RADIATION RESEARCH CENTER MEETING

OPU - 2018, November 27th

INVESTIGATION OF LOW ENERGY X-RAY RADIATED FROM CROOKES TUBE USED IN RADIOLOGICAL EDUCATION

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How Is a Crookes Tube Used for Teaching of Science?

BACKGROUND

2008

The radiological education guideline has been added to the school's curricula by MEXT*.

March, 2011

Fukushima nuclear accident occurred.

Oct., 2011

MEXT accomplished the radiation education materials.

2014

The supplemental reading documents included the accidental information have been published (MEXT).

Crookes tube has been used in the teaching of science at a junior and high school in Japan.

X-ray radiation is possible exposure to a teacher who conducts the demonstrations and experiments as well as participated students.

It was reported in Japan that the X-ray radiated from the Crookes tube had very low energy (about 20 keV) but the dose was very high (up to several hundred mSv/h)[1)] .

It is necessary to accomplish the radiation protection and safety guideline that have not been evaluated sufficiently yet in Japan.

OBJECTIVES

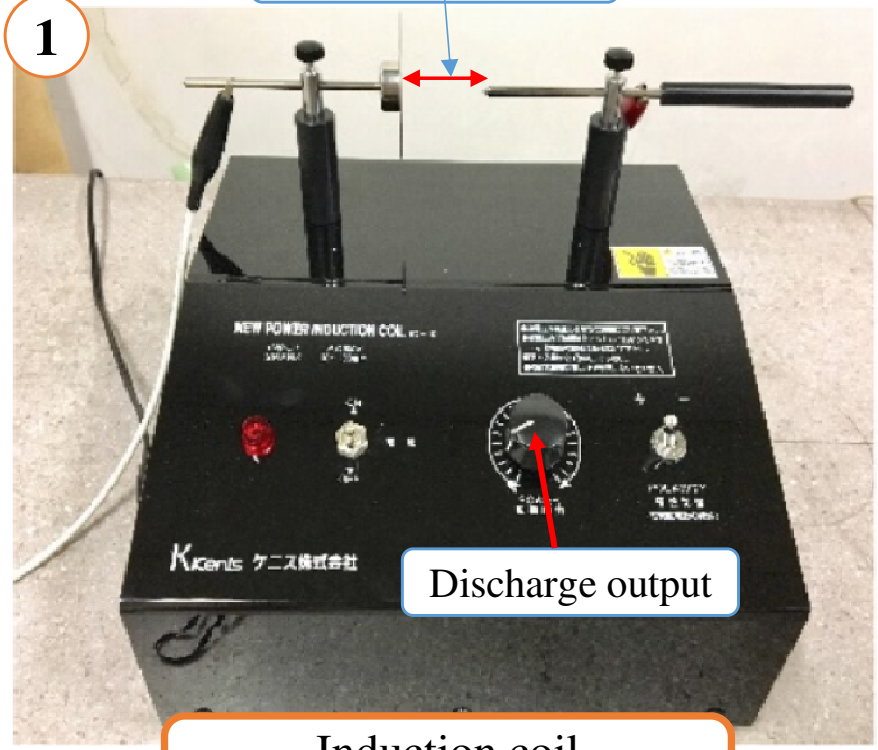
- ❑ Conducting an initial evaluation of the characteristics and properties of X-ray beam radiated from the Crookes tube used in the junior-high school for educational science.
- ❑ Developing the system that actually can be used in measurement of low energy X-rays.
- ❑ Submitting the results as the recommendation and guideline for radiation protection rules to prevent unwanted harmful effects from radiation.

1. Ohmori Giroh (1995). X-ray exposure in the teaching of science at junior and senior high schools. *NIRS-M—105*, Japan, 107-112.

**Ministry of Education, Culture, Sports, Science, and Technology*

What Is a Crookes Tube?

