13th US-Japan Workshop on IEC Fusion
7-9 Dec, 2011
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Overview of Current and Past Research in TITech

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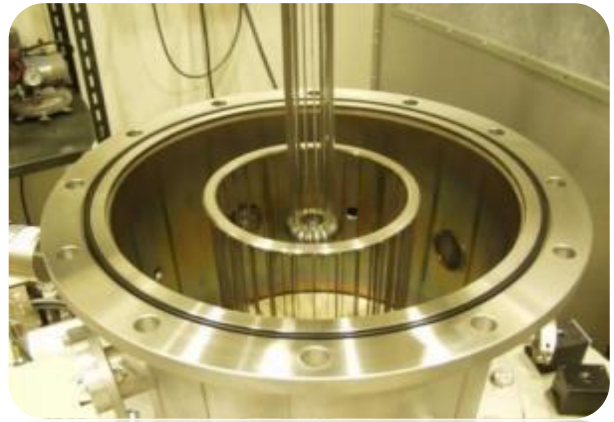
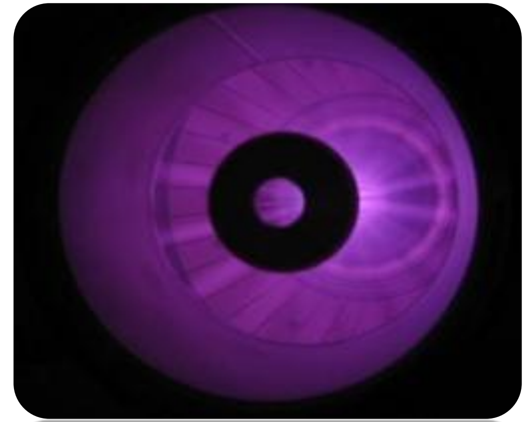
Overview of IEC Research in TITech

- **Fundamental research**
  - **Discharge characteristics, NPR, etc.**
- **Application intended**
  - **Manufacture of PET drug (D-^{3}He)**
  - **Explosive and illicit material detection**
  - **High quality semiconductor production**
- **Device type**
  - **Spherical, Cylindrical, Coaxial double cylindrical**
  - **Operation: DC, Pulsed**
  - **Magnetic-assist (Cusp or uniform magnetic field)**

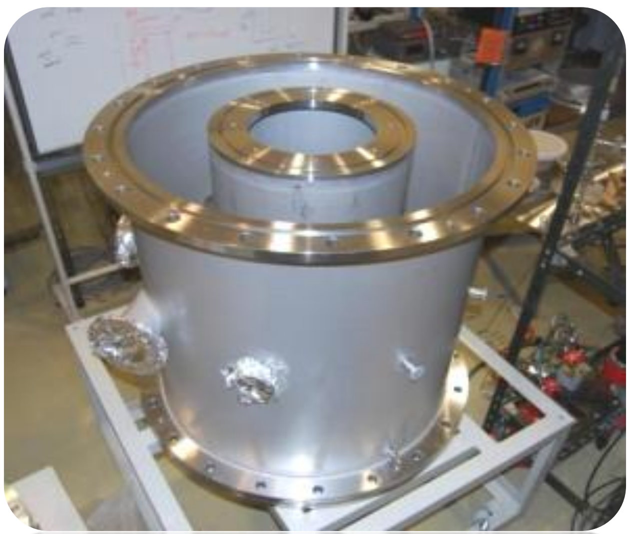
IEC Devices in TITech

Spherical IEC

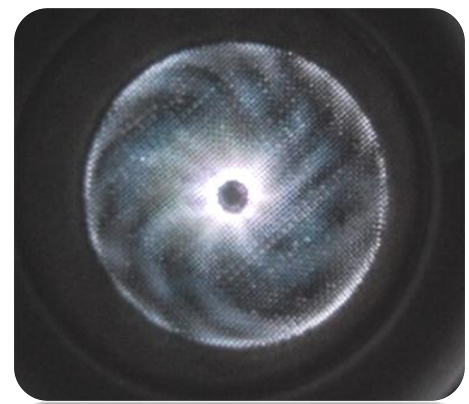




Cylindrical IEC



Coaxial double cylindrical IEC



Magnetic-assisted IEC

IEC Research

- **Started in1997 with a spherical device**
  - **Objectives: Fundamental Characteristics**
    - **Electrical discharge: Breakdown voltage**
    - **Space potential distribution**
    - **Spectroscopic measurement**
    - **NPR**

Spherical IEC Device

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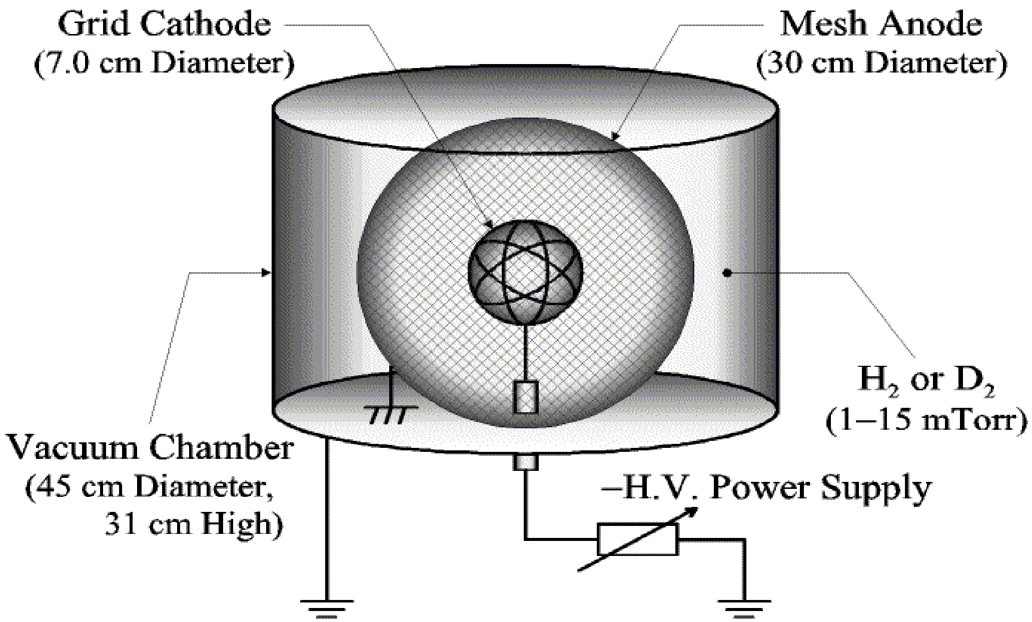
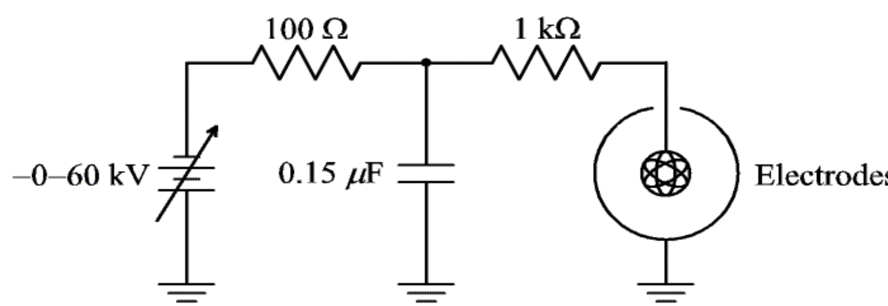
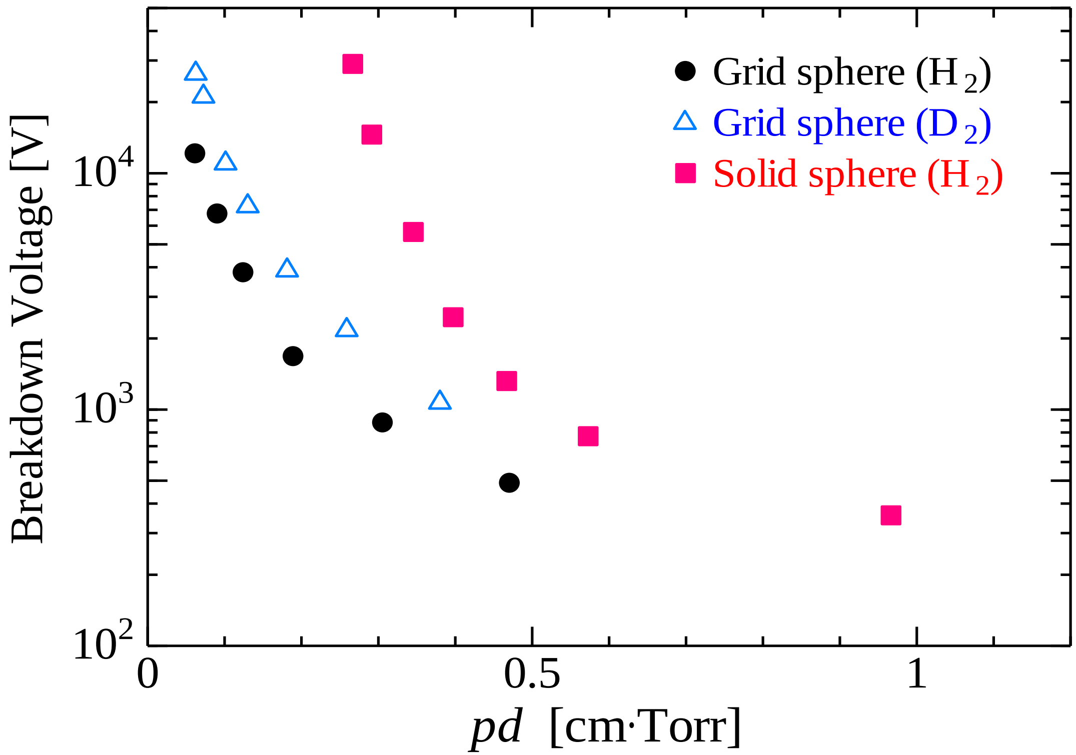




Cathode: ϕ1.2-mm Stainless Steel Wire
Anode: 0.5 mm-pitch Stainless Steel Mesh

Breakdown Voltage



p **: Background Pressure**
d **: Gap Length between Electrodes**

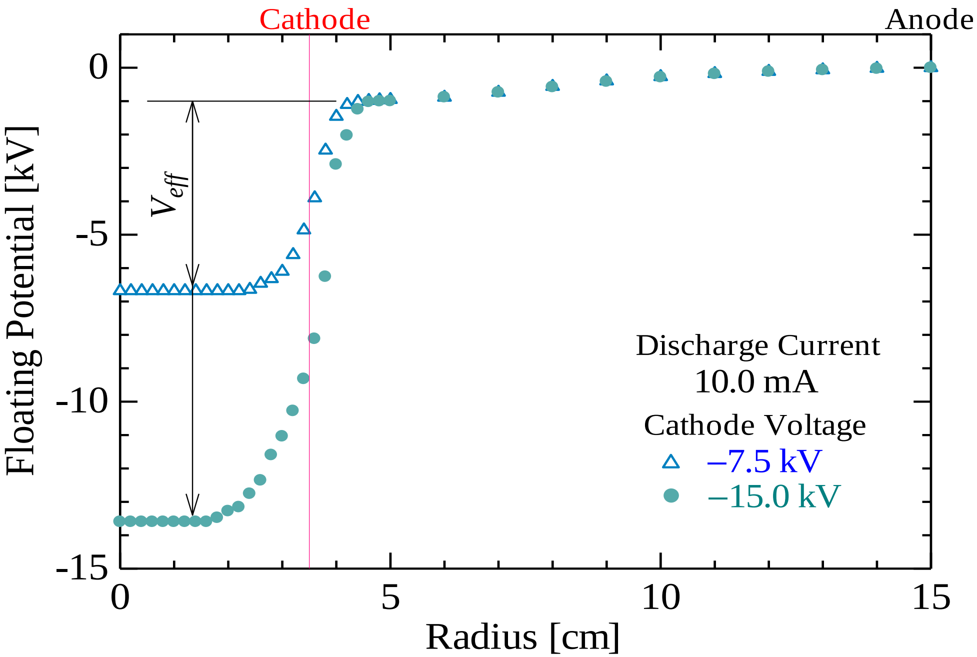
- **Breakdown voltage in D_2 is twice that in H_2**

