SEE TESTING FACILITIES AT FLNR ACCELERATORS COMPLEX: STATE OF THE ART AND FUTURE PLANS*

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Abstract

The Russian Space Agency (Roscosmos) utilizes U400 and U400M cyclotrons at accelerator complex of the Flerov Laboratory of Nuclear Reactions (FLNR) of the Joint Institute for Nuclear Research (JINR) in Dubna for heavy ion SEE testing. The ions up to the Xe and Bi with the energy up to 40 AMeV are available for the users. The detailed overview of the facility and the features of diagnostic set-up used for ion beam parameters evaluation and control during SEE testing are discussed. The road map for the strategic development of this field in FLNR is presented.

INTRODUCTION

Since becoming discovery in 1975 [1], intensive investigations of single-event effects (SEE) in electronic devices have resulted test method and facility developments. As known, the ion energy for such experiments should be high enough as 3 MeV/nucleon. Therefore, heavy ion beams in this energy range are delivered from large accelerators. Usually they are located at basic physics research laboratories. Currently, there are several major heavy ion beam facilities in the U.S. and Europe that are available for SEE testing [2]. The Russian Space Agency (Roscosmos) utilizes U400 and U400M cyclotrons at accelerator complex of Flerov Laboratory of Nuclear Reactions (FLNR) of Joint Institute for Nuclear Research (JINR) in Dubna for heavy ion testing. U400 cyclotron has been in operation since 1978 and delivers ion beams of atomic masses 4÷209 at energies of 3÷29 MeV/nucleon [3]. U400M cyclotron has been in operation since 1991. This cyclotron was originally intended for acceleration of ion beams with A/Z=3÷3.6 (A- atomic weight of the accelerated ion; Z - ion charge when accelerated) at energies of 34-50 MeV/nucleon. The beam is extracted from cyclotron using stripping foil. In 2008 the U400M possibilities have been extended by addition of the ion beams with A/Z=8÷10 at energies of 4.5-9 MeV/nucleon to carry out the experiments on synthesis the new super heavy elements as well as applied researches [3]. Last few decades the SEE testing have been carried out using ion beam transport lines designed for nuclear physics experiments. However, specific requirements to ion beam parameters, like uniformity over large irradiating area, beam intensity variation from units to hundred thousands of particles per second and etc., could not be realized in full by these facilities. To reproduce the effects of a heavy component of cosmic radiation for the SEE testing one should use the low-intensity (10^3 - 10^6 cm^{-2} s^{-1}) heavy ion beams with the LET range in silicon, typical for ion energies of 50-200 MeV/nucleon. But, keeping in mind to test the real DUT which are in metal and plastic housings, as well as ready-to-use electronic boards, the heavy ion beams with energies in the range 5 - 50 MeV/nucleon must be used in experiments.

The main purpose of this report is to describe heavy ion beam lines specialized for SEE testing at FLNR JINR accelerator complex. Originally these facilities were designed to meet demands of EIA/JESD57 and ESCC BS 25100. 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 (20÷40 MeV/nucleon) was successfully commissioned in January'14. The third line is based on U400 and after modernization of this cyclotron in 2015 there will be the possibility to make the SEE testing with the fluent energy variation for every ion [3].

ION BEAM LINE WITH ENERGIES OF 3-6 MEV PER NUCLEON AT U400M.

The ion beam line for SEE testing is a part of the U400M cyclotron. This beam line contains: ion beam transportation system, beam monitoring system, energy measurement system and user's vacuum test chamber with a mounting and positioning assembly to hold the sample in the irradiation field. The photograph of the experimental set up showing its components is given in Fig. 1. The beam leading line is separated from a bending magnet (1) by vacuum gate valve (2). The next transport element is two-coordinate beam-positioning magnet (3) guiding the beam through variable size diaphragm placed in entrance of the 50 Hz X-Y magnetic scanning system (4). Scanning system provides exposure over the target area 200x200 mm with inhomogeneity better 30% in the flux range of 1÷10^5 particles/cm^2s. To choose appropriate ion energy and the LET value we use a degrader with tantalum foils of 5, 9, 12.5, 14, 19, 22.5, 25 of 27 microns thickness. A driver of foils holder is designated as (5) in Fig. 1. Energy of particles passed through the foils as well as initial ion energy is measured by time-of-flight (TOF) method. Ions with 3÷9 MeV/nucleon energy pass the distance between two pick up electrodes (8), 1.602 m, during 39÷67 ns. These parameters were chosen to register the time of passage of one bunch according to the beam time structure at U-400M cyclotron - the duration

