IEC Device Core Physics Explorations*

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IEC Core Explorations for Spherically Converging Ions in the Presence of Grid Wires and Background Gas

- Radial convergence of neutrals and positive ions.
- Positive space-charge near the origin due to converging ions.
- Electrostatic potential confinement of electrons and negative ions.
- Time dependent phenomena related to the filling of the electrostatic potential well by electrons and negative ions.
- Creation of D^- and D_2^-, the latter by electron attachment to excited rotational states of D_2^0.
- Recombination of electrons and ions within the core region.

Early Analyses of IEC Core Convergence Predicted Potential Structures

- R.L. Hirsch, "Inertial-Electrostatic Confinement of Ionized Fusion Gases," *Journal of Applied Physics* **38**, 4522 (1967); erratum, **38**, 4047 (1968).

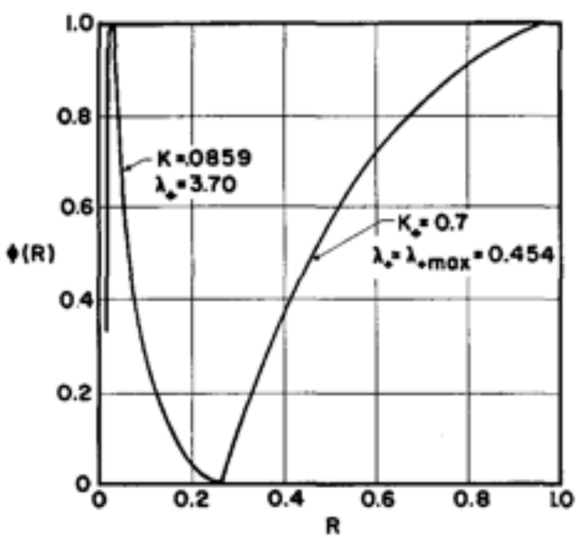
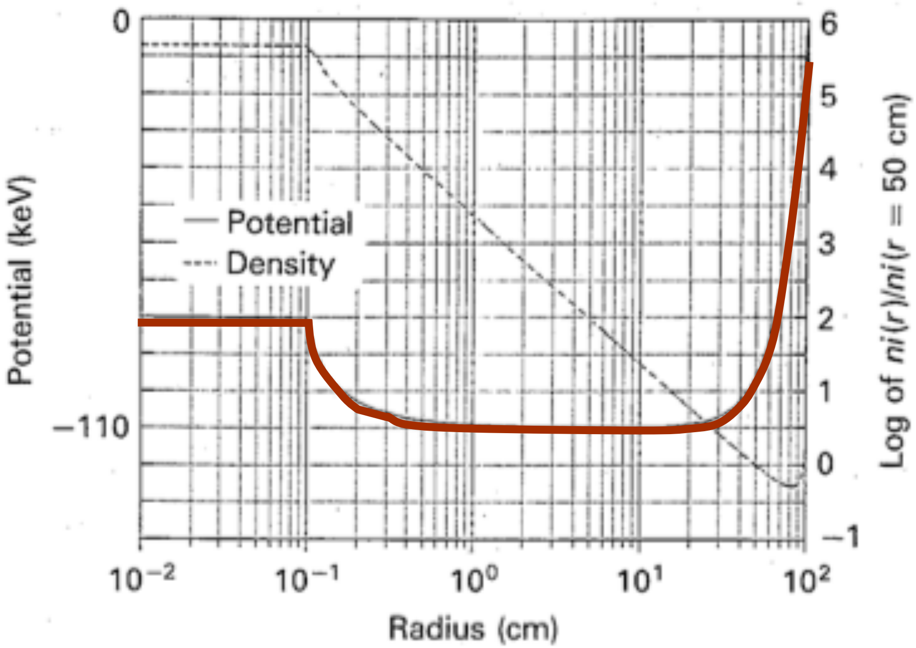


FIG. 1. Potential distribution for $K_{+}=0.7$ and $\lambda_{+}=\lambda_{+max}=0.454$ at the real cathode.

