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for the Cluster Klystron**

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Abstract The cluster klystron project required a beam monitor to check the quality of the hollow beam shape. Since the power density of the beam is very large, a common phosphorescent screen doesn't work. We investigated various types of monitors. The related problems were also discussed.

THE ISSUE

The cluster klystron project required to set up the MIG gun test. A big concern is the quality of the beam: can it pass through the drift tube with a designed ring shape - a good hollow shape beam. First of all, we have to have some way to monitor the profile of the beam. However, the beam current as well as the energy per bunch is pretty high. A normal screen will, most likely, be damaged. Thus a careful investigation is necessary.

Various methods have been investigated. Based on it some options were proposed.^[1] We considered the simplest way is to use a foil intercepting the beam and monitor its infra-red and/or visible light image. The material could be tungsten or tantalum, or carbon. Tantalum seems the best. The disadvantage is that the dynamic range is narrow. Thus if the beam energy is too high, the foil will be burnt. If it is too low, the temperature will be too low to show a clear image. The ratio of maximum to minimum is only 4 to 5, and the level is not adjustable.

An X-ray image detected by a pin-hole camera is another option. The intensity is adequate to be detected and the dynamic range is only limited by the sensitivity of the camera. However, it needs an X-ray image intensifier which converts an X-ray image to a visible image. The resolution depends on the pin hole and is no better than twice of the diameter.

A phosphorescent film layered on the back of beryllium foil is another option. The luminescence is not due to the electrons, but stimulated by the X-rays produced by the electrons hitting the beryllium foil at the point just preceding the phosphorescent. This avoids the risk that direct bombardment will damage the phosphorescent layer.

Following is a list of the beam parameters, on which the quantitative estimate is based.

1. The cluster klystron project was terminated in 2001 due to the shortage of budget and other factors. This file is for documentation that may serve as a reference.

Table 1: The beam parameters

<u>Parameter</u>	<u>Symbol</u>	<u>Value</u>	<u>Unit</u>
Peak Voltage	V	100	kV
Peak Current	I	100	A
Pulse duration	τ	350	nS
Perveance		$3.16 \cdot 10^{-6}$	A/V ^{1.5}
Energy per shot		3.5	Joule
Charge per shot		35	μ C
Electrons per shot		$2.2 \cdot 10^{14}$	particle
Beam outer radius		0.42	cm
Beam inner radius		0.21	cm
Beam cross section		0.416	cm ²
Peak Current density		240	A/cm ²
Peak Power density		24	MW/cm ²
Energy density		8.4	J/cm ² per shot
Electron density		$5.25 \cdot 10^{14}$	1/cm ² per shot
Electron energy density	E	$5.25 \cdot 10^{13}$	MeV/cm ² per shot

Note these data are maximum values. Lower values must be applied during experiment and thus the monitor must also be workable at those lower values.

VARIOUS METHODS

Many methods have been investigated to see if they fit our need. They all have some advantages but are suited only for certain conditions. Following brief descriptions give general ideas for reference.

Normal phosphorescent screen

Phosphorescent screen has been widely used for imagery, but usually limited to low beam current and low voltage. Beam voltage used in image tubes is normally no more than 20 kV. Some accelerator beam profile monitors also use phosphorescent screen, its energy being so high that it penetrates the screen with only a little loss.

SLAC did an in depth study on the phosphorescent screen ^[2] of different manufacturers and colors about their linearity, uniformity, low radiation damage and a suitable emitted wavelength for use with television camera. Most of the screens were produced by settling powdered phosphor onto aluminum substrate with a thickness of 0.016 in.(0.4 mm) or so. The deposited phosphor-binder layer was approximately 0.0035 inches (0.09 mm) thick. The screen was tilted with the beam axis and perpendicular to the camera axis so as to watch the beam profile. The screen resolution is better than 80 microns. Their record showed a maximum beam intensity of 10^{10} particles per pulse. Life tests were up to total 5×10^{15} electrons passing through the screen. Some screens were damaged.

It is considered that phosphorescent screens are suited for a modest beam inten-

sity. Its energy seems not critical providing it can penetrate the screen. The latter is not the case if beam energy only 100 keV or so.

