COSMIC RAY EFFECTS ON THE ISOCAM LONG WAVE DETECTOR

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Abstract.
The ISOCAM detector is subjected to transient effects induced by cosmic rays, the so-called glitches. This paper is focused on the ISOCAM long wave detector. The predicted glitch rates have been re-evaluated by taking into account secondary particles production in the materials surrounding the LW detector. We show in this preliminary study that the difference between the previously predicted glitch rate and the observed rate may be explained by secondary particles.

1. Introduction

The infrared ISOCAM camera is composed of two detectors : the short wave (SW, 2.5-5 μm wavelengths) detector using a InSb substrate and a Charge Injection Device readout method, and the long wave (LW, 4-17 μm wavelengths) detector. The LW is a photoconductor array in Gallium-doped Silicon detector with a pitch of 100 μm and a thickness of 500 μm. 32$\times$32 pixels compose this array. The SiGa array is hybridized by an Indium bump array to a direct voltage readout circuit.

In this paper we consider the single event effects due to the impact of single particles from galactic cosmic rays (GCRs) induced by the radiation environment outside the Van Allen belts, the so-called glitches. A glitch results of the energy deposited in the detector which in turn generates an ionization pulse. The duration spent by the ISO satellite outside the Van Allen belts is 16 hours along its 24 hour orbit, which corresponds to the

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scientific windows. Outside the radiation belts the ISO satelitte is subjected to galactic cosmic rays and also to solar events. We mostly concentrate on the galactic cosmic particle impacts and attempt to interpret their effects on the LW detector.

In Section 2 a brief overview of the radiation environment is made (see [1] for more details) in order to assess which types of particles may induce glitches in the LW detector. A remainder of the glitch rate predictions due to primary GCRs is given in section 3. These later can give rise to secondary particles when they pass through the matter. In section 4, an evaluation of the counting rates induced by these secondary nuclear interaction particles is made. Next, in section 5 we assess the glitch rates due to other secondary particles : the δ rays which are recoil electrons emitted along the tracks of particles in the surrounding detector materials.

2. Overview of the Radiation Environment Seen by the ISO Satellite

Along its highly eccentric 24 hours orbit, the ISO satellite is subjected to various type of ionizing particles :

- trapped protons of energy up to $\approx 200\ MeV$ and mean energy around $\approx 50\ MeV$
- trapped electrons of energy up to $\approx 7\ MeV$ and mean energy around $\approx 3\ MeV$. These electrons produce bremsstrahlung in the detector surrounding materials. The maximum energy of the γ rays produced is about $3\ MeV$ and the mean energy $\approx 0.5\ MeV$. The bremsstrahlung may in turn give rise to secondary electrons which can hit the detector.
- Galactic cosmic rays (GCRs) with an energy range running from tens of MeV/n to hundreds of GeV/n.
- Solar cosmic rays of energy up to $\approx 1\ GeV$ emitted during solar flares.

Outside the radiation belts the satellite is exposed to GCRs. They are fully stripped atoms composed with 87 % protons, 12 % alphas, and 1 % heavier nuclei. Occasional flares such as the solar novembre 1997 proton event will produce additional protons and heavier nuclei. The major part of GCRs cannot be stopped by a shield since its differential spectrum is peaked at about $500\ MeV$. For instance, at such an energy a proton has a range of $55\ cm$ in an aluminum shield. The spacecraft and the additional shieldings represent a total absorber thickness roughly equivalent to $2.5\ cm$ of Al [2]. Only particles having a range greater than $2.5\ cm \times 2.7\ g/cm^3 = 6.75\ g/cm^2$ are on average able to reach the ISOCAM detector. In other words, particles whose energy is greater than $80\ MeV/n$ can get into the detector.

The GCRs are their maximum flux during solar minima and at their lowest level during solar maxima with a modulation period of 22 years. Depending on their energy the GCR fluxes may vary by a factor of about 2 to 10 (about 2-3 in in the 1 GeV energy range).

