CYCLOTRONS BASED FACILITIES FOR SINGLE EVENT EFFECTS TESTING OF SPACECRAFT ELECTRONICS

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Abstract

Space radiation is the main factor limiting the operation time of the onboard equipment of the spacecraft due to the radiation effects occurring in the electronic components. With a decrease in the size of semiconductor structures, the sensitivity to the effects of individual nuclear particles increases and hitting one such particle can cause an upset or even failure of a component or system as a whole. Since the phenomenon occurs due to the impact of a separate particle, these radiation effects are called Single Event Effects (SEE). To be sure that the electronic component is operational in space, ground tests are necessary. SEE tests are carried out on test facilities that allow accelerating heavy ions from C to Bi to energies from 3 to a few dozen MeV/A. Cyclotrons are best suited for this purpose. In this paper, the installations created by request of ISDE based on the cyclotrons of FLNR JINR are described.

INTRODUCTION TO THE SEE TESTING

Space ionizing radiation consists of Earth's radiation belts, galactic cosmic rays and solar energetic particles. Their effect results in different effects in semiconductor microelectronic components. Figure 1 shows the variety of cosmic radiation, its composition and the types of radiation effects it induce.

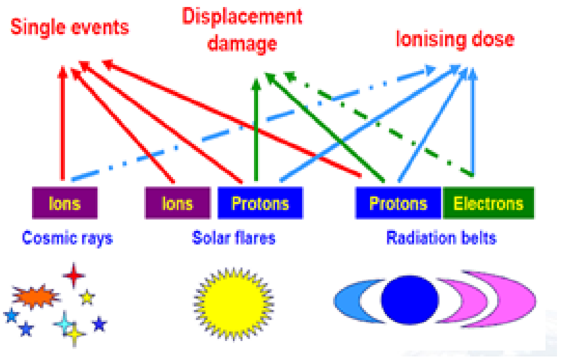

Figure 1: Types of space radiation.

The physical mechanism of interaction between a semiconductor structure and a heavy ion and a proton is illustrated in Fig. 2. The ion induces direct ionization while the proton induces secondary ionization due to knocking out atoms of the semiconductor material.

In the figures below you can see examples of the electronic components failure as a result of heavy ions exposure.

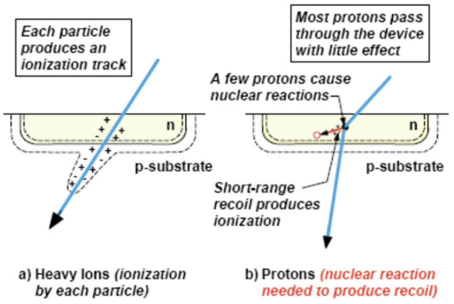

Figure 2: Mechanism for heavy ion and proton SEU effect.

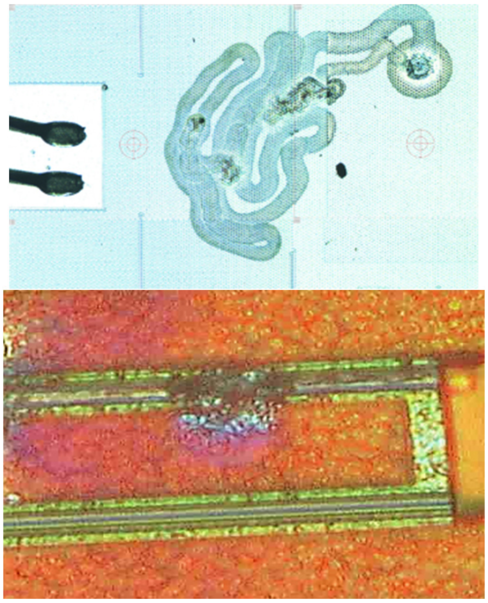

Figure 3: Examples of electronic components failure.

Table 1 represents a classification of heavy ion induced single event effects.

