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**CONCEPTUAL DESIGN OF AN INTENSE NEUTRON SOURCE FOR  
TIME-OF-FLIGHT MEASUREMENTS**

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**Abstract**

Among the accelerator-based neutron sources, the ones which are driven by electron Linacs still appear quite attractive, notably in the case of cross section measurements with the time-of-flight method. This is due to their better beam quality and economy aspects, which make them complementary, rather than inferior to the hadron (protons, deuterons) driven spallation facilities.

A conceptual design study of a powerful neutron source has been developed, aiming at the implementation on a future normal- or super-conducting Linac to be built in the Rome Research Area, but keeping enough flexibility for being installed on any high energy linac. We report in this paper on the first simulation results, mainly about the general design of the target-moderator assembly and the radiation shielding.

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## 1. GENERAL DESCRIPTION OF THE SOURCE

As already suggested by some authors [1,2] the realization of an  $e^-$  Linac – based neutron facility still appears a viable option for high resolution measurements of energy dependent cross-sections with 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 basically dependent on the arrival time spread of the primary beam and on the artificial pathlengthening of neutron within the radiating target.

Hereafter the advantages of using an electron beam appear quite evident, as compared with a primary hadron (proton, deuteron) beam: much shorter bunchlength, much smaller source size, hence possibility of reduced pathlength for TOF measurement, what allows to keep the flux at an acceptable level with good energy resolution. Last but not least, the possibility of running the neutron source as a post-product of electron acceleration seems very appealing, if the Linac is devoted to some beam-non-destroying application such as the Free Electron Laser (FEL). The efficient use of a non-dedicated facility for secondary beam production is again an advantage over hadrons, not to mention the reduced cost of an electron machine.

Therefore the neutron source is conceived as an end product of an electron beam, whose main purpose is the realization of a X-ray FEL Facility in the Rome Research Area, but in such a way that it might be tested and implemented also on the injector Linac of the double annular 500 MeV electron-positron Storage Ring DAΦNE at Frascati Natl. Labs (LNF) of INFN.

The X-FEL initiative (named SPARX) is a joint project carried on by scientists and engineers of the major Italian research institutes and strongly supported by the Italy national and Latium regional governments. Its various articulations are described in the literature extensively [3,4].

For our purpose here we just remark that the superconducting option for the final Linac (energy = 2.5 GeV), by allowing a much higher average power [5], would clearly open more possibilities of experimental research, not strictly confined to the SPARX programme.

While the path to the final goal of the SPARX project is still very long, a ‘day one’ option might also be the installation of the neutron source on the LNF Linac. The Linac is presently devoted to the injection of DAΦNE, what is the main part of the 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  $\sim 1$  kW, while its typical value for injection is  $\sim 60$  W. Incidentally, we may note that the Linac, when running in the positron operation mode with converting target extracted where the gun current can be pushed up to 7 A, 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. 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<sup>2</sup>. On such a short base the separation of fast neutrons from the

prompt  $\gamma$ -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.

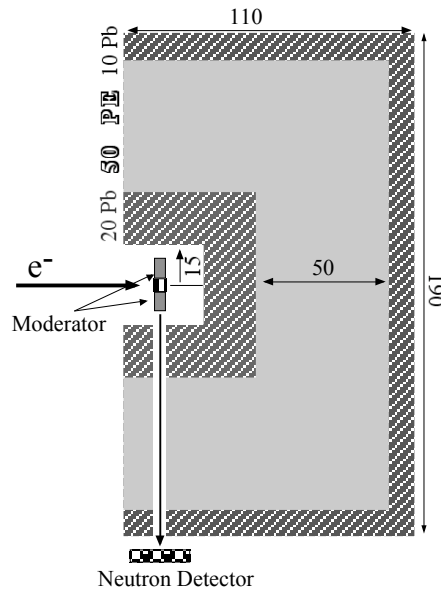
A comparison of the various options for this neutron source with other linac-based facilities, both long-standing, like GELINA[6] and ORELA [1], and recently started, like ELBE [7] and POHANG [8], is reported in Table 1.

