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Physics Procedia 26 (2012) 284 – 293

Physics Procedia

Union of Compact Accelerator-Driven Neutron Sources I & II

Neutron production targets for a new Single Event Effects facility at the 70 MeV Cyclotron of LNL-INFN

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Abstract

A high-current (500 μA) variable energy (35-70 MeV) proton cyclotron is under construction at the INFN LNL for the SPES project and will be commissioned in 2014. This opens up the prospect of a high flux neutron irradiation facility in Italy that could perform various research activities, in particular studies of Single Event Effects (SEE) induced in microelectronic devices and systems by atmospheric neutrons at sea level. In this paper we first review neutron-induced SEE, describe neutron testing facilities and briefly illustrate the project at LNL. We then describe two types of high power production targets under design to produce neutrons with a continuous atmospheric-like differential energy spectra in the energy range accessible to the accelerator. One target is a high power W-based thick target that will completely stop the 70 MeV protons. Another target, under preliminary study, is based on a multi-material target made, in this case, of two different materials, light (Be) and a heavy material such as Ta or Pb.

Keywords: irradiation facility; neutron radiation effects; Single Event Effects; atmospheric neutrons.

1. Introduction: neutron-induced SEE and atmospheric neutrons

Our information technology based society is dominated by an increasing pervasiveness and dependence on microelectronic devices and electronic-based systems. The technological trend in electronics is towards smaller structures, lower operating voltages, higher clock speeds and growing complexity. As a result, devices and systems are increasingly susceptible to neutron-induced Singe Event

doi:10.1016/j.phpro.2012.03.036

Effects (SEE) induced by atmospheric neutrons, i.e. neutrons generated in air showers, the cascades of particles initiated by the interaction of very high energy cosmic rays with the upper atmosphere.

A SEE is a phenomenon whereby the correct operation of a microelectronic device is disrupted by the interaction with a single sub-atomic particle. A neutron that interacts with a nucleus of the constituent atoms of the electronic device (e.g. silicon) may cause it to recoil or break-up into one or more ionizing fragments which create trails of localized ionization in the device: the charge generated by ionization, if collected at a sensitive node, can cause a SEE, an instantaneous anomalous behavior of the device.

Neutron-induced SEE phenomena range from Soft Errors (SE) to Hard Errors (HE), i.e. catastrophic errors. Typically Soft Errors may involve Single Bit Upsets (SEU) that cause memory corruptions or changes in the logic functions of the device. Hard Errors typically involve Single Event Latch-up (SEL) in CMOS technologies and Single Event Burn-out (SEB) in power MOSFETs. Both SE and HE induced by neutrons at sea level and in avionics are a growing concern for critical electronic systems such as computer servers, network routers, onboard computers, power devices and pacemakers.

Neutron-induced SEE events 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, typically increases with neutron energy until a plateau value is reached, as shown in Fig. 1. Until recently it was assumed that SEU only occurred with neutrons with E > 10 MeV; however, modern microelectronic devices and systems are now found to be sensible to neutrons in the 1-10 MeV energy range. Instead HE such as SEL typically need higher energy neutrons.

