CHARACTERIZATION OF THE NEUTRON BEAM AT THE RADIATION RESISTANCE TEST FACILITY IN GATCHINA

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Abstract

The ROSCOSMOS testing facility ISNP/GNEIS with a neutron energy spectrum resembling that of atmospheric neutrons has been developed at the 1 GeV proton synchrocyclotron of the PNPI. The facility is intended for accelerated SEE-testing of semiconductor components and systems. A description of the beam monitor, profile meter and other parts of the facility equipment is presented. The beam parameters are discussed in comparison with the parameters of analogous facilities dominating in this field. The development of the neutron beam and the test facility extends considerably the experimental potential of radiation research at the PNPI. It forms a basis for establishing a unique center for proton and neutron radiation testing of aviation and space electronics in compliance with the requirements of international standards.

1. Introduction

When the high-energy (GeV-range and higher) cosmic rays interact with nuclei (N, O, H, He, etc.) in the upper atmosphere of the Earth, they generate cascades (showers) of secondary particles. The main constituents of these showers are neutrons, protons and mesons. At the sea level, neutrons component dominates (~94%), while at the typical aircraft altitudes about 10-12 km the neutron component decreases down to 52% simultaneously increasing 300-400 times in absolute value. When neutrons collide with the nuclei of Si (main material of semiconductor device), various nuclear reactions are induced: elastic and inelastic scattering, neutron capture, etc. As a result, the energy of a single incoming neutron is transformed through the creation of ionization electron-hole pairs into electric charge. When a value of this charge collected in a sensitive region of the device exceeds a critical value specific for this device, then a so-called <u>*S*</u>ingle <u>*E*</u>ffect <u>*E*</u>vent (SEE) happens. A variety of SEEs includes: upset (SEU), latchup (SEL), burnout (SEB), etc. The SEEs predominantly affect digital devices and were not studied actively until recently. The sharp growth of interest to SEEs about 15 years ago coincided in time with a process IC technology scaling below ~100 nm followed by a substantial decrease of the critical charge required to produce SEE. The initial experimental investigations of the atmospheric neutrons responsible for the SEEs showed that the practically important part of their energy spectrum consists of "spallation" component (0.1-5 MeV) and high-energy "cascade" component (10-1000 MeV). The integrated flux of terrestrial neutrons in the energy range >1 MeV is equal to 20 n/cm^2·hour. At present, according to the JEDEC Standard JESD89A[1], this value is referenced to NY City (sea level, outdoors, average solar activity) along with a shape of the neutron spectrum,. The neutron flux at aircraft altitude 40000 ft (≈ 12 km, latitude 45^0) is recommended by the standard IEC

TS 62396-1[2]. According to this document, the integrated flux of atmospheric neutrons in the energy range > 1 MeV is equal to 8760 n/cm^2·hour. A simple evaluation shows that for the typical 1 Mbit SRAM-memory chip with SEU-cross section of 10^{-14} cm^2·bit, 100 SEU-events can be accumulated after $5.7 \cdot 10^4$ years of irradiation by terrestrial neutrons at sea-level or about 130 years after irradiation at 12 km altitude. It means that the only productive alternative to accelerate SEE-testing on the atmospheric-like neutron spectrum is the use of the artificial neutron fluxes (fields) which could be obtained at the high-energy proton accelerators.

At present the standardized accelerated SEE-tests of electronic components using facilities with atmospheric-like neutron spectra are carried out at several centers, the LANSCE (Los Alamos, USA) ICE House being the best known one. Recently, the testing facility ISNP/GNEIS (testing facility of the electronic components hardness control to atmospheric neutrons) [3] with the energy spectrum resembling that of atmospheric neutrons in a broad energy range 1–1000 MeV, has been developed at the B.P. Konstantinov Petersburg Nuclear Physics Institute of the National Research Centre "Kurchatov Institute" (Gatchina) within the framework of collaboration and financial support of the Branch of the JSC "United Rocket and Space Corporation" – "Institute of Space Device Engineering" (Moscow, ROSCOSMOS). In this report we present a description of the ISNP/GNEIS and its parameters in comparison with other similar facilities.

