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Investigation of Characteristics of Low-energy X-ray Radiated from Crookes Tube Used in Radiological Education

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Investigation of Characteristics of Low-energy X-ray Radiated from the Crookes Tube Used in Radiological Education

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Crookes tubes have been used as fundamental equipment for science education in junior-high schools in Japan. However, radiation protection and safety guidelines have not been evaluated sufficiently to date. Estimations of the X-rays radiated from the Crookes tubes under various systematic conditions are required to establish these guidelines. Energy spectrum of the X-rays was obtained by CZT detector with very fine collimator to avoid pile-up effect. The peak energy of the X-rays was about 20 keV, and the most frequent voltage of pulses applied from an induction coil was matched with this peak energy. The correlation between the distribution of the applied voltage and X-ray spectra was obtained in this study. The energy of the X-rays was also estimated by a linear attenuation coefficient of Al plates. The effective X-ray energy estimated by this conventional method showed good agreement with the result obtained by CZT detector.

Key Words: Crookes tube, CZT detector, radiation education, radiation protection, X-ray energy spectrum

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AWARD

OUTLINES

Section 1 General introduction

Section 2 Characteristics of low-energy X-ray radiated from the Crookes tube

Section 3 Dose distribution from the Crookes tube using thermoluminescent dosimeter

Section 4 Conclusions

SECTION 1

General Introduction

- ***What is a Crookes tube?***
- ***Current state of Crookes tube usage***
- ***Exposure to X-ray radiation from a Crookes tube***
- ***Problems on estimate of a Crookes tube***
- ***Crookes tube project***

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

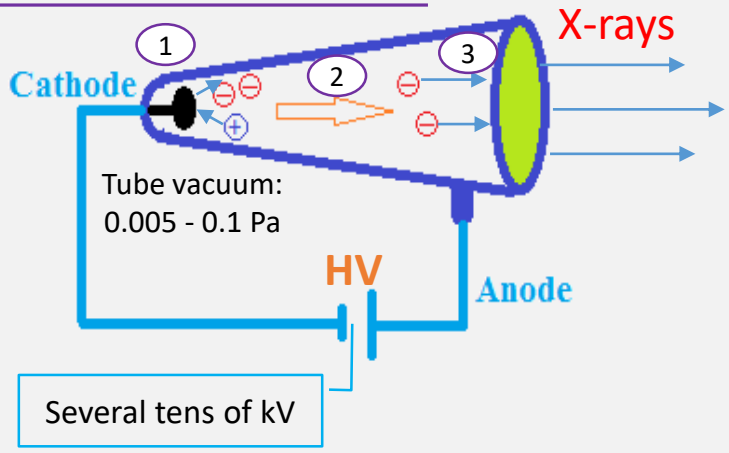
Wilhelm Conrad Röntgen

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.

CURRENT STATE OF CROOKES TUBE USAGE IN JAPAN

Many teachers are demonstrating on Crookes tube in a science class.

Teachers do not know radiation emission from the Crookes tube.

- Teaching of science at junior-high schools.
- Containing information about Crookes tubes in all five science textbooks
- Understanding the nature of the radiation associated with the vacuum discharge (MEXT, 2017).

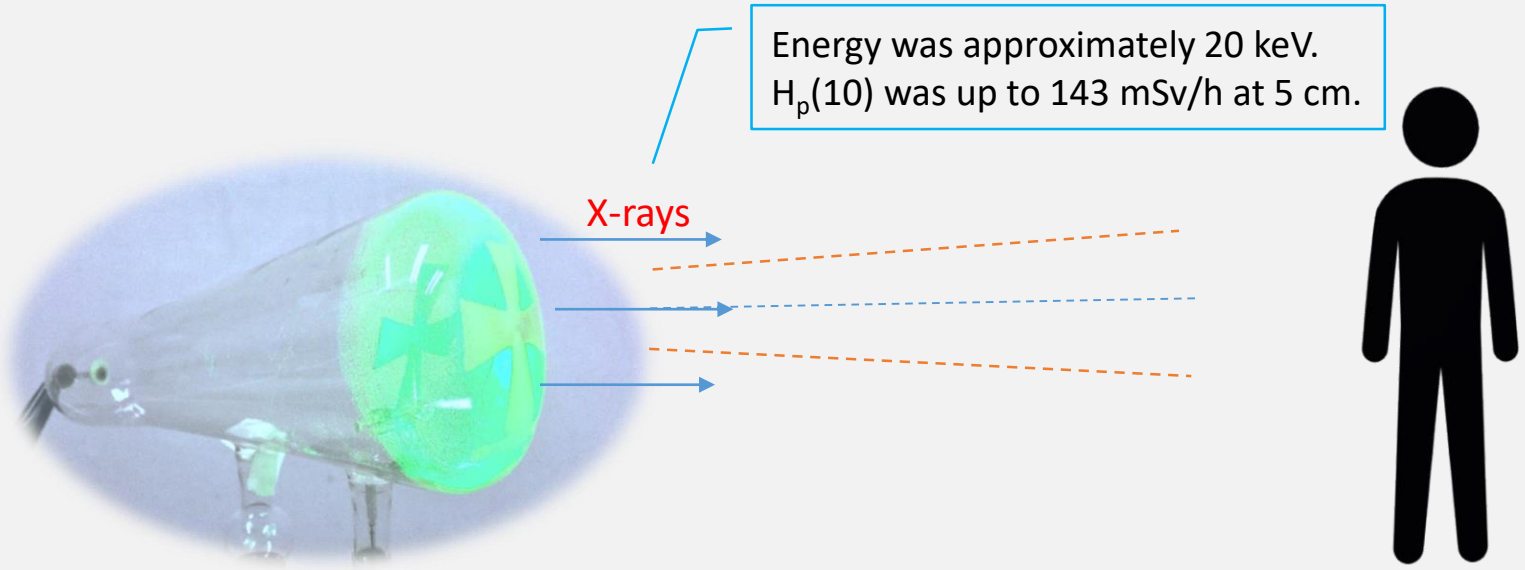
Lack of radiation education in school for a long time.