3. Glitch Rate Due to Primary Galactic Cosmic Rays

3.1. GLITCH RATE INDUCED BY PRIMARY GCRS

As mentioned in the previous section GCRs which have not interacted by nuclear collisions with the detector surrounding materials may easily reach the detector due to their high energy and pass trough it along straight line trajectories. Within this reasoned assumption the number of glitches coming from the primary GCRs may be easily assessed. Let Φ be the particle flux per $cm^2/s/sr$ and dS a surface unit. The incoming flux passing through the surface unit dS is then :

$$\phi = \Phi \int_0^{\pi/2} 2\pi sin\theta dS cos\theta d\theta = \pi \Phi dS \quad (1)$$

Knowing that the LW detector may be taken as rectangle parallelepiped with edges such as $A = B = 0.32\ cm$ and $C = 0.05\ cm$, the incoming flux through all the faces is merely :

$$\phi_{detector} = 2\pi\Phi(AB + BC + AC) = 0.844\Phi \quad (2)$$

The LW detector is shielded by the telescope, the spacecraft and additional shielding. The absorber thickness is roughly equivalent to 25 mm of Al [2], which means that protons of 80 MeV or more can traverse this shielding. Alphas having an energy greater than 80 MeV/n may traverse this shielding. From the latest data provided by the KET (Kinetic Electron Telescope) instrument on board the Ulysses probe (October 1997-February 1998 [3], Ulysses was near the ecliptic plane at that time), the proton and alpha fluxes above 80 MeV/n may be estimated as :

- Protons (E > 80 MeV) : 0.39 (Integral flux in part $/cm^2/sr$)
- Alphas (E > 80 MeV/n) : 0.032 (Integral flux in part $/cm^2/sr$)

Outside the radiation belts, towards the ISO orbit apogee, the rigidity cut off of the Earth magnetic field is negligible (at the perigee for instance, the rigidity cut off is about 12 GV and the corresponding proton energy is 11 GeV). On the other hand, above the energy we consider here (E > 80 MeV/n), the error on the flux intensities due to the difference of location in the solar system between Ulysses and ISO is negligible. Thus we may estimate that the **primary galactic protons and alphas** should produced about **0.36 track per second in the LW detector**. The heavier nuclei contribution to this value is 1 % and does not significantly change this estimation. The previous estimations [4, 5] of direct impacts was also based on KET older measurements made in 1995 and was smaller than this one (0.28 $\sec^{-1}$ instead of 0.36 $\sec^{-1}$).

Incidentally, an assessment of the number of tracks due to the solar energetic proton event of 3-9 novembre 1997 can be performed. From the curve of integral proton flux coming from GOES observations [1], we can infer the average number of protons passing through the LW detector. When the proton flux reached its peak, the flux above 80 MeV was around 50 $part./sec/sr$. This implies about 40 glitches per second in the detector at the peak. This is compatible with what was observed during the event (see [6, 7]).

3.2. MEAN NUMBER OF PIXELS PER TRACK

This number has been estimated by Monte Carlo simulation in Saclay [8] and the results were : 8.4 pixels hitted on average per proton event and 2.3 pixels hitted on average per electron event. The reader is also referred to [9] to see a simulation made with GEANT code.

Note that this result may be easily found only by geometrical considerations. The mean number of pixels per track may be found assuming that the particles follow straight lines in the detector. The total flux traversing the 1024 pixels is $\phi_{all\,pixels} = 1024 \times [2\pi\Phi(ab + bc + ac)] = 7.08 \times \Phi$, where $a = b = 0.01\ cm$ and $c = 0.05\ cm$ are the pixel dimensions. The **mean number of pixels per track** is merely given by : $< n_{pixels} >= \phi_{all\,pixels}/\phi_{detector} =$ **8.4 pixels/track**. For the SW detector (the thickness is 5 μm), the mean number of pixels hit per event is 0.8, which shows its intrinsically low sensitivity to glitches.

4. Evaluation of the Secondary Nuclear Interaction Particles Produced in Shielding Materials

We propose here an analytical method to assess the proportion of secondary charged particles produced by nuclear interactions in the materials surrounding the LW detector.

4.1. ENERGY AND INTERACTION LENGTH

A given particle passing through a material will be mainly slowed down by electromagnetic interaction (ie ionization) if its energy is below a few tens of MeV. If its energy is higher the main process will be nuclear interactions.

We may define a threshold energy E_0 such as the particle range in matter R is equal to nuclear interaction length λ in a given shield. R and λ depend on the particle type so that E_0 will vary from one particle to another. In this section we deal with galactic protons since they represent near 90 % of the GCRs.