2. Description of the facility

The ISNP/GNEIS testing facility was developed at the neutron time-of-flight spectrometer GNEIS (Fig. 1) based on the 1000 MeV proton synchrocyclotron of the PNPI [4]. The spectrometer was constructed to study neutron-nucleus interactions using the TOF technique at neutron energies ranging from ~10^{-2} eV to several hundreds of MeV. The water-cooled lead target located inside the accelerator vacuum chamber produces short (~ 10 ns) pulses of fast neutrons with a repetition rate of 45-50 Hz and average intensity up to $3 \cdot 10^{14}$ n/s.

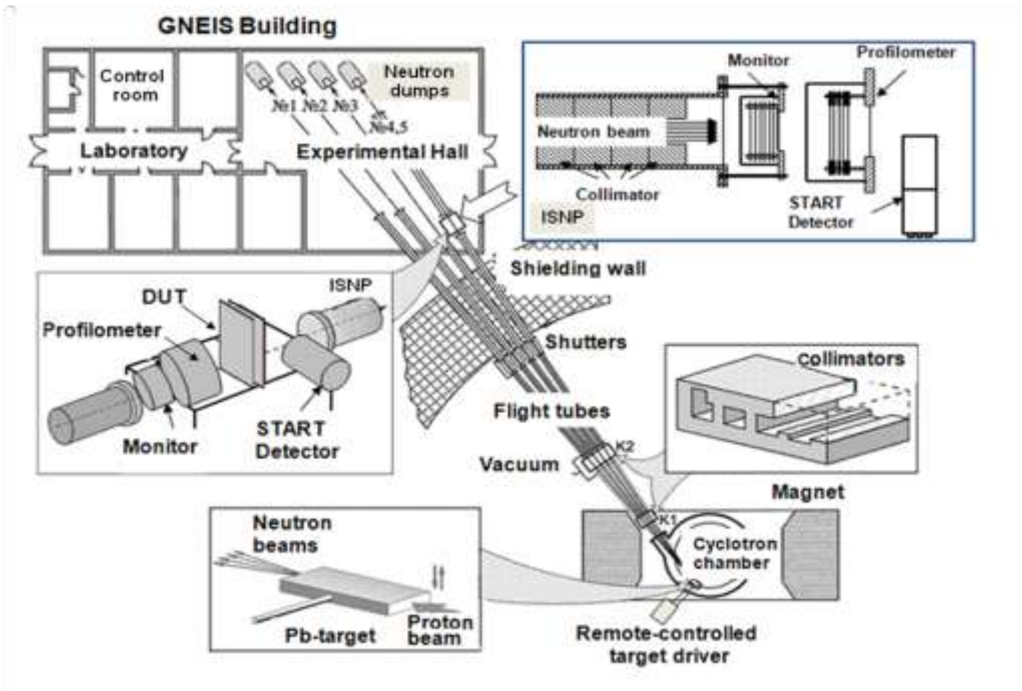


Fig. 1. General layout of the neutron time-of-flight spectrometer GNEIS and ISNP testing facility.

