Advancements in Understanding the 2-D Role of Impurity Radiation for Dissipative Divertor Operation on DIII-D

by
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Presented at the
The 28th International Atomic Energy Agency Fusion Energy Conference (FEC 2020)

May 10-15, 2021
P1 Posters 1 - Virtual
Tuesday 08:30 AM
https://conferences.iaea.org/event/214/contributions/17149/

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Leveraging the broad array of measurements on the DIII-D tokamak has been used to elucidate the physics underlying 2-D detachment processes in the divertor.

Combination of EUV/VUV-VIS-IR spectroscopy, ColRadPy collisional radiative modeling, and 2-D $T_e$ and $n_e$ measurements from Divertor Thompson Scattering have been used to infer divertor impurity densities.

- Inferred spatial profiles reveal a greater radial emission extent compared to UEDGE fluid modeling with full ExB drifts.

Analysis reveal the 2-D nature of detachment is critically important for design of detachment scenarios for next stage devices.
Motivation: Predictions of impurity concentration required for detachment in future machines need experimental validation

• Typical plasma will radiate 40-90% of input power
  – More radiation necessary to ‘detach’ the divertor

• Critical to know impurity content necessary for detachment
  – Radiation from deuterium alone is not enough

• Scalings have major implications for future machines
  – **Upstream conditions**: R.J. Goldston, et. al., PPCF 59 (2017) 055015
  – **Projection of ~10% impurity fraction required in ITER, ~20% for DEMO**
    • Fuel dilution, poor fusion performance
    – However, these rely on 1D scalings
    • **Need experimental validation on current machines**
Recent work (past ~10 years) to characterize divertor impurity concentrations demonstrates the challenges involved

- **JT-60**: VUV and visible C emissions

- **JET/ASDEX-U**: Visible N II emissions
  - S. Henderson, et al., NME 18 (2019) 147

- Both approaches rely on local plasma parameters inferred from spectroscopic line ratios
  - Current work uses unique combination of local $T_e, n_e$ and absolutely calibrated VUV emissions

- Carbon wall + erosion presents the same physics as metal wall + extrinsic impurity
Our approach for determining concentrations relies on an iterative comparison between measured and synthetic spectra.

**Measured spectra**

- Divertor SPRED (EUV/VUV spectra)
- Line fitting
- Multiple charge states
- Calibrated intensities
- Compare
- C-z conc.

**Synthetic spectra**

- Divertor Thomson Scattering
  - Plasma $n_e$ & $T_e$
- UEDGE
  - Plasma $n_n$
- ColRayPy
  - $X^+/X_{tot}$
  - Photon Emissivity Coefficients
  - Excitation, recombination, charge exchange
- Iterate

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A.G. McLean/IAEA FEC 2020/May 2021
Measuring impurity concentrations relies on quantitative accounting of impurity emissions in known plasma conditions

- **Observed emission is a product of atomic processes occurring for all plasma species**
  - Excitation/deexcitation, ionization, recombination
  - Rates determined by local plasma conditions
- **For known conditions along a line of sight:**
  - Measured spectrum can be taken
  - The charge state distribution for each species may be calculated
  - A synthetic spectra can be created
  - Brightness of measured vs. synthetic spectra determines the conc.
Resonance spectral emissions offer the distinct advantage of direct interpretability

- **Volume emission rate, coronal excitation and emission, optically thin:**
  - \( E_{ij} = Br_{ij} Q_{gnd\rightarrow p} n_i n_e \)
  - \( Br \): branching ratio to lower level, \( Q \): electron impact excitation rate \([T_e, n_e]\)

- **For resonance emission \((Br=1)\), brightness along line-integrated sight:**
  - \( B = 1/(2\pi) \int (Q n_i(z) n_e(z)) \, dz \)

- **Valid for ions with no metastable levels: Li-like ion lines O VI, N V, C IV**
  - With metastables, level populated by ionization from next lower charge state, plus excitation from ground

