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

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Virtual conference

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CONTENTS

Introduction
(motivation and revisiting temporal filter)

1

01 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

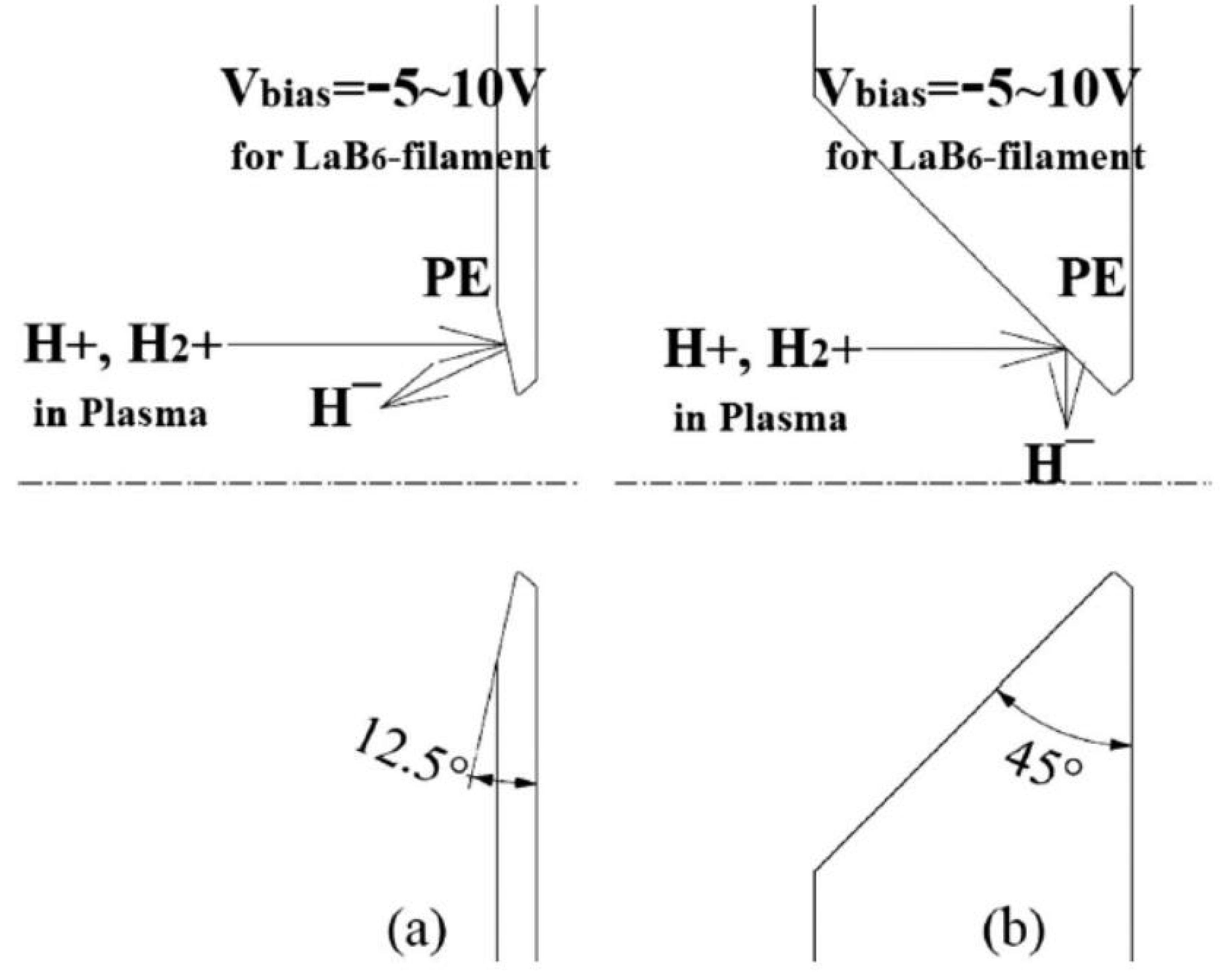


FIG. 4. Schematic of assumed H⁻ ion production processes on PE surfaces with 12.5° taper (a) and 45° taper (b).

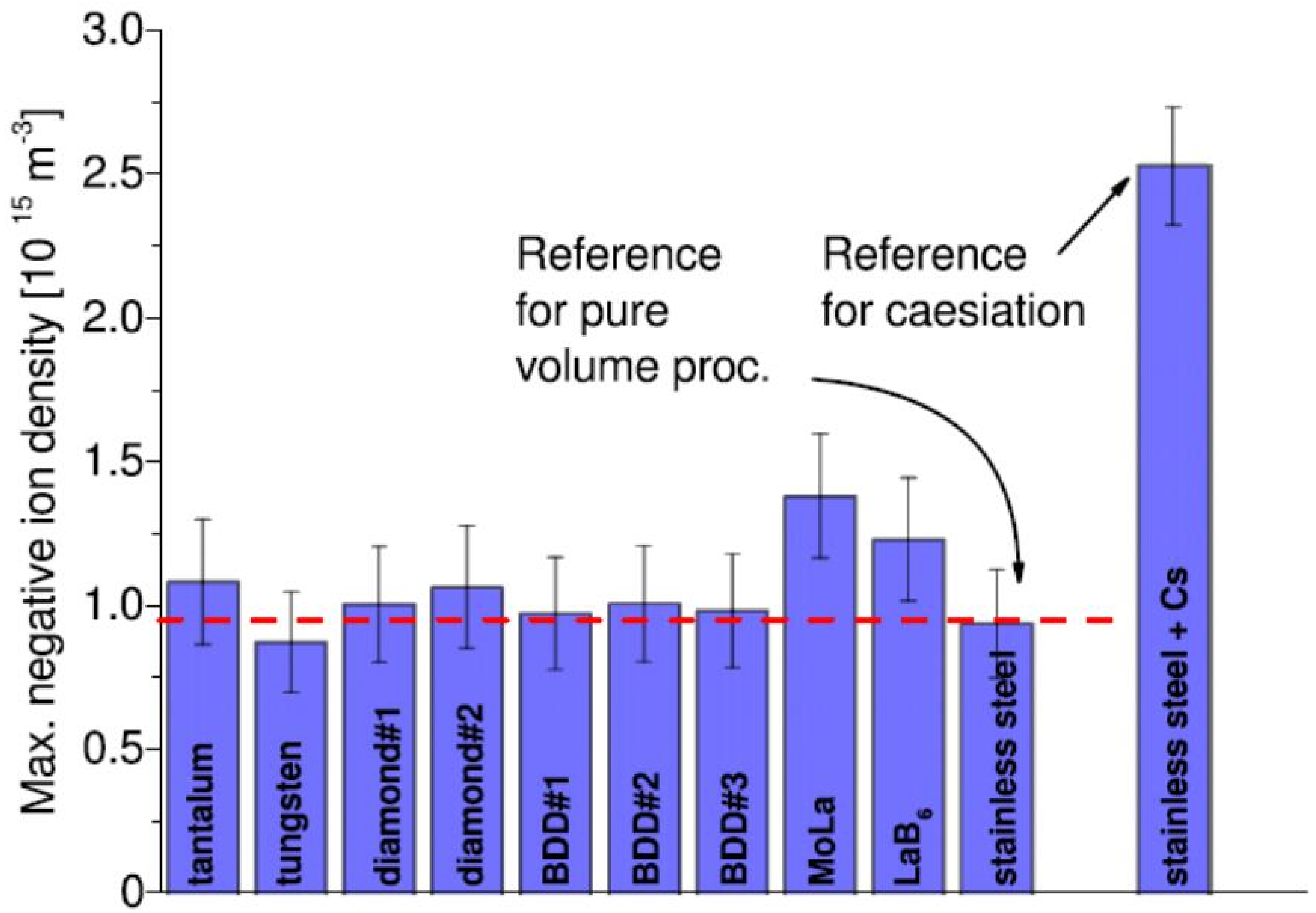
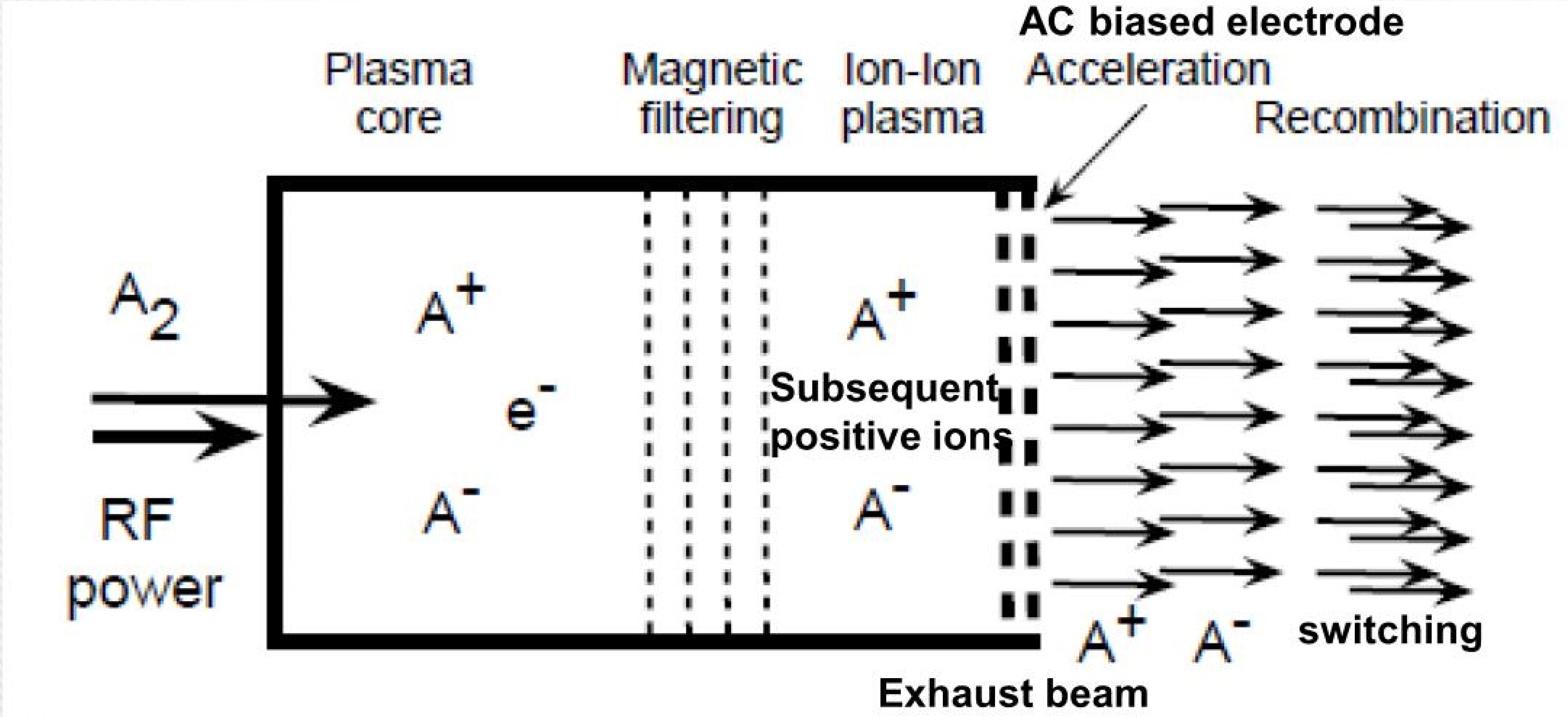


Figure 9. Maximal measured negative ion density for different materials at same external experimental conditions: measured in a distance of 2.5 cm to unbiased samples, at 0.3 Pa H_2 pressure and 300 W discharge power.

A. Ueno *et al*., Rev. Sci. Instrum. **81** 02A720 (2010) / U. Kurutz *et al*., Plasma Phys. Control. Fusion **59** 075008 (2017).

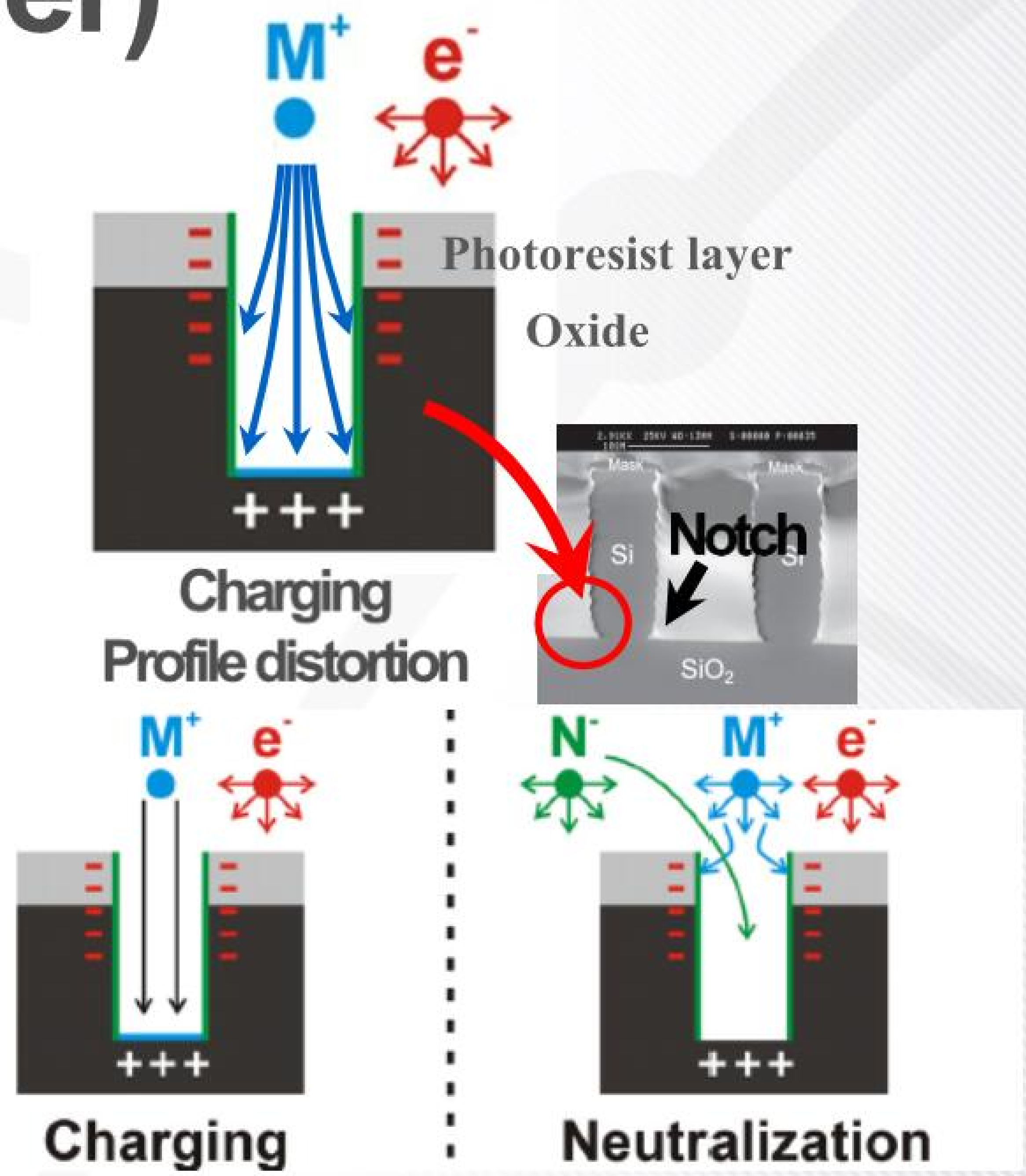
01 Motivation
Ion Thruster and Semiconductor Equipment

» 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

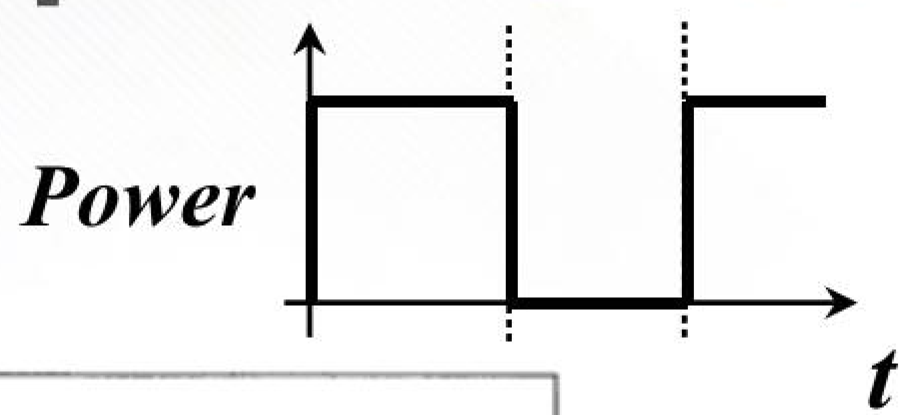
neutralization of charge buildup in features on the wafer

A. Aanesland *et al.*, *arXiv preprint arXiv*: 1411. 1538 (2014) / S. Banna *et al.*, J. Vac. Sci. Technol. A **30** 040801 (2010). / V. Ishchuk *et al.*, J. Appl. Phys. **112** 084308 (2012).

