A Linac based neutron source for measurements with the TOF method

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Abstract

High power, low energy electron Linear Accelerators are widely used to produce high neutron fluxes via bremsstrahlung and (γ, **n**) reactions. Such neutron sources, although of much lower intensity than nuclear reactors and spallation sources, still find interesting applications in high precision nuclear cross section measurements and others.

In particular the project of a new electron Linac in the Rome Research Area with high intensity and high quality beams, or the upgrade of the existing Linac at Frascati Laboratories of the Natl. Institute for Nuclear Physics (INFN), will open the possibility of delivering, as a byproduct, neutron beams with special features, pointing at the complementarity of such kind of neutron facilities with spallation sources.

A short description of the various options and of the main aspects of the research programme is given, including preliminary results from the optimization study through extensive simulations of the target-moderator-beam dump system.

KEYWORDS: Photoneutron, Linac, Time-of-flight, Nuclear Data

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1. Introduction

Nowadays, the accelerator-based neutron sources are deemed to be definitely superior to the more traditional reactors, and radioisotopic neutron emitters. Although the hadron (protons, deuterons) driven spallation mechanism produces higher yields, due to the strong coupling, the neutron sources which are driven by electron Linacs still deserve much attention, due to their better beam quality and economy aspects.

Indeed, the e- Linac – based neutron facilities are even superior to others in a wide energy range, especially if one is interested mainly in measuring energy dependent cross-sections with high resolution by the time-of-flight (TOF) technique.This is because the real figure of merit for many experiments is not just the maximum attainable flux, but the flux at a given energy resolution, which is strongly dependent on the arrival time spread of the primary beam and on the neutron pathlengthening inside the radiating target.

Hereafter the advantages of an electron beam impinging on a heavy metal target appear quite evident: much shorter bunchlength, much smaller source size, hence possibility of reduced pathlength for TOF measurement, what helps keeping the flux at an acceptable level without spoiling the energy resolution. Last but not least, the possibility of running the neutron source as an end product of electron acceleration seems very appealing, if the beam is devoted to some non beam-destructing application such as the Free Electron Laser (FEL). The efficient use of a non-dedicated facility is again an advantage of electron beams, as compared to hadron beams.

A common problem of all high power accelerators is to cope with the generated heat in the target, what leads in most cases to a complicated mechanical design (like a rotating target) or to the use of a liquid metal as active medium. This is particularly true when the neutron yield, which is basically a function of the beam power only, is produced mainly by acting on the beam current rather than on the energy. So in case of high energy electron beams, the requirements on the power dissipation are less stringent, since the energy loss is more gradual and it is distributed on a wider volume, and as a consequence, the use of solid materials is quite possible.

The contribution of neutron physics to the evolutionary process of understanding the basic laws of nature has been enormous, ranging from astrophysics and cosmology (understanding of element formation and phase transitions in the history of our universe) to fundamental forces (strong, electroweak and gravitation). Neutron beta decay measurements provided us with various data to fix the number of particle families at three. There's still a long list of fundamental physics questions that may be answered by neutron experiments in a near future.

Precise measurements of neutron cross sections are of great importance for the safety design of nuclear reactors and for the evaluation of the neutron flux density and energy spectrum around a reactor. The same holds true for fusion reactors, where the interactions of neutron and photon fields from D- T fusion with the surrounding medium (first wall, blanket and vacuum vessel) are still poorly known, so that fusion neutronics experiments using a 'white' spectrum below the 14 Mev-peak are strongly welcome as well as investigations of the elementary nuclear and atomic processes.

2. The accelerator scenario

The neutron source is conceived as an end product of an electron beam, whose main purpose may be the injection of an existing storage ring, but also others, like the realization of a X-FEL Facility in the Rome Research Area. In the last few years the possibility of building X-ray FEL sources, which are based on the SASE (Self Amplified Spontaneous

Emission) principle, became a reality so as to raise a world-wide interest in the synchrotron light scientific community, as well as in the particle accelerator one. In this prospect the Italian Government launched in 2001 a long-term initiative (named SPARX) devoted to the realization in Italy of a large-scale ultra-brilliant and coherent X-ray source.

