Vietnam Conference on Nuclear Science and Technology

VINANST-13

SECTION C: RADIATION MEASUREMENT, RADIATION SAFETY AND ENVIRONMENTAL MONITORING

ESTABLISHMENT OF AN EXPERIMENTAL SYSTEM FOR RADIATION MANAGEMENT IN TEACHING OF SCIENCE USING CROOKES TUBES

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WHAT IS A CROOKES TUBE?

- 1875, William Crookes invented the Crookes tube.
- 1895, Wilhelm Conrad Röntgen discovered X-rays.
- 1901, W. C. Röntgen got the first Nobel Prize in Physics.

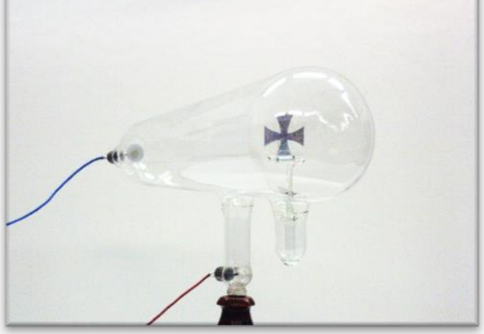
New Crookes tubes

William Crookes

Wilhelm Conrad Röntgen

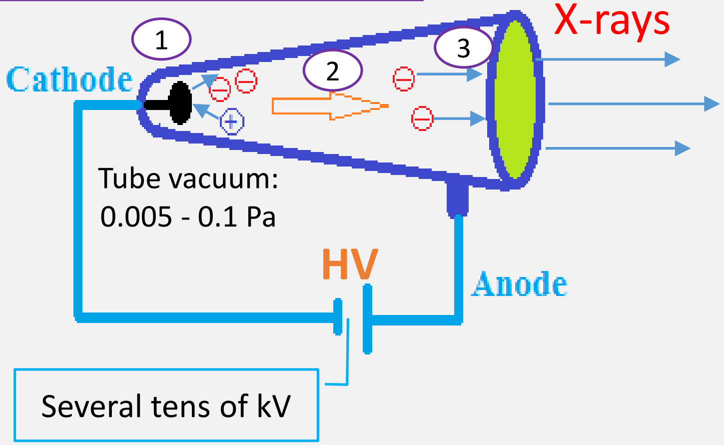
X-ray of Kölliker's hand, made by Röntgen (1896)

Conventional Crookes tube



Induction coil

Mechanism of a Crookes tube

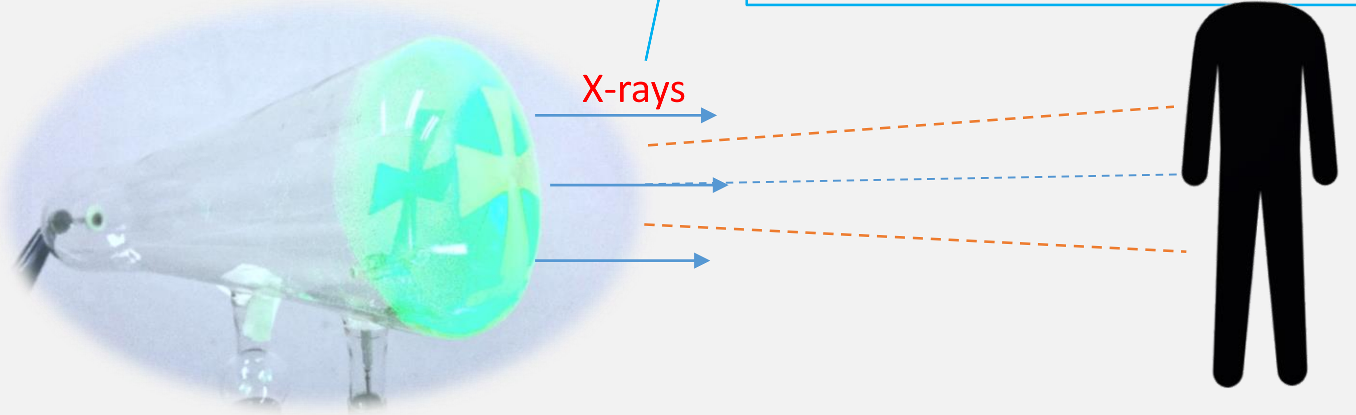


1. Cations in the evacuated tube are accelerated and impact the cathode, which knock out secondary electrons.
2. These electrons are accelerated under the applied HV.
3. Accelerated electrons collide the glass wall to radiate bremsstrahlung X-rays.

EXPOSURE TO X-RAY RADIATION FROM A CROOKES TUBE

Crookes tube has been used in teaching of science at junior-high schools in Japan.

Energy was approximately 20 keV.
$H_p(10)$ was up to 143 mSv/h … cm.



- The primary purpose is to teach the characteristics of electrons and current.
- To date, the leakage dose, properties of X-rays, and their relevance with operating settings have not been investigated systematically and sufficiently yet in Japan.
- From 2017, the project of “Establishment of radiation safety management system for low energy X-rays irradiated from Crookes tubes at education sites” has been started in Japan. Its scopes aim to establish a guideline on radiation safety management at the educational sites.

PROBLEMS ON ESTIMATE OF A CROOKES TUBE

- ❑ Low energy X-rays (approximately 20 keV): hardly measure by conventional meters (even used HPGe, NaI, Ge detectors).
- ❑ The pulse-shaped voltage creates the heterogeneous radiation: produces pile-up effect, broadened energy spectrum.
- ❑ Instability of induction coil and applied voltage: affected by temperature, humidity.
- ❑ Difficult in effective dose estimate:
  - dose distribution in horizontal plane is inhomogenous,
  - cannot assume an aligned and expanded radiation field,
  - cannot use $H_p(10)$ as an approximation of effective dose.

SCOPES OF THE RESEARCH

- ❑ Investigating the characteristics and properties of X-rays:
  - X-ray energy spectrum
  - Applied voltage distribution.
- ❑ Optimizing operating conditions to reduce the dose:
  - Applied voltage (output power)
  - Current
  - As low as reasonably achievable (ALARA principle): time, distance, and shielding
- ❑ Relevance between electric settings and leakage dose.
- ❑ Stimulating X-ray energy spectrum using cloud chamber.
- ❑ Submitting the results as the recommendation and guideline for radiation protection at junior-high school science class.

