Integral Transport Approach for Molecular Ion Processes in IEC Devices

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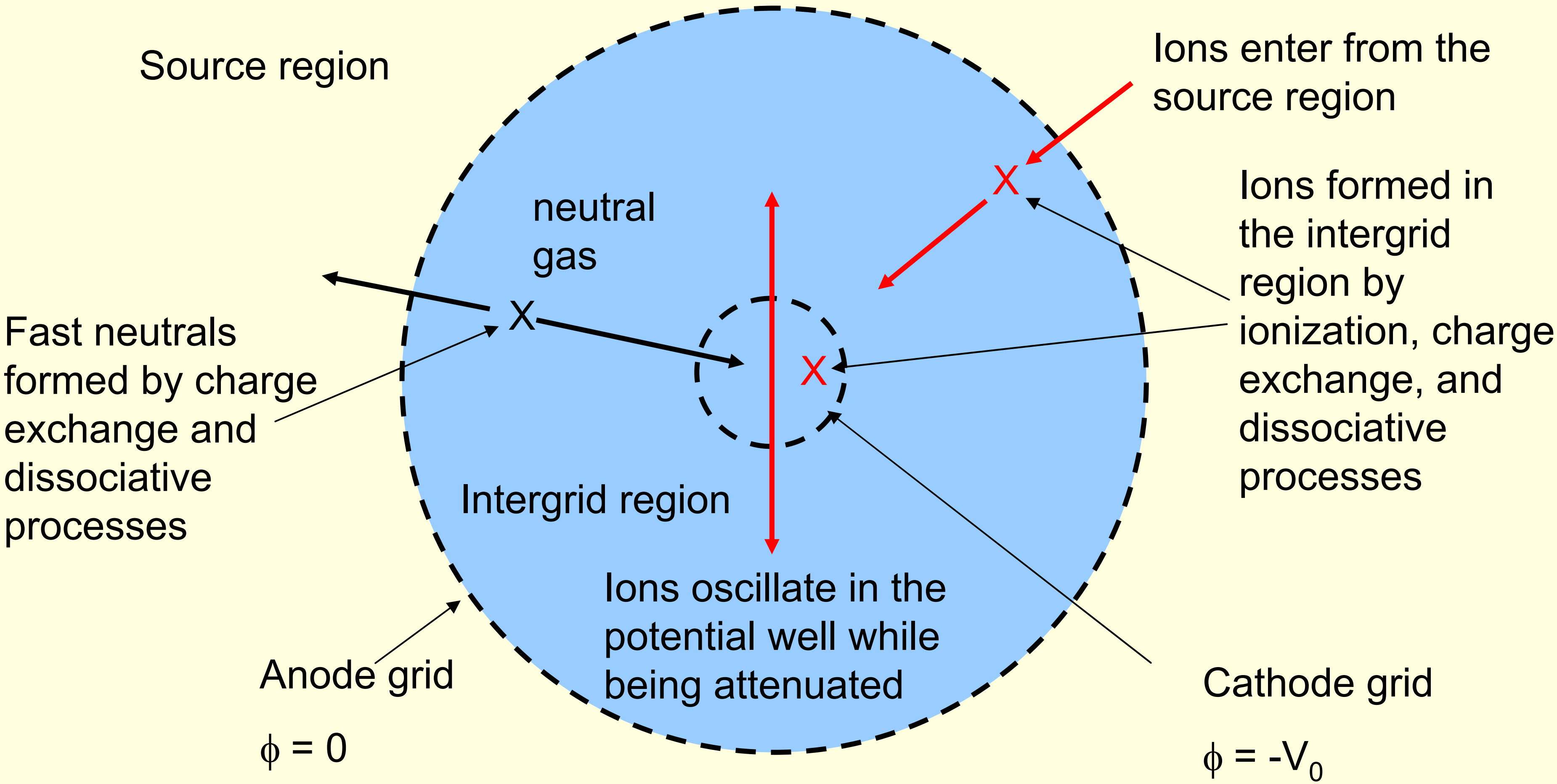
The Goal of this Research

- Understand the role of molecular processes in the flow of ions (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".

