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NUCLEAR EXPERIMENTAL TECHNIQUES

Measurement of Heavy Ion Energy at the Test Facility of Electronic Components[1]

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Abstract—The time-of-flight system for low intensity heavy ion beam energy measurements based on scintillation detectors is presented. Parameters of the experimental setup and the data processing algorithm are described. The accuracy of the method is no worse than ±1.5%.

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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 hardware 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 50–200 MeV/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.

The SEE testing facility is established at the U400M cyclotron at the accelerator complex of the Flerov Laboratory of Nuclear Reactions (FLNR) of the Joint Institute for Nuclear Research (JINR) [1]. The U400M cyclotron [2] is designed to accelerate ion beams in two modes: in the energy ranges of 19–52 and of 6–9 MeV/nucleon. Parameters of low-energy ion beams most frequently used in the testing are given in Table 1.

[1] The article was translated by the authors.

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. Energy measurement with higher accuracy would allow the use of the system in other radiation material science experiments.

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, and energy of ions. It also should be able to verify matching with the spec-

Table 1. Ion beam parameters used for SEE testing

Ion type	Energy, MeV	LET, MeV cm^2/mg	Ion flux, cm^{-2} s^{-1}
^{16}O	56 ± 3	4.5	
^{20}Ne	65 ± 3	7	
^{40}Ar	122 ± 7	16	
^{56}Fe	213 ± 3	28	1–10^5
^{84}Kr	240 ± 10	41	
^{132}Xe	305 ± 12	67	
^{209}Bi	490 ± 10	95	

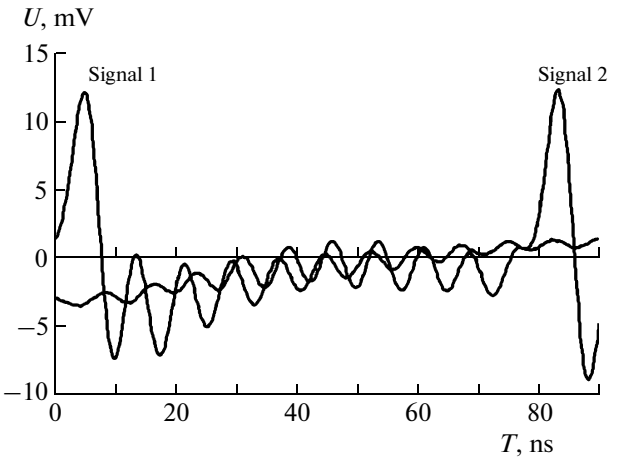

Fig. 1. The signals from pick-up probes induced by ions of $^{84}Kr^{27+}$, obtained with a fast dual-beam oscilloscope.

ified type of ion, the absence or the presence of impurities and their contents. Devices for measuring the ion flux density, fluence and beam uniformity at the facility are described in [4].

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 megaelectronvolts 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 noninvasive method in this energy range is to determine the time of flight by recording signals induced by the same ion beam microbunch from two pick-up probes spaced along the beam line [5–7]. Microbunches are a natural time structure of ion beams accelerated in the circular accelerator. The occurrence of microbunches is caused by a certain acceptance phase band in the acceleration process using a high frequency electric field. On the isochronous cyclotron U400M the acceptance phase band is approximately 20°. For example, when argon ions are accelerated with a frequency of 14.7 MHz, the duration of one microbunch is about 4 ns. The signals from the pick-up 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 on Fig. 1.

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 μA. 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.

METHOD AND INSTRUMENTATION FOR MEASUREMENT OF ENERGY

In this report we present the on-line noninvasive time-of-flight technique in a substance similar to the pick-up probes method, with the difference of using here scintillation detectors instead. Detectors with a substantially smaller size compared with the scanning beam cross section are used. They are mounted on the periphery of the scanning ion beam in such a way that they don't overshadow each other and the device under test, as shown at Fig. 2. Three detectors were used for the method development. Two first START1 and START2 detectors were located at the same plane relative to the beam direction and the third one (STOP) at the certain known flight base. 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.

Figure 3 shows a photograph of the scintillation detector mounted on the flange DN-160. Hamamatsu equipment is used: H6780 series photomultiplier tube (PMT) module (*2*) and C9744 Photon counting unit with the built-in amplifier and discriminator circuits (*1*). Fast organic scintillation detectors are used for registration of the ions.

