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THE NATIONAL SPALLATION NEUTRON SOURCE COLLABORATION: TOWARDS A NEW PULSED NEUTRON SOURCE IN THE UNITED STATES

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Abstract

The US Department of Energy has commissioned Oak Ridge National Laboratory to initiate the conceptual design for a next-generation pulsed spallation neutron source. Current expectation is for a construction start in FY 1998, with commencement of operations in 2004. For this project, ORNL has entered into a collaborative arrangement with LBNL, BNL, LANL (and most recently ANL). The conceptual design study is now well underway, building on the strong base of the extensive work already performed by various Laboratories, as well as input from the user community (from special BESAC subpanels). Study progress, including accelerator configuration and plans for resolution of critical issues, is reported in this paper.

1. INTRODUCTION

In 1992, a DOE panel chaired by Walter Kohn, concluded that neutrons had become an indispensable tool for many areas of basic and applied research, and that the United States was woefully behind the international competition in the availability of up-to-date sources and instrumentation. The panel recommended the rapid construction of the Advanced Neutron Source (ANS), and that studies should commence towards a 1 MW pulsed spallation source. In 1995, however, the US Congress canceled the ANS project, but authorized the initiation of a design study for the new pulsed source, and requested as well that upgrades of existing reactor and accelerator facilities be explored. DOE convened several new panels to provide recommendations from the perspective of the neutron-scattering community. The new-facility panel chaired by T. Russell recommended as follows, "There is an urgent need to build a short pulsed spallation source in the 1 MW power range dedicated to neutron scattering with sufficient design flexibility such that it can be operated at a significantly higher power in a later stage."

DOE has commissioned Oak Ridge to conduct a two-year conceptual design study for this new source. To best draw on the broad national experience base, Oak Ridge has entered into a partnership with four other National Laboratories to share in the design and construction of this new facility. This partnership has been in effect for almost six months now, and significant progress has been made towards identifying a Reference Design, performing cost-optimization studies, evaluating different options and selecting preferred technologies. The names listed at the head of this paper are the team leaders at each of the Laboratories, but many key individuals are making critical contributions. LBNL has been given responsibility for the Front End, Ka-Ngo Leung is leading the ion source effort and John Staples is designing the RFQ as well as the LEBT and MEBT. LANL is designing the linacs; Tom Wangler is handling beam dynamics and Andy Jason the structure designs, Paul Tallerico and Mike Lynch are designing RF systems. Dave Gurd is coordinating the controls system activities of all the Laboratories. Brookhaven has responsibility for the high-energy beam transport lines and the accumulator ring. Studies there are being led by, in addition to Bill Weng, Sandro Ruggiero and Y.Y. Lee. Tony Gabriel, from Oak Ridge, is leading the target and neutronics efforts, while Herb Mook, also from Oak Ridge, is coordinating experimenter input for the specifications and designs of neutron-scattering instrumentation. Argonne is providing valuable assistance in this area, with input from Kent Crawford, Jack Carpenter and Bruce Brown. Evaluation of accelerator options is being performed as well by Dave Olsen (ORNL) and Yanglai Cho (ANL). The project management team and conventional facilities designs are being coordinated at Oak Ridge by John Cleaves.

2. REFERENCE DESIGN

Concept of a Pulsed Spallation Source

Neutron scattering requires low energy (≈millielectron volt) neutrons, with wavelengths commensurate with the size of the structures being studied. Accelerator-based sources of these neutrons offer advantages over reactors as the ease of obtaining sharp pulses (≈1 μsec) of protons onto a neutron-producing target leads to excellent timing of the neutrons arriving at the sample, thus allowing for an easy determination of the neutron wavelength. Proton energies between 1 and 5 GeV prove optimal for neutron production via spallation reactions in heavy-metal targets, production rate is directly related to the *power* deposited on the target. Pulse repetition rates of between 10 Hz and 60 Hz cover the range of experimenter requirements. These specifications map readily into accelerator configurations based on linacs accelerating H^- pulses of around 1 msec length, stripping injection into a ring that serves primarily as a pulse compressor, with single-turn extraction onto a target. Powers in the megawatt range (time-average) are close to current technology limits for a single ring, requiring the stacking of around 1000 turns and storing around 1 to 2 x 10^{14} protons in each pulse. Designing targets for these high powers is very difficult. It is generally believed that a 1 MW target is relatively straightforward, but the shock loads, radiation damage and heat dissipation requirements on a 5 MW target are thought to require designs beyond today's state of the art. Current wisdom leads to a liquid metal such as mercury or lead-bismuth as the best material to use. Achieving millielectron volt neutrons requires moderators placed close to the target, both ambient temperature (water) and cryogenic (liquid hydrogen or liquid methane) cells are employed. A single target will produce neutrons for many experimental lines, typically between 12 and 18 ports are instrumented and can run simultaneously.

