THE RADIATION ASSURANCE TEST FACILITY AT INFN-LNS CATANIA

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Abstract

This paper describes the beam monitoring system that has been developed at the Superconducting Cyclotron at INFN-LNS (Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy) in order to monitor the beam parameters such as energy, flux, beam profile, for SEE (Single Event Effects) cross-sections determination and DD (Displacement Damage) studies.

In order to have an accurate and continuous monitoring of beam parameters we have developed fully automatic dosimetry setup to be used during SEE (with heavy ions) and DD (with protons of 60 MeV/u) tests of electronic devices and systems.

The final goal of our activity is to demonstrate how operating in air, which in our experience is easier than in vacuum, is not detrimental to the accuracy on controlling the beam profile, energy and fluence delivered onto the DUT (Device Under Test) surface, even with non relativistic heavy ions.

We have exposed during the same session, two beam calibration systems, the "Reference SEU monitor" developed by ESA/ESTEC and the beam monitoring and dosimetry setup developed by our group. The results are compared and discussed here.

INTRODUCTION

The LNS Superconducting Cyclotron (CS), is a compact, strong focusing three-sector machine. The pole radius is 90 cm and the magnetic field at the center ranges from 2.2 to 4.8 T. This is obtained with superconducting Nb-Ti coils cooled down to 4.2 K in an LHe bath. The expected maximum energies of the machine are of 20 MeV/u for the heaviest ions, like $^{238}U^{38+}$, and 100 MeV/u for fully stripped light ions as given respectively by the bending limit K_b=800 and by the focusing limit K_f=200.

The measurement of beam flux and uniformity is one of the ingredients for the calculation of SEE cross-section. According to the ESA standard ESCC-25100 these measurements should be done with an accuracy of ±10%.

The relatively high energy of the beams (for this study 20 MeV/u) allows the irradiation of components in air which is used also as a degrader. The selection of the ion species we use in SEE studies is done by taking into account the easiness of beam changing operation and at the same time the necessity to cover as large a LET interval as possible. Hence, four gaseous beams (^{20}Ne, ^{40}Ar, ^{84}Kr, ^{129}Xe) all with 20 MeV/u energy are selected.

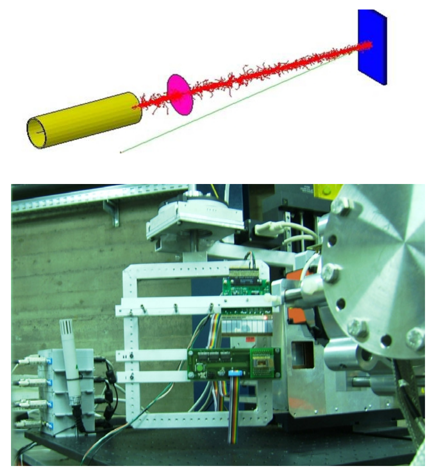

Figure 1: Upper: Geant4 simulation of setup representing, from left to right, vacuum pipe, thin scintillator and silicon detector or DUT. Lower: The beam dosimetry setup. The DS microstrip silicon detector, 3-D stage and rotator to which the DUT holder is attached are shown.

A careful evaluation of energy loss in air end of the energy spread at DUT surface is carried out through a full Monte Carlo simulation of the test setup and comparing the results with data.

The DD studies are performed using 60 MeV/u protons instead.

BEAM MONITORING SYSTEM

At LNS we perform extraction of ion beams in air, where our flux and dosimetry setup resides; additionally we use air as a degrader in order to adjust LET values. A basic schematic of the dosimetry measurement setup is shown in Fig. 1. The upper part of the figure shows the particles getting into air from beam pipe, crossing a thin scintillator and then reaching the DUT or silicon detector surface. The air thickness between beam exit and thin scintillator is fixed while the one between thin scintillator and DUT (or Si detector) is variable (respectively, A1 and A2 in Table 1).

