First Results of Deuterium Beam Operation on Neutral Beam Injectors in the Large Helical Device

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- **Summary**

Neutral Beam Injectors for LHD

2 x P-NBI (Optimized for D)

- **Upgrade beam energy**
  40 keV → **60 keV** (BL4)
  40 keV → **80 keV** (BL5)

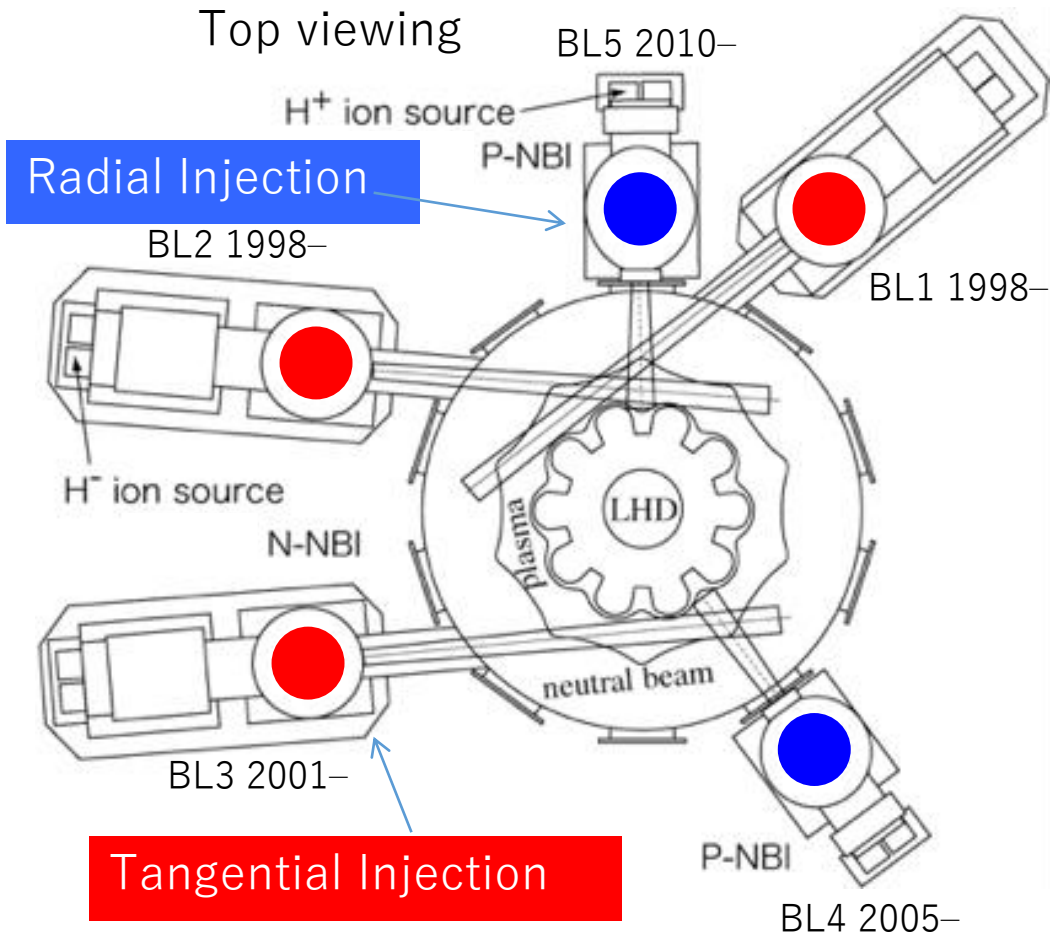
6MW/BL (H)→ **9 MW/BL** for **D operation**

3 x N-NBI (Optimized for H)

- **No energy increase**
  180 keV (BL1, BL2, BL3)

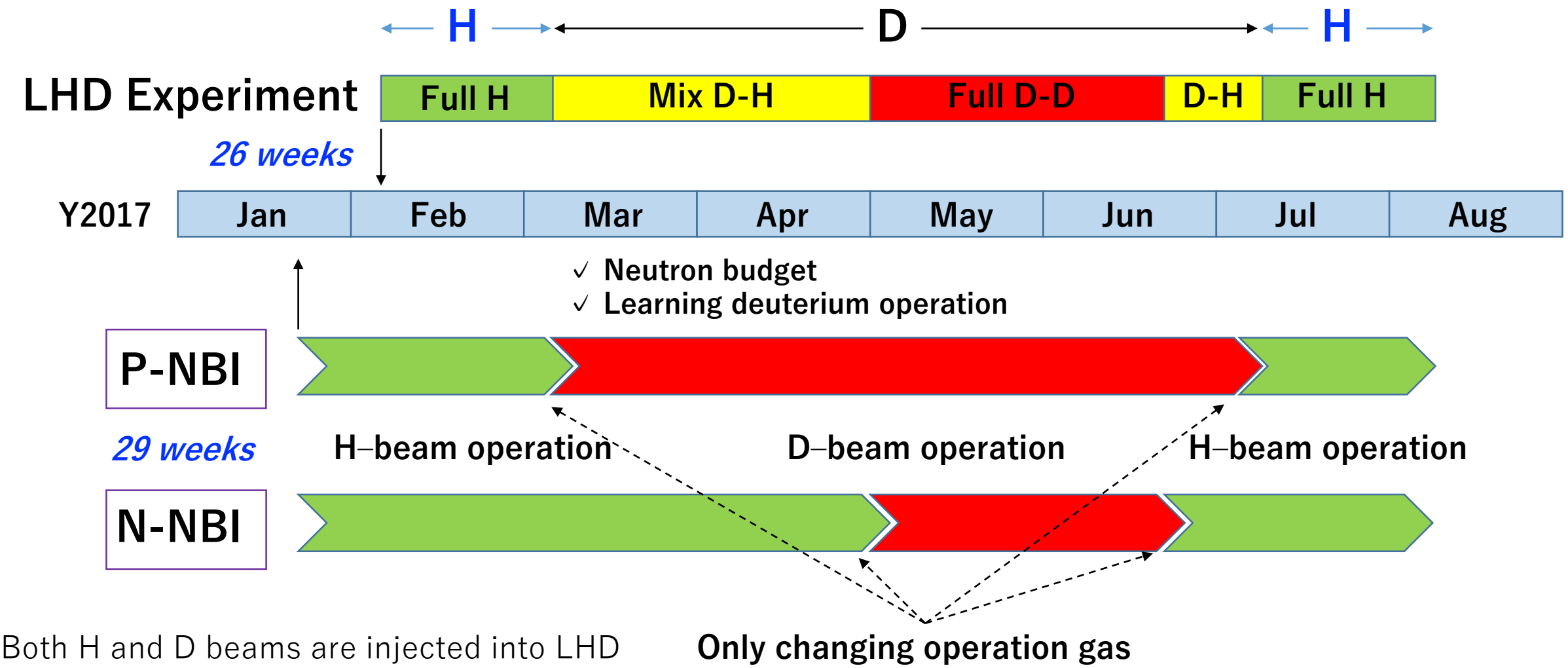
5 MW/BL for **H operation**

(Expectation) **~3.5 MW/BL** for **D operation**



NBI operation in 2017 LHD campaign

Start Deuterium experiment used high power deuterium beam



Both H and D beams are injected into LHD

Result of NB Power in 2017

Update our new record

31MW

P-NBI (Optimized for D)