Risk of radiation hazards.

Radiation protection and safety guidelines for Crookes tubes have not been investigated sufficiently yet in Japan.

No fund for new Crookes tube with no radiation.

EXPOSURE TO X-RAY RADIATION FROM A CROOKES TUBE



PROBLEMS ON ESTIMATE OF A CROOKES TUBE

- Low energy X-rays (approximately 20 keV): hardly measure by conventional meters (even used HPGe, NaI 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.
- Difficulty 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.

CROOKES TUBE PROJECT

http://bigbird.riast.osakafu-u.ac.jp/~akiyoshi/Works/CrookesTubeProject.htm

How to take advantage of old apparatuses but radiation safety must be ensured?

- Assoc. Prof. Masafumi Akiyoshi is the Chief of the project.
- "Crookes tube project" has been launched nationwide in Japan by volunteer scientists since May 2017.
- Aiming to establish and promulgate the radiation safety management guidelines on Crookes tube at educational sites.

Task 1

- Evaluating the electric parameters such as voltage and current.
- Developing measurement methods for safety management at educational sites.

Task 2

- Investigating the actual conditions at the educational sites.
- Examining the operational methods
- Verifying ALARA principle.

Task 3

- Evaluating the effective dose.
- Assessing the eye lens dose.
- Estimating the reference level of dose.

Task 4

- Proposing educational content that utilizes low-energy X-rays.
- Providing dose measurement methods.
- Spreading guidelines at educational sites.

CROOKES TUBE PROJECT

http://bigbird.riast.osakafu-u.ac.jp/~akiyoshi/Works/CrookesTubeProject.htm

- From 2019-2020, the Japan Health Physics Society (JHPS) established the "Specialized study group on radiation safety management for low energy X-rays".
- In 2021, the specialized study group aims to establish the academic standard that contains the following contents:

(a) Crooks tube operation manual,

(b) Measurement methods of low energy X-rays,

(c) Evaluation of radiation protection and technical procedures against low energy X-rays,

(d) Target value management:

- Explanation of items,
- Question and answer (Q&A).

SECTION 2

Characteristics of Low-energy X-ray Radiated from the Crookes Tube

- ***X-ray energy spectrum***
- ***Correlation of operation factors to output X-rays***
- ***Transmission of X-rays***
- ***Leakage dose***

Khiem, D. D., Ando, H., Matsuura, H. and Akiyoshi, M. (2019), ***Radiation Safety Management*** *18, 9-15.*

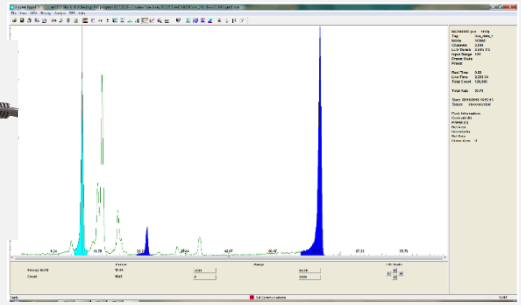
X-RAY SPECTROMETER

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

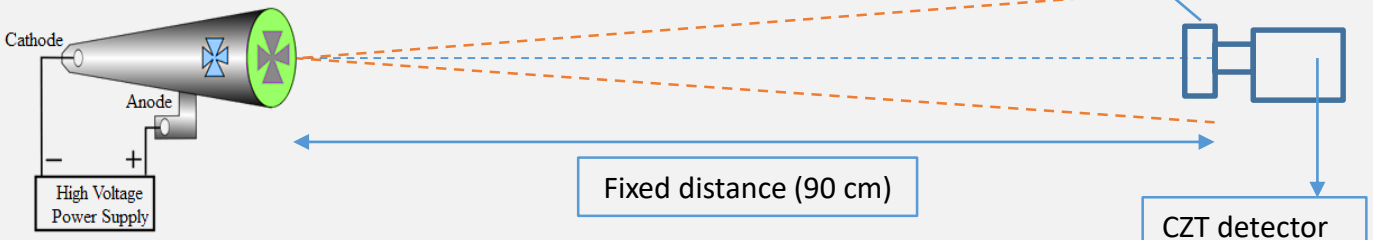
CZT Detector (XR-100T-CZT, Amptek Inc., USA)

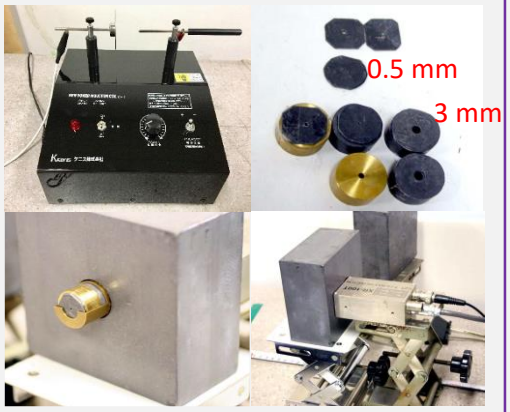
Power supply and Amplifier (PX2T, Amptek Inc., USA)

Pocket Multichannel (MCA8000D, Amptek Inc., USA)