- **For low and medium-\(Z\) elements, resonance emissions are primarily in the EUV/VUV spectral region**
  - Calibrated EUV/VUV spectra is a challenge compared to UV/VIS/NIR
  - Available with divertor view on DIII-D: ‘DivSPRED’
    - SPRED: Survey, Poor Resolution, Extended Domain \((45-170\, \text{nm})\)
    - Originally calibrated at NIST SURF
    - Adapted using branching ratio technique
  - Similar capability on JET, TCV, and MAST-U
Seven distinct emission lines chosen for carbon workflow: C\(^{1+}\), C\(^{2+}\) & C\(^{3+}\)

Each line is separately fit with a ~1nm FWHM gaussian characteristic of the instrumental width, linear background subtraction

- Similar capability for nitrogen: N \(^{II}\), N \(^{III}\), N \(^{IV}\), and N \(^{V}\) emissions in the observed bandwidth for DivSPRED

Radiance [ph/s/cm\(^2\)/ster]

<table>
<thead>
<tr>
<th>Line</th>
<th>Wavelength [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(^{III}) 53.8nm</td>
<td>1e13</td>
</tr>
<tr>
<td>C(^{II}) 68.7nm</td>
<td>1e14</td>
</tr>
<tr>
<td>C(^{II}) 90.4nm</td>
<td>1e15</td>
</tr>
<tr>
<td>C(^{III}) 97.7nm</td>
<td>1e16</td>
</tr>
<tr>
<td>C(^{III}) 117.4nm</td>
<td>1e16</td>
</tr>
<tr>
<td>C(^{II}) 133.5nm</td>
<td>1e16</td>
</tr>
<tr>
<td>C(^{IV}) 155nm</td>
<td>1e16</td>
</tr>
</tbody>
</table>

Resonance lines in red

176235:3322
Divertor Thomson scattering (DTS) provides $T_e$ and $n_e$ critical to interpretation of line-integrated spectra

- $T_e$, $n_e$ coincident with emitting volume measured by DivSPRED
- 8 ch system until 2019
- 12 ch system for 2020
- OSP sweeping
  - Data mapping/reconstruction

1D profile from single time-slice

2D profile from many time-slices
Model for synthetic spectra incorporates variables for CX by neutrals, and $n_e \cdot \tau$ for transport

- **Neutrals**
  \[
  \epsilon_{i \rightarrow j_{CX}} = \sum_{\rho} PEC_{\rho}^{CX} \rho_{i \rightarrow j} n_{H} n_{\sigma}^{(z+1)} + \]

- **Transport**
  - $n_e \cdot \tau$: ‘Non-coronal enhancement factor’
  - Residence time $\tau$; $<1$ ms for low $T_e$, upper limit of inverse ELM frequency

- **Adding CX, and lowering $n_e \cdot \tau$ allow charge states to exist at higher local $T_e$**

- **Analysis framework allows for easy adjustment of these factors**
  - Better match diagnostic data and test models
ColRadPy provides a collisional radiative solution for given plasma conditions

- **Collisional radiative model built in python**
  - Spans Coronal (low density) and LTE (high density) cases
  - Johnson, Lock, Ennis, NME 20 (2019) 100579

- **Inputs:**
  - Electron density and temperature (DTS)
  - Atomic physics (i.e., ADAS adf04 files)

- **Outputs:**
  - Ionization and recombination rates
  - Balance of charge states
  - Photon Emissivity Coefficient (PEC) values
    - Compared to data in ADAS adf15 PEC files
  - **Brightness of any given line or set of set lines**
    - Distribution dependent on divertor conditions
    - C. Samuell, et al., RSI (submitted) 2020

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Curt Johnson, et al., FO34(B) Friday
“Collisional Radiative Modeling of Tungsten for Gross and Net Erosion”

PEC \[ \text{ph cm}^{-3}/\text{s} \]
Synthetic spectra is the summation of emission contributions for conditions along the line of sight.