01 Revisiting temporal filter (pulsing) technology

Pulsing and Pioneering Works in '90s

» Starting point: revisiting temporal filter (pulsing)



time-modulating power fed to an ion source

M. Hopkins & K. N. Mellon (1991)

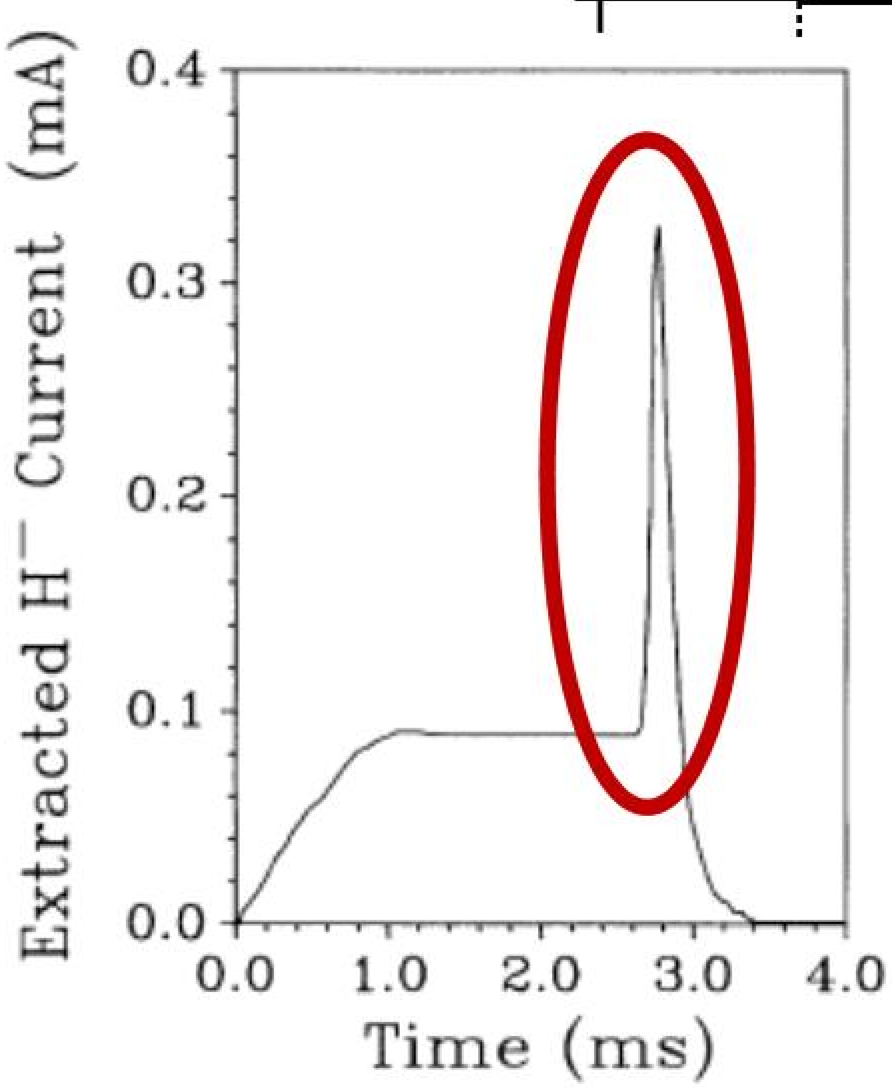


FIG. 2. The extracted negative-ion current from a pulsed hydrogen discharge. The gas pressure is 2.4 mTorr. The discharge pulse length is 2.7 ms and the repetition rate is 87 Hz. The discharge current $I_p = 15$ A.

C. Gorse & M. Capitelli (1992)

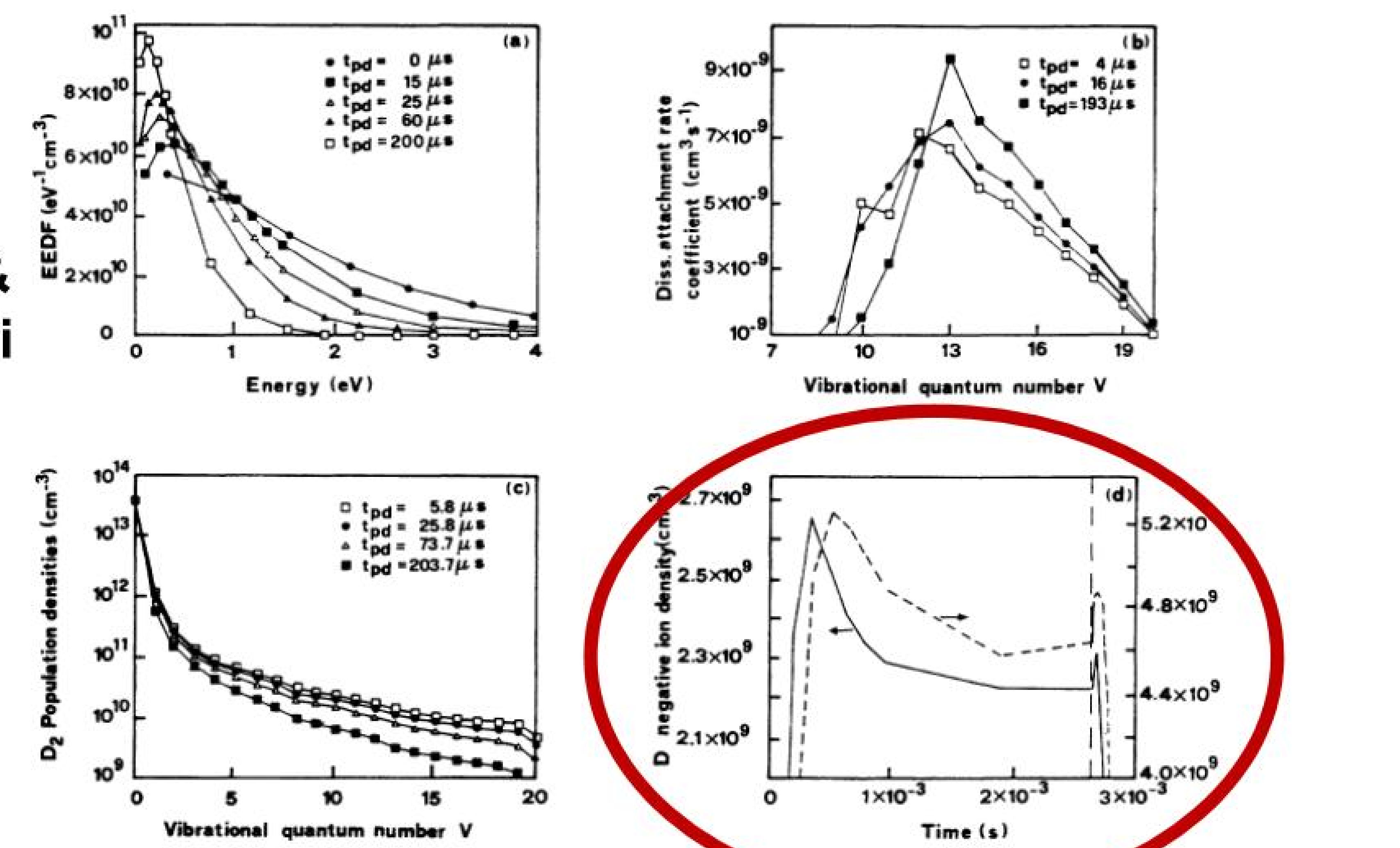


FIG. 1. Relaxation of different quantities in the post-discharge regime. (a) Behavior of electron energy distribution function (EEDF) as a function of energy at different times in the post discharge (t_{PD}). (b) Behavior of dissociative attachment rates vs the vibrational quantum number at different t_{PD}. (c) Behavior of vibrational distribution as a function of vibrational quantum number at different t_{PD}, (d) relaxation of D^- concentration in discharge and post-discharge conditions; in this last figure the dashed line has been calculated by decreasing by a factor of 8 the rate coefficients for the deactivation of vibrationally excited molecules on the metallic surface, the vertical dashed line indicating the onset of the post-discharge regime.

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

M. Hopkins & K. N. Mellon, PRL **67** 449 (1991). / C. Gorse & M. Capitelli, Phys. Rev. A **46** 2176 (1992). / C. Michaut *et al*., Rev. Sci. Instrum. **65** 1207 (1994).
O. Fukumasa & M. Shinoda, Rev. Sci. Instrum. **69** 938 (1998). / T. Mosbach *et al*., PSST **7** 75 (1998).

01 Revisiting temporal filter (pulsing) technology

Fundamentals of Pulsing: Electron Cooling

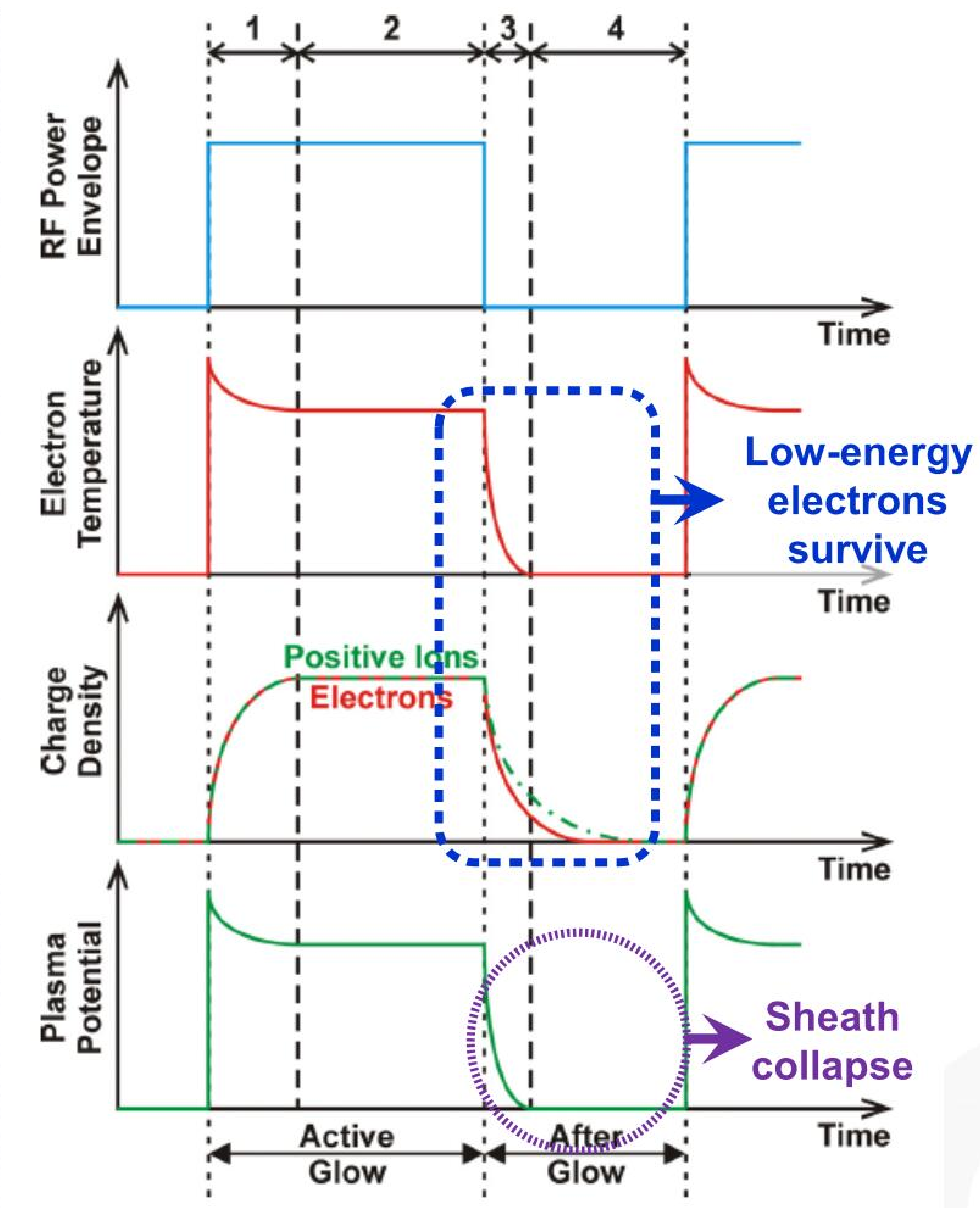
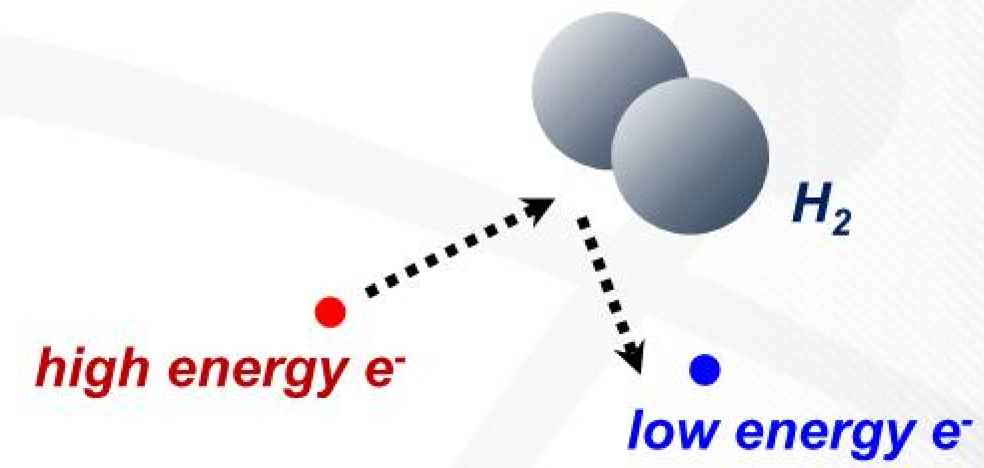


FIG. 3. (Color online) Time modulation of the RF power envelope, electron temperature, density of positive ions and electrons, and the plasma potential during pulsed plasma operation. Region 1 refers to the initial active-glow period, 2 refers to the steady-state active-glow period, 3 refers to the initial after-glow period, and 4 refers to the late after-glow period.

