A graphite-moderated pulsed spallation ultra-cold neutron source

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Abstract

Proposals exist and efforts are under way to construct pulsed spallation ultra-cold neutron (UCN) sources at accelerator laboratories around the world. At the Paul Scherrer Institut (PSI), Switzerland, and at the Los Alamos National Laboratory (LANL), U.S.A., it is planned to use solid deuterium (SD\(_2\)) for the UCN production from cold neutrons. The philosophies about how the cold neutrons are obtained are quite different, though. The present proposal describes a third approach which applies a temperature optimized graphite moderator in combination with the SD\(_2\) and qualitatively combines advantages of the different schemes. The scheme described here allows to build a powerful UCN source. Assuming a pulsed 2 mA, 590 MeV proton beam with an average current of 10 \(\mu\)A one obtains UCN densities in excess of 2000 cm\(^{-3}\), UCN fluxes of about 10\(^6\) cm\(^{-2}\) s\(^{-1}\), and total numbers of UCN in excess of 2 \(\times\) 10\(^9\) every 800 s.

Key words: ultra-cold neutron, UCN, solid deuterium, super thermal, spallation

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1 Introduction

Ultra-Cold Neutrons (UCN) are defined as neutrons which are totally reflected from certain materials at all angles of incidence. They were first considered theoretically in 1959 by Zel’dovich [1], or maybe even earlier by Fermi, and first experimentally observed in 1968/69 [2,3]. Typical UCN kinetic energies are up to a few hundred neV, corresponding to velocities below about 8 m/s. UCN can be stored in material traps, using the total reflection from material surfaces. Due to the neutron magnetic moment, magnetic fields of the order of several Tesla provide potential energies of the same order as UCN kinetic energies. Also the change in the gravitational potential for height differences of a few meters is of the order of the kinetic energy. As a consequence UCN can be confined in material traps, magnetic traps, and combined gravitational
traps.

Storage of UCN is a very important feature for a variety of fundamental experiments. It allows the measurement of the neutron lifetime from a well defined sample and leads to ingenious experiments searching for an electric dipole moment (EDM) of the neutron (see e.g. [4]). Although UCN offer greatly improved sensitivity and systematics compared to cold neutron based experiments, one main limitation of these experiments is the low UCN intensity. Typically, UCN densities of ≈ 10 cm$^{-3}$ are available for the experiments. Sources with increased UCN density of the order of 1000 cm$^{-3}$ may lead to much improved measurements of the neutron lifetime and the neutron EDM.

Traditionally, UCN are produced at reactors. The principal difficulty of UCN production is that their energy region is far out in the tail of a thermal Maxwell distribution. Additional losses in the extraction from the reactor cold source result in large suppression factors (e.g. for a thermal flux $\Phi_0$[cm$^{-2}$s$^{-1}$] one typically obtains $\rho_{\text{UCN}} = 10^{-13} \Phi_0$ cm$^{-3}$). Methods to increase the UCN yield from a cold neutron source include vertical extraction [3], using gravity to decelerate neutrons of higher velocities into the UCN regime; and mechanical deceleration [5], using collisions of faster neutrons with a moving scatterer. These faster neutrons can more easily penetrate windows and can be transported over longer distances with few reflections. The distances for UCN transport to the experiments can thus be short and UCN losses small.

Alternative UCN production schemes have been proposed and demonstrated, such as conversion of cold neutrons into UCN in superfluid helium [6,7] or other suitable cold converters as, e.g., solid deuterium [8–12]. Especially the solid deuterium based pulsed sources have the potential to produce high UCN intensities with densities of about $10^3$-10$^4$ cm$^{-3}$ [13–17].

2 UCN production from solid deuterium

The idea of an effective super-thermal UCN source [9,18] is to have a cold neutron moderator (converter), which produces UCN from cold or thermal neutrons in a downscattering process, while the reverse process of temperature induced upscattering is suppressed. It has been proposed [9,10] that solid deuterium ($\text{SD}_2$) would be a good source, because of a large downscattering cross section in combination with a relatively low neutron absorption cross section.\footnote{\text{SD}_2 \text{ is not considered a super-thermal source in the strict sense that the temperature induced upscattering could be neglected, and the source would thus be independent of the temperature of the converter. The upscattering process at about 4.5 K is still a relevant loss mechanism for UCN. Lower temperatures have not been considered practical for a \text{SD}_2 based UCN source, because the loss due to neutron absorption on deuterons becomes the dominant loss and cannot be avoided.}} It had already been experimentally demonstrated before that \text{SD}_2
indeed is a good UCN production medium [8], but at that time it was not considered feasible to set up a reactor UCN source based on SD$_2$. The reason was, that the heat load close to the core of a reactor was much too high to allow for operating the required amount of SD$_2$.

