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Neutron Science Center

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Proposal for a Fusion Prototype Neutron Source at the Los Alamos Neutron Science Center

Eric Pitcher, Yuri Batygin, and Stuart Maloy

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1 Executive Summary

This study evaluates a target station at the Los Alamos Neutron Science Center dedicated to the mission of irradiating structural materials in an environment that is nearly prototypic of the radiation environment experienced by the first wall of a magnetically-confined fusion reactor burning D-T fuel. Such a station could be located in the existing Area A experimental hall and be driven by an 800-MeV, 1-MW proton beam delivered by the LANSCE accelerator. A neutronics assessment of a target concept shows it satisfies all of the key parameter guidelines stated in the *Summary Report on the Fusion Prototypic Neutron Source Workshop* [1], shown in Table 1.

The concept developed for this application employs an annular spallation target with the sample irradiation volume occupying the central flux trap within the target. The cylindrical flux trap is divided into three 120° sectors, each with its own temperature control. Provided the proton beam is accurately directed onto the target, this arrangement ensures that the only difference between each sector is the irradiation temperature; all other conditions are the same. Sample temperature control is assured using the well-established technique of employing a gas gap between the materials sample cans and the coolant, where the gas composition can be varied continuously from pure argon to pure helium and thereby controlling the thermal conductance from the samples to the coolant by a factor of eight. Sample heating is achieved passively by relying on radiation (mostly protons and gammas) emanating from the spallation target. The spallation target material is pure tungsten, which is widely used for this application, cooled by helium gas. The sample can may be cooled using either heavy water or helium.

The suitability of a high-power spallation source to simulate the radiation environment of a fusion reactor first wall was evaluated for the previously proposed Materials Test Station (MTS) project [2,3] and a higher-power variant of the MTS called the Fission Fusion Facility [4]. As the radiation environments of the MTS and a spallation target station for a Fusion Prototypic Neutron Source (FPNS) are abundantly similar, we draw upon this body of work to evaluate the similarities and differences of the radiation environments between a fusion reactor first wall and a spallation source specifically designed for fusion materials irradiations. The main conclusions may be summarized as follows:

- In a spallation source, Fe-Cr alloys will accumulate trace quantities of S, Cl, K, Ca and Sc in concentrations that are at least two orders of magnitude greater than that expected in a

Table 1. Key parameter guidelines for a Fusion Prototypic Neutron Source (from ref. 1).

Characteristic	Desired Value	1-MW station in Area A
Damage rate	8 – 11 dpa/CY	8 dpa/CY* averaged over 53 cm ³ volume
He/dpa ratio	~10 appm He/dpa in Fe	14.6 appm He/dpa averaged over 53 cm ³ volume
Irradiation volume	>50 cm ³ in high flux zone	53 cm ³
Irradiation temperature	300–1000 °C, 3 zones actively controlled	300–1000 °C, 3 zones actively controlled
Flux gradient	<20%/cm in the plane of the sample	<10%/cm in all directions

*Assuming 3400 hours of 1-MW beam on target per calendar year (CY).

fusion reactor first wall [3]. While quite low in concentration (<1 wppm/dpa and 100 times lower in atomic concentration than helium), one or more of these elements could cause embrittlement [5], although concerted efforts to detect any effects caused by solid transmutants have yet to reveal any impact on mechanical properties [6].

- A fusion reactor will likely operate in a steady-state mode, while the FPNS as proposed here will operate with about 7.5% duty factor at 80 Hz. Studies show pulsed irradiations can enhance void swelling in metals [7,8], but this should not be a concern for the LANSCE beam repetition rate of 80 Hz.
- Beam trips cause the temperature to drop precipitously in the materials samples due to the fact that radiation from the beam-induced spallation reactions is the source of heating for the samples. Depending on the duration of the beam trip, it can take up to ~ 100 seconds for the samples to return to their desired irradiation temperature. At the historical beam trip rate for LANSCE (40 trips per day of duration longer than 1 s), the samples are below the desired irradiation temperature for approximately 5% of the time, which should not be a significant issue.

The LANSCE accelerator is functional but aging. It has recently had issues delivering reliable beam to some of the five facilities that currently operate at LANSCE, particularly those with high average duty factor like this facility would have. The long-term reliability will depend on adequate funding to replace aging equipment and to bring the facility to modern instrumentation and control standards. For the purposes of this study, we assume that the LANSCE accelerator will deliver full-power beam (1 MW) to the FPNS target station for 3400 hours each year. For 2019, LANSCE was scheduled to deliver beam for 3672 hours. To meet the minimum of 3400 hours of delivered beam, the linac (and target station) would need to achieve 93% reliability, which is well above its recent performance. Alternatively, the number of scheduled hours per year could be increased to accommodate lower reliability. Already, LANSCE accelerator physicists are working to implement a cavity phase tuning algorithm with the goal of reducing the time it currently takes to restore the linac from its annual maintenance outage into production mode by up to two weeks, which could add more than 300 hours to the number of scheduled hours per year in the coming years.

If constructed at LANSCE, the FPNS could take advantage of substantial existing infrastructure, reducing both cost and schedule compared to construction at a green field. This includes a large experimental hall with installed utilities (water and electrical), collocated hot cells for post-irradiation examination of irradiated samples, the existing LANSCE accelerator, and, most importantly, extensive expertise in designing, licensing, and operating spallation neutron sources.

The Class 5 cost range derives largely from the cost estimate developed for the MTS project, with corrections for differences in scope between the projects. The point estimate is \$103M, including \$24M in contingency. The project cost is expected to fall within 75% to 200% of this point estimate, yielding a cost range of \$77M to \$206M. The schedule to design, construct, and commission the station is expected to take five to six years following approval of mission need.

2 Target System & Neutronics

This chapter describes the geometrical configuration of the target system and its neutronic performance for fusion materials testing.

