IL NUOVO CIMENTO **42 C** (2019) 72
DOI 10.1393/ncc/i2019-19072-3

Colloquia: EuNPC 2018

The Phase 0 of the NEPIR project at LNL

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received 5 February 2019

Summary. — NEPIR (Neutron and Proton Irradiation facility) is the project of a new irradiation facility at INFN Legnaro National Laboratories (LNL). The facility will exploit the LNL 35-70 MeV high current proton cyclotron of the SPES complex, to feed two different compact neutron sources in order to generate high flux neutron beams with different energy spectra: quasi-monoenergetic neutron beams and atmospheric-like neutrons. This contribution focuses on the first stage of the construction of the facility: the NEPIR Phase 0, financed and in an advanced design phase. It will use a Be neutron production target capable of delivering up to $\sim 2\times 10^6\,\mathrm{n\,cm^{-2}\,s^{-1}}$.

1. – Introduction

NEPIR is a new proposed multipurpose neutron irradiation facility [1]. It was originally conceived to study the Single Event Effects (SEE) induced by solar protons and atmospheric neutrons in microelectronic devices and systems. A neutron-induced SEE occurs when a strongly ionizing secondary particle causes a current spike. In digital devices, these spikes can alter data and lead to errors; in analogue devices, the spikes may even lead to device destruction. To study neutron induced SEE effects, the NEPIR facility will deliver both Quasi Mono-energetic Neutron (QMN) beams, and a complementary continuous energy spectrum beam similar to that of fast neutrons ($E_n > 1\,\mathrm{MeV}$), generated by energetic cosmic rays naturally present at sea level (atmospheric neutrons).

Because of limited funds, the completion of the NEPIR facility is a long-term goal. In this work, we will focus only on a simple initial Phase-0 stage, as it is funded. It will be constructed in 2019 and opened to academic and industrial users in 2021. The direct proton irradiation beam line will be completed in the near future with additional funds.

2. – The neutrons of NEPIR

NEPIR will exploit the SPES variable energy (35-70 MeV) proton cyclotron to deliver two different types of fast ($E_n > 1\,\mathrm{MeV}$) neutron beams: Quasi Mono-energetic Neutrons (QMN) [2] and atmospheric-like neutrons with a continuous energy spectrum.

By varying the accelerator energy, thin lithium targets will produce QMN beams with energy peaks in the 35-70 MeV range. By using a carbon energy degrader, the minimum energy may be lowered to 20 MeV. Protons that pass through the thin targets are deflected magnetically towards a beam dump. The neutron energy spectrum in the forward direction (0°) is not purely mono-energetic: besides a high-energy peak close to the energy of the incoming proton, there is also broad distribution at lower energies coming from nuclear breakup. Each of these two components contain about half of the total neutron intensity, however the fraction of high-energy neutrons in the peak decreases rapidly with angle while the energy tail changes much less. Hence, by taking data at larger angles, one can correct the measure of the flux of neutrons in the energy peak. For a current $I = 10\,\mu$ A of 70 MeV protons, the calculated maximum flux of neutrons in the energy peak at the closest test point (3 m) will be $\sim 2.7 \times 10^5\,\mathrm{n\,cm^{-2}\,s^{-1}}$.

Variable energy QMN facilities are of multidisciplinary interest as they allow, in general, the study of energy-dependent effects of neutrons in matter.

The Atmospheric Neutron EMulator (ANEM) [3] production target is a specialized tool. Energetic neutrons produced in cosmic-ray air showers (atmospheric neutrons) are indeed a great and growing concern to the electronics industry. ANEM will produce neutrons with a energy distribution similar to that of atmospheric neutrons at sea level in the 1-65 MeV energy range, that comprises 65% of fast atmospheric neutrons, which can have energies up to GeV values. ANEM will allow flexible studies and tests for unexpected sensitivity to low energy neutrons, very useful before performing measurements at high-energy facilities. For a current of $10\,\mu$A of 70 MeV protons, the calculated integral flux in the 1–65 MeV energy range at the closest test point (4 m), will be $\sim 7 \times 10^6\,\mathrm{n\ cm^{-2}\,s^{-1}}$ which is $\sim 2 \times 10^9$ times higher than the natural one in the same energy range at sea level. Additional moderator panels can be used to further shape the fast neutron spectrum to resemble that of other environments (eg. the surface of Mars).

