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Target Station Design for a 1 MW Pulsed Spallation Neutron Source

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Target stations are vital components of the 1 MW, next generation spallation neutron source proposed for LANSCE (colloquially referred to as LANSCE-II in this report). By and large, target stations design determines the overall performance of the facility. Many traditional concepts will probably have to be rethought, and many new concepts will have to be put forward to meet the 1 MW challenge. This article gives a brief overview of the proposed neutron spallation source from the target station viewpoint, as well as the general philosophy adopted for the design of the LANSCE-II target stations. Some of the saliant concepts and features envisioned for LANSCE-II are briefly described.

Target stations overview

The present concept calls for two target stations sharing one large building. The first target station is pulsed at 40 Hz, whereas the second station is pulsed at 20 Hz. These specifications are driven by user requirements. The average proton beam current is 1.25 mA at 800 MeV, i.e., 1 MW of proton beam power. The target stations are separated in the middle of the experimental hall by a large service area for remote-handling of the target system, storage of target components, and laboratory space for activities such as sample preparation.

The basic target configuration has not been chosen yet, and we are still exploring the advantages and disadvantages of horizontal vs. vertical proton beam insertion (from below in the case of vertical insertion). However, we have selected a reference case for further study, namely proton beam insertion from below into two target stations. These issues are addressed for the reference case in more detail below and involve far more than the neutronic performance of these different schemes.

The LANSCE-II target stations, although dedicated primarily to the production of thermal neutron beams for materials science and engineering, biology, chemistry, and condensed matter physics, will also include facilities for radiation damage studies and μSR. These issues have not been examined in detail yet.

Basic specifications

We review briefly the general requirements for LANSCE-II, and, more specifically, those requirements that impact significantly the design of the target systems.

Perhaps the most stringent specification is the proton beam power, namely 1 MW at 800

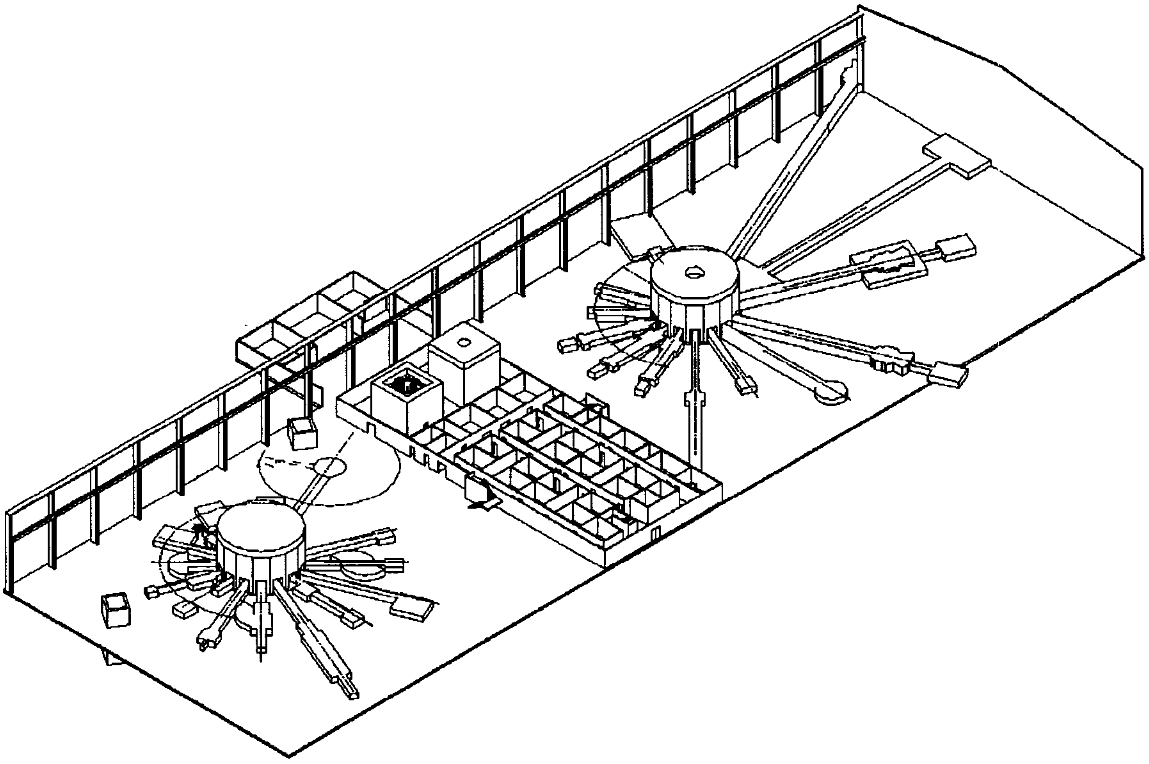


Figure 1: LANSCE-II: View of the experimental hall and the target stations.

