高密度シートプラズマを用いたNBI加熱用非Cs型負イオン源の開発

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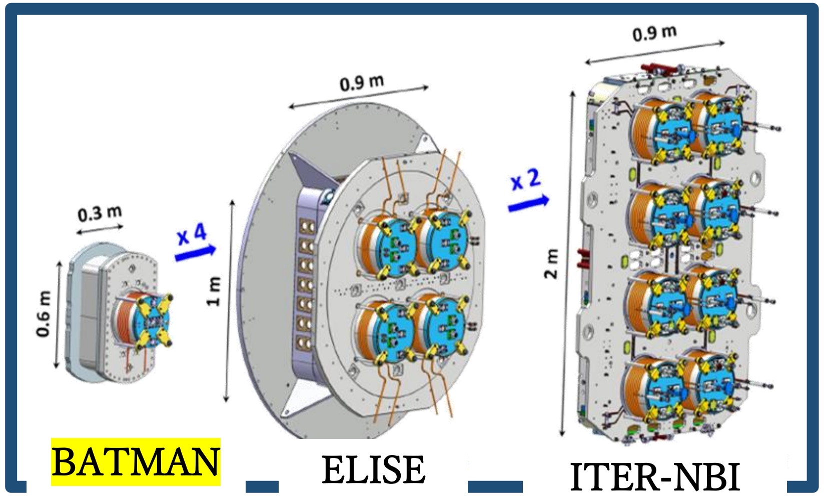
Prototype Cs-Free High Current Negative Ion Source

Ⅰ. Introduction

Most negative-ion sources of ITER-NBI use Cesium(Cs) to achieve a stringent requirements. However, regular maintenance of Cs becomes difficult in long-term operation. Therefore, there is an urgent need to develop an alternative negative ion source that does not contain Cs

Another issue common to the use of negative-ion sources is the reduction of extracted co-electron current ratio (J_{EG} / J_{H^-}) to prevent electric breakdown and to reduce the heat load on the second grid (External Grid: EG) of the extraction system.

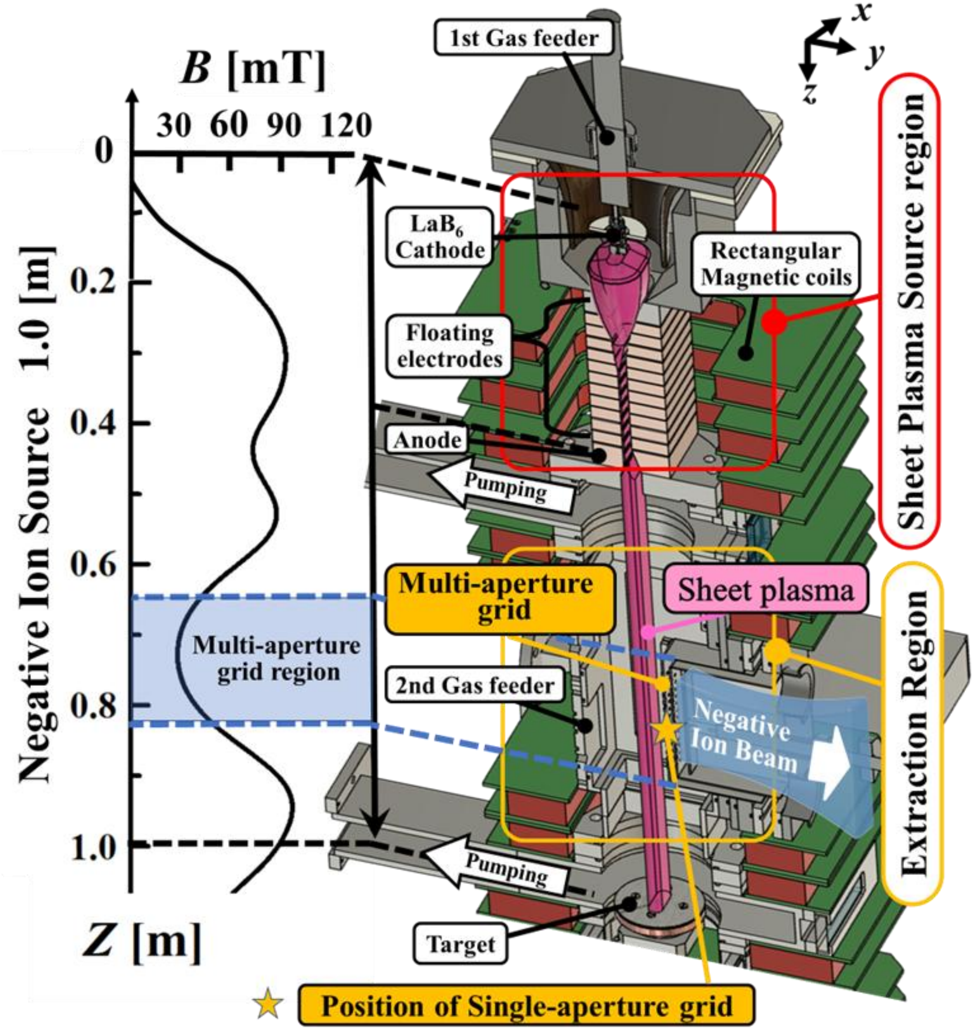
Development process of ITER-NBI



U. Fantz, *et al.*, *Nucl. Fusion* **57** (2017),

		(Target)	(Tokai Univ.	Next plan)
NBI system	**ITER**	**JA DEMO**	**TPDsheet-U**	**TPDsheet-N**
Cs seeding	**W/**	**W/⇒W/O**	**W/O**	**W/O**
Extracted H⁻ Beam	**33 (mA/cm²)**	**23 (mA/cm²)**	**Single hole ～10 (mA/cm²)**	**Multi hole 20 (mA/cm²)**
Current Ratio J_{EG}/J_{H^-}	**≦0.5**	**0.5～1.0**	**0.5～6.0**	**1.0～2.0**
Neutralization method	**Charge exchange**	**Optical**	**ー**	**Optical**

Ⅱ. Experimental apparatus
Cs-Free Negative Ion Source TPDsheet-U(using sheet plasma)



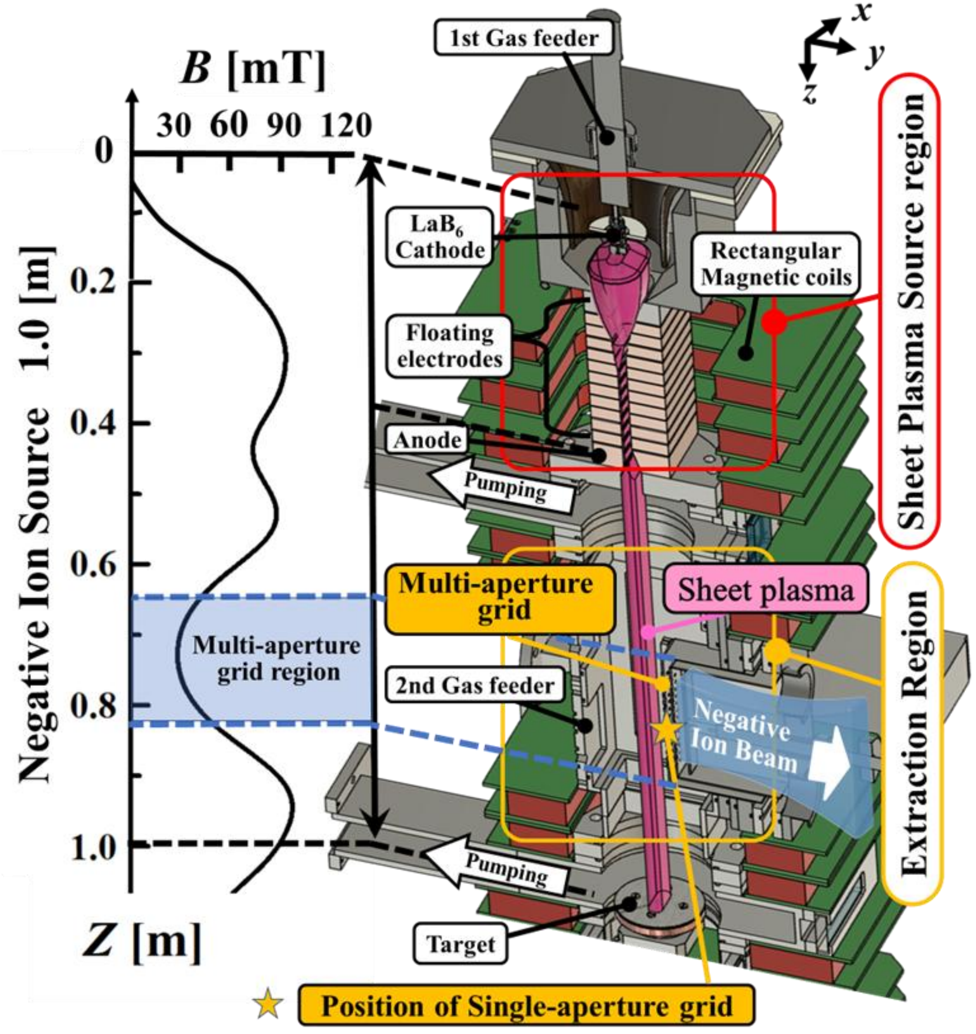
Cs-Free Negative Ion Source TPDsheet-U

High-density magnetized sheet plasmas are suitable for producing hydrogen negative ions in dissociative attachment processes because of the narrow spacing (10–30 mm) between high-energy (10–15eV) and low-energy (~1eV) electron regions.