- Upgrade beam energy
  40keV → **60 keV** (BL4)
  40keV → **80 keV** (BL5)

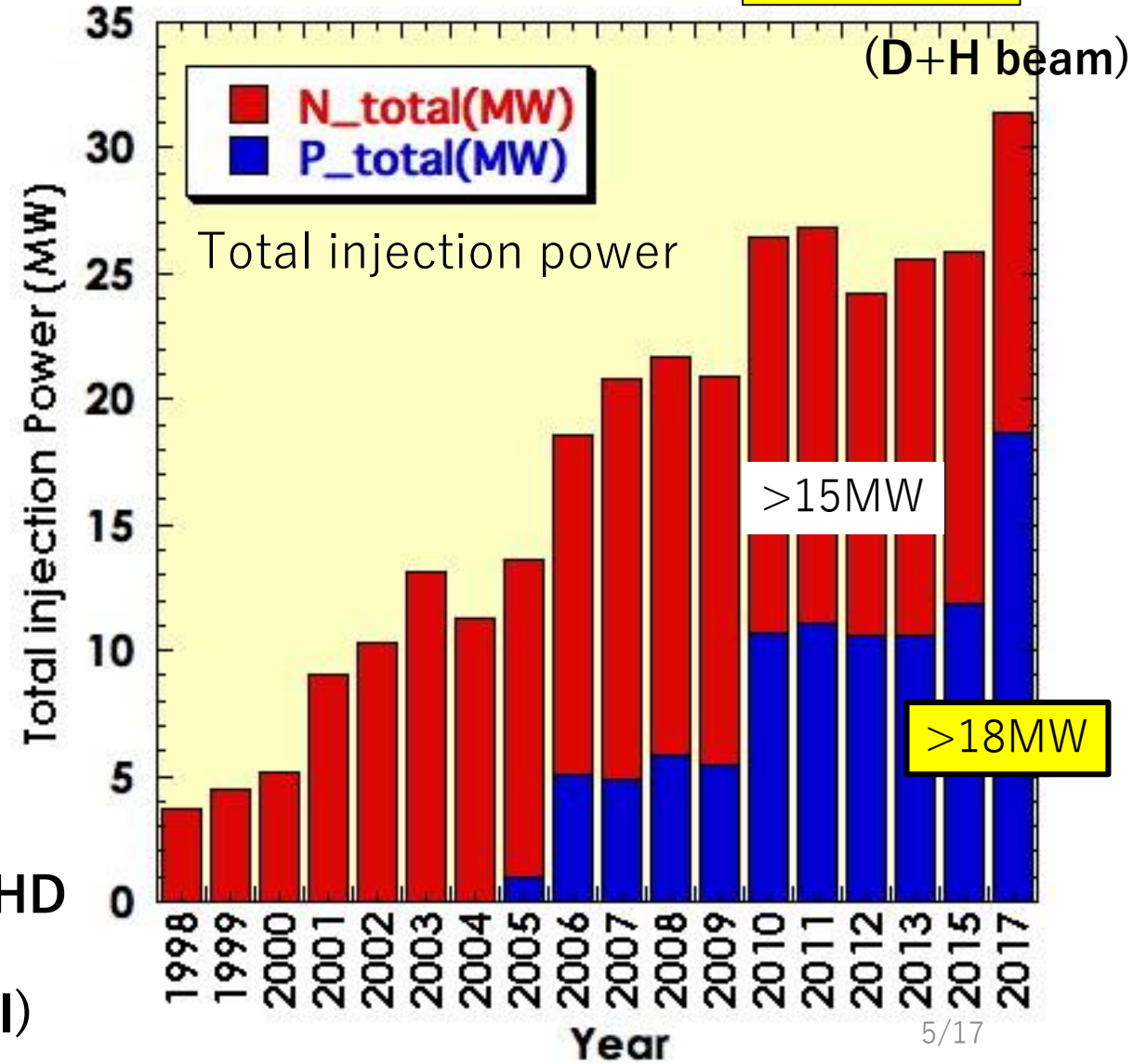
6MW/BL (H)→ **9MW/BL** for **D operation**

N-NBI (Optimized for H)

- Without increase beam energy
  180keV (BL1, BL2, BL3)

5MW/BL for **H operation**

We provided totally 31MW beam power into LHD plasma during mixed D-H phase
(D-beam from P-NBI and H-beam from N-NBI)



