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Temperature dependence of performance in neutron production of a coaxial double cylindrical IEC device

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Neutron Transmutation Doping

Neutron Transmutation Doping (NTD)

NTD is **one of the manufacturing methods for high quality and large size semiconductor.**

＜Principle of NTD method＞

$$^{30}Si + n \rightarrow {}^{31}Si \xrightarrow{(\beta^- \text{ decay})} {}^{31}P + \beta$$

(neutron capture)

natural abundance
3.1%

Si ingot

(http://www.sumcosi.com/products/index.html)

Advantage of NTD

- High quality and large size semiconductor can be produced.
- Phosphorus can be uniformly doped in Silicon by uniform neutron irradiation.
- Phosphorus density can be controlled with high accuracy.

Neutron Transmutation Doping

Nuclear reactors are used as a neutron source for the production.

- Production capacity is limited now.
- Domestic demand increases year by year.

→ More neutron sources are needed.

However, A nuclear reactor is quite expensive.

Development of a new neutron source for NTD by using an IEC device.

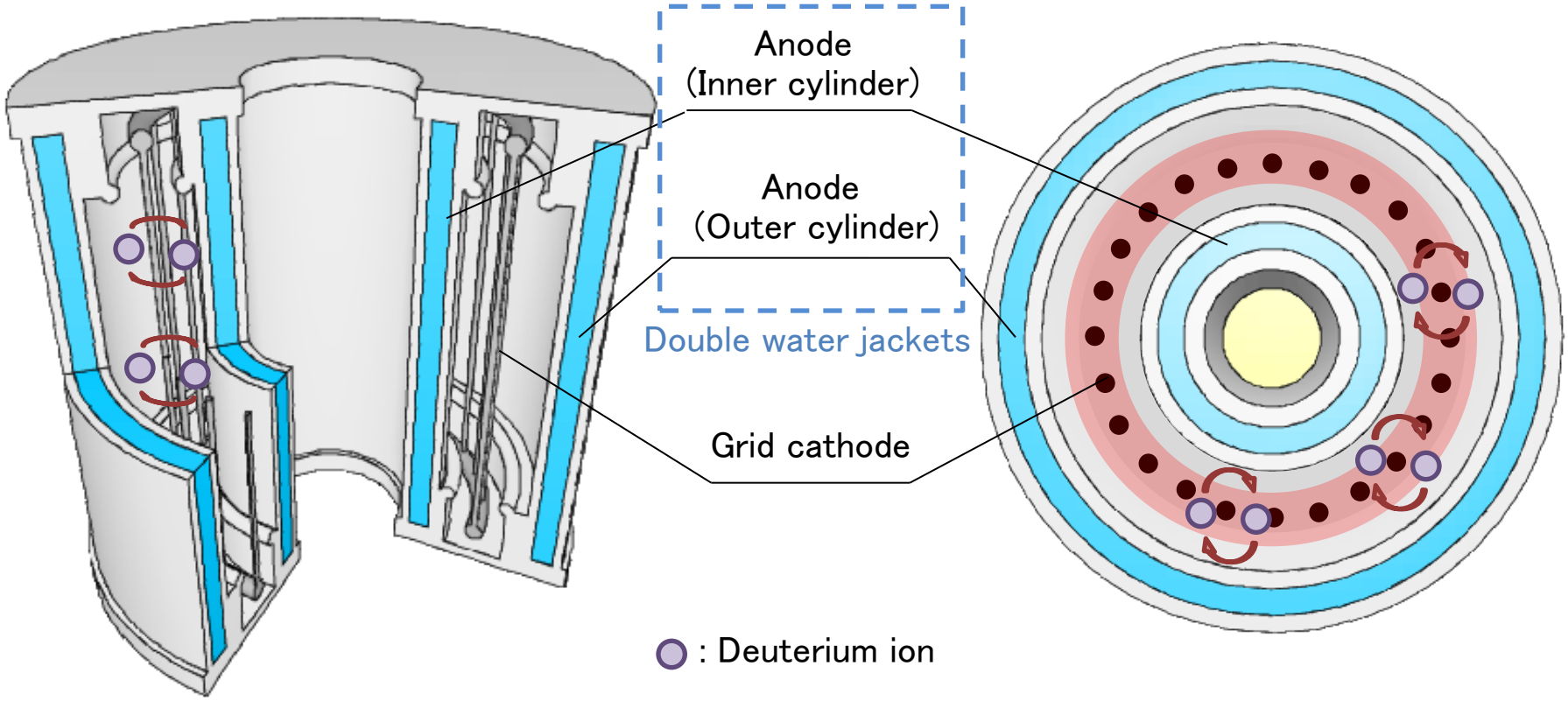
What are needed for NTD?

- Uniform neutron irradiation
- High rate irradiation of neutron flux
- Long time operation