CHARACTERISTICS AND PROPERTIES OF X-RAYS EMITTED BY A CROOKES TUBE

- ❑ ***X-ray energy spectrum***
- ❑ ***Applied voltage distribution***

X-RAY SPECTRUM ACQUISITION AND VOLTAGE MESUREMENT

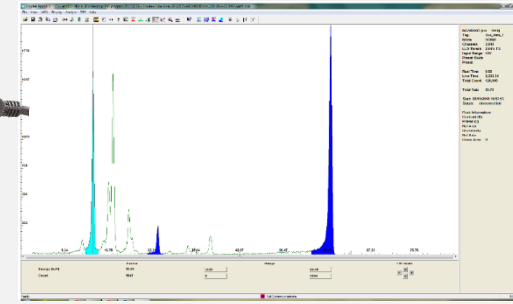
X-ray Spectrometer

Crookes tube (3C-B, Kenis Ltd., Japan)

CZT Detector (XR-100T-CZT, Amptek Inc., USA)

Power supply and Amplifier (PX2T, Amptek Inc., USA)

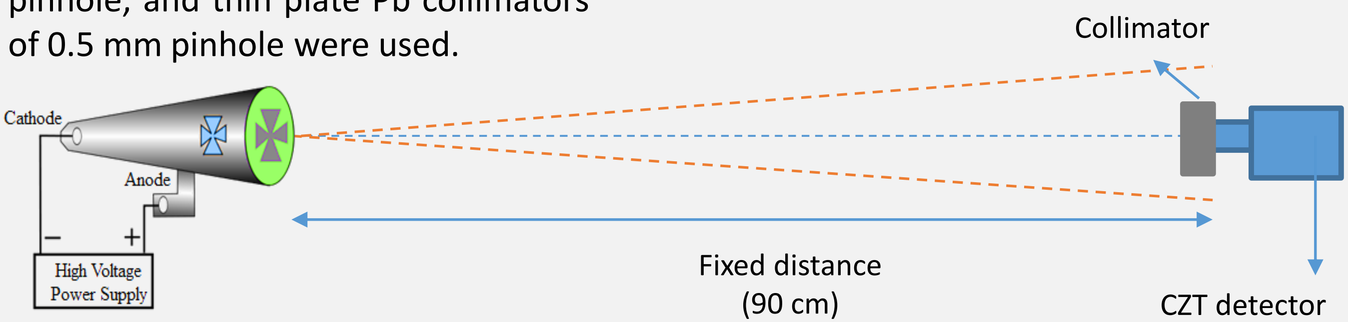
Pocket Multichannel (MCA8000D, Amptek Inc., USA)

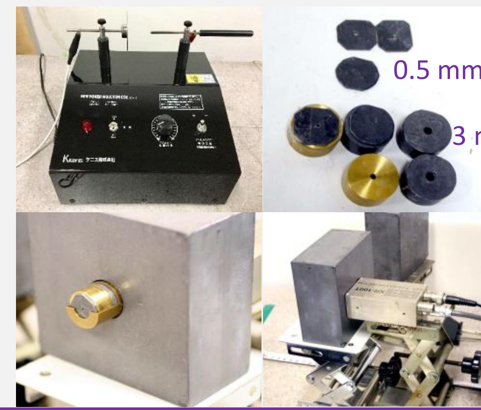


DPPMCA Software (Amptek Inc., USA)

X-ray spectrum setting

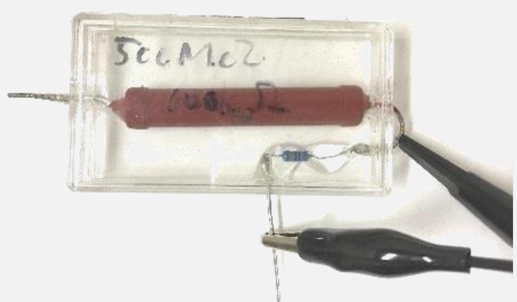
Cylindrical Pb collimators of 3 mm pinhole, and thin plate Pb collimators of 0.5 mm pinhole were used.





PC USB Oscilloscope (6000BD, Hantek Ltd.)

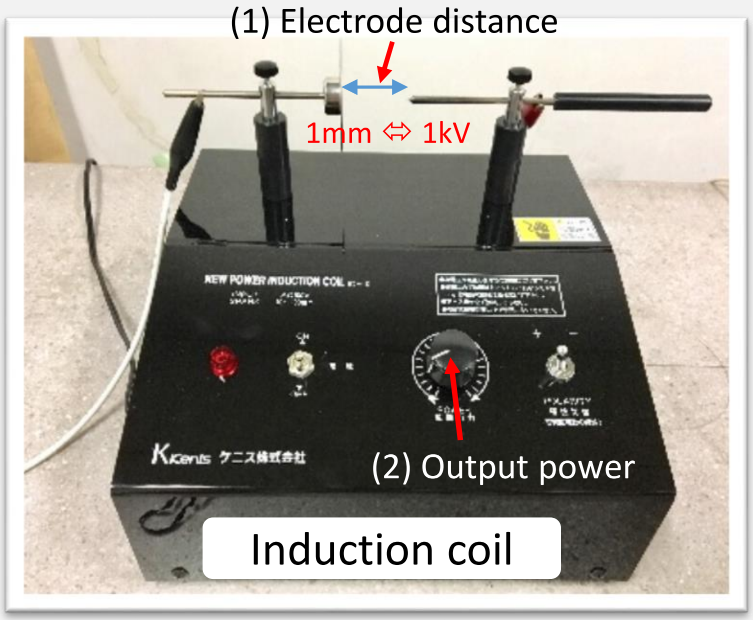
HV distribution

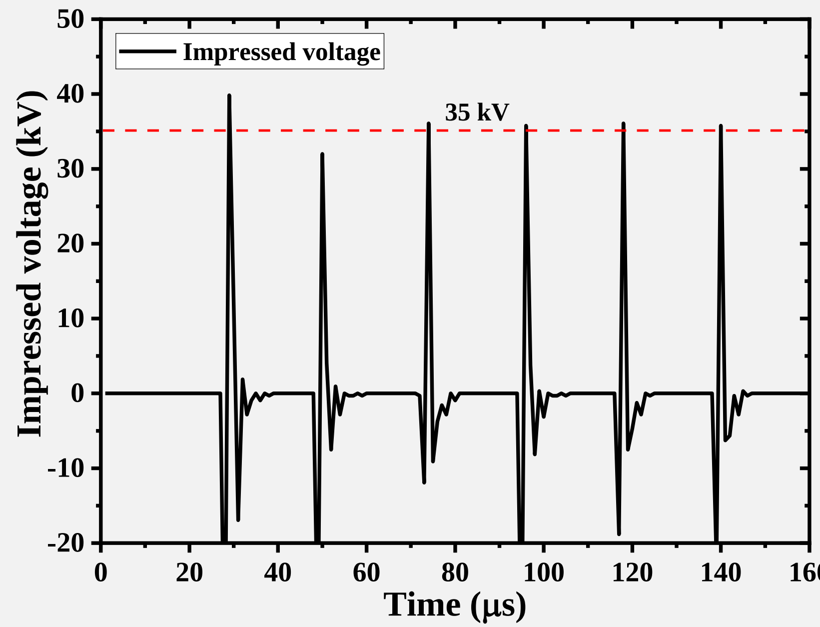


Voltage divider circuit:

- ❑ Reducing the magnitude of voltage during measurement against damage to oscilloscope voltage probes due to high pulse.
- ❑ The circuit consists of two resistors in series, one of **500 MΩ** glass resistor, and another of **100 kΩ**.

HIGH VOLTAGE APPLIED BY THE INDUCTION COIL





The induction coil produces an applied voltage in pulsed-shape.

