Development of a Cs-free Negative Hydrogen Ion Source System using Multi-pulsed Plasma Sources: Prospect and Challenges

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Introduction
(motivation and revisiting temporal filter)
Motivation

Accelerator and Fusion Applications

For developing a Cs-free H⁻/D⁻ ion source based on the volume production mechanism for accelerator and NBI applications.

Figure 4. Schematic of assumed H⁻ ion production processes on PE surfaces with 12.5° taper (a) and 45° taper (b).

Figure 9. Maximal measured negative ion density for different materials at same external experimental conditions: measured in a distance of 2.5 cm to unbiased samples, at 0.3 Pa H₂ pressure and 300 W discharge power.

Motivation

Ion Thruster and Semiconductor Equipment

For implementing the negative ion source technology to the fields of space electric propulsion and semiconductor equipment (e.g., etcher)

CNRS PEGASES thruster

a neutralizer-free plasma propulsion based on the negative ion technology

Negative ions in etchers

neutralization of charge buildup in features on the wafer

Revisiting temporal filter (pulsing) technology

Pulsing and Pioneering Works in ’90s

Starting point: revisiting temporal filter (pulsing)

\[
\text{Power} \quad t
\]

time-modulating power fed to an ion source


C. Gorse & M. Capitelli (1992)

FIG. 2. The extracted negative-ion current from a pulsed hydrogen discharge. The gas pressure is 2.4 mTorr. The discharge pulse length is 2.7 ms and the repetition rate is 87 Hz. The discharge current \( I_p = 15 \) A.

and also C. Michaut et al. (1994), O. Fukumasa & M. Shinoda (1998), T. Mosbach et al. (1998), ...

Recently more often used in semiconductor etching processes especially, the case for electronegative gas plasmas

Revisiting temporal filter (pulsing) technology

Fundamentals of Pulsing: Electron Cooling

- **Active-glow (power-on state)**
  : “electron heating” and collisions / wall losses

- **After-glow (power-off state)**
  : only “electron cooling” by collisions / wall losses

Electron – neutral collisional cooling mechanism

Diffusive cooling mechanism due to the ambipolar potential barrier

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Revisiting temporal filter (pulsing) technology

Fundamentals of Pulsing: \(\frac{d(EEDF)}{dt}\)

A preliminary experiment

Assuming Maxwellian distributions

Figure 6.6 Schematic diagram for explanation of the newly devised \(\frac{d(EEDF)}{dt}\) - electron energy characteristic.

Here, time \(t = 0\) refers to the start of the after-glow.

In the early after-glow, \(e_{low}\): increase  
\(e_{high}\): decrease
Revisiting temporal filter (pulsing) technology

Fundamentals of Pulsing: Electronegative Gas

Volume production process
- Dissociative electron attachment (DA)
- a “sequential two-step” process

**Step 1** high-energy $e^- + H_2 \rightarrow e^- + H_2 (n \geq 5)$

**Step 2** low-energy $e^- + H_2 (n \geq 5) \rightarrow H^+ + H^-$

Volume destruction process
- Electron detachment / Mutual neutralization ($H_x^+$) / Associative detachment (H)

high-energy $e^- + H^- \rightarrow 2e^- + H$

» CW plasmas simultaneously provide high- and low-energy electrons, leading to both the production and destruction of H⁻ ions.

» But, pulsed plasmas can “sequentially” offer high-and low-energy electrons in accordance with the volume production mechanism while also lowering $T_e$ and so the destructions of H⁻ ions.

The early after-glow: favorable for H⁻ ions
Revisiting temporal filter (pulsing) technology

Fundamentals of Pulsing: Filters

Magnetic filter: B-field

Temporal filter: After-glow

The high-energy electrons are filtered…

spatially (in space)  temporally (in time)

Revisiting temporal filter (pulsing) technology

Drawback of Pulsing: Short Duration

A preliminary experiment

Pulsing

- Power-on
  - $H_2$ ($v \geq 5$)
  - Electron cooling
  - Favorable for step 1
- Power-off
  - $H^-$
  - Favorable for step 2 + mitigating destructions

- Negative ion to electron density ratio (%)
- RF power (W)
- Time (μs)

- A decrease due to the consumption of the reactants of the DA reactions

but, too short! transient!

A method for continuously supplying the negative ions?

Remedying the drawback → Development of an efficient and Cs-free $H^-$ ion source applicable to the various fields
Ion Source Concept
One main chamber (ion reservoir) + two pulsed plasma sources + two MFs

Spatiotemporal filter

Alternate dual pulsing (temporal filter)
  : filtering in time

Ion source A: active-glow
  \( \text{H}_2 (v \geq 5) \)
  high energy \( e^- \)

Magnetic filter
  : filtering in space

Ion source B: after-glow
  \( \text{H}^- \)

Main chamber

Electrode
Working Principle: Alternate Pulsing

Two plasma sources generate pulsed plasmas in an “alternating manner” depending on a phase shift (time delay) between the two power pulses.