- **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

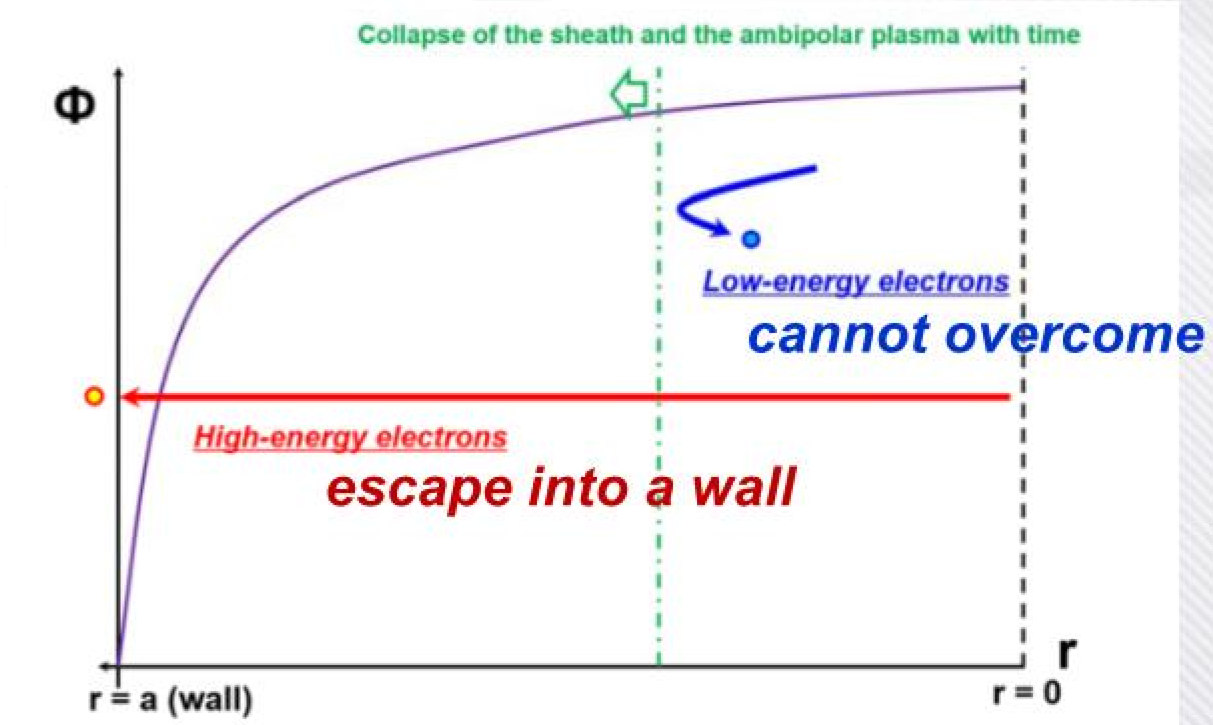


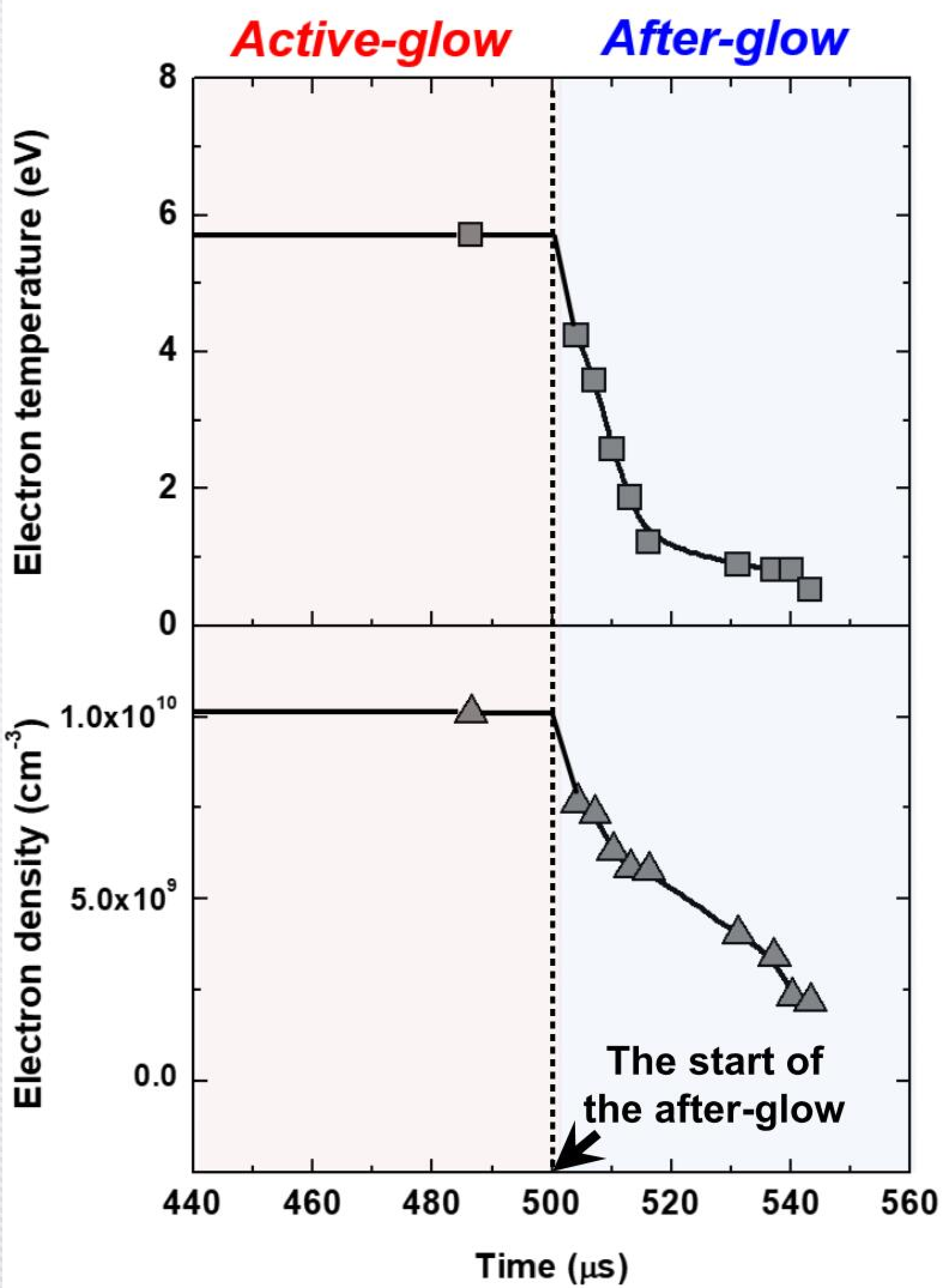
Figure 6.8 Schematic diagram of the diffusive cooling mechanism. Here, Φ is the potential, r = 0 is the radial position of the plasma center, and r = a is the radial position of a wall in the cylindrical plasma system.

S. Banna *et al*., J. Vac. Sci. Technol. A **30** 040801 (2010). / D. J. Economou, J. Phys. D: Appl. Phys. **47** 303001 (2014) .
S.-R. Huh, Ph.D. Dissertation, Seoul National University (2015).

01 Revisiting temporal filter (pulsing) technology

Fundamentals of Pulsing: d(EEDF)/dt

A preliminary experiment



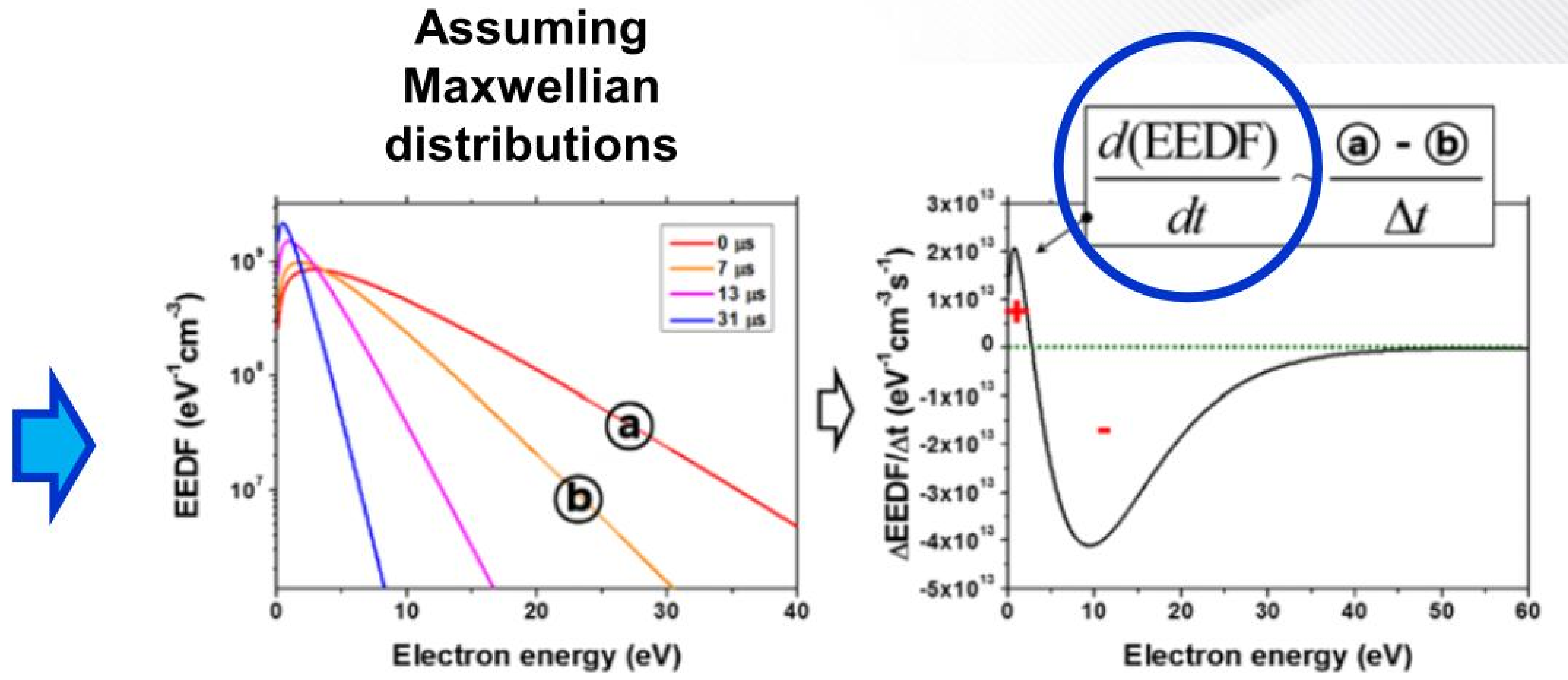


Figure 6.6 Schematic diagram for explanation of the newly devised d(EEDF)/dt – electron energy characteristic.

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

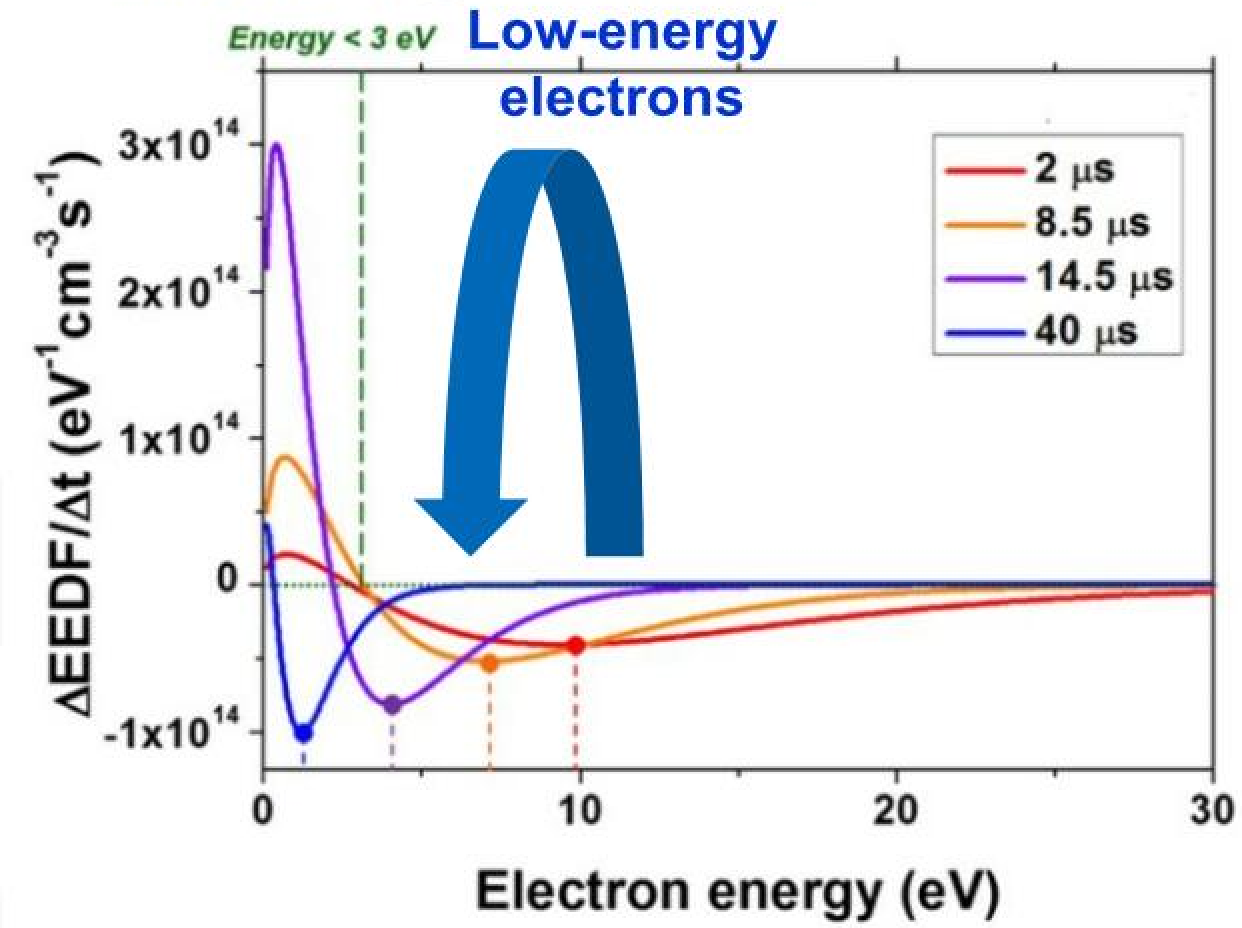


Figure 6.7 Experimental d(EEDF)/dt – electron energy characteristics at 2, 8.5, 14.5 and 40 μs after RF power is turned off.

In the early after-glow,
e_{low}: increase
e_{high}: decrease

S.-R. Huh, Ph.D. Dissertation, Seoul National University (2015).

01 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 $e^{-} + H_2 \rightarrow e^{-} + H_2(\nu \geq 5)$

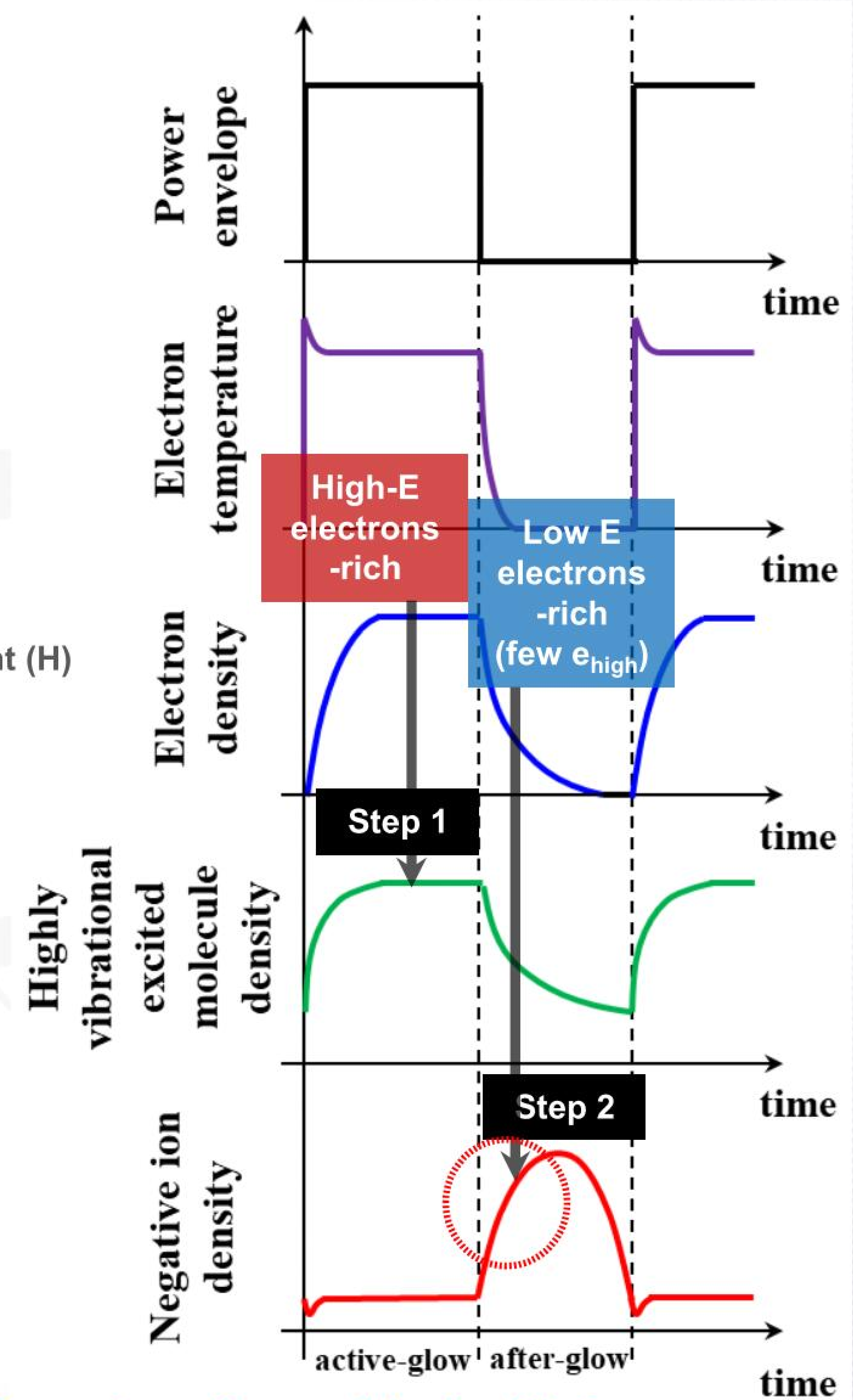
Step 2 low-energy $e^{-} + H_2(\nu \geq 5) \rightarrow H + H^{-}$

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" offers high- and low-energy electrons in accordance with the volume production mechanism while also lowing T_e and so the destructions of H^{-} ions.

