NEUTRON AND PROTON RADIATION TESTING OF ELECTRONIC COMPONENTS AT THE 1 GEV SYNCHROCYCLOTRON OF PNPI

O.A. Shcherbakov[1], A.S. Vorobyev[1], A.M. Gagarski[1], L.A. Vaishnene[1], E.M. Ivanov[1]
S.A. Artamonov[1], V.S. Anashin[2], L.R. Bakirov[2], A.E. Koziukov[2]

[1] *B.P. Konstantinov Petersburg Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, Gatchina, Leningrad district, 188300, Russia*
[2] *Branch of Joint Stock Company “United Rocket and Space Corporation” - “Institute of Space Device Engineering”, Moscow, 111250, Russia*

Abstract

A description of the proton and neutron 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 50–1000 MeV and atmospheric-like neutron beam with broad energy range (1–1000 MeV) spectrum enables to perform complex testing of the semiconductor electronic components and systems within a single testing cycle.

1. Introduction

The proton synchrocyltrotron SC-1000 with the proton energy of 1 GeV and intensity of internal /extracted proton beam up to 3/1 μA is one of the basic installations of the PNPI NRC “Kurchatov Institute”. It is in operation since 1970 [1] and during its exploitation it was significantly modernized. The accelerator complex of the SC-1000 (Fig.1) 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 (proton therapy). 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

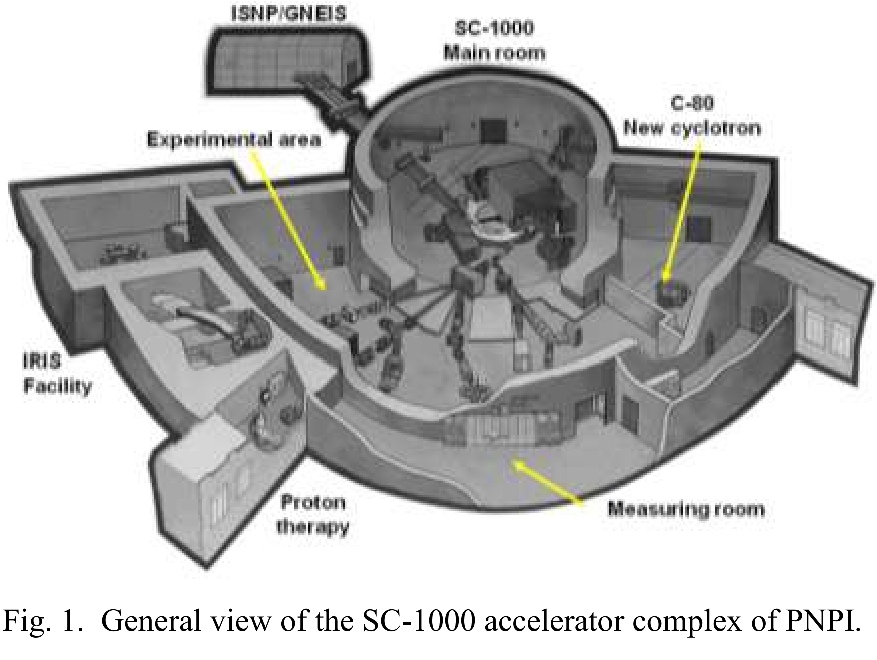

Fig. 1. General view of the SC-1000 accelerator complex of PNPI.

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 description is presented of the proton and neutron test facilities developed at the PNPI in collaboration with the Branch of JSC "United Rocket and Space Corporation"-"Institute of Space Device Engineering", the Head Organization of the ROSCOSMOS Interagency Testing Center. A conjunction of proton beams with variable energy 50–1000 MeV and atmospheric-like neutron beam with broad energy range (1–1000 MeV) spectrum enables to perform complex testing of the electronic components at the SC-1000 within a single testing cycle.

2. Proton test facilities

At present, two of three 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 the system of copper degraders (absorbers) 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.2. 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 2m-long steel collimator with 20 mm aperture is used. All irradiations are carried out at open air and room temperature. Simultaneously, 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^{o}-120^{o}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 and Fig. 3. Both incoming and outcoming 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).