Progress towards realizing a high-performance cesium (Cs)-free negative ion source based on volume production in a magnetized sheet plasma device (TPDsheet-U) has been reported in our group [1-4].

[1] K.Hanai, et. al., Fusion Eng. Des. 146 (2019) 2721.
[2] K.Kaminaga, et. al., Rev. Sci. Instrum. 91 (2020) 113302.
[3] K.Kaminaga, et. al., Fusion Eng. and Des. 168 (2021) 112676.
[4] A.Tonegawa, et. al., Nucl. Fusion 61 (2021) 106030.

Ⅱ. Experimental apparatus
Cs-Free Negative Ion Source TPDsheet-U(using sheet plasma)



Cs-Free Negative Ion Source TPDsheet-U

Previously, hydrogen negative ion current density is H⁻ of over ～10 mA/cm² were obtained at a gas pressure of 0.3 Pa using volume production in TPDsheet-U with a single-aperture grid.

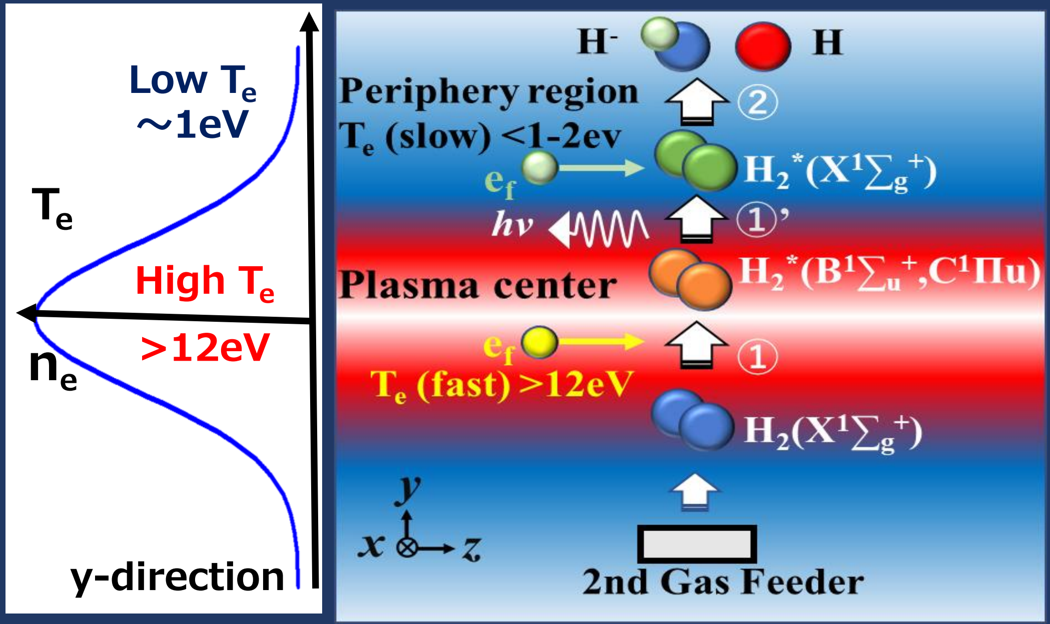
However, the extracted co-electron current ratio (J_{EG}/ J_{H^-}) is ~ 6 times the negative-ion current, and the thermal damage caused by this electron cause a problem in the long-operation of the negative-ion source TPDsheet-U.

The purpose of this study is to increase the negative ion current density and reduce the co-electron current by using the following two methods.

(1) Magnetic filter (SMF) method

(2) Second anode bias method

Ⅲ. Principle of volume production in sheet plasma



①Electron impact excitation

$$H_2(X^1\Sigma_g^+) + \underline{e_f\ (>12eV)}$$
$$\rightarrow H_2^*(B^1\Sigma_u^+, C^1\Pi_u) + e$$

①' Spontaneous radiative transition

$$H_2^*(B^1\Sigma_u^+, C^1\Pi_u) \rightarrow \underline{H_2^*(X\Sigma_g^+)} + h\nu$$

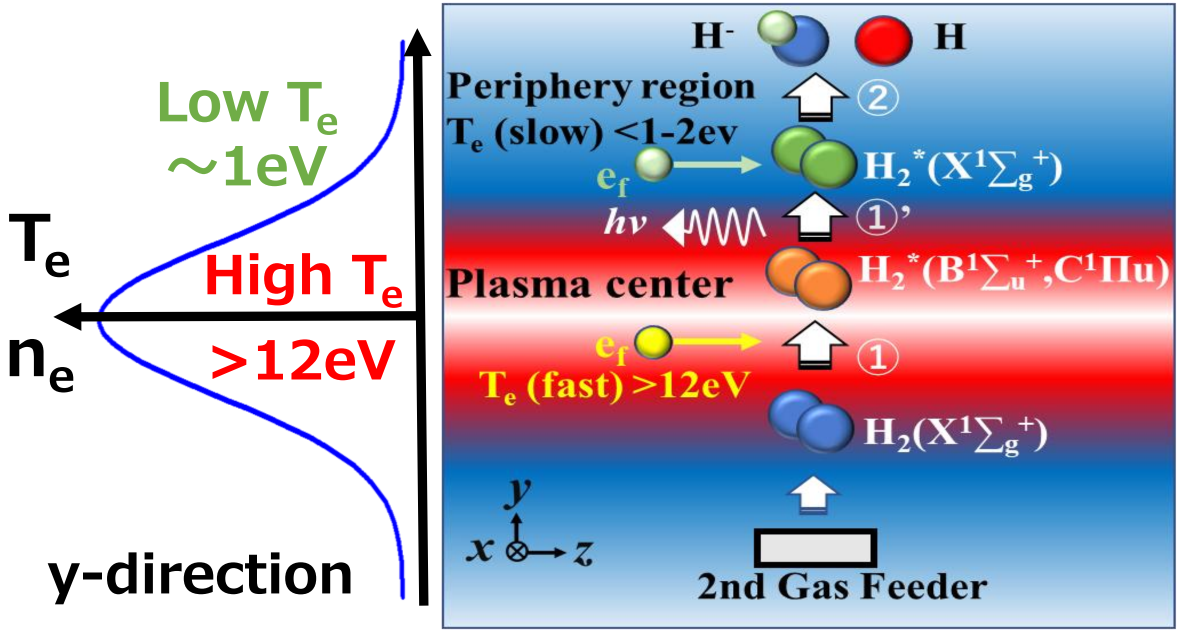
② <u>Dissociative attachment</u>

$$H_2^* + \underline{e_S\ (<1\text{-}2eV)} \rightarrow \underline{H^-} + H$$

In volume production, hydrogen negative ions are formed by the dissociative attachment (DA) of **low-energy electrons e(slow) (Te ~1eV)** to **highly excited molecules H_2^* (v”>5),** which are produced by the impact of high-energy electrons e(fast) (Te >12eV**)** in the plasma.

