IAEA-TECDOC-1439

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*Report of a technical meeting*
*held in Vienna, 18–21 May 2004*

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# FOREWORD

The IAEA's programme on the effective utilization of accelerators helps Member States, in particular developing Member States, in finding new areas of application for their low and medium energy accelerators through activities such as coordinated research projects, technical meetings and conferences.

Small and medium power spallation neutron sources will become more important as many small neutron producing research reactors are being phased out. Recent developments in accelerator technology have made it possible to produce useful neutron fluxes at accelerator facilities suitable for universities and industrial laboratories. In addition to basic research, these alternate neutron sources will be important for educational and training purposes. In a wider perspective, this technology should make it possible to introduce neutron research and applications to industrial and national research centres in Member States unable to afford a high energy spallation neutron source and with no access to a research reactor. Neutron applications in life sciences will be a rapidly growing research area in the near future. Neutrons can provide unique information on the reaction dynamics of complex biomolecular systems, complementing other analytical techniques such as electron microscopy, X rays and NMR. There is a general belief in the life sciences community that neutron methods are an emerging technique and not exploited to their full capacity. This is partly due to the fact that useful neutron beams can only be generated at advanced research reactors and/or high energy neutron spallation sources.

In view of this the IAEA convened a Technical Meeting on Development of Small and Medium Scale Accelerator Driven Neutron Sources in Vienna, 18–21 May 2004. The objective of this meeting was to *explore the possibilities of medium energy accelerator driven neutron sources as complement to research reactors for basic research in neutron science and applications in life sciences and industry.* The topics discussed during the meeting were:

- A model, medium energy accelerator driven neutron source as a complement/ replacement for a small research reactor,
- Possible research areas at a medium energy accelerator driven neutron source facility,
- Educational and training aspects,
- Synergies with high energy spallation neutron source facilities, and
- A possible network of medium energy, accelerator driven neutron source facilities.

The meeting was attended by eight international experts, and chaired by G. Bauer (Germany). The major part of the drafting of the report was done by D. Baxter (USA). The IAEA officers responsible for this publication were U. Rosengard and G. Mank of the Division of Physical and Chemical Sciences.

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SUMMARIES OF PAPERS PRESENTED AT THE MEETING

# 1. INTRODUCTION

Throughout the world, advances in technology have continually produced significant opportunities for economic development over the last several decades. This has occurred in areas ranging from microelectronics, and engineered materials, to advanced pharmaceuticals and medical devices. It is clear that opportunities for the greatest economic benefit to developing nations will be found in areas where they can tap into advanced technologies and foster opportunities for their citizens to attain and apply knowledge in related fields of science and engineering. Technical advances may produce economic benefits through the introduction of new products (such as cellular phones), through improvements in quality control for more conventional manufacturing (e.g. automobile manufacturing), by enabling new ways to manage existing businesses, or other means. It is, of course, difficult to predict a particular area in which technical advances may lead to emergent new markets, but it is clear that in the present world, substantial new markets, or industries, are most likely to be associated with some new technology. For this reason, it may make more sense for developing countries to make investments in enabling technologies, that can increase their overall technical infrastructure, and thereby establish connections to a wider range of fields, where technical advances may provide opportunities for economic growth. This approach will impact the economic well-being of such countries in two ways: directly, by providing the technical expertise to capitalize on new opportunities when they emerge, and indirectly, by helping those countries to retain their brightest minds, so that those opportunities may be recognized early enough for an economic benefit to be realized.

In recent years, several industrialized countries have made substantial investments in major facilities for neutron scattering. Within the next several years, Germany, Japan, the USA and Australia will all complete neutron facilities whose construction cost are in the range of US $ 1 billion or more. These investments are being made in recognition of the impact that neutron-based techniques can have on a wide range of fields in advanced science and engineering, as well as the availability of new technologies for producing neutrons. Providing the world access to these techniques cannot be accomplished by these flagship sources alone. This points to the need for a distributed network of lower power sources. Indeed, the ultimate success of these flagship sources will require such a network. These developments prompted the IAEA to hold an exploratory meeting at its headquarters, to identify ways in which the IAEA could foster opportunities for developing nations to capitalize on these events. This report summarizes the results of this meeting.

## 1.1. Neutron technology

Roughly half a century after the technology of nuclear reactors entered its period of most rapid development, many of the research reactors that were built, and deployed world wide, have more or less outlived their mission. Many of them are actually becoming more of a burden, than an asset to their countries, because there are growing concerns about safety, and waste issues on the one hand, and the research opportunities they offer, are no longer competitive on the other. Some developed countries have responded to this situation, and to the continuing need for ever better neutron sources for high quality research, by developing accelerator driven neutron sources (ADNS) which, while more complex in their technology, offer a number of distinct advantages over nuclear fission reactors.

The principle of the new generation of neutron sources is to have a beam of accelerated particles impact on a target of non-fissile material and release neutrons by processes other than fission. The most prominent of these processes is spallation, which actually is a sequence of different events that leads to the liberation of up to several tens of neutrons by a single proton of a few GeV in energy from a heavy metal target. The low heat release per neutron associated with spallation is the main reason for choosing this process for very high flux sources. A very important advantage of ADNS lies in the fact that they can be operated in pulsed mode with virtually any desired time structure. Taking advantage of this in the design of neutron scattering instruments provides this kind of source with a benefit of up to three orders of magnitude over cw sources with similar time average neutron flux. Obviously, this means that also lower power sources can be of high performance, allowing one to consider also less energy efficient, but also technologically less demanding neutron releasing reactions.

After a period of development of target technology on the one hand and instrument concepts on the other, carried forward by exploiting opportunities for parasitic use of particle accelerators originally built for different purposes, the time has now come where purpose built high power accelerators drive neutron sources which will soon outperform even the best research reactors by an order of magnitude in many fields of research. This will clearly increase the gap between the most advanced neutron sources in the developed countries on the one hand and the low-to-medium power research reactors in developing countries on the other, and put the latter ones even more in question. The most desirable solution would of course be, to have the developing countries participate in the introduction of the new technology. However, the very complexity of the accelerator technology involved is likely to be a natural obstacle to such an effort for any one developing country. This is certainly true for top of the line facilities presently under construction in Japan and in the USA. Yet, there may be opportunities to develop and deploy somewhat less demanding designs of ADNS, with limited but specialized capabilities, that would still serve modern research needs.

This report outlines the impact that small and medium scale ADNS can have on advanced technologies, such as in providing quality control for manufacturing techniques, in education, and in developing links to the world's major centers for neutron scattering. Various designs for neutron sources suitable for exploiting these opportunities are also described, as are the advantages to be gained from linking smaller neutron sources constructed in developing nations among each other, and with existing, and emerging international centers for neutron scattering.

## 2. SYNERGIES WITH HIGH POWER SPALLATION NEUTRON SOURCE FACILITIES

There is a clear synergy between the operations of high and low to medium power sources, which is beneficial to both types. Due to their cost, the high power sources tend to be unique to the continent on which they reside, and their operation is geared to reliably providing intense neutron beams to a wide user community. Such a mode of operation has a number of consequences:

- Overload of available beams with respect to both, the range of instruments that can be accommodated and the beam time available.
- Experimental time is restricted, and usually very little flexibility in schedule can be tolerated to accommodate unknowns.
- Little opportunities to perform tests of more speculative nature.

- Experiments not requiring the high intensity of the source are relegated to other, lower power sources; hence these sources must be available.
- Justification of the full experimental program is necessary. This can lead to situations in which measurements are favored over experiments.
- The pressure to make most efficient use of beam time to produce results, limits the possibility of carrying out training of students or new users.

Small to medium power sources provide a network of facilities that provide an invaluable experimental resource, which also serves for the development of the technique and for training of the community. Not all measurements or experiments require the beam intensity offered by the high power sources, and excellent science programs can be carried out at smaller facilities. The science programs carried out at smaller sources may be adapted to a specialized community, which may better reflect the regional requirements. The use of the facility will certainly not be restricted to neutron scattering experiments. Scientific and technological experience and know-how developed at such sources can be shared effectively with the larger facilities.

Hence, covering all the needs of the user community, low, medium and high power neutron sources should be considered as complementary, each playing an important role in the application of neutron techniques to science and technology.

## 2.1. Calculations, simulations and model improvements

Resources for performing calculations and simulations can often be shared. Typically, the large, high power, user facilities have access to more resources than the smaller facilities. In particular, they have access to computational codes and computing power, which enables them to perform large complex calculations of different components of a spallation source, including the accelerator, target, moderators and instrumentation.

We distinguish the sources depending on their power. However, the power depends on both beam current and energy, each of which is important in its own right.

Many results, which depend only on the beam current, can be normalized on a per proton basis, so comparison between high power and small sized spallation sources can be done via simple scaling. This applies, for example, to quantities like energy and time distributions of ejected particles produced in spallation and nuclear reactions, activation, afterheat and heat deposition or radiation damage in the beam windows.

There are, however some results that do not scale directly with source power: e.g. cavitation erosion, shock waves and energy dependent effects like the number of neutrons generated per proton in the spallation process or other nuclear reactions These calculations may therefore be specific to a particular source, however the general knowledge and resources may be shared. A good example is the work carried out internationally, to study cavitation induced erosion in liquid metal targets.

In order to validate and scrutinize models currently available, gain confidence, and even increase the predictive power of transport codes employed for various applications, experimental investigations have to be performed. In fact, the performance, further development and flexibility of widely used 3D program packages (neutron transport codes) like HERMES, LCS or MCNPX etc. rely on precise experimental data taken during the last few years at small accelerator facilities. To give an example: a particular challenge is the description of hadronic and electromagnetic phenomena over 10 orders of magnitude, ranging from the incident proton energies (GeV) down to the energy of the moderated, sub-thermal neutron (meV). The complex features of neutron cross sections in the low energy region cannot be calculated from first principles using the known properties of the nucleus. Hence, data must be determined empirically as a function of energy for each nuclide and for each reaction. In general, these data cannot be interpolated over large energy intervals, because of the irregular resonance structure, although the Breit-Wigner formula or other semi-empirical relations often allow a characterization of the cross sections in terms of few empirical parameters per resonance. Therefore, cross sections, as well as energy and angular distributions of the resulting secondary particles for hundreds of isotopes, over an energy range ranging from $10^{-5}$ eV to 150 MeV, have been evaluated and collected in nuclear data files (e.g. ENDF, JENDL, JEFF, CENDL-2 and BROND-2). These data files have to be maintained and continuously updated.

## 2.2. Target and moderator development and testing

High power spallation sources do not lend themselves to target, and moderator development and testing. The high beam intensities mean that targets are typically highly active and can only be accessed using complex remote handling equipment, so that even simple experiments tend to be elaborate and costly.

Development of both target and moderator materials, and concepts is important for the production of efficient, low energy neutron sources. Experience shows that factors of two to three in intensity may be achieved by careful tailoring of the target and moderator design to the goals of the source and its instrumentation.

Typically, beams at high power sources are in high demand and experimental areas are not readily available at the facility to carry out tests. It is quite possible to obtain good experimental results at low or medium power sources. Furthermore, low intensity beams are often advantageous for following reasons:

- No or only little radiolysis or damage (leading to longer lifetimes)
- Reduced shielding and background
- Reduced activation levels
- Reduced cooling requirements
- Flexibility, accessibility and hands on maintenance
- Time.

Therefore, the lower neutron intensity available at small and medium sized sources may, for various experiments, even turn out to be mandatory, or at least beneficial, and experimental results can be obtained at these facilities without compromising the scientific quality. One of our motivations for encouraging small and medium sized facilities, as a complement to intense sources, is to develop a library of benchmark experiments for advanced target-moderator-reflector assemblies. We further see the opportunity to test the validity of scattering kernels, cross sections, and physics models for both new and traditional moderator materials, and moderator reflector systems. The experience gained at small sized sources can be leveraged to develop a broad-based knowledge base relevant also to large, high power neutron sources.

There is significant international interest in advanced neutron source target-moderator reflector systems. The Rutherford Appleton Laboratory (UK) has recently received approval for the £100 million ISIS Target Station 2 project. The US Spallation Neutron Source (SNS) and Japanese Spallation Neutron Source (JSNS) projects are currently under construction. In the longer term, there is a proposal to build a Chinese Spallation Neutron Source (CSNS) facility. The US-SNS project has an identified upgrade path that includes a second target station, which will be optimized for the production of long wavelength neutrons, and it is expected that Europe, too, will start construction of an ADNS (the ESS-Project [1]) on the SNS/JSNS scale within the next decade. Others (primarily University groups) have also expressed interest in developing small, local pulsed neutron source capabilities, largely as a part of the infrastructure encouraged by the above world-class projects and facilities.

## 2.3. Instrumentation

The large, high power facilities attempt to serve a wide user base, so that the instrumentation associated with the source is specifically selected to make the most efficient use of the high neutron intensity for a wide range of instrument types. The associated radioprotection needs may lead to compromises in instrument or experiment design. For many experiments, a medium power source in which the design of the source, moderator, and instrument are fully integrated, would be more effective and can be tailored more precisely to the needs of the local (regional) community as exemplified e.g. by the ISIS 2nd target station which, at a beam power of only 50 kW, is claimed to outperform the 1st (300 kW) target station by a large margin for certain experiments.

Specialized instrumentation could be accommodated more easily. Furthermore, as discussed in section 5, not all measurements require high intensity beams. If the time required to change sample or experiment becomes significantly longer than the measurement time, a smaller regional source would be more suitable. Initial, exploratory measurements are also better performed at smaller sources, where access is less restricted. The results may lead to proposals for more detailed measurements at a higher power source.

Small to medium power sources also have an important role to play in the development and testing of new instrument concepts and components.

As directions in science change, instrumentation, which enables new measurement possibilities, must be developed. It is not always possible or reasonable to test components or concepts at a high power source or large facility. Test beams, or time on instruments, may not be available due to the pressure of carrying out the on-going experimental program. Furthermore, high intensity beams are often not the most suitable for test purposes, due to problems of access, shielding, activation and general flexibility for beam line modification. Although concepts for instruments and components may be developed anywhere, in-beam testing is better carried out at small or medium power sources. Once a concept or component has been developed, it may be easily implemented at a larger facility if necessary.

The inverse is also true. Components that have been thoroughly tested and proved at high power sources will, in most cases, be directly usable at low to medium power sources, since the requirements and burdens on the material components and structures are expected to be less severe.

## 2.4. Education and training

Due to the overwhelming pressure at large scale, high power facilities to optimize the use of beam time, they are usually intolerant to trainees. Small and medium power sources offer training possibilities that cannot be entertained at high power sources. In particular, at smaller sources, there are many more opportunities for training in the science of neutron production and instrumentation development, in addition to training in the collection and interpretation of data collected on conventional instruments available at major sources. Examples include training on:

- components of the source itself: accelerators, targets, reflectors, moderators, instruments and shielding;
- the science behind applications;
- experimental techniques;
- related neutron technologies including detectors, optics, and sample environment;
- data acquisition and data analysis methods;
- industrial applications;
- radiation safety.

In addition to having students participate in on-going experiments, beam time to carry out training programs can be specifically allocated. Furthermore, experimental stations can be envisioned, in modular form, which allow hands on training to take place. In general, this would not be possible at high power sources. Small scale, regional sources tend to have close ties to local universities, so that training programs at the sources can be directly linked to university lecture programs in various domains. For example, there are many development programs, which will require the training of a future generation of accelerator physicists. University programs set up to meet this need will require access to hands on training facilities. A network of small to medium power sources, each with specialized instrumentation, would facilitate mobility of students and researchers during training and encourage international collaboration.

The selection of research areas, instruments, and applications to be suitable for a small or medium flux ADNS should mainly be motivated by two considerations:

(i) Is a useful operation, or application, at the low flux source possible at all? This favors instruments and applications which normally, or at least for some application modes, do not suffer from flux limitations. It excludes others, which suffer from low flux already at established higher-flux sources.

(ii) What instrument, or application, has the highest potential for technological and applied research? Competing with modern high-flux sources, small facilities should realistically not be dedicated to basic research at the frontier of science. One exception to this is, in the area of instrumentation development, where the relaxed demands on beam time available at these sources can provide a distinct advantage over international user facilities. Away from the frontiers, low to medium flux sources can well have a high potential for technological applications, dedicated applied research, nondestructive testing, systems development and education.

The following neutron beam instruments and techniques best satisfy the above considerations:

- Small angle neutron scattering (SANS),
- Reflectometry,
- Powder and polycrystal diffraction including strain measurements,
- Radiography,
- Activation analysis and depth profiling,
- Time of Flight (TOF) instrument for incoherent-inelastic measurements,
- Testing of neutron devices, such as detectors and neutron optics, and
- Neutronics engineering such as target/moderator/reflector development/optimization.

Applications of these neutron beam instruments are described in detail.

In addition to these, special applications may need special beam ports, or special inserts for research and development, in such matters as neutron detectors, moderators, optical components etc. These must be considered separately. Many of these techniques have been discussed in the context of small to intermediate-scale research reactors in Ref. [2].