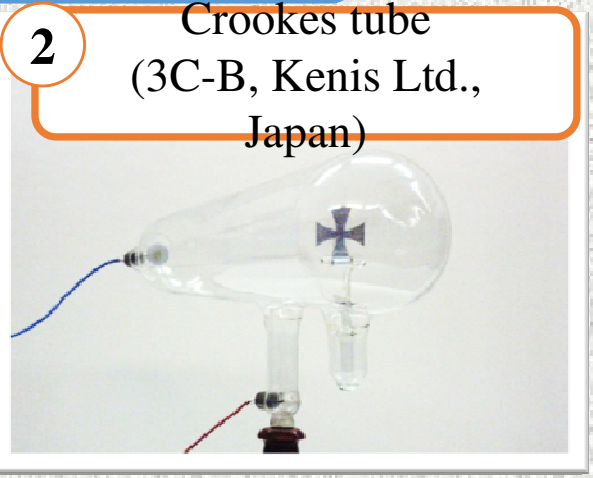
1

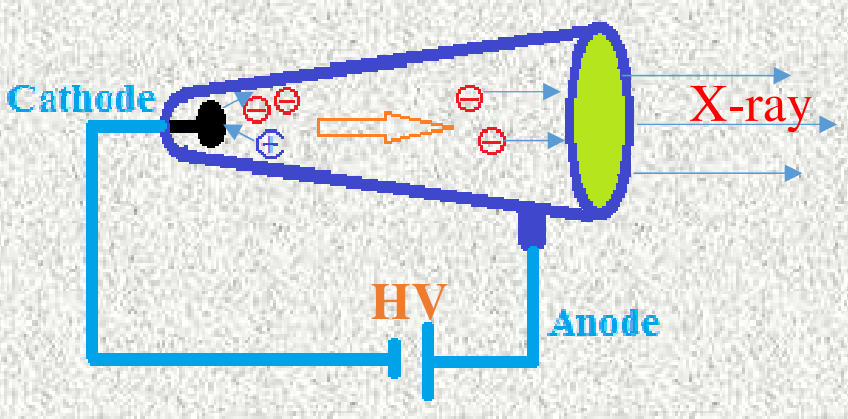


Induction coil
(ID-10, Kenis Ltd., Japan)

2

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





Induction coil:

- The range of spark gap is 10 – 100 mm.
- The nominal dielectric breakdown voltage in the air is about 1 kV at 1 mm,
- The desired output voltage can be obtained by regulating the distance of the discharge electrodes or discharge output (0 to 20) .
- In this experiment, the discharge distance was set at 40 mm, and variable applied voltages were controlled by change of discharge output from 0 to 20 (denoted by PW0 to PW20) in scale.

MATERIALS AND METHODS

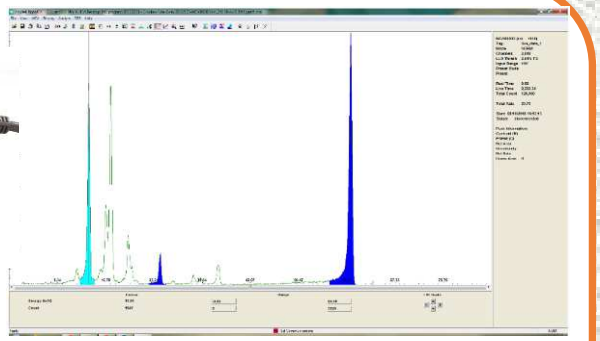
X-ray Spectrometer

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

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

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

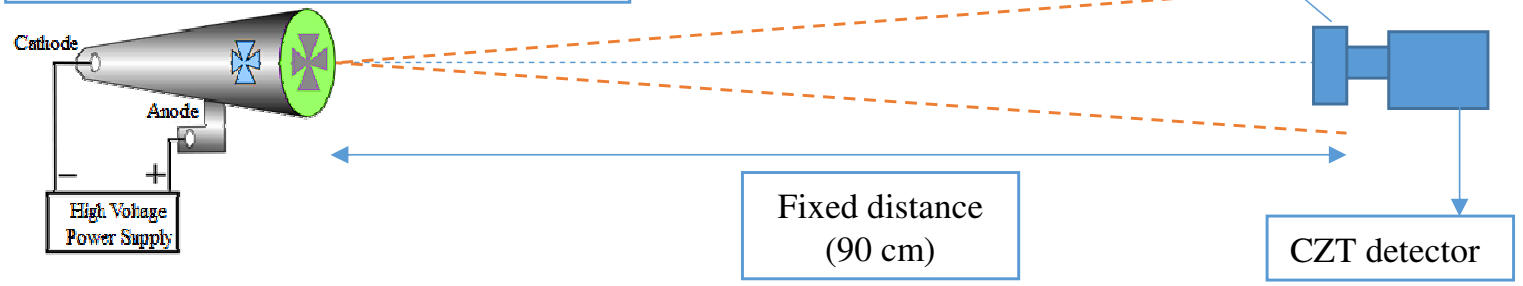
Pocket Multichannel (MCA8000D, Amptek Inc., USA)

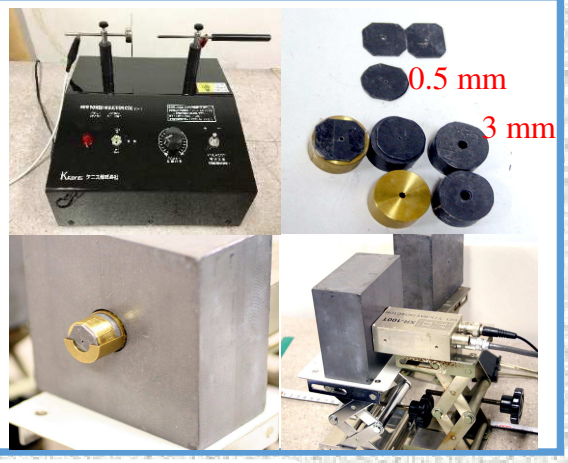


DPPMCA Software (Amptek Inc., USA)