⇨ **Back and force motion of ions affects the ionization**

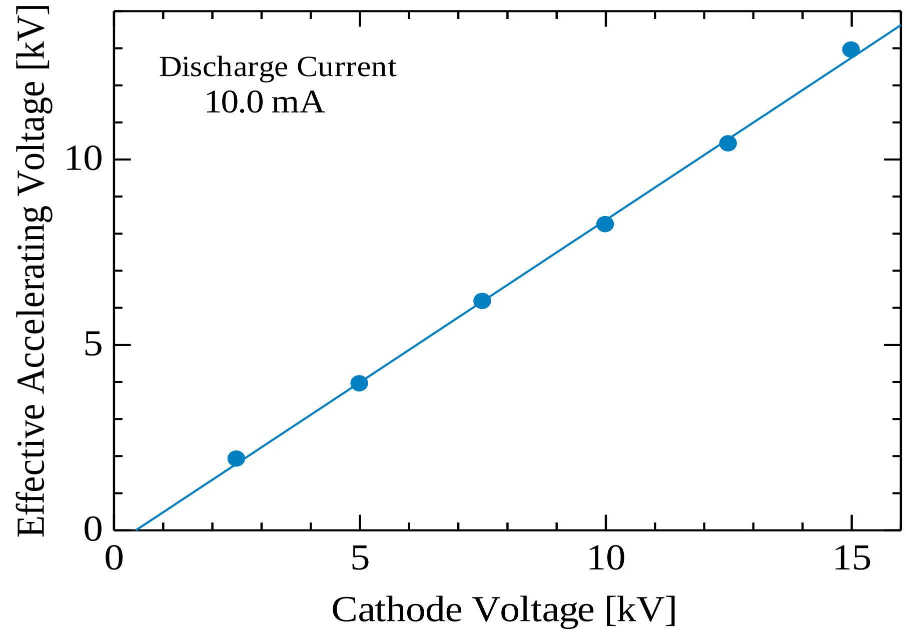
Ratio of kinetic energies: $\frac{m_D {v_D}^2}{m_H {v_H}^2} = \frac{V_D}{V_H}$

Since $\frac{m_D}{m_H} = 2$, $\frac{V_D}{V_H} = 2$ **means** $v_D = v_H$ **is required to initiate breakdown**

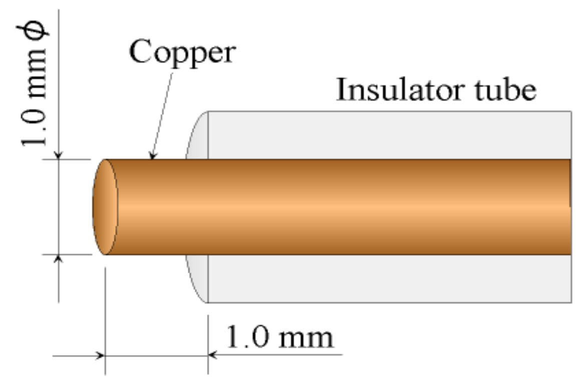
Floating Potential Distribution



V_{eff} : Effective voltage



- **Virtual anode at the center is not observed.**
  Charge neutralization by electrons
- **Effective accelerating voltage is about 0.8 of applied voltage at the center**



Probe structure

Spectroscopic Measurement

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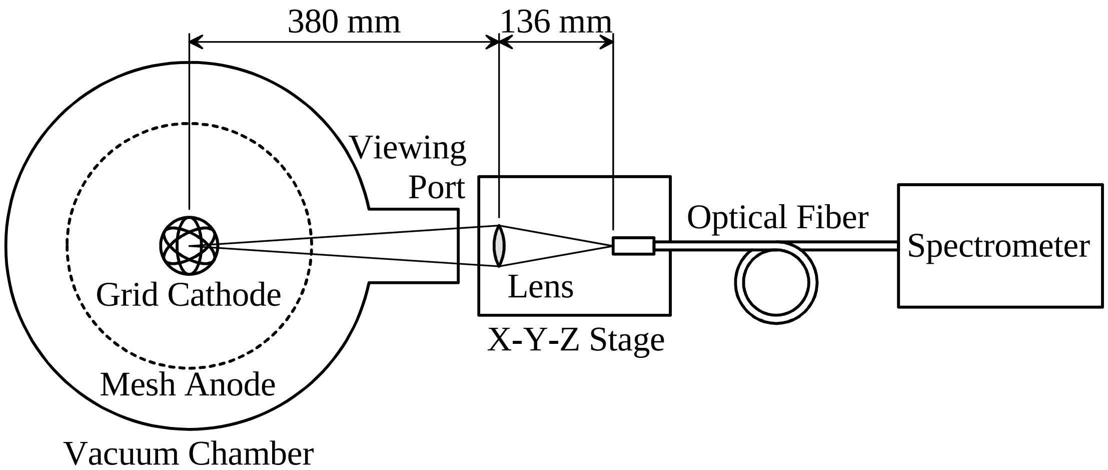
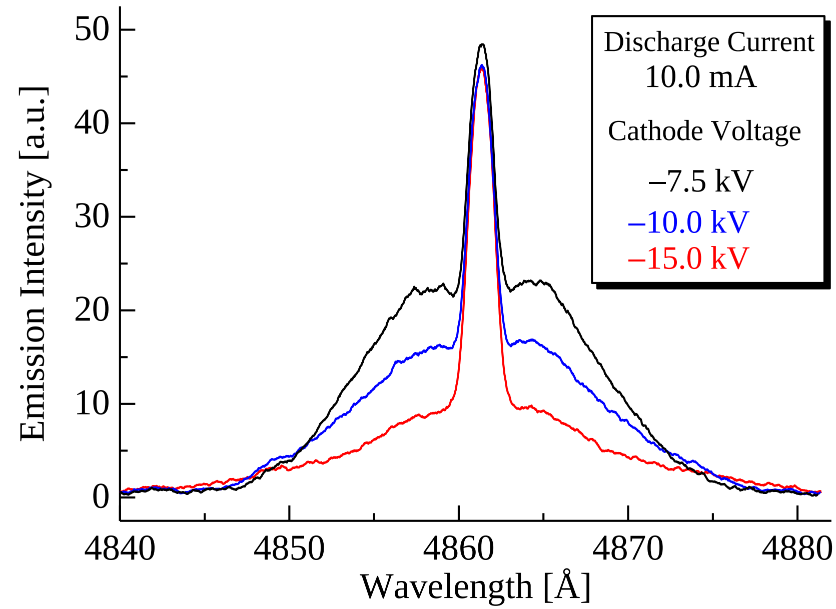


Optical System



Measured H_β Line Spectrum

Resolution along optical axis : 6 cm

CORE PLASMA

Stark broadening ⇒ $n_e \sim 5 \times 10^{20}\ m^{-3}$ (1.6-1.8 times the background neutral density)

NEUTRAL (ION) BEAM

Max. Doppler shift ⇒ Vimax ∼12 keV at applied voltage of 15 kV

Neutron Production Rate

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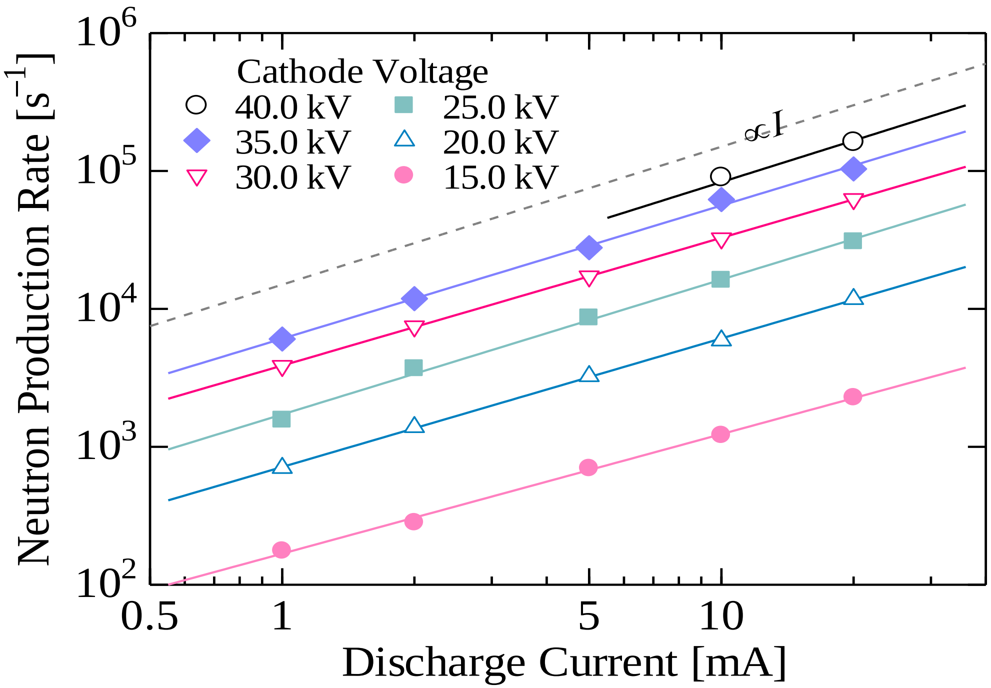
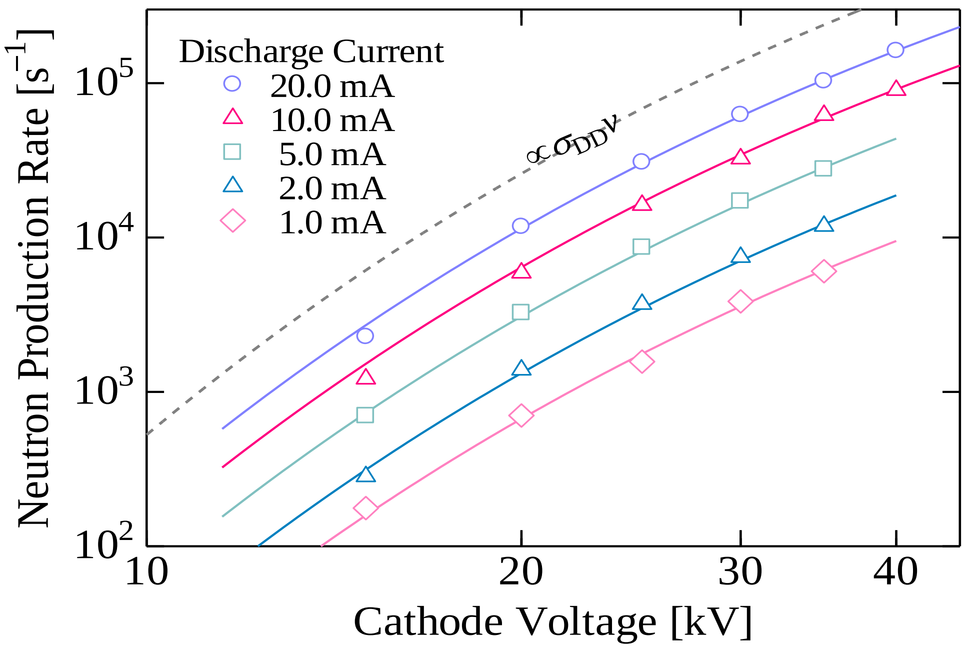