## 3. NETWORKING OPPORTUNITIES AND NEEDS IN THE FIELD OF MEDIUM POWER ADNS

We have described the opportunities that exist for constructing small to mid-sized neutron facilities, as well as examples of the scientific and technical research that can be performed at such facilities. It is clear that many of these opportunities are well within the economic and technical capability of individual developing nations. However, there may be significant benefit to having such sources developed within a more extended context. As outlined above, significant synergy would be expected to result from interactions between smaller sources and existing international facilities. However, establishing networks among nations interested primarily in the smaller sources could be equally important.

### 3.1. The feedback between opportunities and demand

An important driver behind progress in many fields is the awareness of demand. It is important for any developing country to have a community of trained and knowledgeable scientists and engineers, that can develop a vision for the country's way forward, and communicate this vision to decision makers. This is particularly true for less common, but nevertheless powerful techniques such as research with neutrons. Experience shows that, once opportunities to carry out such research exist and are properly publicized, the community willing to use these opportunities grows rapidly. A very striking example is the fast growing demand for neutron use in the USA, even before SNS is finished. In this sense, it will be important to offer opportunities for training and scientific or technical development work at existing facilities. This could well be an important role for existing facilities to play within an emerging network. It would also be to the benefit of the major sources to host qualified and motivated scientists and engineers at their sites. A crucial step that could be made by the Agency would be to initiate the connections between the developing nations' demand for technological advancement and the opportunities provided by the advances in ADNS technology identified above.

## 3.2. Rationale for and opportunities offered by networking in the field of ADNS

Apart from the transfer of knowledge from existing sites to potentially new ones, there are several other arguments that make networking attractive:

- Designing, construction, operation, and utilization of accelerator driven neutron sources will require skills and resources, not all of which may be available in any particular country;
- The opportunities offered by such facilities may be sufficiently broad to serve the needs of more than one country;
- Conversely, special opportunities may be available at some facilities, and not on others;
- Limited resources, that are insufficient to build independent, state-of-the-art facilities within a given nation can be pooled;
- Distributed medium size ADNS can offer possibilities otherwise only available at large facilities (number of instruments!).

## 3.3. The concept of a network versus a user facility

Opening existing facilities up for outside users has become common practice in many laboratories. In general, the assignment of utilization privileges is done on the basis of a proposal evaluation system by a Scientific Council or a similar peer reviewing system. The main emphasis of project evaluation is on the scientific merits but sometimes also with a view on “shares” held by different parties contributing to the operation of the facility.

A step beyond a pure user system can be seen, for example, in the European Program of “Access to Large Facilities”, where institutions can receive funds from the EU if they open their facilities up and provide support for users from outside. This program was highly successful in broadening significantly the range of specialized instruments accessible to individuals, or groups of researchers, in pursuit of their research goals. While institutions that wish to qualify for this program have to fulfill stringent requirements and are judged in competition with other candidates, there is still no coordinated planning on what instruments are made available and how utilization is managed on a trans-facility level.

Networking in the field of ADNS could just be one step beyond such access programs and could include coordinated efforts in the planning, layout, equipment and support provided at the individual facilities, minimizing duplications of efforts and ensuring the highest degree of complementarily between facilities. This would mean that planning and management would be in the style of a large project which, in itself, can be an important training opportunity.

## 3.4. Existing ADNS and ongoing projects

While the goal of a network would clearly be to deploy new facilities, preferably in developing countries, the participation of existing facilities will be essential. A non-exhaustive list of such facilities is included in Figure 1. Neutron performance data depend strongly on the moderator under consideration, and the figures given are therefore only indicative. Nevertheless, it is obvious that ADNS have now become competitive to even the best high flux research reactors (e.g. the High Flux Reactor (RHF) at the Institut Laue-Langevin in Grenoble, with a thermal flux of around 1.3 x $10^{15}$ n/cm$^2$s).

### 3.5. Present status of international collaboration on ADNS

Much of the development work that lead to the design and construction of the existing facilities was carried out in laboratories that had previously agreed to collaborate in the field of advanced neutron sources and to meet more or less regularly to exchange information and provide input to each others' projects. The first four-laboratory agreement was established in 1975, and the collaboration has been growing ever since, clearly demonstrating the virtues of and the desire to have such a forum. The proceedings from the 16 meetings held so far by this "International Collaboration on Advanced Neutron Sources" (ICANS) [3] have become an invaluable source of information for any newcomers to the field. However ICANS, being based on simple declarations of intent by its member laboratories, lacks the kind of forward-looking planning that a network would provide, and there is no obligation for its members to do specific work. Nevertheless, ICANS can serve –and has in the past - as a forum from which more explicit agreements on collaborative efforts originate. An example on the level of targeted R&D work was the ASTE-Collaboration (AGS-Spallation Target Experiment), carried out by a group of laboratories at the Brookhaven Alternating Gradient Synchrotron (AGS), in pursuit of a common goal between Brookhaven National Laboratory, Oak Ridge National Laboratory, Forschungszentrum Jülich, Japan Atomic Energy Research Institute, and Paul Scherrer Institut, to qualify the concept of a liquid mercury target for the ESS, SNS and JSNS projects. This work was carried out in a coordinated way, based on a Memorandum of Understanding, with each party fulfilling their agreed tasks.

However, contrary to large facilities in other fields, in particular high energy accelerators and space projects, no experience exists with international collaboration in the construction of ADNS.

### 3.6. Examples for collaborations on ADNS on a national scale

While no experience exists so far with constructing ADNS in international collaborations, the two ongoing projects, SNS and JSNS, are good examples for task sharing on a national level. For JSNS, two major Japanese research laboratories joined forces to construct a new facility that includes ADNS (spallation neutron source JSNS, and transmutation research facility) within a energy physics research facility (JPARC). The knowledge at JAERI in the field of nuclear engineering, based on their experience with reactors, and KEK's expertise in accelerators and in operating and utilizing the KENS spallation neutron source and high energy physics facilities over many years, complemented each other extremely well to cover all the skills necessary to build a high power spallation neutron source.

In the case of the American source, SNS, the level of collaboration involved is even more impressive. The accelerator system alone involved 4 different national laboratories (Lawrence Berkley for the front-end, Los Alamos for the conventional linac, Jefferson for the superconducting linac, and Brookhaven for the accumulator ring). Oak Ridge and Argonne collaborate on the development of the target/moderator/reflector systems and initial suite of instrumentation. At least two of the instruments at the SNS are being developed in international collaborations.

A network-like co-operation on the international scale with relevance to the present context is the IFMIF-Initiative [4]. The technical concept for this facility foresees utilization of the stripping process of 40 MeV deuterons by lithium, to produce a very forwardly peaked intense flux of neutrons with an average energy around 15 MeV. Such a primary neutron source, although intended for a different use in IFMIF, would also be ideal for efficient coupling of a moderator. The concept is, therefore, of interest also in the present context. So far the work was based on “voluntary” contributions from partners. The next step (“EVEDA-CODA”-phase) clearly requires stronger co-ordination and leadership with executive power.

### 3.7. Organizational and management issues in networking

Contrary to existing user program schemes, which are generally supported by individual funding agencies, a network would aim at pooling resources among independent entities, and be based on contractual agreements between these entities. There would be a joint planning and scheduling scheme, and regular reporting and co-ordination meetings to monitor progress and decide on new activities.

The way forward:

Introducing ADNS facilities in developing nations will be greatly facilitated through the formation of networks like the ones described above (among developing nations, as well as among developing nations and more developed ones). Forming such a network will require a number of actions:

- Identification of possible stakeholders in developing and developed countries
- Analysis of the stakeholders’ research goals and priorities relevant to ADNS
- Training of scientists and engineers on existing facilities (“Awareness of needs” and deployment of skills)
- Selection of a source concept based on the stakeholders’ needs
- Support for interested parties on the scientific and technical level
- Supporting the building of a suitable infrastructure and facility management culture
- Planning of “baseline” suite of research opportunities
- Setting up of funding agreements and site selection
- Construction of “network nodes”, if possible anchored to existing facilities
- Expansion of the network.

The IAEA can play a significant role in first three of these points (for instance this meeting is a first step towards the identification of possible stakeholders in developed nations). Once suitable stakeholders have been identified, and initial priorities established, the IAEA should also be able to aid in the education and training of scientists in developing nations and in the bilateral exchange of information regarding needs and capabilities. It would then be up to the members of the network to develop the appropriate source design and other steps.

## 4. SOURCE OPTIONS AVAILABLE FOR ADNS FACILITIES

A number of different technologies can be used to produce the neutrons needed to use the techniques identified above. In the past, small and medium-scale research reactors have been used in a variety of settings to provide some subset of the above techniques in particular locations. As a result of advances in accelerator, neutron optics and detector technologies ADNS are now a feasible alternative to such reactors for many applications. It has been recognized for some time that accelerator-based systems offer a route for increasing the effective flux available on samples in certain neutron scattering experiments above that achieved at the world’s premier reactor sources (see Fig. 1). These high-power ADNS facilities [5,6] utilize moderate-energy (of the order of 1GeV) particle accelerators to produce neutrons through the very efficient nuclear spallation process (neutron evaporation from heavy nuclei induced by collision with high-energy particles), and consequently such facilities have substantial capital and operating costs. The potential value of ADNS for lower power sources (more comparable to research reactors with power levels from 100kW to 2MW) has not been as well established. Nevertheless, a number of possible technologies for producing neutrons with low to moderate flux exist. This is a welcome result, given the political and economic problems that have become associated with the construction of new research reactors. Here we compare a number of these accelerator-based technologies, with an eye toward identifying candidates for use in neutron facilities, the capabilities of which would be comparable to those of these small to mid-scale research reactors.

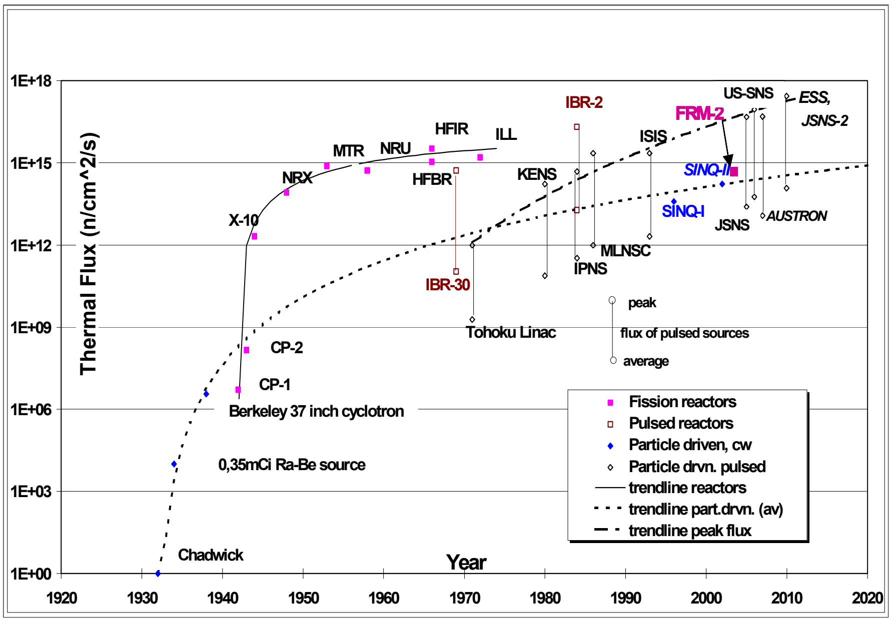

*Figure 1. Thermal neutron flux available at various neutron sources as a function of time since Chadwick's discovery of the neutron. For pulsed sources, the vertical bar indicates the range spanned from the average flux to the peak flux available. Depending on the experiment being considered, the relevant parameter for comparison to a steady-state source could be on either extreme of these bars (or indeed somewhere in the middle). Italics indicate proposed projects.*

The overall importance of ADNS to the field of neuron scattering is displayed in Fig. 1, where it can be seen that the flux available from steady-state reactors has not increased appreciably over the last three decades (and will not in the future), while the available flux at ADNS has increased considerably and has a potential to become even higher in the future.

Commercially produced turn-key neutron sources are readily available with source strengths up to $10^{13}$ n/s (e.g., AccSys Technology, Inc. model PL-11 [7]). Low-power neutron sources, with source strengths up to $10^{14}$ n/s, such as the Low Energy Neutron Source (LENS) facility, now under construction at Indiana University in the U.S.A., require a local capability in accelerator technology and engineering, and a capital investment in the range of \$10M to \$30M, with operating costs that are 10 to 15% of the capital cost. Medium-power pulsed neutron sources (e.g., ISIS in the U.K., and the Lujan Center in the U.S.A.), with source strengths up to $10^{16}$ n/s, require substantial infrastructure to design and construct. Costs associated with a medium-power facility are an order of magnitude more than that of a low-power facility.

For some limited applications, it may be possible to utilize the most economical sources (D-D and D-T), but such sources are unlikely to be adequate for a more general use facility, due to their limited flux. At the other end of the spectrum, spallation sources, which are driven by accelerators with beam energies >150 MeV, are presently unlikely to be a viable option for developing countries due to their high cost of both construction and operation. Looking to the future, alternative accelerator technologies (such as the spoke cavity resonator and the Fixed Field Alternating Gradient Synchrotron (FFAG)) may reduce the cost of such facilities to the point where they could be considered for less than continent-scale facilities, but these technologies are not yet mature enough for consideration here. It should also be noted, however, that the substantially greater shielding requirements, activation levels, and decommissioning concerns associated with spallation sources may still rule them out in many situations, even if the accelerator costs can be reduced considerably through these new technologies. Furthermore, for some time to come, it can also be expected that these newer technologies would impose greater demands on local expertise in the relevant technologies (such as RF power, ion source and accelerator operation/maintenance, etc.).

The opportunities for neutron production provided by (p,n) and (d,n) reactions have been recognized for some time [8], but only recently have suitable accelerators been available at reasonable cost. Neutron producing reactions from protons impinging on Be, have low thresholds (roughly 2 MeV), whereas the (p,n) reaction in Li and (d,n) reactions in both Li and Be are exothermic. These reactions have relatively large cross sections and therefore substantial production can be realized with low-energy, high-current accelerators. Furthermore, as the projectile energy rises above 20 MeV, the neutrons are not produced isotropically, but rather are directed primarily in the forward direction, which affords opportunities to increase the coupling of the moderator to the primary source. This is particularly true for the case of the deuteron reactions.

Significant technical obstacles exist in the optimization of sources based on these reactions. At the power densities needed for significant neutron production, a Li target will be a volatile liquid. Technologies for dealing with this have been proposed [4], but these are likely to require substantial development. Solid beryllium targets for these systems are possible, due to the high melting point and good thermal conductivity of this metal. However, the mechanical properties of Be are such that care must be given to the target design, in order to limit thermal stress.

Accelerator options available within the energy range of interest considered here include linear accelerators and cyclotrons. Commercially produced cyclotrons are readily available at reasonable cost, but they produce continuous beams, whereas linear accelerators can provide pulsed beams. Consequently, a linear accelerator can be designed for substantially larger peak currents than a cyclotron delivering the same average current. As noted above, a pulsed beam provides opportunities for more efficient instrument design at a given average current, and therefore linear accelerators are likely to be the most attractive option for these sources. Typical linear accelerators consist of an ion source coupled to a Radio Frequency Quadrupole (RFQ) which accelerates the particles up to 2-4 MeV, at which point they are fed into a drift-tube linac. These accelerators can be designed to accelerate either protons or deuterons. Therefore, this becomes another system design question that must be considered. Once the deuteron energy exceeds 2.3 MeV in the accelerator, (d,n) stripping reactions on the copper components can lead to the activation of the accelerating structure, which forces severe constraints on the allowable losses for deuteron beams, way beyond those needed for proton beams. An accelerator designed for deuterons does have an advantage in so far as the same structure can be used to accelerate protons, albeit at lower energy, whereas the reverse may not be true due to problems with activation.

Table 1 summarizes various classes of neutron sources with order-of-magnitude estimates for their production rates and costs. The first three options are based on commercially available sources, whereas the latter three are systems that would require substantial construction efforts.

Table 1. Neutron producing nuclear reactions

| SYSTEM | Reaction | Beam Energy (MeV) | Beam Power (kW) | Neutron Production Rate (n/s) | Cost (approximate) |
|---|---|---|---|---|---|
| D-T | $T(d,n)^4He$ | ~0.3 | 0.05 | $10^9$ | \$100K |
| AccSys DL1 | Be(d,n) | 1 | 0.12 | $10^{10}$ | \$0.5M |
| AccSys PL11 | Be(p,n) | 11 | 11 | $10^{13}$ | \$3.5M |
| LENS | Be(p,n) | 13 | 30 | $10^{14}$ | \$20M |
| Model A | Li(d,n) | 20-30 | 100 | $10^{15}$ | >\$50M |
| Model B | Spallation | 400-1000 | 100 | $10^{16}$ | >\$500M |

Some of the characteristics that should be considered in selecting one of these options over the others include:

- **Operational complexity**. Turn-key systems offer the clear advantage of operational simplicity when compared to one-of-a-kind systems. However, development of expertise in the areas of accelerator and target technology may be a motivating factor for acquiring an accelerator-driven neutron source, and commercial, off-the-shelf systems do not offer the opportunity for developing such expertise.
- **Shielding requirements.** Prompt neutron and gamma radiation increases with increasing beam energy. The maximum energy of neutrons produced will match the beam energy (or, in the case of some lower-energy reactions, exceed it by several MeV). Yet, neutrons with energies greater than ~20 MeV are very difficult to shield. This is perhaps the primary drawback of spallation sources, where the beam energy exceeds 150 MeV.
- **Activation/Decommissioning.** Higher intensity neutron sources will lead to higher activation of structure near the target, including local shielding. The zone of activation becomes larger as energy of the neutrons produced increases above 30 MeV, because these neutrons penetrate more deeply into shielding. In this respect, the decommissioning costs will increase with increasing beam energy.

