Development, Injection and Diagnostics for LHD Injectors

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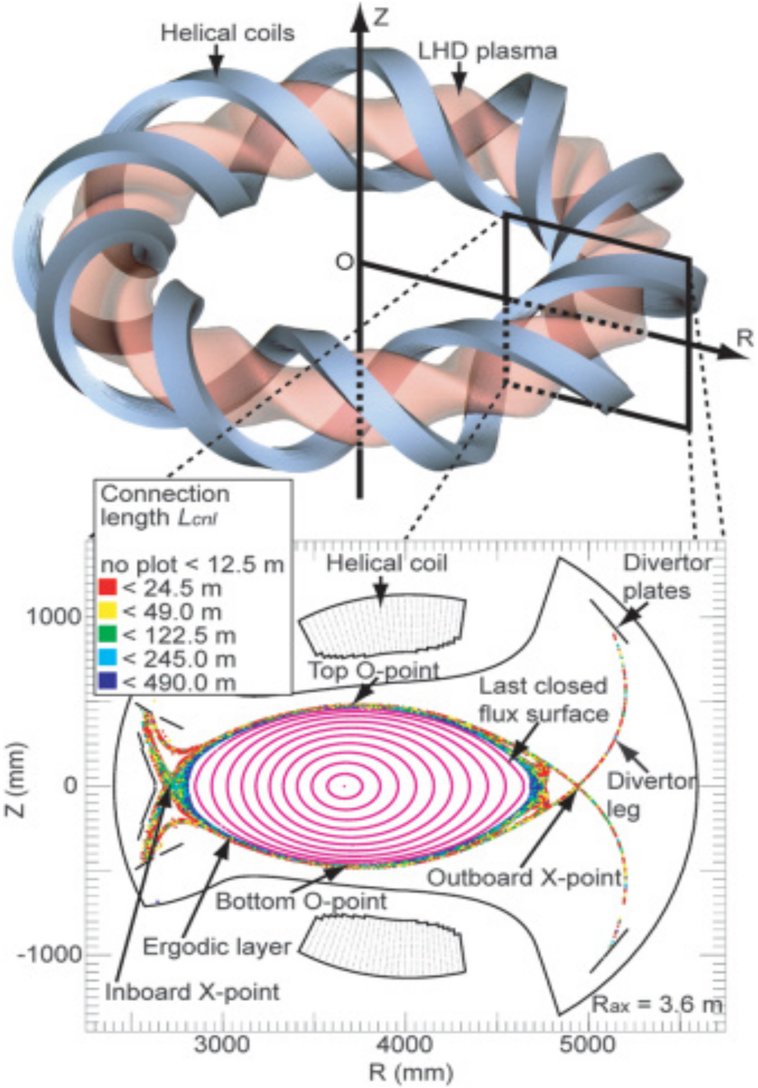
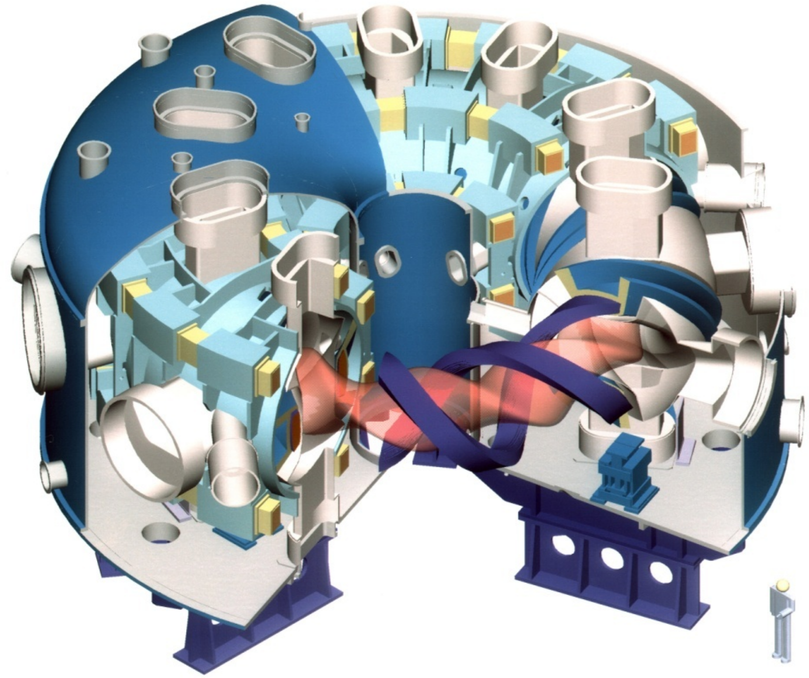
IPAB2016 Conference
"Intense and Powerful Accelerator Beams
for industrial and energy application"
Legnaro, March 14-15, 2016 (Italy)

Outline

1. Large Helical Device and NBI system
2. Deuterium-Plasma Experiment
3. Diagnostics of Negative-Ion Rich Plasma
4. Engineering Improvement
5. Summary

Large Helical Device (LHD)

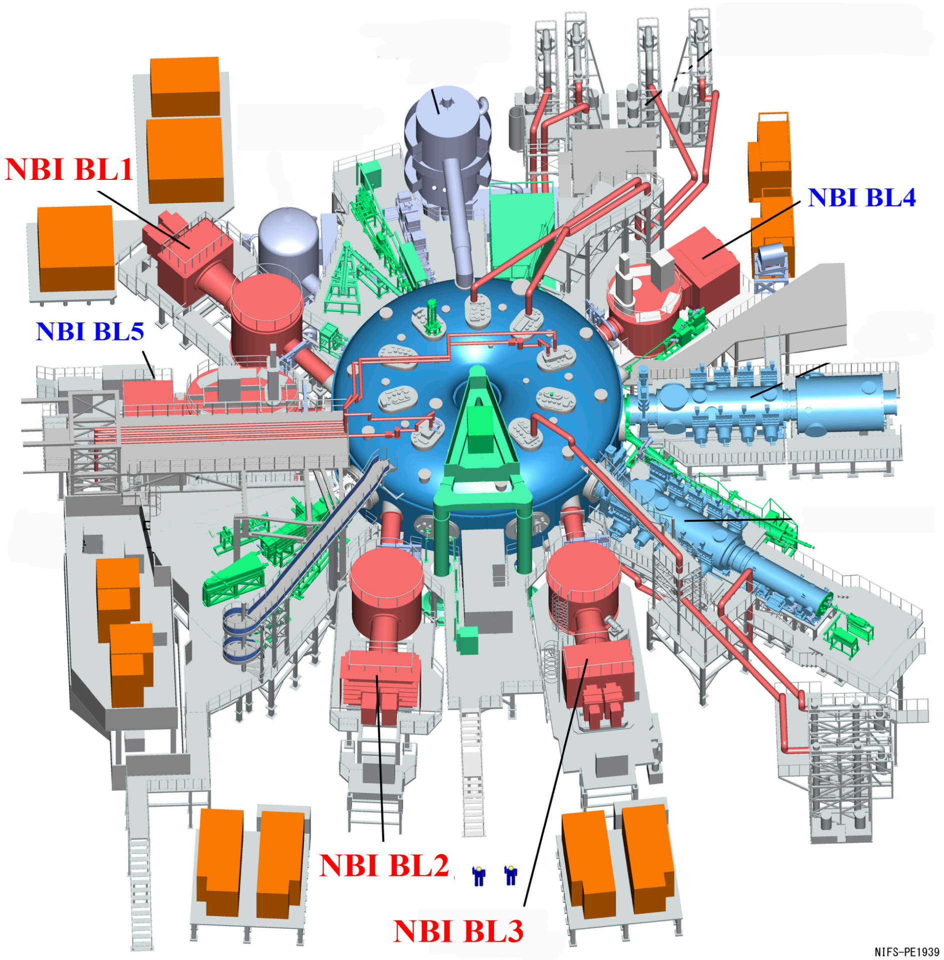


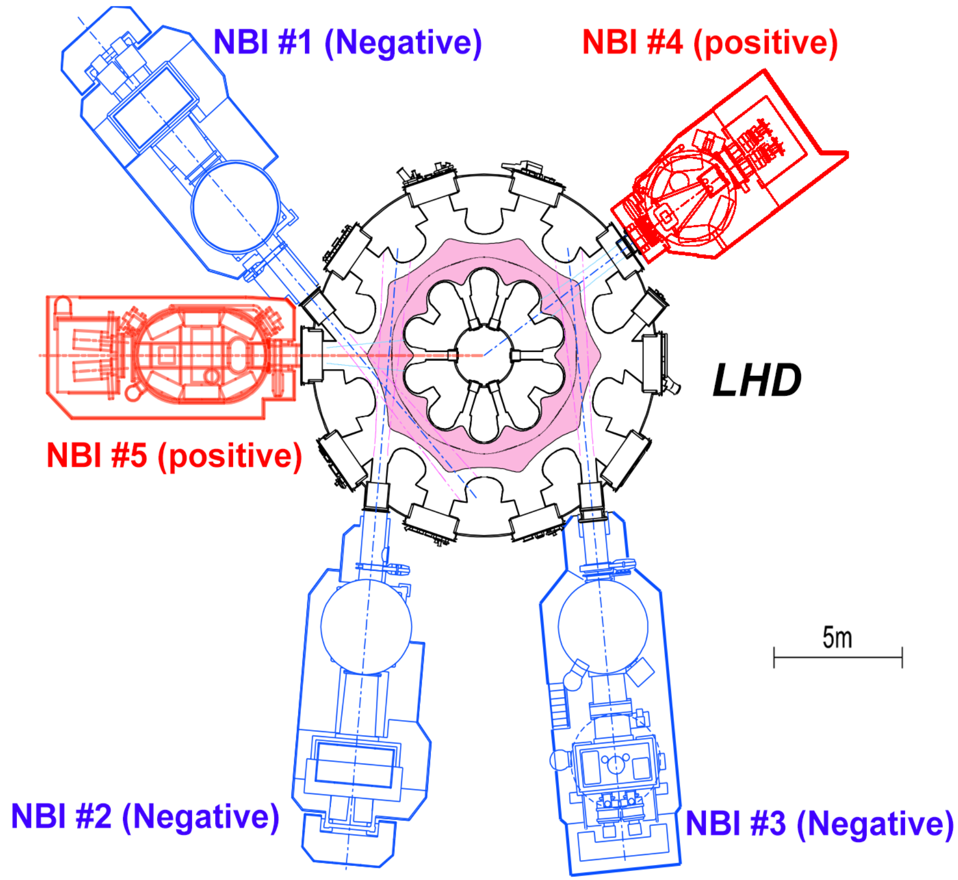


Heliotron configuration of
l=2/m=10 field period
All superconducting coil system

Plasma major radius	3.42-4.1 m
Plasma minor radius	0.6 m
Plasma volume	30 m^3
Toroidal field strength	3 T

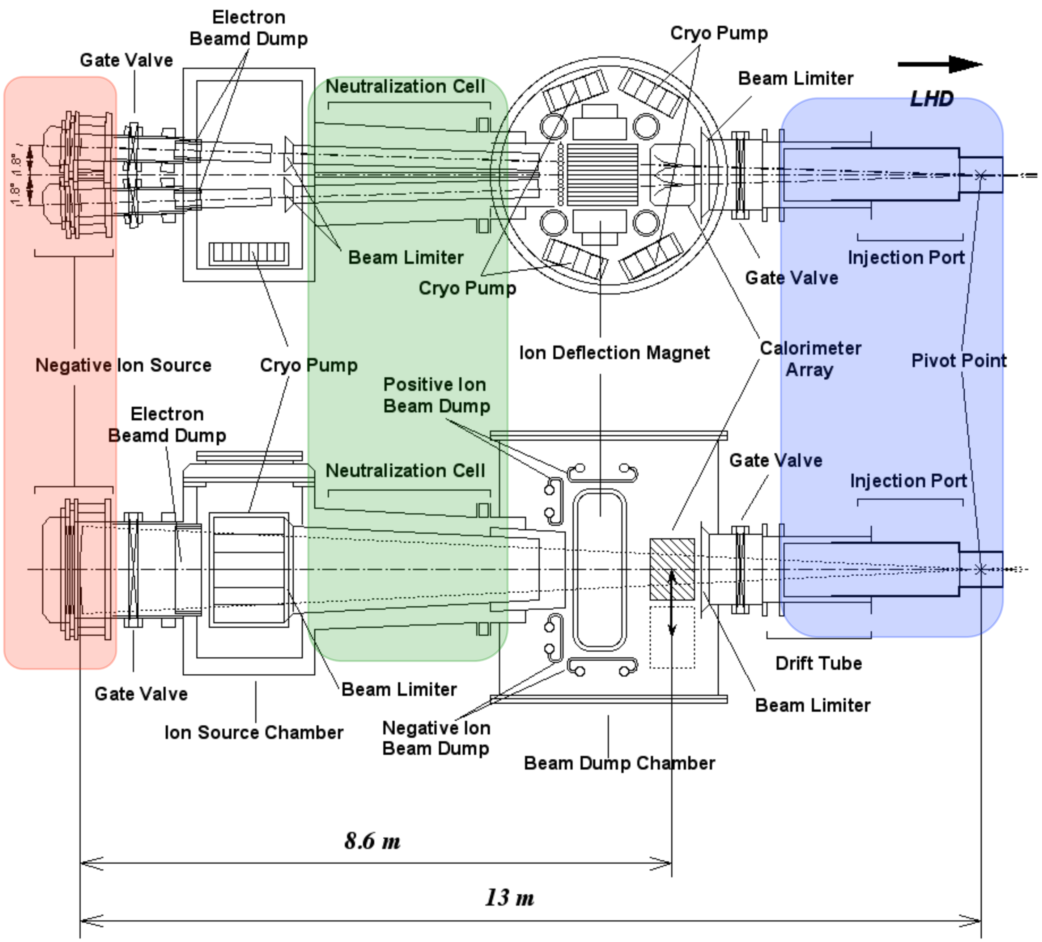
Neutral Beam Injector (NBI) Systems for LHD





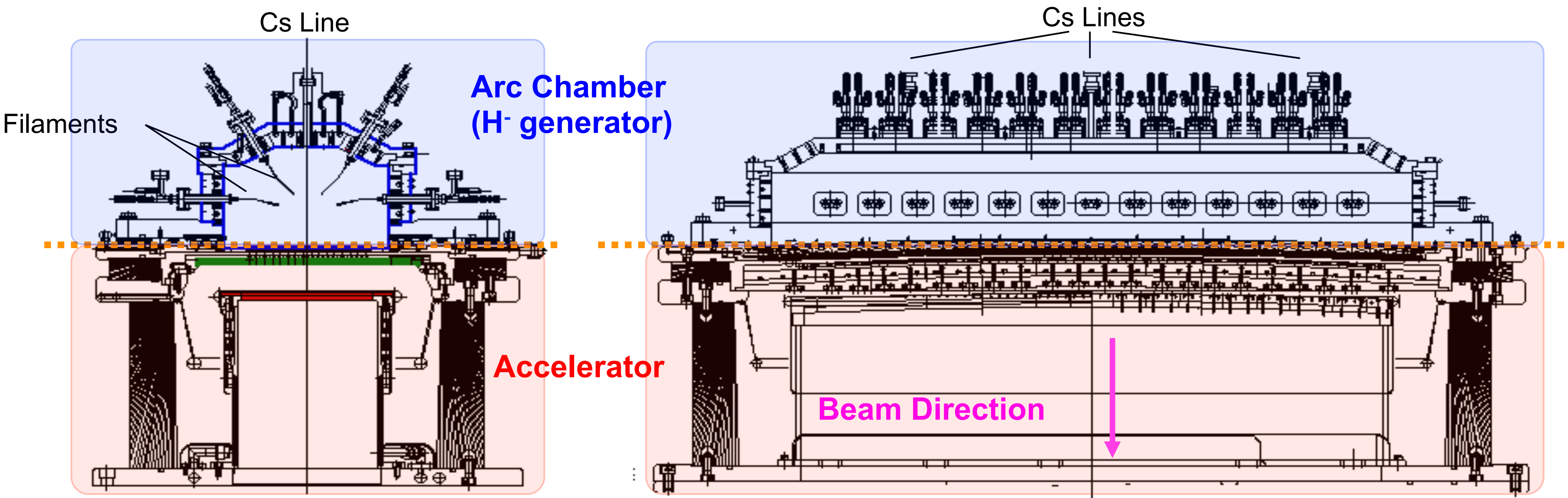
- Two positive-ion-based NBIs (p-NBIs) for perpendicular injection.
- Three negative-ion-based NBIs (n-NBIs) for tangential injection.