Achieving continuous supply of the H⁻ ions at high densities
Ion source concept

Application: Alternating Extraction

On

Alternate pulsing

Off

Ion source A: active-glow

Ion source B: after-glow

Main chamber

positive and negative ions-rich plasma

Magnetic filter

Electrode

Alternating extraction of positive and negative ions

$(+) \leftrightarrow (-)$
Ion Source Development
(apparatus and diagnostics)
Experimental apparatuses for the proof-of-concept

KOMPASS II based on ICP: not used

KOMPASS: Korea atomic energy research institute Multi-Pulsing-Applied ion Source System

KOMPASS II

Impedance matching network

Magnetic filter

RF: 13.56 MHz, Power: 900 W, pulse repetition frequency: 0.2~5 kHz

Not appropriate for experimental proof-of-concept. Why?
Dilemma on Probe Diagnostics

Use of an RF compensated probe in the early after-glow

not caused by actual plasma but by the AC-coupling between the probe compensation electrode and the plasma.

» Dilemma in the pulsed RF ion source
  the active-glow in the RF-driven ion source: an RF compensated probe
  the after-glow: an uncompensated probe

» Avoidance of the dilemma: KOMPASS III (filament-driven DC arc ion sources)
Experimental apparatuses for the proof-of-concept

**KOMPASS III** w/ filament-driven DC arc ion sources

- **Magnetic filter (NdFeB)**
- **Filament**
- **Ion source A**
  - Inner diameter: 80 mm Φ
  - Length: 125 mm
- **Main chamber**
- **Ion source B**
- **Langmuir probe (uncompensated)**
Diagnostics for measuring the negative ion current

Time-resolved $\Delta I$ Measurement System

Time-resolved laser photodetachment technique

Nd:YAG LASER
Wavelength: 1064 nm
Diameter: 7 mm

Laser photodetachment
Laser $h\nu + D^- \rightarrow D + e^-$

Probe current (mA)

![Graph showing probe current over time](image)

$\Delta I$

Shutter: Open
Shutter: Closed

time after the end of the active-glow (μs)

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

120
140
160
180
200

Langmuir probe
Cylindrical tungsten tip
Diameter: 0.3 mm
Length: 7 mm

Laser beam shutter

LASER beam

Photodiode sensor
Diagnostics for measuring the negative ion current

Time-resolved Measurement System
Proof-of-concept Experiment
Results of an experimental proof-of-concept

Single vs. Alternate Dual Pulsing

KOMPASS III (DC): 1 Pa D₂, PRF: 2 kHz, PDC: 50%, Peak power: 1100 W, Δtₐ₋ₐ₋(dual): 250 μs
B⊥, MF, max: ~ 130 G, Probe: @ center of the main chamber
(or Φ (phase shift) = π)

Power pulse
(Ion source A TTL signal)

Power pulse
(Ion source B TTL signal)

Negative ion current

It is experimentally verified that the alternate dual pulsing can provide a continuous supply of the negative ions.

S.-R. Huh et al., 2021, “Manuscript in preparation.”
The spatiotemporal filter (MF + pulsing) is more efficient than the MF.

Some of the high-energy electrons may survive in spite of the presence of magnetic filter, destroying the $D^-$ ions (discount effect).

→ the optimum magnetic filter configuration: future work
Results of an experimental proof-of-concept

(1) Tendency

- Alternate dual pulsing
- Single pulsing (Ion source A)
- Single pulsing (Ion source B)

TTL A (V) vs. Time (μs)

TTL B (V) vs. Time (μs)

ΔI (mA) vs. Time (μs)
Results of an experimental proof-of-concept

(2) Effect of MF on Single Pulsing

KOMPASS III: 1 Pa D₂, PRF: 1 kHz, PDC: 50%, Peak power: 1100 W
equipped with only a single pulsed ion source

This seems that the magnetic filter restricts some of the D⁻ ions as well as the high-energy electrons from moving the ion source to the main chamber.

→ Electromagnet?
Results of an experimental proof-of-concept

(2) Idea: Synchronized Electromagnet MF

Ion source A: active-glow
Ion source B: after-glow

Main chamber

Absence of the B-field
Absence of The B-field

Pulsed B-field by electromagnets

Electrode

kicker?

synchronized with the ion source power pulses

This may promote the system efficiency
Results of an experimental proof-of-concept

(3) Time Delay \rightarrow \textbf{Control Knob}

In the alternate dual pulsing,

- PRF: 2 kHz, PDC: 50%, \(\Delta t_{A-B}: 0 \mu s\)
- PRF: 1 kHz, PDC: 25%, \(\Delta t_{A-B}: 500 \mu s\)
- PRF: 2 kHz, PDC: 50%, \(\Delta t_{A-B}: 250 \mu s\)

Phase shift control: temporal variation
Prospect and Challenges
Prospect and Challenges

Prospect

» Employing both the MF and the temporal filter
  → favorable for the negative ion volume production
  → an **efficient** method

» **Negative ion-to-electron density ratio**: high (due to DA)

» Pulsed operation
  → The reduced average power
  → **Lowering heat loads** to the ion sources

» After-glow state
  → A decrease in the sheath potential
  → This **may help the plasma to be uniform.**
Prospect and Challenges

Challenges (Future Work)

» **Time-resolved measurement of the H⁻/D⁻ ion density** → Analysis

» **Beam extraction** of the negative ions in the DC/RF multi-pulsed ion source system

» **Scale-up** of the system with a high uniformity

» **Introduction of the magnetic filters** made of electromagnets into the system.
The KAERI has recently proposed and developed a novel Cs-free negative deuterium ion source system using multi-pulsed plasma sources.

The system with the spatiotemporal filters operates with two alternate pulsing sequences related to the respective plasma sources, thereby switching the plasmas in the after-glow state in an alternating manner.

It is experimentally verified that the alternate dual pulsing can provide a continuous supply of the negative ions.
Thank You For Your Attention