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ACCELERATOR BASED CONTINUOUS NEUTRON SOURCE (ACNS)

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INTRODUCTION

Until the last decade, most neutron experiments have been performed at steady-state, reactor-based sources. Recently, however, pulsed spallation sources have been shown to be very useful in a wide range of neutron studies. A major review of neutron sources in the US was conducted by a committee chaired by Nobel laureate Prof. W. Kohn: *Neutron Sources for America's Future- BESAC Panel on Neutron Sources 1/93.* This distinguished panel concluded that steady state and pulsed sources are complementary and that the nation has need for both to maintain a balanced neutron research program. The report recommended that both a new reactor and a spallation source be built. This complementarity is recognized worldwide: Europe, for example, recently refurbished its high flux reactor in Grenoble and is considering a European Spallation Source; Japan is planning a high-powered spallation source to complement the refurbished JRR 3 reactor. A more recent report (June 2002) by OSTP recommended "research and development in neutron source technology". Nearly a decade ago, the US canceled its plan to build a new research reactor and is currently constructing the Spallation Neutron Source (SNS) at Oak Ridge. The OSTP report also concluded that while the SNS is a significant new opportunity to provide world-leading capability in the US it "alone cannot provide the necessary neutron scattering capability."

The two existing research reactors at NIST and ORNL are over 35 years old. DOE acknowledged the need for ultimate replacement in its draft document *Facilities for the Future: The Office of Energy Research* in which it was proposed that planning for a new steady state neutron source begin around 2008. In today's political climate building a new reactor-based source would clearly be out of the question. An Accelerator based Continuous Neutron Source (ACNS) of the type currently in operation at the Paul Scherrer Institute (PSI) in Switzerland is, however, a viable and attractive alternative.

BNL is studying an ACNS based on a high power proton super-conducting Linac (SCL) that could be constructed on the BNL campus. The ACNS would be a 1.25 GeV superconducting linac (SCL) about 200 m long with a proton current of 8 mA producing 10 MW of continuous average beam power. The spallation target would be either a liquid heavy metal (Pb/Bi eutectic) or an arrangement of cooled heavy metal elements surrounded by moderators to provide a broad spectrum of neutrons. To be competitive with existing steady state sources, the neutron flux of the ACNS will need to be $\geq 10^{15}$ n/cm^2-sec; i.e. equivalent to or better than that of the world's most powerful steady state source, the ILL research reactor located in Grenoble, France. A continuous source of this type would not only be the first of its kind in the U.S. but would complement the SNS source now under construction at Oak Ridge. It is important to emphasize that this is envisioned for the second decade of the 20-year plan, which is after completion of both the SNS project and the proposed NSLS upgrade.

SCIENTIFIC NEED FOR NEUTRONS

Thermal and sub-thermal neutrons are invaluable tools for condensed materials. Their importance lies in the fact that their wavelengths are comparable to the inter-atomic spacing in solids and their energies comparable to those of collective excitations in these materials. They complement other probes of condensed matter such as x-rays, electrons, laser light scattering, and UV and IR photons, but with a number of important differences that makes them unique. Firstly, the neutron has no charge and interacts directly with the nucleus. This means that the interaction strength varies from nucleus to nucleus and different isotopes of the same element will often have different scattering strengths. This is particularly useful in distinguishing between hydrogen and deuterium, and H-D isotopic replacement has been used extensively, and will continue to be used, in biological and polymeric studies. Also since the neutron-nuclear interactions varies randomly over the periodic table it is easy to observe light elements in presence of heavy elements, which is not the case with x-rays or electrons, where the scattering strength is simply proportional to the square of the number of electrons. Thus, the location of hydrogen and its motion in materials can easily be studied via neutron diffraction and inelastic neutron scattering, respectively. Also, being chargeless, the penetrating power of the neutron is unique. This makes it possible to surround a sample with another material and straightforwardly place it in a variety of different environments. That can be difficult when x-rays or electrons are used as probes. Finally, the neutron has a magnetic moment and interacts very effectively with magnetic moments of atoms in magnetic solids. This has provided much of the atomic-scale understanding of the properties of magnetic materials, many of which are of fundamental importance in our advanced technological society.

