ANEM:
a rotating composite neutron production target
for Single Event Effects Studies
at the 70 MeV Cyclotron of LNL-INFN

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**NEutron and Proton IRradiation Facility at SPES**

**NEPIR**

A *SPES delta-phase project involving:*

**NEUTARGS Padova collaboration**
- INFN / Padova: D. Bisello, L. Silvestrin, J. Wyss
- INFN / Milano: G. Gorini
- CNR: C. Andreani

“Core business”: radiation damage effects in electronics
- **Atmospheric neutrons** (avionics and ground-based electronics)
- **Solar protons** (space applications)

Versatile ⇒ other applications too

L. Silvestrin - 14/04/2014
Neutrons are a widening problem for Industry

"Radiation induced single events could be happening on everyone’s PC, but instead everybody curses Microsoft."

Paul Dodd, Sandia National Laboratories
Physics of neutron-induced SEE

(1) Primary neutron (accelerator, cosmic-rays, ...) → (2) neutron-nucleus reactions with production of ionizing secondaries (Nuclear Physics)

(3) Generation of electron-hole pairs (radiation physics and solid-state physics) → (4) Charge transport in device (device physics)

CMOS SRAM structure

SOFT ERROR

Secondary ionizing particle

SPALLATION:

oxide layer

neutron
Silicon nucleus

nucleon

Excited nucleus

Light nuclei (D, T, α, ...)

Heavy fragments (Mg, Al, Na, ...)

n-boundary layer
If neutron is fast enough a SEE may occur

Typically, neutron-induced SEE occur when the energy of the impinging neutron is above some minimum threshold value; the probability of a SEE occurring, usually expressed as a cross-section, increases with neutron energy, until a plateau value is reached.

Weibull fit function for a typical cross-section curve

$$\sigma(E) = \sigma_p \left( 1 - e^{-\left( \frac{E - E_{thres}}{W} \right)^S} \right)$$

Figure after Chris Frost (ISIS, ChilIR)
Spectrum $\varphi_{atm}(E)$ of fast ($E>1\text{MeV}$) atmospheric neutrons

$\Phi_n(E>1\text{MeV}) = 21\text{ n cm}^{-2}\text{ hr}^{-1}$

Of these:
- 42% are in 1-10 MeV range
- 47% are in 1-20 MeV range
- 63% are in 1-60 MeV range

And the rate of neutron-induced Single Event Upsets (SEU) in a device located at New York City (NYC) is...

$$R_{SEU}^{NYC} = \int_{E_{th}}^{\infty} \sigma_{device}(E)\varphi_{atm}(E)dE = N_{bits} \times \int_{E_{th}}^{\infty} \sigma_{bit}(E)\varphi_{atm}(E)dE$$

JEDEC 2006 reference curve is fit to data (Gordon)
- sea level
- New York City
- mid-level Solar activity
- outdoors

Typical value for SEU
$\sigma_{\text{Plateau}} = 10^{-14}\text{ cm}^2/\text{bit}$
gives
4 SEU / (month $\cdot$ 8 GByte)

(yawn)
I need to speed things up...
I want an accelerator!
# Neutron SEE tests: field and accelerated

<table>
<thead>
<tr>
<th>Type</th>
<th>Experimental Method</th>
<th>Merit/demerit</th>
</tr>
</thead>
</table>
| Neutron Field Tests         | Keep a large number of device under test (DUT) at a certain location for a long time. | • costly, time consuming  
• realistic and reliable  
• few corrections necessary (related to altitude and location) |
| **Monoenergetic Neutrons**  | Irradiate DUT with mono-energetic neutrons. Vary energy of the neutrons to study energy dependent effects | • facilities limited  
• versatile  
• actually neutrons are quasi-mono-energetic (QMN), hence corrections are necessary to account for significant fraction of neutrons with wrong energy. |
| Thin light targets          |                                                                                      |                                                                              |
| **Evaporation and Spallation Neutrons** | Irradiate DUT with neutrons of a broad energy range similar to atmospheric neutron spectrum. | • high fluxes  
• facilities limited  
• continuous (white) spectrum needs to be similar to atmospheric one  
• uncertain in selection of energy range |
| Thick targets               |                                                                                      |                                                                              |
| **Thermal Neutrons**        | Irradiate DUT with thermal neutrons at experimental reactors or using targets with moderators | • facilities limited  
• using reactors the estimation of SEE rate in field is difficult due to great difference in neutron spectra |
| **Proxy mono-energetic protons** | Irradiate DUT with mono-energetic protons. Vary the energy of the protons to study energy dependent effects. | • many facilities available  
• pseudo-equality with neutron nuclear cross-sections  
• ionization dose effects in DUT |
Useful probes:

• (quasi) Mono-energetic neutrons to study energy dependence effects
• Continuous energy neutrons to emulate atmospheric neutrons

\[ R_{\text{SEE}}^{\text{test}} = F \times \int_{E_{\text{th}}}^{E_{\text{cutoff}}} \sigma_{\text{device}}(E) \varphi_{\text{atm}}(E) dE \]

F is the “acceleration factor”

At the INFN National Labs of Legnaro (LNL), a variable energy (35-70 MeV) high current proton cyclotron \( (I_{\text{max}} = 750 \mu\text{A}) \) will soon come into operation. It will open up the prospect of high flux neutron facilities in Italy that could perform various research activities.
Tools at the proposed neutron facility (NEPIR)

Fast Quasi Mono-energetic Neutrons (QMN) from 35-70 MeV protons
- multi-angle collimator for “tail correction”
- assortment of thin (2-4 mm) Li and Be targets

Continuous energy (white) atmospheric-like neutrons from intense 70 MeV protons

Two high power targets:

a) Slow neutrons: a “conventional” thick (stopping) W-based target and moderator system (49 kW) (SLOWNE)

b) Fast neutrons: a “novel” rotating BePb (or BeTa) composite target system, relatively thick (non-stopping), without moderator (ANEM)

Direct protons (35-70 MeV, low current)

L. Silvestrin - 14/04/2014
Well defined energy neutrons are produced in $^7\text{Li}(p,n)$ and $^9\text{Be}(p,n)$ reactions. However, the experimental neutron spectrum is not purely mono-energetic because neutrons released during nuclear break-up can assume a continuous range of energy values.

In the **forward direction** ($\theta = 0^\circ$) only about half of the neutrons form a peak with a well defined energy ($\smile$), while the rest have lower energies distributed over a broad range of values ($\frown$).

Typical **forward** QMN spectrum at Zvedberg (TSL) for $E_{\text{proton}} = 49.5 \pm 0.2$ MeV on **thin** (4 mm) Lithium slab.

- Thin $\Rightarrow$ must pay price of lowered neutron yield/current
- The protons that do not undergo nuclear reactions (~99%) are magnetically deflected towards a beam dump.
QMN tail subtraction

**PERFORMANCE** for 1mm and 2mm Be slabs: n flux at test point $> 3 \times 10^5$ n cm$^{-2}$ s$^{-1}$

Limited neutron yield $\Rightarrow$ high current: $50 \mu A$ max

A $30^\circ$ collimator is likely to be the standard angle for correction, but this must be verified for the 20-35-70 MeV energy range

- data can be taken simultaneously at $0^\circ$ and one or two standard angles (say $15^\circ$ and $30^\circ$)
- flexibility for intermediate values
- but challenging to design magnet/target system
The Report concludes that, out of the worldwide six QMN facilities currently in existence, all operate in sub-optimal conditions for dosimetry. Of the three facilities in Japan, one is at least temporarily out of action, and the only currently available QMN facility in Europe capable of operating at energies above 40 MeV, TSL in Uppsala Sweden, is threatened with shutdown in the immediate future. In Europe, a facility, NFS at GANIL, France, is currently under construction. NFS could deliver QMN beams up to about 30 MeV. It is, however, so far not clear if and when NFS will be able to offer QMN beams or operate with only so-called white neutron beams. It is likely that in about five years, QMN beams with energies above 40 MeV will be available only in South Africa and Japan, with none in Europe.

The QMN beam line of NEPIR would close the gap. It is of the highest priority, as it would be a precious multidisciplinary tool making NEPIR an important reference point for Italian and European research, applied and basic.
SLOWNE: a conventional continuum spectrum target

It is conventional in that
1. it produces the largest amount of neutrons possible...
2. ...and then the neutron spectra is shaped using moderators

The target for the high neutron flux beam line is a thick W-based self-shielding production target that completely stops the proton beam. Moderators and reflectors are then used to SLOW the neutrons and shape the energy spectrum to resemble the desired one, namely the atmospheric spectrum also down to epithermal and thermal energies. Thermal neutrons may cause SEE if $^{10}$B is present in device under test (same used for BNCT).