MeV, with a possible upgrade to 5 MW in the not-too-distant future. These specifications are driven by the need to use as much of the present LAMPF facility hardware as practical to keep costs and performance as favorable as possible. The average current is 1.25 mA and the beam is to be divided between two target stations operating at 20 Hz and 40 Hz, Fig.1. The average proton beam power to the target stations is thus 333.3 kW and 666.7 kW, respectively. The large powers involved (compared, say, to ISIS at the Rutherford-Appleton Laboratory (England) where the average proton beam power is 160 kW, and presently the most powerful pulsed neutron source in the world) complicates greatly target design and the target cooling system. Ideally, the target stations should be designed so that an upgrade to 5 MW can be achieved at minimum cost. Although at this point we do not consider this to be a driving force behind the design of LANSCE-II, the possibility of a 5 MW upgrade has often been kept in mind in the design of many of the components of the target stations.

Other aspects of target design are very strongly affected by the power requirement. Problems associated with radiation damage, corrosion, and activation in the targets, to cite but a few, are likely to be much more severe than in present facilities. Similarly, the shielding requirements increase in size and complexity with proton beam power. To summarize, many problems that do not exist or are secondary problems at lower beam powers become more accute, and sometimes even dominate the design, at 1 MW.

A second important requirement is the *quality* of the neutron beams produced. A compromise must be reached between the number of viewed surfaces and the intensity of the neutron beam current leaking from the moderators. Opening more holes in the reflector to accomodate more flight paths has, generally speaking, a detrimental effect on the neutron beam current. The problem of finding a target configuration that has as many high-intensity beams as possible without sacrificing too many flight paths, or vice-versa, is not trivial.

The intensity of the neutron beam current (in the appropriate energy range for materials studies, typically $E < 100$ meV, but some applications require higher energy neutrons, in the 1-2 eV range) is only one criterion to determine the quality of the beam. Attention must be paid to the higher energy background ($E > 1$ eV), as well as to the shape of the neutron pulses. The former becomes a rather significant problem at 1 MW, and is essentially a function of target-moderator arrangement. The latter is determined mostly by the nature and geometry of the moderators.

A third requirement concerns the reliability and availability of the proposed neutron source. Obviously, this problem is linked directly to the reliability of the accelerator. However, there are many aspects of target station design that are crucial to ensure the regular and continued delivery of high-quality neutron beams to the users. The present goal is to provide beam time nine months per year with an availability of 85 % or more to about 2000 users.

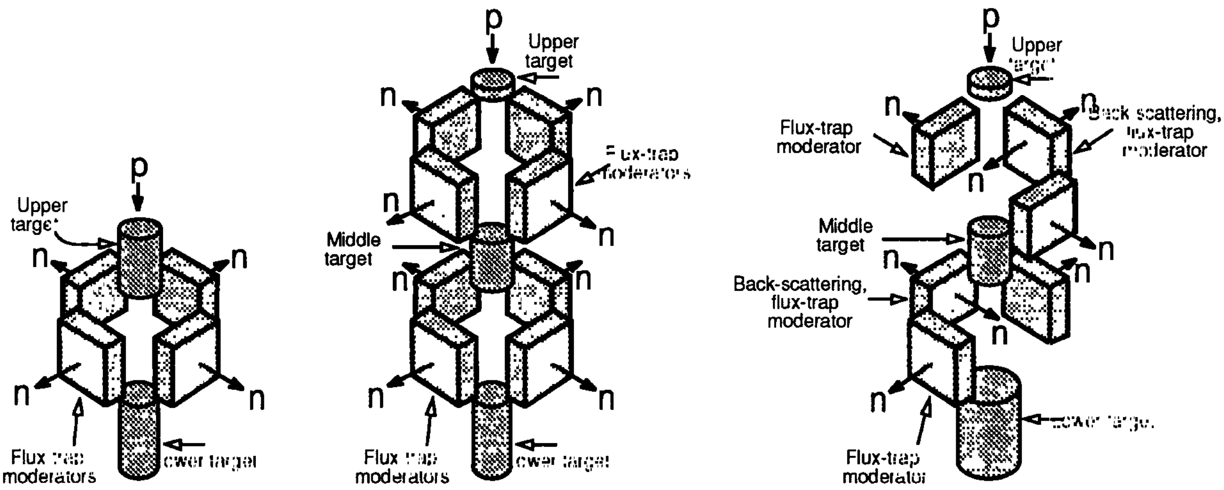
First, and perhaps foremost, is maintenance. This includes routine maintenance operations, or more complex operations such as target or moderators replacement. How quickly, efficiently, and safely these operations can be carried out will depend largely on the remote-handling facilities to be designed and implemented in parallel with the target stations themselves.

