

Proton and neutron test facilities at 1 GeV synchrocyclotron of PNPI for radiation resistance testing of avionic and space electronics

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Abstract. A description of the proton (IS SC-1000, IS OP-1000) and neutron (IS NP/GNEIS) test facilities at the 1 GeV synchrocyclotron SC-1000 of the PNPI used for radiation resistance testing of electronic components and systems intended for avionic and space research is presented. A unique conjunction of proton beams with variable energy 100–1000 MeV and atmospheric like neutron beam with broad energy range (1–1000 MeV) spectrum enables to perform complex testing of the semiconductor electronic devices within a single testing cycle.

1. Introduction

The proton synchrocyclotron SC-1000 with the proton energy of 1 GeV and intensity of extracted proton beam of $1 \mu\text{A}$ is one of the basic installations of the PNPI NRC “Kurchatov Institute”. It is in operation since 1970 and during its exploitation it was significantly modernized. The experimental complex of the SC-1000 is used for investigations in fields of elementary particle physics, atomic nucleus structure and mechanisms of nuclear reactions, solid state physics and for the purposes of applied physics and nuclear medicine. Radiation resistance testing of electronics are conducted at the SC-1000 during more than two decades. Sharp growth of the needs in accelerated Single-Event-Effect (SEE)-testing of electronic components and systems intended for avionic/space and other applications has led to the development of new test facilities at the high-energy accelerators used as powerful sources of protons and neutrons.

In present report, a short description is presented of the proton (IS SC-1000 and IS OP-1000) and neutron (IS NP/GNEIS) test facilities developed at the PNPI in collaboration with the Branch of JSC “United Rocket and Space Corporation” - “Institute of Space Device Engineering”, a Head Organization of the ROSCOSMOS Interagency Testing Center. A unique conjunction of proton beams with variable energy 50–1000 MeV and atmospheric like neutron beam with broad energy range (1–1000 MeV) spectrum enable to perform complex testing of the semiconductor electronic devices at the SC-1000 within a single testing cycle.

2. Proton test facilities

At present, 2 of 3 proton beam lines of the SC-1000 are used for radiation testing of electronics. The IS SC-1000 test facility has fixed proton energy of 1000 MeV and is located on the P2 beam line. At the IS OP-1000 facility located on the P3 beam line, proton energy can be varied from 1000 MeV down to 50 MeV by means of a system of copper degrader (absorber) of variable thickness from 73 mm (at 900 MeV) to 530 mm (at 50 MeV). A scheme of the proton beams and irradiation workstations placed in the experimental room, as well as a photo of the degrader system located in the SC-1000 main room are shown in Fig. 1. The parameters of both proton test facilities are given in Table 1. An adjustment of the proton beam profile is carried out roughly by means of quadrupole lenses whereas for final tuning a 2 m-long steel collimator with 20 mm aperture is used. All irradiations are carried out at open air and room temperature. Both proton and neutron beam lines are equipped with a remotely controlled system intended for positioning the device under test (DUT) and heating in 20° – 125°C temperature range.

Parameters of the proton beam at the outlet of copper absorber of variable thickness have been evaluated by means of the Geant-4 code calculation. Energy distribution of the initial proton beam was supposed to be of Gaussian-type with the parameters of 1000 MeV and 3.83 MeV for proton energy and standard deviation, respectively. The results of Geant-4 calculations are given in Table 2. Both incoming and outgoing proton beam parameters have been verified experimentally by means of the TOF-measurements carried out using microstructure of the proton beam (~ 73 ns between proton micropulses).

Beam diagnostics is carried out using a set of standard tools which includes: (1) thin scintillator- screen coupled