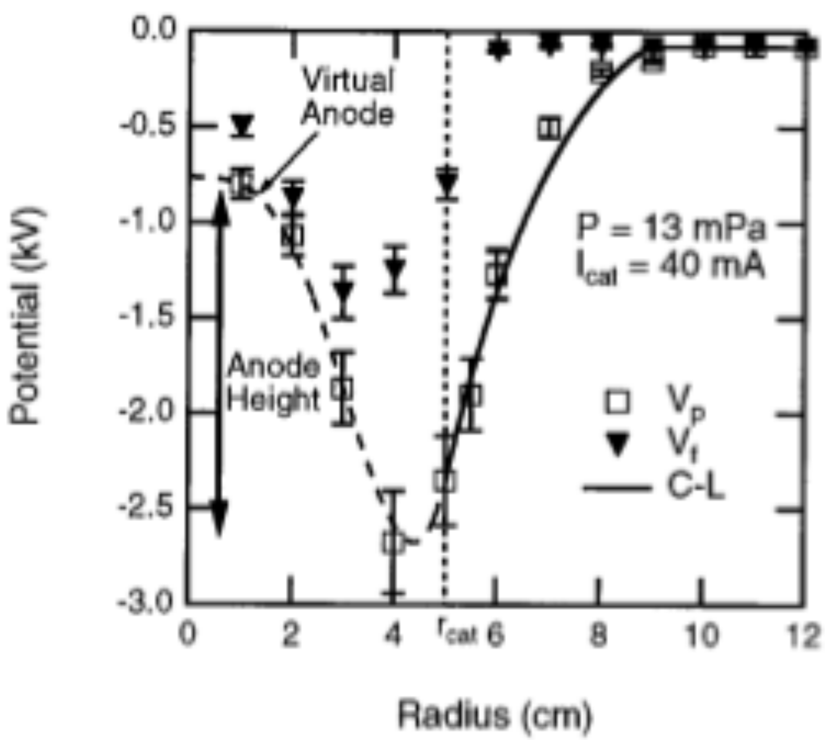
- N.A. Krall, "The Polywell™: a Spherically Convergent Ion Focus Concept," *Fusion Technology* **22**, 42 (1992).



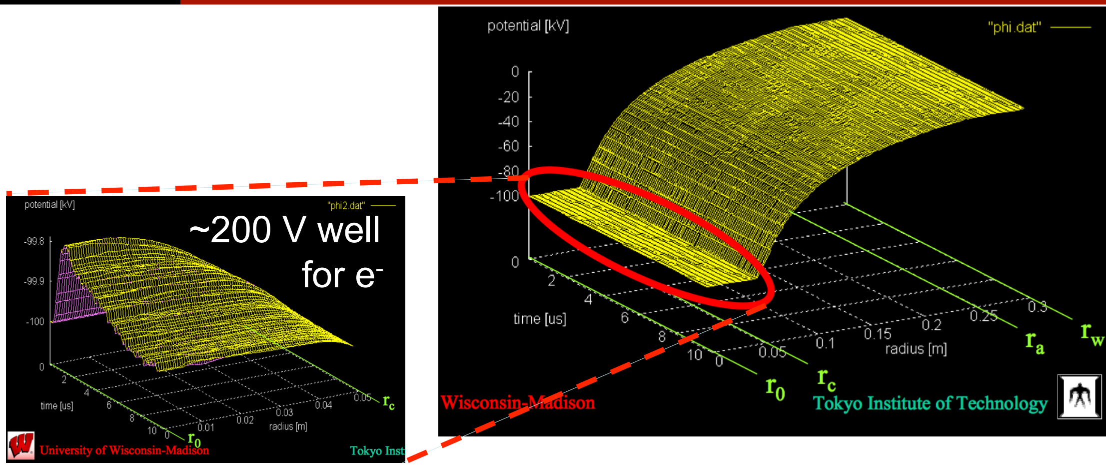
Experimental Measurements by Thorson Indicated a Large Central Virtual Anode

