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Exploration of IEC Device Operating Regimes*

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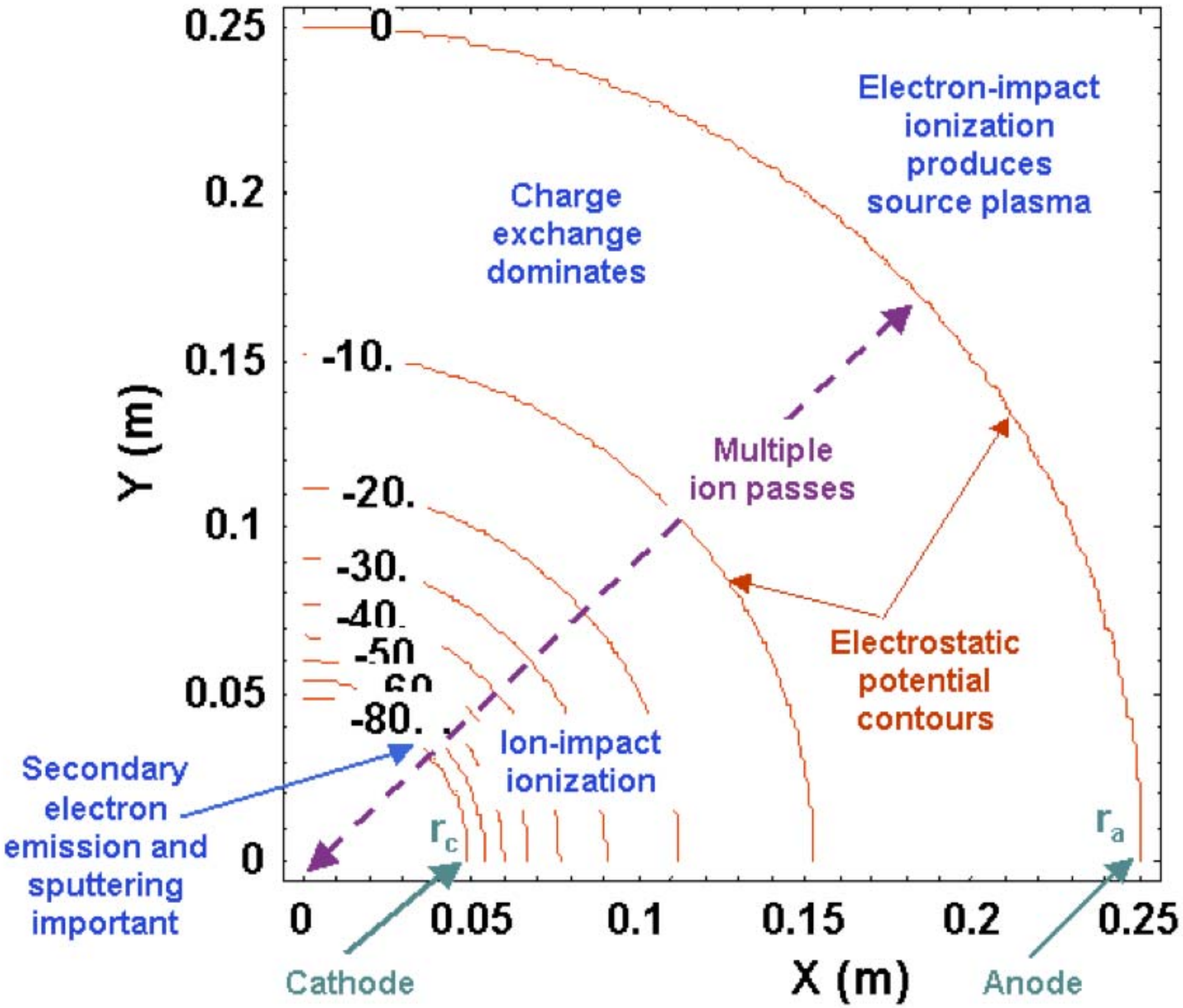
Outline

- Overview of the IEC integral equation approach
- Exploration of parametric depencies:
    - 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 ($^3He^+$ 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