Factors that determine the target lifetime such as radiation damage, thermal stress, and other requirements discussed above also influence directly the reliability of the target stations and must be carefully considered and optimized.

Monitoring the vital signs of the target stations, such as proton beam current, profile and location, coolant flow and pressure, and target temperature among others is even more crucial at 1 MW than in the present LANSCE target station. Extensive, state-of-the-art, and redundant instrumentation will allow us to react quickly and efficiently and eliminate potential problems before they become major problems forcing the target station to shut down. Target station instrumentation is thus a most crucial tool to increase reliability and therefore availability.

The above, sometimes contradictory, requirements ultimately impact the mechanical design and physical layout of the target-moderator-reflector-shield (TMRS) assembly: Increasing the number of flight paths per target station (compared to existing designs) adds to the complexity of the mechanical design of the TMRS assembly. This difficulty is compounded with the increased complexity of the cooling system required to operate at 1 MW and the reliability requirement that would ideally demand quick and easy access to the target and moderators if a problem develops.

All these problems and challenges are being addressed and resolved. The next section is devoted to the neutronics of the target station while the following section deals in detail with some of the engineering aspects of the design. Because there is no difference between the 40 Hz or the 20 Hz station, except for the average power deposited in the target, the design



with a split target
LANSCE I

(a)

with a tiered target
LANSCE II

(b)

with a tiered target
LANSCE II

(c)

Figure 2: TMRS concepts. (a) Present LANSCE design; (b) Tiered target geometry with 8 moderators in flux-trap geometry; (c) Tiered target geometry with backscattering moderators.

procedures are the same for the two stations, and in what follows we will discuss a "generic" target station unless the distinction is explicitely required.

Neutronics - Target/moderator/reflector/shield assembly

The present LANSCE pulsed neutron source is based on the split target concept, [1,2] and provides the highest peak neutron flux of any spallation neutron source. Instead of the traditional solid, cylindrical target with four moderators in wing geometry [3-5], the present LANSCE target is split into two distinct target cylinders with four moderators facing the gap between the target cylinders, Fig.2(a). This geometry has several advantages; among them is the fact that the four moderators now have equal intensity. (In the traditional wing moderator design, the downstream moderators have lower intensity compared to the upstream moderators.) Furthermore, the split-target/flux-trap moderators geometry in combination with a vertical proton beam insertion scheme allows 360° access to the target station. The more common horizontal insertion scheme sacrifices up to ~120° for proton beam insertion and the remote-handling cell.

In an extensive study at Los Alamos, we are probing the vast parameter space associated with the design of a pulsed spallation neutron source, including:

- proton beam energy, pulse width, and repetition rate;
- horizontal versus vertical proton beam insertion;
- choice of target geometry and material;

- target thermal hydraulics;
- moderator geometry (wing, flux-trap, backscattering, coupled, composite, etc ...), material, and neutronic performance;
- number of moderators, viewed surfaces, flight-paths characteristics, etc ... ;
- composite reflector-shield, and bulk shield design;
- neutron beamline, chopper, and beam stop shielding requirements;
- target system engineering, including remote-handling and servicing;
- target instrumentation.

The results of some of these studies are described elsewhere in these proceedings.