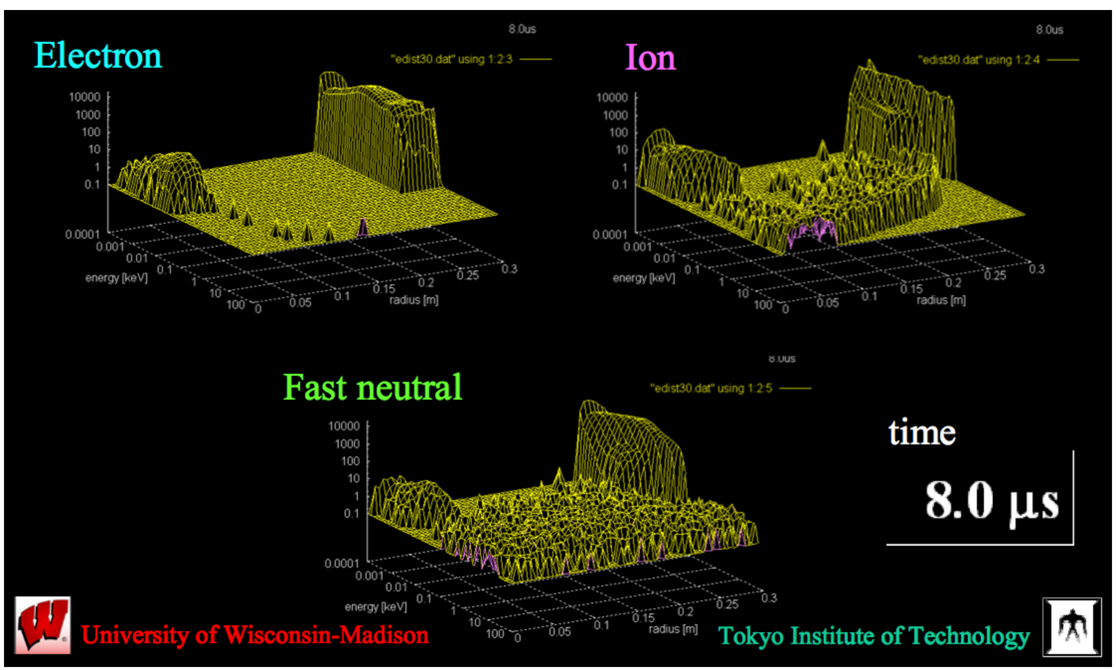
- Measurements were made using a double-probe.
- P = 13 mPa (≈0.1 mTorr)
  V = 5 kV
  I = 40 mA

- T.A. Thorson, R.D. Durst, R.J. Fonck, and L.P. Wainwright, "Convergence, Electrostatic Potential, and Density Measurements in a Spherically Convergent Ion Focus," *Physics of Plasmas* **4**, 4 (1997).



PIC Code Simulation by Tomiyasu Under Different Plasma Conditions Indicated a Small Virtual Anode