Electron-impact ionization produces source plasma

Charge exchange dominates

Multiple ion passes

Electrostatic potential contours

Ion-impact ionization

Secondary electron emission and sputtering important

Cathode

Anode

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 = $g(r, r')$

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

gas density

charge exchange cross-section

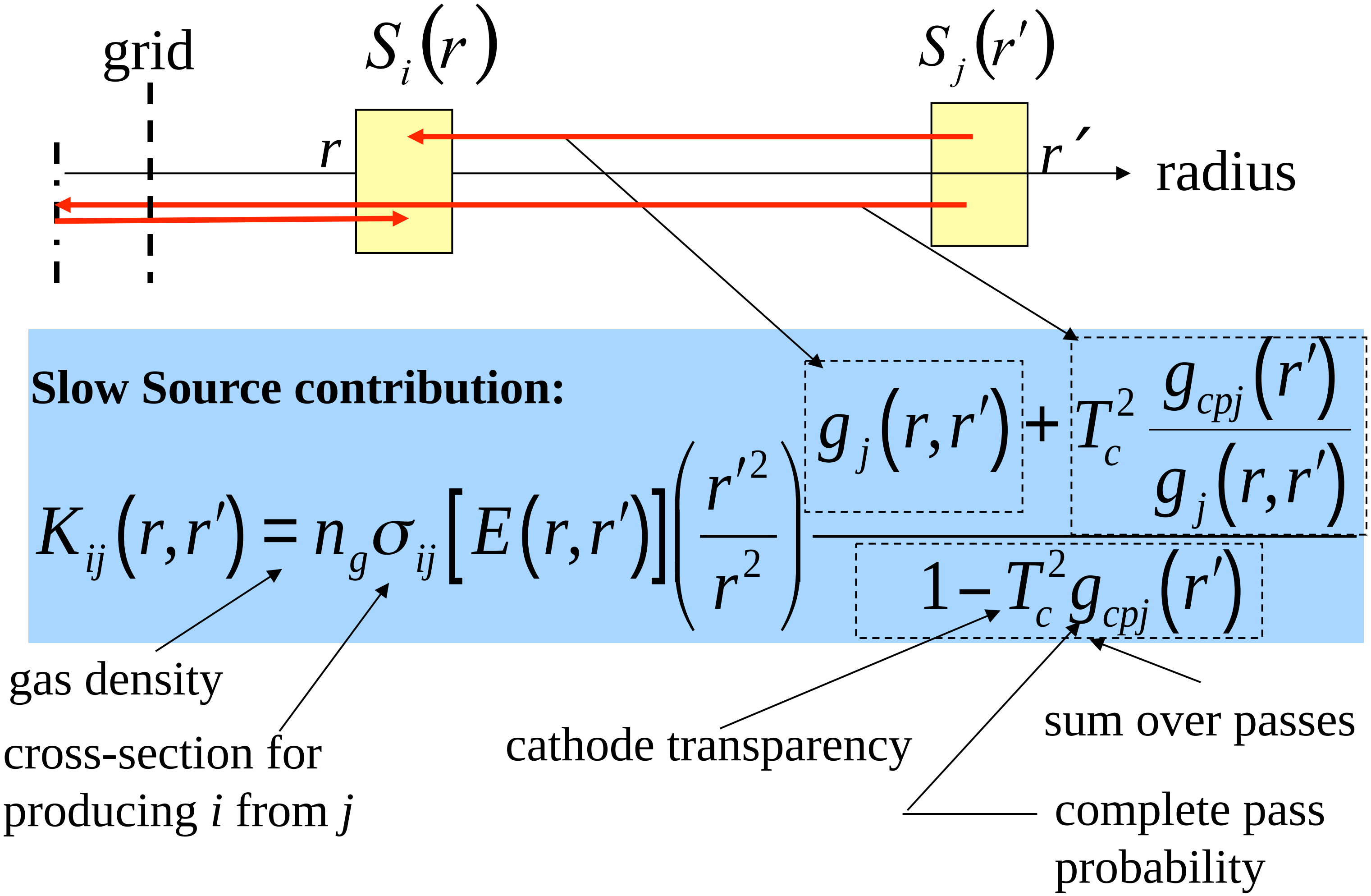
- Ion flux $d\Gamma(r)$ at r due to ions born at r'

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

- 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



Slow Source contribution:

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

gas density

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

cathode transparency

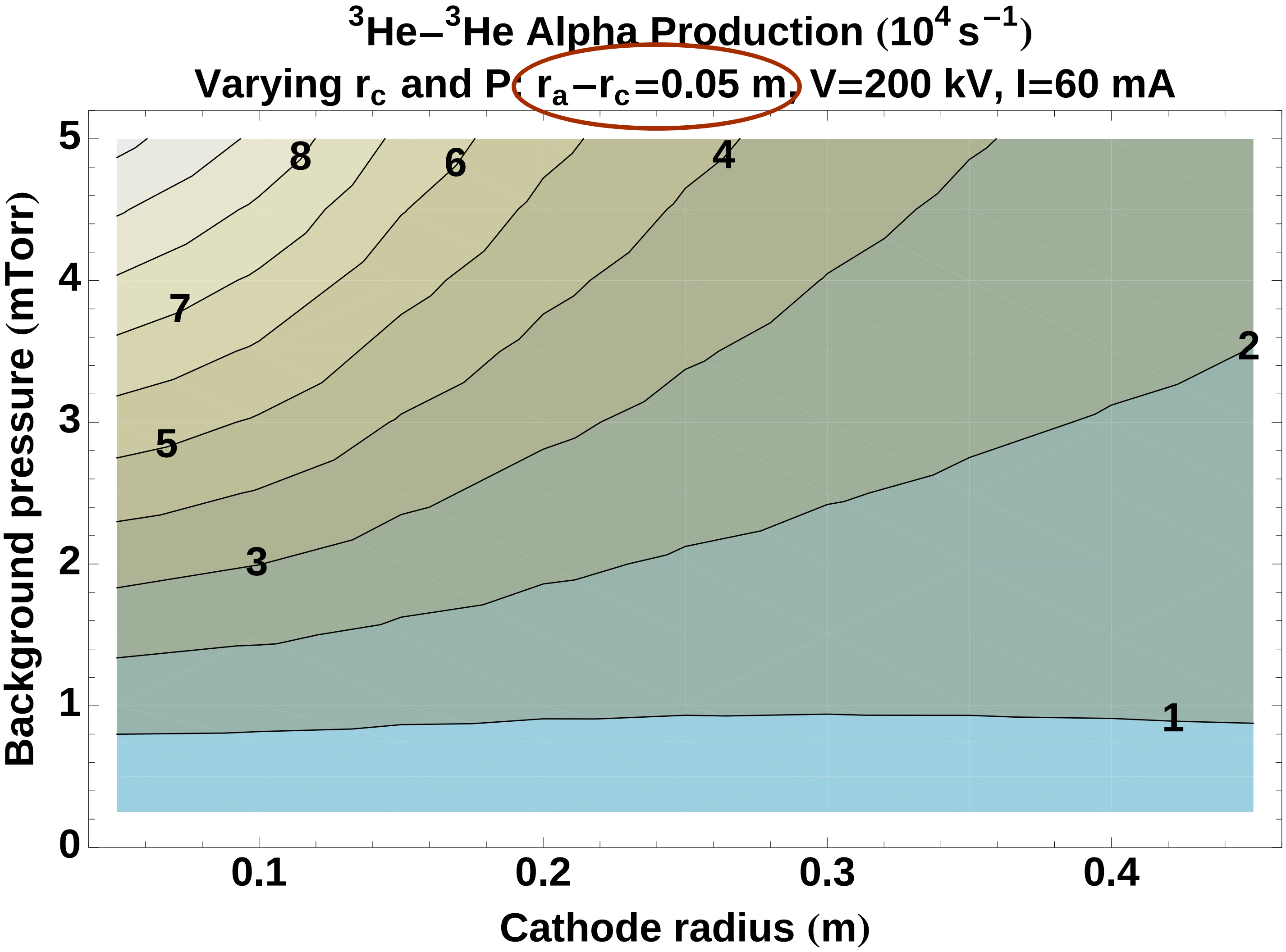
sum over passes

complete pass probability

The “Catch”

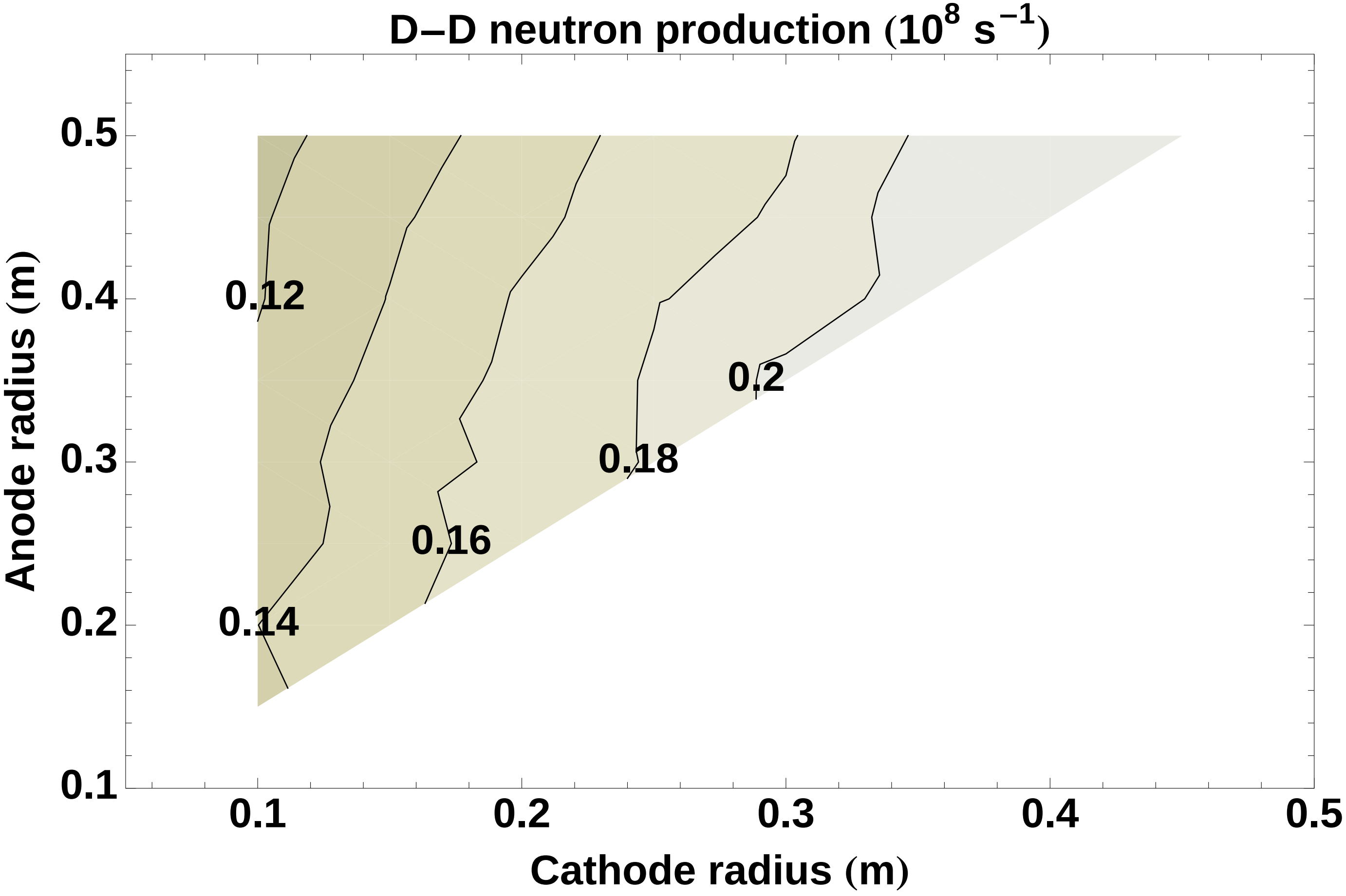
- The ion current leaving the anode is unknown experimentally. We adjust it to match the calculated cathode current with the measured value.
- We then compare calculated and measured neutron generation rates.
- Calculating the cathode current is subject to considerable variation depending on assumptions concerning the cold ions produced in the cathode region.