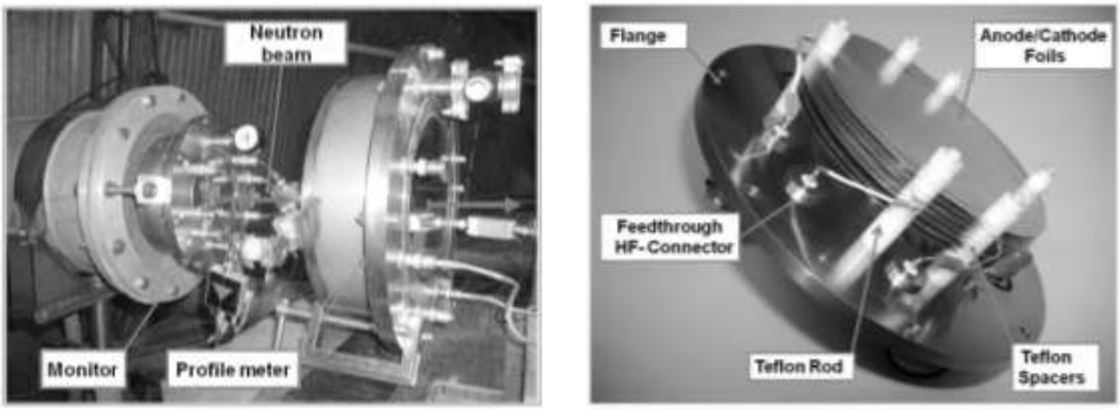


Fig. 2. Arrangement of the monitor and profile meter on the neutron beam line (left). Internal structure of the fission ionization chamber-neutron monitor (right).

Five neutron beams are transported by means of evacuated flight tubes through the 6 m thick heavy concrete shielding wall of the accelerator main room into the experimental hall of the GNEIS. The beams are equipped with brass/steel collimators, steel shutters and concrete/steel beam dumps. A neutron beam #5 is ideally suited for accelerated tests of electronics with atmospheric-like neutrons because its axis comes through a surface of the neutron-production target. It has the hardest neutron spectrum in comparison with other beams whose beam lines “look” at a polyethylene moderator (not shown in Fig.1).

An arrangement of the experimental equipment for the beam diagnostics of the testing facility is displayed in Fig.2. During the irradiation of a DUT (device under test) located at the 36 m flight path of beam #5, control of the neutron beam shape/intensity and profile is carried out by means of the fission ionization chamber (FIC, beam monitor) and position sensitive multiwire proportional counter (MWPC, beam profile meter), respectively. The FIC is permanently placed in the neutron beam to continuously monitor its intensity during irradiations of the DUTs. The MWPC is installed close (downstream) to the FIC and is used either during the beam adjustment or during the whole irradiation shift. A data acquisition system of ISNP utilizes the 250 MSamples/s 12-bit Flash-ADC’s for monitor and profile meter signals processing.

The internal diameter of the final collimator (1 m of length, nearest to the DUT location) has 3 fixed values of 50, 75, and 100 mm which can be changed before and during the irradiation test. The DUT(s) are located at fixed position(s) on a supporting table at room temperature or enclosed in a special box which can be moved with high accuracy in vertical and horizontal directions. The temperature inside the box can be changed by using an air heater within a range of 20°C – 120°C. The box (DUT) position and internal temperature are controlled remotely from the operator control room which is located inside the GNEIS building at a distance of ~25 m from the DUT location.

3. Neutron beam parameters

The neutron beam profile is measured by means of MWPC – the two-coordinate position sensitive multiwire proportional counter 140×140 mm^2 of size. It is used for registration of fission fragments from the ^{238}U(n,f)-reaction induced by neutrons in a 100-150 μg/cm^2 thick

U- converter deposited on a 2 μm aluminized Mylar backing (Fig. 3). The MWPC consists of a cathode with U-converter and X, Y-anodes made of 25 μm gilded tungsten

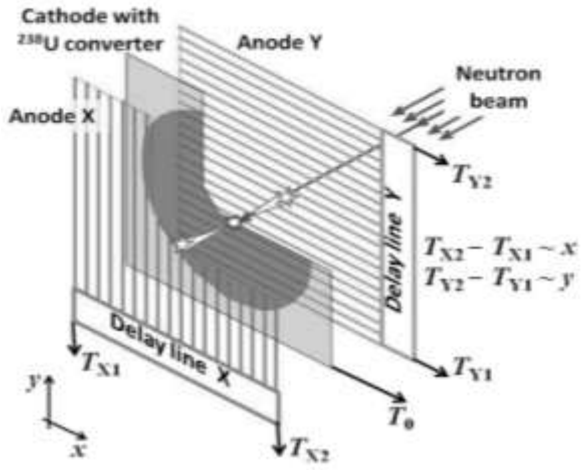


Fig. 3. Schematic view of the MWPC- neutron beam profile meter.