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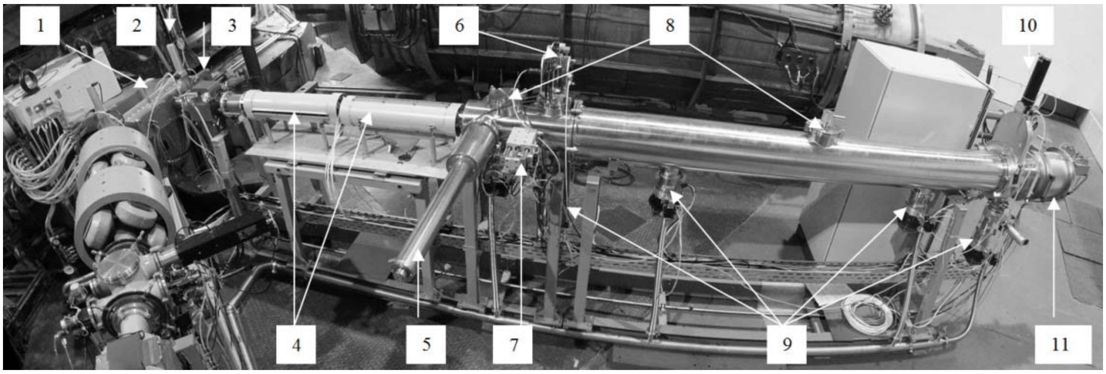

Figure 1: General view of the ion beam transport line and experimental set up for SEE testing at U400M cyclotron. See explanations in text.

of a pulse is 6÷7 ns and frequency 15÷15.5 MHz. The accuracy of ion energy measurements is no worse than 1%. Diagnostic elements such as Faraday cup (6) and luminophor holder (7) are used during beam adjusting and tuning at high intensity. The beam line is pumped by three turbo molecular pumps (9). The user target chamber (11), the out – and inside photographs of which are given in Fig. 2, is separated from the ion transport line by vacuum gate valve (10) and is equipped with own vacuum system. This system is fast enough to pump down in less than 10 minutes. The pumping system is fully interlocked for ease of use and safety of the equipment.

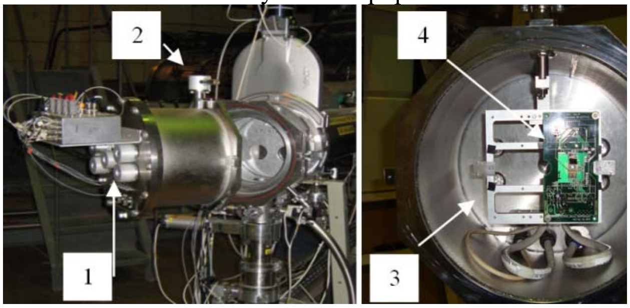

Figure 2: Target chamber for SEE testing.

The internal diameter of a chamber having shape of a barrel is 28 cm, the depth is 30 cm. The beam diagnostic elements (1) and user connectors are placed on the end flange of the chamber. Testing targets (4) are mounted on the frame (3) which can be tilted to the ion beam direction within 0÷75 degrees using turning gear (2).

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	$1 \div 10^5$
$^{22}Ne^{3+}$	$^{22}Ne^{10+}$	65±3	7	$1 \div 10^5$
$^{40}Ar^{5+}$	$^{40}Ar^{16+}$	122±7	16	$1 \div 10^5$
$^{56}Fe^{7+}$	$^{56}Fe^{23+}$	213±3	28	$1 \div 10^5$
$^{84}Kr^{12+}$	$^{84}Kr^{32+}$	240±10	41	$1 \div 10^5$
$^{136}Xe^{18+}$	$^{136}Xe^{46+}$	305±12	67	$1 \div 10^5$
$^{209}Bi^{22+}$	$^{209}Bi^{58+}$	490±10 (820±20)	95 (100)	$1 \div 10^5$

Ion beam parameters used for SEE testing, like ion type and energy, the LET and ion flux range, are listed in Table 1.

ION BEAM LINE WITH ENERGIES UP TO 40 MEV PER NUCLEON

In order to cover the necessary energy range (up to 40 MeV/nucleon) for the SEE testing the high energy beam line was created.

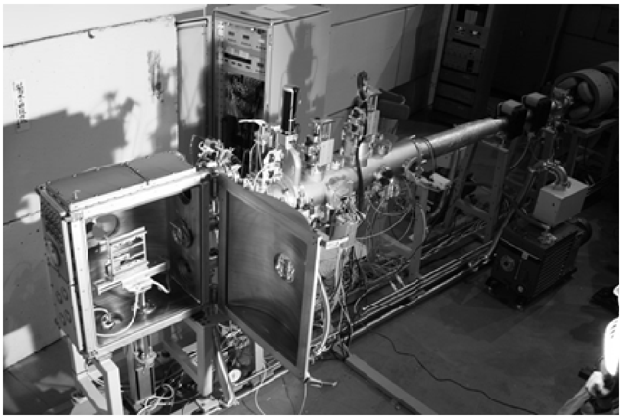

Figure 3: The user target chamber. Outside view.