Deuterium operation on P-NBIs

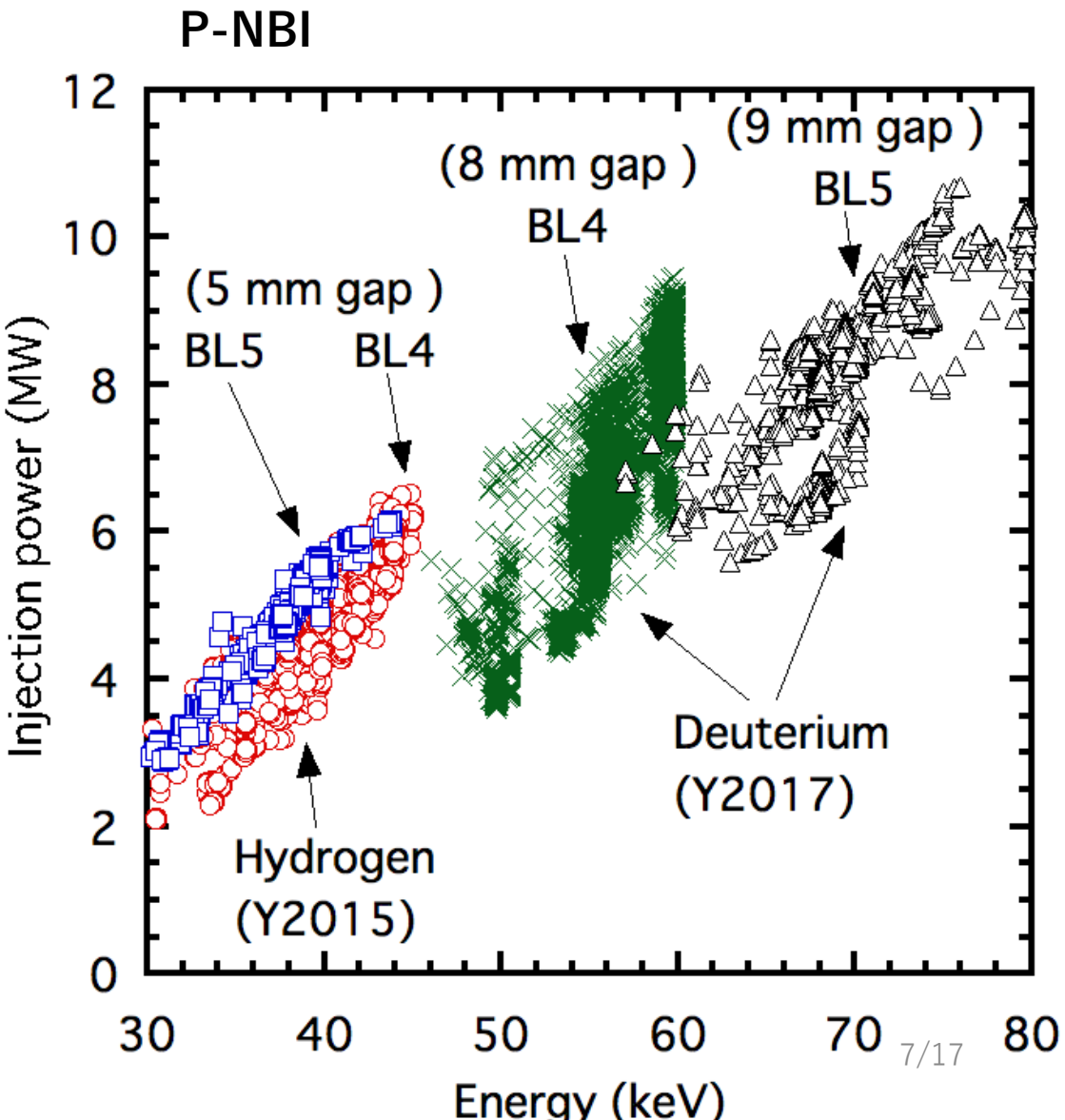
Injection beam power by P-NBI

Y2015 Hydrogen operation

H	Gap distance	Energy	Injection power
BL4	5 mm	45 keV	**6.5 MW**
BL5	5mm	44 keV	**6.1 MW**

Y2017 Deuterium operation

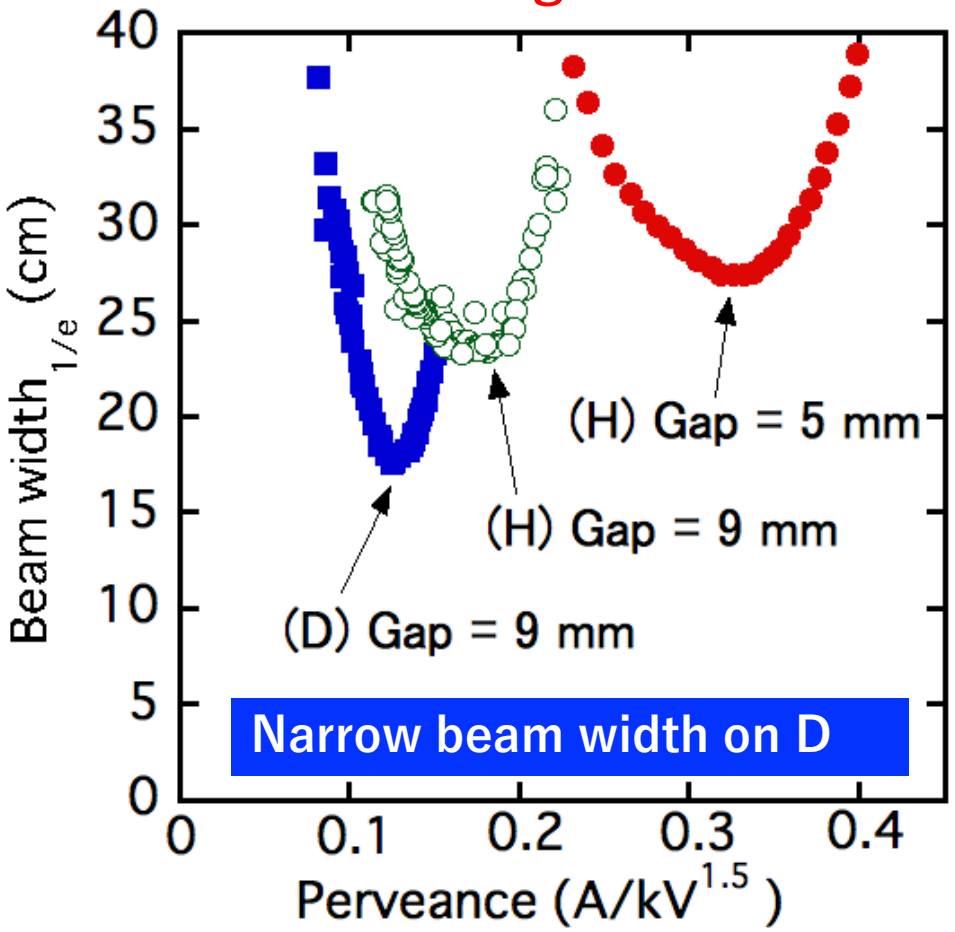
D	Gap distance	Energy	Injection power
BL4	8 mm	60 keV	**9.4 MW**
BL5	9 mm	75 keV	**10.6 MW**