Contributions summed along line-of-sight for iterated $n_C/n_e$

- $T_e=50$ eV $n_e=3E19/m^3$
- $T_e=20$ eV $n_e=2E19/m^3$
- $T_e=5$ eV $n_e=5E19/m^3$
- $T_e=1$ eV $n_e=3E20/m^3$

Excitation
Recomb.
CX

Inferred power constituents

176235, 4040 ms: C fraction=0.2%

Line: Measured
Circle: Inferred

$C^1$, $C^2$, $C^3$
Evolution of impurity fraction appears gradual despite sharp detachment drop

- Example of a density ramp with fixed strike point
  - Attached (~20 eV) plasma transition to detached (<1 eV)

Significant departure from a fixed divertor impurity fraction assumption for modeling
Divertor impurity fraction falls with upstream density, Close agreement with Goldston model for detachment threshold

- Divertor impurity fraction
- Inter-ELM only
  - Filtered to 30-95% of ELM cycle
- Demonstrates similar loss in magnitude in transition to detachment

Low $T_e$, $I_{sat}$ rollover
Onset $n_{e,sep}/n_{GW} \sim 0.29$

$(n_C/n_e)_{detach}$
Goldston model $\sim 1$

$(n_C/n_e)_{detach}$
$\sim 0.5$
Comparing attached and detached divertors shows differences in the dominant impurity species near the target surface.

ColRadPy model allows ease of investigation of neutral role and transport.
UEDGE comparison for the detached case suggests transport playing a smaller role that determined by the code.

**Detached**

- C
- C^+
- C^{2+}
- C^{3+}
- C^{4+}
- C^{5+}
- C^{6+}

Primarily C^0 neutral impinging on surface

**UEDGE with drifts**

- C
- C^+ ion on surface in UEDGE solution

4MW, -1.8T, 0.9MA, n/n_{GW}=0.7  \ n_e*\tau = 2E9 cm^{-3} s

**Powerful tool for quantitative code validation spanning divertor conditions**
UEDGE comparison for the detached case suggests transport playing a smaller role that determined by the code.

Primarily $C^0$ neutral impinging on surface in UEDGE solution.

Primarily $C^+$ ion on surface in UEDGE solution.

4MW, -1.8T, 0.9MA, $n/n_{GW}=0.7$, $n_e^\tau_{\text{e}} = 2\times10^9 \text{ cm}^{-3} \text{ s}$

Powerful tool for quantitative code validation spanning divertor conditions.
Increasing level of broadening observed at higher powers

Observed in both charge-state resolved line emission and total radiated power (bolometry), DTS, and 2-D imaging

Poloidal $E \times B$ drift can dominate the poloidal heat transport in the radiative front

Larger extent provides opportunity for greater dissipation volume

- Demonstrates that fully-2D simulations including cross-field drifts are required for detachment studies
- Working towards a predictive capability of divertor heat loads

The radial extent of the radiative volume in detached H-mode discharges is much broader compared to UEDGE fluid modeling
Conclusions: Ensemble of divertor diagnostics on DIII-D allows for impurity concentration measurements in all plasma conditions

- Inter-ELM intrinsic carbon impurity fraction in DIII-D is measured, showing
  - $n_c/n_e$ at detachment onset consistent with model prediction for evaluated cases
  - Significant departure from a fixed divertor impurity fraction assumption for modeling

- Absolutely calibrated spectroscopy and local divertor Thomson scattering
  - Provide a unique and powerful combination of divertor diagnosis capabilities

- Flexible framework and workflow to evaluate the impact of divertor processes
  - ColRadPy collisional radiative model incorporates all relevant atomic physics and allows reconstruction of the charge state distribution and emission profile

- Future experiments on DIII-D provide critical benchmarks for code validation and detachment scalings
  - Insight into divertor/scrape-off-layer (SOL) impurity transport using 2D visible imaging
  - Reveal how efficiently the intrinsic impurity can be complemented with extrinsic sources
Future device studies with UEDGE have shown lower impurity concentrations at detachment than scalings predict

- **Rognlien, Rensink, Stotler, FED 135 (2018) 380**
  - FNSF modeling with UEDGE and DEGAS 2
  - 0.15-0.4% fixed Neon fraction
  - Weakly detached inner leg, strongly detached outer leg ($T_e \sim 1\text{eV}$)

- **Rensink and Rognlien, FST 67 (2014) 125**
  - ARIES-ACT modeling with UEDGE
  - Cases with 0.4% fixed Ne, or 0.04% fixed Ar