**Table 1:** Old and new 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	LNF 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÷10	2÷24	0.002÷0.01	1800	0.01	0.01	10
flightpath (m)	10	9	4	12	1	1	1
Source strength (n/s)	$3.4 \cdot 10^{13}$	$10^{14}$	$2.7 \cdot 10^{13}$	$4 \cdot 10^{11}$	$1.7 \cdot 10^{13}$	$3 \cdot 10^{14}$	$1.0 \cdot 10^{12}$
Flux/lethargy (#/s/cm <sup>2</sup> ) at 1 eV	$4 \cdot 10^4$	$10^4$	$4 \cdot 10^5$	$0.5 \cdot 10^3$	$\sim 10^6$	$>10^7$	$10^5$

## 2. THE NEUTRON RADIATOR

The integration of the neutron radiator inside the beam dump seems quite natural, owing to the required characteristics (fig. 1). The main problem here is the huge  $\gamma$ -flash coming from bremsstrahlung on the target, what makes the use of heavy metal shielding almost mandatory. Then an adequate thickness of light hydrogenated material is necessary to moderate the big number of neutrons.



**Figure 1:** The basic structure of the radiator shielding system and beam dump

The main items of the optimization work up to now are the target geometry and thermal behaviour, the moderator materials and the general design of target shielding and beam dump.

### 2.1 Target choice and thermal behaviour

The high level of power deposition does not allow, in most of high power accelerators, a simple mechanical design or the use of solid metal for the neutron-producing target. This is particularly true when mainly acting on the beam current rather than on the beam energy produces the neutron yield, which is basically a function of the beam power only. 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 is distributed on a longer volume, while the target radius, which has little influence on the neutron intensity, but rather on the spectrum profile, i.e. on the resolution, can be kept small.

It is worth noting that in case of spallation sources the target size has to be much larger, owing to the bigger size of the hadronic cascades compared with the electromagnetic ones. According to the well known parametrization of e.m. and hadronic showers [9], the radius and length of cylinder target have to be  $R=2.5$  cm,  $L=6.15$  cm and  $R=11$  cm,  $L=35$  cm, for the 1 GeV  $e^-$  and 1 GeV p, respectively, to ensure a full containment of cascade energy. So, since the energy resolution is strongly affected by the target radius, electron-driven sources are somewhat superior to spallation sources, at least from this special point-of-view.

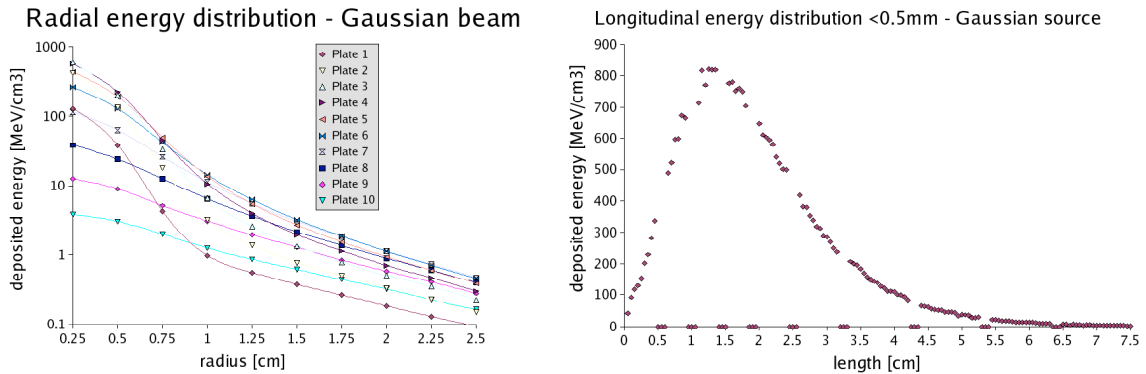
Unlike most high-power facilities, the problem of target heating and stability against thermal stresses is not critical, since the maximum beam power will not overcome 1 kW. Previous simulations [10] have shown indeed that for a  $10 X_0$  Ta target the neutron flux between a model with radius 5 cm and radius 2.5 cm differs by 2% only (where  $X_0$  is the radiation length). The main concern on target radius comes from the neutron pulse width, which affects the TOF resolution. This is given by the convolution of the uncertainty  $\delta L$  on the effective flightpath length  $L$  of the neutron and the uncertainty  $\delta t$  on the time interval between generation in the target and detection at the experimental station of the neutron of energy  $E_n$ , as expressed by the well-known formula:

$$\frac{\delta E_n}{E_n} = \frac{2}{L} \sqrt{\delta L^2 + 1.9 E_n \delta t^2}$$

At low energy the  $\delta L$  term is clearly dominant. Assuming  $\delta L \sim R=2.5$  cm a relative energy resolution of 5% is obtained at  $E_n=1$  keV and  $\delta t=1$  ns. A proper target shaping should allow a further reduction of  $\delta L$ , thereby approaching a resolution of the order of 1%. More detailed calculations about the target optimum profile and optimization of resolution will be reported in a sequel paper.

For the other items here reported, a Tantalum target was adopted, made by plates of various thicknesses, 1.5 mm apart to each other to allow for cooling and arranged in a cylinder of 2.5 cm radius and  $15 X_0$  length (6.15 cm) (fig. 3a). The radial and longitudinal energy deposition in this target is displayed in fig. 2 for a Gaussian source with spatial distribution  $\sigma_{x,y} \approx 2$  mm. The max. density stays well below 1 kW/cm<sup>3</sup> 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 target surface (assumed as a single Ta cylinder), at the maximum allowed  $T = 2500$  K and emissivity  $\epsilon = 0.1$  gives an irradiated

power of  $\sim 3$  kW. In case of much higher beam power mercury cooling will be provided, what does not moderate the neutron spectrum significantly.

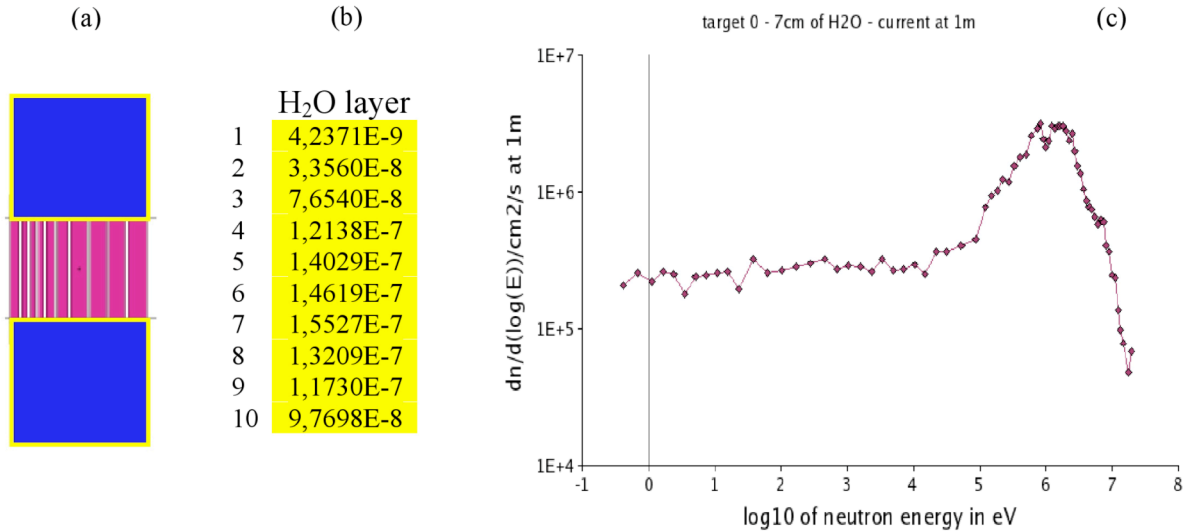


**Figure 2:** Radial and longitudinal (on-axis) density of deposited energy in the target at 1 GeV.

## 2.2 Moderator

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 the target centre was computed with MCNP5 [11] for thermal neutrons ( $E < 0.4$  eV), 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<sup>2</sup>/e<sup>-</sup>.