The scientific need for neutrons has been documented by several recent studies listed as Refs. 1-4. The most complete study of the role of neutrons in science was performed by the European Science Foundation in collaboration with the European Neutron Scattering Association and was published in the form of a report: *Scientific Prospects for Neutron Scattering with Present and Future Sources* (1) prepared by an international group of over 80 distinguished scientists. The list of topics it contains shows the breadth of neutron's applications:

- Magnetism and superconductivity
- Amorphous materials and liquids
- Polymers and soft matter
- Biology
- Atomic and molecular aspects of new materials
- Chemical reactions, catalysis and electrochemistry
- Earth sciences
- Materials sciences
- Engineering
- Production of isotopes, neutron activation and radiography.

Individual groups were formed to address each of the above listed topics. Each described future experiments that will require a high flux of neutrons. Some examples are:

BIOLOGY: By use of small angle neutron scattering (SANS), a faster structural relaxation process can be measured into the millisecond time domain. In combination with contrast variation techniques and specific deuteration this would make it possible to follow the conformational changes in different parts of a protein or macromolecular complex. With higher flux and better resolution, membrane dynamics could be studied.

MAGNETISM AND SUPERCONDUCTIVITY: One of the challenging problems for the future that will require high flux is to verify a Wigner crystallization in doped semiconductors. Another is to search for the Fermi glass. There is also the on-going study of the energy and wave-vector dependence of energy gaps in superconductors and related compounds. This will continue for the foreseeable future because new superconducting materials are constantly being synthesized. Typically, the single crystal samples needed for such studies are small and high flux is required because the signals are very weak. It needs to be emphasized that only neutrons will be able to measure inelastic magnetic scattering. Future time-resolved experiments probing the kinetics of phase transitions can also be envisioned as well as observation of the switching of magnetic domains in small systems.

EARTH SCIENCES: The earth sciences constitute one of several scientific domains that will clearly benefit greatly from neutrons, although only a small number of earth science users have employed them to date. This will surely grow as new and more specialized instruments begin to appear. Surprisingly, neutrons might even play a role in understanding (perhaps even predicting) earthquakes. The dehydration of hydrous phases in cool subducting slabs undergoing compression and heating in the mantle has been proposed as a possible mechanism for producing deep level earthquakes. Since neutrons are ideal as probes of hydrogen in materials, this question could be open to future investigation at neutron facilities.

These are just a few representative cases where neutrons are indispensable to microscopic scale understanding in various disciplines. The references(1-4) give many more examples. The consensus view of the scientific community is that neutrons will always be an important tool in our arsenal of techniques for exploring and understanding condensed matter and that their use will continue to expand as other disciplines come to recognize the unique qualities of the neutron probe. It is well documented that the current supply of neutrons in the US is insufficient for the next quarter century and a new continuous neutron source is needed.

JUSTIFICATION FOR A NEW NEUTRON SOURCE:

The demand for neutrons is increasing while at the same time many of the facilities built in the 1950s and 1960s are approaching the end of their useful lives. This "neutron gap" is internationally recognized and emphasized in the 1998 report of the *Neutron Sources Working Group of the OECD Megascience Forum*(5):

> "…in fact some time between the years 2010 and 2020 the presently-installed capacity of neutron sources for beam research will decrease to a level below one third of that today". (p4, paragraph 12)

Further, the report considers what would result if there is no further investment in major new neutron facilities:

> "The inevitable result of such inaction would be the decrease in the number of sources to less than a third of the present worldwide inventory, in the face of increasing demands for higher intensity and higher quality neutron facilities. Refurbishment and upgrades of the best existing facilities could alleviate the situation in the short to medium term, but would not prevent an eventual widening gap between supply and demand. The Working Group believes this (no new facility) is an unacceptable option." (p5, paragraph 14a)

It is clear that new neutron sources are needed. The world has responded by building or planning three high power spallation sources in the US, Europe, and Japan. Also, a new reactor has been built in Germany and is waiting for approval to start from the German government. Another is now in the early stages of construction in Australia.

