HEAVY ION BEAM FLUX AND IN-SITU ENERGY MEASUREMENTS AT HIGH LET*

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Abstract

The Russian Space Agency with the TL ISDE involvement has been utilizing ion beams from oxygen up to bismuth delivered from cyclotrons of the FLNR JINR accelerator complex for the SEE testing during last seven years. The detailed overview of the diagnostic set-up features used for low intensity ion beam parameters evaluation and control during the corresponding experiments is presented. Special attention is paid to measurements of ion flux and energy at high LET levels and evaluation of ion beam uniformity over large (200x200 mm) irradiating areas. The online non-invasive (in-situ) time of flight technique designed for low intensity ion beam energy measurements based on scintillation detectors is considered in details. The system has been successfully commissioned and is used routinely in the SEE testing experiments.

INTRODUCTION

Onboard equipment of spacecraft is exposed to ionizing radiation from the Earth's natural radiation field, as well as galactic and solar cosmic rays during its operation. There are two types of effects in microelectronic circuits caused by radiation: 1—those related to accumulated dose; and 2—those caused by a singular hit of a swift heavy ion (single event effect, SEE). Despite its relatively minor contribution (~1%) of the total amount of charged particles, it is heavy ions that cause the most damage to microelectronics hard ware components due to the high level of specific ionization loss. Hence, to reproduce the effects of the heavy ion component of cosmic radiation for the prediction of electronic device radiation hardness usage of low intensity (up 10^6 ions cm^{-2} s^{-1}) heavy ion beams with linear energy transfer (LET—the measure of energy losses per path length in the material) levels in silicon, specific for the ion energy range of 50–200MeV/nucleon, is supposed. Taking into account that actual integrated circuits in metal and plastic packages, as well as ready to use electronic boards need to be tested, ion beams with energies in the range of 3–50 MeV/nucleon are used in model experiments. This entire means that the accepted method of SEE testing requires measurements of ion flux in the range from 1 to 10^5 ions ($cm^{-2}*s^{-1}$), ion fluence up to 10^7 ions/cm^2, beam uniformity at the device under test (DUT) and energy of ions. The SEE testing facility is established [1] at the U400M and U400 cyclotrons at the accelerator complex of the Flerov Laboratory of Nuclear Reactions (FLNR) of the Joint Institute for Nuclear Research (JINR) [2]. Ion beam parameters used for SEE testing, like ion type and energy, the LET and ion flux range, are listed in Table 1.

Table 1: Ion Beam Parameters Used for the Low Energy SEE Testing

Accelerated ion	Extracted ion	Energy, MeV	LET, MeV/(mg/cm^2)	Ion flux, $cm^{-2}s^{-1}$
$^{16}O^{2+}$	$^{16}O^{8+}$	56±3	4.5	1 ÷ 10^5
$^{22}Ne^{3+}$	$^{22}Ne^{10+}$	65±3	7	1 ÷ 10^5
$^{40}Ar^{5+}$	$^{40}Ar^{16+}$	122±7	16	1 ÷ 10^5
$^{56}Fe^{7+}$	$^{56}Fe^{23+}$	213±3	28	1 ÷ 10^5
$^{84}Kr^{12+}$	$^{84}Kr^{32+}$	240±10	41	1 ÷ 10^5
$^{136}Xe^{18+}$	$^{136}Xe^{46+}$	305±12	67	1 ÷ 10^5
$^{209}Bi^{22+}$	$^{209}Bi^{58+}$	490±10 (820±20)	95 (100)	1 ÷ 10^5

Since becoming operational in 2010, the low energy beam (3÷6 MeV/nucleon) facility has been available to users. The facility for the SEE testing at high energy (15÷64 MeV/nucleon) was successfully commissioned in January’14. The third line is based on U400 (commissioned in December’14) and after modernization of this cyclotron in 2018 there will be the possibility to make the SEE testing with the fluent energy variation for every ion.

