Modeling Inertial-Electrostatic Confinement Devices in the Moderate Mean-Free-Path Regime

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Objectives and Status

- Objective: *Model inertial-electrostatic confinement devices in order to optimize fusion reaction rates.*
- Status: *Most of the D/He atomic physics database and many of the IEC physics models are in place, but significant work remains to be done.*
- Immediate objective: *Describe models and discuss several issues related to IEC modeling, particularly in the physics regime where mean free paths are on the order of device dimensions.*

Basics of IEC Modeling in the Moderate Mean-Free-Path Regime

- Radial electrostatic potential profile will be nearly Child-Langmuir (balancing ion flow with adiabatic electrons), accelerating ions inward and electrons outward.
- Average ion will make only a few radial passes before being absorbed by the inner grid or undergoing charge exchange or ionization.
  - ➢ Ionization will drain a small amount of energy from an ion, and will create an ion-electron pair that will contribute to the measured current.
  - ➢ Charge exchange will create a hot neutral plus a cold ion that will subsequently be accelerated by the electrostatic potential.
- Sputtering and secondary electron emission can also be important.

Many Atomic Physics Reactions Must Be Included

Fitting functions and data input directory

Neutral-neutral and ion-neutral elastic collisions

Charge exchange

- H^+ charge-exchange with H^0 (G)
- H^+ charge-exchange with H_2^0 (G)
- H^+ charge-exchange with He^0 (G)
- H^+ charge-exchange with He^+ (G)
- He^+ charge-exchange with H^0 (G)
- He^+ charge-exchange with He^0 (G)
- He^+ charge-exchange with He^+ (G)
- Combined H^+ charge-exchange plots
- Combined H^+ and He^+ charge-exchange plots

Dissociation

- H^0 ionization and dissociation of H_2^0 (G)
- H^+ ionization and dissociation of H_2^0 (G)
- He^+ ionization and dissociation of H_2^0 (G)
- e^- ionization and dissociation of H_2^0 (G)

Ionization

- H^0 ionization of H_2^0 (G)
- H^+ ionization of H^0 (G)
- H^+ ionization of H_2^0 (G)
- H^+ ionization of He^0 (G)
- H^+ ionization of He^+ (G)
- Combined H^+ ionization plots
- He^+ ionization of H^0 (G)
- He(2s1) Penning ionization of H^0 (G)
- He^+ ionization of He^0 (G)
- He^+ ionization of He^+ (G)
- He^{+2} ionization of He^0 (G)
- He^{+2} double ionization of He^0 (G)
- Combined He^+ and He^{++} ionization plots
- e^- ionization of H^0 (G)
- e^- ionization of H_2^0
- e^- ionization of He^0
- e^- ionization of He^+
- Combined monoenergetic e^- ionization cross-section plots
- Combined Maxwellian e^- ionization reaction rate plots