The allocation of considerable resources in the Italian National Research Plan (PNR) brought about the formation of a CNR–ENEA–INFN–University of Roma "Tor Vergata" study group. A conceptual design has been developed and two possible schemes for the linac structure (normal - and superconducting) at an electron energy $E = 2.5$ GeV, sufficient for a X-ray λ as short as 1.5 nm, have been investigated, leading to the SPARX proposal [1]. In this framework a R&D program (SPARC) [2] mainly aiming at the realization of a high brightness electron photoinjector at 150 MeV with a FEL experiment in the visible-VUV region, is presently carried on at INFN Labs in Frascati. In the next step (SPARX-I) a magnetic compressor followed by a Linac up to the energy of 1 GeV will be added, but the facility will be moved to a different site, much likely near the "Tor-Vergata University", if sufficient funding is given.

The final step (SPARX-II) [3], subjected to further allocation of funds by Italian Government, aims at pushing the Linac energy up to the original design value of 2.5 GeV.

We just remark that the superconducting option, by allowing a much higher average power, would clearly open more possibilities of experimental research, not strictly confined to the SPARX programme.

A 'day one' option is also the installation of the neutron source on the INFN Linac. The Linac is presently devoted to the injection of the double annular 510 MeV electron-positron Storage Ring DAΦNE, which is the main part of the INFN accelerator complex at Frascati, and is also feeding a Test Beam Facility (BTF), where first tests can be performed. However, this one cannot be a definitive location for the neutron source, owing to the tight limits imposed on the electron beam intensity by safety regulations, which presently set at only 10^{10} electrons/sec.

A more interesting possibility is the installation directly in the tunnel of the DAΦNE Linac, whose maximum average power is ~ 1 kW, while its typical value for injection is ~ 60 W. Incidentally, we may note that the Linac, when running in the positron operation mode with converting target extracted, is able to deliver more than 2 A per pulse at the energy of 510 MeV on its final end, even with some energy spread induced by the increased beam loading [4].

Owing to these power limits from the accelerator, the neutron flightpath anyhow should be as short as just 1 m, in order to get a total flux of the order of 10^5 n/s/cm^2 . On such a short base the separation of fast neutrons from the prompt γ-ray flash as generated by bremsstrahlung puts a constraint on the maximum measurable energy. We shall address this problem later on in a further study.

A comparison of the various options for this neutron source with other linac-based facilities, both long-standing, like GELINA[5] and ORELA [6], and recently started, like ELBE [6] and POHANG [7], is shown in Table 1.

Table 1: Old and new neutron facilities vs. various options for a neutron source at INFN

INSTITUTE Facility	IRMM Gelina	ORNL Orela	FZR Elbe	POHANG Linac	INFN-ENEA Sparx NC	INFN-ENEA Sparx SC	INFN Linac
energy(MeV)	100	180	30÷40	100	2500	2500	510
beam power (kW)	7	8	5	~0.2	8	144	0.5
pulse charge(nC)			1.8		1	1.6	20
rep. rate (Hz)	800	1000	$5 \cdot 10^5$	12	100	5	50
pulse length (ns)	1	2	0.01	1800	0.01	0.01	10
flightpath (m)	10	9	4	12	1	1	1
Source strength (n/s)	$3.4 \bullet 10^{13}$	10^{14}	$2.7 \bullet 10^{13}$	$4 \bullet 10^{11}$	$1.7 \bullet 10^{13}$	$3 \bullet 10^{14}$	$1.0 \bullet 10^{12}$
Flux/lethargy (#/s/cm^2) at 1 eV	$4 \bullet 10^4$	10^4	$4 \bullet 10^5$	$0.5 \bullet 10^3$	$\sim 10^6$	$>10^7$	10^5

3. General structure of the neutron radiator

3.1 Target choice and thermal behaviour

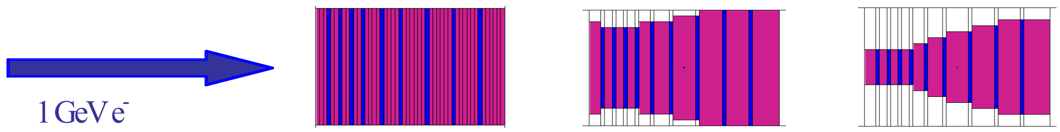
Unlike most neutron facilities, where the problem of target heating and stability against thermal stresses is perhaps the most serious, sometimes leading to a very complicated design, in our case the maximum beam power wouldn't overcome a few kW, allowing a simpler solid state target. A design consisting of Tantalum plates of various thickness, arranged in a cylinder of 2.5 cm radius and 15 X_0 total length (6.15 cm), was adopted. The target active material was chosen according to its good neutron yield, not significantly inferior to other neighbouring metals, like W or Pb, and for its much better mechanical and thermal properties. Actinides, like Thorium or Uranium, would certainly increase the neutron yield by a factor 2-3, due to the neutron contribution from photofission process, which is nearly equal to the one from direct photonuclear reactions, but this enhancement does not appear worth the complicated construction and handling of a target made of fissionable materials.