2.1 Continuous versus pulsed sources

While the source of ref. [8] was the cold moderator and UCN producer at the same time, references [9,10] considered a so called “thin film source”. In this kind of source, a thin SD$_2$ layer would cover the walls of a UCN storage vessel which would be exposed to a continuous cold neutron flux. After a certain time, production and absorption would be equilibrated and deliver the ultimate density of UCN. A temperature of about 30 K for the cold flux was estimated to be optimum for UCN production [10]. Several years later the experimental investigations of SD$_2$ for UCN production were started again [11,12] and the potential of SD$_2$ based sources became more obvious. Still the problem of high heat loads on solid deuterium moderators remained, although lower power reactors were considered to solve the problem [19]. A major step forward was due to the proposal of pulsed SD$_2$ UCN sources for trigger reactors [15] and spallation sources [13,14]. As of today, there are four projects to realize SD$_2$ based UCN sources (compare [20]): A pulsed spallation UCN source at Los Alamos U.S.A. [21], where a prototype source has already been operated successfully [17,22]; a pulsed trigger reactor source at Mainz, Germany, which itself will be a prototype source for a continuous reactor source at Munich, Germany [23]; and a pulsed spallation source at PSI, Switzerland [24]. Advantages of the pulsed sources clearly are the reduction of the average heat load on the cryogenic moderator, the separation of production and storage volumes, and the suppression of reactor and beam related background between two pulses. Common to all source designs is the assumption of a UCN producing layer of SD$_2$ of only a few cm thickness. The ideal thickness is limited by the lifetime of UCN in SD$_2$ and by a mean free path between elastic collisions of about 8 cm. Investigations of SD$_2$ quality aspects with respect to the lifetime of UCN in SD$_2$ in the LANL prototype source [16,17] provide important understanding for both, the theoretical and practical implications. It is of special importance to use rather pure ortho-deuterium (para/ortho fraction $\lesssim 1\%$) because of the much shorter lifetime of UCN in para-deuterium.

2.2 The LANL Source concept

The Los Alamos SD$_2$ UCN source [17,20,21] will use pulses of the 800 MeV proton beam at LANSCE. The protons produce spallation neutrons on a light-
water cooled tungsten rod target. The neutrons are trapped in a Be flux trap and moderated by a cryogenic polyethylene (PE) moderator. The pancake shaped SD$_2$ UCN converter sits in close vicinity of the spallation target in the peak cold flux of the PE moderator. Ultra-cold neutrons are extracted from the SD$_2$ through a vertical guide tube into the storage volume and can be continuously delivered to an experiment. The optimum diameter of the SD$_2$ volume is approximately given by the length of the spallation target, thus about 20 cm. The SD$_2$ thickness will be 5-6 cm. The intermediate storage volume is of order 50 liters. The philosophy is to provide a maximum cold neutron flux with short proton beam pulses using a fast moderation and a compact geometry. Long neutron lifetimes in the moderator system are not that important, therefore the use of W, Be, and hydrogenuous PE is efficient in this setup.

2.3 The PSI source concept

The PSI SD$_2$ UCN source [20,24] will use the 590 MeV proton beam at the Paul Scherrer Institut. The protons produce spallation neutrons on a directly D$_2$O cooled Pb target. The moderator is a large heavy water volume providing a maximum thermal flux. The SD$_2$ has 50 cm diameter and 15 cm thickness, and at the same time serves as cold moderator and UCN converter. UCN are vertically extracted through a guide tube into a large storage volume of about 2000 liters. The philosophy is to provide a maximum cold neutron flux to the relevant SD$_2$ region in a rather long and powerful proton beam pulse. The SD$_2$ has to be further away from the spallation target and fast neutrons have to be suppressed. The neutron lifetime in the moderating system has to be long. The choice of heavy water and deuterium is therefore efficient in this setup.

