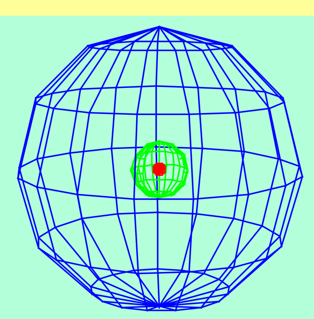
Modeling UW Gridded Inertial-Electrostatic Confinement Fusion Experiments

John F. Santarius, *Fusion Technology Institute*, *University of Wisconsin*

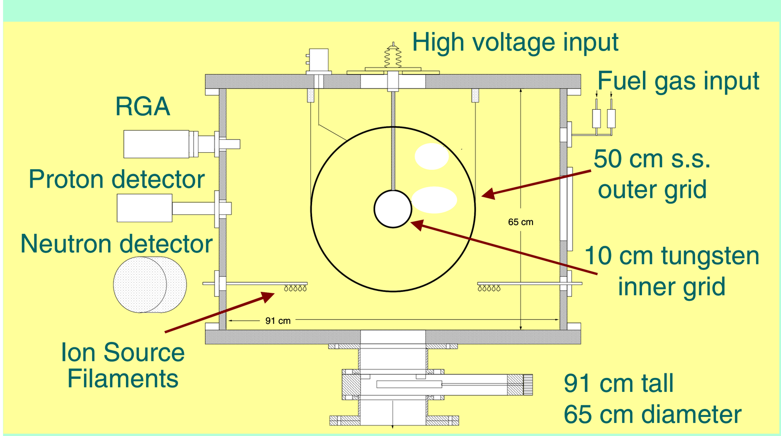
Abstract

Gridded inertial-electrostatic confinement (IEC) devices accelerate and focus ions using voltage differences between nearly transparent concentric grids in spherical or cylindrical geometry. High voltages can be produced relatively easily between the grids, giving the accelerated ions energies (>50 keV) suitable for producing fusion of advanced fuels, such as D-^{3}He. The resulting fusion products potentially can produce radioisotopes useful for positron emission tomography and other applications. Research will be reported on the modeling effort for the UW gridded IEC device and diagnostics, including comparison to experiments. The following physics effects will be discussed: charge exchange; ionization; reaction rates for hydrogen and helium isotopes; spherical Child-Langmuir radial electrostatic potential profile; attenuation by the cathode grid; multiple-pass ion and electron production due to charge exchange and ionization of the initial current; subsequent iterations of the resulting currents of particles; electron currents due to ionization, thermionic emission, and secondary electron emission; and fusion reactions due to several phenomena in the plasma.

Inertial-Electrostatic Fusion Depends on Creation of a Radial Electrostatic Well and Spherically (or Cylindrically) Convergent Ion Flow



1. Inner grid (cathode) is biased to a high negative potential.
2. Fuel gas flows into the chamber and pressure is maintained.
3. Positive ions are created around the outer grid (anode).
4. Ions accelerate toward inner grid, gaining fusion-relevant energies.
5. Ions and electrons ionize neutral gas.
6. Ions charge-exchange with neutrals, fuse with other ions or neutrals, or hit grids.
7. Charge-exchange neutrals fuse with background gas.
8. Particle detectors monitor reaction rates.