Physical mark image

Burn-hole. In VLEPP,^[3] thin Al and Pb films were used to study the focusing for the 14 GHz klystrons. The films were placed inside the beam channel in a series specified locations. The value of expositions (number of shots) was defined at the condition to burn a hole at the film and then the subsequent beam would pass through without loss. Thus one could check the variation of the beam cross-section along the channel, see Fig. 1.

Fig.1 Burn hole as marks of beam shapes.

Fig.2 The images of partly burnt film

Viniprose film. A similar method was also used in Tomsk Polytechnic University, Russian^{[4][5]}. Instead of metal film they used viniprose film, which is coviny chlorid with the methyl methacrylate. see Fig. 2. The center part was burnt, (the center white part in the Figure), the rest part was not completely burnt but the color was changed that the more dark spaces conforms more current density. However, polygraphic opportunities are inhibitory represent exact correspondence between copy and original. The kinetic energy was 240 to 400 kV and 200A with 90 ns.

In Sandia National Laboratory,^[6] people studied the shape of beam with very strong current and relativistic energy, some 400 kV and 6-16 kA, by putting something in the beam path as a "witness plate". Beam hitting these materials will made physical marks on them. They have used graphite plate, brass plate and cellophane.

Graphite plate. The graphite is no less than 1 cm thick, and thus fully stops the beam. The beam leaves a burnt mark on it.

Brass plate. The beam ablates the surface of the smooth brass and leaves an image on it.

Blue cellophane film. The film is only 0.005 in (0.127mm) thick so the beam can pass through it. As it passes through, it deposits a small amount of energy which discolors the blue color leaving a mark of beam profile.

All above methods are destructive, and the witness plate (or films) have to be taken out from the vacuum chamber after testing. The marks are integrated information, can not be watched continuously. The burn-hole method is, of course, not applicable for a hollow beam.

Transition radiation and Cherenkov light image

A particle moving at a constant velocity crossing a boundary between two materials with different dielectric constants will produce transition radiation. A high speed particle moving in a dielectric, of which the light speed is less than the speed of the particle, will produce Cherenkov radiation. The transition radiation is also considered as a second order Cherenkov effect. Both radiations may be used as diagnostic tools.

Watski^{[7][8]} and his collaborators first considered the transition radiation in the optical range (optical transition radiation -- or OTR for short) as a diagnostic tool for relativistic beam. They worked on the beam with energy in the 30 to 72 MeV range. They demonstrated the radiation and its angular dependence. They used metal films (aluminum, gold or silver) deposited on Mylar foils.

It was found that the images produced from OTR were significantly sharper than the images produced from phosphor screen.

Castellano^[9] et. al. studied the OTR of a beam at energy as low as 1 MeV and showed its effectiveness as a diagnostic tool for long pulse beam.

ATF^[10] has studied OTR for use in the FEL experiments to diagnose the energy and the emittance of the electron beam as well as to image the beam profile. The energy they dealt with was about 4 MeV ($\gamma \approx 9$). The transition radiation was spread over a large angle.

In SNL^[6], the Cherenkov radiation was made use of to get time resolved information of a beam of their relativistic klystron. A piece of quartz was struck by the beam of about 400 kV and 5 to 20 kA in pulse. The image of the radiation was received either by a fast gated micro-channel plate camera or a streak camera. In NSLS, Yu^[11] also tried to use quartz to observe the OTR to get time resolution.

The property of almost instantaneous emission of OTR and Cherenkov radiation makes it possible to monitor the beam profile continuously. The property of energy dependence of OTR may also be used to monitor the energy variation along a macro-pulse with a rather high sensitivity.

However, it is recognized that the intensity of OTR is very much dependent on the incident beam energy. A beam of only 100 kV is considered too low to produce enough radiation. The Cherenkov effect seems too weak to work either, because the velocity of a 100 kV beam is only 0.55 of light velocity, slightly higher than light velocity in quartz.