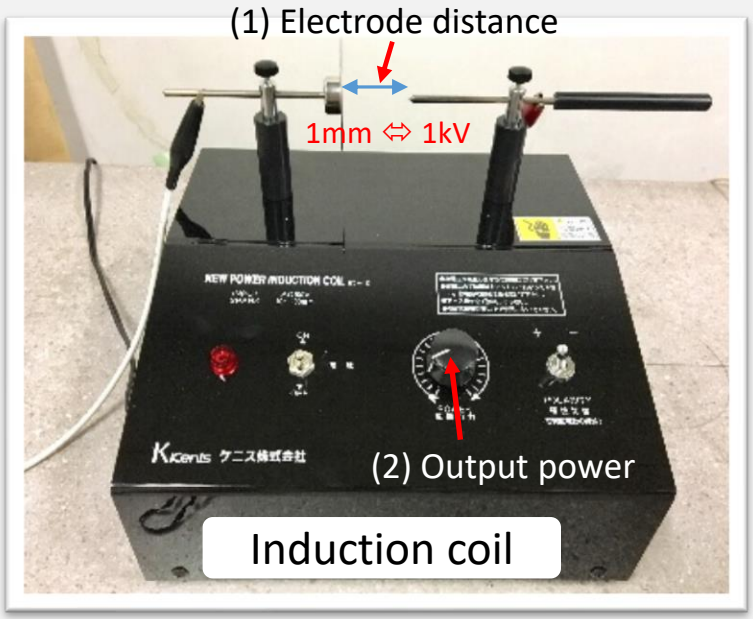


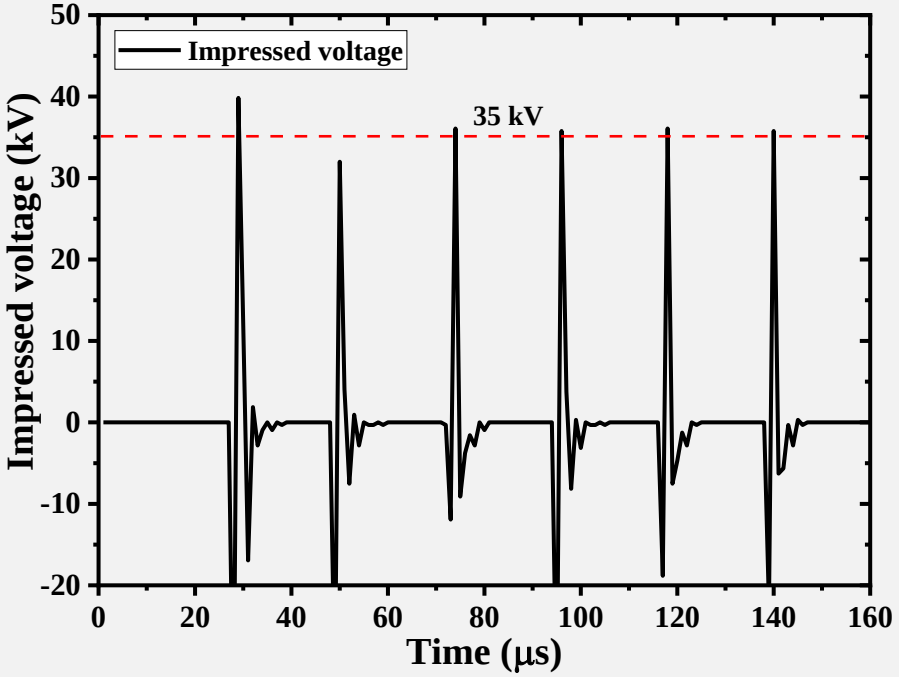
DPPMCA Software (Amptek Inc., USA)



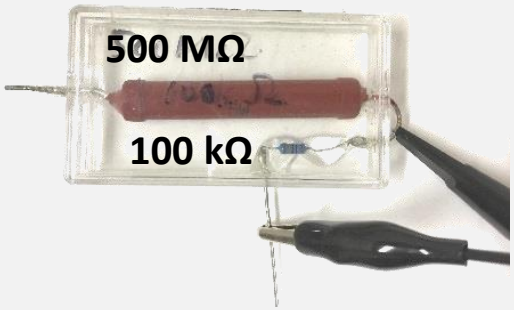


HIGH VOLTAGE APPLIED BY THE INDUCTION COIL





PC USB Oscilloscope (6000BD, Hantek Ltd.)