2.4 Comparison of the LANL and PSI schemes

Some of the parameters of the LANL and PSI UCN source schemes, along with the one to be discussed below, are put together in table 1. The numbers given are at this stage only approximate numbers, which follow from the technical reviews of the projects as well as from their conference contributions. A certain pulse scheme was assumed for the performance of the sources. In case of the PSI scheme, so called “macro-pulsing” was assumed, in which a 4 s long beam pulse of the full 2 mA beam (8 mC) hits the target every 800 s. In case of the LANL scheme 40 µC proton beam charge every 10 s were assumed to hit the target.
3 A graphite moderated system

The idea to analyze the behaviour of a graphite moderated system has several aspects:

(i) The moderators and reflectors used at LANL (Be) and PSI (D$_2$O) are not necessarily available as construction materials to everybody. They usually are quite expensive and, in case of heavy water, require an extensive support system. Graphite of the required purity can be bought in large amounts for comparatively low cost. Machining of graphite is simple; also purchase of suitably custom-shaped pieces is possible.

(ii) The PSI system needs a comparatively large amount of SD$_2$ because the SD$_2$ is the cold premoderator itself. A solid graphite moderator can be cooled to be used as cold premoderator and reduce the required amount of deuterium. This study assumes the reduction in thickness from 15 cm to 5 cm. As a consequence, safety issues might be relaxed, tritium production is reduced (as well of course by avoiding heavy water), the deuterium gas system can be somewhat reduced in size. The time needed to convert para into ortho deuterium will be shorter for less amount of SD$_2$.

(iii) The LANL cold moderator is polyethylene, for which one has to take precautions for possible radiation damage, resulting in hydrogen gas production, clogging of cryogenic lines, dimensional changes, brittleness, and stored energy. Reactor experience with graphite is extensive and provides the ground to exclude these problems for a graphite moderator, as long as it is not used as a structural material.

(iv) The LANL system’s philosophy is to use fast moderation materials. The price one pays for a compact system, is a high heat load on the cryogenic parts and the SD$_2$ which are in close vicinity to the spallation target. A slower but less absorbing moderator allows to move the SD$_2$ further away from the target. The size of the region of maximum cold neutron flux is increased, thus allowing for larger diameter SD$_2$ converters along with increased UCN production. Due to better shielding of the SD$_2$, more powerful proton beam pulses can be used in connection with higher UCN production yields.

3.1 The neutronics

The model system which was considered and optimized for this study was developed around the following basic conditions:

(i) Use a PSI type spallation target. This target is a directly cooled lead target. Instead of the heavy water cooling inside the target, this study assumes the
use of light water cooling. The target is foreseen to withstand the full 1.2 MW
beam for several seconds. The time limit is only determined by the capac-
ity of the cooling water system [25]. Such a target allows for an absolutely
variable pulse scheme, with a pulse structure everywhere between the sev-
eral seconds long “macro pulsing” and very short and frequent pulses [26].
A tungsten (or Densimet) spallation target can easily replace the directly
cooled lead target. Such a target would be water cooled on the outside and
would offer a simpler alternative. It would, however, be limited to shorter
beam pulses of up to 1 s [26].

(ii) Use a large diameter for the SD\(_2\) converter. Because it can be expected in
advance that a slow moderated system will produce a more constant flux
over a larger volume, no disadvantage is being seen in this assumption. The
calculated model assumes 50 cm diameter as the PSI design, thus a SD\(_2\) top
surface area of 2000 cm\(^2\), so it can be directly compared to the PSI model,
and it can be easily scaled to the LANL design. In case a directly cooled
target is used, i.e. with water in beam, the target length has to be increased
due to the smaller stopping power of the water. A stopping target for the
590 MeV proton beam at PSI, with a volume ratio of 50-60% lead to 50-40%
water, has a length of about 50 cm. Therefore, the effective use of such a
target requires either a large SD\(_2\) diameter or a slow moderating system.
The proposed model provides both.

(iii) Only use one single material (graphite) for reflection, moderation and cold
premoderation. Different temperatures for different parts of the graphite are
foreseen as an essential feature of the system.