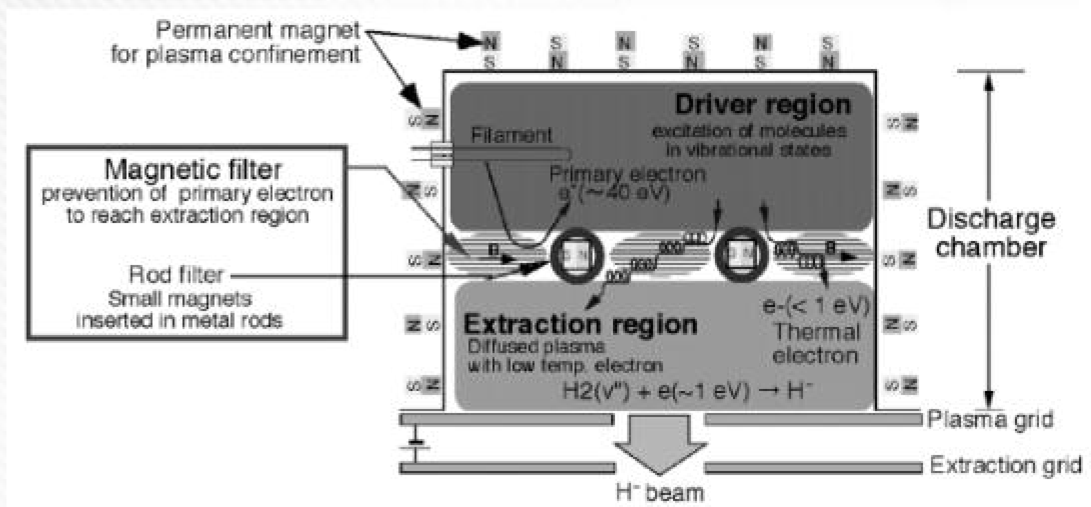


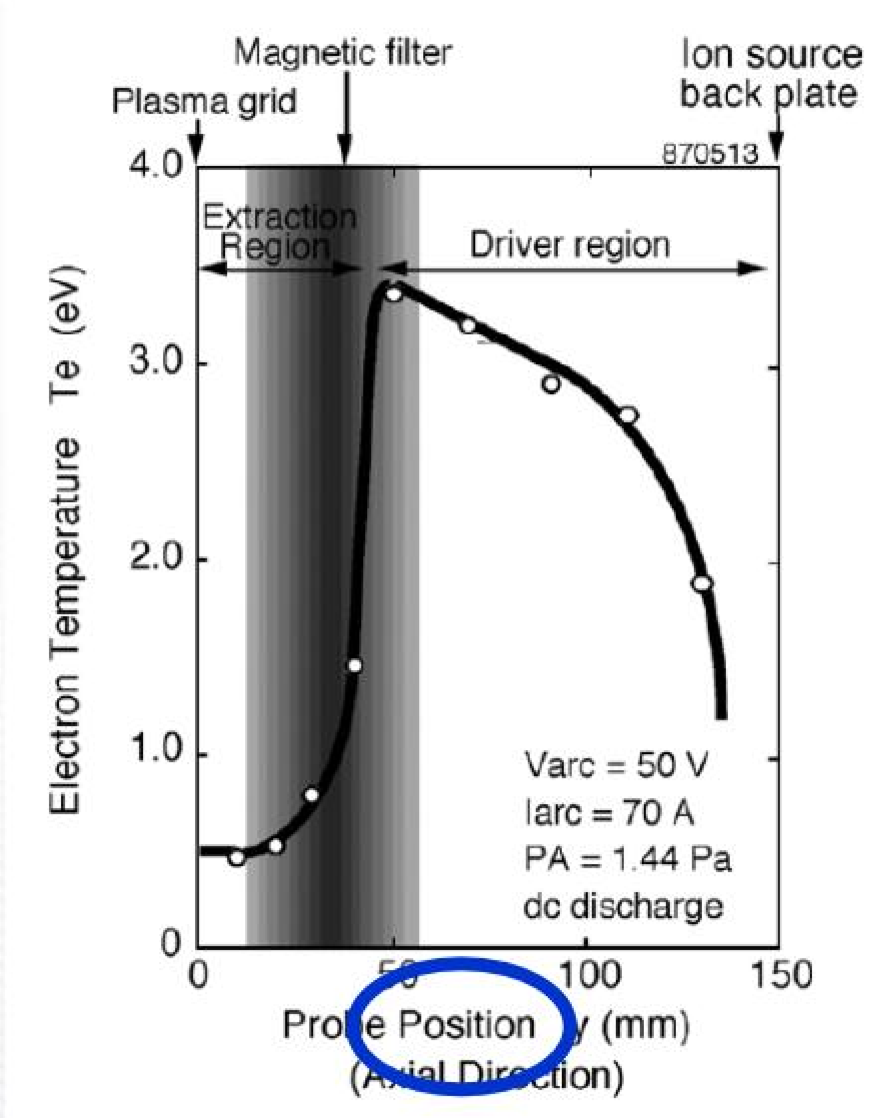
The early after-glow: favorable for H^{-} ions

S.-R. Huh *et. al.*, 2021, "Manuscript submitted for publication."

01 Revisiting temporal filter (pulsing) technology
Fundamentals of Pulsing: Filters

Magnetic filter: B-field





Temporal filter: After-glow

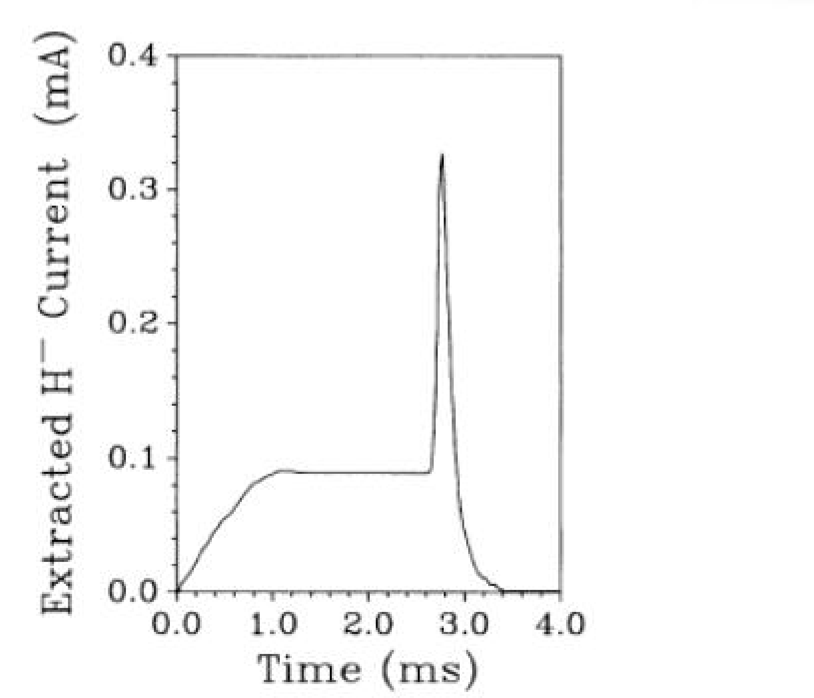
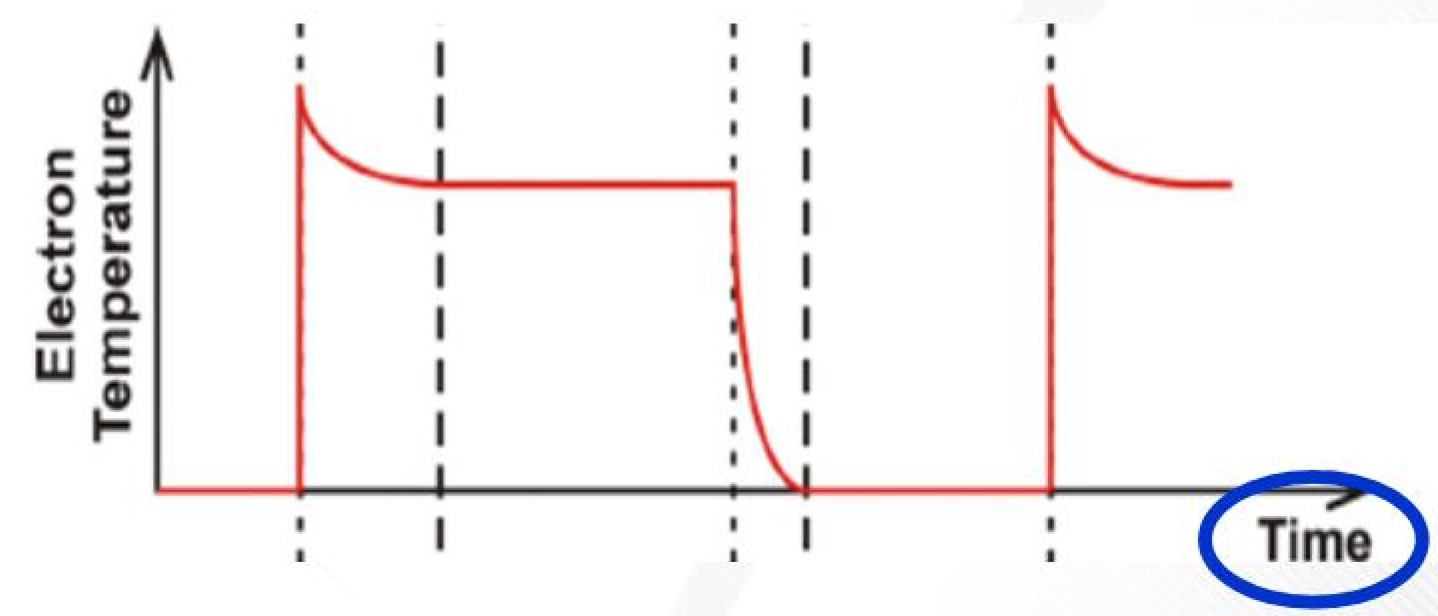


FIG. 2. The extracted negative-ion current from a pulsed hydrogen discharge. The gas pressure is 2.4 mTorr. The discharge pulse length is 2.7 ms and the repetition rate is 87 Hz. The discharge current $I_p = 15$ A.



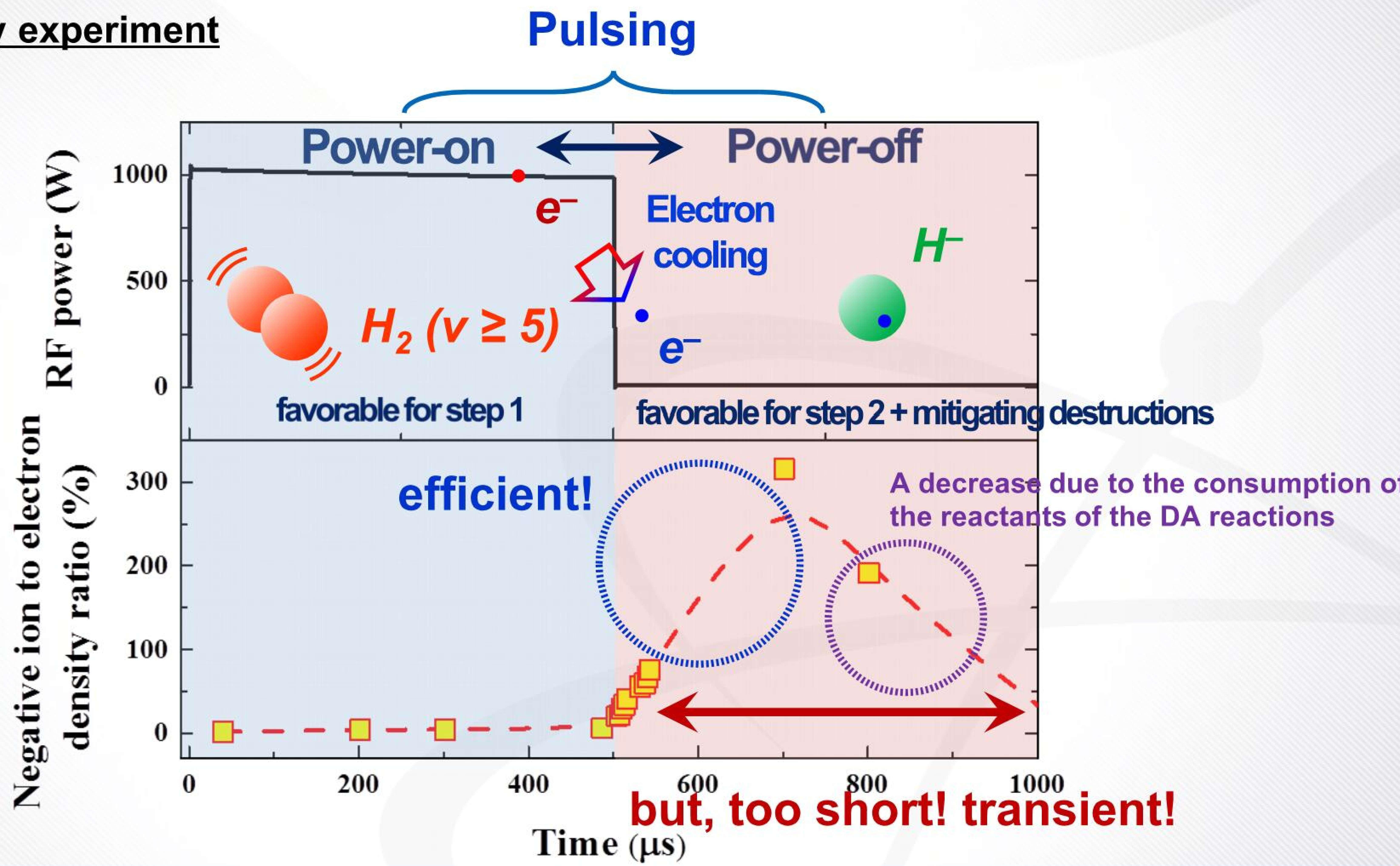
The high-energy electrons are filtered…

spatially (in space) **temporally (in time)**

R. S. Hemsworth and T. Inoue, IEEE Trans. Plasma Sci. **33** 1799 (2005). / M. Hopkins & K. N. Mellon, PRL **67** 449 (1991).
S. Banna *et al.*, J. Vac. Sci. Technol. A **30** 040801 (2010).

01 Revisiting temporal filter (pulsing) technology
Drawback of Pulsing: Short Duration

A preliminary experiment



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

2

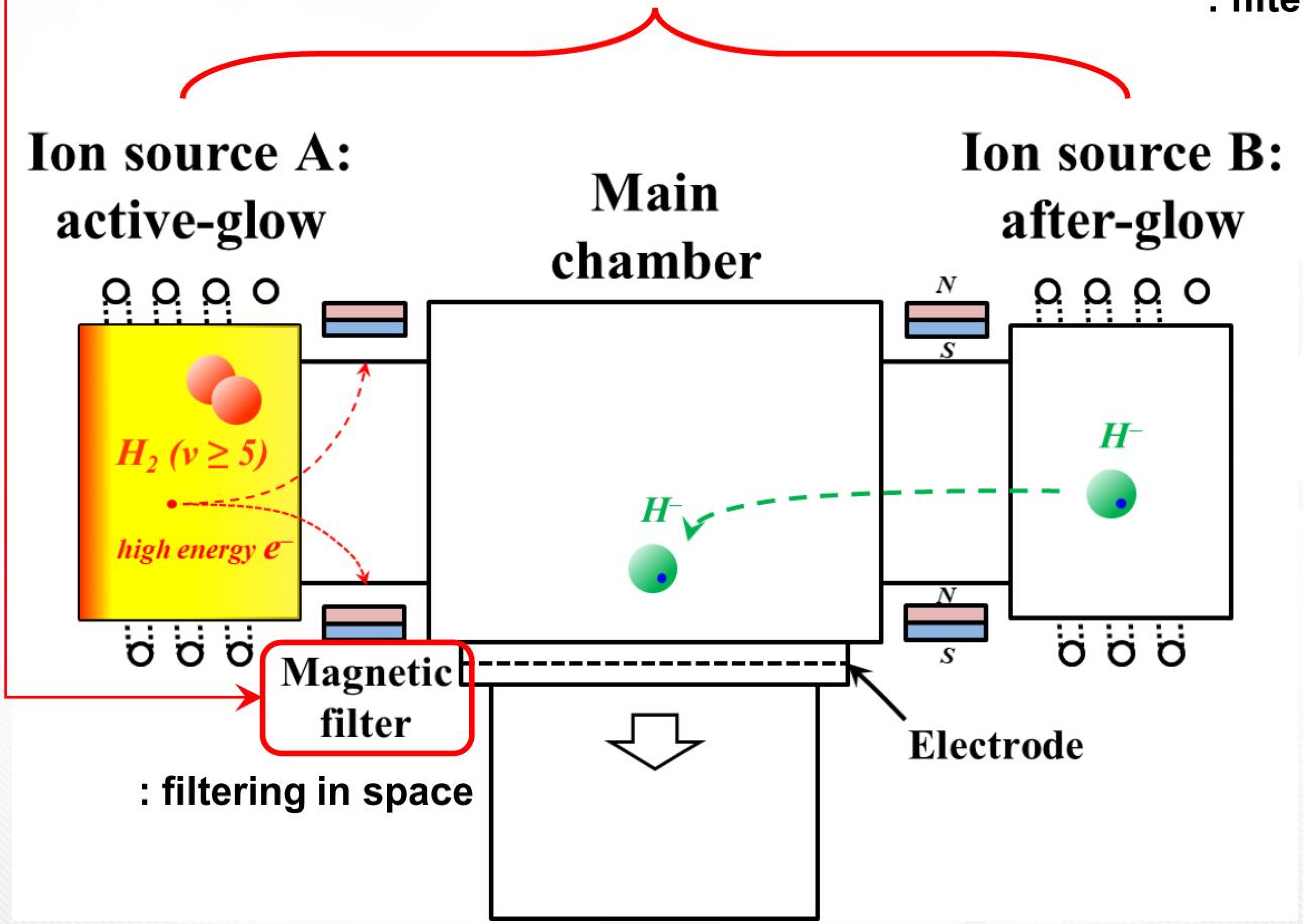
02 Ion source concept

H^- Ion Source System using Multi-pulsed Plasma Sources

» One main chamber (ion reservoir) + two pulsed plasma sources + two MFs

Spatiotemporal filter → Alternate dual pulsing (temporal filter)