Infra-red and visible light image

One way to monitor the beam shape is to use a thin foil of metal or carbon located in the path of a beam, which passes through the foil with some energy lost on it and heats it up with illumination. The Tandem Operation Group^[12] can make many kinds of foils with different materials and thicknesses, the thinnest is less than one micron.

This is considered workable. The difference in our case is that we should not let

the beam pass through but stop completely. The foil will not be too thin but the energy dynamic range is of concern. A detailed analysis will be described later.

X-ray image

The phosphorescent material (usually being powdered) is not durable under bombardment of a strong beam. It is considered that a refractory material can stand the bombardment and meanwhile produce the X-ray at every point where the electrons hit. Its X-ray image is a good representation of the beam profile.

We should define the term "X-ray image". For a medical X-ray diagnostic or a material inspection by X-ray, the obtained image is from a point X-ray source. The X-ray always goes along straight lines without any focus as used in a normal camera. In our case, concerned is the image of the X-ray source itself.

Is an X-ray camera commercially available? The **zone plate** is of most interest for X-ray focusing and under active development. To date the spacial resolution of zone plates for hard X-ray application is about half micron and focusing efficiency about 30 %. But most zone plates are designed for applications in 8 to 25 keV X-ray photon range, though higher energy plates can be developed. In addition, a zone plate is chromatic and a monochromator is required^[13].

In our case, the X-ray photon energy is up to 100 keV, and the spectrum is rather flat below this maximum. Thus a zone plate is not realistic.

A pin-hole X-ray camera, on the other hand, is considered much simpler and realizable. The spacial resolution is not critical in our case and can be arranged at rather short source-optical distance, and the problem of diffraction blurring is negligible^[13]. However, the pin-hole camera has very low optical efficiency. Some laboratories like SLAC have experience using pin-hole X-ray images as a diagnostic of beam interception but took minutes to get one picture. It may be no problem in a very strong beam struck as in the present case, but an intensifier is necessary. The quantitative estimate will be discussed later.

Converted image with a beryllium foil

R. Palmer suggested a scheme that a screen made of beryllium with phosphorescent material on the back. When the beam hits the beryllium, the produced X-ray will excite the phosphorescent material and convert the X-ray image to visible light image. The unique characters of the beryllium are its low specific gravity and high specific heat. The former implies a long particle stop range, the latter combining with a long stop range imply a lower temperature increment. The phosphorescent on the back will prevent the bombardment of the electrons. This is an interesting scheme. The numerical analysis shown later justifies the idea. The concerns are if the phosphorescent material is usable at high temperature, and if the phosphor will saturate and get poor contrast of the image. The toxicity of beryllium is another concern.

Wire net or sweeper

To monitor the profile of accelerator beams, sometimes a wire is used.^[12,14] A wire is swept across the beam and intercepts a certain amount of current, the detected signals as a function of angle can be processed to develop the profile. Tandem Van-de-Graff group has successfully used it to monitor the multi-MeV beam profile.

Thin wire net or matrix can also be used for monitoring particle trace without sweeping. In principle, a matrix of insulated wires intercepting current is able to develop the profile of the beam. However, it is limited to solid beams only. The information obtained from a pair of two perpendicular arrays of wires is not adequate to determine a profile of a hollow beam designed for a cluster klystron.

The net is sometimes called "Harps", that is formed by tungsten alloy wires stretched across the beam line. It can stand very high beam intensities. However, the size is usually rather large. It would be difficult to make small enough to fit our need.

Another scheme

Another method is to put a polaroid film on the path of the beam and then check its image. For a low current beam this may be workable, but very unlikely workable in our case.

HEATING PROBLEMS

Heat transport capability

Now that the beam can not pass through the screen, then a question is: can we increase the thickness of the screen to avoid overheating? Let's estimate the heat transport capability. Assume heat transfer through the thickness only. The transport heat power along the axis z can be expressed as:

$$P = KS \frac{\partial T}{\partial z} \quad (1)$$

where T is the temperature, K the thermoconductivity and S the cross-section area. For aluminum K is temperature dependent as shown below:

unit	cal/°C.cm. sec	Watt/°C.cm
20°C	0.57	2.4
300°C	0.64	2.7
400°C	0.76	3.2
600°C	1.01	4.2

Substituting the power density in question and the maximum thermoconductivity, 4.2 W/°C.cm, we get the temperature gradient to be 5.67×10^6 °C/cm or 567 °C/μm. Certainly this gradient is too high for aluminum. It means the power density is too high to be dissipated by conductivity, even for those materials, of which the conductivity is better than aluminum.