2.1 Target Concept

This target configuration proposed for this application employs an annular spallation target, with the materials samples placed in the irradiation region located in the central hole of the target, as shown in Figure 1. This geometry ensures the materials samples are bathed by neutrons from all directions. A key element to an optimal design is to place the irradiation samples as close to the edge of the proton beam while avoiding significant contamination by scattered protons passing through the samples (energetic protons create relatively more helium than displacements in iron, increasing the He-to-dpa ratio outside the desired range).

The ideal proton beam profile as a function of radius would be a top hat distribution. In the proposed configuration, this is achieved by rastering a small proton beam spot (1.3 mm rms in both transverse directions) over a defined footprint. Rastering a small beam creates a steep gradient in the time-averaged proton beam profile. More details on the rastering scheme and characteristics of the proton beam spot on target may be found in Chapter 3.

The target front face is a half-torus. The target coolant is helium gas. Simulations show that heavy water in lieu of helium reduces the peak displacement rate in the sample can by 1% and increases the He-to-dpa ratio by about 3%. Inlet coolant flows along the inner cylindrical surface of the tungsten (antiparallel to the direction of proton beam propagation), turns 180° around the toroidal

Figure 1. Vertical cuts through the target geometry (a) perpendicular to (at $z = 3$ cm) and (b) parallel to (at $x = 0$) the direction of proton beam propagation. Colors signify: green is SS316, blue is tungsten, yellow is materials specimens or samples, orange is helium, rust is heavy water, and white is vacuum.

front face, and returns along target's outer cylindrical surface. Total heat load from radiation heating in the target cooling loop is 530 kW. For an assumed bulk temperature rise in the helium of 40 K and a helium heat capacity of $5.2 \text{ J.g}^{-1}.\text{K}^{-1}$, the required helium mass flow is 2.5 kg/s. Assuming a 20-bar operating pressure, analytical calculations indicate a 1-mm-wide cooling channel over a 50-cm length yields a pressure drop of 40 kPa, and it is reasonable to assume the remainder of the loop adds 60 kPa or less of pressure drop. Several vendors offer helium circulators that can satisfy these parameters (20 bar absolute pressure, 1 bar pressure drop, 2.5 kg/s mass flow rate). The peak pulse temperature rise in the tungsten is 10 °C. Peak heat flux on the inner surface is estimated to be about 1.5 kW/cm² and about 0.9 kW/cm² on the outer surface. These fluxes are on par with the peak heat flux in the 5-MW ESS helium-cooled tungsten spallation target that is currently under construction, where 2-mm-wide coolant channels cool two faces, each with a similar heat flux. Should subsequent analyses show this design to be an engineering challenge, a more conventional water-cooled design that preserves the annular target geometry can be considered, for example stacked plates separated by coolant channels.

All structural walls in the model are 1-mm-thick SS316. For an internal helium pressure of 20 bar, an analytical calculation indicates the target outer annular wall is subjected to a hoop stress of 100 MPa, which is below the 170-MPa yield stress for SS316L. The peak atomic displacement rate drops by 0.25% and the irradiation volume by 6% for every 0.1 mm increase in thickness of all structural walls. Thus, there is strong motivation from the standpoint of preserving irradiation volume to minimize the thickness of all structural walls.

The outer reflector reflects some fast neutrons back towards the target, and hopefully into the sample can. It is modeled as solid tungsten (no coolant assumed), which simulations show provides 5% higher neutron flux and 5% lower He-to-dpa ratio in the 53-cc tally volume as compared to the use of SS316 as the outer reflector material.

Materials test specimens are placed in the sample can that occupies the central flux trap within the annular tungsten target. The can is divided into three 120° sectors, each with independent temperature control. Temperature is controlled through adjustment of the gas composition in the 0.5-mm-thick gas gap surrounding each of the three sectors. By varying the relative fractions of helium and argon in these gas gaps, thermal conductance to the surrounding heavy-water-cooling channels may be adjusted by as much as a factor of eight. Gas is flowed at an appropriate rate (dependent on needed response time) through these gaps and the composition is dynamically adjusted based on temperature readings from thermocouples embedded with the materials test specimens. The test specimens are heated by radiation escaping the annular target. At full beam power, heat is deposited in the samples at a volumetric rate of 8.4 W/g, averaged over the 53-cm³ “peak irradiation” volume (protons are responsible for 68% of the deposited energy, gammas for 20%, neutrons for 6%, with the remainder due to muons and charged pions). This concept was also proposed for the MTS, where studies showed the irradiation temperature could be varied from ~400 °C to >1,000 °C in the sample can with the highest displacement rate [2]. The lower limit for the MTS design does not meet the key parameter guideline of 300 °C specified in Table 1. While no thermal analysis was performed for this cylindrical three-sector sample can proposed here, it is reasonable to expect that similar limits can be achieved with the current design, and likely that the lower limit specification of 300 °C can also be met.

2.2 Neutronic Performance

Neutronics studies were performed using the MCNPX code version 2.7.0 [9]. Where available, the ENDF/B-VII.0 evaluated nuclear data libraries were used for neutron, proton, and gamma transport. These were augmented by ENDF/B-VI.8 for elemental sulfur and titanium, and ENDF/B-VI.0 libraries for elemental molybdenum, trace quantities of which are included in the material definitions of alloys SS316 and/or T91 (the sample regions were filled with alloy T91 at ~90% mass density to represent a typical ferritic-martensitic steel). Radiation damage tallies, both atomic displacement and gas (hydrogen and helium) production, used the evaluated libraries of Konobeyev et al. from 2011 [10]. All displacement rates in this report are based on the Norgett-Robinson-Torrens (NRT) cross sections from the Konobeyev library. The source definition used 800-MeV protons launched parallel to the z -axis onto the annular tungsten target, with uniform distribution within $3.2 \text{ cm} < r < 4.3 \text{ cm}$.