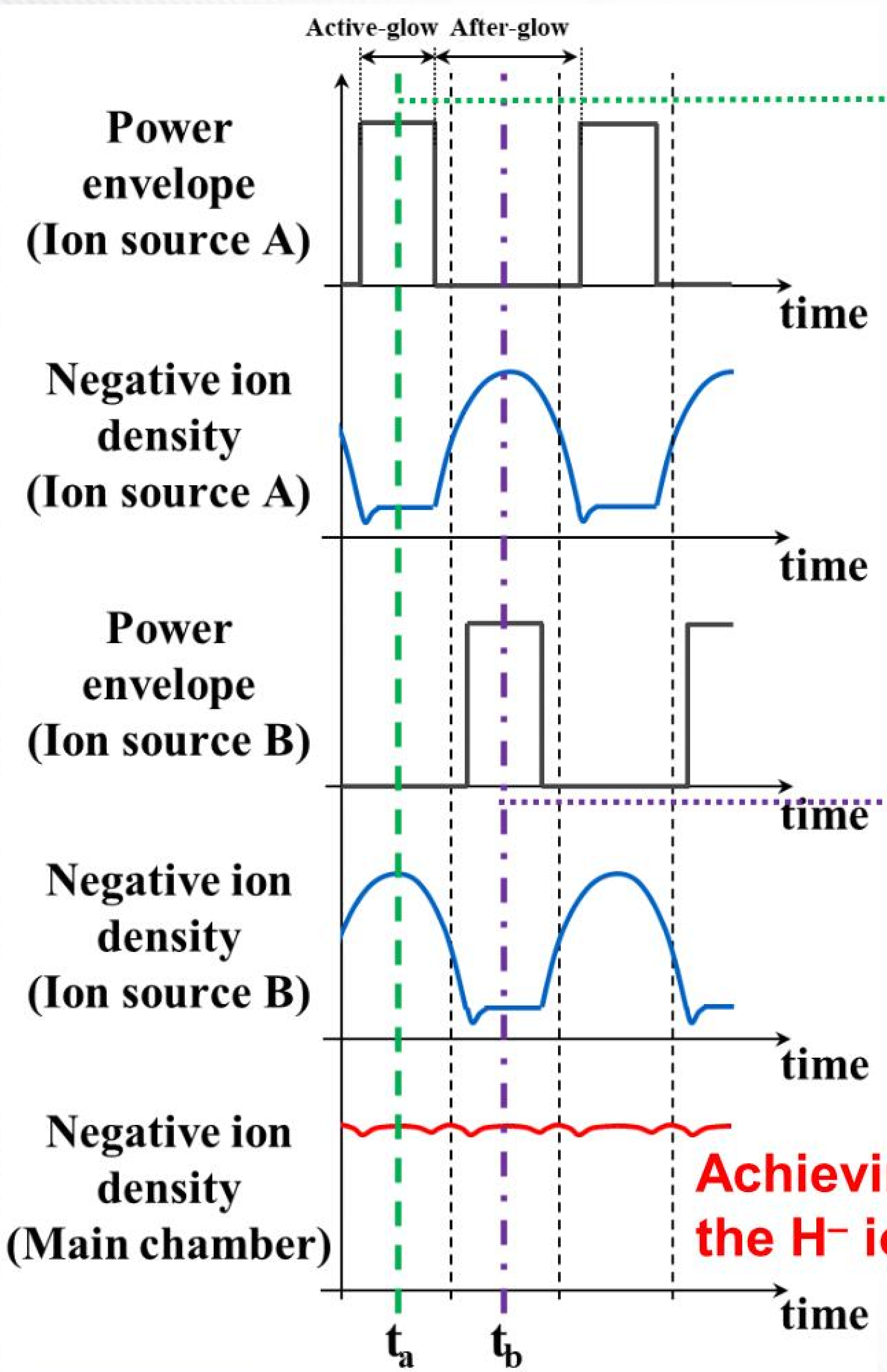
: filtering in time

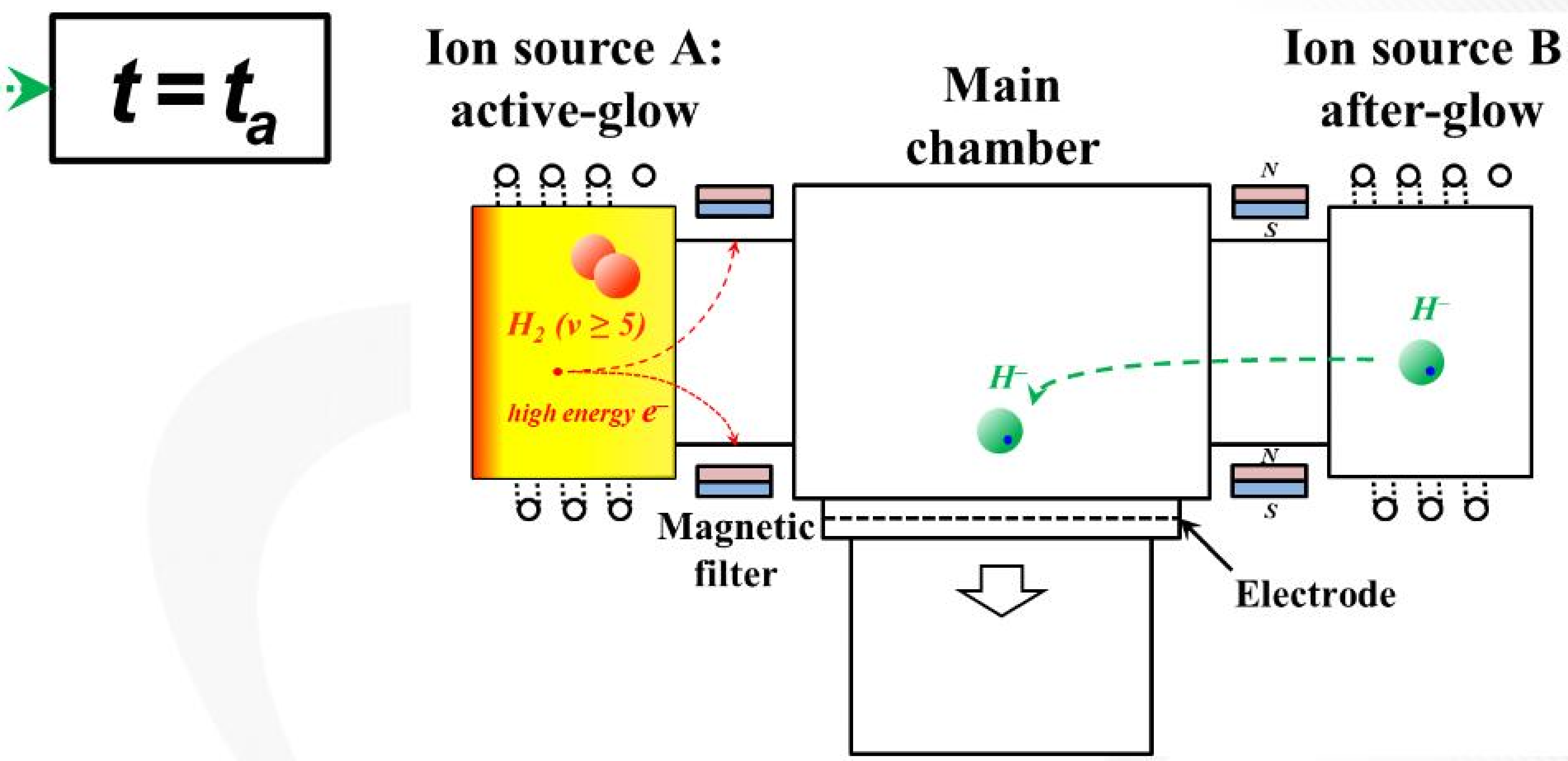


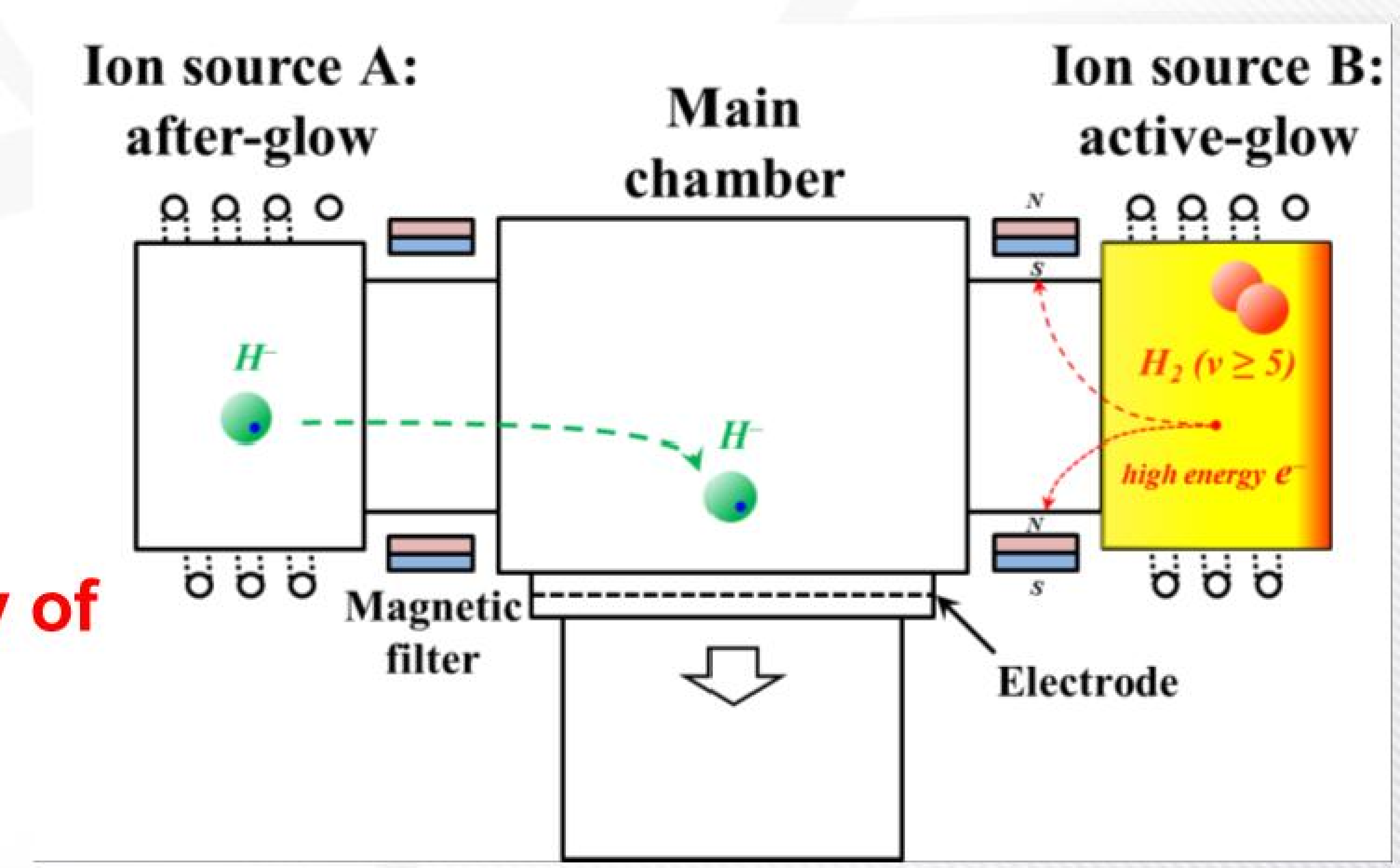
: filtering in space

02 Ion source concept
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.





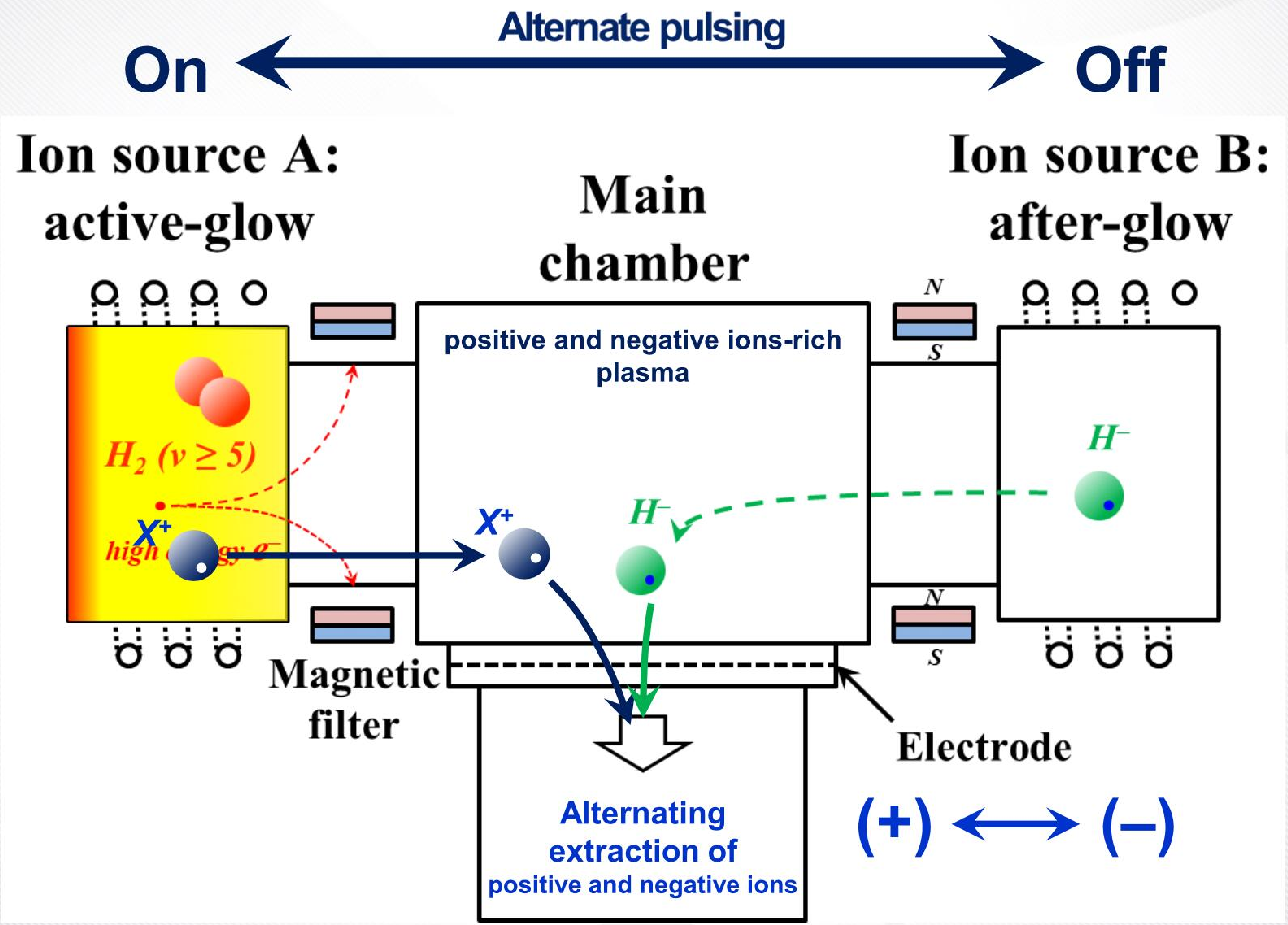


Achieving continuous supply of the H^- ions at high densities

S.-R. Huh *et. al.*, 2021, "Manuscript submitted for publication."