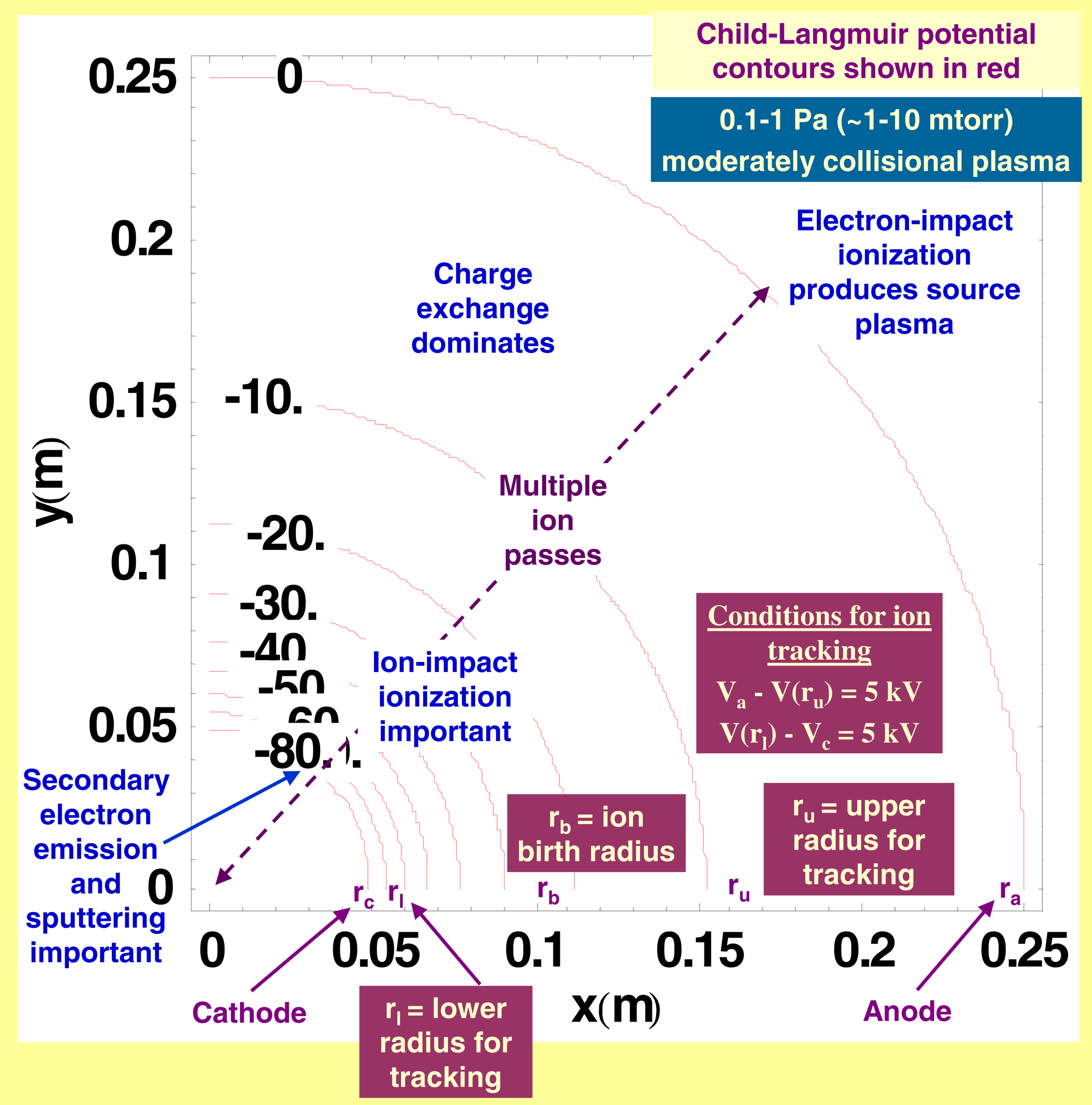


Basics of IEC Model

- UW code includes the key atomic physics and fusion reaction rates for deuterium and helium-3.
  - Species included are D^0, D^+, D_2^0, D_2^+, He^0, He^+, He^{++}.
  - Calculations presented here are for deuterium fuel only.
- 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.
- Sputtering, secondary electron emission, and thermionic electron emission can be important.
- 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.
- Resulting ions and charge-exchange neutrals can undergo fusion with background gas or oscillating ions.
- Converged core physics remains uncertain and is not yet implemented.

Atomic Physics Effects Dominate the Present Operating Regime

Only pure deuterium/electron plasmas have been modeled so far.