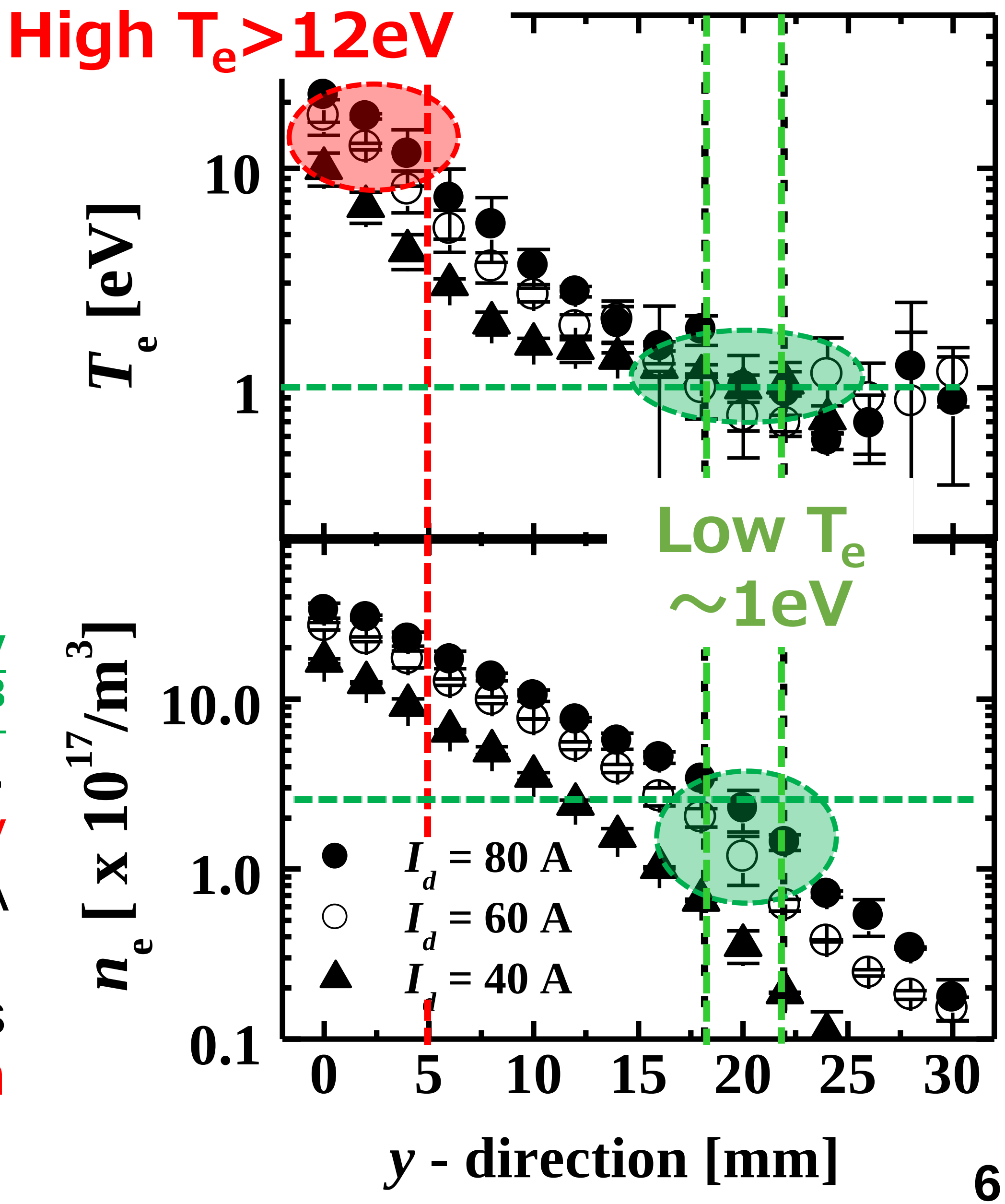
High-density magnetized sheet plasmas are suitable for producing hydrogen negative ions in DA processes because of the narrow space (10 – 30mm) between the high energy (10 ~ 15eV) and low energy (~ 1 eV) electron regions.

Ⅲ. Basic characteristics of sheet plasma

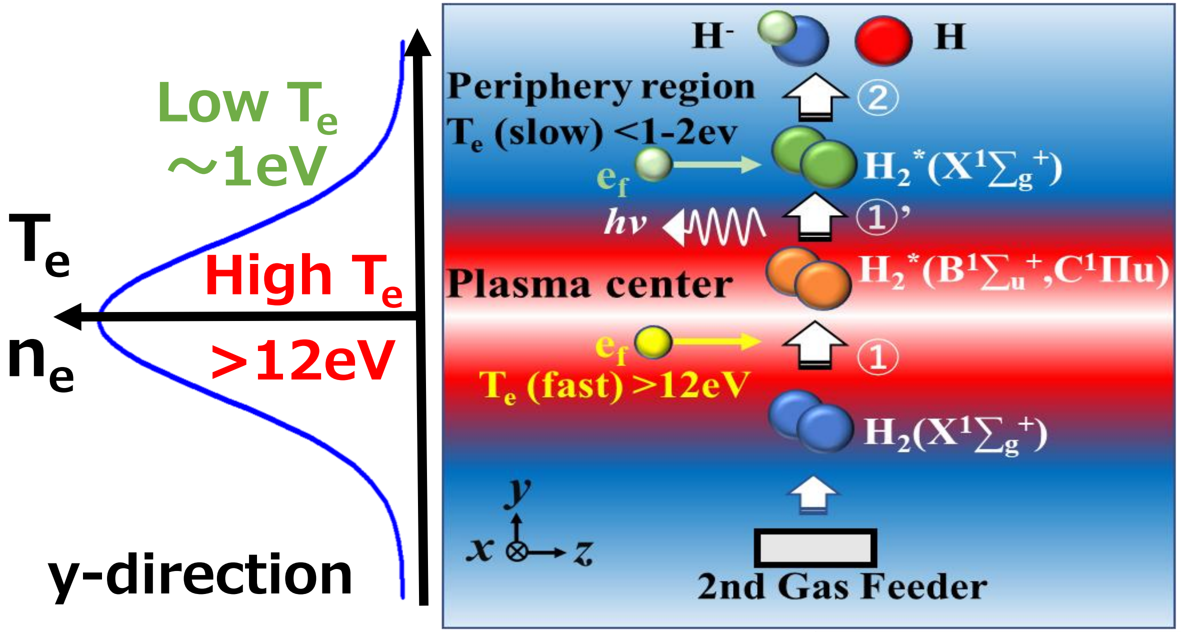


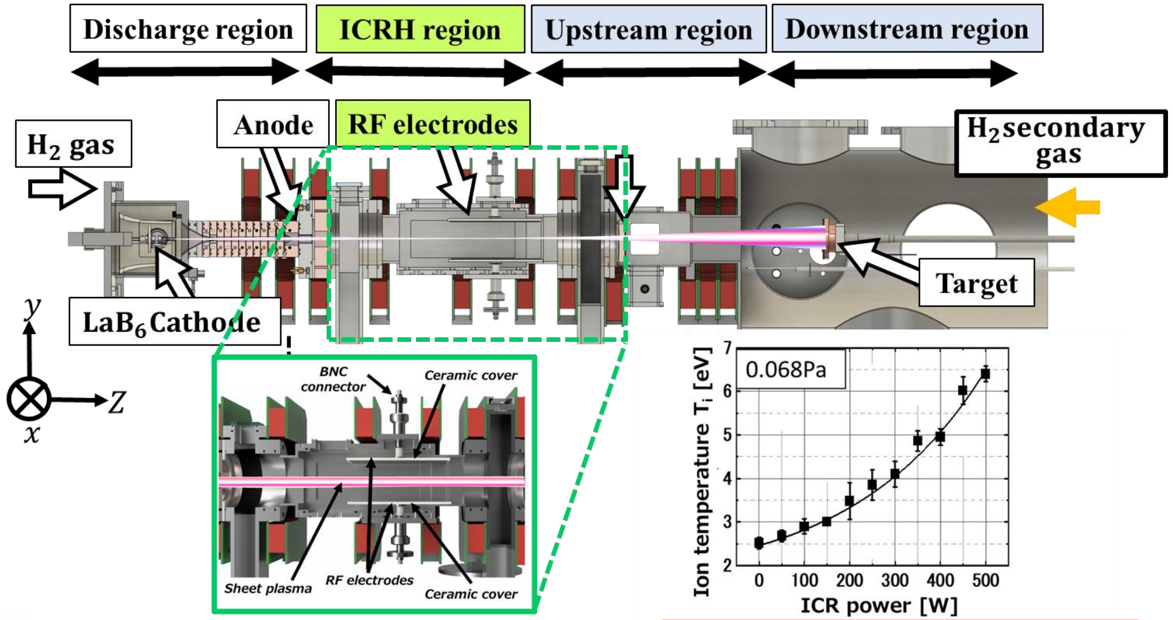
In magnetized sheet plasmas, low-energy electrons (~1eV) with densities exceeding 10^{17} m^{-3} exist close to the high-energy electrons (10-15eV). As a result, high-density negative ions are efficiently produced in the periphery of the sheet plasma by DA with vibrationally excited molecules H_2^*.

In addition, the sheet-like shape of the plasma is providing a large surface area suitable for a high current negative ion source.