The geometrical interaction cross section for the interaction of a particle with an atomic weight A_1 traversing a medium of atomic weight A_2 is given by a Bradt-Peters type law [10] :

$$\sigma = 57.2 \times (A_1^{1/3} + A_2^{1/3} - 0.38)^2 \times 10^2 \quad barn \tag{3}$$

The corresponding interaction length is given by :

$$\lambda = 1.66 \times \frac{A_2}{\sigma} \quad g/cm^2 \tag{4}$$

For a proton traversing an Al shield one get : $\lambda = 53.4\ g/cm^2$. The threshold energy E_0 for which $R = \lambda$ is 270 MeV (it would be 400 MeV for a Pb shield for example). This means that for galactic protons traversing materials, the nuclear interactions will be a dominant process. On the other hand the threshold energy for π-meson production by proton collision on a nucleus is 270 MeV. At energy below the threshold for meson production, the only result of the collision is a momentum and an energy transfer of the incoming particle to the target nucleus which will be disrupted.

4.2. AVERAGE MULTIPLICITY OF THE INTERACTION

The number of particles produced by nuclear reactions : π-mesons, neutrons, etc. vary from one reaction to the other. If we only take into account charged particles, we may reasonably consider an average multiplicity. Most of these particles are more or less emitted in the same direction as the incoming particle. Thus, since the incoming GCR flux is isotropic, the emerging reaction flux will be also isotropic. In the 1 GeV energy range the average multiplicity m of charged secondary particles produced by the collision of a proton flux on target nuclei is around $m = 3$ [11].

4.3. SECONDARY PARTICLE FLUX EMITTED BY DETECTOR SURROUNDING MATERIALS

The shielding materials may be considered as a secondary particle source. The number N of secondary interaction particles which will reach the detector is :

$$N = \int m\ n\ f\ dS, \tag{5}$$

where m is the average multiplicity of charged secondary particles produced in the detector surrounding shield, n the number of interactions produced in the shield by the primary GCRs, f the geometrical factor and dS a surface element of the shield. In order to assess equation (5), we have considered two types of shield geometry : a spherical shell and a slab (cf. figures 1 and 2).

4.3.1. *Spherical shell shield*
The number of interactions produced in the shield by the primary GCRs in a small element of surface ds is :

$$n = \pi \Phi ds (1 - exp(-\frac{\bar{\delta}}{\lambda})), \tag{6}$$

where $\bar{\delta}$ is the mean thickness of the shield traversed by the incoming particles. In order to evaluate $\bar{\delta}$, let us consider a small shield element whose surface is s (cf. figure 3). The number of particles which will traverse this element under an incidence between θ and $\theta + d\theta$ is : $2\pi\Phi sin\theta d\theta \times s\, cos\theta$. The length traversed by an incoming particle under θ incidence is : $\delta = e/cos\theta$, and the mean thickness traversed by the particles is :

$$\bar{\delta} = \frac{\int_0^{\pi/2} 2\pi s\Phi sin\theta cos\theta \times e/cos\theta \; d\theta}{\int_0^{\pi/2} 2\pi s\Phi sin\theta cos\theta d\theta} = 2e \tag{7}$$

The thickness traversed by an incoming particle is on average $2e$.

The proportion of particles produced in the shield and which will reach the detector of surface A (cf. figures 1) is given by the geometrical factor between A and dS : $f = Acos\theta/2\pi d^2$ (d distance between the detector and the shield). For a spherical geometry $dS = 2\pi d^2 sin\theta d\theta$. According to equation (5) the number of secondary interaction particles reaching the detector is then :

$$n = \frac{\pi}{2}\Phi A m (1 - exp(-\frac{2e}{\lambda})), \tag{8}$$

It is more convenient and more explicit to use the ratio secondary/primary particles :

$$r = \frac{m}{2}(1 - exp(-\frac{2e}{\lambda})), \tag{9}$$

4.3.2. *Slab shield*
In this case, $f = Acos^4\theta/2\pi a^2$ (cf. figure 2) and $dS = 2\pi a^2 sin\theta/cos^3\theta d\theta$. The substitution of f, ds and n in equation 5 by their value leads for the slab geometry to the same result as the spherical geometry. The ratio secondary/primary particle is still given by equation (9).