(iv) In analogy to the LANL and PSI designs, make use of the cylindrical sym-
metry around the solid deuterium guide tube. The only breaking of this
symmetry is due to the spallation target and the proton beam tube.

Given these points, a model of the source was analyzed and optimized using
MCNPX 2.1.5 [27]. Figure 1 shows a cut through the calculational model. The
various dimensions of the model have been varied in order to find the optimum
arrangement. The term “cold neutron” was defined to include all neutrons with
energies up to 10 meV. This energy corresponds approximately to the Debye
temperature of solid deuterium and is, therefore, the relevant energy in the
optimization process\(^2\) The optimization was done on the volume averaged
cold flux in a 1 cm thick slice of 50 cm diameter inside the UCN guide tube.
The position of this slice was chosen to be at 15 cm above the bottom of
the guide. However, probably due to a large fraction of the flux coming from
the side walls, the flux does not change considerably for positions between
5 cm and 15 cm. The bottom of the guide tube itself was at 26 cm above the

\(^2\) In the one-phonon Debye approximation, only cold neutrons with energies up to
the Debye temperature can be down-scattered into UCN by creation of a phonon.
In practice, multiple phonon production can shift this limit by some amount. The
higher order contributions are, however, not expected to be dominating.
proton beam axis, but again, the system is not very sensitive to this exact value within several cm. The choice of the graphite moderator’s diameter and vertical extensions were adjusted such as not to lose more than 20% as compared to an infinite graphite moderator. The system for which results are reported in table 1 had a diameter of 1.5 m, a height above the proton beam line of 1 m and a height below the beam line of 0.5 m resulting in a total of 2.5 m$^3$ of graphite. The graphite density was assumed to be 1.7 g cm$^{-3}$ as for commonly used reactor graphites. The innermost 20 cm of graphite around the UCN guide tube and the first 10 cm of graphite below the bottom of that tube have been simulated to be at 40 K. It was found that the 20 cm thick layer could be reduced in thickness, if needed down to 10 cm, below which the cold moderation starts to be less effective. The thickness of the 10 cm layer was chosen because of the high heat load in regions close to the spallation target. The rest of the graphite moderator was simulated at 300 K. One can gain a few percent by going to even higher temperatures of the graphite in the outer regions, which is due to the fact that the neutrons are then less probably absorbed in these regions. However, the system was considered to be simpler at room temperature. The choice of a 40 K temperature for the graphite is relying on the assumption that the ideal neutron temperature for the downscattering into UCN in SD$_2$ is at about this temperature [10,11]. In practice, the cooling system can be laid out in a way to allow for adjusting the temperature in a certain range in order to find the optimum setting.

Table 1 contains the most important results of this study. Most important for UCN production is the cold flux in the SD$_2$ top layers. The table shows that the cold flux $\Phi_{\text{cold}} = 1.0 \times 10^{13}$ cm$^{-2}$ s$^{-1}$ for the graphite moderated system is roughly 30% lower than for the PSI scheme. Most of this reduction can be attributed to the replacement of D$_2$O by H$_2$O as a target coolant. When compared to the LANL system, it has to be taken into account that the flux for 800 MeV proton beam energy would be about $\Phi_{\text{cold}} = 1.5 \times 10^{13}$ cm$^{-2}$ s$^{-1}$ in the graphite scheme, and, thus, be about the same as for the LANL scheme. As the graphite scheme is designed around the UCN guide dimensions of the PSI scheme, the UCN estimates are guided by the PSI numbers.

The other very important point is the heat load in the solid deuterium. Clearly, the schemes with the solid deuterium further away from the spallation target have less specific heat load. The total heat load on the SD$_2$ is 0.5, 1.5, and 0.4 W $\mu$A$^{-1}$ for the PSI, LANL, and the present design, respectively. This is the heat load in the total SD$_2$ volumes, thus the specific heat load per gram is more than 10 times higher in the LANL scheme as compared to the graphite scheme. The fact that the PSI scheme is still a factor 2.5 superior when compared to the graphite scheme is due to the higher efficiency of heavy water in slowing down the fast and medium energy neutrons. The higher heat load in the graphite moderated system is almost completely due to neutrons with energies above 0.625 eV. In practice this results in a limitation for the graphite moderated source. For a given maximum pulse length of the proton beam on the PSI target, pulses will have to be a factor 2-3 shorter for the graphite moderated
system. This system is, therefore, best suited for a pulsed scheme with pulse lengths on the order of 0.05-1 s, corresponding to energy depositions in the SD$_2$ of 0.02-0.5 J g$^{-1}$. Assuming more frequent pulsing (shorter pulses with the same average current) at PSI would lead to a more constant UCN density in the storage volume and would allow to reduce the size of the storage volume. The present design uses about 2 m$^3$ storage, in which the UCN density drops significantly before the next pulse after 800 s.