Especially designed to be capable of the uniform irradiation,

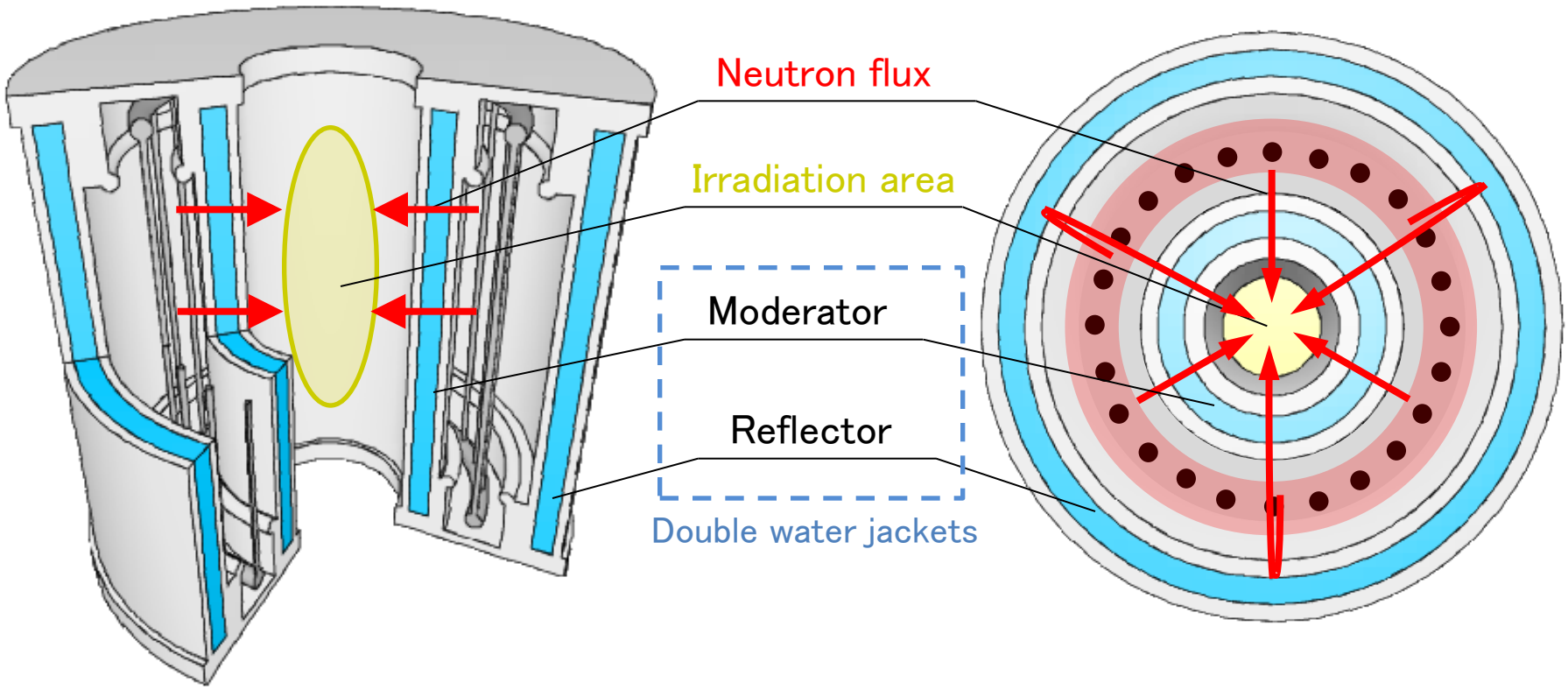
Coaxial Double Cylindrical Device was developed to satisfy these conditions.

Coaxial Double Cylindrical (CDC) Device



- This device has triple electrode structure which consists of a cylindrical grid cathode between inner and outer anode.
- This device has double water jacket for cooling the chamber.

Coaxial Double Cylindrical (CDC) Device



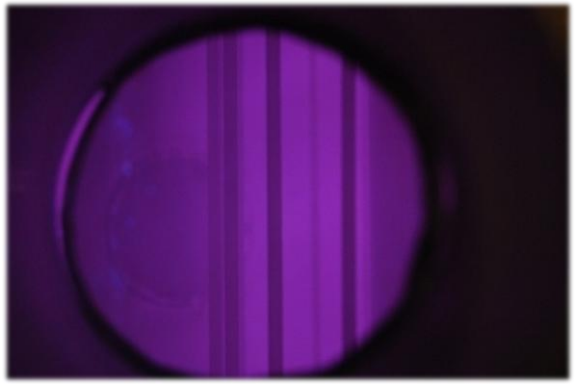
- Neutron flux distribution is almost uniform in the central sample irradiation area.
- Outer water jacket is used for reflecting the neutron.
- Inner water jacket is used for moderating the neutron.

What are measured?

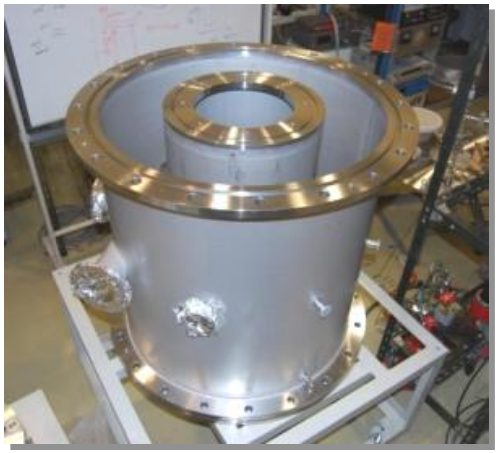
Report topic

- Measurement of the neutron production rate
- Investigation of uniformity of a neutron flux distribution in the sample irradiation area

➡ Comparing NPR and uniform flux distribution by cooling the chamber and by changing shape of cathode



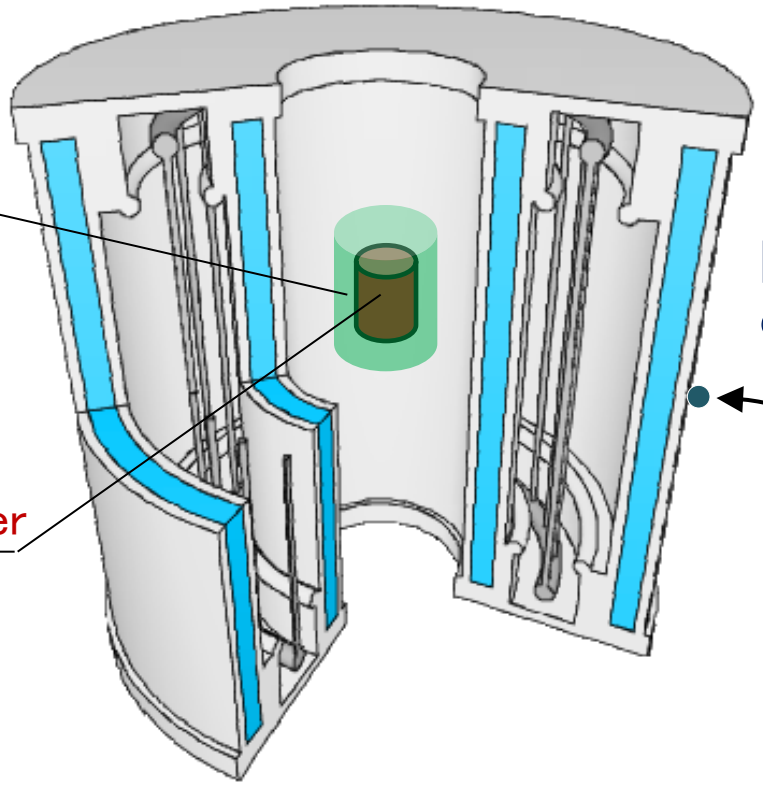
Discharge photograph



CDC device photograph

Investigation of NPR (cooling)

