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**A HIGH RESOLUTION SPALLATION DRIVEN FACILITY AT
THE CERN-PS TO MEASURE NEUTRON CROSS SECTIONS IN
THE INTERVAL FROM 1 eV TO 250 MeV: A *RELATIVE*
*PERFORMANCE ASSESSMENT***

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Abstract

In the proposed facility with 24 GeV PS beam on a Lead target, the number of produced neutrons exceeds 760 per proton. In comparison, with a LINAC (GELINA) one currently obtains only ≈ 0.05 neutrons per electron of ≈ 100 MeV. An additional factor of 2.5 for the CERN facility is due to the strong, forward peaking of the neutron flux, arising from the high proton energy and corresponding longitudinal boost. This huge factor in neutron yield per incident particle, namely $2.5 \times 760 / 0.05 = 3.8 \times 10^4$, is only partially off-set by the higher, time averaged current of the LINAC e.g. 100 μA vs. 2 μA of the CERN-PS. Therefore the useful, initial neutron rate at the CERN facility is about three orders of magnitude larger than in the most performing electron LINAC's, GELINA in Belgium and ORELLA in the US.

The time duration of the PS pulse is presently $\Delta t|_{r.m.s.} = 13.5$ ns and we believe it could be reduced to $\Delta t|_{r.m.s.} = 6.75$ ns. The electron LINAC has much shorter pulses $\Delta t|_{r.m.s.} \leq 1$ ns, to which however the resolution of the counters has to be added. But for neutron energy ≤ 1 MeV, $\Delta t|_{r.m.s.}$ is not affecting the actual TOF energy resolution, dominated by the fluctuations of moderation.

Since these time fluctuations are largely independent of the chosen mechanism to produce the initial neutrons, the initial flux difference between the two methods, e.g. electrons vs. protons, reflects directly in the counting rate — for a given TOF resolution — at the measuring station.

Furthermore the CERN PS ($< 1/2.4 \text{ sec}^{-1}$) has a much smaller repetition rate than the LINAC ($1/800 \text{ sec}^{-1}$) and it presents no problems of time overlaps at the measuring station due to successive bunches. The accidental background due to radio-active targets is also much better suppressed.

Finally the γ -prompt "flash" is considerably smaller for a proton machine than in the case of an electron LINAC and no γ -filters are required.

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1.— THE CERN-PS SOURCE.

1.1. *PS performance and proton pulse duration.* The PS accelerates 4 high intensity bunches which are ejected in succession during the flat top at a time distance which is chosen to be of the order of 50 ms in order to avoid time overlapping at the measuring station of neutrons coming from different bunches. In principle such number of bunches could be increased beyond four, with a corresponding reduction in the duration of the pulse, but this requires new hardware in the kicker system. As we shall see, such additional time compression is not needed, at least at the moment. Therefore the number of bunches is always $n_b = 4$. The number of accelerated protons per cycle is $N_p = 2 \div 3 \times 10^{13}$, evenly distributed over the four bunches. The time allowance for a dedicated cycle in the PS is 2.4 s.

The pulse duration of each of the four bunches $\Delta t|_{r.m.s}$ is determined by the longitudinal emittance of the beam and the performance of the RF. Too short pulses, even if produced inside the ring, cannot be extracted if their momentum spread exceeds the momentum acceptance of the extraction channel, $\Delta p/p = \pm 3.3 \times 10^{-3}$. The normal longitudinal dimension of the RF bunch at the 24 GeV flat-top and *without any specific RF gymnastics* are $\Delta t|_{r.m.s} = 13.5$ ns, corresponding to a $\Delta p/p = \pm 1.6 \times 10^{-3}$. Additional RF gymnastics namely a “phase jump and back” technique is foreseen, which should shorten the bunch by a factor of two, with a corresponding increase of momentum spread up to the acceptance of the channel. With this addition, the expected time spread of each of the four bunches should be $\Delta t|_{r.m.s} = 6.75$ ns. In the rest of the paper we shall conservatively assume that $\Delta t|_{r.m.s} = 10$ ns. This parameter does not contribute appreciably to the energy resolution — at least for neutron energies smaller than 1 MeV in the worst case — since moderation path fluctuations, $\Delta\lambda$ dominate in the error of TOF energy¹ for any path length (see Figure 2). This also means that the relatively comfortable time resolution of several ns may be generally allowed for the detectors without loss of precision in the TOF. The energy of the proton beam, which has to be dissipated in the target is 115 kJoule², corresponding to 48 kWatt and an average current of 2 μ A for the ideal cycle rate of 2.4 s³. For more details on the power dissipation in the target we refer to the main paper [1]

