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Radiation Shielding and Dosimetry at Accelerators II, O2.4

Measurements of low energy X-rays radiated from Crookes tubes in education field by using radiophotoluminescence dosimeter

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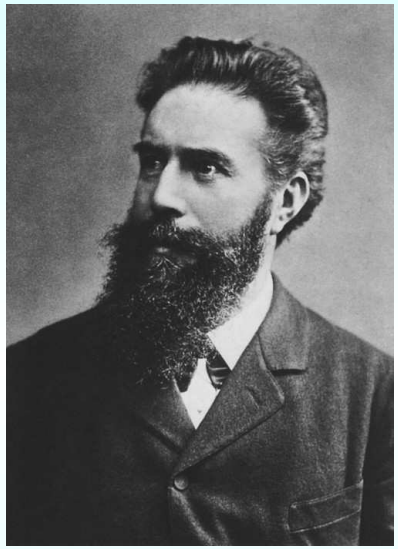
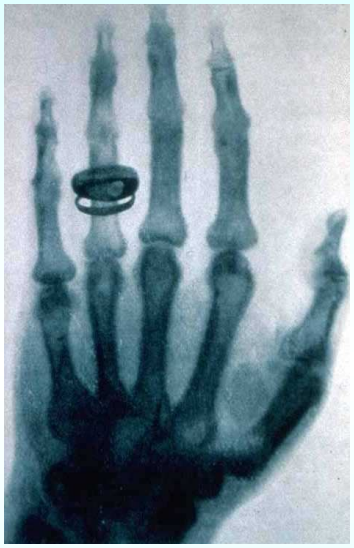
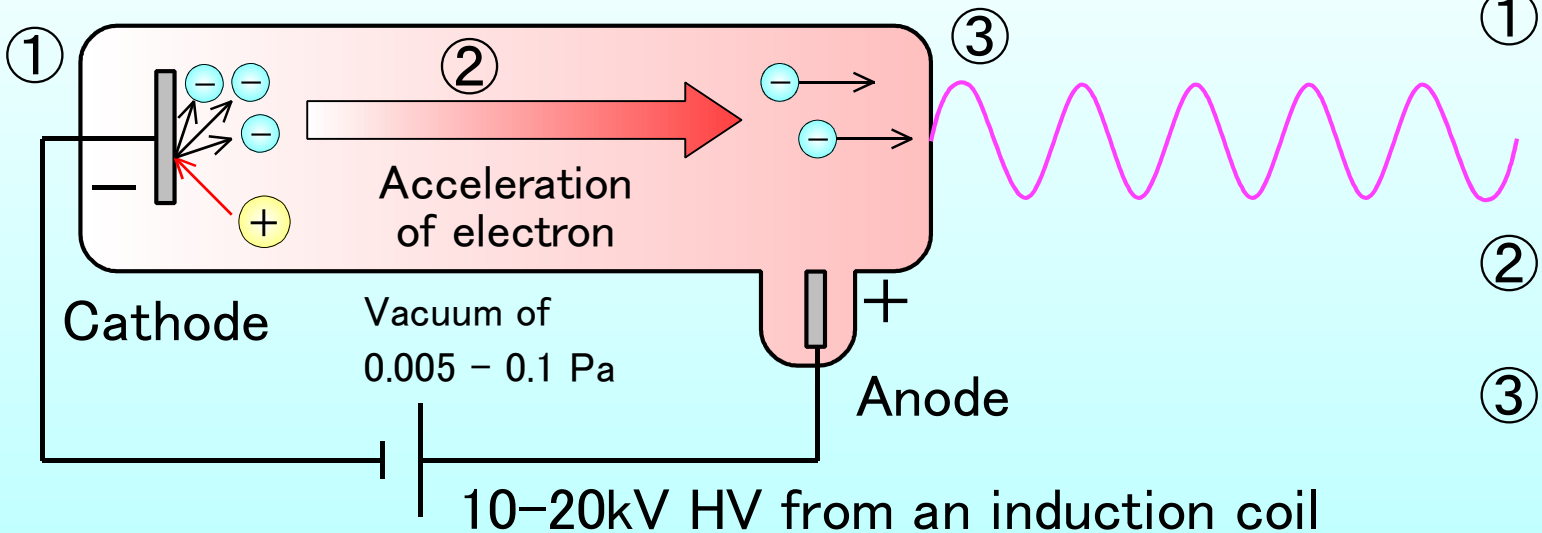
What is Crookes tube?

Wilhelm Konrad Rontgen
1895, Found the X-ray during the experiment of discharge tube
1901, Got the first Nobel prize in physics



William Crookes





① At the cold cathode, cation in air is accelerated and knock out secondary electrons.

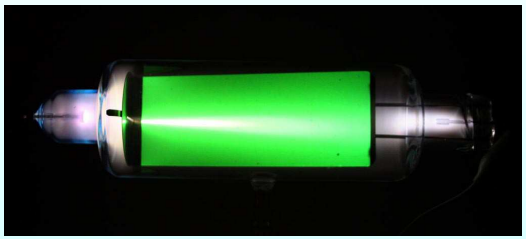
② These electrons are accele-rated as the applied HV.

③ Accelerated electrons hit glass wall and radiate bremsstrahlung X-rays.

How to Establish Safty Management for Crookes tube?

Crookes tube has been used in junior-high science classes in Japan, and the primary purpose is to teach the characteristics of electrons and current, not for radiological education. Therefore, some teachers are not recognizing the radiation of X-ray from Crookes tube, and most of them have no information of the dose. However, it is possible to expose high dose of X-ray to students using a Crookes tube, where Hp(0.07) reaches 200mSv/h at a distance of 15cm.

Some discharge tube that use hot cathode is operated with only several 100V, and even with cold cathode, some equipment can be operated at about 5kV. With this low voltage, radiated X-ray is shielded completely by the glass wall.



A Crookes tube operated by 5kV (Horizon Co. VT-7010)

5kV CW high voltage unit driven by 9V battery

Junior-high school in Japan have quite limited budget!

Basic Plan

By using low voltage type equipment, teachers never required to consider the radiation and students can observe electron beam very safely.

The problem is resolved completely!

Advanced Plan

1) Cannot replace legacy devices with economical reason
2) Advenced education program that utilize X-rays radiated from Crookes tube

Anyway, radiation safty guide line to limit X-rays dose is required.