We have settled on a reference concept which seems to perform well at 1 MW, and incorporates many desirable features of a future high-power target station. The concept will evolve as larger portions of the target station parameter space are explored. Table 1 summarizes some of the issues that affect target station design. A promising target concept on which our efforts are currently being focussed has two (possibly three) target cylinders with two flux-traps and four moderators per flux-trap, see Fig.2(b). This implies a total of eight moderators (and eight viewed surfaces) per target station. At three flight paths per viewed surface, the new facility could provide as many as 48 neutron beams. We also considered the use of backscattering moderators, as shown in Fig.2(c), in a two flux-trap geometry. A global view showing the location of the TMRS inside the shield, and part of the magnet optics is shown in Fig.3. A more detailed, preliminary engineering layout of the TMRS is shown in Fig.4.

Moderators represent another important aspect of target station optimization where much can be done to increase the neutron beam intensity. With a total of 16 moderators, one can consider a great variety of moderators, and thus a great variety of spectra and neutron pulse shape characteristics to suit the users needs. For example, a new, innovative concept being considered at LANSCE is that of a composite moderator where the neutron spectra of different materials (e.g., water and liquid hydrogen) could be mixed in different proportions to yield an intense, "broad-band" spectrum [6,7], or other desirable characteristics from the user's viewpoint. In addition, we have investigated coupled and backscattering moderators, Fig.2(c).

We also use the concept of a composite-reflector shield for the new spallation source. This concept was proposed and has been implemented at the present LANSCE facility [1,2]. We propose to replace the traditional Be reflector surrounding the target-moderators assembly by a composite assembly of Be and Ni. The inner Be core extends some 20 cm or so from the proton beam axis, while the outer part of the reflector is pure Ni. The Ni outer layer is a fast neutron reflector while the inner Be core acts as both a reflector and a moderator. This has several advantages. First, computer studies show a 10% increase in neutron beam intensity. Second, Ni is a better radiation shield than Be, which reduces the total amount of shielding

Target System Configuration		Neutronics	Total Angular Access	Angular Sep. of Instrum.		Shielding	Maintenance
				2 FP/ viewed surface	3 FP/ viewed surface		
Vertical Beam Insertion Upward	Hot cell on top	Allows for more moderator viewed surfaces than does horizontal insertion	360°	8 viewed surfaces		Hot cell displaces downstream shield	Access to 90° bending magnets and target complicated
				22.5°	15°		
	Hot cell on side		300° (60° for hot cell)	6 viewed surfaces		Hot cell shielding displaces intrument floor space	Access to 90° bending magnets complicated; Target maintenance similar to ISIS
				25°	16.7°		
	Segregated detached hot cell		360°	8 viewed surfaces		Shield geometry relatively simple	Access to 90° bending magnets and target complicated; Requires transportation of target to hot cell
				22.5°	15°		
	Integrated detached hot cell		360°	8 viewed surfaces		Shield geometry relatively simple	Access to 90° bending magnets and target complicated; Target maintenance may limit access to experimental hall; Similar to SINQ
				22.5°	15°		
Vertical Beam Insertion Downward	Hot cell below	Allows for more moderator viewed surfaces than does horizontal insertion	360°	8 viewed surfaces		Hot cell displaces downstream shield	Access to target complicated
				22.5°	15°		
	Hot cell on side		300° (60° for hot cell)	6 viewed surfaces		Hot cell shielding displaces intrument floor space	Target maintenance similar to ISIS
				25°	16.7°		
	Segregated detached hot cell		360°	8 viewed surfaces		Simple bulk shielding; Complex beamline shielding	Access to target complicated; Requires transportation of target to hot cell
				22.5°	15°		
	Integrated detached hot cell		360°	8 viewed surfaces		Simple bulk shielding; Complex beamline shielding	Access to target complicated; Target maintenance may limit access to experimental hall
				22.5°	15°		
Horizontal Beam Insertion	Hot cell on top	Good performance obtained from wing + flux trap geometry	300° (60° for beam insertion)	7 viewed surfaces		Hot cell need not displace shield	Relatively difficult access to target
				21.4°	14.2°		
	Hot cell on downstream side		240° (120° for hot cell & beam)	6 viewed surfaces		Hot cell displaces downstream shield	Proven design (ISIS)
				20°	13.3°		
	Hot cell below		300° (60° for beam insertion)	7 viewed surfaces		Hot cell need not displace shield	Conceptually designed (SNQ)
				21.4°	14.2°		

Table 1: Issues to be considered in the selection of a target station design for LANSCE-II.