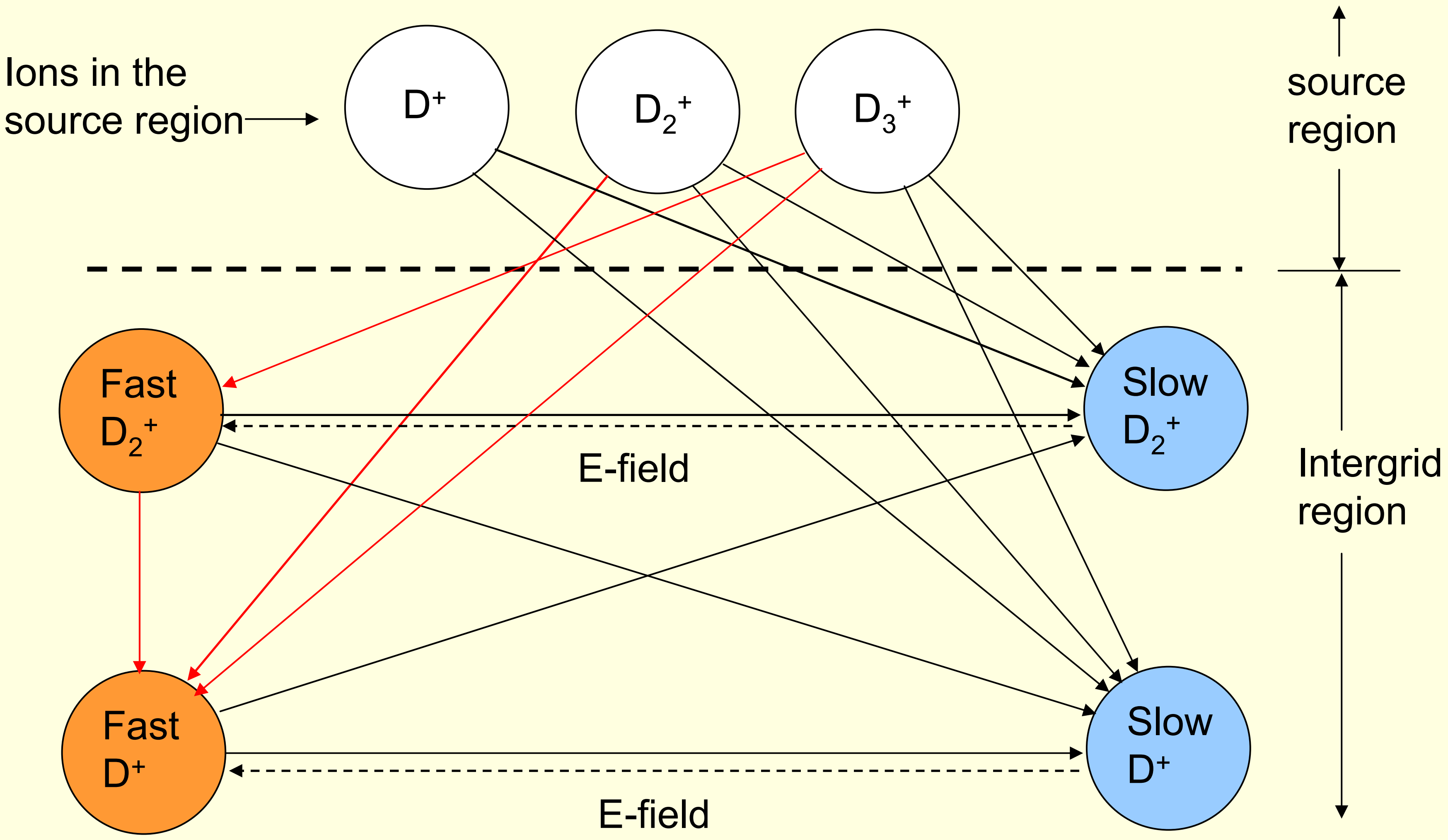
IEC Model


Source region
Ions enter from the source region
neutral gas
Ions formed in the intergrid region by ionization, charge exchange, and dissociative processes
Fast neutrals formed by charge exchange and dissociative processes
X
X
X
Intergrid region
Ions oscillate in the potential well while being attenuated
Anode grid
$\phi = 0$
Cathode grid
$\phi = -V_0$