※ it can separately control voltage and current



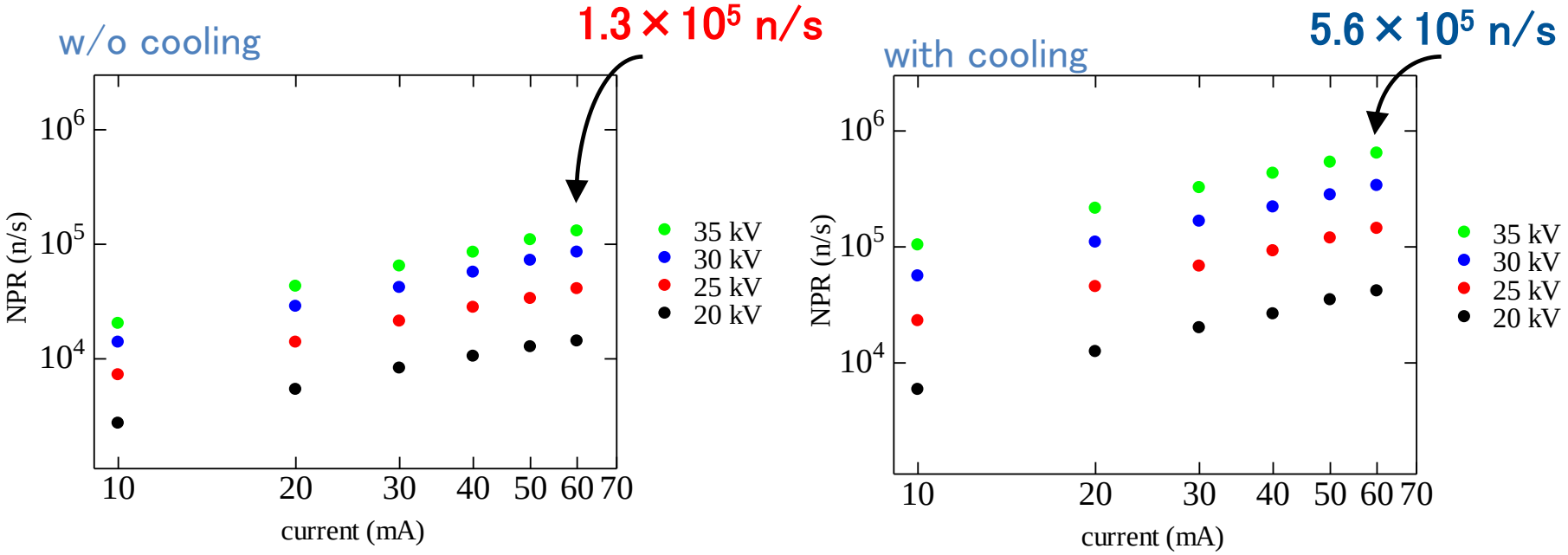
[midpoint temperature of device outer surface, 75 min]

w/o cooling: 60℃
with cooling: 25℃

- D–D fusion reaction, D.C. operation
- Neutron is counted with ^{3}He proportional counter,
  (cylinder, diameter : 2.54 cm, length : 10.16 cm)
  surrounded by polyethylene (diameter : 20.8 cm, length : 28 cm).
- Current : 10 mA – 60 mA (limit), Voltage : 10 kV – 35 kV,

Investigation of NPR (cooling)

