OTR screens: What beam current can they stand?

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Abstract

This note presents a calculation of the temperature rise of aluminum and gold foils traversed by an electron beam. Aluminum foils of 0.8 μm and 1.5 μm oriented at 45 degree with respect to the beam trajectory, are used at several locations in the machine. The results indicate that the foil should stand the full 200 μA current for beam as small as 50 μm in both x and y directions.
A 5 MeV Mott polarimeter is being designed for the polarized source; it uses thin gold foils placed into the beam trajectory; the temperature calculation indicates that foils thinner than 0.2 μm should stand more than 80 μA CW. The transition radiation (TR) emitted from the gold is much weaker with a 5 MeV beam than with the higher energy (> 45 MeV) ones already monitored in the machine. An estimate of the TR power in the visible indicates there is enough light for a CCD camera associated to a digitizer to measure the position and profile of a 25 μA beam.

1.0 Introduction

Several Optical Transition Radiation screens have been built by replacing the standard viewer screen with a thin aluminum foil, they are now installed in the machine (injector, each end of each linac, extraction region, near Hall C target). The calculation presented here indicates that they can easily stand 200 μA, the maximum CW beam of the accelerator.
The same kind of calculation will be applied to the gold foils used in the present design of a 5 MeV Mott polarimeter for the polarized source. In that case, the foil will stand more than 80μA which is much more than needed. Then, a calculation of the intensity of the optical transition radiation shows there is enough light for monitoring the beam position and profile on the foil with a CCD camera placed at the optimum angle; however there is little safety margin.

2.0 Aluminum foil

2.1 Energy deposition

The energy deposition has been computed using the EGS4 fortran code and was found to be, for aluminum intercepting electrons of kinetic energy in the range of 45 to 4000 MeV, about 410 eV/μm. This value takes into account the energy that is taken away by secondary emission of electrons and other neutral particles. An analytical computation we did, using the Bethe formula shows that the energy reduction due to secondary electrons seems to be around 20% for thin foils[1].

Hence the power that is deposited by the beam is:

$$P \approx \left.\frac{dE}{dx}\right|_E \Delta x I$$

where I is the beam current, in Amperes, traversing a foil of thickness Δx.

2.2 Maximum temperature versus beam current

We first simulated a 0.8 μm thick Aluminum foil interacting with a 50 μm beam at 200 μA striking the foil under an angle of incidence of 45 degree in order to check our computation code according to previous paper on this topics [3]. The figure 3 compares the evolution of intensity versus the temperature that is reached at the center of the beam taking into account or not the radiated power.

In the case where the radiated power is considered (lower curve), we assume the emissivity to be linear depend upon energy in the range of temperature we are dealing with. Hence we did a linear regression using the data provided by literature [3] which are plotted in annexe C. Emissivity was then related to energy through the formula:

$$\varepsilon = 0.005 + 0.05 \times E\ (\text{eV})$$

Anyway, as we can see on Figure 2, taking into account radiated power of Al foil does not allow significantly higher intensity beam to interact.