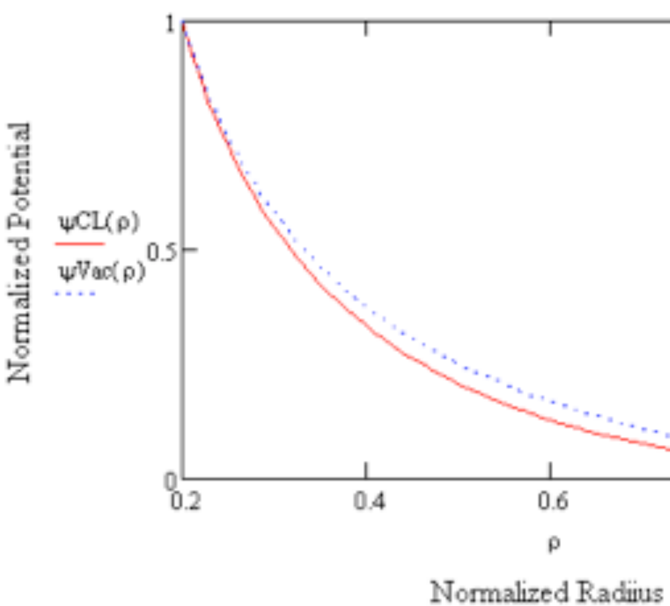




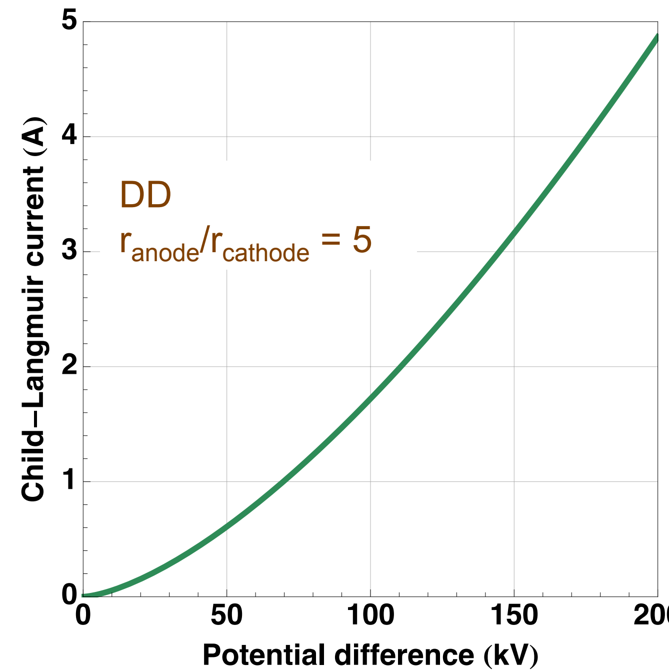
- K. Tomiyasu, J.F. Santarius, and G.L. Kulcinski, "Numerical Simulation for UW-IEC Device," *6th US-Japan IEC Workshop* (Tokyo Inst. of Tech., Yokohama, 21 Oct 2003).
- Used UC-Berkeley's PDS-1 code, modified by R.A. Nebel and K. Tomiyasu
  - 1-D radial, 2-D velocity PIC code
  - Additions to Berkeley version
    - Gridded IEC geometry
    - Atomic processes
    - Collisions with neutral gas
    - Reflecting boundary at origin
    - Fusion reactions
    - Secondary electron energy dependence
- Parameters for case at left, shown after steady-state distributions are reached: r_c=0.05 m, r_a=0.25 m
  P=2 mTorr, V=100 kV, I=5 A

At <<1 A, Typical IEC Device Currents Are Not Space-Charge Limited

- Child-Langmuir (space-charge included) nearly equals vacuum electrostatic potential profiles at low current.
- Parameters for plot below:
  $r_a / r_c = 5$, $I = 10$ mA
- Gil Emmert, "Child-Langmuir Limited Current and Potential Profile in Spherical Gridded IEC Devices," UW FTI Internal Design Memo (15 May 2006).