Adjustment of the equipment allowed us to reduce the absolute systematic measurement error of time delays due to the fluctuation of the amplified signal depending on the amplitude of the input signal to a value of ≤0.5 ns. To achieve this, all three PMTs gain was regulated in such a way that the amplitude of the output pulses was identical. Discrimination thresholds were aligned too. Due to low radiation hardness of the organic scintillators, the energy measurement was performed sporadically. The rest of the working time scintillation detectors were covered with flaps (*4* in Fig. 3), which covers the detector without vacuum destabilization. The flight base between the detectors was 1602 mm. Signal

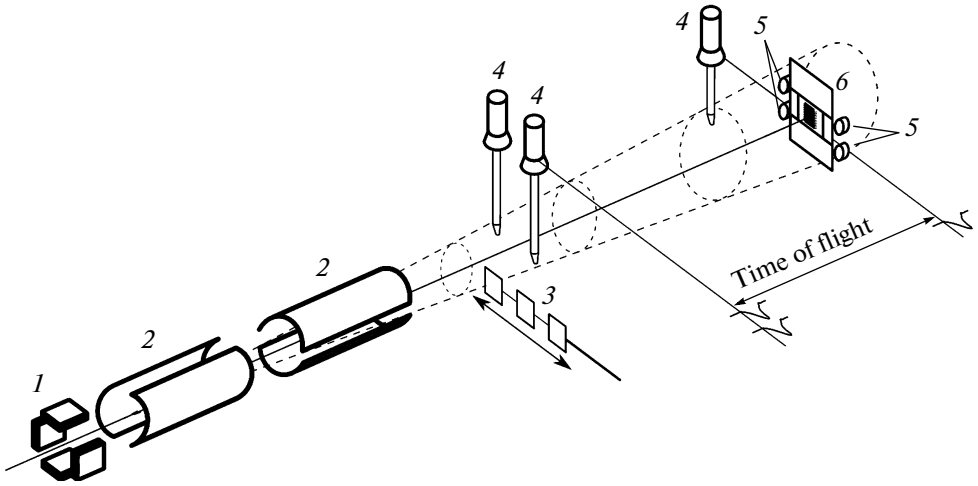

Fig. 2. Scheme of the ion beam transport line and experimental set up for SEE testing at the U400M cyclotron. *1*—Beam-positioning magnet; *2*—*X*–*Y* magnetic scanning system; *3*—set of degrading foils; *4*—scintillation detectors; *5*—proportional counters; and *6*—device under test.

cables with exactly the same length were used to equalize the signal delay from all detectors.

Then, typical for SEE testing ion flux (~10^3–10^4 ions/(cm^2 · s)) and microbunch repetition a frequency of ~10^7 Hz was used, we have a relatively low probability to record start and stop events from the same microbunch. One can observe maxima on the recorded time spectra, which correspond to arrivals of stop events both from the same microbunch that activated a start detector and following microbunches. Time between maxima of microbunches corresponds to cyclotron rf frequency. Two time spectrums were measured simultaneously. One from stop events from the detector placed on the same plane relative to the beam line and another from stop events from the detector placed to the end of the flight base. Three recorded spectrums are presented in Fig. 4 as an example. One can note the close analogy with the image obtained by two-beam oscilloscope measurements with pick-up probes (see Fig. 1). This points to the fact that one can use the algorithm described in [6, 7] to determine time of flight and energy of the ions from measurement results.

According to the pick-up probes measurement method, the flight time is calculated as the time difference between two maxima corresponding to the two time spectrums. Unfortunately, the TDC we used was not able to measure the time spectrum in the range of 0–3 ns. For this reason, the first maximum of the spectrum of the signal from the stop detector placed one the same plane with the start detector is not displayed. Therefore, the time of flight is determined by the difference between the maxima corresponding to the following microbunch. These maxima are marked as *1*–*3* in Fig. 4. The maxima were extrapolated using gauss function to accurately determine the center of distribution. One can find the kinetic energy of the ions E_k using the measured time of flight and the length of the flight base. Non-relativistic formula can be used for the region of interest.

The main parameters of equipment used in the measurement are listed below.

SmartTDC-01 is a universal 2-channel multihit TDC. This complete multifunctional and wide-range device is well suited for industrial applications and for research. The module is based on the chip TDC-GP1 Acam mess electronic GmbH (Germany), it can operate in several measurement modes, which can be selected using the software. SmartTDC-01 has two measurement channels “Stop 1” and “Stop 2” with a 15 bit resolution. The measuring unit for both chan-

