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

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Institute of Space Device Engineering, Moscow, Russia
1 GeV proton synchrocyclotron of the PNPI (in operation since 1970)
## Synchrocyclotron SC-1000

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proton energy</strong></td>
<td>1 GeV</td>
</tr>
<tr>
<td><strong>Internal proton beam current</strong></td>
<td>≤ 3 μA</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>40–60 Hz</td>
</tr>
</tbody>
</table>

### Pulsed neutron source

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td><strong>Average fast neutron intensity</strong></td>
<td>≤ 3·10^{14} n/s</td>
</tr>
<tr>
<td><strong>Duration of fast neutron pulse</strong></td>
<td>~ 10 ns</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>≤ 50 Hz</td>
</tr>
<tr>
<td><strong>Neutron energy range</strong></td>
<td>Thermal – 1000 MeV</td>
</tr>
<tr>
<td><strong>Type of neutron spectrum</strong></td>
<td></td>
</tr>
<tr>
<td>Beam #1-4 (En &lt; 0.1 MeV)</td>
<td>1/E^α, α=0.65-0.82</td>
</tr>
<tr>
<td><strong>Type of neutron spectrum</strong></td>
<td></td>
</tr>
<tr>
<td>Beam #5 (En &gt; 0.1 MeV)</td>
<td>“spallation”</td>
</tr>
</tbody>
</table>
GNEIS NEUTRON TOF-SPECTROMETER (since 1975)

NEUTRON STOPS
No 1  No 2  No 3  No 4, 5

LABORATORY  EXPERIMENTAL AREA

STUDY OF THE (n,γf) – REACTION
HIGH-PRECISION MEASUREMENTS
OF LEAD NEUTRON TOTAL CROSS SECTIONS:
NEUTRON ELECTRIC
POLARIZABILITY

MEASUREMENTS OF FISSION
CROSS SECTIONS AT
INTERMEDIATE ENERGIES
UP TO 200 MeV

“FORWARD - BACKWARD”
ASYMMETRY
IN SLOW NEUTRON FISSION
OF U-233 AND U-235
RESONANCES

NEUTRON CAPTURE REACTION FOR
U-238 UP TO 100KeV
CROSS SECTION
MEASUREMENTS

"FORWARD - BACKWARD"
ASYMMETRY
IN SLOW NEUTRON FISSION
OF U-233 AND U-235
RESONANCES

COLLIMATORS
MAGNET

CYCLOTRON CHAMBER
TARGET / MODERATOR
REMOTE CONTROL DRIVERS

NEUTRON BEAMS
POLYETHYLENE MODERATOR
Pb TARGET
PROTON BEAM
## COMPARISON OF THE GNEIS FACILITY WITH OTHER NEUTRON SOURCES

<table>
<thead>
<tr>
<th>Neutron source (Laboratory)</th>
<th>$&lt;I_n&gt;$, $10^{15}$ n/s</th>
<th>$\Delta t$, ns</th>
<th>$Q$, $10^{30}$ n/s$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORELA (ORNL, USA)</td>
<td>0.13</td>
<td>30</td>
<td>0.14</td>
</tr>
<tr>
<td>GELINA (IRMM, Belgium)</td>
<td>0.05</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>LANSCE (LANL, USA)</td>
<td>10</td>
<td>125</td>
<td>0.64</td>
</tr>
<tr>
<td>CERN PS n_TOF (CERN, Switzerland)</td>
<td>0.4</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>LUE-40+IBR-30 (JINR, shutdown)</td>
<td>0.5</td>
<td>1600</td>
<td>0.0002</td>
</tr>
<tr>
<td>IREN (JINR, project)</td>
<td>1.0</td>
<td>400</td>
<td>0.0062</td>
</tr>
<tr>
<td>GNEIS (PNPI, Gatchina) neutron beam N5</td>
<td>0.3</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>

$<I_n>$ - average intensity of neutrons emitted in $4\pi$ solid angle  
$\Delta t$ - neutron pulse width  
$Q = (<I_n>/\Delta t)^2$ - “quality” coefficient of the neutron source
What are Single Event Effects and why are they important?

Single Event Effects are created when an energetic particle (alpha, neutron, heavy ion) generates enough charge (so-called critical charge) to upset the function of integrated circuit Single Event Effect – SEE
ELASTIC ENERGY TRANSFER IN SILICON

Energy and momentum from cosmic caused neutron can be transferred to a silicon or other IC nucleus.