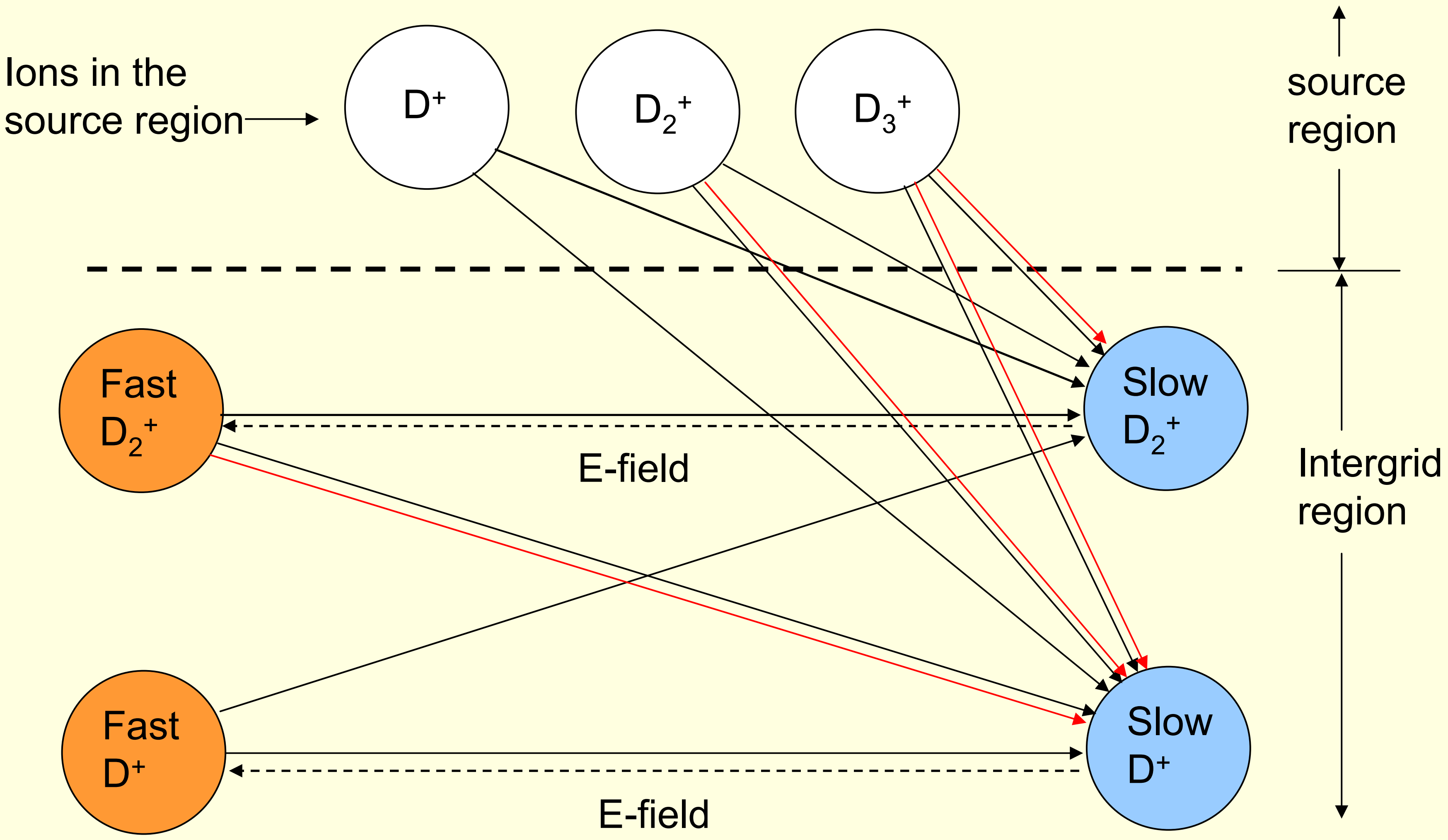
Basic Assumptions of the Model

- Background D_2 gas
- Deuterium (D^+, D_2^+, and D_3^+) ions enter from the source region
- D^+, D_2^+ ions created in the intergrid and cathode regions
- Collisionless ion motion except for charge exchange, impact ionization and dissociative interactions with D_2 background gas
- Interactions occur without momentum transfer between nuclei
- Prescribed electrostatic potential profile
  - Child-Langmuir or vacuum potential in intergrid region
  - Flat in the cathode region
- Spherical symmetry – ignore stalk and defocusing

Molecular Processes due to Interaction with Background D_2 Gas



Molecular Processes due to Interaction with Background D_2 Gas



Formalism

$S_1(r)$ = cold D^+ source function

$S_2(r)$ = cold D_2^+ source function

S_1 and S_2 determined by ionization, charge exchange and dissociative processes involving the hot species interacting with the background D_2 gas.

Two Coupled Volterra Integral Equations Determine the Source Functions

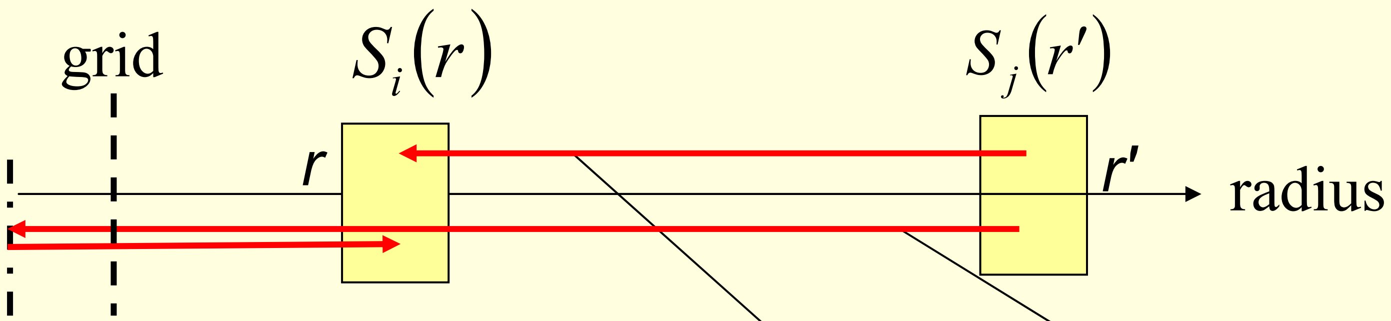
Sum over all generations of cold ions and all ion passes for D^+ ($i = 1$) and D_2^+ ($i = 2$)

$$S_i(r) = A_i(r) + \sum_{j=1}^{2} \int_r^{\text{anode}} K_{ij}(r, r') S_j(r') dr', \quad i = 1,2$$

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

$K_{ij}(r, r')$ = kernel that relates the source function at one point to another point through molecular processes and acceleration by the electric field.