The chosen geometry ensures the full containment of the shower energy. The target radius is expected to influence considerably the spectrum width, which affects the TOF resolution. Previous simulations [9] have shown indeed that for a 10 X_0 Ta target the neutron flux between the case with radius 5 cm and the one with radius 2.5 cm differs by 2% only. The reference electron energy for all simulations was chosen to be 1 GeV according to the SPARX-I programme.

The optimization procedure was mainly addressing the problem of target heating and shielding. The number of plates and their thicknesses were chosen to have a more uniform heat deposition on the surfaces, thereby allowing a more efficient cooling, if needed. Three target models were considered for MCNPX simulations, aiming at reducing the physical size of the neutron source, without affecting too much its strength. The criteria used was to reduce the radius of some plates in order to keep 99% and 90% of deposited energy, hence an adequate shower containment for target #1 and #2, respectively. Source strength per incident electron and neutron current at 1 m distance are displayed in table 2 in case of no external cooling and mercury cooling through a 1.5 mm gap.

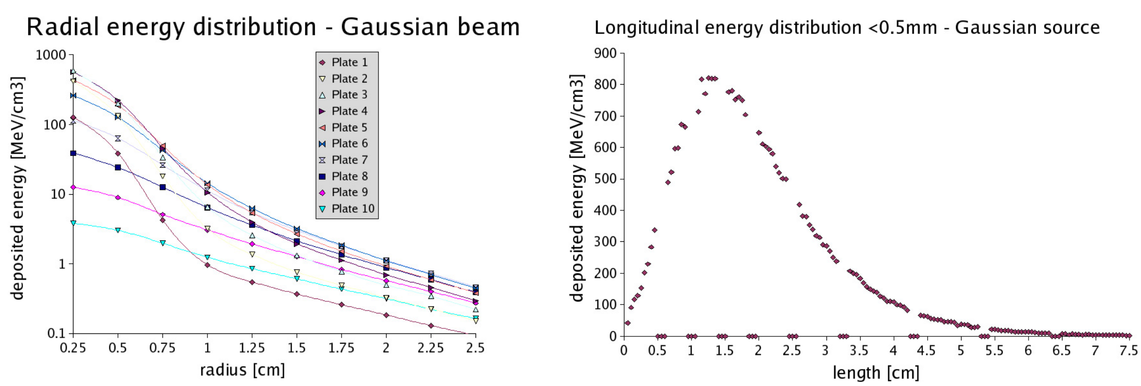
Table 2: Comparison of three target models

	Target # 0	Target # 1	Target # 2
n/e⁻ air gap	0.320	0.319	0.308
$n/cm^2/e^-$ air gap	2.497e-6	2.583e-6	2.464e-6
n/e⁻ Hg gap	0.319	0.317	0.307
$n/cm^2/e^-$ Hg gap	2.768e-6	2.808e-6	2.698e-6



No significant change is observed, although the time spread of neutron flux was not calculated, so the target #0 was chosen for further simulations because of its simplicity. The radial and longitudinal energy deposition in this target are displayed in fig. 1 for a gaussian source with $\sigma_{xy} \approx 2$ mm. The max. density stays well below 1 kW/cm^3 at 1 kW power in the beam, what can be considered a safe value. Target cooling by water should be avoided, because the neutron spectrum is strongly affected. At this power level radiation cooling seems sufficient indeed, since a conservative estimate of heat loss through the

Figure 1: Radial and longitudinal (on-axis) density of deposited energy in the cylindrical target at 1 GeV and 1 μA beam currrent