Therefore, we can conclude that the heat stays in the volume where the electrons transfer their energy within the pulse period. Increasing the thickness won't help.

Stop range

Now that the heat can not dissipate instantly, the second question is: what is the volume which absorbs the beam energy? Then we have to know the depth that a beam

can pass through, i.e. the stop range.

The definition of the "stop range" of an electron is the distance that the electron travels before coming to rest. Usually it is measured by g/cm^2 , the mass in gram per unit area, because the range is not sensitive with materials but depends on the mass it penetrates. Nevertheless, there is difference between high Z (atomic number) and low Z materials.

For an electron beam with energy of 100 KeV¹, the range for heavy material is^{[15](a)}:

$$R = 0.03 g/cm^2 \quad (1)$$

For low- Z material and $0.01 \leq T \leq 2.5$ MeV, an empirical equation is^{[15](b)}:

$$R = 0.412 T^{1.27-0.0954 \ln T} \quad (2)$$

where R is in g/cm^2 , T is the kinetic energy in MeV. For $T = 0.1$ MeV, it figures out²

$$R = 0.0133 g/cm^2 \quad (1)$$

The stop range in cm is:

$$\delta = R/\rho$$

where ρ is specific gravity in g/cm^3 .

Temperature increment

Assuming the specific heat is constant, and the beam energy loss is uniform along its range, and omitting the heat dissipation during the pulse (350 ns), the instant temperature increment, averaged³ in the volume, due to a single pulse is:

$$\Delta T = \frac{E}{C\rho\delta} = \frac{E}{CR}$$

where C is specific heat, E is energy density in J/cm^2 . Substituting $E = 8.4 J/cm^2$ from Table 1, the temperature increment was calculated as shown in Table 2. If the heat can not be dissipated completely before next pulse comes, the temperature increment will be accumulated by a certain amount (see analysis later). That makes things worse.

Table 2 shows the beam stop range of different materials with the beam energy of 100 KeV, as well as those parameters like specific gravity, specific heat, thermal conductivity. Note that all those parameters are not exact constants, they normally change with temperature. Nevertheless it is a reasonable approximation.

As is shown, the instant temperature increment of aluminum can be 700°C, so it will melt. On the other hand, as expected, the temperature increment of beryllium is

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1. For other energy, see Appendix Fig. A-1
 2. There are some discrepancy between this empirical formula and calculated table, e.g. [16], published in 1965, which gives a little optimistic results. We are not sure which is more precise. Note this is only an estimate, the discrepancy will not make significant change on the conclusion.
 3. The average means omitting the non-uniformity.

Table 2: Beam stop range in different material

Material			Al	C	Be	W	Ta
	Symb	Unit					
Atomic number	Z		13	6	4	74	73
Specific Gravity	ρ	g/cm ³	2.7	≈ 2	1.848	19.3	16.6
Specific Heat	C	J/g K	0.9	0.712	1.825	0.133	0.14
Thermoconductivity	K	W/m K	237	80-240	201	173	57.5
Melt point		°C	660	3650	1278	3410	2996
Mass stop range	R	g/cm ²	0.0133	0.0133	0.0133	0.03	0.03
Stop range	δ	μm	49	67	72	16	18
Instant temp. increment	ΔT	°C	700	884	345	2105	2000

much lower than the others, only 345°C, much less than the melting point. The refractory materials can also stand the temperature increment.

IMAGE RESOLUTION AND MAXIMUM REPETITION RATE

It is of concern that if the heat dissipation is too fast, the edge of the temperature image will be smeared during the camera shutter time, meaning the resolution is poor. On the other hand, if the heat dissipation is too slow, the temperature remains pretty high when the next pulse comes, the images of two pulses overlap and may cause over-heat. It means the repetition rate is limited. Therefore, we have to check quantitatively the heat dissipation rate.