Silicon nucleus recoil

Maximum recoil energy is 13.3-13.6% of incident neutron. For incident neutron of 100MeV => range up to 5μ (most < 2μ).

R. Baumann, Texas Instruments [1]
INELASTIC ENERGY TRANSFER IN SILICON

High energy neutron:
\(~100 \text{ MeV to } >10 \text{ GeV}\)

\(^{28}\text{Si}\) nucleus fragments:
pions, \(n, p, ^2\text{H}, ^3\text{H}, ^4\text{He}, \) &
other light ions receive energy from incident neutron.

Burst of electronic charge

R. Baumann, Texas Instruments [1]
ACCELERATED NEUTRON TESTING OF SEE

- Whole system or component testing of representative equipment to establish the risks and reliabilities

- These include:
  - Memory devices
  - Processors
  - Field Programmable Gate Arrays (FPGAs)
  - Solid state power switching
  - Electro-optical devices

- Test Requirements:
  - High neutron flux for accelerated testing
  - Atmospheric spectrum
NEUTRON COMPONENT OF COSMIC RAYS

Source of atmospheric neutrons

Incident Primary Cosmic Ray

Electromagnetic ‘Soft’ Component

Mesonic ‘Hard’ Component

SEE Neutrons

Nucleonic Component

Sea Level

11 km

25 km
NEUTRON COMPONENT OF COSMIC RAYS

Intensity and Composition with Altitude

- ~300x Sea Level at flight altitudes

1000 Feet = 304.8 m

Source: Boeing Radiation Effects Lab

NEUTRON COMPONENT OF COSMIC RAYS

- **Intensity with Latitude and Time**

- **SUNSPOT NUMBERS**

- **IGY JUNGFRAUJOCH % BELOW MAY 1965**

- **1-10MeV Flux (n/cm²/s)**

Source: Jungfraujoch neutron monitor data were kindly provided by the Cosmic Ray Group, Physikalisches Institut, University of Bern, Switzerland.

**Table: Sources of Variation**

<table>
<thead>
<tr>
<th>Source</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of Day</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>Date in Year</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Solar Cycle</td>
<td>&lt;20%</td>
</tr>
<tr>
<td>Lat/Long</td>
<td>400-600%</td>
</tr>
</tbody>
</table>

Source: Boeing Radiation Effects Lab
TYPICAL SEA LEVEL NEUTRON FLUX

Альянс предприятий электронной промышленности (Electronics Industries Alliance), до октября 1997 г. назывался Electronics Industries Association. Профессиональная организация в США, разрабатывающая электрические и функциональные стандарты с идентификатором RS (Recommended Standards). Самый известный из её стандартов - RS-232C.

В 1958 году в США Ассоциацией предприятий электронной промышленности был создан Объединённый инженерный совет по электронным устройствам (Joint Electronic Device Engineering Council - JEDEC).

В настоящее время JEDEC является мировым лидером по разработке открытых стандартов в микроэлектронной промышленности. JEDEC насчитывает более 3000 членов, представляющих около 300 компаний.
Figure A.2.1 — The differential flux of cosmic-ray-induced neutrons as a function of neutron energy under reference conditions (sea level, New York City, mid-level solar activity, outdoors). The data points are the reference spectrum, the solid curve is an analytic fit to the reference spectrum, and the dashed curve is the model from a previous version of this standard, JESD89 (2001).
INTERNATIONAL STANDARD (by IEC)

Atmospheric Neutron Spectrum for SEE Testing

- SEE effects above ~1MeV

- Flux profile is IEC standard

International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes international standards for all electrical, electronic and related technologies.

\[
\frac{dN}{dE} = 0.346E^{-0.922} \times \exp(-0.0152(LnE)^2) \quad \text{E<300 MeV}
\]

\[
\frac{dN}{dE} = 340E^{-2.2} \quad \text{E>300 MeV}
\]
AVIONIC NEUTRON SPECTRUM AT 12 Km

5680 n/cm²/hr


400x more intense than terrestrial levels
WHY ACCELERATED NEUTRON TESTING IS NEEDED?