Secondary electron emission

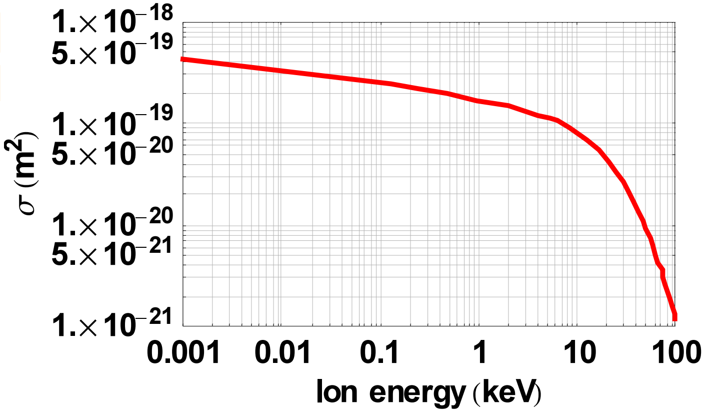
Sputtering

Example: D^+ D^0 Charge Exchange as Implemented in Mathematica Notebook

- *σ*
  - **Chebyshev fit**

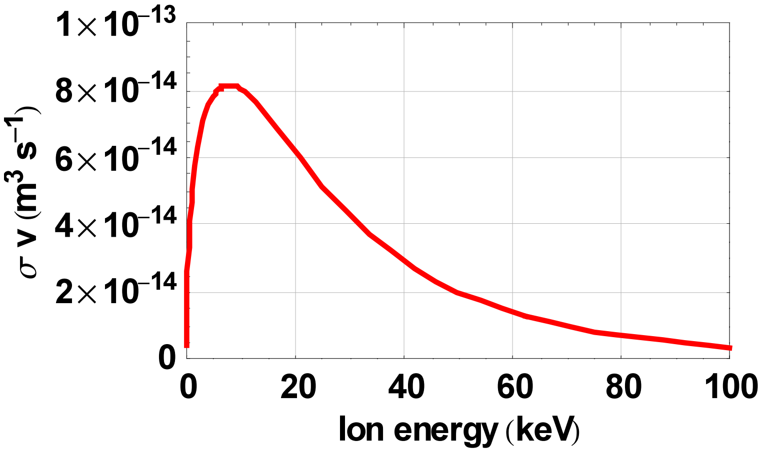
```
lsCxXsHp1H0toH0Hp1Cheb =
  Import[dataDir <> "cx_xs_H+H0toH0H+_cheb.dat"][[{3, 4}]] // Flatten
{-72.6656, -5.49142, -3.42948, -1.98377, -0.878009,
  -0.198932, 0.0837431, 0.121252, 0.0827182, 0.12, 630000.}

Table[{Eh, CxXsHp1H0toH0Hp1Cheb[Eh]}, {Eh, 0.1, 0.3, 0.02}] //
  TableForm
0.1       2.498×10^-19
0.12      2.43636×10^-19
0.14      2.38221×10^-19
0.16      2.33399×10^-19
0.18      2.29062×10^-19
0.2       2.25129×10^-19
0.22      2.21537×10^-19
0.24      2.18239×10^-19
0.26      2.15194×10^-19
0.28      2.12371×10^-19
0.3       2.09743×10^-19
```



- *σ* **v**

```
CxSvHp1H0toH0Hp1Cheb[amu_, EkeV_] =
  CxXsHp1H0toH0Hp1Cheb[EkeV] * v[EkeV, amu];
```



Data comes from the IAEA AMDIS database.

Specifying Deuterium Fraction, Edge Plasma Properties, Grid Transparency, Voltages, and Device Dimensions Gives Key Parameters

Dimension, density, and temperature setup

Define deuterium density fraction, fD; rest assumed to be ^{3}He, fraction fHe. Assumed ioniza
fraction fz. The "average" ion mass and charge are used.

```
fD = 1.0;
fHe = 1 - fD;
fz = 10^-4;
```

Grid transparency

$\gamma_g = 0.92;$

$P_g = 2.0 * 10^{-3};$

$r_a = 0.25;$

$r_c = 0.05;$

$r_{ch} = 0.455;$

$z_{ch} = 0.65;$

$T_e = T_i = 3 * 10^{-3};$

$T_{wall} = 300\ \mathrm{Kelvin};$

$V_c = -80;$

$V_a = 0;$

Singly ionized He assumed

```
zHe = 1;
```

$\{\mathrm{mIon} = 2 * \mathrm{fD} + 3 * \mathrm{fHe},\ m_i = \mathrm{mIon} * m_p,$
$\ \mathrm{zIon} = \mathrm{fD} + \mathrm{zHe} * \mathrm{fHe},\ z_i = \mathrm{zIon} * q_i\}$