- **Within ~factor of 2 for full multi-charge state cases**

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**Table 2. Estimated impurity fractions required for detachment for Ne, Ne and Ar assuming $f_{\text{det}}=1.2$, $f_{\text{det}}=0.9$ and $n_{\text{det}} = 1.0 \times 10^{20} \text{ m}^{-3}$. Calculations are made for pure D and mixed-D-T (50%D-50%T) plasmas.**
DivSPRED on DIII-D is capable of quantifying emissions from a variety of impurities
Goldston model for impurity concentration at detachment predicts ~1% N (or C) in DIII-D with $P_{sep} = 2.5$ MW

<table>
<thead>
<tr>
<th></th>
<th>C-Mod</th>
<th>DIII-D</th>
<th>ASDEX-U</th>
<th>JET</th>
<th>ITER</th>
<th>FNSF (A=4)</th>
<th>EU Demo 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{sep}$ (MW)</td>
<td>3.83</td>
<td>2.5</td>
<td>10.7</td>
<td>14</td>
<td>100</td>
<td>96</td>
<td>154.7</td>
</tr>
<tr>
<td>$B_t$ (T)</td>
<td>5.4</td>
<td>2</td>
<td>2.5</td>
<td>2.5</td>
<td>5.3</td>
<td>7</td>
<td>5.7</td>
</tr>
<tr>
<td>$R_0$ (m)</td>
<td>0.7</td>
<td>1.73</td>
<td>1.6</td>
<td>2.9</td>
<td>6.2</td>
<td>4.5</td>
<td>9.1</td>
</tr>
<tr>
<td>$P_{sep}/R$</td>
<td>5.47</td>
<td>1.45</td>
<td>6.69</td>
<td>4.83</td>
<td>16.13</td>
<td>21.33</td>
<td>17.00</td>
</tr>
<tr>
<td>$P_{sep}B_t/R$</td>
<td>29.55</td>
<td>2.89</td>
<td>16.72</td>
<td>12.07</td>
<td>85.48</td>
<td>149.33</td>
<td>96.90</td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>0.82</td>
<td>1.3</td>
<td>1.2</td>
<td>2.5</td>
<td>15</td>
<td>7.5</td>
<td>20</td>
</tr>
<tr>
<td>$A$ (m)</td>
<td>0.22</td>
<td>0.59</td>
<td>0.52</td>
<td>0.9</td>
<td>2</td>
<td>1.13</td>
<td>2.94</td>
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<tr>
<td>$\kappa_{95}$</td>
<td>1.51</td>
<td>1.64</td>
<td>1.63</td>
<td>1.73</td>
<td>1.8</td>
<td>2.1</td>
<td>1.7</td>
</tr>
<tr>
<td>$\langle B_p \rangle$ (T)</td>
<td>0.58</td>
<td>0.33</td>
<td>0.34</td>
<td>0.39</td>
<td>1.03</td>
<td>0.81</td>
<td>0.98</td>
</tr>
<tr>
<td>$q_{cyl}$</td>
<td>3.75</td>
<td>2.81</td>
<td>3.23</td>
<td>2.81</td>
<td>2.42</td>
<td>3.57</td>
<td>2.62</td>
</tr>
<tr>
<td>$n_{GW}$</td>
<td>5.39E+20</td>
<td>1.19E+20</td>
<td>1.41E+20</td>
<td>9.82E+19</td>
<td>1.19E+20</td>
<td>1.87E+20</td>
<td>7.37E+19</td>
</tr>
<tr>
<td>Proj. $c_N$</td>
<td>1.0%</td>
<td>1.0%</td>
<td>4.0%</td>
<td>4.0%</td>
<td>10.0%</td>
<td>8.5%</td>
<td>18.5%</td>
</tr>
</tbody>
</table>

Large values suggest a challenge for pedestal and core compatibility
Impurity fraction is a critical component for detachment control & physics understanding

- Understanding & predicting detachment.
  - Metal walled devices require impurity-driven detachment
  - Impurities play a dominant role for detachment in DIII-D even in “unseeded” discharges
    - Are carbon and nitrogen equivalent?
  - What level of impurity seeding is required for a fusion reactor to detach?

\[ c_z \propto \frac{P_{\text{sep}}}{\langle B_p \rangle (1 + \kappa^2)^{3/2} (n_{\text{sep}}/n_{GW})^2 l^*} \]  

\[ c_z \approx B_T^{0.88} R^{1.33} \]  

\[ c_z \approx \frac{P_{\text{sep}}/R}{p_0 \lambda_{\text{int}} R^{r^z}} \]  

Scalings are 1D or 0D!

