Theoretical Exploration of Some Issues Affecting IEC Fusion Rates

John F. Santarius and Gilbert A. Emmert

UW Fusion Technology Institute

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Objectives

• Examine effect of voltage and background gas pressure on ion and fast neutral energy distributions.

• Investigate the effect of molecular species mix in the source region on the D-D neutron production rate.

• Extrapolate the D-T neutron production rate from D-D IEC parameters.
Objective 1

• Examine effect of voltage and background gas pressure on ion and fast neutral energy distributions.

• Investigate the effect of molecular species mix in the source region on the D-D neutron production rate.

• Extrapolate the D-T neutron production rate from D-D IEC parameters.
Increasing Neutral Gas Pressure Softens the Ion and Charge-Exchange Neutral Energy Spectra

100 kV, 60 mA, \(r_c=0.05\) m, \(r_a=0.25\) m, Source: 0.1 D\(^{+}\), 0.1 D\(_2\)\(^{+}\), 0.8 D\(_3\)\(^{+}\)

- **Note:** D\(_3\)\(^{+}\) point is in total ions per second, not per second per keV.
### Increasing Voltage Increases Neutron Production Rate and Affects the Origin of the Fusion Neutrons

2 mtorr (0.27 Pa), 60 mA, \( r_c = 0.05 \) m, \( r_a = 0.25 \) m, Source: 0.1 D\(^+\), 0.1 D\(_2^+\), 0.8 D\(_3^+\)

\( \dagger \) “Neutrals” means the fast neutrals from charge-exchange or dissociation collisions.

<table>
<thead>
<tr>
<th>Units of ( 10^7 ) n/s</th>
<th>50 kV</th>
<th>100 kV</th>
<th>150 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>D(^+) Neutrals( \dagger ) - Gas</td>
<td>0.84</td>
<td>1.54</td>
<td>2.04</td>
</tr>
<tr>
<td>D(_2^+) Neutrals( \dagger ) - Gas</td>
<td>0.47</td>
<td>1.24</td>
<td>2.27</td>
</tr>
<tr>
<td>D(_3^+) Neutrals( \dagger ) - Gas</td>
<td>5.78</td>
<td>5.11</td>
<td>5.31</td>
</tr>
<tr>
<td>D(^+) - Gas</td>
<td>0.22</td>
<td>0.91</td>
<td>1.98</td>
</tr>
<tr>
<td>D(_2^+) - Gas</td>
<td>0.09</td>
<td>0.54</td>
<td>1.36</td>
</tr>
<tr>
<td>D(_3^+) - Gas</td>
<td>0.14</td>
<td>0.66</td>
<td>1.28</td>
</tr>
<tr>
<td>Total neutrons</td>
<td>7.54</td>
<td>10.0</td>
<td>14.2</td>
</tr>
</tbody>
</table>
Objective 2

• Examine effect of voltage and background gas pressure on ion and fast neutral energy distributions.

• Investigate the effect of molecular species mix in the source region on the D-D neutron production rate.

• Extrapolate the D-T neutron production rate from D-D IEC parameters.
Increasing the Voltage Increases Neutron Production and Changes the Optimal Species Mix

2 mtorr (0.27 Pa), 60 mA
Source D\(^+\) Gives a Faster Ion Spectrum than D\(_3^+\), but the same neutron production rate

100 kV, 60 mA, 2 mtorr (0.27 Pa), \(r_c=0.05\) m, \(r_a=0.25\) m

**All D\(_3^+\) in Source: 1.0x10\(^8\) n/s**

**All D\(^+\) in Source: 1.0x10\(^8\) n/s**

• Note: D\(_3^+\) point is in total ions per second, not per second per keV.
Source $\text{D}_2^+$ Quickly Produces $\text{D}^+$ for the 100 kV, 60 mA, 2 mtorr Case

100 kV, 60 mA, 2 mtorr (0.27 Pa), $r_c=0.05$ m, $r_a=0.25$ m

All $\text{D}_3^+$ in Source: $1.0 \times 10^8$ n/s

All $\text{D}_2^+$ in Source: $8.0 \times 10^7$ n/s

- Note: $\text{D}_3^+$ point is in total ions per second, not per second per keV.

