Theoretical and Experimental Studies of Negative Ions in IEC devices at UW – Madison:

Current Results and Plans for Future Work

By: Eric C. Alderson
21/10/2010

12th US Japan Workshop on Inertial Electrostatic Confinement Fusion
Outline

Background
  Negative Ion Reaction Physics
  Previous Measurements

Theory
  Simulation of Currents born in the IEC Core
  Integral Code Negative Ion Implementation

Experimental
  Faraday Cup
  Radial Scan Results

Future Work
  Integral Code
  System Parametrics
  Longitudinal Scan
  Alternate Cathode
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Negative ions can be created and stripped by collision with background gas. A variety of reactions relevant to the IEC give rise to negative ions. **Dissociative Charge Exchange Reactions**

**Thermal Electron Attachment**

**Negative Ion Creation**

![Graph showing cross section vs. projectile energy for various negative ion creation reactions](image)

Production of $H^-$ (negative ion) from interaction with $H_2$

Occurring wherever there are energetic nuclei
Negative ions can be created and stripped by collision with background gas. A variety of reactions relevant to the IEC give rise to negative ions. **Dissociative Charge Exchange Reactions**

**Thermal Electron Attachment**

**Negative Ion Creation**

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**Negative Ion Stripping**

Neutralization of $H^-$ (negative ion) from interaction with $H_2$.

Occurring wherever there are energetic nuclei.
A variety of reactions relevant to the IEC give rise to negative ions. Dissociative Charge Exchange Reactions

Thermal Electron Attachment

Occurring inside the cathode, where there are thermal electrons.
Negative ion currents in IEC discovered in 2009 by D. Boris using a bending arm to isolate negative ion currents and provide Energy/Mass decomposition.
Analysis shows evidence of the negative ion origins.

Negative ions born from dissociative charge exchange

Negative ions born in the core from electron attachment
Negative ion parametrics were carried out by D. Boris using a “Faraday Trap”

Acceptance aperture roughly 2 cm²

Theory work has examined survival of negative ions born in the core.

Model of attenuation of negative ions born in the IEC core from thermal electron attachment.

If this intensity was measured at the chamber wall, what was the negative ion current born at the cathode?

How much survived to reach the anode?

Measured intensity 0.0042 [a.u.] (arbitrary units)
Attenuation of negative ions born in the core is a tractable problem.

The change in current is described by this differential equation:

\[
\frac{dI}{dr} = -I_0 n_g \sigma [E(r)] dr
\]

Where the Energy of the particles born in the cathode at zero is described by the potential as a function of radius

\[
E = V_c - V_c \frac{(r_a - r) r_c}{(r_a - r_c) r}
\]

The above is solved as an integral equation:

\[
I(r) = I_0 e^{-n_g \int_{r_c}^{r} \sigma(r') dr'}
\]
A code has been developed to simulate attenuation of negative ions born in the IEC core.

Surviving negative ion fraction from a 20 cm diameter cathode and 50 cm anode at 2 mTorr

2 mTorr = 0.267 Pa
The measured negative ion current was \(~80\%\) stronger leaving the cathode.

The intensity of negative ion current born from the cathode is shown in the graph. The initial intensity at the cathode is 0.02 [a.u.].

The graph shows a fit with $R^2 = 0.9991$ for the sum of five Gaussians to the data. The coefficients are:

- $c_1 = 91.66$
- $c_2 = 70.83$
- $c_3 = 63.28$
- $c_4 = 59.74$
- $c_5 = 52.20$
Negative ion physics is being added to the UW-Madison Integral Equation Code.
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This function consists of two parts:
- **Generation**
- **Propagation**

Ions from Source Region

Particles from Inter-grid Region
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Negative ion:
  Generation

  Propagation

Ions from Source Region

Particles from Inter-grid Region

\[
\begin{align*}
D^+ & + D_2^+ & + D_3^+ \\
D_0^{\text{fast}} & D_0^{\text{2,fast}}
\end{align*}
\]
An enclosed Faraday Cup has been designed and constructed for negative ion measurement.
The enclosed Faraday Cup has been installed in the IEC.

View from angle

View from across chamber
Anode-cathode: 50-20 cm; Pressure: 2 mTorr; aligned with jet
Faraday Cup Current Results
Current and Voltage Parametrics

Anode-cathode: 50-20 cm; Pressure: 2 mTorr; aligned with jet

Green 5 cm outside anode
Blue 11 cm outside anode
Anode-cathode: 50-20 cm; Pressure: 2 mTorr; aligned with jet

Red 2 cm outside anode
Green 5 cm outside anode
Blue 11 cm outside anode
Faraday Cup Current Results
Pressure Comparison

Anode-cathode: 50-20 cm;
Pressure: 2, 2.5 mTorr comparison;
aligned with jet

The Faraday cup has show slight but consistent increase in collected negative ion current at 2.5 mTorr over 2 mTorr.
Alignment comparison shows there is 19%-135% more negative ions on jet than off.

Anode-cathode: 50-20 cm; Pressure: 2 mTorr; jet alignment comparison
Future Work

Integral Code
  Complete negative ion propagation and integrate in main code

Parametrics
  Extend Voltage – Current data
  Pressure
  Anode-Cathode

Longitudinal Scan
  Determine total negative current in a jet

Alternate Cathode
  Look for superior focusing and generation of negative ions
  Explore application potential
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Conclusions

Measurements of negative ion current aligned with cathode jet show:
- Clear dependence on cathode voltage and current
  - Reduction in current collected with increasing distance from anode
  - but without clear radial scaling
- Dependence on pressure that requires greater study

Measurements of negative ion current not aligned with cathode jet show:
- Reduced negative ion current compared with jet aligned measurements
- Much less dependence on cathode voltage

Forthcoming parameterization should reveal:
- Improved understanding of IEC physics
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Questions?

Thank you for your attention.
Negative Ion Parametrics
Anode-Cathode: 50-20 cm

30 mA; 2 mTorr

Not aligned with cathode hole
Aligned with cathode hole

100 kV; 30 mA,

Current collected in Faraday Trap
Potential Applications

IEC Physics diagnostic
Atomic and Molecular Physics
Space Thruster
Plasma Processing
Fusion Technology
Fast Neutral from Cathode Born
Negative Ion Spectrum

Cathode-Anode: 20-50 cm
100 kV; 2mTorr