Atomic Physics Effects on Convergent, Spherically Symmetric Ion Flow

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Outline

One-population model

Source region model

Multiple-population model

Child-Langmuir equation
IEC Model

Vacuum wall
Source region
Intergrid region
Anode grid
\( \phi = 0 \)

Ion trajectory
Flux \( \Gamma_0 \), Energy \( E_0 \)

Cathode grid
\( \phi = -V_0 \)

neutral gas
Charge Exchange Produces Fast Atoms and Cascading Down of the Ion Energy

\[ \Phi(r) \]

\[ \text{Ions} \]

\[ \text{Atoms} \]

\[ \text{CX event} \]
Ionization Produces Cold Ions without Loss of Energy

\[ q \phi(r) \]

Ions

Ionization event
Charge Exchange “Attenuates” Initial Ion Current as Ions Oscillate Radially

Region where charge exchange creates a “2nd generation,” low-energy ion

Region of low ion energy, where charge exchange has little effect on the ion distribution.
Assumptions of the One-Population Model

• Background $D_2$ gas

• Deuterium ions (no molecular ions)
  ➢ Collisionless motion except for charge exchange and ion impact ionization interactions

• Fast deuterium atoms
  ➢ Collisionless motion

• Prescribed electrostatic potential profile
  ➢ Child-Langmuir or vacuum in intergrid region
  ➢ Flat in the cathode region

• Spherical symmetry – ignore stalk and defocusing

• No electrons
Multiple Ion Passes Are Modeled Using an Integral Equation Formalism

- 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

$$S(r) = A(r) + \int_r^{\text{anode}} K(r, r') S(r') dr'$$

- $A(r) =$ cold ion source due to ions from the anode

\[ JFS / GAE \quad \text{Fusion Technology Institute} \quad 2006 \]
Kernel Relates the Source at One Radius to the Source at Another Radius

\[ K(r, r') = n_g \sigma_{tot}(E(r, r')) \left( \frac{r'^2}{r^2} \right) \left( g(r, r') + T_c^2 \frac{g_{cp}(r')}{g(r, r')} \right) \]

- Grid
- \( S(r) \)
- \( S(r') \)
- Radius
- Gas density
- Total cross-section
- Cathode transparency
- Sum over passes
- Complete pass probability
• Set up a mesh in the intergrid region (the Volterra equation is only defined there).

• Calculate the attenuation coefficients in the intergrid region numerically and in the cathode region analytically.

• The ion current $\Gamma_0$ leaving the anode is unknown experimentally and is adjusted to match the calculated cathode current with the measured value.

• The model reproduces the general trends of neutron production rate with changes in cathode current, cathode voltage, and gas pressure.

• The calculated neutron production rates are close to the measured values at low voltage and about a factor of 4 low at high voltage.
Cold Ion Source Function Can be Significantly Larger than the Ion Source at the Anode

Deuterium fuel

$V_c = 166 \text{ kV}$
$p = 2 \text{ mtorr}$
$I_c = 68 \text{ mA}$
Average Ion Energy Can Be Substantially Below the Anode-Cathode Voltage Difference

Energy Spectrum at Cathode

- Deuterium fuel
- $V_c = 166$ keV
- $p = 2$ mTorr
- $I_c = 68$ mA

**Notes:**

- Inward
- Outward
Single-Pass Ions at Low Pressure Possess Nearly Their Full Energy at the Cathode

Helium fuel

\[ V_c = 60 \text{ keV} \]
\[ p = 0.5 \text{ mtorr} \]
\[ I_c = 7.5 \text{ mA} \]
Zero-D Model for the Source Region

- Treat the source region (outside the anode) using 0-D rate equations
- Atomic processes driven primarily by energetic electrons emitted from negatively biased (~ -200 V) filaments
- Goal is to calculate the mix of atomic and molecular ions entering the intergrid region (crossing through the anode)
Various Atomic Physics Processes Play a Role

• It turns out that only atomic processes involving D$_2$ are significant. This is because D$_2$ gas is, by far, the dominant species. Consequently, ionization of D$_2$, dissociative ionization of D$_2$, and interchange reactions are the dominant atomic processes.