Many Atomic Physics Reactions Have Been Implemented

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

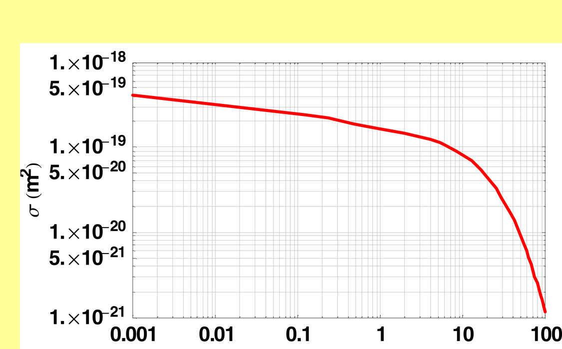
- H^0 ionization of H_2^0(G)
- H^+ ionization of H^0(G)
- H^+ ionization of H_2^0(G)
- H^+ ionization of He^0(G)
- H^+ ionization of He^+(G)
- Combined H^+ ionization plots
- He^+ ionization of H^0(G)
- He(2s1) Penning ionization of H^0(G)
- He^+ ionization of He^0(G)
- He^+ ionization of He^+(G)
- He^{+2} 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 a Mathematica™ Notebook

- Data comes from the IAEA AMDIS database http://www-amdis.iaea.org/amdis.htm



- H^+ charge-exchange with H^0(G)
  - σ
  - Chebyshev fit

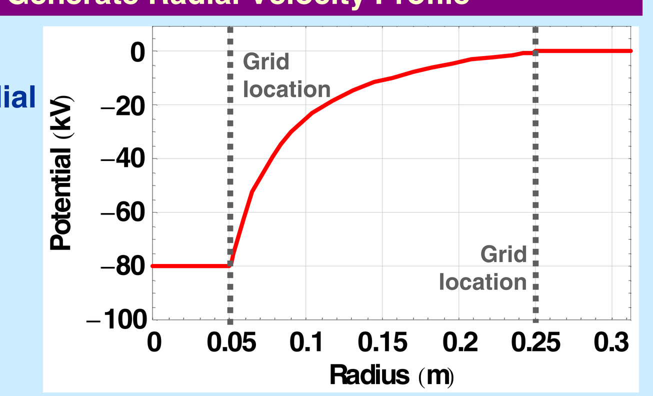
```
In[300]:= lsCxXsHp1H0toH0Hp1Cheb =
    Import[dataDir <> "cx_xs_H+H0toH0H+_cheb.dat"][[{3, 4}]] //
     Flatten
Out[300]= {-72.6656, -5.49142, -3.42948, -1.98377, -0.878009,
    -0.198932, 0.0837431, 0.121252, 0.0827182, 0.12, 630000.}

In[301]:= CxXsHp1H0toH0Hp1Cheb[amu_, EkeV_] =
    10^-4 Cheb[lsCxXsHp1H0toH0Hp1Cheb, EkeV / amu];
```

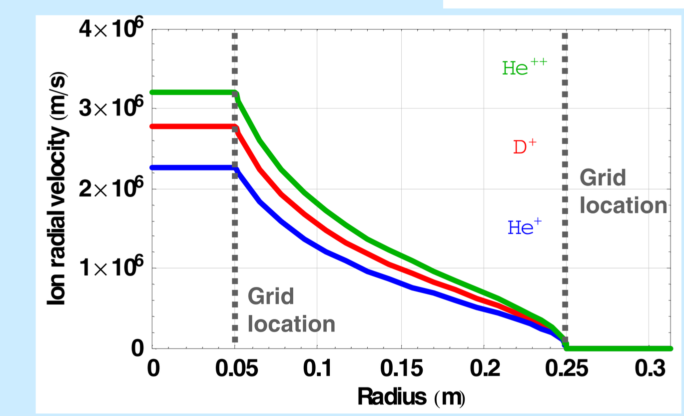
Analysis Tracks Deuterons and Electrons during Multiple Passes through Core