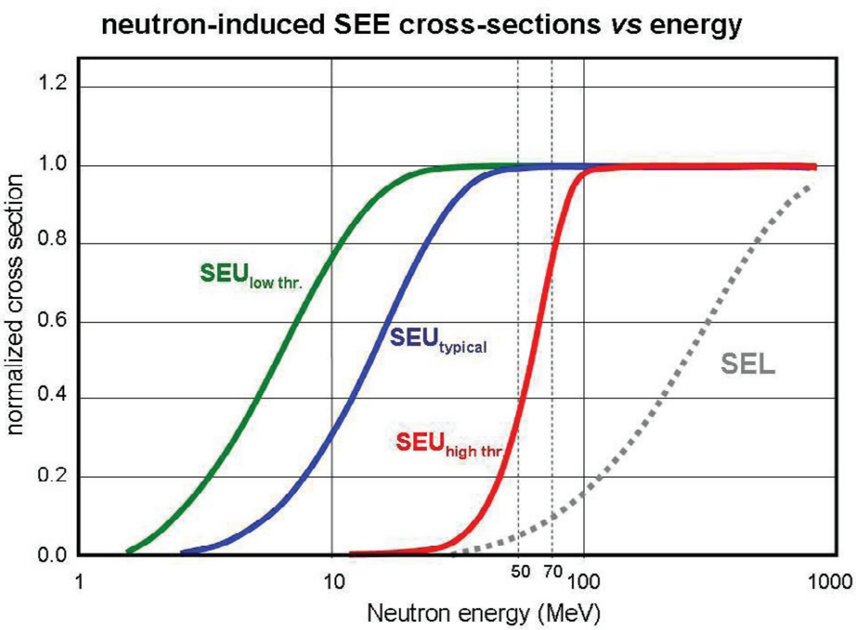

Fig. 1. Normalized cross-section curves for SEU and SEL versus neutron energy of current electronic devices [1].

Fig. 2 shows the JEDEC Solid State Technology Association reference differential energy spectrum for fast atmospheric neutrons at sea level: the integral flux of neutrons with energy higher than 1 MeV is 21 neutrons/(cm^2×hr) [2][3][4]. About 40% of the atmospheric neutrons with E > 1 MeV have an energy in the 1-10 MeV energy range.

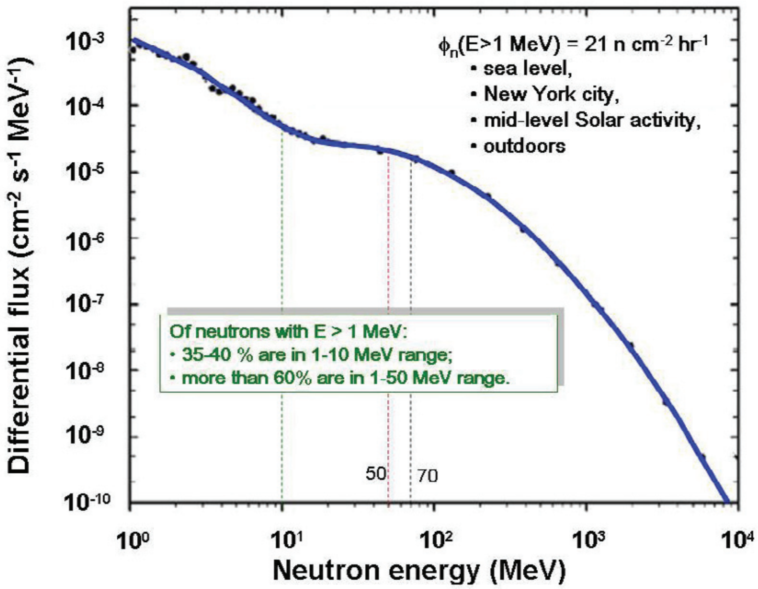

Fig. 2. Neutron differential flux of atmospheric neutrons having energy higher than 1 MeV. The blue curve plotted is the JEDEC (JESD89A) standard reference fit.

There is also a growing concern regarding the SE susceptibility to low energy neutrons, mainly thermal neutrons. Boron (^{10}B), often present as a p-type dopant in semiconductors, such as in p-MOSFET, will promptly capture slow neutrons and break-up into alpha and lithium ionizing fragments.

2. Neutron-induced SEE testing using atmospheric-like neutron sources

There are two ways to study the susceptibility of electronics to atmospheric neutrons. One way is to typically perform high altitude (mountain) tests. Such an approach is very time-consuming but on the other hand has the great advantage of giving a direct measurement of the SEE rate of the device under test. The other, more commonly used approach, makes use of intense artificial neutron sources to speed up the SEE rate by many orders of magnitude. A few hours of irradiation therefore simulates damages as high as many years in the real environment. In general the results of the accelerated tests must be extrapolated to the natural conditions.

Material Testing nuclear Reactors (MTR), although providing quite high neutron yields are however of limited interest for SEE studies. The continuous energy spectrum from neutron-induced fission reactions does not extend to the required high energies. To meet such a need higher energy neutrons are generated using proton beams from particle accelerators which impinge specially designed targets where neutrons are produced by nuclear evaporation and spallation reactions.

