RADIATION ATTENUATION OF CFRP WOLFRAM LAMINATE STRUCTURES

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ABSTRACT

Electronics and its housings have potential for spacecraft mass savings. The use of composite materials, especially CFRP is a well known approach to mass reduction. However, in electronics housing the CFRP structure has to be able to protect electronics from spatial radiation. In order to reduce cost the use of standard (non-space qualified) electronics has been increased. These circuits cannot tolerate as high radiation levels as space qualified components. This poses challenge to the radiation protection capability of the electronics housings.

The most important particles in LEO and MEO orbits are energetic electrons and protons. These form the total energy deposition (dose) of a component. Energetic particles passing through material can undergo a variety of interactions leading to energy loss, scattering and the generation of secondary particles.

The topic was studied in the ESA study “Advanced Equipment Design”. The radiation protection concept studied was based on so called low Z – high Z – low Z concept where Z refers to atomic number of the material. The low Z material was CFRP and the high Z material was wolfram. In the study certain radiation attenuation tests were performed with CFRP/W laminates and a reference aluminium plate. However, partly due to deficient test specification the test results were difficult to interpret and their information content was incomplete.

A new ESA study called “Radiation Protection for Advanced Equipment Design” was established to better understand the phenomena and to be able to model it. The primary objective of this study was to deepen the understanding of particle radiation protection behaviour of CFRP wolfram layered composite structures. This was aimed with theoretical and experimental studies.

The validation of GEANT4 model was the second objective of the study. With validated model it is possible to simulate radiation attenuation in various laminate structures in various radiation environments.

The following results can be summarised:

1) The best attenuation properties of tested samples with equal 2.0 mm thickness in proton and electron irradiation had the aluminium reference sample and the second best was the laminate sample with two 50 μm wolfram layers. However, in electron irradiation the aluminium reference sample had almost identical attenuation properties with the laminate sample with two wolfram layers.

2) The proton transmission was simulated in GEANT4 for the CRFP with a wolfram layer and for the aluminium plate with equal areal masses. The CFRP/W structure turned out to have higher shielding efficiency than the aluminium plate.

3) The validation of the GEANT4 model was successfully carried out. This was mainly driven by careful selection of the most important components for the experimental setup and the high quality of the acquired test data.

4) The performed experiments and simulations indicate that there is a considerable potential for mass savings in structures with radiation attenuation requirement when using laminates with low Z – high Z – low Z concept instead of typical aluminium alloys.

1. INRODUCTION

Radiation damage in electronics has been studied extensively. In the past these studies have concentrated on failure aspects in digital electronics and were motivated by their relevance to various applications, including space and military ones.

In electronics the radiation-induced damage changes the doping concentration, which in general is not so important. Important are, however, other aspects of the bulk and oxide damages. As the gate oxide is the key element of MOS transistors, the device is very sensitive to changes in its properties. Ionization radiation causes build-up of positive charge within the oxide and the creation of interface states in the oxide-semiconductor interface. The rate of creation is dependent on the size and polarity of the electric field in the oxide and thus on the gate voltage applied during irradiation. The change in the transistor threshold voltage due to the oxide charge build-up can cause catastrophic failures in circuits, in particular in digital circuits when *n*-channel enhancement transistors change to depletion-type and thus cannot be turned off any more in inverters etc. The resulting continuous current flow and the heat generated will eventually destroy the circuit. A further effect, important for devices having the conducting channel directly at the $Si\text{-}SiO_2$ interface (as in the case for most enhancement type MOS transistors), is due to the reduction of mobility near the interface, causing a reduction of the transconductance, [1]

Mass reduction of spacecraft electronics was studied in ESA study “Advanced Equipment Design (AED)” where the main focus was in structural integrity and thermal conductivity of CFRP based applications [2]. Also, the problem of spatial radiation effects on spacecraft electronics when CFRP structures are used instead of traditional aluminium alloys was slightly studied. A follow up study called “Radiation Protection for Advanced Equipment Design” was launched by ESA. The aim in this study was to get a deeper understanding of radiation attenuation properties of the selected layered CFRP wolfram structure (low Z – high Z – low Z [3] structural concept). Also, the capability of modelling the attenuation phenomena was aimed. The simulation tool used was GEANT4 software toolkit, which has been developed in CERN. The studied structure is shown in FIG. 1.