The above-mentioned OECD report concluded that in Europe the anticipated shutdown of research reactors would be nearly compensated if all new sources planned and built were put into operation. The situation, however, is completely different in the United States. Here we refer to a recent (June 2002) study by OSTP(6) of *The Status and Needs of Major Neutron Scattering Facilities and Instruments in the United States,* which describes the current situation for neutron scattering in the US. This study finds that:

> "…in spite of early roots in North America, leadership for neutron scattering capability moved to Western Europe in the 1970's and has remained there ever since. With the majority of the new sources developed in Asia and Europe, the Unites States finds itself with a serious shortfall in overall neutron scattering capability. This shortfall is apparent both quantitatively, in terms of the number of instruments available for needed science and qualitatively, in terms of the leadership position of the ILL and ISIS facilities in Europe" (p.16)

Successful completion and operation of the SNS will help address the neutron shortage in the US and to some extent ameliorate US deficiencies when compared to Europe and Asia. However the SNS alone is not sufficient. The report concludes(6) (in its Executive Summary):

> "SNS is the most significant new opportunity to provide world-leading neutron scattering capability in the United States. However, the IWG (Interagency Working Group) also finds that the SNS alone cannot provide the necessary neutron scattering capability" (p.1).

This can be quantified by comparing the total number of neutron instruments capable of producing publishable research in Europe and the US as shown in Table 1.

Table 1: NUMBER OF NEUTRON INSTRUMENTS

Year	**1996**	**2001**	**2010**
Europe*		171	168
United States**	60	45	72

* Ref. 2, p. 26

** Ref. 6, Table 3 and Fig. 4

The decrease in the number of US instruments from 1996 to 2001 was due to the shutdown of the High Flux Beam Reactor (HFBR). The projected increase from 2001 to 2010 assumes the SNS is operational and fully instrumented and that new instruments are installed at the High Flux Isotope Reactor (HFIR) reactor at Oak Ridge. In Europe, the change is due to a balance between the shutdown of facilities and the expectation that the new German reactor will begin operation and the proposed European Spallation Source (ESS) will come on line. It needs to be emphasized that the US figure does not make allowance for the shutdown of any currently operating facilities which could drastically reduce the projected figure. Also, it is arguable whether the Intense Pulsed Neutron Source (IPNS) is a truly competitive facility since its flux is about 20 times less than the ISIS spallation source in the UK and will be 200 times less than SNS.

Further evidence that the SNS alone will not be sufficient to close a US neutron gap comes from the February 2000 *BESAC Sub-panel on Neutron Scattering*(7) assessing the effects of the shutdown of the HFBR on the neutron community. This report (the Blume/Rowe report) concluded that:

> "…the capacity lost by the HFBR shutdown is in fact truly lost – it cannot be replaced in the short term by any feasible actions. Of course when the SNS comes on line powerful new capability will be available for neutron-based research, but this will not completely substitute for the lost reactor capabilities." (p. 6)

Finally, BES itself recognized the need for a new continuous neutron source in their contribution to *1998 Facilities for the Future: the Office of Energy Research*(8). Listed as existing neutron projects were the SNS construction and the HFIR and HFBR upgrades. For new projects related to neutron capabilities the report recommends a new steady state neutron source with R&D beginning in 2008 and operation to begin in 2018, the same time frame that we are proposing here for a Continuous Neutron Source. In the above document it is stated that:

> "Once the useful lifetimes of the present U.S. research reactors have run their course, consideration must be given to a new steady state neutron research facility (p.26)"

STEADY STATE (CONTINUOUS) VS PULSED NEUTRON SOURCE

It could be claimed that a new steady state source is not needed because future neutron demand could be accommodated by the SNS with its upgrades and with future upgrades of the HFIR and NIST reactors. In terms of a simple count of the number of instruments this might be arguable, but such an argument would ignore the kind of science being done. There is agreement that instruments that can fully exploit the peak neutron flux, such as powder diffractometers and time-of-flight inelastic spectrometers, are best placed at pulsed sources and that instruments whose performance depends on the time-averaged flux are best located at continuous sources. The most obvious case of the latter is the triple axis spectrometer but this also applies to irradiation-based studies and isotope production. Instruments that are not as easily classified are the broadband types that make use of an extended wavelength band, but for these the benefit of pulsing is usually small. Examples would be small angle scattering spectrometers, spin echo spectrometers and, to a limited extent, instruments for diffuse scattering. What is clear is that the science to be done determines the instrument that is needed and this in turn determines the type of source that is needed. All studies of neutron needs clearly state that both types of sources, continuous and pulsed, are necessary.