Neutron Production Rate

∝ Discharge Current

Neutron Production Rate

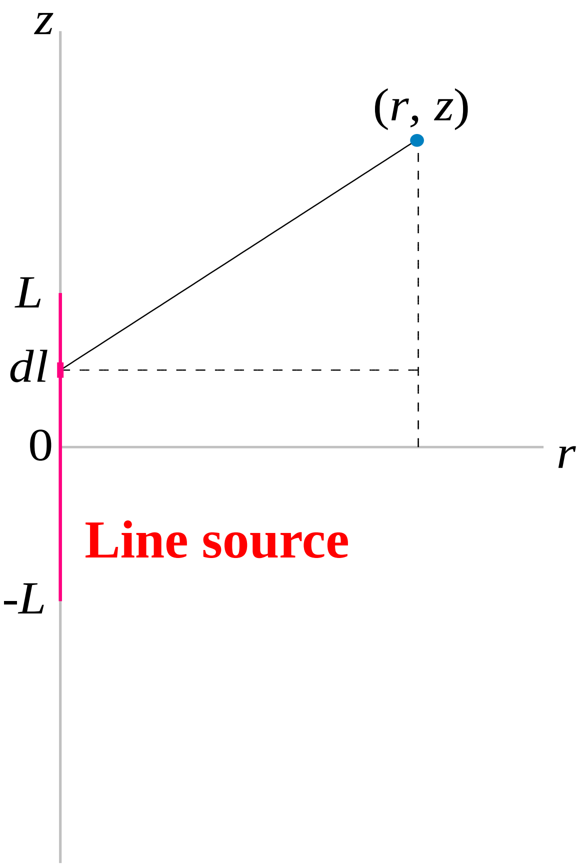
∝ Fusion Reactivity $\sigma_{DD}v$ of Beam-Background Reaction

Beam-background reaction is dominant

Cylindrical IEC Device

- **Objectives: Improvement of performance**
  - **Increase the neutron flux near the device**

Neutron Flux



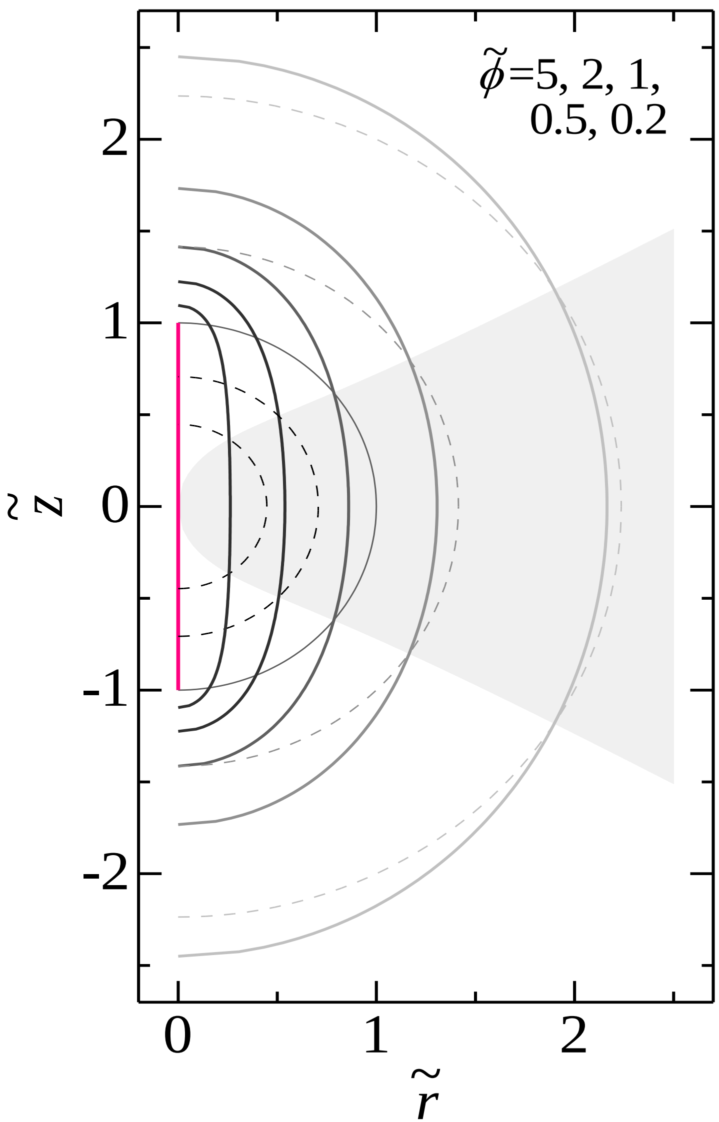
$$\phi = \int_{-L}^{L} \frac{N/2L}{4\pi\left\{r^2 + (z-l)^2\right\}} dl$$

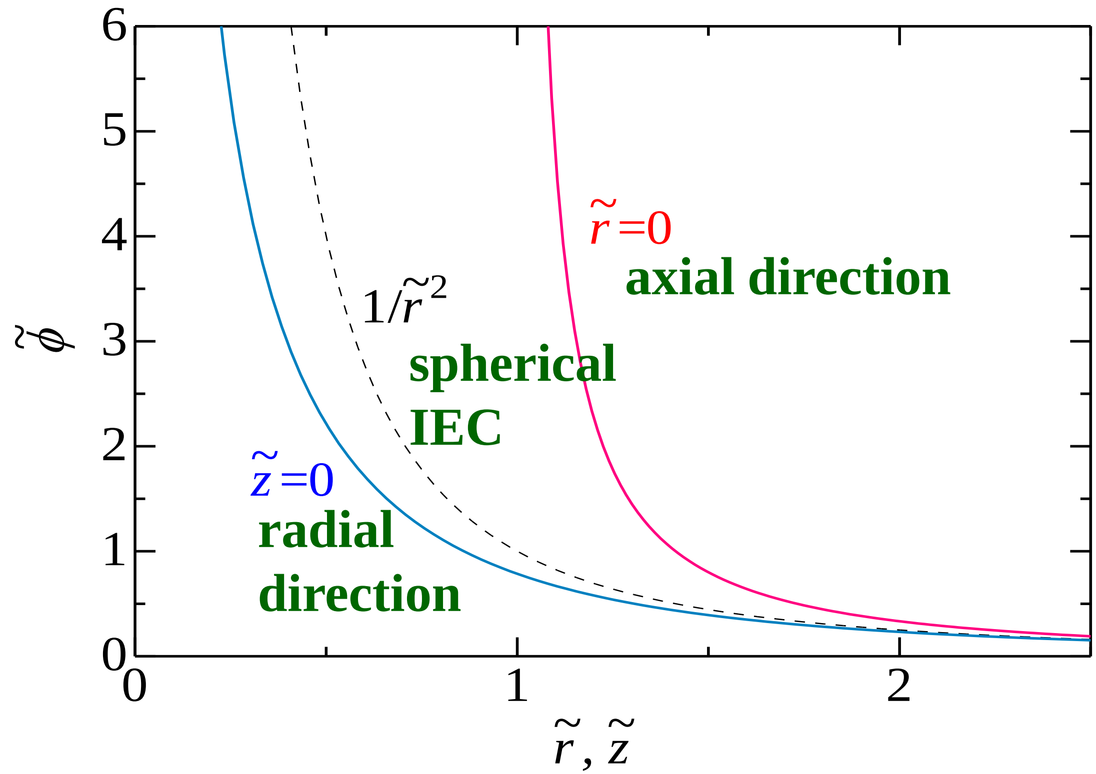
$$= \frac{N}{4\pi L^2} \frac{L}{2r} \left(\tan^{-1} \frac{z+L}{r} - \tan^{-1} \frac{z-L}{r} \right)$$

Normalization

$$\begin{cases} \tilde{r} = \dfrac{r}{L} \\ \tilde{z} = \dfrac{z}{L} \\ \tilde{\phi} = \dfrac{\phi}{N/4\pi L^2} \end{cases}$$

Neutron Flux Distribution





Strong flux in axial direction

Gradual decrease in radial direction

Schematic of Cylindrical IEC Device

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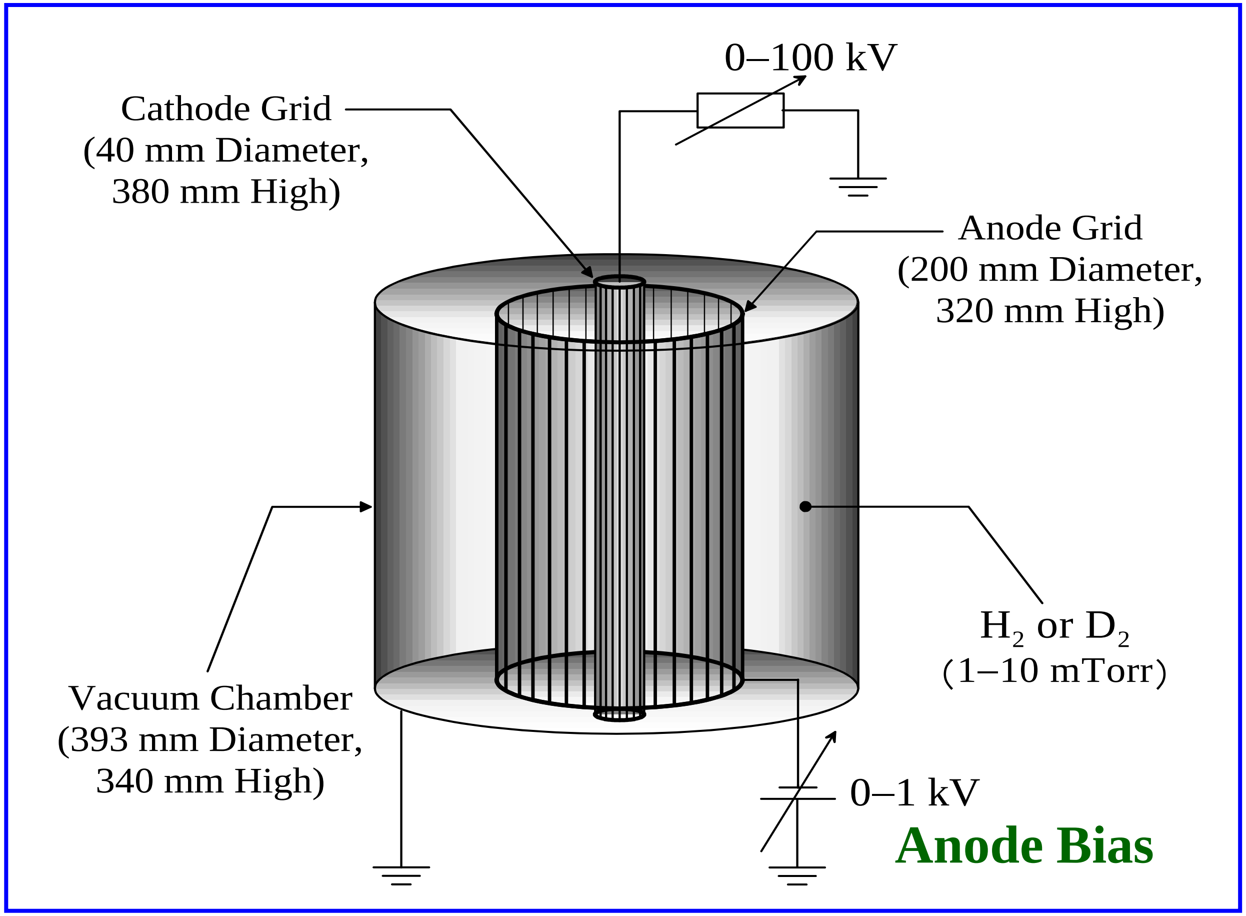
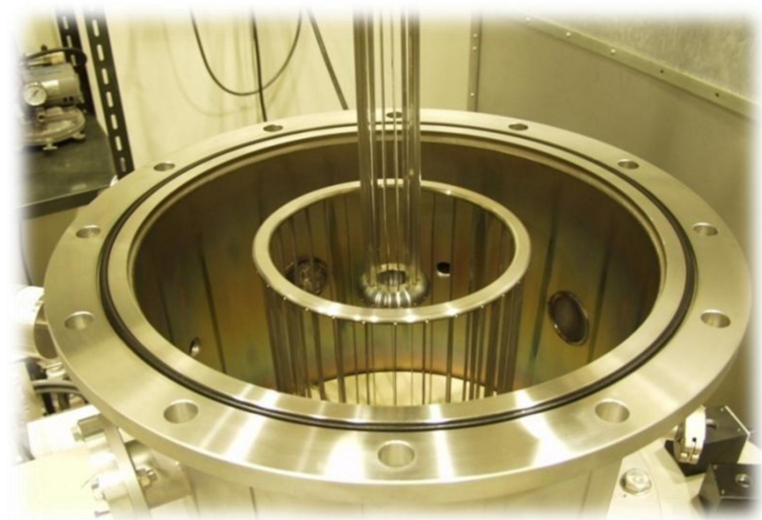
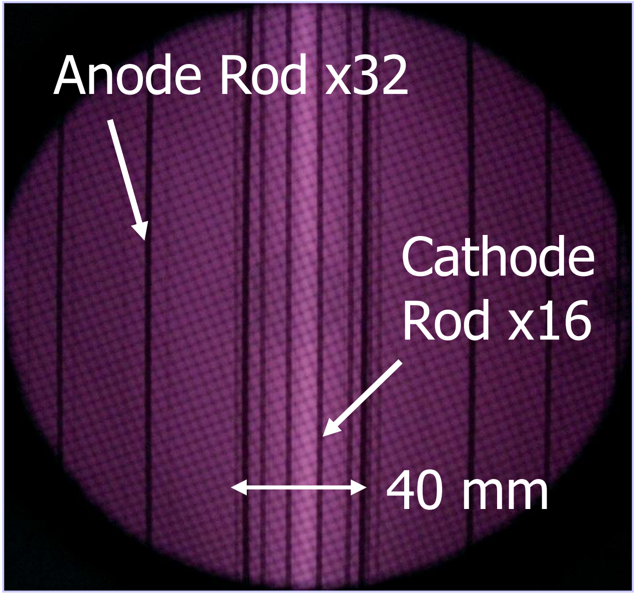