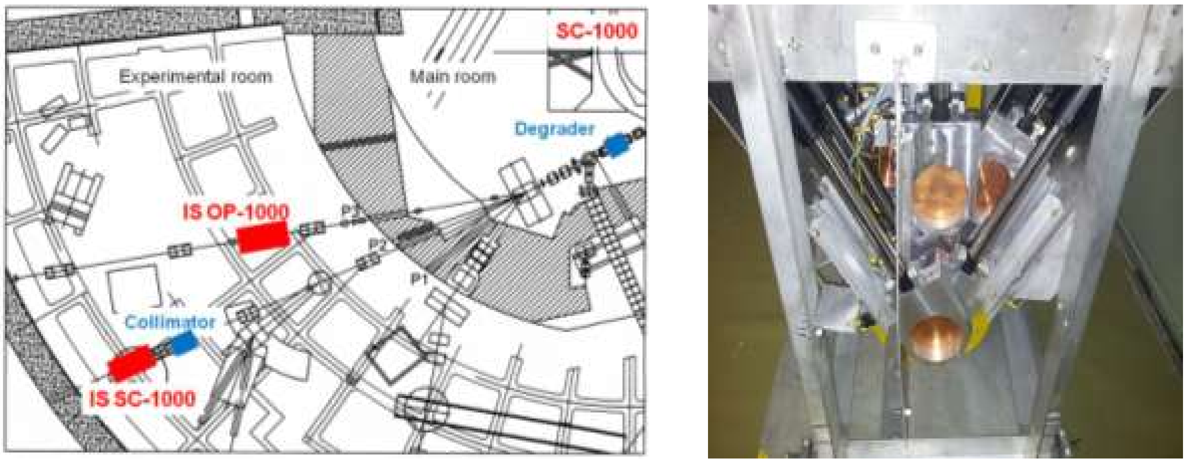

Fig. 2. Left: scheme of the proton beam lines, P2 - protons with the energy of 1000 MeV, P3 – protons with variable energy of 50–1000 MeV. Right: device for remote variation of the absorber length and the proton energy.

Table 1. Parameters of 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 (1998)	In operation (2015)

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

Proton energy, MeV	Absorber thickness, mm	Absorber transmission, %
62.1	530.5	1.6
100.09	521.2	2.3
197.93	490.8	3.4
300.21	448.7	5.4
399.12	398.0	8.4
499.24	340.9	13.5
601.03	279	22.0
699.88	213.1	35.6
800.18	144.3	56
899.85	73.11	82.1

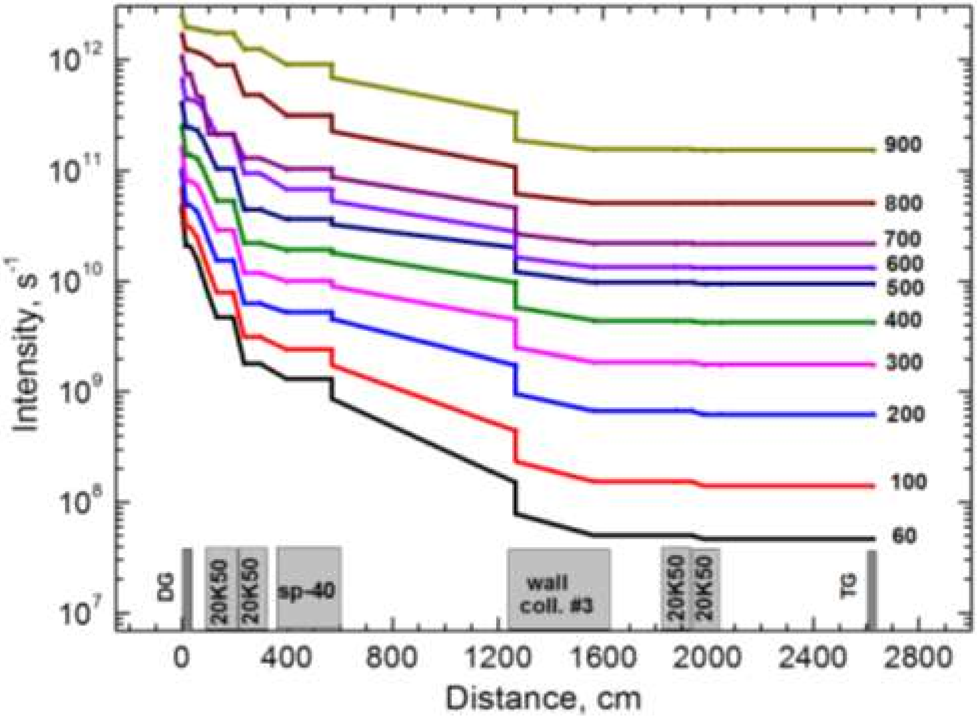

Fig. 3. Dynamics of proton losses at different energies along the beam line P3: DG-absorber; 20K50-quadrupole; SP-40- bending magnet; wall, coll. #3 – wall with collimator #3 between the main and experimental room of SC-1000; TG - target.