$\{2.,\ 3.34\times10^{-27},\ 1.,\ 1.6\times10^{-19}\}$

Tables

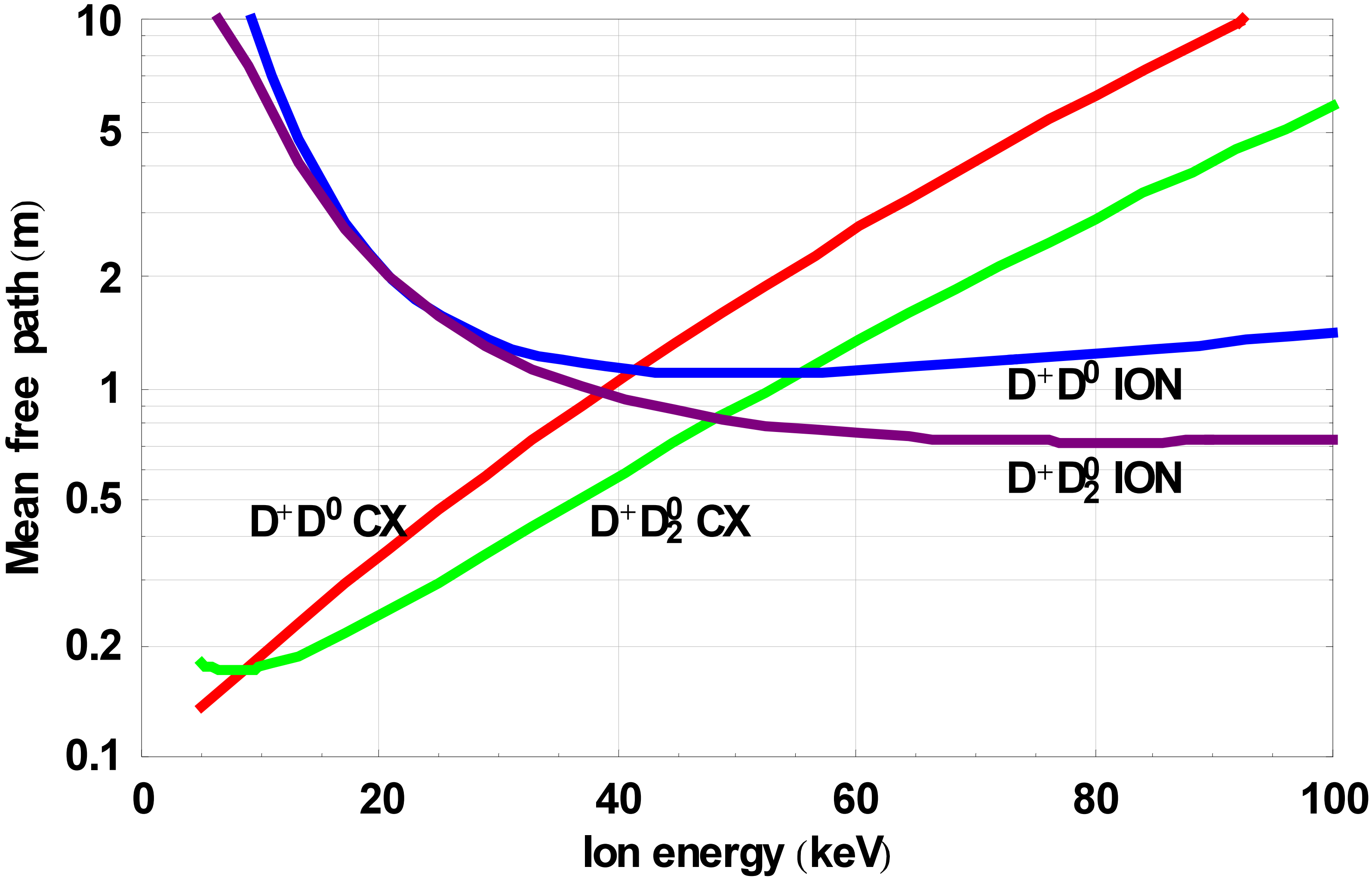
```
TableForm[Transpose[{lsPropNames, lsProperties, lsPropUnits}]] // N
```

```
D fraction                1.
3He fraction              0.
Ionization fraction       0.0001
Grid transparency         0.92
Average mass              2.               amu
Ave. ion charge           1.
Neutral density           6.43268×10^19    m^-3
Source region plasma
   n_e                    6.43268×10^15    m^-3
   n_i                    6.43268×10^15    m^-3
   T_e                    0.003            keV
   T_i                    0.003            keV
```