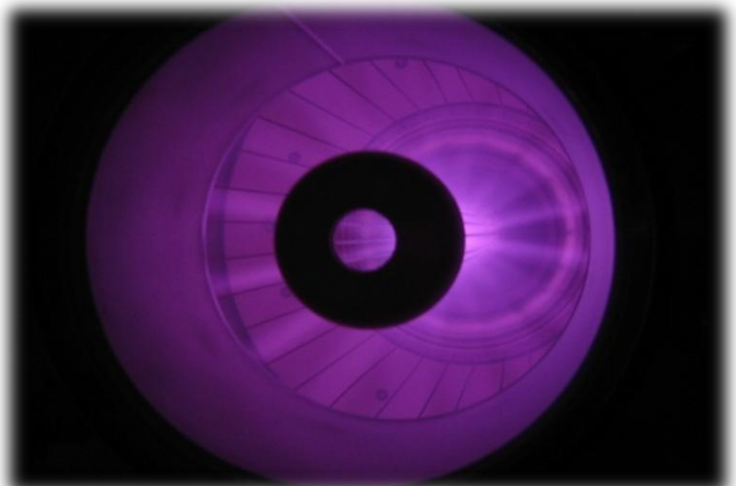
Grid electrodes

Cathode: ϕ1.6-mm Stainless Steel Rod x16
Anode: ϕ1.2-mm Stainless Steel Rod x32

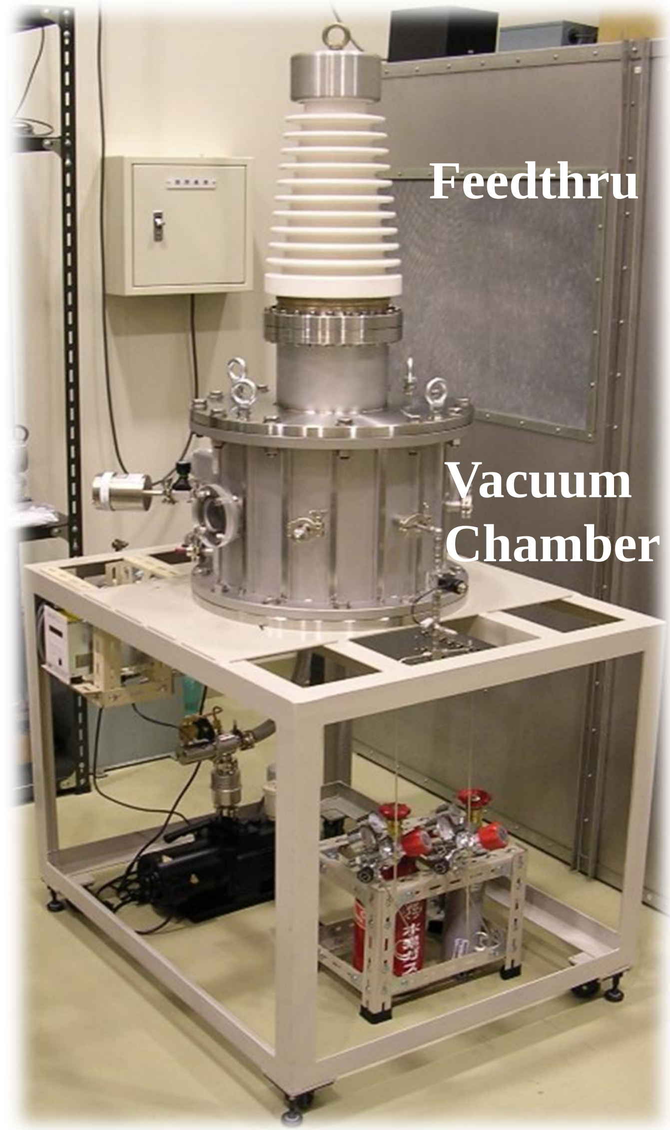
Cylindrical IEC Device



Side view of discharge



Bottom view of discharge



Whole system

Magnetic Cusp Field + Anode Bias

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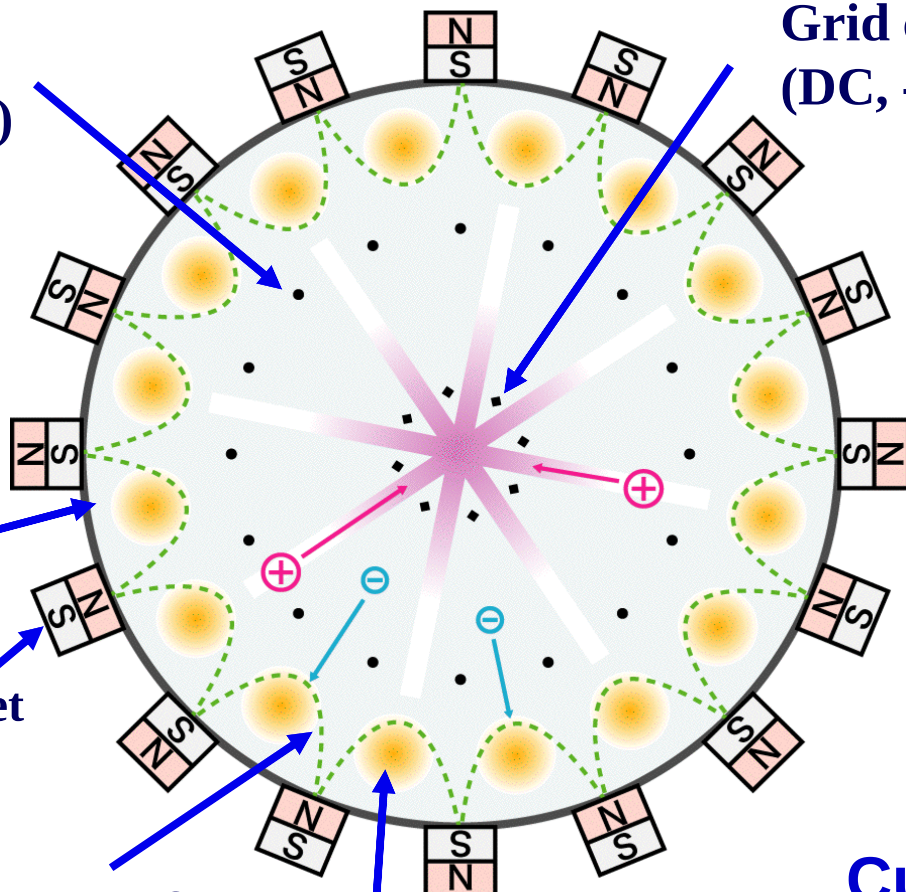
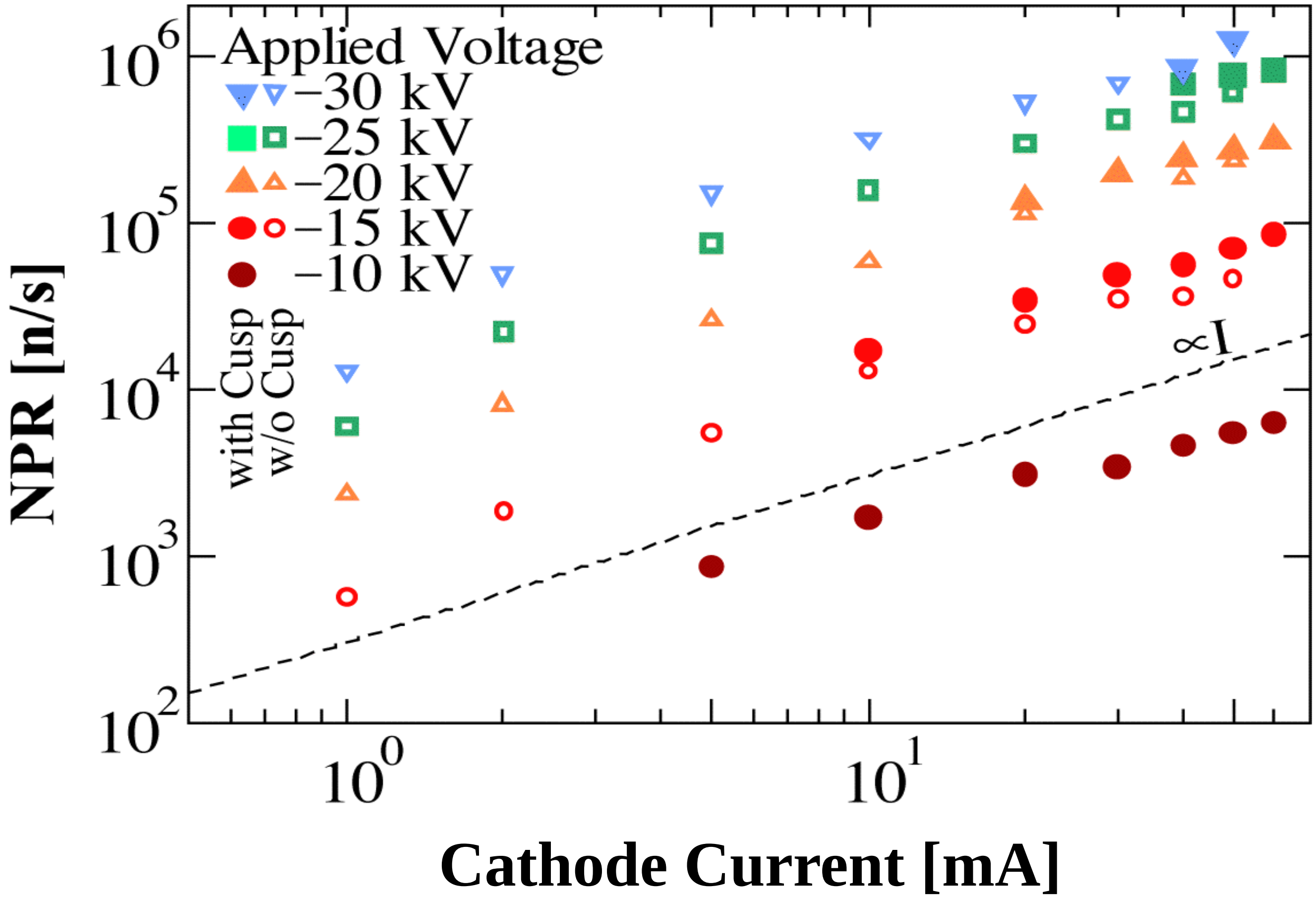