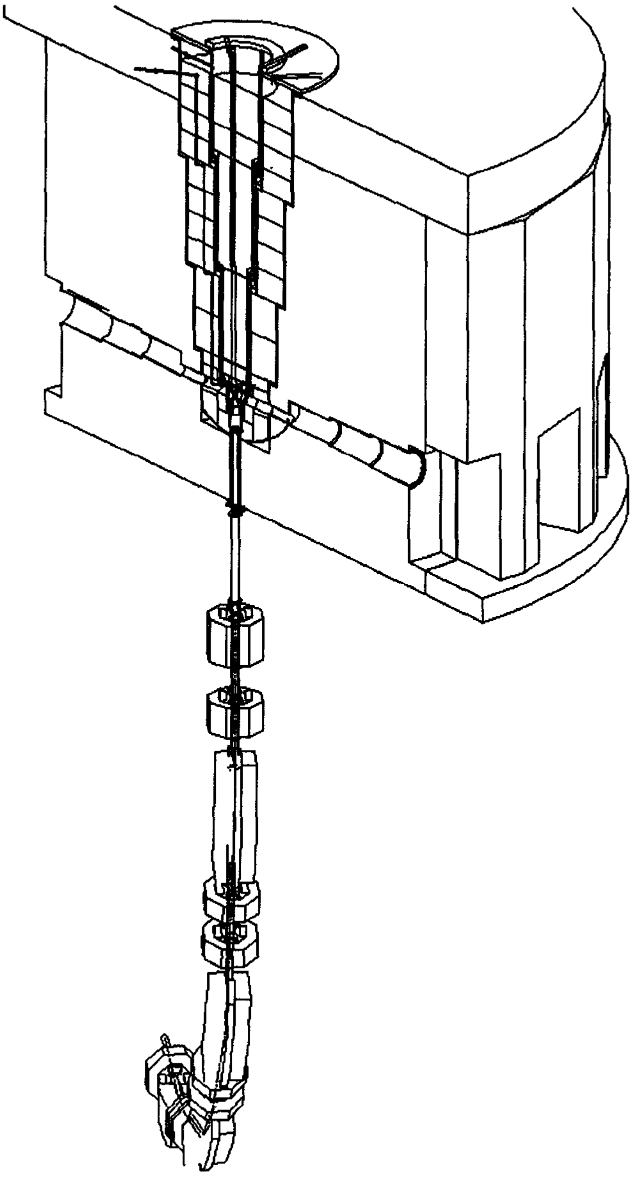


Figure 3: Cross-sectional view of the reference LANSCE-II target station. Access to the TMRS module is obtained by removal of a number of shielding segments shown explicitely in the diagram. Also shown is the magnet optics under the target station, including the 90° bending magnet. The bulk shield is approximately 12 m in diameter and 9 m high.