Table 1: Typical Set of LET(Si) Values and corresponding Ion Species, Ranges and Air Thicknesses

Ion	E (MeV/u)	A1 (cm)	A2 (cm)	Impact Angle (°)	Scintillator Thickness (μm)	Ek Tot (MeV)	Ek at Si Surf. (MeV)	Range in Si (μm)	LET in Si (MeV/mg/cm^2)
^{20}Ne	20	5	5	0	50	400	341	402	3,66
^{20}Ne	20	5	30	0	50	400	259	254	4,39
^{40}Ar	20	5	5	0	50	800	617	252	10,56
^{40}Ar	20	5	30	0	50	800	347	105	14,26
^{84}Kr	20	5	5	0	50	1680	1074	150	30,76
^{84}Kr	20	5	15	0	50	1680	751	93	34,69
^{129}Xe	20	5	5	0	50	2580	1473	109	57,99
^{129}Xe	20	5	15	0	50	2580	923	70	56,62

The setup consists in a thin scintillator counter (NE102A of 50 or 100 μm thickness) read by a photomultiplier just after the beam exit into air, an XYZ stage with submicron absolute position resolution. The scintillator is inserted into a metallic box with variable size beam hole to allow the adjustment of the beam size. The DUT is placed onto a supporting frame (DUT holder) which is held by a rotator fxed to the positioning stage. On the same structure close to DUT holder a double sided, 1.5 mm thick microstrip detector (500 μm readout pitch and 3x3 cm^2 active area) is mounted for energy, fluence and beam profile measurements. Because of its thickness the silicon detector behaves like a calorimeter to the above mentioned ion species in non relativistic regime, containing all their energy: the stopping range in silicon is, for all ions we use, at least 30 μm, in accordance to the minimum penetration depth required by the ESA standard ESCC-25100.

The dosimetry setup includes two additional important features. A laser device, which is used to measure the distances in Z (beam) direction with 200 μm position accuracy. Such level of accuracy in measurement of the relative distances (i.e. silicon detector surface to delidded DUT surface, DUT surface to beam exit in air, etc.) is important to achieve as small as possible overall systemic error on LET value in silicon. The other feature of the setup is a custom module (SELDP) built specifically to monitor the current drawn on power line of a DUT. The SELDP cuts the power supply to DUT for an adjustable time duration whenever the current drawn by DUT exceeds a preset current limit. This both protects DUT from burnout because of Single Event Latchup (SEL) effect and registers the number of SEL occurred by incrementing a counter.

The overall configuration of beam setup is given in the block diagram below. The two PCs indicated inside the red frame are located in the beam, while all the rest of the boxes are representing tasks carried out by a single laptop in the control room communicating via TCP-IP with the PCs inside the beam area.

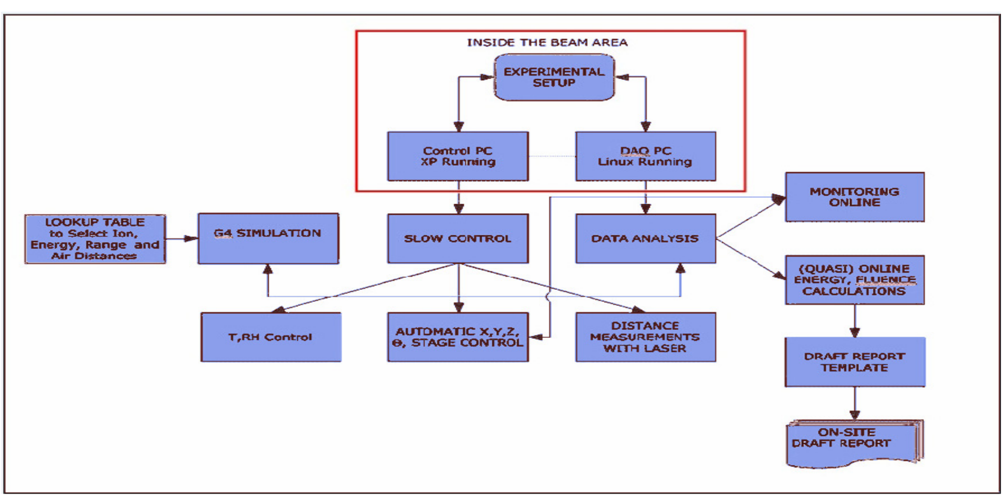

Figure 2: The configuration of DAQ and control PCs (inside the beam area) and laptop in control room. The tasks carried out by each computer are also shown.

