LINUS, the Integrated LNL Neutron Source facility

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Abstract. LINUS is a project at the INFN Legnaro National Laboratories (LNL, Italy) to create a suite of different neutron sources (LSNS, NEPIR, SLOWNE) driven by existing accelerators. LSNS, driven by a 40 mA, 5 MeV proton RFQ, will use Li and Be targets to deliver cold, thermal, epithermal and fast neutrons. The SPES high current (0.75 mA), 70 MeV proton cyclotron will drive the NEPIR and SLOWNE facilities. NEPIR will alternatively deliver quasi mono-energetic neutrons with energy peak down to 20 MeV, and a neutron beam with a continuous energy distribution similar to that of neutrons present in the Earth atmosphere in the accessible energy range. SLOWNE is an intense neutron source for applications outside the LSNS range.

1. LINUS: a multipurpose neutron facility from cold to fast neutrons

Reactors play an essential role in delivering intense neutron beams but many are being retired and will not be replaced. On the other hand, present and future large, high-energy, high-neutron-yield spallation source facilities (ISIS at RAL, ESS…) cannot possibly fulfill the future demands of all the users from Europe and elsewhere. [1]

Lower-energy non-spallation-based Compact Accelerator-driven Neutron Sources (CANS) can bridge the capacity insufficiency and the widening expanse of neutron applications. However, the majority of CANS are not new and many do not allow a broad range of applications under variant configurations. Therefore, the realization of new Accelerator-driven, Brilliant, and Compact (ABC) Neutron Sources is an imminent goal to ensure an expansive neutron R&D landscape.

The Legnaro Integrated NeUtron Source facility (LINUS) wants to be an important contributor to this effort. LINUS consists of three parts: the Legnaro Slow Neutron Source (LSNS) at a high current RFQ 5 MeV accelerator, and a fast (Eν > 1 MeV) Neutron and Proton Irradiation (NEPIR) facility and an intense source of slower neutrons (SLOWNE) at the 70 MeV SPES cyclotron facility.

2. LSNS

LSNS is based upon state-of-the-art accelerator and neutron production technologies already developed at LNL: a high-power, high-current radio-frequency-quadrupole (RFQ) proton accelerator [2] and Li and Be neutron producing targets [3]. The LSNS design will deliver high-brilliance neutron beams over the cold, thermal and epithermal energy ranges for independent utilization to serve diverse users across different fields ranging from basic nuclear science, to experimental nuclear astrophysics, materials research, life science, medical therapy, nuclear instrumentation, cultural heritage and
education of the next generation of neutron scientists and engineers. Significant savings in construction and operation costs are expected due to the low proton energy, compactness and modularity of the accelerator and target systems.

2.1. Proton beam Pulse Selection and Distribution Station (PSDS)
The LSNS is conceived as modular in structure, see Fig. 1a, and a schematic of the layout is shown in Fig. 1b. A Pulse and Selection Distribution Station (PSDS) will deliver an intense low energy (≤ 5 MeV) proton beam from the RFQ to the various parts of LSNS. Continuous Wave (CW), Short Pulse (SP) and Long Pulse (LP) modes will be all available. The LSNS suite shown schematically in Fig. 1b includes a cryogenic Cold Neutron Target Station (CNTS) and a Thermal Neutron Target Station (TNTS). The TNTS system is identical in design to CNTS, but it will operate at ambient temperature. The PSDS system also delivers beams to the LENOS [4] (astrophysics) and BNCT [5] (oncology) targets stations.

![Figure 1a. LSNS beam characteristics for different applications](image)

![Figure 1b. A sketch of the LSNS multiplexed structure.](image)

All the neutron experiments at the CNTS, TNTS and the LENOS systems are conducted in the time-of-flight (TOF) mode. However, each system entails different time structures for the various epithermal, thermal and cold neutron applications. The PSDS makes the best use of the RFQ proton beam for concurrent service to neutron production at all the facilities with high efficiency.

A chopper upstream of the RFQ will condition the proton beam to be pulsed at 125 kHz with a pulse width (FWHM) of ~200 ns. These short pulses are shortened further to 1-2 ns by a series of choppers and bunchers: a clock starts the accumulation of the short pulses to achieve a pulse width of ~10 μs in conjunction with the defocusing of the proton beam to a cross-section of 10 cm × 10 cm. This proton pulse is then delivered to TNTS and the process is then repeated every 20 ms to enable a short pulse (SP) neutron source running at 50 Hz. After each SP a second clock starts at to accumulate a defocussed long pulse (LP) of ~500 μs width to feed the CNTS. This process repeats every 40 ms for a LP cold neutron source running at 25 Hz.