ICRP Basic Radiation Safety Criteria

Justification:

No practice shall be adopted unless its introduction produces a net positive benefit.

・Is the experiment required? Is it accepted to show with photo or video?

→The experiment using Crookes tube gives quite strong impact to students and have excellent educational effects.

Optimization:

All exposure shall be kept as low as reasonably achievable (**ALARA** concept), economic and social factors being taken into account.

・Low voltage operated equipments can make the exposure to zero and it is firstly recommended. However, economic factor make it difficult to replace all equipments in all schools. Therefore, optimization on operation conditions (applied voltage, current, distance, time and shielding) is required.

Dose limitation:

The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commition.

・In Japan, dose limit for general public proposed by ICRP Pub1990/2007 is not taken into the domestic low. Now we survey international regulations and the actual control conditions to settle the reasonable management target dose.

Problems on management of X-rays from Crookes tube

Dose Constraint for Education Field is not Discussed well

Dose limit for general public have been proposed by ICRP Pub1990/2007 as 1mSv/y, but it is for all additional exposure. ICRP Pub 36 is the only instance.

Definition of X-ray Device is not Clear

In Japanese domestic low, `X-ray device' is not defined strictly. There is no exemption level that gives a confusion to safety management of X-rays in many fields.

Difficult Estimation of Effective Dose

For 20keV X-rays, the half value layer is about 1cm in human body. The absorbance dose to tissues in body depends on its depth from the surface. The transmittance is changed with energy of X-ray drastically around this energy range and the X-rays have broad spectrum.
Further more, dose distribution in horizontal plane is not uniform. Therefore we cannot assume aligned and expanded radiation field, and we cannot use 1cm dose equivalent as approximation of effective dose.

Problems on Estimation of X-rays from Crookes Tube

Low Energy X-Rays (arround 20keV)

Not only conventional survey meters for public use, but also reliable NaI survey meters for general radiological management are useless for low energy X-rays from Crookes tube.
(below 50keV pulse is ignored by conventioal NaI surver meters)

Radiated in Sharp Pulse

Even using detector with Be window for low energy X-rays measurement, radiation in sharp pulse give pile up and dose is estimated as very small value. Only ionization chamber that measure averaged current or solid detector that integrate the absorbed dose is useful.

Instability of Induction Coil and Applied Voltage

Induction coil generate high voltage pulse mechanically, that is affected by conditions such as temperature, and firing voltage between discharge electrodes is also affected by temperature or humidity. For systematic measurement, some physical parameter is required to compare results.

Dose Measurement by Various Survey Meters

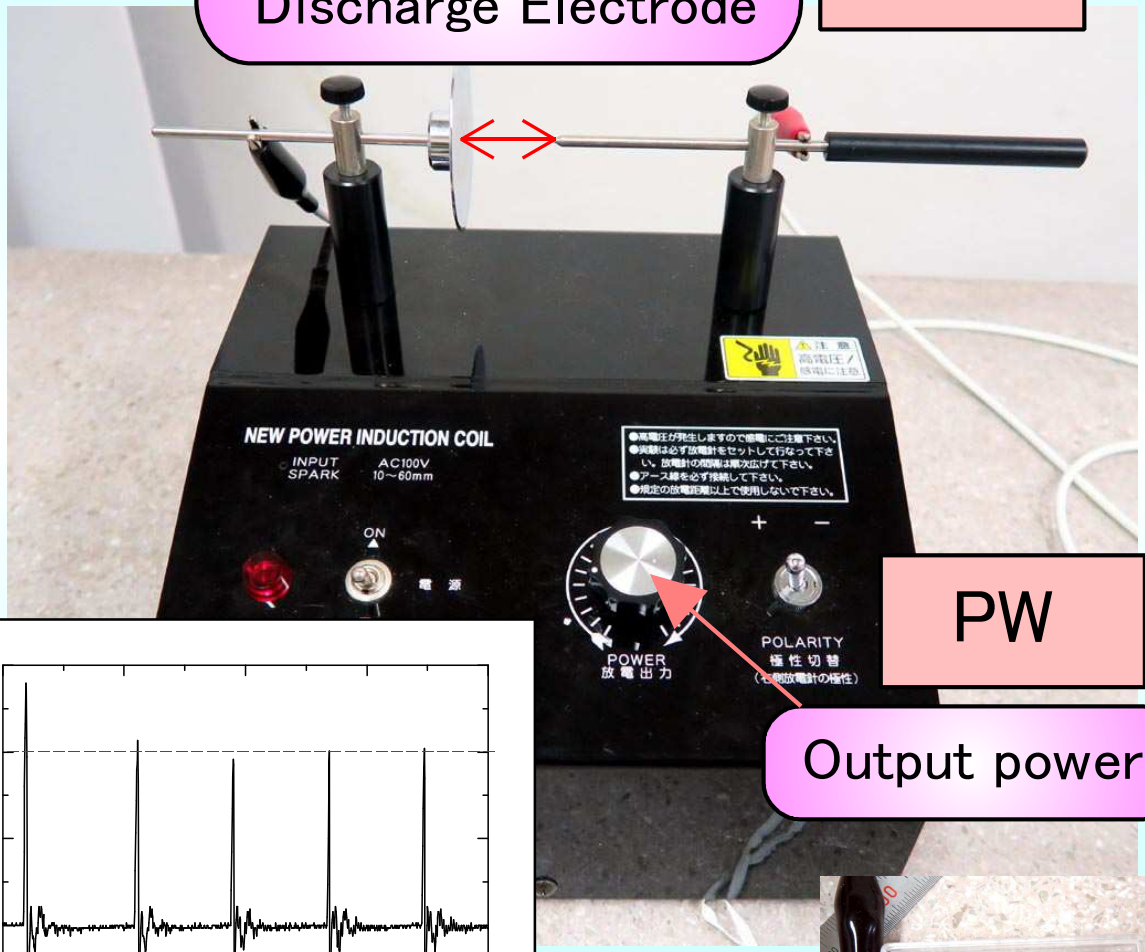
Crookes tube: Kenis 3C-B with Maltese cross plate, Induction coil: Kenis ID-6
Distance of discharge electrodes: 25 mm、Output power 6、Averaged current 40 μA
Measured in front direction of the tube without Maltese cross plate.