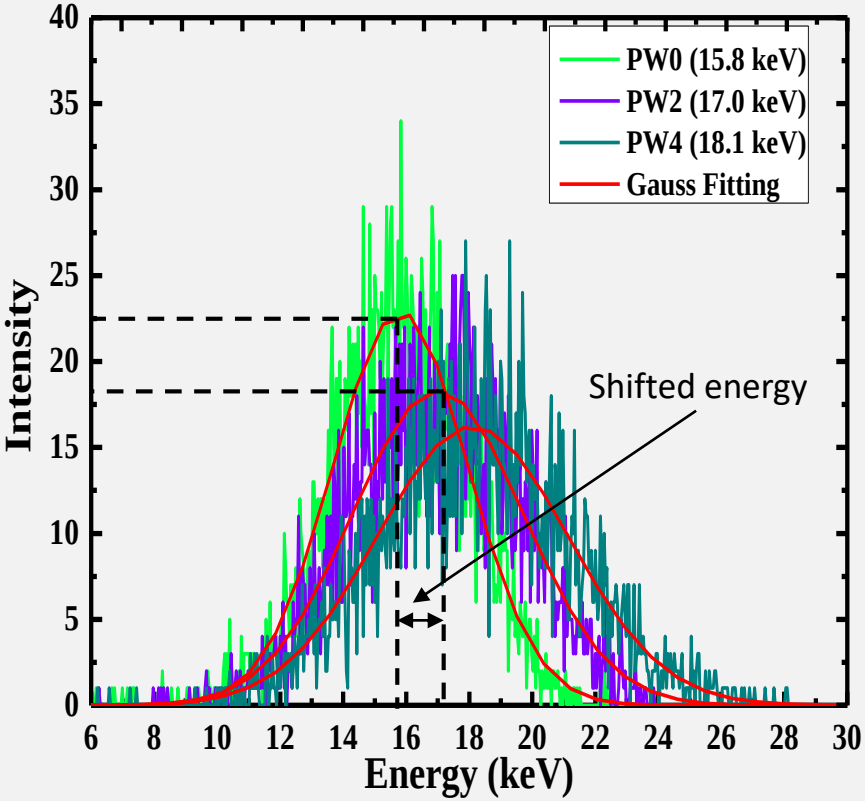


Voltage divider circuit

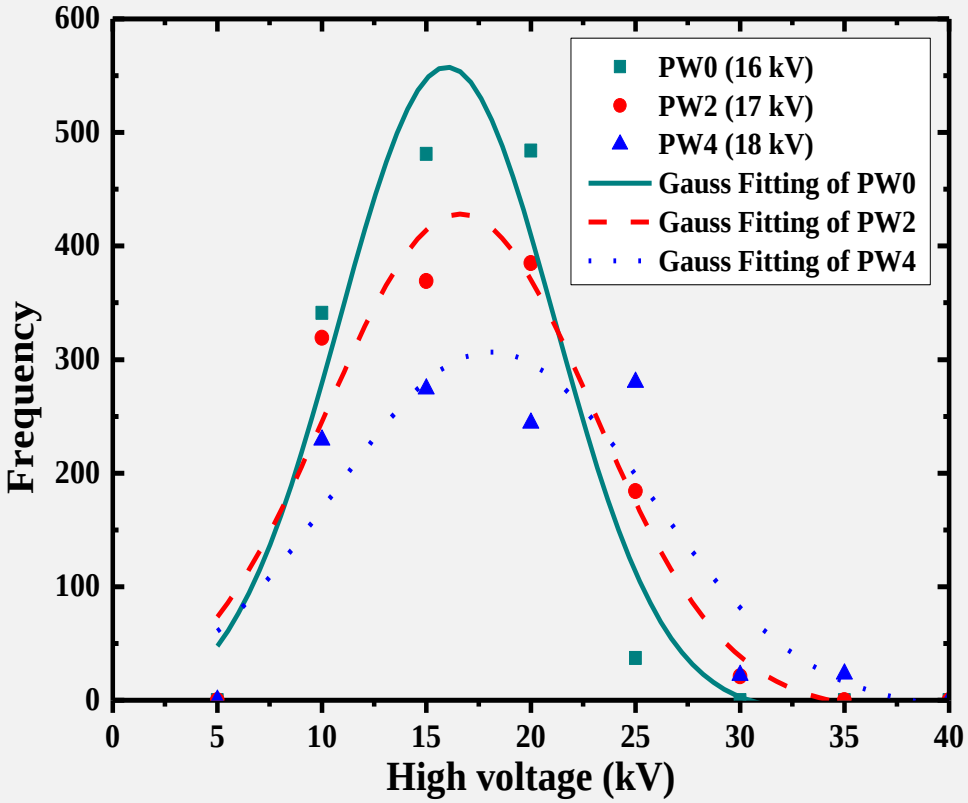
The induction coil

- Producing an applied voltage in **pulsed-shape,**
- Creating **pulsed radiation** with heterogeneous energy of X-rays.