^{3}He-^{3}He Fuel Performs Best at Small Radii and High Pressure



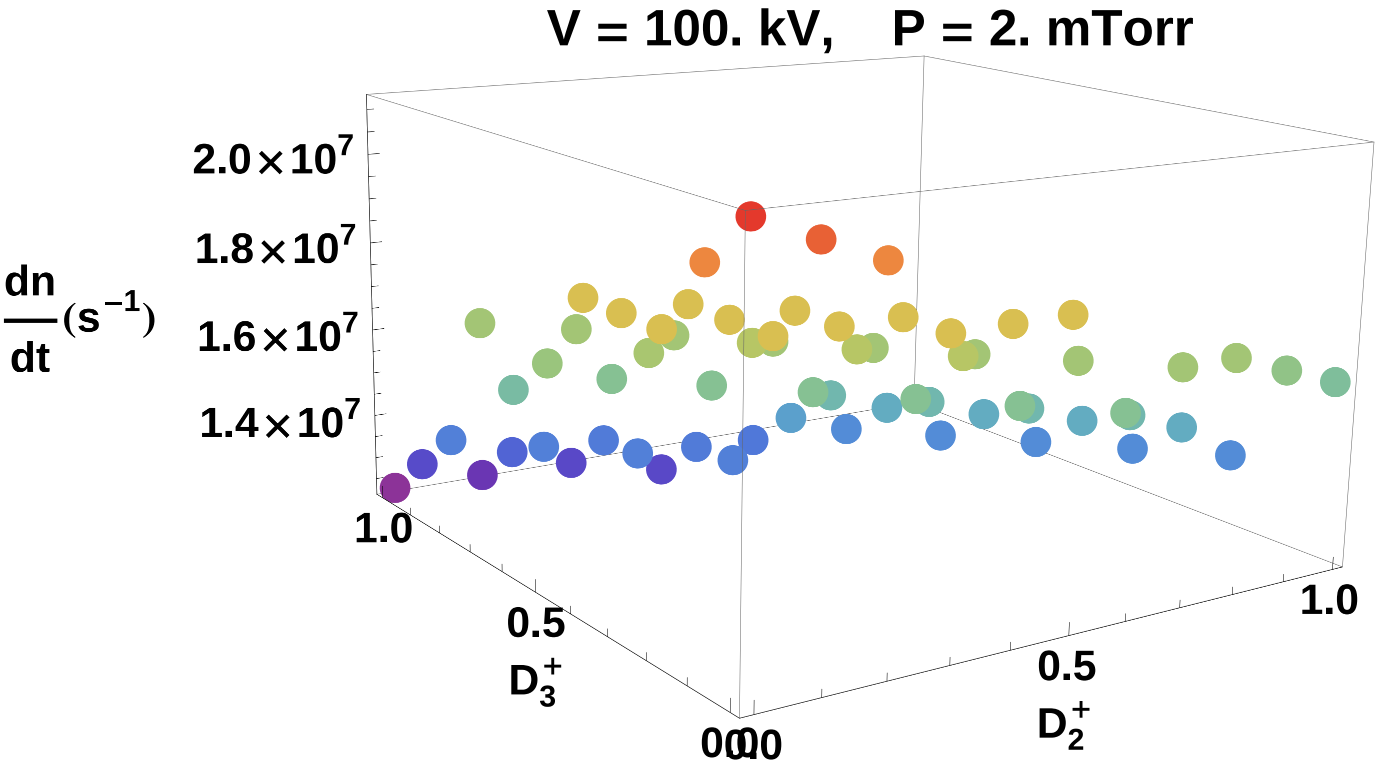
D-D Performs Best at Large Radii for Constant Cathode-Anode Spacing

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.