¹ The contribution of a given incoming beam uncertainty Δt in terms of effective $\Delta\lambda$ is $\Delta\lambda|_{beam} = c\beta\Delta t = 30\beta\Delta t(ns)$ [cm] = 1.34 cm for $\Delta t|_{r.m.s} = 10$ ns and 10^4 eV neutrons.

² During the effective pulse duration of 20 ns the peak power is 5.7 TWatt corresponding to a current of 240 A !

³ Note that in general the PS is shared amongst different programmes and therefore the average dissipated power is correspondingly less.

1.2. Optimisation criteria for the neutron producing target. In paper [1] we have chosen Lead as the material for the target. The reasons for this choice are low activation and high spallation yield. An Uranium target would give about a factor 2 higher neutron yield, but at the price of a higher activation and considerable complications because of safety requirements. Although this factor could be recovered with a future construction of a properly engineered Uranium target, at this point we are prepared to accept the loss in flux as a trade-off for a better safety, easiness of operation and much lower cost.

The specific geometry of the spallation target and the subsequent neutron moderation are application dependent, as a compromise between neutron flux in the energy domain under study and uncertainties in the moderation path fluctuations, $\Delta\lambda$. For instance in our main paper [1] the described geometry of the Lead target has been optimised in order to provide a neutron spectrum as close as possible to the one of the Energy Amplifier (EA), i.e. peaked at about 450 keV with a mean energy of about 500 keV, for which a vast measuring campaign is anticipated. In these conditions, the neutron flux at 200 m is as large as 7×10^6 neutron/ cm²/pulse, but with $\Delta\lambda \approx 35$ cm, i.e. relatively large, but sufficient to resolve the majority of resonances in the relevant cross sections at the prescribed measuring distance and with adequate counting rates ($10^3 - 10^5$ ev/pulse/gram of target, depending on the element, see Appendix of [1]).

It should be pointed out that in the evaluation of the neutronic characteristics of the EA with a Montecarlo method, the utilisation of measured cross sections do not require resolving all resonances. An "effective" cross section can be directly derived from the experimental data, provided that the energy steps of the measurement are much smaller than the "lethargic" energy loss in the moderator. As shown in Figures 18 and 20 of the main paper [1], such a spectrum ensures for instance a uniform "illumination" of the major fission cross sections for transuranic elements, relevant to the projected transmutation programme.

In the case of Actinides and long-lived Fission Products, resonances are concentrated in the relatively low energy domain between 0.1 and 10^4 eV. Therefore a substantial improvement of the energy resolution of TOF may be welcome, which in turn means a much smaller value of $\Delta\lambda$, since, as we have already pointed out, the beam time uncertainties are masked by the fluctuations in $\Delta\lambda$.