	Ionization chamber		radiophotoluminescence dosimeter		GM tube
	Hitachi ICS-1323		Chiyoda Tech. Glass Badge type FX		S.E. International Ranger
distance	Hp(0.07)	Hp(10)	Hp(0.07)	Hp(10)	1min scaler
cm	mSv/h	mSv/h	mSv/h	mSv/h	kcpm
15	7.3	3.0	4.6	1.6	34
30	1.7	0.73	1.3	0.48	32
50	0.58	0.27	0.48	0	27
	NaI scintillator		Plastic scintillator	CsI scintillator	Si semiconductor
	Fuji Electric NHC6	Aloca TCS-172	JSF Kind-mini	Aircounter EX	Aircounter S
distance	Be window	general purpose	without cover	without cover	
cm	μSv/h	μSv/h	μSv/h	μSv/h	μSv/h
15	1.3	0.17	118	13	<9.99
30	10	0.17	64	13	0.05 blink
50	13	0.15	24	8	<9.99

High Voltage Applied by a Induction Coil

Distance of Discharge Electrode

DDE



PW

Output power

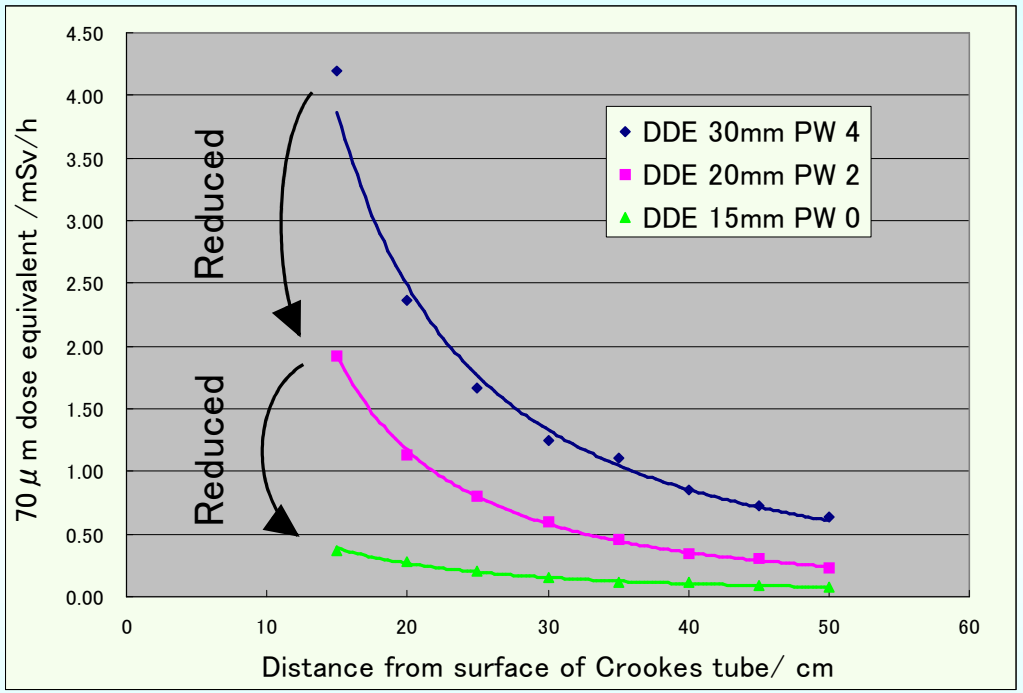
Output power dial changing the voltage impressed to the primary side of a transformer, and that control output voltage continuously.
Since the dielectric breakdown voltage in the air is about 1 mm for 1 kV, the distance of discharge electrodes can limit the maximum voltage. If the distance is settled to 20mm, the maximum voltage impressed to a Crookes tube was limitted to 20keV, therefore it work as a safety device.

Distance of discharge electrodes 20mm,
Output power 4, Averaged current 80 μA

To measure high voltage pulse, voltage divider that use a large registor (＜100MΩ) and a small resister (about 100kΩ) is used to protect a oscilloscope.
In the most case, an induction coil is not connected to the ground. In such case, the electric potential is floating and must be used 2 divider and 2 probe to take difference between anode and cathode.

Dose Control

Distance of discharge electrodes: 30, 20, 15mm
Output power was set to the just firing voltage.



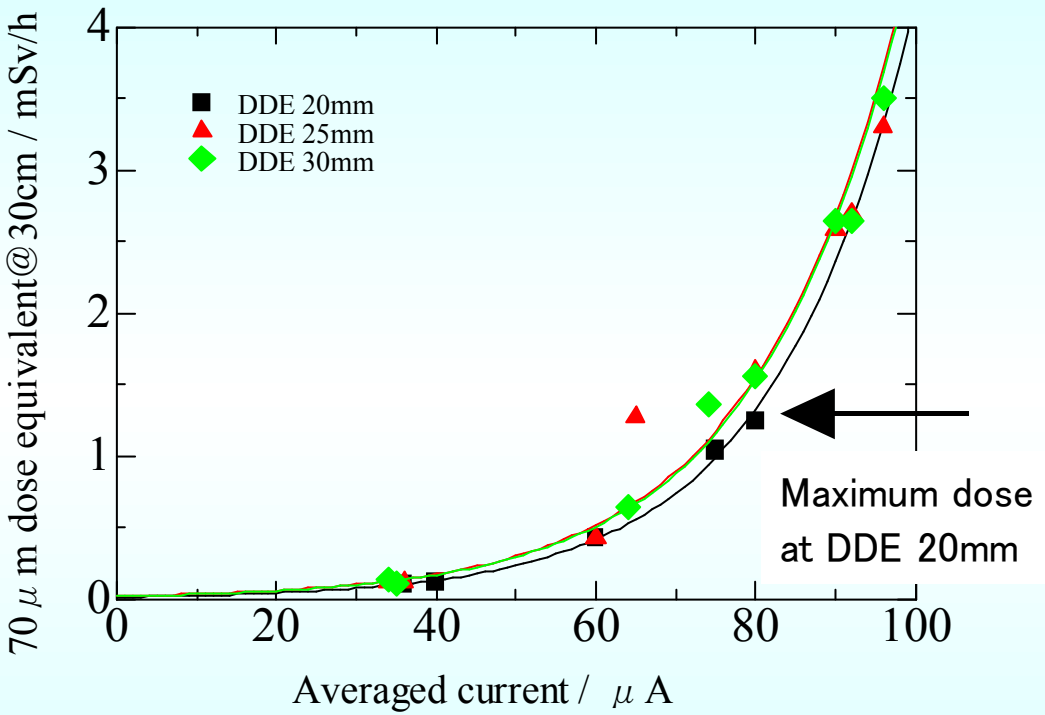
・Dose is reduced drastically with the voltage limitation

Distance of discharge electrodes must be shorter than 20mm

・Dose is changed with distance as the inverse square law

At a distance of 1m, dose is reduced to 1/100 from that of 10cm.