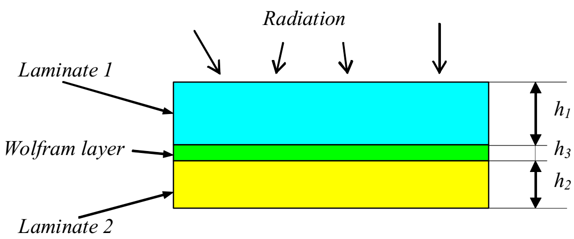

FIG. 1 Studied structural concept for radiation protection.

In the course of the AED study sample laminates with a wolfram layer were manufactured and irradiated with electrons and protons. Helsinki Institute of Physics (HIP) made radiation attenuation simulations based on the actual test conditions. However, partly due to deficient test specification the test results were difficult to interpret and their information content was incomplete. Also, only four different sample configurations were irradiated.

The tests left several questions unanswered like:

- what is the actual attenuation of the structure for higher energy electrons?
- what effect has the thickness ratio of CFRP to wolfram?
- what effect has the unsymmetrical thickness of CFRP on different sides of wolfram?

In simulations the matrix material was ignored as the attenuation parameters were unknown. One can make sophisticated guesses of the values but the actual values seemed to be almost impossible to get from the manufacturer or from public sources.

The questions above were studied in the “radiation Protection for Advanced Equipment Design” by the Radiation Detection Laboratory of the Helsinki Institute of Physics (HIP) & the Department of Physical Sciences of the University of Helsinki, and the Helsinki University of Technology (TKK), Laboratory of Lightweight Structures (KRT).

2. INITIAL SIMULATIONS

The objective of initial simulations was to study the radiation attenuation properties of matrix materials and CFRP laminate structures. Matrix materials included different epoxies and cyanate esters. Also, the effects introduced by the layered structure of the laminate itself were addressed in these studies.

As the basic analysis tool, a GEANT4 based model was created. The model included as accurate as possible description of the materials under study and the relevant physics processes on which the proton and electron transport calculations are based. A series of simulations was carried out to obtain radiation transmission data of the materials used in laminate structures in heavy radiation environments.

In the analysis, the radiation attenuation of different types of epoxies and cyanate esters and carbon fibre laminates were studied by subjecting the material samples to incident electrons with energies in the range of 2 – 6 MeV and protons in the range of 15 MeV – 26 MeV. For radiation transport studies in the materials, a Monte Carlo simulation tool based on the GEANT4 was used. The tool is available as open source software and is maintained by the world wide collaboration lead by CERN.

The simulations were mainly carried out in the University of Helsinki computer clusters (supercomputer) called Ametisti and Mill. For this study, the clusters were configured mainly with GEANT4, Root and other auxiliary software required to submit and monitor the simulation runs. The results were stored as large data files with sizes of the order of hundreds of megabytes. A powerful computational infrastructure was set up specifically for the goal of analysing laminate structures in terms of their radiation attenuation properties.

The matrix materials analysed in the simulations were selected partly on the basis of available information of their chemical composition. The materials are listed in TAB. 1. The material compositions used in simulations were incomplete. Thus, if there were unknown components in the materials, the amount of known components was increased in proportion to cover the missing ones. This is that if it was known that component A had concentration of 50 % and component B 40 % and the remaining 10 % was unknown, the concentration of A was increased to 55,6 % and the concentration of B to 44,4 %. Also, when only a range of component materials was known, an estimate based on engineering aspects of the laminate structures was used. This is that if component A had a range from 60 % to 70 % and component B had a range from 30 % to 40 % then the concentration of A and B was set to 65 % and 35 % respectively. For each epoxy and cyanate ester compound, a representative molecule was described and used in the simulations to model the matrix material.

TAB. 1 Matrix materials of initial simulations

Matrix	**Resin**	**Hardener**	**Ratio by weight** [1)]
Epoxy	Araldit LY 5052	Aradur 5052	72 % & 28 %
Epoxy	Prime 20	Prime 20 Fast	79 % & 21 %
Epoxy	Fibredux 913		100 %
Cyanate ester	Primaset PT-30		100 %

[1)] Weight proportion of resin and hardener in the matrix material.