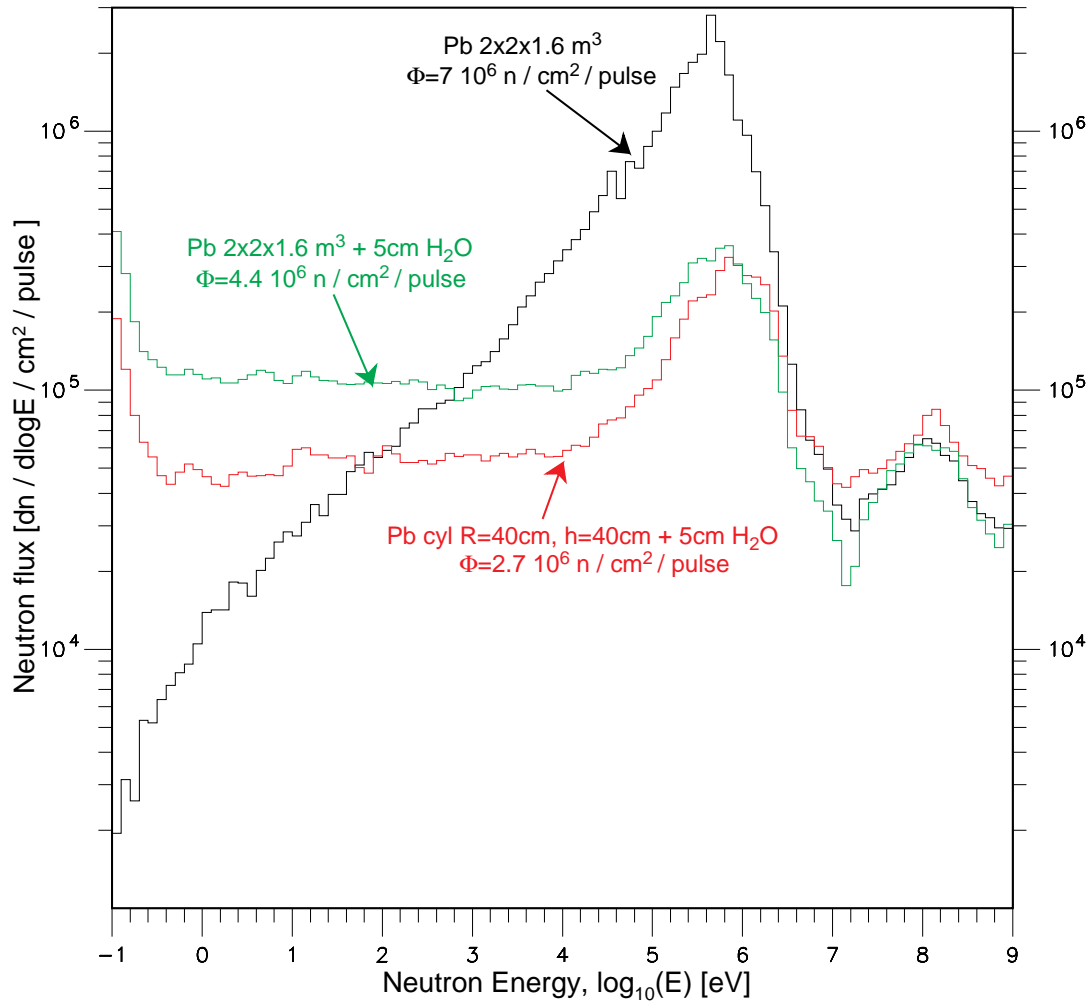


Figure 1 : Neutron energy spectrum for various Lead target configuration, with and without a 5 cm water moderator. The TOF path is 200 m.

A much smaller $\Delta\lambda$ can be indeed obtained, but at the price of a lower average energy spectrum, as suitable for the measurements at lower energies. To such an effect, the spallation target is to be followed by a thin (5 cm) Hydrogen (water) moderation. The physical idea is that if at the exit of the Lead (spallation) target, the neutron speed v is abruptly reduced by a large factor, for instance with a hydrogen rich moderator slab, also the value of $\Delta\lambda = v\Delta t$ will be correspondingly reduced. Note that the time fluctuations Δt of the moderation process are essentially unchanged because of the small thickness of the hydrogen layer. *There is evidently a trade-off between energy resolution and kinetic energy of the TOF neutrons.* For instance, if the speed v is reduced by a factor 20 (energy of a factor 400), the value of $\Delta\lambda$ will be reduced by a corresponding factor, from 35 cm to about 1.75 cm.

This method is well applicable in our case, since the initial neutron energies are generally high, in view of the high incident proton beam energy