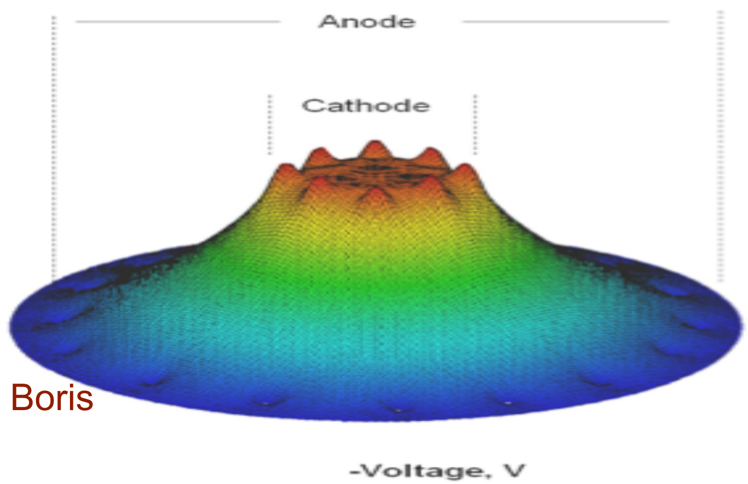


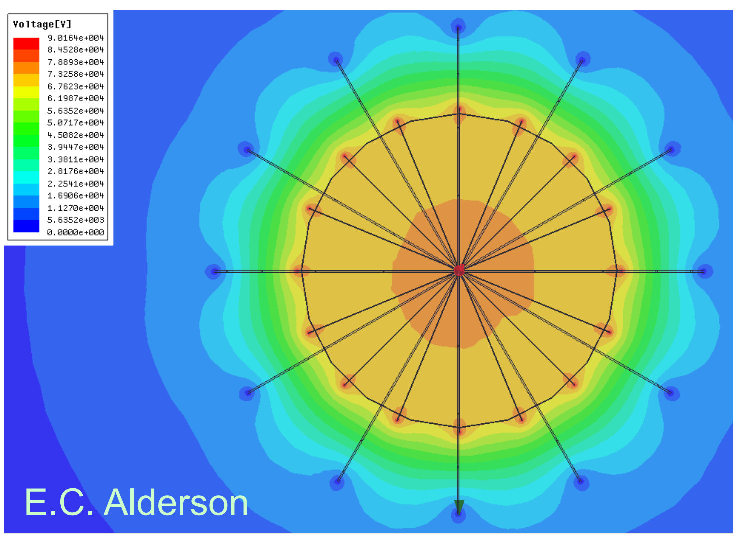
- Child-Langmuir current limit appears in the plot below for one typical IEC case.



- Space-charge effects become more important at low perveance ≡ $I / V^{3/2}$.

Ion Space Charge Inside a Gridded IEC Device's Cathode Will Always Create a Potential Well for Negative Particles

