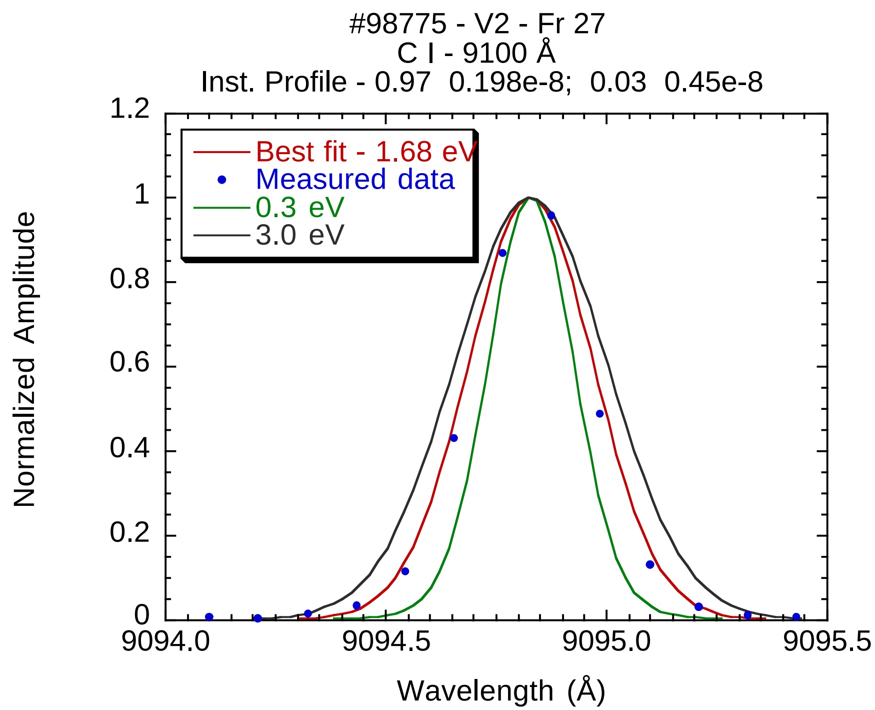




Do “effective” C I temperatures indicate production mechanisms ?

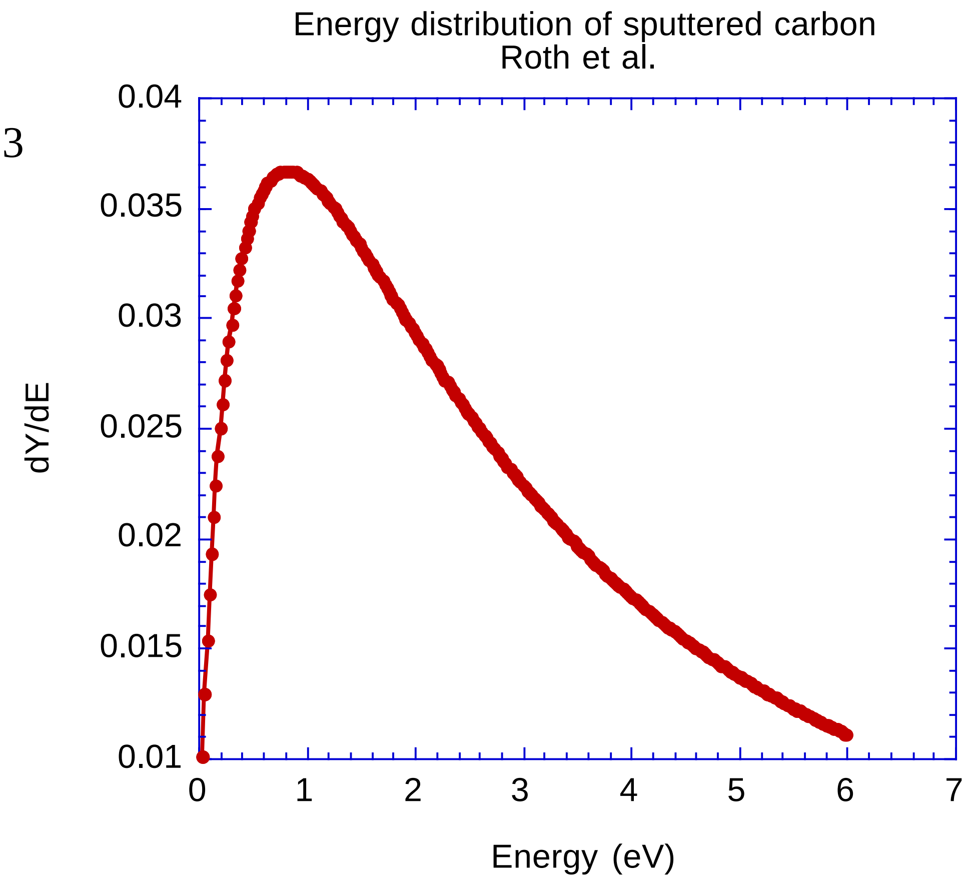






Energy of sputtered carbon (Roth, ,Vietzke, Haasz)

$$\frac{dY}{dE} = \left[E / (E + U/3)^4 \right]^{2/3}$$



C I Line Profiles

- In principle, C I line profiles need not be symmetric since the distribution in velocity space is generally nonisotropic. However, the profiles do not usually exhibit an obvious asymmetry.
- We define an effective temperature by fitting C I line profiles to Maxwellian distributions.