The types of plates and laminates were modelled:

- One single layer of homogenous epoxy or cyanate ester was set. The thickness of the plate was 1,0 mm.
- A CFRP laminate was set on both sides of the 50 micron wolfram foil. The CFRP laminate had a layer of carbon (60 % of thickness) and a layer of matrix material (40 % of thickness). Total thickness of the laminate was 2,05 mm.
- The laminate was constructed of thin layers of carbon and matrix material through the laminate thickness. The total number of interlaced layers was 200 on each side of the 50 micron wolfram foil. Total laminate thickness was 2,05 mm.

The initial simulations showed that there were no major differences between epoxies and the cyanate ester concerning their electron attenuation properties. However, in the case of incident protons, significant differences were observed between studied matrix materials.

It is well known that in interactions of radiation with matter, the material density plays a major role. In the case of electrons, the small differences in attenuation could be explained due to the almost identical densities of the laminate structures under study.

As the main conclusion of these initial studies it was found that the laminates should be tested further individually, i.e. a specific epoxy matrix material and a specific cyanate ester matrix material should be chosen for a more detailed analysis. Another crucial conclusion was that the used GEANT4 based model has to be properly verified.

3. TEST SAMPLES

Based on the results of preliminary simulations and availability of materials, the samples presented in TAB. 2 were manufactured for radiation attenuation tests. The sample geometry was of rectangular shape with size of 10 cm x 10 cm.

The sample thickness was measured from 9 points on the laminate. The latter number in thickness column is the standard deviation of thickness. The density of each sample was determined from the material constituent densities and masses.

TS1 was the aluminium reference sample. All laminate samples were manufactured at the TKK Laboratory of Lightweight Structures using standard prepreg specific 180 ºC autoclave curing procedures. The samples TS3 and TS4 were fabricated of carbon fibre prepreg with cyanate ester and epoxy matrix materials, manufactured by YLA Inc. and Hexcel Corporation respectively. The volume composition was fixed to be 60 % of carbon fibre and 40 % of the matrix material in both samples. Samples TS5 and TS6 were similar to each other and included a 50 micron thick wolfram layer in the middle of the laminate. Sample TS7 had two wolfram layers of 50 micron thickness in the middle of the laminate thickness direction. However, there were two prepreg layers in between the wolfram foils for bonding reasons and due to laminate symmetry.

TAB. 2 Test samples

Sample	**Configuration**	**Thickness, mm**	**Density, g/cm^3**
TS1	Aluminium, reference plate AA6082-T6	1,977 ± 0,007	2,69
TS3	M40J/RS-3C: cyanate ester – no wolfram	2,056 ± 0,013	1,48
TS4	AS4/3501-6: epoxy – no wolfram	2,079 ± 0,008	1,52
TS5	M40J/RS-3C: 50 µm wolfram in the middle	2,101 ± 0,019	1,89
TS6	AS4/3501-6: 50 µm wolfram in the middle	2,071 ± 0,014	1,94
TS7	AS4/3501-6: 2 x 50 µm wolfram in the middle	2,060 ± 0,010	2,37
TS8A/B	AS4/3501-6: 0.65 mm CFRP, 50 µm wolfram and 1.3 mm CFRP	2,087 ± 0,010	1,94

Sample TS8A/B was asymmetric with respect to the middle plane, i.e. the thickness of the carbon fibre laminate was varied on each side of the 50 micron wolfram layer. As an example, in the case of TS8A the beam first hits a CFRP layer with a thickness of 0,65 mm before getting into the 50 micron wolfram layer and, subsequently, into a 1,3 mm thick CFRP layer. In the case of TS8B, the beam hits the thicker CFRP side first.

4. RADIATION TESTS

4.1. Proton test set-up

The Accelerator Laboratory of the University of Jyväskylä has a cyclotron with a versatile system to produce different beam cocktails of ions. The centre is recognized worldwide and has been awarded the centre of excellence status by the Academy of Finland. The experiments were carried out at the RADEF facility which offers beam lines dedicated to proton and heavy ion irradiation studies of semiconductor materials and devices. The heavy ion line consists of a vacuum chamber with an apparatus for moving the components inside and ion diagnostic equipment for real-time analysis of beam quality and intensity. In the proton line, irradiations are performed in air. A system for moving the components and beam diagnostic setups were available in the proton line, as well. Both irradiation lines are located in the same cave.