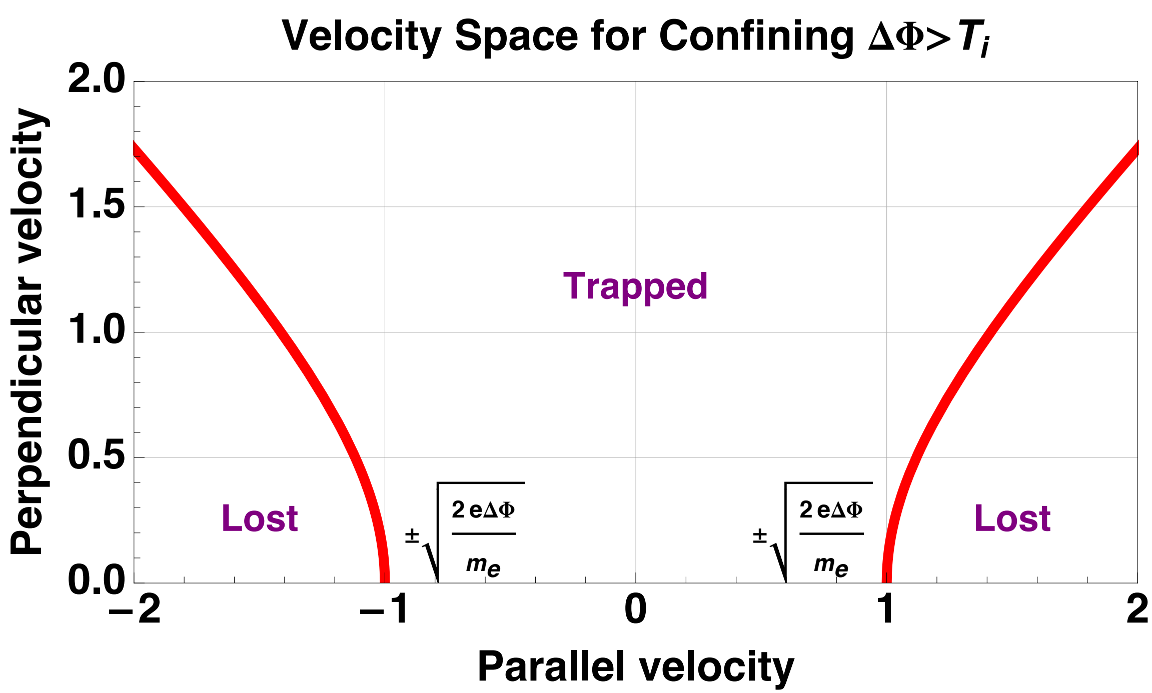




- Plot at left (David R. Boris, UW PhD Thesis, 2009) shows the vacuum electrostatic potential created by discrete wires in cylindrical geometry:
  - Channels formed between grid wires, and
  - Potential peak near origin due to converging ion space charge.
- Spherical geometry will lead to a 3D well that is more difficult to illustrate.
- Plot at left (Eric C. Alderson, UW PhD Thesis, 2012) shows a midplane cut of the vacuum electrostatic potential for an IEC cathode and anode with all longitude wires included plus the two latitude wires above and below the equator.

Well Researched Solutions Exist for Magnetic Mirror End-Plugging by an Electrostatic Potential

- The so-called *Pastukhov problem* has been analyzed in depth:
  - VP Pastukhov; RH Cohen, et al.; F Najmabadi, et al.; VN Khudik
    - See Bibliography slide at end of talk.
- Nominally applicable to Φ >> T, but the analysis works reasonably well for Φ ~ T, however we need the solution for B = 0.



Problem of Calculating the Loss of Electrons Trapped *only* by an Electrostatic Potential Has Been Solved

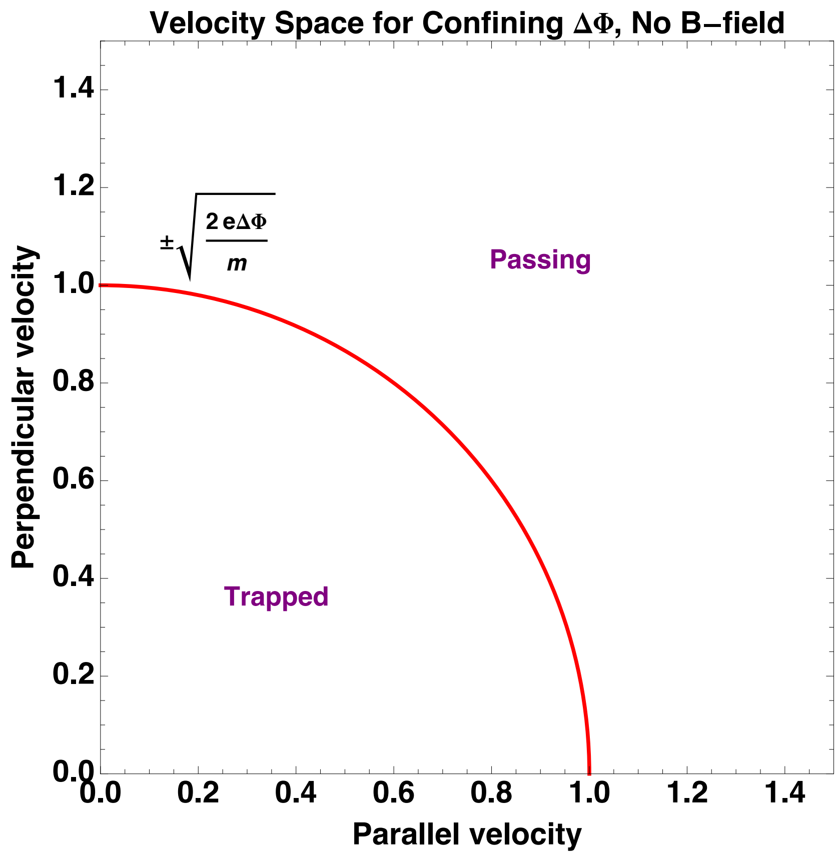
- V.N. Khudik, "Longitudinal Losses of Electrostatically Confined Particles from a Mirror Device with Arbitrary Mirror Ratio," *Nuclear Fusion* **37**, 189 (1997).