The heat dissipation equation is:

$$\frac{\partial T}{\partial t} = \frac{1}{C\rho}[KV^2T - L_R(T)] \quad (1)$$

The first term on the RHS is the contribution due to heat conduction, while the second term is due to radiation. Where C is the specific heat, and ρ specific gravity, K conductivity coefficient. We assume they are constants for simplicity. L_R is a radiation loss parameter with

$$L_R(T) = \frac{2R}{\delta} \quad (2)$$

where δ is the thickness of the foil, and R is the radiation-temperature dependence with

$$R = \varepsilon\sigma T^4 \quad (3)$$

where T is the Kelvin temperature, ε is the emissivity, and σ is the radiation coefficient of black body:

$$\sigma = 5.670 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4 = 5.670 \times 10^{-12} \text{ W/cm}^2 \cdot \text{K}^4$$

For simplicity, let's consider those contributions separately.

Heat dissipation due to conductivity

At first, we omit the radiation loss, then the above equation becomes the standard heat-conduction equation.

$$\frac{\partial T}{\partial t} = a \nabla^2 T \quad (4)$$

where $a = \frac{K}{C\rho}$ is considered to be constant. (5)

For the case of a foil, we assume cylindrical symmetry, and that at the edge of the foil is a heat sink with constant temperature of 300K, or room temperature, and the initial temperature distribution is a rectangular function that the inner part (beam spot, assuming $r < 0.5\text{cm}$) is at an uniform temperature of T_0 , while the rest is at the same temperature as that of the heat sink. Then the above equation is:

$$\frac{\partial T}{\partial t} = a \left[\frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \right] \quad (6)$$

with initial condition:

$$T(r, 0) = \begin{cases} T_0 & 0 \leq r \leq 0.5 \\ 300 & 0.5 < r \leq R_{max} \end{cases}$$

and boundary condition: $T(R_{max}, t) = 300$ (unit of temperature is K)

For normalization, using the following conversion:

$$u = \frac{T - 300}{T_0 - 300} \quad \rho = \frac{r}{R_{max}} \quad \tau = \frac{at}{R_{max}^2} \quad (7)$$

we get:

$$\frac{\partial u}{\partial \tau} = \frac{1}{\rho} \frac{\partial u}{\partial \rho} + \frac{\partial^2 u}{\partial \rho^2} \quad (8)$$

and

$$u(\rho, 0) = \begin{cases} 1 & 0 \leq \rho \leq 0.5 \\ 0 & 0.5 < \rho \leq 1 \end{cases}$$

$$u(1, \tau) = 0$$

The solution is:

$$u(\rho, \tau) = \sum_{m=1}^{\infty} C_m e^{-\mu_m^2 \tau} J_0(\mu_m \rho) \quad (9)$$

where $C_m = \left(\int_0^{0.5} J_0(\rho) \rho d\rho \right) / \frac{1}{2} [J_1(\mu_m)]^2$ (10)

J_0 and J_1 are the zero and first order Bessel functions;

μ_m is the m-th root of zero order Bessel function;

Fig.3 shows the numerical results via computer.^[17]

Fig. 3 The temperature distribution at different times

Table.3 shows the parameter α and T_0 for different materials

Table 3:

	Unit	W	C	Al	Be	Ta
α	cm^2/sec	0.67	~1	0.98	0.6	0.25
T_0	K	2378	1153	973	617	2273

Substituting the parameters we get the temperature distribution at different times

Heat dissipation due to radiation

Omitting the first term on RHS of (1) and substituting (2) and (3), we get:

$$\frac{\partial T}{\partial t} = -bT^4 \quad (11)$$

where $b = \frac{2\epsilon\sigma}{C\rho\delta}$ is again considered to be constant. (12)

The solution of Equation (11) is:

$$t = \frac{1}{3bT_0^3} \left(\frac{T_0^3}{T^3} - 1 \right) \quad (13)$$

This indicates the time needed to reduce temperature from T_0 to T . Following table shows the numerical examples.