3.2 Possible problems with a graphite moderated system

3.2.1 Stored energy

Under irradiation of graphite carbon atoms are displaced from their lattice places and store energy. The general hazard is the quick release of this energy in connection with a sudden temperature rise and, if oxygen is available, rapid self sustaining oxidation. The proposed system will use helium gas as coolant during operation. Measures can be taken in order not to expose the graphite to air in an uncontrolled way. Based on the existing experience from reactors with stored energy in graphite, the stored energy problem in a graphite moderator for the UCN source is expected to be negligible [28–30]. This is mainly due to the much lower integrated neutron fluxes. While graphite moderators in reactors are easily exposed to $10^{13}$ neutrons cm$^{-2}$ s$^{-1}$, the highest average exposure (close to the spallation target) will be a factor of 10 lower for the proposed pulsed spallation source. Problems with stored energy that might occur in a reactor after 1 year would therefore show up only after 10 years. Of some concern might be the fact that parts of the graphite are kept at cryogenic temperatures, where there exists no experience with the stored energy problem. However, the neutron flux in the cryogenic parts is even smaller. Moreover, because the moderator system will be helium gas cooled, it will also be possible to use helium gas at high temperatures to anneal the system. The effect of stored energy in the cold graphite can therefore be analyzed in-situ, but there is absolutely no reason to expect the necessity of annealing more frequently than on a year’s basis.

3.2.2 Self-poisoning

Due to the operation of the source, specifically due to irradiation with slow and fast neutrons, neutron absorbing impurities might be produced and build up to a level which is no longer acceptable. In ref. [31] it was estimated that for the PSI spallation source SINQ for carbon close to the target the absorption cross section due to carbon and produced impurities will rise from an initial 3.4 mb to about 43 mb at one year (assuming
3 mA of 590 MeV proton beam on target). As the UCN spallation target at PSI would operate with 2 mA beam but 0.5% duty factor only\(^3\) we can divide the numbers of [31] by 300. After 20 years of continuous operation one might therefore expect an increase of the neutron absorption in the carbon closest to the proton target by a factor of roughly 2.

In order to be somewhat more quantitative we give an estimate of the build-up of absorbing impurities in the first graphite layer, which is at a radius of 7.5 cm from the beam axis. The average proton beam of 10 $\mu$A and the average production of 10 neutrons per proton lead to an average neutron flux of $10^{12}$ cm$^{-2}$ s$^{-1}$. Table 2 gives a comparison of the important contributions. The last column gives the ratio of the effective absorption of the impurity with respect to carbon after accumulation of 300 C on the target (which corresponds to one year of continuous running at 10 $\mu$A average proton beam current and neglects regular shutdowns). As a result, the moderator can be operated for more than 10 years before the self-poisoning becomes an issue. If considered necessary, the moderator can be designed to allow the replacement of the graphite closest to the spallation target after that time.

### 3.2.3 Material property changes under irradiation

It is known from reactor physics experience that graphite changes its properties under irradiation (see e.g. [29,30]). Among these changes one finds dimensional changes, changes in thermal properties as well as changes in mechanical properties. While dimensional changes of the order of a few percent and changes in mechanical properties can be taken into account easily for the design needs of a UCN source, changes in thermal properties, especially reduction in heat conductivity, might have a more severe impact. Despite the vast amount of high temperature data, there is only very little data for graphite in cryogenic environments. Generally, the increase in thermal resistivity under irradiation has been found to be more severe for lower irradiation temperatures. The neutron dose relevant for drastic changes is on the order of $10^{20}$ neutrons per cm$^2$. This number has to be compared to a typical number for 1 year of operation of the spallation UCN source, which is about $10^{19}$ cm$^{-2}$.

