Exploration of IEC Device

Operating Regimes*

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Outline

• Overview of the IEC integral equation approach
• Exploration of parametric dependencies:
  - Species mix
  - Pressure
  - Voltage
  - Anode and cathode radii
• Comparison to experiments
• Future directions
• Summary and Conclusions
Goal of this Research

• Understand the role of atomic and molecular processes in the flow of ions ($^3$He$^+$ or combination of D$^+$, D$_2^+$, and D$_3^+$) in gridded spherical IEC devices

• Develop a model to predict the performance of these devices, especially the neutron production rate.

• The goal is a “first principles” model using experimental data for cross sections, and with no “adjustable parameters”. 
Atomic and Molecular Physics Effects Dominate the Present Operating Regime
Multiple Ion Passes Are Modeled Using an Integral Equation Formalism

- \( A(r) = \) cold ion source due to ions from the anode region
- Cold ion source function = \( S(r) \)
- Attenuation function = \( g(r, r') \)

\[
g(r, r') = \exp\left\{ - \int_{r}^{r'} n_g \sigma_{cx} [V(r'')] dr'' \right\}
\]

- Ion flux \( d\Gamma(r) \) at \( r \) due to ions born at \( r' \)

\[
r^2 d\Gamma(r) = r'^2 g(r, r') S(r') dr'
\]

- Sum over all generations of cold ions and all ion passes

\[
S(r) = A(r) + \int_{r}^{\text{anode}} K(r, r') S(r') dr'
\]
Kernel relates the Source at one Radius to the Source at another Radius

\[ K_{ij}(r,r') = n_g \sigma_{ij} \left[ E(r,r') \right] \left( \frac{r'^2}{r^2} \right) \frac{g_j(r,r') + T_c^2 \frac{g_{cpj}(r')}{g_j(r,r')}}{1 - T_c^2 g_{cpj}(r')} \]

- Grid
- \( S_i(r) \)
- \( S_j(r') \)
- Radius
- Slow Source contribution:
- Gas density
- Cross-section for producing \( i \) from \( j \)
- Cathode transparency
- Sum over passes
- Complete pass probability
The “Catch”

- The ion current leaving the anode is unknown experimentally. We adjust it to match the calculated cathode current with the measured value.

- We then compare calculated and measured neutron generation rates.

- Calculating the cathode current is subject to considerable variation depending on assumptions concerning the cold ions produced in the cathode region.
$^3$He-$^3$He Fuel Performs Best at Small Radii and High Pressure

$^3$He–$^3$He Alpha Production ($10^4$ s$^{-1}$)
Varying $r_c$ and $P$: $r_a-r_c=0.05$ m, $V=200$ kV, $I=60$ mA

Cathode radius (m)

Background pressure (mTorr)
D-D Performs Best at Large Radii for Constant Cathode-Anode Spacing

100 kV, 60 mA, \( P=2 \) mTorr, source \( D^+:D_2^+:D_3^+=0.06:0.23:0.71 \)
D\(^{+}\) is Slightly Favored for Source Species

- Dots at each level independently rainbow colored with purple low and red high.

2 mTorr (0.27 Pa), 60 mA, 100 kV, \(r_{c}=0.1\) m, \(r_{a}=0.2\) m
Increasing Gas Pressure Increases Neutron Production

- Note: filament-assisted discharge; pressure is varied until glow-discharge regime reached.

100 kV, 60 mA, $r_c=0.1$ m, $r_a=0.2$ m, Source: 0.06 D$^+$, 0.23 D$_2^+$, 0.71 D$_3^+$
Typical Ion Energy Spectra at Cathode Show Peaks from Full-Energy Ions Passing through Cathode

100 kV, 60 mA, $r_c=0.1$ m, $r_a=0.2$ m, Source: 0.06 D$^+$, 0.23 D$_2^+$, 0.71 D$_3^+$
Theoretical Neutral Energy Spectrum at Cathode Agrees Well with Measured Spectrum of Reacting Neutrals and Ions