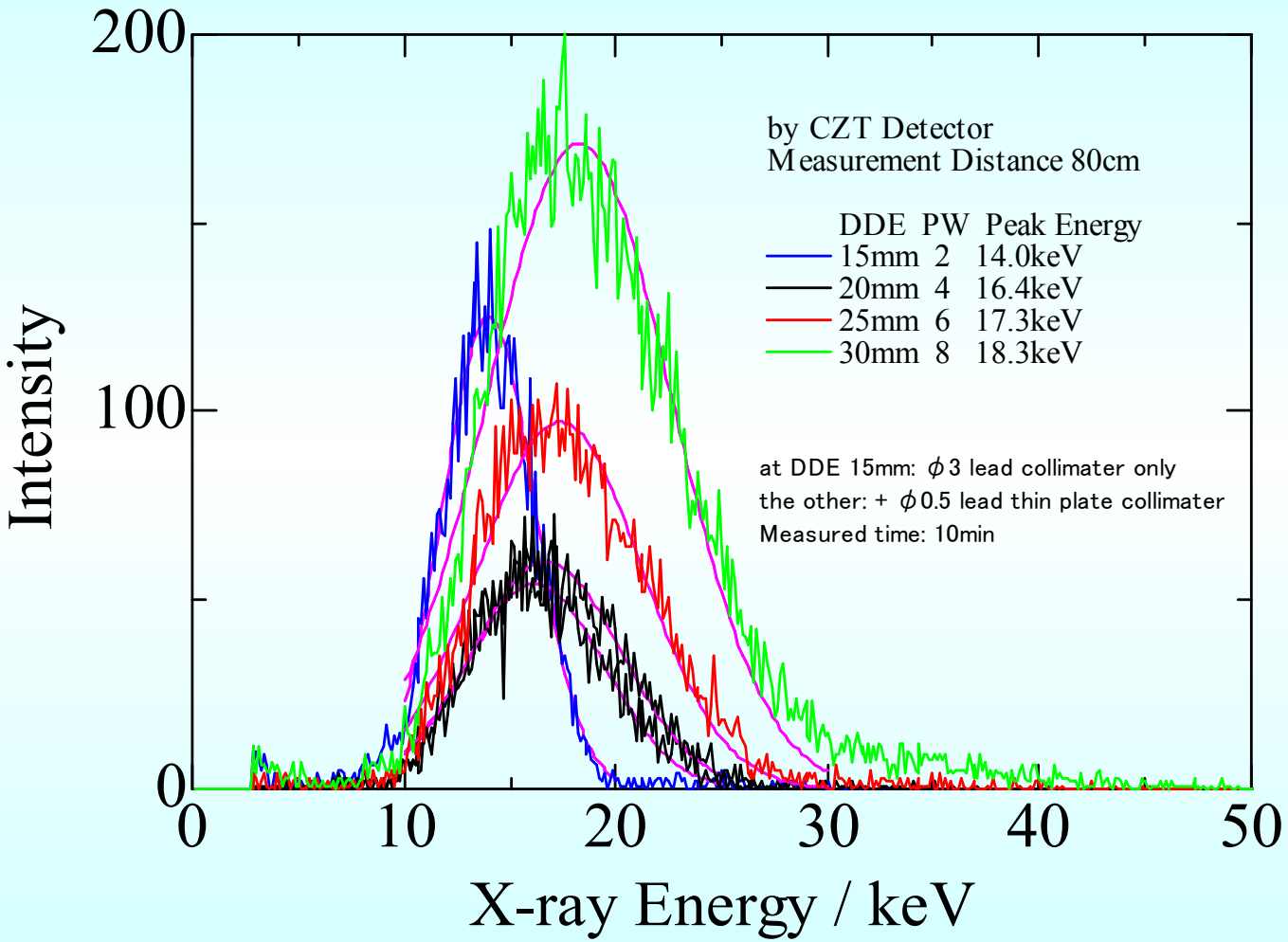
Averaged current was changed with output power.
The averaged current was measured by simple analog current meter.

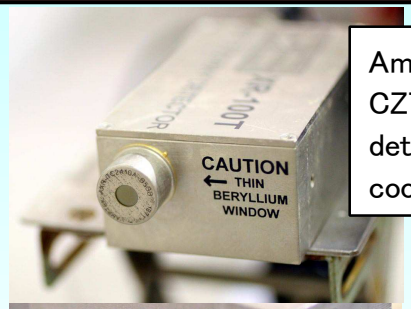


・Increasing current rising dose exponentially

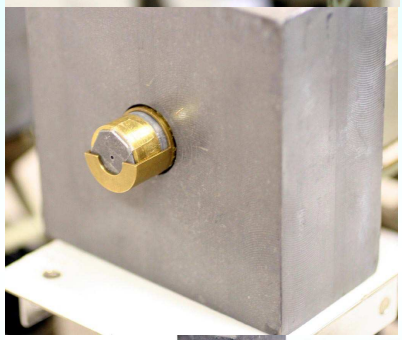
The output power increase current and also voltage. The voltage changes the energy of X-rays that changes transmittance drastically. Therefore, output power must be kept as small as possible. Furthermore, discharge electrode act as a safety valve to limit the voltage.