Cusp magnetic field for electron confinement and ion production: Magnetron discharge

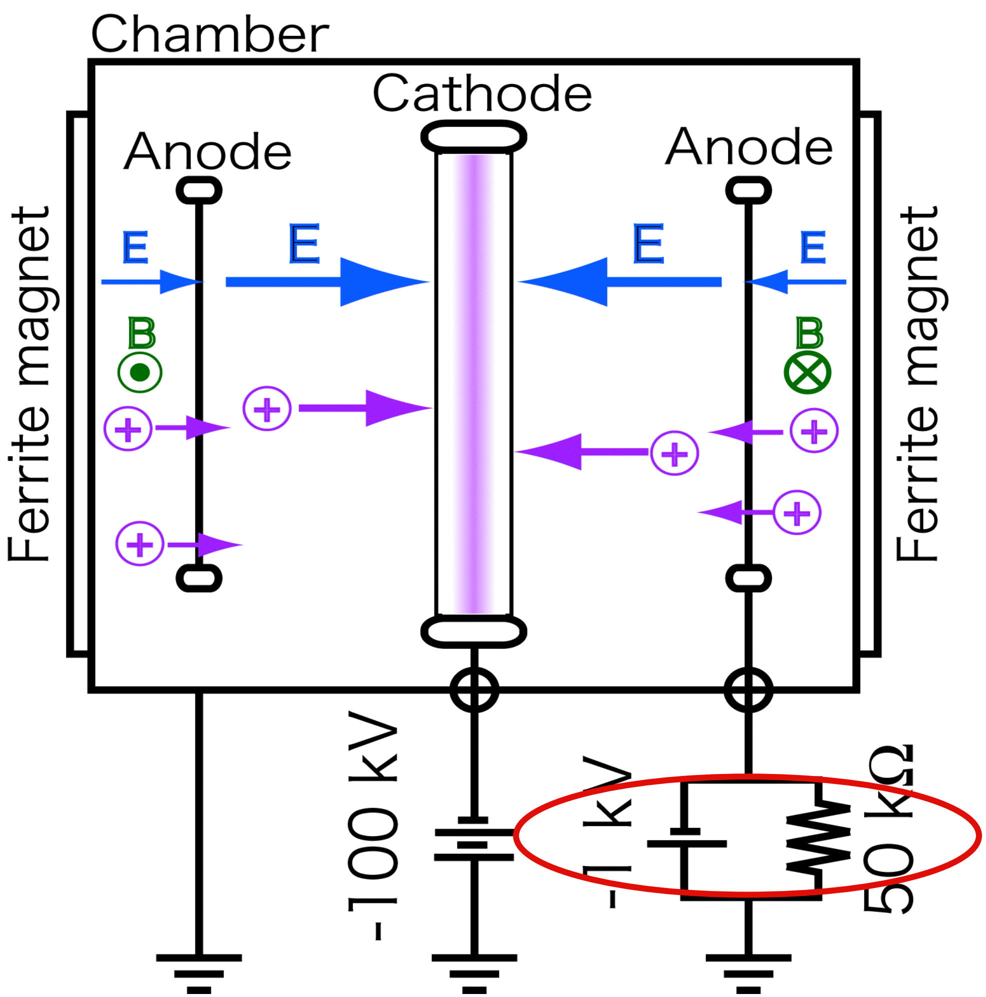
Effect of cusp magnetic field on NPR



Max. NPR
1.1×10^6 n/s
(30 kV, 50 mA)

With cusp magnetic field ➡ **<u>~1.5 times higher NPR</u>, although NPR ∝ *I* does not change**

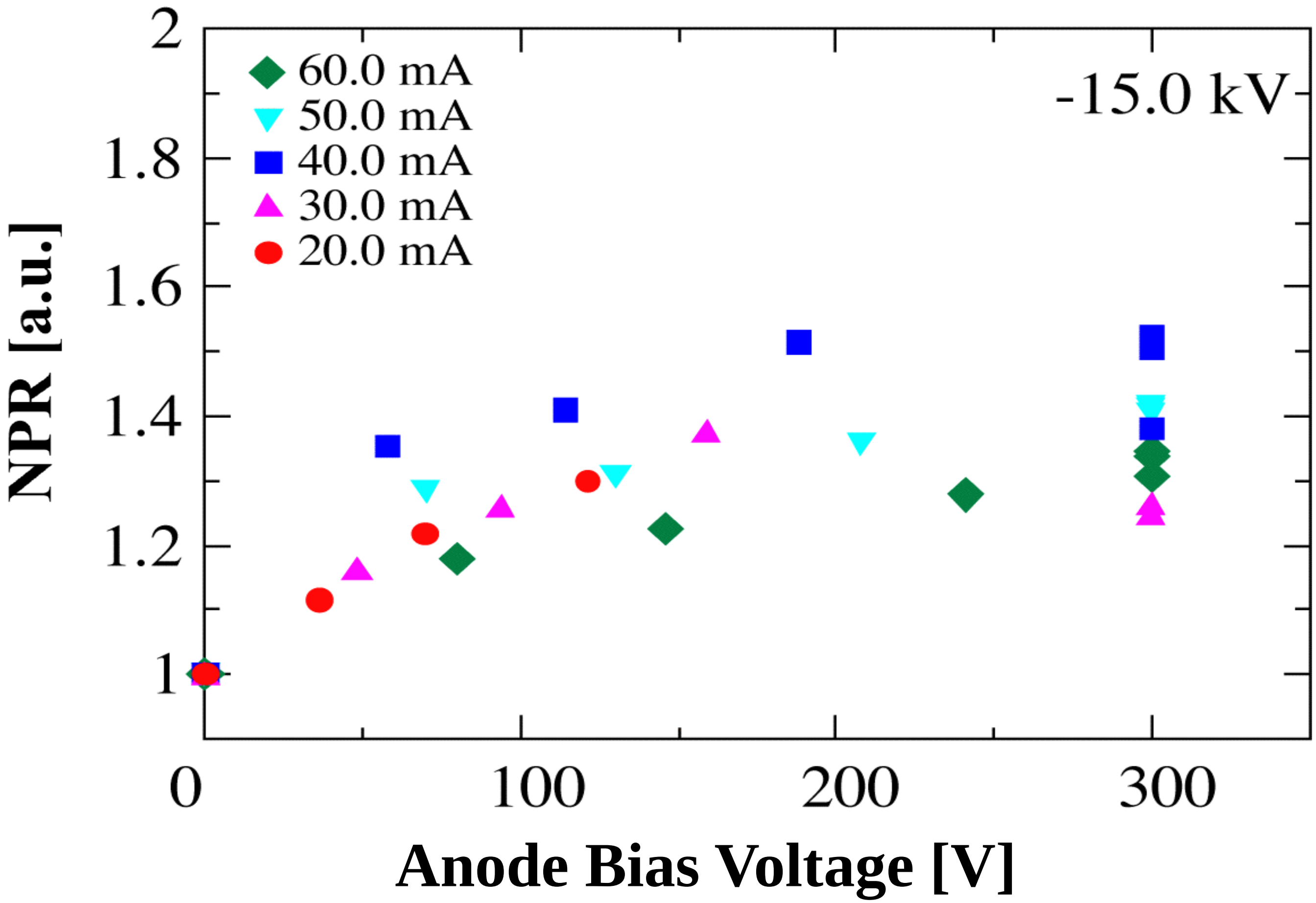
Anode Bias



Biased with <u>anode resistor</u> and <u>DC power supply</u>

…ions extracted by bias voltage towards the center effectively

Effect of Bias Voltage on NPR



NPR increases with the bias voltage, then saturates.

⇨ **Number of generated ions is limited.**

Region of Stable DC Discharge

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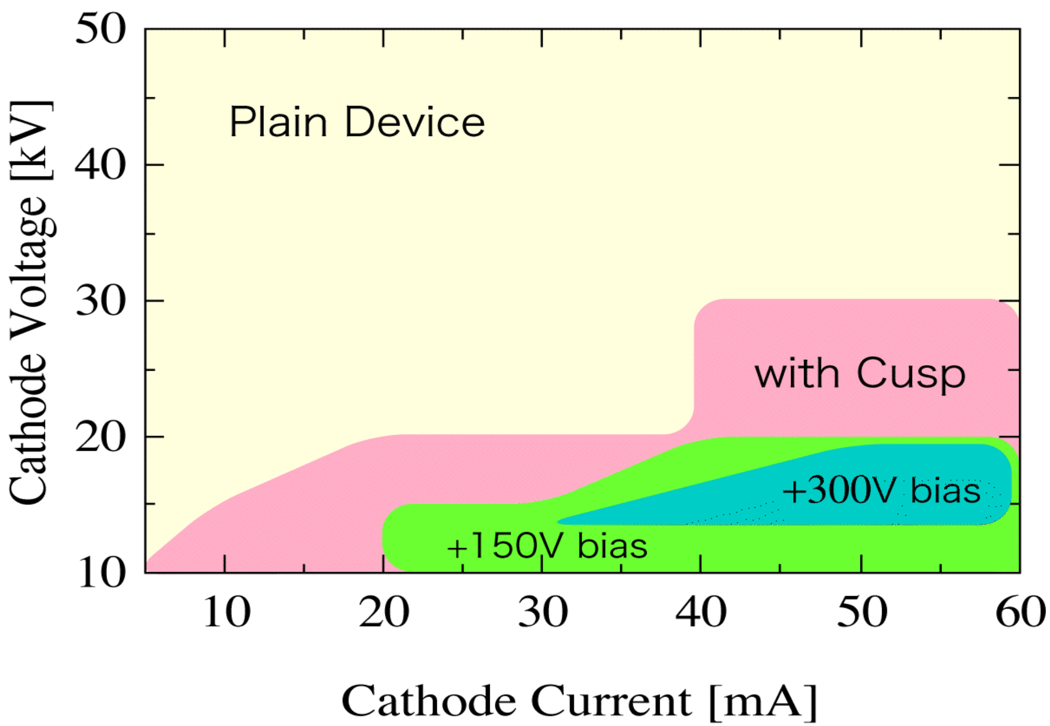
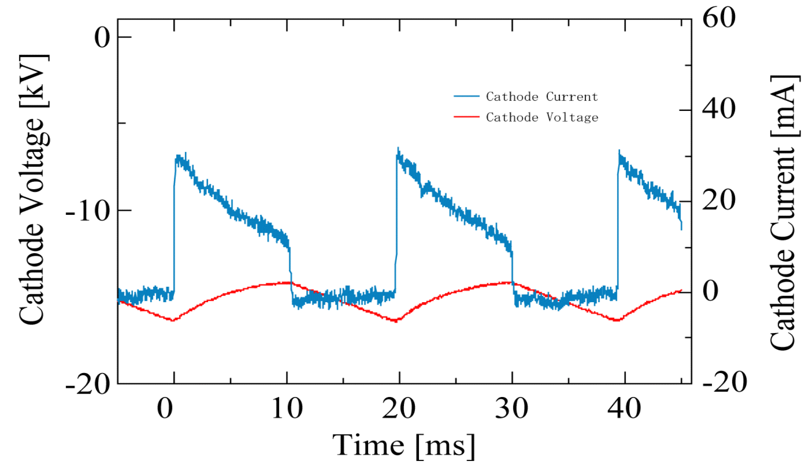