70 kV, 30 mA, 1.25 mTorr, rc=0.1 m, ra=0.2 m, source D⁺:D₂⁺:D₃⁺=0.06:0.23:0.71

Energy Spectrum at Cathode

Number per second per keV

E (keV)

0 10 20 30 40 50 60 70

10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸

Chosen point of agreement

Theory (neutrals)

Exp’t (ions & neutrals)
Theoretical Neutral and Ion Energy Spectra at Cathode Depend on Voltage in a Complicated Way

60 kV, 60 mA, 2 mTorr, \( r_c=0.1 \) m, \( r_a=0.2 \) m, source \( D^+ \)

Energy Spectra at Cathode

Number per second per keV

\[ 10^{17} \]
\[ 10^{16} \]
\[ 10^{15} \]
\[ 10^{14} \]

E(keV)

\( D^+ \)

\( D_{2}^+ \)
Theoretical Neutral and Ion Energy Spectra at Cathode Depend on Voltage in a Complicated Way

140 kV, 60 mA, 2 mTorr, \( r_c = 0.1 \) m, \( r_a = 0.2 \) m, source \( D^+ \)

![Energy Spectra at Cathode](image-url)

- Neutrals
- \( D^+ \)
- \( D_2^+ \)
Contributions to Neutron Production Rate Vary Significantly with Voltage

60 mA, P=2 mTorr, r_c=0.1 m, r_a=0.2 m, Source: D⁺

<table>
<thead>
<tr>
<th>Units of 10⁷ n/s</th>
<th>Neutrals†</th>
<th>Ions</th>
<th>Fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 kV</td>
<td>2.3</td>
<td>1.7</td>
<td>4.0</td>
</tr>
<tr>
<td>100 kV</td>
<td>3.3</td>
<td>4.3</td>
<td>7.6</td>
</tr>
<tr>
<td>140 kV</td>
<td>3.6</td>
<td>6.8</td>
<td>10.4</td>
</tr>
</tbody>
</table>

† “Neutrals” means the fast neutrals from charge-exchange or dissociation collisions.
Theoretical Neutron Production Agrees Reasonably Well with the Measured Neutron Production

70 kV, 30 mA, 1.25 mTorr, $r_c=0.1$ m, $r_a=0.2$ m
source $D^+:D_2^+:D_3^+=0.06:0.23:0.71$

- NB: need to include cold ion recombination with cold electrons to make agreement "reasonable"
Activities Since Previous IEC Workshop

• Added switch to include cold ion recombination in cathode region.

• Wrote papers on the atomic and molecular versions of the theory and submitted them to *Physics of Plasmas*:
  
  Ø G.A. Emmert and J.F. Santarius, “Atomic and Molecular Effects on Spherically Convergent Ion Flow II: Multiple Molecular Species.”
  Ø http://fti.neep.wisc.edu/pdf/fdm1369.pdf
  Ø http://fti.neep.wisc.edu/pdf/fdm1370.pdf

• Submitted renewal proposal to DOE Office of Fusion Energy Sciences, Theory branch.

• Capability to plot combined neutral and ion energy spectra is in progress.
Future Directions

• Areas where refinement of the models will be pursued include
  ➢ reducing gaps and uncertainties in cross section data,
  ➢ adding other atomic and molecular cross sections, if necessary,
  ➢ allowing a glow discharge ion source distribution,
  ➢ implementing planar and cylindrical geometries,
  ➢ including other fuels (D-T, D-\(^3\)He, \(^{11}\)B) and ionization
    (\(\text{He}^+, \text{He}^{++}\)) levels,
  ➢ adding negative ions, and
  ➢ including neutral particle transport.

• Other tasks
  ➢ further benchmarking against experimental data,
  ➢ optimizing the configuration and plasma parameters
Summary and Conclusions

• This theoretical approach gives reasonably good agreement with experimental results in much of parameter space for
  ➢ neutron production and
  ➢ energy spectra of ions and neutrals.

• More work remains to improve the agreement with experiments in some parameter regimes and optimize the configuration.

• Limited parametric variation indicates that the optimal configuration may be a large anode and cathode, closely spaced.

• Papers describing the method have been submitted to Physics of Plasmas and require slight revisions.