- **Accelerator Engineering**. For neutron sources other than turn-key systems, expertise in accelerator physics and engineering will be required to design, construct and operate an accelerator-driven neutron source. The development of this expertise, or application of existing expertise to the construction of a neutron source, should be viewed as one of the benefits that developing countries would derive from funding such a source.
- **Target Engineering.** The design of a neutron production target requires expertise in the areas of nuclear and mechanical engineering. This is an area that is crucial to the successful development of source of the latter three categories in Table 1 and would be an ideal area for collaboration between the host institution and others.

### 4.1. Model sources considered

The turn-key systems identified above are clearly the least complex of the various options, but they can be limited in terms of the techniques they can support. D-T sources are very portable and ideal for applications such as detector development, well-logging, and perhaps radiography. These sources also have a disadvantage that their tubes often have a limited lifetime. The low-power (p,n) and (d,n) sources have greater intensities, significantly longer target lifetimes, and have been marketed for a variety of purposes, including radiography, activation analysis, and medical applications. In many cases, the same accelerator may be used to produce medical isotopes such as $^{18}$F. So these systems have the added advantage of serving dual purposes.

With the higher power sources (such as LENS, and the model A), some neutron scattering techniques become feasible. The operating energy of these sources is an important consideration. The (p,t) reaction on Be has a threshold energy of roughly 13.5 MeVAbove this energy substantial radioactivity builds up in the target over time. On the other hand, if this is not an overriding issue, going to higher energies opens up other possibilities, such as using the same accelerator for the production of greater range of industrially useful isotopes, such as $^{57}$Co and $^{201}$Tl, in addition to an increased neutron flux. For a fixed proton beam power, the useful neutron flux available from sources such as this can be varied by as much as a factor of 3-4, by choices made in the moderator/reflector design. For instance, the use of a fully coupled Be/graphite reflector can increase the average thermal flux by a factor of two over that available from a water reflector, but this gain comes at the expense of a much broader emission time distribution. Situations where radiography and neutron activation are the dominant applications may be best served by a Be/graphite design, whereas a site more interested in scattering applications, would more likely want to opt for a design employing a partially coupled Be or water reflector.

The systems marked “Model A” and “Model B” are considerably more speculative in their design than are the other four. Model A represents the likely ultimate limit for (d/p,n) sources. Making a source with these characteristics would involve a considerable investment in the accelerator and its associated power systems, and it would also require a great deal of engineering to develop a practical target design. Although the nuclear reactions at the heart of such a source are known to be forward peaked, it would take more detailed studies to asess how much of a gain in thermal flux could be realized from the increased coupling to the moderator available in such a source. There is an opportunity for research in identifying the optimal configuration for sources of this general type, and this area could provide fertile ground for the type of synergistic interactions between researchers in developing countries and those at existing sources that was described in the previous section. Model B represents a possible entry-level spallation system. As described above, spallation sources introduce complications regarding shielding and decommissioning that must be addressed. Nevertheless, this class of system is included here for sake of completeness and because it ultimately opens the route to higher performance. It should also be remembered, that the cost of developing such a source could change dramatically, if new more economical accelerator technologies become available.

# 5. RESEARCH AND DEVELOPMENT OPPORTUNITIES

## 5.1. Instruments

### *5.1.1. SANS (Small Angle Neutron Scattering)*

Typical SANS instruments probe the atomic structure of materials over length scales from one nano-meter, to a few hundreds of nano-meters.Using this technique, the nano-scale structures of various materials can be measured, such as the shape and size of a polymer chain inside plastic materials, super molecular structures, precipitation structure in alloys, micro-domain structures in magnetic materials, etc.

Compared to X rays, neutrons have relatively large cross sections for light atoms, such as hydrogen, oxygen, carbon and nitrogen, the constituent atoms of organic materials, or soft-matter. In X-ray scattering, such light elements can be very difficult to detect in the presence of atoms with greater atomic number. For neutrons, the macroscopic cross section can in many cases be dominated by these light elements. Moreover, the scattering lengths for hydrogen and deuterium are quite different - hydrogen has a negative value and deuterium has positive one - providing opportunities to use the so-called contrast variation technique to provide element-specific structural information through isotope substitution. Neutrons have another unique feature, their "spin" associated with a magnetic moment. Neutron spins interact with electron spins, thus providing unique information about magnetic structure, or spin configuration, in magnetic materials.

There are many applications using the SANS technique, especially in the industrial area. Fuel cell and battery development are good examples. The nano-pore structure of electrolytes can be investigated in various conditions to develop better materials. This is also applicable for many types of food, like chocolate and milk. Such kinds of food are complex nano-size emulsions, whose details can be related to the quality of such food stuff. Many fundamental research studies with SANS can be performed at small and medium ADNS, such as polymers, micelles, emulsions, protein solutions, magnetic nano-phase, etc.

A SANS instrument is a perfect tool for a small or medium ADNS that is equipped with a cold source with wavelengths on the order of 1 nm or greater. It could also be installed at an ambient temperature thermal moderator beam line, but in this case it would be difficult to perform measurements below 0.01 $A^{-1}$. With a flux at the sample of as little as $10^4$-$10^5$ neutrons/$cm^2$/s and with a reasonable collimation of say 1-3 mrad useful research can be performed in a variety of fields.

Possible areas of research include:

- Structure of soft matter
    - polymers, rubbers, polymer blends
- Structure study of emulsions/micelles and porous materials

  - paint, milk, chocolate,
  - cement
- Micro structure of alloys
- Composite and nano-structured materials
- Micro-domain magnetic structures

### *5.1.2. Reflectometry*

When neutrons are incident on a surface at a very shallow angle of incidence, they are reflected. By measuring the reflectivity as a function of angle, and wavelength, the nano-scale scattering-length density variation perpendicular to the surface, may be determined as a function of depth. Using this technique, one can measure, the thickness of single-layer surfactant on liquid surfaces, interface structure of multi-layer metallic coatings, polymers, or magnetic materials, etc..

There are many industrial applications that can benefit from using small/medium size ADNS. Catalysts would be a good example, as would be adhesives.

The flux requirement varies from application to application, depending on the information required. If critical angle is the only information needed, a neutron flux of $10^4$ neutrons/cm$^2$/s would suffice, with a few mrad collimation in one dimension, and ten times more beam divergence perpendicular to it. Reflectivities down to $10^{-6}$ are accessible with about $10^5$ - $10^6$ neutrons/cm$^2$/s peak flux with the above collimation. There are many applications that can be served by using this kind of instrument. Again, a cold neutron moderator is desirable, but a thermal neutron beam can also be used for this kind of instrument.

Possible areas of research include:

- Catalysts
- Adhesives
- Surfactants on liquid surfaces
- Interface structure of magnetic multi-layers
- Polymer-polymer interfaces
- Metal surfaces.

### *5.1.3. Powder/polycrystalline diffraction and strain measurements*

The powder diffraction technique for crystallographic characterization of materials and materials composites, or mixtures, stems from the early days of X-ray diffraction. Since thermal neutrons are in the same wavelength range as the X rays from a conventional X-ray tube, the Bragg diffraction from neutrons in principle accesses the same resolution regime, and the same structural information as X rays. The difference, or the important complement, is related to the different response of neutrons to materials. The ability of neutrons to penetrate deep into materials allows using closed, massive, sample containers (cryostats, furnaces, pressure cells etc.). The strong interaction of neutrons with light nuclei, in particular hydrogen, gives some elements a strong weight in the diffraction pattern which are almost invisible to X rays. The magnetic moment of neutrons also enables scientists to measure magnetic moment correlations, to distinguish magnetic and crystalline structure, and correlations on the lattice (atomic) scale, etc.. Again, the sensitivity of neutron scattering to isotopes is an important asset in solving complicated structures.

One special application of a powder diffraction instrument is strain/stress analysis in structural components, e.g. at and around welds, in machine parts as fabricated, and after prolonged service. This special application is in high demand among engineers for guidance in design, structural optimization, manufacturing quality control and lifetime predictions. Strain mapping imposes special requirements to the instrument design, such as high lattice spacing resolution, a scattering geometry with near $90^0$ take off for the relevant Bragg-reflections (for precise definition of the gauge volume within the sample), precise sample translation devices for the component under investigation, and load bearing capacity for heavy components (up to some 100 kg).

Texture measurements fall into the same category of application as strain measurements. The demand for this application comes from the same industry groups, including applied mechanical fabrication technology, and it imposes similar requirements on the instrument design.

These instrument requirements should be kept in mind when proposing, and designing a powder diffraction instrument at a medium, or low flux neutron source.

An innovative design for a time-of-flight (TOF) based powder/polycrystal diffraction instrument dedicated for strain mapping, but also allowing high-resolution powder diffraction, was commissioned in 2003 at the SINQ spallation neutron source at PSI, Switzerland [9]. This instrument design could well serve as reference concept for a powerful instrument for such applications at a low to medium flux source, regardless of the mode of source operation, be it pulsed or continuous.

The neutron flux requirement for this instrument is comparable to that needed for the SANS instrument, but the wavelength range of interest tends to be narrower, and centered on shorter wavelengths, around 0.1 to 0.2 nm.

Possible research areas include:

- Crystallographic structure determination and refinement for both conventional and composite materials
- Magnetic materials/magnetic structures on lattice/atomic scale
- Texture
- Strain-stress mapping.

### *5.1.4. Radiography*

Neutron radiography/tomography works exactly in the same way as X-ray radiography/tomography. A collimated beam passes through an object, and the 'shade' picture is monitored behind. The object may be static, or rotated stepwise, the latter allowing 3-dimensional reconstruction (tomography). Although the principle is very simple, well known, and has been widely applied for decades (at least with X rays), the rapid development of new imaging technologies in the past 5 years, combined with the availability of specially tailored neutron beams (like at SINQ of PSI), has opened a variety of new fields of application. This has been a very interesting development for both science and technology.

Again, the particularly strong interaction of neutrons with light elements (H, Li, B and others) can make devices in the interior of an object clearly visible, which would disappear in a fuzzy background if using X rays. In many cases, it is such devices, which are of particular interest to be inspected in detail. Here again, the complementarities of X rays and neutrons must be emphasized.

Further, with the computer power presently available in combination with the high penetration potential, neutron tomography allows destruction free three dimensional analysis of complicated structures, or devices, with high resolution and separating selected inner components. Besides identifying such internal components, or qualifying their integrity (like seals in valves, igniters and explosives in pyrotechnical devices), neutron tomography can be applied for "reverse engineering", i.e. analyzing the design of components, which are physically not, or not easily accessible.

The strong interaction with hydrogen makes neutron radiography a very useful, and partly unique tool for applications where hydrogen (or water) is dominantly involved. For example, it allows following in-vivo, the plant-root growth in soil, where the influence of soil contamination, or poisoning, on the root growth can directly be imaged. Other applications include the study of water ingress, or water diffusion in construction materials, such as wood and wood products or visualizing the flow of fluids in fuel cells and conventional engines.

The non-destructive nature of neutron radiography, combined with the strong interaction between neutrons and light elements, is a valuable prerequisite for physical investigations relevant to cultural heritage. Examples include proof of originality (or discovering fakes), analyze ancient manufacturing techniques, inner signatures, hidden devices, etc.

Most applications of neutron radiography/tomography do not depend on a particularly high neutron flux. More important is a well collimated, widely open neutron beam in a low-background environment. On the other hand, to be competitive, neutron radiography stations must be equipped with modern, state-of-the-art imaging techniques and computing power.

Possible research/application area:

- Non-destructive inspection and testing
- Reverse engineering
- Engine development (imaging inner working parts and functions)
- Fluid dynamics in closed systems
- Construction/building physics
- Life science
- Soil physics/agriculture
- Archeology.

### *5.1.5. TOF-instrument for incoherent-inelastic measurements*

Inelastic scattering studies are difficult to perform at small and medium flux neutron sources, especially for coherent-inelastic scattering. However, there are broad possibilities of using incoherent-inelastic scattering techniques. Since hydrogen has an extraordinarily large incoherent cross section of 80 barns in the thermal energy regime, it is possible to have a spectrometer that can access the neutron energy range from sub-meV to a few hundred meV. An inverted geometry crystal-analyzer spectrometer would be a candidate.

Chemical vibration spectroscopy is one of the available research fields.

A neutron flux of at least$10^6$ n/cm$^2$/s or more, with a 3-10 mrad collimation in horizontal and vertical direction, is needed to undertake this kind of measurement.

### *5.1.6. Activation analysis*

Activation analysis is a well-established tool to quantify trace elements, and materials with relatively high precision and sensitivity. To make a neutron source that is suitable for this kind of application one has to choose the design of the target moderator system such that it provides sufficient and suitable positions to insert samples to be analyzed. The neutron energy spectrum at this location must be well characterized and stable, for quantitative analysis. More details may be found in an earlier IAEA report [3].

Possible applications are widely spread, including environmental and biological research of trace elements in blood and tissue.

### *5.1.7. Special stations (neutronics engineering/instrumentation)*

Small-power ADNS with a relatively low neutron flux can provide very good opportunities for neutronics engineering research, neutron instrument component development, testing new instrument ideas and new devices.

Such sources would allow optimization studies for target/moderator/reflector assemblies for higher power sources, in combination with neutronics simulation methods. The electron-linac facility at Hokkaido University is a very good example of this kind of application. With only 45 MeV of energy and 3 kW of power, which provides about $6x10^{12}$ $n_f$/s ($n_f$: fast neutrons), and about $6x10^{10}$ $n_{th}$/s ($n_{th}$, thermal neutrons) many new developments on ADNS, particularly of cold moderator development have been performed there.

For design and optimization studies, suitable neutron fluxes may be achieved with relatively modest proton currents, using source designs such as those outlined in section 4. In order to avoid unnecessary radiation doses when modifying the arrangement of the assembly, it is desirable to have as low integral number of protons as possible. In order to perform neutron energy spectrum measurements, one requires about $10^{10}$ $n_f$/s, and for pulse-shape measurements, about $10^{12}$ $n_f$/s.

For detector development, about $10^2$ - $10^4$ n/cm$^2$/s at the detector position is desirable. For testing other neutron optical devices, a relatively good collimation of the neutron flux is needed, of the order of 1-3 mrad in one direction. Neutron flux needs for testing new concepts/instrument ideas varies from application to application. Many studies can be made with relatively low fluxes, $10^2$ - $10^4$ n/cm$^2$/s neutrons, and with about 3 mrad beam divergence in one direction.

Possible research/application area:

- Neutronics/facility development
    - Design/optimization of target/moderator/reflectors
    - Moderator materials
    - Cross section measurements

- Device development
  - Novel devices/instruments
  - Detectors
  - Collimators
  - Neutron guides/neutron optics

- Testing new concepts
  - Prepare experiments on high-power sources
  - Sample characterization (quality and orientation)
  - New sample environments.

### *5.1.8. Medical applications*

Possible medical applications of spallation neutron sources are the production of radioisotopes for diagnostic purposes and for neutron capture medical therapy. It should be noted that this therapy depends on the development of pharmaceutical products, which can successfully be deposited in a tumor. This development is a task of molecular biology, and suitable drugs to achieve this goal have not yet been developed. For the production of isotopes, ADNS have the added advantage of offering also a charged particle beam because some isotopes may be more readily produced using the charged particle beam, rather than solely through neutron activation.

## 5.2. Education

One of the primary educational issues of building and operating an accelerator driven neutron source is that the scientific and technical staff involved in such projects have to utilize a wide knowledge. This includes accelerator technology, nuclear engineering, neutronics of target/moderator systems, control system, safety considerations, health physics, dosimetry, etc.

Small to medium power ADNS can provide good opportunities for educating young scientists. They could acquire practical knowledge, and broaden their general horizon in science and technology. Education of scientists at all levels in the techniques of neutron scattering, will also introduce them to complementary techniques employing X rays.

# 6. CONCLUDING REMARKS

Accelerator driven neutron sources (ADNS) provide an effective new means for constructing neutron sources for multi-purpose applications on a variety of scales. Such sources offer unique tools for basic and applied research in physics, chemistry, biology, material science, medicine, energy production, nuclear physics, etc. These sources avoid many of the local and global political problems associated with nuclear reactors, while providing opportunities for much of the same education and training as can be found with those reactors. Moreover, due to the time structure of the neutron beams produced by ADNS, these sources can be much more powerful and versatile facilities for research and training in advanced technological areas than are the existing suite of aging research reactors. Starting with KENS (Japan) in 1980, a number of spallation-based ADNS have been built in several sites around the world (IPNS, USA; ISIS, UK; Lujan Center, USA), and several new facilities are presently under construction. These newer facilities include not only facilities that aim to be the best in the world (SNS in the US, and JSNS in Japan), but also significant sources in China (CSNS expected to be complete in 2010) and a second target station at ISIS (completion 2008), and even one source of the class described in section 4 of this report (LENS, USA, completion in 2006).