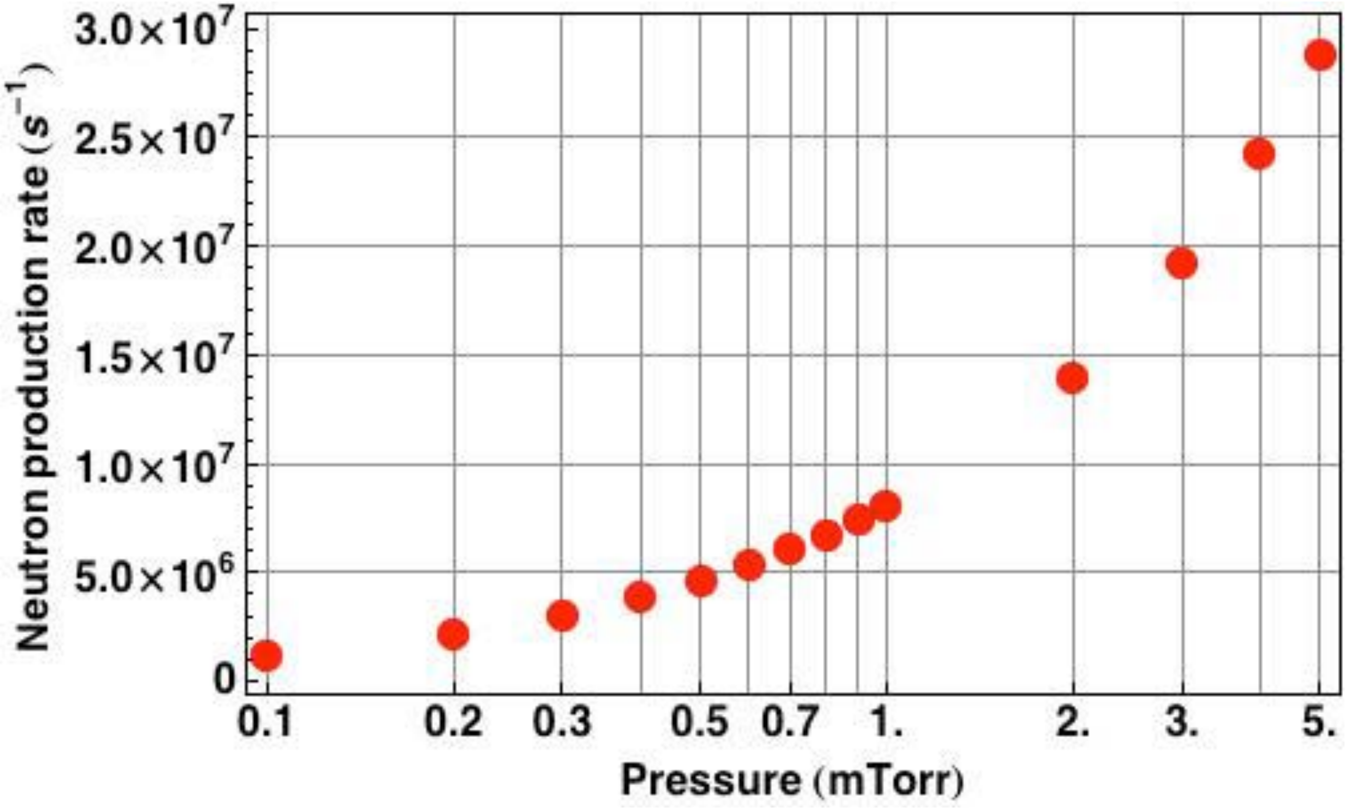


2 mTorr (0.27 Pa), 60 mA, 100 kV, r_c=0.1 m, r_a=0.2 m

Increasing Gas Pressure Increases Neutron Production

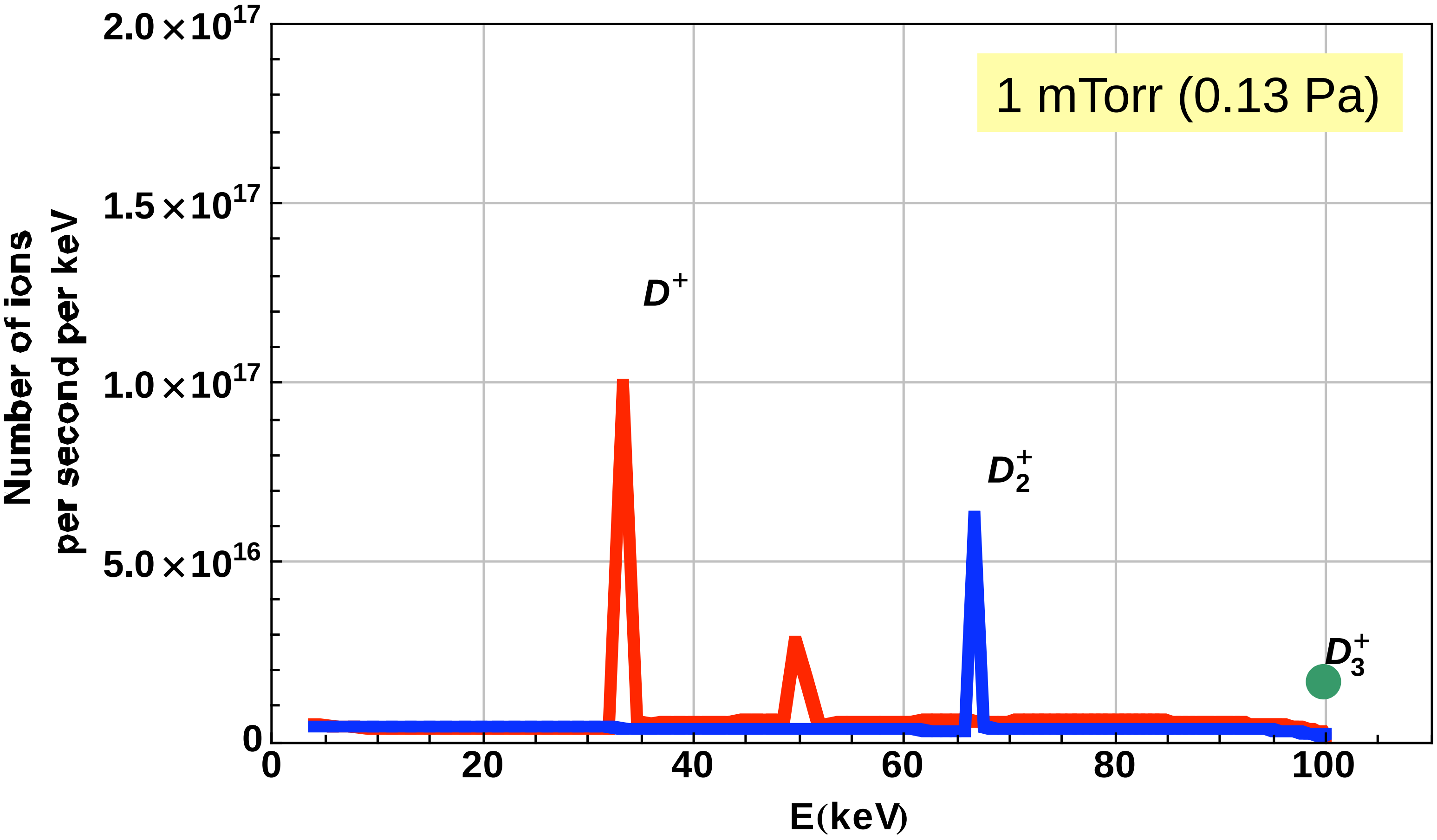
- Note: filament-assisted discharge; pressure is varied until glow-discharge regime reached.