Structure of N-NBI in LHD



- Hydrogen beam injection with 180 keV-5 MW / injector (2 ion sources).
- Length of gas-neutralizing cell : 5 m
- Focal length of the ion source is 13 m, and pivot point of two ion sources locates 15.4 m in the horizontal direction.
- Injection port is ~3 m long, and the narrowest part is ~0.5 m in diameter with the length of ~0.7 m.

Hydrogen Negative Ion Source

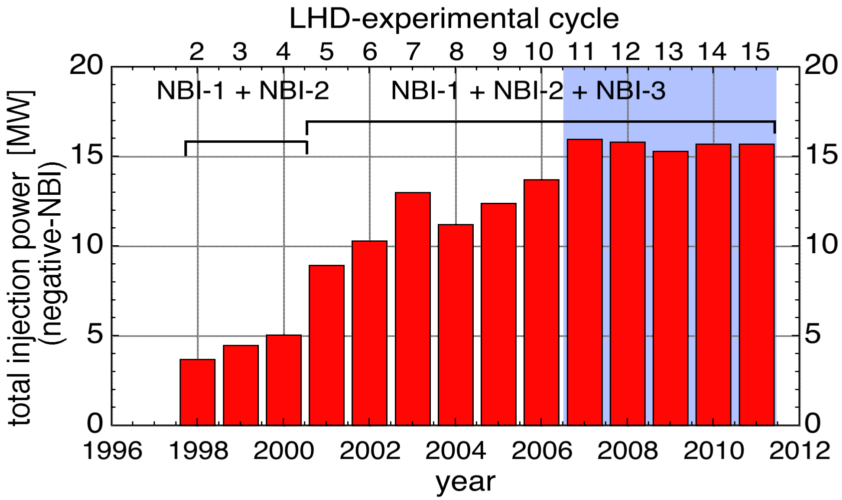


Cross-sectional view of ion source in the direction of the short side

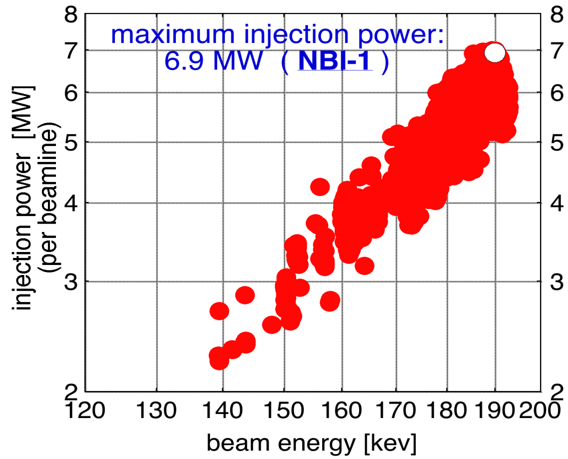
Cross-sectional view of ion source in the direction of the long side

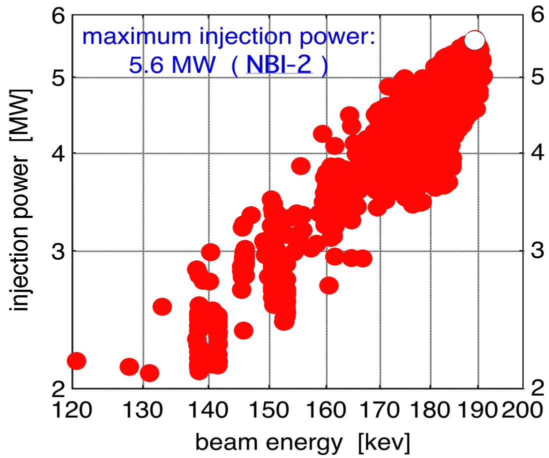
- Multi-cusp source with external magnetic filter
- Plasma production : Filament arc discharges
- Cs vapor is seeded to enhance H^- production
- Inner dimensions : 1400 mm (H) x 350 mm (W) x 230 mm (D)
- H^- beam : Single stage acceleration
- Beam extraction area : 1250 mm (H) x 250 (W)

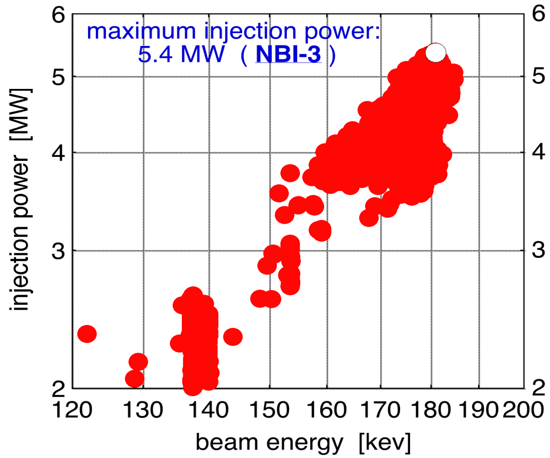
Evolution of Injection Status (n-NBI)



- Using three negative-ion-based NBI systems, total injection power of **~16 MW** has been achieved.
- Since 2007, injection powers of more than 15 MW have continued to inject.







- Individual maximum injection power of negative NBI systems
  - BL1: **6.9 MW** at 190 keV (maximum), **6 MW** (average).
  - BL2: **5.6 MW** at 188 keV (maximum), **4 MW** (average).
  - BL3: **5.4 MW** at 182 keV (maximum), **4 MW** (average).

From H to D Beam Injection

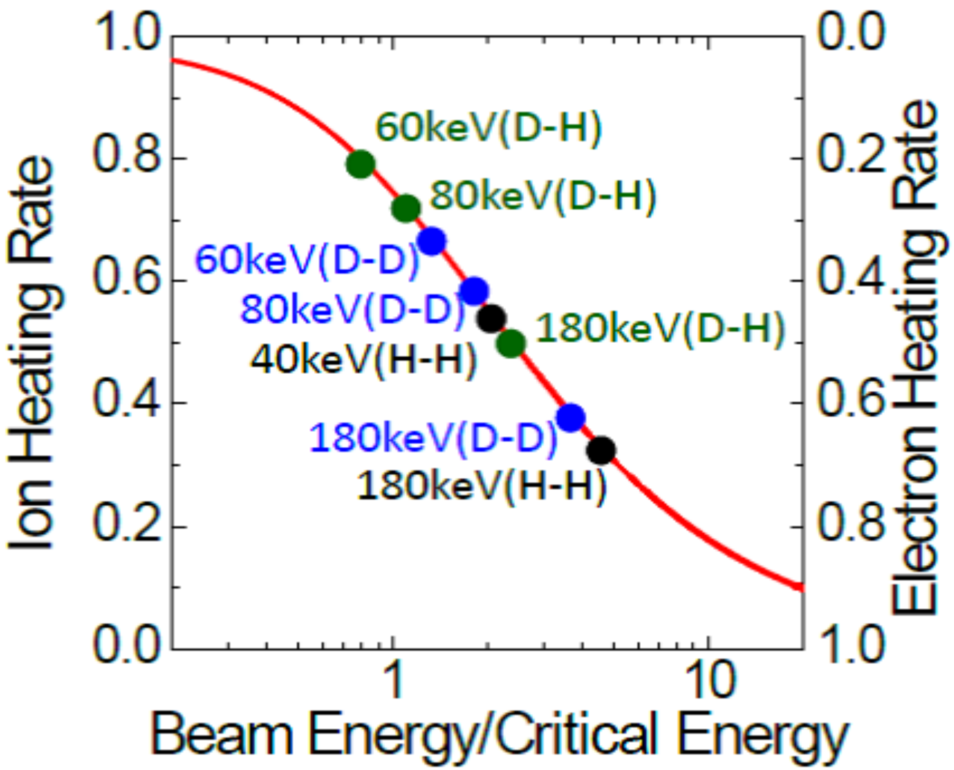
Deuterium-Plasma Experiment

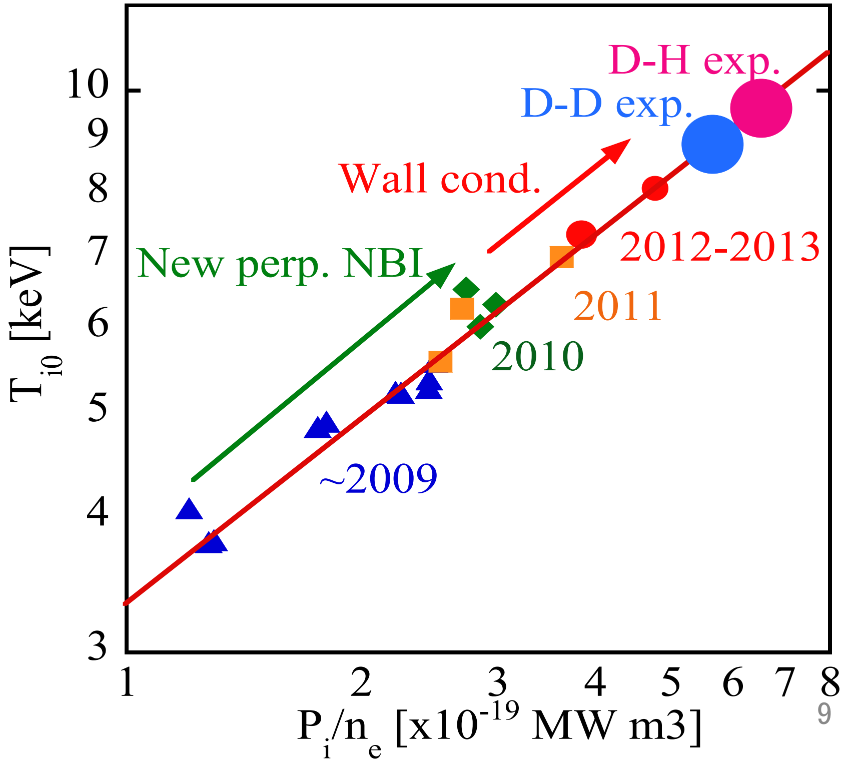
Neutral beam Injectors (NBIs) will be upgraded for deuterium beam injection, which have higher ion heating efficiency

Positive NBI (40kV, 6MW, H_0) + (40kV, 6MW, H_0) ➔ (60kV, 9MW, D_0) + (80kV, 9MW, D_0)

Negative NBI (180kV, 5MW, H_0) x 3 ➔ (180kV, ~3.5MW, D_0) x 3

In LHD deuterium experiment, T_{i0} = 10 keV will be achieved with deuterium beam injection and further improvement of confinement due to the isotope effect





D-Beam Injection (p-NBI)

- Due to mass difference, D^- current density becomes $1/\sqrt{2}$ times lower than that of H^- according to Child-Langmuir's law.

$$J_{D+} = \frac{4\varepsilon_0}{9}\sqrt{2e/m_D}\,\frac{E^{3/2}}{d^{1/2}}$$

- The beam energies are increased from 40 keV to 60 keV (NBI #4) and 80 keV (NBI #5) to upgrade p-NBIs.
- The power supplies are prepared for the energy enhancement.
- Injection power is improved from 6 MW to 9 MW each of the p-NBI.

D-Beam Injection (n-NBI)

- The ion heating rate becomes higher in D injection with n-NBI of 180 keV.
- As well as p-NBI, the current density of D^- becomes $1/\sqrt{2}$ times lower than that of H^-.

$$J_{D-} = \frac{4\varepsilon_0}{9}\sqrt{2e/m_D}\,\frac{E_{ext}^{3/2}}{d_{ext}^{1/2}}$$

- Extraction field (E_{ext}) is hard to increase by reducing the gap, because the acceleration field (E_{acc}) reaches the breakdown limit under the focusing condition that $E_{\mathrm{acc}}/E_{\mathrm{ext}} = const$.
- Consequently, we need to enhance D^- current.

How to Increase the Power of D Beam Injection

Improvement for D^- beam

Physics of H^- production and extraction

- Diagnostic investigation on H^- production
- Beamlet monitoring
- PIC simulation

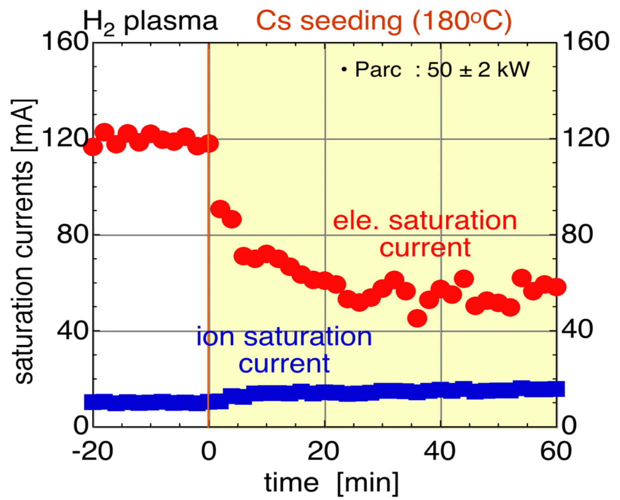
Engineering approach to enhance H^- current

- Improvement of beam accelerator
- Cs recycling
- Control of H^- production

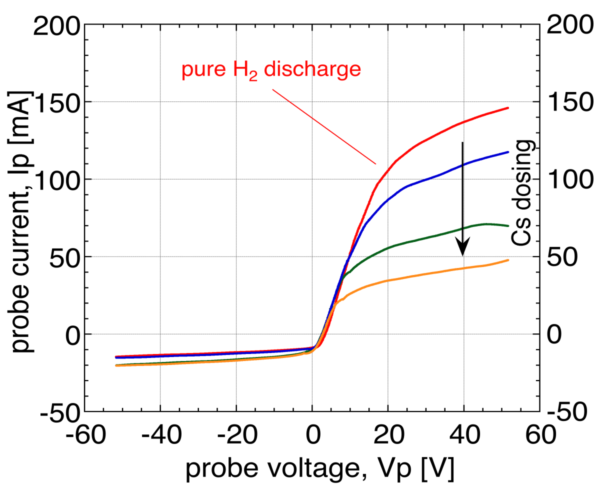
Empirical Validation

Diagnostics of Negative-Ion-Rich Plasma

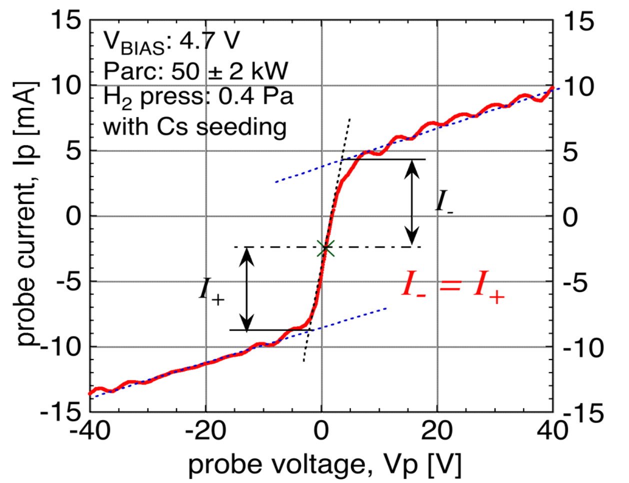
Production of Negative-Ion-Rich Plasma



Decrease of electron saturation current during Cs seeding



Changes in V-I curve of single-tip Langmuir probe



Ion-ion plasma in beam extraction region of a Cs seeded ion source.