The world's high demand for neutrons cannot be met by these few sources alone; a broad network of smaller-scale facilities is needed to make the technology available to a wider community, allow the development of new techniques, and train new users and operators. Such a network will thereby enhance the impact of the major facilities. Moreover, developing nations have a need to expand opportunities in education, research and industrial applications, using nuclear technology, but they do not always have sufficient resources, technology, or human infrastructure to build sources suitable for fulfilling these roles. This presents a number of obstacles for developing nations to design and build these sources. In order to promote the application of ADNS in developing countries, a network of medium energy spallation source facilities is proposed to generate and strengthen international cooperation in this area. Cooperation must include training scientists, engineers, and users coming from developing nations, but should also include individuals from developed nations with experience in the relevant technology.

The case of the Chinese spallation neutron source (CSNS) may be taken as an example of this sort of collaboration. There are some 1000 universities in China, but only a few offer special courses in accelerator physics. Therefore, some time will be required to train the engineers and scientists who can design and build the CSNS facility. Fortunately, in the interim, international collaborations have given the CSNS project considerable assistance. For instance, experts from several existing ADNS facilities participated in a review of the CSNS target station. JAERI provided Monte Carlo simulation codes, and others provided important technical support in target engineering. Following these interactions, the Chinese Academy of Sciences joined the ICANS collaboration in 2003.

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# ABBREVIATIONS

| | |
|---|---|
| ADNS | Accelerator driven neutron source |
| BROND-2 | Russian evaluated nuclear data |
| CENDL-2 | Chinese evaluated nuclear data list |
| ENDF | Evaluated Nuclear Data File (maintained at LANL) |
| ESS | European Spallation Source |
| FFAG | Fixed field alternating gradient synchrotron |
| HERMES | A system of interrelated Monte Carlo codes for simulating particle transport, generated in Juelich Germany |
| ICANS | International Collaboration on Advanced Neutron Sources |
| IFMIF | International Fusion Materials Irradiation Facility |
| ISIS | the pulsed 200 kW spallation source at Rutherford Appleton Lab in the UK |
| JEFF | European evaluated nuclear data file |
| JENDL | Japanese evaluated nuclear data list |
| JPARC | Japanese Particle Accelerator Research Complex, under construction at the JAERI Tokai site, Japan |
| JSNS | Japanese Spallation Neutron Source (under construction in Japan) |
| LCS | LAHET Code System, a Monte Carlo code for simulating neutron transport |
| LENS | low energy neutrons source (under construction in Bloomington, IN, USA) |
| MCNPX | A Monte Carlo computer code for simulating neutron transport, written in Los Alamos. USA. |
| RFQ | radio frequency quadrupole |
| RHF | high flux reactor (Reacteur à Haut Flux) at the Institut Laue Langevin in Grenoble France |
| SANS | small angle neutron scattering |
| SINQ | 1 MW cw Spallation Neutron Source in operation at PSI since 1997 PSI Paul Scherrer Institute |
| SNS | spallation neutron source (under construction in Oak Ridge TN, USA) |
| TOF | time of flight |

# SUMMARIES OF PAPERS PRESENTED AT THE MEETING

# THE SPALLATION NEUTRON SOURCE

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The Spallation Neutron Source (SNS) is a 1.4 MW pulsed neutron spallation source under construction at Oak Ridge National Laboratory. The project is in the fifth year of a seven-year construction phase, with facility operations scheduled to begin in 2006. The SNS will deliver a 60 Hz, 1.4 mA average current, 1 GeV beam to a liquid mercury target for short-pulse neutron scattering experiments. A collaboration of six national laboratories (ANL, BNL, TJNAF, LANL, LBNL, ORNL) is responsible for the design and construction of the various subsystems. The SNS has been planned as a dedicated user facility for neutron scattering research. As such, it is expected to eventually accommodate 1000 to 2000 national and international users per year, carrying out research in such diverse fields as materials science, condensed matter physics, chemistry, mineralogy and geology, and biology.

The accelerator chain consists of the following components. An $H^-$ ion source provides a 65 keV beam of 50 mA peak current to the linear accelerator (Linac). This beam is accelerated in four separate accelerating structures, each of which is optimized for a particular beam energy range. First, a Radiofrequency Quadrupole (RFQ) accelerates the beam to 2.5 MeV. Second, a Drift-Tube-Linac (DTL) accelerates the beam to 87 MeV. Third, a Coupled-Cavity-Linac (CCL) accelerates the beam to 186 MeV. Fourth, a Superconducting Linac (SCL) accelerates the beam to 1 GeV. An RF pulse is applied to the Linac accelerating structures to provide a 1 msec long beam pulse. This high-energy beam is transported to an accumulator ring that has a revolution time of 1 msec. The 1 msec beam pulse is continuously injected into the accumulator ring in order to compress the beam pulse length to 700 nsec. Once accumulation is complete, the beam is extracted and delivered to a liquid mercury target. The acceleration, accumulation and delivery cycle proceeds at 60 Hz.

The SNS will be the first high-beam-power superconducting proton accelerator, and as such, several technical challenges must be met. First, high gradient superconducting accelerating structures with peak surface electric fields of 35 MV/m and with resonator quality factors in excess of $5.10^9$ will be produced by making use of state-of-the-art niobium handling and preparation techniques. Second, the cavities are dynamically deformed by the strong pulsed-RF fields themselves, which has the effect of changing their resonant frequency during a pulse by a significant fraction of their bandwidth. This detuning effect has important consequences for the design and RF control of the cavities and RF power sources.

The target systems include a mercury target and the associated loop; a moderator system including three cryogenic hydrogen and one ambient moderator surrounding the target within a beryllium reflector; a vessel to maintain an inert atmosphere around the target with 18 ports for neutron beam lines; 10-meter-diameter iron shielding around the target with 18 shutters; heavy and light water cooling loops; remote handling systems; and the associated instrumentation and controls. The mercury target is designed to sustain a time-averaged proton beam power of 2 MW, which is deposited in nearly instantaneous (~1 ms) pulses at a 60 Hz repetition rate. Mercury, rather than a water-cooled solid heavy metal, was selected as the target material for SNS primarily because of its potential for increased power handling capability and greatly reduced waste stream.

The mercury target has a width of approximately 400 mm, a height of 100 mm, and an effective length for neutron production of 700 mm. The mercury is contained within a structure made from 316-type stainless steel. Mercury enters from the back side (side outermost from the proton beam window) of the target, flows along the two side walls to the front surface (proton beam window), and returns through a 206 mm x 80 mm rectangular passage in the middle of the target. The target window, i.e., the portion of the target structure in the direct path of the proton beam, is cooled by mercury which flows through the passage formed between two walls of a duplex structure. In this way, the window cooling and transport of heat deposited in the bulk mercury are achieved with separate flow streams. This approach is judged to be more reliable and efficient (minimal pressure drop and pumping power) than using the bulk mercury to cool the window. A shroud (safety container) is provided around the mercury target. The shroud is a water-cooled duplex structure made from austenitic, 316-type, stainless steel.

The reflector assembly consists of an inner plug assembly and an outer plug assembly. The inner plug is to be replaced approximately every three years, and the outer plug should last the life of the facility. The shielding in these plugs outside of the beryllium consists of stainless steel plates cooled by heavy water in the regions near the target. The three supercritical hydrogen moderators and the water moderator have been integrated into the aluminum structure of the reflector plug assembly containing the beryllium to minimize structure and gaps and therefore increase performance. The cadmium decoupling material on the beam lines and the gadolinium poison in the one decoupled hydrogen moderator have increased thickness to give a three-year life at 2 MW. A simplified constant mass pressure control concept using a cryogenic accumulator for the hydrogen system has been developed.

The vessel that holds the reflector plugs and target comprises 18 beam ports, designed to very tight tolerances in order to have inserts containing neutron beam optics point to the moderator centers. Six of the 18 beam ports have been designed to accommodate 2 instruments allowing a total of 24 instruments.

The guiding philosophy for selection, design, and construction of the neutron scattering instruments at SNS is that every instrument should be best in its class. In addition, where possible, upgrade paths have been designed into each of the initial instruments to enable the instrument ultimately to reach the full potential performance practical with available technology. Standard component designs are being developed and are being used for all instruments as appropriate in order to minimize duplication of design effort from instrument to instrument and to greatly facilitate maintenance and operation of the instruments.

The design of these instruments makes extensive use of bandwidth limiting choppers to provide the flexibility to select the wavelength bands optimized for particular measurements. This is particularly important for matching the instrument capabilities optimally to the 60 Hz source operation. The efforts to maximize instrument counting rates have produced two significant challenges. One is in the massive amounts of data produced and the rates at which these data are generated. The other major challenge is the need for detectors or detector arrays capable of providing the desired spatial resolution, time-of-flight resolution, and counting speed at a reasonable cost.

SNS has been designed to allow upgrade to higher proton beam powers. Complete build out of the superconducting linac will allow a beam energy of 1.3 GeV to be reached and a beam power of 3 – 4 MW. Some of this extra beam power will be diverted to a second target station serving 22 additional instruments optimized for the use of long wavelength neutrons and operating at 15 – 20 Hz.

# ACCELERATOR DRIVEN NEUTRON SOURCES — THEN AND NOW *)

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## Spallation and Spallation Sources

For almost half a century fission based research reactors have served researchers and scientists to obtain otherwise inaccessible information on the structure, dynamics and magnetic properties of matter in its various states as well as on the properties and physics of nuclei. They also served as tools to explore the effects of radiation on the properties of materials and to produce new isotopes or analyse the isotopic composition of elements and many purposes more. These applications made research neutron sources an invaluable tool in the quest of mankind to ever improver their living conditions through increased knowledge. Soon after the most powerful (high flux) research reactors went into operation in the late 60ies and early 70ies of the last century (cf. Fig. 1) it was recognized that further progress in increasing the time average neutron flux would be extremely difficult, due to the heat dissipation of almost 200 MeV per useful neutron in a fission reactor.

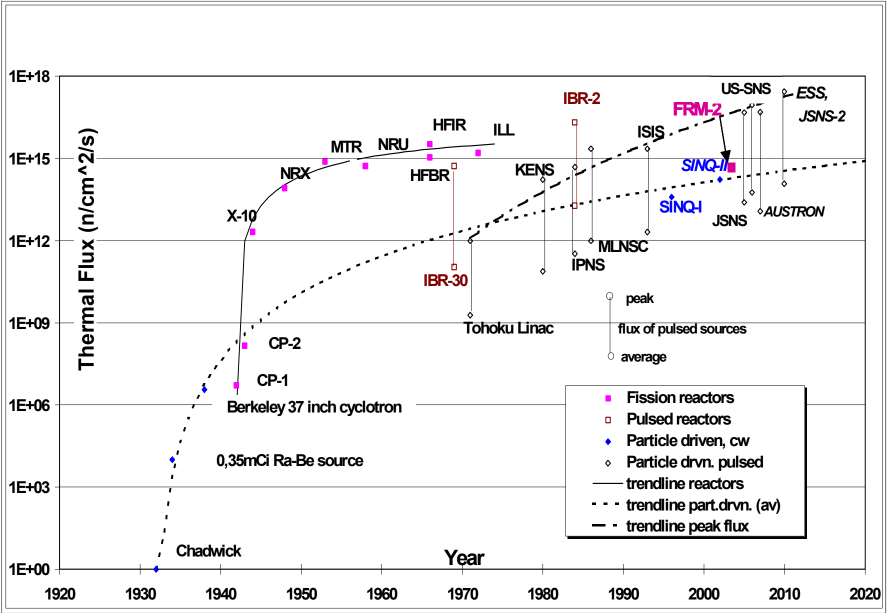

*Figure 1. Development of neutron sources. Italics: proposed projects.*

In this situation neutron source designers started thinking about ways to circumvent this difficulty and it was soon recognized that for many techniques *pulsed operation of neutron sources would be a distinct advantage, allowing to profit from a high peak flux and still being able to work with a relatively modest time average flux*. However, of the various projects for pulsed research reactors proposed in the late 60ies, only the IBR-2 at Dubna, Russia finally

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* A more extensive recent account on the design and technology of spallation neutron sources can be found e.g. in G.S. Bauer "Physics and technology of spallation neutron sources" Nucl. Inst., Meth. in Phys. Res. A 463 (2001) 505-543, from which much of the material presented here was taken.

matured. In parallel, different processes to release copious numbers of neutrons from matter by employing nuclear reactions with accelerated charged particles were being explored. Since these were "parasitic" uses of existing accelerators and many of the then available accelerators were proton synchrotrons that worked in a pulsed mode, pulsed neutron scattering techniques were quickly developing. After exploratory work done at Argonne (USA) and at the Tohoku linac (Japan), the fist spallation neutron source with a full set of neutron scattering instruments, KENS (see e.g [2]) became operational in 1980 at KEK (Japan). Together with IPNS (Argonne) and the LANSCE-facility in Los Alamos (now Lujan Center [3]) it paved the way for the first purpose built spallation neutron source, ISIS, that became operational in the UK in the early 90ies. Today ISIS, with its proton beam power of 160 kW is one of the world's leading neutron facilities and its success has motivated scientists all over the world to propose more powerful spallation neutron sources in the Megawatt range of beam power.

For high performance pulsed neutron sources there are several good arguments to use the spallation reaction, the foremost one being the lower heat per neutron than in other nuclear processes, which opens up the route to higher fast neutron flux density. Furthermore, in addition to the possibility of exploiting a time structure it also gives a large degree of design flexibility on both, the the accelerator and of the neutron source proper to match the neutron output to the users' needs. *Finally, proliferation safety, the absence of criticality issues and actinide waste are important arguments that make spallation neutron sources more easily acceptable.*

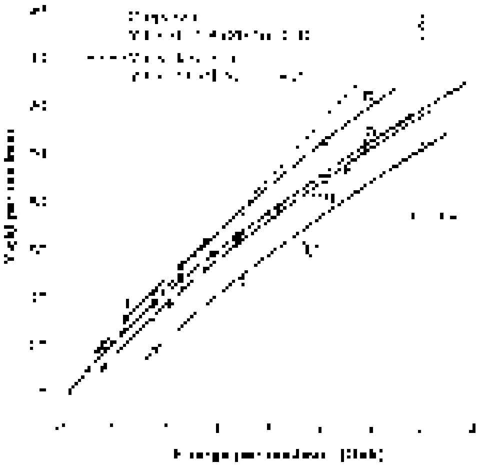

*Figure 2. Measured neutron yield from thick lead targets [4].*

The neutron yield from heavy metals increases with proton energy as shown in Fig. 2, but it does so in a less than linear fashion (in proportion to $E^{0.75}$). Nevertheless, given the current limitation in virtually all types of accelerators, the way to really high performance neutron sources at present seems to be via higher proton energies.

However, the primary neutron spectrum generated in the spallation process extends up all the way to the energy of the proton beam impinging on the target. As an illustration the calculated spectra from a fission reaction and a spallation reaction with 800 meV protons on tungsten are shown in Fig. 3. Measured spectra confirm this finding.