Kernel relates the Source at one Radius to the Source at another Radius



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

gas density

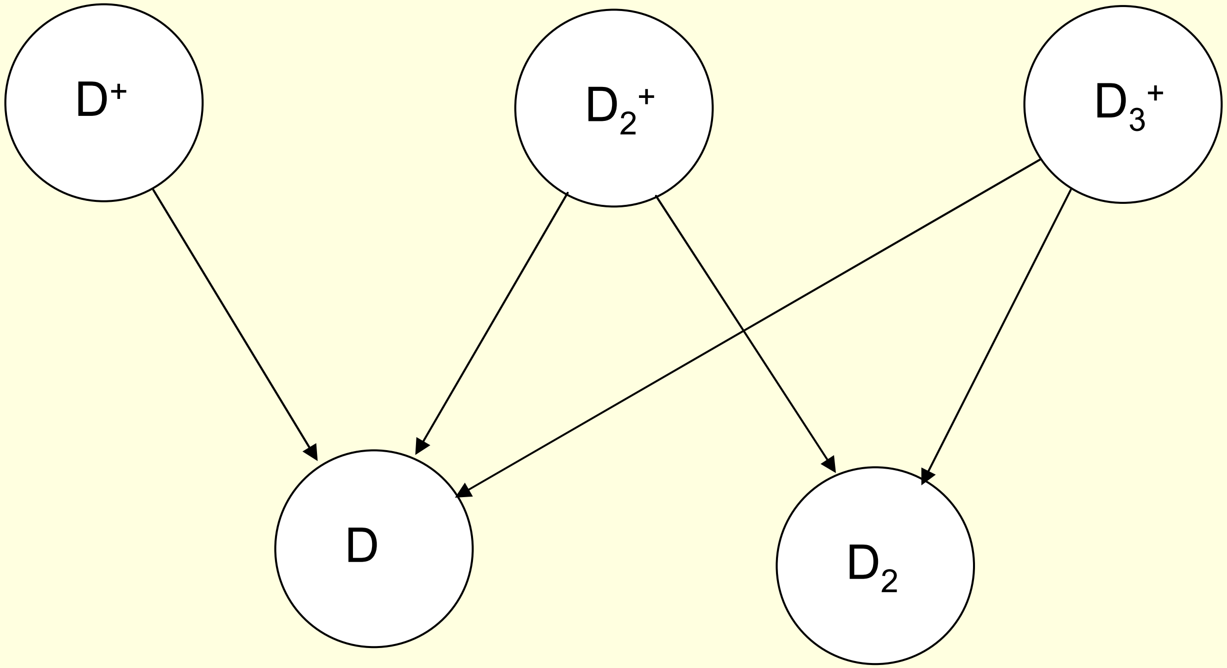
cross-section for producing *i* from *j*