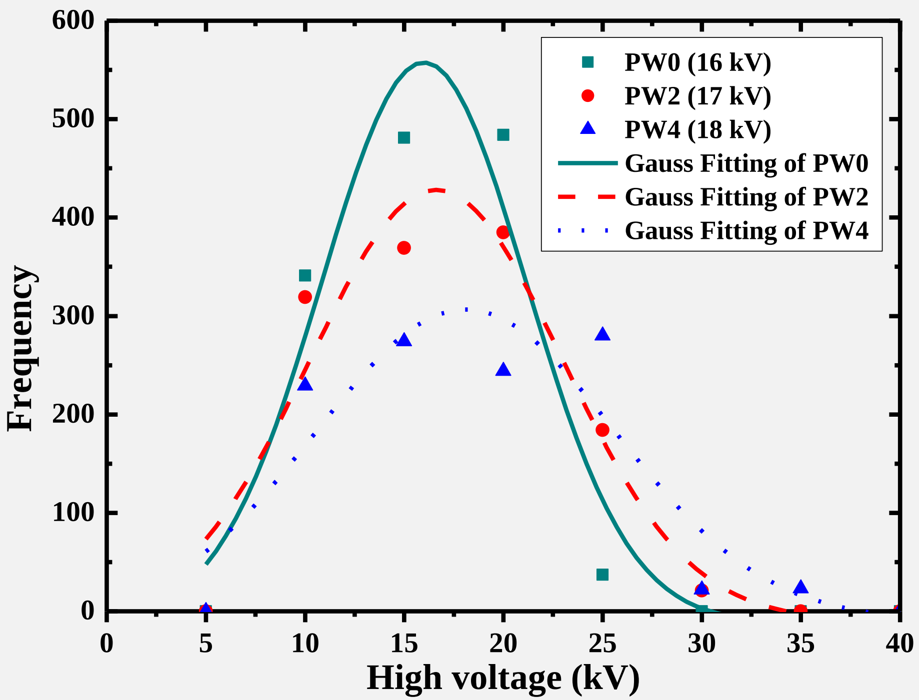
- ❑ The desired output voltage can be obtained by regulating (1) electrode distance or (2) output power on the induction coil.

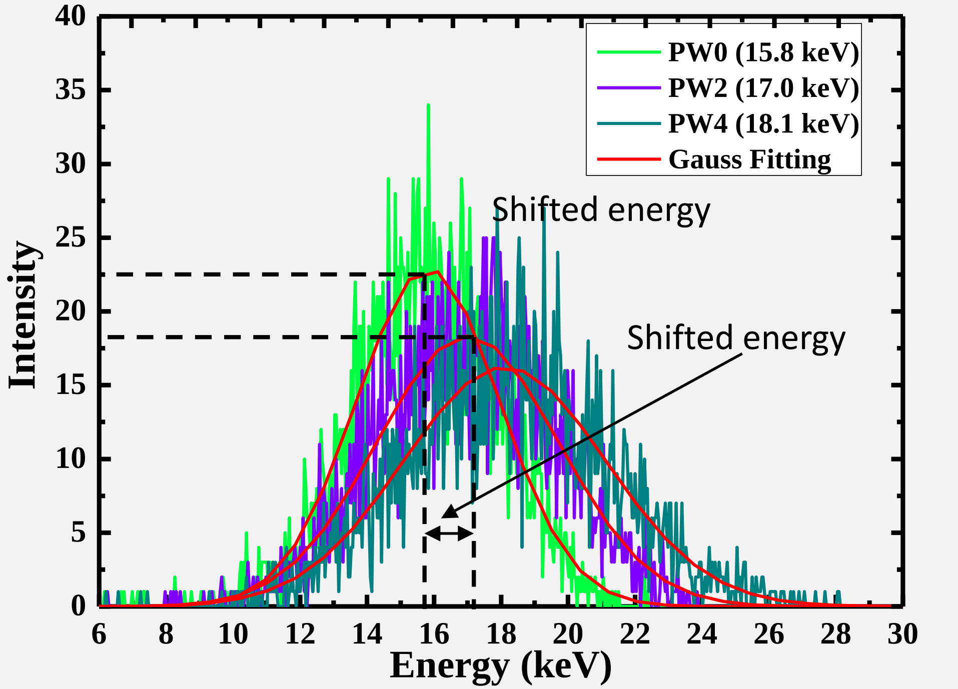
(1) The electrode distance ranges from 10 to 100 mm. Each of the distances limits a maximum voltage to the Crookes tube.

(2) The output power controller (PW) has twenty-one scales (from 0 to 20). By increasing the output power, the applied voltage will continually increase until a spark occurs to reach the maximum voltage.

- ❑ The nominal dielectric breakdown voltage in the air is approximately 1 kV at 1 mm. For instance, the electrode distance of 35 mm produces a maximum voltage approximately of 35 kV.

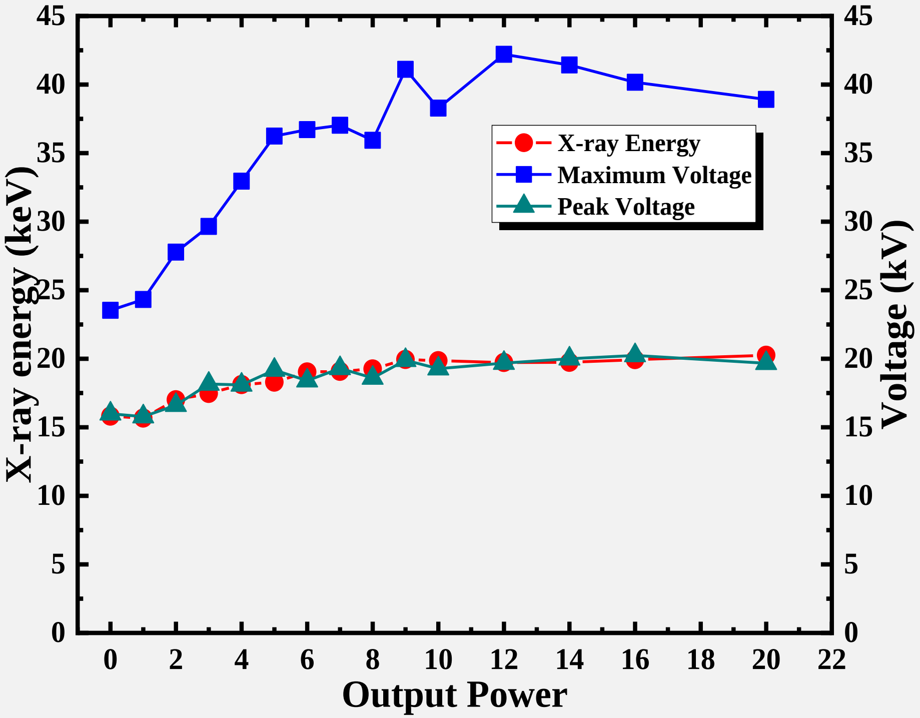
EFFECT OF CHANGES IN APPLIED VOLTAGE





- ❑ Electrode distance was fixed at 40 mm, and output power controlled from 0 to 20.
- ❑ The applied voltage in pulsed-shape created pulsed radiation.
- ❑ X-ray energy spectrum had a broadened distribution due to heterogeneous radiation and Bremsstrahlung photons.
- ❑ X-ray energy was shifted to higher region in the spectrum with increasing HV.
- ❑ The results indicated a good correlation in the distribution behavior between the X-ray energy spectrum and the applied voltage.

CORRELATION BETWEEN APPLIED VOLTAGE AND X-RAY ENERGY



The relevant graph of the applied voltage and the spectral distribution corresponding to the output voltage distribution from PW0 to PW20.