A number of sensitivity studies were performed to arrive at dimensions for the proposed design. One critical parameter is the outer radius of the sample can. The needed structural walls in the can dividing the three sectors and segregating coolant and insulating gas can occupy a significant fraction of the volume within the can at small radius, as shown in Figure 2. This drives the design to a larger sample can radius. But the peak displacement rate in the sample can drops with increasing radius. The selected outer radius of 2.5 cm is a compromise between adequate displacement rate and sample volume. At this radius, only 32% of the volume within the sample can is available for sample placement [this is the region colored yellow in Figure 1(a)]. The spallation target inner and outer radii are adjusted along with the sample can radius. A 1-mm vacuum gap exists between the sample can and the target, allowing the target and sample can to be extracted independently from their operating positions, if needed. The target radial thickness is equal to the beam width (11 mm) plus a 4-mm edge on either side of the beam (that is, 19 mm overall). The edges provide tolerance for beam positioning on target, and accommodate the finite width of the beam edges.

Figure 2. Volume fraction available for samples within the sample can as a function of can outer radius (assumes structural walls are 1 mm thick, heavy water coolant channel is 1 mm, and insulating gas gap is 0.5 mm).

The 53-cm³ tally volume where volume-averaged particle fluxes, displacement, gas production, and heating quantities are tallied is shown in Figure 3. It extends from 1.5 cm to 7 cm downstream of the tungsten target front face. The spatial distribution of the proton flux in the r - z geometry depicted in Figure 3(b) is shown in Figure 4. Protons are reasonably well confined within the tungsten target, where the peak proton flux of $3.0 \times 10^{14} \text{ p.cm}^{-2}.\text{s}^{-1}$ corresponds to the incident proton beam current density of $48 \text{ }\mu\text{A.cm}^{-2}$. The damage rate on the front window of the spallation target is 17 dpa per calendar year, indicating the need to replace the target annually (the Pb-filled SS316 cannelloni tubes of the SINQ spallation target have run to 22 dpa).

Figure 3. (a) x-y (at $z = 3$ cm) and (b) r-z (at $x = 0$) cuts through the target geometry depicting the location of the 53-cm³ tally volume.

Figure 4. Spatial distribution of the proton flux as a function of r and z (note the logarithmic scale of the color bar).

As the secondary and scattered primary protons leak from the tungsten, their ranges increase, as is evident at the inside radius of the target where the $2.154 \times 10^{13} \text{ p.cm}^{-2}.\text{s}^{-1}$ contour line protrudes through the SS316 and vacuum layers, towards the sample can. The scattered protons pass into the sample can, particularly in the downstream region, where they cause elevated gas production. Throughout the sample region, the proton flux is never more than 4% of the neutron flux.

On average, each proton striking the tungsten target generates 22 neutrons, so the neutron production rate at a beam current of 1.25 mA exceeds 10^{17} neutrons per second. The resulting neutron flux is shown in Figure 5. The peak neutron flux occurs in the tungsten target, where the neutrons are created by proton-induced spallation reactions. Neutrons leak from the target in all directions, and those leaking radially inward from all around the annular target produce a peaking of the neutron flux that extends to zero radius, near $z = 4.5 \text{ cm}$. The neutron flux is rather uniform in this peak region, with a radial gradient of about 5%/cm and an axial (along the z direction) gradient that is flat within 3% over the central 2 cm, with a slope of 6%/cm on either side. Within the 53-cm^3 tally volume, the neutron flux varies from 1.0×10^{15} to $1.2 \times 10^{15} \text{ n.cm}^{-2}.\text{s}^{-1}$. There is space in the sample can outside of the 53-cm^3 tally volume with appreciable neutron flux. Over a 20-cm length (from $-2.5 \text{ cm} < z < 17.5 \text{ cm}$), there is a total of 193 cm^3 available for sample placement in neutron flux exceeding $5 \times 10^{14} \text{ n.cm}^{-2}.\text{s}^{-1}$.

Shown in Figure 6 is the iron displacement rate that would occur if iron were to occupy a point in the plot. In the sample region, the peak displacement rate of 22 dpa/fpy (fpy = full power year, or $3.156 \times 10^7 \text{ s}$) aligns with the peak neutron flux near $z = 4.5 \text{ cm}$. Over the entire 184-cm^3 sample region volume from $-2 \text{ cm} < z < 17 \text{ cm}$, the displacement rate exceeds 8 dpa/fpy. Averaged over the 53-cm^3 tally volume, the displacement rate is 20.6 dpa/fpy. Neutrons are responsible for 97% of this damage, while protons contribute 3%. Outside of the annular target, the reflector region boasts respectable damage rates, exceeding 18 dpa/fpy. This region could serve as additional irradiation volume for materials testing, with slightly lower displacement rates but significantly more volume than the central sample region.

Figure 7 shows the helium production rate in iron. Both neutrons and protons contribute significantly to helium production, with the proton contribution shifting the peak helium production rate

Figure 5. Spatial distribution of the (a) fast ($>0.1 \text{ MeV}$) and (b) total neutron flux as a function of r and z .

Figure 6. Spatial distribution of the iron displacement rate.

Figure 7. Spatial distribution of the helium production rate in iron.

downstream (to $z \approx 7$ cm) relative to peak displacement rate. Averaged over the 53-cm³ tally volume, the helium production rate is 300 appm He/fpy (appm = atomic parts per million), with neutrons responsible for 85% of this production, and protons the remainder.

The He-to-dpa ratio for iron is shown in Figure 8. It has a broad range within the sample region, varying from 7 appm/dpa at $z = -2.5$ cm to 35 appm/dpa at $(r,z) = (2$ cm,17.5 cm). This broad range is valuable to materials scientists, providing them the ability to assess the sensitivity of an alloy's mechanical properties to this important quantity while keeping the dose constant. Within the 53-cm³ tally volume, the He-to-dpa ratio varies from 11 to 18 appm/dpa, with a volume-averaged value of 14.6 appm/dpa. At a fixed radius r , the ratio increases monotonically with axial position z in the sample can. The peak gradient within the 53-cm³ tally volume is 9%/cm in the z -direction, and lower in the radial direction.