UW Experiment Key Modeling Input Parameters	
Fuel	D only
Neutral gas pressure	0.27 Pa (2 mtorr)
Neutral gas density	6.4 x 10^{19} m^{-3}
Anode radius	0.25 m
Cathode radius	0.05 m
Grid potential difference	80 kV

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

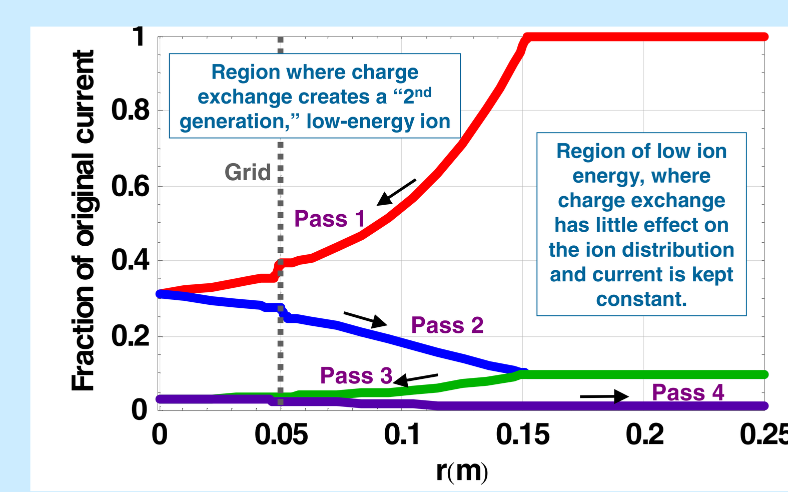
Child-Langmuir radial potential profile





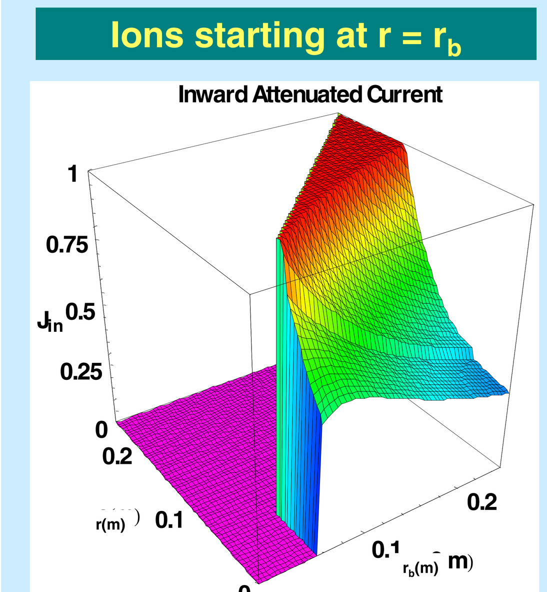
Resulting radial velocity profile

Charge Exchange "Attenuates" Initial Ion Current as Ions Oscillate Radially

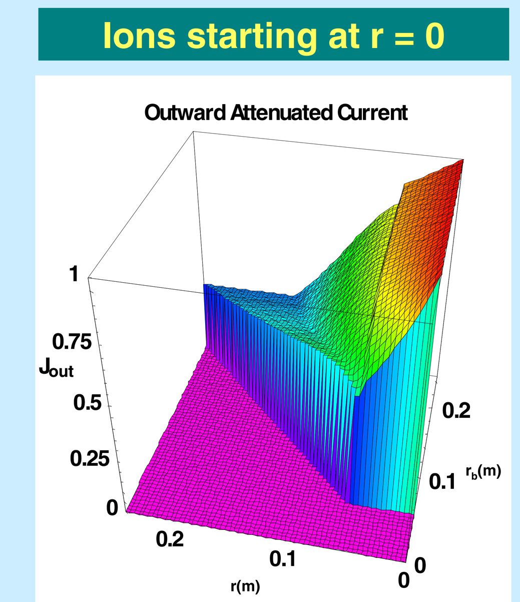


Ion-Current at Radial Position r Can Be Calculated for Arbitrary Birth Position r_b