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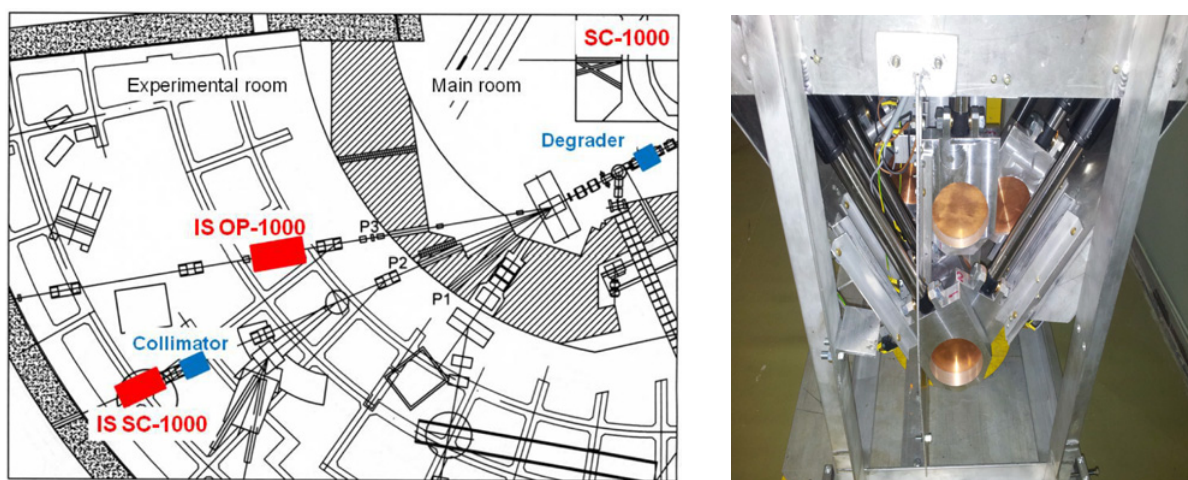


Figure 1. Left: scheme of the proton beam lines, P2 – protons with the energy of 1000 MeV, P3 – protons with variable energy of 50–1000 MeV. Right: device for remote variation of the absorber length and the proton energy.

Table 1. Parameters of the proton test facilities.

Parameter	IS SC-1000	IS OP-1000
Irradiation conditions	Atmosphere	Atmosphere
Particles	Protons	Protons
Energy, MeV	1000	50–1000
Flux, protons/cm ² ·s	10 ⁵ –10 ⁸	10 ⁵ –10 ⁸
Irradiation area, mm	Ø ≥ 25	Ø ≥ 25
Uniformity, %	≤ 10	≤ 10
Status	In operation	In operation
Status	(1998)	(2015)

Table 2. Parameters of the proton beam after transmission through the copper absorber (Geant-4 calculation).

Proton energy, MeV	Standard deviation, MeV	Absorber thickness, mm	Absorber transmission %
62.1	28.20	530.5	1.6
100.09	24.63	521.2	2.3
197.93	15.77	490.8	3.4
300.21	12.12	448.7	5.4
399.12	10.24	398.0	8.4
499.24	8.92	340.9	13.5
601.03	7.89	279	22.0
699.88	7.01	213.1	35.6
800.18	6.13	144.3	56
899.85	5.13	73.11	82.1

with a CCD-sensor for rapid evaluation of the beam profile image; (2) 2D-moving Se-stripe-type beam profile meter (Fig. 2); (3) double-section ionization chamber for “on-line” control of the proton intensity (fluence); (4) Al-foil activation technique in conjunction with a high-resolution HPG-detector as absolute “off-line” monitor of proton fluence.

3. Neutron test facility

The ISNP/GNEIS test facility is operated since 2010 [1] at the neutron TOF-spectrometer GNEIS based on the SC-1000. Its main feature is a spallation source with neutron spectrum resembling that of terrestrial neutrons in the energy range of 1–1000 MeV. The water-cooled

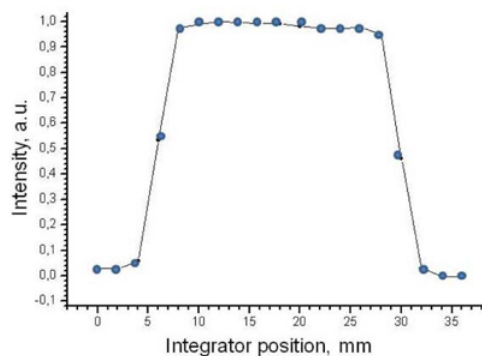


Figure 2. Proton beam cross section measured by means of the semiconductor Se-stripe-type profile meter.

lead target located inside the accelerator vacuum chamber (Fig. 3) 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. The ISNP/GNEIS test facility is located on the neutron beam #5 inside the GNEIS building at a distance of 36 m from the neutron source.

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

- neutron energy range: 1-1000 MeV;
- neutron flux: $4 \cdot 10^5$ n/cm²·s (at 36 m flight path);
- beam diameter: 50–100 mm (at 36 m flight path);
- uniformity of the beam profile plateau: ± 10%.