$$J_e \equiv \frac{n_e^2}{(n\tau)_e} = \frac{4}{\sqrt{\pi}} \frac{n_e}{\tau_e} e^{-e\Phi/T_e}$$

$$\tau_e \equiv \sqrt{\frac{m_e}{2}} \frac{T_e^{3/2}}{\pi n e^4 \Lambda}$$

$$\Longrightarrow \quad (n\tau)_e = \sqrt{\frac{\pi}{4}} n_e \tau_e e^{e\Phi/T_e}$$

- Earlier solutions (Yushmanov?) are rumored to exist, but I have not yet tracked these down.



Application to IEC Core Particle Loss Requires Solution of the Time Dependent Problem

- In general, time dependent equations must be solved for electron and negative ion input current (sources of secondary and ionization electrons plus negative ions) vs. loss:

$$I_- \equiv I_{se} + I_{iz} + I_{i-}$$

If electrons only:

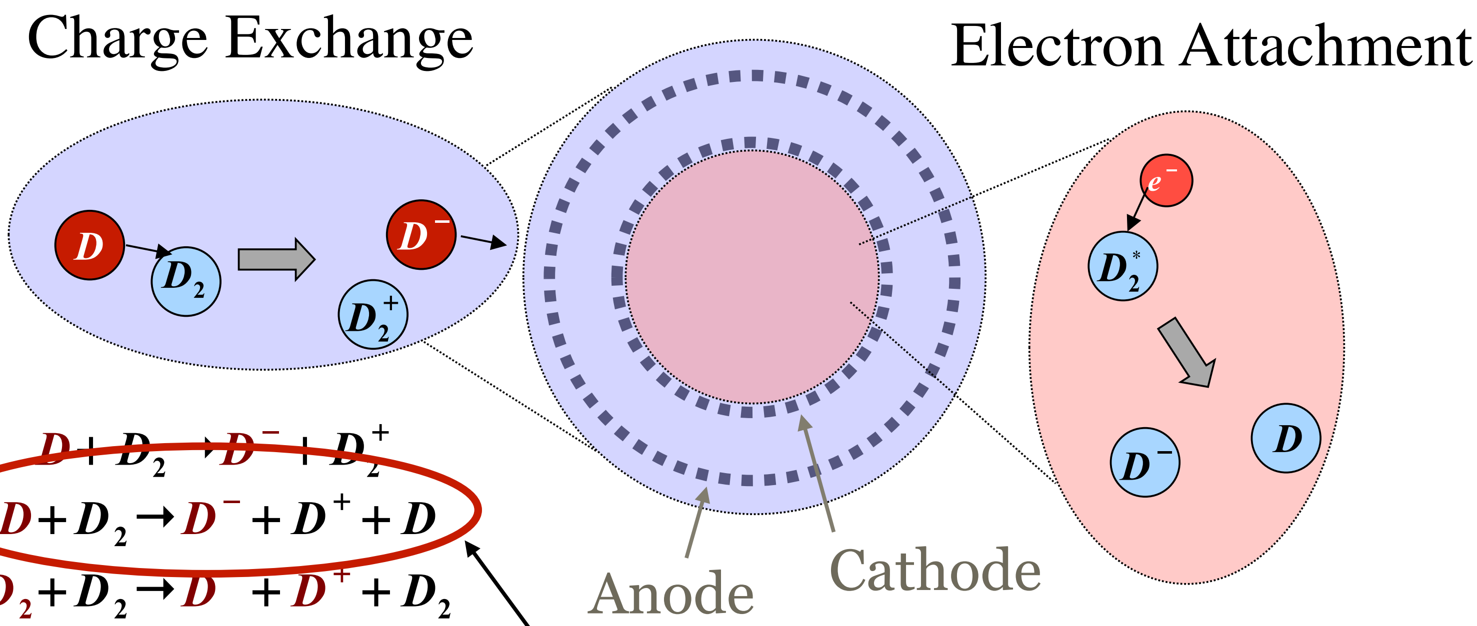
$$\int_{well} \frac{d n_e}{d t} d^3 r = I_e - \int_{well} \frac{n_e}{\tau_e} d^3 r$$