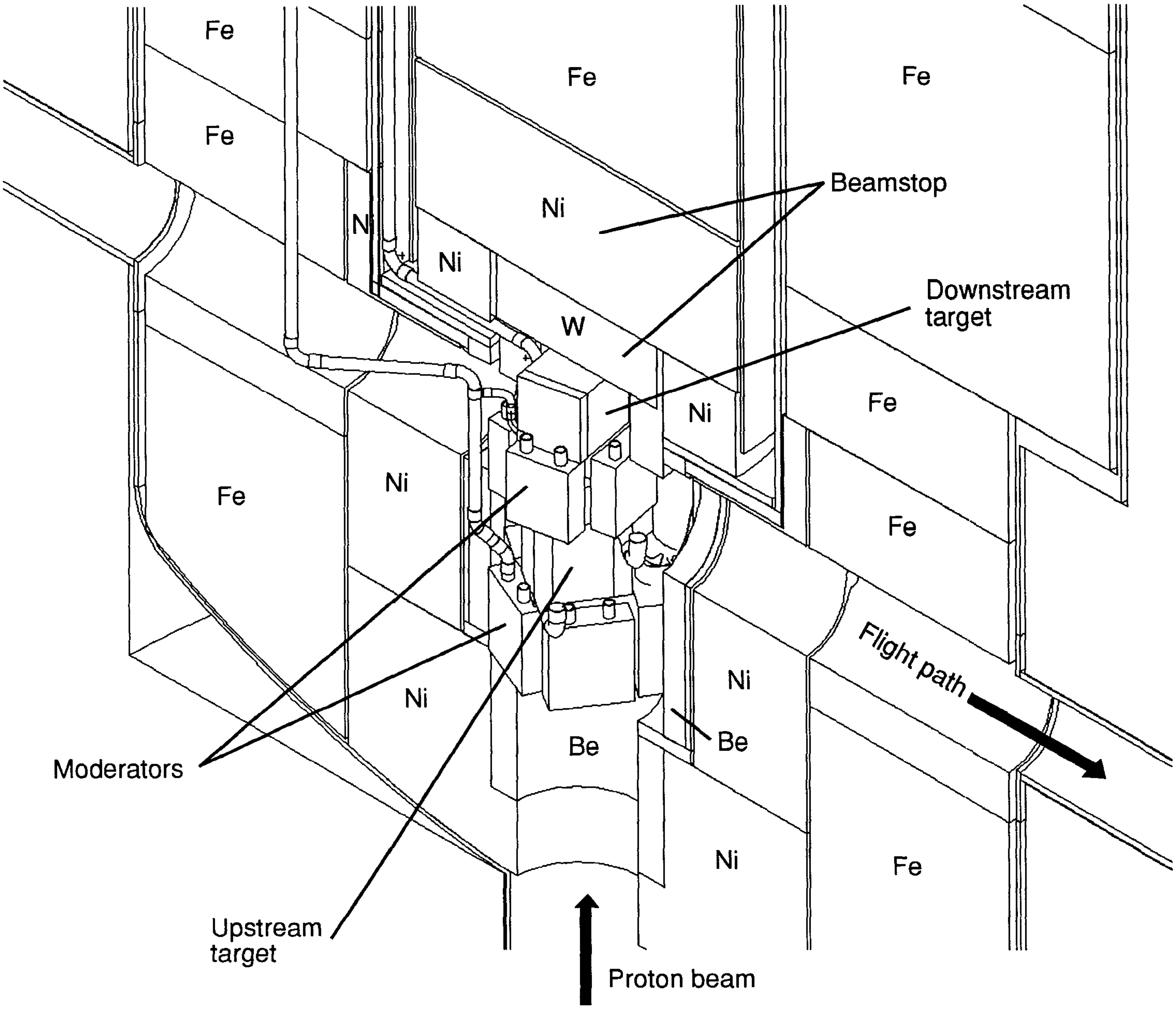


Figure 4: LANSCE-II preliminary TMRS layout.

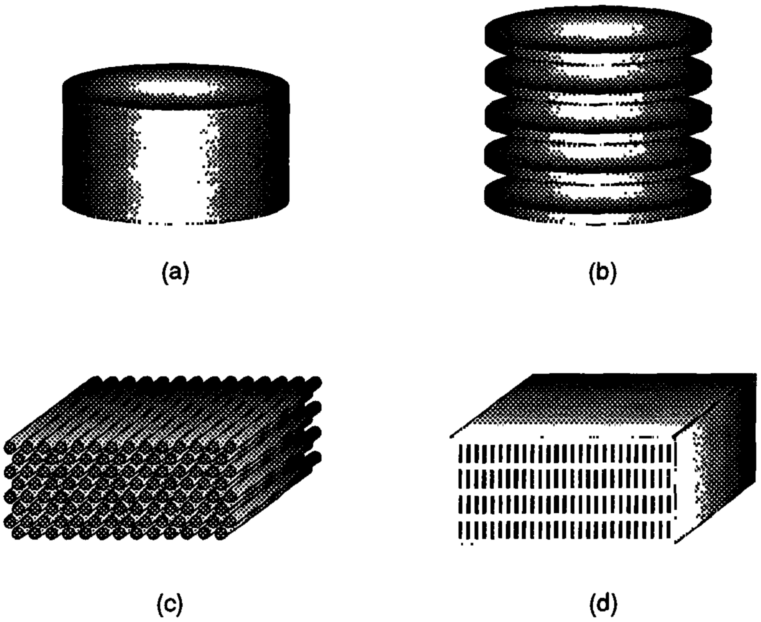


Figure 5: Target concepts for LANSCE-II. (a) Monolithic target, (b) Plates, (c) Rod bundles, (d) Microchannel target.

material required for the bulk shield. Third, less Be is needed – a distinct advantage in view of the materials cost, cost of machining, and toxicity of Be metal.

This summarizes very briefly an extensive set of studies aimed at neutronics optimization. The new concepts proposed to meet the 1 MW challenge call for the resolution of many engineering problems, such as target thermal hydraulics.