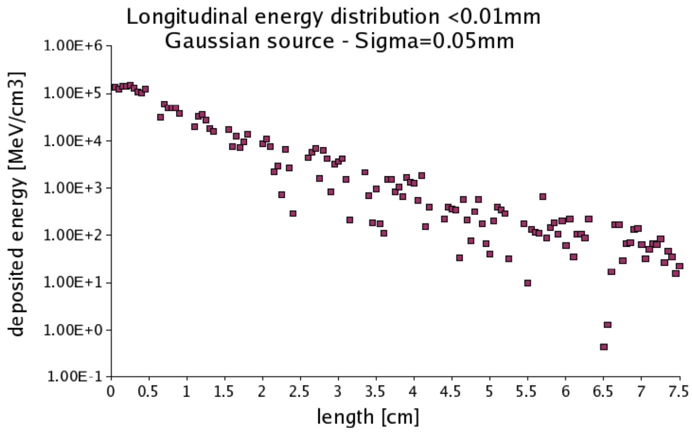
target surface (assumed as a single Ta cylinder), at the maximum allowed T = 2500 °K and emissivity ε = 0.1 gives an irradiated power of ~ 3 kW. In case of much higher beam power mercury cooling will be provided, which doesn't moderate the neutron spectrum significantly.

Target's thermal and mechanical behaviour under the very high peak current beam (Q_b = 1 nC, $4\sigma_t$ = 10 ps) and small spot (σ_{xy} = 0.05 mm) from the SPARX source has still to be investigated with appropriate analysis codes, in order to evaluate both steady state and transient effects. A crude estimate of the pulse temperature rise for target # 0 gives

$$\Delta T_p = \frac{Q_b \delta E}{4.18 \bullet \delta \bullet C_{sp}} = 50\ ^{o}C$$

only where δE ~ 100 GeV/cm^3 is the max. energy deposition density (as from Fig. 2), δ = 16.6 [g/cm^3] is Ta density and Csp=0.03 [cal/g/°C] the specific heat.

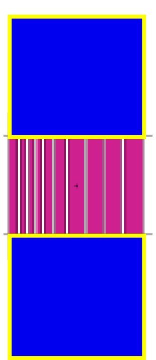
Figure 2: The on-axis energy deposition density for the SPARX Linac



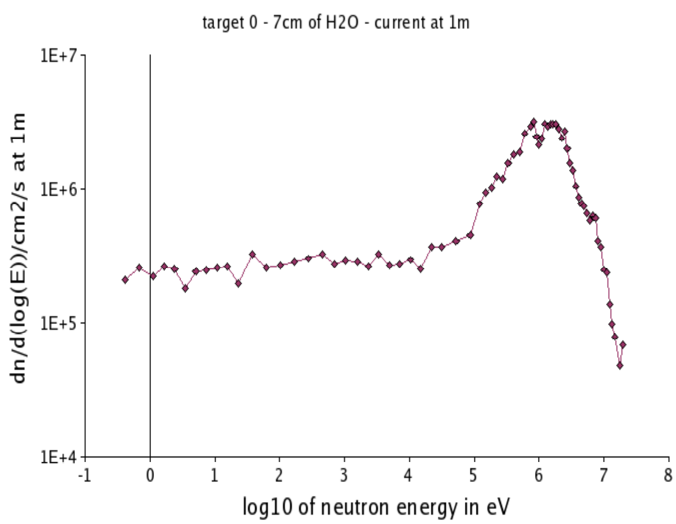
3.2 Moderator studies

Since a neutron beamline only is foreseen, the moderator is represented by a thin annular layer of liquid, concentric with the target, as in fig. 3 in order to get the maximum slow neutron intensity. The neutron current per electron at 1 m distance from target centre was computed with MCNPX for thermal and epithermal neutrons (e < 1 keV), showing a maximum at a thickness of 7 cm for light water (annexed Table) , while the maximum current obtained with heavy water is $2.7 \cdot 10^{9}$ n/cm^2/e$^-$.