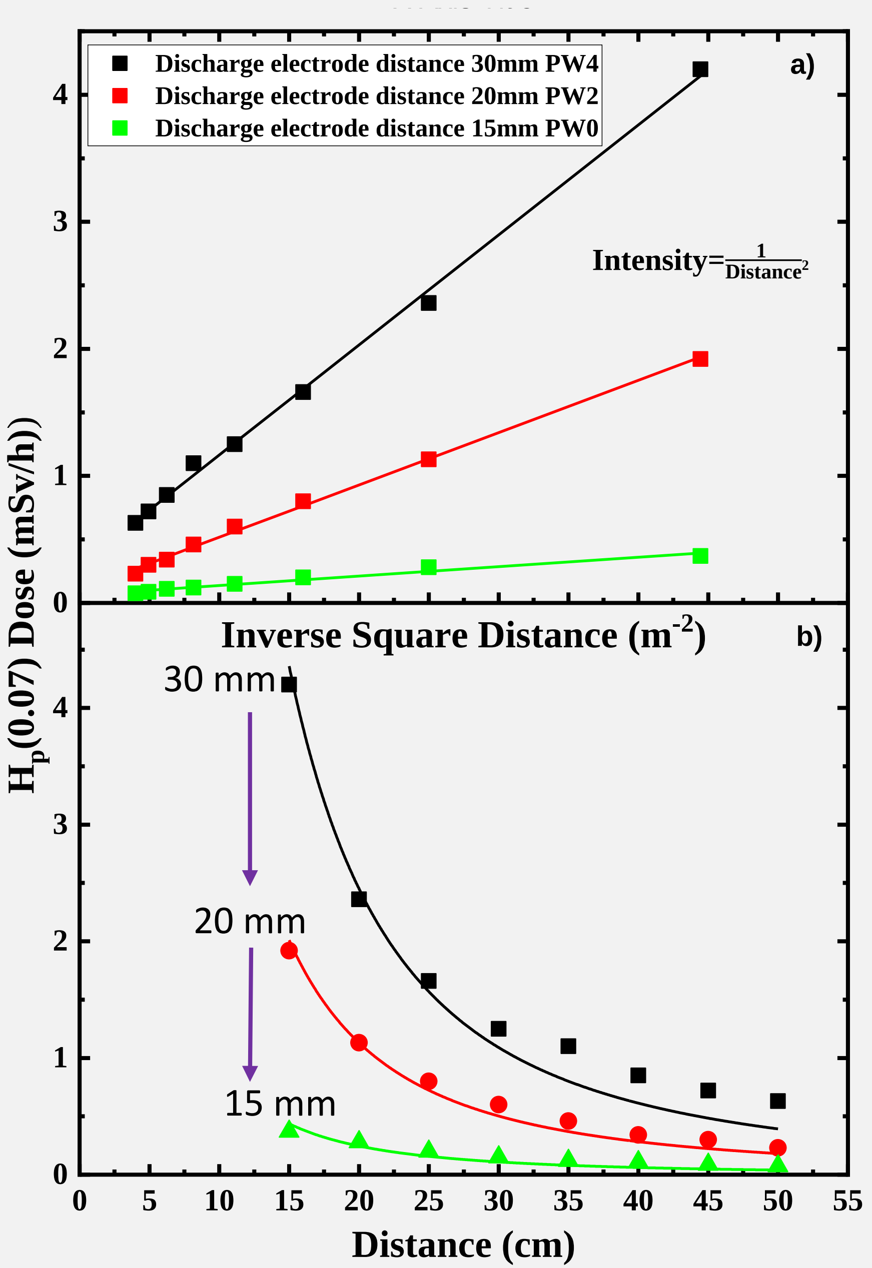
- ❑ X-ray energy and applied voltage kept stability when a spark occurred.
  - ○ Effective energy was approximately 20 keV.
  - ○ The maximum operating voltage was roughly 40 kV that matched the nominal voltage at electrode distance of 40 mm.
- ❑ There was a good agreement between the peak energy of X-rays and the peak voltage.

OPTIMIZATION OF OPERATING CONDITIONS TO REDUCE THE DOSE

- ***Distance***
- ***Shielding***
- ***Time***
- ***Current***
- ***Applied voltage***

ALARA principle (Distance, Shielding, Time)

EFFECT OF DISTANCE ON DOSE



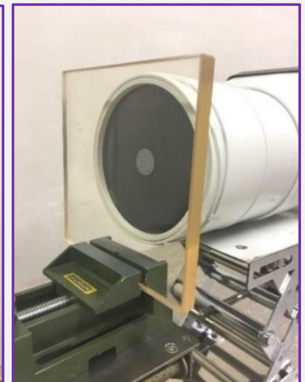
Experimental settings:

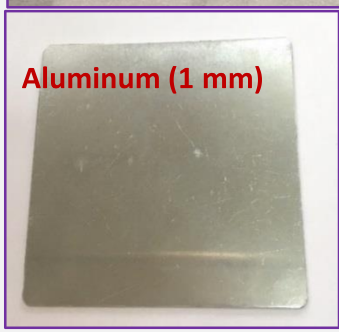
- Electrode distance at 15 mm, 20 mm, and 30 mm.
- Glass badge dosimeters (type-FX, Chiyoda Technol) were put at a distance from 15 to 50 cm.
- The $H_p(0.07)$ equivalent dose measured in 10 min, then it was converted to dose rate per hour.

- The output power was set at which spark just occurred.
- Dose decreased with distance as the inverse square law. At a distance of 1 m, dose was declined to 1/100 from that of 10 cm.
- Dose decreased significantly with the voltage limitation (electrode gap). It should be fixed the gap shorter than 20 mm during a demonstration.

EFFECT OF SHIELDING ON DOSE

Transmission measurement





The Lambert-Beer law:

$$I = I_0 \, e^{-\mu x}$$

μ: Linear attenuation coefficient

I_0: Initial intensity

I: Transmitted intensity

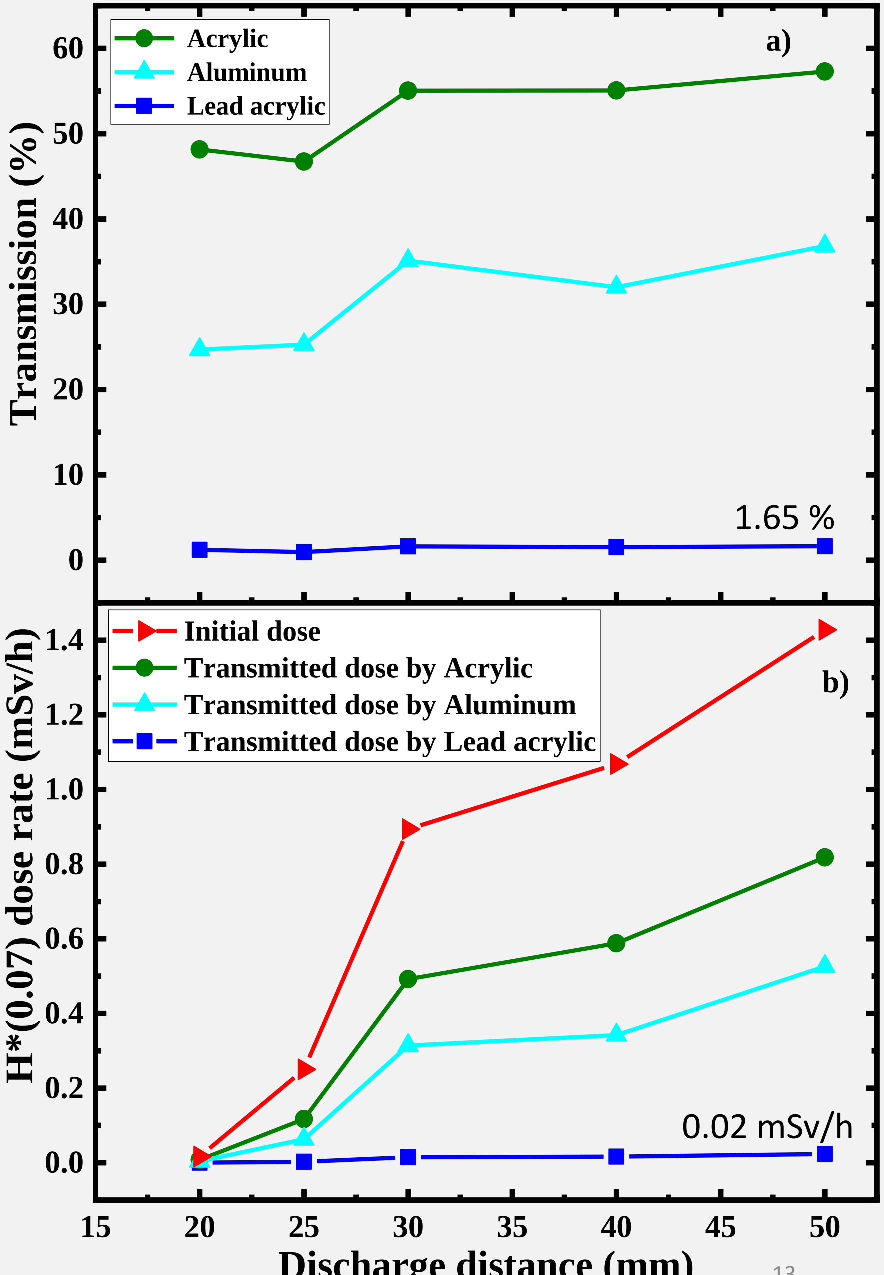
x: Thickness of an attenuator

- For teaching science, shielding materials should ensure radiation safety and demonstration observation for students.
- Transparent shielding materials:
  - **Lead acrylic**: 0.3 mm lead equivalence, Kyowaglas-XA H-8, KURARAY Co., LTD.
  - **Acrylic**: 9.9 mm, Amersham Pharmicia Biotech LTD.
  - **Pure aluminum**: 99.5%, A1050
- The transmission of X-rays was estimated by the ambient dose equivalent H*(0.07) using an ionization chamber (ICS-1323, Hitachi Ltd., Japan).

EFFECT OF SHIELDING ON DOSE

Experimental settings:

- Electrode distance was fixed at 20 mm, 25 mm, 30 mm, 40 mm, and 50 mm.
- For each electrode distance, the output power was set at the position that the spark just occurred.
- H*(0.07) dose measured for 3 min at a distance of 50 cm.

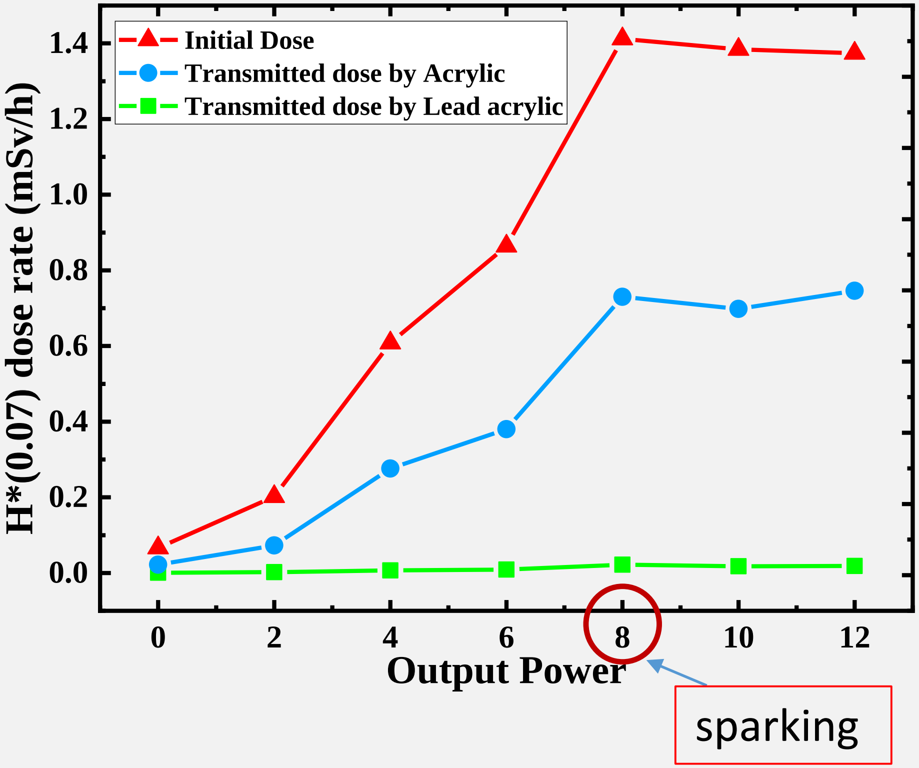


- The percentage of transmission was calculated as a ratio of initial dose to transmitted dose.
- The transmitted dose of acrylic is higher than aluminum. It caused a higher transmission for acrylic.
- Lead acrylic predominated in radiation absorption with the transmission of less than 2%.

EFFECT OF OUTPUT POWER ON DOSE

Experimental settings:

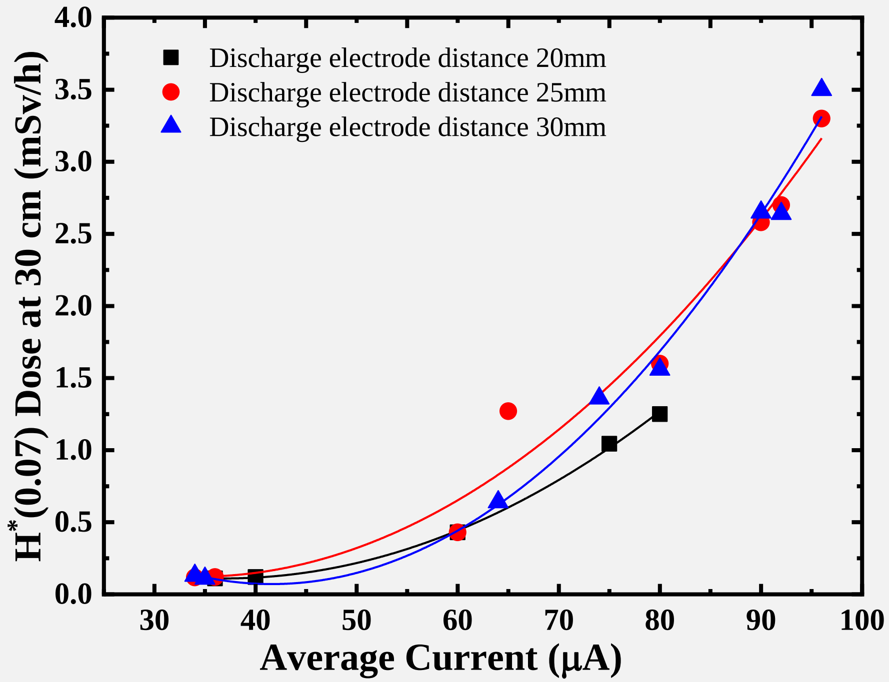
- ❑ Electrode distance at 30 mm.
- ❑ Changing output power.
- ❑ H*(0.07) dose measured for 3 min at a distance of 50 cm.