1. In the case of wire, a CERN rule of thumb gives that the energy deposited is 30% (cf ref[1])

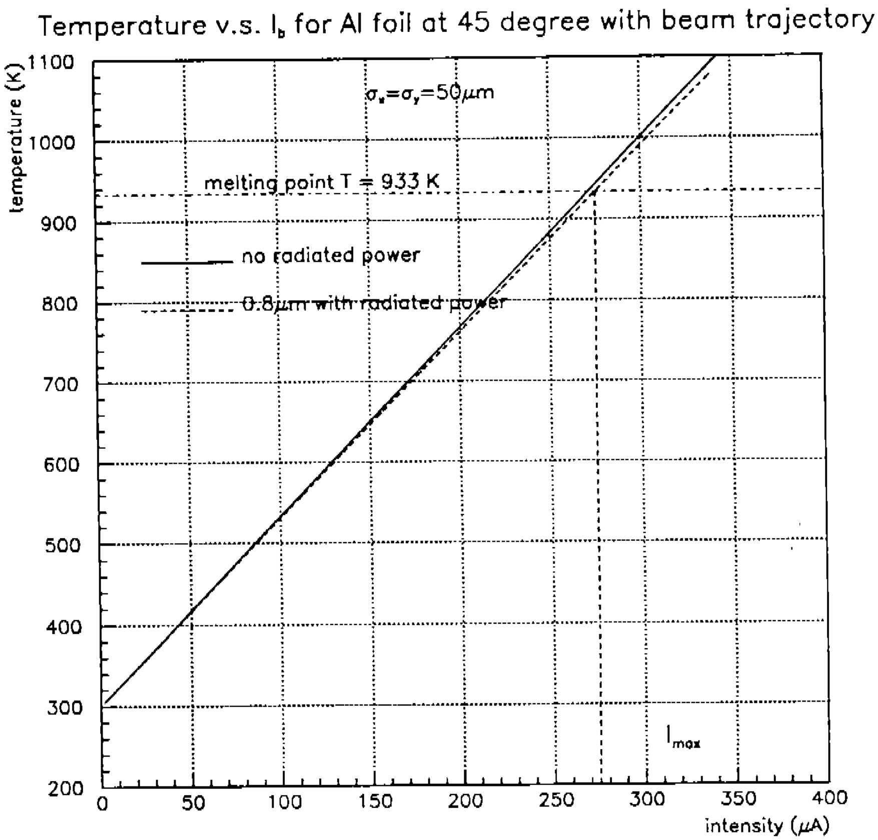


FIGURE 1. Effect of radiated power on T v.s. I curve for Al foil of thickness 0.8μm, beam sizes $\sigma_y = \sigma_x$ =50μm, angle of incidence: 45 degree. Without considering the radiated power, the temperature at the center of the beam trajectory does not depend on the foil thickness provided that the support can evacuate the heat the beam deposits

2.3 Maximum beam current versus beam dimension σ

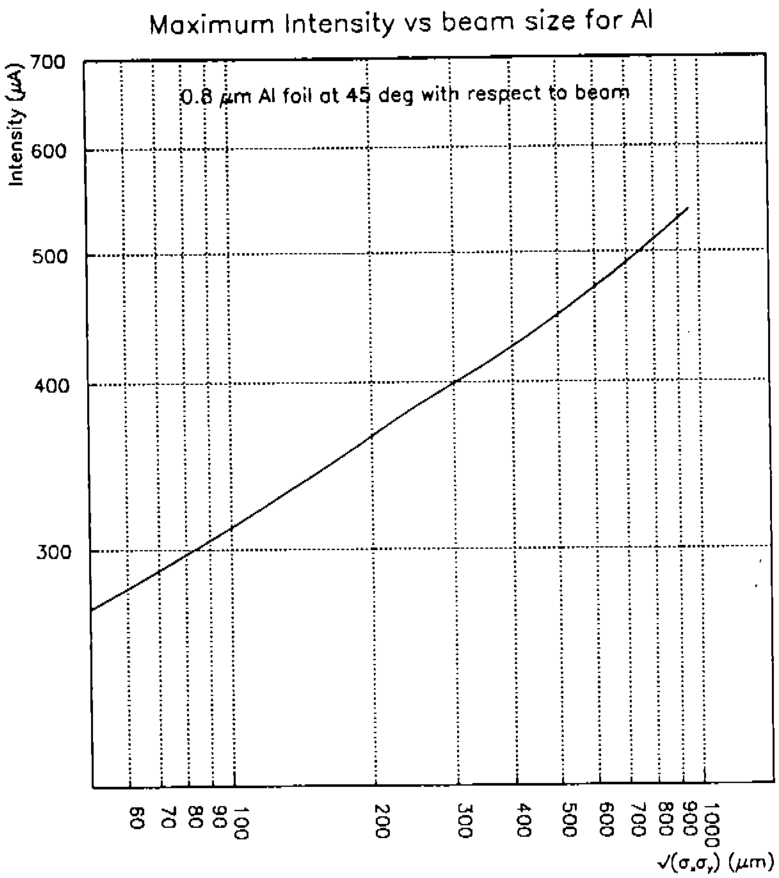


FIGURE 2. Imax v.s. beam dimensions for an incidence angle of 45 deg and a aluminum foil thickness of 0.8 μm.

2.4 Heat radiated power versus OTR power

One the other hand, we tried to estimate what is the total power which is radiated in the visible spectrum in order to check if this power is much less important compare to the power associated to the optical transition radiation. This will allow us to state if an optical filter is required. We assume the emissivity to be constant over the visible spectrum and took its value equal to 0.08.