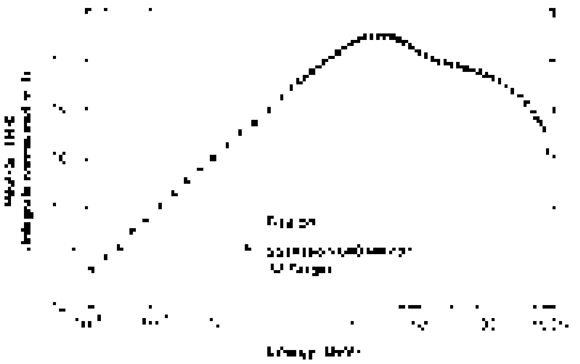

*Figure 3. Calculated spectra from fission and spallation by 800 MeV protons on tungsten (integrated over all angles). The spallation neutrons extend in energy all the way up to the energy of the incident proton, whereas the fission spectrum is confined to energies below ca. 20 MeV. [5]*

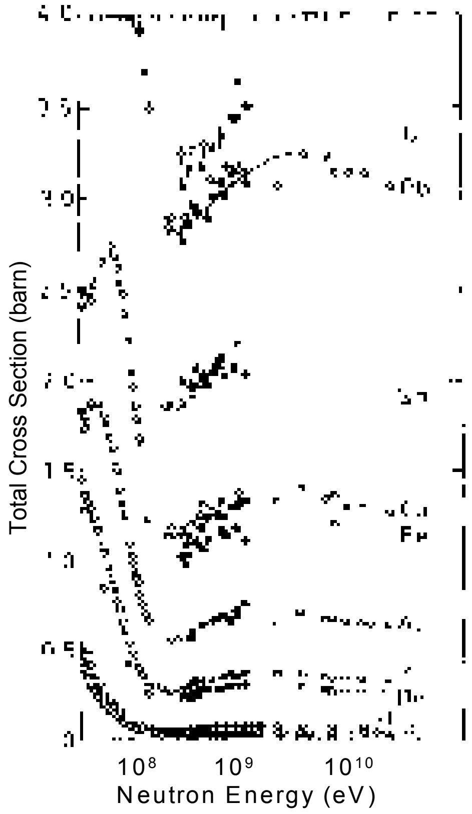

*Figure 4. Energy dependence of the total neutron cross section for different materials.*

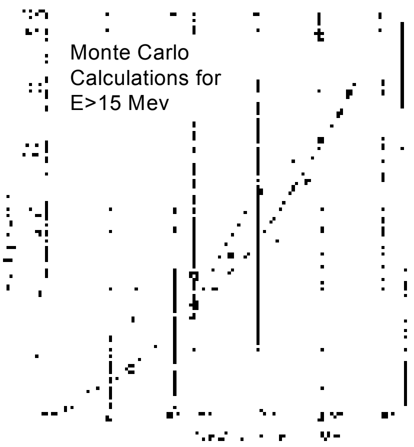

*Figure 5. The build-up factor as a function of incident neutron energy.*

The problem with these high energy neutrons is that they are difficult to moderate and hence also to shield, because, as shown in Fig. 4, the cross sections of virtually all materials have a pronounced minimum around 100 MeV in neutron energy. In particular the cross section of hydrogen, which is as high as 20 barns or more below 100 keV (1 barn at 10 MeV) becomes very low above 100 MeV. This means that the preferred shielding method, namely moderation and subsequent absorption of neutrons is not directly applicable in this case. Instead, the average neutron energy must be reduced through nuclear interactions (secondary spallation) in high density materials. This leads to significant build-up of the neutron population in the shielding material, as shown in Fig. 5.

The dose at a point from which the neutron source is seen under a solid angle $\Omega$ is given by:

$D(\theta) = \Omega \int dE \, \{\Phi(E,\theta) * F(E) * B(E) \, \Pi_i \, [\exp(-s_i/\lambda_i)]$, where

$\Phi(E,\theta)$ is the source spectrum in direction $\Omega$, $F(E)$ is the flux-to-dose conversion factor, $B(E)$ is the buildup factor mentioned above (Fig. 5) $\Pi_i \, [\exp(-s_i/\lambda_i)]$ is the dose reduction by stretches $s_i$ of different materials with attenuation lengths $\lambda_i$ .

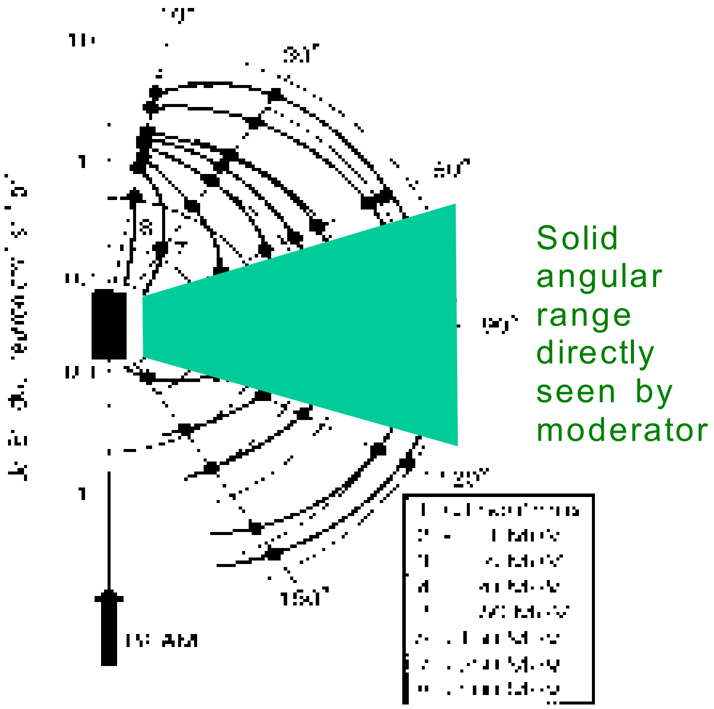
Solid angular range directly seen by moderator

*Figure 6. Measured angular distribution of neutrons in different energy groups for a 20 cm diameter lead target bombarded by protons of 2 GeV [7].*

From this feature it follows that, unlike reactors, spallation neutrons cannot be easily absorbed in a large water pool, but must be shielded by heavy steel and concrete structures which will become rather radioactive on the long run. This is the most serious drawback of spallation neutron sources in terms of accessibility, decommissioning and, of course, cost. Furthermore, since solid targets are generally water cooled, and spallation occurs in all materials, spallation products from the target and the oxygen of the water will be found in the cooling loops, leading to much more difficult loop technology than on a neutron source which do not involve particles with energies above 50 MeV, such as reactors.

An important feature of the spallation neutron spectrum in this context is the angular distribution of the neutrons emitted. Fig. 6 shows a measured distribution for 2 GeV protons on lead. The strong forward peaking of the highest energy neutrons is clearly visible, and so is some self-shielding of the long target. This has two important effects: (1) shielding requirements in the forward directions become particularly serious and (2) the preferred positions for moderators are in the lateral and backward directions relative to the incident beam. In practice the backward direction difficult to access and, since the evaporation neutron leakage distribution has a maximum some 5 to 15 cm downstream of the target head, this is the preferred moderator position.

Contrary again to a reactor, moderators at spallation neutron sources are generally designed to obtain a narrow pulse in time. For this reason, hydrogenous rather than deuterium-containing moderator materials are preferred, because of the much higher slowing down density of hydrogen. The dimensions of spallation source moderators are therefore relatively small, typically 10x10 $cm^2$ viewed face and 5 cm thickness. The angular range of neutron emission from the target seen by such a moderator is relatively limited, as indicated in Fig. 6. Although, in the interest of a tight coupling, moderators are placed as closely as possible to the target, they are generally viewed in a “wing” or tangential geometry, meaning that the extraction beam hole does not see the target behind the moderator. this is done to reduce the fraction of fast neutrons entering the beam tube and requiring heavy shielding of the extracted beam lines although experiments and calculations have shown that this results in about a factor of 2 lower extracted intensity as compared to “slab” or direct (radial) viewing,. The small moderators used on spallation sources only cover a limited solid angle, while useful neutrons (“evaporation” neutrons with energies below 20 MeV) are emitted almost isotropically from the target, as shown in Fig. 6. Although some of the neutrons not captured by the moderators directly can be recovered by placing a reflector around the moderator, it would be a big advantage to have a target which emits neutrons preferably in the direction, where the moderator can be placed. We will return to this question below.

## Neutron Source Drivers

Spallation and other neutron producing reactions with the exception of fission, are endothermic reactions, i.e. energy is consumed in the process and needs to be supplied by an external source driver, i.e. a particle accelerator. There are several different types of accelerators with different characteristics, which make them more or less suitable as spallation source drivers, depending on the desired source characteristics:

**Linear Accelerators** (linacs) use a once through passage for the accelerated particles. There length therefore depends on the desired end energy (a linac of 1 GeV final energy is more than 500 m long). They are limited in peak current to about 100 mA by space charge effects in the low energy part. While they can be operated in a very wide range of pulse lengths and repetition rates and are certainly an option for low power sources, such as LENS [8], their time average current is a product of their peak current and duty cycle.

In practice, linacs alone are suitable for long pulse neutron sources with pulse lengths of 1 or a few milliseconds. If short pulses at high intensity are desired, a **pulse compressor** (as in the case of SNS, cf. [9] must be added, which is filled over a large number of turns and emptied during a single revolution of the stored particles.

**Rapid Cycling Synchrotrons** (RCS) are another option to obtain short pulses at high intensity. They are similar in design to linacs with compressor rings. However, after injection in the ring is completed, the RF frequency and magnetic field strength in the ring bending magnets are increased with time and the particles are further accelerated before being extracted in a single turn. RCS require less installed RF-power than linacs of the same final energy but are also less flexible in their operational parameters. RCS are the drivers for ISIS in the UK and the new Japanese JSNS [2].

**Cyclotrons** are a cost effective way of building high power accelerators up to a few MW power. Their injection energy is usually very low, which means that their peak beam current is even more limited than in a linac. Acceleration is over many turns like in a synchrotron, but the magnetic fiels and RF-frequency are constant in time and the radius of the particle orbit in the machine increases as the energy grows. Cyclotrons are suitable for essentially cw neutron sources as SINQ [10], which is presently still the world's most powerful spallation neutron source, and is very similar to a reactor in its mode of utilization.

**Fixed Field Alternating Gradient Synchrotrons** (FFAG) are a sort of hybrid between a synchrotron and a cyclotron in that their RF-frequency is varied with time while their magnetic field is kept constant and the radius of the particle orbits increases during acceleration. While the concept was successfully demonstrated for electrons in the late 1950ies, serious development work for a proton-FFAG has only started recently at KEK in Japan (cf. [2]). Due to their time constant magnetic field FFAGs can operate at much higher pulse repetition rates than RCS's and, if pulse stacking can be successfully accomplished, they may well become cost effective drivers fot future spallation sources.

Of course, the question which accelerator concept to select for a given neutron source depends on many boundary conditions and no general answer can be given. In particular, if reactions other than spallation are to be used for neutron generation (see below) , the required particle energy is usually of a few tens of MeV only, and in this case a linac is a more or less obvious solution.

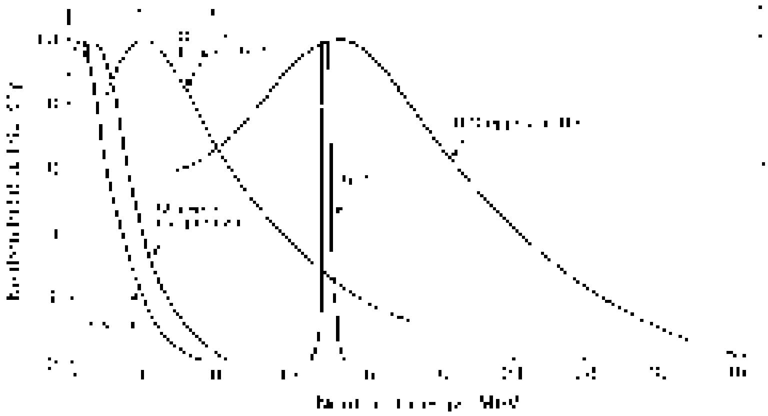

*Figure 7. Neutron spectra from different reactions.*

## Alternative neutron producing reactions

While, barring fission for the time being, spallation by energetic protons in targets of heavy metals is the preferred reaction for the design of high flux (pulsed) neutron sources, there are a number of other nuclear reactions that have lower threshold energies and that can be and have been used to build research neutron sources with specific properties. The most important ones are listed in the Table. Examples of the neutron energy distributions obtained are shown in Fig 7. It is important to note that these reactions generally have an even higher energy release per neutron than fission.

Table 1. Neutrons producing nuclear reactions

| **Nuclear process** | **Example** | **Neutron yield** | **Heat release** (MeV/n) |
|---|---|---|---|
| D-T in solid target | 400 keV deuterons on T in Ti | $4*10^{-5}$ n/d | 10 000 |
| Deuteron stripping | 40 MeV deuterons on liquid Li | $7*10^{-2}$ n/d | 3 500 |
| Nuclear photo effect from $e^-$-bremsstrahlung | 100 MeV $e^-$ on $^{238}$U | $5*10^{-2}$ n/$e^-$ | 2 000 |
| $^{9}$Be (d,n) $^{10}$Be | 15 MeV d on Be | 1 n/d | 1 000 |
| $^{9}$Be (p,n;p,pn) | 11 MeV p on Be | $5*10^{-3}$ n/p | 2 000 |
| Nuclear fission | fission of $^{235}$U by thermal neutrons | 1n/fission | 180 |
| Nuclear evaporation (spallation) | 800 MeV p+ on $^{238}$U<br>on Pb | 27 n/p<br>17 n/p | 55<br>30 |

This means that, if high time average neutron fluxes are desired, target cooling may become very demanding, but in the low-to-medium flux regime the problems may be manageable.

## The IFMIF neutron source

In order to exemplify how the specific properties of a nuclear reaction may be taken advantage of, we briefly describe here the concept of the International Fusion Materials Irradiation Facility(IFMIF, [11]. This source aims at having one limited volume of very high neutron flux in which materials irradiation by neutrons (of a specific energy characteristics) can be performed. This source is based on the stripping of 40 MeV deuterons in lithium, which was chosen in order to obtain the right neutron energy distribution. A schematic layout is shown in Fig. 8.

Deuterons are accelerated to 40 MeV in two linear accelerators of 125 mA each and are directed on a flowing lithium target with an open surface on the accelerator side and a curved supporting back wall. In the lithium some of the deuterons break up into a proton and a neutron with the most probable energy for each of the two products being about 15 MeV. The protons are strongly ionizing and are stopped in the target, whereas the neutrons are mainly forward directed and leave the target through the back wall. Since, in contrast to most other nuclear reactions, these neutrons are not emitted isotropically, they produce a very high flux in the test volume, where also a moderator could be placed.

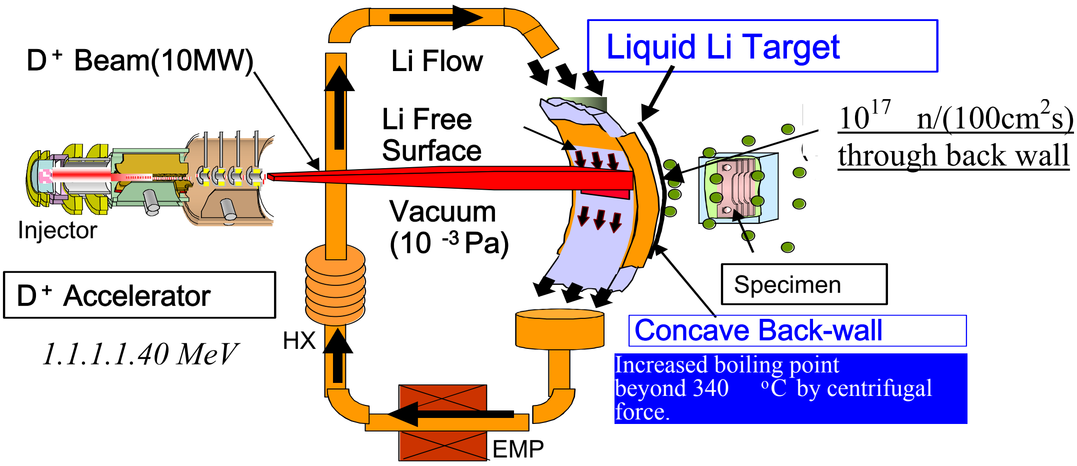

*Figure 8. The IFMIF design concept*

While IFMIF with its demanding design parameters is a B$ 1 class project and of significant technical complexity, this example shows that opportunities exist to take advantage of specific properties of neutron reactions to convert the neutrons very efficiently into thermal flux. A specific advantage of this reaction is that there are no neutrons above 55 MeV (this value result from rare exothermic reactions in the Li), and hence shielding and activation problems will be much lower than in spallation neutron sources.

## Conclusions

Accelerator driven neutron sources are a clear alternative to research reactors for the future. Accelerator technology has matured to a point where reliable and cost effective machines can be built and operated routinely. In the field of very high performance neutron sources spallation is the reaction of choice due to its low energy release per neutron. Spallation neutron sources operated in a pulsed mode will soon outperform the best high flux research reactors for neutron scattering by orders of magnitude. While the need for an accelerator and the sometimes demanding target technology adds complexity to the system relative to a research reactor (in particular, if liquid metal targets are used), the design and construction of this novel type of neutron sources presents a challenge which has been taken up in several parts of the world. With somewhat relaxed specifications the technology will soon be within reach also for developing countries and regions, as exemplified by the Chinese project [12]. It is conceivable that neutron producing reactions other than spallation might be used with advantage to relax the technological demands if medium or low power sources are considered. Such sources, if properly equipped with suitable experiments will still be valuable research tools.

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# PULSED NEUTRON SOURCES FROM LOW ENERGY PROTON BEAMS

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The efficiency with which neutrons may be produced using (p,n) reactions in Be and Li is substantially less than that of spallation. Only about 1 neutron for every 100 or more protons for these reactions in contrast to 10's of neutrons per proton in the case of spallation.[1] Nevertheless, the large currents available from linear accelerators with energies in the range from 3 to 30MeV allow the construction of a pulsed neutron source with reasonable flux based on these reactions because of their low threshold energies. At least one line of commercial neutron sources is presently being marketed for use in radiography medical applications and various research applications using these reactions[2]. These sources provide neutrons at rates up to $1\text{x}10^{13}$ n/s and couple the source to a simple room temperature moderator.