Beam diagnostics is carried out using a set of standard tools which includes: (1) thin scintillator - screen coupled with a CCD-sensor for rapid evaluation of the beam profile; (2) 2D-moving Se-stripe-type beam profile meter; (3) double-section ionization chamber (DIC) 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

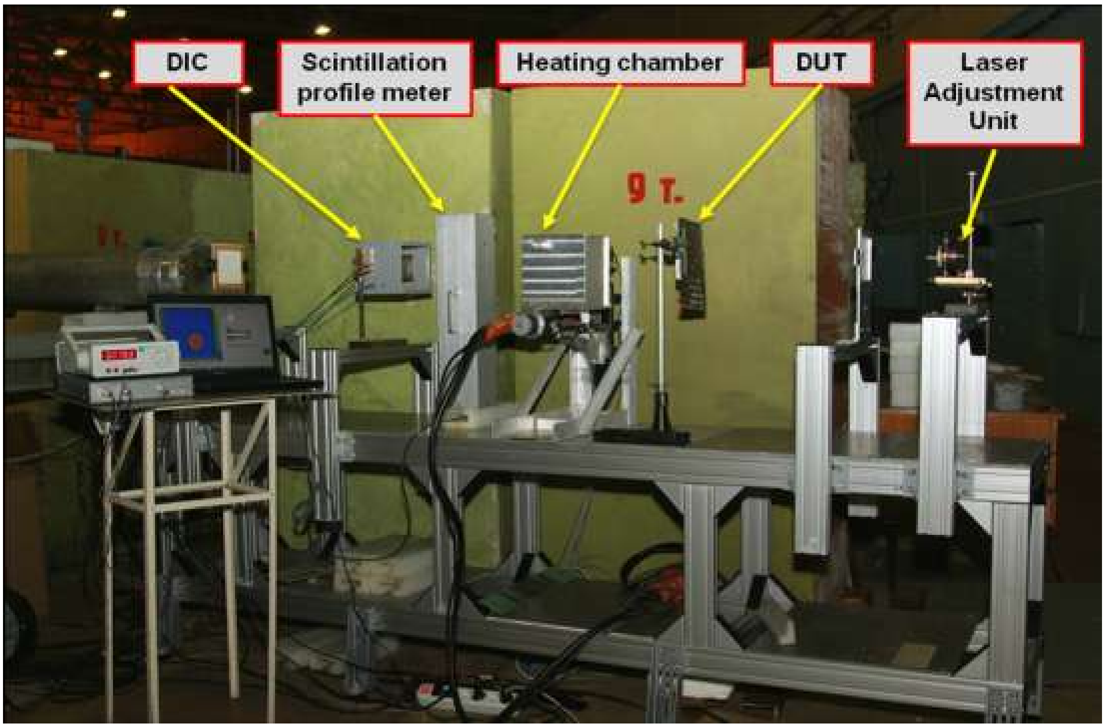

Fig. 4. The IS SC-1000 test bench with fixed proton energy of 1000 MeV.

fluence. The scintillation profile meter and DIC are shown in Fig. 4 together with other units of the IS SC-1000 testing bench, including the laser unit for proton beam adjustment and heating chamber as a part of the DUT positioning and heating unit.

3. Neutron test facility

The ISNP/GNEIS test facility is operated since 2010 [2] at the neutron TOF-spectrometer GNEIS [3] 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 lead target located inside the accelerator vacuum chamber (Fig. 5) 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. 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 lead 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. 5).

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/cm$^2 \cdot$s (at 36 m flight path);
beam diameter: 50–100 mm (at 36 m path); uniformity of beam profile plateau: ± 10%.