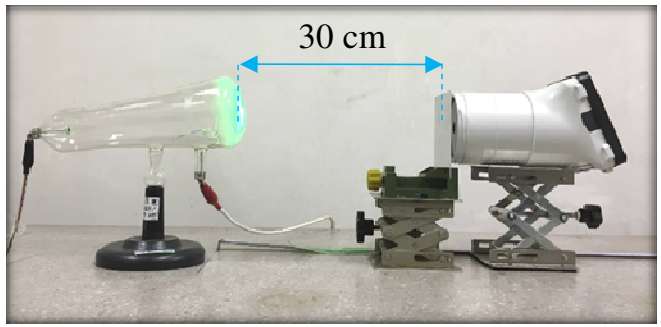
X-ray spectrum measurement

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





Transmission measurement



Aluminum layers 0.5 ÷ 6 mm in thickness

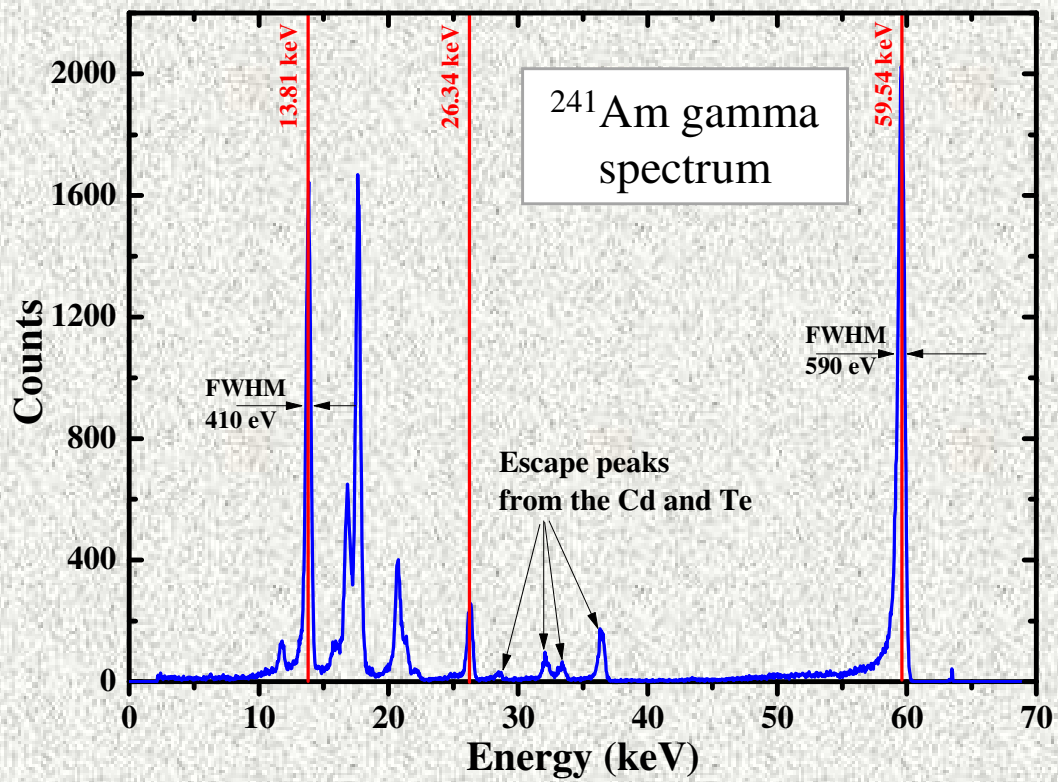
HV distribution

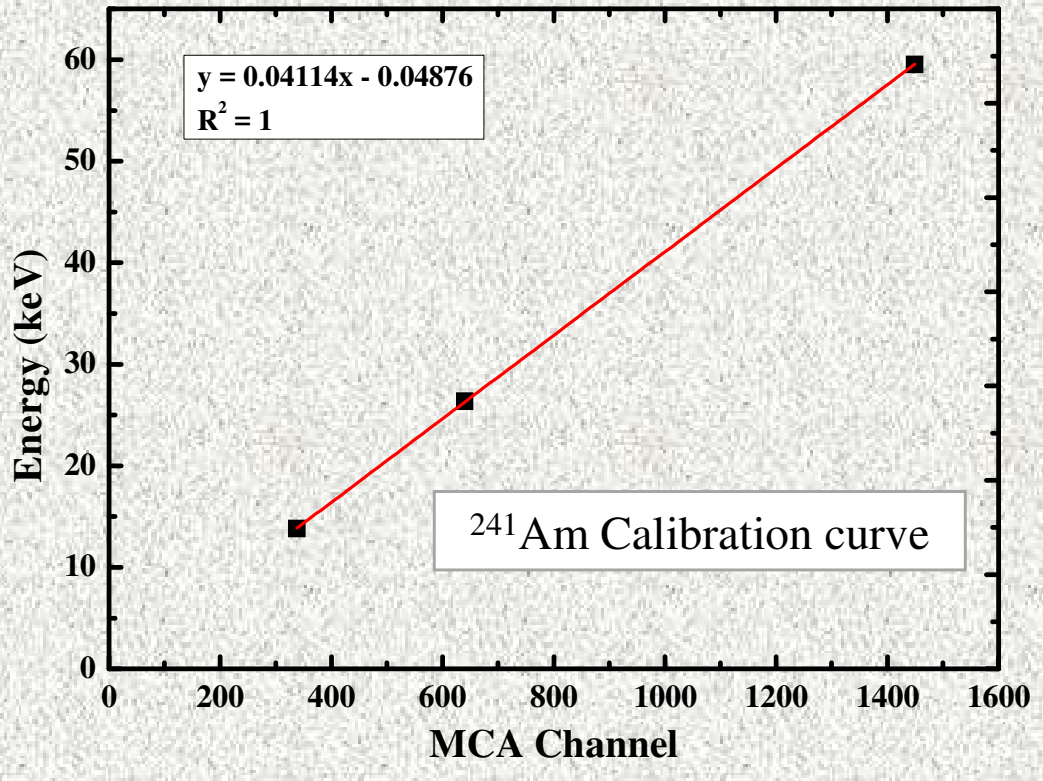
PC USB Oscilloscope (6000BD, Hantek Ltd.)