In Table 1, we compare emitted power due to heating and to the emitted power due to TR for different beam current. To compute the heating power value we state that its major contribution comes from the area traversed by the beam.

The total radiated power due to transition radiation have been evaluated using the formulae of Annexe A.

Beam current (μA)	50	100	150	200
Heating power (W)	3.6×10^{-23}	3.2×10^{-19}	2.0×10^{-16}	2.3×10^{-14}
OTR power (mW)	0.07	0.28	0.63	1.12

TABLE 1. comparison of heating power and radiated power for aluminum (thickness =0.8 μm and beam energy is 45 MeV)

As we can notice, for aluminum foil OTR power is much more important than 'black body' power. Heating power should not prevent adequate devices from seeing optical transition radiation.

3.0 Gold foil

3.1 Energy deposition

To compute the energy deposition, we took again the $\frac{dE}{dx}$ obtained using EGS4 computer code, which is 63.8 MeV.cm^{-1} for gold.

3.2 Maximum temperature versus beam current

As we already mentioned, investigating the Au foil 'T v.s I curve' will allow us to determine if such foil could be used to design O.T.R instruments in order to make some measurement at the injector location. At such location, we are expecting a beam energy of 5 MeV, a beam radius (σ) of 0.5 mm. Different foil thicknesses are under consideration (t=0.2, 0.1, 0.05 μm).

For gold, we assumed that the emissivity could be considered as a constant over the range of energy we are dealing with (*cf* Annexe C). We took for emissivity value: 0.005.

Figure 4 represents the temperature of the foil versus the beam intensity for three thicknesses. At first sight, it seems we could reach a beam intensity up to about 80 μA for a thickness of 0.05 μm which is more than what we need.

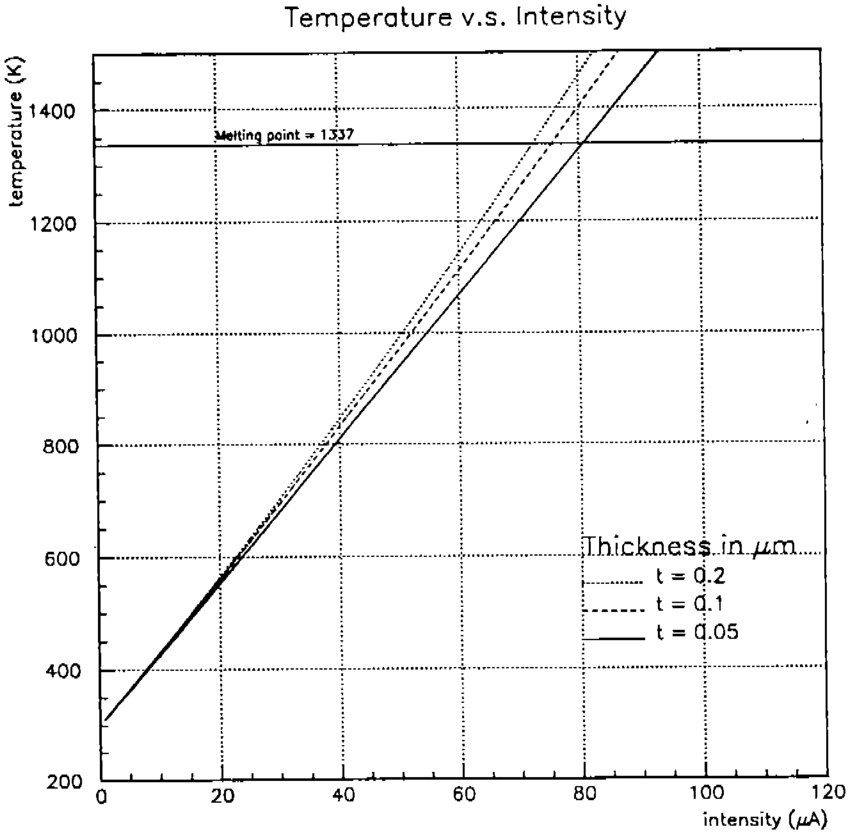


FIGURE 3. Temperature vs. Intensity curve for different thicknesses beam size: $\sigma_y = \sigma_x = 0.5$ mm, angle of incidence=0 degree