The neutron flux of $4 \cdot 10^5$ n/(cm$^2 \cdot$s) is an integral over neutron spectrum in the energy range 1-1000 MeV. It corresponds to the maximum value of 3μA of the average internal proton beam current. The neutron flux and shape of the neutron spectrum are measured using FIC (neutron

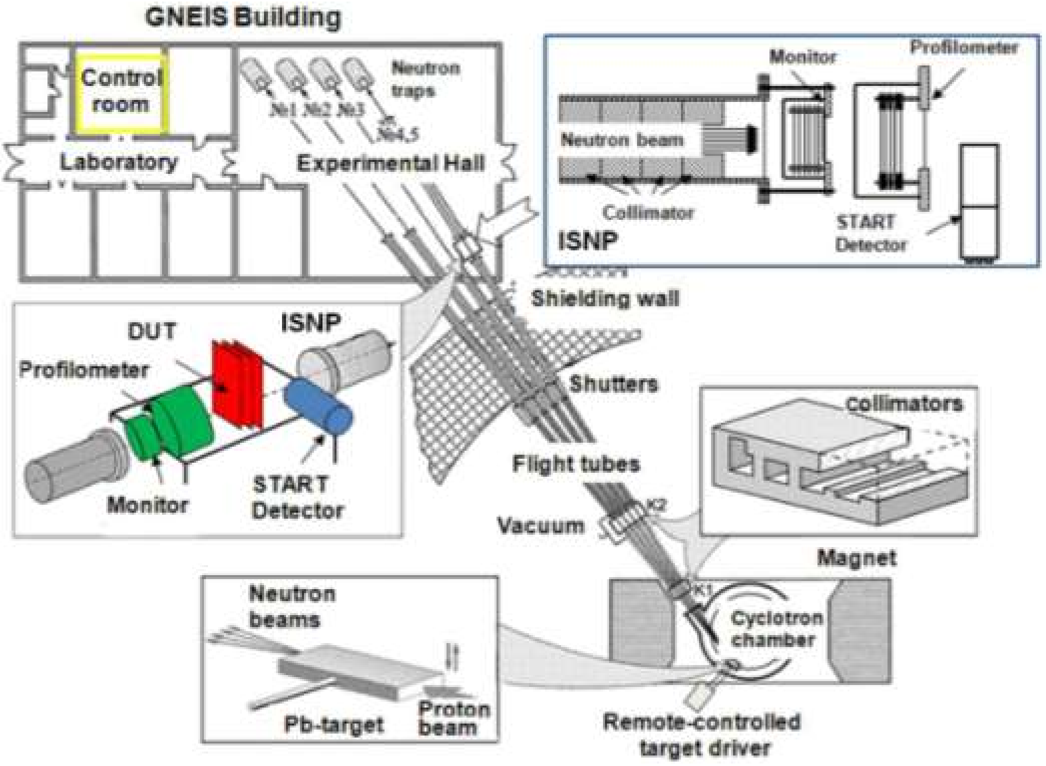

Fig. 5. General layout of the neutron spectrometer GNEIS and ISNP/GNEIS test facility.

monitor, Fig. 6) and TOF-technique. The neutron beam profile is measured by means of MWPC (Fig. 7) - the 2-coordinate position sensitive multiwire proportional counter 140×140 mm^2 of size used for registration of fission fragments from the ^{235}U target deposited on the MWPC's cathode [4].

The FIC is a fast parallel-plate ionization chamber which contains two targets of ^{235}U and ^{238}U. The 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] while the data above 200 MeV are taken from the JENDL High Energy Library [6]. The neutron spectrum (differential neutron flux) of the ISNP/GNEIS is shown in Fig. 8 together with the JEDEC standard terrestrial neutron spectrum from JESD89A [7] referenced to New York City and multiplied by scaling factor $7 \cdot 10^7$, as well as the neutron spectra of leading test facilities [8-12]. 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 demonstrates that the ISNP/GNEIS is successfully competing with the other first-grade test facilities with the atmospheric - like neutron spectrum. A more realistic comparison of the testing facilities with different neutron spectrum shape and intensity, which takes into account energy dependence of the neutron soft error cross-section of the DUT, can be found in Ref. [4, 13].

An arrangement of the experimental equipment for the beam diagnostics of the testing facility is displayed in Fig. 9. During the irradiation of the DUT located at the 36 m flight path of beam #5, a control of the neutron beam spectrum /intensity and profile is carried out by means of the FIC and MWPC, 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/GNEIS utilizes the 250 MSamples/s 12-bit Flash-ADC's for monitor and profile meter signals processing.

The internal diameter of the final neutron 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.