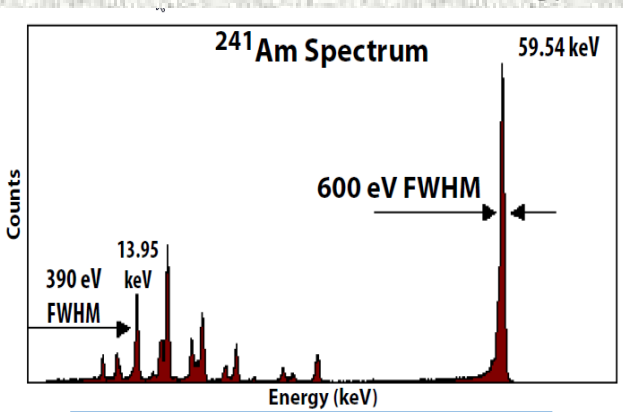
Voltage divider 500 MΩ + 100 kΩ

RESULTS AND DISCUSSION

CZT DETECTOR CALIBRATION







Spectrum from the manufactory (Amptek)

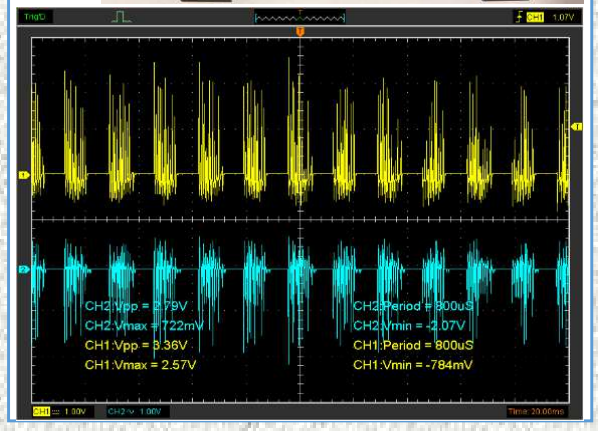
- The spectrometer is good energy resolution and accurate, so it adapted well to low energy X-ray measurement.
- The standard calibration spectrum was established using a ^{241}Am standard source with three main energies 13.81 keV, 26.34 keV, and 59.54 keV.
- The X-ray energy (keV) was determined basing on the calibration spectrum.

APPLIED VOLTAGE MEASURMENT

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**.

PC USB Oscilloscope (6000BD, Hantek Ltd.)



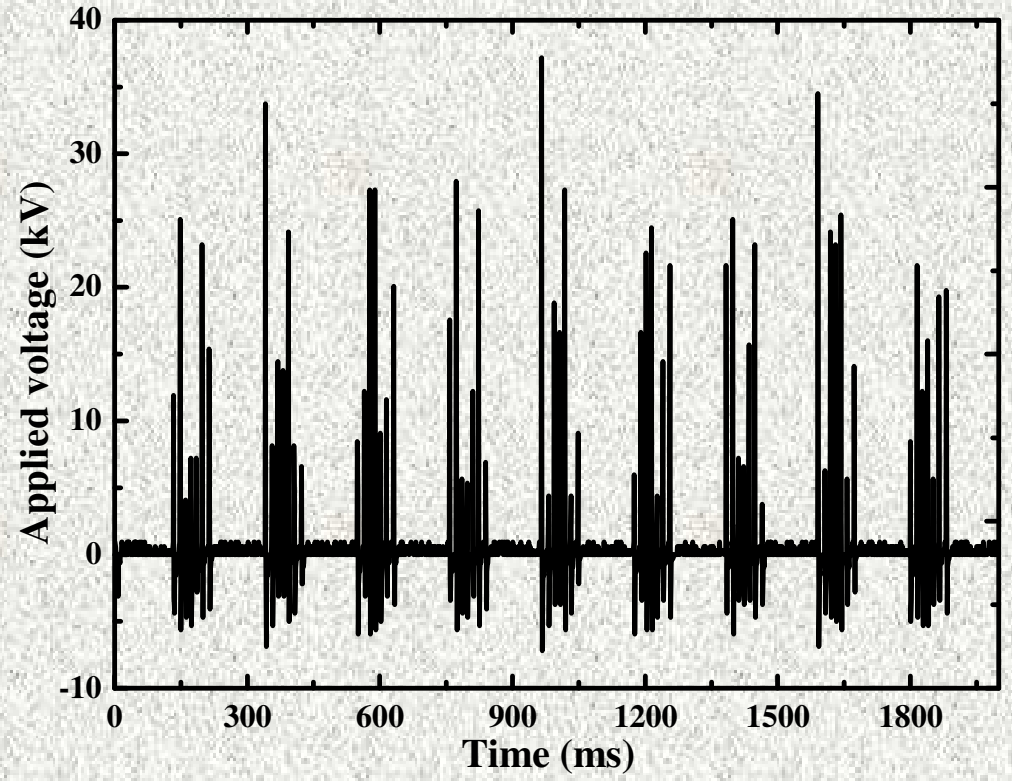


Figure 1. The high voltage pulse was observed by the oscilloscope with a buffer length of 32K, and a Time/DIV of 20 ms.