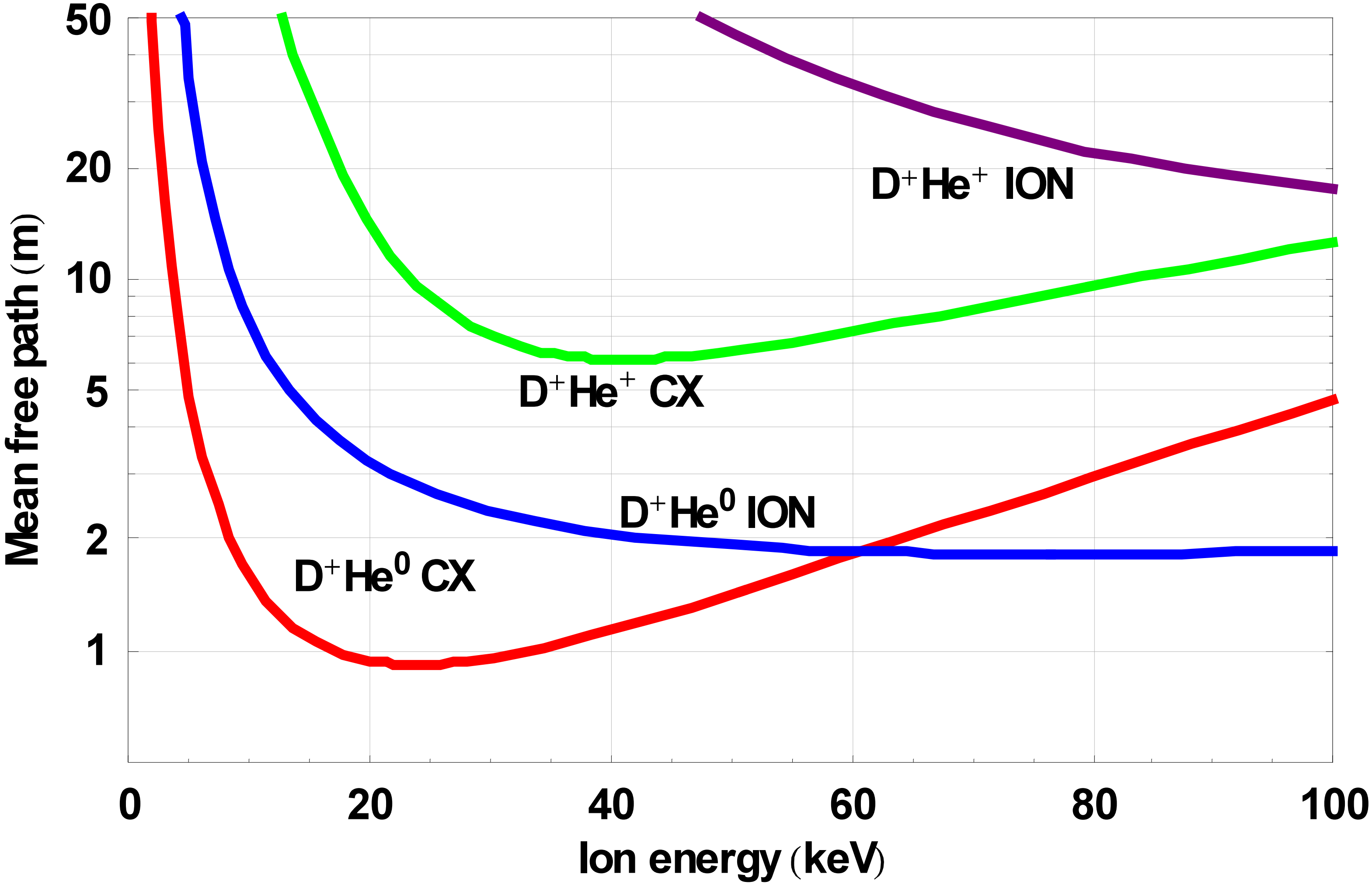
$\mathrm{plasmaParamsHz}[\mathrm{mIon},\ 0,\ 5/3,\ n_{ea},\ n_{ia},\ T_e,\ T_i,\ \mathrm{zIon}]$

```
CoulombLog                          20.
DebyeLength                         0.000160484     m
electronCollisionFrequency          72032.4         s^-1
electronPlasmaFrequency             7.19938×10^8    Hz
electronThermalVelocity             1.02972×10^6    m/s
ionAcousticVelocity                 15500.          m/s
ionElectronCollisionFrequency       830.456         s^-1
ionPlasmaFrequency                  1.19145×10^7    Hz
ionThermalVelocity                  16963.7         m/s
```