cathode transparency

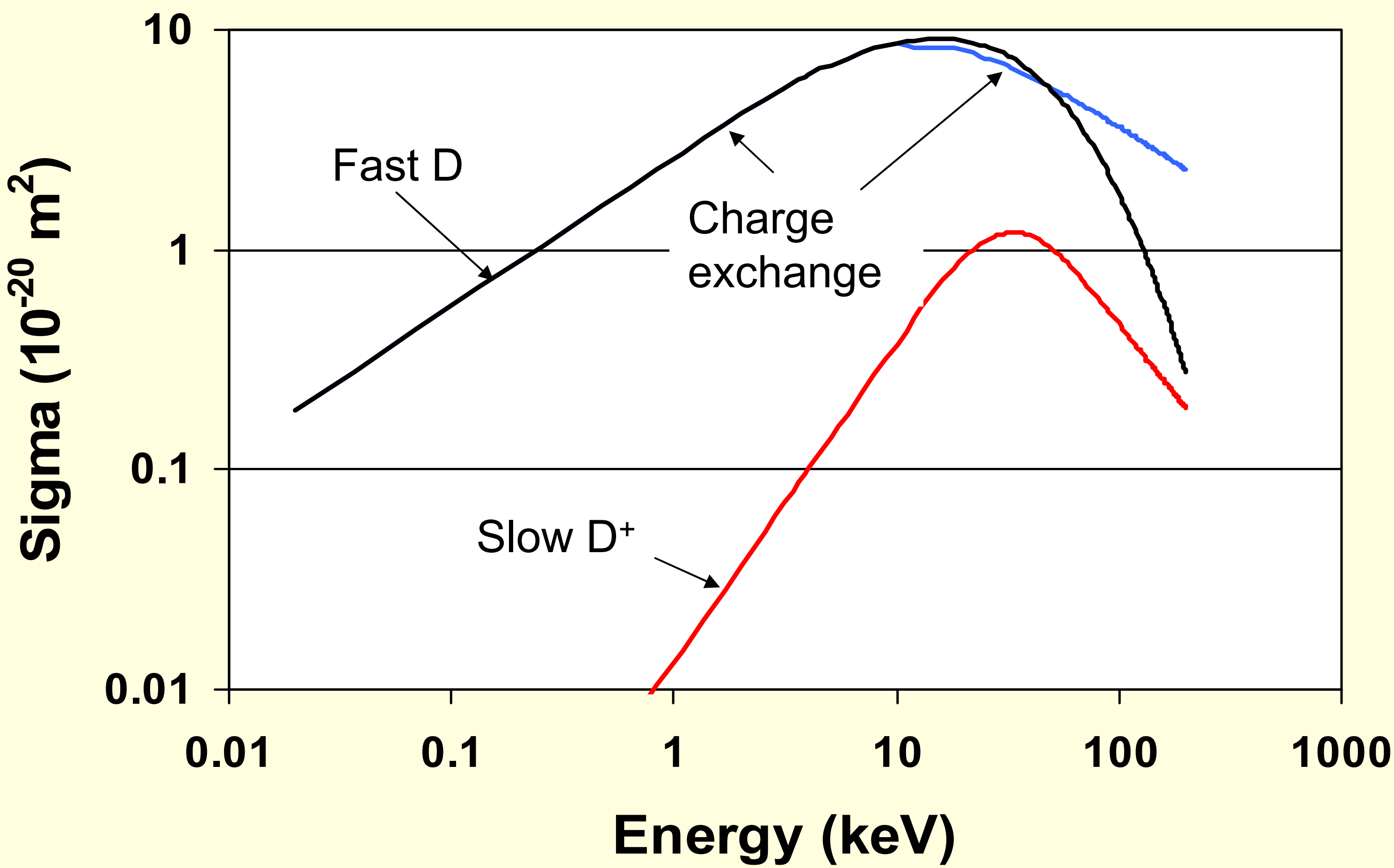
sum over passes

complete pass probability

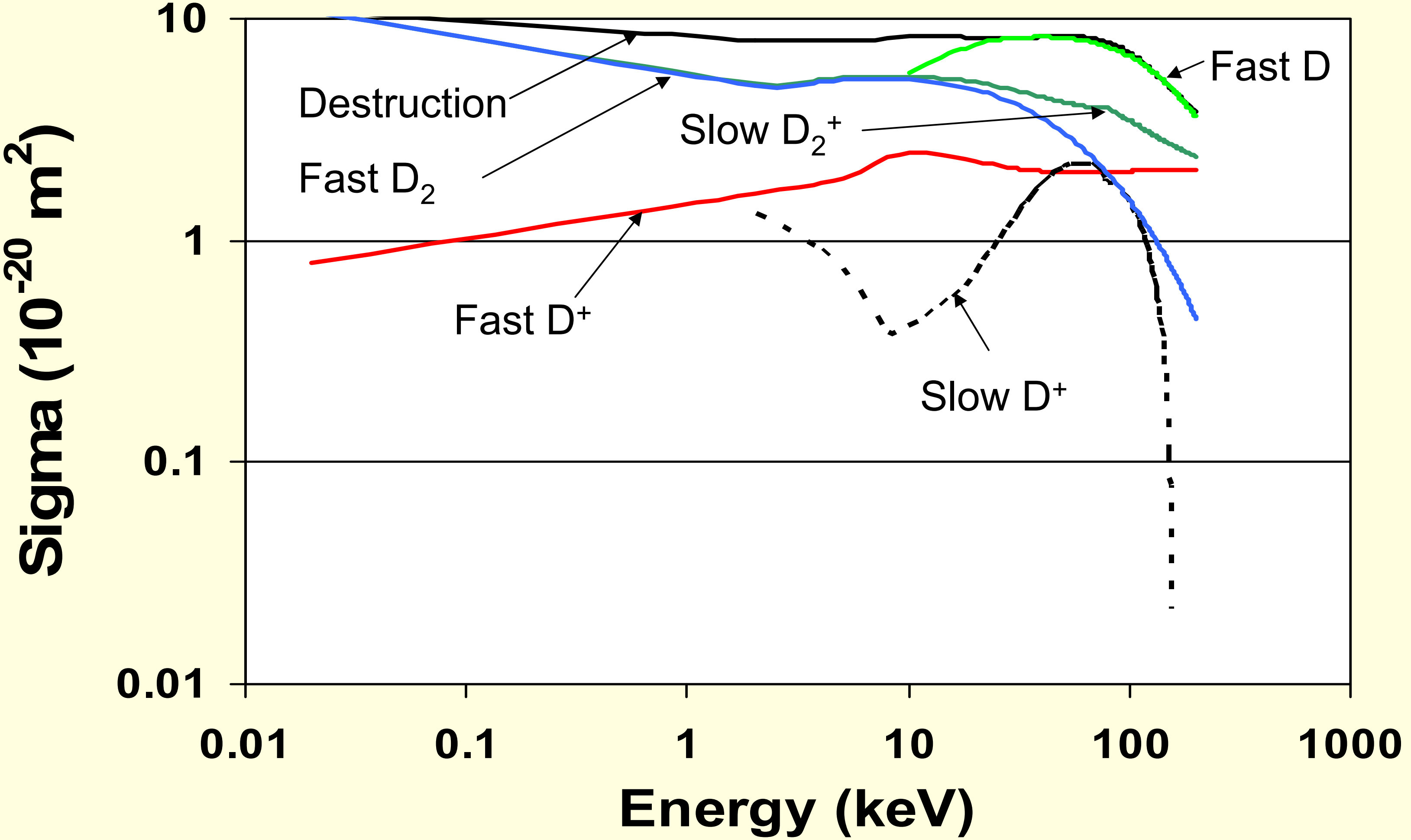
Generation of Fast Atoms and Molecules by Interaction with Background D_2 Gas