The neutron flux of $4 \cdot 10^5$ n/(cm²·s) is an integral over neutron spectrum in the energy range 1–1000 MeV. It corresponds to the maximum value of 3μ A of the internal average proton beam current. The neutron flux and shape of the neutron spectrum are measured using FIC (neutron monitor) and TOF-technique (Fig. 4). The neutron beam profile is measured by means of MWPC - the 2-coordinate position sensitive multiwire proportional counter 140 × 140 mm² of size used for registration of fission fragments from the ²³⁵U target deposited on the MWPC’s cathode [12].

The FIC is a fast parallel-plate ionization chamber which contains two targets of ²³⁵U and ²³⁸U. The neutron fission cross sections of these nuclei are recommended standards in the energy range 1–200 MeV. These data are

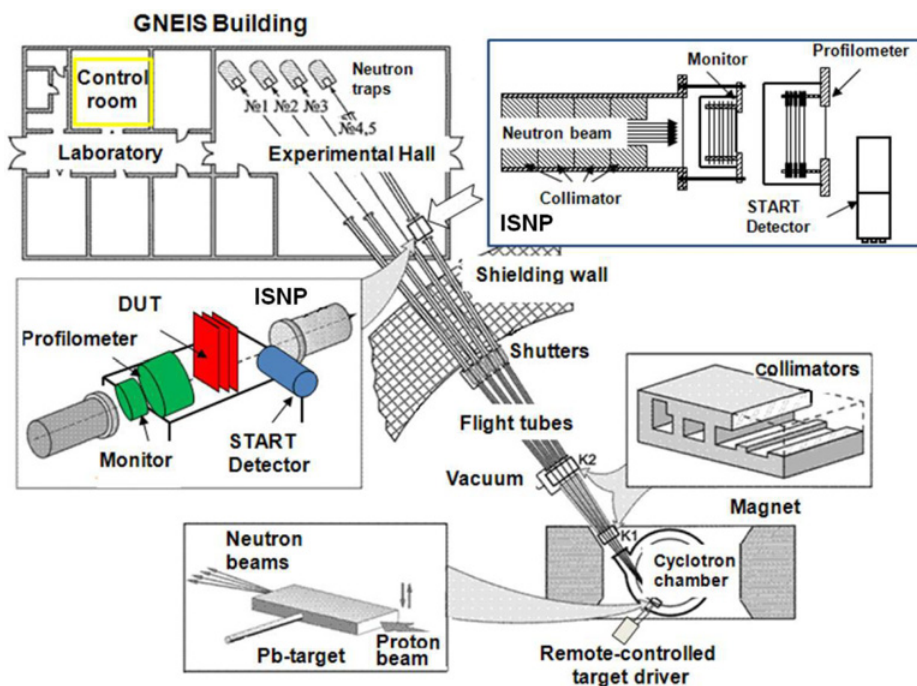


Figure 3. General layout of the neutron time-of-flight spectrometer GNEIS and ISNP test facility.

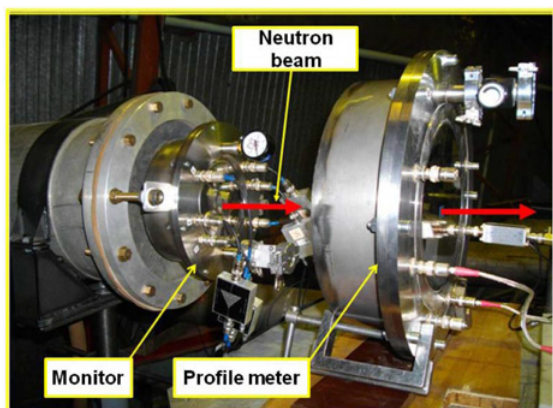


Figure 4. FIC (neutron monitor) and MWPC (profile meter).