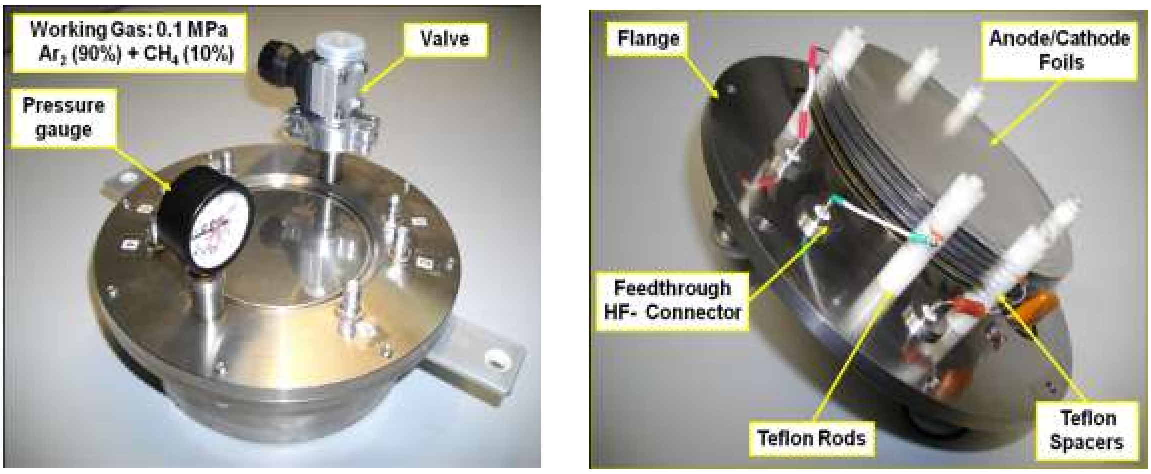

Fig. 6. General view (left) and internal structure (right) of the FIC (neutron monitor).

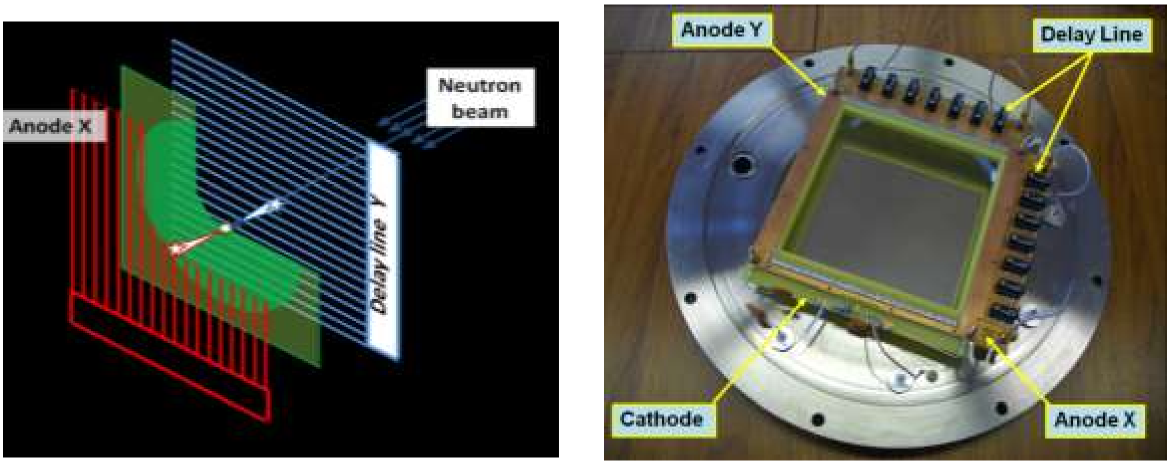

Fig. 7. Schematic view (left) and Internal structure (right) of the MWPC (profile meter).

The parameters of the proton and neutron test facilities based on the SC-1000, first of all, intensity of the protons (neutrons), energy of the protons and shape of the neutron spectrum, uniformity of the beam spot and quality of the beam collimation meet the requirements of the industry standards for accelerated SEE-testing of the electronic components. The tests of the CCD devices used in space navigation systems carried out at the SC-1000 simultaneously with protons and neutrons [14] became an initial point of the routine tests of electronic components, a number of which is permanently growing during the last years.