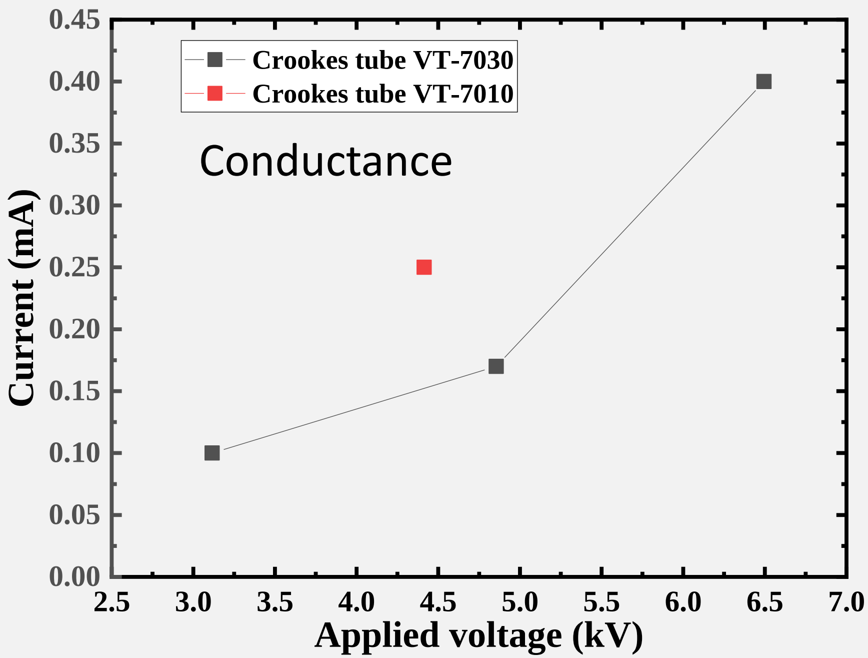


- ❑ The output power increased energy and HV.
- ❑ The dose was proportional to the output power which control applied voltage.
- ❑ Therefore, output power must be kept as small as possible.
- ❑ Dose and energy kept stability when the spark occurred on the induction coil.

Output Power	Peak energy of X-ray (keV)	Initial dose (μSv)	Transmitted dose (μSv) Lead acrylic	Acrylic
0	16.4	3.31	0.04	1.10
2	17.5	10.1	0.11	3.65
4	18.1	30.4	0.34	13.8
6	18.0	43.2	0.45	19.0
8	18.6	70.6	1.09	36.5
10	18.6	69.2	0.89	34.9
12	18.4	68.7	0.92	37.3

EFFECT OF CURRENT ON DOSE



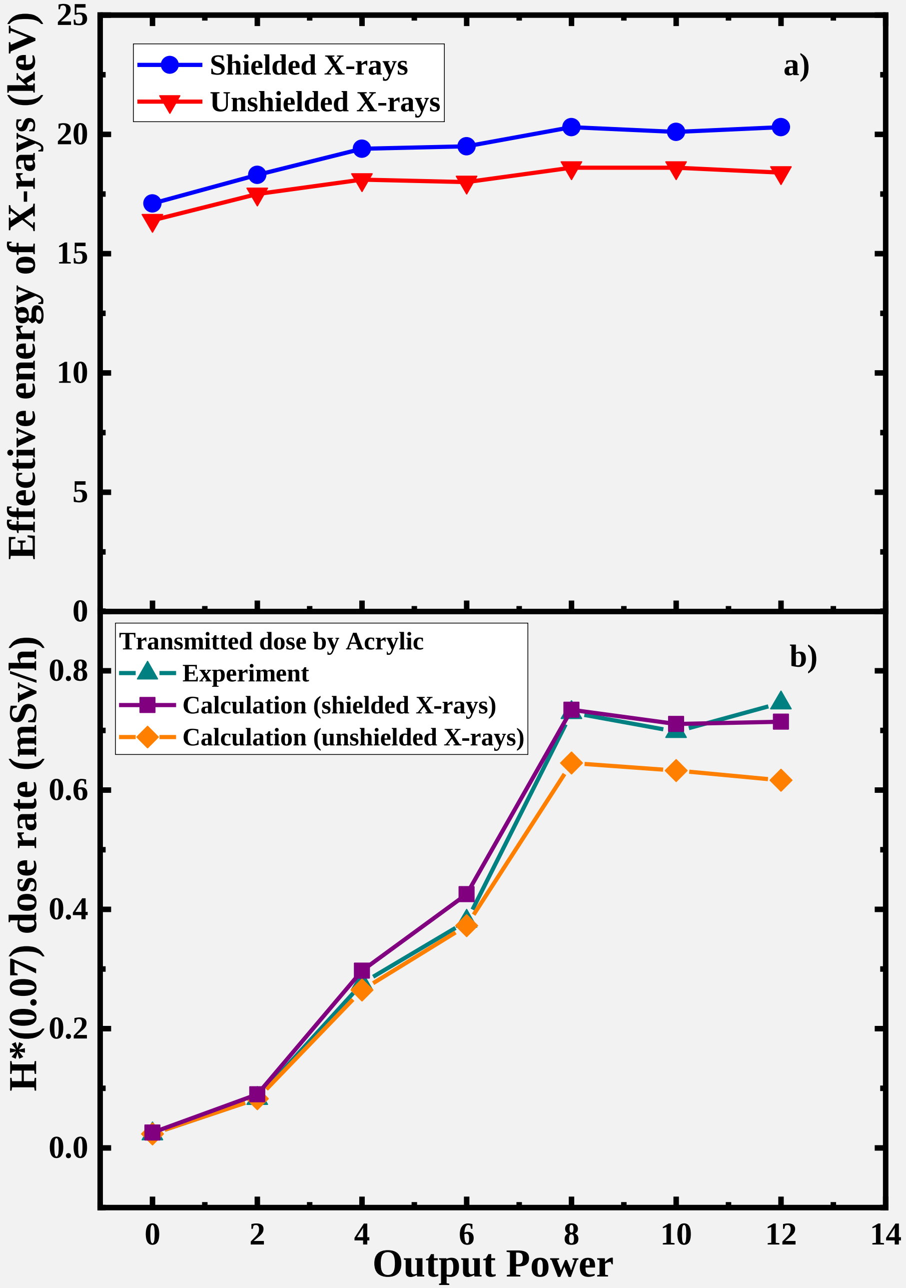


- Increasing current caused increasing dose exponentially.
- At the electrode distance of 20 mm, the spark becomes intense at PW4 then it keeps stability.
- Whether the transmissivity of glass (forming the Crookes tube itself) changed the dose exponentially.
- Some new Crookes tubes releasing a large current at a low voltage expose very low leakage dose or complete elimination.
- Current releases from 0.1 to 0.45 mA, and the voltage applied from 3.1 to 6.5 kV.