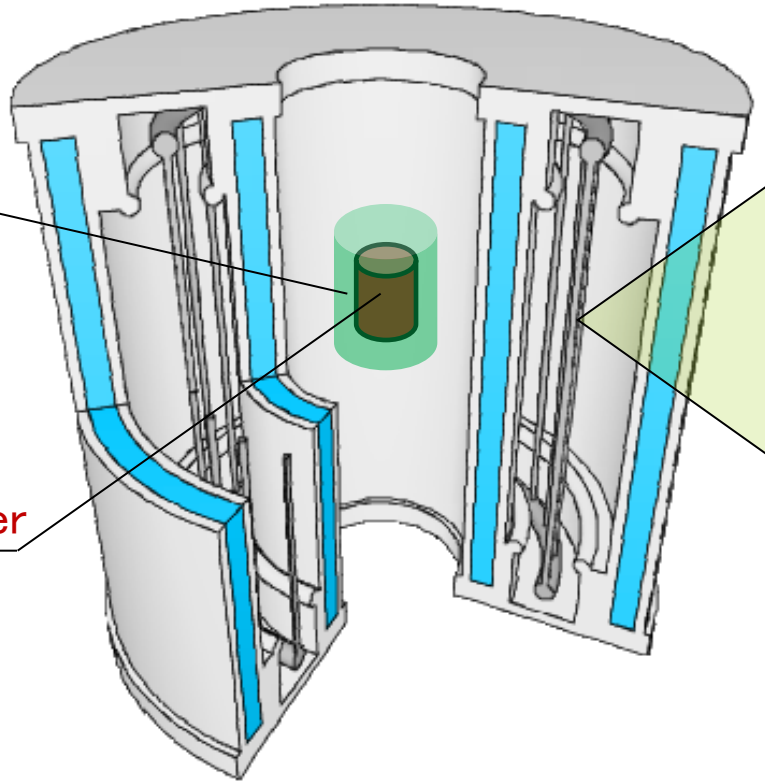
Comparison of NPR between cooling

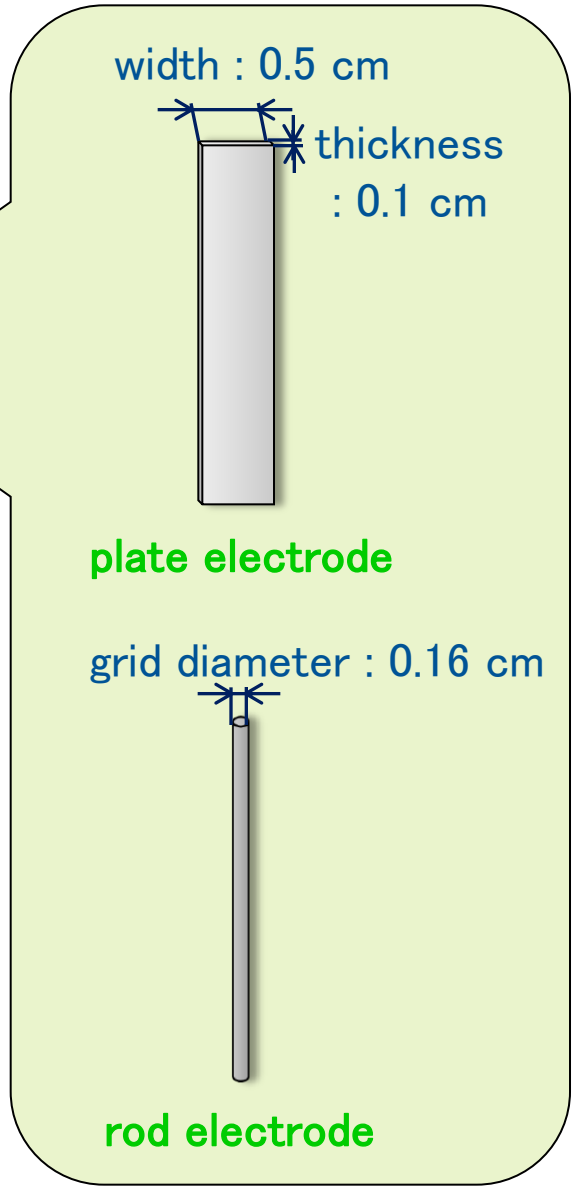


Maximum NPR : w/o cooling < with cooling

(3～4 times higher at each current and voltage conditions)

Investigation of NPR (shape of cathode)

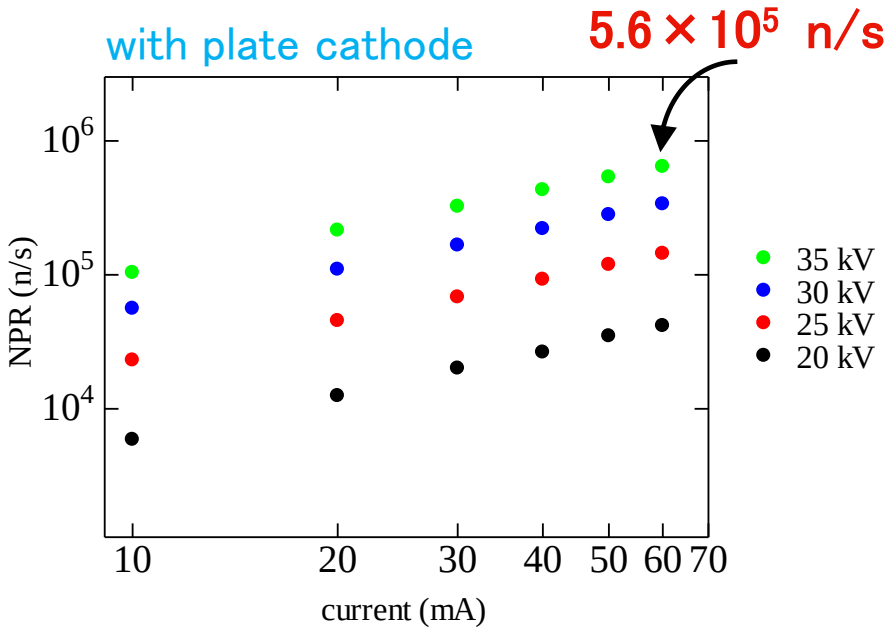


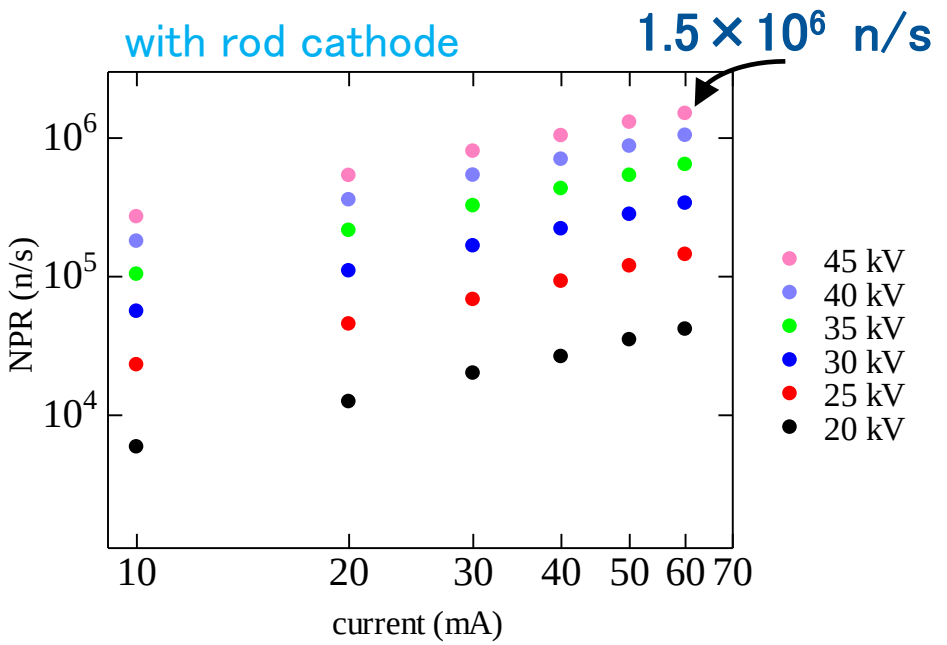


- D–D fusion reaction, D.C. operation
- Current : 10 mA – 60 mA (limit)
- Voltage : 10 kV – 35 kV (with plate electrode)
  10 kV – 45 kV (with rod electrode)

Investigation of NPR (shape of cathode)

Comparison of NPR between electrode shape





NPR { 5.6 × 10^5 n/s : plate
6.4 × 10^5 n/s : rod
(at 35 kV, 60 mA)