02 Ion source concept

Application: Alternating Extraction



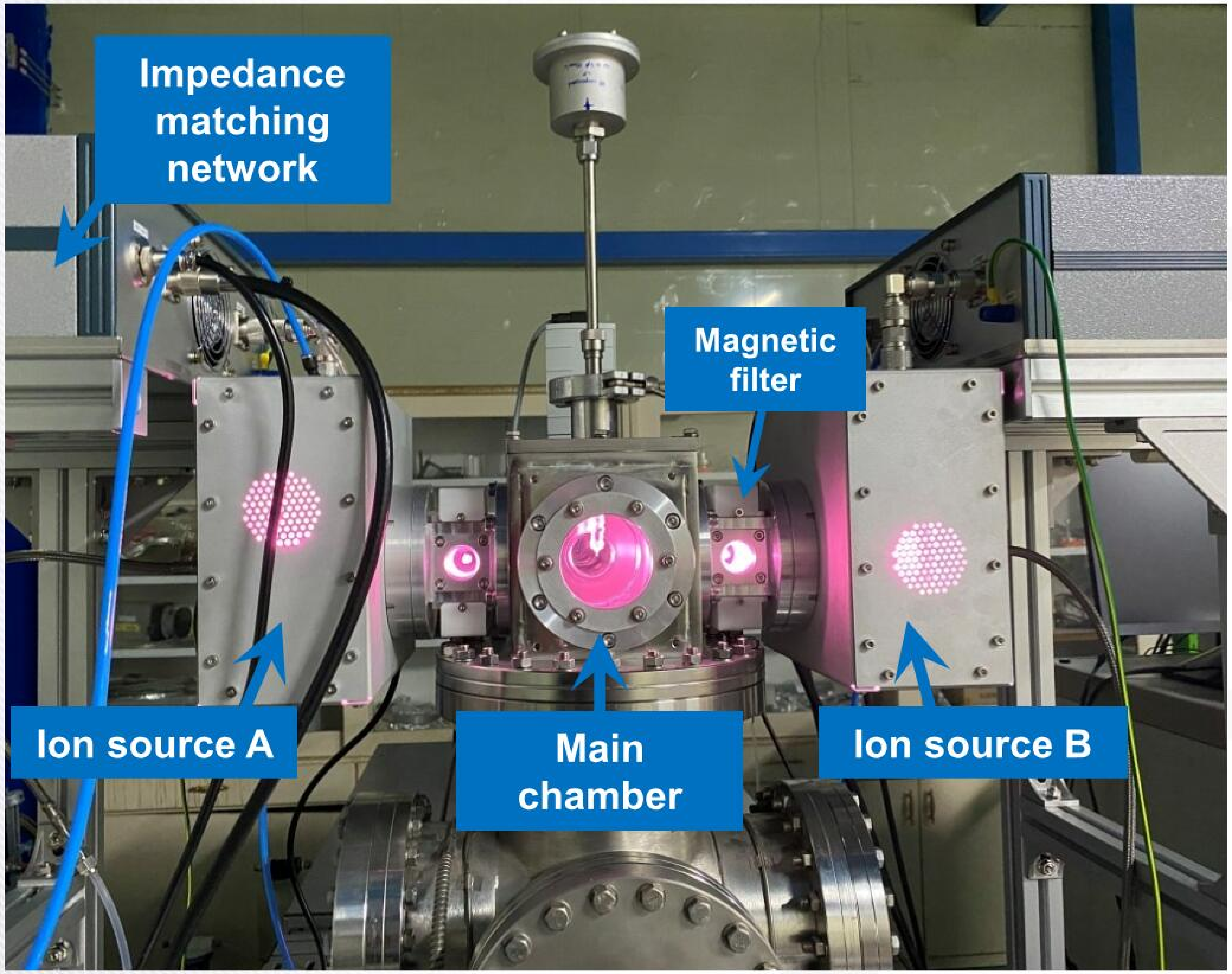
Ion Source Development (apparatus and diagnostics)

3

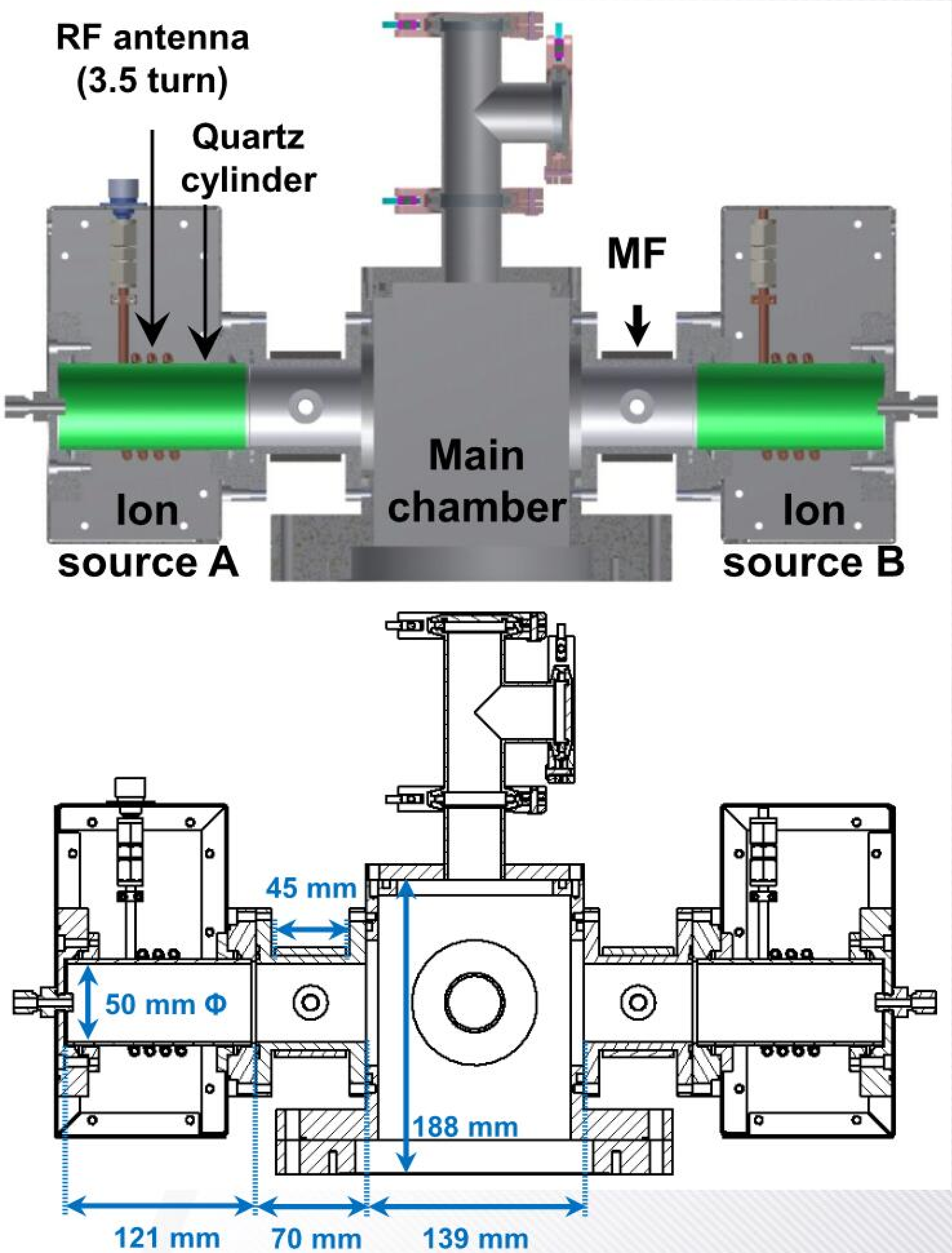
03 Experimental apparatuses for the proof-of-concept
KOMPASS II based on ICP: not used

» **KOMPASS**: KOrea atomic energy research institute Multi-Pulsing-Applied ion Source System

KOMPASS II



RF: 13. 56 MHz, Power: 900 W, pulse repetition frequency: 0.2~5 kHz

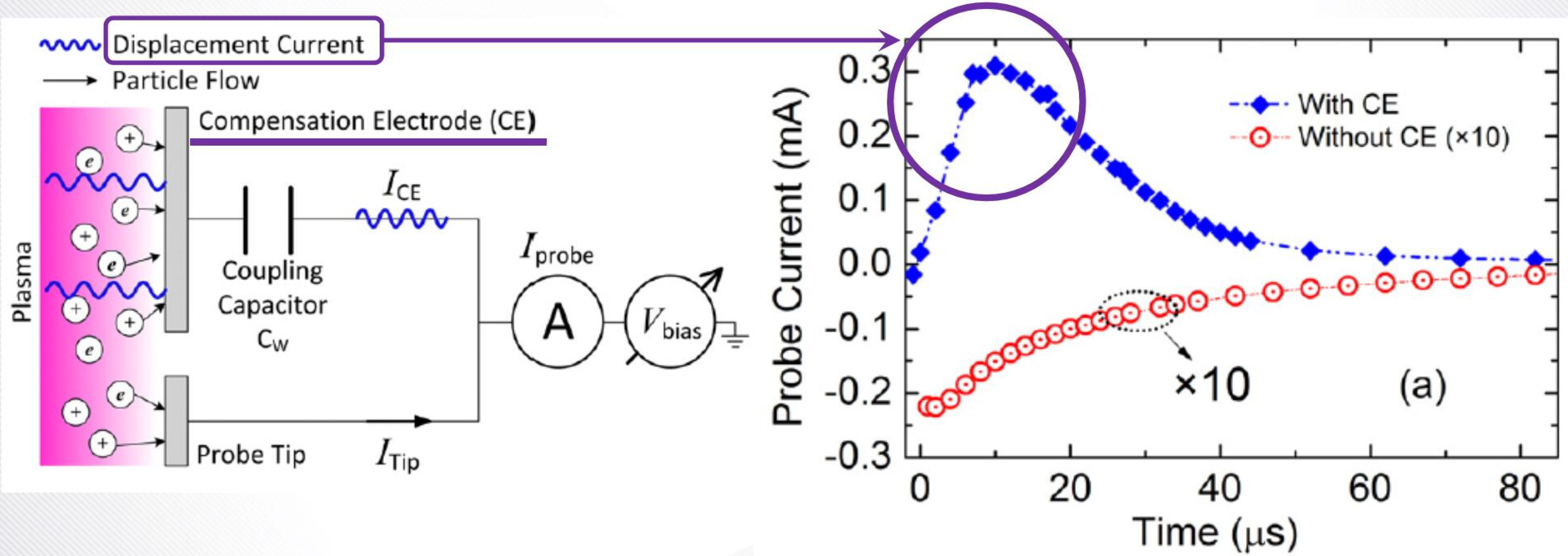


Not appropriate for experimental proof-of-concept. **Why?**

03 Experimental apparatuses for the proof-of-concept
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**

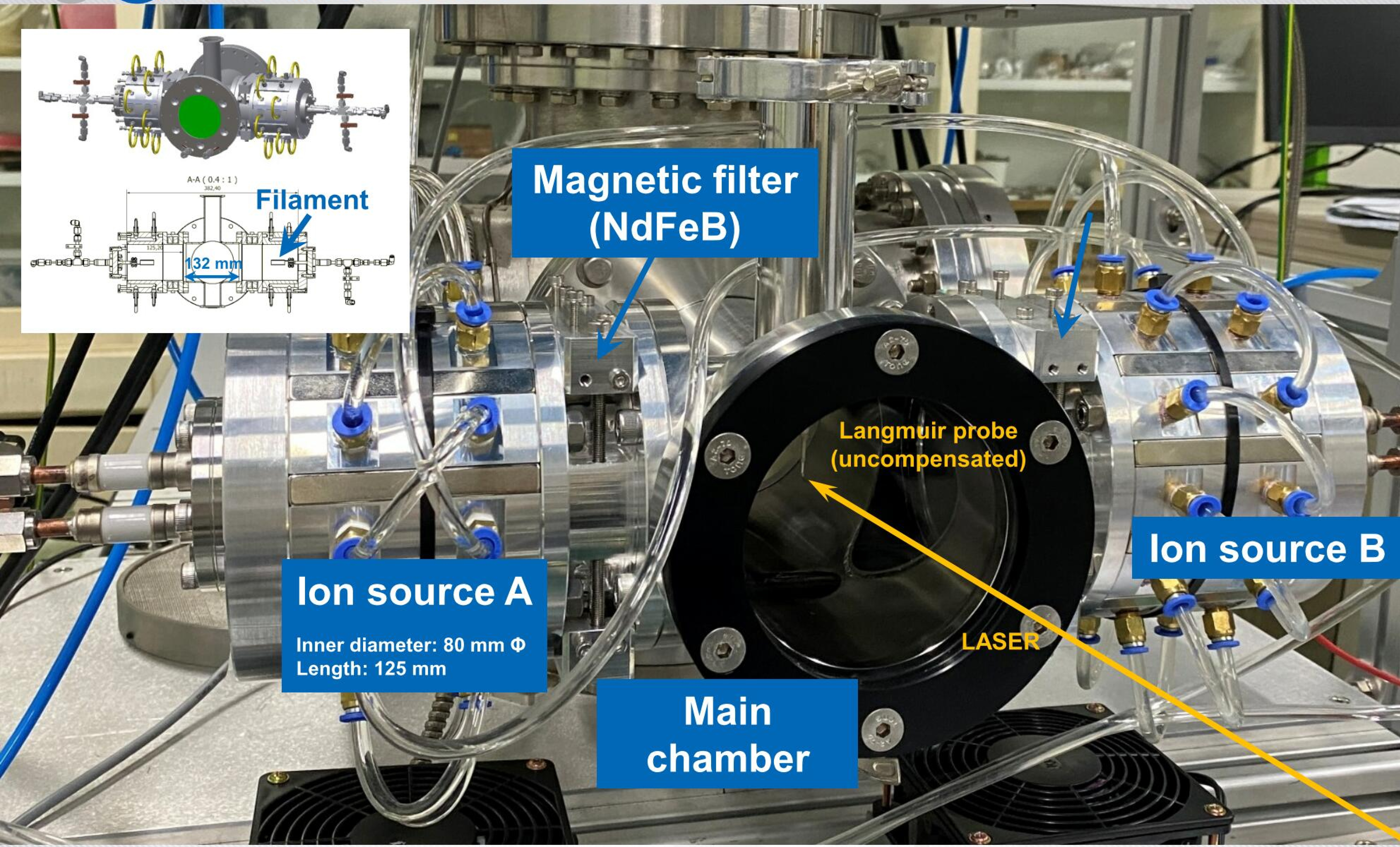
the **active-glow** in the RF-driven ion source: an **RF compensated probe**

the **after-glow**: an **uncompensated probe**

» **Avoidance of the dilemma: KOMPASS III (filament-driven DC arc ion sources)**

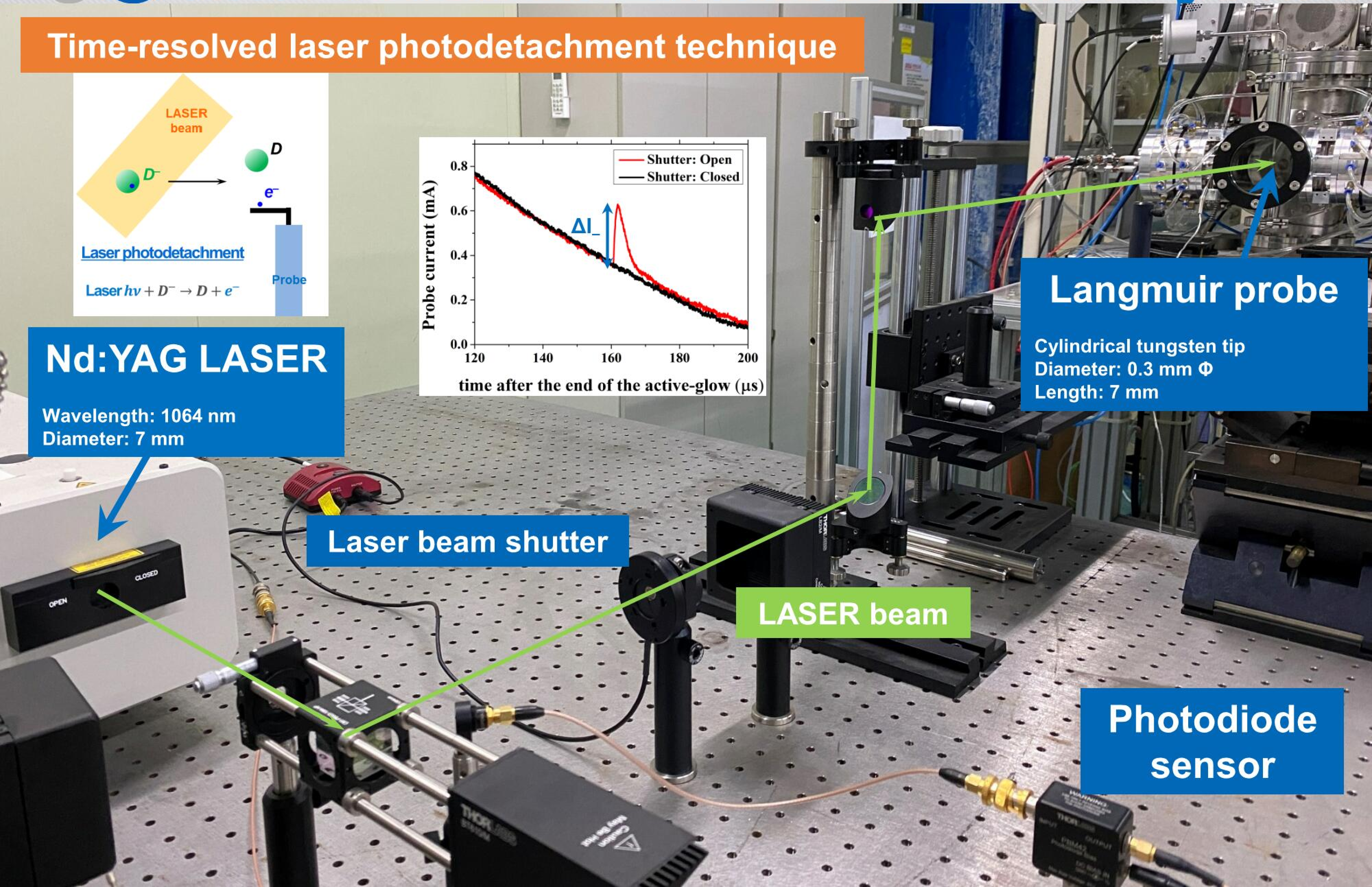
F.-X. Liu *et al.*, J. Phys. D: Appl. Phys. **47** 075201 (2014) .