Figure 3: The moderator optimization: the target + moderator sketch, the neutron current vs. moderator thickness (cm) and the spectrum at the optimum thickness



	H_2O layer
1	4,2371E-9
2	3,3560E-8
3	7,6540E-8
4	1,2138E-7
5	1,4029E-7
6	1,4619E-7
7	1,5527E-7
8	1,3209E-7
9	1,1730E-7
10	9,7698E-8

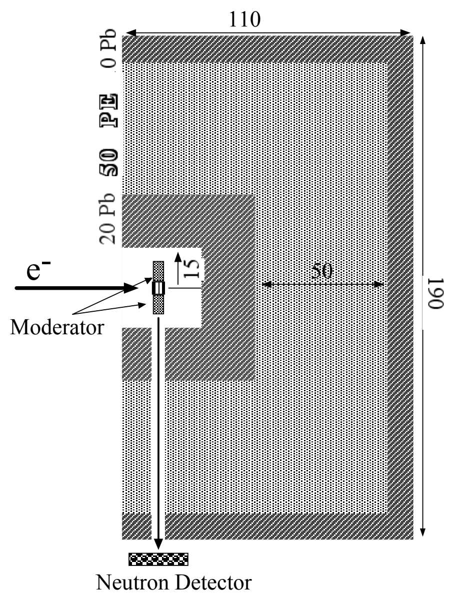


The resulting neutron spectrum is also shown in fig. 3 for 1 μA beam current. The presence of fast neutrons is unavoidable since the beam port views the target directly through the moderator, but it can be reduced by means of time-of-flight.

3.3 Target shielding and beam dump

The integration of the neutron radiator inside the beam dump seems quite natural, owing to the required characteristics (fig. 4). The main problem here is the huge γ-flash coming from bremsstrahlung on the Ta target, what makes the use of heavy metal shielding mandatory. Then a sufficient thickness of light hydrogenated material is used to moderate the big number of neutrons.

Figure 4: The basic structure of the radiator shielding system and beam dump



Several possibilities were investigated by means of the MCNPX code and the dose profiles on the outer surface of the dump were calculated. The simulated structure has a quadratic, rather than cylindrical symmetry, for ease of construction. No high temperature materials, like graphite, were considered, owing to the modest level of deposited power. A summary of simulated configurations is shown in Table 3.

Table 3: Side and rear dose profiles [Sv/e⁻] for neutrons and photons at 100 cm from the target for several shielding materials (PE= Polyethylene)

Materials	Side n [Sv/e⁻]	Side γ [Sv/e⁻]	Total [Sv/e⁻]	Rear n [Sv/e⁻]	Rear γ [Sv/e⁻]	Total [Sv/e⁻]
PE 55 cm thick, no Pb	1,19E-18	9,04E-17	9,16E-17	4,66E-18	4,02E-16	4,07E-16
Al 55 cm thick, no Pb	2,25E-17	2,56E-18	2,51E-17	2,93E-17	1,80E-17	4,73E-17
PE 55 cm thick + 30 cm Pb	2,02E-18	6,13E-22	2,02E-18	1,03E-17	2,61E-21	1,03E-17
55 PE + 0.2Cd + 15 Pb	2,99E-18	8,57E-20	3,07E-18	1,81E-17	5,24E-19	1,86E-17
55 PE+10borax+15Pb	2,38E-18	5,49E-20	2,43E-18	1,60E-17	3,67E-19	1,64E-17
Pb 20 cm + PE 50 + Pb 10	5,36E-20	2,59E-21	5,62E-20	5,59E-20	2,93E-21	5,88E-20

The use of a single light material, like Aluminium, was adopted elsewhere [7], but doesn't seem enough to reduce both neutron and photon doses adequately. A layer of heavy metal like Pb has to be added externally to the neutron moderator (PE) anyway, and to reduce the number of photoneutrons which are generated inside it, also an inner layer of Pb is necessary. So the adopted solution is the one in the last row of Table 3 and depicted in fig. 4 , but further simulations are necessary to evaluate the effect on the neutron pulse from scattering inside the Pb walls. The situation doesn't improve by the use of neutron absorbers like Cadmium and Borax.

4. Conclusion

A general presentation of the main features of a neutron time-of-flight facility in the Rome Research Area is given, together with the basic aspects of the neutron radiator. After completion of the physical/engineering design within end 2006, if adequate funding is provided, the programme will go on with

- the construction of a prototype and its characterization on the BTF of the DAΦNE injector Linac at Frascati
- the realization of a neutron beamline and the implementation of a neutron detector for test measurements with the time-of-flight method
- the feasibility study of the installation of a neutron source on the future Linac to be built or upgraded from the existing one in Frascati and devoted to the X-FEL Facility.

Acknowledgements

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