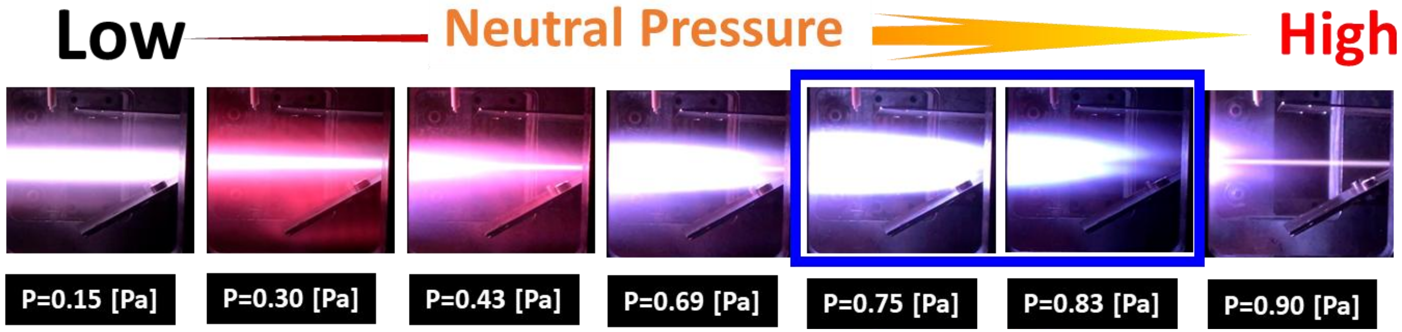


Ⅲ. Applications of sheet plasma to other research fields





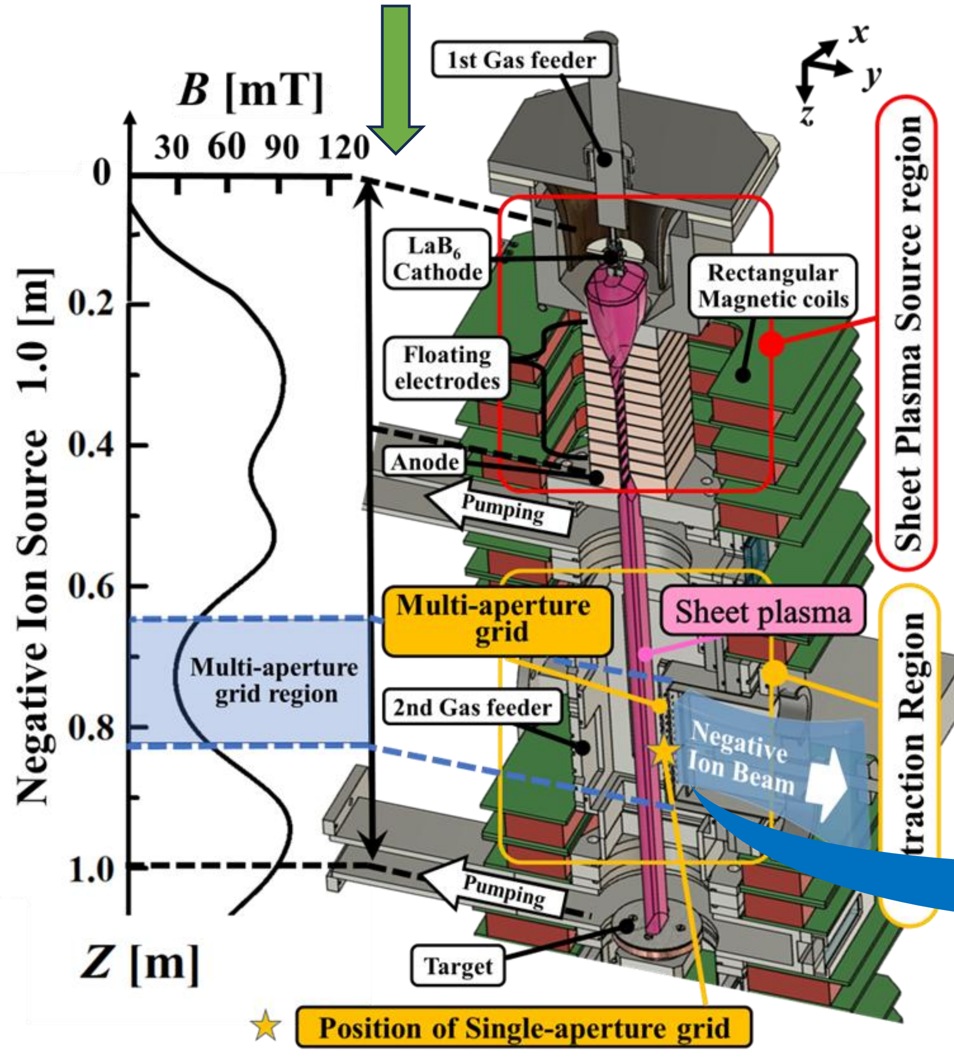
High efficiency ICR heating



Sheet plasma has also been applied to detachment plasma research of fusion divertor and electric propulsion for satellites.

A.Tonegawa, *et al*, Fusion Eng. & Des, 203 (2024) 114441.
A.Tonegawa, *et al*, Nucl. Materials & Energy, 41(2024) 101802.

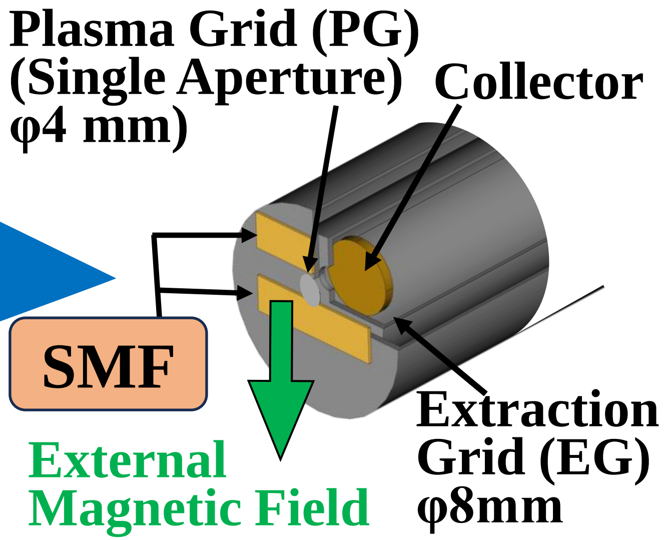
Ⅳ. Experimental results (1) Magnetic filter (SMF) method

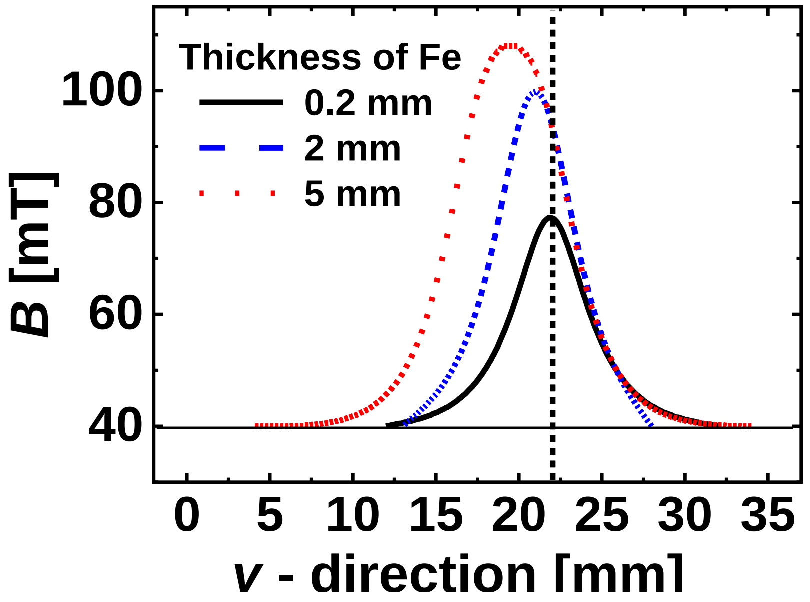


Cs-Free Negative Ion Source
TPDsheet-U

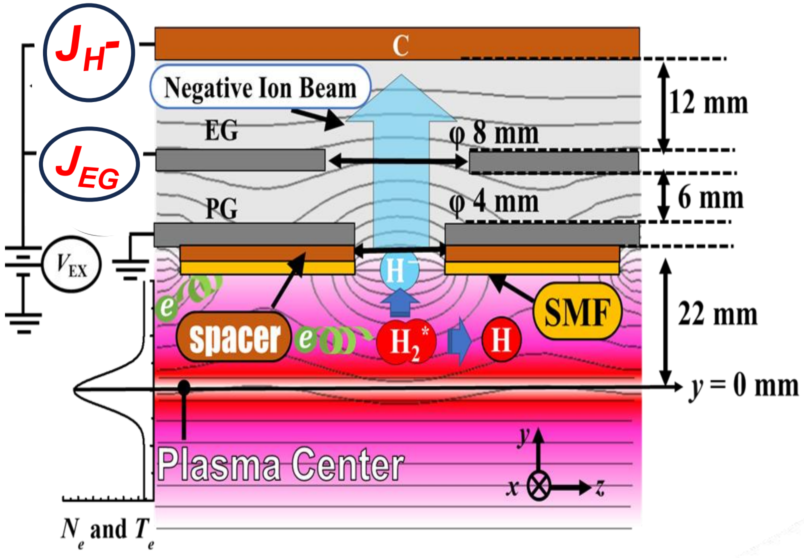
The extraction system consists of a **plasma grid (PG) with a magnetic filter (SMF),** an extraction grid (EG) and a collector. The extraction system is located 22 mm from the center of the sheet plasma along the Y direction.

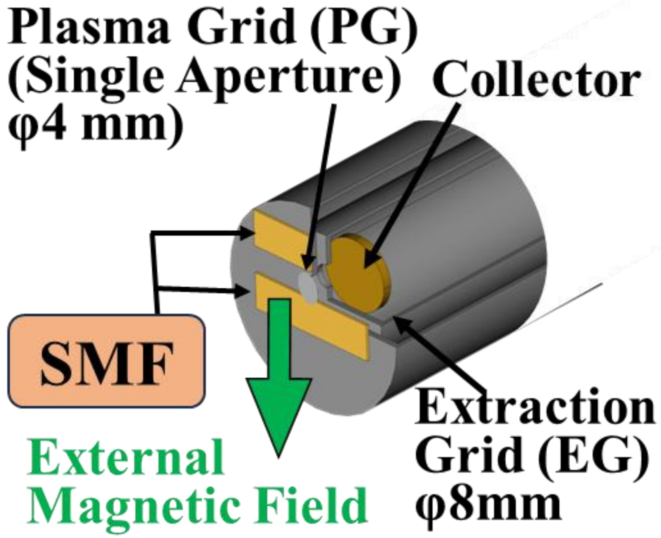
The **SMF** is positioned near the PG on the sheet plasma side (thickness: 0.2 mm; width: 10 mm; and length: 30 mm).