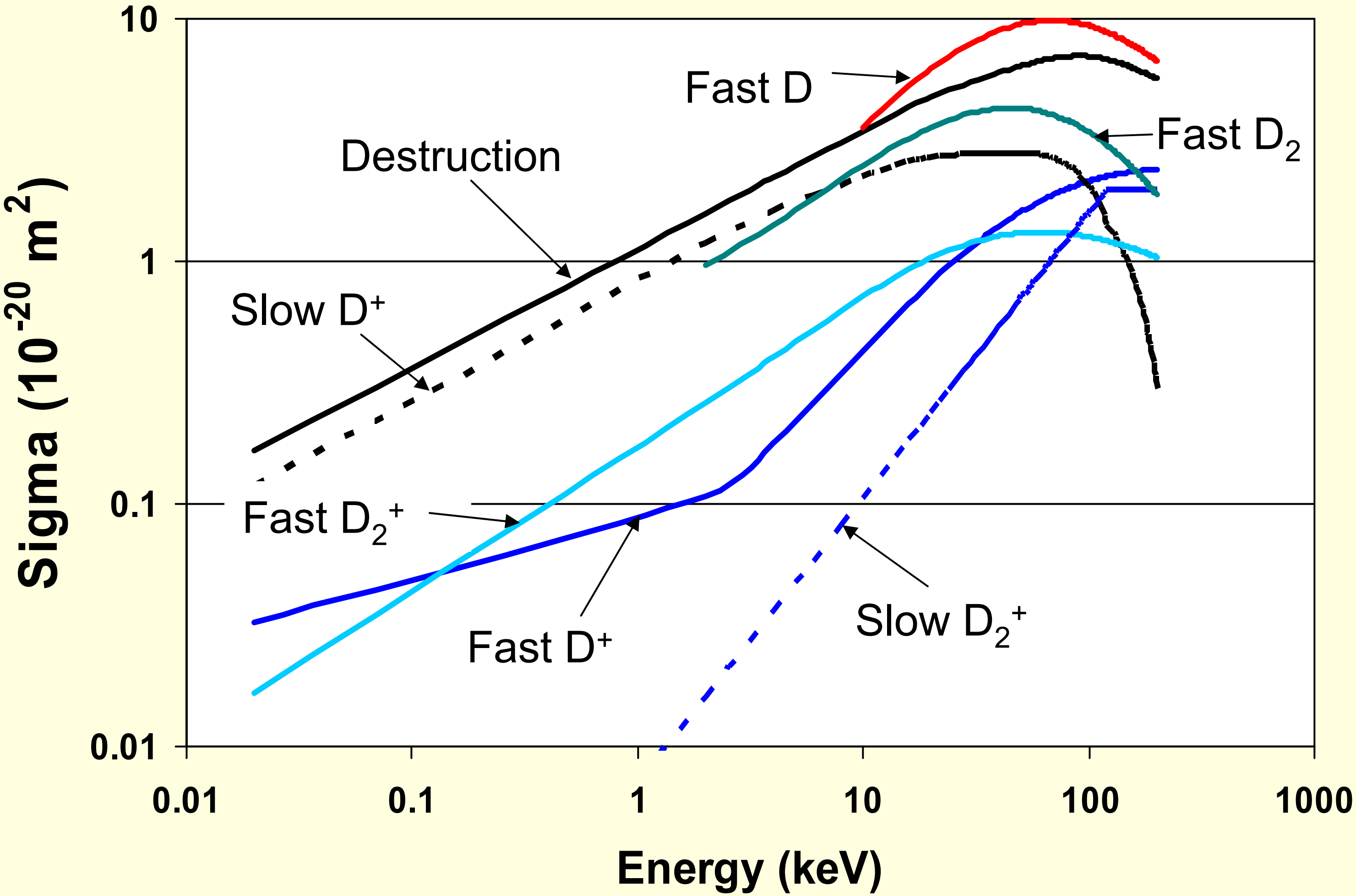
D^+ Cross Sections



D_2^+ Cross Sections



D_3^+ Cross Sections



Given $S_i(r)$ We Can Calculate:

- Energy spectrum of the fast ion flux, $f_i(r,E)$
- Energy spectrum of the fast neutral flux, $f_n(r,E)$
- Ion current collected by the cathode
- Neutron production rate
- etc

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.

Example Calculation

Input:

Cathode voltage	166 kV,
Gas pressure	2 mTorr,
Ion mix	80% D_3^+, 14% D_2^+, 6% D^+
Cathode Current	68 mA

Results

energetic ion current striking cathode	10 mA
cold ion current striking cathode	41 mA
secondary electron emission	17 mA

Example Calculation - II

- Neutron Generation (model)
  - by ion-gas fusion 6.2 x 10^7 n/s
  - by fast atom-gas fusion 1.1 x 10^8 n/s
  - total **1.7 x 10^8 n/s**

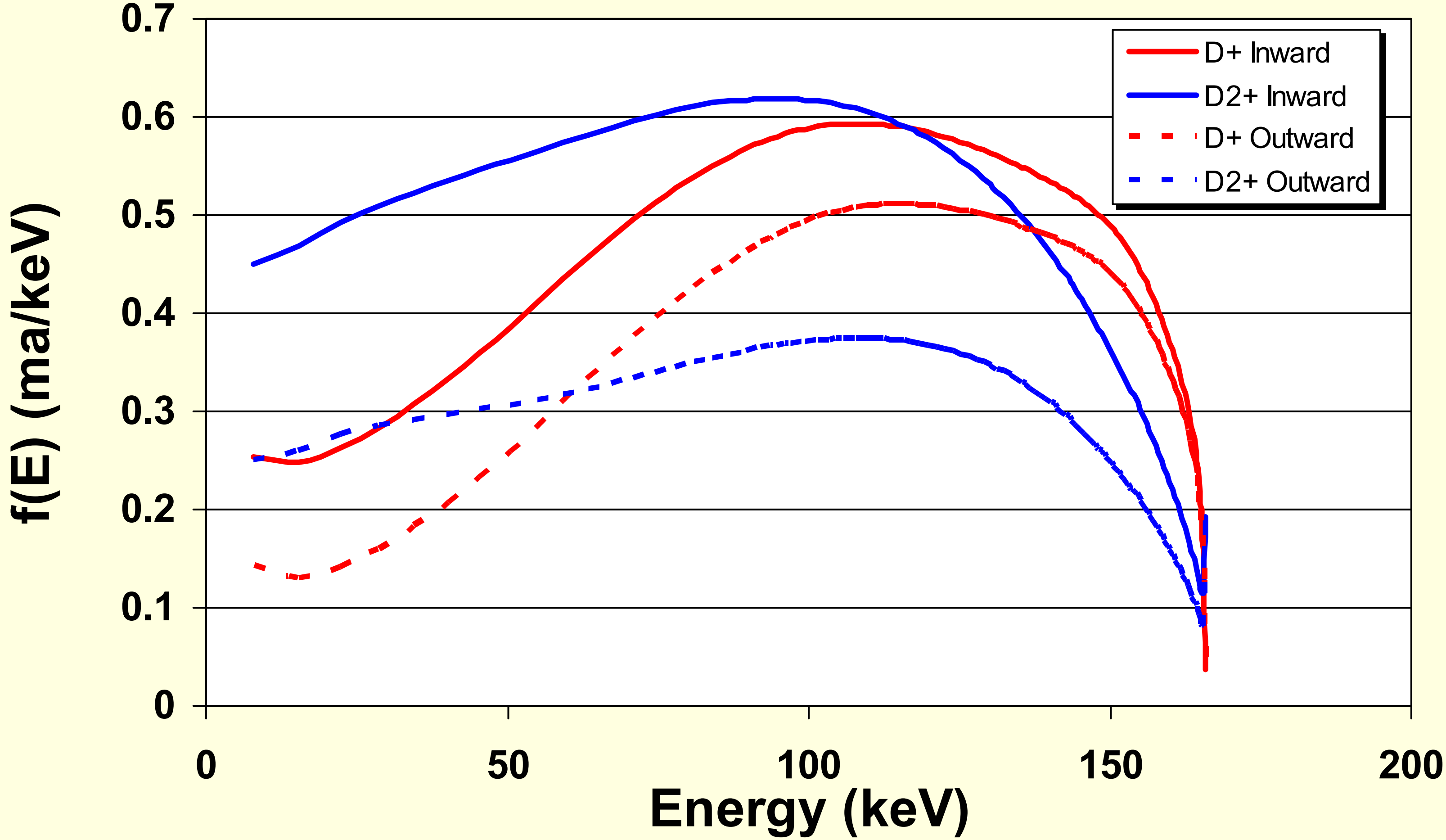
- Neutron Generation (experimental) **1.8 x 10^8 n/s**