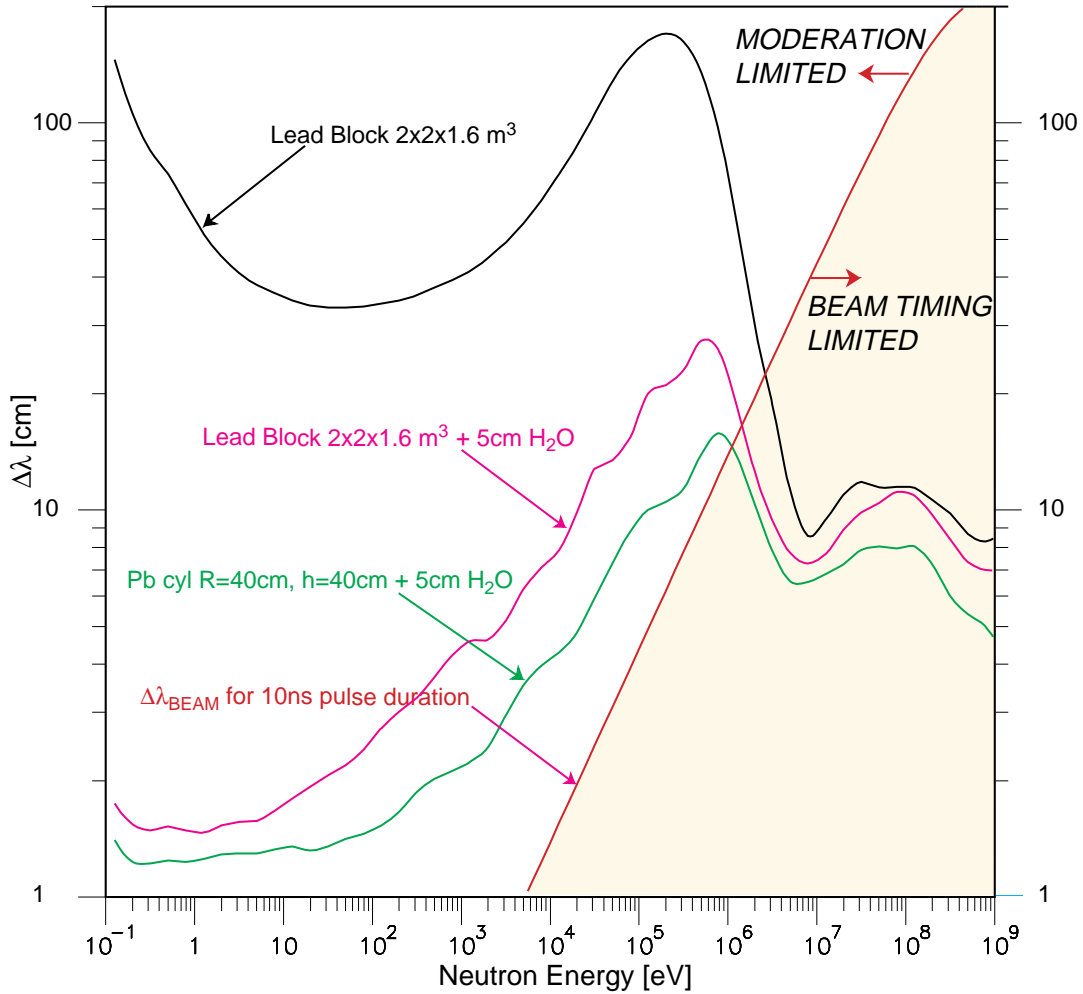


Figure 2 : The uncertainty in the path $\Delta\lambda$ as a function of neutron energy for various target configurations. The reflected $\Delta\lambda$ uncertainty due to the CERN-PS pulse duration is also shown.

and of the generally large longitudinal boost in the collision processes. *This method will be particularly useful whenever cross sections between 0.1 and 10^4 eV have to be studied in detail.*

An overall optimisation of the layout made of a Lead spallation target of length h , diameter R followed by a water moderator of thickness W has been performed for the neutron emission angle of 10° from the proton beam direction, as set by the configuration of Ref. [1]. As result of a general trade-off between neutron flux and $\Delta\lambda$ resolution, we have chosen the parameters $h = 40$ cm, $R = 40$ cm and $W = 5$ cm. The resulting spectrum is given in Figure 1. We also show for comparison the energy spectrum obtained with the Lead configuration of Ref. [1] (unchanged), with and without a water layer of 5 cm. One can see that the general drop of the integrated flux — from 7×10^6 n/cm²/pulse without hydrogen post-moderation to 2.7×10^6 n/

cm²/pulse for the optimal parameters — is accompanied with a substantial increase in the flux at lower energies and an almost exact iso-lethargic behaviour.