• Processes included:
  - Ionization, dissociation, interchange \((D_2 + D_2^+ \rightarrow D_3^+ + D)\)
  - Flow to walls
  - Flow through anode grid
Rate Equations for Source Region

\[
\frac{d}{dt}(n_{11}) = n_p n_{20} \sigma_5 V_p - \frac{1}{2} n_{11} C_1 \left( \frac{A_g + A_w}{Vol} \right)
\]

\[
\frac{d}{dt}(n_{21}) = n_p n_{20} \sigma_1 V_p - \alpha_2 n_{21} n_{20} - \frac{1}{2} n_{21} C_2 \left( \frac{A_g + A_w}{Vol} \right)
\]

\[
\frac{d}{dt}(n_{31}) = \alpha_2 n_{21} n_{20} - \frac{1}{2} n_{31} C_3 \left( \frac{A_g + A_w}{Vol} \right)
\]

Ionization

Interchange reactions

Flow to walls and grid

\[
e(n_{11} C_1 + n_{21} C_2 + n_{31} C_3) A_g = 2 I_{ion}
\]
Species mix of current into intergrid region

\[ D^+_3 \quad 80\% \]
\[ D^+_2 \quad 14\% \]
\[ D^+ \quad 6\% \]

Conclusion: we need to include molecular ions in the IEC model.
Many Reaction Chains Occur in the IEC Plasma
We Simplify the Reaction Chains by Assuming Ions Are Always Born at Zero Energy

- Simplification: newly created fast ions are approximated as slow ions.
Analysis Requires Coupled Integral Equations

- Note: only two species shown for simplicity.

\[ S_1(r) = A_1(r) + \int_r^b K_{11}(r, r')S_1(r)dr + \int_r^b K_{12}(r, r')S_2(r)dr \]

\[ S_2(r) = A_2(r) + \int_r^b K_{21}(r, r')S_1(r)dr + \int_r^b K_{22}(r, r')S_2(r)dr \]

Subscripts: 1 = D\(^+\) ions \quad 2 = D\(_2\)^+ ions

\( S_i(r) = \) number of ions of species i born at r per unit volume per unit time

\( A_i(r) = \) source at r of ions of species i produced by the D\(_3\)^+ ions from the source region
Kernels Include the Creation of the Same Species Plus Cross Terms for the Other Species

\[
K_{11}(r, r') = n_g \sigma_{11s}(E(r, r')) \left( \frac{r''^2}{r^2} \right) \left( \frac{g_1(r, r') + \frac{T_c^2 g_{cp1}(r')}{g_1(r, r')} 1}{1 - T_c^2 g_{cp1}(r')} \right)
\]

\[
K_{22}(r, r') = n_g \sigma_{22s}(E(r, r')) \left( \frac{r''^2}{r^2} \right) \left( \frac{g_2(r, r') + \frac{T_c^2 g_{cp2}(r')}{g_1(r, r')} 1}{1 - T_c^2 g_{cp2}(r')} \right)
\]

\[
K_{12}(r, r') = n_g \sigma_{21}(E(r, r')) \left( \frac{r''^2}{r^2} \right) \left( \frac{g_2(r, r') + \frac{T_c^2 g_{cp2}(r')}{g_1(r, r')} 1}{1 - T_c^2 g_{cp2}(r')} \right)
\]

\[
K_{21}(r, r') = n_g \sigma_{12s}(E(r, r')) \left( \frac{r''^2}{r^2} \right) \left( \frac{g_1(r, r') + \frac{T_c^2 g_{cp1}(r')}{g_1(r, r')} 1}{1 - T_c^2 g_{cp1}(r')} \right)
\]

\[
\ldots \text{ (for species 3)}
\]

where \( \sigma_{21} = \sigma_{21s} + \sigma_{21f} \)
Summary and Status

• The one-population model reproduces the general trends of neutron production rate with changes in cathode current, cathode voltage, and gas pressure.

• The calculated neutron production rates are close to the measured values at low voltage and about a factor of 4 low at high voltage.

• A source-region model indicates that molecular species are important, even at 2 mtorr; the amount of dissociation in transit is under investigation.

• Numerical solution of coupled Volterra equations is underway.

• Parametric variation cases will be run this Summer.