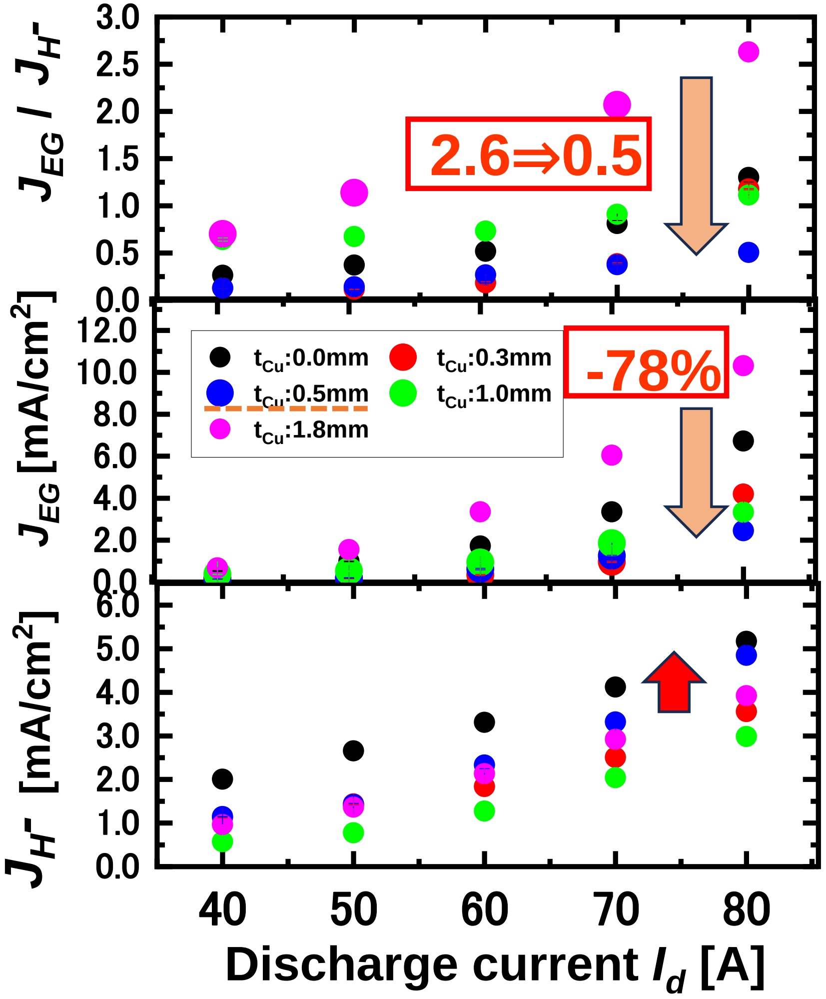
Ⅳ. Experimental results (1) Magnetic filter (SMF) method





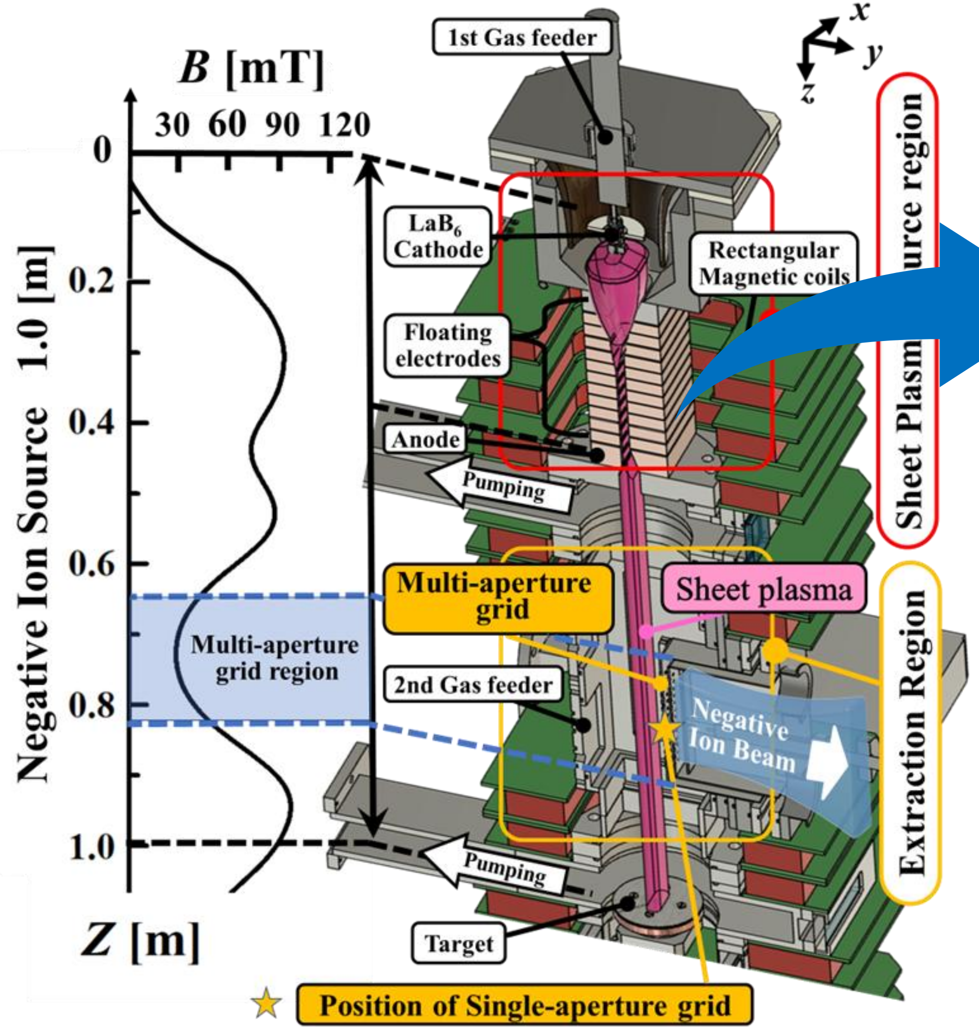
The SMF can reduce the co-electron current density by confining electrons in the plasma boundary layer (meniscus) near the extraction grid (PG). This is achieved by generating an external magnetic field and a local mirror field with soft magnetic material.

The reduction of the extracted co-electron current J_{EG} was more effective when a spacer made of Cu with a thickness of about 0.5 mm was placed between the SMF and the PG.

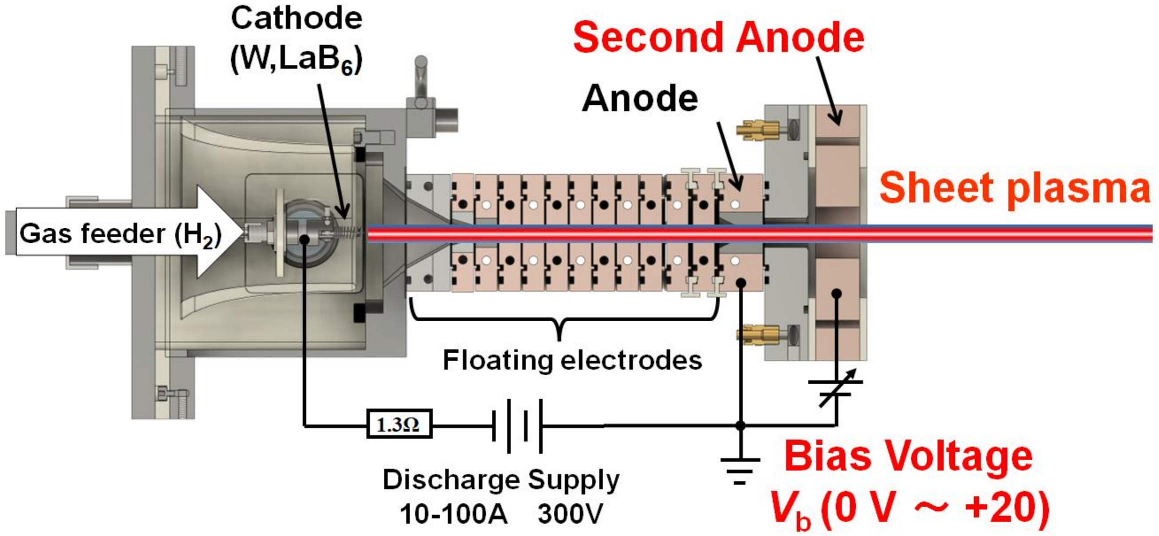


The co-electron current J_{EG} can be effectively reduced by -78% by trapping electrons in the SMF.