A schematic representation of the experimental setup is provided in FIG. 2. The main components of the proton irradiation are: proton beam, collimators, degraders, samples and tracker. The aluminium degraders were used to degrease the energy of protons to the desired level when hitting the sample. The distance from the proton beam exit window to the sample frame supporter was 170 cm, and the distance between the silicon detectors was 1 cm.

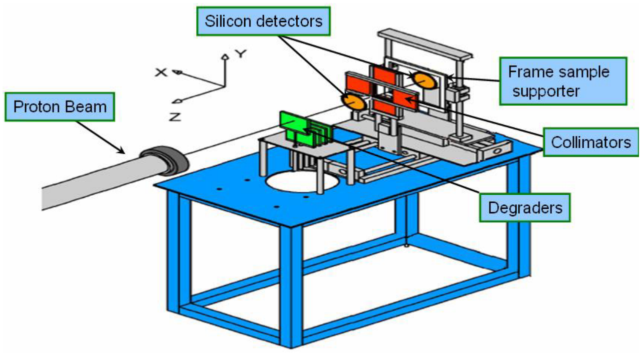

FIG. 2 Schematic illustration for the proton beam geometry.

4.2. Electron test set-up

The Helsinki University Central Hospital - Meilahti hospital in the Department of Oncology has a dedicated set of 8 accelerators for radiotherapy treatments. This facility is mainly used to deliver doses of gammas or electrons for patients with cancer diseases. This laboratory has equipment for very high uniformity electron beam field, which was used in the irradiation test of the samples. The accurate dosimeter method used in this laboratory made it possible to get a good assessment of the energy spectra at the sample level. In FIG. 3 a schematic view of the electron beam experiment is shown.

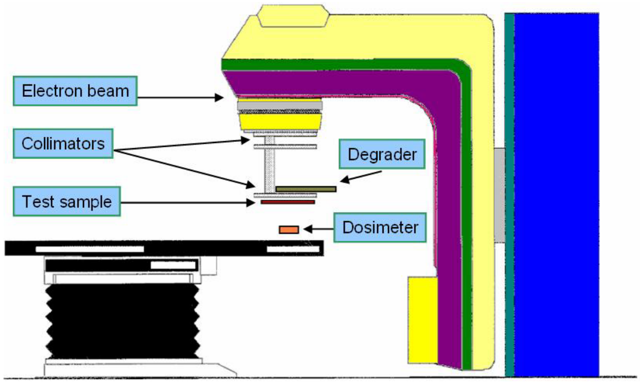

FIG. 3 Schematic illustration of the electron beam geometry.

The electron beam test was set up in the main chamber of the Varian Clinac 2100C accelerator. The electron beam window located in the accelerator head was set in a vertical position. Collimators were used to reduce the beam size and the intensity of the electrons. The collimator holder was also used to support the Plexiglas degraders and the test sample. For supporting the dosimeter, a mechanical system, normally used for supporting the patients, was utilized to allow moving the detector in back/forward and up/down directions.

The distance between the electron beam head and the test sample was 100 cm. From the sample to the modulators the distance was very small due to the fact that the modulator was placed on top of the sample facing up to the primary beam.

5. DATA PROCESSING AND TEST RESULTS

The raw data acquired during the beam tests with protons and electrons were processed using case-by-case calibration procedures. The selection of the method was mainly driven by the used data acquisition method during testing. The objective of the data processing was to transform the raw data into a format that makes it possible to present the results in a more comprehensive manner. Thus the relative comparison of attenuation properties between different structural configurations is possible.

5.1. Proton tests

The protons traversing the aluminium degraders were simulated and the data calibrated to a given energy according to the peak centroid of each measured distribution. The method provides a transformation between the thickness of the aluminium degrader and the proton energy. The transformation was not linear due to difficulties in maintaining a constant narrow beam geometry condition and also due to the scattering between the silicon detectors. FIG. 4 shows the energy distributions of the protons traversing different aluminium degraders. A fit was made to find an analytical expression for calibrating the aluminium degrader thicknesses in energy scale (see FIG. 5).