EFFECT OF VOLTAGE ON OUTPUT X-RAYS

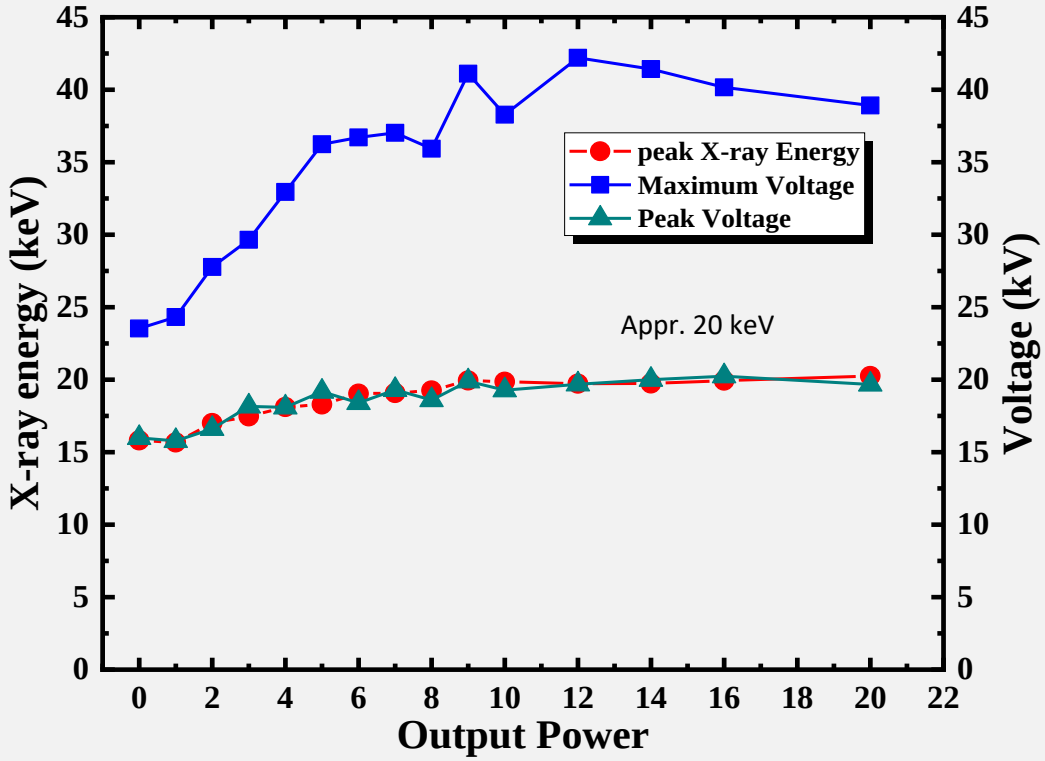


X-ray spectra radiated by the Crookes tube acquired by the CZT detector



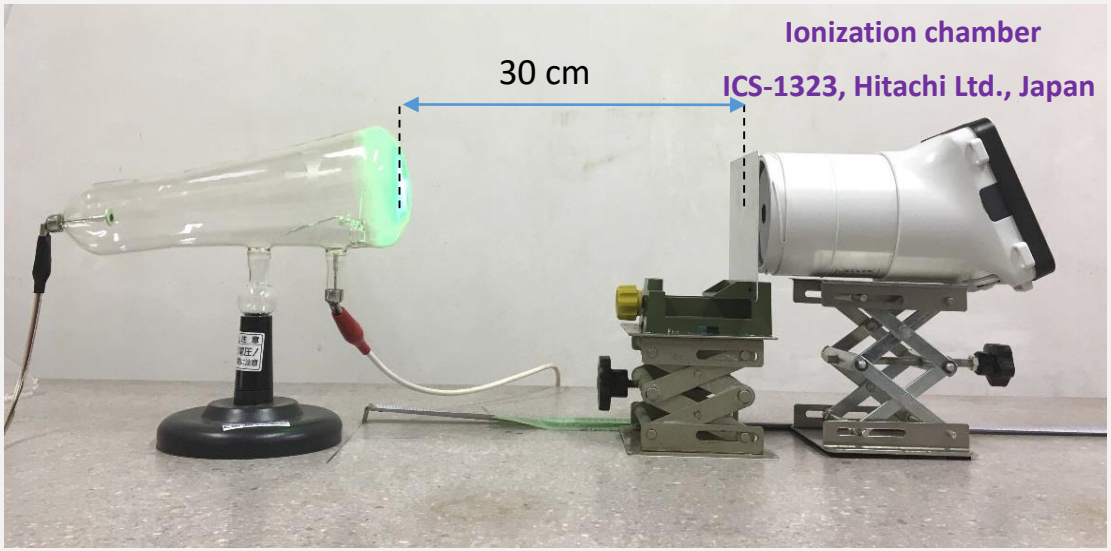
The distribution of the applied voltage shows an increase in the output voltage

EFFECT OF VOLTAGE ON OUTPUT X-RAYS



- X-ray energy and applied voltage kept stability when a spark occurred.
  - effective energy of approximately 20 keV,
  - maximum voltage of roughly 40 kV, equal to nominal voltage at an electrode distance of 40 mm.
  - peak energy of X-ray matched well peak of voltage distribution.
- **Change in applied voltage (kV):** affecting both amplitude and energy of X-ray.
  - intensifying of photon intensity,
  - shifting X-ray energy to higher in the spectrum.

TRANSMISSION ESTIMATE



Al linear attention measurement setting

- Using Lambert-Beer equation:

$$D = D_0\, e^{-\mu x}$$

μ: Al linear attenuation coefficient

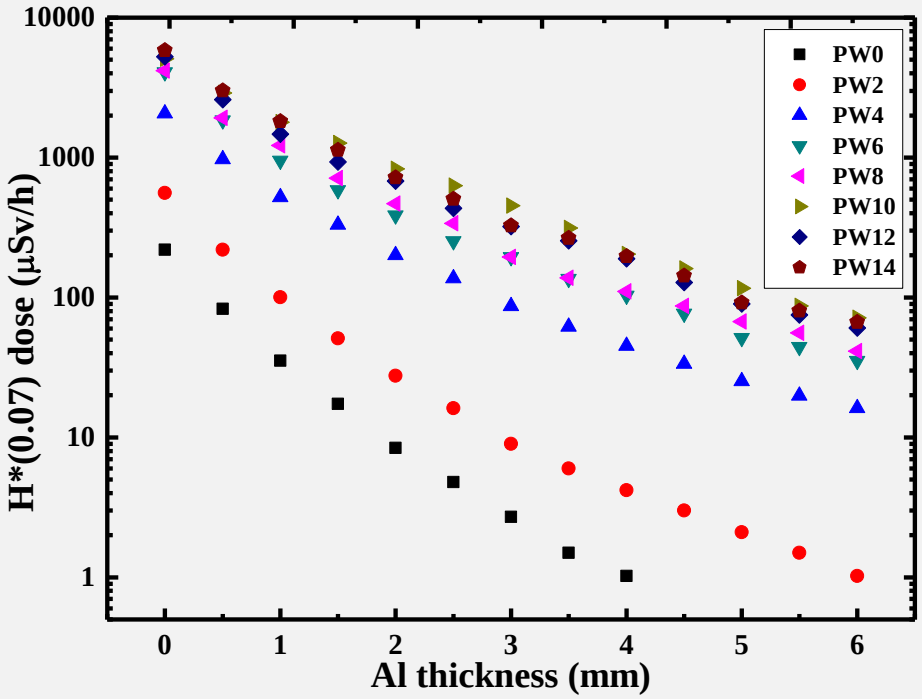
D_0: initial dose

D: transmitted dose

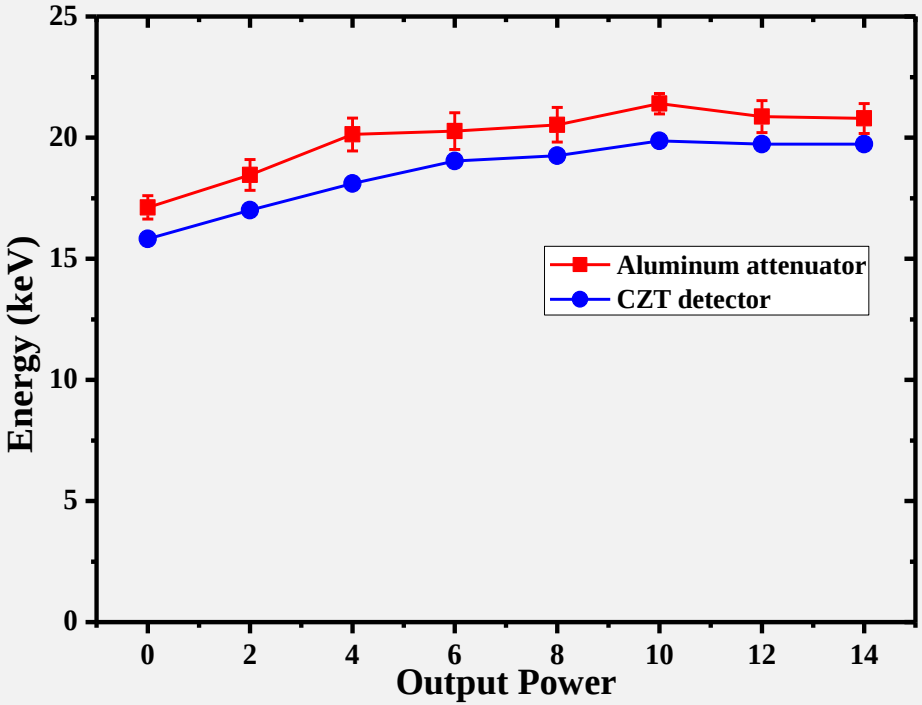
x : Al thickness (0.5 – 6 mm)