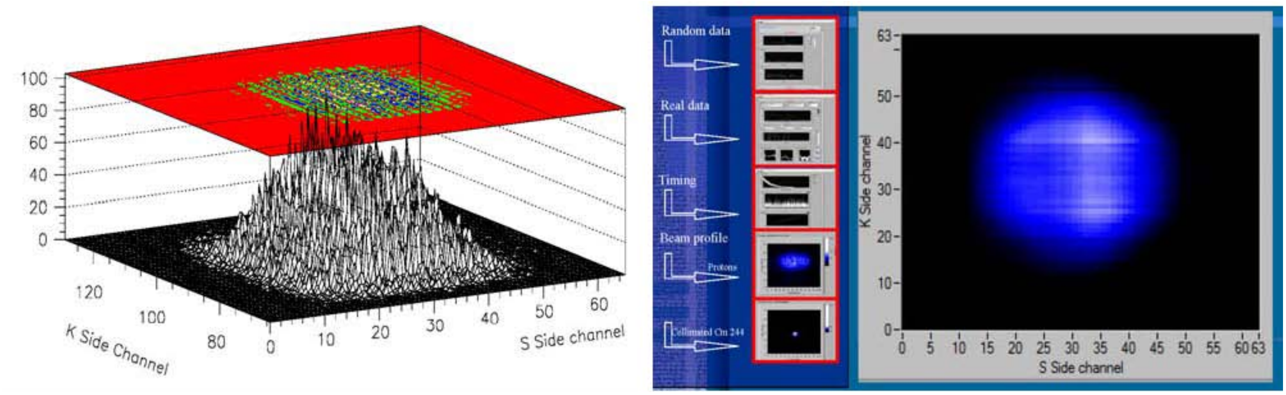

Figure 3: The online monitoring of beam parameters with silicon detector. Left: The beam profile is shown in 3D. Each channel corresponds to 0.5 mm (strip pitch of double sided silicon detector). Right: The beam profile reconstructed from data.

PERFORMING SEE AND DD MEASUREMENTS

Prior to go to LNS for a test period, all dosimetry system including DUT mounting and performance is tested in MAPRAD laboratories (REF) onto a mock-up mechanical system of the beam setup which includes also a pulsed IR laser source. All mechanical parts necessary are produced and tested on this mock-up, as well as electronics parts which are tested under the pulsed laser beam to verify the behaviour of the entire DAQ system.

Test Procedure for SEE Studies

A full Geant4 Monte Carlo description of the setup has been done and run for the four different ion species in use to prepare a detailed look-up table. This table includes, among others, the range and LET values achieved for each experimental configuration differing by 1 mm increments of air thickness between thin scintillator and DUT surface.

For each device to be tested several LET values over an agreed LET range are selected and corresponding parameters are extracted from the table. A typical set of LET values and corresponding air thicknesses are listed in Table 1. The effective LET values larger than 100 MeV/mg/cm^2 can be obtained by altering the beam impact angle on the DUT, since $LET_{eff} = LET_{(0)}/Cos(\Theta)$.

The SEE test procedure consists in following steps;

- For each ion, we memorize on the control PC the data taking positions (see A1 and A2 distances and impact angles given in Table 1).
- Start with the beam profile on the silicon detector to get the beam shape and position with respect to DUT, so that it can be automatically moved under the beam.
- Start data acquisition by monitoring; the flux measured by thin scintillator and DUT parameters.
  The beam parameters (energy, profile, flux, time tag) measurement is done by moving silicon detector under the beam for short periods without stopping the run (see Fig. 3). A possible alternative procedure is to keep the silicon detector off-beam close to DUT and monitor continuously the tail of the beam. A calibration run with thin scintillator "on" and silicon detector "on/off" beam will provide normalization factors to achieve the real flux.