For non-accelerated soft error testing:

\[ \text{Fail Count} = (\text{FIT/Chip}) \times (\text{Number of Chips}) \times (\text{Time-hr}) \times 10^{-9} \]

No significant error count will be observed unless soft error rate is >10,000 FIT/chip

For product with < 10,000 FIT/chip soft error rate, data is of limited statistical value

FIT: Failure In Time; 1 FIT is one error in $10^9$ device-hours.
Testing at high altitude allows a 3 to 10x acceleration factor. Neutron flux increases about 1.3x for each 1000 ft. altitude to >10,000 ft. Testing can require months and thousands of devices under test.
FACILITIES FOR RADIATION TESTING
WITH ATMOSPHERIC – LIKE NEUTRON SPECTRUM

- Los Alamos National Laboratory, New Mexico, USA
  - Weapons Neutron Research Facility
  - ICE House ‘Irradiation of Chips and Electronics’

- Tri-University Meson Facility, Vancouver, Canada
  - Neutron Irradiation Facility

- Uppsala University, Sweden
  - Theodor Svedberg Laboratory
  - ANITA Irradiation facility

- Vesuvio, ISIS at the Rutherford Appleton Lab., Oxfordshire, England
  - Neutron Irradiation Facility

- Research Center for Nuclear Physics at Osaka University (RCNP), Japan

- Petersburg Nuclear Physics Institute
  - GNEIS Neutron TOF Facility
Replication of higher energy (>100MeV) spectra depends upon the facility.
RUSSIA
Test Facilities at JINR (Dubna) and PNPI (Gatchina) managed by
Branch of Joint Stock Company “United Rocket and Space Corporation” - Institute of Space Device Engineering (ROSCOSMOS)

<table>
<thead>
<tr>
<th>Technical features of Test Facilities expected in 2013 – 2015</th>
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<tbody>
<tr>
<td><strong>IS VE</strong></td>
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<tr>
<td>Conditions</td>
</tr>
<tr>
<td>Ions</td>
</tr>
<tr>
<td>Range in Si, mm</td>
</tr>
<tr>
<td>Energy, MeV/nucleon</td>
</tr>
<tr>
<td>Flux, particles/cm(^2) (\times) s</td>
</tr>
<tr>
<td>Irradiation area, mm</td>
</tr>
<tr>
<td>Uniformity, %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IS SC-1000</th>
<th>IS C-80</th>
<th>IS SC-1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditions</td>
<td>Atmosphere</td>
<td>Atmosphere</td>
</tr>
<tr>
<td>Particles</td>
<td>Protons</td>
<td>Protons</td>
</tr>
<tr>
<td>Energy, MeV</td>
<td>200 (\div) 1000</td>
<td>40 (\div) 80</td>
</tr>
<tr>
<td>Flux, particles/cm(^2) (\times) s</td>
<td>(10^5 \div 10^8)</td>
<td>(10^5 \div 10^8)</td>
</tr>
<tr>
<td>Irradiation area, mm</td>
<td>(\varnothing \geq 25)</td>
<td>(\varnothing \geq 25)</td>
</tr>
<tr>
<td>Uniformity, %</td>
<td>(\leq 10)</td>
<td>(\leq 10)</td>
</tr>
</tbody>
</table>
TESTING OF ELECTRONIC EQUIPMENT AT THE PNPI PROTON AND NEUTRON BEAMS

Proton testing site

Neutron testing site

Location of equipment under test

SC experimental hall

SC main room

GNEIS Building

Laboratory

Experimental Area

Neutron flight tubes

Collimators

Internal neutron-producing target
General View of the GNEIS and NICE Test Facility

Neutron Irradiation of Chips and Electronics = NICE (home nickname!)
IS NP – official bureaucratic name, direct English transcription of ИСНП
Neutron Energy Spectra of Standard and GNEIS

“Evaporation” neutrons >90%

“Cascade” neutrons <10%
Comparison of Broad Spectrum Neutron Sources

Neutron Energy (MeV)

Neutron Flux (n / cm² x sec x MeV)

PNPI (Russia)
NYC x 7E7 (Standard)
LANSCE (USA)
ISIS (UK)
TRIUMF (Canada)
ANITA (Sweden)
RCNP (Japan)
How to Compare Various Broad Neutron Spectrum Test Facilities?