Beam & source characteristics on D

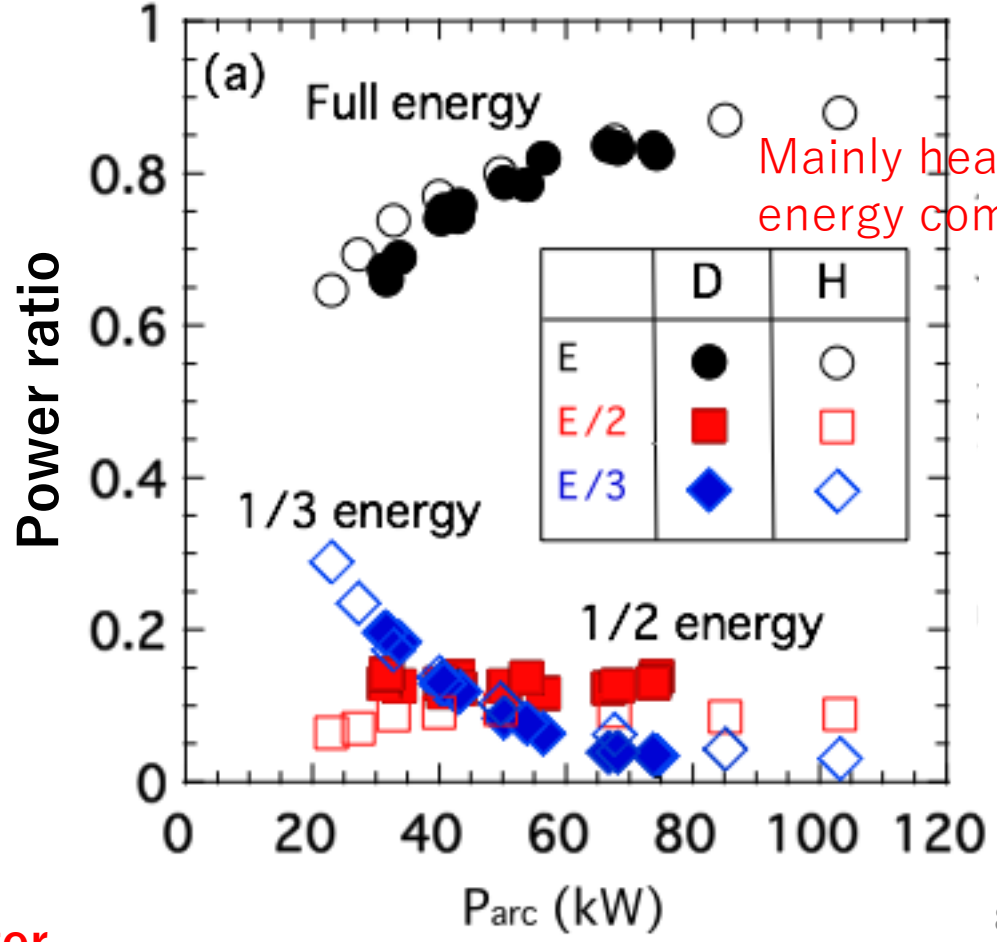
Small optimum perveance with same arc efficiency for beam current .

Good beam divergence on D



Concentration of heating power at plasma center

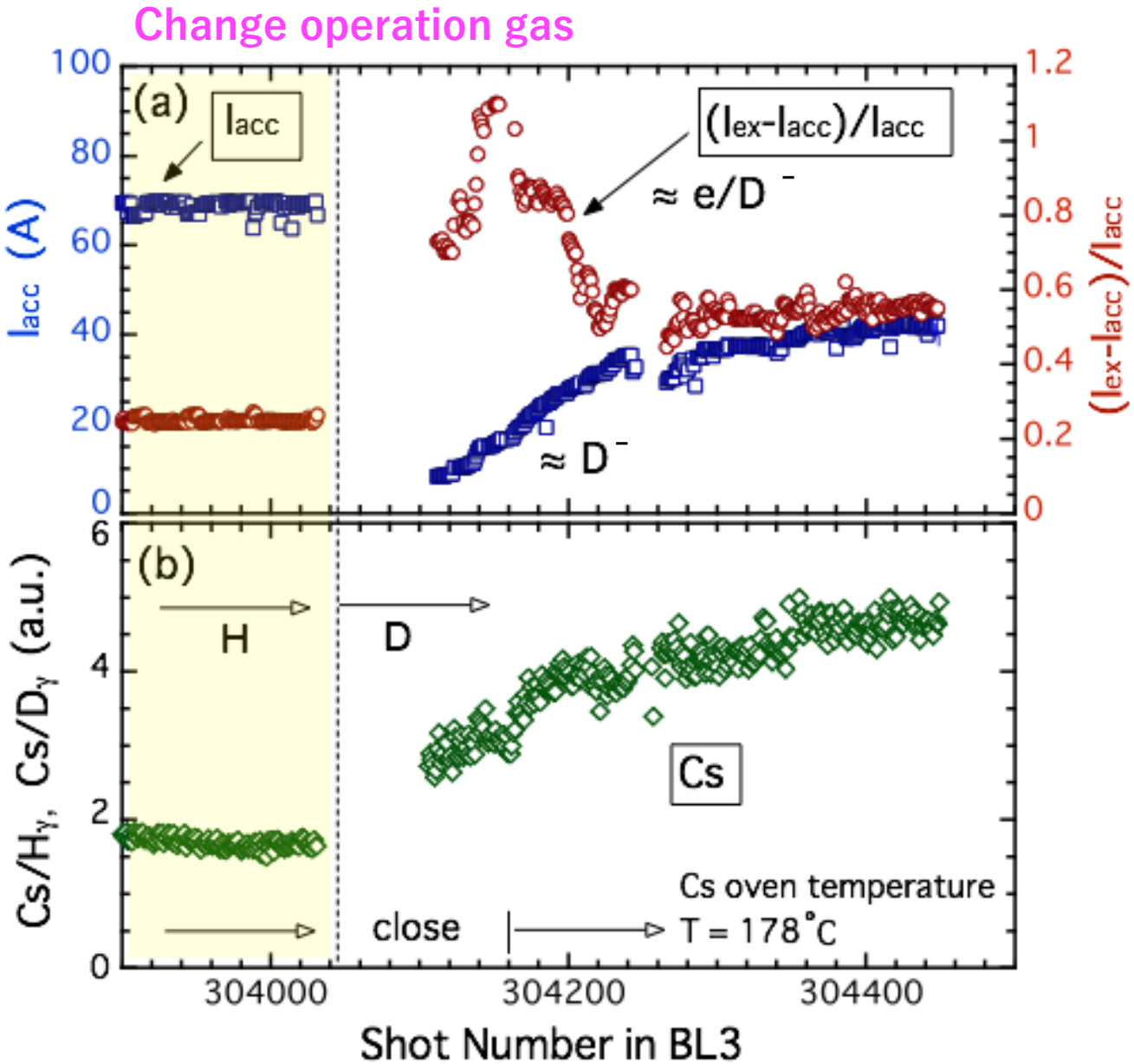
Good beam quality of high Deuteron ratio (83%) same as hydrogen discharge



Mainly heated by full energy component

Deuterium operation on N-NBI

First trial of D-operation in N-NBI



- Replacement of discharge gas from H to D by evacuating residual gas into a pipe and buffer tank.

