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The QMN beam line of the neutron-induced Single Event Effects facility at the 70 MeV Cyclotron of LNL-INFN

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Abstract

The SPES project, based on a variable energy high current proton cyclotron (35-70 MeV; 750 μA), soon to be operational at LNL, foresees a neutron irradiation facility for Single Event Effects (SEE) studies on microelectronic components and systems. The proposed facility will comprise both a beam line with continuous energy atmospheric-like neutron production targets, and a Quasi Mono-energetic Neutron (QMN) beam line. A direct proton beam line is also foreseen. Here we describe the general features of the proposed QMN beam line. The quasi mono-energetic neutrons will be produced in various thin Be and Li targets and the spent proton beam will be magnetically deflected towards a beam dump. The layout of the facility with a multi-angle collimator scheme for tail corrections is presented and the proton currents necessary to deliver high neutron fluxes using thin Be targets are estimated.

Keywords: neutron irradiation facility; quasi mono-energetic neutrons; single event effects;

1. Introduction: Quasi Mono-energetic Neutron fields

Quasi Mono-energetic Neutron (QMN) reference fields allow one to study energy dependent neutron interaction mechanisms with matter, be it electronic, detector, dosimeter material, or living tissue. Fast neutrons with energy above tens of MeV are of course present at the accelerator facilities and in spacecrafts, but they are also produced in cosmic-ray showers in the atmosphere and are found at aircraft altitudes and even at sea-level. Here the flux of neutron with energy $E_n > 1$ MeV is low, around 21

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neutrons cm$^{-2}$h$^{-1}$, but huge is the number of commercial electronics that can be affected. Therefore strong is the interest of the micro-electronics industry toward accelerated neutron-induced Single Event Effects tests of electronic devices used in critical environments, avionics, automotive, medical, space applications, etc.. Moreover other research fields can take advantage from energetic QMN facilities, e.g.:

- accelerators for oncology (studies related to: direct neutron treatment of certain types of tumors; exposure to secondary neutrons);
- manufacturers and users of radiation instrumentation and dosimeters important in high-energy neutron work places (energy response and calibration);
- radiation protection (shielding-benchmark experiments);
- high-energy and nuclear physics (cross-section data for basic science, MC code development and nuclear applications such as accelerator-driven subcritical fission reactors, transmutation of radioactive waste, online quality control and contraband detection).

Energetic QMN fields are produced using thin Li and Be targets, according to the reactions $^7\text{Li}(p,xn)^9\text{Be}$ and $^9\text{Be}(p,xn)$. The protons that pass through the thin targets without causing nuclear reactions are magnetically deflected towards a beam dump. The resulting neutron energy spectrum in the forward direction is not purely mono-energetic: it does present an high energy peak close to the energy of the incoming proton, but also a broad distribution at lower energy (tail) coming from nuclear breakup. Each of these two components (peak and tail) contains about half of the total neutron intensity. However the fraction of high-energy neutrons in the mono-energy peak decreases rapidly with angle while the continuous tail of low energy neutron changes much less. This characteristic angular dependence can be used to correct data taken in the forward (0°) direction by subtracting data obtained at larger angles (usually in the 15°-30° range).

At present there are five QMN facilities worldwide. Three facilities are in Japan (TIARA, CYRIC, RCNP), one in South Africa (iThemba Labs), and one, TSL at Uppsala, (Sweden). A sixth facility, NFS, limited to energies below 40 MeV, is under construction at GANIL (France). However TSL, the only European QMN facility capable of operating even at energies above 40 MeV, does not have a multi-angle collimator (the tail correction method cannot be applied) and there is the threat of shutdown in the immediate future. Without the proposed fast QMN facility at LNL to close the gap, it is likely that in about five years from now, QMN beams with energies above 40 MeV will be available only in South Africa and Japan [1].

### 2. Overview of the proposed neutron irradiation facility of Legnaro

A high-current (750 μA) variable energy (35-70 MeV) proton cyclotron is currently under construction at the INFN Legnaro National Laboratory (LNL) to be used as the primary driver for the Selective Production of Exotic Species (SPES) project [2][3]. The basic accelerator complex is expected to be commissioned at the end of 2014 and will open up unique possibilities for neutron-effects studies in Italy.