(Position of probe tip: 9 mm from PG)

Cs optimization

Hydrogen discharge
(positive ion) : (electron) ≈ 1 : 10

Cs-seeded plasma (optimized)
(positive ion) : (negative ion) ≈ 1 : 1

In Cs-optimized plasma:

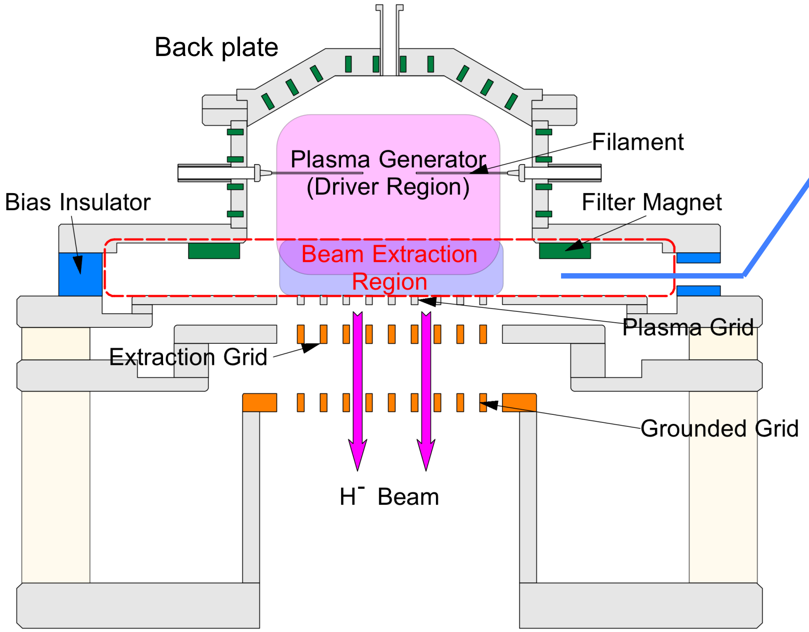
(1) very symmetric V-I characteristic

(2) quite low electron density (less than 1% of H^- density).

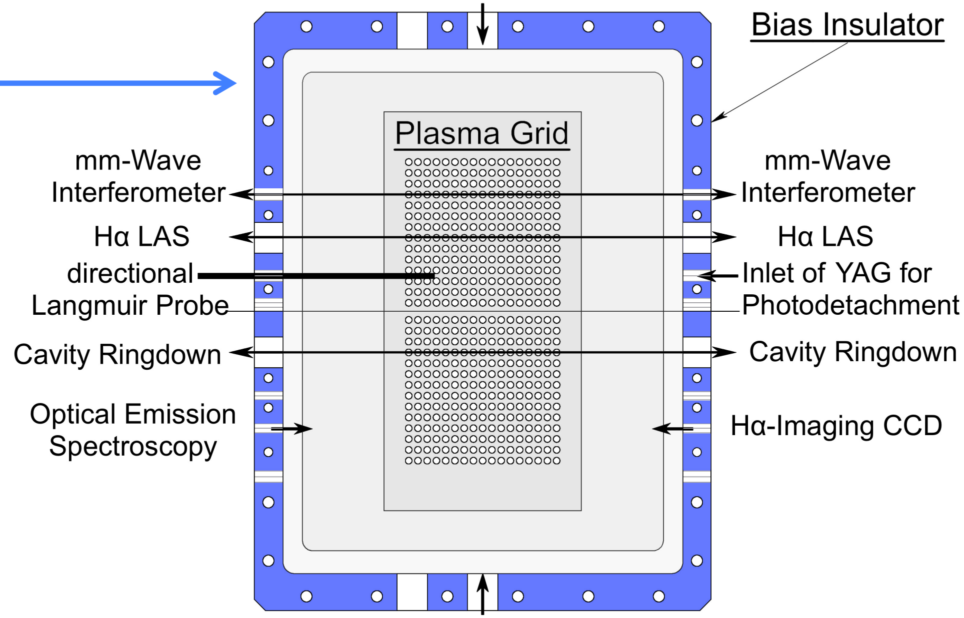
* "*electron*" saturation current → "*negative*" saturation current

Diagnostic System for Negative-Ion-Rich Plasma

Schematic cross-sectional view of R&D negative ion source

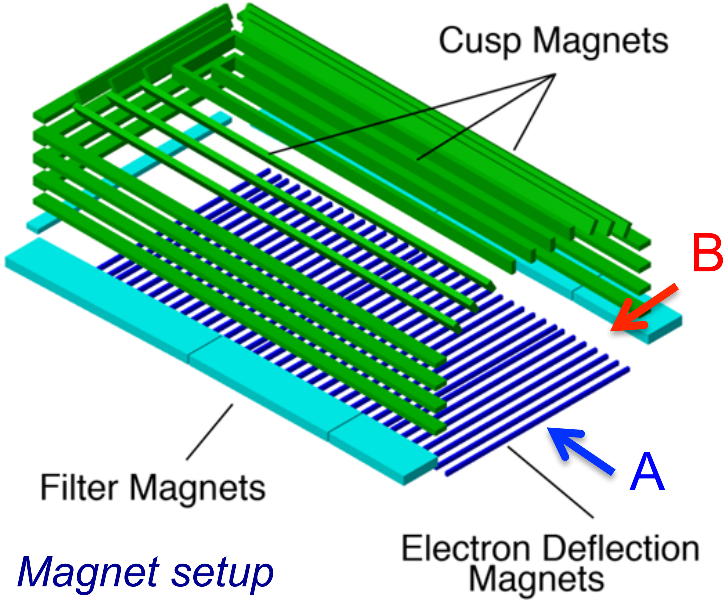


Measurement region viewing from back plate



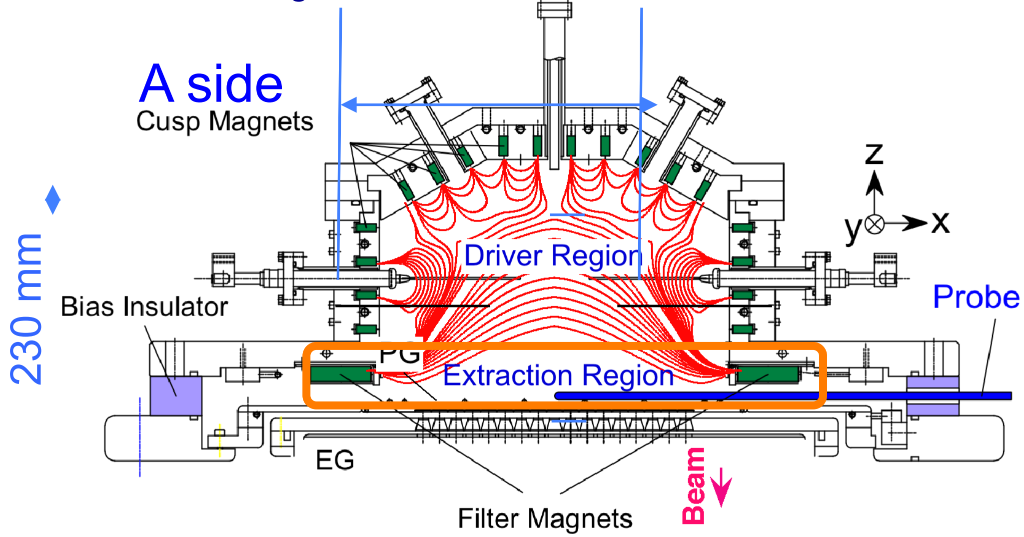
- Plasmas in extraction region are measured with multiple diagnostic system.
- Density, temperature and flows of charged and neutral particles are measured with those systems at the same time.
- Some new diagnostic techniques are developed for the system.

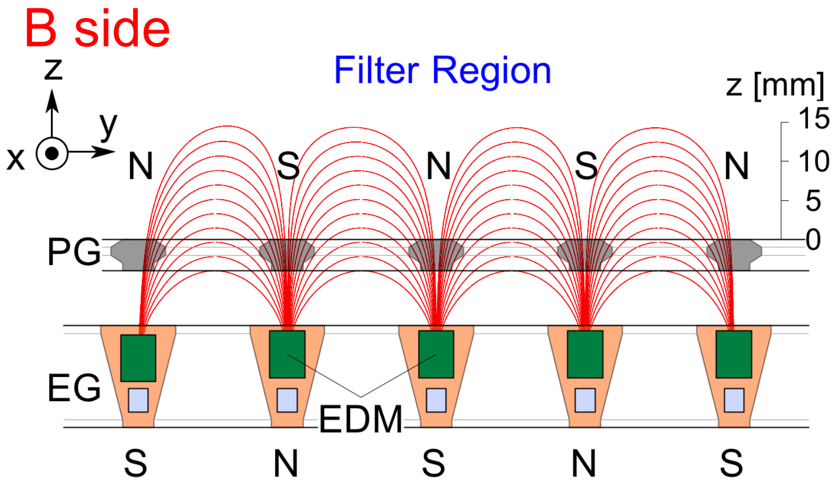
Diagnostic System for Negative-Ion-Rich Plasma



Magnet setup

Magnetic field in NIFS R&D source

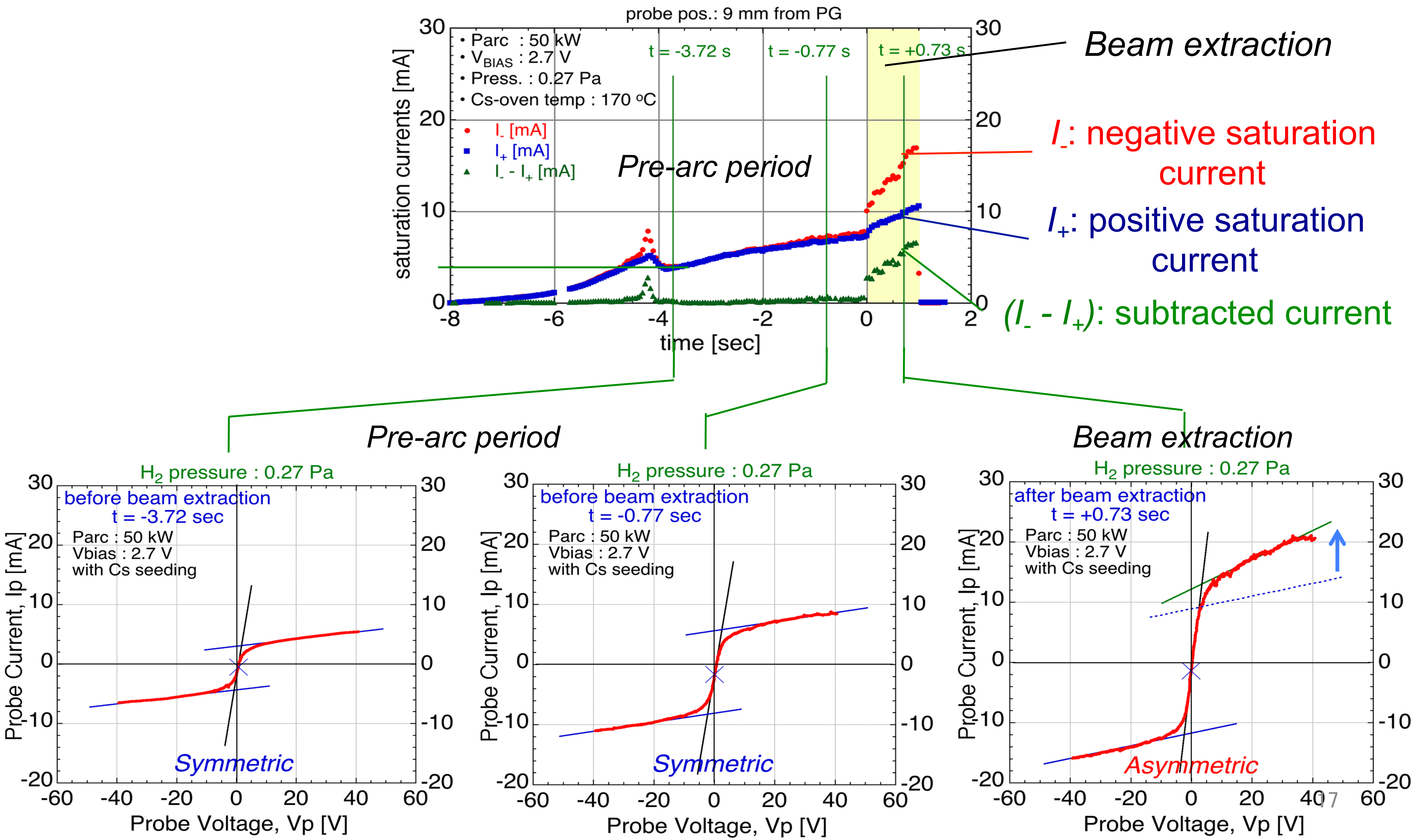




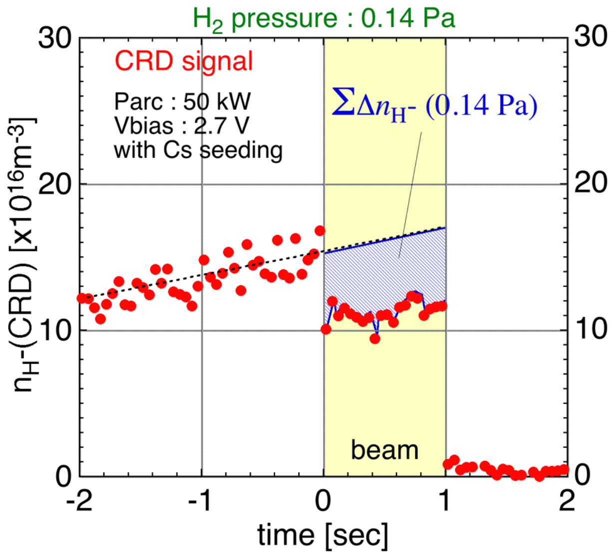
Magnetic field near plasma grid

- Multi-cusp source with a pair of filter magnets.
- Inner size: 700 mm (Height) x 350 mm (Width) x 230 mm (Depth).
- Beam extraction region from PG to filter magnets are the target of this research.
- Filter and electron deflection fields combines in the region.

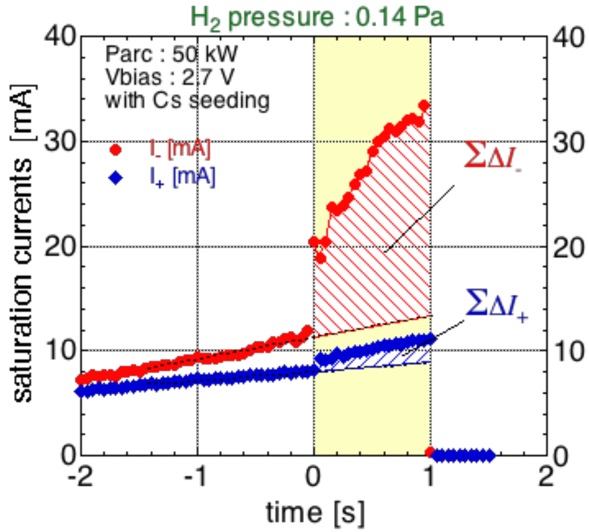
Beam Extraction and Negative-Ion-Rich Plasma



Changes of H^- and Electron Densities During Extraction



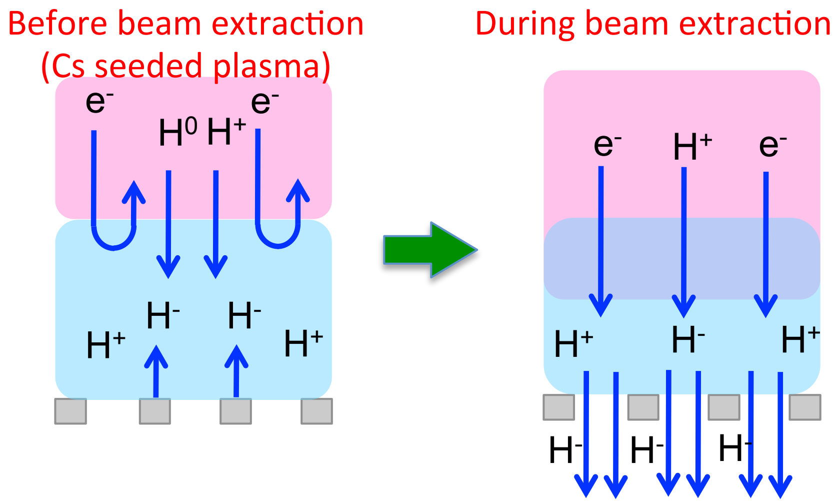
H^- density



ele. density

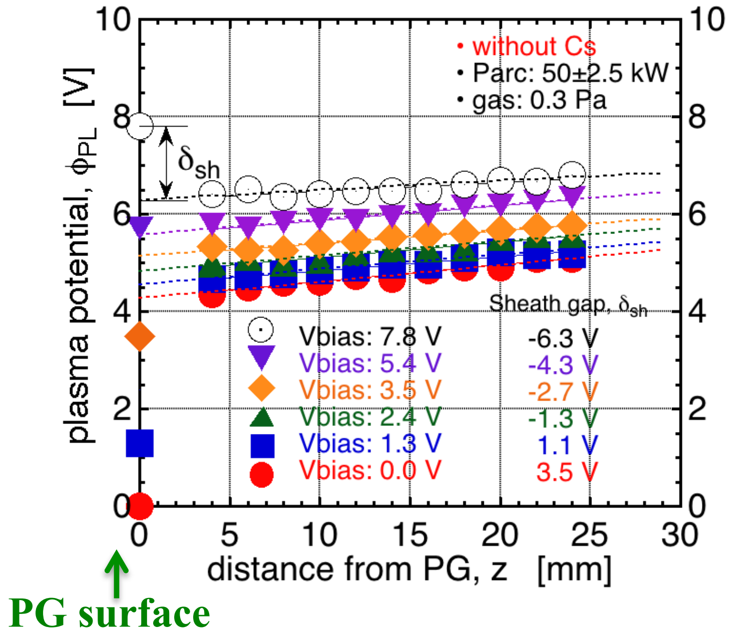
- Electrostatic response of negative-ion-rich plasma in beam extraction region.
- By applying the beam extraction field, H- density decreases.
- Simultaneously, electron density increase.