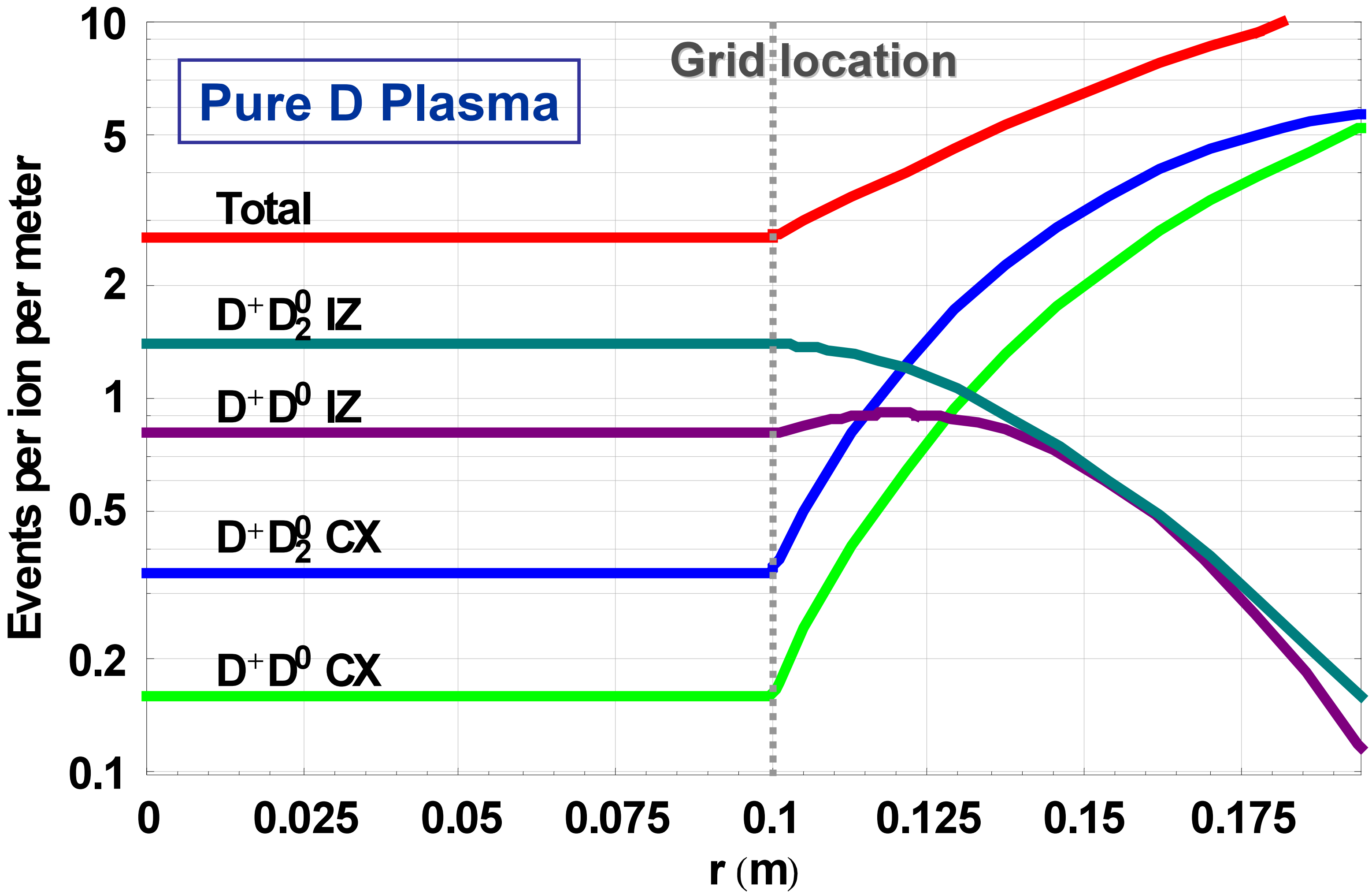
Mean Free Paths for D^+ Interacting with D^0 and D_2^0 Indicate Low-Energy CX Dominates