- Distance of 30 cm.
- Interpolating the effective energy from μ of Al using data from the National Institute of Standards and Technology (NIST, USA).

TRANSMISSION ESTIMATE



Transmission of X-rays with various output applied voltages through Al.



X-ray energy with various output powers obtaining by attenuation measurement and CZT detector.

- ❑ Dose increased with increasing output power.
- ❑ Dose kept stability when a spark occurred.
- ❑ Effective energy of 19 keV acquired by CZT detector and 20 keV by attenuation measurement, average difference of 7.5%.
- ❑ **Change in the filtration:** hardening the X-ray beam
  - ○ reducing the photons with low energy,
  - ○ shifting energy to the higher region.

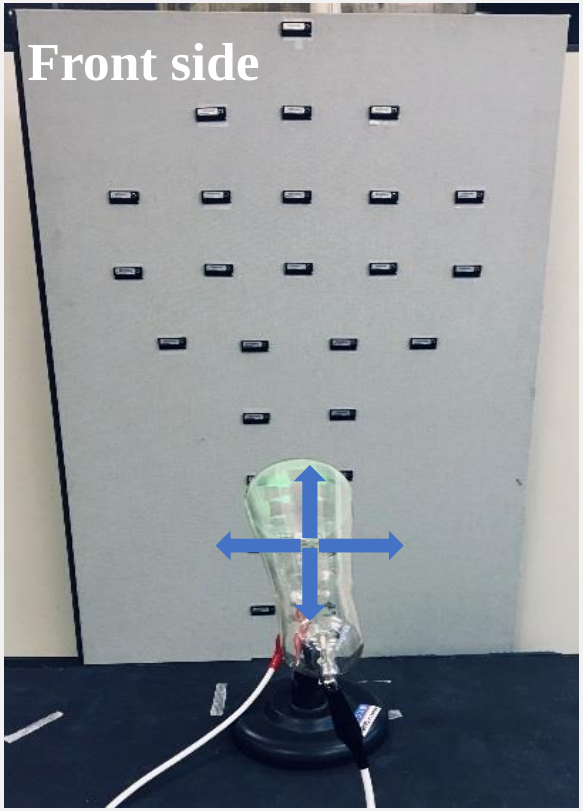
SECTION 3

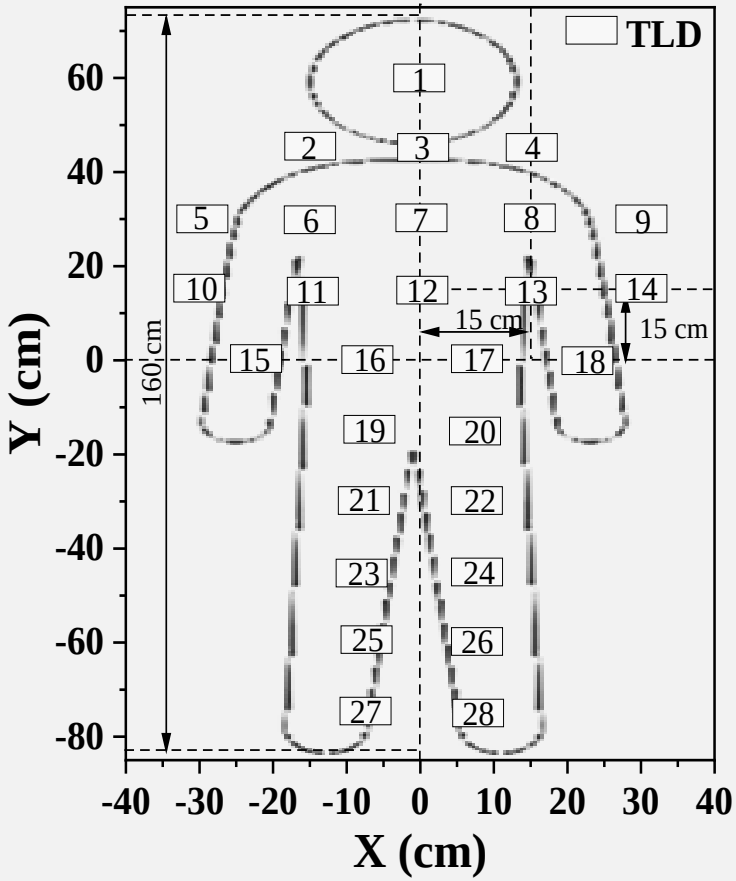
Dose Distribution from the Crookes Tube Using Thermoluminescent Dosimeter

- ***Evaluating the spatial dose distribution of the Crookes tube.***
- ***Indicating the aspects of the Crookes tube with high dose.***
- ***Estimating $H_p(0.07)$ as an experimental index for effective dose estimate.***

Khiem, D. D., Matsuura, H. and Akiyoshi, M. (2020), ***Radiation Measurements*** *134, 106312.*