**Acceleration Factor - Definition**

\[
A = \frac{\int_{E_{\text{min}}}^{\infty} \Phi_{\text{acc}}(E) \, dE}{\int_{E_{\text{min}}}^{\infty} \Phi_{\text{jedec/iec}}(E) \, dE}
\]

where \( E_{\text{min}} = 10\text{MeV} \) as specified in JEDEC and IEC

\( \Phi_{\text{acc}}(E) \) - differential neutron flux from the test facility

\( \Phi_{\text{jedec/iec}}(E) \) – differential terrestrial (standard) neutron flux
### Acceleration Factor of Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>JEDEC*) Acceleration Factor</th>
<th>IEC **) Acceleration Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANITA</td>
<td>2.7e8</td>
<td>6.1e5</td>
</tr>
<tr>
<td>LANSCE</td>
<td>1.3e8</td>
<td>2.9e5</td>
</tr>
<tr>
<td>TRIUMF</td>
<td>7.6e8</td>
<td>1.7e6</td>
</tr>
<tr>
<td>ISIS</td>
<td>1.5e7</td>
<td>3.5e4</td>
</tr>
<tr>
<td>RCNP</td>
<td>1.8e8</td>
<td>4.0e5</td>
</tr>
</tbody>
</table>

### Acceleration Factor of NICE/PNPI Facility

- **PNPI**
  - JEDEC*) 5.0e7
  - IEC **) 1.2e5

*) relative to the sea level
**) relative the altitude of 12 km

**Exact acceleration factors will vary due to state of tune of the accelerator facilities**
The neutron soft error rate is

\[ R = \int_{E_{\text{min}}}^{\infty} \sigma(E)\phi(E) \, dE \]

where \( \phi(E) \) is the differential neutron flux and \( \sigma(E) \) is the energy dependent soft error cross sections defined as

\[ \sigma(E) = \frac{\text{Number of Soft Error Events}}{\phi(E)T} \]

and \( T \) is time
Theoretical Weibull Approximation of Cross-section

\[ \sigma(E) = \sigma_L \left(1 - e^{-\left(\frac{E - E_0}{W}\right)^S}\right) \]

where \(\sigma_L\) - asymptotic high energy cross section
\(E_0\) - cut-off energy (i.e. no upsets below \(E_0\))
\(W\) - “width” parameter
\(S\) - “shape” parameter
Error Ratio – Due to Mismatch of Beam Facility and Real Neutron Spectra

\[ \text{Error Ratio} = \frac{R_{\text{measured}}}{AR_{\text{jedcliec}}} = \frac{\int_{E_{\text{min}}}^{\infty} \sigma(E) \phi_{\text{acc}}(E) \, dE}{\int_{E_{\text{min}}}^{\infty} A \sigma(E) \phi_{\text{jedcliec}}(E) \, dE} \]

- Error Ratio < 1  Accelerated measurement is under-predicting SER
- Error Ratio = 1  Accelerated measurement is correct
- Error Ratio > 1  Accelerated measurement is over predicting SER
Error in SER estimate as a function of $W$
for $E_0 = 10$ MeV and $S = 1$ (devices with low critical charge)
Error in SER estimate as a function of $W$
for $E_0 = 10$ MeV and $S = 4$ (devices with low critical charge)
Error in SER estimate as a function of $W$
for $E_0 = 100$ MeV and $S = 1$ (devices with large critical charge)
Error in SER estimate as a function of $W$
for $E_0 = 100$ MeV and $S = 4$ (devices with large critical charge)
Devices Used at the PNPI Test facility for Characterization of the Neutron Beam

Monitor: Fission Ionization Chamber (FIC)

- differential neutron flux (energy spectrum), $\Phi(E)$, n/cm$^2$·sec·MeV
- integral neutron flux, $I = \int \Phi(E) dE$, n/cm$^2$·sec
- neutron fluence, $T \cdot I$, n/cm$^2$

Frofilometer: Multiwire Proportional Counter (MWPC)

- 2D-distribution of neutron flux, $I(X,Y)$, over beam cross section
- center of gravity of the beam cross section
- uniformity of the beam cross section
- “effective” width of the beam cross section along X,Y-axes
Neutron Beam Monitor - Fission Ionization Chamber (FIC) with U-235 and U-238 targets

- Working Gas: 0.05-0.2 MPa \( \text{Ar}_2 \) (90%) + \( \text{CH}_4 \) (10%)
- Manometer TM-110P.00
- Valve VAT-KA01
Internal structure of the Neutron Beam Monitor - FIC with U-235 and U-238 targets

Flange
Anode/Cathode Foils
HF feedthrough Connector
Teflon Rod
Teflon Spacers

Targets: Ø130mm
   Double-sided
   Al-backing, 0.1 mm
   Spacing 3mm
   U235, 0.25 mg/cm²
   U238, 0.46 mg/cm²
   HV: 300-400V
TOF – Spectra Measured with FIC (Neutron Beam Monitor)