$(I_{ex} - I_{acc}) \approx$ electron current

$I_{acc} \approx$ negative ion current

- Start 0.3 Pa D_2 source gas pressure.
- Low D^- current and high electron current ratio at the beginning.
- That is recovered by Cs conditioning

  D- ⇒ 40 A

  I_e/I_{D-} ⇒ 0.55

  Necessary optimization for D

- Increasing Cs signals

  ⇒ High sputtering

  ⇒ Change surface condition

  ⇒ High Cs consumption

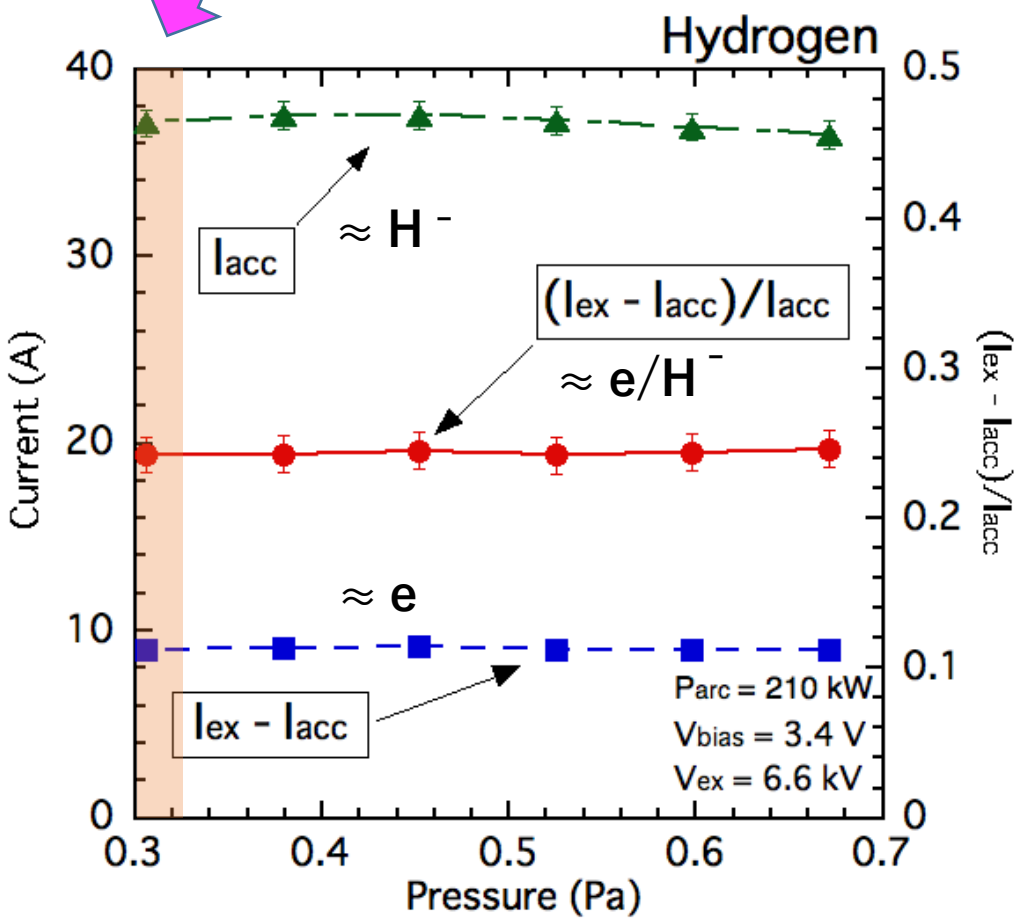
Pressure dependence

Checking extracted current by operation gas pressure in low arc discharge power