(1) Goldston R 2017 PPCF 59 055015
(2) M.L. Reinke 2017 Nucl. Fusion 57 03400
(3) A Kallenbach et al 2016 PPCF 58 045013
Henderson, IAEA Div Con, 2019
Carbon Impurity fraction in detached plasmas inferred to be around 0.1-0.5%.

- Recombination and CX plays a role in the ionization balance; but not total emissivity.
Transport, $n_e * \tau$, value used affects the charge state balance

**$n_e \tau$ [m$^{-3}$ ms]**

- 2E20
- 0.2E20
- 0.02E20

**Figure 3.** Radiative loss functions calculated from ADAS for possible divertor seeding gases N, Ne, Ar and $n_e = 1 \times 10^{20}$ m$^{-3}$. Solid lines have been calculated for the non-coronal parameter $n_e \tau = 0.5$ as used throughout this study, the upper and lower dashed lines for each species correspond to values $n_e \tau = 0.2$ and $2 \times 10^{20}$ ms m$^{-3}$. 
Resonance spectral emissions offer the distinct advantage of direct interpretability

- **Volume emission rate:** $E_{ij} = B_{ij} Q_{gnd \rightarrow p} n_i n_e$
  - $E$: emission rate, $B$: branching ratio to lower level, $Q$: electron impact excitation rate

- **Valid for ions with no metastable levels:** Li-like ions: O VI, N V, C IV
  - With metastables, level populated by ionization from next lower charge state, plus excitation from ground

- **For low and medium-$Z$ elements, resonance emissions primarily in the EUV/VUV**
To baseline importance of CX, UEDGE was used to find $T_e$ dependence of neutral fraction.

- UEDGE case with enhanced diffusivity chosen to match shots with best DivSPRED data
- Neutral fraction as a function of $T_e$ calculated in throughout grid
  - $\Psi_n > 1.1$ rejected to avoid main chamber recycling artifacts near X-point
  - Deuterium temperature assumed to be 3.5eV (dissociation fragments)

$$\frac{n_D}{n_e} \sim \exp \left[ a \log(T_e) + b(\log(T_e))^3 + c \right]$$
Including CX causes charge states to appear at higher temperatures

- Charge states $C^{2+}$ and above have relative abundances that extend to higher temperatures
- $C$ & $C^+$ largely unaffected
- A move to more intuitively expected values (e.g. position of $C^{2+}$ peak)
Carbon/Nitrogen simulations comparison

**Left Panel: Carbon Relative Abundance vs. $T_e$ (eV)**
- $C^0^+$
- $C^{1^+}$
- $C^{2^+}$
- $C^{3^+}$
- $C^{4^+}$
- $C^{5^+}$

**Right Panel: Nitrogen Emissivity vs. $T_e$ (eV)**
- $N^0^+$
- $N^{1^+}$
- $N^{2^+}$
- $N^{3^+}$
- $N^{4^+}$
- $N^{5^+}$

**Graphical Data:***
- The graphs compare relative abundance and emissivity trends for Carbon and Nitrogen at different electron temperatures ($T_e$).
- The graphs illustrate how ionization states and energy levels affect these properties.
Detached nitrogen-seeded and un-seeded cases show similar impurity charge distribution in ionization front

C: 2.5MW, -2T, 1.2MA, n/n_{GW}=0.8
N: 5MW, 01.8T, 0.9MA, n/n_{GW}=0.7
CX causes a significant broadening of ionization front in detached case, greater mixing of charge states, and reduced role of $C^{4+}$

4MW, -1.8T, 0.9MA, $n/n_{GW}=0.7$

$n_e \cdot \tau = 2E9 \text{ cm}^{-3} \text{ s}$

NB: top DTS channel now removed also
Further improvement though adding transport via $n_e \tau$

With CX

<table>
<thead>
<tr>
<th>C</th>
<th>C$^+$</th>
<th>C$^{2+}$</th>
<th>C$^{3+}$</th>
<th>C$^{4+}$</th>
<th>C$^{5+}$</th>
<th>C$^{6+}$</th>
</tr>
</thead>
</table>

