Fundamental Study of Radially Convergent Beam Fusion

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Outline

- Introduction — Why cylindrical device?
- Experiments
  - Basic Discharge Characteristics
  - Spectroscopy
  - Neutron Production Rate
- 2-D PIC Simulation
- Conclusions
- Future Works
Spherically convergent beam fusion (SCBF) has been studied for many years. However, the detailed mechanism has not been made clear. This depends on a fact that it is difficult to measure the physical quantities precisely in a central region of spherical configuration.

We devised to change the electrode shapes from spherical to cylindrical.
Advantages of Cylindrical Device

- For Practical Use
  - Effective Neutron Irradiation
    - Spherical ⇒ Point Source: Decay with 1/r^2
    - Cylindrical ⇒ Line Source: Decay with 1/r^1
  - Easy Water Cooling of Grid Cathode

- For Measurements and Analyses
  - Easy Computing: 3-D ⇒ 2-D
  - Low Disturbance by Probe Inserting
Objectives

- To reveal the fundamental characteristics of cylindrical RCBF
  - Basic discharge characteristics
  - Emission properties
  - Neutron production characteristics

- To make 2-D PIC simulation code
  - Comparison between the experimental and simulation results
Experimental Setup

Cathode: $\phi 2.0$-mm Stainless Steel Rod x8
Anode: 0.5 mm-pitch Stainless Steel Mesh
Photograph of Discharge Plasma

- Discharge Pattern
  - Spherical: Spoke-like (Star mode)
  - Cylindrical: Uniform
- Intensity
  - Strong
  - Weak

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Breakdown Voltage vs. $pd$

$pd$ : Background Pressure
$d$ : Gap Length between Electrodes

H$_2$ gas gives lower breakdown voltage than D$_2$ gas.
$V_B/A$ vs. $pd$

Breakdown voltage of $D_2$ gas is about twice that of $H_2$ gas at the same $pd$.

Sloshing ions play important roles in ionization.

$V_B$: Breakdown Voltage
$A$: Mass Number

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V-I Characteristics

In low current region, operating voltages are nearly constant. But in high current and low pressure region, operating voltage becomes higher abruptly.
Floating Potential Profiles

$V_{\text{eff}}$: Effective Accelerating Voltage

Ions are accelerated near the cathode. Most of fusion reactions are occurred inside the cathode.
Floating Potential Profiles

Cathode Voltage: -7.5 kV
Discharge Current:
- 5.0 mA
- 10.0 mA
- 20.0 mA

$V_{\text{eff}}$: Effective Accelerating Voltage

Electrostatic Probe
Optical Measurement System

Spectrometer:
- Czerny-Turner type, $f_1=250$ mm, $f_2=280$ mm
- Grating: 1800 grooves/mm
- Maximum spectral resolution: 0.03 nm
- Detector: Multichannel CCD image sensor
Emission Intensity of H$_\beta$ Line

Emission intensity is proportional to discharge current.
Emission Intensity of $H_\beta$ Line

![Graph showing emission intensity vs. cathode voltage for different discharge currents. The graph includes lines for 20 mA, 15 mA, 10 mA, and 5 mA, with the jet mode indicated.]
Spatial Distribution

The detected intensity is integrated over the device in the direction of the optical axis.

HWHM
- 10 kV (Star mode)  13.1 mm
- 2.5 kV (Jet mode)   13.9 mm

Abel Inversion

Cathode Voltage
- 10.0 kV
- 2.5 kV

Cathode Radius

Emission Intensity [a.u.]

Lateral Profile

Radial Profile

Shade of Grid
Neutron Production Rate

![Graph showing Neutron Production Rate vs. Discharge Current]

- Neutron Production Rate $\propto$ Discharge Current
- Beam-background reactions are dominant.
Neutron Production Rate

Fusion Reactivity $\sigma_{DD} \nu$ of Beam-Background Reaction

Beam-background reactions are dominant.
2-D PIC Simulation

- Cylindrically Symmetric
  - On the two cyclic boundaries, a particle is reflected totally.
  - An influence of magnetic field is ignored.
- Collisionless
- Number of Ion and Electron Superparticles: $10^4$ each
  - To conserve the number of particle, following procedure is used.
    - When electrons reach the anode, the same number of electrons is generated in space according to a function of ion distribution.
    - As for the ions, when they reach the cathode, the same number of ions is generated in space according to a function of ion distribution.
- Time Step: $\Delta t_i = 20$ psec, $\Delta t_e = \Delta t_i / 60$
2-D PIC Simulation

Dimension of Device and Electrical Condition:

- Cathode
  - Diameter: 5.0 cm
  - Rod Diameter: 2.0 mm
  - Number of Rods: 8
  - Cathode Voltage: -10 kV

- Anode
  - Diameter: 16 cm
Initial Condition

- Velocity distribution functions of ions and electrons are Maxwellian.
  - Temperature: Ion 0.03 eV, Electron 2.0 eV
- Ions and electrons are uniformly distributed.

Ion Distribution

Electron Distribution
Potential Profiles in Vacuum

![Graphs showing electrostatic potential profiles in vacuum.](image)

- **Graphs:** Electrostatic potential profiles for different radii, with cathode and anode marked.
- **Diagram:** Cross-sections of potential distribution along the radius.
The flat potentials at the central region are almost the same with the ones in vacuum and experimental results. However, potential profile near and outside the cathode is different from experimental one.
Concentration of ions and electrons likes spoke, which is the remarkable feature of Star mode was observed.
Distributions of ion and electron are almost the same, and quasi-neutral of plasma is formed in the central and spoke region.
Particle Tracking

Trajectories of Electrons

Trajectories of Ions

Radius [cm]
Conclusions

- Fundamental characteristics of cylindrical device were revealed.
  - Because of the weak convergence, the strong light emission like spokes could not be observed.
  - Beam-background reactions are dominant.
  - Neutron production rate of $10^5$ s$^{-1}$ was observed at a discharge of 40 kV, 20 mA.
- 2-D PIC Simulation was carried out.
  - Potential profile near and outside the cathode is different from experimental one. (Ion sheath effect)
Future Works

- Experiments
  - Measurements with changing cathode diameter
- PIC Simulation
  - Including collisions
  - Including ion sheath effect
  - Computing neutron production distribution
  - Comparison between experimental and simulation results