SEE testing is carried out with: Ion accelerator (dominating), Proton accelerator, Laser simulator (result calibration on the ion or proton accelerators is necessary!).

Guidelines using for SEE testing: "Methods of high energetic protons and heavy ions radiation testing of digital VLSI ICs performed on charged particles accelerators", "Methods of high energetic protons and heavy ions radiation testing of analog and mixed ICs performed on charged particles accelerators", "Methods of high energetic protons and heavy ions radiation testing of power MOSFETs performed on charged particles accelerators", "Methods of ICs radiation hardness characteristics calculation in the results of heavy ion facility direct experiments".

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Table 1: SEE Classification

Type / Subtype	Description	Impact	Susceptible Electronics
SEU (Single Event Upset) / MBU (multiple-bit upset), MCU (multiple-cell upset), SMU (single-word multiple-bit upsets)	Upset in a regular logic as a bi-stable structure information loss, including multiple	Recoverable failure	Storage and Logical Devices
SEDU (Single Event Destructive Upset)	Single bit corruption	Destructive Failure	Storage and Logical Devices
SEL (Single Event Latch-up)	Radiation latching induced by turning on a parasitic thyristor-like structure	Recoverable effect with possible destructive failure	CMOS, BiCMOS
SEHE (Single Event Hard Error)	Microdose effect (local energy deposition in a sensitive volume with following dose failure)	Recoverable or destructive failure	Storage elements and Logical Devices
SEFI (Single Event Functional Interrupt)	Function Interrupt Effect	Operation failure	Complex Devices
SEB (Single Event Burnout)	Burnout effect in power MISFETs, caused by opening of parasitic bipolar transistor	Destructive failure	High-voltage transistors
SEDR (Single Event Dielectric Rupture) / SEGR (Single Event Gate Rapture)	Dielectric rupture effect/ Gate dielectric rupture effect in MISFETs	Destructive failure	High-voltage devices with MOS-structures
SET (Single Event Transient)	Ionizing reaction (current or voltage pulses in output circuit)	Short-time failure	Analog Devices prevalent
SESB (Single Event Snapback)	Parasitic n-p-n transistor occurrence in n-channel (Secondary breakdown effect)	Destructive failure	N-channel MOS and SOI transistors

Typical Test Procedure for corresponding type of facility: “SEE test procedure for Roscosmos Test Facilities with the use of U-400 and U-400M accelerators” (All documents are based on MIL-STD-833, ASTM F1892, ESCC 25100 and detail them).

Typical SEE Test Procedure included: Studying the features of the test object, possible effects, Selection of the electrical parameters for monitoring and irradiation modes, the choice of test and measuring equipment; Test Plan Development and Agreement with Customer; lot Identification (incl. electrical measurements); Samples Preparation (De-capsulation); Test Setup Design (PCB); Test Software Development; Test Setup Adjustment and Trial Run; Test Setup Assembling in Irradiation Chamber; Irradiation Process; Test Results Calculation and Interpretation; Test Report Development.

TEST FACILITY

SEE facilities based on the FNRL JINR accelerators are used for electronic components testing. The layout is shown in Fig. 4. Specifications of the test facilities are listed in Table 2.

The scanning system provides an increase of irradiation area from 4-10 cm to 11.5-20 cm with minimum non-uniformity (Figs. 5 and 6).

Figure 7 shows the typical configuration of the test chamber.