The output-signal was counted to show the distribution of applied voltage.

X-RAY SPECTRUM AND APPLIED VOLTAGE DISTRIBUTION

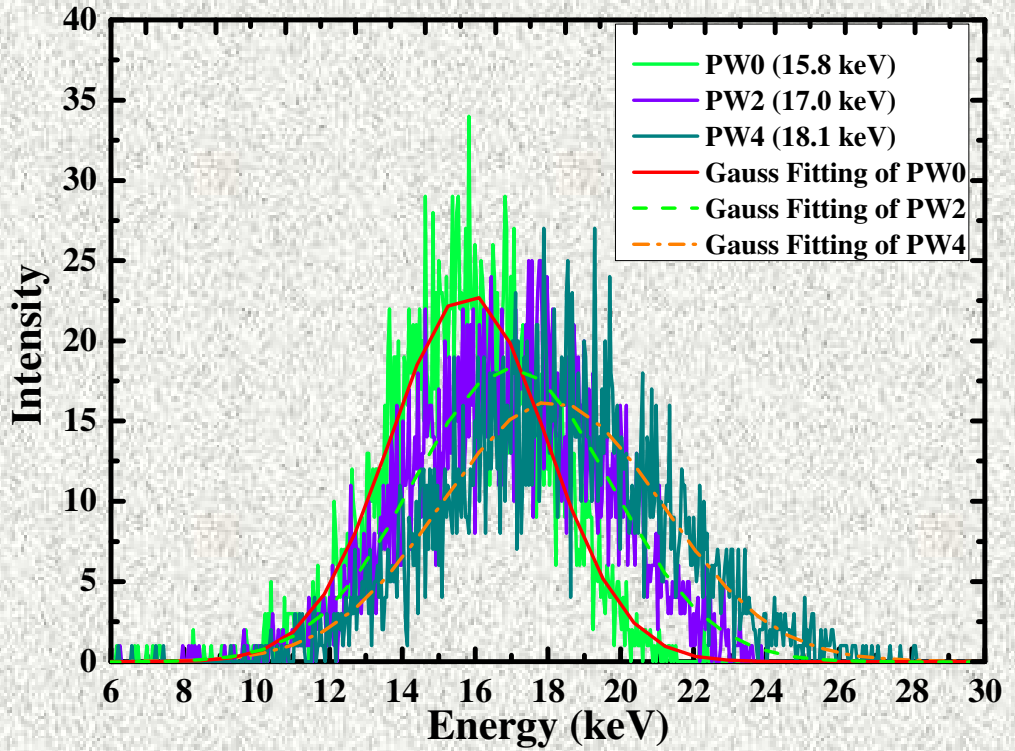


Figure 2. X-ray spectra radiated from Crookes tube acquired by CZT detector. Each X-ray spectra corresponds to output power of PW0, PW2, and PW4.