Thick target W-based target (FARETRA*-like)

* FARETRA = FAst REactor simulator for TRAnsmutaion studies
Atmospheric-Neutron Emulator (ANEM) for SEE studies

Composite Be-Pb system: Two complementary disks, rotating on a common hub, alternatively intercept the off axis proton beam; the beam is NOT stopped by Be (to avoid damaging due to blistering), the spent protons are the magnetically defected towards a beam dump (shared with QMN).

The LENOS chamber with modified innards to house Be and Pb (or Ta) “disks” and water flow system.

ANSYS simulations under way.
Thermal tests with Al disk foreseen in the next months.
Fast neutron energy spectrum of ANEM (BePb variant)

Atmospheric neutrons at sea level at New York integrated flux $E > 1$ MeV
\[ \phi_n (E > 1 \text{ MeV}) = 21 \text{ cm}^{-2} \text{ hr}^{-1} \]

Neutron FLUX at 6 m from the target: $20-30 \times 10^9 \text{ n cm}^{-2} \text{ s}^{-1}$
(current: 50-100 $\mu$A)
An “acceleration factors” of few $10^9$ can be achieved with few tens of $\mu$A.
The ANEM rotating composite target system will exchange position with the QMN multi-target system and will share the 0° line with the dipole sweeping magnet.

Layout (top view) of the neutron irradiation facility at LNL in SPES halls A8 and A9

Layout of the NEPIR facility
NEPIR fast neutron line (QMN/ANEM)

Chicane to:
- avoid neutrons towards cyclotron
- have test point at same distance from floor and ceiling (minimize albedo)
- use degradator for lower energy neutrons

The rotating composite BePb target system will exchange position with the QMN multi-target system and will share the 0° line with the dipole sweeping magnet.

Optics of halls A1 and A9 of the fast neutron NEPIR neutron lines (QMN and ANEM).
At the test point, the neutron beam is 1.50 m from the false floor (3.91 m from the bottom cement floor). The optics consists of two dipole magnets, two quadrupole doublets and a single one, and a bending magnet for the spent proton beam. The supplementary shielding is not shown.
The ANEM prototype (mock-up) system

A mock up of the target was manufactured to perform the measurements of power dissipation necessary to tune the ANSYS simulations, to test the rotation system and tune the cooling system.

The mock up employes the existing vacuum chamber of the Lenos project while new innards were manufactured. The element exposed to the beam is a 7mm thick Al (99%) ring.

Vacuum chamber and cooling system
ANSYS thermal simulations

Simplified structure of the simulated target.

26 mm thick Be element thermal map

Sim. 008SS.wbpi
Steady State Analysis
Power = 5kW
No water cooling
$T_{be \ min} = 1639 \ °C$
$T_{be \ max} = 1727 \ °C$
021.wbpj

\[ T_{\text{Be min}} = 33 \, ^\circ\text{C} \quad T_{\text{agua-min}} = 15 \, ^\circ\text{C} \]
\[ T_{\text{Be max}} = 85 \, ^\circ\text{C} \quad T_{\text{agua-max}} = 58 \, ^\circ\text{C} \]
\[ m. = 0,18 \text{ l/s} \quad 1\text{m/s} \]

Heat Transfer Model: conservative interflux

2,5 kW

024.wbpj

\[ T_{\text{Be min}} = 31 \, ^\circ\text{C} \quad T_{\text{agua-min}} = 15 \, ^\circ\text{C} \]
\[ T_{\text{Be max}} = 113 \, ^\circ\text{C} \quad T_{\text{agua-max}} = 61 \, ^\circ\text{C} \]
\[ m. = 0,283 \text{ l/s} \quad (1,5\text{m/s}) \]

Heat Transfer Model: conservative interflux

5 kW
### Thermal Simulation Results

#### Steady State Analysis

Varying water speed (Power = 5 kW)

<table>
<thead>
<tr>
<th>Sim. #</th>
<th>Power</th>
<th>H₂O s.</th>
<th>Be [°C]</th>
<th>H₂O [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>.wbpj</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>008SS</td>
<td>0</td>
<td>0</td>
<td>1639</td>
<td>1727</td>
</tr>
<tr>
<td>020</td>
<td>0,09</td>
<td>0,5</td>
<td>53</td>
<td>159</td>
</tr>
<tr>
<td>023</td>
<td>0,18</td>
<td>1</td>
<td>36</td>
<td>130</td>
</tr>
<tr>
<td>024</td>
<td>0,283</td>
<td>1,5</td>
<td>31</td>
<td>113</td>
</tr>
<tr>
<td>025</td>
<td>0,377</td>
<td>2</td>
<td>27</td>
<td>112</td>
</tr>
<tr>
<td>026</td>
<td>0,471</td>
<td>2,5</td>
<td>25</td>
<td>108</td>
</tr>
</tbody>
</table>