Keeping low electron current ratio in wide range

Low gas pressure can be used in H^-

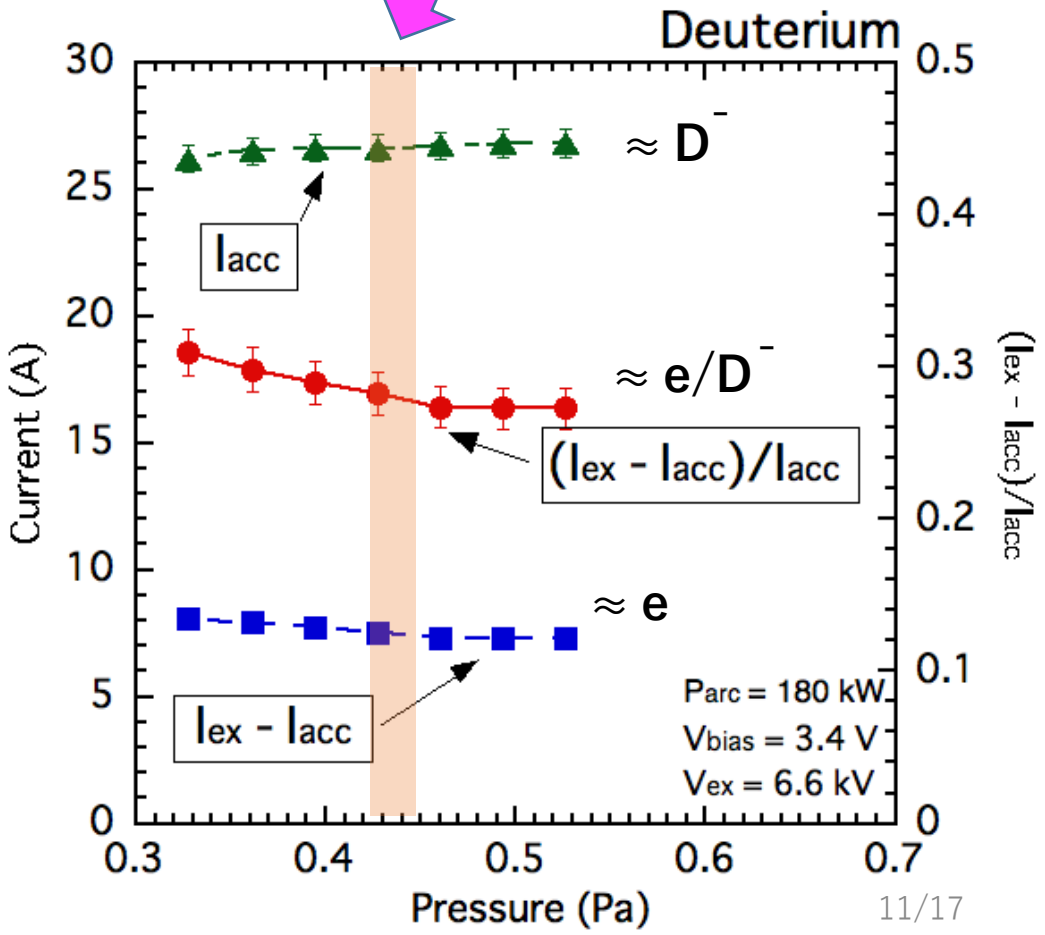
~ 0.3 Pa



e/D^- slightly increase in low pressure region

High gas pressure assists D operation

~ 0.43 Pa



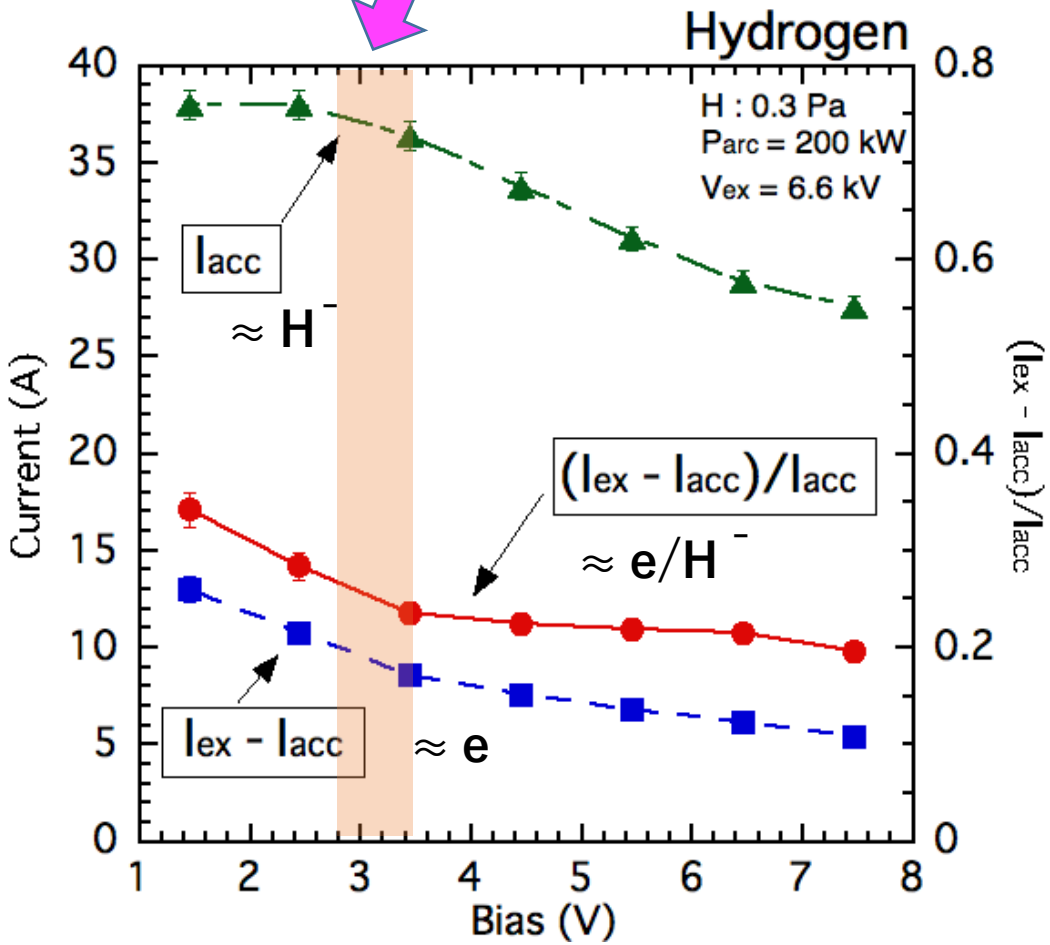
Bias voltage dependence

Bias voltage plays a role of suppressing the entry of electrons into the beam

Negative ion current is also suppressed by high bias

Keeping low e/H⁻~0.2 in low bias

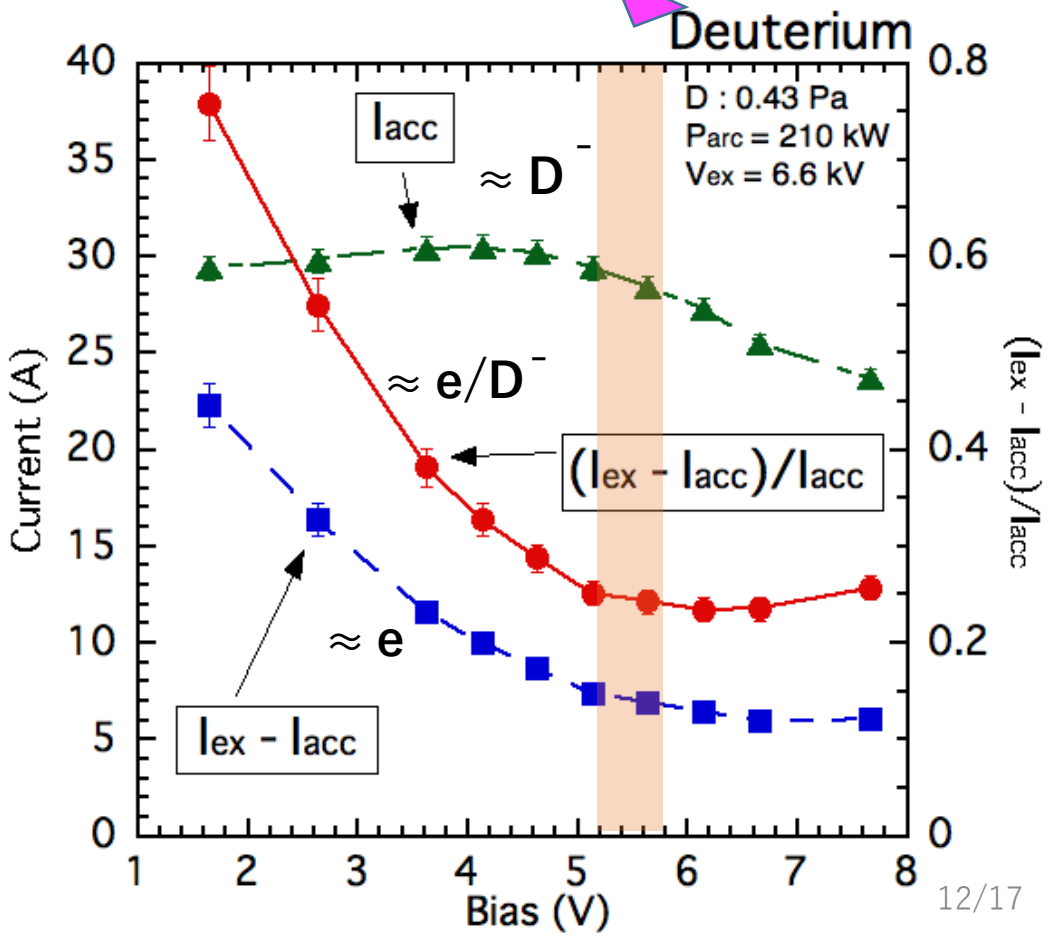
3 V bias on PG