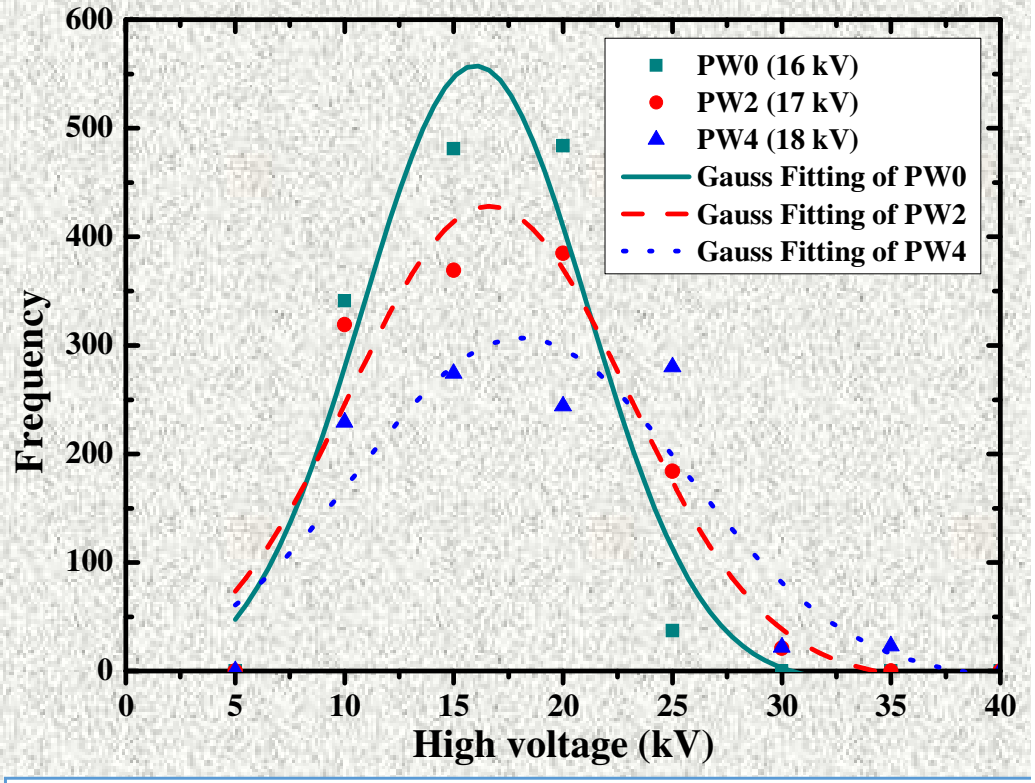


Figure 3. The distribution of applied voltage shows the increase in the output voltage of PW0, PW2, and PW4.

Correlation between applied voltage and X-ray energy:

- There was a good correlation in the distribution behavior between the X-ray spectrum and applied voltage.
- With the output voltages of PW0, PW2, PW4:

  The X-ray energies were **15.8 keV**, **17.0 keV**, and **18.1 keV**, respectively.

  The average voltages were **16 kV**, **17 kV**, and **18 kV,** respectively.

THE CORRELATION IN THE DISTRIBUTION OF X-RAY SPECTRUM AND APPLIED VOLTAGE

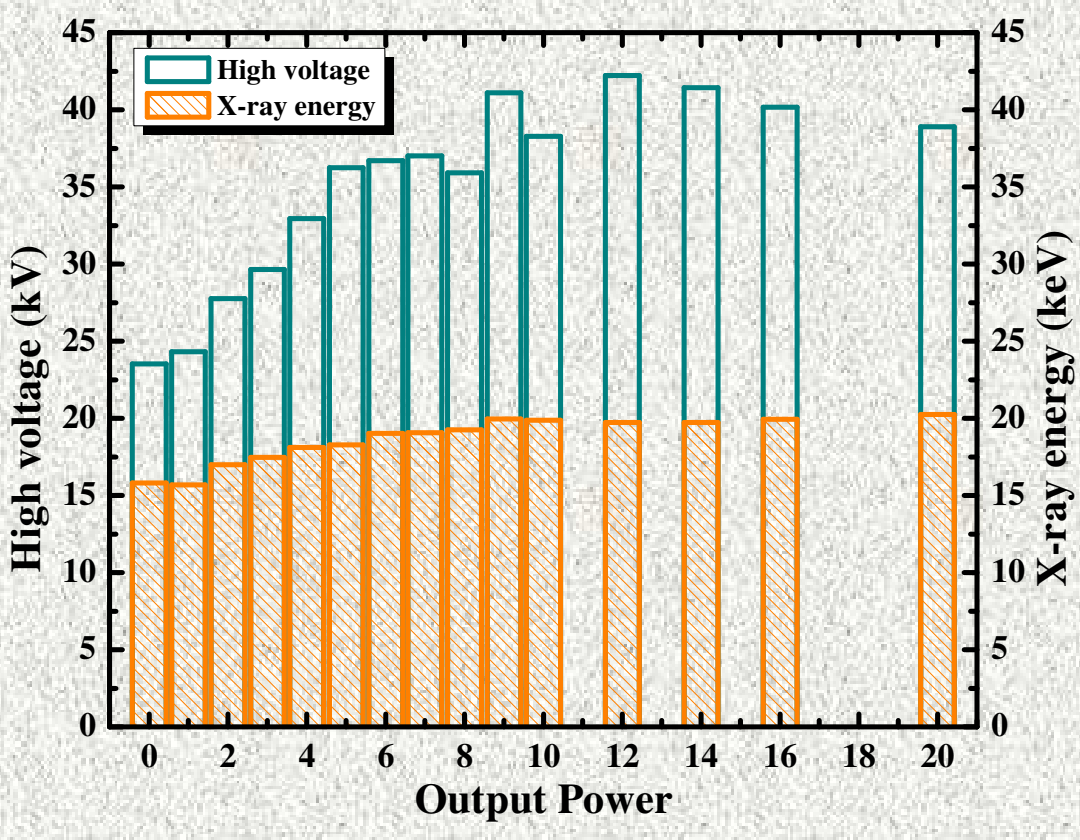
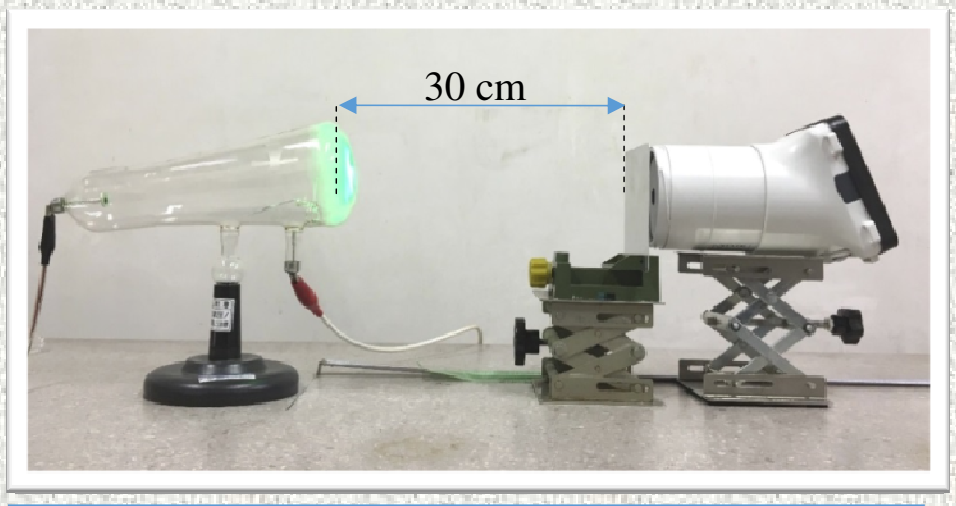