- The phenomena above is schematically explained that H^- ion is limited to extract.
- Electrons move from hot plasma region (driver region) to compensate extracted H^-.

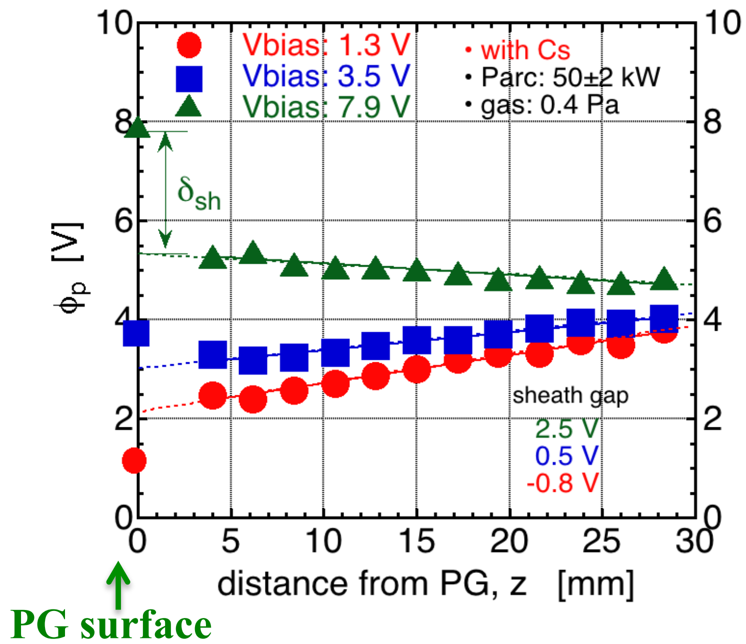


Electrostatic Response of Ion-Ion Plasma

pure H_2 plasma



Cs-seeded plasma



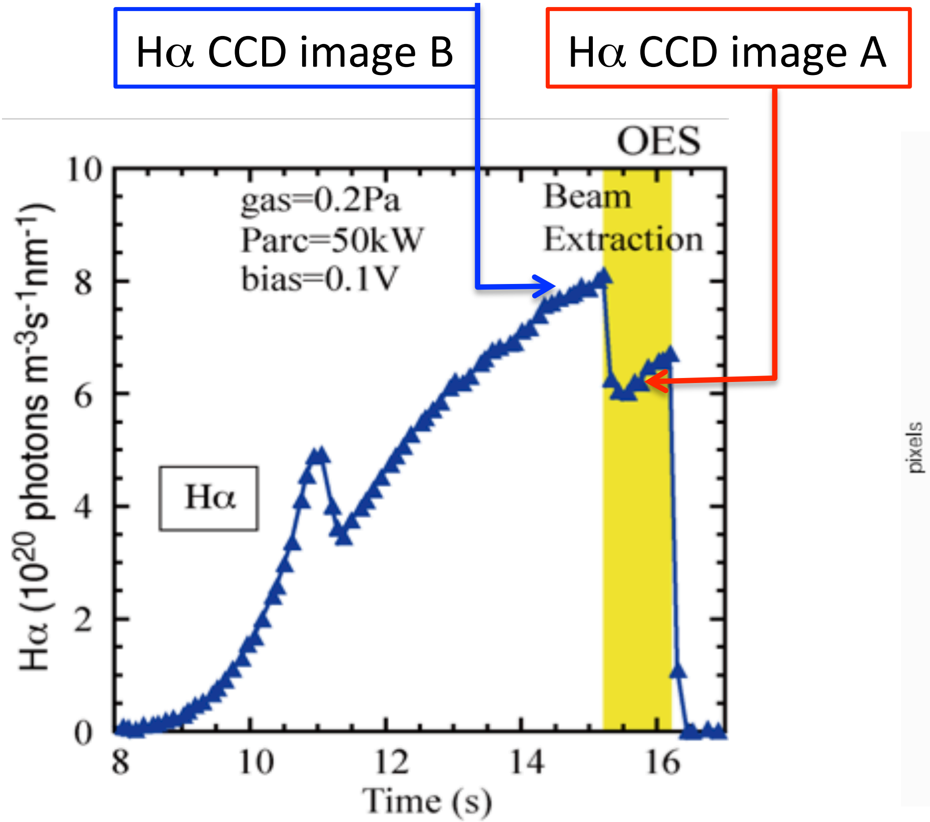
- **pure H_2 plasma**
  Potential slope do not change and deep sheath. → **metal-like shielding**
- **Cs-seeded plasma**
  Potential slope is affected with bias voltage → **Simi-conductor-like shielding**
- Acceptance to electrostatic field is lower in the sheath of negative-ion-rich plasma (ion-ion plasma in this case).

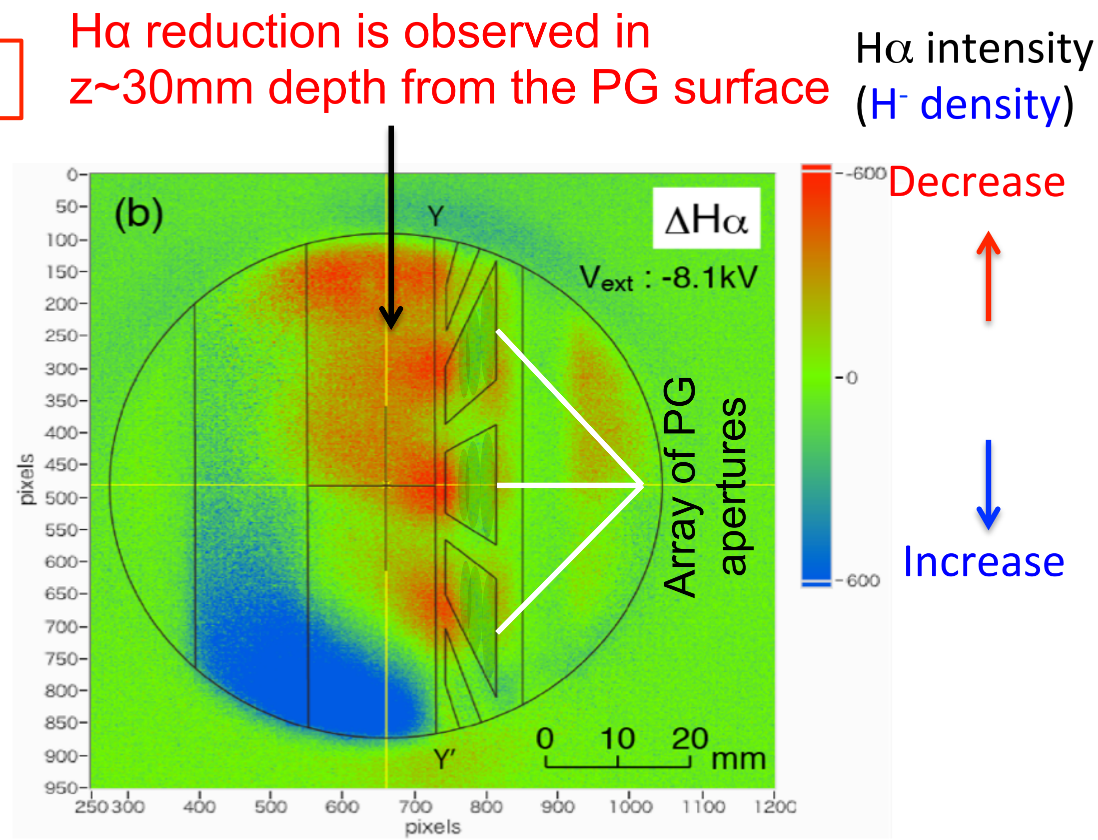
Where are H⁻ ions extracted?

Distribution of Hα spectrum → Estimation of negative ion behavior

Waveform of Hα intensity

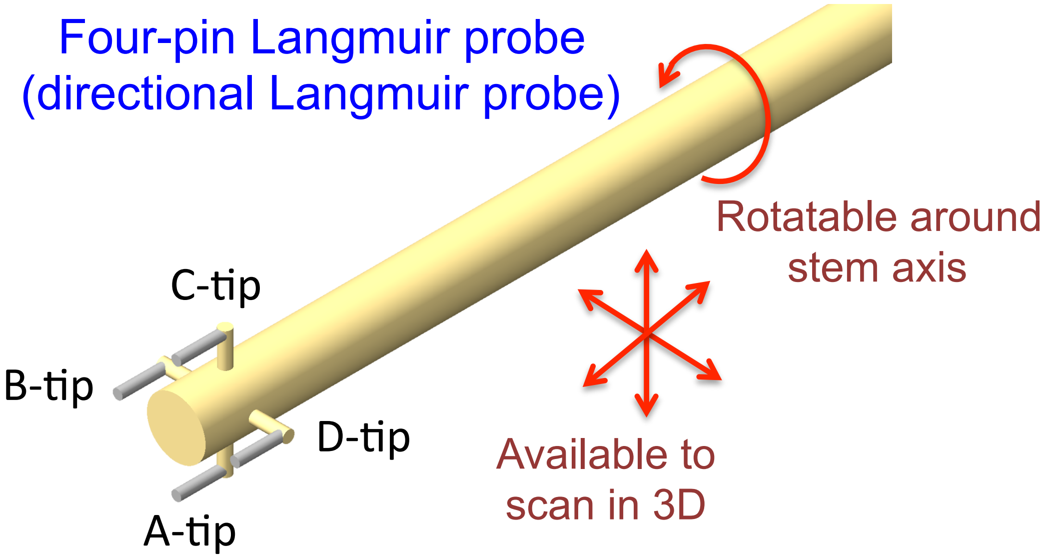
Subtracted CCD image: (image A) – (image B)

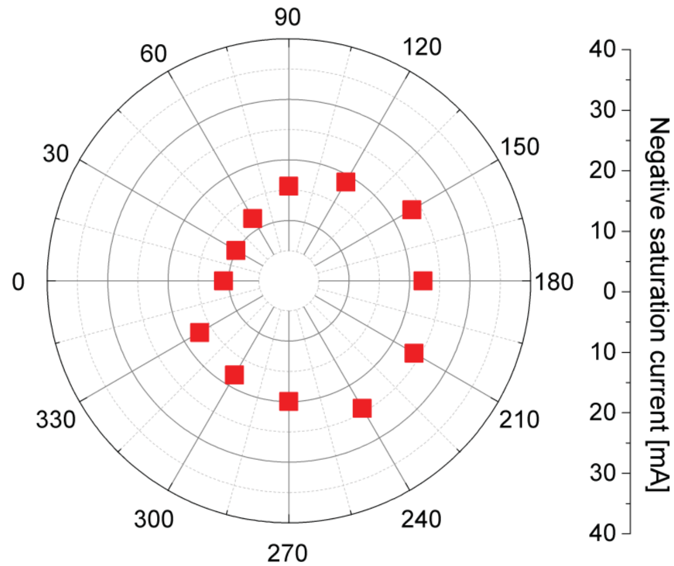


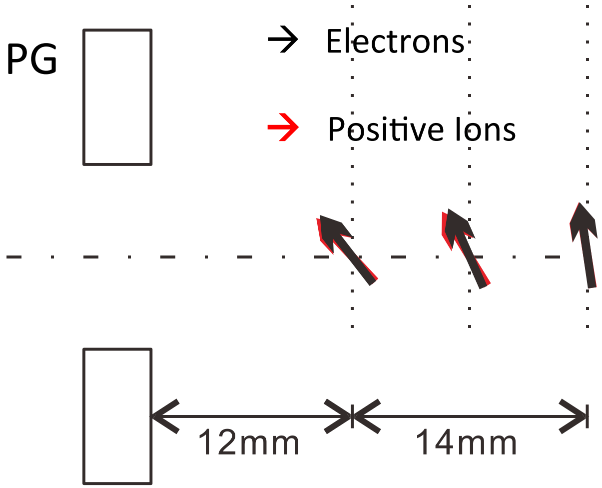


Hα reduction around the extraction apertures corresponds to H⁻ decrease in case of hydrogen ionic plasma.

Positive Ion Flow

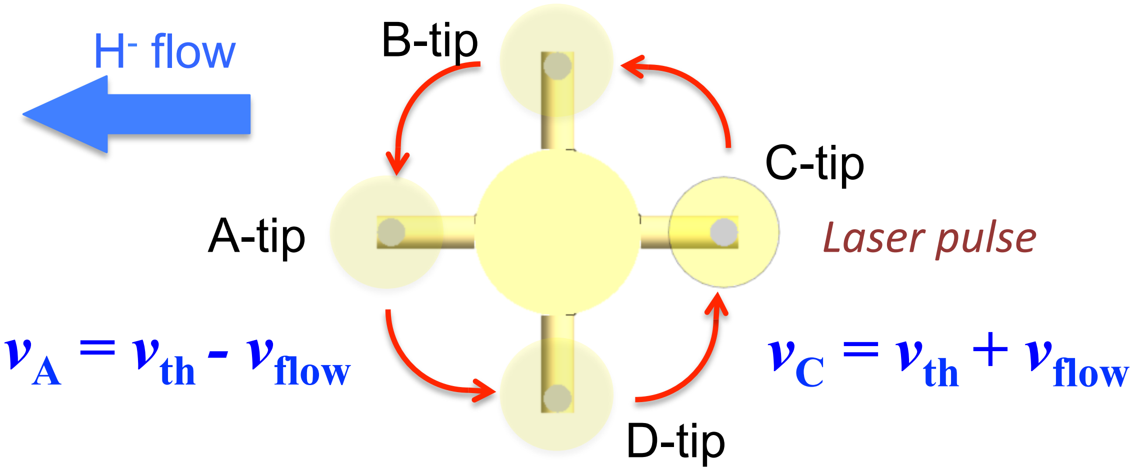






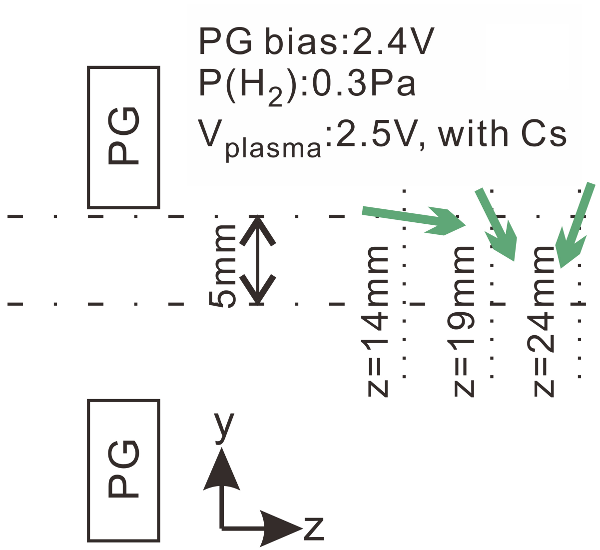
Flow directions of electron and positive ions are similar due to ambipolar diffusion