With CX & $n_e \tau$

4MW, -1.8T, 0.9MA, $n/n_{GW}=0.7$

$n_e \tau = 2E9 \text{ cm}^{-3} \text{ s}$

NB: top DTS channel now removed also
(Some) history of measuring impurity concentrations in fusion devices

- **O/C/N/Mo (EUV) in Alcator:** Terry, Chen, Moos, Marmar
  - COO-2711-3 (1977)
- **O/C/N/Ti (EUV) in 2XIIB mirror:** Drake and Moos
- **O/C/N (EUV) in TMX mirror:** Allen
  - OCID-18883 (1981)
- **O/C/N/Ti (EUV) in TMX-U mirror:** Yu, Allen, and Moos
- **Mo (VUV) in Alcator C-Mod:** Graf, Terry
- **O/C/Ni/Fe (EUV) in PBX-M and ISX-B:** Isler
- **C (EUV) in ASDEX-U:** Wenzel
- **C (VUV) in JT-60U:** Nakano
- **N (visible) in ASDEX-U:** Henderson
- **N (visible) in JET and ASDEX-U:** Henderson
Cooling curves

Figure 1. Radiative loss parameter $L_z$ for seed impurities from ADAS and an electron density of $10^{20}$ m$^{-3}$, as the sum of line radiation, recombination-induced radiation and bremsstrahlung. (a) Data for carbon, nitrogen, neon, argon and krypton in coronal equilibrium. 
(b) Non-equilibrium enhanced values for N and Ar (dashed lines). Appropriate values for the non-equilibrium parameter $n_e \tau$ are used for the divertor and pedestal parameter regions, as indicated by the broad horizontal bars. In between the $T_e$ values marked, a linear interpolation of $n_e \tau$ in $T_e$ was used to obtain smooth curves.
Radiated power from hot plasma includes the following processes:

- **Line radiation:**
  - Deuterium, $P_{\text{line,D0}}$
  - Impurities, $P_{\text{line,imp}}$
  - Molecular radiation, $P_{\text{mol}}$

- **Continuum:**
  - Bremsstrahlung (free-free emission), $P_{\text{brems}}$
  - Recombining (free-bound emission), $P_{\text{recomb}}$
  - Blackbody radiation, $P_{\text{blackbody}}$

Critical to accurately measure and predict $P_{\text{rad}}$

Sample spectra for each process
EUV/VUV emissions are primarily those connected to the ground state; “Resonance” lines

- Direct interpretation, few lines

- Resonance lines for low-Z elements lie in EUV (10-121 nm) and/or VUV (10-200 nm)
Cross Calibration of the EUV/VUV is Made Possible Using Visible/NIR Emissions with the Same Transition Upper Level

- Absolute sensitivity calibration is transferred from one spectral region to another
- Two emission lines from the same upper energy level $p$
- Ratio of their radiances, $L$, is given by:

\[
\frac{L(\lambda_2)}{L(\lambda_1)} = \frac{\lambda_1}{\lambda_2} \frac{A(p \rightarrow q')}{A(p \rightarrow q)}
\]

- Independent of local conditions ($T_e, n_e$)

- Useful because NIST-calibrated light sources are available and can be directly used at UV-VIS-NIR wavelengths

<table>
<thead>
<tr>
<th>Line</th>
<th>EUV/VUV</th>
<th>VIS/NIR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transition</td>
<td>$\lambda$ (nm)</td>
</tr>
<tr>
<td>D I</td>
<td>4→1 Ly-β</td>
<td>102.5442</td>
</tr>
<tr>
<td>C II</td>
<td>2s$^2$3d $^2D$→2s$^2$2p $^2P^0$</td>
<td>68.7053</td>
</tr>
<tr>
<td></td>
<td>2s$^2$3d $^1D$→2s$^2$2p $^1P^0$</td>
<td>68.7345</td>
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<tr>
<td>C III</td>
<td>2s3d $^1D$→2s2p $^1P^0$</td>
<td>57.4281</td>
</tr>
</tbody>
</table>
Power Accounting with Calibrated DivSPRED Agrees with Bolometry