1.3. Fluxes vs. resolution. The resulting uncertainty in $\Delta\lambda$ is shown in Figure 2, for the same exemplar configurations of Figure 1. It is evident that values of $\Delta\lambda \leq 1.5$ cm can be attained for neutron energies $\leq 10^3$ eV, with an improvement of over a factor 20 in the ultimate resolution. This extra factor can be used, for instance, (1) either to improve the resolution of the measurement or (2) to increase the flux at a constant resolution, by nearing the counting station by about a factor 20 in distance. This would increase the flux by the fantastic factor of 400, bringing it to $2.7 \times 10^6 \times 400 = 1.1 \times 10^9$ n/cm²/pulse or about 10^{12} n/pulse over a target surface of 1000 cm², as foreseen in Ref. [1]. It is doubtful that the detector station might operate in such an incredible flux !

The very high instantaneous flux is also of considerable interest in the study of radio-active targets. Reducing the TOF length implies reducing the corresponding time window in which counting is performed and therefore it means reducing the accidental background. In addition for a given number of events/pulse, the target mass can be reduced correspondingly. Therefore the signal/background is reduced by the factor $1/400 \times 1/20 = 1/8000$, which is considerable.

Let us consider for instance the case of ²⁴³Cm ($t_{1/2} = 28$ y) which has an activity of 51.6 Ci/g = 1.9×10^9 Bq/mg. The fission rate is (Ref. [1] appendix 2) is of the order of 10^2 ev/mg/pulse. The time window corresponding to 10 eV at 250 m is 6.5 ms (correspondingly less for shorter distances). In this time window, the spontaneous α -decays are 1.2×10^7 /mg, out of which one has to identify the fission signal. Hence the detector must provide a rejection of the order of 10^5 against natural background. Making use of the improvement in $\Delta\lambda$ and the corresponding factor 1/8000, the initial signal to background ratio is reduced to 1/12.5 which can be trivially separated out.

2.— COMPARISON WITH EXISTING TOF FACILITIES

2.1. *Event rates.* Large electron currents can be accelerated by modern LINAC's to energies of several hundred MeV. These electrons give rise to intense Bremsstrahlung with photon energies exceeding the binding energy of neutrons of target nuclei. Therefore copious neutrons are produced by (γ,n) processes. Their yield is even larger for Uranium target, since, in addition, also photo-fission may contribute to neutron production. The neutron (evaporation) spectrum of an Uranium target bombarded with energetic electrons has an average neutron energy of about 2 MeV. An electron LINAC can generate very short pulses, typically of a duration of a few nanoseconds. This neutron source is therefore generally used for TOF measurements ever since the 1950s.

The Uranium target of a LINAC is normally surrounded by a moderator (plastic, water etc.), where the emitted neutrons are slowed down to lower energies, as required by most measurements. The TOF length, limited from neutron surviving flux, rarely exceeds 200 m. As in our case, the main TOF energy uncertainty is essentially determined by the fluctuations in the slowing-down time (thermalization) of the neutrons, rather than the initial time definition of the electron beam. The slowing-down process being largely independent of the nature of the source (e.g. electrons vs. protons) the ultimate TOF resolution is primarily determined by the practical TOF distance, in turn determined by the initial neutron source intensity.

When comparing initial neutron intensities, for the proposed facility with 24 GeV PS beam interacting on a Lead target, the number of produced neutrons exceeds 760 per each proton. In comparison, for a LINAC one currently obtains only ≈ 0.05 neutrons per accelerated electron. Actual Montecarlo simulations give an additional factor of 2.5 for the CERN facility due to the strong, forward peaking of the neutron flux, arising from the high proton energy and corresponding longitudinal boost. This huge factor in neutron yield per incident particle, namely $2.5 \times 760 / 0.05 = 3.8 \times 10^4$, is only partially off-set by the higher, time averaged current of the LINAC e.g. 100 μA vs. 2 μA of the CERN-PS. Therefore the useful initial neutron rate at the CERN facility is more than three orders of magnitude larger than in the most performant electron LINAC facilities, GELINA in Belgium [2] and ORELLA in the USA [3]. This initial flux difference between the two methods, e.g. electrons vs. protons, reflects directly in the counting rate at the measuring