In particular three tools are under study at LNL [4][5] for neutron irradiation purposes (Fig. 1):

- a quasi mono-energetic neutron source with a controllable peak energy in the 35-70 MeV energy of the cyclotron using an assortment of thin Li and Be production targets (1-4 mm thick). A multi-angle collimator will be used to correct data taken in the forward (0°) direction by subtracting data obtained at larger angles (typically in the 15°-30° range). Well controlled proton beam focusing on the targets will avoid (p,xn) reactions in the more massive nuclei of the target holder. This multidisciplinary line is of particular interest for studying threshold effects and to calibrate simulation codes;
- two continuous (white) energy neutron beam lines. In one line, essentially tailored for Single Event Effects studies, the neutrons are produced in a rotating composite target made of Be and a heavy element such Pb or Ta: the incident proton beam impinges alternatively on the two materials and the
neutron energy spectrum is directly shaped to the seal-level atmospheric one [6][7] without the use of moderators. The proton beam is not stopped by the target materials: the protons that emerge from the target are magnetically deflected towards a beam dump. The second beam line is a multipurpose line based on a thick (proton stopping) W high power target: added moderators can be tailored to produce neutrons with the energy spectrum of interest for the measurements on the floor, in particular to mimic the neutron atmospheric one, down to epithermal and thermal energy range, for irradiation purposes.

The QMN and the SEE composite target lines coincide and share the same bending magnet/beam dump and multi-angle collimator (hall A9). The two target systems will be made to exchange positions.

This fast-neutron facility would integrate the present irradiation tools available at LNL which include a proton and heavy ion beam line (with micrometric capabilities too) at the 15 MV Tandem XTU and ALPI post-accelerator complex, a proton and neutron beam line at the 7 MV CN, and X-ray and gamma sources.

3. A preliminary QMN Be target thickness study

In the energy region above 20 MeV, the $^7$Li(p,n) and $^9$Be(p,n) reactions are used to produce intense quasi mono-energetic neutrons. The width of the mono-energetic peak comes from two contributing factors: the energy loss of the primary proton beam in the target, and the fact that the $^7$Li(p,n) and $^9$Be(p,n) reactions reach both the ground and first excited states. Thin Li targets are normally used at
QMN facilities as the mono-energetic peak is sharper for equal target thickness, even though Be has better physical properties (see Table 1), is stable and more manageable.

Table 1. Relevant physical properties of Lithium and Beryllium.

|                | Melting point (°C) | Thermal conductivity (W m⁻¹ K⁻¹) | Coefficient linear thermal expansion (K⁻¹) | Density (kg m⁻³) |
|----------------|-------------------|----------------------------------|------------------------------------------|------------------|
| Li             | 181               | 85                               | 46×10⁻⁶                                   | 535              |
| Be             | 1287              | 190                              | 11.3×10⁻⁶                                 | 1848             |

The mono-energetic neutron peak from Be can be kept narrow by using thinner targets, but at the price of a lower neutron yield. However this can be re-established by increasing the proton current, an option that we can use at the high current SPES accelerator.

We used MCNPX [8] to study the behavior of the mono-energetic peak of Be as a function of proton energy and target thickness to determine the proton current required to produce a sharply energy peaked neutron flux of \( \Phi_{\text{peak}} = 3\times10^5 \text{ n cm}^{-2} \text{ s}^{-1} \) in the forward direction (0°) at a distance D = 3.5 m, values similar to the target distance and typical flux value at the QMN facility of TSL [9]. We first evaluated four different intra-nuclear cascade and de-excitation models implemented in MCNPX (Bertini-ISABEL; ISABEL-ABLA; INCL4-ABLA; CEM03) [10] to produce neutrons and checked them against experimental data in the forward (0°) direction from 70 MeV protons on a 4 mm Be target [11] (Fig. 2a, Fig. 2b, Fig. 2c and Fig. 2d).