3. – NEPIR Phase 0

NEPIR has been partially funded within the italian SPARE (Space Radiation Shielding) project. Health risks due to cosmic radiation are a major showstopper for safe colonization. Shielding is the only practical countermeasure, but it is poorly effective against very high energy nuclei from galactic sources, and exposure to secondary neutrons remains even if the charged particles are stopped. New, highly hydrogenated materials are under development for the shielding of spacecraft. Active shielding using high temperature superconductor magnets are a promising alternative and arguably the ultimate solution of the problem, but they also have to be tested. SPARE consists in a test campaign of active and passive materials using high energy protons and QMN neutrons at the complementary accelerator facilities in Trento (TIFPA) and LNL (NEPIR).

However the available funds from SPARE are insufficient to complete the construction of NEPIR. In order to produce neutrons as soon as possible, we are designing a low cost but still useful phase-0 version.

Figure 1 shows the layout of the NEPIR facility during Phase 0. In this stage, no bunker will be built in the experimental hall. Only one neutron production target, a

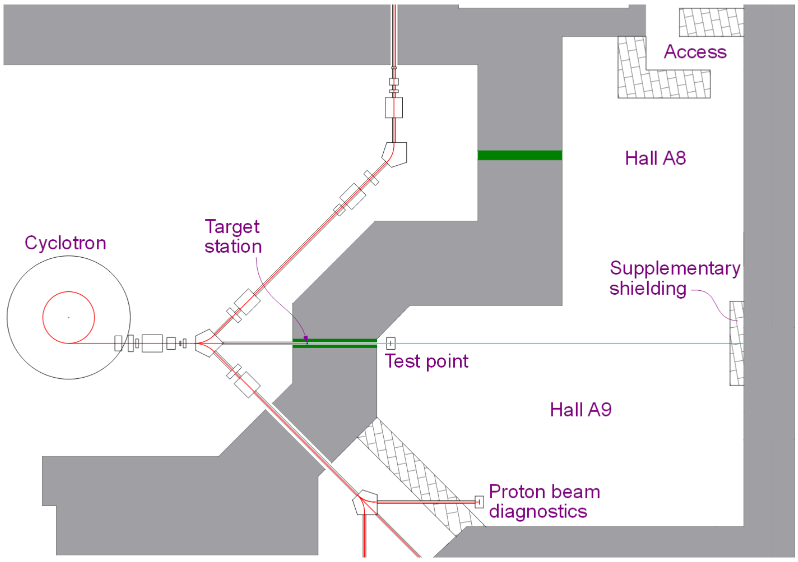

Fig. 1. – Layout of the NEPIR Phase 0 facility: the cyclotron feeds the target, located inside the conduit from the cyclotron hall to Hall A9. The second beamline entering hall A9 will be used for future direct protons irradiations

thick Be target, will be available and it will be placed inside the conduit (diameter 30 cm) through the 3 m thick wall that separates the cyclotron hall from the experimental hall (A9). High density polyethylene pellets will fill the gap between the conduit surface and a 10 cm diameter aluminum beam pipe. This structure acts as a collimator and defines the neutron beam (shown in cyan) towards the test point in A9. Only minimal additional shielding will be provided.