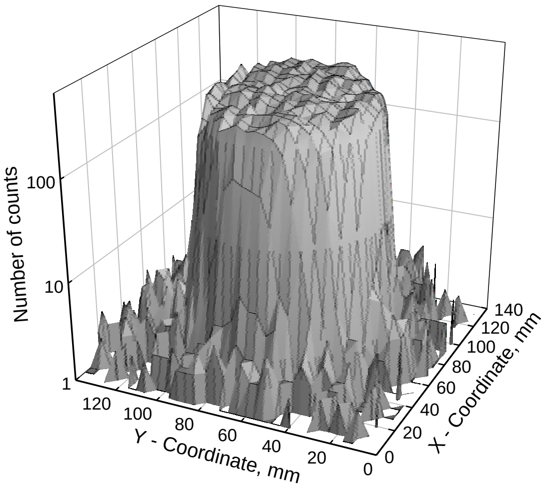


Fig. 4. 3D-neutron beam profile measured with the use of MWPC.

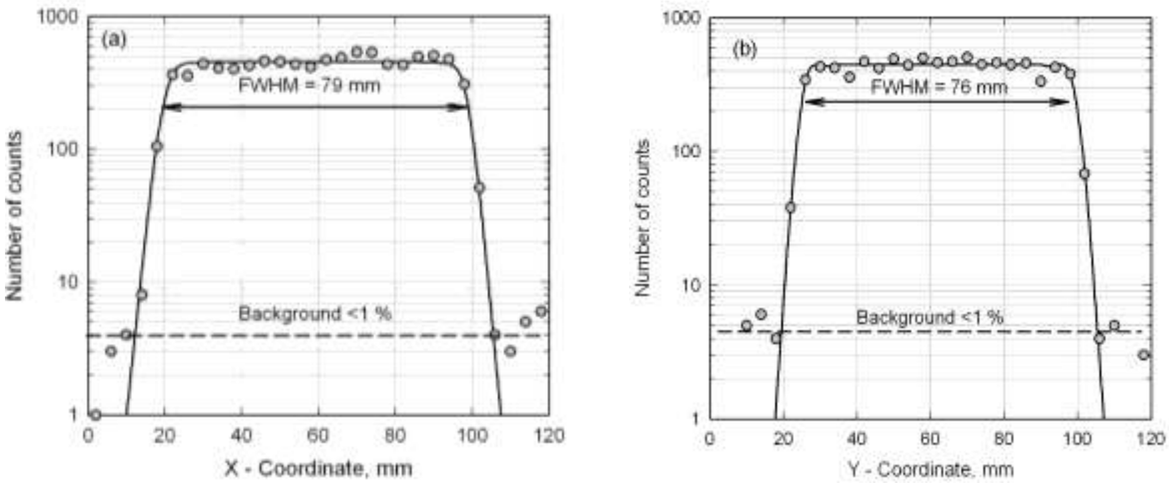


Fig. 5. Horizontal (left) and vertical (right) neutron beam profiles.

wires with 1 mm spacing and 3 mm anode-cathode gaps. Anode wires (140 in all) are connected parallel in pairs to the 70 taps of a delay line with a specific delay of 2 ns/step for coordinate information readout. The timing signals from corresponding ends of the delays carry information about the position of neutron interaction with converter material and, therefore, about the beam profile. A spatial resolution of the MWPC is determined by wire spacing and lies within a range of 2 mm < FWHM < 4 mm.

The 3D-distribution of neutron intensity in the beam measured using the MWPC with final collimator 75 mm in diameter is shown in Fig. 4. Horizontal and vertical neutron beam profiles obtained as sections of the 3D-distribution along X- and Y-axes, respectively, are shown in Fig. 5. The uniformity of the beam was evaluated by a calculation of a standard deviation of the data points within a plateau of distributions shown in Fig. 5: StD(X) ≈ 11% and StD(Y) ≈ 10%. It should be mentioned that the 10-11% variations observed include the effect of counting uncertainties, the latter being equal to $1/\sqrt{N} \approx 5\%$. The background events observed on the "wings" of the profile distributions are mainly due to the "non-ideal" collimation of the neutron beam and separation of the fission fragments from other products of neutron-induced reactions in structural materials of the MWPC, and the electronic noise. Anyway, the level of total background does not exceed ~1%.

