Analysis of
Spatial Fusion Reaction Distributions
in a Spherical IECF Device
using a Particle Code

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Outline

- Objectives and previous works
- Simulation code
- Results
  - Discharge characteristics
  - Fusion reaction
- Summary and future plans
Objectives of This Study

Previous simulations

- Without atomic and molecular processes
- Including atomic and molecular processes
  - Only within cathode
  - Too short simulation time

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- Simulation of steady discharge
- Comparing with experimental results
Our Previous Works

2000  Simulation of an IEC discharge with He gas
       Constant voltage control

2001  Changed operation gas to \( D_2 \)
       Changed to constant current control

2002  Improve stability of simulation
       Implement fusion reaction calculation
Modified PDS1 Code

- Cathode modeling to change transparency depend on energy
- Including various atomic and molecular processes (e.g. dissociation), to allow D$_2$ as operation gas
- Implementation of fusion reaction calculation code
Modeling of the Cathode

Cathode model to change transparency depend on energy

\[ T_{\text{max}} = 0.95 \]
\[ E_{\text{th}} = 0.02 \times V_c \]
\[ E_{\text{sat}} = 0.04 \times V_c \]
Atomic and Molecular Processes

- **D⁺**
  1) $D^+_{(beam)} + D^0_{(back)} \rightarrow D^0_{(beam)} + D^+_{(slow)}$
  2) $D^+_{(beam)} + D^0_{(back)} \rightarrow D^+_{(beam)} + D^+_{(slow)} + e$
  3) $D^+_{(beam)} + D^0_{(back)} \rightarrow D^+_{(slow)} + D^+_{(beam)} + D^0_{(back)} + e$

- **D₂⁺**
  4) $D^+_{2(beam)} + D^0_{2(back)} \rightarrow D^0_{2(beam)} + D^+_{2(slow)}$
  5) $D^+_{2(beam)} + D^0_{2(back)} \rightarrow D^+_{2(beam)} + D^+_{2(slow)} + e$
  6) $D^+_{2(beam)} + D^0_{2(back)} \rightarrow D^+_{2(beam)} + D^0_{2(beam)} + D^0_{2(back)}$
  7) $D^+_{2(beam)} + D^0_{2(back)} \rightarrow D^+_{3(slow)} + D^0_{2(beam)}$

- **D₃⁺**
  8) $D^+_{3(beam)} + D^0_{2(back)} \rightarrow D^0_{2(beam)} + D^+_{3(beam)} + D^0_{2(back)}$
  9) $D^+_{3(beam)} + D^0_{2(back)} \rightarrow D^0_{3(beam)} + D^+_{2(beam)} + D^0_{2(back)}$

- **D⁰**
  10) $D^0_{(beam)} + D^0_{2(back)} \rightarrow D^+_{(beam)} + D^0_{2(back)} + e$
  11) $D^0_{(beam)} + D^0_{2(back)} \rightarrow D^0_{(beam)} + D^+_{2(slow)} + e$
  12) $D^0_{(beam)} + D^0_{2(back)} \rightarrow D^0_{(beam)} + 2D^0_{(slow)} + 2e$
  13) $D^0_{(beam)} + D^0_{2(back)} \rightarrow D^0_{(beam)} + D^0_{(slow)} + D^0_{(back)} + e$

- **D₂⁰**
  14) $D^0_{2(beam)} + D^0_{2(back)} \rightarrow D^+_{2(beam)} + D^0_{2(back)} + e$
  15) $D^0_{2(beam)} + D^0_{2(back)} \rightarrow 2D^+_{(beam)} + D^0_{2(back)} + 2e$

- **Electron**
  16) $e + D^0_{2(back)} \rightarrow D^+_{2(slow)} + 2e$
  17) $e + D^0_{2(back)} \rightarrow D^+_{2(slow)} + 2e$
Cross Sections

- \(D^+\)
- \(D_{2}^+\)
- \(D_{3}^+\)
- \(D^0\)
- \(D_{2}^0\)
- electron

C. F. Barnett ed. ORNL-6086, 1990
IAEA Atomic and Molecular Data Information System
Basic Simulation Parameters

- cathode radius $r_c = 3\text{cm}$
- anode radius $r_a = 15\text{cm}$
- time step $\Delta t = 2\text{ps}$
- mesh step $\Delta r = 0.2\text{mm}$
- weight of super particle $2 \times 10^7$  

pressure $P$ given 
current $I$ given 
discharge voltage $V$ obtained.
The simulation results show good agreement with that of experiment.

Discharge voltage does not depend on discharge current.
Mode I (high pressure, low voltage)

40mTorr, 10mA, 14µs → -2.2kV

- Positive column
- Electron-impact ionization between both electrodes
Mode II (low pressure, high voltage)

8mTorr, 10mA, 100µs → -25.5kV

• Electron impact ionization hardly occur
• Ion and neutral impact collisions supply ion and electron
Self-maintain Discharge Mechanism

Mode I

Mode II
Calculation of Fusion Reaction

- Energy distribution → Fusion reaction rate (beam-background)
- Cross-sections of D$_2$-D$_2$ and so on are converted from that of D-D reaction
Time Evolution

8mTorr, 20mA

Time evolution of NPR

Time evolution of cathode voltage

- NPR (Neutron Production Rate) oscillates following cathode voltage.
- But these oscillations converge → Steady state

-25.8kV

1.7 x 10^5
Spatial Distributions of Fusion Reaction

6mTorr, 20mA → 47.7kV, 5.0x10^5/s

- Ions-background – peak around the cathode
- Neutral-background – uniformly distributed all over the device

(low energy (<10keV))

(high energy (>10keV))
High Pressure Case

10mTorr, 20mA → 17.0kV, 6.3x10⁴/s

high $P$ → low $V$ → low NPR

low energy ($<10$keV)

high energy ($>10$keV)
Energy Distributions along Radius

6mTorr, 20mA $\rightarrow$ 47.7kV, $5.0 \times 10^5$/s
Averaged Energy Distributions

$P = 6\text{mTorr}, I = 20\text{mA}, V = 47.7\text{kV}$

averaged ion energy depends on local electric field strength.

$P = 6\text{mTorr}$
Contribution of Ions and Neutrals to Fusion Reaction Rate

$I = 20mA$

V, NPR

P

10mTorr, 17.0kV, 6.3e4/s
8mTorr, 25.8kV, 1.7e5/s
7mTorr, 34.5kV, 3.4e5/s
6mTorr, 47.7kV, 5.0e5/s

ion neutral ion neutral

fusion reaction particle number
Summary

Discharge characteristics

- low $V$, high $P$ \rightarrow electron maintain discharge
- high $V$, low $P$ \rightarrow energetic neutral maintain discharge

Fusion characteristics

- Ion-background \rightarrow peak around the cathode
- Neutral-background \rightarrow uniformly distribute
Future Plans

• Simulation of large current discharge
• Assisted discharge by ion injection

• Development a new 2-D code
  (simulation of cylindrical IECF)
$P = 5\text{mTorr}$ (glow discharge does not occur without ion injection)