03 Experimental apparatuses for the proof-of-concept
KOMPASS III w/ filament-driven DC arc ion sources



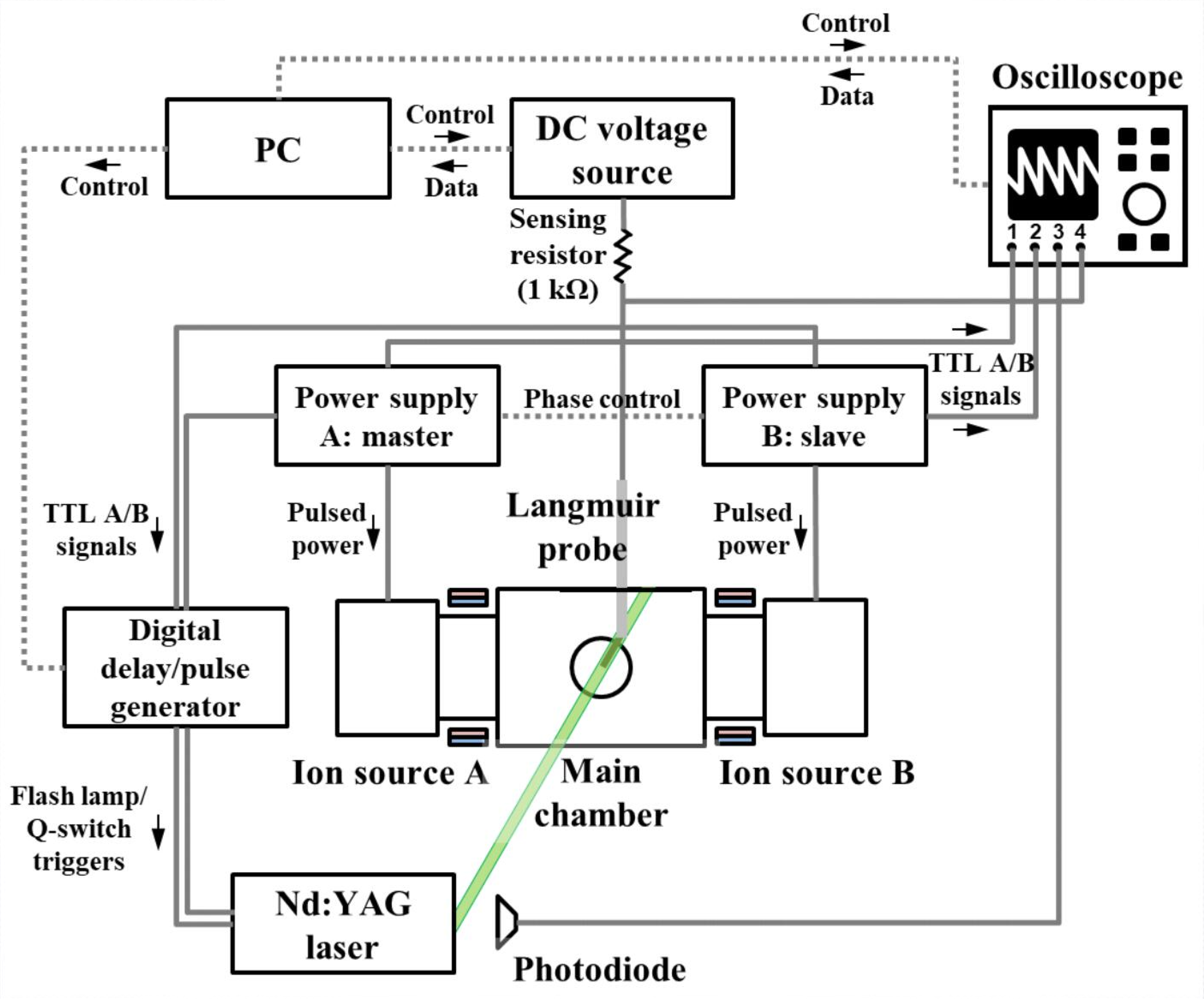
03 Diagnostics for measuring the negative ion current

Time-resolved ΔI_ Measurement System



03 Diagnostics for measuring the negative ion current

Time-resolved Measurement System



S.-R. Huh *et. al.*, 2021, "Manuscript submitted for publication."

Proof-of-concept Experiment

4

04 Results of an experimental proof-of-concept

(1) Single vs. Alternate Dual Pulsing

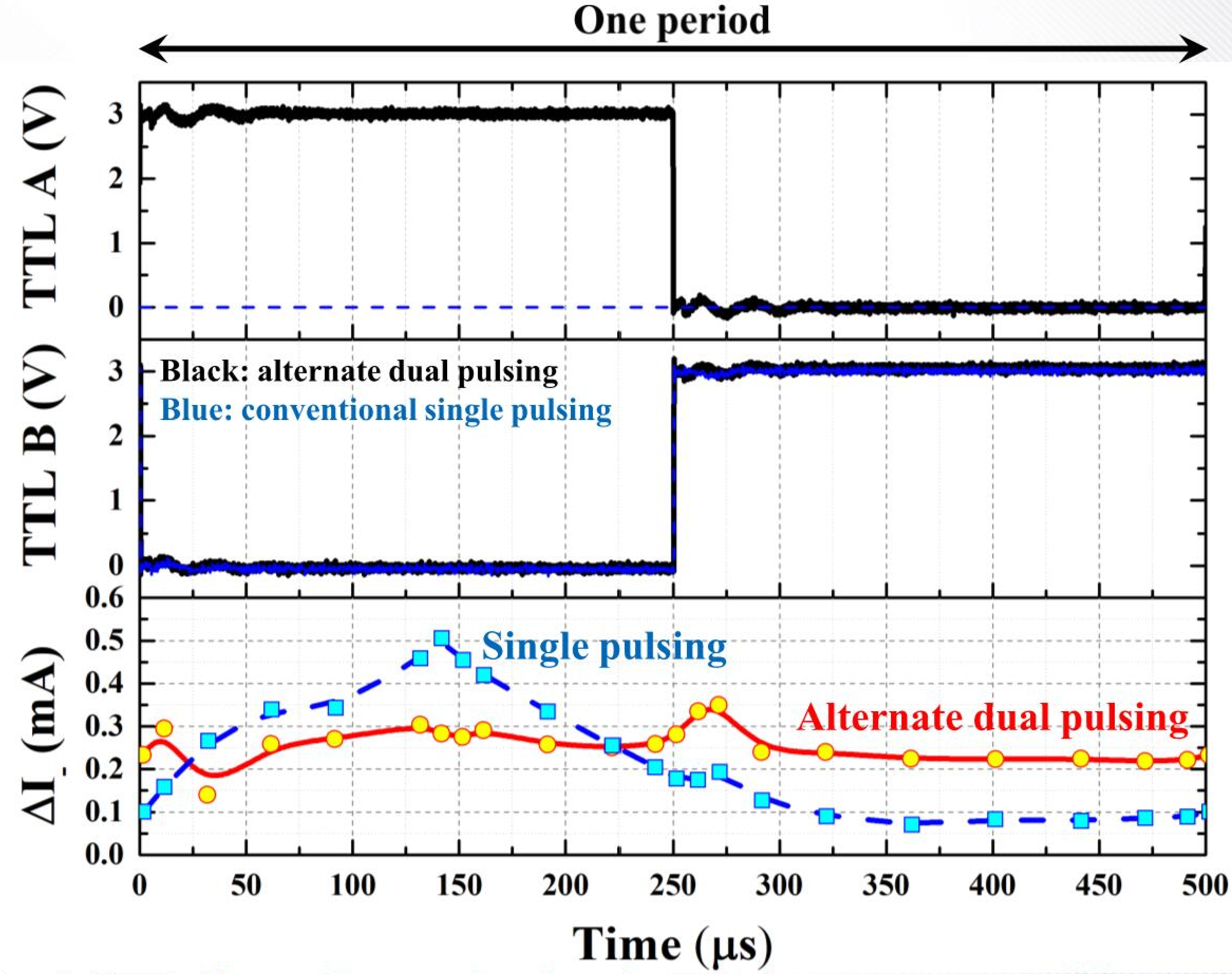
KOMPASS III (DC): 1 Pa D_2, PRF: 2 kHz, PDC: 50%, Peak power : 1100 W, $\Delta t_{A\text{-}B}$(dual): 250 μs (or Φ (phase shift) = π)

$B_{\perp, MF, max}$: ~ 130 G, Probe: @ center of the main chamber

Power pulse
(Ion source A TTL signal)

Power pulse
(Ion source B TTL signal)

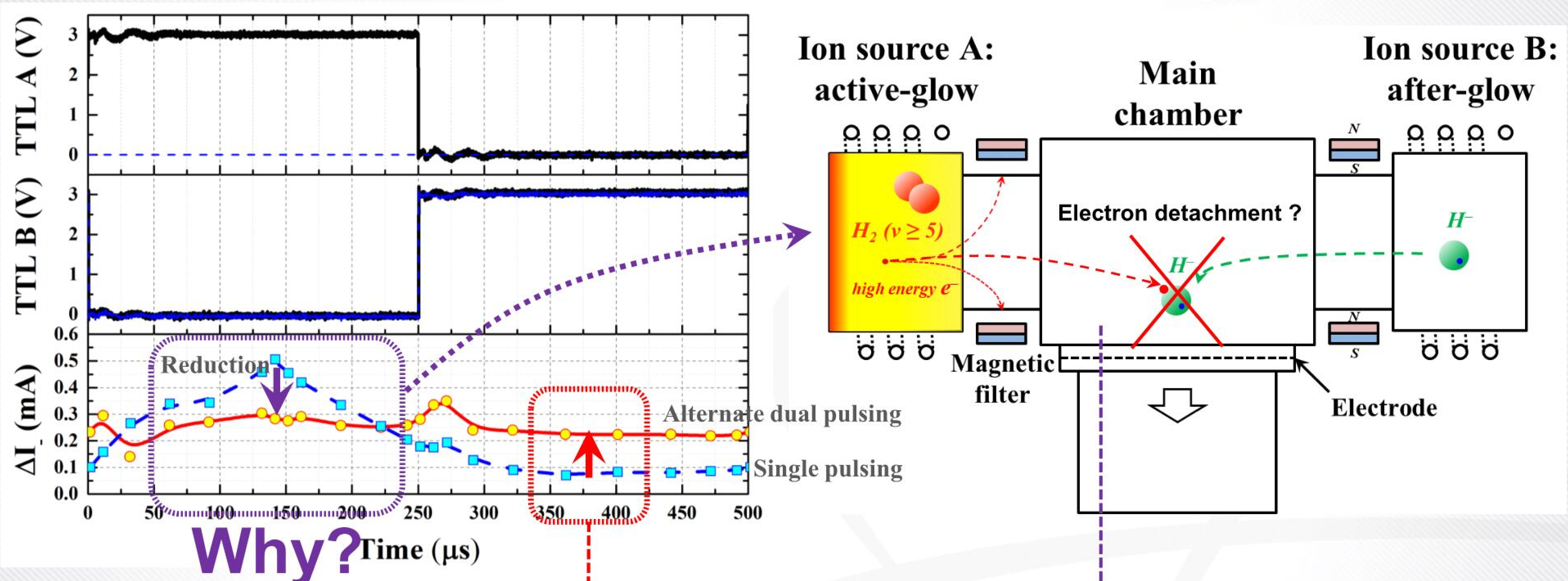
Negative ion current



» 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."

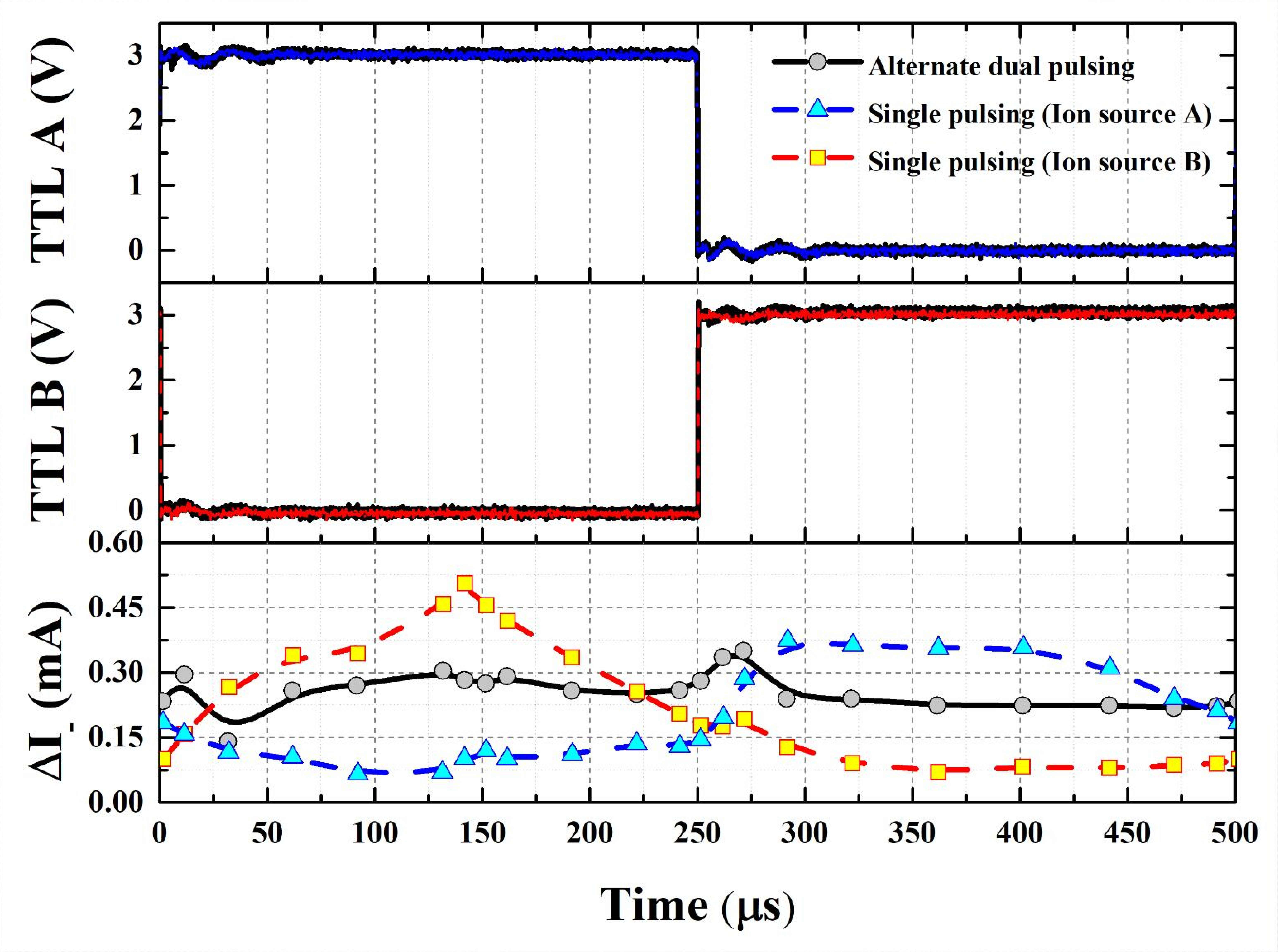
04 Results of an experimental proof-of-concept
(1) Efficiency and Discount