The neutron beam of the ISNP/GNEIS facility has the following parameters:

- neutron energy range: 1- 1000 MeV;
- neutron flux: $\leq 4\cdot10^5$ n/(cm$^2\cdot$s) (at the 36m flight path);
- beam diameter: 50-100 mm (at the 36m flight path);
- uniformity of the beam profile plateau: ±10%.

The neutron flux of $4\cdot10^5$ n/(cm$^2\cdot$s) given above is an integral over neutron spectrum $F_{ISNP}(E)$ in the energy range 1-1000 MeV. It corresponds to the maximum value of 3μA of the average internal proton beam current dumped into the neutron-production target. The neutron flux and shape of the neutron spectrum are measured using FIC and TOF-technique. The FIC is a fast parallel-plate ionization chamber which contains two double-sided targets of ^{235}U and ^{238}U 120 mm in diameter and 200-300 μg/cm^2 of thickness deposited on a 0.1 mm thick Al-foil backing (Fig. 2, right). A choice of ^{235}U and ^{238}U as reference materials is explained by a fact that neutron fission cross sections of these nuclei are recommended standards in the energy range 1-200 MeV. These data are taken from the ENDF/B-VII.1 Library [5]. Neutron fission cross sections of ^{235}U and ^{238}U above 200 MeV are taken from the JENDL High Energy Library [6]. The TOF-spectra measured with ^{235}U and ^{238}U targets are transformed into the neutron energy spectra and after averaging are fitted with the analytic expression

$$F_{ISNP}(E) = 4.281\exp(9.7999+0.5557(\ln E)+1.4006(\ln E)^2+0.3706(\ln E)^3-0.0312(\ln E)^4), \quad (1)$$

where $F_{ISNP}(E)$ – neutron energy spectrum, n/(cm$^2\cdot$s$\cdot$MeV); E – neutron energy, MeV. The neutron spectrum $F_{ISNP}(E)$ of the ISNP facility is shown in Fig. 6 together with the JEDEC standard terrestrial neutron spectrum $F_{JEDEC}(E)$ from JESD89A [1] referenced to New York City and multiplied by scaling factor $7\cdot10^7$. Also given in Fig.6 are the neutron spectra of the other testing facilities [7-11].

3. Comparison with standard and other neutron sources

Besides the ISNP/GNEIS test facility at the PNPI, there are at least five other facilities with atmospheric-like neutron spectra, currently used by semiconductor industries for accelerated tests of electronics. These facilities use high-energy proton accelerators as neutron sources of various intensity, operation mode (continuous or pulsed), and neutron spectrum shape. Fig.6 shows that the shape of neutron spectrum of the ISNP/GNEIS facility is very close to the standard one competing with the ICE House (LANSCE) and having an advantage of ~200 MeV higher upper energy edge. At the same time, it is obvious that the ISNP's neutron flux available at the DUT position at present is lower than that of other facilities. The distribution of spectra in three energy segments given in Table 1 enables to make a more detailed comparison of spectrum shape. From this point of view, the ISNP/GNEIS, ICE House (LANSCE) and RCNP have very similar segment distribution, the most close to the standard. More elaborate comparison of the various facilities can be done by taking into account the integrated neutron fluxes of these facilities. For this purpose, for any facility with differential neutron flux $F_{ACC}(E)$, the acceleration factor A defined by Eq.(2) is calculated, which characterizes its integral neutron flux relative to that of the standard terrestrial neutron spectrum:

$$A = \int_{E_{\min}}^{\infty} F_{ACC}(E)dE \,/ \int_{E_{\min}}^{\infty} F_{JEDEC}(E)dE, \tag{2}$$