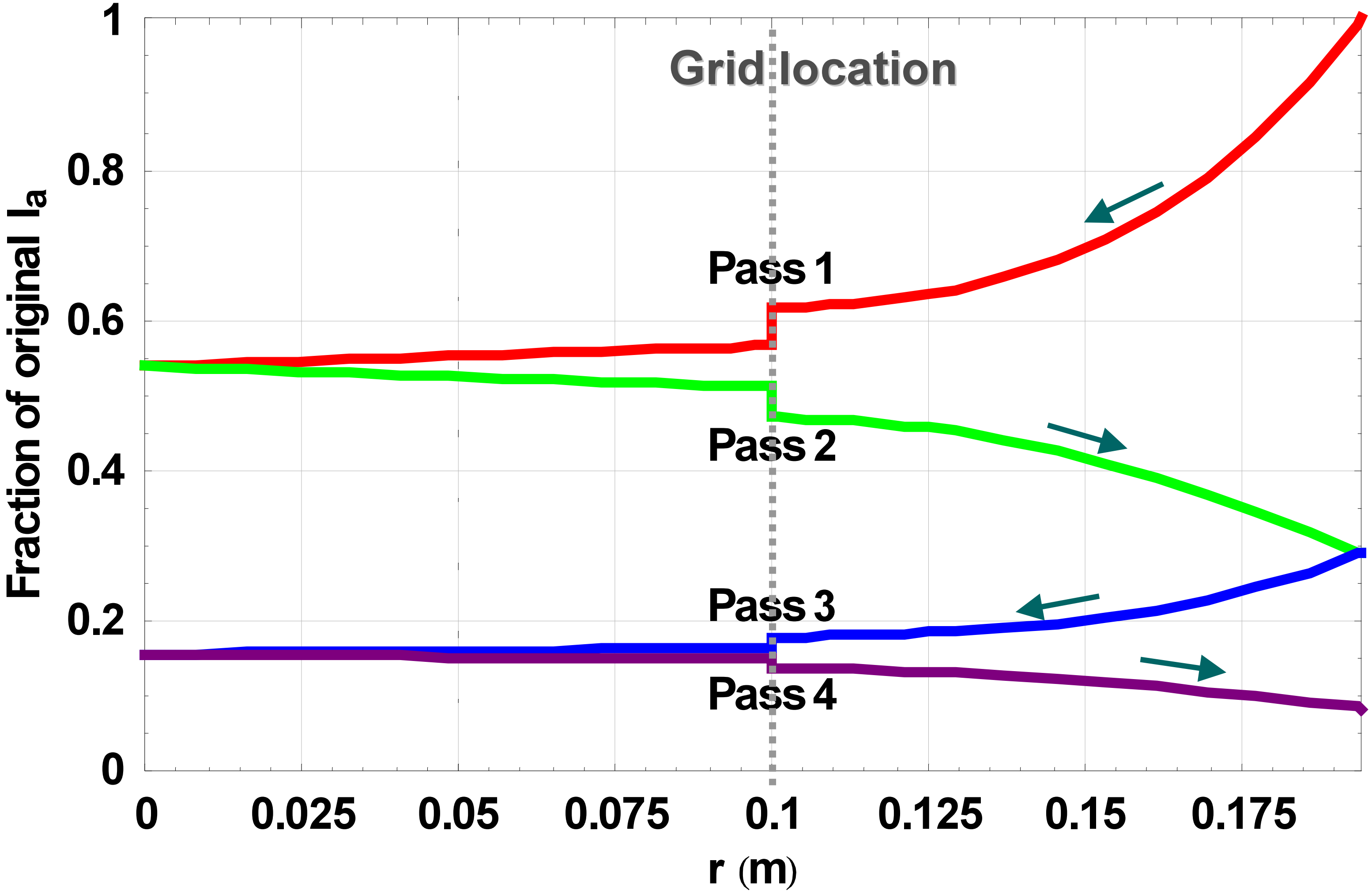
Mean Free Paths for D+ Interacting with He0 and He+ Are Much Longer than Device Dimensions