Table 4:

	Unit	W	C	Be
Foil thickness δ	$10^{-3}cm$	1.55	7	7.25
Initial temp. T_0	K	2378	1153	617
b	$10^{-10}/sec K^3$	2.85	1.14	0.46
$t (T/T_0 = 0.5)$	sec	0.61	13.35	214
$t (T/T_0 = 0.1)$	sec	87	1905	30554

This shows that the temperature reduction due to the radiation is very slow. Therefore we can ignore it in comparison with the conductivity dissipation.

Cumulative effect

There is a question that a bunch of beam hits the screen will result in a temperature increment and will not drop down to the original temperature before the next pulse comes. The next hit will result in a higher temperature than the former hit, and the temperature will get higher and higher. The question is: will it be eventually overheated?

Assuming T_n , the temperature above room temperature, is a series as follows (i.e. a function of n):

$$T_1, T_2, T_3, \dots, T_n \dots$$

$$T_1 = 0 + \Delta T$$

$$T_2 = qT_1 + \Delta T$$

$$T_n = qT_{n-1} + \Delta T$$

q is the drop rate, meaning the percentage of the temperature drop down before next pulse coming. $q < 1$.

It is easy to figure out:

$$T_n = (q^{n-1} + q^{n-2} + \dots + q + 1)\Delta T$$

$$\lim_{n \rightarrow \infty} T_n \rightarrow \frac{\Delta T}{1 - q} \quad (14)$$

Therefore, the final temperature is limited. e.g. $q = 0.1$, $T_n \rightarrow 1.11 \Delta T$, i.e. 11% higher than the first hit. This is acceptable. The parameter q and the relation (14) is a way to check the acceptable maximum repetition rate.

X-RAY IMAGE

A beam hitting a target will produce X-rays. Every spot hit by electrons is an X-ray source. Thus if a target or a foil is put in the path of the beam, the X-ray image will represent the beam profile. The X-ray image can also be a diagnostic of the locations which

intercept the beam undesirably. As mentioned before, an X-ray camera is not commercially available so far. A pin-hole camera was considered. Since the beam in question is very strong in power, say 100 kV times 100 ampere, the X-ray emission is much stronger than a common X-ray tube, a pin-hole camera is considered workable, though its receiving efficiency is much less than a normal camera. A structure is shown in Fig. 4. The quantitative analyses are described below.

Fig. 4 The structure of a pin-hole camera

The X-ray radiation intensity

The energy loss of a beam hitting a target includes collision loss and X-ray radiation (i.e. bremsstrahlung radiation) loss. For low energy beam, like 100keV, collision loss dominates and eventually is converted to heat, while the radiation loss accounts for only a small part. The radiation yield, Y , is defined as the average fraction of its energy that an electron radiates. The average means not only for all particles, but also the radiation of one particle from its initial velocity until completely slowing down. The latter is by no means uniform because a low speed electron has little radiation. It can be calculated according to the following approximate formula^{1,[15][18]}:

$$Y = \frac{6 \times 10^{-4} \cdot ZT}{1 + 6 \times 10^{-4} \cdot ZT}$$

where Z is the atomic number, and T the incident kinetic energy in MeV. In our case the T is rather small, the yield is almost proportional to the atomic number. So, a high- Z material is preferable if an X-ray image is applied.

The total energy per pulse is the product of the number of electrons and the kinetic energy in electron-volts.

$$E = 5.25 \times 10^{14} \times 100 \text{ kV/cm}^2 = 5.25 \times 10^{13} \text{ MeV/cm}^2 \text{ per pulse}$$