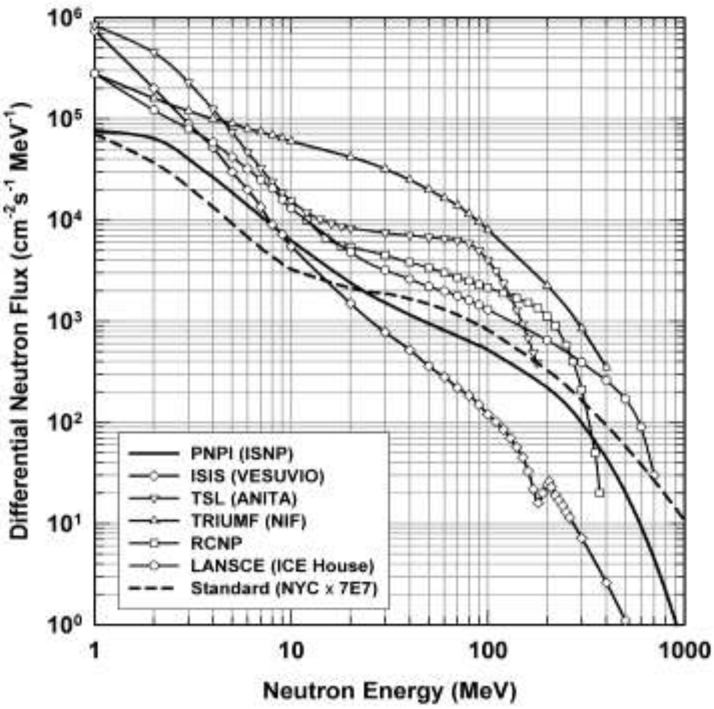


Fig. 6. Neutron spectrum $F_{ISNP}(E)$ of the ISNP facility compared to standard terrestrial neutron spectrum from JESD89A [1] and neutron spectra of other testing facilities [7-11].

Table 1. Neutron flux structure and acceleration factors of neutron testing facilities with atmospheric-like spectrum in comparison with standard fluxes

Standard / Facility (location, proton energy, target material)	Neutron Flux				Accel. factor, *A*
	1-10 MeV	10-100 MeV	>100 MeV	Total >1MeV	
	%	%	%	n/cm^2·s	
JEDEC (NYC, sea level, outdoors, mid level solar activity) JESD89A [1]	35	35	30	20	-
IEC (12 km, latitude 45^o) IEC TS 62396-1 [2]	35	35	29	8760	-
ISNP/GNEIS (PNPI, Gatchina, 1000 MeV, lead) [3]	57	28	15	$1.5\cdot10^9$	$4.6\cdot10^7$
ICE House (LANSCE, Los Alamos, USA, 800 MeV, tungsten) [7]	52	26	22	$3.4\cdot10^9$	$1.3\cdot10^8$
RCNP (Osaka University, Japan, 180 MeV, lead) [9]	57	25	18	$5.4\cdot10^9$	$1.8\cdot10^8$
ANITA (TSL, Uppsala, Sweden, 400 MeV, tungsten) [8]	65	28	7	$9.9\cdot10^9$	$2.7\cdot10^8$
NIF (TRIUMF, UBC, Vancouver, Canada, 500 MeV, aluminum) [10]	24	54	21	$1.3\cdot10^{10}$	$7.6\cdot10^8$
VESUVIO (ISIS, RAL, Chilton, UK,800 MeV, tungsten/tantalum) [11]	92	7	1	$2.5\cdot10^9$	$1.5\cdot10^7$

where E_{min} is the minimum neutron energy necessary to produce a SEE. In the JESD89A, it is postulated that E_{min} = 10 MeV. Acceleration factors calculated for the ISNP facility and other test facilities using Eq.(2) are given in Table I. It should be noted that current acceleration factors depend on a state of tune of the accelerator facilities. Therefore the data given in Table I must be taken as indicative values only.