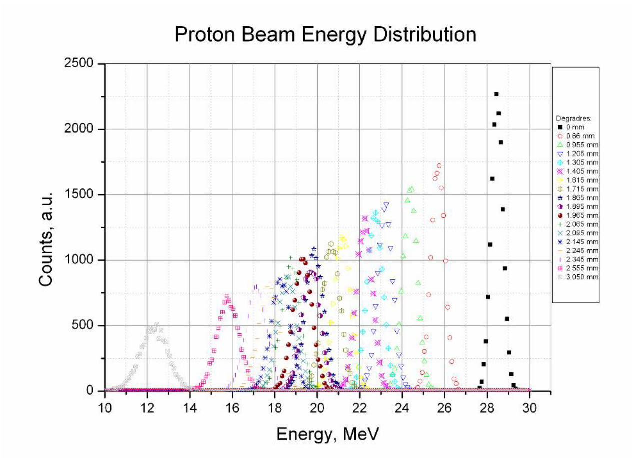

FIG. 4 Energy distributions for protons passing through different aluminium degraders.

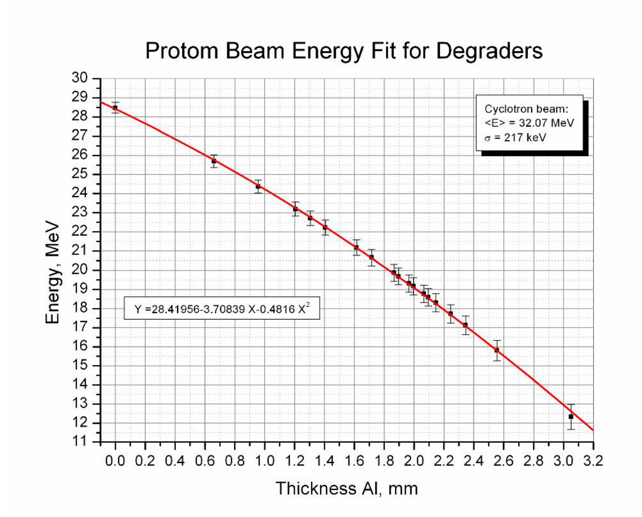

FIG. 5 Fit of the energy of the protons for the total thickness of aluminium.

By using the calibration process described above, all the transmissions curves obtained for the irradiated test samples were renormalized as a function of energy. The summary of attenuation efficiencies is seen in FIG. 6.

The best attenuation efficiency is exhibited by TS1, which is the aluminium reference sample. On the opposite TS3 and TS4 (both without wolfram layers) exhibit the lowest attenuation. Good performance is observed for the laminates with one layer of wolfram in the middle i.e. samples TS5 and TS6. The highest radiation attenuation among the laminates tested corresponds to sample TS7, which contains two wolfram layers. Finally, no major differences are observed in the radiation attenuation for the asymmetric samples TS8A and TS8B.

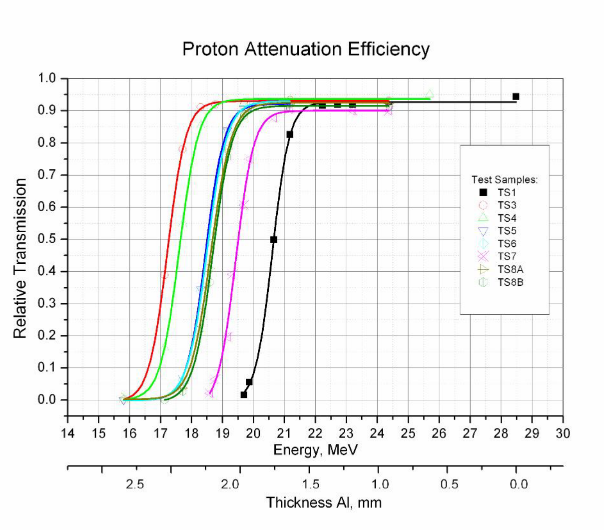

FIG. 6 Attenuation efficiency of the test samples. The x-axis (Thickness Al, mm) corresponds to the thicknesses of the degraders used to generate the proton energy shown in the scale above.

5.2. Electron tests

The processed data of electron tests is shown in FIG. 7. As expected the transmitted energy is linearly depending on the primary beam energy. The relative variations of the mean energy transmitted through all the samples are very small and the slopes of the curves (only data points shown) are nearly identical.