BEAM FLUX CONTROL

The wide range of beam control systems are used during irradiation. To catch the beam movable probes inside the U400M are used. Diagnostic elements such as the luminophor and the Faraday cup are used during rough beam adjusting at high intensity. For the fine beam tuning and beam profile control, double side Si strip detector (Fig.1) and arrays of scintillators detectors are installed.

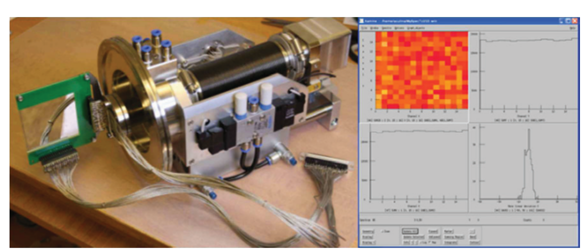

Figure 1: Double-side Si strip detector. Dual axes (X-Y) orthogonal beam detection Kr beam profile as example.

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The last one provides on-line control of beam flux. The beam uniformity and flux are determined using an array of five active particle detectors. Two kind of active detectors utilized in the diagnostic system routinely - proportional counters and scintillation detectors. The four detectors are placed in corners (for the ion beam halo control of DUT irradiating area and the fifth in its center (Fig.2). The choice for this type of counters was done due to their operation simplicity.

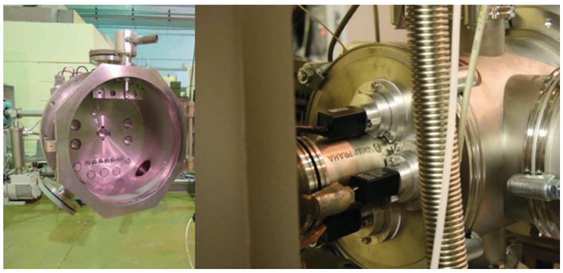

Figure 2: Arrays of scintillators detectors.

To increase the reliability of ion fluence measurements, total number of ions which hit the target is controlled additionally by using polycarbonate or polyethylene terephthalate track detectors placed in close vicinity of any testing device in all irradiation sessions (Fig.3).

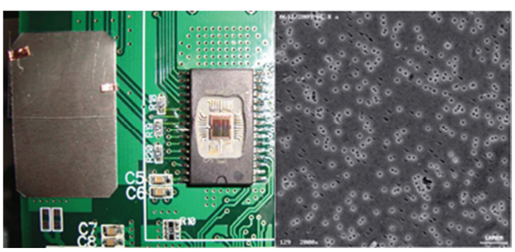

Figure 3: Polymer track detector and the DUT. SEM micrograph of polymer track detector.

The efficiency of swift heavy ion registration by such detectors is close to 100%. Besides of ex situ monitoring of accumulated ion fluence, polymer track detectors are used also for precise determination (with accuracy no worse than 5%) of the beam uniformity over the irradiating area after change from one ion to another (Fig.4.).

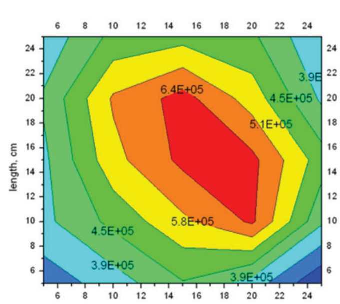

Figure 4: Ar beam distribution over the irradiating area.

As a future development of the low intensity ion beam monitoring, it's suggested to use the SiC based detectors. Therefore, the special attention in research should be payed to study the response of such detectors at high 60-100 MeV/(mg/cm2) LET levels.