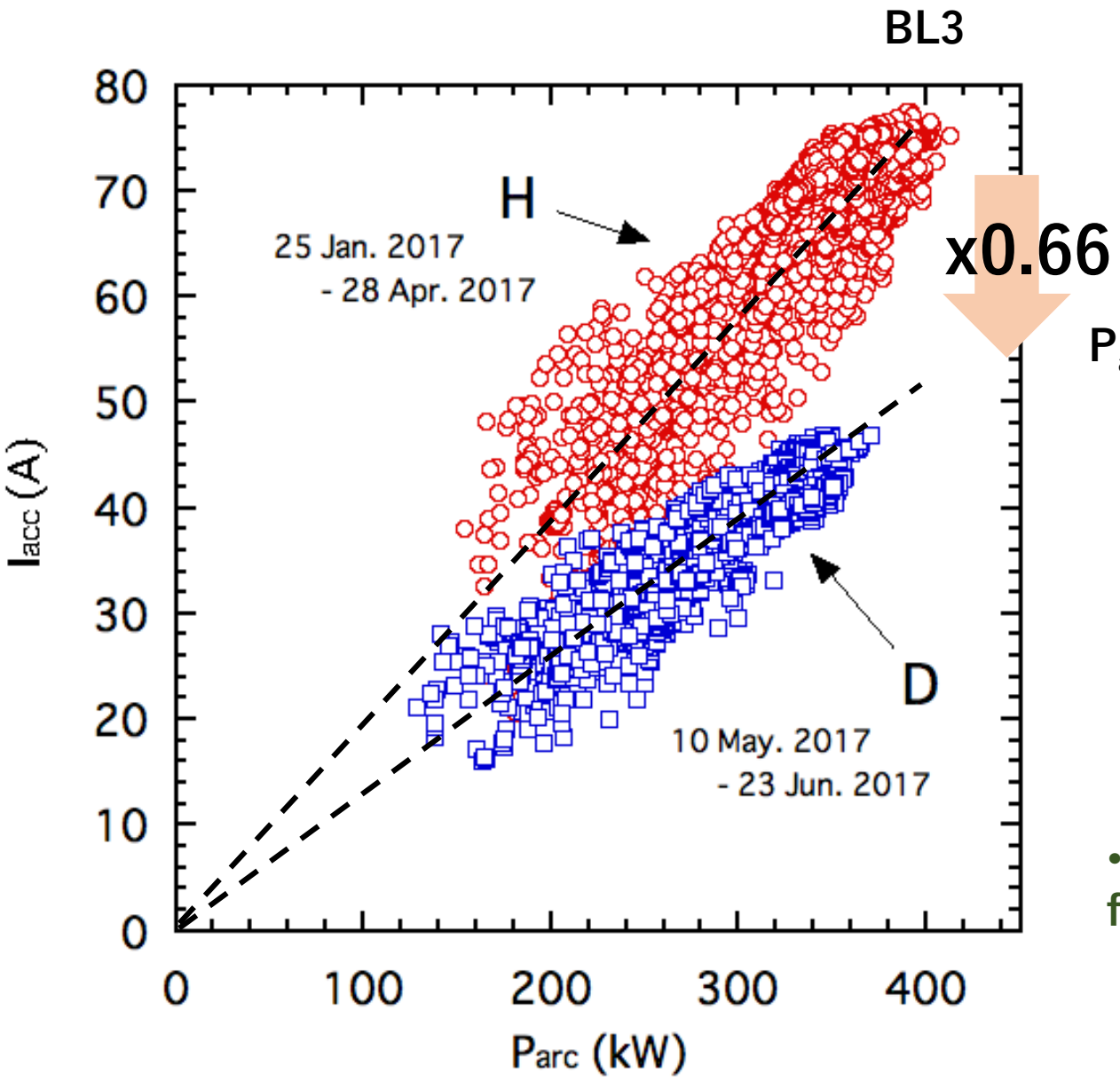
Large increase of electron in low bias in D

High bias effectively decrease e/D⁻

5.6 V bias on PG



Arc efficiency on N-NB source



- Result of beam current for H and D during beam injection as the function of P_{arc} .

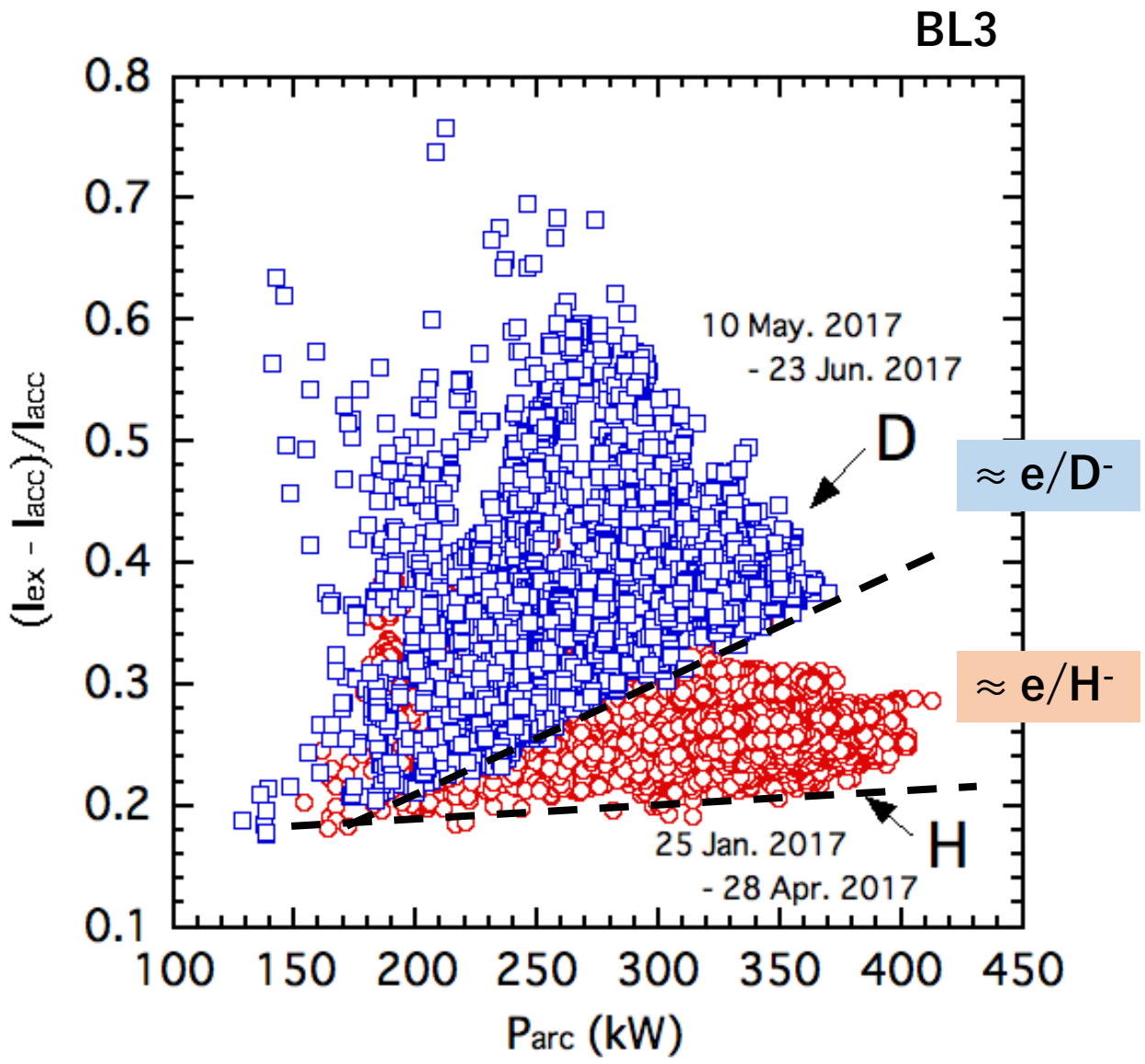
P_{arc} : Total arc discharge power used two source

- Beam current linearly increases by arc discharge power. (No saturation in D)

- Deuterium beam current is 66% of hydrogen beam current (averaged value), which reachs to 190A/m^2.