3.3 Maximum beam current versus beam dimension σ

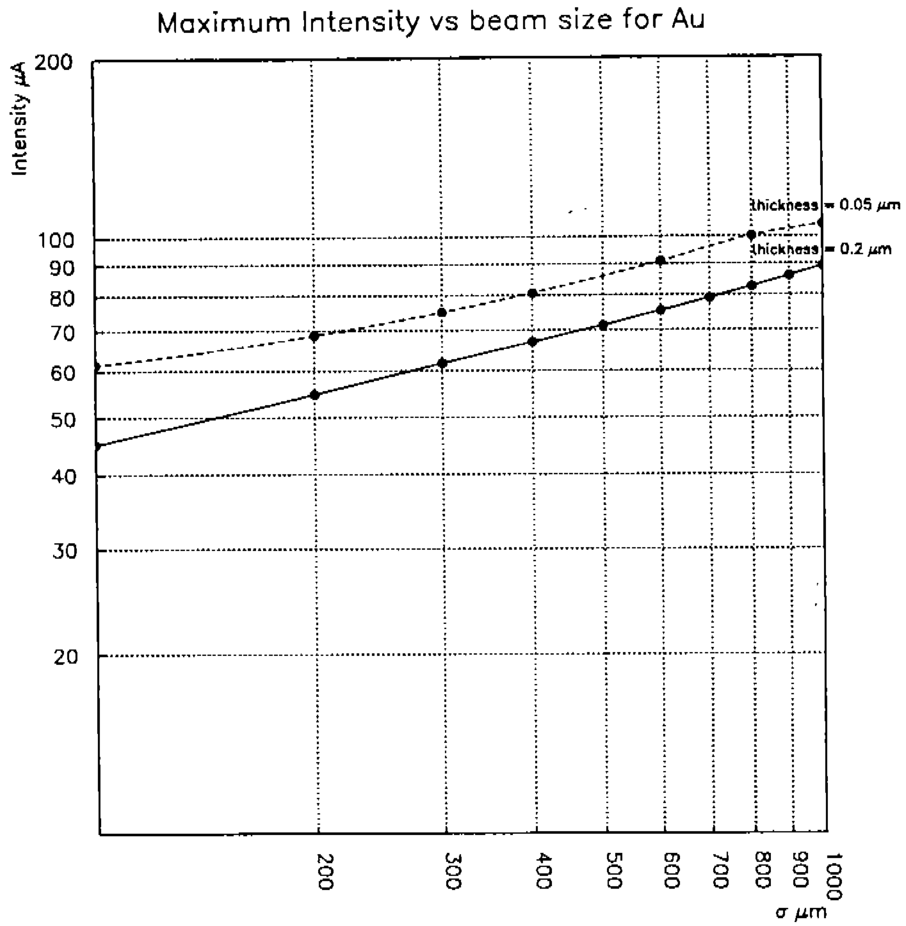


FIGURE 4. Maximum current vs. beam dimension for two different thicknesses. The dots represent results obtained by numerical computation. The angle of incidence is 0 degree.

3.4 Heat radiated power *versus* OTR power

In Table 2, we compare OTR power with heat power for gold foils at different intensity. We assume that over the optical range, gold emissivity can be described as follow:

$$\varepsilon = 0.024\,E_{photon} \quad \text{for } 1.5\text{ eV} < E_{photon} < 2.1\text{ eV}$$

$$\varepsilon = 1.18\,E_{photon} - 2.43 \quad \text{for } 2.1\text{ eV} < E_{photon} < 2.6\text{ eV}$$

$$\varepsilon = 0.64 \quad \text{for } 2.6\text{ eV} < E_{photon} < 4\text{ eV}$$

or expressed in term of wavelength (in μm):

$$\varepsilon = 0.64 \quad \text{for } 0.3\ \mu m<\lambda<0.48\ \mu m$$

$$\varepsilon = 1.46/\lambda - 2.43 \quad \text{for } 0.48\ \mu m<\lambda<0.6\ \mu m$$

$$\varepsilon = 2.99/\lambda \quad \text{for } 0.6\ \mu m<\lambda<0.8\ \mu m$$

Beam current (μA)	10	20	50	80
Heating power (W)	3.3×10^{-21}	9.4×10^{-16}	3.9×10^{-9}	3.2×10^{-7}
OTR power (W)	1.4×10^{-6}	5.7×10^{-6}	3.6×10^{-5}	9.2×10^{-5}

TABLE 2. comparison of OTR power with radiated power for gold foils, beam energy is 5 MeV and foil thickness is 0.05μm.