Mission of the Spallation Source Study

The Oak Ridge study has been charged by DOE to develop a design which satisfies three basic requirements: it must achieve initial performance in the 1 MW power range with a high degree of confidence, it must be upgradable to a power level in the 5 MW range, and the initial configuration must cost less than $1B ($10^9$ US dollars).

Parameter and Technology Selection

The team began by performing a careful study of the relative merits of a full-energy linac plus accumulator ring versus a lower-energy linac and a synchrotron. While it was realized that the synchrotron option would in all likelihood be less expensive, the technical risks and upgrade paths would be less attractive than those associated with the accumulator option. The primary technical risk is controlling beam loss. Not only are very significant power levels involved -- e.g. 1% beam loss at 5 MW represents 50 kW of beam power -- that can severely damage accelerator components, but also the activation levels resulting from stopping stray beam in these components renders them inaccessible for hands-on maintenance, significantly adding to costs due to need for remote handling systems. As a result, total uncontrolled beam loss at energies above the Coulomb barrier are specified to remain below a part in 10^5.

The critical element remained, then, whether the accumulator ring design could be built for under the cost ceiling. A cost-model code was developed by John Galambos with assistance from Dave Olsen (ORNL) based on parameters from several studies and recent construction projects at LANL, BNL and ANL. This code was employed to perform a detailed comparison between the accumulator and synchrotron options, and showed that the synchrotron-based facility would indeed be slightly less expensive (around 5%), but also confirmed that the total costs for the 1 MW accumulator-ring scenario was extremely close to the desired cost target. In fact, costs arrived at by the model agreed quite closely with detailed costs provided by the design groups.

As a result of these studies we have adopted the accumulator-ring option as our reference design, and have proceeded to specify system parameters, component design and costs around this concept. The table below summarizes the principal parameters of our reference design.

Table 1: Reference Design Parameters

Beam Power	1 MW
Beam Energy	1 GeV
Repetition Rate	60 Hz
Ion Source Current (peak)	35 mA
Source Emittance (90%, norm)	0.5π mm-mrad
Chopping Ratio	0.65
Linac Duty Cycle	6%
Linac Length (total for all structures)	566 m
Injected Turns	1280
Accumulator Ring Circumference	208 m
Particles Stored in Ring (ppp)	$1x10^{14}$
Extracted Pulse Length	500 nsec
Target	Mercury
Beam Spot on Target	7 x 20 cm
Operating Temperature	80° C
Moderators, Ambient Temp	2 (water)
Moderators, Cryogenic	2 (LH_2,CH_4)
Beam Ports	18

Having established these parameters, we have devoted our attention to identifying the technological challenges, and designing an R&D program to address these challenges.

3. TECHNOLOGICAL CHALLENGES

Front End

The ion source technology selected by LBNL is the multi-cusp volume source, chosen primarily because of its stable, low-noise and high-efficiency operation. This source was selected for use at the SSC, and on a test stand has delivered over 100 mA of H^- beam, within the required emittance, and with an acceptably low e/H^- ratio. SSC application was at a very low duty factor, however, and an effort is planned to develop the specified 35 mA at 6% duty factor with the very long service life required for the source. As a backup, the Penning source used at ISIS is undergoing continuing development, and on a test stand is performing close to the required levels.

The LEBT will be based on a compact electrostatic, twin Einzel lens design that has been recently built and tested with positive ions at LBNL. This LEBT provided excellent transmission and matching to the RFQ only 10 cm away from the source extractor, without the chromatic aberrations normally associated with electrostatic transport lines. An electron dump must be integrated into the design.