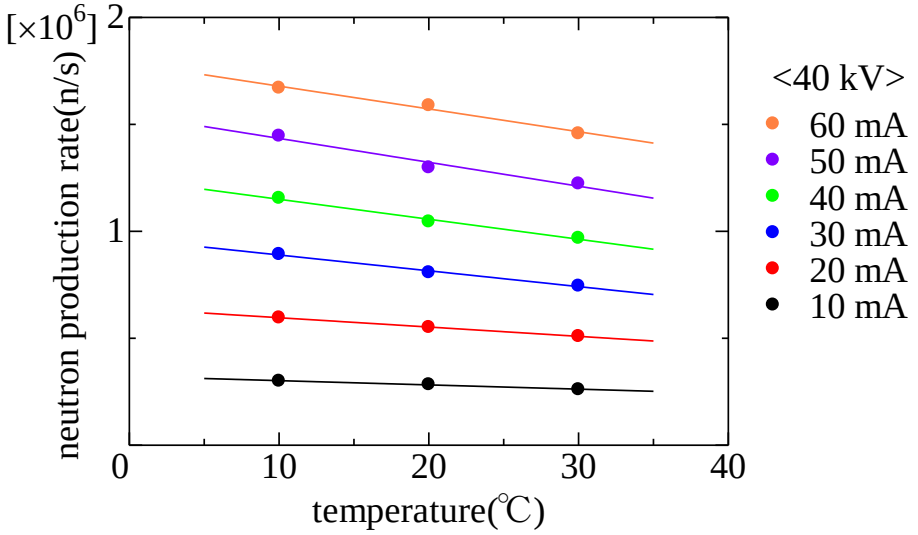
Maximum input voltage

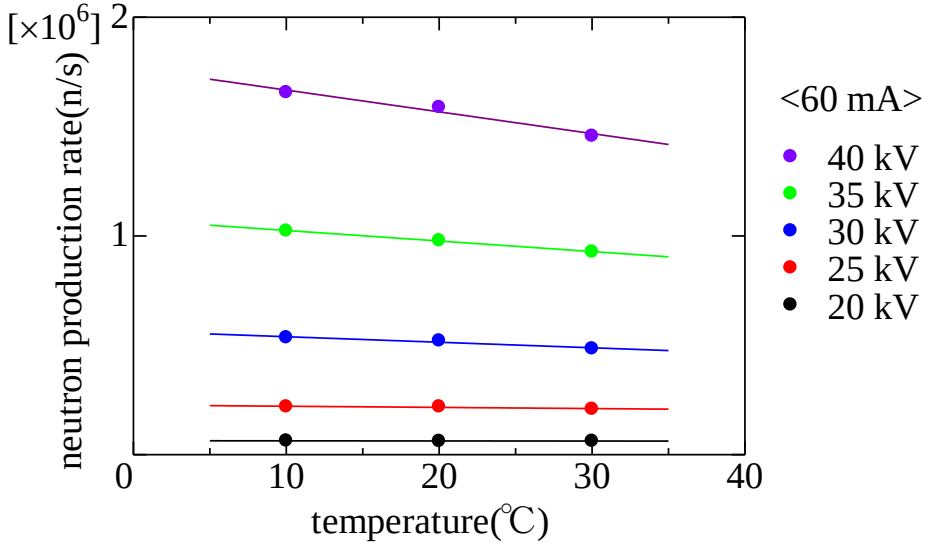
plate electrode (−35 kV) < rod electrode (−45 kV)

⇒ Maximum NPR : plate electrode < rod electrode

Temperature dependence of NPR

To investigate how much temperature affects NPR
NPR is measured while the temperature changes from 10 to 30 degrees.





NPR increases as the temperature becomes lower.

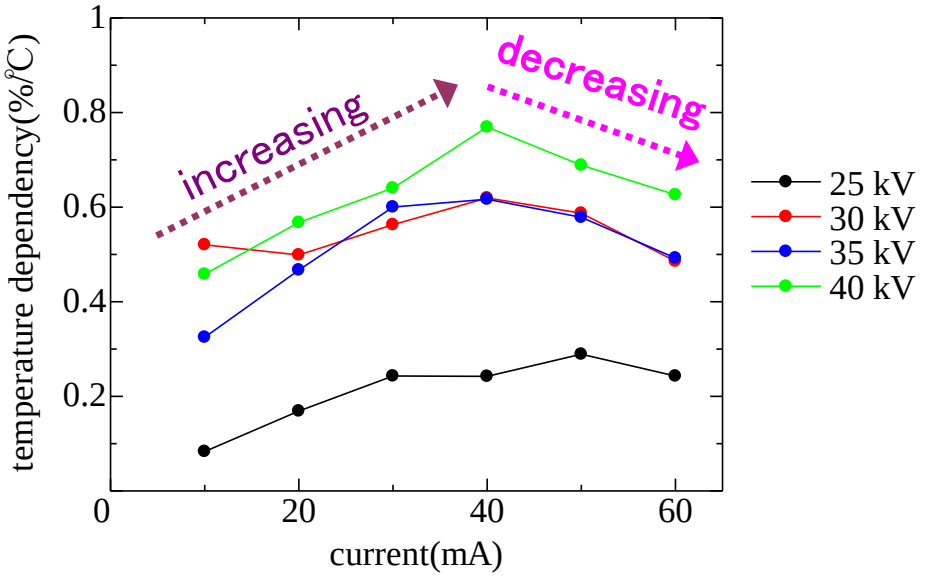
⇒ It is likely that implant fusion occurs.

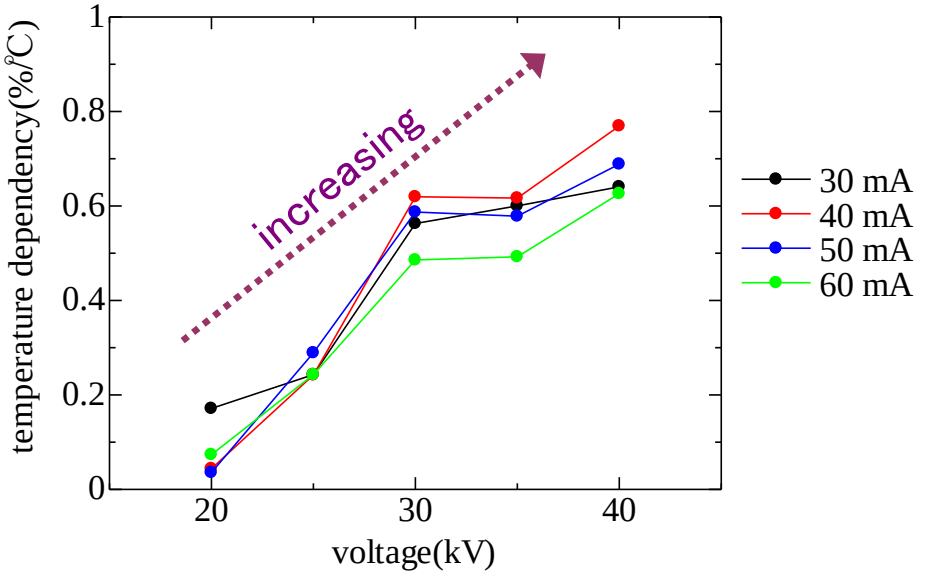
The slope of NPR to temperature is different for
different voltage and currents.