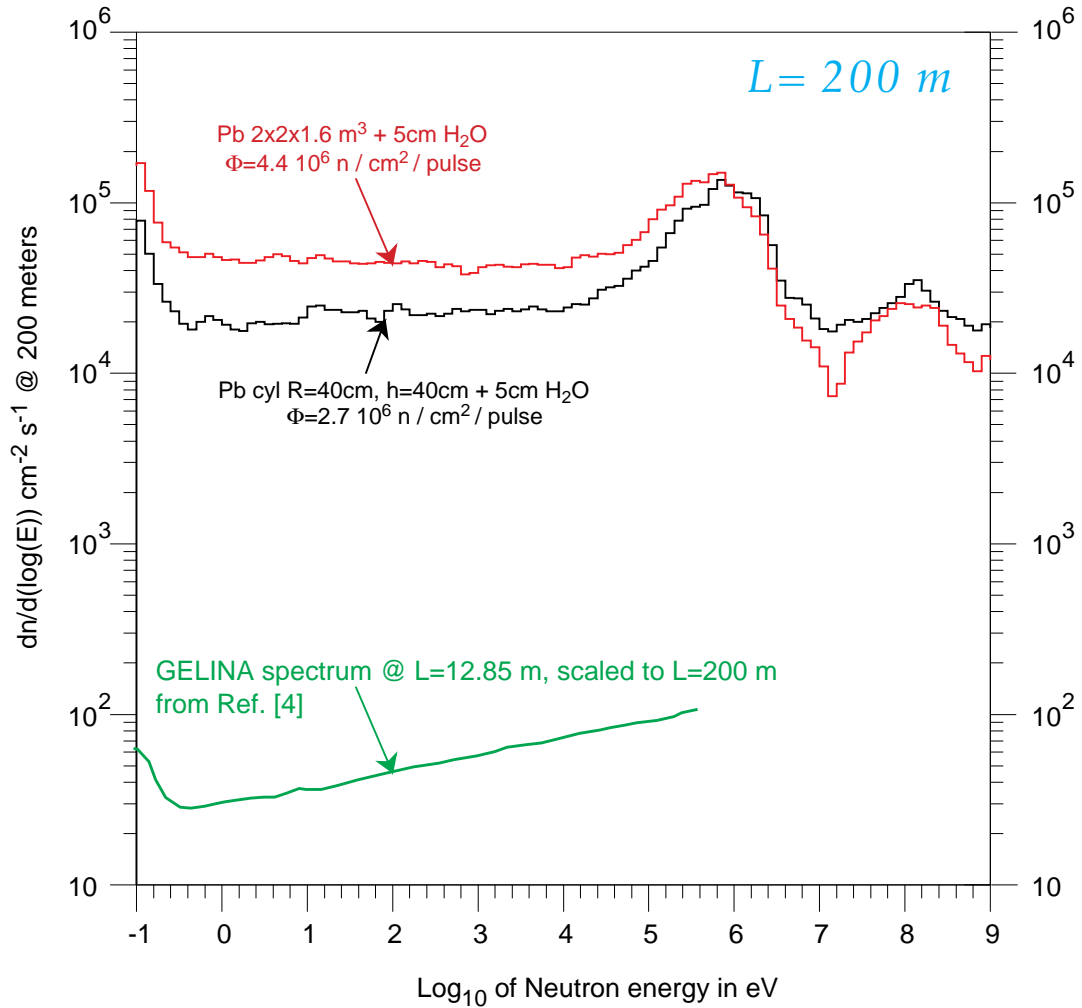


Figure 3. Comparison between the fluxes at a measuring station at $L = 200$ m for two reference configurations of the present proposal with hydrogen (5 cm H_2O) moderator and the experimental flux at GELINA [4]

station, since moderation times are largely independent of the chosen mechanism to produce the initial neutrons.

In order to make an explicit comparison, we compare in Figure 3 the known flux at GELINA [4] at 12.85 m distance, scaled at 200 m, and the calculated flux for the corresponding CERN facility and 200 m, with a similar moderating lay-out, which in particular ensures in both cases the same value of $\Delta\lambda \leq 1.5$ cm. The LINAC is operated at an average energy of 100 MeV, 800 Hz and an average current of 70 μA .