Thick production targets, that completely stop the primary proton beam, made of heavy elements such as Tungsten (W), provide neutrons with a continuous range of energies (white energy spectrum). Moderators are added to slow neutrons down and shape the neutron energy spectrum. To simulate the effects of atmospheric neutrons, over the energy range of interest, the neutron energy spectrum should resemble the atmospheric one to a high degree. The atmospheric neutron spectrum may extend to energies well above 1 GeV and the maximum neutron energy from a white spectrum facility is an important figure of merit. The most energetic white spectrum neutron source currently available is LANSCE at LANL in USA with a cut-off energy of 800 MeV. The future European Spallation Source (ESS) in Sweden will be able to furnish neutrons up to 2.5 GeV (Table 1).

The neutron flux performance at energies higher than 10 MeV reported in Table 1 is often quoted, but it is very inadequate when comparing different facilities with different cut-off energies and different production targets. To better compare different white spectrum test facilities, one should compare the shapes of the neutron energy spectra over an energy range of interest and quote a normalizing acceleration factor. The acceleration factor parameter is the scaling factor that allows to equate an irradiation time interval at the accelerator test facility to a natural exposure time interval over the energy range of interest. The acceleration factors of the existing and planned facilities range from 10^8 to 10^9. An acceleration factor of 10^8 implies that one hour of irradiation may provide damage effects as high as more than 10^4 years of exposure at sea level.

A general description of SEE test facilities and methods is given in [5]: neutron field tests, accelerator based facilities using evaporation and spallation neutrons from thick targets, monoenergetic neutrons from thin Li targets, direct proton beams, and slow (epithermal) and thermal neutrons produced copiously at reactors but also at accelerator-based facilities (by adding moderating materials to the production target).

Table 1 List of white-spectrum neutron facilities in Europe, Unites States and Canada.

Facility	**LAB**	**Country**	**Neutron flux E > 10 MeV (cm^2s^{-1})**	**Cut-off energy (MeV)**	**STATUS**
LANSCE *ICE*	LANL	USA	4×10^5	800	Operating
TNF	TRIUMF	Canada	3×10^6	500	Operating
ANITA	TSL	Sweden	$10^1\div10^6$	180	Operating
ISIS *Vesuvio*	RAL	UK	6×10^4	800	Operating
ISIS *Chip-IR*	RAL	UK	$10^6\div10^7$	800	In construction
SNS *RID*	ORNL	USA	$10^7\div10^8$	1000	Proposed
European Spallation Source (ESS)	LUND	Sweden	up to 2×10^8	2500	Proposed

3. The proposed neutron irradiation facilities at the LNL cyclotron

A high-current (500 μA) variable energy (35-70 MeV) proton cyclotron is currently under construction as primary driver for the Selective Production of Exotic Species (SPES) project at the INFN Legnaro labs (LNL) and will be commissioned in 2014 [6].

The proposed neutron facility will be used to study neutron induced Soft Error (SE) effects in the neutron energy range accessible to the accelerator. It should be noted that, although the maximum output energy provided by the SPES cyclotron is limited, more than 60% of fast atmospheric neutrons with E > 1 MeV are in the 1-50 MeV energy range (Fig. 2). However the facility will not be able to study many important neutron induced effects that are known to occur at higher energies (> 200 MeV), such as Single Event Latchup (SEL) and catastrophic Hard Error Effects such as Single Event Burn-outs (SEB) (Fig. 1). The basic mechanisms of these effects are studied at LNL using heavy ion beams at the SIRAD facility [7], although the correlation with neutron-induced SEE is not immediate.

The proposed SEE neutron facility under considerations at LNL will provide three interesting tools:

- an intense white energy spectrum neutron source with a high degree of resemblance with the atmospheric differential spectrum of fast neutrons in the 1-50 MeV energy range and an extension to lower epithermal and thermal energies;
- a quasi mono-energetic neutron source (QMN) with a controllable peak energy. The QMN neutrons will be obtained by using few mm thin Lithium (^{7}Li) or Beryllium (^{9}Be) production targets. Most (~ 90%) of the proton beam will pass through the targets without causing nuclear reactions and must be magnetically deflected towards a heavily shielded beam dump. QMN sources are attractive for SEE testing to the extent that the neutrons at the test point truly have a well-defined and adjustable energy.
- a proton beam line for general purpose irradiations using directly protons of variable energy up to 70 MeV. Protons induce SEE and to a certain extent can be used as a substitute for neutrons.