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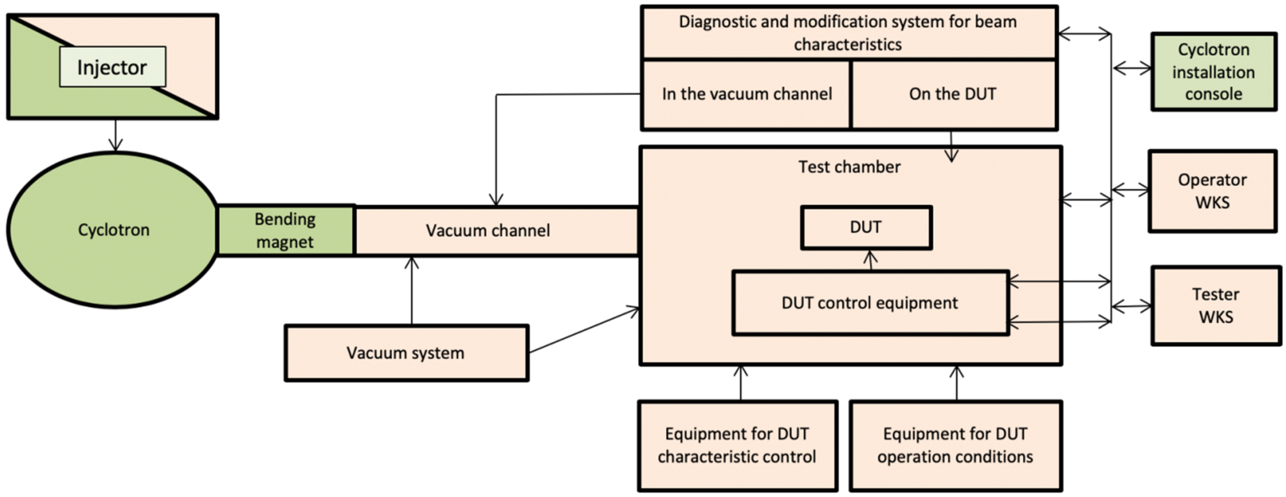

Figure 4: General structure of the SEE test facilities based on ion sources. Green for JINR; Beige for ISDE.

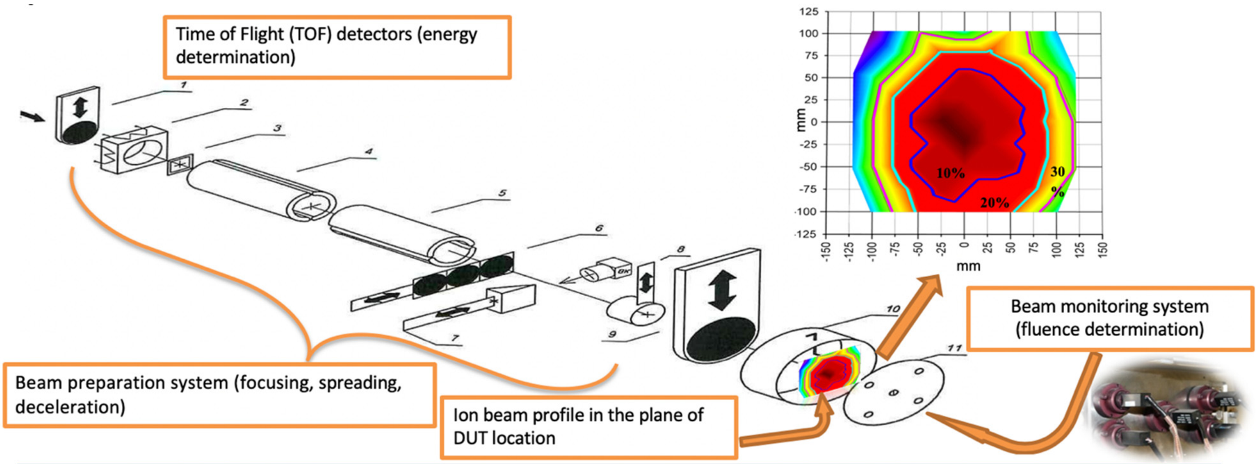

Figure 5: Beam transfer channel layout. 1- slide gate; 2- bending magnet; 3- diaphragm; 4- X-axis magnetic scanner; 5- Y-axis magnetic scanner; 6- degraders; 7- luminophore; 8- Faraday cup; 9- slide gate; 10- target node;11- beam monitoring system.

