Effects of azimuthal cusp magnetic field on neutron production rate in a cylindrical IEC device

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13th US-Japan IEC Workshop
Sydney, Australia, Dec. 7-8, 2011

The ways to enhance NPR

Fusion reaction rate $R = \int_V n_1 n_2 < \sigma v > dV \ [s^{-1}]$

- **To increase ion density**
- **To increase ion energy**
  - ✓ **Low pressure operation**
    - ⇨ **To reduce ion energy loss by charge exchange reaction**
  - ✓ **Increment of Ion production near the anode**
    - ⇨ **To fully accelerate ion by electric field**

New trial

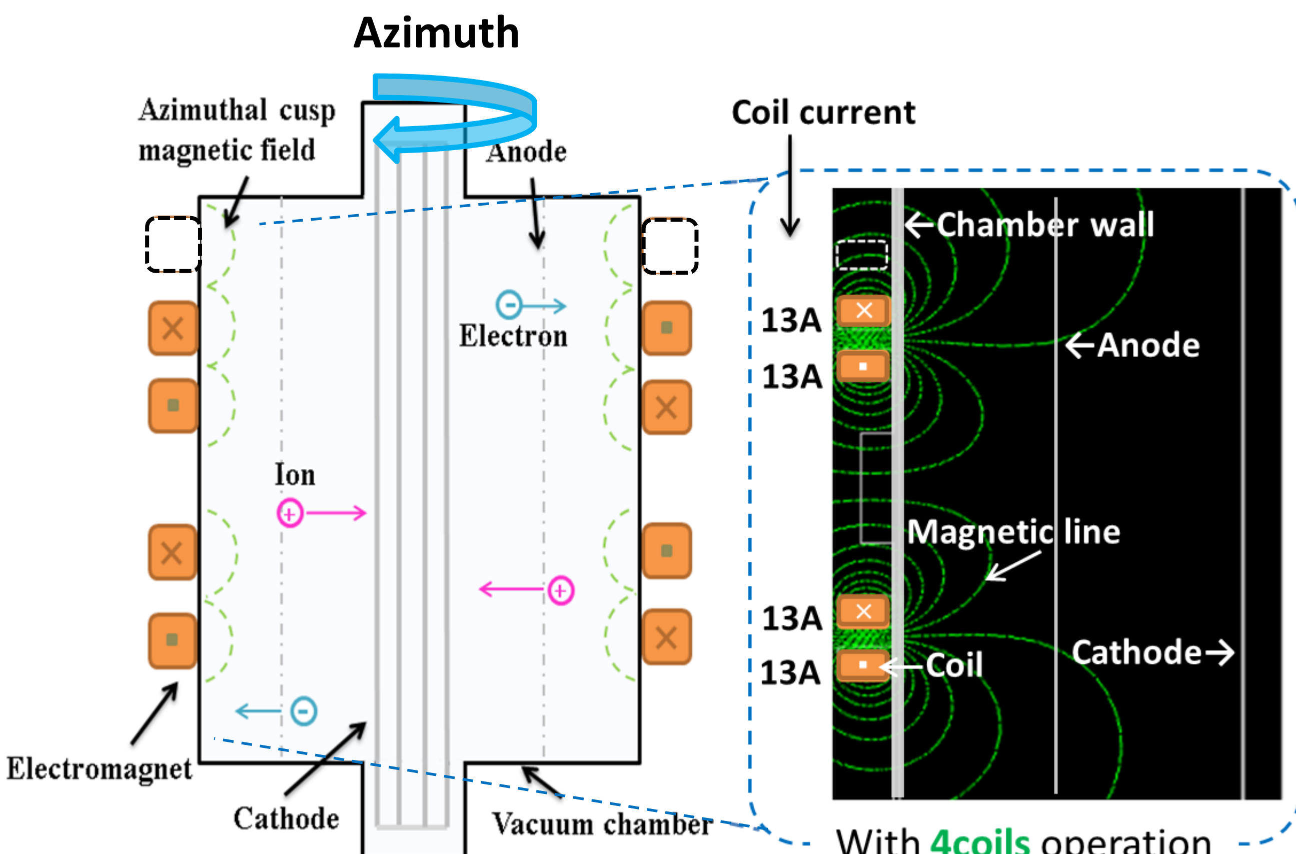
Applying **Azimuthal Cusp magnetic field** to a cylindrical IEC device

Motivation of the new IEC device

Azimuthal Cusp magnetic field

To **confine electrons** and **produce ions** more effectively near anode at **low pressure**

→ Electrons move in Azimuthal direction by E x B drift.