1. For very low Z , the yield is higher than that by this formula^[16], but still in the same order.

The total radiation energy is YE . It can also be expressed in joules via the conversion formula:

$$1 \text{ MeV} = 1.602 \times 10^{-13} \text{ joule}$$

The maximum energy of an X-ray photon is equal to the initial kinetic energy of the incident beam. However, the photon energy spectrum is approximately flat out to this maximum. We assume the average photon energy is 75 KeV or 0.075 MeV. Then the photon density radiated from unit area of the target is:

$$D_{pt} = YE/0.075$$

Receiving intensity in a pin-hole camera

For a high energy beam the bremsstrahlung radiation is emitted mostly in the forward direction. But 100 kV is not a high energy to this point. To be conservative, we assume it radiates uniformly along all 4π steradian. If a pin-hole is applied, the radiation intensity at the screen located at the back of the pin-hole will be much reduced. The reduction rate is¹:

$$\alpha = \frac{d^2}{16f_2^2} \cdot \frac{f_1^2}{f_1^2 + r_b^2}$$

where d is the diameter of the hole, f_1 is the distance between the hole and the target (radiation source), f_2 is the distance between the hole and the receiver screen, and r_b is the radius of the beam. Assuming $d = 0.03\text{cm}$, $r_b = 0.42 \text{ cm}$, $f_1 = 2 \text{ cm}$, $f_2 = 3 \text{ cm}$, then $\alpha = 6.0 \times 10^{-6}$. The photon density at the receiver screen D_{pr} , is shown on the 6th row of the Table 5

Table 5:

Material			C	Be	Ta	W
	Symbol	Unit				
Atomic number	Z		6	4	73	74
X-ray yield ^a	Y	10^{-3}	0.36	2.4	0.44	4.44
X-ray production ^b	YE	10^{11}MeV/cm^2	0.19	0.13	2.3	2.3
X-ray energy density	D_E	10^{-2}J/cm^2	0.30	0.21	3.7	3.7
X-ray density at target	D_{pt}	10^{12}p/cm^2	0.25	0.17	3.1	3.1
X-ray density at receiver	D_{pr}	10^7p/cm^2	0.15	0.10	1.9	1.9
Photon density after intensifier		10^9p/cm^2	0.22	0.15	2.8	2.8

a. At incident beam energy of 100 keV = 0.1 MeV

b. At incident electrons energy density of $E = 5.25 \cdot 10^{13} \text{ MeV/cm}^2$.

1. See Appendix B for detail

Luminosity and camera features

Now we know the X-ray photon (or quantum) density, the next question is: can it fit a camera, of which the sensitivity is high enough to monitor the beam shape in a single shot and in a real time, or on the contrary, do we have to use a film exposed to many pulses and then develop it?

A camera usually specifies its sensitivity by illuminance and shutter time. The product of them corresponds to the received photon density. The unit of illuminance is Lux, which can be converted to the photon density by formula:¹

$$1 \text{ lux} \approx 4.1 \times 10^{11} \text{ photon/sec.cm}^2$$

For example, a PULNiX CCD camera of type TM-745E² has features of sensitivity of 0.5 Lux and smearless shutter 1/60 to 1/10,000 sec. Then the required photon density is:

$$\begin{aligned} & 8.3 \times 10^{-3} \text{ to } 5 \times 10^{-5} \text{ Lux-sec} \\ \text{or} & 3.4 \times 10^9 \text{ to } 2.1 \times 10^7 \text{ photon/cm}^2 \end{aligned}$$

Comparing it with Table 5, it shows that the intensity is in the margin of the camera sensitivity. It is also questionable if the specifications of sensitivity and the fastest shutter time can be satisfied simultaneously. Besides, the specification is for visible light, it will most likely reduce the sensitivity for X-ray. Therefore, an X-ray CCD intensifier is necessary. A DEP Co. (Delft Electronische Producten) intensifier can convert an X-ray quantum into visible light with 150 times photo gain.^[19] The last row of the Table 5 shows the results, which is within usable range for a camera. Table 5 shows the data for different materials.

Resolution and edge sharpness

The definition of the resolution is the minimum distance between two points on the target, that their images will not overlap each other. For a pin-hole camera it is:

$$\Delta = \left(1 + \frac{f_1}{f_2}\right)d$$

where d is the diameter of the hole. This can be determined from Fig.5.