Even if one assumes that severe damage occurred, and the thermal conductivity might be reduced by one order of magnitude [32] it will still be large enough to remove the deposited heat. The helium gas cooling system as well as the surface to volume ratios of the graphite components to be cooled have to be designed in a way to allow for large variations of the thermal conductivity.

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\(^3\) If the beam current is increased to 3 mA at a later time, the duty factor will drop to 0.33%. The average current will stay at 10 $\mu$A.
3.2.4 Cooling issues

The most challenging part of the graphite moderator is the engineering of the helium gas cooling. For the calculations an optimum value of 40 K for the cryogenic premoderator was assumed. However, the producibility of this temperature will depend on the available cooling power of a suitable refrigerator. Some systems might beneficially use temperatures of 60-80 K, with a sacrifice in UCN output of 10-20%. An important point will be the actual energy deposit in a proton beam pulse, depending on beam current and pulse length, which determines the instantaneous temperature increase in the graphite, although thermal properties of different graphites can be quite different. Typical numbers for the thermal conductivity of graphite at 40, 80, and 300 K are about 0.1, 0.3, and 1 W cm\(^{-1}\) K\(^{-1}\), respectively; typical numbers for the specific heat are 25, 100, and 800 J kg\(^{-1}\) K\(^{-1}\), respectively [32]. For the discussed graphite system, a 1 s long beam pulse (2 mA, 590 MeV) would heat the cold graphite below the UCN guide by about 0.6 J g\(^{-1}\). For a system at 40 K, the temperature would rise to about 60 K during the pulse, if no heat would be removed. For a system at 80 K, the corresponding temperature increase would be around 5 K. Assuming a segmentation of the graphite with surface over conduction length ratios (\(A/l\)) around 10 cm would already allow to cool both temperature schemes over time periods below 100 s. In order to allow for a decrease in the thermal conductivity of up to one order of magnitude, as discussed in 3.2.3, one could reduce the \(A/l\) ratio to 3 cm. This would allow for a safe operation with 1 s long beam pulses every 200 s, corresponding to 10 \(\mu\)A average proton beam current. The energy deposit in the warm part of the moderator is a simpler problem. It will be sufficient to use the thermal conductivity of the graphite and radiative cooling on the outside. There is no need to keep the temperature constant around 300 K, one can allow for a substantial temperature increase. At a temperature of 400 K the radiative cooling of the graphite facing a 300 K wall would be already 1 kW m\(^{-2}\), which would limit the possible temperature increase.

The design of a realistic helium cooling system is presently under way.

4 Conclusions

It was shown that a comparatively simple moderator system for a spallation UCN source can be set up using graphite, in part at cryogenic temperatures. The performance of the scheme presented is superior to the LANL scheme and comparable to the PSI scheme, but less complex and less expensive.
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|                           | PSI          | LANL         | new scheme   |
|---------------------------|--------------|--------------|--------------|
| energy                    | 590 MeV     | 800 MeV     | 590 MeV      |
| proton beam: pulse mode   | 8 mC / 800 s| 40 μC / 10 s| variable     |
| $I_p$ [μA]                | 10           | 4            | 10           |
| spallation target         | 1.2 MW       | 5 kW         | 1.2 MW       |
| Pb + D$_2$O               | Pb + H$_2$O  |
| neutron moderator         | D$_2$O, SD$_2$| H$_2$O, Be, CH$_2$| Graphite |
| UCN converter             | SD$_2$       | SD$_2$       | SD$_2$       |
| $A_{SD_2}$ [cm$^2$]       | 2000         | 300          | 2000         |
| $V_{SD_2}$[liters]        | 30           | 2            | 10           |
| SD$_2$ heat load [W μA$^{-1}$] | 0.5        | 1.5          | 0.4          |
| $E_{SD_2}$ deposit per pulse [J g$^{-1}$] | 0.7        | 0.15         | variable: 0.02 - 2 |
| 4K heat load [W μA$^{-1}$] | 1           | 7            | 1            |
| $Φ_{cold}$ [cm$^{-2}$ mAs$^{-1}$] | $1.3 \times 10^{13}$ | $1.4 \times 10^{13}$ | $1.0 \times 10^{13}$ |
| $I_{UCN}$ [cm$^{-2}$ s$^{-1}$] | ($\sim 10^6$) | $10^4$ | $\sim 10^6$ |
| $ρ_{UCN}$ [cm$^{-3}$]     | 2400         | (400)        | 2000         |
| $V_{store}$[liters]       | 2000         | 40           | 600 - 2000   |
| $N_{UCN}$ = $ρ_{UCN} \times V_{store}$ | $4800 \times 10^6$ | (16 $\times 10^6$) | 1200 - 4000 $\times 10^6$ |