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^+



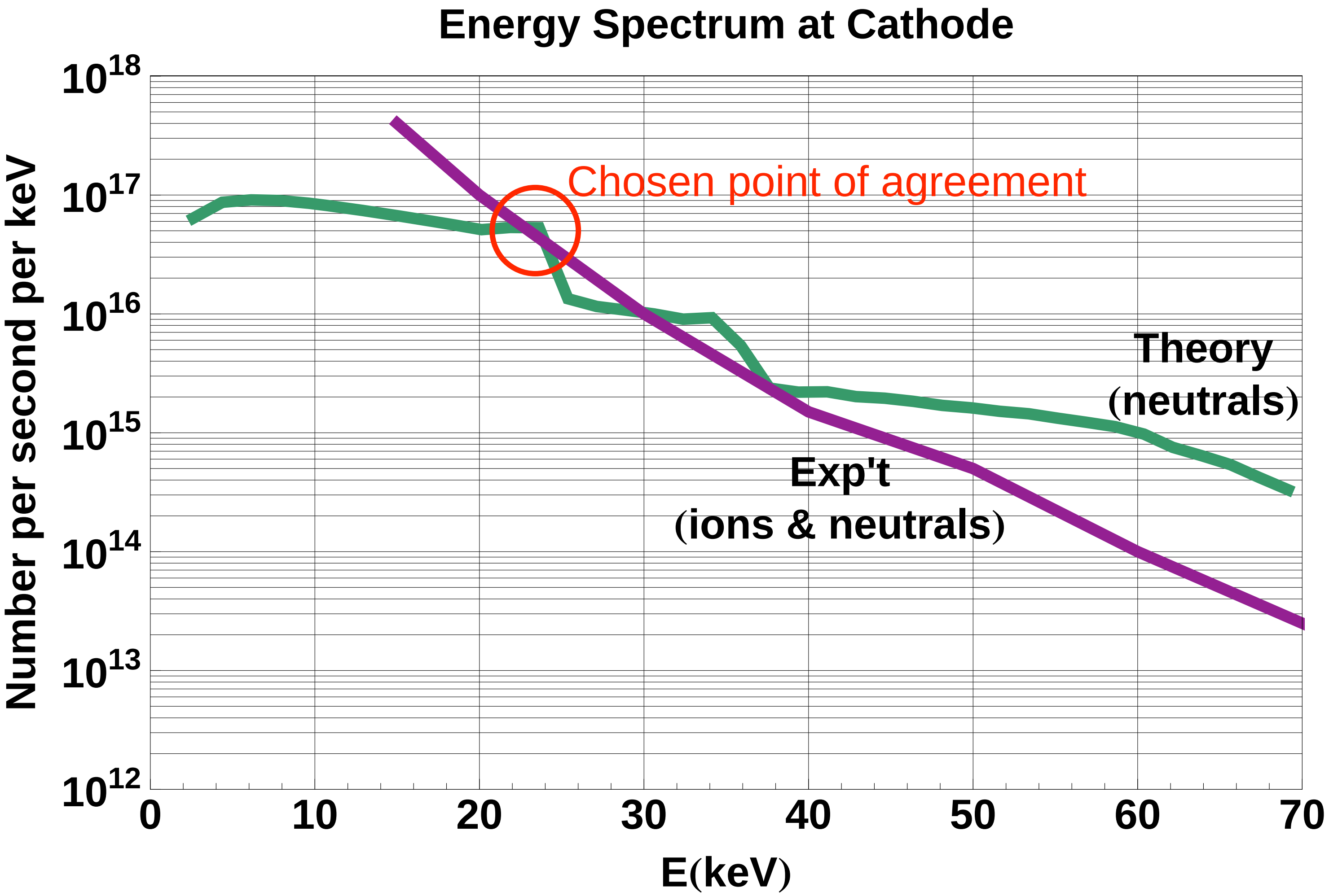
Typical Ion Energy Spectra at Cathode Show Peaks from Full-Energy Ions Passing through Cathode