H^- Flow



v_{th}: thermal velocity
v_{flow}: flow velocity

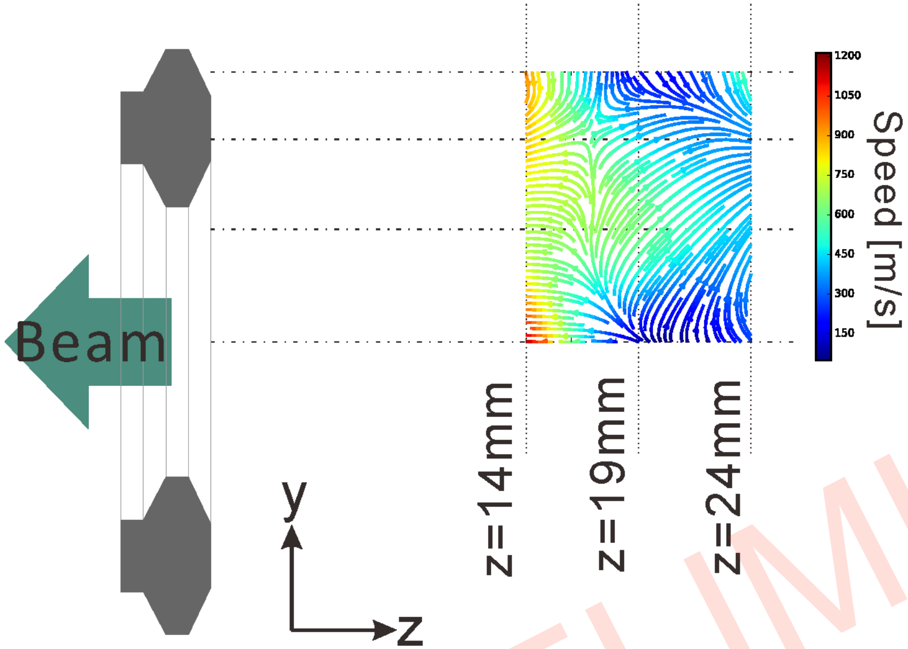
$$\boxed{\begin{aligned} v_{th} &= (v_A + v_C)/2 \\ v_{flow} &= (v_A - v_C)/2 \end{aligned}}$$



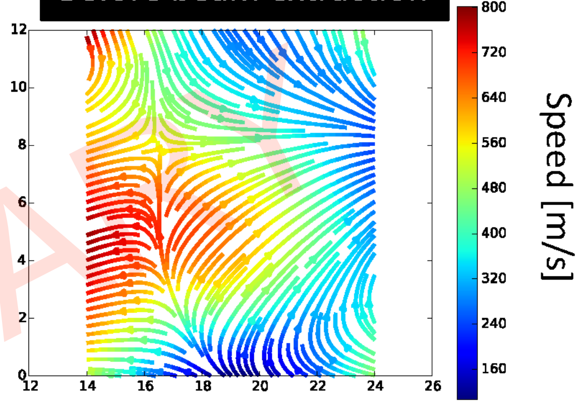
- Flow direction is opposite to electron and positive ions.
- This suggests the source region of H^-, electron and positive ions are different.

Recent result of H^- Flow

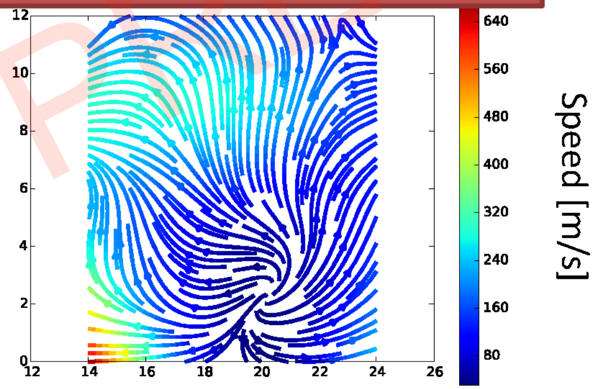
Vb: 2.4 V; $P(H_2)$: 0.3 Pa



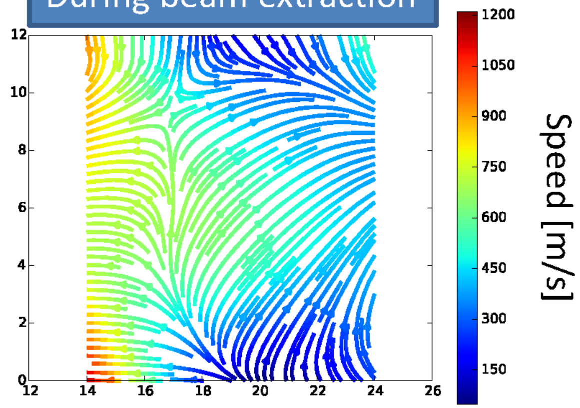
Before beam extraction



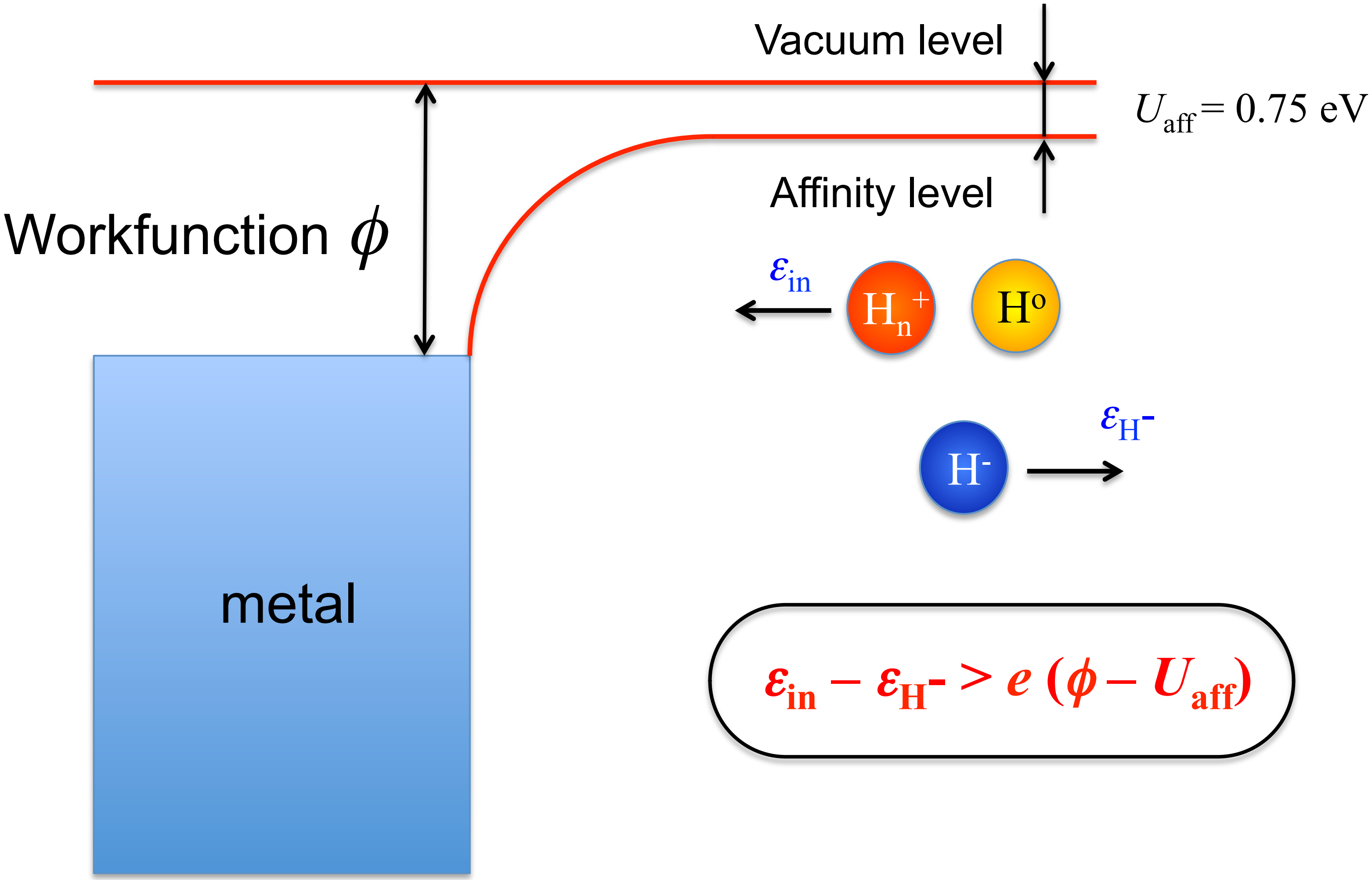
Velocity change due to extraction



During beam extraction



Energy Relation and Parent Particle of H^- ion



$$\varepsilon_{in} - \varepsilon_{H^-} > e\,(\phi - U_{aff})$$

Energy Relation and Parent Particle of H^- ion

Affinity level: 0.75 eV

$e(\phi - U_{aff})$ is 0.8 eV (at ϕ of 1.45 eV)

ε_{H^-} (outgoing energy of H^-)

Experimental results:

- 0.10 - 0.15 eV (*CRD*)
- 0.12 ± 0.03 eV (*Photodetachment*)

ε_{in} (incident energy of H^o / H_m^+)

Experimental results:

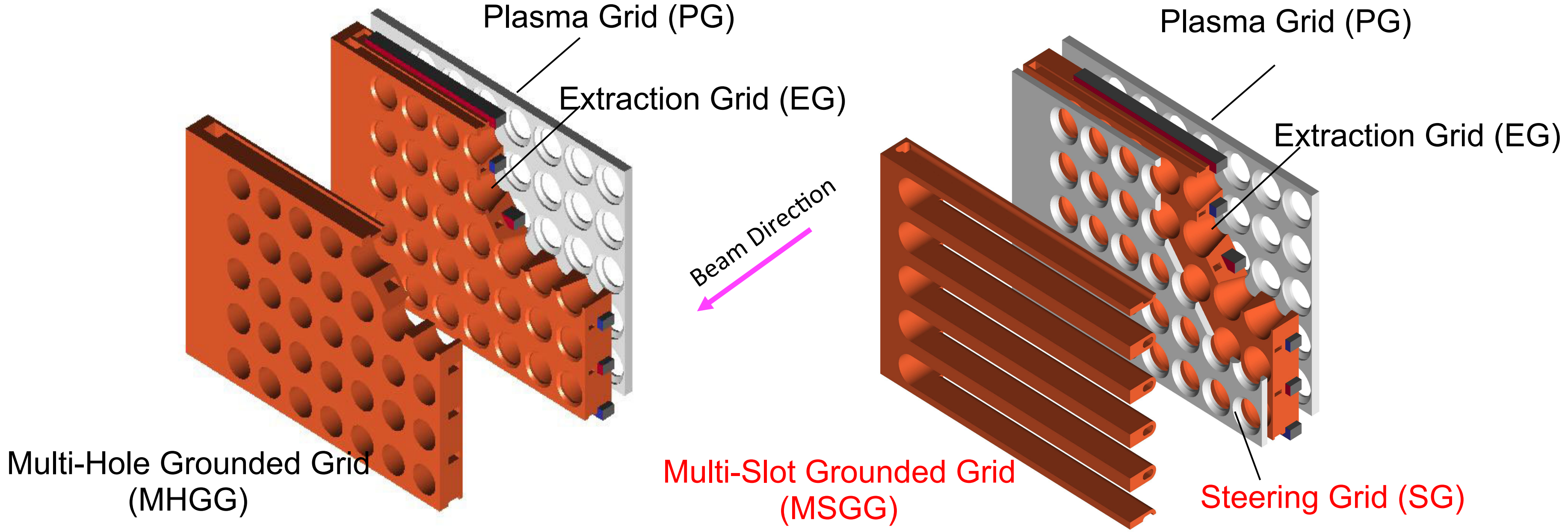
- H^o: 0.3 eV (*Hα LAS*)
- H_m^+: 0.8 – 1.0 eV (*HR-OES*)

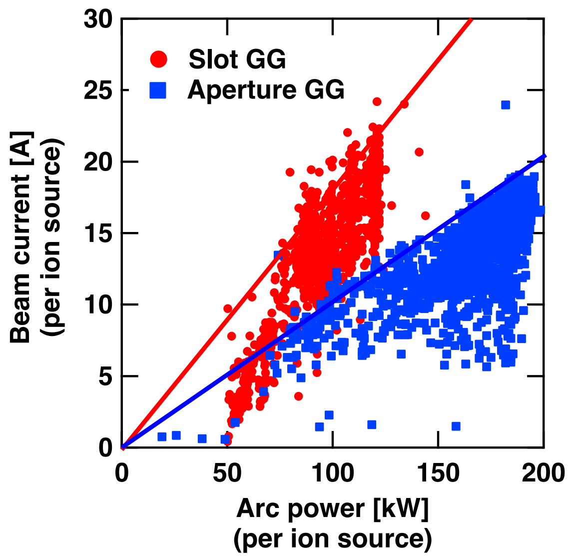
$$\varepsilon_{in} > \varepsilon_{H^-} + e(\phi - U_{aff})$$
$$= 0.15 + 0.8 \text{ [eV]}$$
$$\sim 1 \text{ [eV]}$$

parent of H^- is positive ions

Engineering Improvement

Accelerator with Multi-Slot Grid

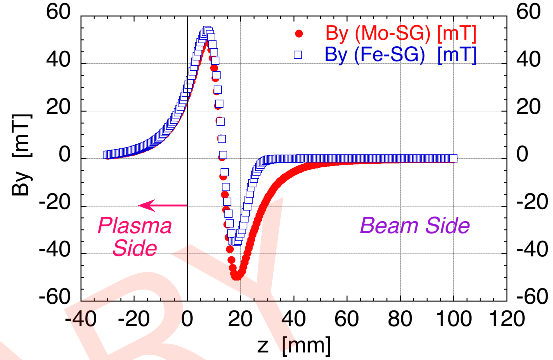




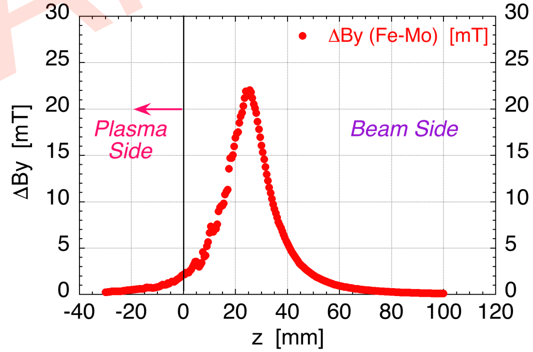
- N-NBI beamline #1 has been installed an accelerator with multi-slot grounded grid since 15 years ago.
- We researched the characteristics sufficiently, and the accelerator is scheduled to install beamline #2 and 3.
- By replacing the accelerator, arc efficiency defined as a ratio of H^- current to input arc power increases twice.
- It is considered caused by back streaming.