Ions starting at $r = r_b$



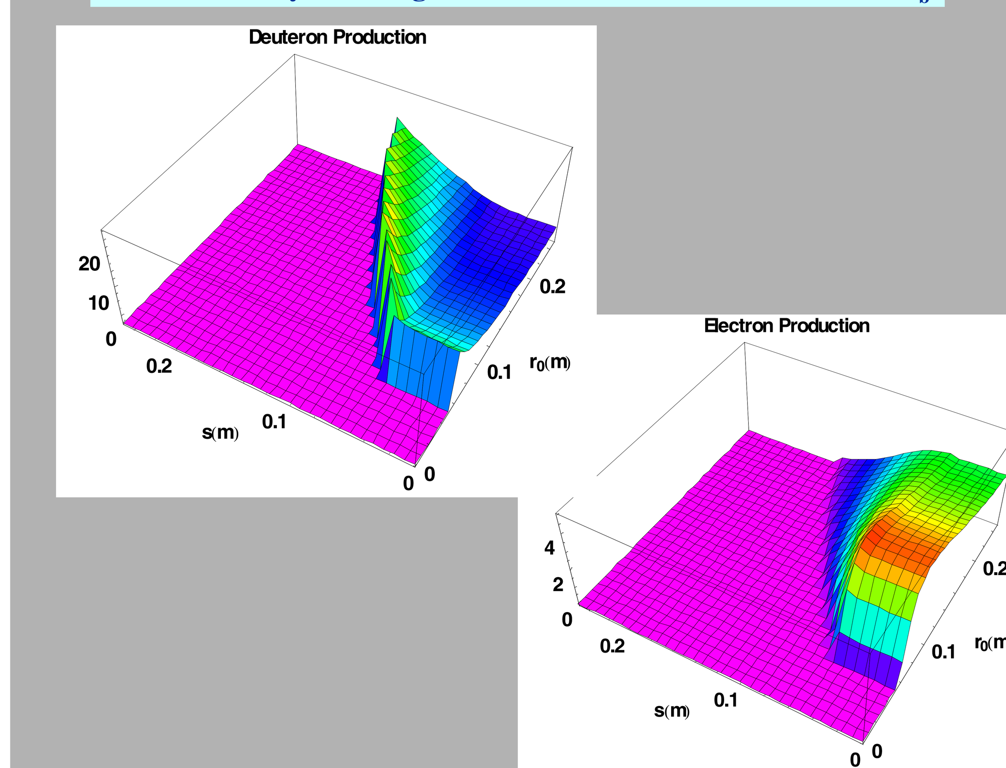
Ions starting at r = 0



Results

"Production" Due to Charge Exchange Plus Ionization Can Be Substantial

- Production by second-generation ions that started at radius r_b



Two-Generation Calculation of Proton Production Falls Short of Experimental Value

- Experimental D-D proton production at 80 kV and 30 mA is 2x10^7 protons/s
- Two-generations of the present computational method give ~10^6 protons/s total
  - Main contribution stems from charge-exchange neutrals and radially moving ions reacting with background gas.
  - Converged-core and counter-streaming-ion fusion terms give very small contributions.

Summary

- Gridded IEC device models have been developed.
  - Atomic physics
  - Child-Langmuir potential profiles
  - Fusion reactions
- Fusion product production as a function of radius has been estimated.
  - Using only the initial current plus first and second generations of created ions gives values ~20 times lower than those found in the UW IEC experiments.
  - Preliminary indications are that following several more generations of ion production may reconcile these differences, but much work remains.
- Neglected effects, particularly embedded ions, can be important. Work on including these is in progress.