Figure 9 shows the sample irradiation volume as a function of the minimum displacement rate for two ranges of He-to-dpa ratio. In the fusion-relevant range of 6 to 16 appm/dpa, more than 30 cm³ has a displacement rate exceeding 20 dpa/fpy. Note the peak displacement rate of 22.8 dpa/fpy is within the fusion-relevant range for the He-to-dpa ratio. Within the fusion-relevant range of 6 to 16 appm/dpa, there is 50 cm³ of sample volume with a displacement rate exceeding 17 dpa/fpy. Note there is considerable irradiation volume that does not meet the high dose requirements but produces a sufficient dose to perform in situ irradiations such as irradiation/corrosion or fatigue under irradiation. This is extremely valuable space as well. Calculated damage parameters for the 53-cm³ tally volume are summarized in Table 2.

Figure 8. Spatial distribution of the helium-to-dpa ratio for iron.

Figure 9. Minimum displacement rate as a function of volume available for placement of materials test specimens within the sample can. The displacement rate is plotted per full power year on the left axis and per calendar year on the right axis (assuming 3400 hours per year at full beam power). Data are plotted for two different ranges of the He-to-dpa ratio.

Table 2. Radiation damage quantities for iron averaged over the 53-cc tally volume shown in Figure 3.

Displacement rate	20.6 dpa/fpy
Helium production rate	300 appm He/fpy
He-to-dpa ratio	14.6 appm He/dpa
H-to-dpa ratio	77.4 appm H/dpa
Neutron flux	$1.2 \times 10^{15} \text{ n.cm}^{-2}.\text{s}^{-1}$
Fast ($E > 0.1 \text{ MeV}$) neutron flux	$9.2 \times 10^{14} \text{ n.cm}^{-2}.\text{s}^{-1}$

2.3 Irradiation Conditions Relative to the DEMO First Wall

The irradiation conditions in certain regions of a properly designed spallation source are in many respects similar to those experienced by the first wall of a magnetically-confined fusion reactor burning D-T fuel. Table 3 compares radiation conditions in the LANSCE-driven FPNS (using values from the 53-cm³ tally volume shown in Figure 3) with the first wall for the proposed DEMO reactor operating at 3.4 GW with a helium-cooled lithium-lead blanket (HCLL), as represented by the neutron flux spectrum reported by Fischer et al. [11]. For comparison, the conditions in the high flux test module (HFTM) of the proposed IFMIF facility are included as well, using the spectrum reported by Simakov et al. [12]. These key parameters are similar for all three facilities, with the largest differences being gas production. The LANSCE-driven FPNS has a hydrogen-to-dpa ratio that is 2.1 times greater than DEMO and a helium-to-dpa ratio that is 1.6 times greater. As shown in Figure 8, there are regions within the sample can and in the outer reflector of the FPNS where the He-to-dpa ratio is 9 and the displacement rate is 12 to 14 dpa/fpy.

Table 3. Key parameters for the proposed DEMO reactor, FPNS at LANSCE, and IFMIF HFTM.

Key Parameter	DEMO (HCLL)	LANSCE-driven FPNS	IFMIF HFTM ¹
Displacement rate in Fe (dpa/fpy)	30	21	26
He/dpa ratio in Fe (appm He/dpa)	9	15	13
H/dpa ratio in Fe (appm H/dpa)	37	77	53
Neutron flux ($\text{n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$)	1.5×10^{15}	1.2×10^{15}	0.7×10^{15}

The similarities and differences of the radiation environments between a fusion reactor first wall and a spallation source specifically designed for fusion materials irradiations include potential impact of differences in the primary knock-on atom spectra, the pulsed nature of the proton beam driving an FPNS at LANSCE, the impact of beam trips on irradiation temperature, and the production of solid spallation products that are different from nuclear transmutation in a fusion reactor first wall. Each of these is addressed in turn below.

2.3.1 Primary Knock-on Atom Spectra

Radiation damage morphology depends on the spectrum of nuclear recoils (also called primary knock-on atoms, or PKAs) that induce atomic displacements. Low-energy recoils, less than 10 keV, are more likely to produce isolated vacancies and interstitials that enhance solute segregation and irradiation creep. Recoils with energies greater than 50 keV produce damage cascades (and sub-cascades) that are responsible for radiation embrittlement and hardening. The primary recoil energy spectrum for the peak damage rate position in the fuel irradiation region of the proposed radiation damage mechanisms that are driven by these low-energy recoils should occur in the same way in both the LANSCE-driven FPNS and the DEMO first wall. Above 50 keV there is significant difference between the two functions, owing principally to the high-energy neutrons present in the LANSCE-driven FPNS that produce nuclear recoils with energies exceeding 20 MeV. If these very energetic recoils produce isolated sub-cascades in the same way as recoils with energies of ~ 100 keV, then the damage morphology in these two irradiation environments will be similar, despite the differences in the two damage production functions. This conclusion is consistent with that of Zinkle and Möslang [5], who note “the primary damage state produced by fission, fusion and spallation neutrons are all comparable.”

Figure 10. Damage production functions for DEMO and MTS versus PKA energy.

¹ Values reported here use the IFMIF spectrum provided by S.P. Simakov and reported in ref. 12, folded with the NRT displacement and gas production cross sections of Konobeyev et al. [10]. These values differ slightly from the values reported in references 11 and 12, but are calculated in a manner consistent with the values reported here for DEMO and LANSCE-driven FPNS.