Modification of Grid materials

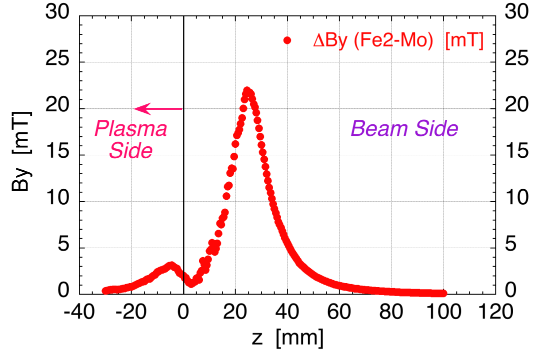
Normal configuration



Fe-SG configuration



Fe-SG-e configuration

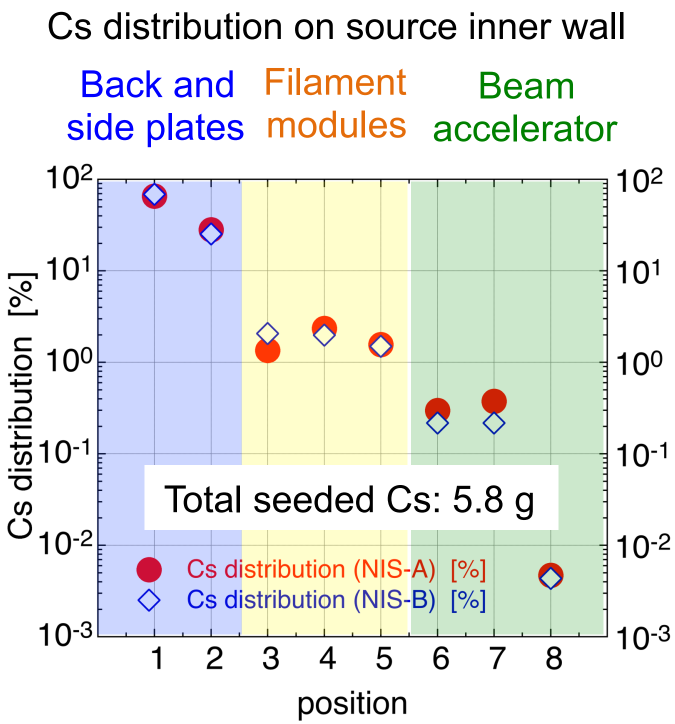


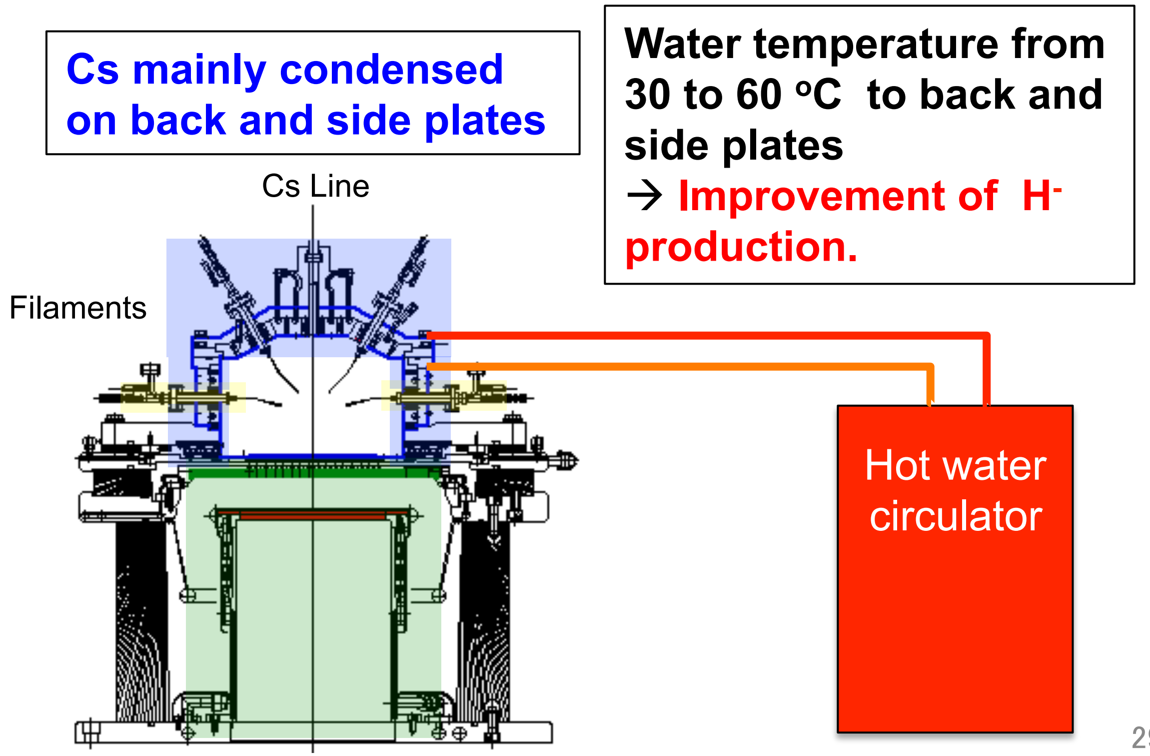
Active Control of Cs Pressure

Improvement of Cs recycling

Enhancement of H^- production (Active control of Cs vapor pressure)

Proper Caesium (Cs) is very effective to increase H^- current density. To obtain optimal Cs recycling, it is necessary to control Cs distribution inside source camber.



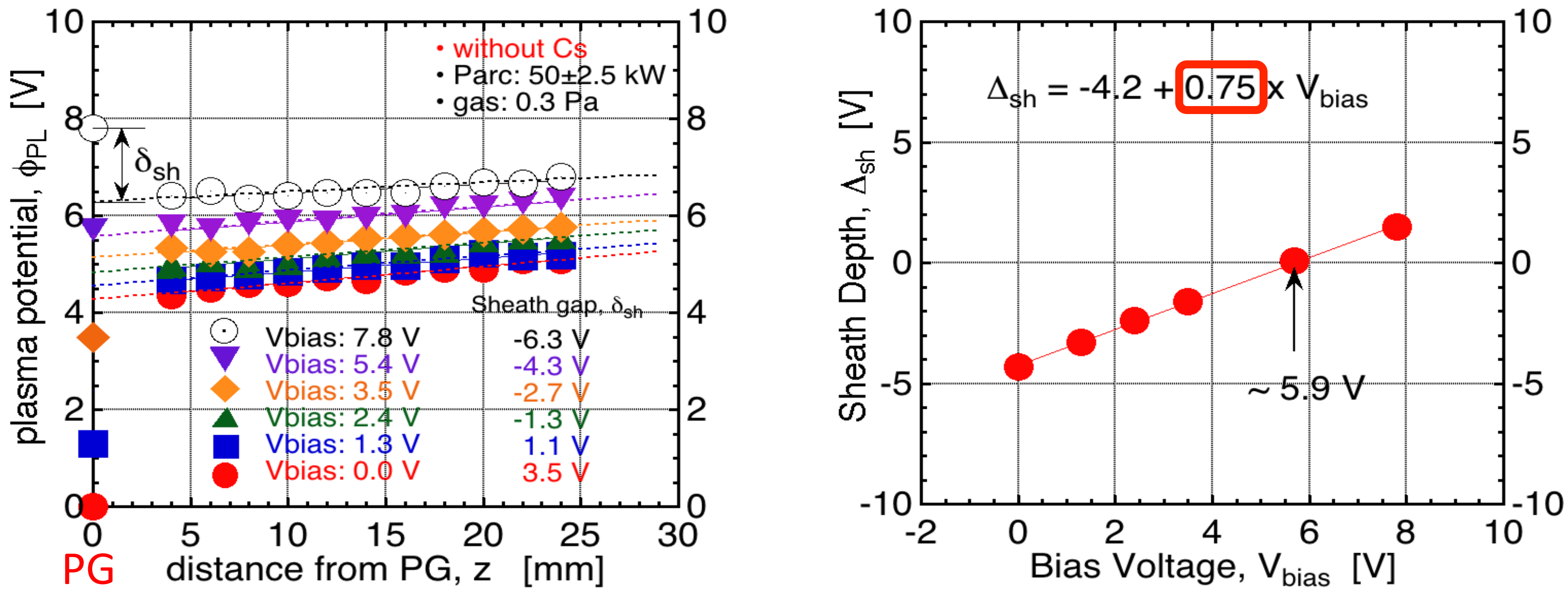


Summary

- Two p-NBIs and three n-NBIs provides intense neutral beams to LHD.
- For deuterium plasma experiment, p-NBIs increase their energy and n-NBI needs to improve.
- Comprehensive diagnostics has been carried out to investigate hydrogen negative-ion-rich plasmas.
- In our research, the parent particle of H^- is proton and the temperature is ~ 0.1 eV.
- The diagnostic results can be applicable to the other field of plasma processing, astrophysics and fundamental processes.
- Engineering improvement will be carried out by replacing the accelerator and by modifying the materials to ferromagnetic materials.

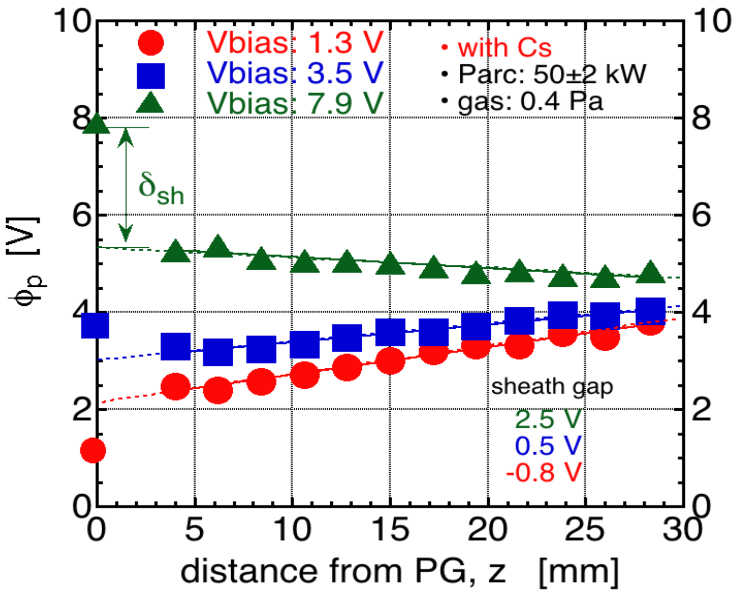
Appendix

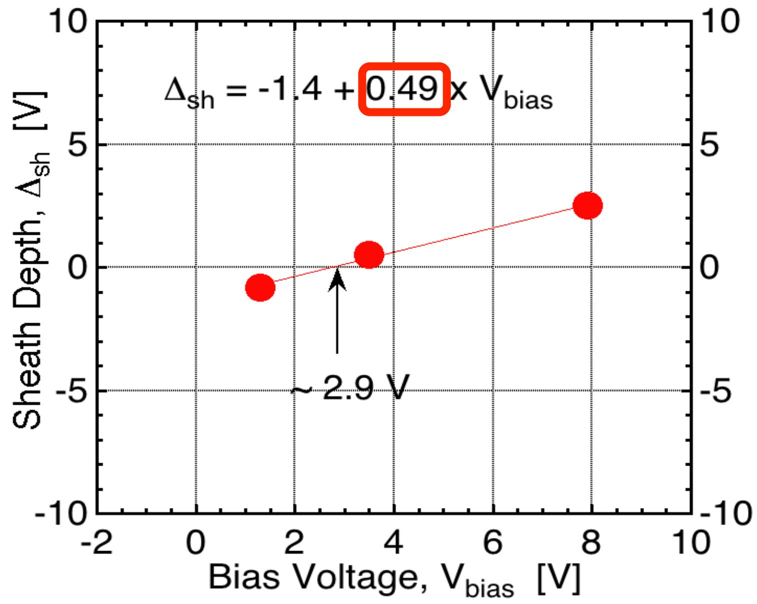
Distribution of plasma potential (bias dependence in H_2 plasma)



- Electric field, slope of potential distribution, does not change in pure H_2 plasma → **metal like character**
- The field strength is 20~30 V/m
- Sheath gap at PG is proportional to bias voltage

Distribution of plasma potential (bias dep. in Cs seeded plasma)

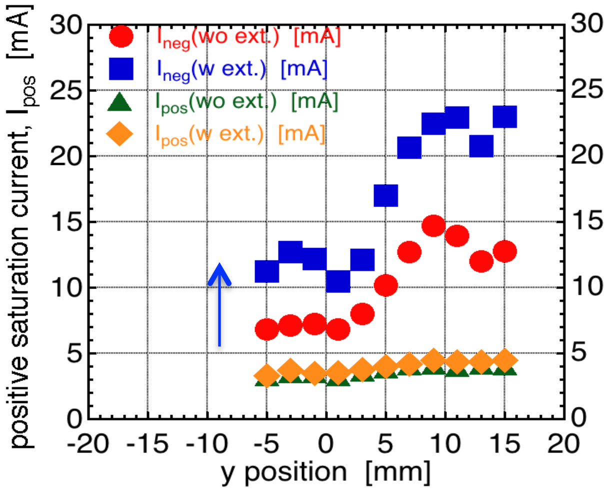


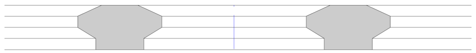


- Slope of potential distribution changes the by increasing the bias voltage in Cs seeded plasma → **Simi-conductor like character**
- This indicates the applied field penetrates inside Cs seeded plasma.
- Sheath gap is less sensitive to bias voltage than the case of H_2 plasma → Applied field is relaxed less with H^--rich sheath.

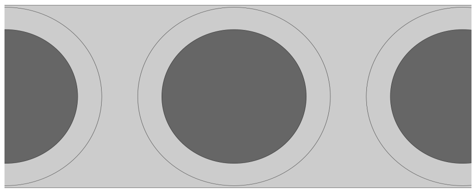
Change of saturation currents before and during extraction

Change of negative and positive saturation currents near PG with beam extraction.

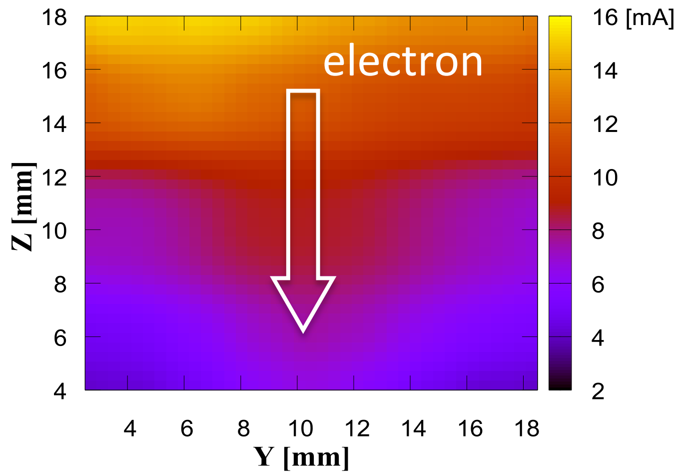




PG



2D mapped negative saturation currents near PG with beam extraction.