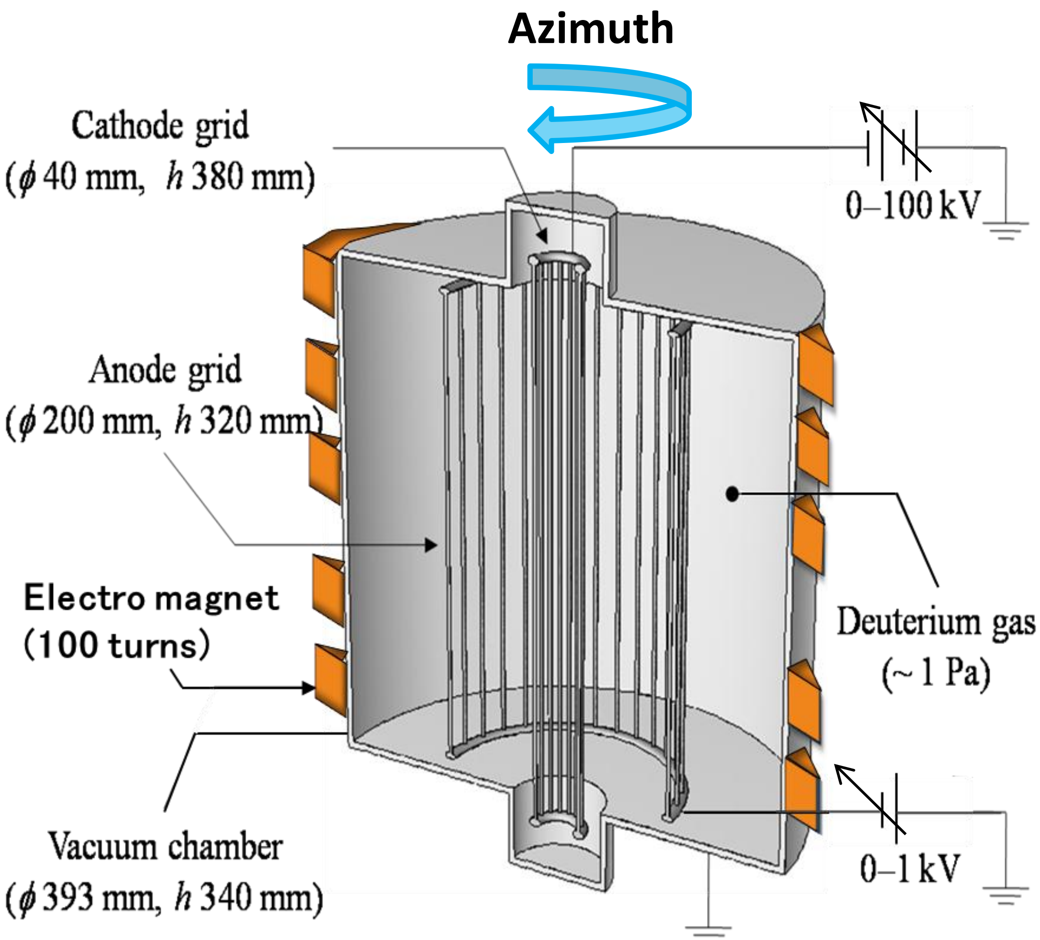


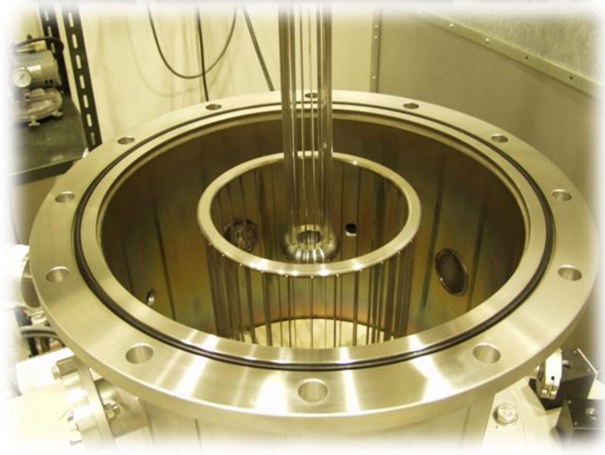
With 4coils operation

Experimental setup

Cylindrical IEC device with Azimuthal Cusp magnetic field

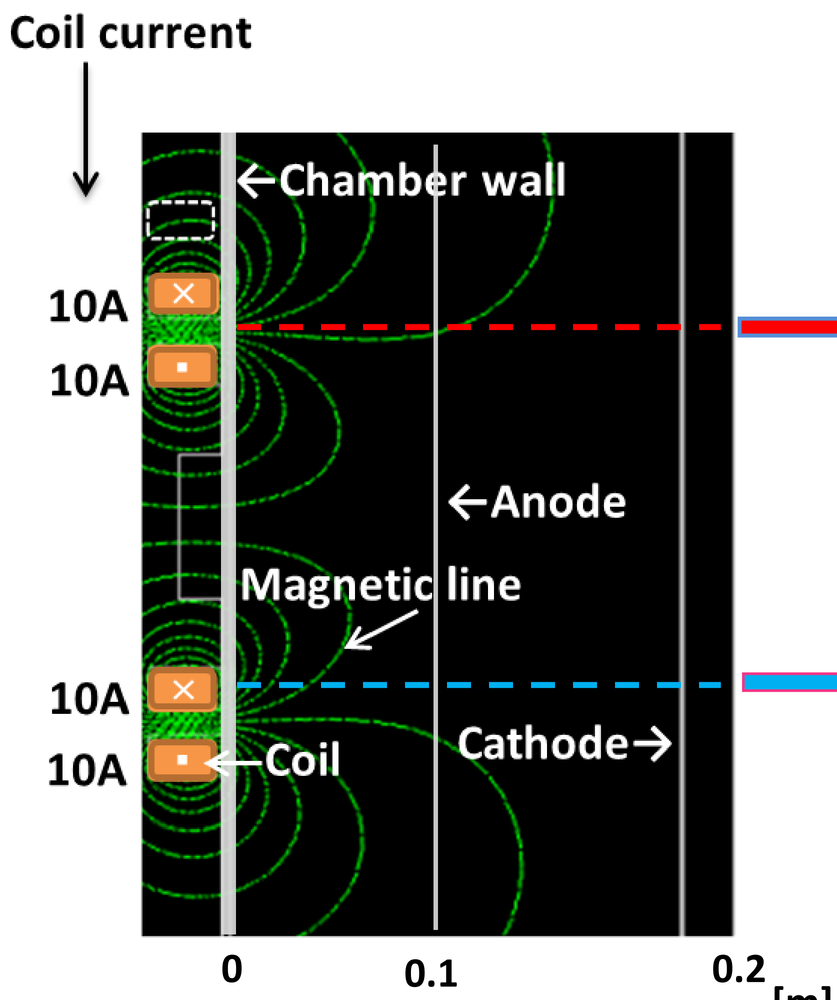
To confine electrons and produce ions near anode more effectively at low pressure