2.3.2 Beam Temporal Structure

A fusion reactor is expected to operate in a steady-state mode, while the LANSCE accelerator operates with 6.8% duty factor with a pulse repetition rate for an FPNS target of 80 Hz. Each 0.85-ms-long macropulse is comprised of 170,000 60-ps-long micropulses with 5-ns separation. For the MTS, detailed calculations of the temporal dependence of the displacement rate [4] show a peak of 3×10^{-4} dpa/s during a micropulse and an average rate of 1.7×10^{-5} dpa/s over a macropulse. While the implications of this exact time structure have not been evaluated in detail, Trinkhaus

Figure 11. Increase in void radius as a function of temperature for several pulse frequencies (from ref. 7).

and Ullmaier [8,13] have investigated the pulsing conditions that can lead to effects on irradiation creep and cavity nucleation that are different than those expected in continuous sources. They conclude that the 80-Hz pulse frequency proposed for the LANSCE-driven FPNS does not influence bubble nucleation because of the extremely small defect yield per pulse at this frequency. They further conclude that irradiation pulsing in spallation sources does not significantly affect creep by climb-controlled dislocation glide. Cottrell and Baker [14] point out that these conclusions depend strongly on the irradiation temperature, although the temperature dependence was explicitly addressed by Trinkhaus and Ullmaier [13].

Compared to steady-state irradiations, Ghoniem and Gural [7,15] showed that pulsed irradiations can enhance void swelling in metals at repetition rates of 10 Hz and lower (see Figure 11) but this should not be a concern for a LANSCE-driven FPNS given the beam repetition rate of 80 Hz.

2.3.3 Beam Trips

Beam trips cause the temperature to drop precipitously in the materials samples due to the fact that radiation from the beam-induced spallation reactions is the source of heating for the samples. This desirable attribute greatly reduces diffusion-driven radiation damage repair mechanisms when the beam is off, and restores them reasonably soon after the beam comes back on. Eriksson [16] analyzed the beam trip characteristics for the LANSCE accelerator, concluding that the H^+ beam trip frequency is 1.64 trips/h, or about 40 trips per day. The great majority of these are due to the injector, which Eriksson notes have durations of 10 to 20 s.

For an MTS sample can geometry which is similar in concept to that proposed for the LANSCE-driven FPNS, the time-dependent sample temperature is plotted in Figure 12 following beam trip durations of 1 s, 10 s, and 100 s, assuming an irradiation temperature of 1000 °C and a coolant temperature of 80 °C. In equilibrium, cooling water removes heat at the same rate it is deposited, which is roughly 10 W/g. When the beam trips, cooling continues at the same rate, causing the samples to cool at the rate of approximately -20 °C/s. In the first 10 s, sample temperatures will

Figure 12. Sample temperature time dependence for three different beam durations (from ref. 2).

drop by about 200 °C. For a 100-s-long beam trip, the sample temperature drops to within 100 °C of the coolant temperature. Upon beam restoration, samples well below the desired irradiation temperature rise in temperature at a rate of ~ 20 °C/s until they approach the desired irradiation temperature. For trips of 100 s in duration or longer, it takes about 120 s to return to within 40 °C of the desired irradiation temperature. At the historical LANSCE beam trip rate of 40 trips per day, the samples are more than 40 °C below the desired irradiation temperature for approximately 6% of the time $[(40 \text{ trips/day}) \times (120 \text{ s/trip}) / (86,400 \text{ s/day})]$ if we conservatively assume that every beam trip is 100 s or longer in duration. In reality, most trips are much shorter and the fraction of time that samples spend more than 40 °C below the desired irradiation temperature is well less than 6%.

One might consider adding resistive heaters to the sample can to augment radiation heating, but this is likely to induce undesirable thermal gradients in the can, and not greatly influence the thermal response while occupying precious irradiation volume. With a radiation-induced energy deposition rate in a steel sample of 8.4 W/g and a heat capacity of $0.5 \text{ J.g}^{-1}.\text{°C}^{-1}$, the adiabatic temperature rise in an uncooled sample is an impressive 17 °C/s. Radiation heating has the highly desirable attribute that it is uniformly deposited throughout the samples in an amount proportional to the sample mass, whereas heat supplied by resistive heaters must transport via conduction into the samples, which takes time and requires thermal gradients to drive the heat into the samples, so samples are not at a uniform temperature. In the 53-cm³ tally volume alone, radiation deposits 3 kW of heat. Resistive heaters cannot match the heating rate, uniformity, and zero volume requirements that radiation heating provides.

2.3.4 Solid Spallation Products

There is broad recognition that nuclear transmutations in irradiated samples can introduce undesirable elements that may enhance irradiation embrittlement. However, results in the

published literature appear frustratingly sparse. The SPIRE project conducted under the 5th EURATOM Framework Program from 2000–2004 was a well-coordinated effort to study the irradiation effects in martensitic steels under neutron and proton mixed spectrum. As noted in the final scientific and technical report [6], “The programme aimed to evaluating the different contributions to damage induced in structural materials in a spallation target environment: atomic displacements produced by high energy protons and neutrons, effects of gas production (hydrogen and helium) and other solid elements (Ca, Ti, P, S, etc.) produced by spallation reactions.”

The evolution of the elemental composition in a material depends on its initial composition and on the radiation environment. Several estimates of spallation product yields in irradiated iron or martensitic-steel-based samples exist in the literature [6,17,3]. They consistently show that samples not directly subjected to the proton beam have phosphorous and sulfur production levels at a dose of 200 dpa that are below as-manufactured impurity concentrations [11,18]. Therefore, it is safe to conclude that build-up of these elements is of negligible concern [17].