Neutron generation processes not calculated:

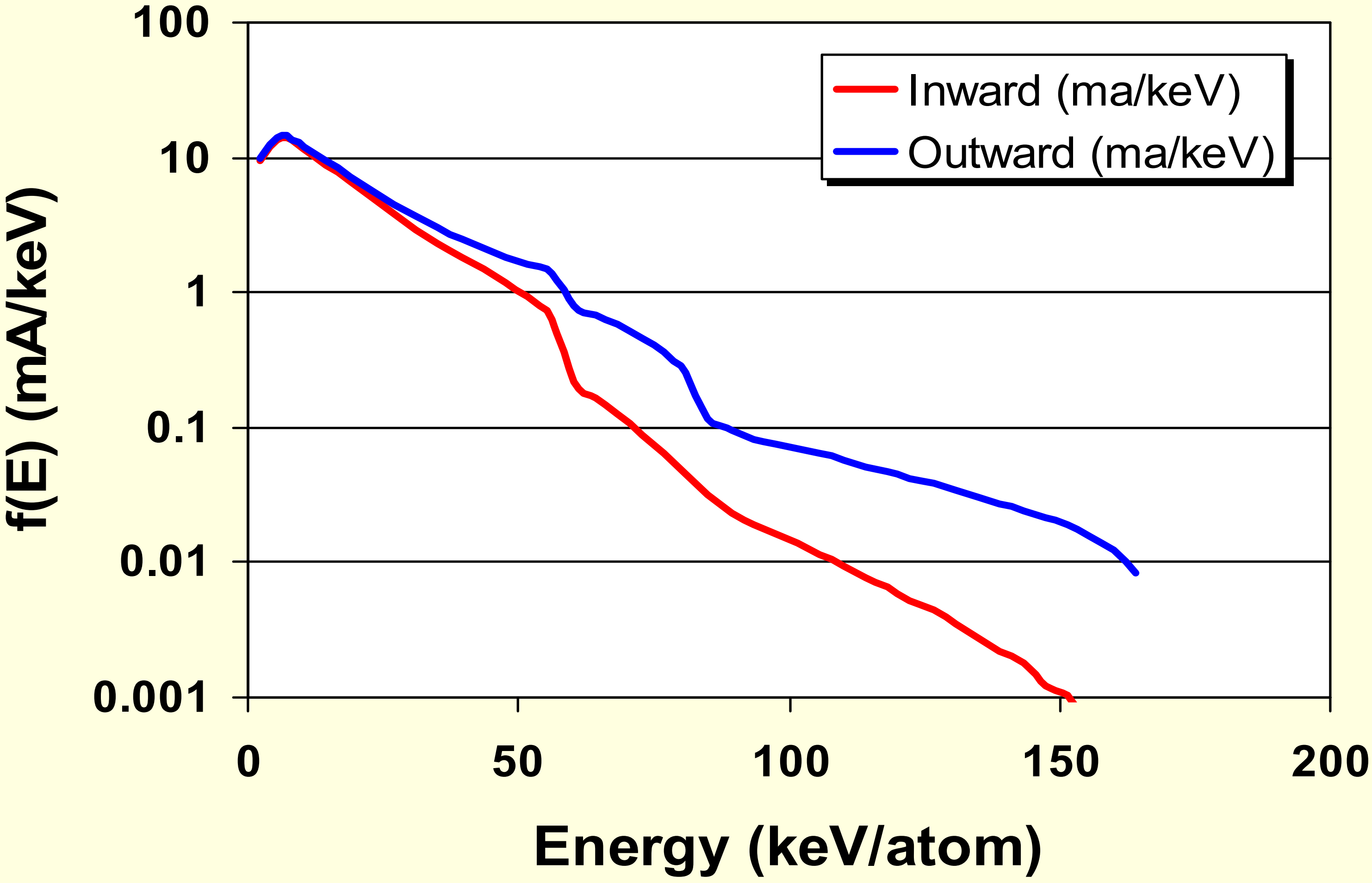
Ion-ion fusion

Implantation in grids or walls

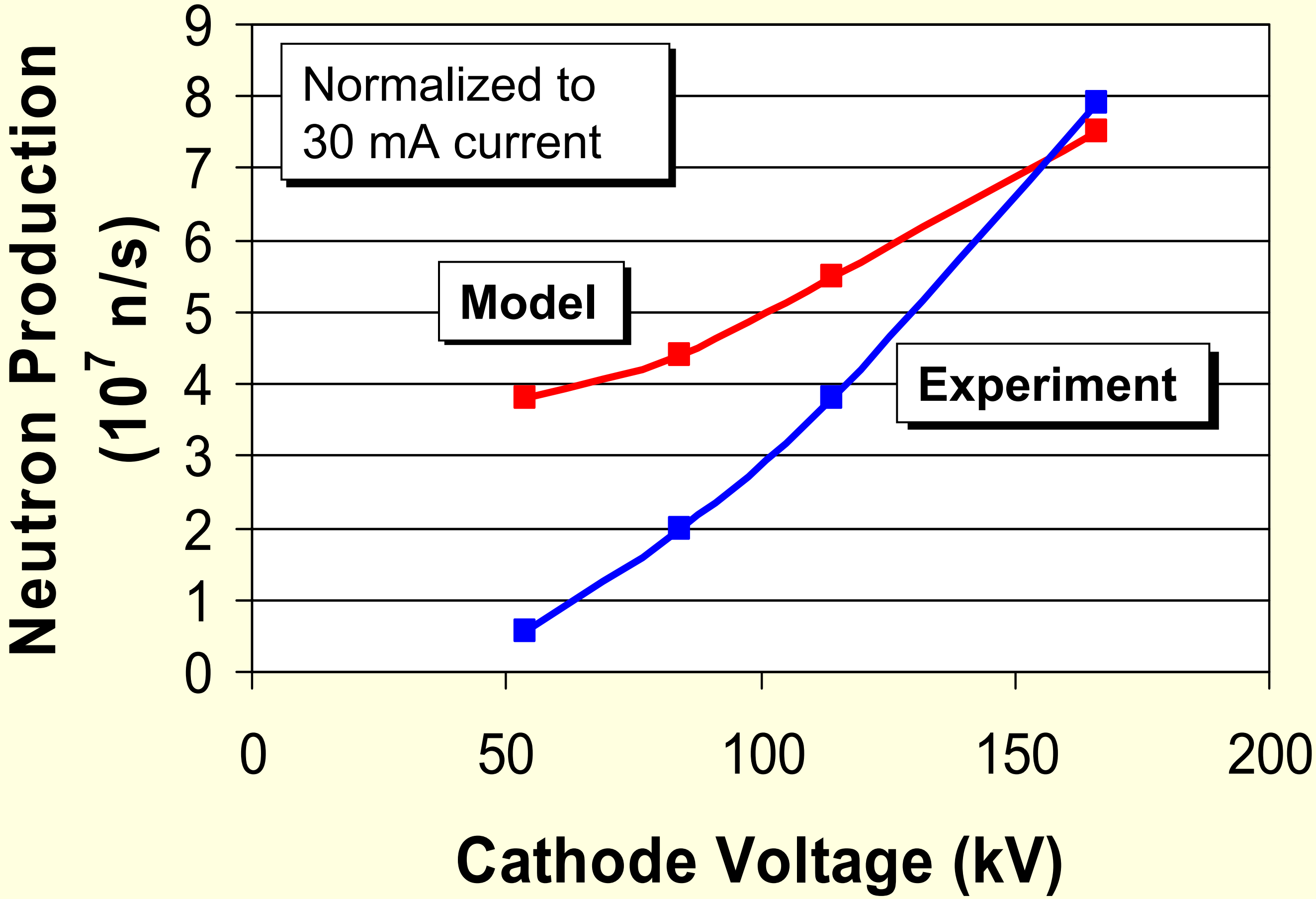
Ion Energy Spectrum at Cathode



Neutral Energy Spectrum at Cathode



Neutron Production Agrees Well at High Voltage but is Optimistic at Low Voltage



Weaknesses in the Model

- Gaps in the molecular ion cross section data
- Uncertainties in the secondary electron emission coefficient
- Angular scattering of ions neglected
- Energy loss by fast neutrals neglected
- Energy of fast ions created by dissociation neglected
- Ionization by electrons streaming from the cathode to the anode neglected

Summary and Conclusions

- A model that incorporates molecular processes involving the interaction of D^+, D_2^+, and D_3^+ with the background D_2 gas has been developed, although there are gaps in the available cross section data.
- The calculated neutron production rates are too high compared with the measured values at low voltage and give good agreement at high voltage.

Acknowledgement

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Related Talks in this Workshop

- Tuesday, 3:30 p.m., "*Theoretical Exploration of Some Issues Affecting IEC Fusion Rates*", J.F. Santarius

- Wednesday, 11:30 a.m., "*Plasma Characteristics of the Ion Source Region in the University of Wisconsin IEC Device*", D.R. Boris