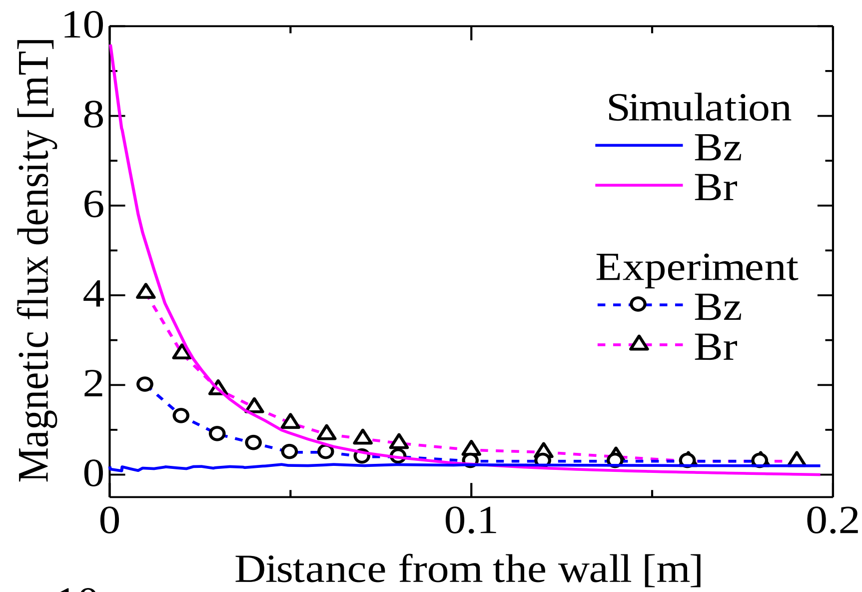


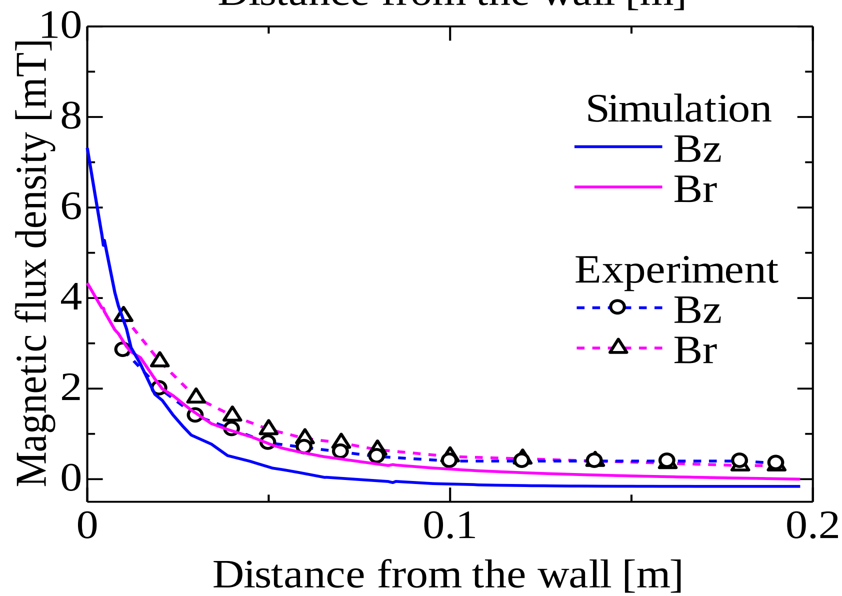
Confirmation of Cusp magnetic field

Magnetic line in the device



Spatial distributions of magnetic flux density





Outline

Research topic

To investigate the effects of Cusp magnetic field on NPR and ion energy

Experiments

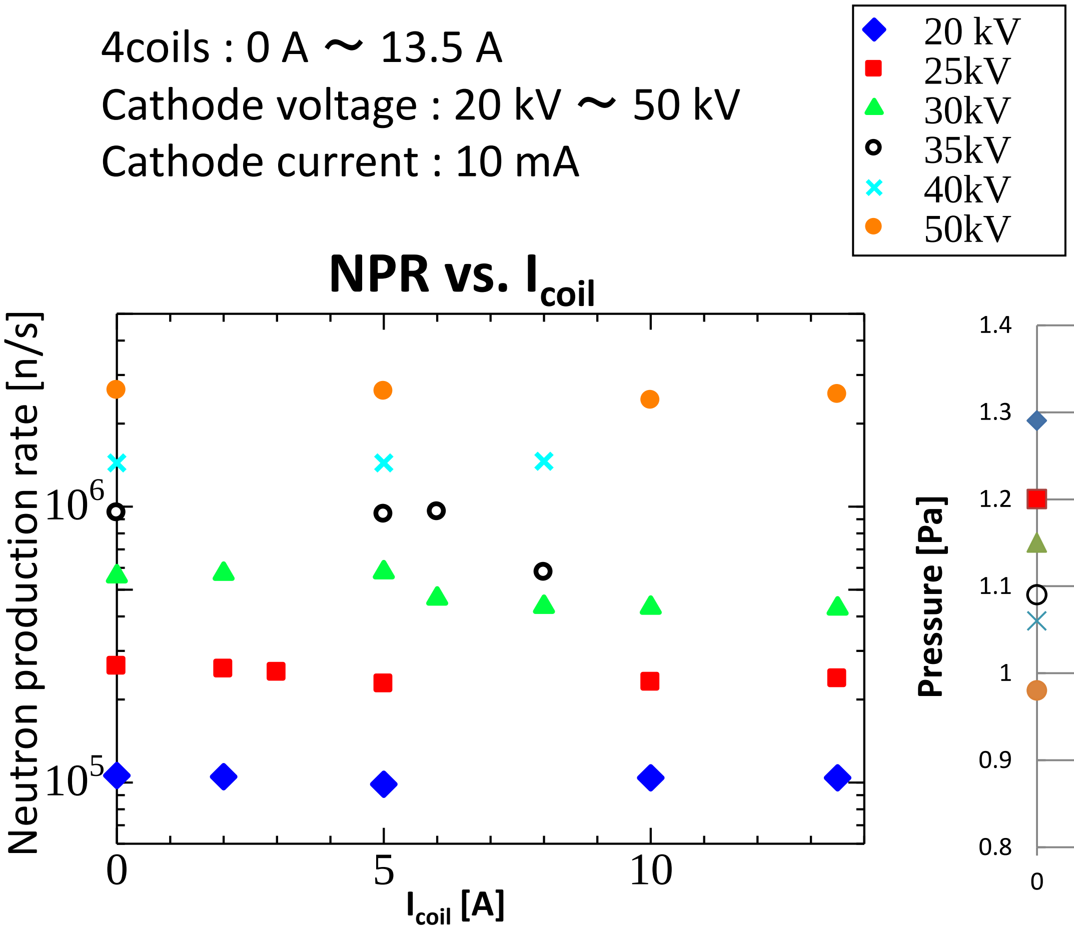
- **Coil current dependence of NPR at different Cathode voltage**
- **Cathode voltage dependence of NPR at different Coil current**
- **Cathode current dependence of NPR at different Coil current**

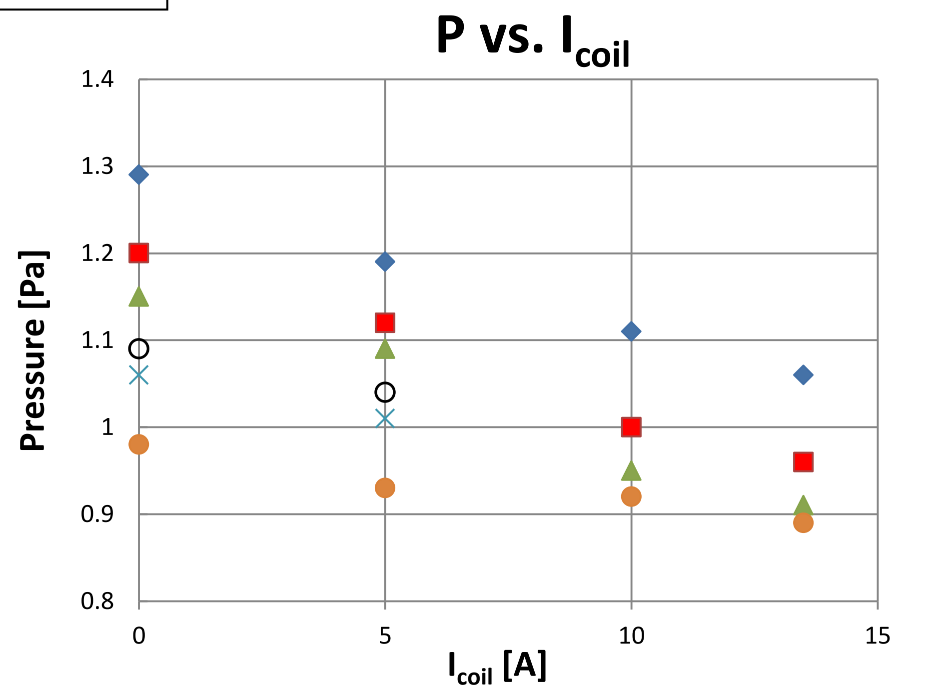
  ....comparing to numerical calculations
- **Cathode temperature measurement**

  ....comparing to numerical calculations

Coil current dependence of NPR and Pressure

4coils : 0 A ～ 13.5 A
Cathode voltage : 20 kV ～ 50 kV
Cathode current : 10 mA





If Cusp magnetic field only causes the pressure reduction,
Reduction tendency of NPR agrees with that of pressure?

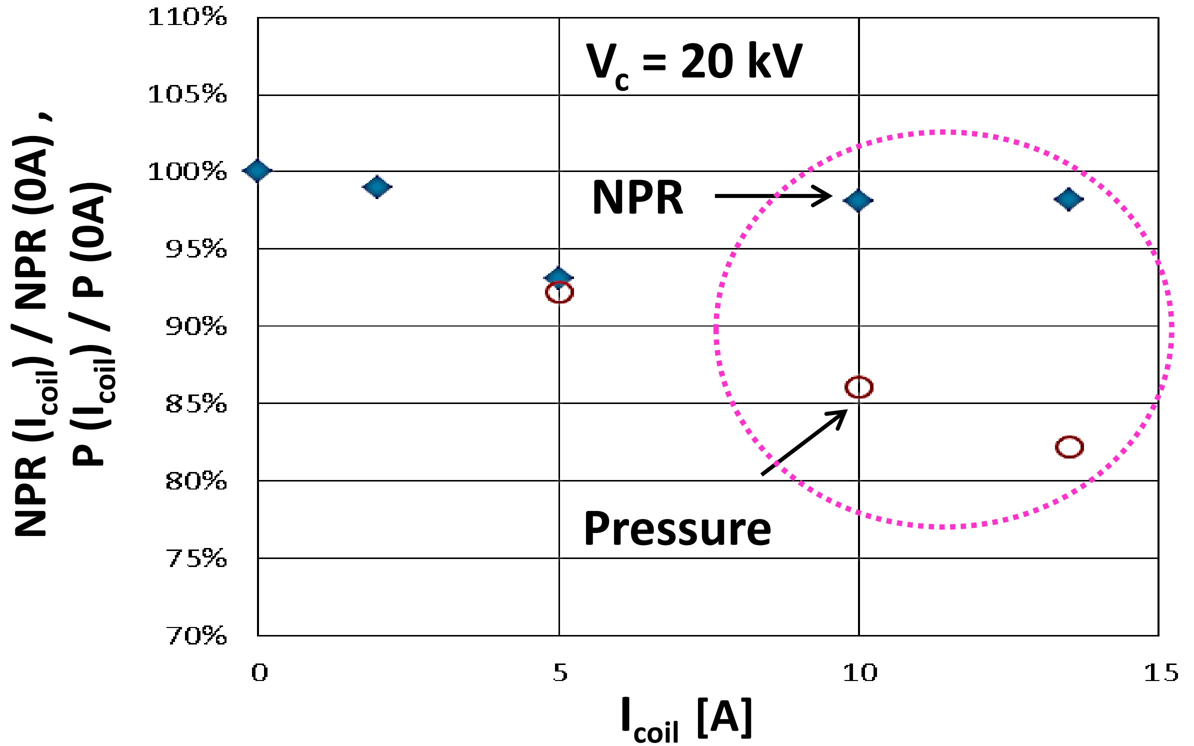
(Pressure affects NPR : **Beam-Background reaction ∝ P**)

Coil current dependence of NPR and Pressure

Pressure reduction rate : P (I_{coil}) / P (0 A)

vs. I_{coil}

NPR reduction rate : NPR (I_{coil}) / NPR (0 A)