Calcium production, however, is a factor of 20 greater than sulfur [3] and could be an additional source of embrittlement beyond that caused by helium production. This is one of the elements studied under the SPIRE Framework Program, where the possible effects of calcium on microstructural evolution and hardening of EM10 martensitic steel was investigated by Ca⁺ ion implantation experiments [6]. After implantation, the microstructure was characterized using Transmission Electron Microscopy [19] and Atom Probe Tomography (APT) [20], while the induced hardening was measured via nanoindentation experiments. Reported results are not in complete agreement. The final report [6] notes that clustering of the implanted species was not detected, even for Ca concentrations as high as 1 at%, and that neither calcium nor calcium hydride precipitation was detected. On the other hand, Cadel et al. [20] observed Ca clustering and note that “Small areas (< 2 nm in size) are calcium enriched, up to 5 at%.” The effect of implantation on the hardness of EM10 steel was found to be negligible. Researchers concluded that, if tiny Ca clusters were formed during implantation, they do not lead to significant hardening of the EM10 steel. They further concluded that “the results obtained in the frame of SPIRE tend to indicate that solid spallation products are not a major source of degradation of mechanical properties under spallation irradiation conditions.”

Another effort under the SPIRE Framework Program involved the production of EM10 steel doped with P, S, and Ti, which were then irradiated in Russia’s BOR60 fast reactor [6]. To mimic the spallation environment, Danylova et al. [21] expended great effort to achieve uniform distribution of the dopants via solution annealing, with mixed success. Solid solution of Ti was achieved when it was the only dopant (at 0.17 wt%). They concluded “that the solubility of S in a matrix containing 9% Cr is very low” due to the formation of very small CrS precipitates. With respect to P, they concluded it was probably in solid solution in the ferrite and martensite phases, although at higher concentration in the ferrite. These doped EM10 samples were irradiated in BOR60 at 325 °C to as high as 42 dpa, and then underwent post-irradiation examination. The researchers concluded, “No significant effects of doping elements could be detected, especially after irradiation. The main contributions to hardening and ductility loss seem to be defined by the matrix behaviour. However, some possible second order effects should be also due to sulphur and phosphorus.”

Kuksenko et al. investigated F82H samples irradiated under the STIP irradiation program at the SINQ facility using APT [22]. This material was irradiated to a dose of 20 dpa in a mixed proton-neutron spectrum. Because the F82H samples were subjected to ~500-MeV proton irradiation in

addition to neutrons, the production rate of solid transmutants per dpa (e.g., 18 appm Ca/dpa) is much higher than what samples irradiated in a LANSCE-driven PFNS would reach (1 appm Ca/dpa [3]). The authors observed three distinct cluster populations: “(i) diluted Si-enriched clusters which contain a relatively large quantity of solid spallation products (Ca, Ti, Sc), (ii) diluted C-enriched clusters enriched by carbide forming elements, such as Cr, W, V, and by a spallation product Ti (in a lesser extent by Ca and Sc), and (iii) a large carbide highly enriched in the spallation product Ti with a low Fe content.” They conclude that solid spallation products “heavily participate” in cluster formation, particularly Ca, presumably due to its low solubility in Fe. Dai and colleagues have recently observed irradiation-induced grain boundary segregation of solid spallation and alloying elements in the same sample of F82H [23]. Still, the degree to which solid spallation product segregation enhances embrittlement and hardening, particularly relative to that induced by the much higher levels of helium (~100 appm He/appm Ca), is an open question. One advantage that this facility has is that through placing samples in different irradiation locations, different rates of transmutation could be achieved, allowing one to study this possible issue in different metal alloys with potential fusion applications.

2.4 Target Safety

Safety is paramount in the design of the target station. Radioactive isotopes are produced as a byproduct of the spallation process and by the radiative capture of liberated neutrons in the surrounding structures. By far, most of the radioactivity is confined to the tungsten target and the uncontrolled dispersal of this radionuclide inventory would likely result in a significant radiation dose consequence to workers and the public. Therefore, an overarching design goal for the target station must be to ensure that none or almost none of the tungsten is dispersed during postulated accidents. If a source of energy were to heat the tungsten to an unsafe temperature, the tungsten may oxidize whereupon the oxide vapor could readily disperse. The onset for runaway oxidation of tungsten in the presence of water vapor occurs at approximately 800 °C [24]. Thus, the radionuclide inventory in the tungsten will remain substantially intact so long as the tungsten temperature does not exceed 800 °C or, alternatively, there is no possibility of contact with water vapor or moist air.

While a detailed safety analysis is well beyond the scope of this study, analyses performed for proposed and currently operating spallation sources, such as the Lujan Center, the proposed MTS project, and the European Spallation Source, offer a sound basis from which to draw some preliminary conclusions. There are most likely two sources of energy that can heat the tungsten during an off-normal event: the 1-MW proton beam, and the residual decay heat within the tungsten. The proton beam must be shut off under errant beam conditions, such as a failure of the raster magnets that paint the beam onto the target, or when the target loses coolant or the coolant loses flow. Beam shutdown can rely on either active or passive safety systems or features, with passive safety strongly preferred over active safety systems. One means of achieving passively safe shutdown of the beam is to operate the target in the same vacuum environment as the accelerator. Under this scenario, any errant condition that leads to target overheating will lead to a failure of the structural wall containing the helium coolant, whereupon the helium will leak into the accelerator vacuum and cause radiofrequency breakdown in the accelerating cavities, thereby shutting off the proton beam in a matter of seconds or less.

The radioactive inventory within the spallation target will produce ~3 kW of decay heat. Under loss-of-coolant and loss-of-flow scenarios, the design must ensure the tungsten does not exceed

800 °C by removing this decay heat either passively (highly preferred) or by means of an active heat removal system.

Pending approval by the Department of Energy (DOE), the target station would be permitted to operate under the DOE Accelerator Safety Order 420.2C. The Accelerator Safety Envelope would identify both engineering and administrative controls credited for its safe operation.

3 Accelerator Systems

The primary function of the accelerator systems is the safe and reliable delivery of 1.25-mA proton beam current at 800-MeV beam energy from the Switchyard to the target station located in the Area A experimental hall. The present study is a further development of a previous concept proposed for the Materials Test Station project [25,26].