Target thermal hydraulics

We evaluated a variety of target design concepts, including monolithic targets, plates, concentric annuli, packed meshes, microchannels, and a variety of rod bundle configurations. In selecting concepts for further studies, we focused on neutronic performance, thermal-hydraulics, stress, and fabrication issues. We also kept in mind the possibility of increasing the proton beam power to 5 MW. Two of these concepts, the microchannel and rod bundle targets, were selected for further study, Fig.5.

Microchannel Target Design: The microchannel target is an extremely compact heat exchanger design composed of multiple, thin tungsten layers with channels etched on each layer surface using photolithography, Fig.5(d). The layers are furnace-brazed together using an alloy as the braze material. The brazing allows for a large heat transfer area and minimizes temperature differences within the target. The design provides a total temperature difference from the beam hot spot to the fluid exit on the order of 10-20°C. Because of the small dimensions of the individual flow passages, the resulting assembly behaves as a monolithic unit under thermal and mechanical loads. The fluid distribution headers can be made an integral part of the target, and the low flow requirement allows the inlet and exit piping to be kept small. The target structure is insensitive to internal pressure loads because of the small fluid passage dimensions, and it has minimal thermal loads because of the low temperature differentials. Microchannel cooling technology has been used in a variety of high power density applications including laser mirrors, hypersonic infrared windows, semiconductor chips, and compact heat exchangers.

Our main objective in the design of the microchannel target is to cool an average power density of at least 1 MW/l so that the target may accomodate full beam power in a manner that minimally impacts the neutronic performance of the target. From a neutronics standpoint, desirable characteristics are: use of heavy water (instead of light water) as coolant; and minimize the volume of coolant in the proton beam path. We can achieve this thermal power density by ensuring low thermal stress using a low temperature differential between the inlet and outlet streams as well as low temperature differences in the solid metal sections of the target. Structural integrity of the target under induced thermal and mechanical stress is another important objective as well as low coolant fraction and flow rates, allowing a compact, mechanically simple design. The target concept should be scalable to an average power density of 5 MW/l in order to handle potential beam power increases. Further studies are required, however, to assess target performance at this power level.

The microchannel target design provides a very high thermal capacity with low fluid fraction. Because the metal cross-sections are small and the individual flow passages distributed throughout the target, the maximum temperatures resulting from the beam are low. As a result, the temperature-induced stresses in the target are also low. In addition, because of the distributed nature of flow passage voids in the target material, the moment of inertia of the target is high. The microchannel target is similar to a monolithic target in its structural behavior but without the large temperature differences and high resulting stresses seen in the monolithic target. Commercial suppliers have demonstrated fabrication of microchannel structures in tungsten and tungsten/rhenium alloys, and the fabrication of the proposed target configuration does not present any new process development problems.

Rod-Target Design: The rod-target concept is based on an array of short, tightly packed tungsten rods oriented perpendicular to the incident beam, Fig.5(c). The rod bundles, comprised of approximately 800 tungsten rods, are arranged into two target tiers and provide a total effective tungsten thickness of 22.5 cm (stopping length for 800 MeV protons on W). Coolant plena are provided at both ends of the rod bundles, and forced flow along the bundle length provides cooling for the target. Within each target tier, the tungsten rods and associated coolant (water) are contained inside an Inconel-718 target canister.

One of our main goals in the design of a target for LANSCE-II is to minimize the coolant fraction interior to the target tiers, thereby minimizing neutron moderation and parasitic absorption within the target. We used parameter studies to characterize the influence of rod diameter and pitch-to-diameter ratio on the coolant volume fraction; pressure drop across the rod bundle; and temperature gradient across the rods. To support 1 MW total beam power, we chose tungsten rods 0.6 cm in-diameter arranged on a triangular pitch with a rod pitch-to-diameter ratio of 1.05. The 10-cm-long rods are arranged in 27 and 24 rows for the first and second target tiers, respectively, and the maximum number of rods per pin row is 16. This configuration yields 10 cm^2 target tiers with effective tungsten thicknesses of approximately 12 cm and 10.5 cm. Each row is mechanically supported at both ends by a slot and hanger arrangement, and the Inconel-718 structure provides the mechanical and pressure boundaries around each target tier. To minimize unnecessary coolant volume and bypass flow at the edge of the bundles the interior Inconel surfaces would be designed with a scalloped shape corresponding to the adjacent rod rows.