D^+ Charge-Exchange and Ionization Rates vs Radius Indicate CX Importance at Large Radius

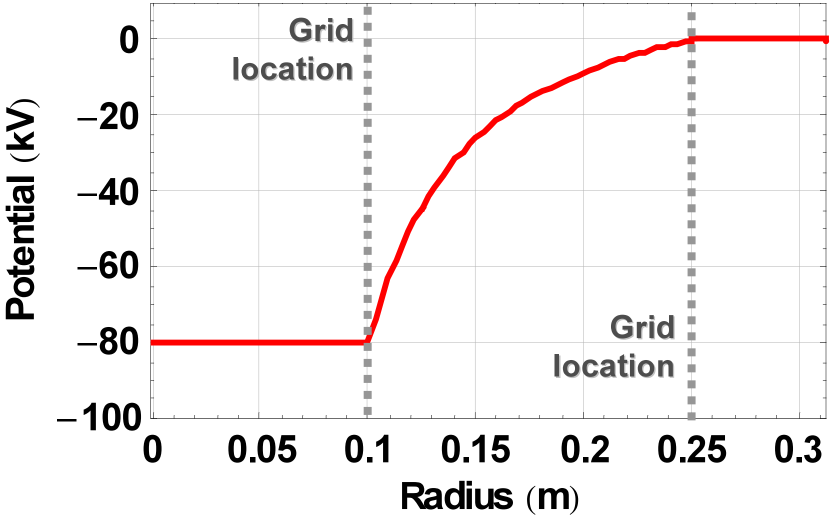


Initial Ion Current Decreases as Ions Oscillate Radially

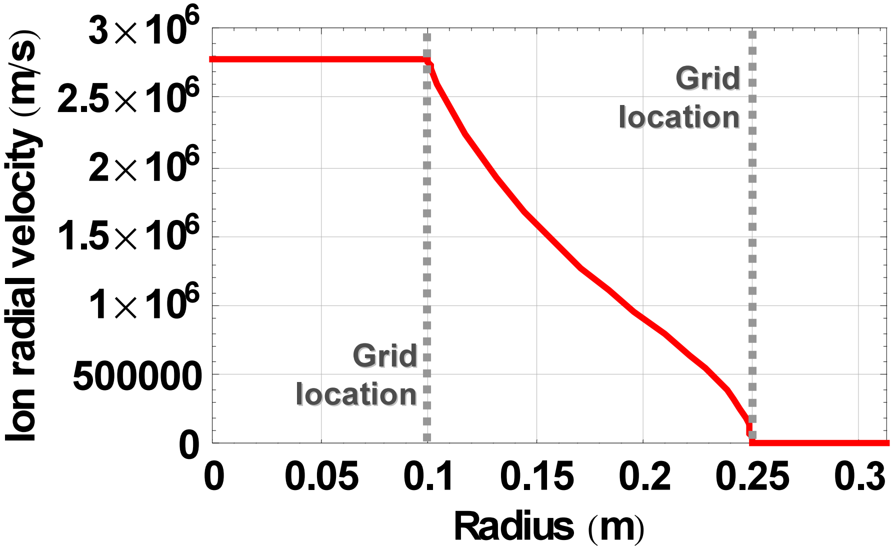


Child-Langmuir Electrostatic Potential Profile Is Calculated and Used to Generate Radial Velocity Profile