Of course the neutron flux at the measuring station can be adjusted with the choice of the TOF distance, the flux being roughly proportional to the inverse of the square of the distance. Therefore fluxes must be compared for a given energy resolution.

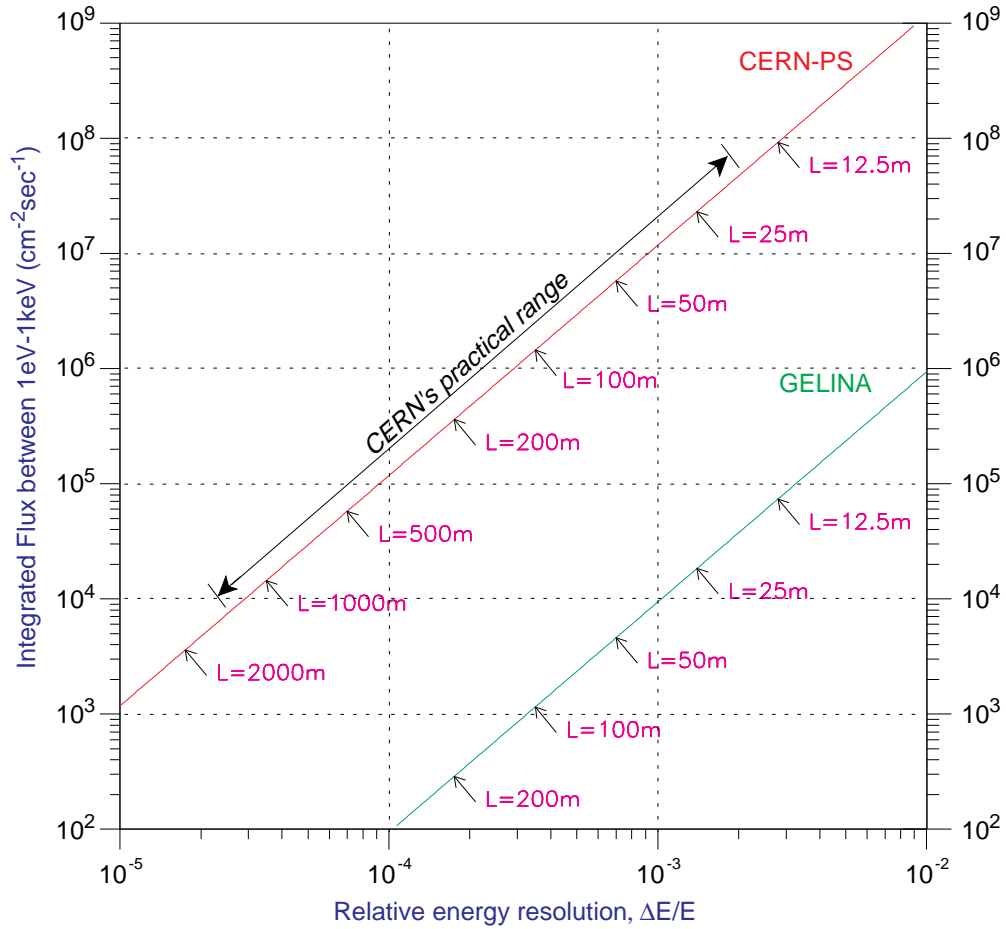


Figure 4. Comparison of the integrated flux for the energy region of 1 eV to 1 keV versus the energy resolution between CERN facility ($R = 40$ cm, $h = 40$ cm and 5 cm H_2O) and GELINA [4].

This higher neutron flux at the CERN facility implies the possibility to use 1000 times smaller targets or at equal rates to increase the TOF flight path by a factor 33, reducing thus the energy resolution by an additional factor 33 down to 5×10^{-6} . The importance of using small mass samples is extensively presented in section 3.1 of Ref. [1]. The comparison of the neutron flux and the energy resolution between the CERN facility and for instance GELINA is presented in Figure 4, where the flux between 1 eV and 1 keV is given as a function of the attainable average r.m.s. resolution in energy. This evidences that the extra flux offered by the CERN set up can be used either to improve the resolution for a given flux, or, alternatively to increase the flux for a given energy resolution. In both cases the expected gains are very substantial.