#### Transient Analysis

Regime condition reached in less than 10 minutes with 5 kW

<table>
<thead>
<tr>
<th>Sim. #</th>
<th>Power</th>
<th>Water Speed</th>
<th>Time</th>
<th>Input Pressure</th>
<th>Be [°C]</th>
<th>H₂O [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>020.03</td>
<td>6</td>
<td>5 bar</td>
<td>60 s</td>
<td>3</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>020.04</td>
<td>7</td>
<td>5 bar</td>
<td>10 min</td>
<td>3</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>020.05</td>
<td>10</td>
<td>5 bar</td>
<td>10 hr</td>
<td>3</td>
<td>16</td>
<td>4</td>
</tr>
</tbody>
</table>

#### Steady State Analysis

Varying proton beam power

(Water speed = 2.5 m/s, input pressure = 3 bar). Maximum power tolerated by Be element: 10 kW

<table>
<thead>
<tr>
<th>Sim. #</th>
<th>Power</th>
<th>Be [°C]</th>
<th>H₂O [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>.wbpj</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>026.03</td>
<td>6</td>
<td>27</td>
<td>55</td>
</tr>
<tr>
<td>026.04</td>
<td>7</td>
<td>29</td>
<td>61</td>
</tr>
<tr>
<td>026.06</td>
<td>8</td>
<td>29</td>
<td>61</td>
</tr>
<tr>
<td>026.07</td>
<td>9</td>
<td>35</td>
<td>81</td>
</tr>
<tr>
<td>025.03</td>
<td>10</td>
<td>35</td>
<td>81</td>
</tr>
<tr>
<td>026.05</td>
<td>12</td>
<td>39</td>
<td>94</td>
</tr>
</tbody>
</table>

ANSIS Heat Transfer Model used: “conservative interface flux“
What’s next

**MCNPX/Fluka simulations** to assess target shielding and collimator system are ongoing. The design of beam dump will limit the maximum neutron flux.

To experimentally define key heat transfer parameters, **thermal tests** will be performed with the mock up target in the next months, using a high power electron gun.

**New ANSYS simulations** will be performed using the experimentally defined parameters. These will be used to validate the final design of the target, or to suggest modifications.
<table>
<thead>
<tr>
<th>Particle and spectrum</th>
<th>Energy</th>
<th>Max flux at test point (SPES current)</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutron (discrete)</td>
<td>Adjustable QMN peak in 35-70 MeV energy range</td>
<td>Few $10^6$ n cm$^{-2}$ s$^{-1}$ (50μA max)</td>
</tr>
<tr>
<td>neutron (continuous)</td>
<td>Atmospheric-like over 1&lt;E&lt;70 MeV energy range</td>
<td>$20-30\times10^9$ n cm$^{-2}$ s$^{-1}$ (50-100 μA)</td>
</tr>
<tr>
<td>neutron (continuous)</td>
<td>Slow (moderated) neutrons depending on special applications</td>
<td>Flux depends on moderator system (up to 500 μA)</td>
</tr>
<tr>
<td>proton (discrete)</td>
<td>Adjustable in 35-70 MeV peak; using absorbers down to ~10 MeV</td>
<td>(&lt; 50 nA for pencil, &lt; 250 nA for broad)</td>
</tr>
</tbody>
</table>

(*) $F = 10^9$ corresponds to an integral neutron flux of $\Phi_{E>1\text{MeV}} \sim 6\times10^6$ n cm$^{-2}$ s$^{-1}$
Thank you for your attention,
extra slides follow

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13.1.2.2. Heat Transfer

Determines whether or not heat transfer models are applied between the sides of the interface.

The options are:

- **Conservative Interface Flux**

  This option enables you to define the Thermal Contact Resistance or Thin Material, which are two ways of defining the same characteristic. That is, if you do not know the contact resistance, you can define the thin material and its thickness and have the solver derive the resistance.

- **Side Dependent**

13.1.2.2.1. Conservative Interface Flux: Interface Model

13.1.2.2.1.1. None

No models are provided for any additional heat transfer between side 1 and side 2 of the interface.