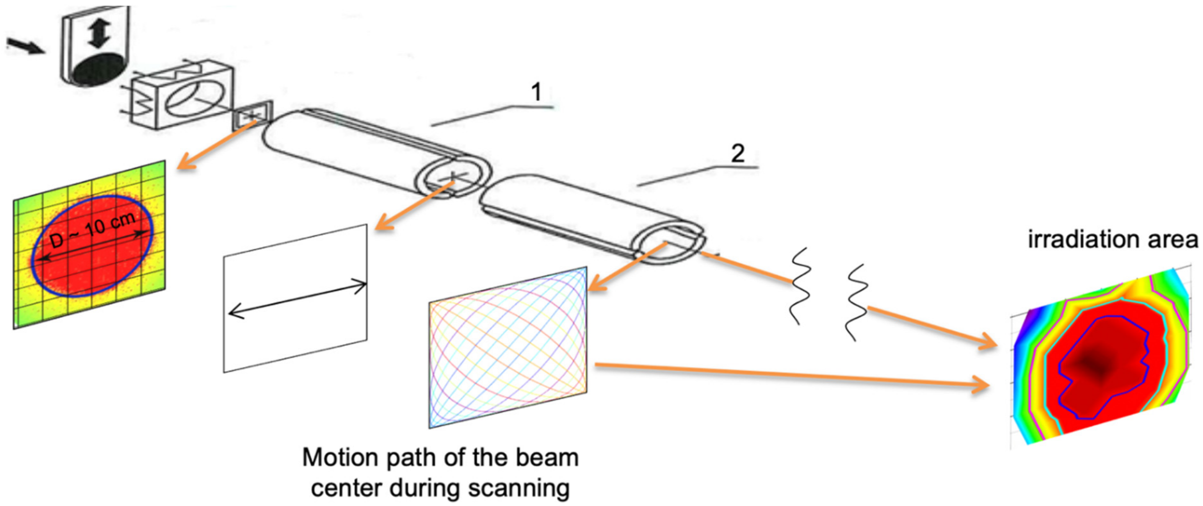

Figure 6: Beam modification system. 1- X-axis magnetic scanner; 2- Y-axis magnetic scanner.

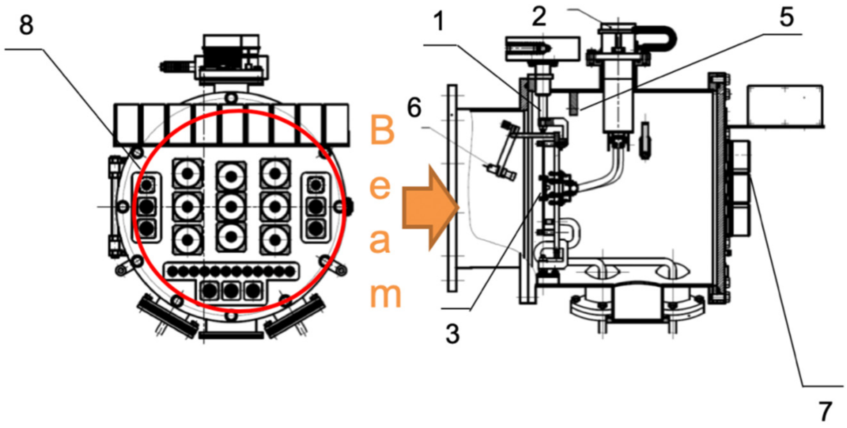

Figure 7: Vacuum test chamber. 1- rotary support frame; 2- conductive heating and cooling device; 3- PCB with a DUT; 4- flexible online detectors; 5- webcam; 6- non-contact heater; 7- beam monitoring system; 8- DUT/measuring instrumentation interfaces.