Ⅳ. Experimental results (2) Second anode bias method



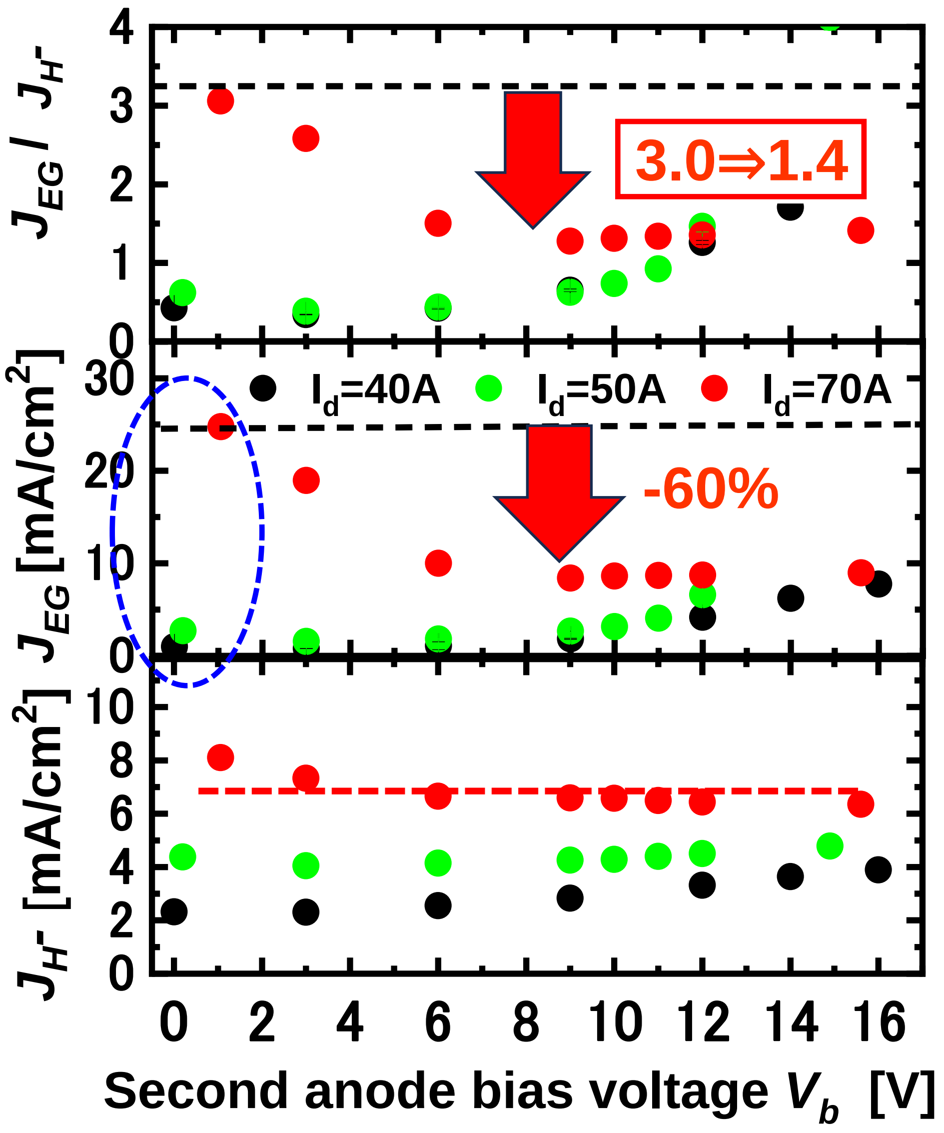
Cs-Free Negative Ion Source
TPDsheet-U

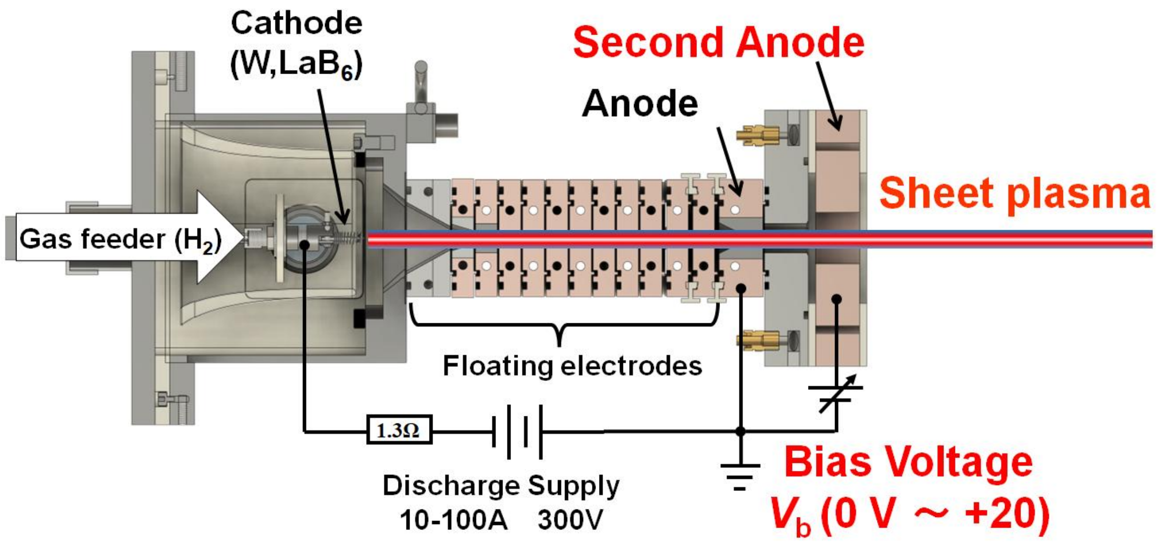


This plasma source consists of a cathode, a floating electrode, an anode, and a second anode.

A bias voltage of 0 V to +20 V can be applied to the second anode to control the peripheral plasma and reduce the co-electron current density.