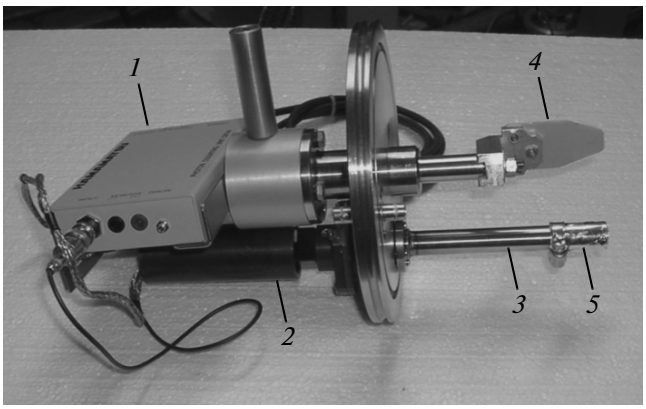

Fig. 3. One of the scintillation detectors used to measure the time of flight. *1*—photon counting unit, *2*—PMT, *3*—lightguide, *4*—flap, and *5*—scintillator.

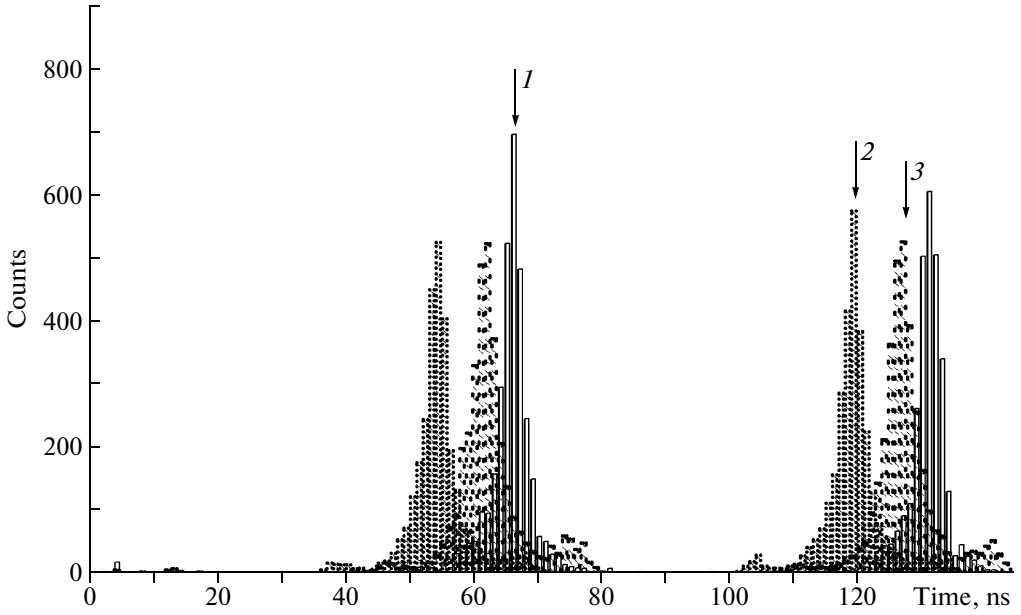

Fig. 4. The time-of-flight spectrum measured for Ar ions with scintillation detectors, mounted at zero distance from start (*1*) and at 1602 mm from start after passage of 5 (*2*) and 9 μm (*3*) Ta degrader foil. The time of flight was determined as time between *1* and *2* or *1* and *3*.

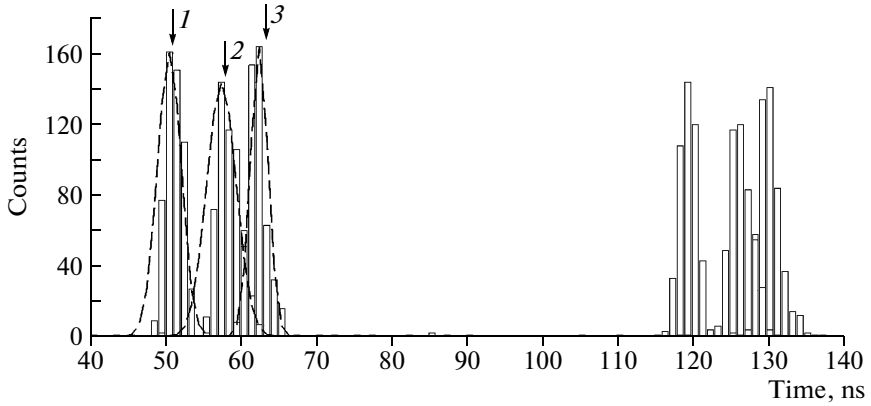

Fig. 5. The time-of-flight spectrum measured for Ar ions with the DRS Evaluation Board after passage of 9 (*1*), 12.5, (*2*) and 15 μm (*3*) Ta degrader foil. The maxima were extrapolated using the gauss function to accurately determine the center of distribution.

nels is started by the sensitive edge of the "Start" pulse. Every channel can receive four independent stops.