Table 2: Basic Technical Features of the SEE Test Facilities Based on Ion Sources

Technical features	**IS OE PP (LE)**	**IS OE VE-M (HE)**	**IS OI 400-N (LE)**
Ion source	Cyclotron U-400M FLNR	Cyclotron U-400M FLNR JINR	Cyclotron U-400 FLNR
E [MeV/u]	3 - 6	15 - 40 (60 for light ions)	3 - 9
Flux [part./(cm^{2}s)]	$10 \text{x} 10^5$	$10 * 10^5$ (10^4 for Bi)	$10 * 10^5$
Non-uniformity, %	± 15	± 10	± 10
Ions	C, O, Ne, Ar, Fe, Kr, Xe, Bi	Ne, Ar, Kr, Xe (C, O, Fe, Bi)	C, O, Ne, Ar, Fe, Kr, Xe, Bi
LET (Si), [MeV• cm^2/mg]	1 - 100	1 - 98(with degraders)	1 - 100
Range in Si [μm]	> 30	130 - 2000	> 30
Irradiation area, mm	200 x 200	Ø 60 (Ø 40 for Bi)	150x200
Operational pressure	$2.2 \text{x} 10^{-3}$ Pa	Forevacuum/atmosphere	$2.2 \text{x} 10^{-3}$ Pa
Pumping time [min]	6	5/0	8
Temp. [˚C]	-40 to 125	-40 to 125	-40 to 125

IC tests are performed in at a temperature from -40 to 125 °C with the help of special equipment. Heating and cooling is carried out through thermal contact between a DUT and several thermoelectric coolers (TEC) on Peltier elements (Fig. 8).

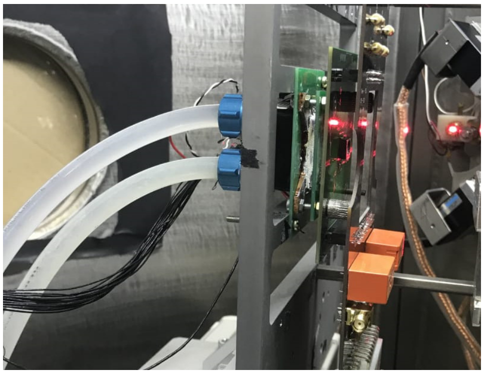

Figure 8: Heating and cooling facility.

HEAVY-ION FLUENCE DETERMINATION PROCEDURES

The fluence evaluation method is quasi-on-line (on-line - scintillators, off-line – track detectors) and yet it shows excellent accuracy.

On-line detectors are used to determine the moment for 10^5 for Power MOSFETs).

To obtain a precise value, the track detectors placed close to the DUT are used.

For operational evaluation of ion fluence in the DUT location the K coefficient is determined. K interrelates fluence according to track detectors ($\Phi_{\text{track detectors}}$) and dimensionless quantity characterizing ion fluence according to data from online monitoring counters (Φ_{count}).

$$\Phi_{\text{track detectors}} = K * \Phi_{\text{coun}}. \tag{1}$$

The methodology of fluence determination consists in a TD positioning close to the DUT (Fig. 9), irradiation, chemical etching of the TD after irradiation, holes calculation and determination of the true fluence value in the TD location or all over the beam profile, and non-uniformity determination.

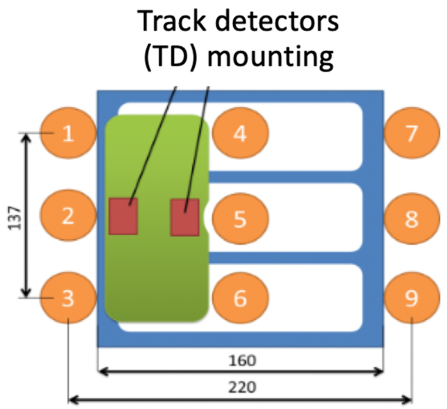

Figure 9: DUT Position.