Ⅳ. Experimental results (2) Second anode bias method

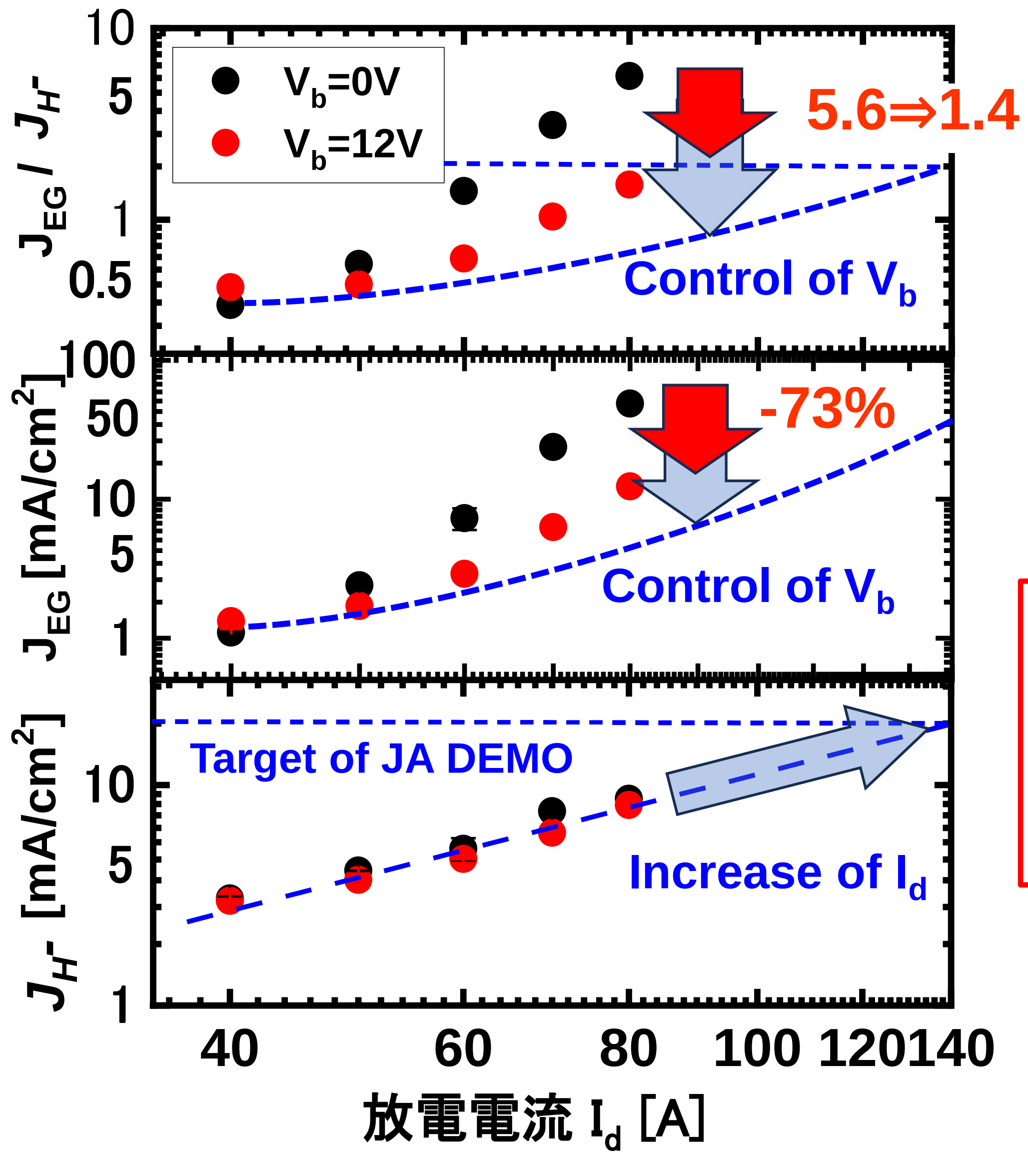


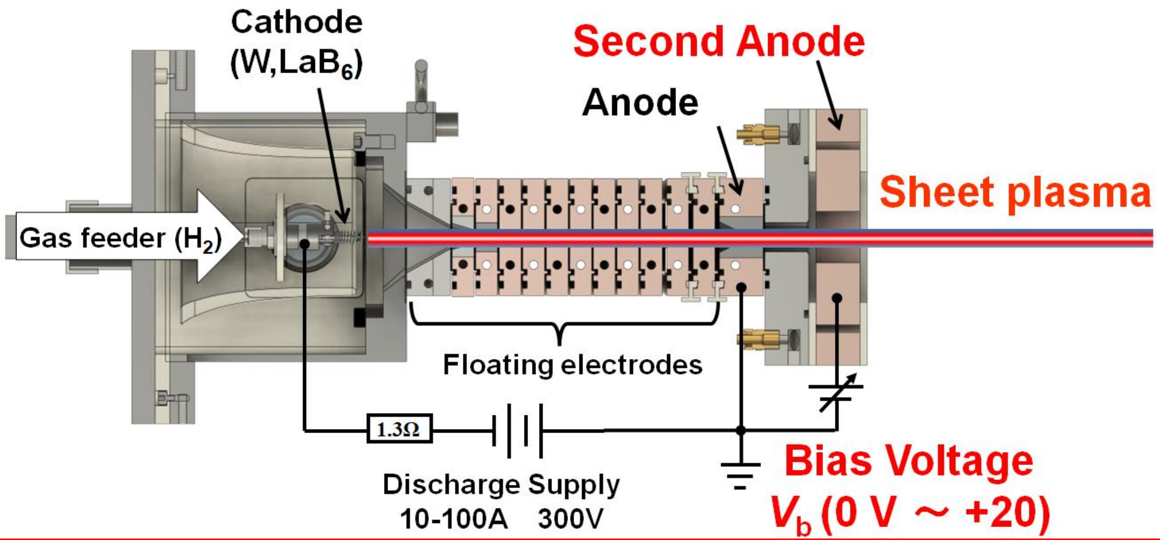


Without the second anode bias voltage V_b, the co-electron current J_{EG} increases rapidly when the discharge current I_d is increased.

On the other hand, when the bias voltage of the second anode V_b is increased from 0 V to 16 V, the co-electron current can be effectively reduced by -60% and the current ratio J_{EG}/J_{H^-} can be suppressed to about 1.4 while the negative ion current J_{H^-} is almost maintained.

Ⅳ. Experimental results (2) Second anode bias method

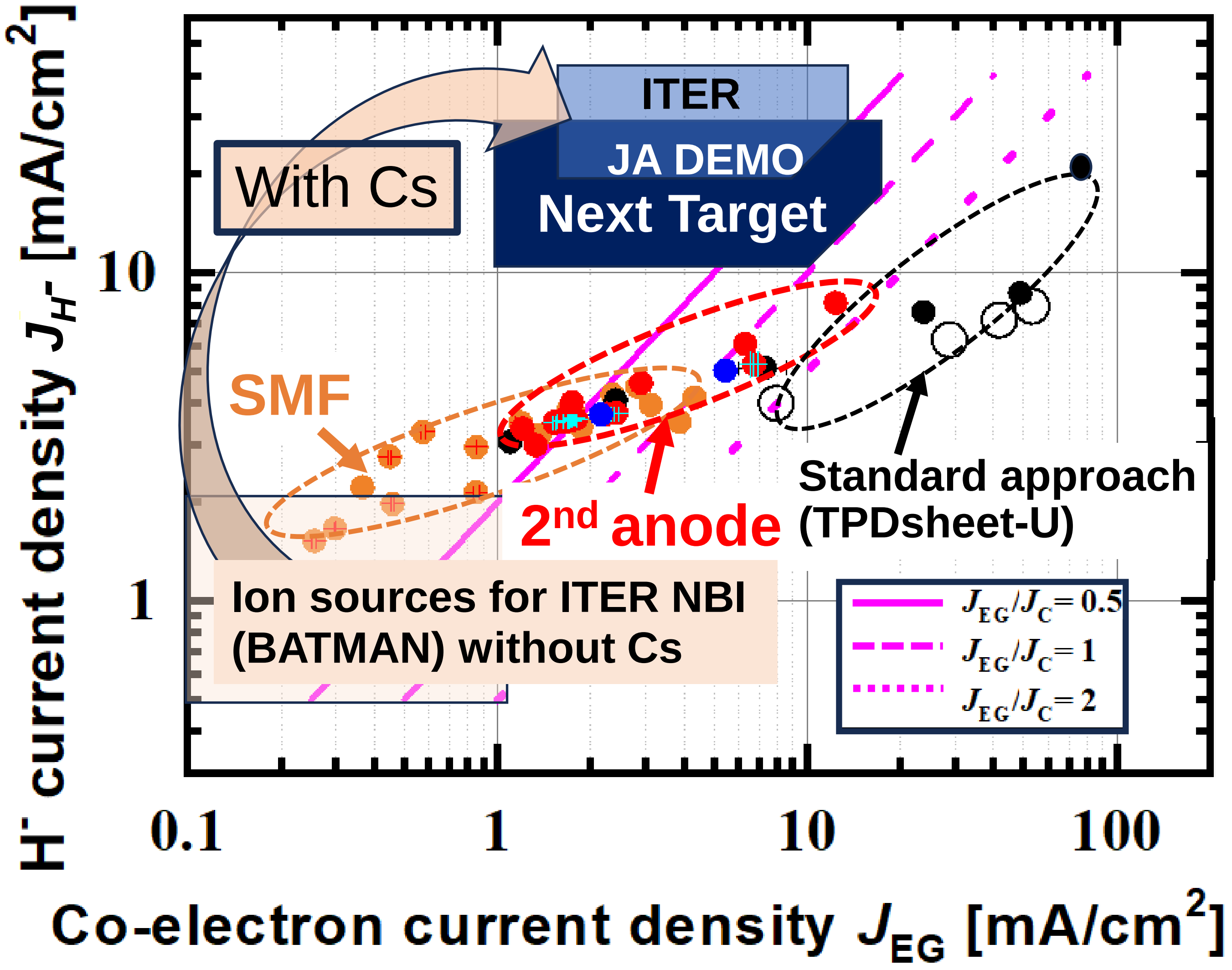




Applying a bias voltage of +12 V reduces the co-electron current J_{EG} by 73% while maintaining the negative ion current value, and the current ratio J_{EG}/J_{H^-} can be reduced to about 1.4 below 2.

Future plans are to increase the negative ion current J_{H^-} to JADEMO target while reducing the co-electron current by controlling the bias voltage V_b and increasing the discharge current I_d.