The steps described above, are repeated for different DUT distances (air thicknesses) or impact angles, to obtain various LET values using the same ion species.

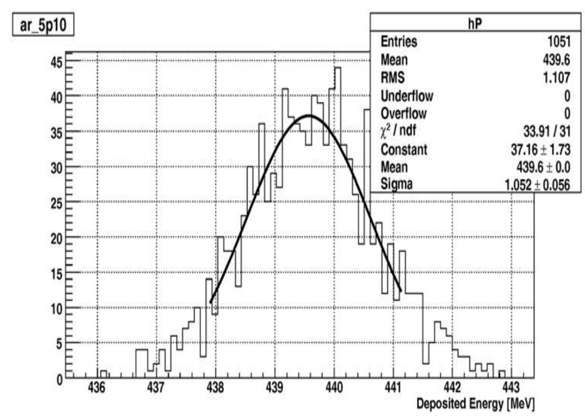

Figure 4: For ^{40}Ar beam at 10 cm air thickness (A2) Distribution of energy deposited in silicon simulated by Geant4.

Systematic Error Evaluation

A careful evaluation of systematic errors is necessary to estimate overall error introduced on LET and on fluence values. Definition of LET and cross section is given in Eq. 1 where ρ is silicon density.

$$LET(MeV \cdot cm^2 / mg) = \frac{dE}{dX} \cdot \frac{1}{\rho}; \qquad \sigma(\neq / cm^2) = \frac{N_{SEE}}{Fluence \cdot Cos\theta}; \tag{1}$$

Systematic errors on LET values are;

- Distance (air thickness) measurements. This is done with a 200 μm accuracy laser system only once during the initial calibration phase. All other positions are relative to that point with submicron precision 4-D stage (X,Y,Z, Theta)

- Fragmentation in air. It is negligible (i.e. $<10^{-4}$ for 20 MeV/u ^{40}Ar after 15 cm of air) according to Geant4 simulation performed using "binary light ion cascade" and "Wilson abrasion" models.
- The determination of energy deposited and range in DUT by Geat4 simlation; the energy distribution from Monte Carlo has less than 3% error at FWHM (see Fig. 4), and there is a good correlation with the charge measured by the silicon detector, which provides the possibility to convert the charge values to deposited energy. The correlation between charge collected in silicon and simulated energy for different air thicknesses for ^{40}Ar is given in Fig. 5.
- Positioning of beam spot to the center of DUT and correction of non uniformity of beam over the beam spot. Fig. 6 shows a typical beam spot and DUT dimensions. This error includes a 180 µm contribution from the silicon detector spatial resolution, as well as a ~300 µm one from the accuracy of the DUT mounting on the holder frame; the two contributions are summed in quadrature since they are independent.

The detailed analysis of errors have shown that the overall error, on determination of both fluence and LET, is less than 4% which is well below the upper limit (10%) required by ESCC-22500. Table 2 lists the overall systematic errors on LET values for different ion species at 10 cm of A2.

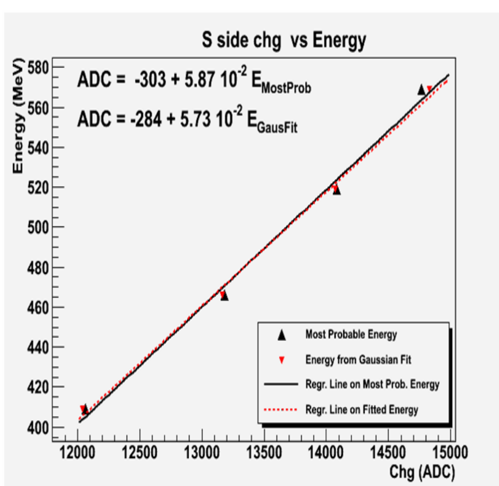

Figure 5: Correlation curves between charge deposited in silicon (ADC counts) and simulated energy release (MeV). The two data sets and curves refer to different ways to estimate energy from Monte Carlo distribution: black triangles use the most robable value taken from energy histogram; red upside-down triangles use the mean from a gaussian fit.