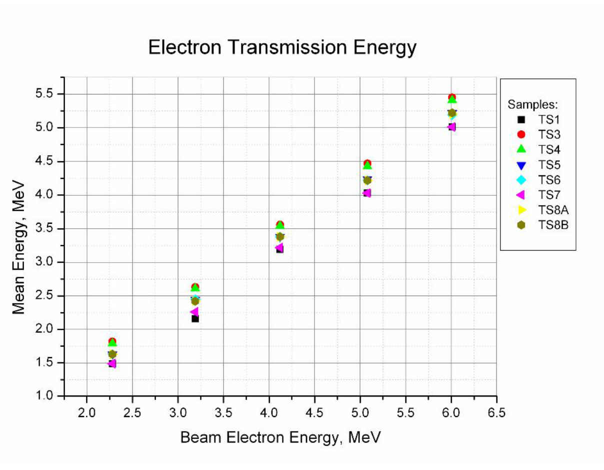

FIG. 7 Electron mean energy transmitted through the samples.

The plot shows that the mean transmitted energy for the aluminium sample (TS1) is the lowest one and the CRFP laminate with two wolfram layers (TS7) has almost identical values. For the asymmetric case (TS8A and TS8B) there are not any differences.

5.3. GEANT4 model validation

The radiation transmission results obtained for samples TS1 and TS5 were used to validate the used GEANT4 based model for proton exposure. The model was validated for electrons only with sample TS1 due to analogue with proton transmission and also due to limited time for further data processing.

The GEANT4 model was in excellent agreement with the test data for the aluminium sample (TS1) both with proton and electron irradiation.

FIG. 8 shows the comparison between the experimental and simulated proton radiation transmission for the sample TS5. It can be seen from the figure that the experiment and simulations match very well. This indicates that the model created in GEANT4 correctly describes the radiation attenuation in the studied aluminium plate and the wolfram CFRP laminate.

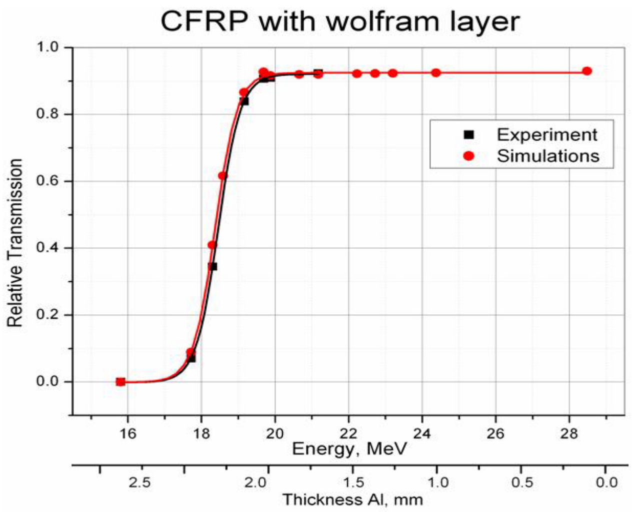

FIG. 8 Comparison between experimental and simulated radiation transmission for the test sample TS5.

Having validated the GEANT4 model for the homogeneous aluminium and the CFRP laminates with a wolfram layer, the model can be used for further optimizations of laminate structures.

6. PROTON ATTENUATION WITH EQUAL AREAL MASS

After the validation process of the GEANT4 model was carried out, the comparison of the proton radiation transmission for the samples TS5 and the aluminium was made. These simulations were performed to get evaluation of the goodness of the low Z – high Z – low Z concept. For this study both the laminate (TS5) and the aluminium plate were adjusted to have the same areal mass of 0,31 g/cm^2, corresponding to the thickness of 1,64 mm and 1,15 mm respectively. The results of the simulations are shown in FIG. 9.

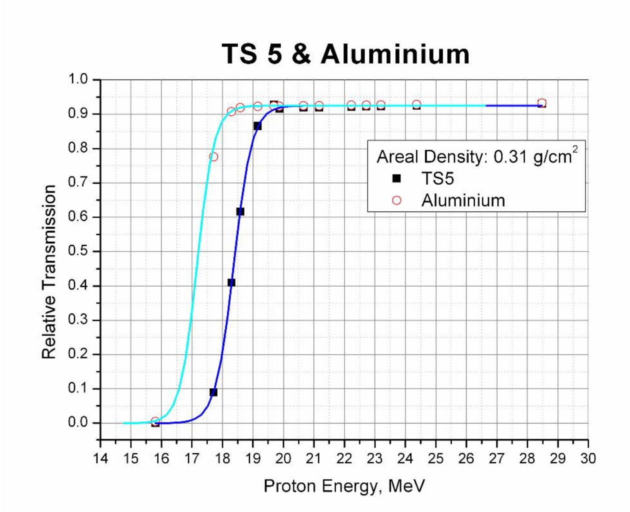

FIG. 9 Relative proton transmissions for the samples TS5 and aluminium with the same areal mass.