2.2. The Cold and Thermal Neutron Target Stations
The core of the CNTS consists of a Be target and a cryogenic moderator to contain solid methane at ~10 K, and a reflector (typically graphite or water as employed by other neutron sources). It is set on a concrete base and surrounded by shielding materials (alternating shells of lead and borated polyethylene) with overall typical dimensions: 4 m (diameter of the pile) by 3 m (height). The configuration of the TNTS is the same as that of CNTS except that the moderator contains water at ambient temperature. The identical design of the TNTS and CNTS results in substantial saving in shielding fabrication and instrumentation design costs. Up to 6 neutron exit ports with individually operated beam gates are installed at TNTS. Three beam lines are planned at the initial stage.
2.3. Instruments System

Behind the target station is a biological shield wall through which neutron guides deliver the neutron pulses with minimal intensity loss along incident flight paths that define the neutron beamlines. Each beamline serves a neutron instrument. The beamlines and instruments to be installed in the initial phase of LSNS are four cold-neutron instruments at CNTS: a Small-Angle Neutron Scattering, a General-Purpose Neutron Reflectometer, a Cold-Neutron Imaging & Radiology, and a Cold-Neutron Instrumentation Development beamline, and three thermal-neutron instruments at TNTS: a High-Intensity Powder Diffractometer, a Multiple-Purpose Materials Interrogation, and Neutron Device and Detector Development in the TNTS hall.

3. NEPIR and SLOWNE at the SPES cyclotron

The fast Neutron and Proton Irradiation (NEPIR) and the SLOWNE facilities will be driven by the SPES accelerator, a proton cyclotron able to produce proton beams in the 35-70 MeV energy range with currents up to 700 µA [6]. Both will be housed in the Hall 9 of the SPES building.

3.1. NEPIR

The original purpose of NEPIR is to study radiation damage effects in electronics induced by fast neutrons present at flight-altitudes and sea level and by solar protons. It will deliver two complementary neutron beams: Quasi Mono-energetic Neutron (QMN) beams in the 30-65 MeV energy range and a neutron beam (ANEM) with a continuous energy distribution, up to 65 MeV, similar to that of neutrons found in the Earth atmosphere (an extension to emulate the Mars atmosphere is foreseen). A direct variable energy proton beam line, not described here, will be also available.

The QMN and ANEM targets will share the same proton beam line. The ANEM target is installed upstream of the QMN target: an aperture on the ANEM target will allow alternate operation with the QMN source and direct proton beam. The energy range of both QMN and direct protons will be extended down to 20 MeV by proton-energy degraders.

QMN reference fields allow one to study energy dependent neutron interaction mechanisms with matter [7]. Many diverse research fields can take advantage of this facility: nuclear physics, both pure and applied, neutron detector development and calibration, shielding experiments, neutron effects on electronics and biological matter, etc.

QMN will be produced by using thin (1-4 mm) Li or Be targets, the emerging protons being magnetically deflected towards a beam dump. In the forward direction (0°), the neutron energy spectrum presents a peak close to the energy of the impinging proton beam and a broad low energy tail coming from nuclear breakup [8], each of which contains about half of the total neutron intensity. The calculated flux of neutrons in the energy peak is ~5×10^5 n cm^{-2} s^{-1}, for a 10 µA 70 MeV proton current on a 4 mm Li target, at 3 m from the target. The unwanted effects due to the low energy tail can be assessed by taking data concurrently at larger angles (15°-30°), where the high energy peak is absent [9] and subsequently corrected in data treatment. To this end, a static multi-angle collimator system, as at iTHEMBA and CYRIC [10][11], will be initially used.

The QMN at LNL [12] will be an important part of the landscape of European neutron facilities. The recently closed TSL [13] was capable of operating in the 22-175 MeV energy range and did not allow the correction for data collected at forward direction. NFS, under construction at GANIL, is limited to energies below 40 MeV [14].

The Atmospheric Neutron Emulator (ANEM) system will produce an atmospheric-like neutron spectrum by using a weighted convolution of neutrons coming from different target materials. This is achieved by using a rotating composite target (a 5 mm thick W disk and a 24 mm thick Be sector). Rotation allows to distribute the deposited energy over a large area of target elements (Fig. 2a). The target is housed in a cylindrical vacuum chamber connected to the beam pipe; heat transfer is ensured by a water cooling system. The proton beam is not stopped by the Be sector (to avoid excessive damage) and the protons that emerge from it are stopped by a W disk [12]. With 10 µA of 70 MeV
protons, a neutron flux of $3.5 \times 10^6 \text{ n cm}^{-2} \text{ s}^{-1}$ is delivered at a downstream distance of 6 m. That allows accelerated test (acceleration factor $F = 10^9$) of the effects of atmospheric neutrons on electronic devices and systems and on biological matter.

**Figure 2a.** The ANEM rotating target.

**Figure 2b.** The self-shielding neutron source developed for the FARETRA project.

### 3.2. SLOWNE

SLOWNE is an independent high flux neutron line for those special applications that require neutron energies outside the energy range of LSNS, such as transmutation studies and radiation damage in electronics. It is based on a high-power conical water cooled 5 mm thick W target housed inside a neutron reflector and energy spectrum shifter with related elements for radiation shielding (Fig. 2b). With a 500 µA current of 70 MeV protons the source flux of neutrons is $5.6 \times 10^{14} \text{ n/s}$.

The target was originally developed for FARETRA, a Fast Reactor Emulator for TRAnsmutation studies, the purpose of which is to obtain new data about neutron induced reactions on actinides, fission fragments and structural materials. Application to BNCT is also under study [5].

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