Electrons plus negative ions:

$$\int_{well} \frac{d (n_e + n_{i-})}{d t} d^3 r = I_e - \int_{well} \frac{n_e}{\tau_e} d^3 r - \int_{well} \frac{n_{i-}}{\tau_{i-}} d^3 r$$

- The detailed potential well structure will be difficult to calculate, but reasonable estimates of well's volume and the trapped distribution functions should be feasible.

Negative Ions Slightly Complicate the Problem



$$D + D_2 \to D^- + D_2^+$$
$$D + D_2 \to D^- + D^+ + D$$
$$D_2 + D_2 \to D^- + D^+ + D_2$$
$$D^+ + D_2 \to D^- + 2D^+$$
$$D_2^+ + D_2 \to D^- + D^+ + D_2^+$$
$$D_3^+ + D_2 \to D^- + D_2^+ + D_2^+$$

Most significant reaction

$$D_{2,(\nu)} + e^- \to D_2^- \to D^- + D$$
$$D_{2,(\nu,J)} + e^- \to (D_2^-)_m$$

Red denotes fast species

Slide modified from Eric Alderson's 2011 US-Japan IEC Workshop talk; see also D.R. Boris, E. Alderson, G. Becerra, et al., "Deuterium Anions in Inertial Electrostatic Confinement Devices," Physical Review E 80, 036408 (2009).

Sample Case Input Parameters

Cathode Radius	0.10 m
Anode Radius	0.20 m
Wall Radius	0.45 m
Cathode Voltage	70 kV

Potential Model: vacuum potential

No cold ions in cathode region

Source ion fractions:

D+	0.06
D2+	0.23
D3+	0.71

Cathode Current	30 mA
Gas pressure	2 mTorr

Ion energy at anode	0.01 keV
Gas density	6.400e+19 m^-3
Cathode transparency	0.92
Anode transparency	1.00

Number of zones:

Intergrid region	100
Cathode region	30
Source region	30
Energy grid	30

Electron and Negative-Ion Production in the Core for the Sample Case

- Secondary electrons
  - $I_{se} = 17.7$ mA
- Ionization electrons
  - Ions from ionization events in the core are assumed for this case to recombine with electrons in the core, making the net contribution of core electrons from ionization events negligible.
  - $I_{iz} = 0$ mA
- Negative ions
  - Based on the theory and VICTER implementation discussed by Gil Emmert and Eric Alderson at the previous US-Japan IEC Workshop:
  - $I_{i-} = 2.4$ mA
- Net negative particle creation rate in the IEC core
  - $I^{-}_{net} \sim 20$ mA

Summary

- Positive ions will create a space-charge well in the interior of the cathode region. Questions remain:
  - How deep will the well be for given plasma parameters?
  - At what rate will the well be filled with electrons and negative ions?
  - Will the electron and negative ion populations reach a steady-state balance between creation and loss, or will the negative populations oscillate in density?
  - What will be the detailed shape of the well?
- Stay tuned.

Bibliography

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5. V.P. Pastukhov, "Collisional Losses of Electrons from an Adiabatic Trap in a Plasma with a Positive Potential," *Nuclear Fusion* **14**, 3 (1974)
6. R.H. Cohen, et al., "Collisional Loss of Electrostatically Confined Species in a Magnetic Mirror," *Nuclear Fusion* **18**, 1229 (1978)
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8. V.N. Khudik, "Longitudinal Losses of Electrostatically Confined Particles from a Mirror Device with Arbitrary Mirror Ratio," *Nuclear Fusion* **37**, 189 (1997).