- Conservative beam operation have been done for safety reasons in this campaign.

Lower limit for electron current ratio



- **Lower limit for co-extracted electron current ratio as the function of P_{arc} clearly change in D operation.**

$$\frac{(I_{ex} - I_{acc}) \approx \text{electron current}}{I_{acc} \approx \text{negative ion current}}$$

- **e/H^- <0.3 in high power operation in H.**
- **e/D^- increased 0.38 at 370 kW arc discharge.**

⇒ electron current limits beam power

Slope	
(e/I_{acc})/100kW	9 %/100kW (D)
	1.4 %/100kW (H)

- **Input discharge power strongly affects to electron current ratio in D operation. Its may due to an increase of momentum flux.**

Injection beam power by N-NBI

Negative ion source is optimized for H operation

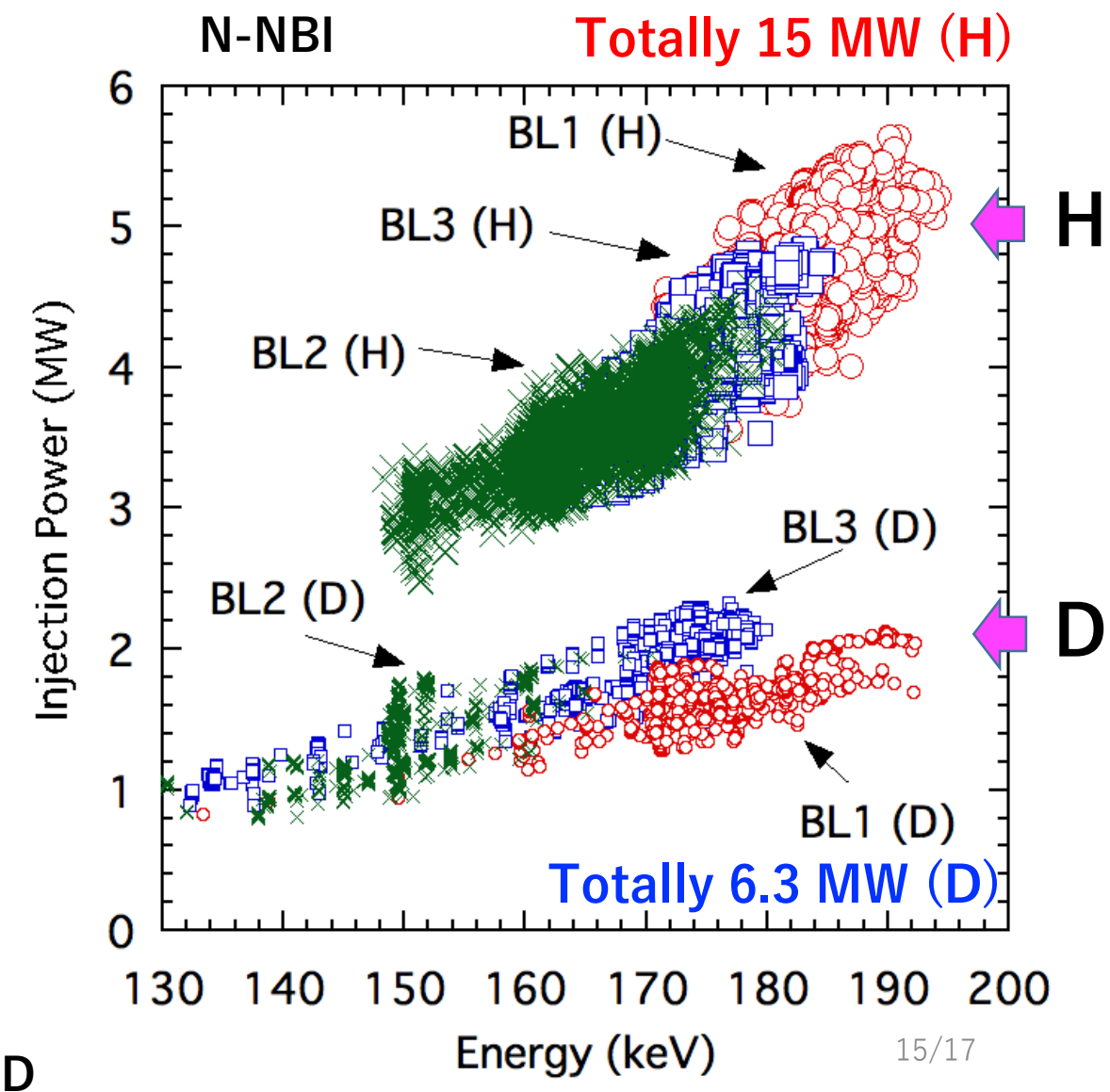
Y2017 hydrogen operation

H	I_e/I_H-	Energy	Inj. power
BL1	0.27	190 keV	**5.6 MW**
BL2	0.30	178 keV	**4.6 MW**
BL3	0.23	185 keV	**4.8 MW**

Y2017 Deuterium operation (only Gas change)

D	I_e/I_D-	Energy	Inj. power
BL1	0.49	190 keV	**2.1 MW**
BL2	0.54	171 keV	**1.9 MW**
BL3	0.39	178 keV	**2.3 MW**

Conservative beam operation in D



Summary (1)

- **First Deuterium beam injection have been done safely in five beam lines in LHD**
- **Total injection beam power up to 31 MW. [P-NBI(D)/N-NBI(H)]**
- **10.6 MW (75 keV) deuterium beam with shape width and 83% deuteron ratio has achieved on P-NBI by upgraded beam energy and optimizing electrode gap distance.**
- **Negative ion current for D is 66% of H, that is reached 190 A/m^2. Injection beam power is less than half with conservative beam operation.**

Summary (2)

- **In the D^- beam, lower limit of the electron current ratio strongly depends on P_{arc} .**
- **This result suggests that deuterium momentum flux strongly influences to the surface condition and the production rate of deuterium negative ions.**
- **Improvement of deuterium negative ion and additional electron suppression method will be required for high power deuterium beam injection.**

Thank you for your attention !