The resulting neutron spectrum is also shown in fig. 3 for 1  $\mu$ A 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.



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

## 2.3 Target shielding and beam dump

Several possibilities were investigated by means of the MCNP5 code and the dose profiles were calculated on the surface at 1 m distance from the target centre. 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 2.

**Table 2:** Side and rear dose profiles [Sv/e<sup>-</sup>] for neutrons and photons at 1 m from beam axis for several shielding materials (PE= Polyethylene).

Materials	Side n [Sv/e <sup>-</sup> ]	Side $\gamma$ [Sv/e <sup>-</sup> ]	Total [Sv/e <sup>-</sup> ]	Rear n [Sv/e <sup>-</sup> ]	Rear $\gamma$ [Sv/e <sup>-</sup> ]	Total [Sv/e <sup>-</sup> ]
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 + 30 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
20 Pb + 40 PE	8,08E-20	7,04E-19	7,85E-19	1,23E-19	8,31E-19	9,54E-19
20 Pb + 50 PE	4,31E-20	4,50E-19	4,93E-19	4,76E-20	5,22E-19	5,70E-19
Pb 20 + PE 50 + Pb 10	5.36E-20	2.59E-21	5.62E-20	5.59E-20	2.93E-21	5.88E-20

The first stage of the computations consisted in selection of the optimal thickness of the neutron shield. Aluminum, which had been adopted elsewhere [7], and Polyethylene were investigated. Thickness of both materials varied from 20 cm to 75 cm, with a 5 cm increment. Polyethylene is a better neutron moderator but aluminum reduces  $\gamma$ 's more efficiently. Nevertheless, because the gamma dose can be easily reduced by means of lead, it was decided to use Polyethylene as the neutron shield and the optimal thickness of this material appeared to be 55 cm.

In the second step an external layer of lead was added. The range 10 cm up to 30 cm with an increment of 5 cm was examined. A 55 cm layer of Polyethylene followed by 30 cm of lead turned out to be the best configuration. The total dose in the foregoing arrangement originates actually from neutrons only. Hence, it is crucial to reduce the neutron component. Some attempts were carried out to get rid of thermal neutrons by means of cadmium or borax placed between Polyethylene and lead, however they failed. The next idea was to introduce the internal layer of lead since still some photons and electrons leave the target and may produce photoneutrons in the neutron shield.

The final series of the simulations consisted of three steps. First, a fixed layer of Polyethylene (40 cm was arbitrary selected) followed the internal lead shield of a varying thickness (5 cm to 25 cm with a 5 cm increment). The optimal size of the internal lead appeared to be 20 cm. Then the 20 cm layer of lead was followed by the neutron shield of the varying thickness (20 cm to 55 cm with a 5 cm increment). These calculations suggested using 50 cm of Polyethylene. Finally, the layers of 20 cm of lead and of 50 cm of Polyethylene were followed by the external layer of lead (5 cm, 10 cm and 15 cm were examined).

The optimal thicknesses of the beam dump appears to be 20 cm for the internal layer of lead, 50 cm of Polyethylene and 10 cm of external lead. The total dose is about two orders of magnitude lesser than in the configuration with 55 cm of Polyethylene followed by 30 cm of external lead. Although the photon dose rises significantly the decrease of the neutron dose recompenses this effect with surplus.

### 3. CONCLUSIONS

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 design of the neutron radiator. The possibility of a flux of  $10^5$  n/cm<sup>2</sup>/s at almost 1% energy resolution for neutron energies below 1 keV seems within reach.

A detailed study of the resolution function of such system is in progress, together with the optimization of the neutron collimator and detector.

After completion of the physical/engineering design within end 2006, if adequate funding is provided, the programme will go ahead with

- the construction of a prototype and its characterization on the BTF at the LNF Linac
- 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 at the LNF Linac

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