TABLE 1. Properties of surrounding detector materials

material	density (g/cm^3)	atomic number	atomic weight	λ (g/cm^2)
Ti	4.54	22	47.9	97
Cu	8.96	29	63.5	106
Al	2.70	13	27.0	78
Ge	5.35	32	72.6	92

4.4. EVALUATION OF THE PROPORTION OF SECONDARY PARTICLES FOR A SIMPLIFIED ISOCAM DETECTOR GEOMETRY

The simplified ISOCAM detector geometry that we have taken is shown on figure 4. In table 1 are summarized the properties of the main materials surrounding the detector (Titanium, Copper, Germanium, Aluminum).

For the materials surrounding the detector (Cu, Ge, Ti), the radiation lengths are nearly the same so that we may make the approximation that the detector is shielded by a material whose thickness is 6.5 g/cm^2 and the radiation length is $\lambda \approx 100$ g/cm^2. Within these assumptions we find that **the ratio secondary/primary particle is about 18-20 %**. If now we consider that the body of the satellite is roughly equivalent to a shell 25 mm of Al one may say that the satellite should add another 15-20 % contribution to glitch rates due to secondary particles.

5. Glitches Due to δ Ray Emission

5.1. δ RAY PRODUCTION

The δ rays are secondary electrons of a target material which are ejected along the track of an incoming particle. They can in turn ionize the matter. They are produced by particles of sub-relativistic velocities. The maximal energy of a secondary electron (or δ ray) is approximately [12] :

$$E'_m = 2m_e\beta^2c^2, \tag{10}$$

where βc is the primary particle velocity. Table 2 shows the maximum energy that can be acquired by a δ ray according to the primary particle energy.

The number of δ rays with energies in an elementary energy interval $[E,\ E+dE]$ emitted by a particle traversing x g/cm^2 of matter is given by the Rutherford formula :

TABLE 2. Maximum δ ray energy according to the primary particle energy in GeV per nucleon.

$E_{incoming\ part.}$ (GeV/n)	1	2	4	10
E'_m (MeV)	3.2	8.7	26	132

$$dn = \xi \frac{dE'}{E'^2} x, \quad \xi = 0.075 \frac{Z^2}{\beta^2} \tag{11}$$

x may be expressed as a function of the electron range in matter by the following power law : $x = \alpha_1 E'^{\gamma_1}$, where α_1 and γ_1 are coefficients defined for a given energy interval (in the energy interval 0.1-10 MeV $\alpha_1 \approx 0.60$ whereas $\gamma_1 \approx 1.38$ in the interval 0.1-1 MeV and $\gamma_1 \approx 1.0$ in the interval 1-10 MeV. Equation (11) may be expressed as :

$$dn = \xi \frac{dE'}{E'^2} \frac{1}{cos\theta} \alpha_1 E'^{\gamma_1}, \tag{12}$$

θ being the incidence angle of the incoming particle. The total number of δ rays escaping from the shield is obtained by integrating equation (12) between E'_0 and E'_m. E'_0 corresponds to the minimum energy that a δ ray must have to traverse the detector. On the other hand, above the critical energy E_c the energy loss by radiation becomes larger than the energy loss by collision and electromagnetic showers can occur. This gives rise to a great number of electrons. This critical energy may be assessed by the following equation :

$$E_c = \frac{800}{Z + 1.2} \ \ MeV, \tag{13}$$

where Z is the charge of the target material. In Titanium an electron will be able to give rise to electromagnetic showers for energies $E > E_c =$ 34.5 MeV. Only protons with energy larger than 5 GeV can generate δ rays whose energies are greater than this threshold energy of 34.5 MeV. The proportion of protons of energy greater than 5 GeV is about 5 %. In other words, only 5% of the protons will be able to produce electromagnetic showers.

5.2. δ RAY CONTRIBUTION TO GLITCH RATES

We have calculated the ratio of the glitch production in the detector surrounding materials to the primary protons through the detector. Table **??**

TABLE 3. Proportion of δ rays hitting the detector with regard to primary proton reaching the detector according to proton energy in GeV. From 5 GeV protons, electromagnetic showers can occur.

$E_{GCR\,proton}$ (GeV)	1	2	4
ratio $\frac{\delta\ rays}{primary\ GCR\ protons}$	0.32	0.36	0.38

shows that the proportion of δ rays produced in the shield and reaching the detector slightly increases over the 1-4 GeV energy range of the incoming protons. This ratio is around 0.33. This means that for 1 one primary galactic proton hitting the detector we have to add a contribution due to δ of about 33 %.