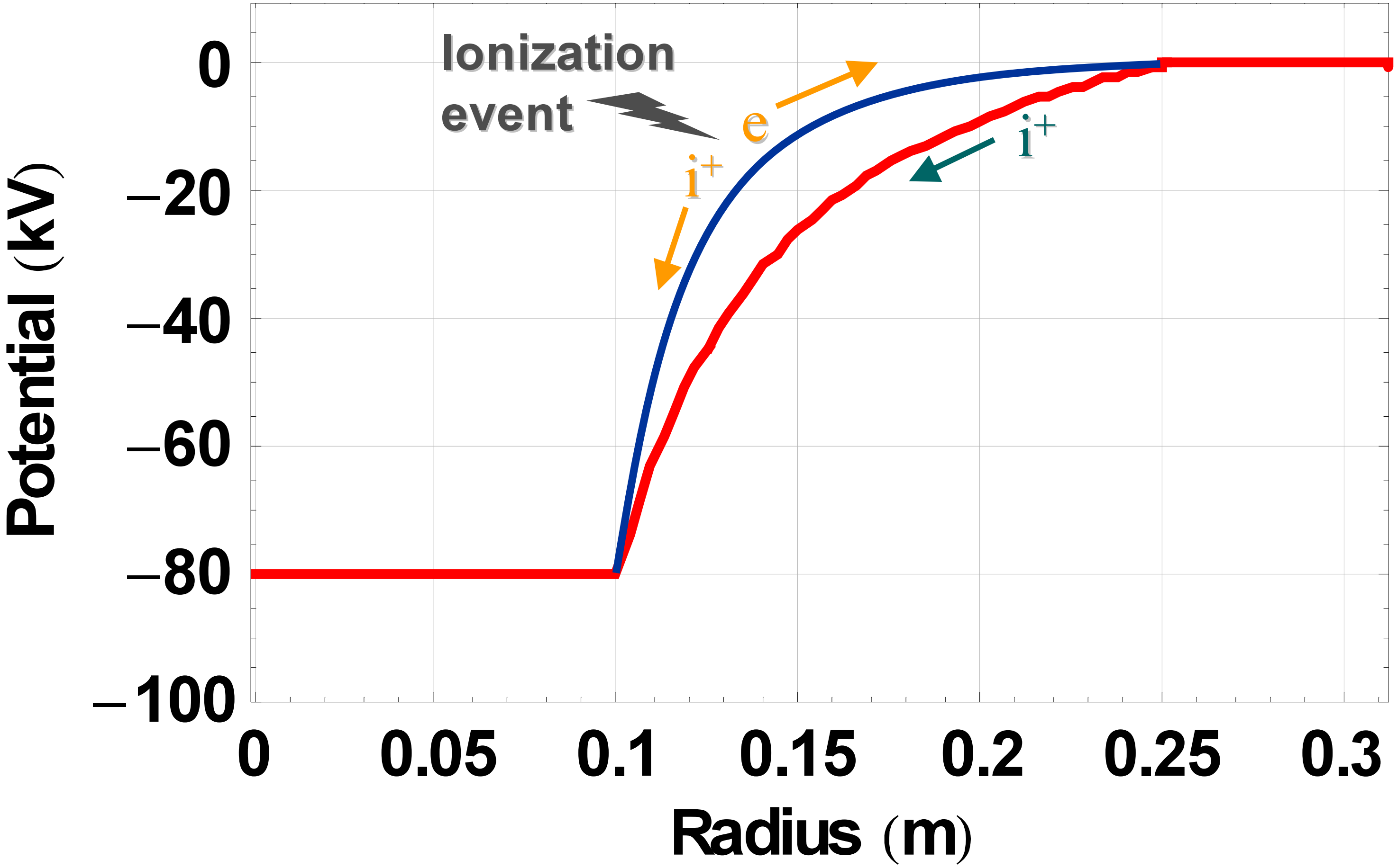
Child-Langmuir radial potential profile



Resulting radial velocity profile



Electrostatic Potential Profile Should Steepen Due to Atomic-Physics Processes



- Note: steepened curve shown is conceptual, not calculated, and this effect is not presently included in the calculations.

Several Important Pieces of the Physics Puzzle Remain to Be Implemented

- Converged-core physics
- Projectile-target fusion reactions
  - ➢Charge-exchange neutrals reacting with neutral background gas
  - ➢Radially moving ions reacting with background gas
  - ➢Radially moving ions reacting with other radially moving ions outside of the core
- Electron currents due to ionizations

Summary

- The atomic-physics foundations for modeling IEC devices in the moderate mean-free-path regime have been implemented.
- Models for the fusion reaction rates have been identified, and incorporating them into the code has begun.
- Benchmarking the code against experiments and identifying techniques for optimizing proton and neutron production will begin in the near future.