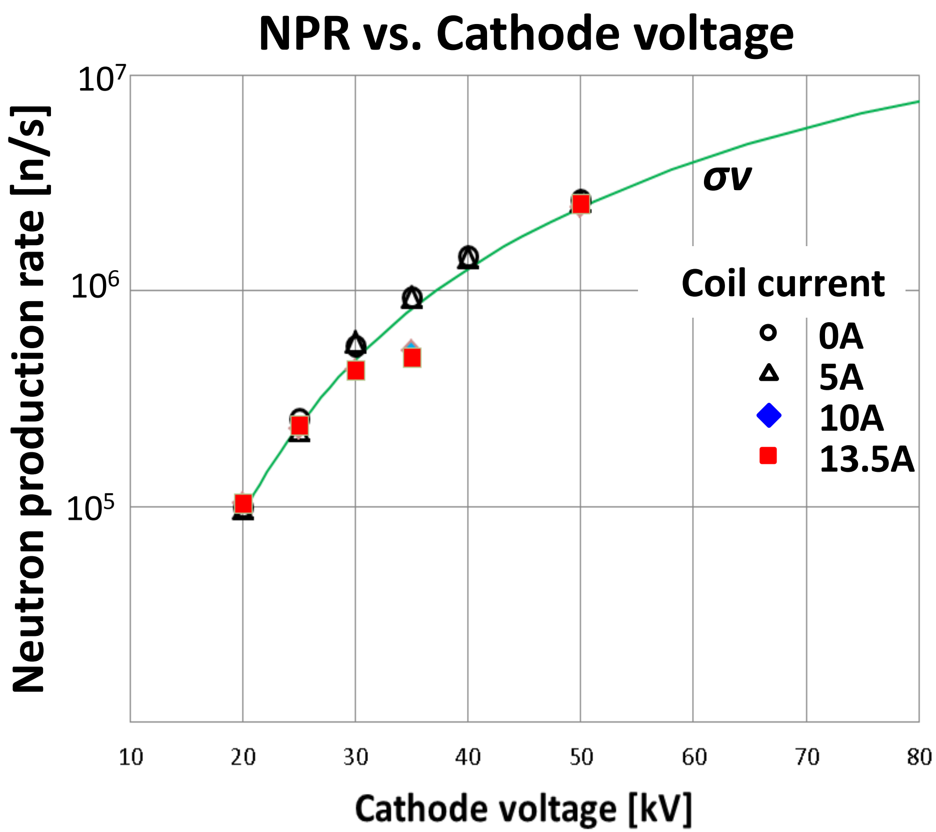
NPR (13.5 A) / NPR (0 A) > P (13.5 A) / P (0 A)

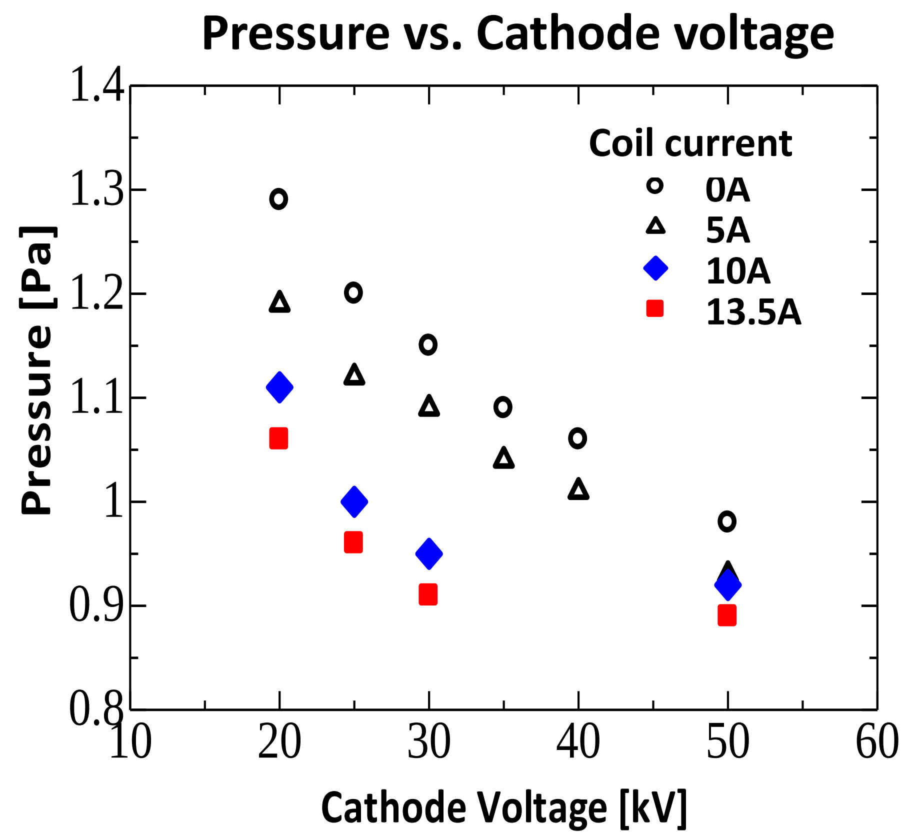
Cusp magnetic field causes

Reduction of ion energy loss and or Increment of ion production near anode

Cathode voltage dependence of NPR

Cathode current : 10 mA





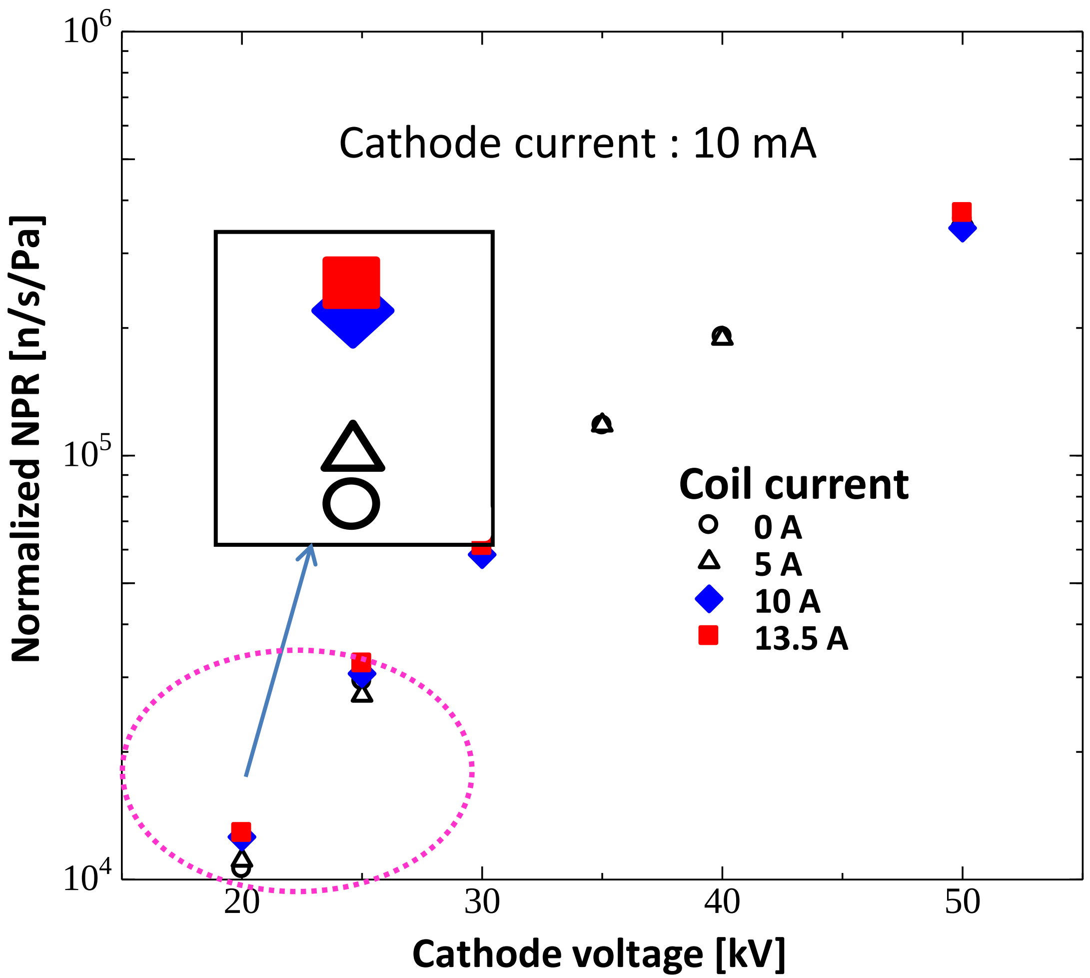
Gas pressure increases with decreasing cathode voltage.