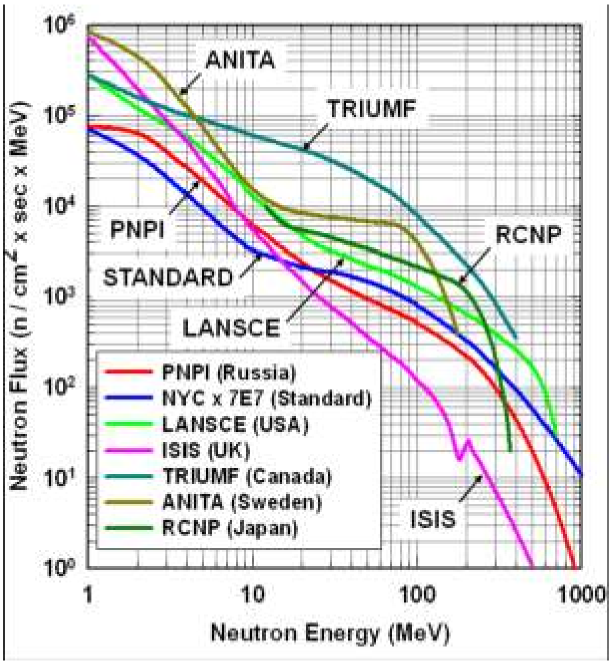

Fig. 8. Differential neutron flux of the ISNP/GNEIS compared to standard and spectra of other testing facilities.

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

Standard/Facility (location, proton energy, target material)	Neutron Flux, n/cm^2·hour
JEDEC (NYC, sea level, outdoors) JESD89A [7]	20
ISNP/GNEIS (PNPI, 1000 MeV, lead) [13]	$1.5 \cdot 10^9$
ICE House (LANSCE, 800 MeV, tungsten) [8]	$3.4 \cdot 10^9$
RCNP (Osaka University, 180 MeV, lead) [10]	$5.4 \cdot 10^9$
ANITA (TSL, Uppsala, 400 MeV, tungsten) [9]	$9.9 \cdot 10^9$
NIF (TRIUMF,Vancouver, 500 MeV, aluminum) [11]	$1.3 \cdot 10^{10}$
VESUVIO (ISIS, Chilton, UK, 800 MeV, tungsten/tantalum) [12]	$2.5 \cdot 10^9$

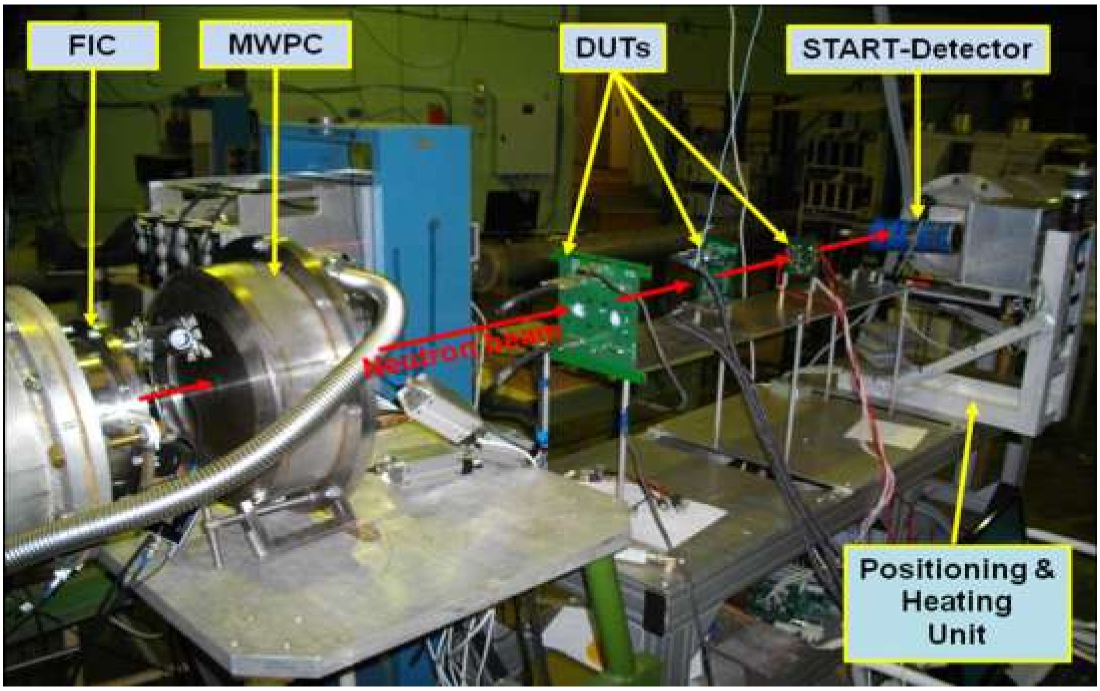

Fig. 9. The IS NP/GNEIS test facility with atmospheric-like neutron spectrum.

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". 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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