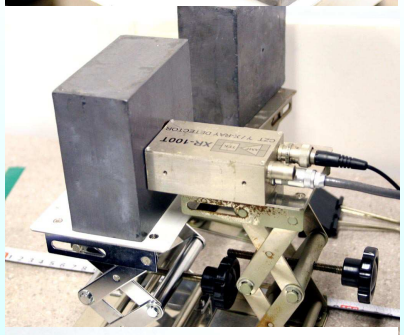
Spectrum Measurement by a CZT Detector





Amptek XR-100T-CZT
CZT(Cd0.9Zn0.1Te)
detector with Be window,
cooled by Peltier device



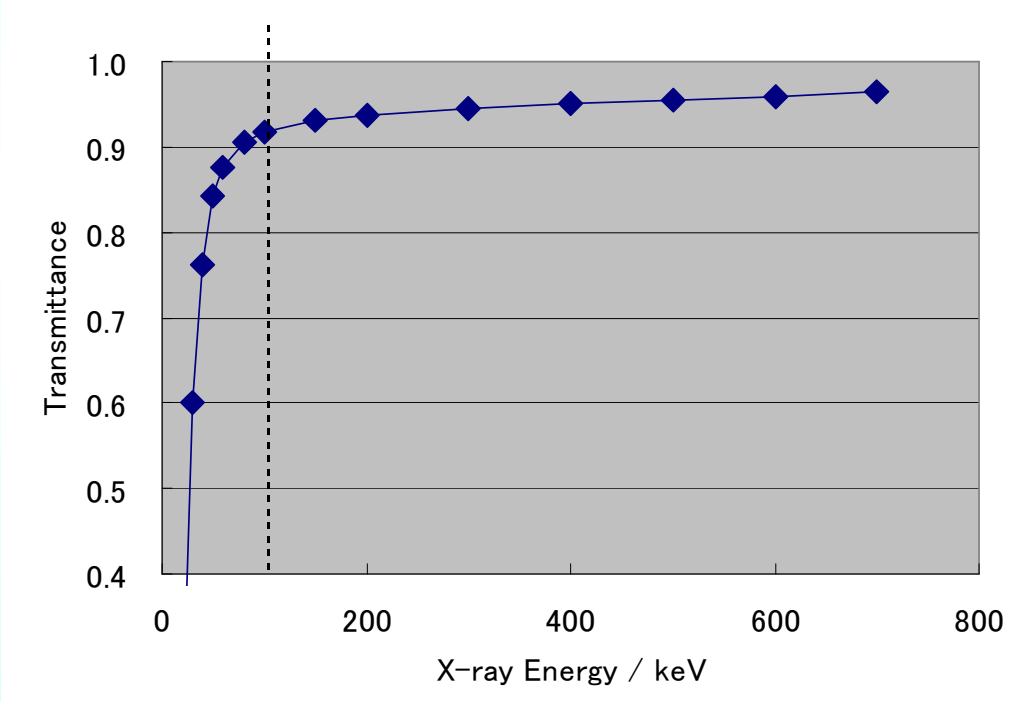


Collimaters
φ0.5 lead thin plate
φ1.0 lead thin plate
φ2 co-axial brass
φ3 co-axial lead

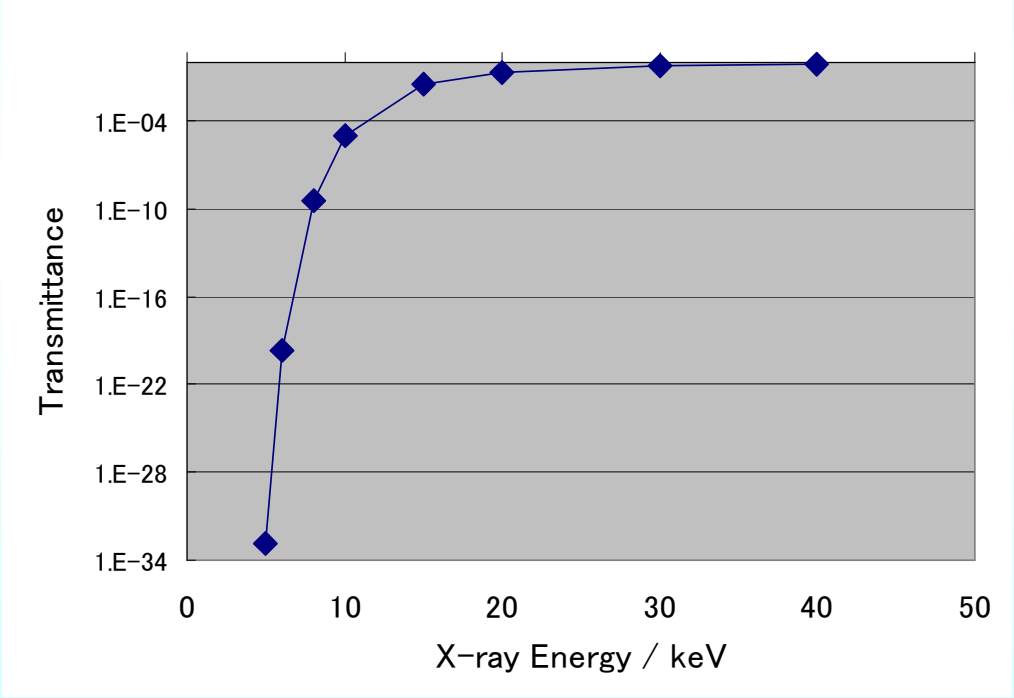
φ0.5mm lead collimater can reduce count rate to several cps
that avoid pile up in the spectrum

Drastic Dose Change with Slight Voltage Change

The radiated X-rays are shielded by the grass tube that forms Crookes tube it self. Slight energy change around 20keV gives drastic change in transmittance.



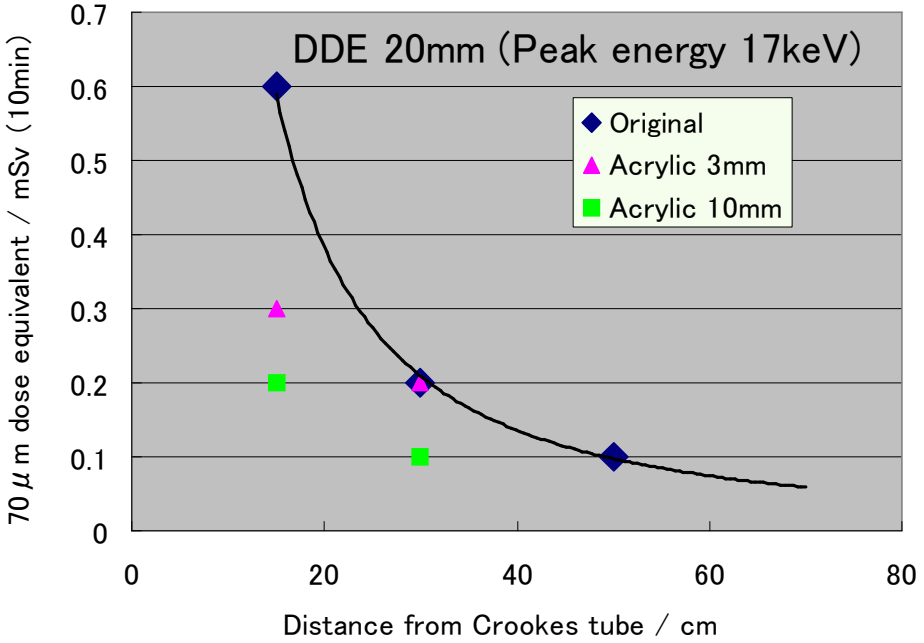
Above 100keV, transmittance changes slightly



Transmittance at 30keV is higher 100 times than that of 15keV

Transmittance of 2mm glass for X/ γ -rays

Efficiency of Shielding



In calculation, 20keV X-rays are shielded to 1/2 with 1cm acrylic and 1/50 with 5mm glass.