⇒ Pressure affects NPR : Beam-Background reaction $\propto P$

NPR should be normalized by pressure to clarify the effects of **Cusp.**

Cathode voltage dependence of normalized NPR

Normalized NPR by pressure [n/s/Pa] vs. Cathode voltage



Cusp magnetic field improves normalized NPR

Reduction of ion energy loss and or Increment of ion production near anode

Outline

Experiments

- ☐ Dependence of NPR on Coil current at different Cathode voltage
- ☐ Dependence of NPR on Cathode voltage at different coil current

☐ **Cathode current dependence of NPR at different coil current**

Low pressure operation in order to increase ion energy

To reduce energy loss of ions due to Charge exchange reaction

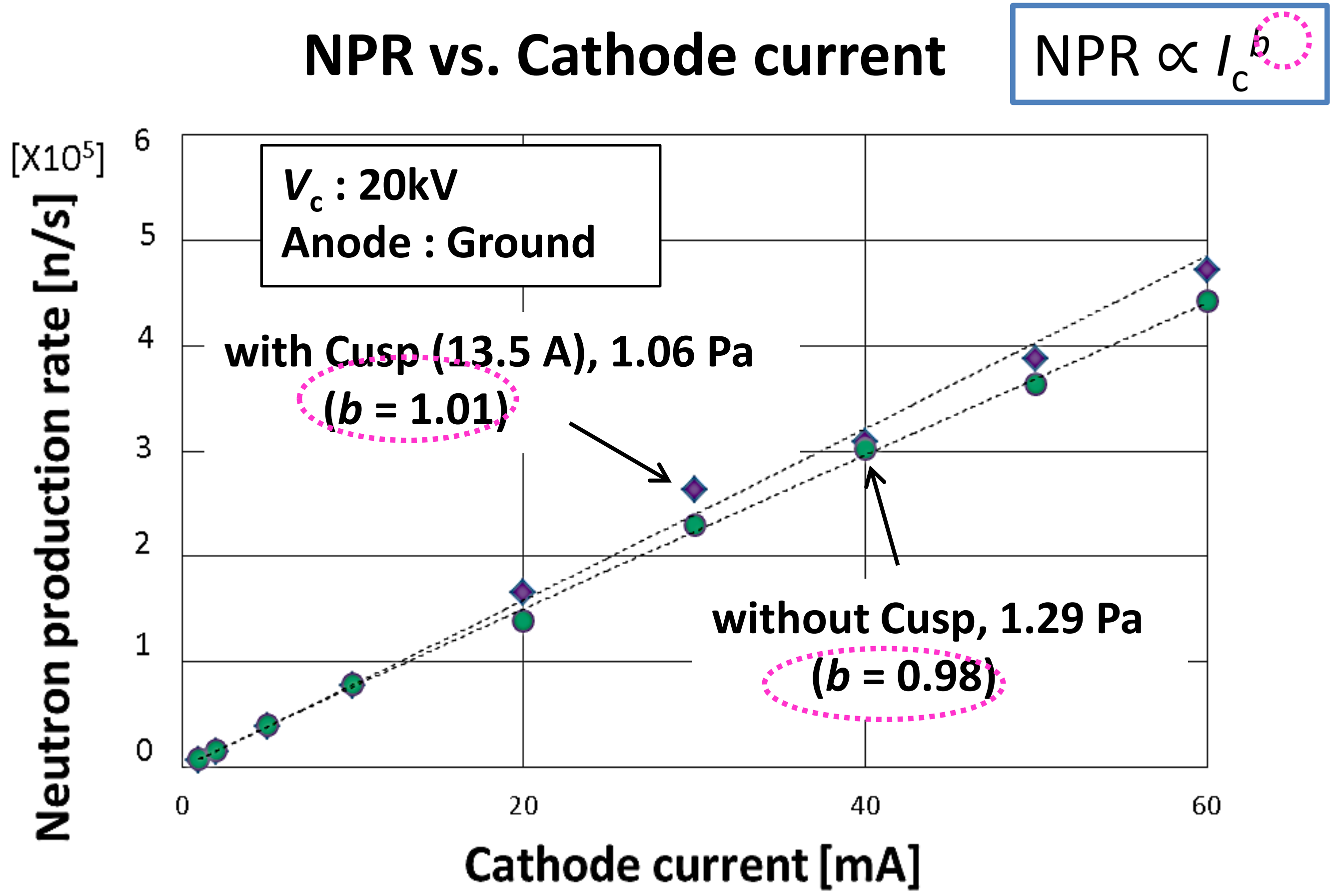
To enhance Beam-Beam reaction $\propto I_c^2$

To focus on the **contribution of Beam–Beam to total NPR**

(dependence of NPR on **Cathode current**)

in order to investigate the effects of **Cusp magnetic field**

Cathode current dependence of NPR



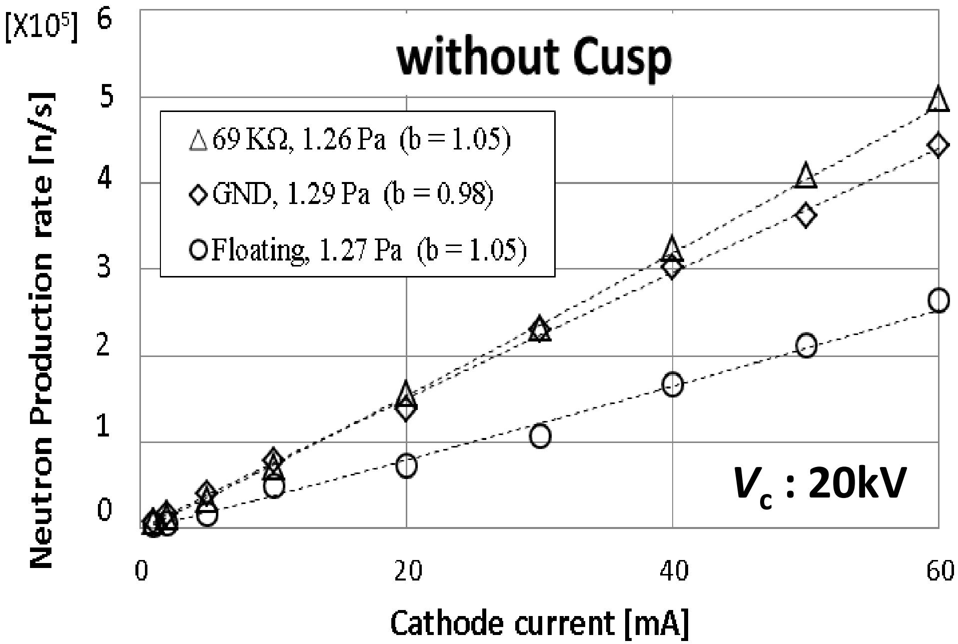
- ✓ " *b* " of "**with Cusp**" is larger than that of "**without Cusp**".
- ✓ **Total NPR seems to be enhanced by Cusp magnetic field.**