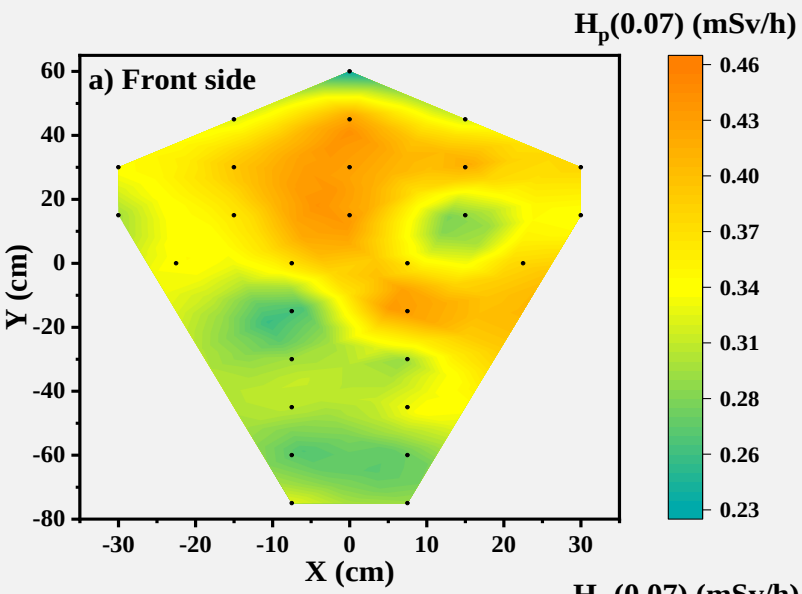
SPATIAL DISTRIBUTION OF DOSE

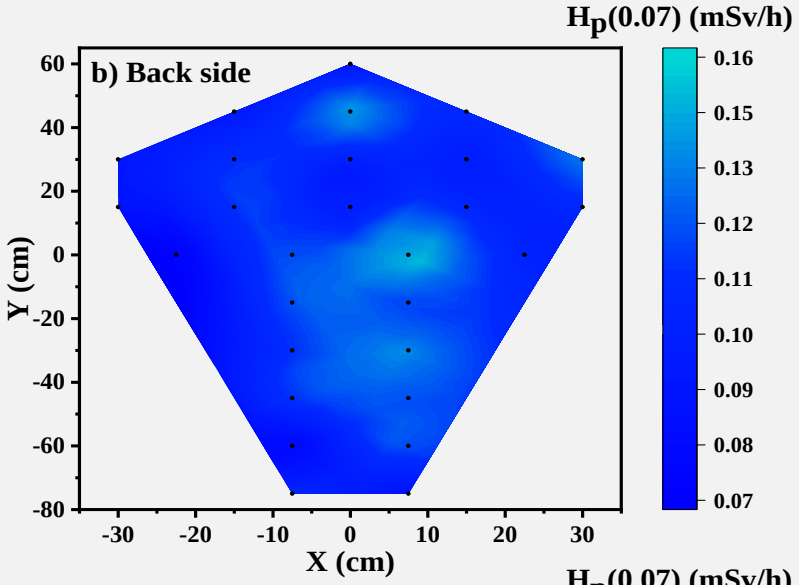


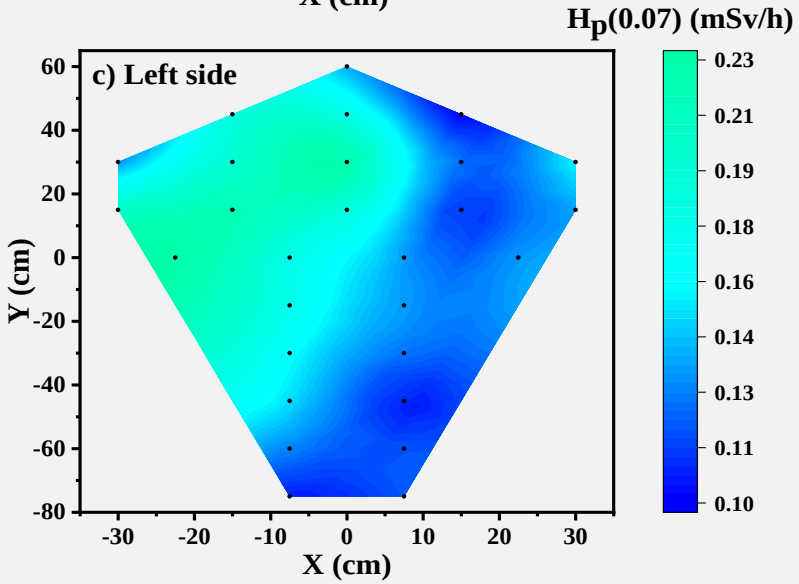


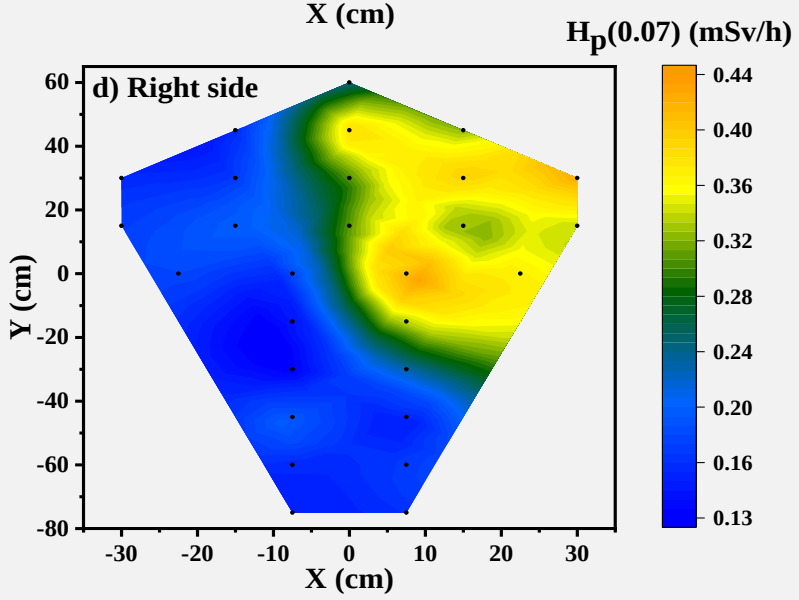
- Fitting 2-D human-body-shape with a junior-high school student.
- Distributing 28 TLDs (Panasonic UD-802PQ) on the 2-D human body shape.
- Placing at four sides of the tube.
- Irradiating at a distance of 1m for 1h to integrate dose.