At Indiana University we are taking this concept slightly further in constructing the Low Energy Neutron Source (LENS) to provide neutrons at rates up to $1\text{x}10^{14}$ n/s and combining the source with a cryogenic moderator[3]. LENS is designed to be a very flexible facility fulfilling three missions: to provide a rich educational environment for students to learn the details of neutron techniques, to develop new types of neutron instrumentation, and to conduct materials research using neutrons. The source will have a variable pulse structure (from as short as 5 μsec to as long as 1.2msec) and variable frequency (up to 100 Hz when using shorter pulses). We envision that sources such as LENS will provide a viable model for constructing networks of small sources that can support the major new spallation sources under construction in the USA and Japan in a manner similar to the support that national reactor sources presently provide for the ILL and ISIS in Europe. In this sense, LENS will serve as a prototype for the type of source this meeting was convened to discuss.

LENS will is being constructed in two phases over the next three years within the Indiana University Cyclotron Facility. This facility served as a major center for nuclear physics for many years, and for the first phase of LENS we will employ a 7MeV linac that had previously supplied particles to a pair of light-ion synchrotrons. This phase, which is expected to commence operation early in 2005, will utilize a 7MeV proton beam with a peak current of 20mA and a duty factor of up to 1% to provide as many as $2\text{x}10^{11}$n/s. With this flux, LENS will be able to conduct experiments on moderator design and materials, to support PhD research into neutron production and instrument design, and facilitate the commissioning of the primary flight paths of the first neutron instruments to be built at the facility.

The ultimate goal for LENS is to operate with a proton beam of 13MeV with a peak current of 50-100 mA and a duty factor of up to 5%. The 13 MeV energy has been chosen to maximize the neutron production rate while avoiding the production of tritium and $^7$Be in the target (the $^9$Be(p,t) reaction has a threshold of roughly 13.4MeV). At this energy, and with judicious selection of construction materials near the target, we expect to be able to exchange moderator vessels within a few days after beam shut down without a need for elaborate remote handling facilities. This makes LENS an ideal source for conducting experiments into new moderator materials and designs, and this is expected to be a major part of the research program at the facility for the first several years of its life. To facilitate this research program even further, the LENS design includes a 50cm diameter cylindrical water reflector so that different shaped moderator vessels may be easily accommodated. Exchanging this water reflector for one composed of Be would increase the cold neutron flux from the source by as much as 30% with little change in the neutron emission time structure so this is being considered as a possible means for increasing the LENS flux in the future. An even greater increase in cold neutron flux is possible if a larger graphite reflector is used in place of the water, but this increase comes at the cost of an increase in the neutron pulse widths that is unacceptable for the scattering instruments to be installed at LENS. A second target station that is being considered for LENS to support neutron radiation effects research may make use of this slower type of reflector.

As suggested above, the low proton energy involved in the LENS design leads to a considerable reduction in the build up of radioactivity in the vicinity of the target. This low energy also reduces the shielding requirements for the source since no neutrons are produce with energies above 11MeV, and the primary reaction also produces relatively few high energy photons (less than 1 gamma for every 10 neutrons and essentially no hard X rays). Unlike conventional neutron sources, therefore, the photon background at LENS will be completely dominated by capture gammas in the reflector and shielding. This reduced gamma field is expected to facilitate operation of the LENS moderator at lower temperatures than is possible at spallation sources in addition to simplifying the shielding design. The primary shielding design for the target/reflector/moderator (TMR) assembly consists of cylindrical layers of borated polyethylene and lead out to a radius of roughly 100 cm. The TMR is situated inside a vault defined by 3-4 feet thick concrete walls.

The Be target is one of the more challenging aspects of the LENS source design. At full power LENS will deliver over 30kW of average beam power to this target with the peak power being a factor of 20 greater than this. To minimize the thermal energy density in the target, the proton delivery system employs two octupole magnets to spread the beam roughly uniformly over a 50cm$^2$ area. The average power density of some 600W/cm$^2$ is relatively easily handled with water cooling techniques such as the hypervapotron (HV)[4,5]. At present, the peak thermal stresses in the target are expected to be the factor that limits the neutron production rate for the LENS source. Proton linacs operating at 13MeV and delivering 100mA with up to a 5% duty factor can be built but it is not clear that the target could hold up to the resulting thermal stresses.

The LENS TMR will have three neutron beam lines, one devoted to Small Angle Neutron Scattering (SANS), one devoted to neutron radiography and moderator studies, and a final one devoted to neutron instrumentation development. LENS produces its most useful neutron beams for scattering studies in a long-pulse mode which lends itself most obviously to low-resolution techniques such as SANS. With simple pin-hole collimation designed for $Q_{min}$=0.005 A$^{-1}$, the SANS instrument at LENS should have a neutron current on the sample of greater than 10$^4$n/s for a single pin-hole with 7 times this current available through a multiple pin-hole option for a sample that is 2 cm in diameter. The instrument will be constructed with an option for using wider collimators for cases where the sample flux is a more important consideration than reaching the lowest Q. Our present radiography design indicates a cold neutron flux at the detector of roughly 10$^5$/cm$^2$.s for an L/D of 300. The final beam line at LENS will initially be devoted to the construction of a Precession Scattering Instrument ($\Psi$) that will employ zero-field spin echo techniques for encoding momentum transfers in small-angle scattering, high-resolution diffraction, and reflectometry. These techniques have recently been demonstrated at a small reactor in the Netherlands[6], but they have not yet been developed for a long-pulsed source.

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# JSNS OF THE J-PARC PROJECT AND OTHER ACCELERATOR DRIVEN SMALL NEUTRON SOURCES IN JAPAN

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The spallation neutron source KENS utilizes the beam from the 500 MeV-10 μA-20 Hz (5 kW) proton booster synchrotron, which is an injector to the 12 GeV main ring for nuclear and particle physics experiments. The main ring only uses about 9 pulses out of 72 pulses, and the KENS and the muon facilities utilize the rest of the beam, which was discarded if not used by the facilities. The KENS facility is a very good example of a medium-scale accelerator-driven neutron source (ADNS). Because it is a relatively small-power source, we could fully optimize the target-moderator-reflector assembly using an ambient-temperature moderator and a solid methane cold moderator. It is noteworthy that solid methane gives us higher neutron flux than a hydrogen moderator, which cannot be used at a high-power source because of radiation damage to methane.

Currently, the KENS facility has an instrument suite of 16 instruments. High-resolution powder diffractometer, Sirius, is one of such instruments, which has a Q-resolution of about 0.1%. Performance of the Sirius is almost similar to that of the HRPD at ISIS, which has more than 30 times higher proton intensity. One other example is the small and wide-angle diffractometer SWAN. It has a wide-angle detector bank as well as small-and medium detector banks, and give us unique opportunities to measure the very wide Q-range of $0.007\ (0.013) \leq Q \leq 20\ A^{-1}$ without moving the detector banks.

KEK and Japan Atomic Energy Research Institute (JAERI) are jointly constructing the JSNS (Japanese Spallation Neutron Source) of the J-PARC (Japanese Particle Accelerator Research Complex) project. The J-PARC is a interdisciplinary research facility based on a 50 GeV proton synchrotron for nuclear and particle physics including neutrino facility, and a 3 GeV rapid cycle synchrotron for the JSNS and muon facilities, and 400 (600 MeV) linac for a nuclear transmutation experimental facility. JSNS is a 1-MW spallation neutron source, similar to the SNS at the ORNL in the US. Unlike the SNS, JSNS is based on the 3 GeV synchrotron accelerator that is running at 25 Hz, much slower than the 60 Hz of the accumulator ring of the SNS. It is in the fourth fiscal year of the construction and aim to have first beam to the JSNS in FY2007. The front-end part of the linac has already been constructed at KEK and successfully accelerated to about 20 MeV with 30 mA of proton current.

The JSNS will become one of the three world regional centers, the SNS in America, the ESS in Europe and the JSNS in the Asia/Oceania region. In the region, there are several medium flux reactors under operation or under construction, such as the KAERI reactor in Korea and the Replacement Research Reactor under construction in Australia. Medium-flux spallation neutron sources are also under planning in China and in India. The JSNS is nicely located in the middle of the surrounding counties in the region.

There will be 23 neutron-beam ports available to neutron instruments at the JSNS. The project team selected most important 10 instruments, which are shown in the page 20 of the presentation file. In 2002, there was a call for letter of intent (LOI), 18 instrument proposals were submitted and 9 were passed the primary review and preceded to the next step. In 2003, there was a next call for LOI and 9 proposals were received. The facility is open to international users, but charging policy and conditions for the access etc are under discussion.

JAERI received a preparation budget for designing three of the 10 instruments and hope to receive a full funding for the three instruments next year. Ibaraki-prefecture, the local government, decided to fund two instruments, a high-intensity powder and a protein crystallography instruments.

Wide variety of researches will be performed at the JSNS. Material structure study is one of such fields, and neutrons will play an important roll for designing, synthesis and characterization of novel functional materials. Neutrons are also indispensable to study protein-structure in relation to hydrogen or water molecules in the protein or at the surface. Protein crystallography gives only structural information, and next step is to understand the functionality of it. One of the methods to attack this problem is to use neutron inelastic scattering method, and the Bio-molecular spectrometer at the JSNS will provide very good opportunities for such research.

There will be only 3 moderators, which are all supercritical hydrogen ones and no water moderators will be installed. The one below the target is a coupled one and it will have very wide angular coverage of nearly 50 degrees on each side of the moderator. The other two are decoupled, and decoupled and poisoned ones above the target. We will put a rather big ortho-/para-converter to keep the hydrogen para to get higher performance. For the decoupler, we will employ silver-indium-cadmium (AIC), to have higher decoupling energy of about 1 eV, in place of cadmium that has only 0.4-0.5 eV.

In the Hokkaido University, there is a 45 MeV - 3 kW electron linac facility for neutronic performance test experiment and for detector development, parametric X-ray, pulsed radiolysis, neutron radiography study, etc. It generates about $3.5 \times 10^{12}$ n/s fast neutrons with 1.75 kW of electron beam and about 1 % of the fast neutrons are converted to thermal or cold neutrons if a proper moderator/reflector system is used. It is a very unique facility in the world, which gives us rare opportunities to perform mockup test experiment for various systems, such as the JSNS moderator system. Actually, the methane moderator being used at KENS was developed and tested at the facility. It is perfect for such purposes because of very low power and hence generates very low activation to mockup system.

The concept of FFAG (Fixed Field Alternating Gradient) accelerator was proposed in 1953, but has not been realized until quite recently, especially for proton acceleration, because of several difficulties. The FFAG is very suitable for ADNS because it is compact, cost is relatively low, and space charge limit is rather high compared with a synchrotron. A 500 keV proof-of-principle proton FFAG accelerator was developed at KEK and successfully accelerate proton beam by Mori and his group. The 150 MeV FFAG is also under construction at KEK.

The same kind of FFAG is also under construction at Kyoto University Research Reactor Institute (KUR). The beam will be injected to the existing critical assembly and transmutation R&D will be performed using the systems. The beam will be also used for medical applications and other purposes. The construction will be finished in 2006.

**Acknowledgement:**

The author would like to thank all the people who kindly provided necessary information and figures of this presentation. Prof. S. Nagamiya (KEK) provided information related to the J-PARC project, many people involved in the development of JSNS also provided information about the target station and instrument. Prof. Kiyanagi (Hokkaido Univ.) provided the information related to the electron linac based pulsed neutron source, Prof. Mori (KEK) the FFAG and T. Fukunaga (KUR) the ADS based on the FFAG.

# NEUTRON PRODUCTION AND NUCLEAR PERFORMANCE OF SPALLATION TARGET SYSTEMS

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The contribution presented was essentially splitted into two aspects: First (**Part I)** the neutron production and nuclear performance of spallation target systems was discussed in the framework of high energy transport models and calculational tools instancing the parameters of the ESS spallation neutron source. **Part II** deals with a set of benchmark nuclear physics experiments performed at the Cooler Synchrotron COSY at Jülich. The experiments are understood as valuable asset for validating and improving the models and understanding of the complex nuclear reaction mechanisms involved.

**Part I:** A detailed program on radiation transport phenomena and questions concerning the nuclear (in particular neutron-) performance has been carried out in order to design the ESS target stations. Various options of the so-called "Short Pulse Target Station" (SPTS) and the "Long Pulse Target Station" (LPTS) have been investigated for achieving the desired neutron flux intensities. The emphasis of this theoretical work was directed toward assessing physics feasibility and optimization of the engineering design of both target stations. While the main purpose of these Monte-Carlo particle transport simulations in the target-moderator-reflector system is on request of the users for different experiments on the neutron scattering utilization other important design questions have to be answered:

(a) the magnitude of the radiation environment within and near the target, (b) energy deposition/heating of components including heating of cold moderator systems, (c) the induced radioactivity, the radiation damage and the afterheat in the target material, structures and other near target components as reflectors and shield, (d) estimation of dpa´s and gas production for windows and other structure materials of the TMR, (e) and the magnitude of the bulk shield of the target stations, beam dumps and beam stops. The model approach has to use the latest state-of-the-art of radiation transport computer codes with 3-dimensional material and geometry descriptions of the target stations and employs in general Monte Carlo techniques. The simulation is frequently even the only way to understand particularly complex systems. Today with the development of models, methods and data from the reactor physics, fusion technology, nuclear physics and high-energy physics information is accessible, which enables the application of particle transport computer simulations to certain specific queries. The particular challenge requested to the models is due to the description of hadronic and electromagnetic phenomena over 10 orders of magnitude ranging from the incident proton energies (GeV) down to the moderated sub-thermal neutron energies (meV).

**Part II:** To scrutinize several of such codes, reaction cross sections, hadronic interaction lengths, average neutron multiplicities, neutron multiplicity and energy distributions, and the development of hadronic showers were investigated by validation of specific experiments at COSY Jülich. Here in particular the nuclear physics experiments NESSI, JESSICA and PISA carried out at COSY for the energy range up to 2.5 GeV incident proton energy were subject.

- As for example the *NESSI* **(**Neutron Scintillator and Silicon Detector at COSY Jülich) experiment evaluates the systematics of neutron production cross sections and neutron energy spectra as a function of incident proton energy, target material, and target geometry. These measurements covers a large range of incident proton energies, as well as a variety of target materials and geometries.

- *JESSICA* (Jülich Experimental Spallation Target Setup in COSY Area) is a 1:1 ESS Hg target-reflector-moderator mockup at the COSY low-intensity pulsed proton beam at FZ Jülich which aims at studying (sub)-thermal neutrons using thermal and advanced moderators. Time-dependant neutron spectra are investigated by Bragg reflection and TOF-methods. The measurements include a thorough characterization of the neutron beams coming from a variety of moderator-reflector configurations, to include not only absolute spectral intensity over the neutron energy range typically used in neutron scattering applications (0.1 meV < E < 100 eV) but also energy-dependent emission time distributions over a similar range.
- *PISA* **(**Proton Induced SpAllation at COSY Jülich) is an experiment located in the internal ring of COSY and aims at the measurement of spallation products and recoil spectra for a large charge, mass, energy and angular range. PISA provides high quality double differential production cross sections for elements (including isotopic identification of ejectiles!) of interest in the context of radiation damage, DPA‘s and embrittlement by gas production and allows e.g. the i Investigation of radioactivity (tritium and Be-7 production), direct measure of gas production (H-, He-,…) causing e.g. embrittlement.

## Summary

The extensive set of benchmark data obtained in the NESSI, JESSICA and PISA experiments imposes strong constraints on the theoretical modeling of the occurring interactions and allows one to calibrate and improve widely-used high-energy transport codes. However due to large range of relevant targets and the vast amount of product nuclides it will not be possible to measure all the cross sections needed. Thus, one has to rely widely on models and computer codes as mentioned above to calculate the required cross-sections. The demand for reliable theoretical predictions of production cross sections is by no means satisfied by the models and codes which are available today. Recent investigations have shown various insufficiencies of theoretical models describing these reactions. The physics tools for the modeling of the Intra-Nuclear-Cascade (INC) and evaporation stage of the spallation reaction seem to be relatively well known while the intermediate pre-equilibrium stage leading to the emission of energetic composite light charged-particles is poorly understood. None of the presently available codes is able to meet the challenge of predicting reliably the pre-equilibrium emission of composite particles. For a reliable modeling of the spallation module/target station of ADS and spallation neutron sources in general detailed theoretical models are essential and indispensable for the calculation of the neutron production, radiation damage of materials (window), production of radioactivity (for instance tritium, 7Be, heavy residues etc) in the target medium. Moreover, up to now different theoretical models do not agree among themselves in the predictions of cross sections.

In this context it is essential that reliable and comprehensive experimental data---especially for p-energies beyond 1 GeV exist which can serve as benchmarks for code development and validation. The accuracy of such codes is critical for the design of small and high-power target stations, since the optimization of geometrically expendable high power target stations will finally rely on general Monte-Carlo particle transport codes having maximum predictive power. The performance and flexibility of program packages like HERMES, LCS or MCNPX and the validation (using our experiments and the literature) is demonstrated. The overall objective of our effort is to obtain a comprehensive understanding and modeling of nuclear reactions in a broad energy region, which are specific to spallation physics aspects. The essential goal can only be accomplished by means of a well-balanced combination of basic cross section measurements, nuclear model simulations and data evaluations.