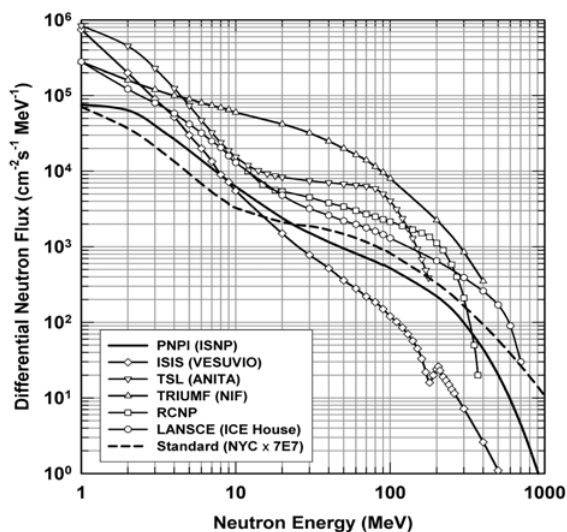


Figure 5. Neutron spectrum $F_{ISNP}(E)$ of the ISNP/GNEIS facility in comparison with standard terrestrial neutron spectrum [4] and spectra of other world-class test facilities [5–9].

Table 3. Integrated ($E_n > 1$ MeV) neutron flux of various neutron test facilities and Standards.

Standard/Facility (location, proton energy, target material)	Neutron Flux ($n/cm^2 \cdot hour$)
JEDEC (NYC, sea level, outdoors, mid level solar activ.) JESD89A [4]	20
IEC (altitude 12 km, latitude 45°) IEC TS 62396-1 [10]	8760
ISNP/GNEIS (PNPI, Gatchina, 1000 MeV, lead) [11]	$1.5 \cdot 10^9$
ICE House (LANSCE, Los Alamos, USA, 800 MeV, tungsten) [5]	$3.4 \cdot 10^9$
RCNP (Osaka University, Japan, 180 MeV, lead) [7]	$5.4 \cdot 10^9$
ANITA (TSL, Uppsala, Sweden, 400 MeV, tungsten) [6]	$9.9 \cdot 10^9$
NIF (TRIUMF, UBC, Vancouver, Canada, 500 MeV, aluminum) [8]	$1.3 \cdot 10^{10}$
VESUVIO (ISIS, RAL, Chilton, UK, 800 MeV, tungsten/tantalum) [9]	$2.5 \cdot 10^9$

taken from the ENDF/B-VII.1 Library [2] while the data above 200 MeV are taken from the JENDL High Energy Library [3]. The TOF-spectrum measured with ^{235}U and ^{238}U targets is 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 spectrum of the ISNP facility, $n/(cm^2 \cdot s \cdot MeV)$; E – neutron energy, MeV. The neutron spectrum $F_{ISNP}(E)$ is shown in Fig. 5 together with the JEDEC standard terrestrial neutron spectrum from JESD89A [4] referenced to New York City and multiplied by scaling factor $7 \cdot 10^7$, as well as the neutron spectra of

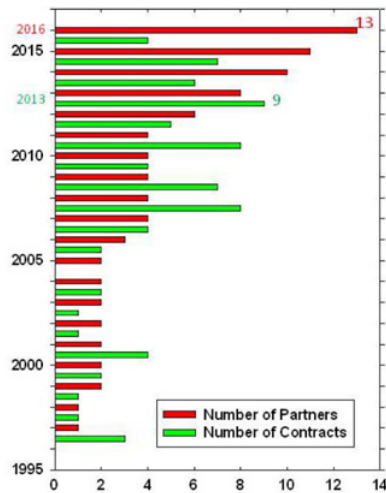


Figure 6. Yearly based statistics of electronic testing activities at the SC-1000 proton and neutron test facilities.

leading test facilities [5–9]. The corresponding values of 1-hour neutron fluence in the energy range above 1 MeV are given in Table 3. Both the shape of the neutron flux and neutron intensity demonstrate that the ISNP/GNEIS is successfully competing with the other first-grade test facilities with the atmospheric – like neutron spectrum. The SC-1000 possesses a potential of the neutron intensity growth. A new irradiation station located at a distance of 5–6 m from the neutron-production target operated on the extracted proton beam enables to increase neutron flux at least 10 times at the DUT position. Simultaneously, an irradiation of the bulky equipment will be possible.

4. Conclusion

A versatile complex of test facilities has been developed at the SC-1000 accelerator of the PNPI. A number of Russian research organizations specialized in radiation testing of the electronics conduct their research on the proton and neutron beams under direct agreements with the PNPI or with the Branch of JSC “URSC” - “ISDE” (Fig. 6). A convenient location of the PNPI close to St. Petersburg

with its highly developed transportation system makes it very attractive for potential users both from Russia and abroad.

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