ESTIMATE OF X-RAY ENERGY USING TRANSMISSION MEASUREMENT

- ***Lead acrylic attenuators***

TRANSMISSION IN ENERGY ESTIMATION



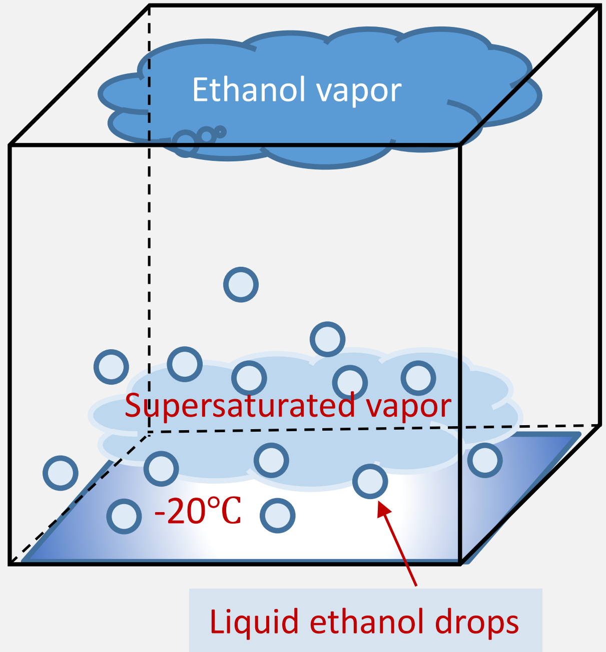
- ❑ The acrylic shielding caused hardening of X-rays owing to absorbing photons with lower energy. As a result, it produced a difference in the energy of X-rays, 7.4%.
- ❑ The calculation of transmitted dose was based on Lambert-Beer equation.
- ❑ The linear attenuation coefficient μ of acrylic for each energy was interpolated using data from the National Institute of Standards and Technology (NIST, USA).
- ❑ For shielded X-rays, calculation matched well experiment with a difference of 5%.
- ❑ For unshielded X-rays, calculation was smaller than the experiment roughly 6.6%.
- ❑ Transmission might be considered as a relatively precise approach to measure X-ray energy substituting for other complicated methods.

SIMULATION OF X-RAY ENERGY SPECTRUM USING A CLOUD CHAMBER

- ❑ ***Radiation tracks observation***
- ❑ ***Simulation of X-ray energy spectrum***

WHAT IS A CLOUD CHAMBER?

- ❑ A high-performance "fog box" used a Peltier-cooler to drop the temperature.
- ❑ To support students to visualize radiation interaction in radiological education.

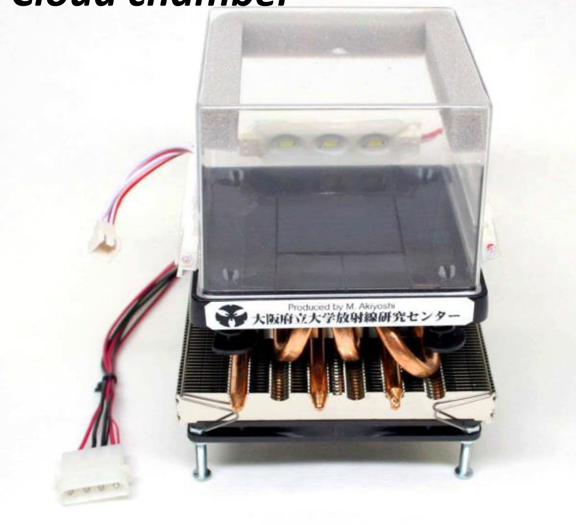


High vapor pressure at high temperature

↓

A saturation vapor pressure decreases at low temperature

Cloud chamber

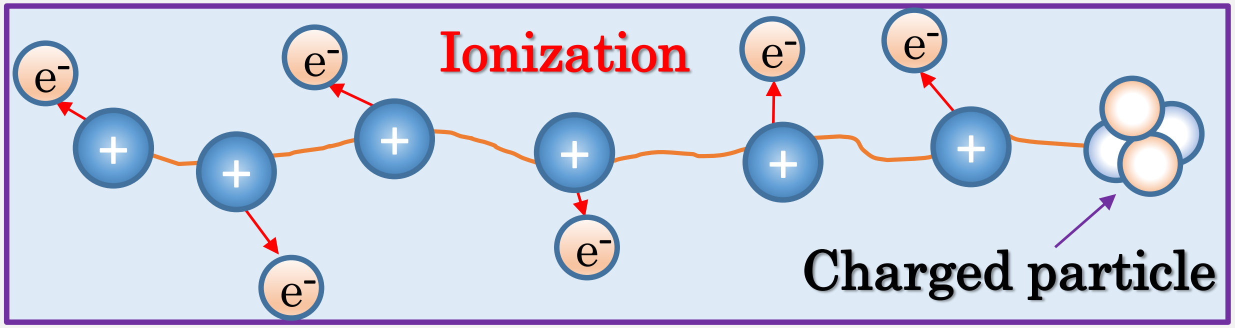


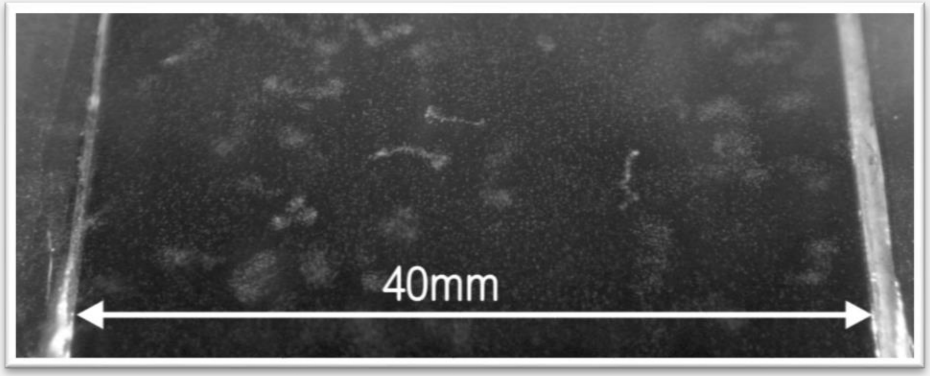
Cooled by a Peltier device to less than -20℃