Region of stable discharge

Periodic discharge occurs with cusp magnetic field



10 mA, 15 kV, no bias

Stable region shifts to
<u>higher current, lower voltage</u>

High neutron yield is available in PULSED operation with an adequate power supply

Pulsed Operation of IECF Device

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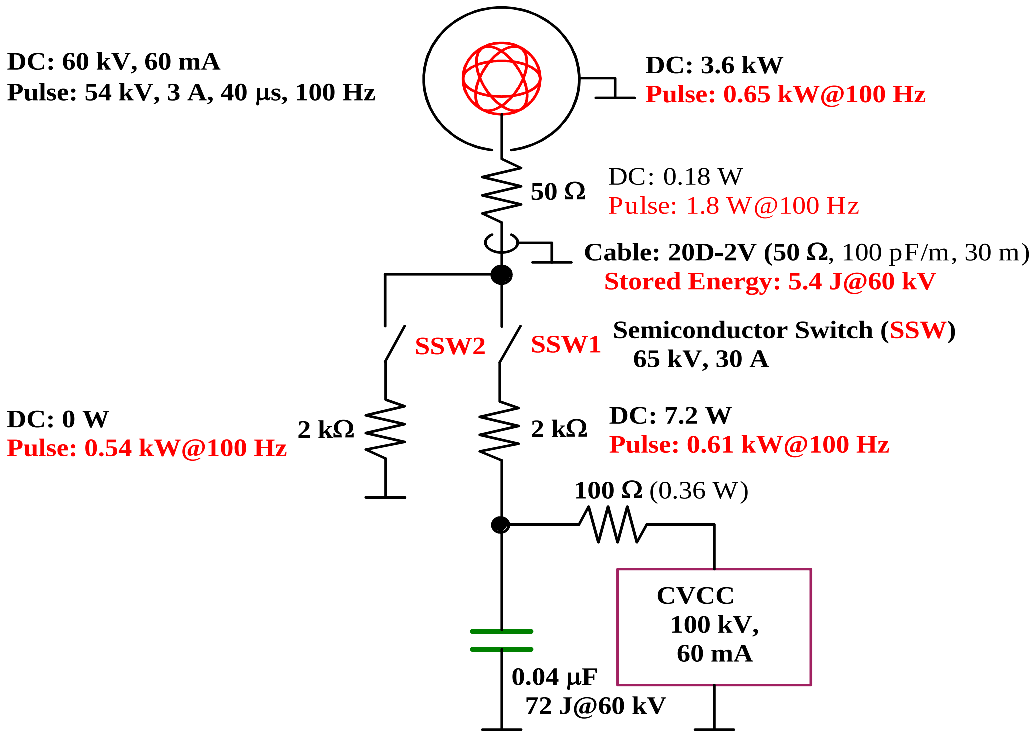
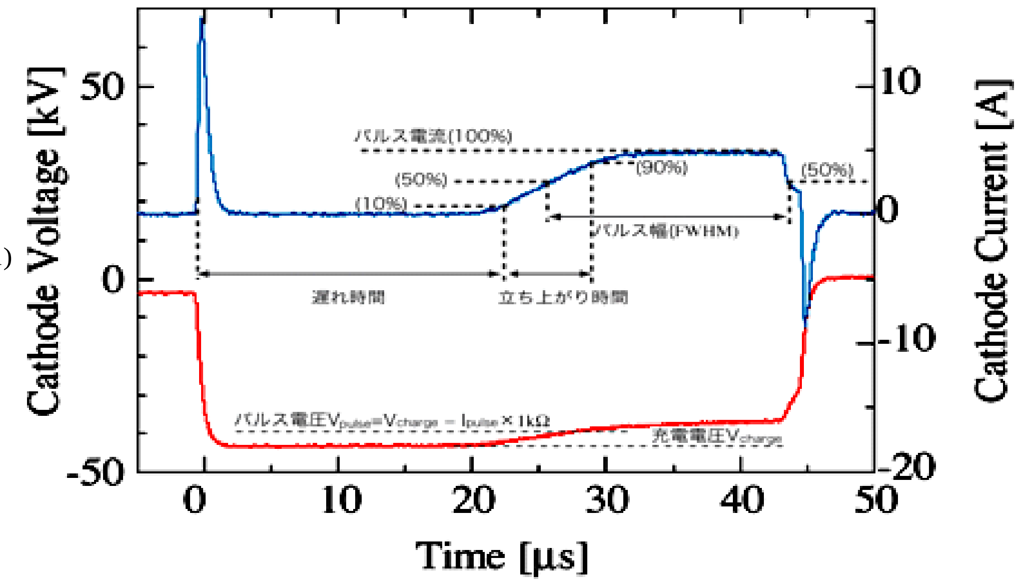
The pulsed power supply was developed for landmine detection system

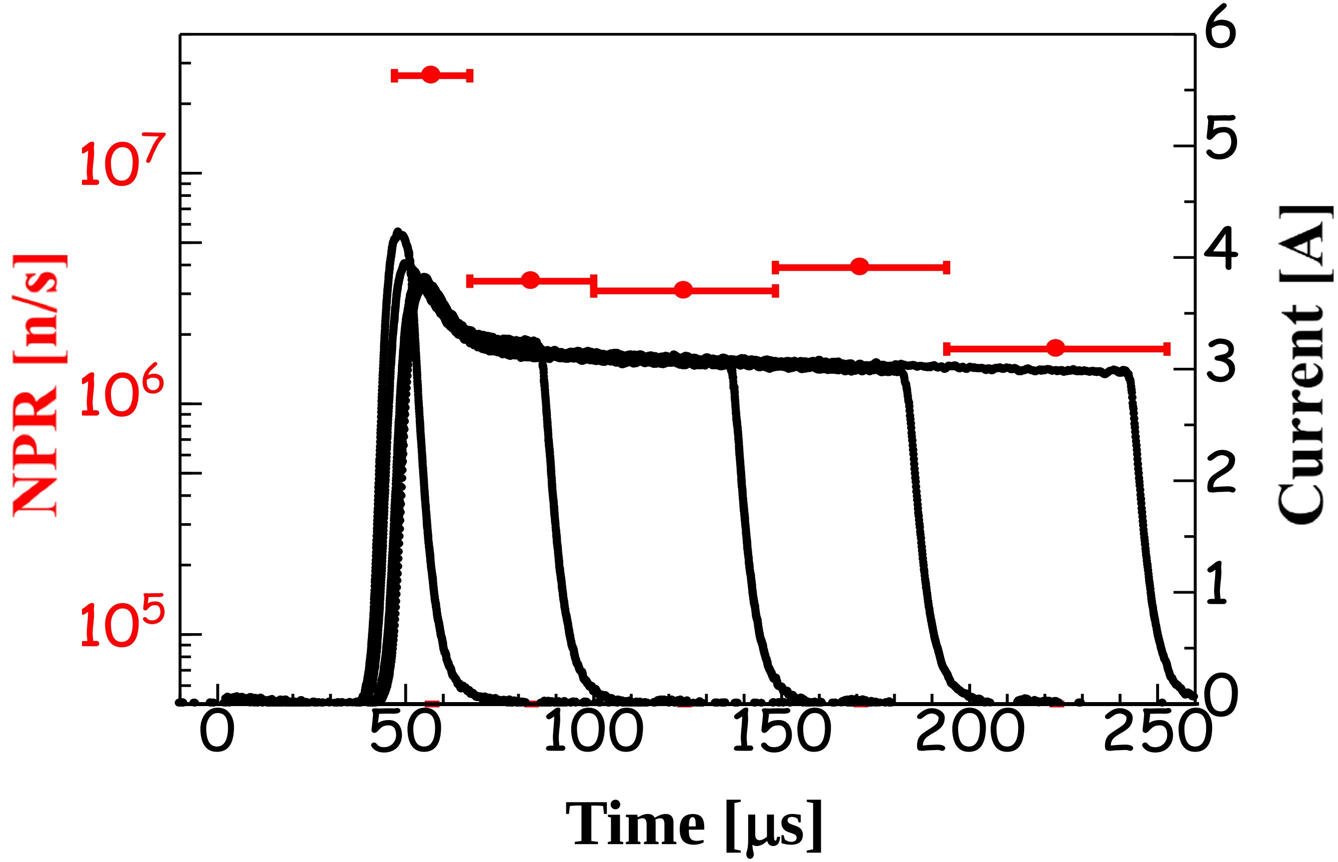


Electric circuit



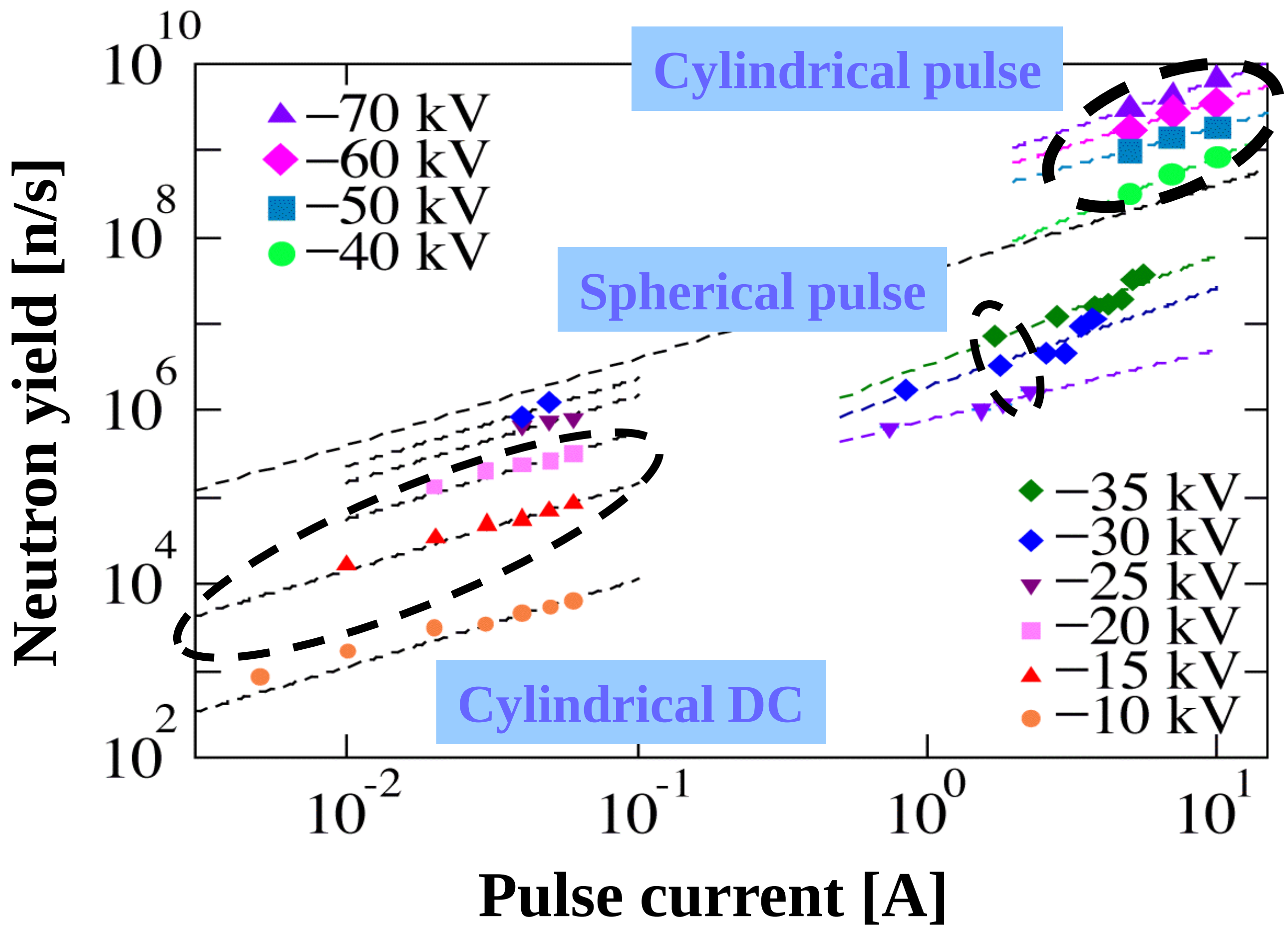
Practical waveform of pulsed operation
(40 kV, bias 50 kΩ, 8.08 mTorr)