Based on the data obtained, a map of non-uniformity was plotted (Fig. 10). The typical shape of the ion beam is in the form of a "Gaussian" curve with a "plateau" that is clearly distinguished in the central region of irradiation.

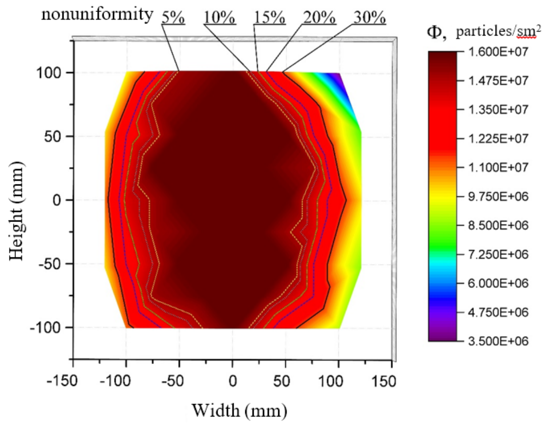

Figure 10: Beam profile with designated zones of non-uniformity.

Based on the map of non-uniformity, it can be concluded that in almost the entire irradiation area (150 x 200 mm^2) a non-uniformity of no more than 30% is provided. However, regardless of the entire irradiation field non-uniformity in the standard zone (100 x 150 mm^2) of the samples location (Fig. 11), the non-uniformity does not exceed 10%.

ION BEAM CHARACTERISTICS DETERMINATION

For determination of the ion energy, the Time of Flight technique is used (Fig. 12).

The energy measurement method based on one-to-one correspondence between the kinetic energy E_k and the particle velocity v.

Energy measurements are performed once after ion ejection (may be repeated if required).

This method provides energy determination with up to 2% accuracy.

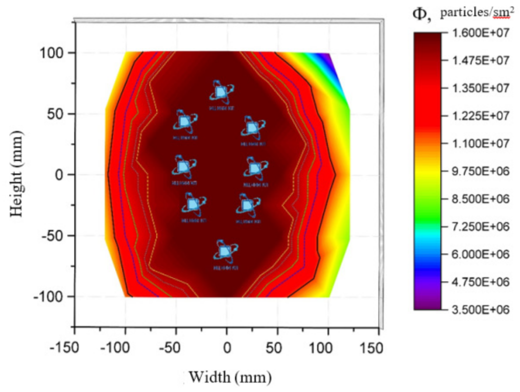

Figure 11: Beam profile with recommended sample area.

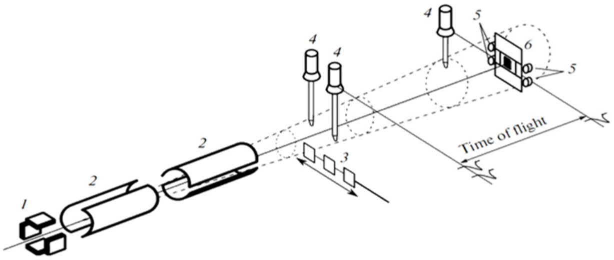

Figure 12: Beam profile with designated zones of nonuniformity. 1- bending magnet; 2- X-Y magnet modification system; 3- degrader foils set; 4- Scintillation detectors TOF; 5- Scintillation detectors; 6- DUT.

DIRECTIONS FOR THE DEVELOPMENT OF TEST FACILITIES

Improvement the accuracy of technical characteristics. Creation of on-line beam monitoring system (energy, non-uniformity, flux, fluence, etc.).

Creation of test facilities with milli- and micro- beams for fundamental investigations.

Creation of technological bench for ensuring decapsulation of electronic components.

Creation of new test facilities based on accelerators that exist or under development in JINR.

CONCLUSION

ISDE in collaboration with JINR operates the modern high-quality SEE Test Facilities, which allow to make the best use of up to 4000 hours of the test time per year and provide tests of electronic components of all functional classes to all types of radiation effects, taking into account the specific technical features.