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^+



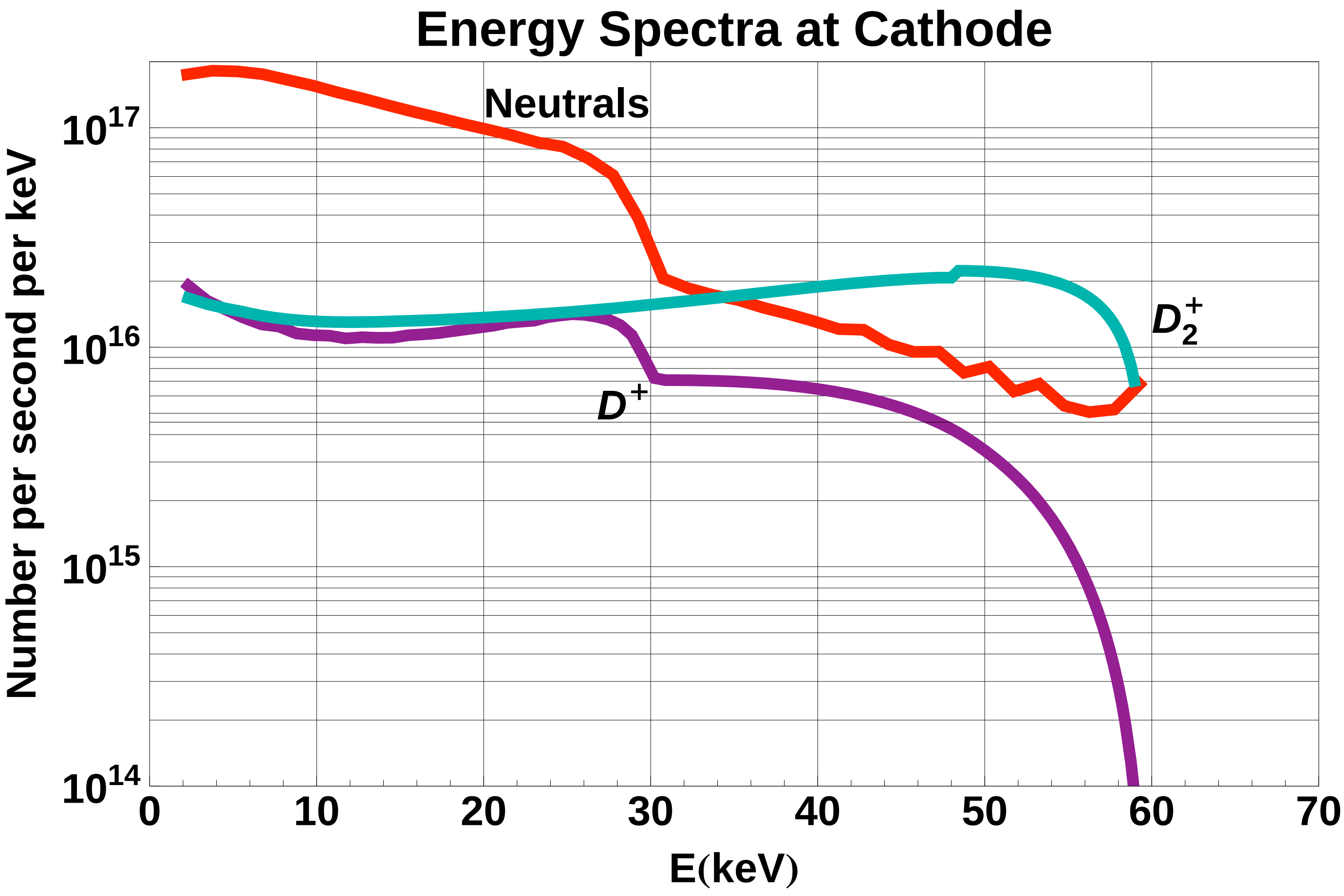
Theoretical Neutral Energy Spectrum at Cathode Agrees Well with Measured Spectrum of Reacting Neutrals and Ions