Actually, energy of X-rays from Crooks tube is a little low, therefore acrylic showed shielding of 1/2 with 3mm and 1/3 with 1cm.
A very light (1.5kg) aqualium with 1.9mm glass showed 1/20 – 1/50 shielding. It was too light and feel like plastic, so it is not incredible to shield with glass aqualium at the real education field.

The cost of aqualium is only 12.3US

	Hp(0.07) (μSv/h)		Transmittance (%)
PW	Original	Shielded	
0	600	11	1.8
1	620	12	1.9
2	1300	60	4.6
3	3000	160	5.3

Measured distance from Crookes tube 15cm, DDE 20mm
Shielded with 1.9mm thick glass aqualium
https://www.amazon.co.jp/gp/product/B00W5DSU0C

Measurement at Real Education Field

Setting of induction coil were same as their usually.

Measurements of leaked X-rays from 37 Crookes tubes at junior-high school in Japan were performed using radiophotoluminescence dosimeters by science teachers.

The dosimeter were sticked on 2L PET bottle and put from distances of 15, 30, 50cm and irradiated during 10min for each. The radiophotoluminescence dosimeter was Glass Badge type FX (Chiyoda Technol) that can estimate effective energy and can estimate back ground radiation with Sn shielded element.

In the 37 Crookes tubes, Hp(0.07) with 10min exposure was;

25 tubes < 50 μ Sv @ 1m (extrapolated)

18 tubes < 50 μ Sv @ 15cm (detection limit)

One tube radiate 600 μ Sv in 10min at 1m with minimum output power.

The tube showed intermittent beam and lookes current was small.

Minimum power、at a distance of 30cm

DDE 30mm: 2mSv/h

DDE 50mm: 30mSv/h

DDE 20mm: 40 μ Sv/h

at 1m、10min radiation gives only 0.6 μ Sv exposure

Charactor of High Dose Crookes Tube

Inside of the Crookes tube, vacuum is not so high and some gas molecules are enclosed. These molecules are ionized by natural radiation and anions are accelerated to cathode to knock out secondary electrons (cold cathode).

There is some Crookes tube that lack of gas. In old equipment, gas molecules are absorbed to glass wall gently or some equipment lack gas on the manufacturing.

With such Crookes tube, electrons are difficult to flow and more high voltage is required to emit beam. With induction coil, electromagnetic energy is charged to the coil until enough voltage is obtained that applies higher voltage than aimed with the output power . That increase transmittance of X-ray to glass wall.

At the age of Roentgen, necessity of gas-pressure control is well known and some "softener" devices were incorporated that released a small amount of gas.

How To Reduce the Dose from Crookes tube

First of all

Replace to low voltage equipment

10,000 Junior-High School × 400USD / ea. = 4Million USD is required in Japan
But Crookes tube is used at just a 1 lecture in 3 year.

Inherent Safety
No concern is required

With Economic Factor, Safety Guideline for Conventional Crookes tube is Required

1) **Applied Voltage**
2) **Beam Current**
3) **Diatance**
4) **Shielding**
5) **Time**

Reduce Radiated X-rays

Radiation Protection Three Principles

Reduce applied voltage gives low transmission of X-rays to the glass wall drastically.
When we shielding, acrylic is not effective but thin glass is enough effective.
To take distane is most easy way to reduce dose.

Provisional Guideline with our study

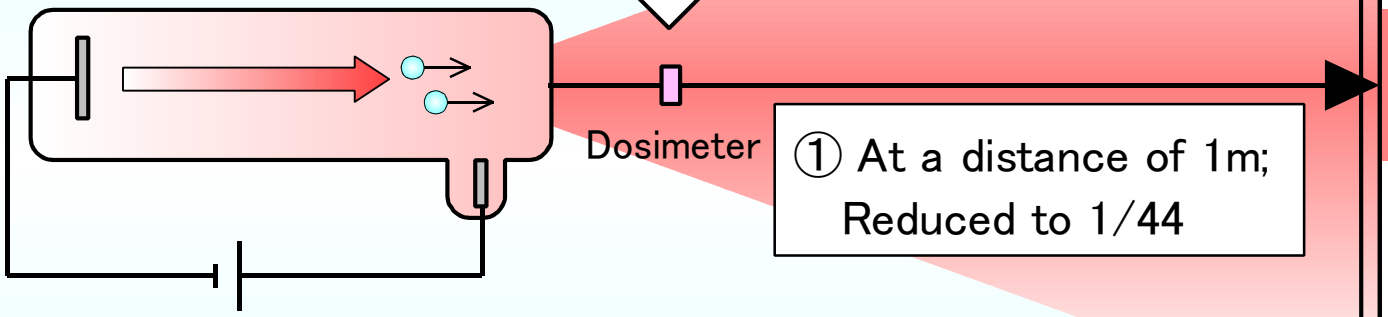
Is it enough?
Substantiate study is required.

- **Set output power as low as possible**
- **Never remove discharge electrodes and set the distance smaller than 20mm**
- **Take distance as far as possible. For student, more than 1m is recommended.**
- **Keep the display time shorter than 10min.**

To Estimate Effective Dose

EVEN

At the center of front,
Hp(0.07)=200mSv/h at 15cm



For Eye Lens, Equivalent Dose is also must be estimated.

① At a distance of 1m; Reduced to 1/44

② 20keV X-rays are reduced to one half every 1cm in body. Hp(10) does not represent Effective Dose.