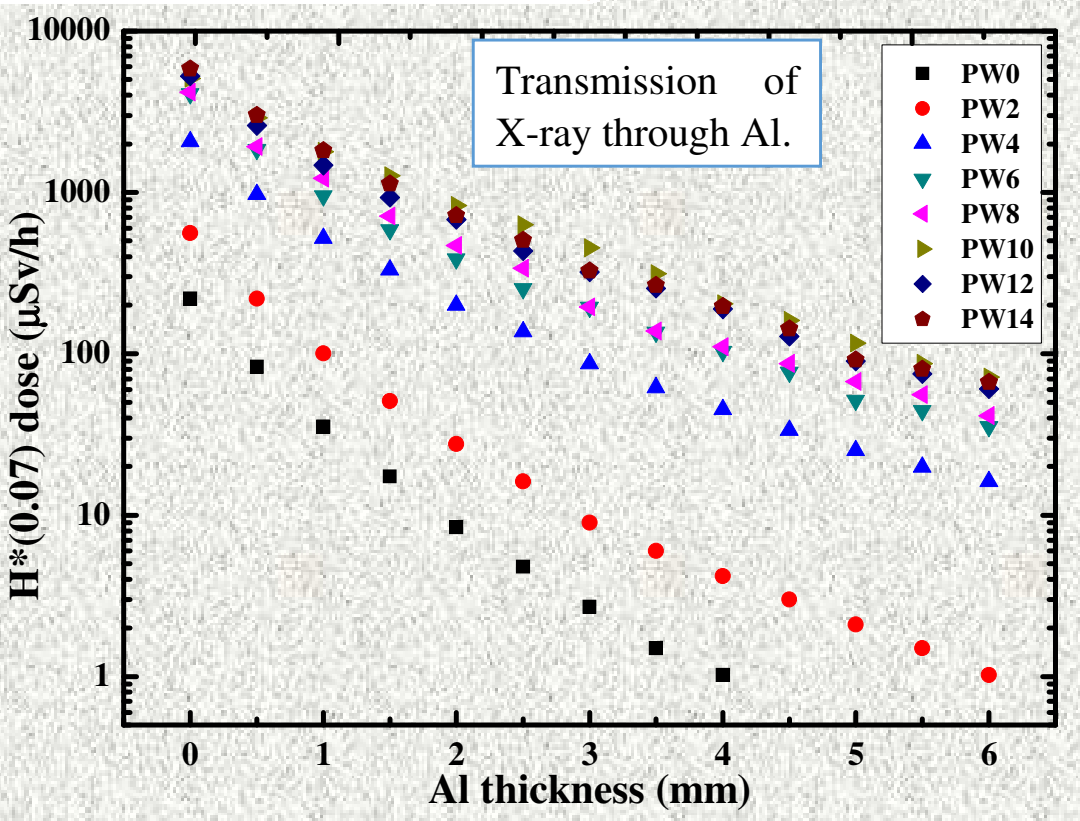
Figure 4. The relevant graphic of the applied voltage and spectral distribution corresponding to output voltage from PW0 to PW20.

Correlation between applied voltage and X-ray energy:

- The output voltage distributed increasingly in 23.5 ~ 38.9 kV along with increasing output power.
- A spark appeared at PW9 then the output voltage kept relatively consistent.
- The actual average operating voltage was about 40 kV that shows good agreement with the nominal discharge voltage at 40 mm of plate-needle distance.
- The spectral distribution changed in 15.8 ~ 20.3 keV corresponding to the applied voltage change.
- With the consistency of applied voltage, the X-ray energy also showed saturation at PW9 (applied voltage reaches 40kV) with an average energy of about 19.5 keV.

ESTIMATION OF THE TRANSMISSION





- Linear attention coefficient:

$$= {}_{0}{}^{-\mu x}$$

μ: Al linear attention coefficient
I_0: Initial intensity
I: Transmitted intensity through Al layers
x: Al thickness

- Monitoring with Al thickness range from 0.5 mm to 6 mm, step of 0.5 mm.

- The transmission curve was fitted with the linear expression of $\ln(I) = -\mu x + \ln(I_0)$.
- The slope of the graph is the Al linear attenuation coefficient (μ) with the best fitting coefficients rather than 0.98.
- The effective energy of X-ray was determined from the linear attenuation coefficient of Al using data from the National Institute of Standards and Technology (NIST, USA) and X-COM program[2].