# LUJAN CENTER COLD SOURCE UPGRADE STUDIES

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The Manuel Lujan Jr. Neutron Scattering Center (Lujan Center) at the Los Alamos National Laboratory is the most powerful pulsed neutron scattering facility in North America. It currently produces the highest time-averaged cold source brightness of any pulsed neutron scattering facility in the world, and efforts are underway to increase this even further.

The Lujan Center is a part of the Los Alamos Neutron Science Center (LANSCE), a complex centered around an 800-MeV proton linear accelerator capable of accelerating 1 mA beam current. The LANSCE accelerator delivers 125 μA of $H^{-}$ beam in 0.65-ms-long pulses at 20 Hz to a proton storage ring, which compresses them to a width of 300 ns, each of which contains $4\times10^{13}$ protons per pulse. These pulses are then transported to a 90° dipole magnet which directs them vertically downward onto the Lujan Center target system.

The protons induce spallation reactions in the split tungsten target, producing mostly evaporation neutrons, some of which are reflected by the surrounding Be reflector into one of six moderator. Four (three water and one liquid hydrogen) of these are arranged in flux-trap geometry between the upper and lower portions of the split tungsten target; the other two (one water and one liquid hydrogen) are located above the upper portion of the target in what is known as upstream backscattering geometry. Those arranged around the flux trap are called lower-tier moderators, and the other two are known as upper-tier moderators.

The lower-tier moderators serve three flight paths each, while the upper-tier moderators serve two flight paths each, for a total of 16 flight paths. Fourteen of these flight paths have operating instruments on them, one more has an instrument under construction, and one is unassigned. The instruments serve a variety of applications, including materials science, biology, chemistry, nuclear physics, and engineering.

The Lujan Center is currently operating on a third generation target system. The first, called Mark 0, operated from 1985 to 1997. It included a number of innovative concepts that are still in use today, including flux-trap geometry and a composite reflector. After two years without operating, the second generation target system, called Mark I, operated from 1999 to 2002.This was the first target system in the world to implement upstream, backscattering moderators and partially coupled moderators in a pulsed neutron scattering facility. It also used a composite Be-Pb reflector. The third generation target system, called Mark II, is a slight variation of the second target system, the only difference being that the reflector was changed to Be-stainless steel to address cooling problems encountered with the Pb in the Mark I system; it has been operating since 2002.

The target system must be changed periodically to remain within regulatory limits of accumulated radionuclide inventory. For eight months per year of operation at 125 μA, replacement must occur every three years. This target system replacement provides regular opportunities to introduce new features that enhance performance. With this in mind, we are investigating concepts to improve the neutronic performance of the Mark III target that will replace the currently operating Mark II target, with the goal of boosting the long-wavelength (>5 Å) source brightness of the lower-tier hydrogen moderator by a factor of two, and that of the lower-tier water moderators by 20%. To date, our efforts have been focused on the low-tier hydrogen moderator, and we report the results of these efforts here.

Of the many concepts that were evaluated for boosting cold source brightness, three proved to be sufficiently beneficial to recommend they be implemented in Mark III. These are: a light water flux-trap premoderator, a light water perimeter premoderator, and a cold (77 K) Be reflector-filter. Simulations of these concepts have been carried out using the Monte Carlo radiation transport code MCNPX [1]. The calculated gain in long-wavelength source brightness derived from the introduction of a cold Be reflector on the lower-tier hydrogen moderator is shown in Figure 1, assuming a 90% para-hydrogen fraction. Here, brightness is plotted as a function of moderator thickness with, and without, the reflector-filter. It shows a 30 to 50% gain in source brightness over the range of moderator thicknesses studied. Also shown in this figure is the additional gain derived from adding a light-water flux-trap premoderator, with the Be reflector-filter in place. Compared to the present Mark II configuration, which is identified in the figure, a factor of two gain is realizable by introducing both a flux-trap premoderator and a reflector-filter.

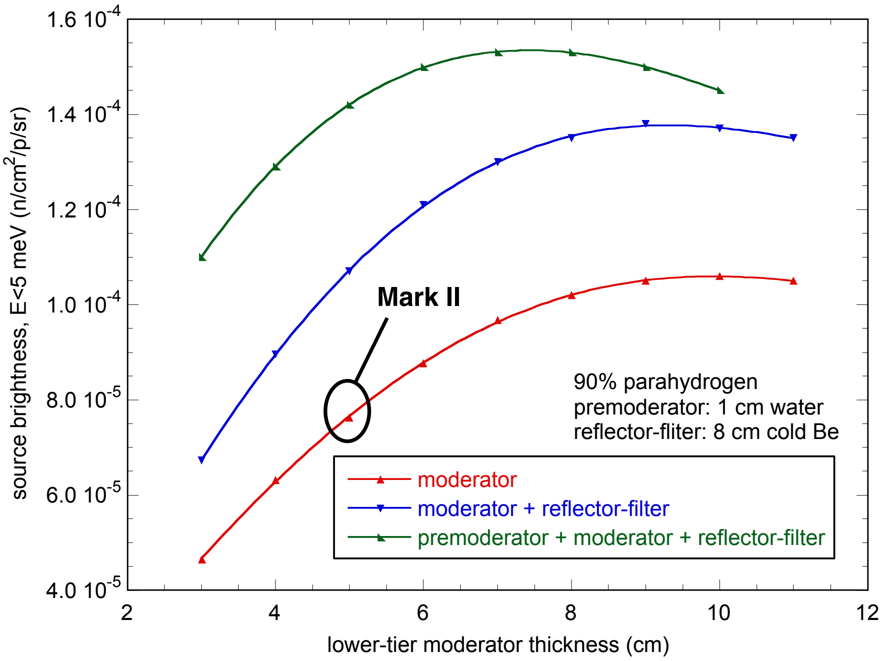
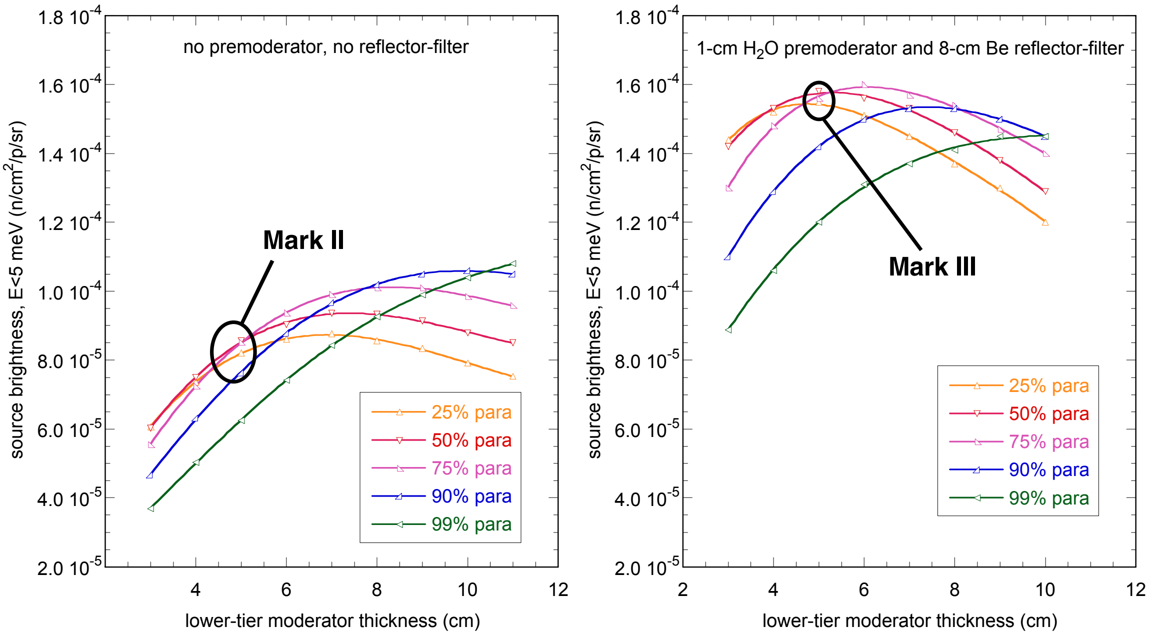


*Figure 1. Calculated long-wavelength source brightness as a function of moderator thickness for the Lujan Center lower-tier liquid hydrogen moderator. Three configurations are presented: (1) moderator alone, (2) moderator with reflector-filter, and (3) moderator with reflector-filter and flux-trap premoderator.*

Calculations indicate that the neutronically optimal configuration depends sensitively on the para-hydrogen fraction. This is shown in figure 2, where the same moderator thickness study shown in Figure 1 is performed for a number of para-hydrogen fractions ranging from 25% to 99%. Figure 2a shows results for a bare moderator, while Figure 2b shows results for a moderator with a reflector-filter and flux-trap premoderator. Note that, for a bare moderator, the optimum thickness ranges from 7 cm for 25% para-hydrogen fraction to >11 cm for 99% para-hydrogen. Pure (99%) para-hydrogen shows the greatest source brightness in this case. However, for the case where the flux-trap premoderator and reflector-filter are present, the greatest source brightness occurs with 75% para-hydrogen.



(a)

(b)

*Figure 2. Source brightness as a function of moderator thickness for para-hydrogen fractions ranging from 25% to 99%. (a) bare moderator, (b) moderator with reflector-filter and flux-trap premoderator.*

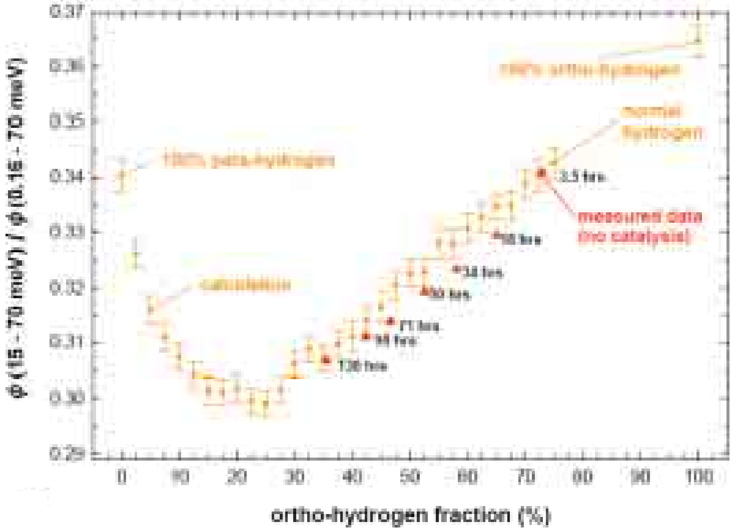


*Figure 3. Fraction of integral flux 15–70 meV.*

Recent experimental results provide indirect evidence of how the para-hydrogen fraction in the hydrogen moderators changes during operation of the current Mark II system [2]. The flux spectrum of the lower-tier hydrogen moderator was carefully measured as a function of time after condensing the gaseous hydrogen from room temperature to a liquid state at 20 K. In addition, the flux spectrum was calculated for a large number of para-hydrogen fractions. By inspection of the measured and calculated data, bounds of energy-integrated flux were identified that showed particular sensitivity to the para-hydrogen fraction. Results are displayed in Figure 3, which shows the fraction of the integral flux to 70 meV with energy greater than 15 meV. As indicated in this figure, calculations show this flux fraction drops as the para-hydrogen fraction increases over that of normal hydrogen (25% para-hydrogen), until the para-hydrogen fraction reaches 75% to 85%, where a minimum in the flux fraction is seen. Above 85% para-hydrogen, the flux fraction rises. Also plotted are the measured flux fractions, plotted at a para-hydrogen fraction that is consistent with the assumption that conversion of the ortho-hydrogen to para-hydrogen occurs at a natural, uncatalyzed rate of K = 0.0114 per hour, as described in Russell, et al. Good agreement between measurement and calculation is observed, providing strong evidence that the hydrogen conversion is not catalyzed or significantly influenced by the radiation environment.

As previously described, designing the moderator to produce the maximum source brightness requires a constant para-hydrogen fraction, which we now believe does not currently exist at the Lujan Center. Typically, constant para-hydrogen fraction is achieved by adding a catalyst to the system, which drives the fraction to 100% para-hydrogen. A second way may be called “bleed and feed,” whereby a small slip stream of hydrogen circulating in the loop is boiled off and replaced by freshly condensed hydrogen. Assuming a natural conversion rate, a constant condensation rate of 0.8 g/h for the 11-liter hydrogen loop volume at Lujan will preserve a maximum para-hydrogen fraction of 75%. This would place an additional heat load on the refrigerator of about 1 W, which is negligible compared to the existing 200-W heat load. Correspondingly, a 50% para-hydrogen fraction would require a condensation rate of 3 g/h, or a refrigerator heat load of approximately 4 W.

An experimental program is underway to validate the calculated gains in source brightness derived from a reflector-filter. The experiments are conducted in the “Blue Room” at LANSCE, which can accept up to 100 nA (limited by shielding) of 800-MeV protons on to target-moderator-reflector mock-ups. A 6-m-long vertical flight path directs neutrons to a shielded cave where energy spectra and time distributions may be measured. Using this facility, we measured the change in the neutron spectrum resulting from the use of a reflector-filter for a cooled (77 K) coupled polyethylene moderator. The gain in long-wavelength source brightness was measured to be 64%. This gain comes at the expense of a factor of 3 drop in the flux near 3 Å. Very recently, we measured the time distributions with and without a reflector-filter, and analysis of these data has been initiated.

There are three instruments served by the lower-tier hydrogen moderator: SPEAR (reflectometer), LQD (diffractometer), and ASTERIX (reflector/diffractometer). Of these, SPEAR is most negatively impacted by the loss of 3-Å neutrons. LQD is less impacted, while ASTERIX would suffer very little in performance (in fact, ASTERIX inserts a cold Be filter in its beam line for 90% of its experiments!). Thus the design effort focused on methods for preserving the current level of 3-Å flux, principally to SPEAR but also to LQD, while still providing a factor of two gain in long-wavelength flux to all three instruments. This can be accomplished by putting “holes” in the reflector-filter that allow some of the 3-Å neutrons that are emitted by the hydrogen moderator to pass unattenuated through the reflector-filter and down the SPEAR beam line.

Several “hole” geometries were evaluated. The “megaphone” consists of a large square hole that gives the SPEAR instrument full field-of-view (10 cm by 5 cm) to the moderator leakage surface. This fully preserves the 3-Å flux, but the long-wavelength flux gain is severely compromized. The “chevron” configuration filled half of the “megaphone” hole with a series of vertically oriented 5-mm-thick flat plates. This concept satisfies the requirements of providing 3-Å flux to SPEAR equal to that of the Mark II target while nearly doubling (~1.9) the long-wavelength flux to all three flight paths. However, this is thought to be difficult to construct in such a way that is preserved its shape when cooled from room temperature to 77 K. Finally, a “Swiss cheese” geometry consists of many 5-mm-diameter circular holes drilled on a triangular pitch that provides 50% transparency over the SPEAR field-of-view. This geometry gives satisfactory neutronic performance, and discussions with machinists lead us to believe it can be built in a straightforward manner.

In summary, the use of a “bleed and feed” scheme will ensure a para-hydrogen fraction in the 50-75% range shortly after cooldown. By judicious application of water premoderation (both flux trap and perimeter) and a reflector-filter, calculations indicate that the goal of boosting the long-wavelength source brightness by a factor of two on the flight paths served by the lower-tier hydrogen moderator can be met. Use of a “Swiss cheese” geometry in the refector-filter preserves the 3-Å flux to SPEAR that is currently delivered by Mark II. Compared to the original Mark 0 target system, long-wavelength source brightness from a Mark III target with these features is predicted to be five times greater on a per-proton basis.

It is important to note that the incremental improvements made in moderator source brightness over the years make low- and medium-power sources that are the topic of this meeting, more viable in the sense that these same improvements can be applied to these sources. In addition, low-and medium-power sources can play an important role in serving as testing facilities for developing advanced moderator concepts prior to their implementation on high-power sources. The well-established history of the neutron source facility operated at Hokkaido University is a prime example of this role.

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# THE SWISS SPALLATION NEUTRON SOURCE SINQ – LAYOUT, OPERATION, UTILIZATION AND R&D FOR OPTIMIZED NEUTRON YIELD

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## 1. SINQ: layout and operation

SINQ is a continuous spallation neutron source, operated at the Paul Scherrer Institute (PSI), Switzerland. It is driven by PSI´s 590 MeV proton accelerator, providing its final target after a cascade of two graphite targets for meson production. The whole accelerator facility is serving a variety of disciplines, particle physics, muon spectroscopy, medicine, solid state physics and materials science.

At present this accelerator is capable to deliver a stable proton current of 1.8 mA, equivalent to a power of 1.06 MW. After having passed the meson targets, about 1.25 mA of the primary proton beam reach the SINQ spallation target. Thus, receiving routinely 0.75 MW or more, SINQ is presently the most powerful spallation neutron source worldwide. For the future, a program is initiated to push the accelerator power to 2.5 or even 3 mA, i.e. distinctly beyond 1MW.