The 1993 *Report on Neutron Sources for the Future*(9) of a committee chaired by Nobel Laureate Walter Kohn confirmed this by concluding that the two types of sources are complementary. The committee strongly recommended that both are needed for the future:

> “The panel concluded that the nation has a critical need for a complementary pair of sources: a new reactor, the ANS, which will be the world’s leading neutron source; and a 1-MW pulsed spallation source (PSS), more powerful than any existing PSS and providing crucial additional capabilities, particularly at higher neutron energies. The ANS is the Panel’s highest priority for rapid construction. In the Panel’s view, any plan that does not include a new, full-performance, high-flux reactor is unsatisfactory because of a number of essential functions that can be best or only performed by such a reactor.” (p. 2)

THE ACCELERATOR BASED CONTINUOUS NEUTRON SOURCE (ACNS)

A new research reactor in the US seems out of the question in today’s climate. However, there exists a proven method of generating a continuous flux of neutrons using the spallation process which we propose as the basis of a future steady state (continuous) neutron source. The Swiss Spallation Neutron Source(10) (SINQ) facility at the Paul Scherrer Institute in Switzerland is a 1MW continuous spallation source. It employs a cyclotron operating in a continuous mode that provides a 1.8 mA beam of 590 MeV protons that strike a lead target. Surrounding the target is a heavy water moderator tank with beam tubes through which the neutrons used by experimenters exit. SINQ produces a thermal neutron flux of 1 x 10^{14} n/cm^2-sec, equivalent to a medium flux reactor. This is a continuous source with many of the same experimental features as a reactor but without the environmental drawbacks associated with the fission process.

Our proposal is to build a similar continuous source based on a linear proton accelerator for the US with a power of 10 MW. This would supply a thermal neutron flux of $>10^{15}$n/cm^{2}-sec, and would be equal to or better than the two highest flux reactors in the world today, HFIR and ILL. The schematic of Figure 1 shows its basic elements.

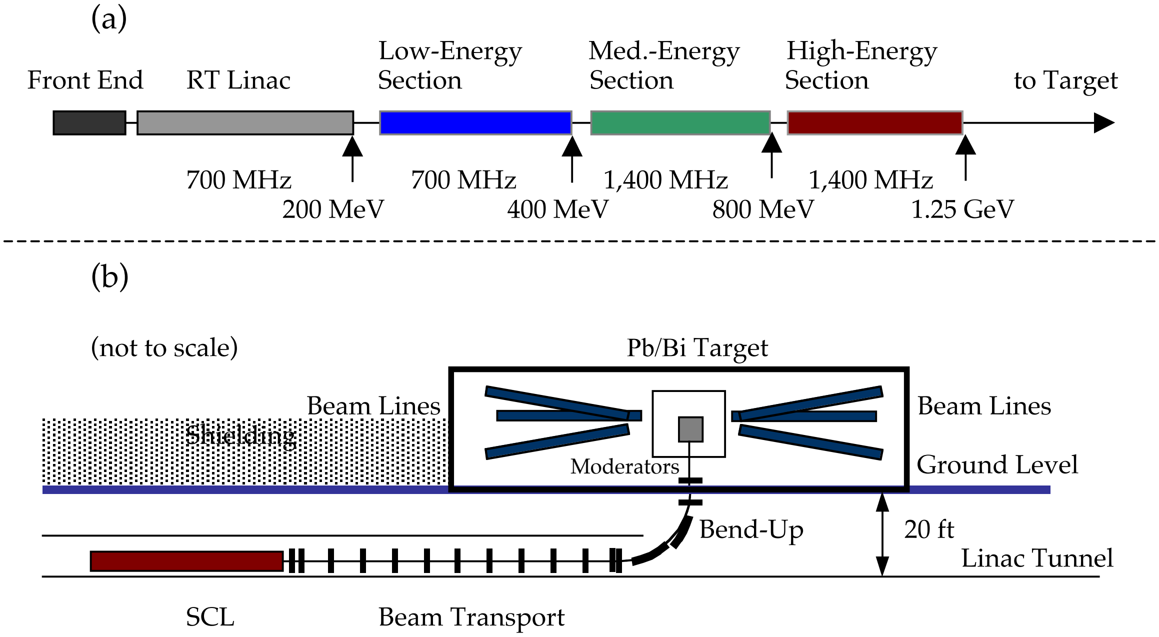

Figure 1. Schematic of the Accelerator based Continuous Neutron Source (ACNS)
(a) Accelerator portion
(b) Total facility