The number of emitted δ rays being proportional to the square of the incoming particle (see equation 11) the proportion of δ rays hitting the detector with regard to primary GCR alphas reaching the detector will be 1.32 and for heavier nuclei, mainly C, N, O, one get about 20 δ *rays* per nuclei. Finally, taking into account the composition of the GCRs, we find that the total proportion of δ rays is : $0.87 \times 0.33 + 0.11 \times 1.32 + 0.01 \times 20 = 0.63$. Thus the glitch prediction due to primary GCR particles should be **enhanced by about 60 % to take into account the δ ray emissions.**

6. Glitch Rate Prediction

In table 4 is summarized the latest glitch rate prediction taking into account the contribution of secondary particles due to nuclear interactions and δ rays emitted by the primary GCRs passing through the materials surrounding the ISOCAM LW detector. We have also added the contribution due to the anti-reflection coating of the lenses which contains Thorium [5]. Thorium generates a flux of low energy α particles which depends on the solid angle of the lens viewed from the array.

The glitch rate measured in flight is about **1 glitch/sec**. This number cannot be only explained by the GCRs direct impacts since they represent **0.36 track per second in the LW detector** (cf. section 3). This estimate is robust since it relies only on an in-flight measurement made during the same period as the ISOCAM observations and on geometrical considerations of the LW detector. More than 50 % of the glitches are due to secondary particles. On figure 2 of [6] some examples of production of secondary particles in the LW detector itself are shown. The secondary nu-

TABLE 4. Predicted glitch rates (unit sec^{-1}). Due to the Thorium contribution of anti-reflection coating of the lenses, the total glitch rate prediction depends on the lens selected for the observation. The contribution of secondary particles and δ-rays should represent about 80% of direct contribution. Neither the electro-magnetic showers, nor the secondary particles and δ-ray emissions from the body of spacecraft have been taken into account here (see text). They could represent another 10 to 30 % additional contribution.

Contribution	1.5" lens	3" lens	6" lens	12" lens
primary GCRs	0.36	0.36	0.36	0.36
Secondary particles and δ-rays	0.29	0.29	0.29	0.29
α-particles from Thorium	0.002	0.02	0.16	0.35
TOTAL	**0.65**	**0.67**	**0.81**	**1.0**

clear interaction particles produced in shielding materials should represent **about 20 % of the incoming GCRs** (cf. section 4). The contribution of δ-rays emission, taking into account the GCR composition should be around **60 %** (cf. section 5). One may conclude that one could get less glitches if the detector was less protected by shielding materials. This is not true since these materials protect the detector against dose effects and they prevent it to be hit by lower energy particles (below 50-80 Mev) which are numerous along the ISO orbit.

7. Conclusion

The observed glitch rate outside the Van Allen belt is about 1 glitch/sec. They direct impact of GCRs represents about 30-40 % of this value. The remainder should come from secondary particles. The results given in this paper must be taken as an order of magnitude but they provide a clue for a better understanding of the glitch mechanisms. However they should be considered as a crude estimate since the calculation are base on an analytical approach where simplifications had to be made. Only the contribution of the detector surrounding materials were taken into account and the contributions of the body of the satellite have been neglected. On the other hand, other phenomena such as electrons coming from electromagnetic showers remain to be investigated even if they represent a smaller contribution to the observed glitch rates.

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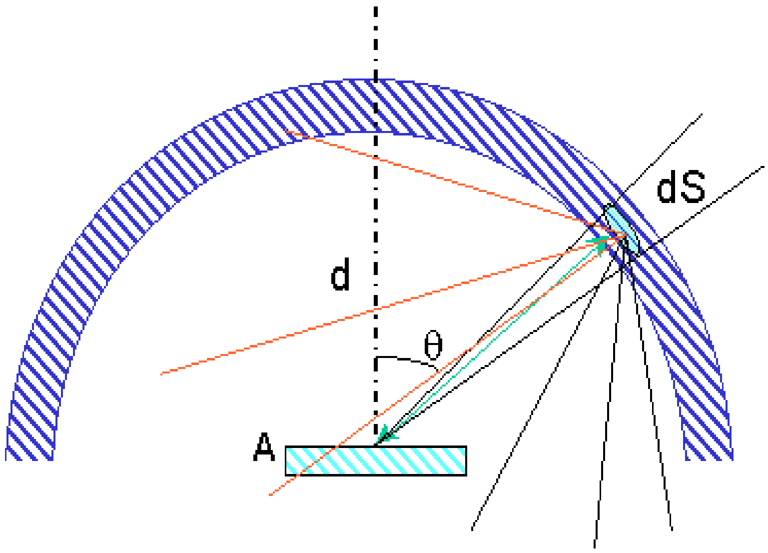