③ In Holizontally, Peripheral Dose is smaller than that measured at the cente (50cm shift gives 2/3 reduction)

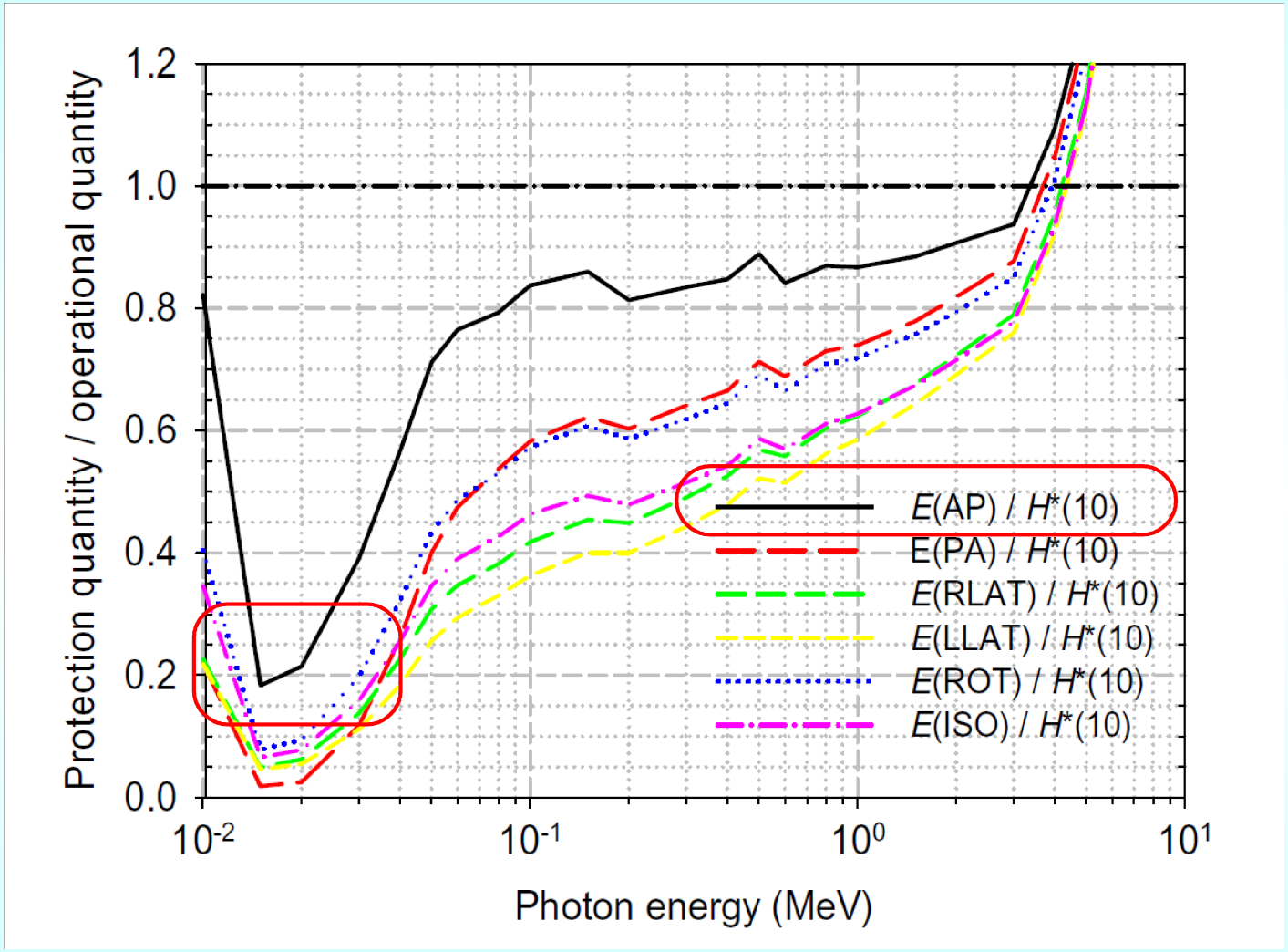
ICRP Pub116 Fig.5.2

E(AP) ≒ 1/5 Hp(10)
≒ 1/10 Hp(0.07)
at 20keV

It is assumed that in 10min demo, Effective Dose is resulted within 50 μ Sv.

Calculation with PHITS code using:
- Hp(0.07) or Air Kerma
- Energy spectrum
- Horizontal Distribution

Difference Between Protection and Operational Quantity



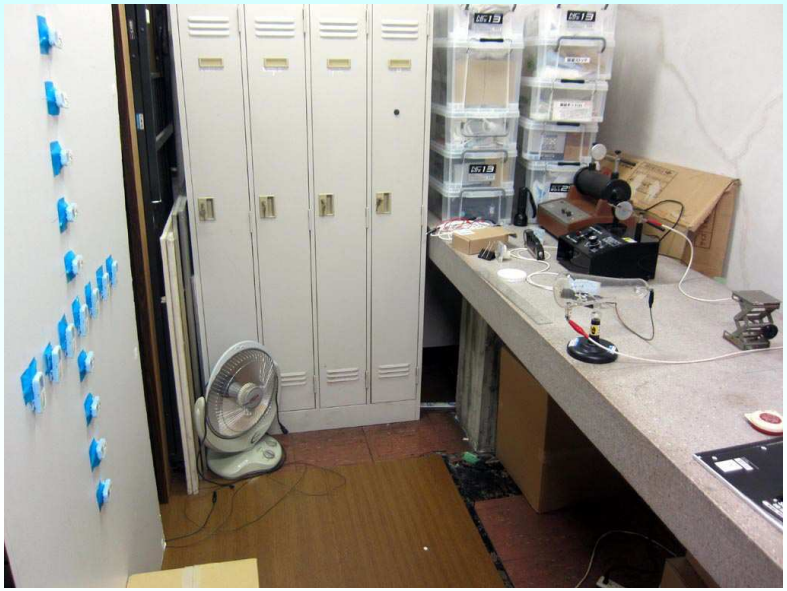
ICRP Pub116
Fig. 5.2

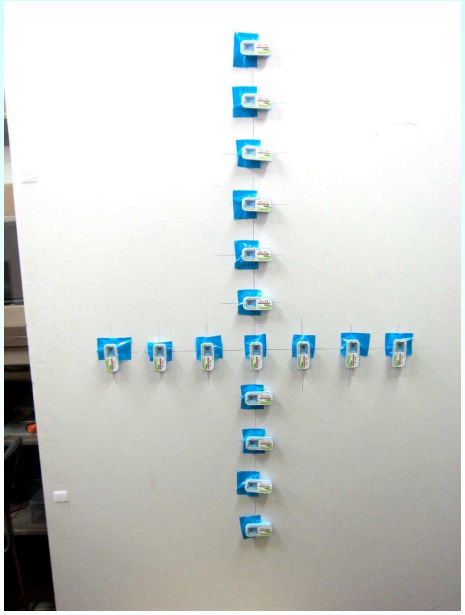
Ratios of photon effective dose (present report) to ambient dose equivalent.
Students observe a Crookes tube, then orientation is fix to AP.
At 20keV, H*(10) gives 5 times overestimation than Effective Dose.