⇒ In order to bring out the difference, the normalized slope is plotted.

Temperature dependence of NPR

$$\text{Temperature dependence} = \left| \frac{\Delta NPR / \Delta temperature}{NPR(at\,20°C)} \right|$$





Maximum temperature dependence = **0.8 %/℃** (at 40 mA, 40 kV)

Temperature dependence increases as increasing voltage and current.

However, temperature dependence begins to decrease at 40 mA.

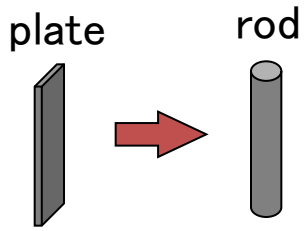
Tendency of temperature dependence between current and voltage is different.

Discussion Ⅰ

In the high current region,
temperature dependence decreased with increasing current.

The structure of cathode affects its temperature.

- Transparency of plate is higher than rod. Hence more ions hit rod cathode by higher current, so temperature of cathode increases easily with rod type.
- Surface area of the rod is smaller than the plate, so heat cannot be released from rod cathode.



- Thickness : 0.10 cm → 0.16 cm
- Surface area : 1.2 cm^2 → 0.5 cm^2

It is necessary to change the structure of cathode.

Discussion Ⅱ

How to increase temperature dependence

By increasing input voltage and current,
it is expected to improve NPR more with cooling.

Current : limit of power supply	By changing power supply circuit, it is expect to input more current without melting.
Voltage : limit of temperature	Because arc discharge often occurs, although NPR can be measured at 45 kV, temperature dependence cannot be measured.

Temperature dependence will be almost **2 %/℃**

Temperature : limit of cooling capability

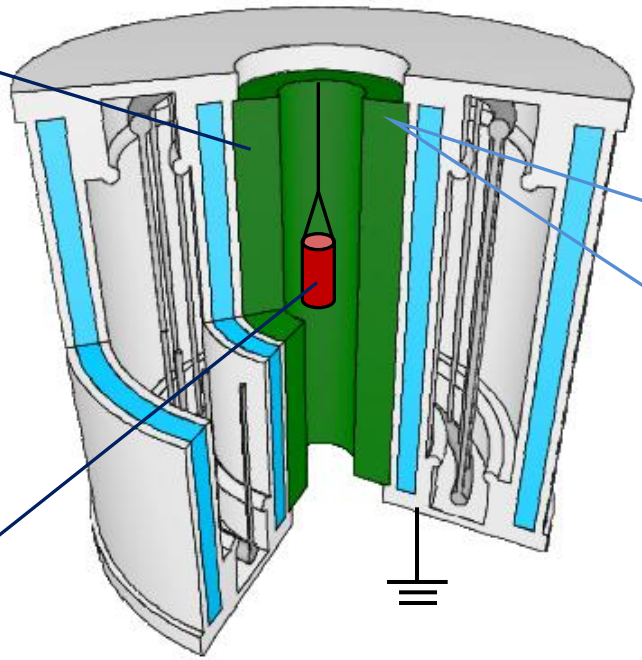
By changing ambient condition, it is expected to operate at 5 degrees.

By cooling to 5 ℃, NPR will increase by 30 %.

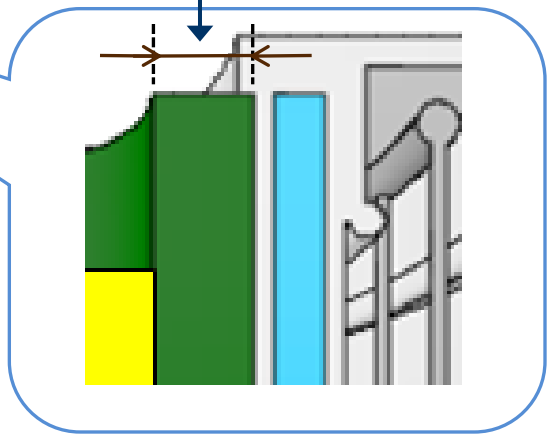
Investigation of uniform area

Polyethylene (PE) block
(External moderator)