The facility will be set up in different construction steps. The white spectrum facility and the proton beam line should be operational soon, after the commissioning of the SPES cyclotron.

The following section describes two different white spectrum production targets that are under study. The QMN and direct proton lines are not described in this paper.

4. White-spectrum atmospheric-like neutron production targets

In order to produce a white spectrum, two high power production targets are under study. The production targets have to sustain high power (up to 35 kW) as the maximum design proton current of the SPES cyclotron is 500 μA at the energy of 70 MeV. The acceleration factor at the proposed neutron-induced SEE facility may therefore be easily be made equal to those at existing facilities, for the accessible neutron energy range, by using just a reduced fraction of the maximum available beam current from SPES cyclotron. Both the white-spectrum neutron beams under study are wide and uniform to allow the irradiation of large electronic systems (e.g. entire computers, aircraft navigation systems). The neutron beams propagate from the production targets to the user area through collimators with different apertures.

The first white spectrum production target, shown in Fig.3, is based on the neutron irradiation facility under developed in the framework of the SPES project, for the FARETRA (FAst REactor simulator for TRAnsmution) experiment. It is a high power W-based thick target that will completely stop the 70 MeV protons; moderating materials (Pb and reactor grade graphite) surrounding the targets are used to shape the neutron energy spectrum. The neutron converter (target) is designed to include dedicated shielding to meet the radio-protection requirements at full power. One way to allow such an irradiation facility to be used alternatively with the QMN system, under the same proton beam line, is to conceive it as a movable system .

The FARETRA-like target facility modeling has been performed using W(p,xn) experimental double differential data for neutron production available at 50 MeV protons [8]. The proton transport in such a calculation approach was skipped because nuclear models implemented inside most used transport codes are known to underestimate neutron yields by a factor 2-4 in the 50-80 MeV proton energy range.

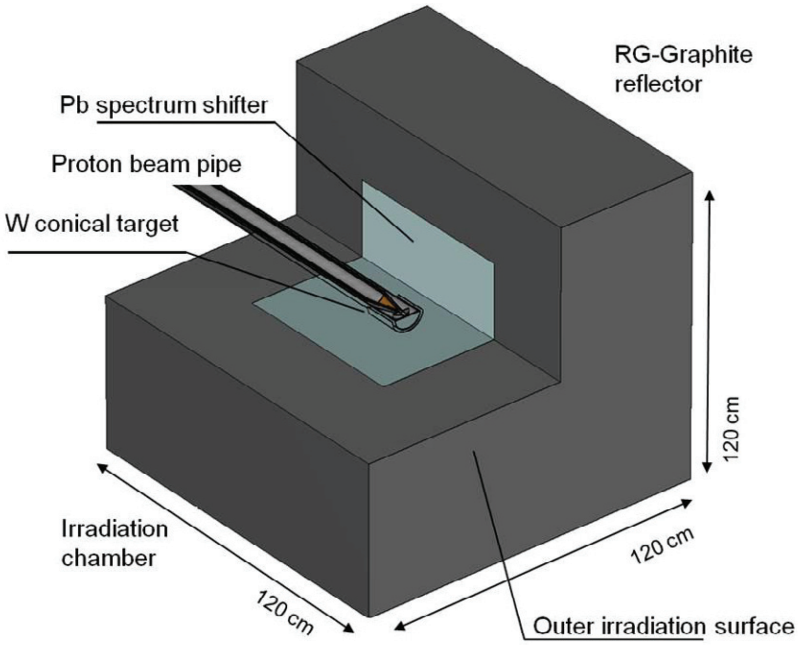

Fig. 3. The FARETRA-like neutron production target at the SPES cyclotron used to obtain an atmospheric-like neutron differential energy spectrum.