Horizontal Distribution

At a distance of 1m, holizontal distribution is measured by Glass Badge at once.

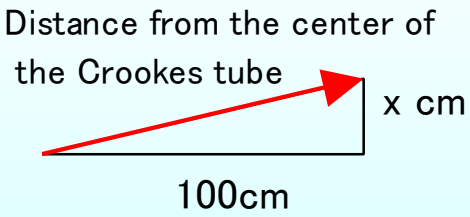
At 60cm shift from the center, the dose was gently reduced to 70%.





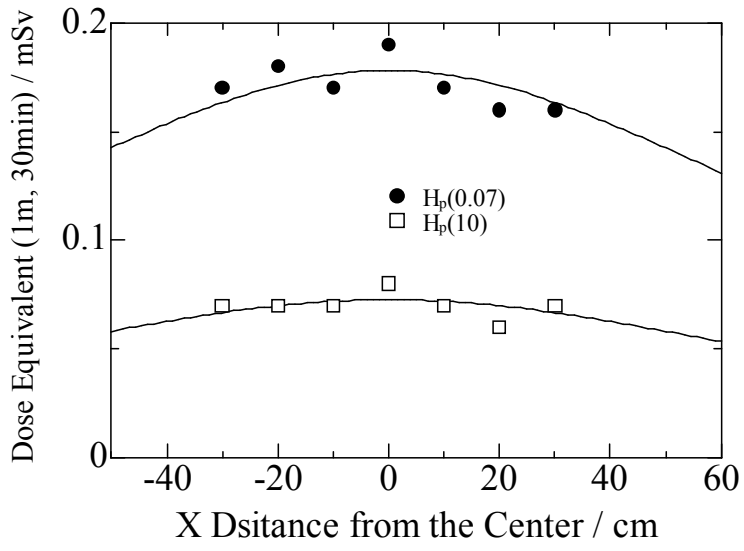
Fitting curve was obtaind as

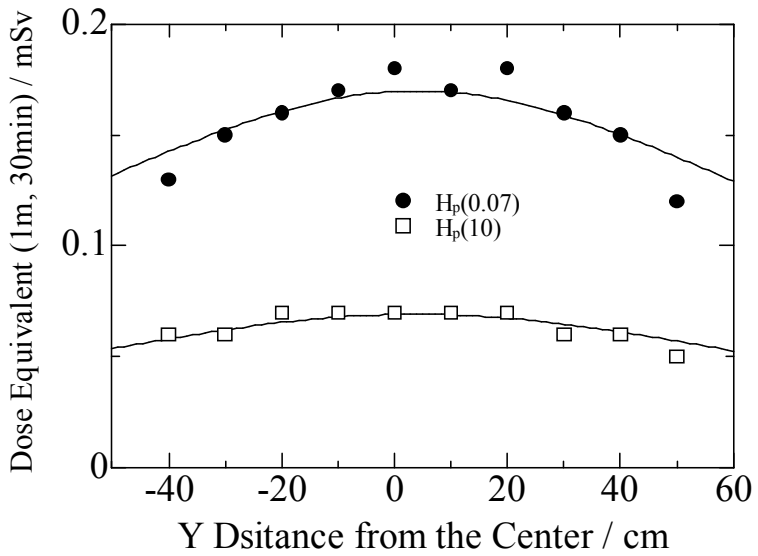
$a/(100^2 + (x+b)^2)$



Fitting curve showed a little higher value than the experimental for Hp(0.07).

It may represent the angle to the glass of tube.





Conclusion

・Character of X-rays from Crookes tube was investigated.

・Conventional survey meters shows quite low dose that gives misunderstand for protection.

・Solid state dosimeters like radiophotoluminescence badge is good solution to investigate the dose distribution in education field.

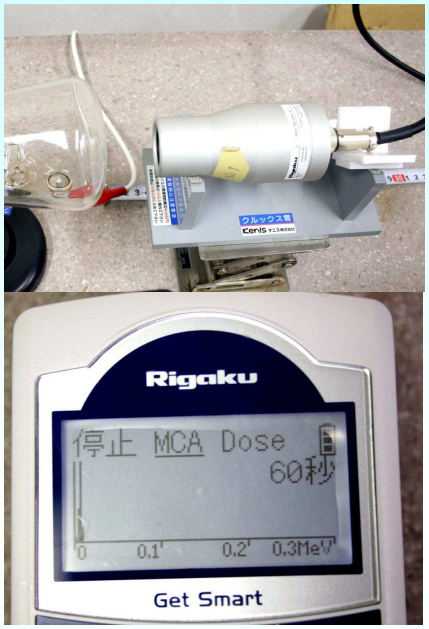
・Some equipments which hold few gas inside radiate quite strong X-rays even with the minimum power setting. Then, Discharge Electrode works as safety device. The distance must be kept smaller than 20mm.

・For low energy X-rays, $H_p(10)$ does not represent effective dose. Protection quantity is now investigated with experimental values and PHITS code.

・Radiation protection for general public people is not adopted to Japanese domestic law. Furthermore, dose constraint for education field is not discussed well. Protection rule and regulation situation in the world is required to establish the ***Comon Guideline for Radiation Safty in Education field***.

NaI scintillation survey meters for low energy X-rays

Fuji Electric NHC6
ϕ 12.7 × 12.7mm NaI scintillator
Range X-ray 8～300keV（～60 μ Sv/h),
γ -ray 50～1500keV（～600 μ Sv/h）



Rigaku Get Smart XU
NaI scintillator
Range 5～300keV（～10 μ Sv/h）

Not only general purpose NaI scintillator covered by SS housing, but also special equipment for low energy X-ray cannot measuree X-rays from Crookes tube.

Arrised from the pulse shape radiation