Counts / channel

Time - of - Flight, channel (4ns)

0, 500, 1000, 1500, 2000

0 - 2.6 s

$1000 \text{ MeV} > E_n > 1 \text{ MeV}$

$^{238}\text{U Target}$

$^{235}\text{U Target}$
Fine Structure of FIC-spectrum
Used for TOF vs Neutron Energy Calibration
MWPC – Neutron Beam Profilometer
(2D-type MultiWire Proportional Counter)

Anodes / Cathode: 140 W-wires, Ø25µm
Au-gilded, 1mm step,
3mm thick fiberglass plastic frame

Working Gas: isobutene (iC₄H₁₀), pressure 3-10Torr
MWPC – Neutron Beam Profilometer
MWPC – Neutron Beam Profilometer
(Mask – Collimator)

Al, 0.5mm

17 holes, Ø5mm
Cathode Pulse-Height Spectrum (α-particles)

Counts

Pulse-height, a.u.

Registration

Threshold

Short Ranges

Long Ranges

1

2

3
Anode 2D Pulse-Height Spectrum of $\alpha$-particles
(In Coincidence with Cathode Pulses, Reg. Threshold #3)
Anode 2D Pulse-Height Spectrum of $\alpha$-particles (In Coincidence with Cathode Pulses, Reg. Threshold #2)
Anode 2D Pulse-Height Spectrum of $\alpha$-particles (In Coincidence with Cathode Pulses, Reg. Threshold #1)
NEUTRON BEAM PROFILE
Collimator Ø96mm
Neutron Beam Profile vs Neutron Energy

Collimator Ø40 mm

Intensity, a.u.

X Axis, mm

- $E_\text{n} = 100 - 1000$ MeV
- $E_\text{n} = 10 - 100$ MeV
- $E_\text{n} = 1 - 10$ MeV
Comparative Study of Dark Currents in CCD – Matrix Irradiated by PROTONS and NEUTRONS

CCD (Charge-Coupled Device) - Matrix:
- image sensor Avionic and Space equipment
- commonly used in for coloured and black/white video cameras;

Irradiation of CCD-Matrix by high-energy protons and neutrons leads to:
- overall degradation
- appearance of isolated pixels, the so-called “spikes”;
- “spikes” look as isolated white spots, which lead to the image distortion and subsequent equipment failure;
- example: failure of the navigation system during the process of spaceship docking.

High-priority task: CCD – matrix testing with 1GeV protons and atmospheric-like neutron spectrum (1MeV – 1GeV).

This is first experiment at the GNEIS (2010)

devoted to the neutron radiation resistance test of electronics.
Neutron Irradiation of CCD-Matrix (2010)
Neutron Irradiation of MOS - Transistors (2012)
Neutron Irradiation of SRAM - Chips (2014)
System for DUT (Device Under Test) Positioning and Heating

DUT enclosed in the Heating Chamber can be:

- heated, temperature range 20°C – 130°C
- max. heating / cooling time
  300 sec (closed chamber)
  600 sec (upper cover removed)
- moved along X-Y axes,
  max. displacement range
  200 mm
- max. DUT dimensions
  150 mm x 150 mm
- Distant Computer control
Neutron Testing Facility at GNEIS (2015)

- FIC- Neutron Monitor
- MWPC- Beam Profilometer
- DUT- positioning and heating
- START- Detector
CONCLUSION

1) at the neutron TOF-facility GNEIS based on the 1 GeV proton synchrocyclotron of the PNPI, it is developed a neutron resistance test facility with atmospheric – like neutron spectrum in energy range 1 – 1000 MeV and integral neutron flux $5 \cdot 10^5 \text{n/cm}^2 \cdot \text{s}$ (at 36m);

2) our facility enables to carry out accelerated neutron resistance tests of electronic equipment; 1 hour of neutron irradiation at the GNEIS is equal to 125 000 hours of natural neutron irradiation at the altitude of 10-12 km and $5 \cdot 10^7$ hours (5700 years) at the sea level;

3) during 2010-2014, the neutron irradiation tests of various electronic devices at the PNPI have been done simultaneously with the proton irradiation tests;

4) in 2014, the neutron resistance testing of the electronic devices used in avionic and space equipment at the atmospheric – like neutron spectrum is included in a national system of standards.
Welcome to NICE House GNEIS in Gatchina!