Chopping, required to provide a beam hole in the accumulator ring free of any particles for clean extraction, is provided in three stages: pre-chopping in the ion source, first-stage chopping in the electrostatic LEBT (each Einzel lens is split into four quadrants for beam steering, pulsing one of the quadrants allows deflection of unwanted beam), and final chopping via a traveling wave chopper in the MEBT. The LANL group expects to extend existing technology in this area to achieve around 2 nsec wave fronts.

The RFQ is a 3.2 meter 4-vane structure operating at 402.5 MHz. While beam dynamics are well understood, experience with long duty factor structures is very limited. Significant design and engineering effort will be devoted to this topic.

Linac

A 402.5 MHz DTL will take the beam to 20 MeV, a CCDTL accelerates it further to 100 MeV, followed by a CCL to the final 1 GeV energy. The last two structures will operate at 805 MHz. A continuous periodic lattice of magnets will provide uniform focusing of the beam throughout the linac section, a concept believed to greatly reduce the problem of beam halo. Specification for beam loss is set at less than 10^{-7} per meter, and requires very careful beam dynamics calculations and structure design. Minimizing costs for RF equipment and linac fabrication is also a source of study.

Transport and Injection

Efficient injection into the accumulator ring is crucial. Shaping and matching the beam is performed in the transport line, which consists of a 60° achromat with several stages of transverse and momentum scraping. Injection will occur through a 200 $\mu g/cm^2$ carbon foil, with stacking in both momentum and transverse phase space. Very careful design of this region is taking place, as this is a major source of beam loss. Of particular concern is the handling of metastable H^0 atoms that are Lorentz stripped downstream of the foil, that form beam halo in the ring. Design of a suitable scraping system is taking place to minimize activation of components from this source. An additional issue is the lifetime of the carbon foil, which must operate at close to 3000°C.

Ring

The accumulator consists of a 3-superperiod lattice of FODO cells with achromats providing zero dispersion in the 20-meter straights. Designed to operate at a tune-shift of 0.2, the acceptance/emittance ratio is around 8. This is achieved with a dipole gap of 18 cm. Controlling the growth of transverse coherent instability in the ring may require addition of an octupole component to introduce tune spread. Mitigating instability growth, also, is that the storage time of the beam in the ring is essentially zero, it is extracted immediately after the conclusion of the stacking process. Careful tracking studies and space-charge simulations are taking place to assure acceptable performance of the ring. RF system design must ensure that no beam migrates into the space reserved for the extraction kicker risetime. Multi-harmonic and barrier-cavity concepts are being explored.

Target

Mercury offers some very attractive advantages over solid targets: higher neutron brightness (no cooling water channels), it is its own primary cooling circuit, residual activation products are less than other materials, and the beam shock problem is greatly reduced. Issues of material compatibility with the target vessel (embrittlement, corrosion), and specific engineering designs and layouts are being studied.

4. UPGRADE PATH

The first upgrade will involve construction of a second target station operating at 10 Hz. This will allow for maximum experimenter flexibility for effective use of a wide range of neutron velocities. Following this will be a series of upgrades leading to higher power. The linac and ring will all be designed to handle 70 mA from the ion source, and it is believed that this current level is achievable. This will increase power of the facility to 2 MW. An additional 2 MW will be provided by adding a second front end and DTL, with funneling at 20 MeV. Every bucket in the 805 MHz linacs will now be filled. Additional RF equipment will be provided to handle the extra beam power. A second accumulator ring will be needed to maintain tune shifts to acceptable levels. An additional upgrade would consist of adding a synchrotron to boost the energy from one of the accumulators to 3 GeV, providing a full 1 MW of average beam power on the 10 Hz target, and bringing the total facility up to 5 MW.

5. SUMMARY

Although many challenges lie ahead, both technical and financial, we believe that the NSNS Project is on very solid footing. A great luxury for us, compared to the ESS Project is that our Day-One performance will be at the 1 MW power level instead of 5 MW, allowing a much more conservative approach to increasing power through incremental improvements. Our very strong team, with excellent communications with parallel efforts in Europe and Japan provides us with the best possible resources for bringing this project to a successful conclusion.

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