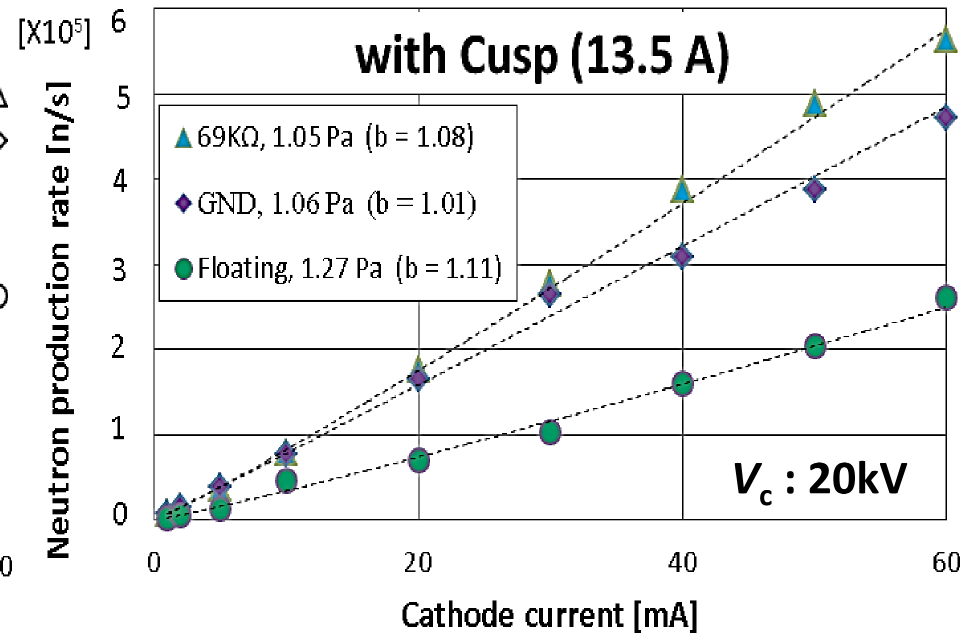
Cathode current dependence of NPR

To investigate the effects of the anode bias on NPR

Anode condition	**GND**	**Anode = ground**
	69 kΩ	**Connect anode resister (－10 V～－280 V)**
	Floating	**Anode = floating potential**

$\mathrm{NPR} \propto I_c^{\,b}$





- ✓ **“ *b* ” of “****with Cusp****”** is larger than that of **“without Cusp”.**
- ✓ **Anode resister enhanced NPR.**

← Because bias accelerates ion from between anode and wall to cathode effectively.

NPR calculation

Fusion reaction rate

Ion energy distributions at cathode are adopted.

- **Beam-Beam**

$$R_{BM-BM} = \int_V \frac{n^2{}_{BM}}{2} < \sigma v > dV \propto I_c{}^2$$

- **Beam-Background**

$$R_{BM-BG} = \int_V n_{BG} n_{BM} < \sigma v > dV \propto I_c$$

- **Beam-Cathode**

$$R_{BM-C} = \int_S n_C n_{BM} < \sigma v > dS \propto I_c$$

- **Charge exchanged fast neutral – Background**

$$R_{CX-BG} = \int_V n_{CX} n_{BG} < \sigma v > dV$$

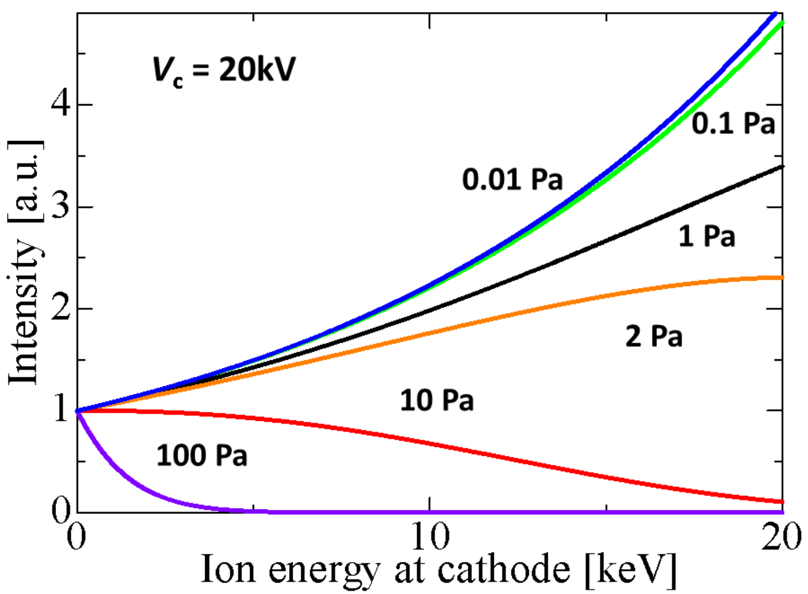
- **Charge exchanged fast neutral – Cathode, Anode, Wall**

$$R_{CX-C,A,W} = \int_S n_{CX} n_{S,A,W} < \sigma v > dS$$

Assumptions

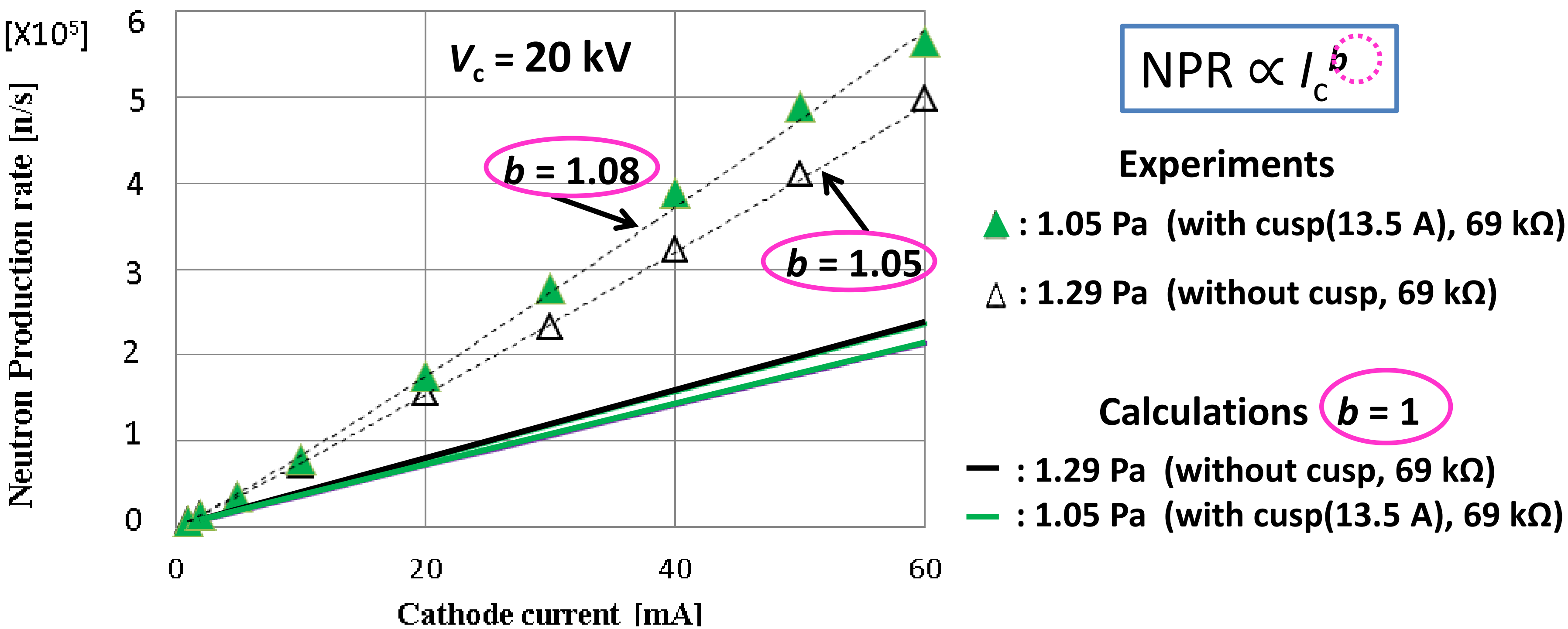
- **All the ions (D^+) originate at anode.**
- **Vacuum potential**
- **Charge exchange reaction : dominant**
- **Imbedded deuterium density : constant**

Calculated ion energy distributions at cathode



Comparison with experimental results

Calculated NPR vs. experimental NPR



✓ Calculations can not explain why "experimental ***b*** " ≠ 1.

According to the calculations, Beam-Beam reaction is negligible near 1 Pa.

→Total NPR should be proportional to cathode current (***b*** = 1).