![Fig. 2. Simulated energy distributions (histograms) of neutrons produced in the forward direction (0°) by 70 MeV protons on a 4mm Be target by models Bertini-ISABEL (a), ISABEL-ABLA (b), INCL4-ABLA (c) and CEM03 (d) compared to experimental values (red data points) [11].](image-url)
In the simulations the incident proton beam spot on the target is Gaussian with a FWHM = 2 cm, the energy of the incident proton beam is not spread out and the neutrons exiting the target are freely propagated to the tally surface, a spherical dome with a 3.5 m radius and 3° semi-angle. The protons exiting the target were counted and characterized (energy and direction cosines) but not propagated. We verified these ideal assumptions with dedicated simulations. First, we performed a simulation of 70 MeV protons on 4 mm Be that included a 50 cm thick Portland cement collimator with a conical aperture (3° semi-angle with 8 cm entrance diameter) placed 1.5 m from the target, followed by an additional 1.5 meters. The effects of the collimator and air on the neutron energy spectrum on the tally surface were, for our purposes, found to be negligible. Moreover we verified that the proton energy spread (SPES design values $AE/E < 0.5\%$ at 70 MeV and $AE/E < 0.1\%$ at 35 MeV) is ineffective in the neutron energy distribution, at least for the considered target thicknesses.

The INCL4-ABLA and CEM03 models (Fig. 2c and Fig. 2d respectively) reproduce the correct forward (0°) mono-energetic peak yield, but none of the models describe the forward neutrons outside the mono-energetic peak, especially below around 25 MeV. At 0° the CEM03 model is best, but it does not correctly model the angular dependence of neutron energy spectrum (Fig. 3b, Fig. 3d). Overall the INCL4-ABLA model is the best.

We proceeded to study the forward going neutrons and determined the average energy of the neutrons in the mono-energetic peak, the FWHM and the neutron yield of the peak; i.e. the number of neutrons in the energy peak per steradian per μA. The results are reported in Fig. 4. For both the INCL4-ABLA and CEM03 models, the mean energy of the neutrons in the peak and the peak shape (FWHM) are degraded.
by the target thickness and, for thin targets, the yield of neutrons in the peak scales linearly with the thickness. However CEM03 disagrees with both INCL4-ABLA and common sense expectations in the dependence of the degradation by the proton beam energy.

The proton currents required to achieve an integral flux value of $\Phi_{\text{peak}} = 3 \times 10^5$ n cm$^{-2}$ s$^{-1}$ of narrowly peaked forward neutrons at a comfortable distance $D = 3.5$ m downstream of the target are reported in Table 2. We conclude that, by using 2 mm Be targets, there is ample margin to reach high neutron flux values ($\Phi_{\text{peak}} \sim 10^6$ n cm$^{-2}$ s$^{-1}$) with the SPES cyclotron. Indeed the distance $D$ from the neutron production target to experimental test point will be set by the design of the multi-angle collimator system, deflection magnet and the beam dump system; even higher neutron flux values can be achieved by using a compact design.

The QMN target and the rotating composite target systems must be designed in concert as they share the bending magnet, beam dump and shielding system. In particular the design of the beam dump will
directly set the maximum current that can be used for producing quasi-mono-energetic neutrons. As a first goal, the prototype design should aim to dissipate at least 7 kW (100 μA at 70 MeV), value that allows the rotating composite neutron production target system to achieve the minimal goal of delivering 6 meters downstream a broad beam of continuous energy neutrons with a very competitive acceleration factor of $\sim 6 \times 10^5$; i.e. that many times more intense than the flux of atmospheric neutrons at sea level produced in cosmic ray showers [6].

Once we assess the best modeling configuration for the different types of proposed targets, collimator and beam-dump complex, a more detailed radiation transport simulation involving the radioprotection analyses will be performed in collaboration with the radioprotection physicists of LNL using the FLUKA code [12].

4. 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 fast quasi mono-energetic neutron irradiation facility.

The QMN beam line of the SPES facility will be a very precious general-purpose tool for European research in many fields, from radiation physics to detector and nuclear physics for both basic science and industrial and home-land-security applications.

Quasi-mono-energetic neutron fluxes suitable for SEE studies in the accessible energy range can be achieved at test points along the beam lines using only a fraction of the maximum proton current. In practice the maximum neutron fluxes will be set by the final design of the proton beam dump.

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