4. – The thick Be target

The phase-0 Be target under study will produce neutrons with a continuous energy spectrum. The 70 MeV proton current will be less than 1 μ A (maximum power of 70 W) to limit radioprotection issues. The chosen material is Be, for the abundant production of high energy neutrons and the high melting point (much higher than the alternative Li). The low power proton beam will be extracted in air through a thin (50 μ m) Ti window and imping on 30 mm thick beam stopping Be target. The first 2 mm will be solid Be plate, followed by Be under the form of pellets or granules, for an additional effective thickness of 28 mm. These will be enclosed in an aluminum canister to prevent the dispersion of the toxic metal eventually pulverized by defoliation and blistering caused by hydrogen accumulation in the material. The solid Be slab will seal the canister. The 20 MeV minimum energy used at the facility guarantees that the impinging protons will pass through the initial Be plate and stop in the pellets; the energy deposition in the initial plate is minimum. A closed circuit fluxing inert gas through the pellets would be used for cooling and for venting any hydrogen. The simulated (MCNPX) neutron energy spectrum in the forward direction (inside a 3° semi-aperture cone) generated by a thick Be target is shown in fig. 2(left), for different energies of the impinging proton beam. It is characterized by a relatively flat energy distribution up to a sharp cutoff value that can

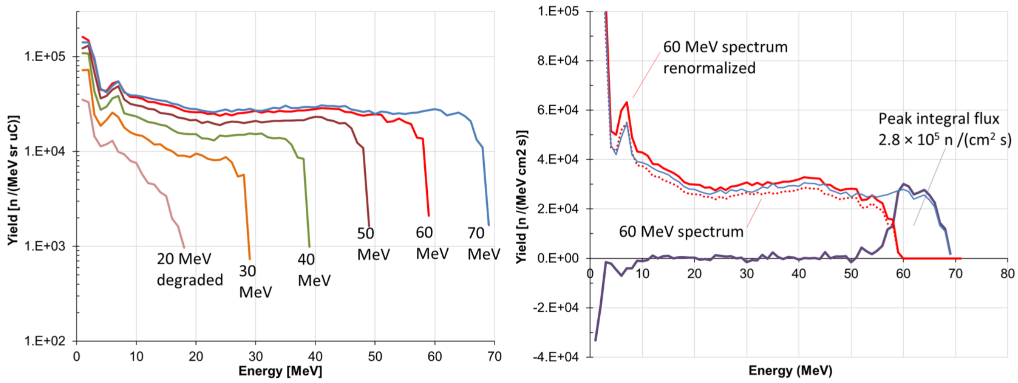

Fig. 2. – (Left) Neutron yield in the forward direction for different energy of the impinging proton beam on a thick Be target. (Right) Lin-lin plot of the effective neutron spectrum obtained by subtraction of neutron spectra generated by 60 MeV (renormalized) and 70 MeV proton beams. The integral yield in the 52-69 energy interval is $\sim 2.8\times10^5$ n cm^{-2} s^{-1}.

be adjusted by changing the energy of the proton beam (the time required for a change is 10–15 minutes). The maximum neutron flux with a 70 MeV, 1 μ A proton beam is $\sim 2 \times 10^6\,\mathrm{n\,cm^{-2}s^{-1}}$ at a test point distance of 3 m.

By exposing a microelectronic device under test (DUT) to two such neutron beams, one can measure the SEE sensitivity to the neutrons in the energy interval defined by the two cutoff values. Figure 2(right) shows the 60 MeV spectrum (solid red) renormalized to match the 70 MeV spectrum (blue) in the 10-50 MeV energy region. The difference (purple) approximates a box-like energy distribution in the 58-68 energy region. By sampling this way different energy intervals with a width of few MeV, one may precisely reconstruct the energy dependence of the cross section of the DUT to neutron-induced SEE. This technique gives the phase-0 facility QMN-like capabilities, making it a very attractive general purpose tool.

5. – Conclusions

The basic design of the NEPIR facility, its beam-optics, the beam dump and the ANEM target is defined. We expect minor adjustments before we can completely fix the QMN system, especially in the design of the collimator. An ANEM prototype exists and will undergo thermal tests by the end of 2018.

To produce neutrons as soon as possible, we are designing a Phase 0 version of the facility with the available limited funds. Construction will begin in 2019. We plan to characterize the NEPIR Phase 0 neutron beam by the end of 2020, and open it up to academic and industrial users by 2021. This new neutron activity at the Legnaro Laboratories will then lead up to the building of the final NEPIR facility.

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