NPR in pulsed operation



30 kV, spherical IEC device

NPR Dependence on I_{pulse}



Cylindrical device: NPR

6.8×10^9 n/s (at 70 kV, 10A, anode bias -1 kV in 2005)

7.4×10^9 n/s (at 80 kV, 15 A, 20 μs)

Coaxial Double Cylindrical IEC Device

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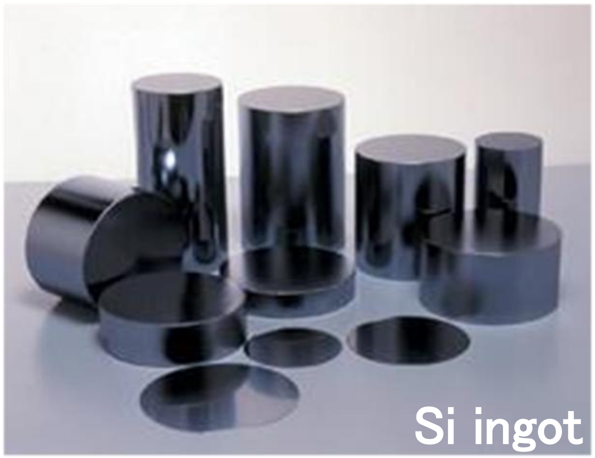
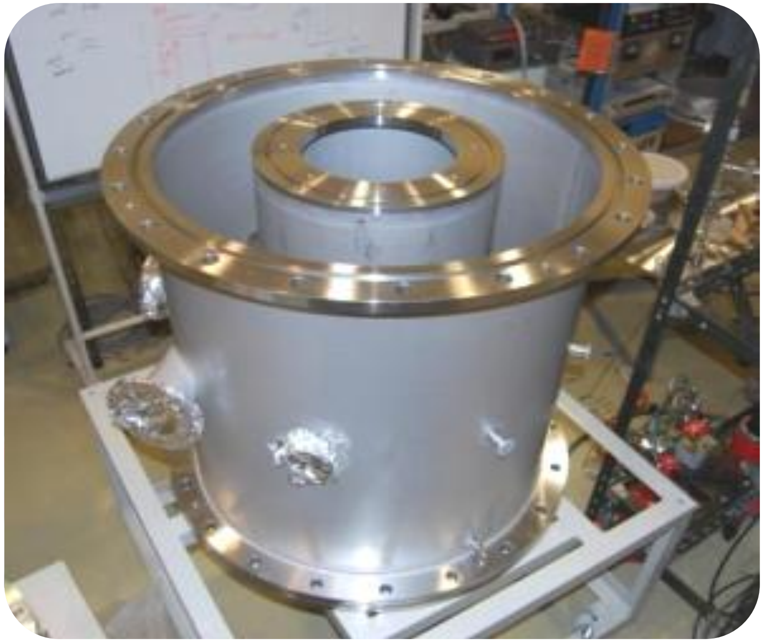
- **Objectives:**
  - **High quality semiconductor production by Neutron Transmutation Doping (NTD)**
- **Improvement of performance**
  - **Uniform irradiation area**
  - **Increase of NPR**
  - **Long operation time**





Neutron Transmutation Doping

http://sangaku.jaea.go.jp/3-facility/02-field/index-16.html

Neutron Transmutation Doping (NTD)

＜Principle of NTD＞

$^{30}Si + n \rightarrow {}^{31}Si \rightarrow {}^{31}P + \beta$

（Neutron capture） （β⁻ decay）

Silicon ingot

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

Development of New IEC Neutron Source

Requirement

- Uniform irradiation
- Increase of NPR
- Stable long time operation

→ **Coaxial double cylindrical device**

Coaxial Double Cylindrical IEC

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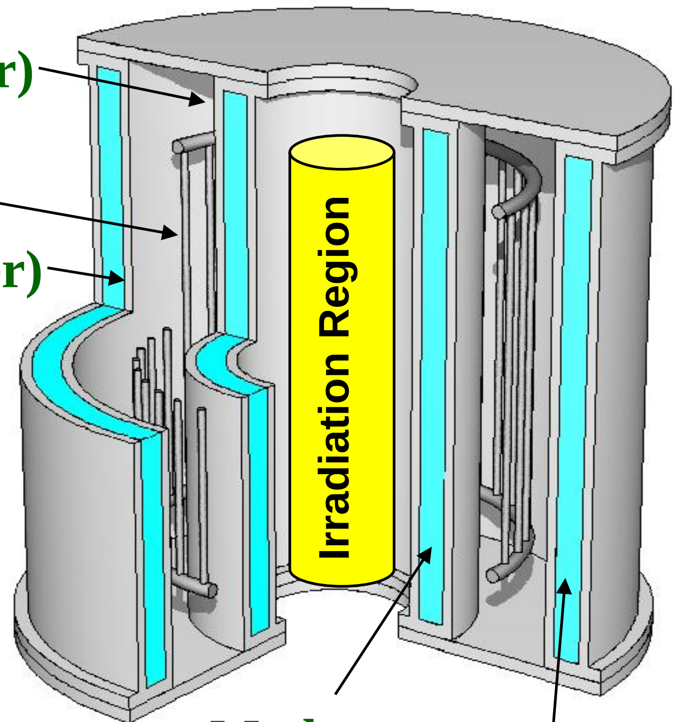
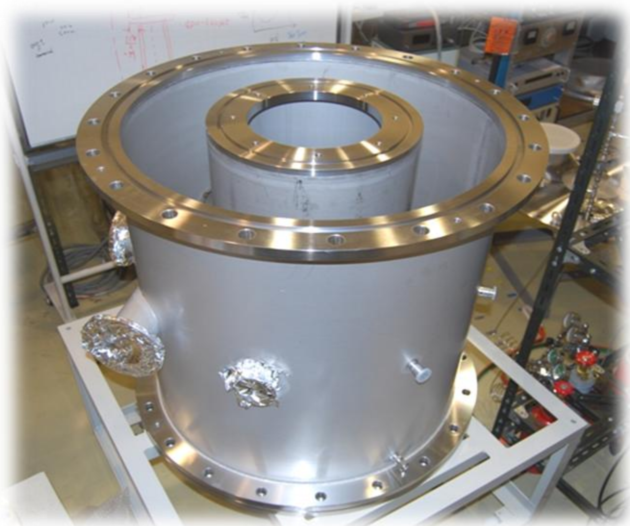
- **Uniform neutron irradiation aiming at NTD : ^{30}Si (n, β) ^{31}P**





Chamber

Cathode grid

Measurement of NPR, Uniformity of Irradiation

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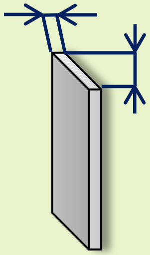
Polyethylen (PE) block (Moderator)

<1mm Plate electrode>

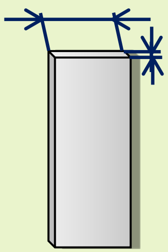
width : 1 mm



depth :5 mm

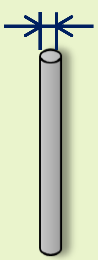
<5mm Plate electrode>

width : 5 mm

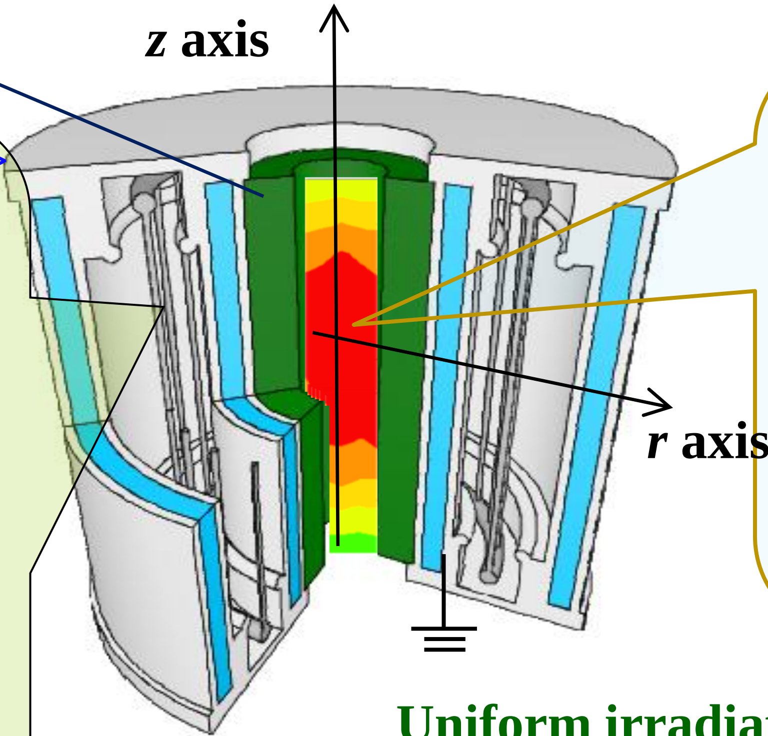


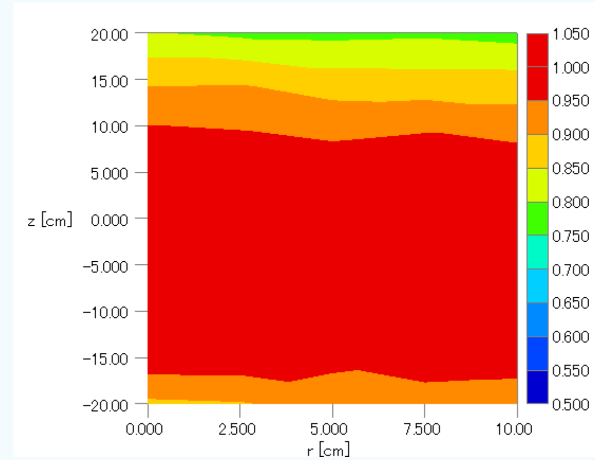
depth : 1 mm

<Rod electrode>



diameter : 1.6 mm





Uniform irradiation area:
Neutron flux density within ±5%

Experimental condition

- **D-D fusion, DC power supply, -30 kV, 60 mA**
- **Rod cathode**
- **Coolant temperature:17℃ - 8.3℃**