2.2. *Prompt Gamma backgrounds.* The gamma flux accompanying the neutrons has been calculated in Ref. [1] and it amounts to a mere $0.08 \gamma/n$. As

shown in Ref. [1] this produces a negligible background at the measuring station. The presence of the H₂O moderator does not appreciably affect this conclusion. The situation is substantially less favourable for a neutron producing electron LINAC.

As already mentioned, neutrons at the source are produced as a result of photo nuclear reactions, i.e. (γ,n) and (γ,f), on a bare Uranium target. Electrons slowing-down inside the target produce copiously γ 's through bremsstrahlung. The resulting γ flash, travelling at the speed of light, precede the neutrons along their flight path and is diffused by the sample to be measured. The γ flash is sufficiently intense as to saturate the detectors which then become insensitive to the neutrons which follow.

Such a flash is attenuated by placing along the flight path (far away from the measuring station) a series of filters consisting of high Z materials (⁹²U and ⁸²Pb are commonly used) for which the γ -ray absorption cross sections are very important. The main drawback of this method lies in the fact that the neutron flux is correspondingly reduced depending on the energy range of the neutrons and the total cross section of the material used.

In Ref. [5], it is quoted that a 2 cm thick depleted-Uranium filter (0.096 at/barn) positioned about half-way before the measuring station, reduces significantly the γ -flash intensity but at the same time diminishes the neutron flux by about 50%. Additional Lead and Copper collimators are also required to collimate the neutrons diffused from the Uranium filters in order to conserve the cylindrical geometry of the neutron beam, thus introducing a priori the risk of a deterioration of the spectrometer resolution.

2.3. Bunch time overlapping. The high repetition rate of the LINAC (1000 Hz), required to achieve a good neutron flux limits the maximum useful duration of the TOF to about 1 ms. Neutrons which have a TOF time > 1 ms are necessarily associate to the wrong bunch and therefore their energy assignment is incorrect. This tends to produce an apparent, high energy background, actually caused by low energy neutrons¹. In order to remove this background it is customary to use "Anti-recouvrement" filters made of ¹⁰B₄C (0.7 g/cm²) in order to attenuate low-energy neutrons ($E_c < 135$ eV) from previous pulses, otherwise recorded as fast neutrons, resulting in a further deterioration of the TOF resolution.

¹ For instance the TOF for ≤ 130 eV neutrons exceeds 1 ms at L = 200 m.

The combination of these effects (γ -flash and "Anti-recouvrement" filters tends on the one hand to widen the difference in the neutron flux obtained with the proposed CERN TOF Facility of Figure 3. They also introduce selective neutron absorption and wrong energy assignments.

It is a fortunate circumstance that the PS pulses can be extracted at a pace which is deliberately sufficiently far apart (≥ 20 ms) to remove these problems from their root.

2.4. Rejection power for radioactive samples. In order to accumulate the same number of neutrons on the sample, the GELINA neutron source needs a data collecting time a thousand times longer than at CERN due to the difference in neutron intensities. In addition, it takes 480 times more data taking windows since the CERN beam comes as 4 bunches every 2.4 seconds, as opposed to 800 bunches per second at GELINA. If we assume that similar detectors are used (same time window), a GELINA measurement requires 4.8×10^5 times more live time than CERN. This means that for γ background induced by radioactive materials, the CERN system rejection power is 5×10^5 times better!

2.5. Conclusions. In the proposed facility with 24 GeV PS beam on a Lead target, the number of produced neutrons exceeds 760 per each proton. In comparison, with a LINAC (GELINA) one currently obtains only ≈ 0.05 neutrons per electron of ≈ 100 MeV. An additional factor of 2.5 for the CERN facility is due to the strong, forward peaking of the neutron flux, arising from the high proton energy and corresponding longitudinal boost. This huge factor in neutron yield per incident particle, namely $2.5 \times 760 / 0.05 = 3.8 \times 10^4$, is only partially off-set by the higher, time averaged current of the LINAC e.g. $100 \mu\text{A}$ vs. $2 \mu\text{A}$ of the CERN-PS. Therefore the useful, initial neutron rate at the CERN facility is about three orders of magnitude larger than in the most performing electron LINAC's, GELINA in Belgium [2] and ORELLA [3] in the US.

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