^{3}He proportional counter



PE block thickness

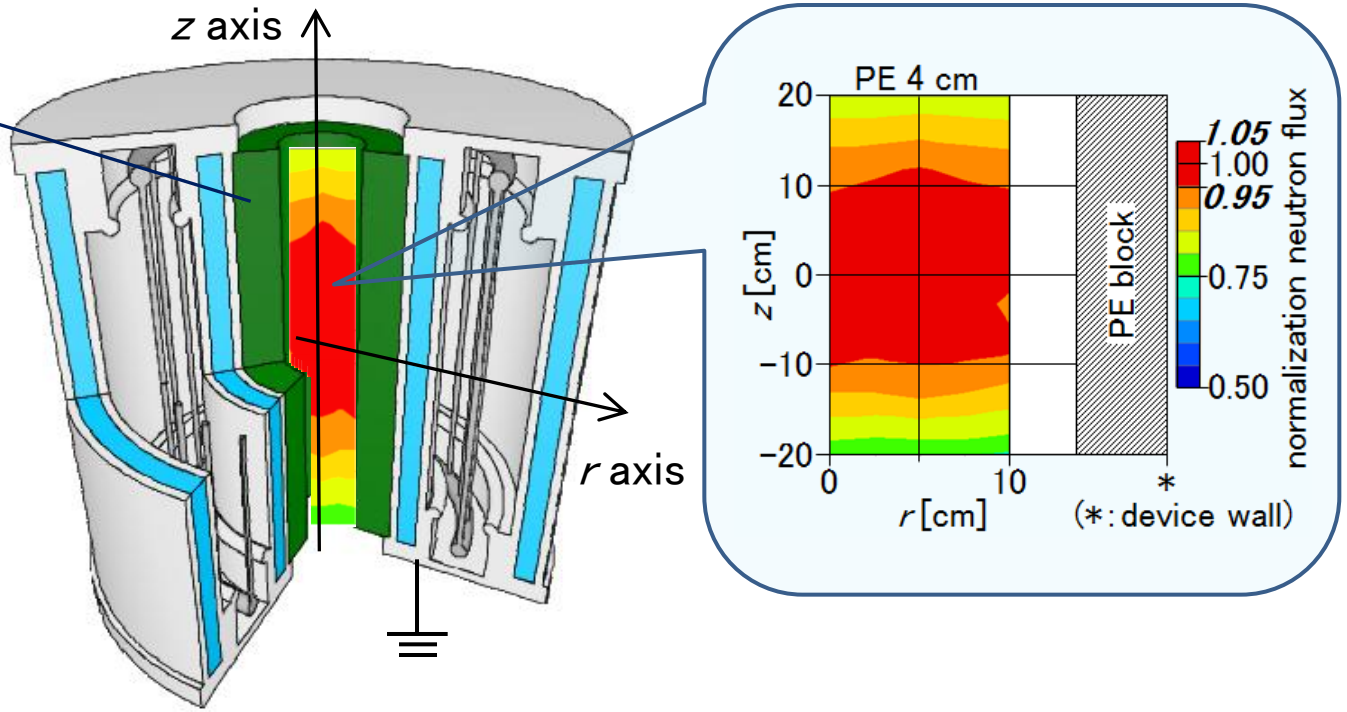


Conditions

- D–D fusion reaction, D.C. operation, −30 kV, 60 mA
  - plate electrode – w/o cooling
  - plate electrode – with cooling → First, comparing them
  - rod electrode – with cooling → Second, comparing them

Investigation of uniform area

Polyethylene (PE) block
(External moderator)



Most important matter ・・・ uniform neutron flux area

- Defined as an area equal to more or less than 5% of neutron count
  - This definition is the same as NTD use.
- Normalized by the value at the origin

Investigation of uniform area (cooling)

plate electrode – w/o cooling

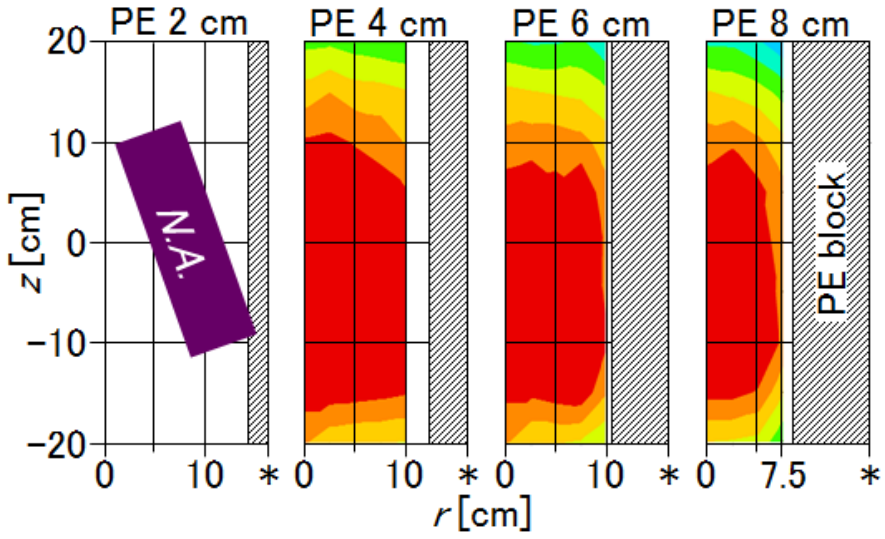
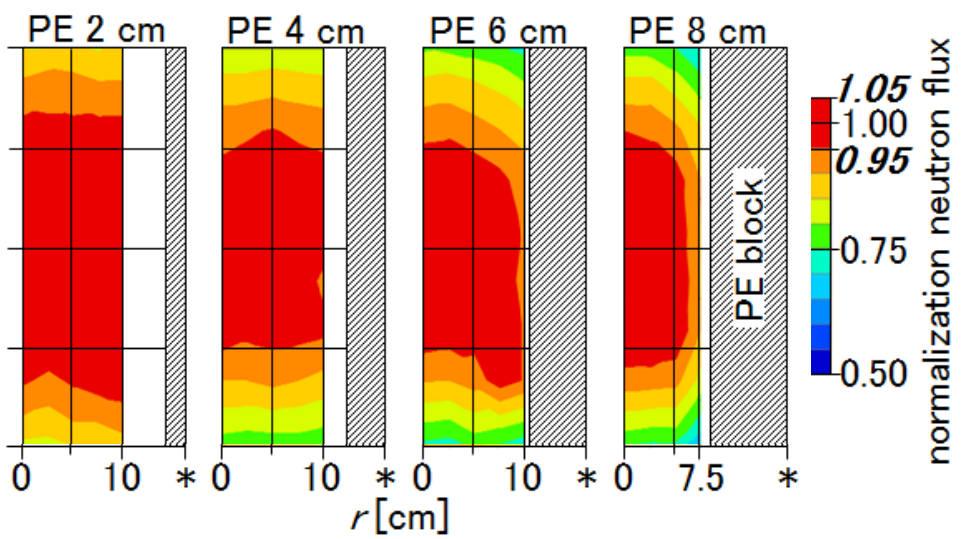