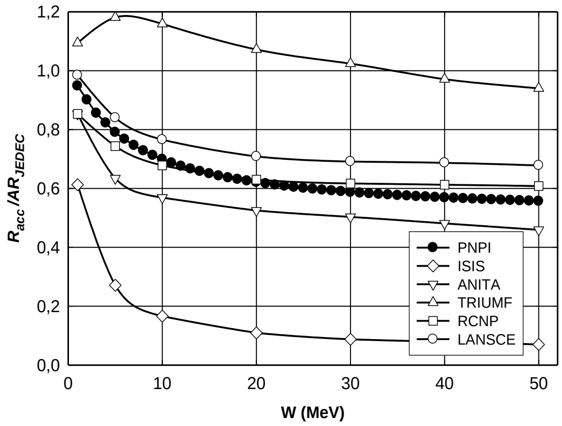
For more realistic comparison of the testing facilities with different neutron spectrum shape and intensity, it's convenient to use accelerated soft error rate (SER) calculated in accordance with Eq.(3):

$$R_{ACC} = \int_{E_{\min}}^{\infty} F_{ACC}(E) \cdot \sigma(E) dE \tag{3}$$

As it is postulated in JESD89A, the energy dependent neutron soft error cross-section *σ(E)* of a DUT can be approximated by a Weibull distribution

$$\sigma(E) = \sigma_0 \cdot (1 - \exp(-((E - E_0)/W)^S)), \tag{4}$$

where σ_0 is the asymptotic cross-section, E_0 is the cutoff energy, W and S are the width and shape parameters, respectively. The ratio of the accelerated SER measured at a given facility and the value obtained using standard JEDEC spectrum $R_{ACC} / A{\cdot}R_{JEDEC}$, calculated as a function of E_0, S and W parameters and normalized using the acceleration factor A, enables to evaluate the error in measured SER due to the deviation from the standard. As it was proposed by S.P. Platt et al.[12] and C. Slayman [13], this ratio can be used for effective comparison of various testing facilities. Following C. Slayman, we have calculated the ratio $R_{acc}/A{\cdot}R_{JEDEC}$ for the ISNP/GNEIS and compared it with other facilities included in Table I. Fig. 7 shows the ratio as a function of W with shape parameters S=1 and cutoff energy parameter E_0 = 1, 10 MeV. With a given set of the parameters, it is possible to cover practically all types of the commercially available devices, including those produced using modern technologies. The data presented for the case of electronic devices with especially low critical charge (E_0 = 1 MeV) show that the value of SER measured at ISNP/GNEIS is 10-50% lower than the JEDEC standard measurement, the result comparable with that of LANSCE and RCNP. The same tendency is observed for the devices with more high critical charge which are modeled with the cutoff parameter E_0 = 10 MeV.



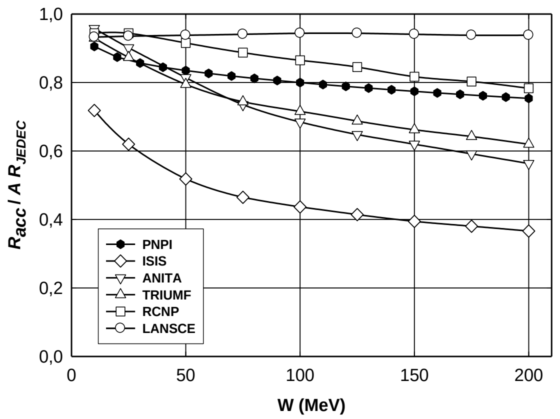


Fig. 7. Error in the SER estimate as a function of width parameter W for shape parameter S = 1 and cutoff energy E_0 = 1 MeV (left) or E_0 = 10 MeV (right).

4. Conclusion

The ROSCOSMOS testing facility ISNP/GNEIS with a broad atmospheric-like neutron spectrum has been developed at the PNPI. The main parameters of the ISNP/GNEIS neutron beam, namely: neutron spectrum shape in the energy range 1-1000 MeV, differential/integral neutron intensity, uniformity of the beam spot and quality of the beam collimation meet the requirements of the electronic industry standards for accelerated SEE-testing of the electronic components. User-friendly possibilities are also available: user control of the beam intensity, remote control of the DUT-positioning/heating system with laser alignment, low neutron/gamma dose level in the user area. The characteristics of the ISNP/GNEIS facility and practical results of the accelerated tests of various types of electronic components shows that it can be qualified as a high-grade neutron testing facility.

Acknowledgment

The authors sincerely thank colleagues from Neutron Research Department and Accelerator Department of the PNPI who participated in the development of the ISNP/GNEIS facility.

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