Key features:

—2 channels with 250 ps resolution or 1 channel with 125 ps resolution;

—4-fold multihit capabilities per channel;

—2 measurement ranges, 3 ns–7.6 μs and 60 ns–200 ms;

—reference frequency range from 500 kHz to 35 MHz.

More information about the performance characteristics of the TDC and the software developed for this module is given in [8]. Currently, the USB-oscilloscope DRS Evaluation Board and single photon counting module PicoQuant PicoHarp 300 are used to improve the accuracy of the energy measurement.

The DRS Evaluation Board is based on the DRS4 chip [9] and can digitize the signals from the four channels with a rate up to 5 GS/s. It comes with software required for data collection and processing.

Key features:

—Bandwidth of 750 MHz;

—Flexible configuration of triggers;

—14-bit ADC;

—USB interface.

The DRS4 Evaluation Board can handle signals directly from the PMT without use of amplifiers. It reduces the systematic error of the time measurement up to 0.2 ns. One Start and one Stop signals are used to build time spectrum. Figure 5 shows the spectra measured during the ion beam passage through tantalum degrader foils of 9, 12.5, and 15 μm. The time of flight is determined by the distance from zero to the first maximum. The distance between the maxima corresponds to the period of the accelerator's RF generator.

The DRS oscilloscope digitizes signals from PMT and passes them to the computer for subsequent software processing. For each event, the time of flight is defined as the time difference between the starts of Start and Stop signals. The starting time of the signal is determined by the algorithm described in [10]. At first, it detects the two adjacent samples on the signal edge with the maximum difference. This corresponds to the steepest rise of the recorded signal. The starting time is then obtained by calculating the intersection of the line through these samples with the baseline of the signal (Fig. 6). Processing takes place in real time.

The time-correlated single photon counting system PicoHarp 300 [11] is designed for use in fluorescence lifetime analysis, quantum cryptography, optical time-domain reflectometry, time-of-flight as well as general coincidence correlation. The device is equipped with two independent channels, start and stop, each equipped with its own constant fraction discriminator, and builds a time histogram, which is then transmitted to a computer for processing. The maximum count rate is 10^6 events per second, resolution is up to 4 ps, and the histogram scale range is from 260 ns to 33 μs. The counter reduced the systematic error down to 50 ps. The energy of the bismuth ions was measured with an accuracy no worse than ±0.4%. Real-time data processing has not been implemented yet.

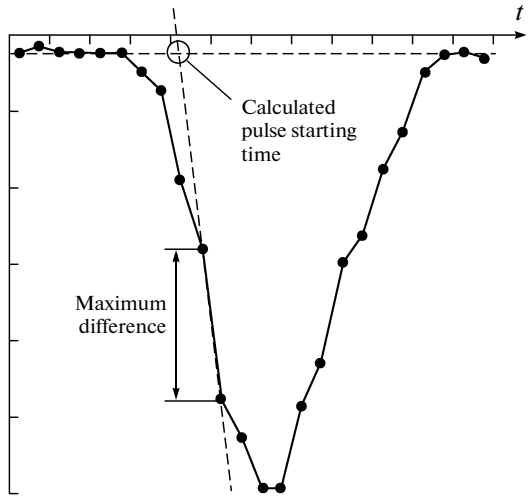

Fig. 6. Calculation algorithm of the pulse starting time.

MEASUREMENT RESULTS

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 7.5 MeV/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. 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 [12], 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. Table 3 shows the comparison of the energy measurements with the SmartTDC-01 and DRS Evaluation Board.

Comparison of measurements and calculations showed that the measurement error is no worse than ±3% for SmartTDC-01 and ±1.5% for the DRS Eval-

Table 2. Comparison of measured and calculated 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

Table 3. Comparison of Ar ion energy measured with the SmartTDC-01 and with the DRS Evaluation Board

Ta degrader thickness, μm	SmartTDC-01		DRS Evaluation Board	
	measured time of flight, ns	measured ion energy, MeV/nucleon	measured time of flight, ns	measured ion energy, MeV/nucleon
9	50.9 ± 0.5	5.17 ± 0.1	51 ± 0.23	5.15 ± 0.05
12.5	59.1 ± 0.5	3.83 ± 0.07	58 ± 0.23	3.99 ± 0.04
14	61 ± 0.5	3.6 ± 0.06	59.4 ± 0.23	3.7 ± 0.03
15	63.2 ± 0.5	3.56 ± 0.06	61.8 ± 0.23	3.52 ± 0.03

uation Board 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.

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. 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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