Comparison of Results with SEU Monitor

The reference SEU (Single Event Upset) monitor system [1] was developed specifically for inter-site calibrations to address the issue that in different

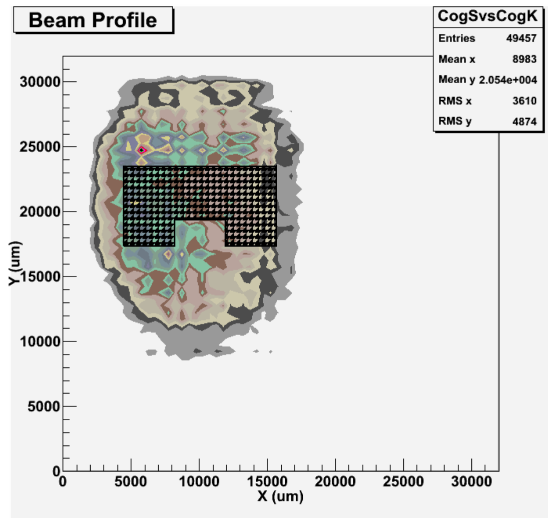

Figure 6: Beam spot is centred over the DUT surface. Form this profile one can extract the real fluence distribution over DUT surface. The beam spot positioning accuracy is at most 400 µm.

irradiation facilities the user usually has no means of checking suspicious beams and of discovering data discrepancies on-site.

In order to minimize test errors becasue of faulty beams a simple reference system allowing beam re-checking capabilities was necessary. The reference SEU monitor system was developed for this purpose by using a SRAM (Atmel AT60142F) as active detector.

We have used in LNS reference SEU monitor pre-calibrated with heavy-ions, protons and neutrons, provided by ESA/ESTEC to check the quality of the dosimetry systems we described above, as well as the beam quality of LNS site. After each irradiation of the SEU monitor, the user has to supply the measurements for LET and fluence from his own dosimetry system to the SEU monitor own software, which carries out the calculation of cross section independently of the operator and adds a new data point to a comparison plot. The results are given in Fig. 7. The blue points are data points for LNS site which are in good agreement with calibration points obtained in two other irradtion facilities (HIF in Belgium and RADEF in Finland).

Table 2: LET(Si) values and corresponding systematic errors for different ion species at the 10 cm of Air (A2) thickness experimental configuration

Ion	LET(Si) ($MeV/mg/cm^2$)	Error on LET(Si) ($MeV/mg/cm^2$)
^{20}Ne	3.7	0.1
^{40}Ar	13.1	0.2
^{84}Kr	30.6	0.7
^{129}Xe	52.9	0.8