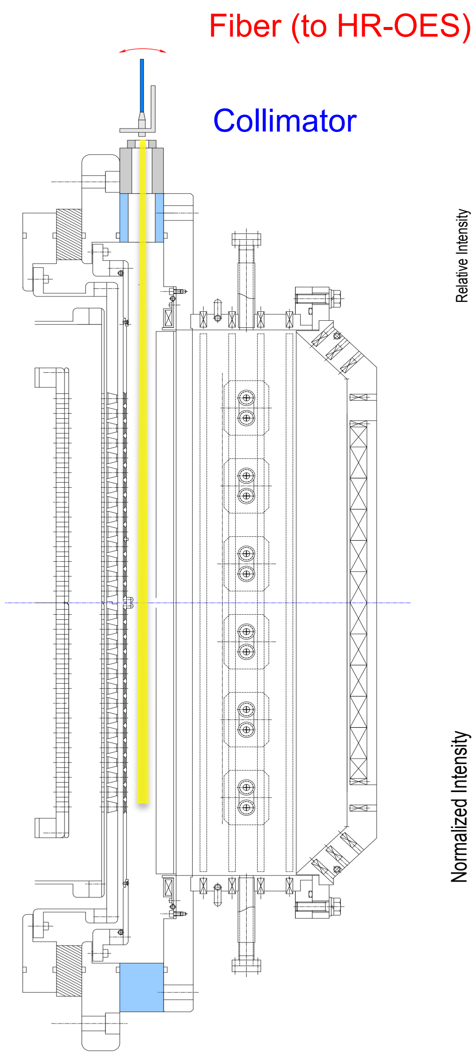


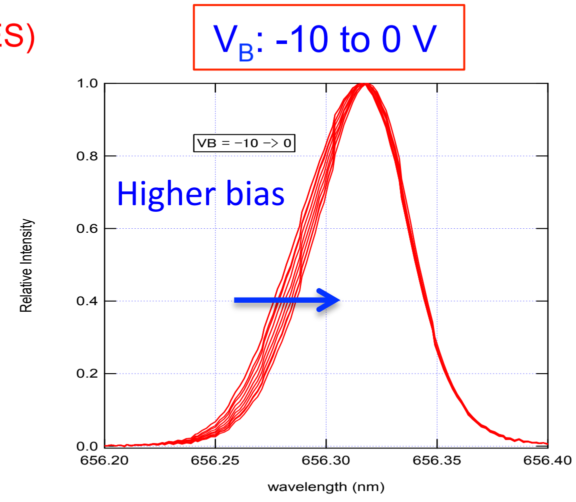
- 2D distribution of negative saturation current shows the electron concentrates along the magnetic field of electron deflection magnet

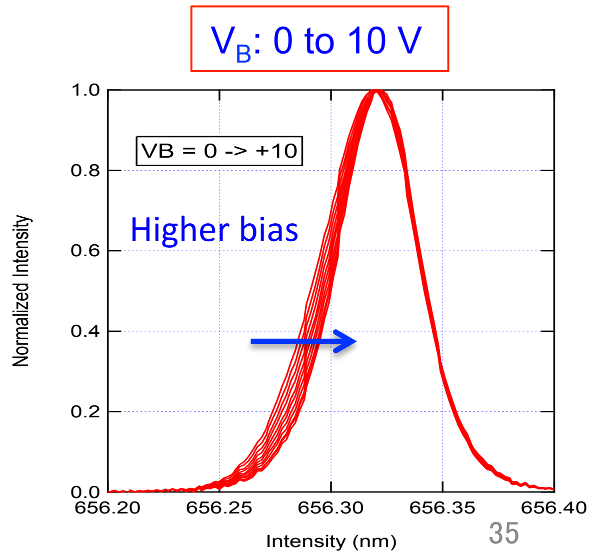
S. Geng et al., *Plasma Fusion Res*. **10**, 3405016 (2015)

$H^o(H^+/H_2^+)$ temperature (OES)

- Collimated window of HR- OES (High Resolution Optical Emission Spectroscopy) is installed at the top of bias insulator.
- Wavelength precision: 1 pm
  Resolution: 10 pm
- Blue wing of Hα has strong bias dependence.
- H^o temperature is estimated more than 1 eV from Doppler shift.
- Parent particles are H_2^+ or H^+ in this measurement.
  - $H_2^+ + e \rightarrow H(n=3) + H(n=1)$
  - $H^+ + H^- \rightarrow H(n=3) + H(n=1)$



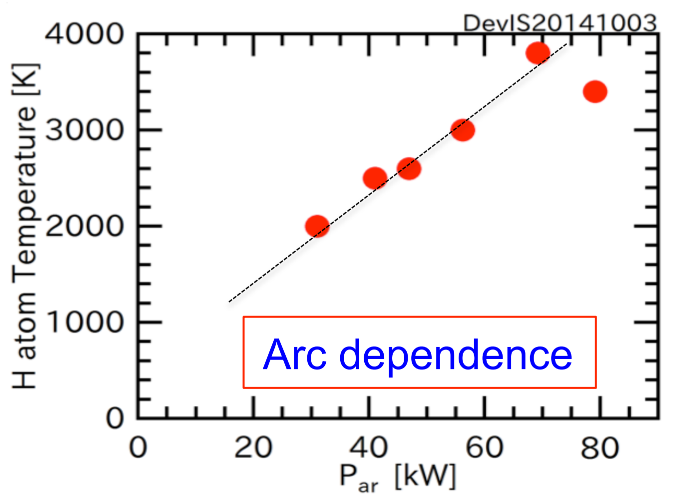


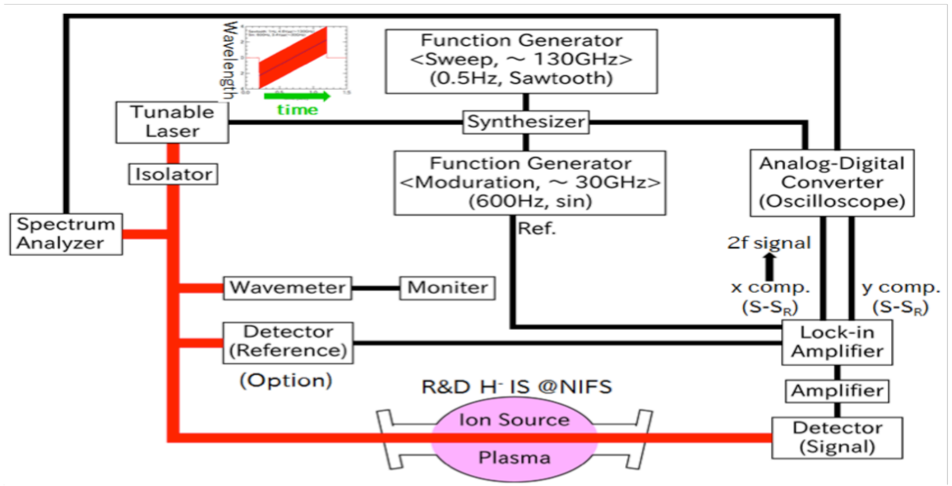


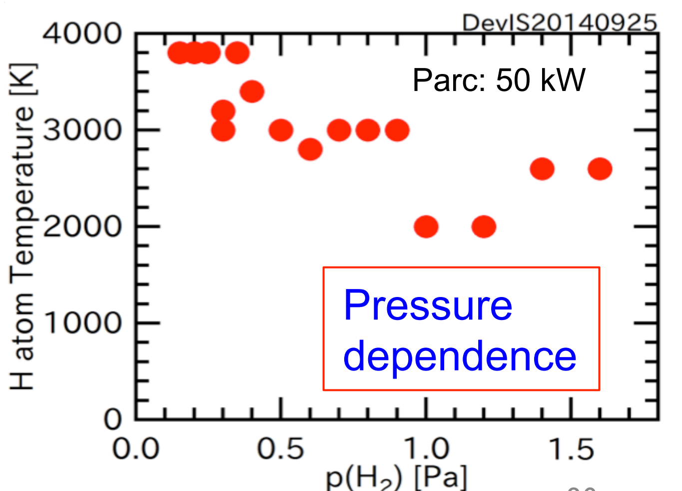
M. Wada et al., **TuePE35**: *ICIS 2015*, *this conference*

H^o temperature ($H\alpha$ LAS)

- $H\alpha$ laser absorption spectroscopy ($H\alpha$ LAS) is applied to measure H^o temperature, T_{H^o}.
- The temperature is almost proportional to input arc power.
- T_{H^o} ~ 0.3 eV at 50 kW of input.
- T_{H^o} decrease by increasing operational pressure.
- parent particle is H(n=2) in this diagnostic.

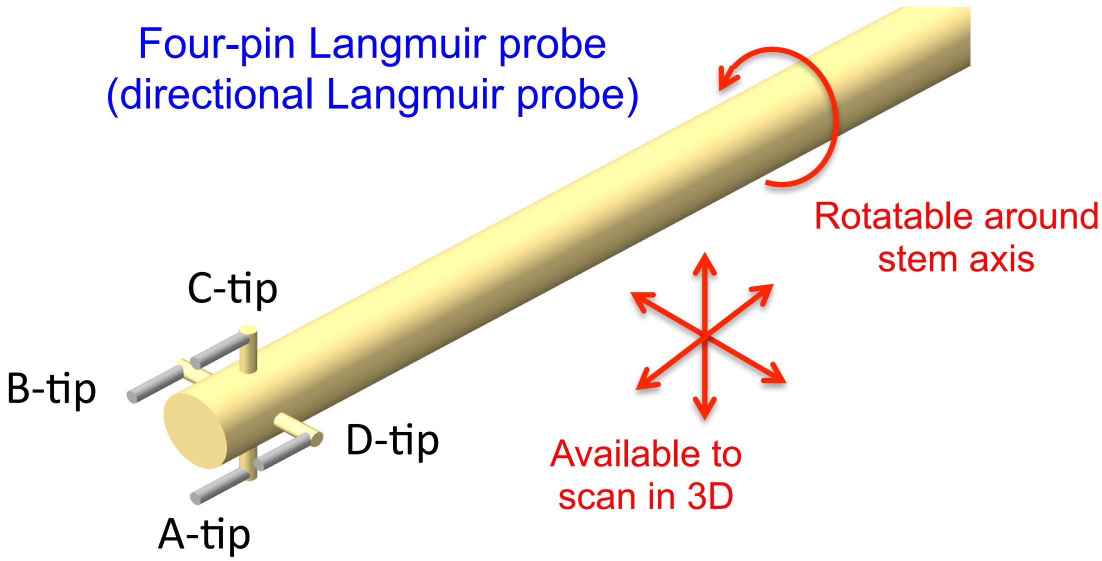


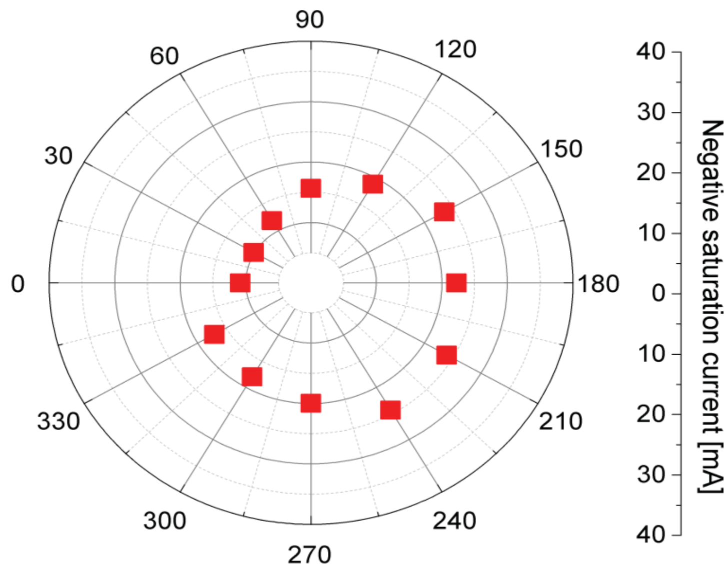


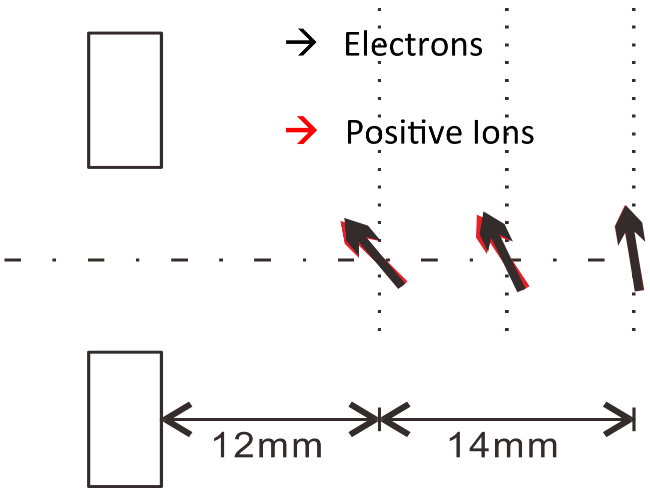


H. Nakano et al., *AIP Conference Proceedings* **1655**, 020018, (2015)

Flow of electron and positive ions (four-pin Langmuir probe)



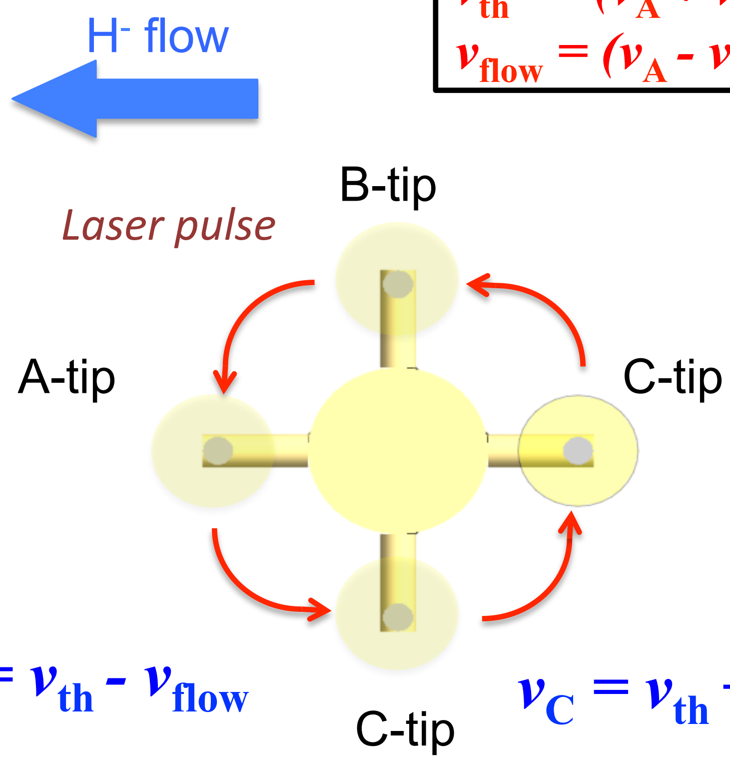




Flow directions of electron and positive ion are similar due to ambipolar diffusion

H- temperature and flow measured with 4-pin PD

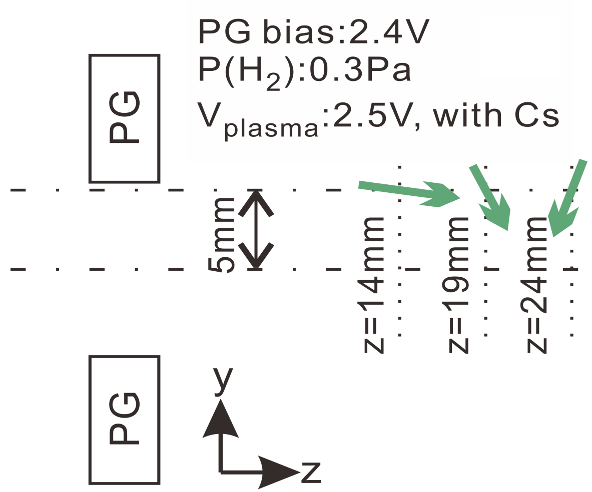
$$v_{th} = (v_A + v_c)/2$$
$$v_{flow} = (v_A - v_c)/2$$



$$v_A = v_{th} - v_{flow}$$

$$v_C = v_{th} + v_{flow}$$

v_{th}: thermal velocity
v_{flow}: flow velocity

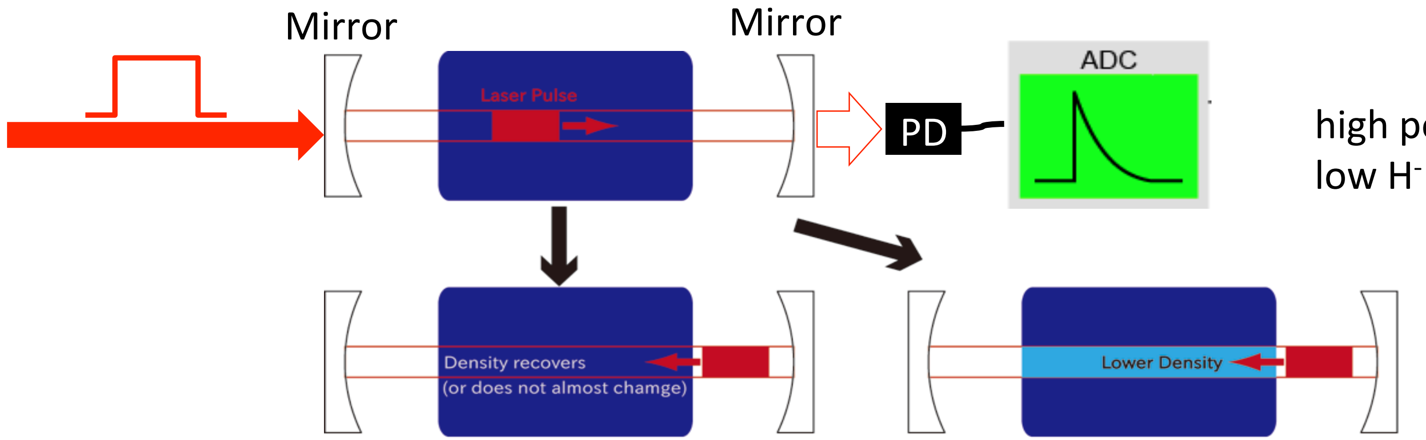


Flow direction is opposite to electron and positive ions.

$$v_{th} = \left(v_A + v_C\right)/2 = \sqrt{\frac{8kT_{H-}}{\pi m}}$$

Using the decay time of photodetachment signal, H- temperature is estimated as 0.12 ± 0.03 eV.