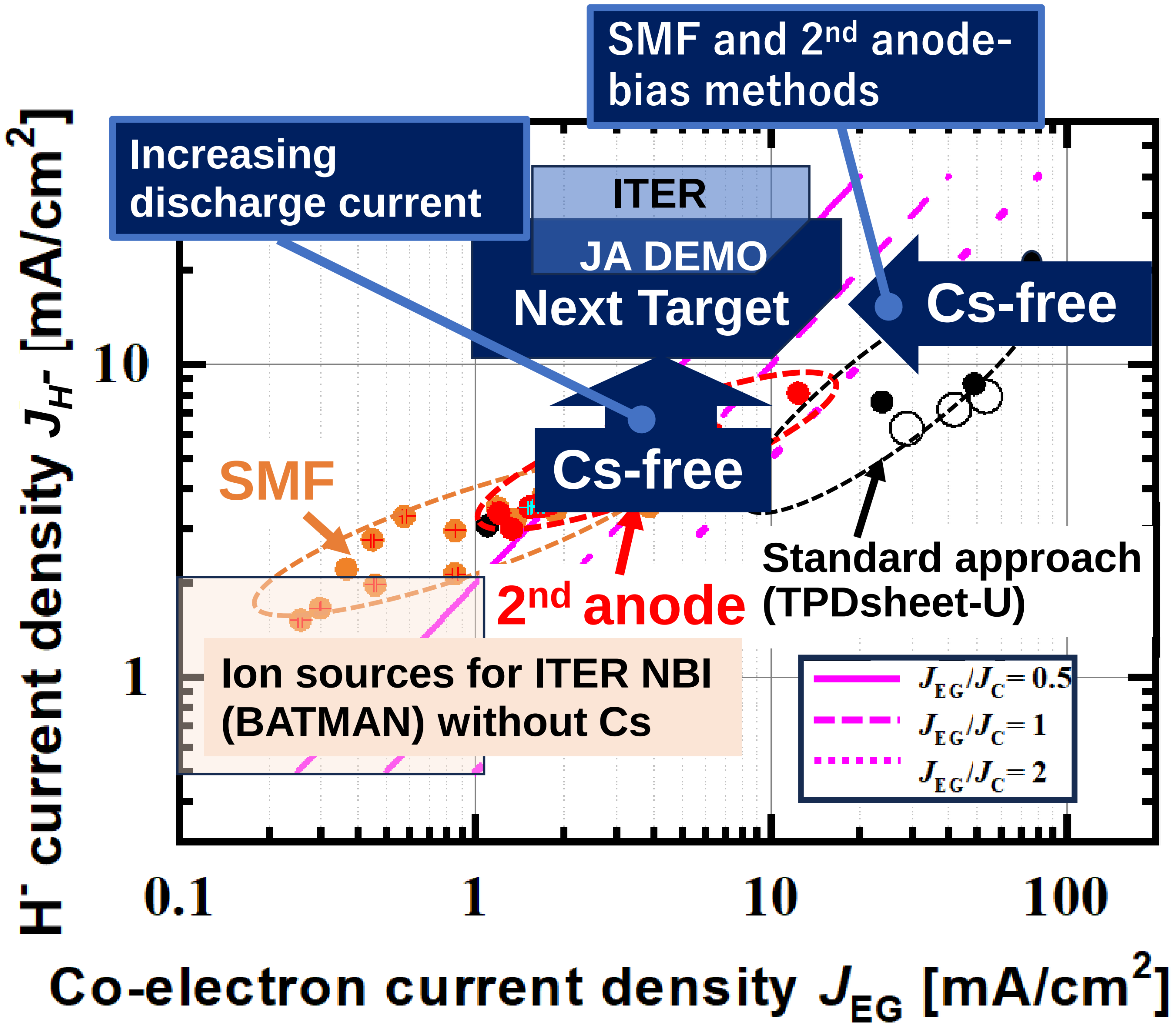
Ⅴ. Conclusion & Next plan



The negative ion current density has been successfully increased with the suppression of the extracted co-electron current by the following two methods.

(1) Magnetic filter (SMF) method.
(2) Second anode bias method.

Ⅴ. Conclusion & Next plan



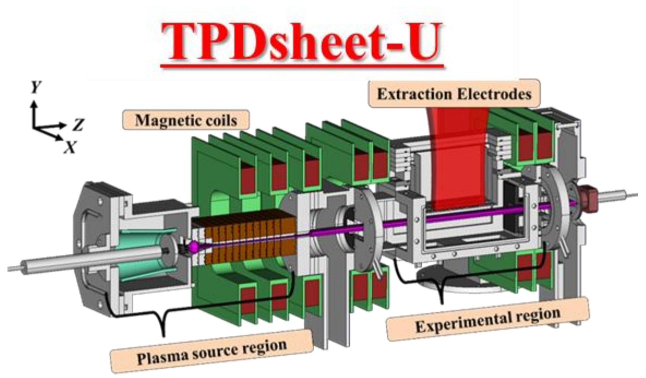
The negative ion current density has been successfully increased with the suppression of the extracted co-electron current by the following two methods.

(1) Magnetic filter (SMF) method.

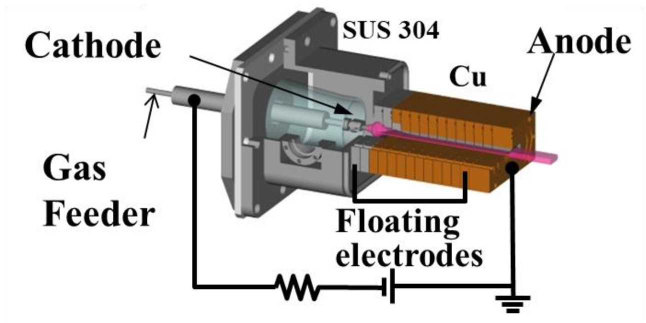
(2) Second anode bias method.

The next plan is to increase the negative ion current density and suppress the co-electron current by increasing the discharge current and optimizing the SMF structure and second anode bias to achieve the JA DEMO Target.

Next plan (TPDsheet-N)
(Prototype Cs-Free High Current Negative Ion Source)

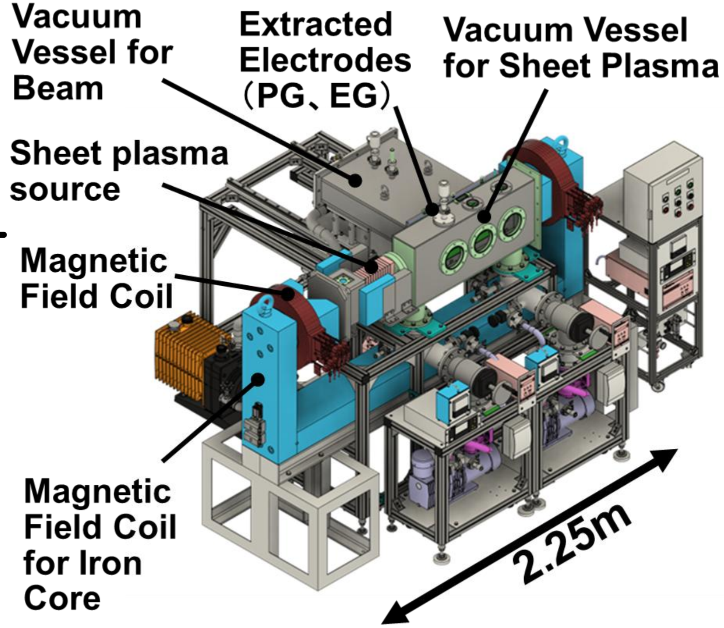


Basic study



TPDtype plasma source

Prototype Cs-free High Current Negative Ion Source (TPDsheet-N) with Multi-hole Extracted Electrodes



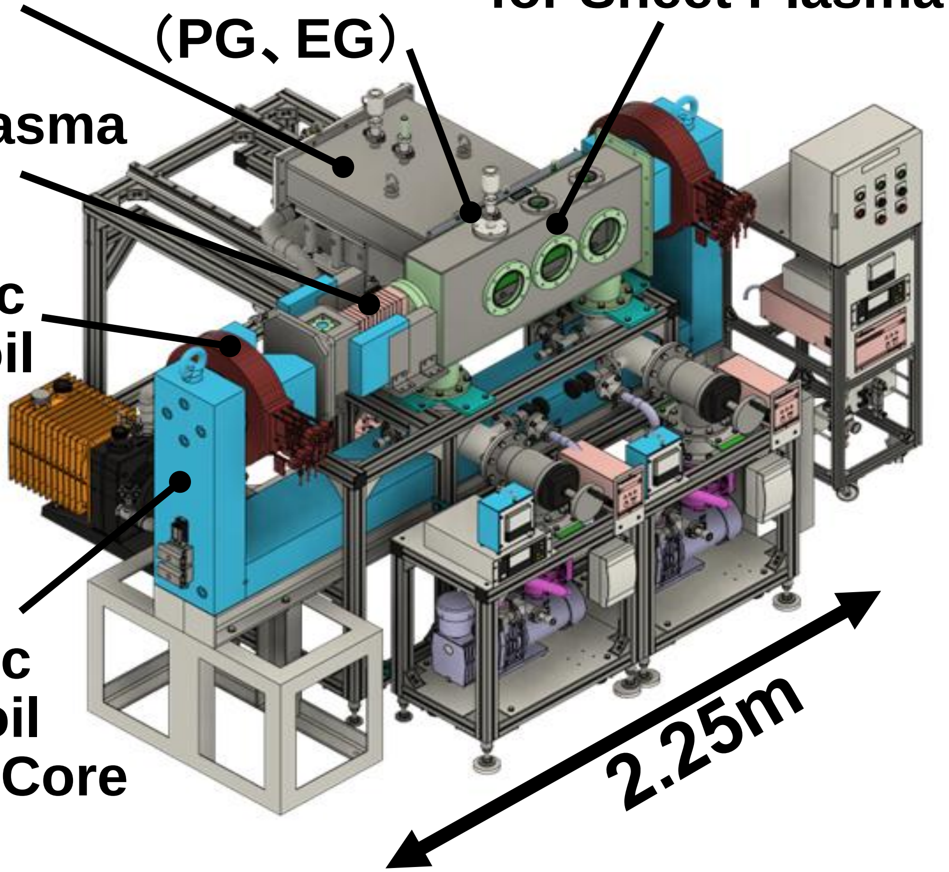
Advantages

1. Use of iron core magnetic field coil
⇒ Large area and High current
(J_{H^-} :20mA/cm2) Sheet width:4cm
160x60cm(3x13:ϕ3, 4.9m2)50mA
⇩
418x60cm Sheet width:6cm
(3x23: ϕ6, 20cm2) 400mA (8 times)
(6x21: ϕ8, 63cm2) 1.2A (25 times)

2. SMF and 2nd anode-bias methods
⇒Reduction of co-electron current ratio
($J_{EG} / J_{H^-} < 2.0$)

3. Multiple negative ion sources installations
⇒ Scaling up to higher current

Next plan (TPDsheet-N)
(Prototype Cs-Free High Current Negative Ion Source)



Target	TPDsheet-N (Prototype)	JA DEMO-NBI
Gas	Hydrogen	Hydrogen
Beam current Operation	0.4～1.2 A (one source) CW	3.5A (one source) (total 28 A) CW
Negative ion current density J_{H^-}	20 mA/cm^2	23 mA/cm^2
Development task	Carbon heater filament	Filament less RF ion source
Pressure	0.3 Pa	0.1 Pa
Cesium	**W/O**	W/ ⇒ W/O
J_{EG}/J_{H^-}	< 1.0～2.0	< 0.5～1.0