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



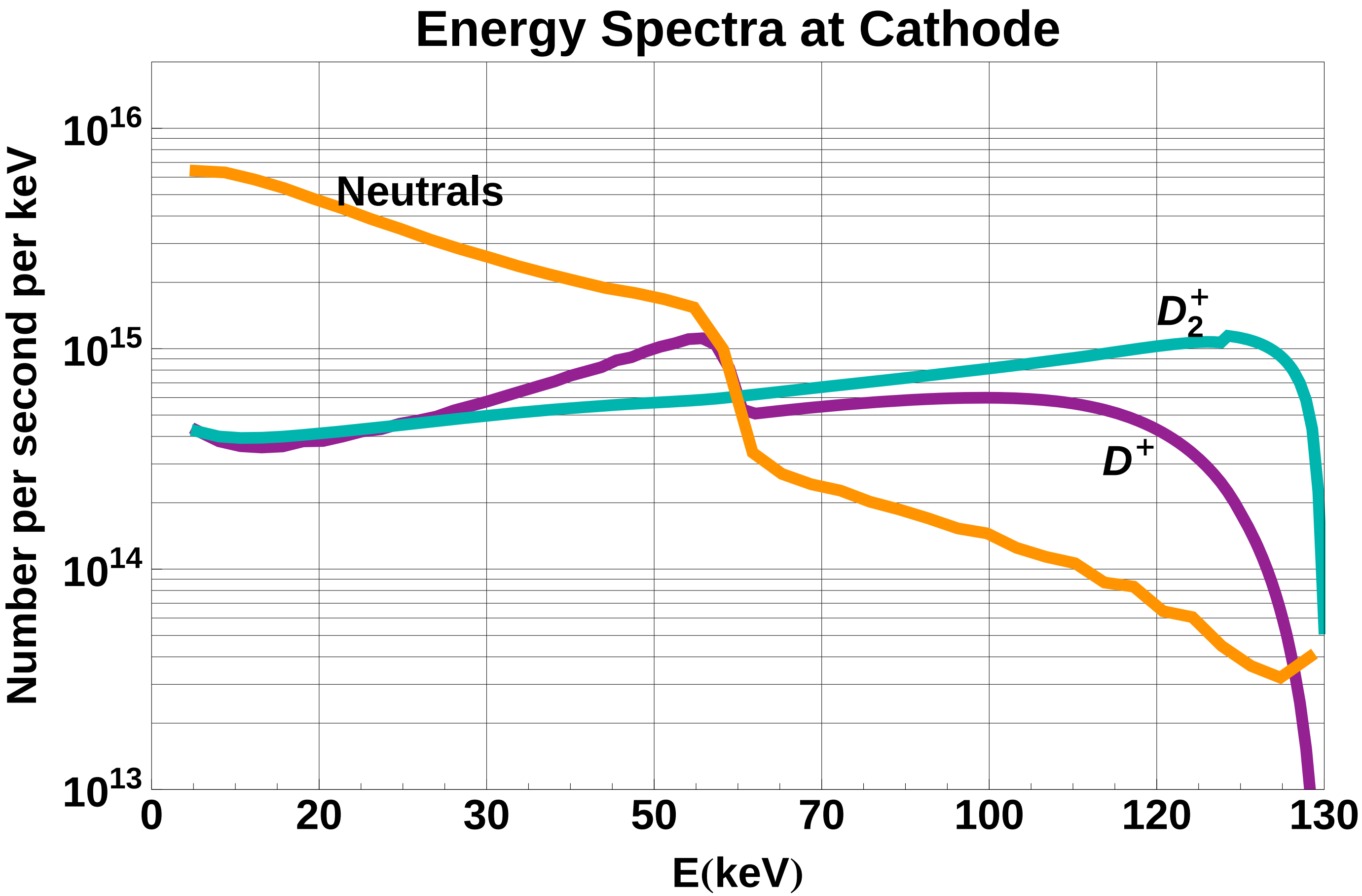
Theoretical Neutral and Ion Energy Spectra at Cathode Depend on Voltage in a Complicated Way

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



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^+



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^+

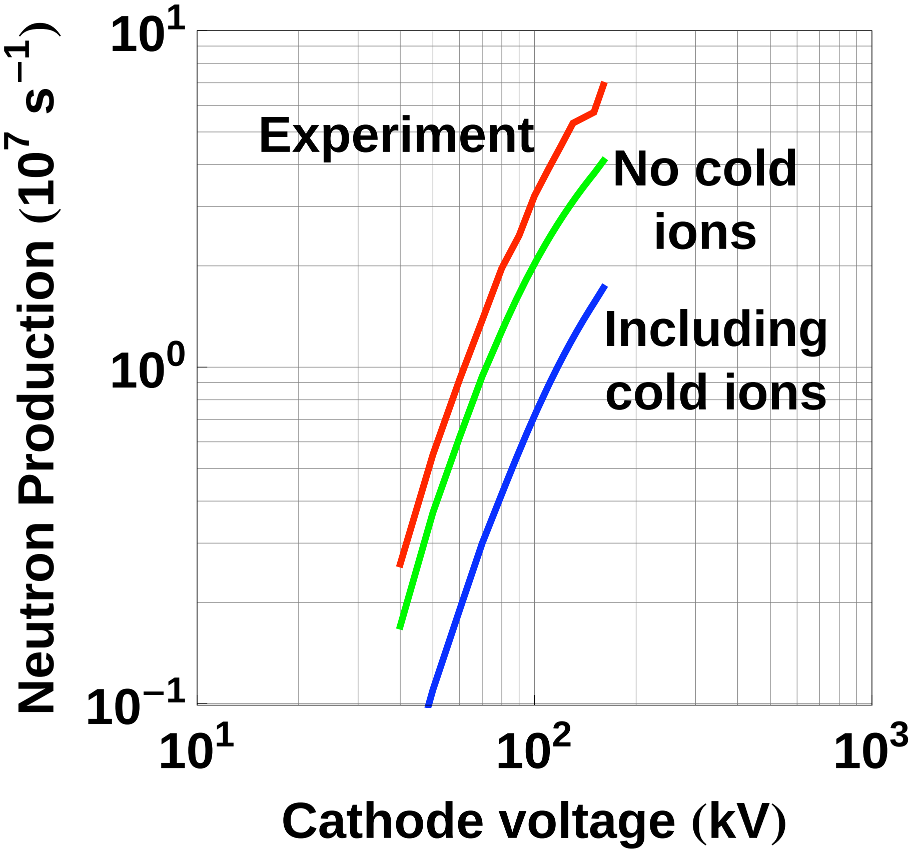
Units of 10^7 n/s	Neutrals[†]	Ions	Fusion
60 kV	2.3	1.7	4.0
100 kV	3.3	4.3	7.6
140 kV	3.6	6.8	10.4

[†] "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:*
  - G.A. Emmert and J.F. Santarius, “Atomic and Molecular Effects on Spherically Convergent Ion Flow I: Single Atomic Species.”
  - G.A. Emmert and J.F. Santarius, “Atomic and Molecular Effects on Spherically Convergent Ion Flow II: Multiple Molecular Species.”
  - http://fti.neep.wisc.edu/pdf/fdm1369.pdf
    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, p-^{11}B) and ionization (He^+, 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.