Fig. 4 shows the surface-averaged differential energy spectrum of the epithermal-fast neutron components on the front outer surface of the FARETRA-like facility, together with the atmospheric spectrum one (sea-level at the equator). The same simulated data are shown in the lethargy representation in Fig. 5 together with the lethargy spectra of existing white-spectrum facilities and the JEDEC reference atmospheric spectra (data and fit at sea level at New York). Target simulations for 70 MeV protons are underway in order to improve the agreement of the neutron spectrum of the proposed system with the JEDEQ fit, by reducing the oscillations of the simulated data (also present in the atmospheric data).

It is important to note that an acceleration factor of 3×10^8 can be achieved on the front outer irradiation surface of the FARETRA-like neutron facility by using a proton beam current of ~3 μA. Such a beam current level is as low as 1% of the maximum available current from SPES cyclotron. In order to study SE effects with small cross-sections, or for non-standard applications, it will be possible to increase the flux more than tenfold because the target is designed to handle full power.

A novel second white-spectrum production target, based on an entirely different approach, is under preliminary investigation. A rotating composite target presents different materials of different areas to intercept the proton beam (Fig. 6); the effective spectrum is composed by a weighted convolution of neutrons coming from the different target materials. By adjusting the ratio of the areas of the different target materials one can shape the effective neutron energy spectrum to be nearly atmospheric-like at a chosen test point (Fig. 7).

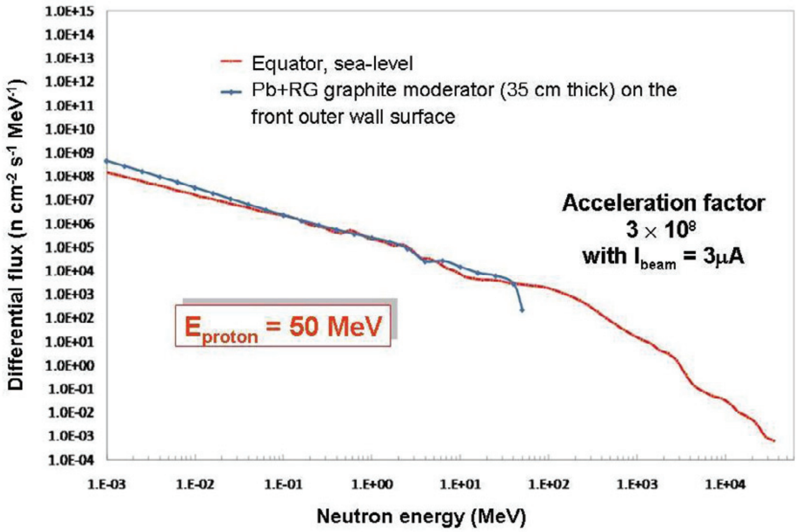

Fig. 4. Simulated (MCNPX) differential energy spectrum of the FARETRA-like production target for a 50 MeV incident proton beam at 3 μA (blue curve). The red curve is the measured differential energy spectrum of atmospheric neutrons at sea level at the equator multiplied by 3×10^8.

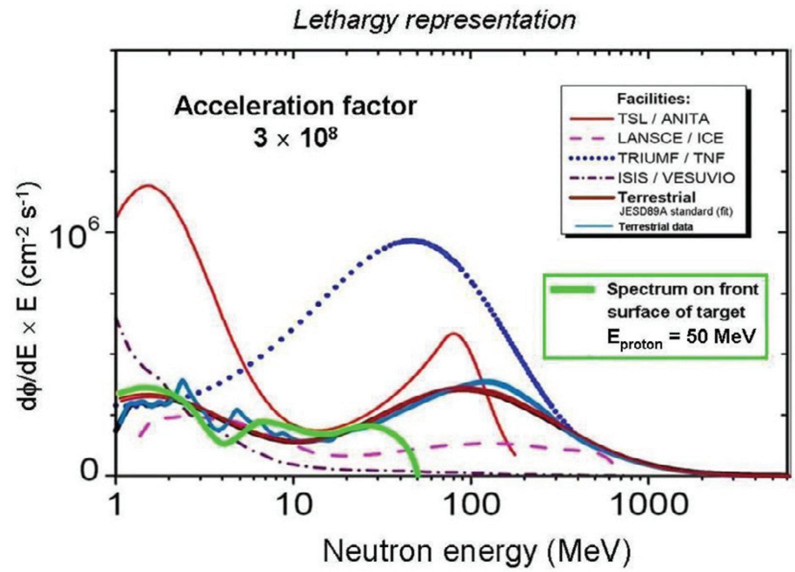

Fig. 5. The lethargy differential neutron flux of 4 existing white-spectrum facilities. The black curve is the JEDEC (JESD89A) reference curve multiplied by 3×10^8. The simulated spectrum of the Be-Pb (23%, 77%) rotating target (red) resembles the atmospheric one in the 1-60 MeV energy range.