3.1 Accelerator Requirements

The basic parameters of the FPNS beam setup are presented in Table 4. The accelerator should safely and reliably deliver 1.25-mA proton beam current at 800-MeV beam energy from the switchyard to the FPNS target located in Area A. The FPNS beamline will be incorporated into LANSCE's Fast Protect, Run Permit, and Radiation Security Systems.

The basic parameters of FPNS beam setup are presented in Table 1. The accelerator should safely and reliably deliver average 1.25-mA proton beam current at 800-MeV beam energy from the switchyard to the FPNS target located in Area A. The FPNS beamline will be incorporated into LANSCE's Fast Protect, Run Permit, and Radiation Security Systems. The rastering system should have capability to raster the proton beam within a ring area at the target with minimal radius = 3.2 cm and maximal radius = 4.3 cm and time-averaged beam current density non-uniformity of less than $\pm 3\%$. Spatial dimensions of the rastered beamlet on target (including beamlet spreading resulting from beam jitter in the linac) should be within 2.3 mm FWHM, with capability to image the beam spot on target. An active feedback system to adjust the beam spot position on target based on beam diagnostics is required. A low-power (20 kW) tuning beam dump will be located at the target area to provide the capability to quickly tune the beam for delivery to FPNS. In order to provide flexibility in the rastering system for evolving target requirements, the design presented in this report assumes larger rastering area with minimal radius at the target $R_{\min} = 5.5$ cm and maximum radius of $R_{\max} = 6.9$ cm.

Table 4. FPNS beam parameters.

Average beam power	1 MW
Beam energy	800 MeV
Average beam current	1.25 mA
Pulse repetition rate	78 Hz
Beam pulse length	850 μ s
Peak beam current (during the pulse)	18.87 mA
Beam FWHM size at target	2.3 mm
Raster pattern	Circular
Minimum rastered beam radius	3.2 cm
Maximum rastered beam radius	4.3 cm
Current density non-uniformity on target	$<\pm 3\%$

3.2 Linac Overview

To create a test volume with a sufficiently high neutron flux, a 1.25-mA time-averaged current of 800-MeV protons must be delivered to the target. To achieve this current, FPNS must receive beam at 78 Hz, with a beam peak current of 18.87 mA during the macropulse. Operation with pulsed beam current of 21 mA was successfully demonstrated as a test for the proposed LANL Long Pulse Spallation Source, delivering H^+ beam with energy 800 MeV, average current 315 μA and reliability of $\sim 88\%$ for 12 hours [27].

To achieve reasonably uniform neutron flux in the test volume, the beam impinges on the target with the beam raster system painting a ring area uniformly within $R_{\min} = 3.2$ cm and $R_{\max} = 4.3$ cm. The area of target irradiated by the beam is $S_{\text{target}} = \pi(R_{\max}^2 - R_{\min}^2) = 25.92 \text{ cm}^2$. The average beam current density on the target is $48.2 \text{ } \mu A/\text{cm}^2$. The circular spiral beam-centroid motion is achieved with a pair of raster magnets with sinusoidal variation of magnetic field shifted by 90° , with amplitudes changing with time proportionally to $\sqrt{t}$, where t is the time within the beam macropulse. With the presently proposed instantaneous beam-spot size (2.3-mm full-width at half-maximum, FWHM, beam width) and the presently proposed raster pattern, the current density non-uniformity within the beam spots is expected to be less than $\pm 1\%$.

The design assumes placement of a shield wall with a rather small aperture to minimize the backstreaming neutrons that will activate upstream components and facilitate differential pumping between the target and beamline vacuums. The pumping issue arises because there is no beam window segregating these two vacuum environments. A beam window is not used because Coulomb scattering in a beam window would degrade the desired small instantaneous beam spot at the target, and because its elimination increases passive safety, as described in Section 2.4.

In order for the FPNS to meet the minimum damage rates in the tested materials specimens, the accelerator must deliver 1 MW of beam for 3400 hours per year, or 9.55×10^{22} protons per year at a beam energy of 800 MeV. The accelerator must deliver this beam while simultaneously delivering beam to the five existing facilities (IPF, Lujan Center, WNR, UCN, and pRad).

3.2.1 Beam Setup for Delivering 1 MW Beam to the Target

An average beam current of 1.25 mA in the FPNS beamline at a proton energy of 800 MeV is required for 1.0 MW of beam power on the FPNS target. Currently the LANSCE accelerator facility delivers 800-MeV H^- beam to four experimental areas and 100-MeV H^+ beam to one experimental area (see Table 5 and Figure 13). The accelerator facility is equipped with two independent injectors for H^+ and H^- beams, merging at the entrance of a 201.25-MHz Drift Tube Linac (DTL). The DTL accelerates the two beams to 100 MeV. After the DTL, the Transition Region (TR) beamline directs the 100-MeV proton beam to the Isotope Production Facility (IPF), while the H^- beam is accelerated up to the final energy of 800 MeV in an 805-MHz Coupled Cavity Linac (CCL). The H^- beams, with different time structures created by a low-energy chopper, are distributed in the Switch Yard (SY) to four experimental areas.

The LANSCE accelerator time structure must be adjusted to accommodate the FPNS (see Table 6 and Figure 14). The Lujan Center continues receiving $20 \text{ Hz} \times 625 \text{ } \mu s$ pulses of H^- beam with 10 mA/bunch peak current, which is translated into beam with average current of 100 μA and average beam power of 80 kW. Further upgrade of this beam to 125 μA and beam power of 100 kW would be achievable with an increase of the beam pulse width from 625 μs to 781 μs , or by an upgrade

Table 5. Current beam parameters of the LANSCE accelerator.