METHOD AND INSTRUMENTATION FOR ENERGY MEASUREMENT

Testing is carried out according to the procedure based on international standards, such as those given in [3]. The standards apply to ions with energies <10 MeV/nucleon. These standards have the following requirements to the ion beam. Set of ions with different LET values in the material of tested devices should be used in the tests. There should be no impurities of other atoms in the irradiating ion beams. In this case it is impossible to clean out the ion beam of impurities, a minor presence of impurities is allowed, and their content must be known. It is required by the standards that the LET be known with an accuracy no worse than ±10%. Based on this, the energy of the ions must be measured with the same accuracy. It also should be able to verify matching with the specified type of ion, the absence or the presence of impurities and their contents. It is recommended in [3] to use surface barrier semiconductor detectors for measuring the energy of ions. From our point of view this method is not convenient as it requires constant calibration of the detector. Since the ion types in one irradiation session can vary in a broad range, from oxygen to bismuth, for example, one takes into account a well-known difficulty, namely a strong signal dependence on the LET level, while using the surface barrier semiconductor detectors. The time of flight method is free of this disadvantage. It is often used in experimental high energy particle physics (more than tens of MeV per nucleon). In this method one and the same charged particle is consistently recorded by two fast detectors installed along the beam at a known distance flight base. One of the principal conditions of this method is that the energy loss in the particle detector that is mounted in the beginning of the flight base must be so small that the speed change can be neglected. It is difficult to implement this condition for heavy ion energy within the range of interest because of the short path of the ions in matter. The most often used non-invasive method in this energy range is to determine the time of flight by recording signals induced by the same ion beam micro bunch from two pickup probes spaced along the beam line [4–6]. Micro bunches are a natural time structure of ion beams accelerated in the circular accelerator. The occurrence of micro bunches is caused by a certain acceptance phase band in the acceleration process using a high frequency electric field. The signals from the pickup probes can be registered with a fast dual beam oscilloscope. The image obtained with the oscilloscope during measurement of energy of krypton ions $^{84}Kr^{27+}$ is shown below on Fig. 6.

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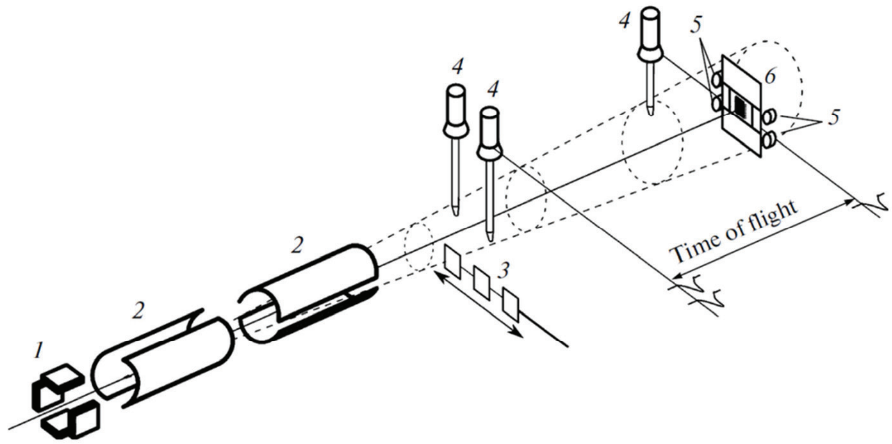

Figure 5: Scheme of the ion beam transport line and experimental set up for low energy SEE testing at the U400M cyclotron: 1—Beam positioning magnet; 2—X–Y magnetic scanning system; 3—set of degrading foils; 4—scintillation detectors; 5—proportional counters; and 6—device under test. See explanations in text.

There are certain complications in the application of this method for the described task. One of them is that due to the fact that the minimum beam current necessary for the correct method to work is 0.3 mkA. Beam currents used for SEE testing are smaller by several orders. Moreover, existing accelerators cannot achieve this value of current for all types of ions used for testing.

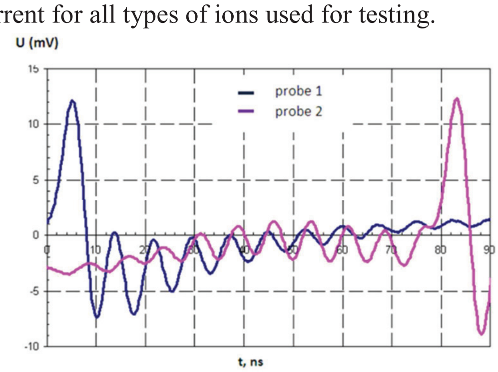

Figure 6: TOF signals generated by 3 MeV/amu Kr ions. Distance between pick-up probes – 1.9 m. Ion beam current – 0.3 μA