Here, the radiated power by heat is very small compared to OTR power. However, we should point out that OTR power will not be detectable at 5 MeV, for beam current below 20 μA, with an usual Vidicon camera (4 Lux) and consequently should require a CCD camera (0.4 Lux).

4.0 Conclusion

Using the case of an aluminum foil, we saw that the radiated power due to heat does not radiate significant amount of power. Integrating this power only over the visible spectrum showed that such power is negligible compare to the OTR power.

Also we investigated, in the case of gold foils, the maximum temperature we should expect for a given intensity, and for the three different thicknesses that are under consideration for the Mott polarimeter. For beam current of 20μA and a foil thickness of 0.05μm, foil temperature at the center of the beam will be less than 600 K which is well below the melting point of gold. In fact for a thickness of 0.05μm, we should be able to reach currents up to 80μA. For low current (<20μA) as we said, the OTR total power should be around 10^{-6} W. Since the power received by the detecting device is roughly 1000 time less (because of the camera aperture), we will have to use a CCD camera which with a better sensitivity.

The heat generated radiation is negligible with respect to the OTR and will not distort the beam profile.

References:

[1]: R. Yung, Beam intercepting monitors, Frontiers of particle beams; Observation, Diagnosis and Correction, Lecture Notes in Physics vol 343 pp 403-422, Springer-Verlag Editor, Anacapri, Isola di Capri, Italy 1988.

[2]: Particle Physics Booklet, extract of the review of Particle Properties, Physical review D50, 1173, p127, July 1994.

[3]: J.C Denard and *al*, Experimental diagnostic using Optical Transition Radiation at CEBAF, Beam Instrum. Workshop, AIP conference proceedings 333, pp 224-230, Vancouver, October 1994.

Annexe A:
Element of heat theory and OTR formulae

- Element of heat theory

When a particle beam is intercepted by a foil of metal, it an amount of energy that depends upon the intrinsic properties of the foil material.

This energy deposition will contribute to increasing the temperature of the foil locally but also globally as the heat spreads. Hence, It can be show that the temperature increase at the center of the beam is:

$$\Delta T = \frac{P}{2\pi K t}\left(\log\left(\left(\frac{r_{foil}}{r_{beam}}\right)+\frac{1}{2}\right)\right)$$

The factor 1/2 in the right hand side correspond to the increase of temperature between the edge and the center of the beam; let's note that it does not depends on the beam size.
The power deposited by the beam is given by:

$$P \approx \left.\frac{dE}{dx}\right|_E \times t \times I$$

Where I is the beam intensity, K the thermal conduction. r_{foil} and r_{beam} represent respectively the foil and beam radii. We can introduce a thermal resistance that is defined as:

$$R = \frac{1}{2\pi K t}\log\left(\frac{r_{foil}}{r_{beam}}\right)$$

Then the temperature drop ΔT induced by the flow of heat power P is:

$$\Delta T = RP$$

Moreover, when a body has a given temperature T, it radiates power given by the Stefan-Boltzman law:

$$P_{rad} = 2\sigma\varepsilon S(T^4 - 300^4)$$

σ is the stefan constant, ε the emissivity of the body that depends on photon energy and S its surface.

In order to take into account the energy dependence of emissivity, we used the Planck's law that gives the spectral density of power in W/cm^2/unit of wave length:

$$\frac{dI}{d\lambda} = \frac{37418}{\lambda^5 \times \left(e^{\frac{14388}{\lambda(T-300)}} - 1\right)}$$

In this equation, λ is in μm and T in Kelvin.

We then computed the wavelength for which the spectral density is maximum and get the corresponding energy:

$$E = \frac{hc}{\lambda_{max}}$$

Hence, using emissivity *vs.* energy table, we can find out the emissivity values.

The total power emitted in the visible is given by the following integral:

$$P_{total} = \left[\int_{0.4}^{0.8} \frac{dI}{d\lambda}\varepsilon(\lambda)d\lambda\right] \times S$$

S is the surface that is radiating.