The choice of the different materials is driven by the requirement that the composite target provides a suitable energy spectrum and has a high total neutron yield.

The rotating target does not stop the proton beam: the thickness of the component materials is chosen so that most of the beam passes through the target while losing about 70% of the energy. As the proton beam is not stopped, there is no hydrogen build-up inside the target (an issue for target lifetime). The spent beam is then bent by a dipole magnet and directed into to a dedicated beam dump. The composite target is designed to handle the full power of the SPES cyclotron, but in practice the maximum usable proton beam current will be set by the design of the beam dump.

Two materials, a light element and a heavy one, are enough to reproduce in an acceptable way the atmospheric neutron spectrum in the energy range almost up to 70 MeV. Heavy target materials such as Pb, W or Ta reproduce the lower MeV part of the atmospheric neutron energy spectrum and provide a long high energy tail. Light materials such as Be ensure that the high energy part of the spectrum remain nearly flat. The use of Li in combination with a heavy material is problematic, while Al or C have much lower neutron yields.

The proposed rotating composite target, made of Be and Pb, is shown in Fig. 6. For 70 MeV protons, the effective simulated differential energy spectrum at a test point 6 m downstream of the composite target (Pb 77%, Be 23%) is shown in Fig. 7. The JEDEQ standard reference curve is shown for comparison.

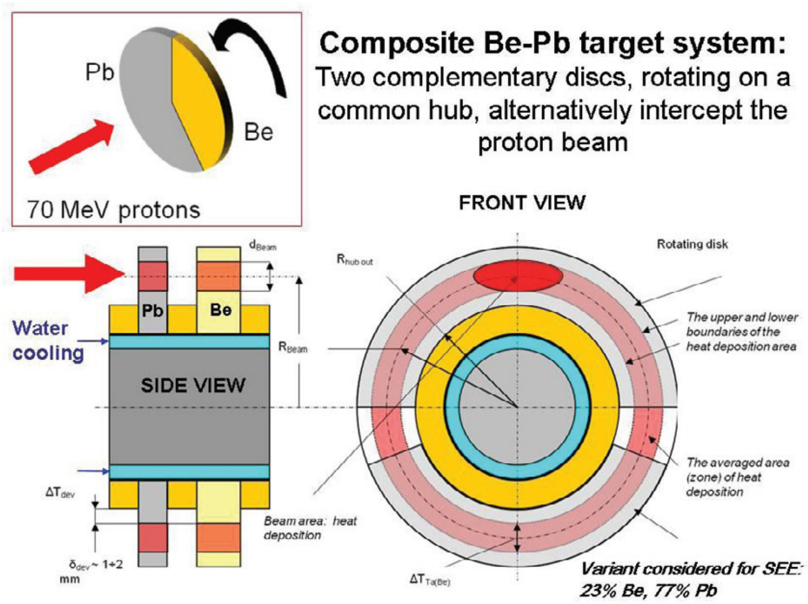

Fig. 6. Scheme of the rotating composite Be-Pb target. The system is water cooled to increase power dissipation.

Fig. 8 shows the lethargy representation of the effective simulated data of Fig. 7, comparing it to the spectra of existing white-spectrum facilities. The energy spectrum of the composite Be-Pb target resembles the JEDEQ reference curve in the 1-60 MeV energy range.