SPATIAL DISTRIBUTION OF DOSE



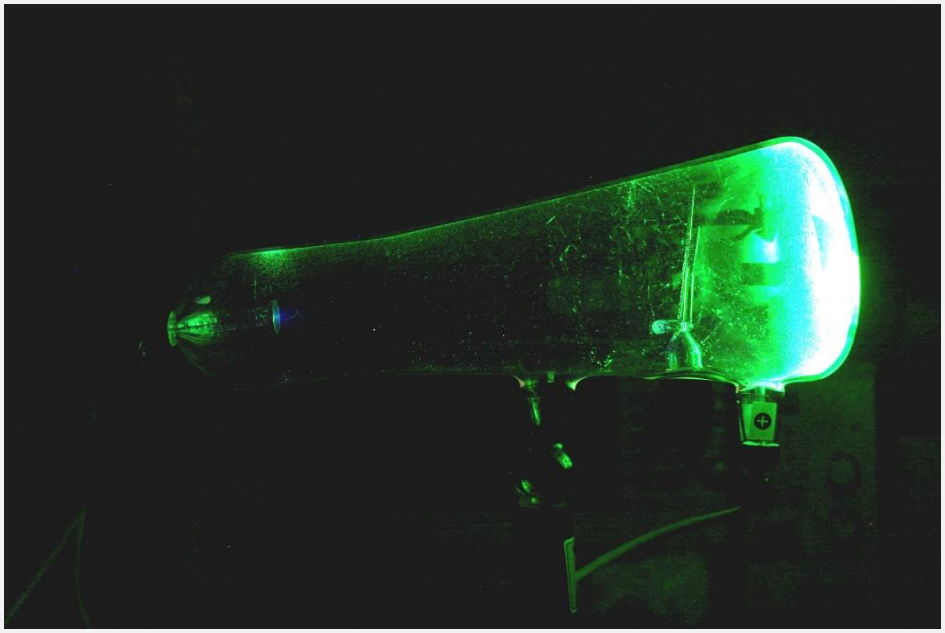


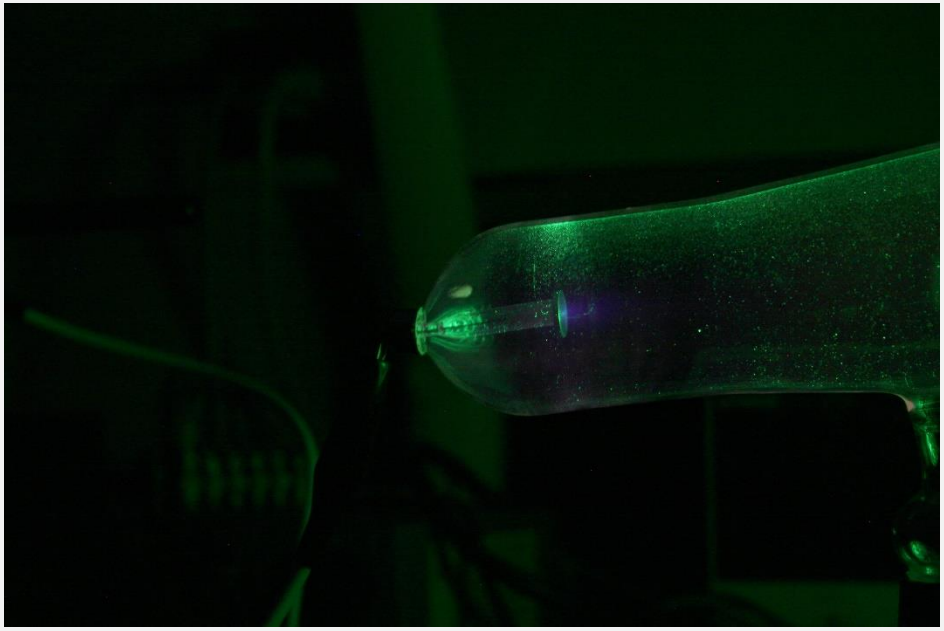




- Highest dose on the aligned direction to the head of the Crookes tube
- Distributing highly in the central area and having spatially non-uniform.

SPATIAL DISTRIBUTION OF DOSE





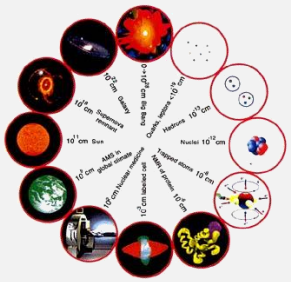
- The fluorescent green inside the tube pointed out where the electrons strike the glass and emit X-rays.
- It validated the experimental results that the dose was high at the top-rear and the head tube.

SECTION 4

Conclusions

CONCLUSIONS

- Investigating properties and characteristics of X-rays emitted by Crookes tube:
  - Emitting X-rays with soft energy of approximately 20 keV,
  - Producing applied voltage in pulsed-shape,
  - Creating inhomogeneous radiation,
  - Changing electric operation causes changing exposure and X-ray energy.
- Dose distributes spatially non-uniform with highest dose on the head tube.
- Recommendations and guidelines on radiation protection:
  - Strictly avoiding the position facing the front of the tube,
  - Setting output power as low as possible,
  - Setting the electrode distance shorter than 20 mm, never remove them,
  - Taking distance as far as possible, upon 1 m as recommendation,
  - Keeping the demonstration time shorter than 10 min,



THANK YOU FOR YOUR ATTENTION