- Optical transition radiation

A particle that is travelling at constant velocity and that encounters a medium of different dielectric constant will emit radiation called optical transition radiation. The spectral energy of this radiation, in the case of a relativistic electron, is given by:

$$\frac{dW}{d\omega d\Omega} = \frac{2e^2 Z_0}{8\pi^3}\left(\frac{\beta \sin\theta}{1 - \beta^2(\cos\theta)^2}\right)^2$$

Which is constant over the whole spectrum.

Hence, for a beam pulse of duration t at the Intensity I, the OTR power is:

$$P = \frac{Z_0 T I^2}{2\pi t}\log\gamma$$

T is period of the pulse train and *t* the pulse duration.

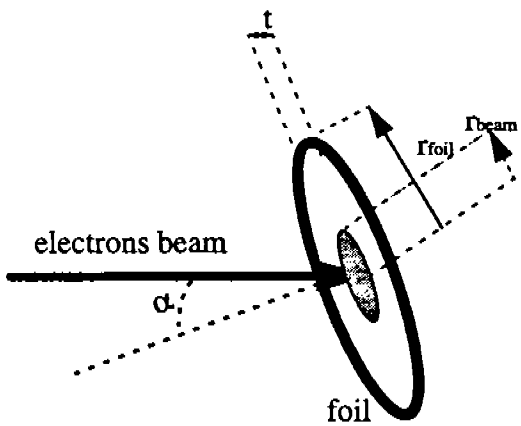


Figure A1: Notations

Annexe B:
Computation of the temperature rise at the center of the screen

To compute the evolution of temperature at the edge of the beam as a function of the beam intensity, we used an iterative method.

Let's first assume, in the case of a circular foil, that the conduction power is evacuated radially. Hence we can modelise such a foil using a finite number of elements denoted i that have got a specific thermal resistance R_i as it is shown on the following figure. Each element is at the temperature T_i.

We introduce a parameter, P_{ext}, the power that is evacuated from the foil toward the outside of the vacuum chamber. Therefore, to compute the temperature in the ith element, knowing the temperature in the (i-1)th element, we just have to use the formula:

$$T_i = T_{i-1} + R_i P_i$$

Where R_i is the thermal resistance we defined above and P_i is the total power coming from the i th element. Part of the power is heat radiated and the rest is transmitted by conduction to the next element.

$$P_i = P_{i-1} + 2\pi\sigma(T^4 - 300^4)(r_i^2 - r_{i+1}^2)$$

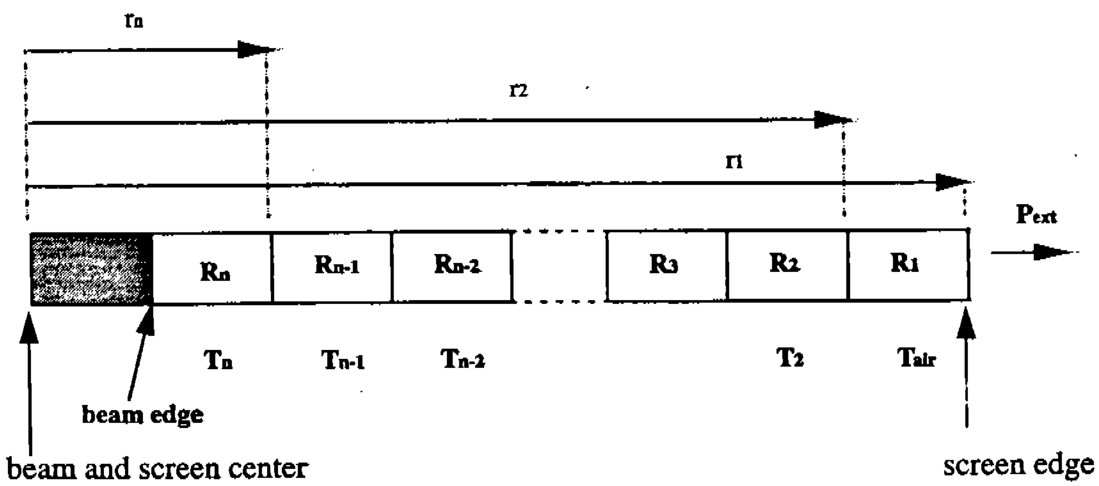


Figure B1: One dimension finite element division of the screen for the thermal analysis.