2. *National Institute of Standards and Technology. Available on http://physics.nist.gov/xcom (Tuesday, 25 September 2018).*

ALUMINUM LINEAR ATTENUATION COEFFICIENT

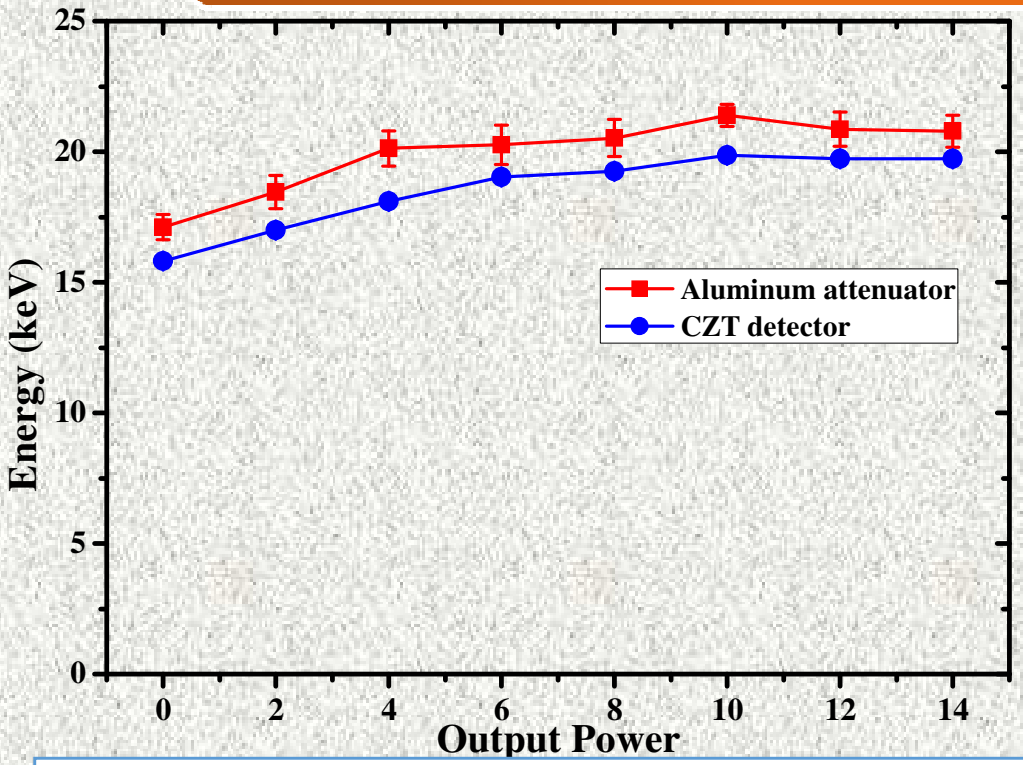


Figure 5. X-ray energies with various output powers obtaining by attenuation measurement and CZT detector.

Table 1. X-ray energy estimated from Al attenuator and CZT detector. The ambient dose equivalent H*(0.07) measured at a distance 30 cm from the Crookes tube.

Output power	H*(0.07) (μSv/h)	μ (cm^{-1})	Energy (keV)	
			Al attenuator	CZT detector
PW0	219	14.58	17.1	15.8
PW2	557	11.70	18.5	17.0
PW4	2064	9.12	20.1	18.1
PW6	4086	8.94	20.3	19.0
PW8	4182	8.62	20.5	19.3
PW10	5070	7.66	21.4	19.9
PW12	5244	8.22	20.9	19.7
PW14	5838	8.32	20.8	19.7

μ: Aluminum linear attenuation coefficient

Relevance of X-ray energy between CZT detector and transmission measurement:

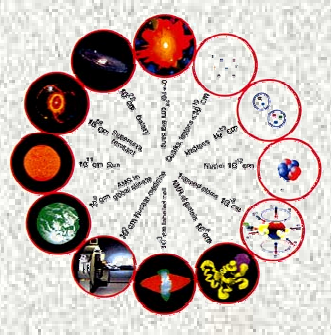
- The effective energy from the transmission measurement was relatively good agreement with the spectra from CZT detector.
- The average percent difference between the two measurements was 7.5%, and the average energy was about 19.5 keV for CZT detector and about 20 keV for attenuation measurement (Table 1).
- Added filtration caused hardening the X-ray beam because it absorbed the lower energy photons. As a result, it produced a shift in the effective energy of the X-ray beam.

SUMMARY

- We estimated low energy X-ray from the Crookes tube with variable voltages that considered hardly to perform. It was about 19.5 keV with the discharge distance of 40 mm.
- We estimated the correlation in distribution between applied voltage and X-ray energy. The X-ray energy was shifted to higher region in the spectrum when increasing the applied voltage.
- We used the attenuation measurement as an effective approach to yield information of low photon energy as well as reflected the change of energy along with the change of output power. It should be considered as an alternative approach of CZT detector in the estimation of low X-ray energy in the teaching of science at junior-high school.

NEXT PLAN

- Estimating the conductance of Crookes tubes.
- Estimating of an effective dose in the relevance to other electrical components and X-ray energy.
- Suppressing an applied voltage to a certain level and evaluate effective dose to assure extremely safe for education.



THANK YOU VERY MUCH FOR YOUR ATTENTION