The interception effectiveness for X-rays is determined by the attenuation formulated as:

$$A_{tt} = I / I_0 = e^{-\mu \rho T}$$

where ρ is the specific gravity, T is the thickness of the lens. and μ is the attenuation coefficient, a function of photon energy. For tungsten, μ equals $5.91 \text{ cm}^2/\text{g}$ in 50 keV and $4.43 \text{ cm}^2/\text{g}$ in 100 keV , but has a minimum $2.49 \text{ cm}^2/\text{g}$ in 69.5 keV . If we choose

-
1. 1 Lumen $\approx 1.47 \times 10^{-3} \text{ Watt}$ @ $\lambda = 5.55 \times 10^{-7} \text{ m}$, the energy of a photon with $\lambda = 5.55 \times 10^{-7} \text{ m}$ is $3.579 \times 10^{-19} \text{ Joule}$, therefore 1 Lumen approximately equal 4.1×10^{15} photons, and $1 \text{ Lux} = 1 \text{ Lumen/m}^2$, so, $1 \text{ Lux} \approx 4.1 \times 10^{11} \text{ photons/sec.cm}^2$.
 2. That is one we have in hand.

$T = 0.5 \text{ cm}$, then minimum A_{tt} is 3.67×10^{-11} . For a tantalum lens it will be 1×10^{-9} . So the thickness should be adequate for interception in both cases

Fig. 5 The resolution for a pin-hole camera

At the edge of the hole, the thickness t increases linearly (see Fig. 4) as:

$$t = 2x \cot \theta$$

The edge sharpness can be featured by the differentiation of the attenuation with respect to the distance from the edge, x . It is:

$$\frac{dA_{tt}}{dx} = -\mu \rho e^{-\mu \rho t} \frac{dt}{dx}$$

$$\left. \frac{dA_{tt}}{dx} \right|_{x=0} = -2\mu \rho \cot \theta = -\frac{1}{\delta}$$

where $\delta = \frac{\tan \theta}{2\mu \rho}$ and we have $A_{tt} = e^{-\frac{x}{\delta}}$

δ has the dimension of length, implying that the intensity will decay to $1/e$ at a distance of δ from the edge. Substituting $\theta = 25^\circ$, then for tungsten, $\delta = 0.049 \text{ mm}$, for tantalum $\delta = 0.056 \text{ mm}$. So, the image edge sharpness should be satisfied. From the above formula, the smaller the span angle θ , the better. But the span angle should be large enough that the image can be viewed from the hole.

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APPENDIX A The ranges of different materials and inject energy

The following figure shows the ranges of electrons, protons and alpha particles in light materials (water, bone and muscle) and heavy material (lead) expressed in g/cm^2 . (Quoted from J. E. Turner^[15], Fig.4.4, p.83.)

Heavy Charged Particles and Matter

APPENDIX B Pin-Hole Reduction Factor

Assume: ΔS_1 is the cell area of the target, ΔS_2 the corresponding image cell area, f_1 the distance between the target and the pin-hole, f_2 the distance between the image and the pin-hole, d the diameter of the pin-hole, ($\pi d^2 \ll \Delta S$), R the radiation intensity (total number of photons radiated from unit area, and assume it radiates uniformly along the 4π solid angle.)

Then the luminous intensity is:

$$\Delta S_1 I_1 / 4\pi$$

The solid angle of the pin-hole is:

$$\pi d^2 / 4f_1^2$$

The total number of photons passing through the hole and reaching the ΔS_2 is:

$$\Delta S_1 I_1 d^2 / 16f_1^2$$

Note
$$\frac{\Delta S_2}{\Delta S_1} = \frac{f_1^2}{f_2^2}$$

The luminous intensity at the image is:

$$I_2 = \frac{\Delta S_1}{\Delta S_2} \cdot \frac{I_1 d^2}{16f_1^2} = \frac{d^2}{16f_2^2} I_1$$

So the reduction factor is:

$$\alpha = \frac{I_2}{I_1} = \frac{d^2}{16f_2^2}$$

and the magnification is f_2 / f_1 .

At the beam edge, where the distance to the hole is a little larger, the reduction factor will be :

$$\alpha = \frac{d^2}{16f_2^2} \cdot \frac{f_1^2}{f_1^2 + r_b^2}$$

where r_b is the radius of the beam.