We realized the online noninvasive time of flight technique in a substance similar to the pickup probes method, with the difference of using here scintillation detectors instead. Detectors with a substantially smaller size compared with the scanning beam cross section were used. They were mounted on the periphery of the scanning ion beam in such a way that they don't overshadow each other and the DUT as shown at Fig.6. The signals from the detectors were sent to a two channel time to digital converter (TDC). Signal from one of the front detectors was used as the "start" event and signals from two other detectors were used as "stop" events. The TDC was connected to a computer outside the experimental hall via Ethernet connection. As an example, the result of the measurements performed on the beam line is given. Argon ions were extracted from the cyclotron with energy of 7.5MeV/nucleon. The specified energy range for SEE testing typically is 3–6 MeV/nucleon. A degrader with a set of tantalum foils of different thickness is used to choose appropriate ion energy. The measured flight times and the corresponding energy values of argon ions are listed in Table 2.

Table 2: Comparison of the Measured and Calculated (SRIM) Ar Ion Energy

Ta degrader thickness, μm	Measured time of flight, ns	Ion energy, MeV/nucleon	
		measured	calculated
0	42 ± 0.5	7.53 ± 0.16	7.53±0.16
5	46 ± 0.5	6.28 ± 0.14	6.28 ± 0.17
9	50 ± 0.5	5.32 ± 0.10	5.21 ± 0.18
12.5	56 ± 0.5	4.24 ± 0.08	4.28 ± 0.19
15	61.5 ± 0.5	3.51 ± 0.06	3.47 ± 0.20

Measurements were carried out on the ion beam both extracted from the accelerator and after passage of tantalum degraders with thickness of 5, 9, 12.5, and 15 μm. Calculated with SRIM software [7], values of energy are also listed. Beam energy after extraction was taken as the initial value in the calculations. Errors in the results of the calculations correspond to error of the initial value.

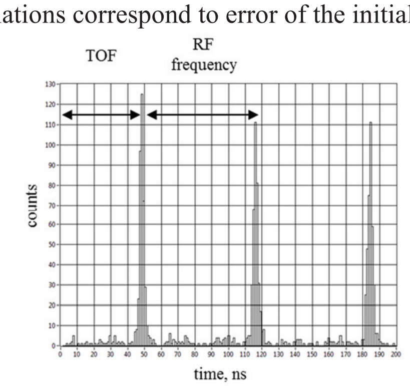

Figure 7: Ar experimental spectrum.

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Comparison of measurements and calculations showed that the measurement error is no worse than ±3% and it is caused both by statistical and by systematic errors of the time of flight measurement. The measurement duration is about 1–2 min.for our method. The usual TOF spectrum measured for Ar-40 ions (initial energy - 301 MeV) at the U400M cyclotron shown at Fig.7. Total ion energy (after 5 mkm of Ta) 250 MeV is determined by time between zero and first bunch maximum. Time between maxima of bunches corresponds to cyclotron RF frequency. The method fully meets the requirements for SEE testing. If it is required to improve accuracy to use this method for other experiments, one can increase length of the flight base. Use of degrading foils additionally allows one to determine the content of impurities in the ion beam. A clean from impurities ion beam corresponds to one peak on the recorded spectrum. An ion beam with impurities results in split peaks on the spectrum after passing the degrader (Fig.8).

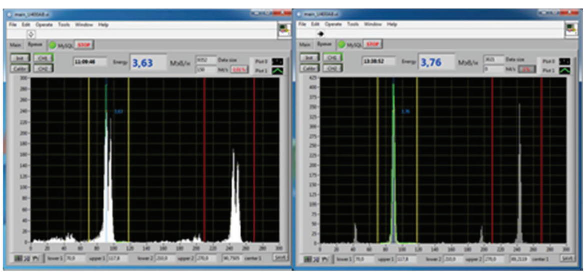

Figure 8: Intensity ratio of the peaks occurred after splitting corresponds to the proportion of impurities. One can determine LET of the impurity by the offset of the peak on the spectrum.

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