The plot shows that the relative proton transmission for the TS5 sample corresponding to the CRFP laminate with one wolfram layer is lower than for the aluminium. This clearly indicates that for the case of protons, the CFRP/W structure has higher shielding efficiency than the commonly used aluminium when they have equal areal mass.

7. CONCLUSIONS

1) The validation of the Monte Carlo - GEANT4 model was successfully carried out. This was mainly driven by the careful selection of the most important components for the experimental setup and the high quality of the acquired data. The deep knowledge of the GEANT4 simulation tool was also an important aspect of the validation process.

2) The attenuation efficiency of several laminate structures with similar thickness was measured for protons. The best attenuation properties had the aluminium reference sample (TS1) and the second best was the laminate sample with two wolfram layers (TS7).

3) For the case of electrons, the mean transmitted energy measured in the water phantom clearly showed similar tendency as with protons. Now the aluminium reference sample had almost identical attenuation properties as the laminate sample with two wolfram layers.

4) The asymmetric laminate (TS8A/B) was irradiated from both sides. The data indicated that neither for protons nor for electrons there were not any measurable difference for the attenuation efficiency and for the mean transmitted energies.

5) The proton transmission was simulated in GEANT4 for the CRFP with a wolfram layer and for the aluminium with the same areal mass. The first one proved out to have higher shielding efficiency than the second one.

6) The performed measurements and simulations indicate that there is good potential for mass savings in electronics housings. Lightweight composite housings with low Z – high Z – low Z (CFRP/W/CFRP) structure can fulfil general radiation attenuation requirements with lower mass than traditional aluminium alloy housings.

8. DISCUSSION

It has been demonstrated that the approach based on first building a detailed GEANT4 based model for radiation transmission studies and then validating the model assumptions by a set of thorough electron and proton beam tests was a successful one. The simulation package is now available for further studies, where optimization of the laminate structures used in various radiation environments is required.

The simulations match very well to the test data obtained in proton and electron irradiation experiments. The main reason for being able to reproduce the measurements was the inclusion of all the relevant radiation interaction processes with matter. The precise descriptions of the geometries of the material samples in the GEANT4 based model were also crucial.

Another important factor in the validation process was the uniformity of the laminates used in the studies. It is important to note that the manufacturing process of the test samples was of high quality as proven by the tests in which the test samples were irradiated by protons.

Concerning the radiation transmission for protons, it was found that at high energies the full transmission was not reached. This effect was found to be related to two major effects: the narrow beam condition and the secondary radiation produced by the beam interactions with air and material surrounding the first silicon detector. These effects cut the overall radiation transmission by about 6% in all samples.

The analysis of the simulations carried out for the validation of the GEANT4 model in the case of protons, was mainly done using only the primary particles. Thus the existing vast simulation data from the secondaries has not yet been analysed. In the case of electrons irradiation both primaries and secondaries were taken into account in the present study.

The whole study was carefully carried out in all aspects to achieve the final validation of the GEANT4 model. A significant amount of CPU time has been used mainly in the Mill and Ametisti clusters generating a total of about 400 GB of raw data.

REFERENCES

[1] G. Lutz. Semiconductor radiation detectors: device physics. Berlin: Springer, 1999, ISBN 3-540-64859-3

[2] A. Abusafieh, G. Tremblay, Lightweight electronics enclosures using composites, SAMPE Journal, Vol. 38, No. 6, November/December 2002

[3] T. Brander, K. Gantois, H. Katajisto, M. Wallin, CFRP electronics housing for a satellite, Proceedings of the European Conference on Spacecraft Structures, Materials & Mechanical Testing 2005, SP-581, European Space Agency 2005, ESTEC, The Netherlands, ISBN 92-9092-892-1, ISSN 1609-042X