The results of extensive studies are that: (1) the rod target design concept can achieve relatively small coolant volume fractions with a high-surface-to-volume ratio; (2) the rod target concept can also be readily scaled with energy deposition while still preserving the small coolant volume fractions; and (3) the target cooling system operates at low pressure, which greatly simplifies mechanical and safety aspects of the design.

Further analysis effort should be devoted to system level performance of the target cooling system for the microchannel and rod-target design. This should include evaluation of off-normal transient scenarios such as loss of heat sink, loss of flow, loss of power, and loss of pressure/coolant.

Remote-handling

The remote-handling systems initially considered for the LANSCE-II reference case make use of the monitor/servo-manipulator system developed at LAMPF [8,9]. This system of remote-handling utilizes servo-manipulators mounted on hydraulic booms, cranes, and remotely operated vehicles. Because the reference LANSCE-II design calls for beam delivery from below with the target stations located in two large experimental halls, the large remote-handling area is located between the two experimental halls, Fig.1. This concept permits a central, single facility to service both target areas. Remote-handling, removal, and reinstallation of the target system is done from the top of the target monolith. The ventilation system over the target monolith would be designed to give a forced flow of air across the top into High Efficiency Particulate Air (HEPA) filter intake ducts. If any airborne particulate radiation is expected or found, ventilation containment enclosures could be placed over the top of the monolith.

The targets, moderators, and part of the reflector form a modular assembly inside the target crypt. This module is removed from the crypt into a shielded cask, which is transported by crane to the remote-handling area. The module is then placed into storage wells in the floor or in shielded assembly/disassembly caves if immediate replacement or repair of the target-moderator-reflector module components is required.

The assembly cells will be designed to permit the precise locating and alignment of all system components. Remote-handling procedures will be developed and carefully tested prior to implementation. Major components will be designed in a modular fashion so they can easily be removed, repaired, or replaced. Rack-mounted tools and positioning devices will be designed for the system. The most advanced equipment will be placed in this facility to give the largest possible ability for performing delicate tasks on complicated hardware. The disassembly cell will be designed to accommodate the remote-handling tasks and constructed from stackable shielding. A water-tight liner connected to the facility contaminated waste system will be used to contain any liquid spills. A HEPA-filtered ventilation system will be installed to control the air emissions. Facilities must be provided to decontaminate remote handling equipment, tools, and experimental hardware.

This approach corresponds to the vertical beam insertion (upward)/detached hot-cell concept presented in Table 1 and is our reference case. However, we are revisiting the remote-handling issue as we probe more of the parameter space of target station design.

Other aspects of target station design

It is not possible to give here an exhaustive overview of all those aspects that affect target station design. Beside the crucially important issues discussed above, many other, equally important, problems have to be addressed.

Among those problems is the poorly understood issue of target and target coolant radiochemistry. The intense radiation field to which the target is subjected modifies drastically its physical and chemical properties. This, in turn, complicates the thermal hydraulics of the target and its resistance to thermal stress for instance, but also contributes to a decrease in the target lifetime. Indeed, the formation of spallation products and their subsequent chemical interaction with the coolant and the target material, coupled with the radiation damage and the likely modification of the materials microstructure under thermal stress and radiation could ultimately lead to the early demise of the target if no precautions are taken to alleviate these problems. Unfortunately little information is available regarding these difficulties. However, present operational experience with various types of targets at spallation sources indicates that these problems already exist at the power levels currently used. At proton beam powers of 1 MW or more, these problems could very well become a vital aspect of target design.

Another important problem that was deliberately ignored here is that of target station instrumentation and control. Proper instrumentation is necessary to ensure that the various target station components are operating as expected within the operational safety limits. The consequences of an undetected failure, particularly at 1 MW, in any one of these systems can result in costly repairs and loss of valuable experiment time for the users. In addition to satisfying basic safety requirements, target instrumentation should be sufficiently varied and flexible to be useful in collecting data for target station development. Of particular importance is proton beam monitoring. The exact beam profile, intensity, and location on target are most crucial pieces of information, and should be monitored at all times. With high-power targets such as those proposed for LANSCE-II, cooling requirements (target, moderators, reflector, shield, beamstop) are likely to be complex. Monitoring (temperature, flow, pressure) of the cooling circuitry is thus essential.

Other problems include: target decay heat, radionuclides production, mechanical design and layout, activation of ancillary equipment, radiation protection, vacuum enclosures, interfacing with the accelerator and the scientific instruments, etc. Clearly these are out of the scope of this review.

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