Table 1
Comparison of various source parameters of the PSI and LANL sources along with the new scheme. $A_{SD_2}$ and $V_{SD_2}$ denote the top surface area and the volume of the solid deuterium, respectively. The SD$_2$ heat load is given for the total SD$_2$ volumes. The energy deposit $E_{SD_2}$ deposit per pulse is the specific heat load for the given proton beam pulse structure. Additional materials at liquid helium temperature contribute to the 4K heat load. The cold neutron flux $Φ_{cold}$ is given for the top SD$_2$ layer. The UCN flux and density which can be obtained from the source are denoted by $I_{UCN}$ and $ρ_{UCN}$, respectively. For a given storage volume $V_{store}$, one obtains the number of available UCN, $N_{UCN}$. The numbers for the PSI and LANL sources have been extracted from [21,24] by the author and might be subject to change. They merely serve as guidelines for the comparison with the proposed graphite scheme. Numbers given in parenthesis are non-optimized numbers. While the PSI source is not foreseen to run in a constant current mode so far, the LANL source is not optimized for highest densities. The numbers for the new scheme have been calculated for 590 MeV protons. For 800 MeV protons, the number of neutrons per proton is increased by roughly a factor 1.5. Calculations for the new scheme were done using the MCNPX 2.1.5 code package [27].
| nuclide | $< \sigma^i_p(E) >$ [mb] | $\sigma_{abs}$ [mb] | $\frac{N^{impurity}(Q_p=300C)}{N^{12C}}$ | $\frac{\sigma_{abs}(Q_p=300C)}{\sigma_{abs}^{12C}}$ |
|---------|--------------------------|---------------------|----------------------------------|----------------------------------|
| $^{12}$C | n.a.                     | 3.53                | 1                               | 1                               |
| $^3$He  | 1.8                      | $5.333 \times 10^6$| $5.3 \times 10^{-9}$            | 0.008                           |
| $^6$Li  | 20.0                     | $9.40 \times 10^5$ | $5.9 \times 10^{-9}$            | 0.016                           |
| $^7$Be  | 3.9                      | $4 \times 10^7$    | $\approx 4 \times 10^{-9}$†     | $\approx 0.06$†                 |
| $^{10}$B| 14.0                     | $3.835 \times 10^6$| $4.1 \times 10^{-8}$            | 0.045                           |
| total   |                          |                     | 1+0.06+0.07 n                   |                                  |

Table 2
This table lists the impurities and their relevance for poisoning the graphite moderator. The production cross section averaged over the spallation neutron energy spectrum for 590 MeV protons, $< \sigma^i_p(E) >$, was taken from [31]. The symbol $\sigma_{abs}$ denotes the thermal ($v = 2200$ m/s) absorption cross section. The † labels the saturated numbers for $^7$Be (half life of 53 d) which only builds up to an equilibrium (see [31]). The n in total denotes the number of 300 C-years. The last column suggests that the absorption on in-situ produced poison contaminations in graphite close to the spallation target will match the absorption on carbon only after more than 10 years of continuous running.
Fig. 1. Schematic view of the calculational model for the graphite moderated system. The spallation target is a Pb/H\textsubscript{2}O mixture with 60\% to 40\% volume ratio. The target has a length of 50 cm and a diameter of 15 cm. For the calculations, the aluminum proton beam tube has 2 cm wall thickness, the UCN guide tube 3 mm. The guide tube’s diameter is 50 cm. Spallation neutrons with an average energy of about 2 MeV are moderated and thermalized in the graphite. Cold neutrons (CN) which leave the graphite moderator into the solid deuterium can be down-scattered into ultra-cold neutrons (UCN). SD\textsubscript{2} can be placed in the guide tube at various positions.