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The Origin of the Fusion Neutrons Depends Strongly on the Molecular Species Mix in the Source Region

100 kV, 2 mtorr (0.27 Pa), 60 mA, $r_c=0.05$ m, $r_a=0.25$ m

† “Neutrals” means the fast neutrals from charge-exchange or dissociation collisions.

<table>
<thead>
<tr>
<th>Units of $10^7$ n/s</th>
<th>D$^+$ Source</th>
<th>D$_2^+$ Source</th>
<th>D$_3^+$ Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>D$^+$ Neutrals† - Gas</td>
<td>6.2</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>D$_2^+$ Neutrals† - Gas</td>
<td>1.6</td>
<td>4.9</td>
<td>0.7</td>
</tr>
<tr>
<td>D$_3^+$ Neutrals† - Gas</td>
<td>0</td>
<td>0</td>
<td>6.6</td>
</tr>
<tr>
<td>D$^+$ - Gas</td>
<td>1.6</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>D$_2^+$ - Gas</td>
<td>0.9</td>
<td>1.4</td>
<td>0.4</td>
</tr>
<tr>
<td>D$_3^+$ - Gas</td>
<td>0</td>
<td>0</td>
<td>0.9</td>
</tr>
<tr>
<td>Total neutrons</td>
<td>10.3</td>
<td>8.0</td>
<td>10.3</td>
</tr>
</tbody>
</table>
Objective 3

• Examine effect of voltage and background gas pressure on ion and fast neutral energy distributions.

• Investigate the effect of molecular species mix in the source region on the D-D neutron production rate.

• **Extrapolate the D-T neutron production rate from D-D IEC parameters.**
Ratio of D-T to D-D(n+3He) Fusion Cross Sections Depends on Energy and Which Species is the Projectile
The D-T to D-D Neutron Production Rate Ratio Ranges from 50 to 120, Depending on Projectile Energy

- Define total fast neutral or ion density = \( n_{if} \) and total target neutral density = \( n_{it} \).

- In a D-D plasma, the fusion rate for \( \text{D+D} \rightarrow \text{n+}^3\text{He} \) is
  \[ \Gamma_{\text{DDn}^3} = n_{if}n_{it} \langle \sigma v \rangle_{\text{DDn}^3} \]
  where \( \langle \sigma v \rangle_{ij} \) means projectile species \( i \) colliding with background species \( j \).

- In a D-T plasma, each species has half of its D-D density and the fusion rate for \( \text{D+T} \rightarrow \text{n+}^4\text{He} \) is
  \[ \Gamma_{\text{DT}} = \frac{1}{4} n_{if}n_{it} (\langle \sigma v \rangle_{\text{DT}} + \langle \sigma v \rangle_{\text{TD}}) \]

- Therefore, the ratio of D-T to D-D neutron production rate is
  \[ R = \frac{\langle \sigma v \rangle_{\text{DT}} + \langle \sigma v \rangle_{\text{TD}}}{4 \langle \sigma v \rangle_{\text{DDn}^3}} \]
The ion and fast charge-exchange neutral nucleon distributions are weighted with the energy distributions and D-T:D-D fusion cross section ratios.

Total weighting equation becomes

\[ X = (f_{\text{ion}} \cdot w_{\sigma}) \frac{\dot{N}_{\text{ion}}^{DD}}{\dot{N}_{\text{ion}}^{\text{total}}} + (f_{\text{neutral}} \cdot w_{\sigma}) \frac{\dot{N}_{\text{neutral}}^{DD}}{\dot{N}_{\text{neutral}}^{\text{total}}} \]
Conclusions

• For the parameter regimes investigated so far:
  
  ➢ Increasing the neutral gas pressure softens the ion and charge-exchange neutral energy spectra, leading to an optimal background gas pressure.
  
  ➢ Increasing the voltage increases the neutron production rate and increases the importance of reactions related to D+ and D2+.
  
  ➢ The molecular species mix in the source region alters the ion spectra inside the anode, but the neutron production rate varies only slightly.

• Replacing D fuel by a D-T 50:50 mix should lead to D-T fusion neutron production rates ~80 times higher than the D-D rates.
  
  ➢ Optimized parameters may increase this ratio slightly.