- Agreement through dynamic range of multiple bolometer channels
- Validation of DivSPRED absolute intensity calibration
EUV/VUV Spectrum Suggests that a Molecular Feature May be Present and Constitutes a Significant Fraction of $P_{rad}$

- DivSPRED data plotted with a log Y-scale
  - Instrumental profile characterized with an electrodeless Kr lamp
    - Resonant lines at 116.5 and 123.6 nm
    - Primary Gaussian: FWHM ~ 0.95 nm
  - Synthetic fits to individual emission lines add up to less than the total integrated radiance in the spectra
    - 83% of the emission spectrum is accounted for by line radiation
    - 17% is unaccounted

DivSPRED radiance accounting, 176235 OSP view at the detachment point (n/n$_{GW}$=0.68)
EUV/VUV Spectrum Suggests that a Molecular Feature May be Present and Constitutes a Significant Fraction of $P_{rad}$

- DivSPRED data plotted with a log Y-scale
- Synthetic fits to individual emission lines add up to less than the total integrated radiance in the spectra
  - 83% of the emission spectrum is accounted for by line radiation
  - 17% is unaccounted
- Synthetic Lyman-Werner $D_2$ band
- Any band structure, however, is unresolvable at the DivSPRED resolution

*DivSPRED, outer target, point of detachment*
The DIII-D Divertor Diagnostic Suite Includes Necessary Tools to Quantify Divertor Emissions

- Ohmic plasmas with beam blips ($P_{\text{ohm}} \approx 0.9 – 1.4$ MW) and H-mode plasmas ($P_{\text{ohm}} + P_{\text{inj}}$ up to 13 MW), $I_p = 1.1$ MA, $B_T = 2.1$ T, both ion $B_x \nabla B$ directions
- Upstream (core, SOL) density scans to achieve low-recycling, high-recycling and detached conditions
- Strike points swept across lower floor for div. profiles
- Divertor Thomson scattering (DTS) for $T_e$, $n_e$ in 2D
- Vis. spectroscopy ⇒ $D_\alpha$, $D_\gamma$, Fulcher band, CII, CIII
- EUV ⇒ Ly-$\alpha$, Lyman-Werner bands, CIV, CIII
- Data from diagnostics are used as critical input and/or comparators to code modeling
DIII-D Diagnostic Suite Includes SXR/EUV/VUV Coverage in Both the Core (Midplane) and Divertor
Divertor SPRED: EUV/VUV Spectroscopy Provides a Window Into the 45-170 nm Emission Region

- SPRED: Survey, Poor Resolution, Extended Domain spectrometer
- Grazing incidence vacuum instrument designed with Schoeffel/McPherson
- Same/similar unit to that used for core SPRED on TFTR, PBX, JET, NSTX, and DIII-D
- Used on DIII-D from 1997-1999
- Absolute calibration at NIST SURF-III facility (MD)
- New CCD/sCMOS camera and optical relay, plus radiation, magnetic shielding
EUV/VUV Emissions Through OSP Sweep, and Density Ramp at the OSP Suggest that Unaccounted-for Emission is Pervasive – With Wide Gaussian Instrumental

- Shot 174273: X-point sweep across lower divertor to characterize both divertor targets
- CIV dominates through most of the radial profile, except in the outer SOL
- Suggests that getting $T_e$, $n_e$ profiles correct throughout the divertor region critical to matching CIV resonance emission and $P_{rad}$

- Shot 176235: Density ramp with DivSPRED aligned to the outer SOL
- Rapid increase in all emissions approaching detachment, then ~steady
- Unaccounted-for emission reduces approaching detachment, then also ~steady
The Solar Spectrum is Well Approximated by a Blackbody Due to Opacity in the Photosphere

- **Peak solar spectral irradiance at Earth:**
  - 2 W/m²/nm
  - 0.16 W/m²/ster/nm
  - $1.6 \times 10^{-5}$ W/cm²/ster/nm
  - $1.6 \times 10^{-6}$ W/cm²/ster/Å

- **Compared to divertor plasma, Ly-α line (VUV):**
  - ~0.1 W/cm²/ster/Å
  - 63,000X brighter in the plasma