» 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

04 Results of an experimental proof-of-concept
(1) Tendency

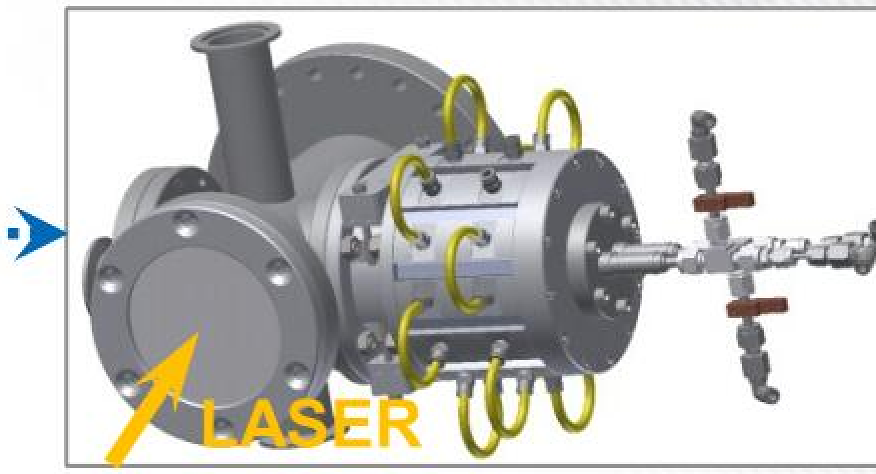


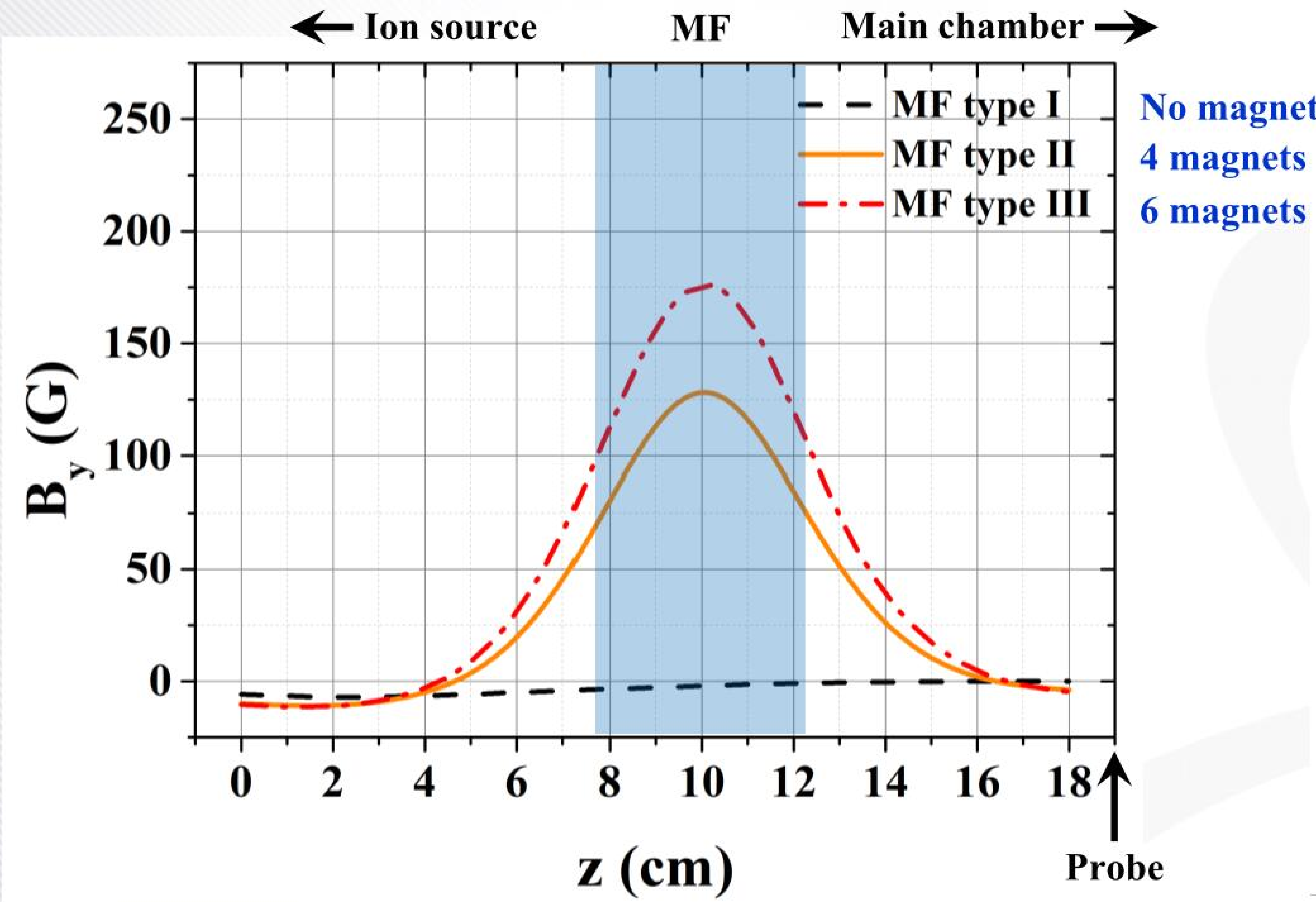
S.-R. Huh *et. al.*, 2021, "Manuscript in preparation."

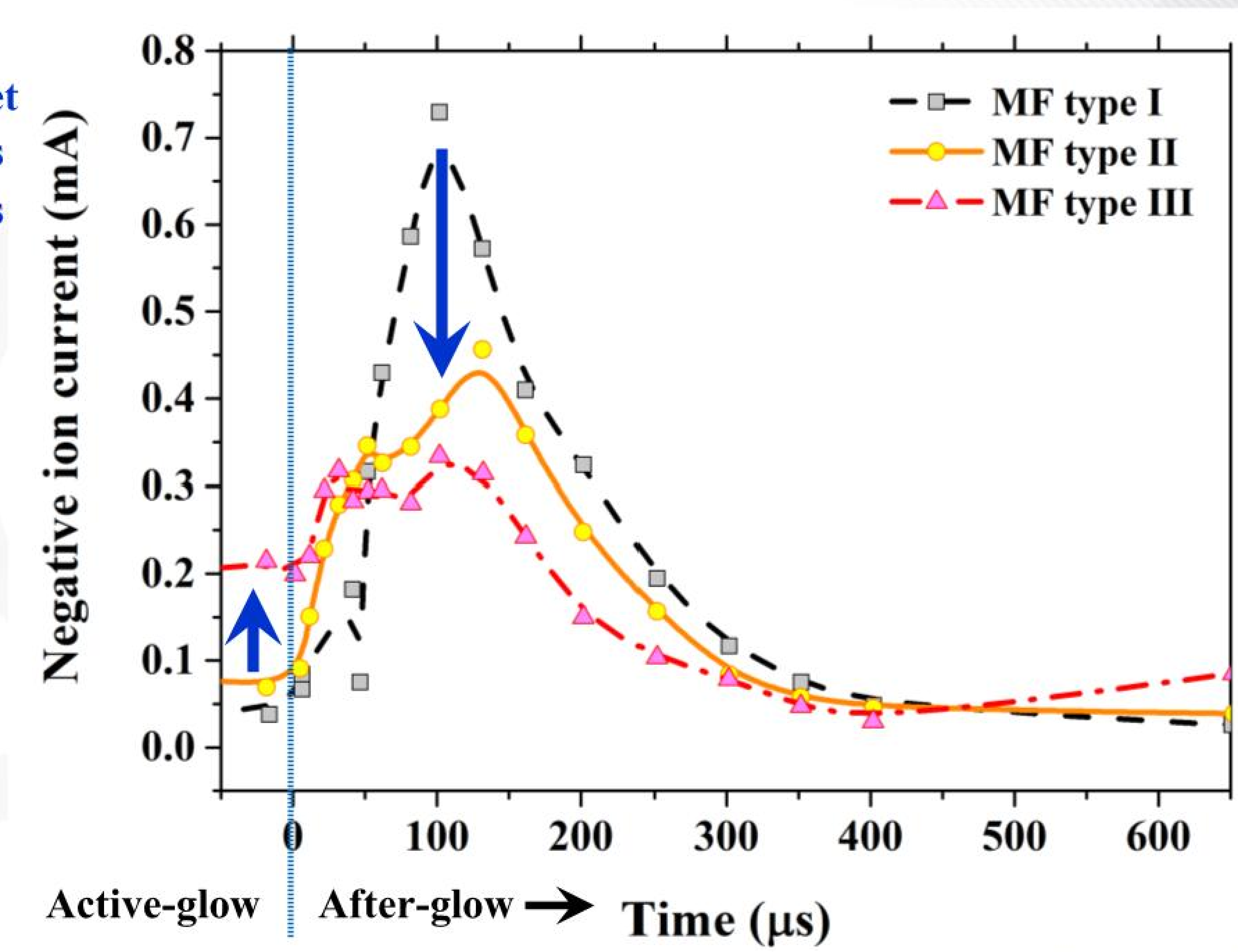
04 Results of an experimental proof-of-concept
(2) Effect of MF on Single Pulsing

KOMPASS III: 1 Pa D_2, 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?

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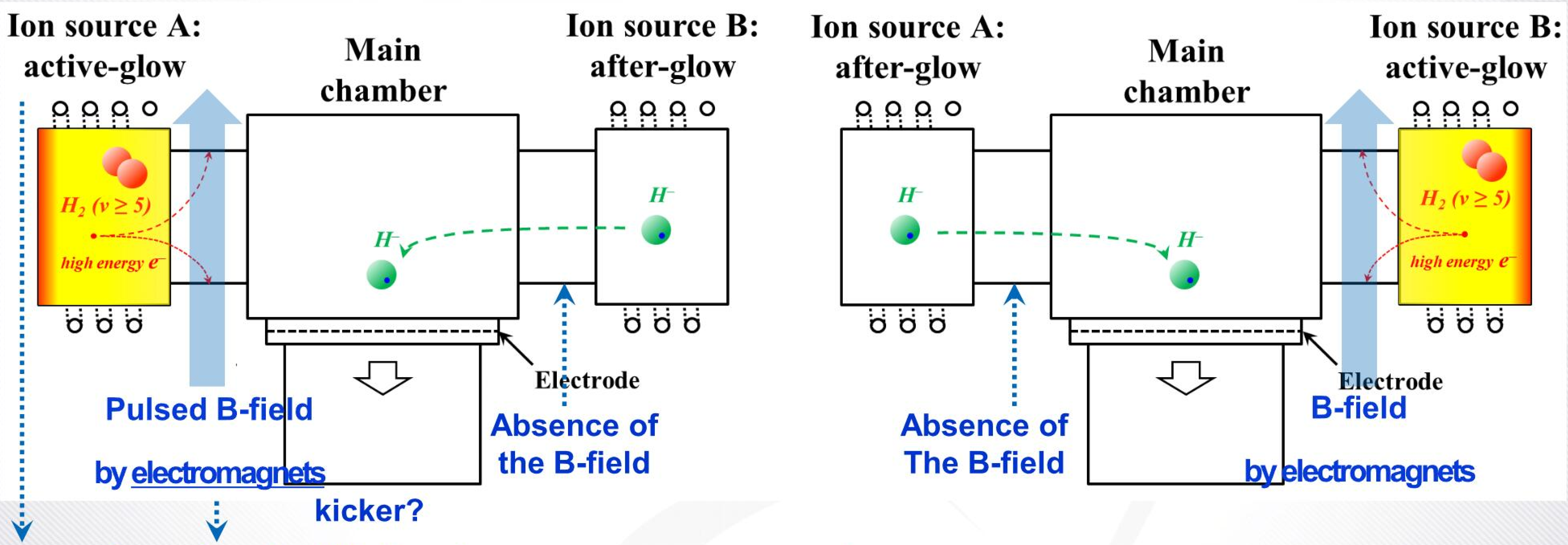
04 Results of an experimental proof-of-concept

(2) Idea: Synchronized Electromagnet MF

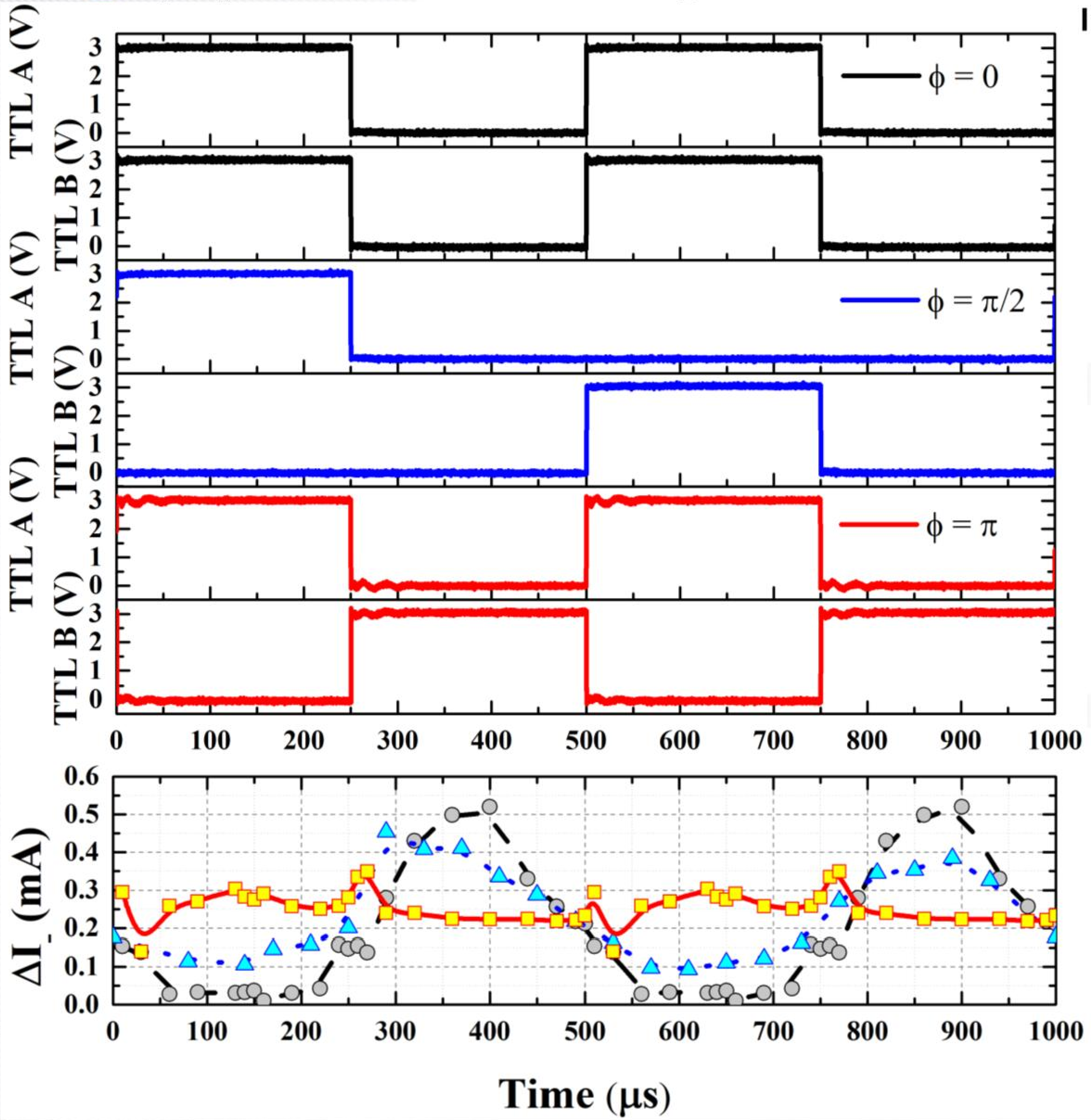


synchronized with the ion source power pulses

→ This may promote the system efficiency

04 Results of an experimental proof-of-concept

(3) Time Delay → Control Knob



In the alternate dual pulsing,

PRF: 2 kHz, PDC: 50%, $\Delta t_{A\text{-}B}$: 0 μs

PRF: 1 kHz, PDC: 25%, $\Delta t_{A\text{-}B}$: 500 μs

PRF: 2 kHz, PDC: 50%, $\Delta t_{A\text{-}B}$: 250 μs

Phase shift control: temporal variation

S.-R. Huh *et. al.*, 2021, "Manuscript in preparation."

Prospect and Challenges

5

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.**

05 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.

05 Prospect and Challenges

Concluding Remarks

- 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