plate electrode – with cooling



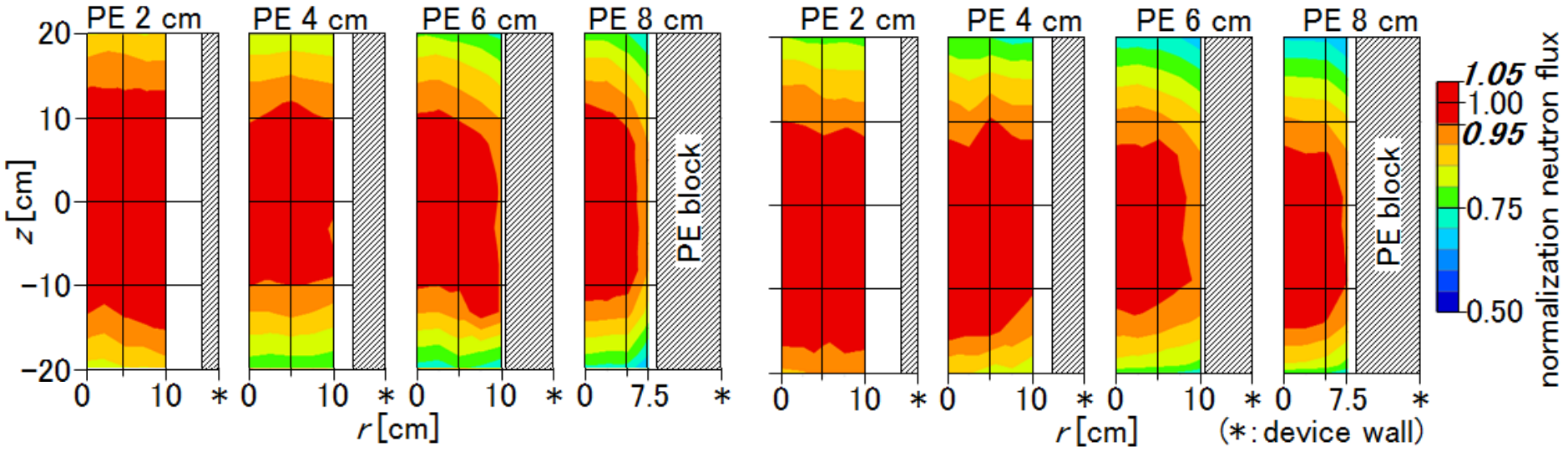
The uniform area is shifted to middle position by cooling the chamber.

- Neutron flux distribution has symmetry in the z–axis direction with cooling.
- As a PE block moderator becomes thick, the uniform neutron flux area becomes small.

Investigation of uniform area (cathode type)

plate electrode – with cooling

rod electrode – with cooling



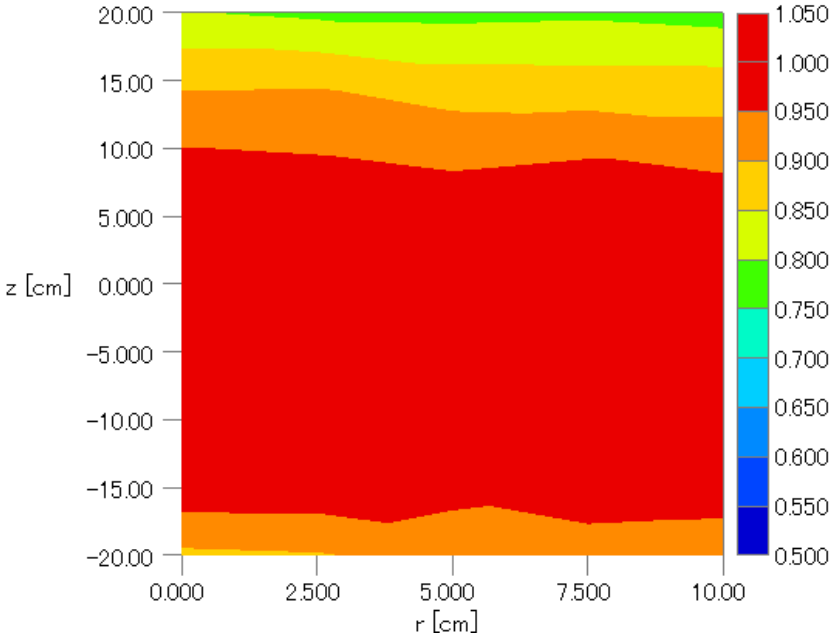
Shift downward again by using rod electrode.

- Neutron flux distribution has no symmetry in the z-axis direction after changing cathode.
- Uniform neutron flux area is larger in the lower area.

Investigation of uniform area (cooling more)

To move uniform area to middle position with rod electrode,
neutron flux distribution was measured by cooling more.

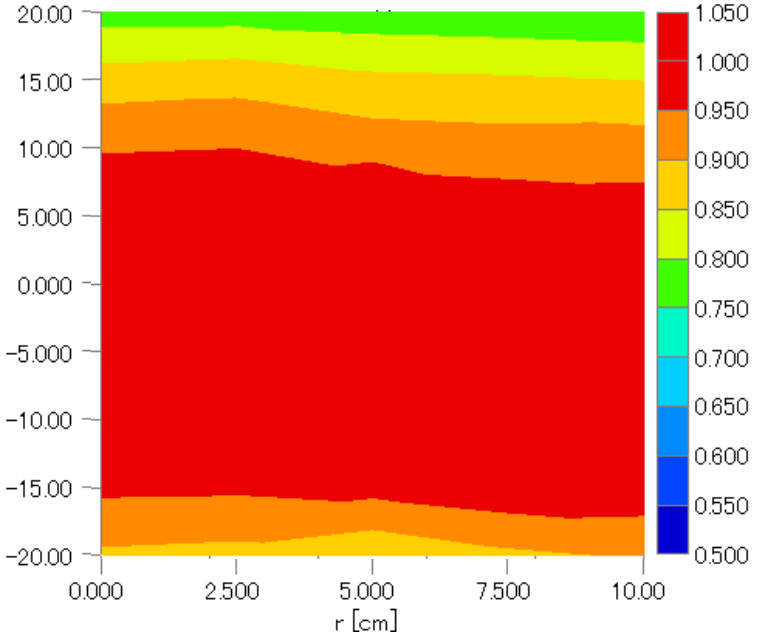
PE 2 cm



neutron flux distribution (at 17℃, with rod)

cooling

PE 2 cm



neutron flux distribution (at 8.3℃, with rod)

No difference can be found between two figures.

Discussion Ⅲ

Uniform area is not shifted by cooling after changing cathode.

The structure of cathode affects its temperature.

- ✔ Temperature of cathode increases easily with rod type.
- ✔ Heat cannot be released easily from rod cathode.

(Already discussed at “discussion Ⅰ”)

Shape of cathode affects not only improvement of NPR but also movement of uniform area.

It is necessary to change the structure of cathode.

Optimal : both of rod and plate merits.

Rod merit	Input high voltage	Plate merit	Heat

Summary and future plan

Summary

- ✔ NPR and uniform area were measured in various conditions.
- ✔ Temperature affects NPR and uniform area.
  - ⇨ NPR increases as the temperature becomes lower.
  - ⇨ Although uniform area is shifted with plate cathode by cooling the chamber, area is not shifted with rod cathode.

Future plan

- ✔ The optimal structure of cathode will be developed.
- ✔ The relationship between NPR and the number of implant particles will be studied.
  - ⇨ Implant fusion will be investigated further.

Thank you for your attention