THE ACCELERATOR: A proton superconducting linac (SCL) operating in a continuous mode, accelerating an 8mA beam of protons to 1.25 GeV and generating an average proton beam power of 10 MW would serve as driver. An SCL is preferred over a cyclotron because of the high power required and beam losses are more easily managed. The linac would be made up of a front-end (a 10 mA positive-ion source) followed by 2.5 MeV RFQ and a 200 MeV Drift Tube Linac (DTL) that would in turn be followed by the superconducting linac proper. Altogether, the length of the source would be about 200 m. The technology for this type of source is well understood; in fact a continuous proton source of about 10 mA has been demonstrated at several institutions throughout the world. The proposed accelerating system is based on the selection of 700 and 1,400 MHz RF readily available from major power supply sources. The total AC power requirement is expected to be around 30 MW. The total cryogenic power needed is 5 kW at 2.1°K. BNL, with its accelerator expertise, has established an LDRD in the Center for Neutron Science to optimize such a SCL for continuous production of neutrons. Included in the study will be a detailed examination of the advantages of using a room temperature drift tube linac (DTL) or a system of quarter-wavelength superconducting cavities. Other issues that will be explored are the thermal power dissipated in the cavity systems, cryo-modules and RF cavities design, optimization of the power needs, and an appropriate location for the facility on the BNL site. A preliminary design of such an accelerator facility already exists. No major technical limitations have surfaced during the study.

THE TARGET: Neutron production depends critically on the type of target and moderators. A continuous stream of protons puts smaller demands on the target than does a pulsed beam of protons for a high power pulsed source. In a pulsed source the proton beam energy is deposited in a very short time which creates problems associated with the shock wave. In a continuous target, however, this is not a problem. Calculations show that a solid composite target consisting of a high melting point core surrounded by an outer lead multiplier might be a suitable choice but a liquid Pb/Bi eutectic target is also under consideration. High power density targets do, however, imply high proton currents on target beam windows. A combination of allowable window current densities and the heat removal capability of the targets determine the limits of the overall source brightness. A variety of window designs compatible with the proposed targets are currently being studied and optimized within the LDRD program. The type and placement of the various moderators is also important in determining the flux and these, too, are being investigated. Preliminary results are encouraging; they show that a thermal flux of at least 1.3×10^{15} n/cm^2-sec can be obtained 20 cm from a Pb/Bi target surrounded by a heavy water moderator.

LOCATION AT BROOKHAVEN

A new continuous neutron source would fulfill DOE’s commitment to provide user facilities for the nation’s scientific community well into the middle of this century. Brookhaven has a well-established scientific infrastructure to support a new neutron facility based upon the past work at the HFBR. Also, BNL has a very strong expertise in high intensity proton accelerators. These two strengths make Brookhaven an ideal site for a new accelerator based neutron facility.

Additionally, BNL pioneered the synergy between neutrons and x-rays by co-locating an X-ray source (NSLS) next to the neutron source (HFBR). This concept has proven very successful and many other countries have copied this paradigm. In the US, the Advanced Photon Source was built at Argonne where the IPNS neutron source is also operating. France built its 3rd generation light source (ESRF) on the same site as the high flux reactor at ILL. The Swiss built the Swiss Light Source next to the SINQ neutron source. A new neutron facility at Brookhaven located next to a state-of-the art light source would extend the tradition of co-locating the complementary x-ray and neutron probes of condensed matter.

BNL’s highest priority for BES projects for the first decade of the 20-year plan is clearly the next-generation upgrade of the NSLS that has been proposed. The present proposal for a continuous neutron source is post-NSLS upgrade and post-SNS construction. It should not be seen as competitive in any way with either of these.

CONCLUSION

A new continuous neutron source is needed for the second decade of the 20 year plan to replace aging US research reactors and close the US neutron gap. It is based on spallation production of neutrons using a high power continuous superconducting linac to generate protons impinging on a heavy metal target. There do not appear to be any major technical challenges to the building of such a facility since a continuous spallation source has been operating in Switzerland for several years. The thermal neutron flux of such a facility would be $\geq 10^{15}$ n/cm^2-sec which would equal (or exceed) the highest flux available at reactor based sources. A continuous accelerator-based spallation source would fulfill the recommendations of numerous review committees and satisfy the total demand for neutrons through the first half of the 21st century. It deserves serious consideration in future DOE planning.

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