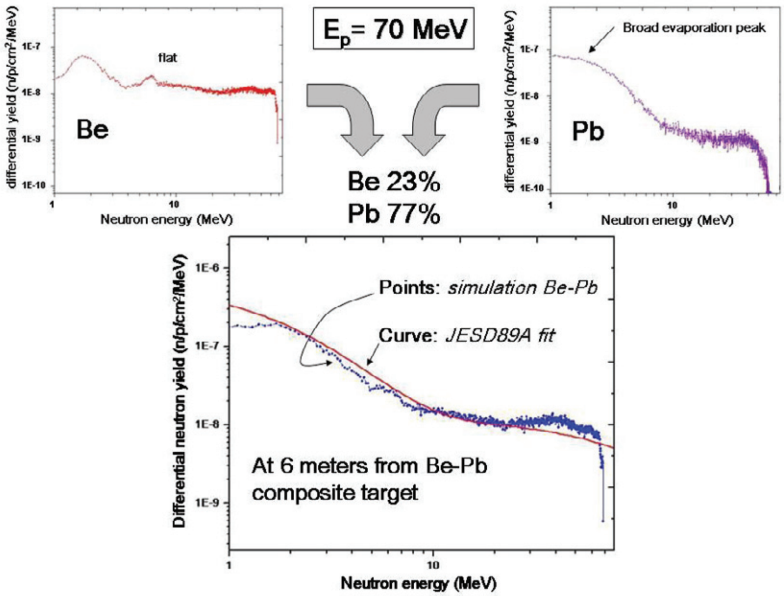

Fig. 7. The simulated (MCNPX) differential neutron yields from Be (upper left) and Pb (upper right), convoluted to form an effective atmospheric-like spectrum from 70 MeV protons (bottom). The JEDEC (JESD89A) standard reference curve is rescaled and shown for comparison. The high quality spectrum of the ISIS chip-IR facility, under construction, is not shown.

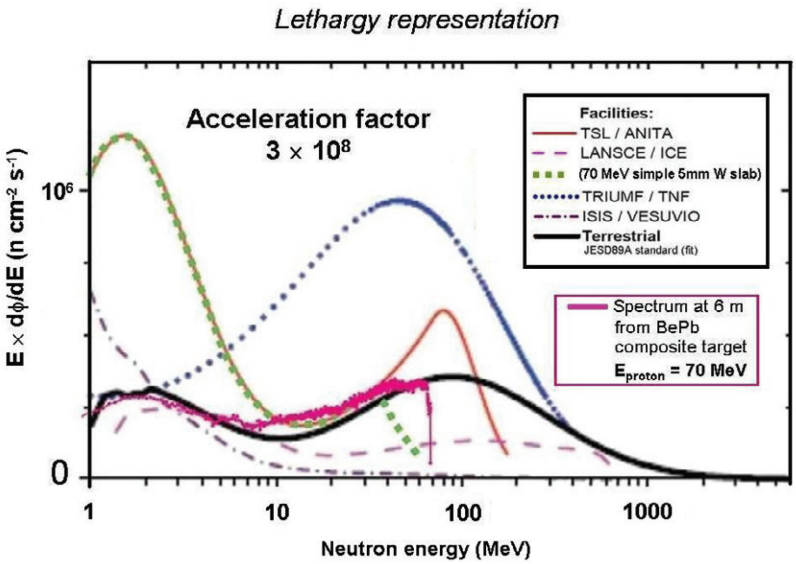

Fig. 8. The lethargy differential neutron flux of 4 existing white-spectrum facilities. The black curve is the JEDEC (JESD89A) reference curve multiplied by 3×10^8. The simulated spectrum of the Be-Pb (23%, 77%) rotating target (red) resembles the atmospheric one in the 1-60 MeV energy range.

Since the atmospheric-like neutron spectra is composed directly by the composite target, the use of moderator is not necessary. In such a configuration, the epithermal and thermal part of the spectrum is switched off. The epithermal and thermal part of the atmospheric neutron spectrum can be reproduced by adding a small amount of moderator.

5. Conclusions

The future installation at LNL of a variable energy, high current proton cyclotron will open up the possibility of high flux neutron facilities to perform various research activities. In particular, the project foresees the construction of a neutron irradiation facility to study neutron-induced SEE, in particular Soft Errors, in the accessible energy range. This facility would integrate the present radiation damage irradiation facilities at LNL which include proton and heavy ion beamlines, also with micrometric capabilities, and X-rays and gamma sources.

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