NPR Dependence on Current

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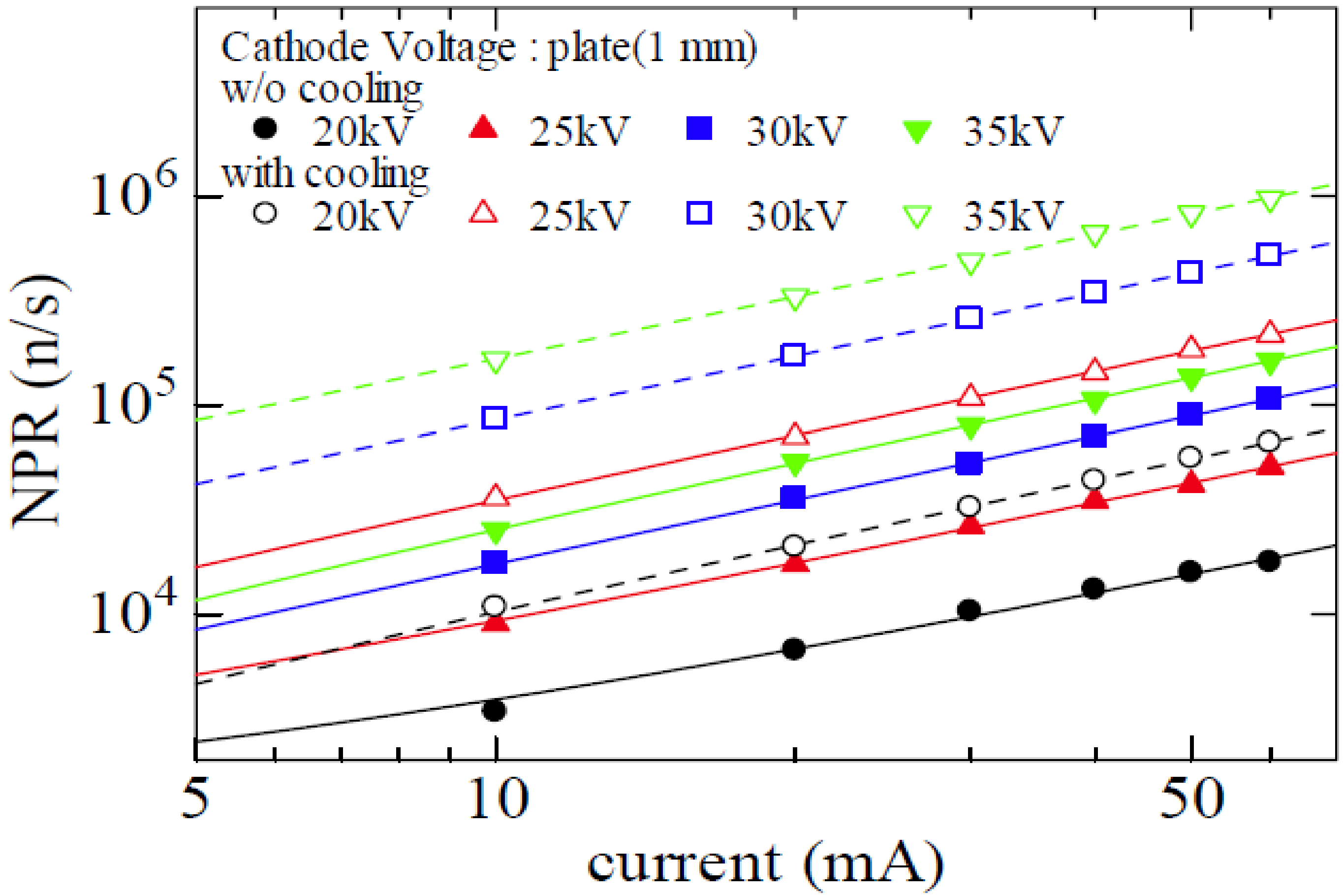

Max. NPR 1.5×10^6 n/s

(Rod electrode, with cooling, -45 kV, 60 mA)

Dependence of Uniform Irradiation Area on Electrode Shape

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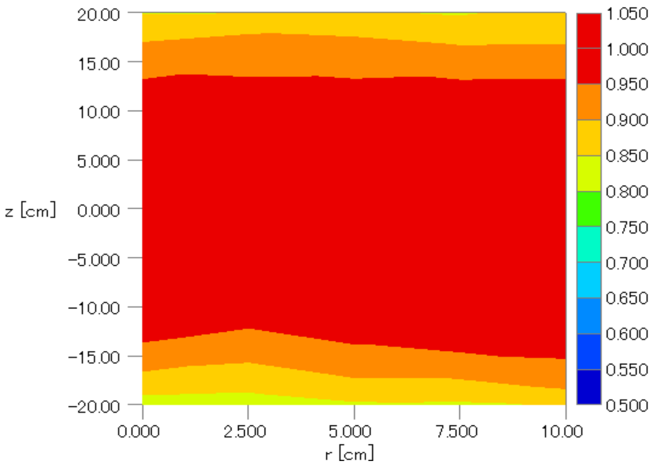
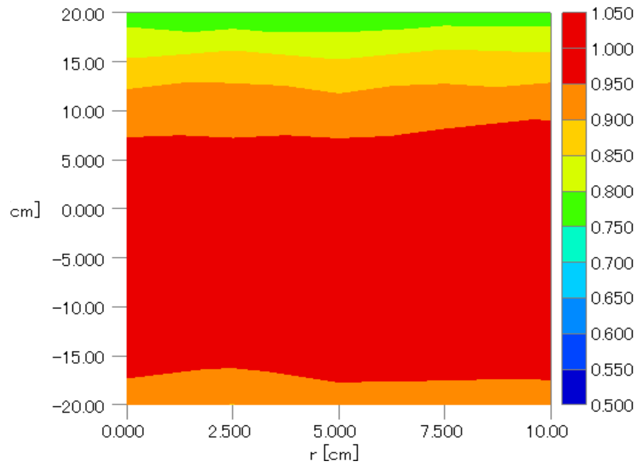
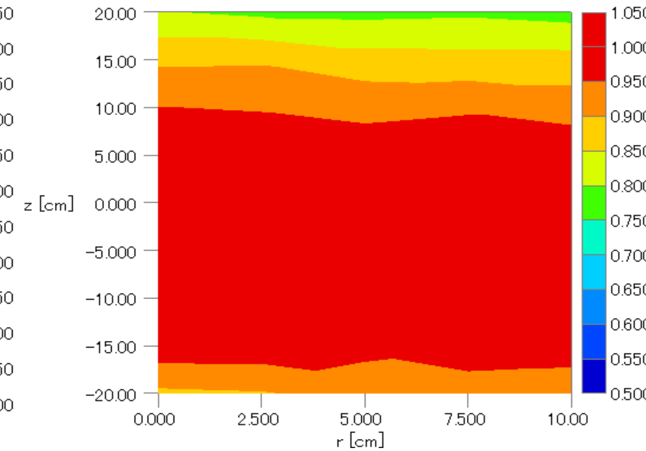
<1mm Plate Electrode>



<5mm Plate Electrode>



<Rod Electrode>



Neutron flux distribution (17℃)

Uniform area location depends on electrode shape

Recent IEC Research

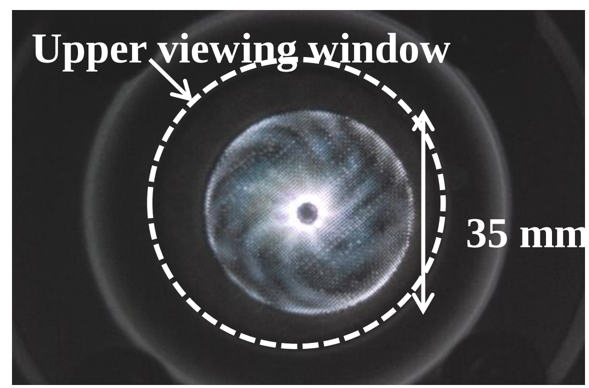
◆Beam-Beam fusion reaction

- ✓ Distributed Ion source
  - ✓ High current operation
  - ✓ Low pressure operation

Azimuthal cusp magnetic field

- ✓ Magnetic field
  - ✓ <u>Low pressure operation</u>
  - ✓ <u>Ion confinement</u>

Magnetic assist



Cusp magnetic field: From axial to azimuthal

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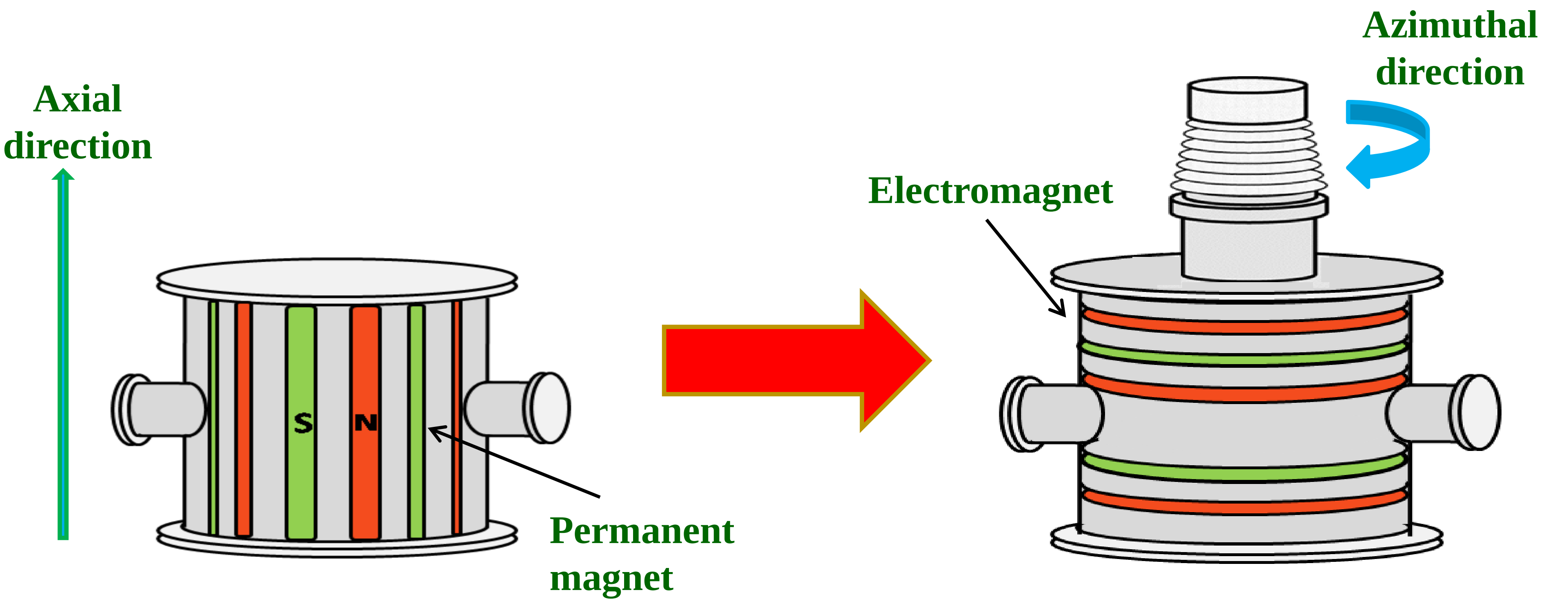

Axial cusp magnetic field

Azimuthal cusp magnetic field

Electrons move in axial direction by ExB drift
→ Electron confinement is not good enough

Electrons drift in azimuthal direction
→ Better electron confinement

Kei Takakura will introduce the results this afternoon

Summary

- Several types of IEC devices : DC and pulsed operation
  - Spherical device: Point source
    - fundamental research
    - Beam-beam fusion using differential pumping ion sources
  - Cylindrical device: Line source
    - Line cusp magnetic field was tested
      - Pulsed operation: Max. NPR 7.4 x 10^9 n/s at 80 kV, 15 A, 20 μs
    - D-^{3}He reaction was demonstrated to get high energy proton (14.7 MeV)
  - Coaxial double cylindrical device: Cylindrical source
    - Uniform neutron irradiation area
    - For high quality semiconductor production by NTD
- Recent research: Effect of magnetic field
  - Uniform magnetic field
  - Azimuthal cusp magnetic field


Thank you for your attention