SINQ is operating on a routine basis since 1997. The usual period of ‘around-the-clock’ operation extends from spring (March or April) to Christmas, interrupted each Wednesday for a one or two day’s maintenance or beam development. After the first operation experience in 1997, an updated control and safety system was licensed that allows unmanned operation of SINQ. Only daily rounds and system checks by the duty operator are required. An engineer in waiting is always within reach and shows up on-site latest within one hour from the alarm initiation by the operator in the accelerator control room.

The target of SINQ, a 4 m long slim structure, is vertically inserted into a massive shielding block, the proton beam being injected from underneath. The current target design is an array of $D_2O$-cooled lead rods in steel cladding. The rod array is contained in a double walled Al-shell and suspended from a heavy shielding plug.

SINQ is optimized for high time average neutron flux by surrounding the target with a large (2 m diameter) $D_2O$-moderator and avoiding neutron absorption in the inner regions of SINQ to the largest possible extent. A cold moderator, i.e. an aluminium vessel containing about 20 liters of liquid $D_2$ at a temperature of $\approx$25K, is positioned at a distance of 10 cm from the target surface, feeding a system of seven neutron guides on one side and two beam-lines for a neutron-decay experiment and a Cold Neutron Radiography on the other.

## 2. Target development - achievements and opportunities

Since commissioning in 1997, SINQ improved the annual neutron production by a factor of 16, and the availability related to the accelerator charge delivered improved from initially 75% to now routinely above 98%. Figure 1 illustrates the proton charge and neutron yield development since the startup of SINQ.

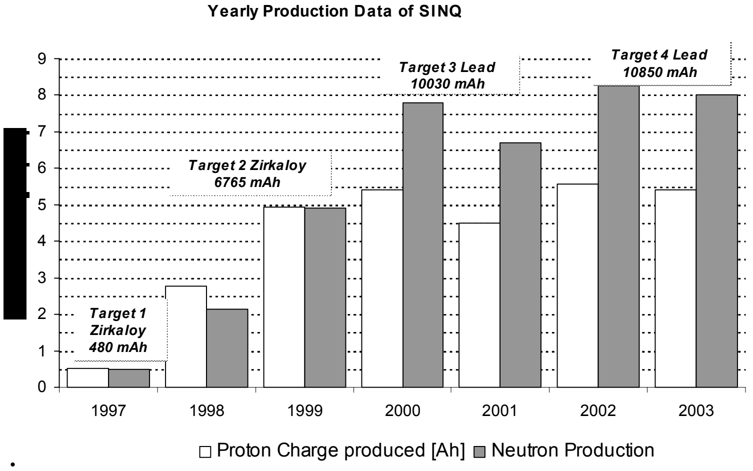

*Figure 1. SINQ yearly accumulated proton charge and neutron production since start-up of operation.*

The first two targets for SINQ where made of solid Zircaloy rods, a qualified material in nuclear applications, although its neutron yield is not optimal. Having gained satisfactory start-up experience, the first target was removed after only 480 mAh of operation and replaced by a second Zircaloy target (Target 2), now partly instrumented with thermocouples and equipped with test rods filled with about 1500 miniaturized samples for materials irradiation under realistic spallation conditions. This initiated the SINQ Target Irradiation Program (STIP), see below. The follow-up targets (Targets 3 and 4) were made of stainless steel clad lead rods, replacing the solid Zircaloy rods. With that the neutron yield was found increased by a factor of 1.44.

### *Work towards a Liquid Metal Target for SINQ*

It is now generally acknowledged that, for high beam power and in particular for high beam power density as required for efficient neutron flux generation, liquid metal targets are the concept of choice for several reasons. Therefore an initiative was launched by Commissariat à l'Energie Atomique, Cadarache (France) and Forschungszentrum Karlsruhe (Germany) in collaboration with PSI to develop a liquid metal target for SINQ, the **Mega**watt **Pi**lot Target **E**xperiment, MEGAPIE. The aim of this initiative is to demonstrate, in an international collaboration, the feasibility of a liquid lead-bismuth target for spallation facilities at a beam power level of 1 MW. Meanwhile the MEGAPIE target reached the stage of manufacturing. Implementation to SINQ and irradiation is planned for the year 2006.

## 3. STIP: SINQ Target Irradiation Program

All targets (except the first one) contain sample rods for an extensive materials irradiation program (STIP), aiming to ascertain the potential for extended duty cycles and higher proton charges and to provide a database for materials selections and optimizations for future high-power spallation targets.

In Target-2 there were 10, and in Target-3 even 17 rods holding a large number of miniaturized test specimens (altogether about 1500 and 2000, respectively) from different materials and of different shapes (tensile test, bending fatigue, TEM-disks, Charpy test etc.). The specimens were enclosed between aluminium or steel fillers and encapsulated in Zircaloy or steel tubes. Target 2 also contained rods with liquid metal–solid metal combinations:

Mercury in steel containers, Lead and Lead-Bismuth-Eutectic in steel containers, in all cases together with various steel samples. Dosimeter packages were placed with the test specimens. The test sample capsules are arranged along the central axis of the target, and exposed to a proton spectrum of different energies and intensities, while the fast and thermal neutron spectrum is similar for all positions.

In order to monitor the temperatures of the test specimens and experimental rods during the irradiation, thermocouples were placed in several rods. The temperatures of most of the test specimens were in the range of 250 to 400°C; In Target-3, the maximum temperature was up to 480 °C. These are temperatures at which beam windows of future liquid metal targets are likely to run and for which presently almost no data are available. Also, the frequent thermal cycling the samples are subjected to makes for a realistic simulation of the situation also in future spallation neutron sources.

### *Analysis of irradiated test specimens*

For examination, among other techniques three neutron instruments at SINQ are equipped with hot sample handling capabilities, which allow investigating whole target rods or sections thereof. These instruments are the SANS facility, the strain mapping instrument POLDI, and the radiography station NEUTRA. With the latter, the test rods containing the liquid metal-solid metal combinations were inspected immediately after being retrieved from the target. Comparison with radiographs taken before irradiation from the same rods allows a first judgment of the materials' integrity after irradiation. In particular one mercury capsule was found leaking and the mercury was drained out into the containing rod hull.

Extended effort was spent for determining the ductile-to-brittle transition temperatures (DBTT) of irradiated steels T91 and F82H. These ferritic-martensitc steels are possible candidates for the enclosure hull and beam window of future high-power spallation targets. The data reveal that the DBTT of T91 increases to ~250°C after irradiation at 275°C to 9.4 dpa/770 appm He. This temperature is uncomfortably close to the operation temperature of a beam window in a spallation target, indicating that in these materials the radiation induced embrittlement may be more severe than anticipated.

### *The safety hull*

Integrated part of the safety philosophy of SINQ is a double walled safety hull to ensure a reliable enclosure of the materials in the proton beam reaction zone. Since aluminum is known having good thermal conductivity and, more important, excellent radiation damage resistance, a type of aluminum alloy, AlMg3, has been chosen for the safety-hull.

The analysis of the safety-hull of Target-2 has been performed on several 40 mm discs cut from the beam window and side wall. γ-mapping revealed the proton beam center. Tensile test specimens were cut from all the discs and have been tested. The engineering strain-stress curves demonstrated: a) significant hardening has been introduced by the irradiation already at very low doses; and b) the material remained ductile to the highest fluence of $3.1\times10^{25}$ p/m$^2$ although irradiation embrittlement effects exist.

## 4. SINQ Utilisation

SINQ is declared an open user facility giving access to user groups worldwide on the basis of scientific or technologically motivated proposals. A suite of 13 instruments is presently in routine user operation, grouped around the target block and along the neutron guides (Fig. 2).

The actual user statistics is impressive: in 2003, totally 575 experiments were performed at the diffractive instruments and the radiography stations. About 400 different scientists were actively participating, many of them involved in more than one experiment. They came from 21 different countries and covered a variety of different topics from many fields of solid state physics, soft matter, materials science and technology.

Examples of recent investigation in applied science and technology demonstrate the capability of neutrons in these fields:

- the investigation of ferrofluids by SANS,
- strain scanning in thick welded steel plates and on real railway wheels from 10 mm below the treat on the strain scanner instrument POLDI
- application of real-time or time-resolved radiography at NEUTRA in life science on engine development.

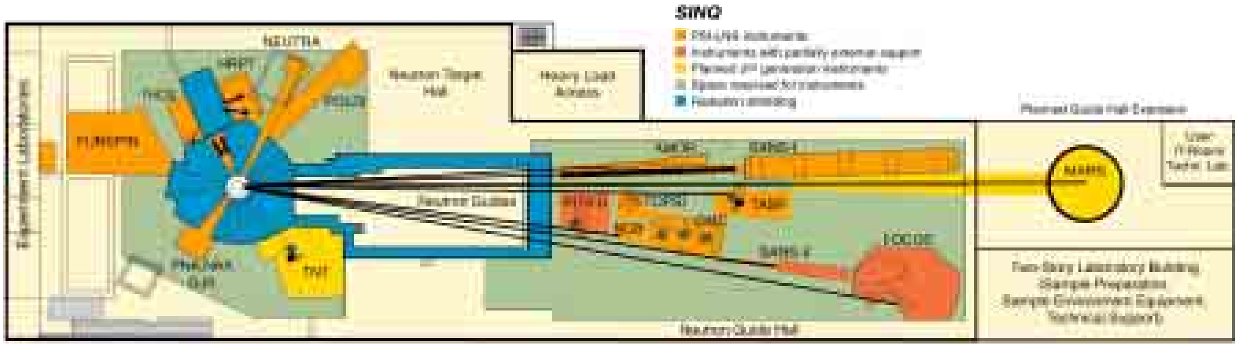

*Figure 2. Configuration of the SINQ experimental hall (status spring 2004), including the recently finished hall extension to the right.*

# THE CHINESE SPALLATION NEUTRON SOURCE PROJECT

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The proposal of the Chinese Spallation Neutron Source (CSNS) project was granted in the beginning of 2002 after three review meetings, organized by the Chinese Academy of Sciences (CAS) and other scientific organizations. Physicists from the Institute of Physics (IP) and the Institute of High Energy Physics (IHEP), both belonging to CAS, consequently started a conceptual design and feasibility study. The CSNS plan calls for a 70-MeV $H^-$ linac and a 1.6 GeV rapid cycling synchrotron producing a proton current of 62.5 **µ**A (100kW) at a 25 Hz repetition rate. It should be able to be upgraded to a higher beam power in its second phase. The CSNS target station design team, has initiated to conceptual design of the target-moderator system based on the suggestions and comments from an international advisory team, in the first moderator-target planning meeting of CSNS project (21-26, April 2002 in Beijing). In consideration of the characteristics of the spallation neutron source, the budgets and possible requests for future users in China, five multi-purpose neutron scattering spectrometers were proposed as the first step.

## 1. Proton acceleration complex

The CSNS plan calls for a 70-MeV $H^-$ linac and 1.6 GeV synchrotron producing a proton current of 62.5 µA (100kW) at a 25 Hz repetition rate. The design goal of the CSNS is listed in Table 1 and the schematic layout of the CSNS is shown in Figure 1.

Table 1. The design goal of the CSNS

| Item | Unit | Value |
|---|---|---|
| RFQ injection energy | keV | 75 |
| DTL injection energy | MeV | 3.5 |
| RCS injection energy | MeV | 70-130 |
| Beam energy on target | GeV | 1.6 |
| Repetition of RCS | Hz | 25 |
| Average beam current | µA | 62.5-125 |
| Average beam power | kW | 100-200 |

## 2. Target-Moderators system

The CSNS target station will be composed of the 40 pieces of tungsten plates with $D_2O$ as the coolant. Along with the target, there are the Beryllium/Iron reflectors (Beryllium:φ1200 mm and Iron φ1200-2000 mm) and Iron/High- density- Iron- Aggregate- Concrete biological shielding(φ2000-12000 mm). Three wing-mounted moderators: Water (room temperature), Liquid-Methane (100K) and Liquid-Hydrogen (20K) and 18 horizontal Neutron-Apertures with three in front and three behind of the moderator.

The designed CSNS target station uses the flat tungsten target, which allows the moderator to be as close as possible to the High-Neutron-Flux area in the center of the target. The preliminary target consists of 40 tungsten plates of size, 40 mm(high)×100 mm(width) ×10 mm(thickness) for each with a 1.5mm gap between each plate enabling coolant flow through for heat dissipation. The Monte Carlo algorithm NMTC/JAM [2], developed by the researchers of JAERI, is used for our simulation. The influence of Beryllium/Iron reflector and Iron/High-Density- Iron-Aggregate-Concrete is also considered in this simulation. We simulated the temperature distribution in the target stacks with the coolant velocity of 2m/s. Figure 3 shows the results of temperature for the first 15 pieces target plates. The highest temperature reaches almost 92ºC, which may be lowered by a relatively high coolant velocity.

## 3. Scattering instruments

It is well known that, as a micro-probe, neutron scattering technique has been and will be widely used in various fields of science and industry, especially recently in the fields of nano and biological technologies, due to its widely covering of wavelength and energy. Neutron scattering is used to study the arrangement, motion, and interaction of atoms in materials, usually provides valuable information that often cannot be obtained by other techniques, such as optical spectroscopy, electron microscopy, and X-ray diffraction. Researchers need all these techniques to provide the maximum amount of information on materials. In consideration of the characteristics of the spallation neutron source, the financial support and the users in China, five multi-purpose neutron scattering spectrometers: the high resolution powder diffractometer(HRPD) and high intensity powder diffractometer (HIPD), broad Q-range small angle diffactometer (SANS), multi-purpose reflectometer (MPR) and direct geometric inelastic spectrometer (DG-INS)-are proposed to be constructed by CAS as the first step.

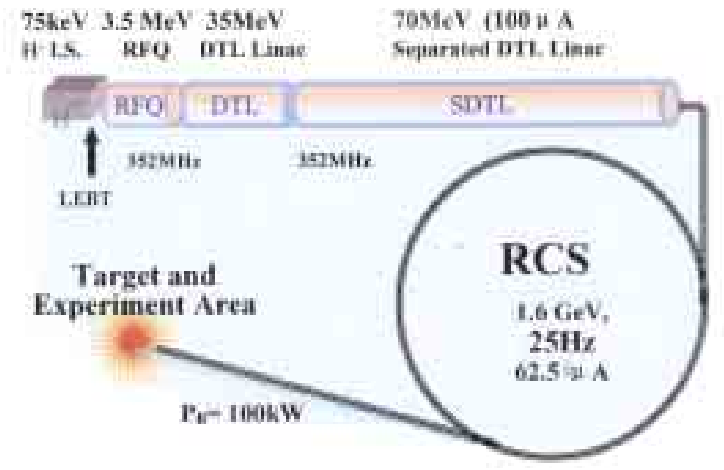

*Figure 1. A schematic layout of the CSNS*

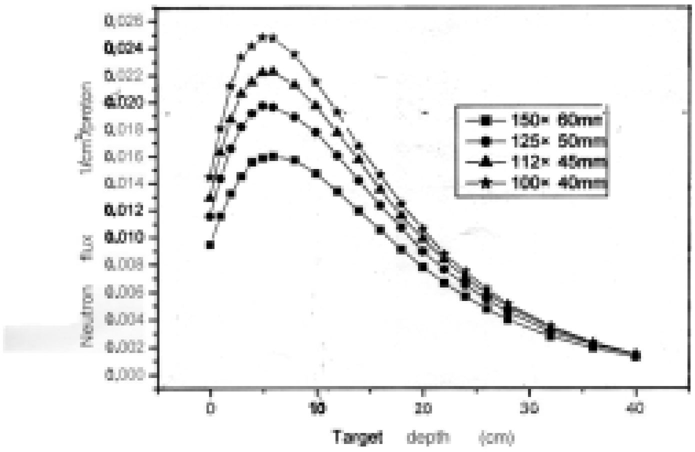

*Figure 2. Transgress neutron production*

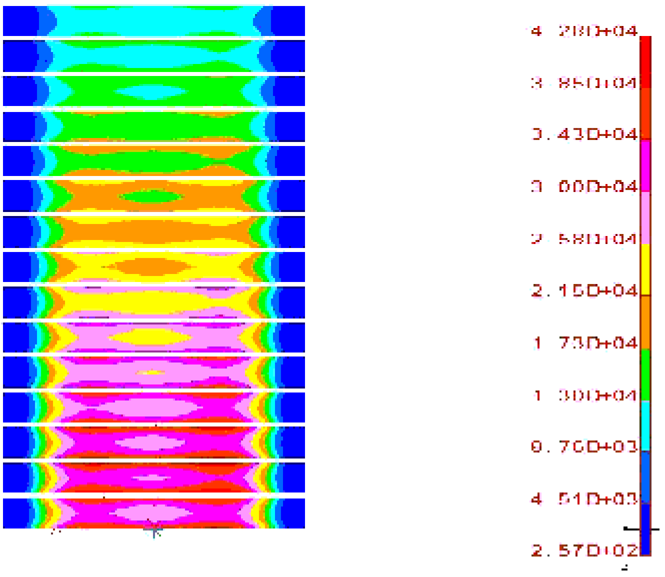

*Figure 3. The simulated temperature distribution of the first 15 pieces of target plates*

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