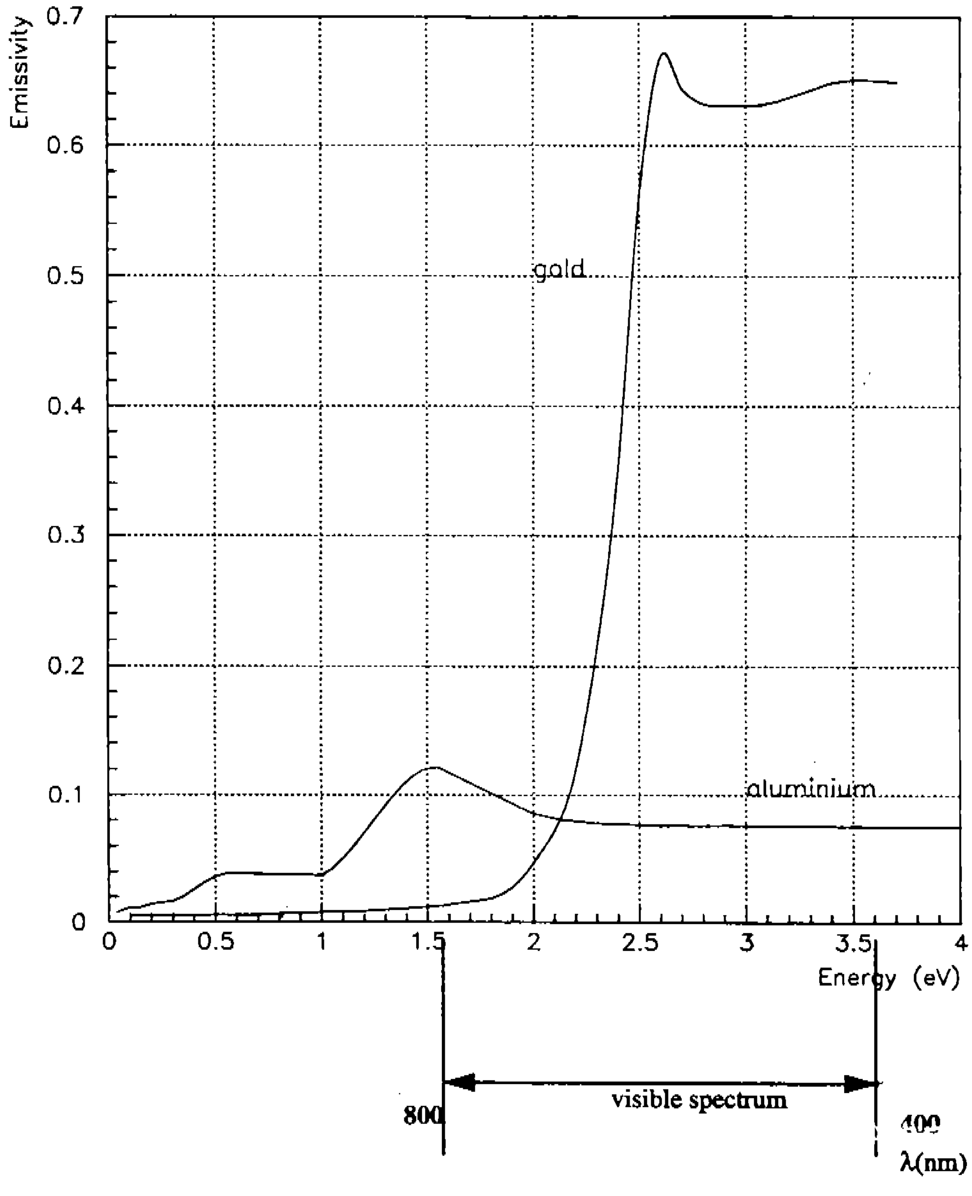
Iterating this relation up to the edge of the beam allows to determine the temperature at the center of the beam and the deposited power from which we can get the intensity through the relations:

$$T_{center} = T_n + \frac{1}{4\pi K t} P_n$$

$$I = \frac{P_n}{\Delta E \times t} \times \cos\alpha$$

In this last expression, α denotes the incidence angle of the beam on the foil (*cf* figure A1, Annexe A).

Annexe C:
Emissivity of Aluminum and gold[1]



1. Curves deduced from the reflection coefficient Table pp 12.109-12.112 in the Handbook of Chemistry and Physics, 74 th Edition.