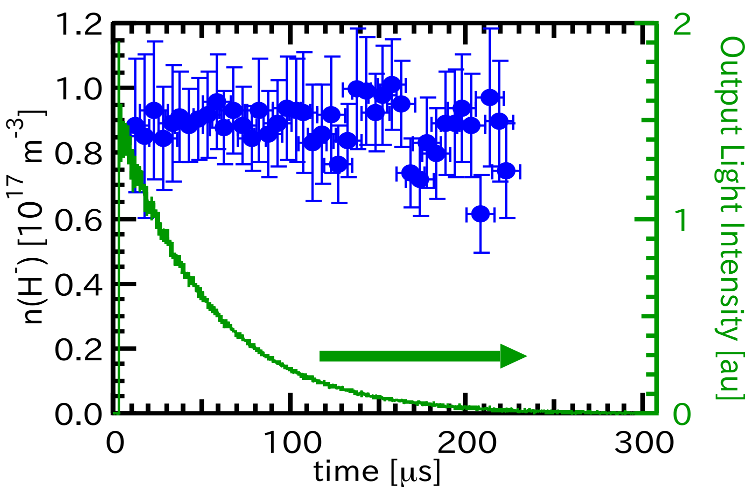
Saturated CRD

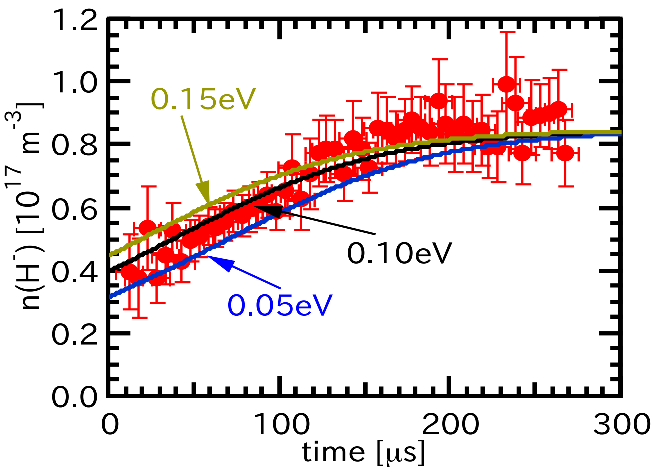


high power laser
low H^- temperature

Requirement for density measurement

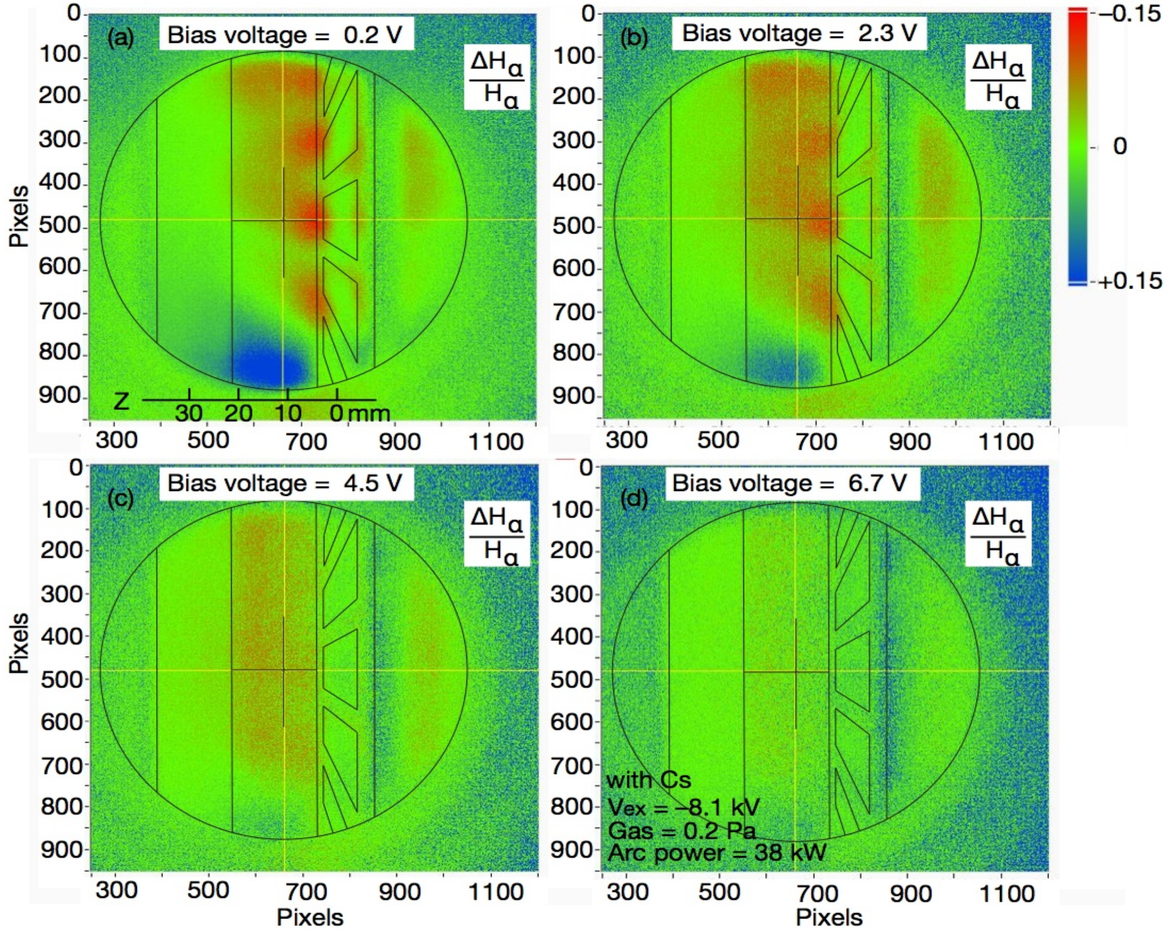
Density is underestimated





- Using higher power of YAG, over-neutralization occurs in cavity path.
- H^- temperature of 0.1 eV is obtained by comparing the saturation.

Hα CCD Imaging



- Ha CCD imaging, which subtracts image with beam off from beam on phases, shows the H^- decrement due to the extraction.
- By increasing the bias voltage, the reduction rate of H^- decreases as shown in the left-side figure.
- Next question is how the decreasing H- is extracted from PG apertures.

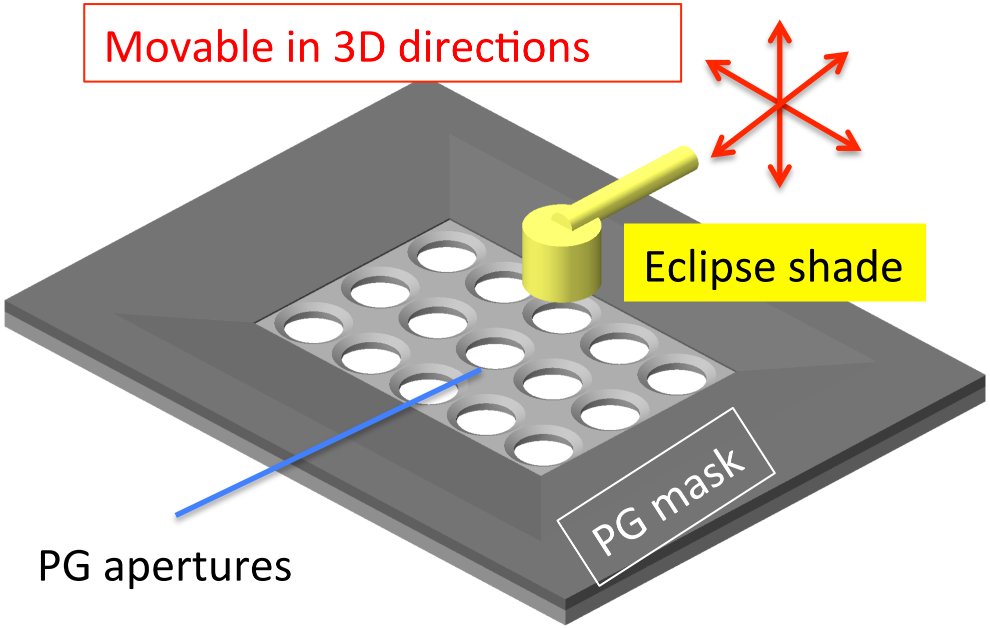
K. Ikeda et al., *AIP Conference Proceedings* **1655**, 040005 (2015)
K. Ikeda et al., **MonPE11** *ICIS 2015*, this conference

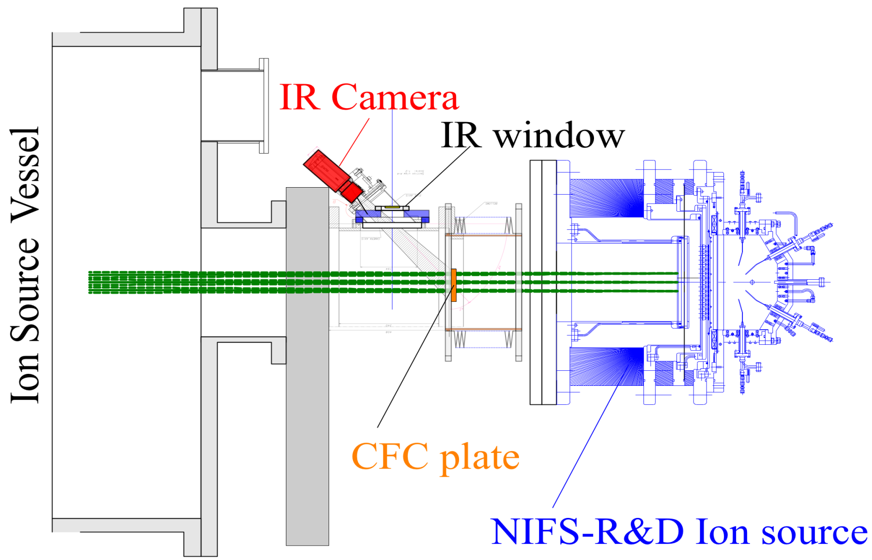
Beamlet eclipse: Setup

- PG aperture was shaded with movable ceramic cylinder (eclipse shade) to investigate influences of an obstacle for

  (1) H^- production and

  (2) beamlet interaction.
- H^- beamlets extracted from ion source was monitored with beamlet monitor called mini-STRIKE.

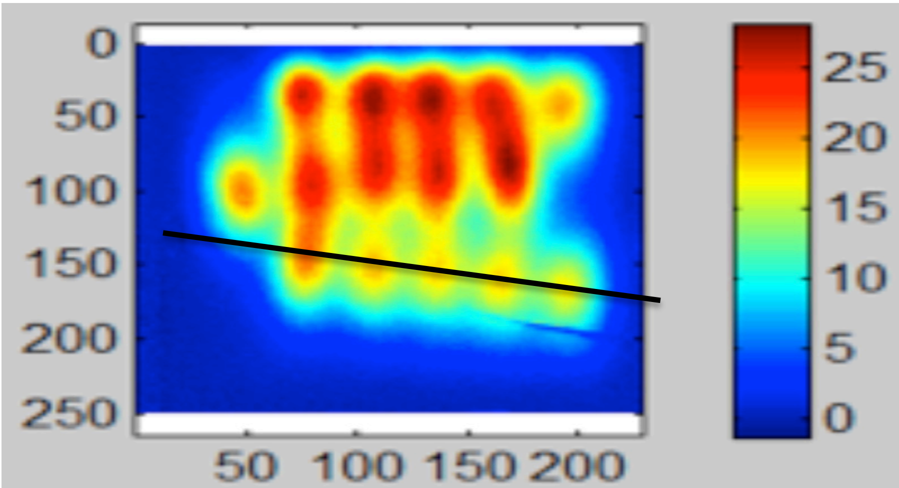




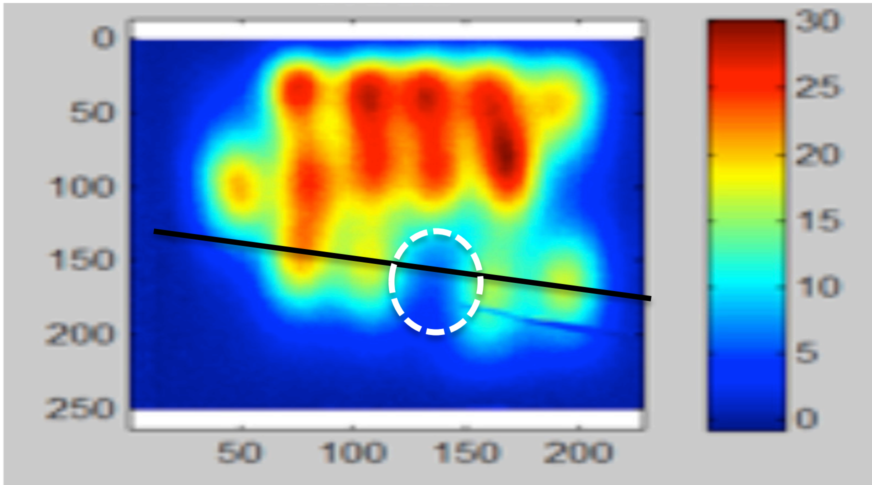
Idea of Dr. H. Nakano and M. Kisaki P. Veltri et al., **TuePS34** *ICIS 2015*, this conference

Beamlet eclipse: IR images

- Beamlet-eclipse shade changes the beamlet pattern drastically as shown below.
- Nearest neighbor beamlets shift due to beamlet interaction.

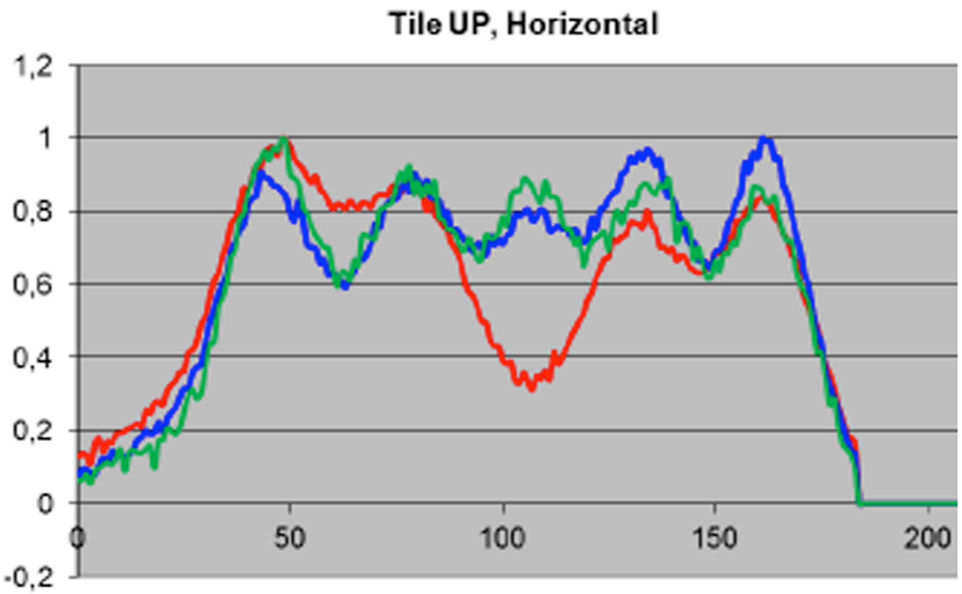


Normal extraction



with beamlet eclipse shade

Beamlet eclipse: 2D profiles



Green: w/o PG-aperture plug
Blue: PG-aperture plug@18.5 mm
Red: PG-aperture plug@ 8.5 mm

- By setting the beamlet-eclipse shade at 8.5 mm apart from PG, shaded beamlet decreases the intensity down to ~30 %.
- This decrease is mainly caused by shading the parent particle of H^-.
- Beamlet-eclipse method has possibilities to provide more information on beam extraction and formation.