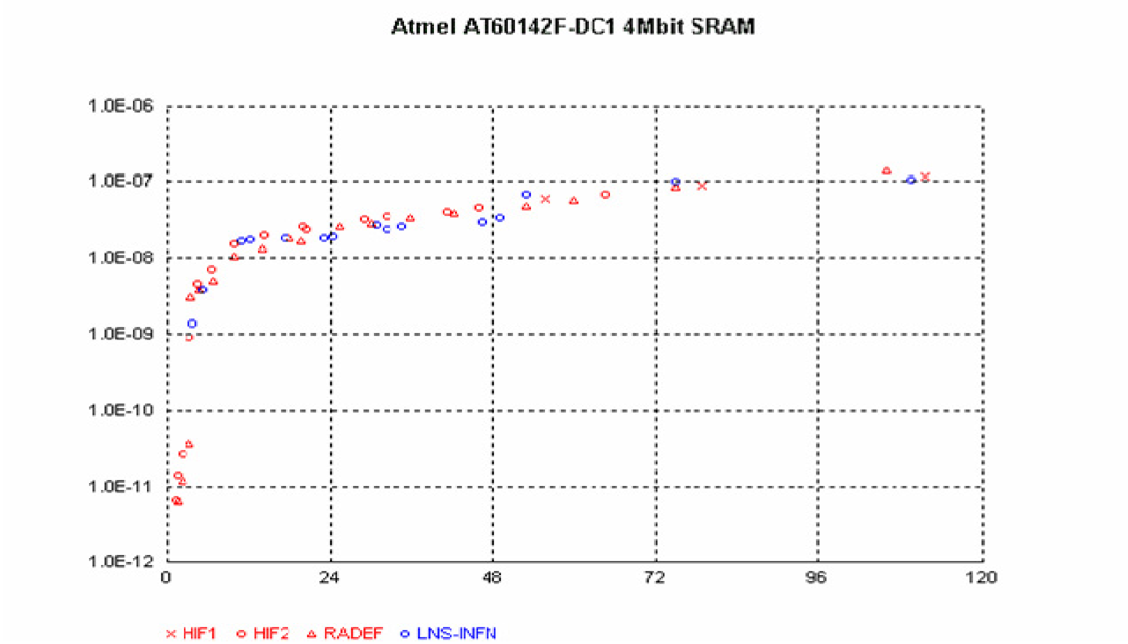

Figure 7: Comparison of cross section versus LET for the SEU monitor from different sites: the blue points are data points for LNS site, the red points are series obtained previously by ESA at other facilities (HIF in Belgium and RADEF in Finland) as calibration points. The measurements taken at LNS are in good agreement with the ESA calibration.

Test Procedure for DD Studies

The displacement damages are non ionizing effects caused mostly by protons and neutrons on silicon lattice structure by dislodging or displacing the atoms from their lattice sites. The DD studies at LNS are carried out using 60 MeV protons. Here the testing procedure is simpler than that of SEE since tests are realised at a fixed A1 and A2 distances. The DUTs under proton irradiation are usually unbiased (unless otherwise requested). The critical parameters of DUT are tested before and after irradiations. The test points are after different dose values delivered to the DUT, which are calculated as:

$$Dose(rad(Si) = LET(SiO_2) \cdot Fluence \cdot 1.6 \cdot 10^{-5} \qquad (2)$$

In this kind of test, the main problem is that test equipment materials do activate after prolonged exposition to the proton beam. For this reason we designed the supporting frame so that only the DUT and a minimal amount of test board is directly under the beam, in order to reduce activations as much as possible. To avoid putting the silicon detector under the beam for long times, it is possible to use it to monitor the intensity of the beam tails after an initial intercalibration phase with a gas chamber put in front of the beam outlet; the chamber can then be removed during actual DUT irradiation. The electrical connections of the DUT's pins to power supply, bias line and measurement apparatus must be designed so that it is possible to (dis)connect them remotely to avoid getting close to a possibly activated DUT.

CONCLUSIONS

In Europe there is a limited number of accelerator sites whose delivered ion beams fulfil the requirements of ESCC standards for SEE testings. We have developed a fully automatic dosimetry system to demonstrate the validity of beam charaterictics of LNS sites for SEE and DD tests as well as to accurately measure the parameters relevant to perform detailed SEE and DD studies. With energies available at LNS and with four selected gaseous beams it is possible to perform SEE studies from few up to 110 MeV/mg/cm^2 of LET.

The beam changing time is relatively short (few hours) and beam size and fluence are stable in time. Furthermore, the presence of air gives possibility to reach “fine-tuned” LET values by adjusting the air thickness accordingly. Last but not least, operating the setup in air has the obvious advantages of reducing setup time and complexity.

REFERENCES

[1] R. Harboe-Sorensen, F.-X. Guerre and A. Roseng, Design, Testing and Calibration of a "Reference SEU Monitor" System. Proceedings of RADECS 2005.