⇨ Implant fusion contributes to "experimental ***b*** "? $a\, I_c{}^b = \mathrm{A}\, I_c + \mathrm{B} I_c{}^2 + F(I)$

Outline

Experiments

- ☐ Dependence of NPR on Coil current at different Cathode voltage
- ☐ Dependence of NPR on Cathode voltage at different Coil current
- ☐ Dependence of NPR on Cathode current at different Coil current

☐ **Cathode temperature measurement**

Ion energy increment

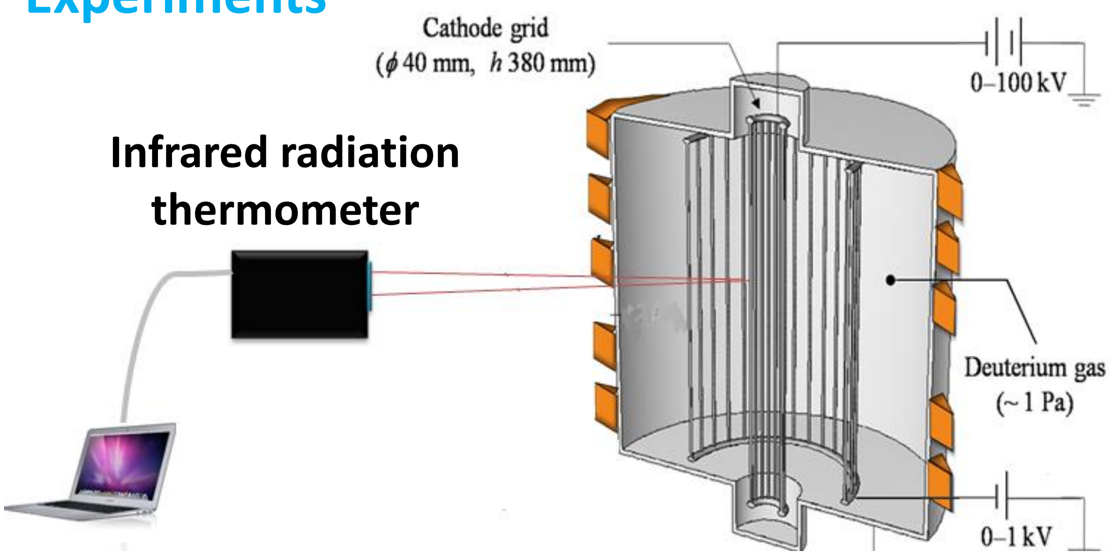
Ion collides with the cathode at higher energy.
⇒Cathode temperature increases.

- To focus on the time dependence of Cathode temperature at different Coil current in order to investigate the effects of Cusp magnetic field
- Experimental data of Cathode temperature is necessary for the investigation of the contributions of the implant fusion in the future.

Cathode temperature measurement

Experiments

Infrared radiation thermometer



Infrared radiation thermometer

Measurement range
493 K～2273 K
Equivalent wavelength
1.95 μm～2.5 μm
Accuracy
±4 K

Calculations

$$\frac{dT}{dt} = \frac{(P_{ion} + P_{cx} + P_J) - (P_{rad} + P_{therm})}{C}$$

P_{ion} : Energy deposited by ion
P_{cx} : Energy deposited by charge exchanged fast neutral
P_J : Joule heating
P_{rad} : Energy of radiation
P_{therm} : Heat transmission

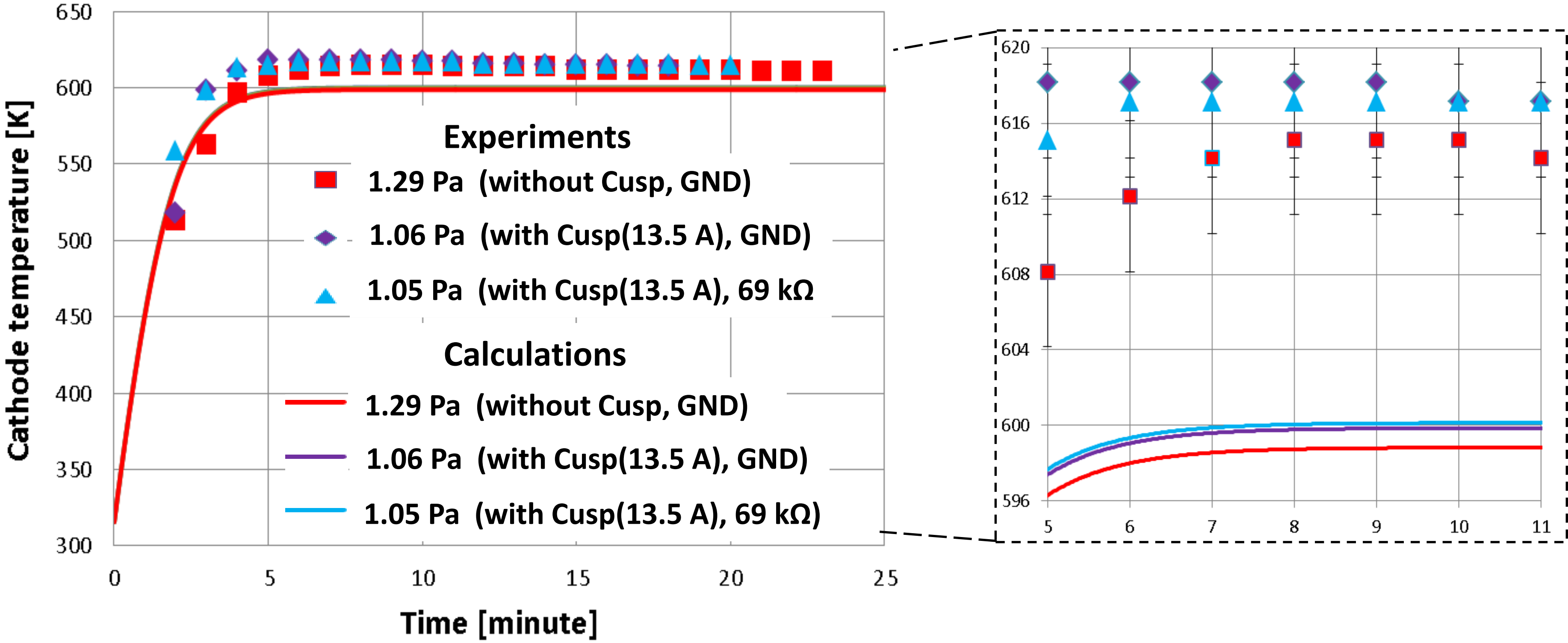
Cathode

SUS electrode
Emissivity : 0.74
Size : 5 mm x 1 mm

Cathode temperature measurement

Time dependence of Cathode temperature at different Coil current

V_c = 20 kV, I_c = 60 mA



- Cathode temperature "with Cusp" is slightly higher than that "without Cusp"
- Tendency of measured temperature agrees with calculations.

Cusp magnetic field causes ion energy increment.

Conclusion

Experiments of Cylindrical IEC device with Azimuthal Cusp magnetic field

- ☐ Coil current dependence of NPR at different Cathode voltage
- ☐ Cathode voltage dependence of NPR at different Coil current
- ☐ Cathode current dependence of NPR at different Coil current
- ☐ Time dependence of cathode temperature at different Coil current

Effects of Azimuthal Cusp magnetic field

- Low pressure operation
- Ion energy improvement

Future plan

Experiments

- To enhance magnetic flux density and expand the range of magnetic field
- To investigate anode bias effect
- High cathode current operation with pulsed power

Numerical analysis

- To calculate embedded deuterium density in electrodes and wall

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Thank you for your kind attention.