Figure 1. Spherical shell model of shield. The detector is represented by the element of surface A at the bottom of the scheme. Each element of surface dS is taken as a secondary particle source activated by the primary GCRs.

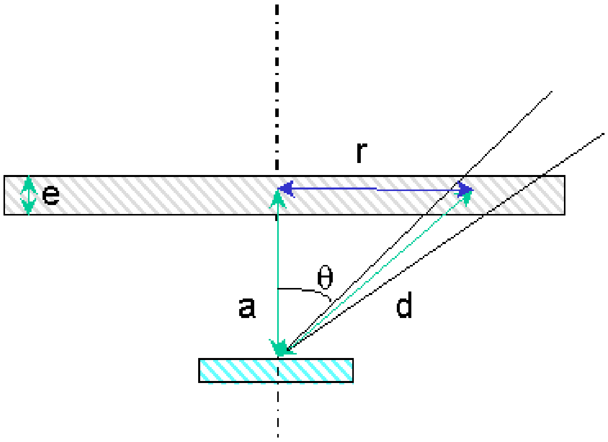

Figure 2. Slab shell model of shield. The detector is represented by the element of surface A at the bottom of the scheme.

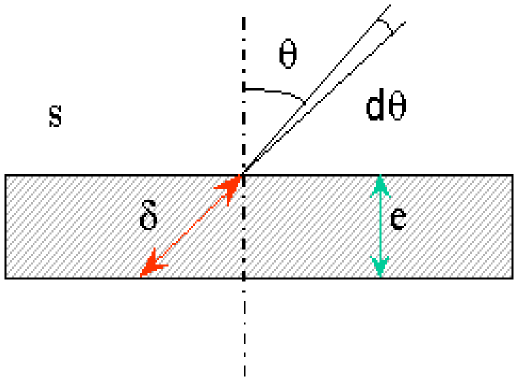

Figure 3. Small shield element of surface s.

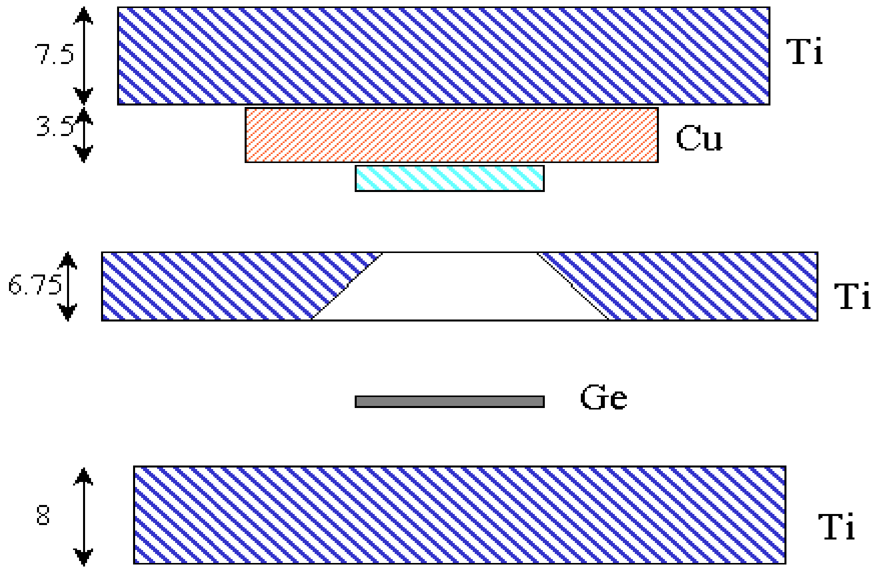

Figure 4. Simplified ISOCAM detector geometry taken for the evaluation of secondary particle production by nuclear collisions. The dimensions indicated on the scheme are in mm. The LW detector is just below the Cu layer.