The beam line was named A1S and consists of a part of existing physical channel for the ion beams extraction and transportation and the new part by using. The line has length about 6 meters. The scheme of the experimental equipment is given in Fig. 4. The beam leading line is separated from a last bending magnet M4 by vacuum the gate valve (1). The two- magnetic quadrupole lenses (2) provide exposure over the target area with uniformity better 20% in the flux range of $1\div10^5$ particles/cm2s. After lenses two steering magnets (3) are places for the vertical beam correction. The A1S beam line consists of: ion beam transportation system (is pumped by three turbo molecular pumps (4)), beam monitoring system (5, 6,8,10, and 11), energy measurement system (to measure the ion energy the TOF technique is used(7)) and DUT's chamber (12) with a mounting and positioning assembly to hold the sample in the irradiation field. The user target chamber (Fig.3), is separated from the ion transport line

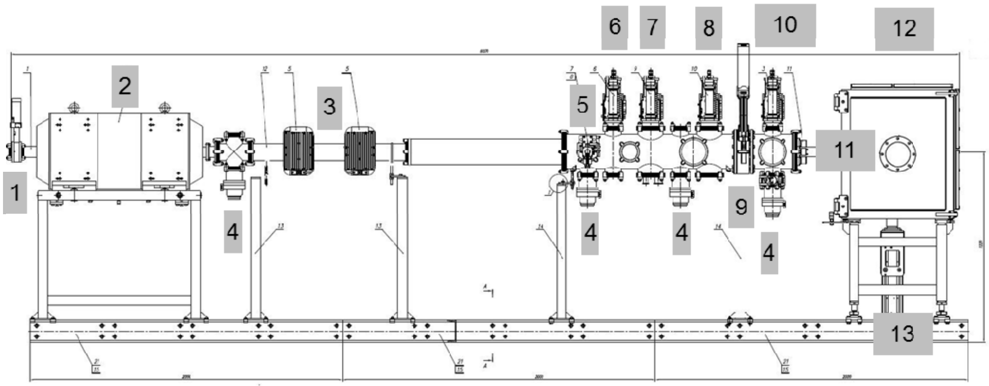

Figure 4: General scheme of the high energy ion beam transport line and the experimental set up for SEE testing at U400M cyclotron. See explanations in text.

by the vacuum gate valve (9) and is equipped with own vacuum system. This system is fast enough to pump down in less than 2 minutes. The pumping system is fully interlocked for ease of use and safety of the equipment. The target chamber provides two operational modes: at atmospheric (ATM) pressure and at vacuum (VAC) of 10 mbar. To provide the ATM mode shaped ion beam extracted from beam-line to the chamber through a stainless steel foil of 12.6 µm thickness with diameter up to 60 mm (the extraction window). The DUT frame has possibility to move remotely (13) in X-Y directions (to place the DUT into beam spot area with accuracy 0.1 mm) and can be tilted to the ion beam direction within 0÷90 degrees using turning gear.

ION BEAM DIAGNOSTIC

The wide range of beam control systems are used during beam run. 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, double side Si strip detector (Fig.5) and arrays of proportional counter are installed. The last one provide on-line control of beam flux with air ambient as working gas. The choice for this type of counters was done due to their operation simplicity, radiation-resistant and almost infinite resource. The beam uniformity and flux are determined using an array of five active particle detectors. Two kind of active detectors can be utilized in the diagnostic system - 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. 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. 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.

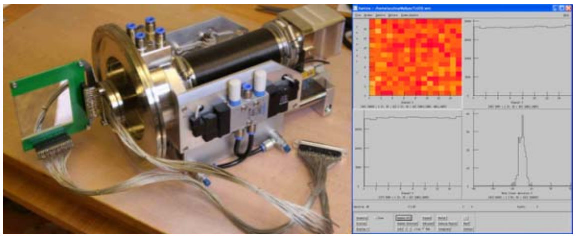

Figure 5: Double-side Si strip detector. Dual axes (X-Y) orthogonal beam detection Kr beam profile as example.

CONCLUSION

The only facility in Russian Federation dedicated for the SEE testing with heavy ions up to 40 MeV/ nucleon is open for the users. The LET range 4.5÷100 MeV/(mg/cm^2) meet in full the requirements for SEE testing experiments. Since becoming operational in 2010, more than 500 devices have been tested (10000 hours of heavy ion beam operation time). All needed infrastructure was created in the way to provide to the users the friendliest atmosphere during the irradiation procedure.

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