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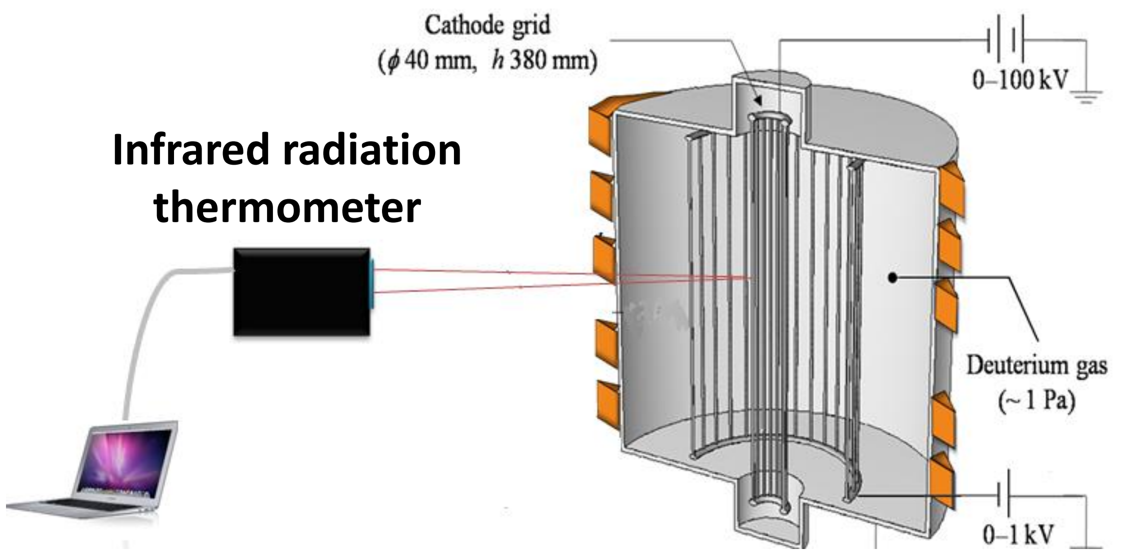

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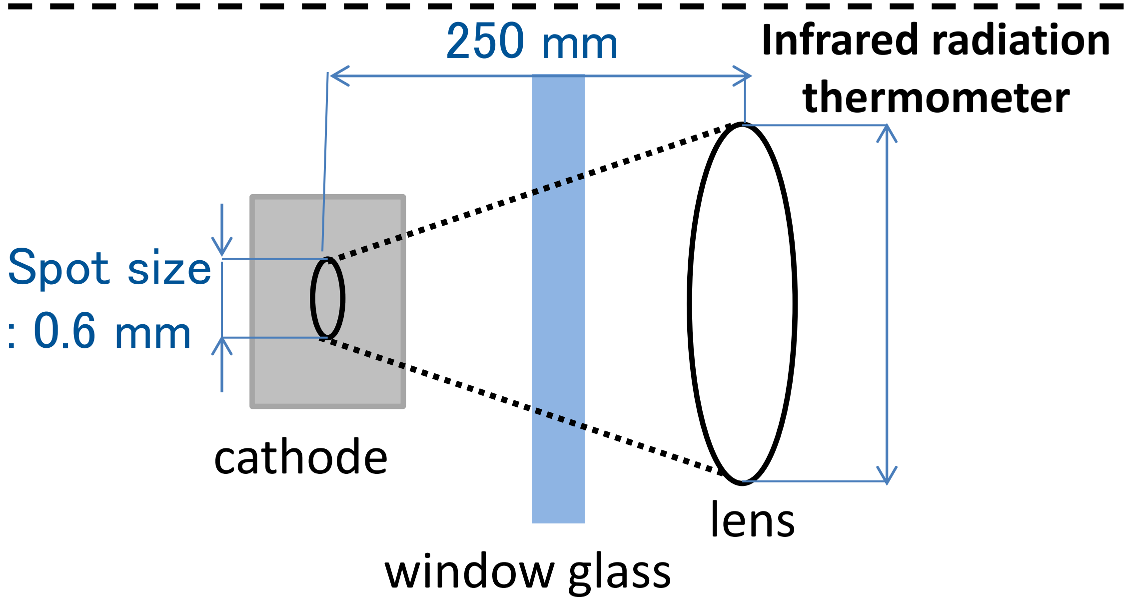

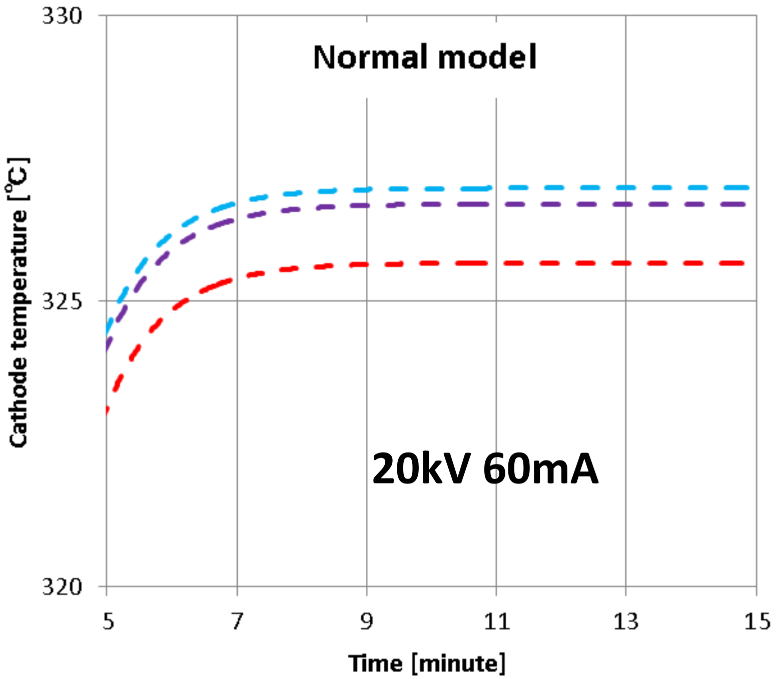

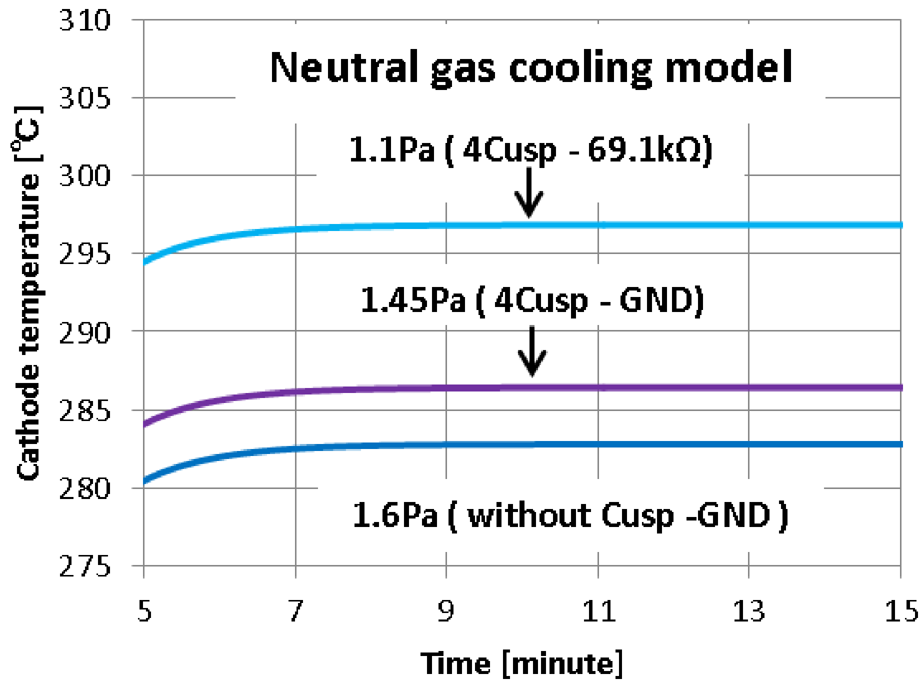

Calculations (with neutral gas cooling)

$$\frac{dT}{dt} = \frac{(P_{ion} + P_{cx} + P_J) - (P_{rad} + P_{therm} + P_c)}{C}$$

P_{ion} : Energy deposited by ion
P_{cx} : Energy deposited by charge exchanged fast neutral
P_J : Joule heating
P_{rad} : Energy of radiation
P_{therm} : Heat transmission

P_c : Heat transfer through convection

S. Krupakar Murali, G. A. Emmert, J. F. Santarius and G. L. Kulcinski: "Effects of chamber pressure variation on the grid temperature in an inertial electrostatic confinement device", Physics of Plasmas Vol.17, 102701 (2010)