13.1.2.2.1.2. Interface Model Option: Thermal Contact Resistance

Enter a numerical quantity or CEL expression that specifies the value of the thermal contact resistance from side 1 to side 2 of the interface.

13.1.2.2.1.3. Interface Model Option: Thin Material

Select a material and enter a numerical quantity or CEL expression that specifies the value of the thickness of the material spanning from side 1 to side 2 of the interface.

13.1.2.2.2. Side Dependent

**Side Dependent** has no suboptions.

13.1.2.3. Electric Field

Determines whether or not electric field models are applied between the sides of the interface.

The options are:
Heat Transfer Model: conservative interflux

020.wbpj

T_{Bemin} = 53 \, ^\circ C \quad T_{agua-min} = 15 \, ^\circ C

T_{Bemax} = 159 \, ^\circ C \quad T_{agua-max} = 103 \, ^\circ C

m. = 0,09 \, l/s \quad 0,5 \, m/s

2,5 kW

021.wbpj

T_{Bemin} = 33 \, ^\circ C \quad T_{agua-min} = 15 \, ^\circ C

T_{Bemax} = 85 \, ^\circ C \quad T_{agua-max} = 58 \, ^\circ C

m. = 0,18 \, l/s \quad 1m/s

2,5 kW

Heat Transfer Model: conservative interflux

L. Silvestrin - 14/04/2014
Heat Transfer Model: conservative interflux

023.wbpj

$T_{\text{Bemin}} = 36 \, ^\circ\text{C}$  $T_{\text{agua-min}} = 15 \, ^\circ\text{C}$

$T_{\text{Bemax}} = 130 \, ^\circ\text{C}$  $T_{\text{agua-max}} = 73 \, ^\circ\text{C}$

$m. = 0,18 \, \text{l/s} \quad (1 \, \text{m/s})$

5 kW

024.wbpj

$T_{\text{Bemin}} = 31 \, ^\circ\text{C}$  $T_{\text{agua-min}} = 15 \, ^\circ\text{C}$

$T_{\text{Bemax}} = 113 \, ^\circ\text{C}$  $T_{\text{agua-max}} = 61 \, ^\circ\text{C}$

$m. = 0,283 \, \text{l/s} \quad (1,5 \text{m/s})$

5 kW
025.wbpj

\[ T_{\text{B min}} = 27 \, ^\circ \text{C} \quad T_{\text{agua-min}} = 15 \, ^\circ \text{C} \]
\[ T_{\text{B max}} = 112 \, ^\circ \text{C} \quad T_{\text{agua-max}} = 53 \, ^\circ \text{C} \]
\[ m. = 0,377 \, \text{l/s} \quad (2 \, \text{m/s}) \]

Heat Transfer Model: conservative interflux

026.wbpj

\[ T_{\text{B min}} = 25 \, ^\circ \text{C} \quad T_{\text{agua-min}} = 15 \, ^\circ \text{C} \]
\[ T_{\text{B max}} = 108 \, ^\circ \text{C} \quad T_{\text{agua-max}} = 48 \, ^\circ \text{C} \]
\[ m. = 0,471 \, \text{l/s} \quad (2,5 \, \text{m/s}) \]

Heat Transfer Model: conservative interflux
<table>
<thead>
<tr>
<th>item</th>
<th>Proton beam energy, current</th>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>QMN system</td>
<td>35-70 MeV, 10-100 µA↑ (possible upgrade)</td>
<td>QMN line has high priority (multi-disciplinary). Thin Li and Be target system to be designed within 2014, in concert with the rotating target. Multi-angle collimator preliminary study began.</td>
</tr>
<tr>
<td>Rotating target</td>
<td>70 MeV, 50-100 µA↑ (possible upgrade)</td>
<td>0-level prototype, funded by INFN, is ready for extensive power tests with test disks (Al and Pb) in 2014. ANSYS calculations underway. Construction of the final target with Be disk in 2015.</td>
</tr>
<tr>
<td>W-target</td>
<td>70 MeV, 500 µA (35 kW)</td>
<td>High power dissipation studies are proceeding in the context of APOTEMA, the experiment for the production of the radioactive marker $^{99}$Te from $^{99}$Mo with the SPES cyclotron. The design of the moderator system is on hold (given limited funding, manpower, and change in priorities).</td>
</tr>
<tr>
<td>Direct proton line</td>
<td>35-70 MeV, max 1 µA</td>
<td>Foreseen</td>
</tr>
</tbody>
</table>