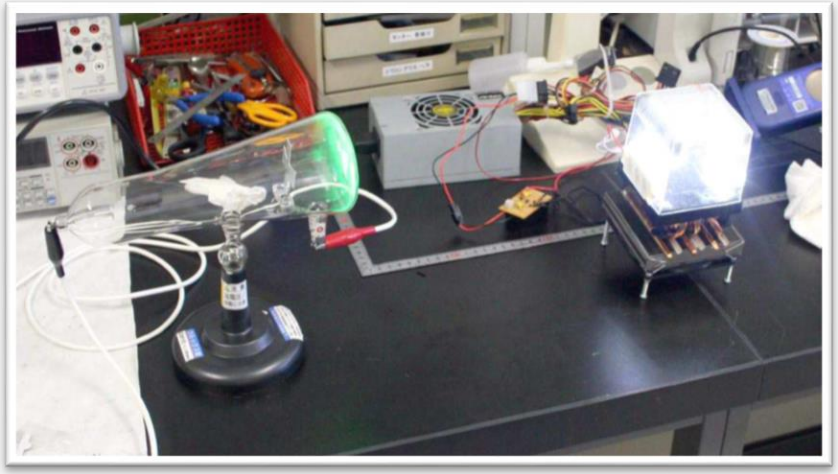
- ❑ At room temperature, vapor pressure of ethanol is relatively high.
- ❑ Ethanol vapor gets cold at bottom of the chamber, and then a saturated vapor pressure decreases.
- ❑ The vapor comes to supersaturated condition.
- ❑ At less than -20℃, small stimulation makes the supersaturated vapor to tiny liquid drops.

MECHANISM OF A CLOUD CHAMBER

- Charged particle travels through the air and repels many electrons from atoms to form positive and negative ion pairs (ionization).
- These ions are formed in supersaturated ethanol vapor as a core of small liquid particles.
- Many of the particles of this liquid are formed after the radiation passed, so the radiation trace is observed as a white line.

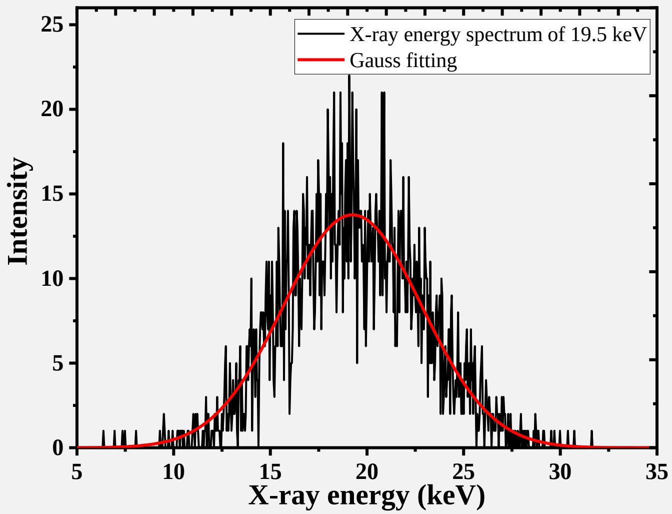






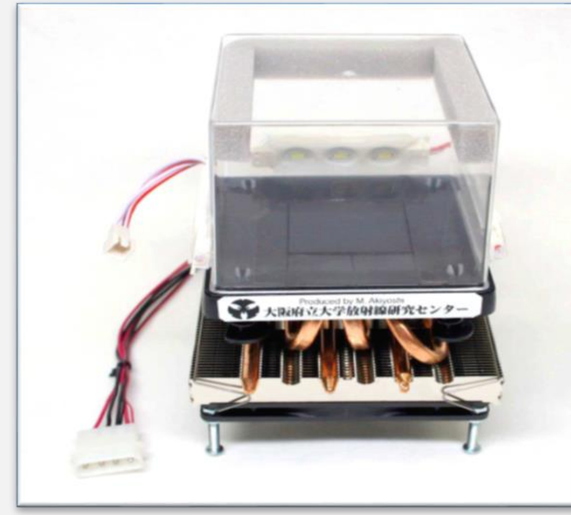
- The cloud chamber can observe not only alpha particles but also beta particles, and X-rays irradiated from a Crookes tube.
- Basing on the correlation between X-ray track length and X-ray energy, the cloud chamber was applied to simulate the X-ray energy spectrum from the Crookes tube.

X-RAY ENERGY SPECTRUM SIMULATION BY A CLOUD CHAMBER



A camera attached outside the cloud chamber.

1



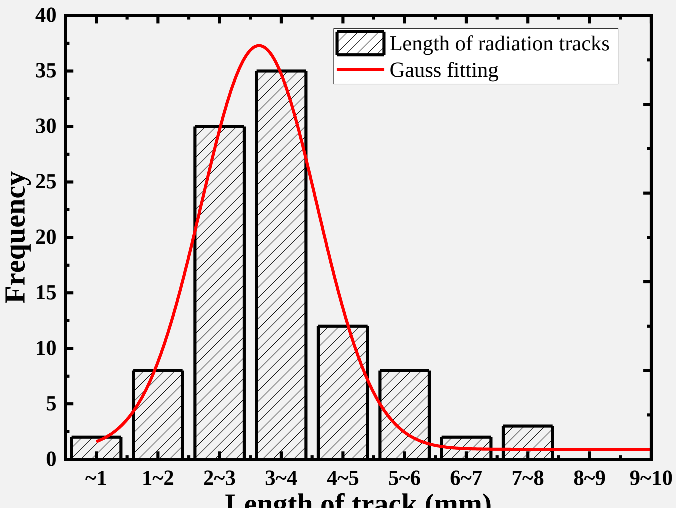
A low energy electron of 20 keV travels a mean free path approximately 8.1 mm in the air (density of air at 20^0C) (*ICRU 37*).

2

Image analysis of the length of radiation track.

4

The correlation between the X-ray spectrum and simulating spectrum.



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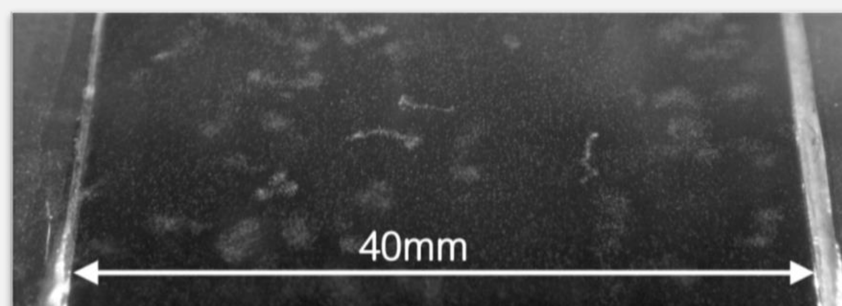
Counting length of radiation tracks to build the spectrum.



The mean free path of X-ray energy of 20 keV is approximately 3.6 mm in cloud chamber.

SUMMARY

- Properties and characteristics of X-rays emitted by Crookes tube:
  - X-rays emitted with soft energy of approximately 20 keV.
  - The exposure and X-ray energy changed with electrical settings such as output power, and electrode distance.
- Optimizing in operations:
  - Set output power as low as possible.
  - Never remove discharge electrodes.
  - Set the distance shorter than 20 mm.
  - Take distance as far as possible. For student, more than 1 m is recommended.
  - Keep the demonstration time shorter than 10 min.
- Cloud chamber is practical in radiation tracks observation for student.
- X-ray energy spectrum might be stimulated by a cloud chamber.
- According to ICRP 36, the dose limit recommended 0.05 mSv per each teaching exercise. The lead acrylic shield was well-suited to radiation safety for the Crookes tube.

THANK YOU FOR YOUR ATTENTION