Area	Beam	Rep Rate (Hz)	Pulse Length (μ s)	Chopper	Peak Current (mA)	Average Current (μ A)	Average Power (kW)
Lujan Center	H ⁻	20	625	0.8	10	100	80
Isotope Production	H ⁺	100	625	1.0	4	250	25
Weapons Neutrons	H ⁻	100	625	0.0028	25	4.5	3.6
Proton Radiography	H ⁻	1	625	-	10	<1	<1
Ultra-Cold Neutrons	H ⁻	10 (every 5 s)	625	0.8	10	10	8

of the H⁻ ion source to deliver higher peak current. FPNS beam is operated at 78 Hz $\times$ 850 μ s pulse pattern with 18.87mA per bunch H⁺ peak current producing a beam with average current of 1.25 mA and average beam power of 1 MW. FPNS beam shares the same RF pulses (that is, both beams are accelerated simultaneously) with the Weapons Neutron Research facility (WNR) beam, which is operated at 100 Hz $\times$ 850 μ s pattern delivering H⁻ beam with average current of 5.95 μ A and average power of 4.76 kW to the WNR target. H⁻ beam delivered to the Ultra Cold Neutron (UCN) research facility consumes 8 Hz $\times$ 850 μ s every 5 sec, which is approximately equivalent to 2 Hz of continuous operation. UCN beam “steals” these cycles from FPNS beam, and is accelerated in the same RF pulses with WNR beam. H⁻ beam delivered to the Proton Radiography

Figure 13. Layout of LANSCE Accelerator Facility.

Figure 14. LANSCE beam distribution scheme with FPNS.

Facility “steals” single 850- μ s macro-pulses of H^- beam from WNR beam. The remaining 20 Hz of RF pulses are consumed by H^+ beam delivered to Isotope Production Facility (IPF). That beam with the same peak current of 18.87 mA as FPNS beam is accelerated at $20 \text{ Hz} \times 662 \mu\text{s}$ pulse pattern up to an energy of 100 MeV in the DTL only. Currently the linac delivers H^+ beam with average current of 250 μ A and energy of 100 MeV, or an average power of 25 kW, to the IPF target. Higher beam power up to 31 kW is achievable with an increase of the IPF beam pulse width to 826 μ s.

An upgrade to 1.8 MW of beam delivery to FPNS is a future option that is not within Project scope, but has the capability of nearly doubling the neutron flux achieved in the FPNS irradiation volume. Such a power upgrade will rely on replacing the CCL klystrons with more powerful klystrons, enabling an increase of average H^+ current up to 2.25 mA, or replacing sections of the CCL linac with superconducting linac (see Section 3.8 of this report). To deliver beam to FPNS, the IPF kicker-magnet modulator (IPMP10) must be operational and the stainless-steel beam pipe within the IPF kicker magnet must be replaced with ceramic or glass beam pipe. Currently, the H^+ beam is directed towards IPF using a DC power supply. The IPF kicker magnet is a laminated dipole that can be operated with a pulsed power supply (see Section 3.2.3 for more details).

Table 6. Beam parameters of the LANSCE accelerator with FPNS.

Area	Beam	Rep Rate (Hz)	Pulse Length (μ s)	Chopper	Peak Current (mA)	Average Current (μ A)	Average Power (kW)
Lujan Center	H^-	20	625	0.8	10	100	80
Isotope Production	H^+	20	625 – 826	1.0	18.87	250 – 312	25 – 31
Weapons Neutrons	H^-	100	850	0.0028	25	5.95	4.76
Proton Radiography	H^-	1	850	-	10	<1	<1
Ultra-Cold Neutrons	H^-	8 (every 5 s)	850	0.8	10	10.8	8.6
FPNS	H^+	78	850	1.0	18.87	1251	1001

3.2.2 RF Requirements

The present project does not require any specific upgrade of accelerator RF systems. Recent completion of the LANSCE Risk Mitigation Project [28] included significant upgrade of RF power feeding the DTL. Three out of four 201.25-MHz amplifiers (Modules 2-4) were replaced with newly developed RF power systems based on TH628L Diacodes [29]. Replacement of the Module 1 amplifier for a more powerful one is scheduled for winter 2020. In addition, a new digital low-level RF (dLLRF) control system was installed for the 201.25 MHz RF systems, and end-of-life CCL klystrons were replaced to ensure further stable beam operation. Upgrade of the dLLRF for the 805-MHz RF systems will be required to accommodate both existing feedforward and adaptive feedforward modes working through the CCL. Also, dLLRF for bunchers should be installed.

New spare klystrons are already purchased and available if operations cause a notable increase in the failure rate of the still operating, 40-year-old LANSCE klystrons. The installation philosophy for integrating these new klystrons into operations is to immediately replace existing klystrons that show clear signs of end of life. However, many of the existing, installed klystrons are still providing reliable performance in support of existing user programs. Operation of FPNS beam with peak current of 18.87 mA will result in pulse beam power consumption of 245 kW in addition to the nominal klystron power of 750 kW. The total required klystron power will be 1 MW. Klystrons are designed to work reliably with power up to 1.25 MW. Therefore, operation of FPNS beam will be within safe operating margins of available klystron power limits.

Operational beam duty factor is a combination of that of the most powerful beams delivered to the various experimental areas: (FPNS) $80 \text{ Hz} \times 850 \mu\text{s} + (\text{IPF}) 20 \text{ Hz} \times 662 \mu\text{s} + (\text{PSR}) 20 \text{ Hz} \times 625 \mu\text{s} = 9.4\%$. The drift tube linac RF gate requires an additional $250 \mu\text{s}$ to each of the beam gates to allow the low-level RF control system to lock and stabilize amplitudes and phases of DTL tanks within the level of 1%, 1° correspondingly. It results in the following value for DTL RF duty factor: (FPNS) $80 \text{ Hz} \times 1100 \mu\text{s} + (\text{IPF}) 20 \text{ Hz} \times 912 \mu\text{s} + (\text{PSR}) 20 \text{ Hz} \times 875 \mu\text{s} = 12.4\%$. The coupled-cavity linac requires $120 \text{ Hz} \times 950 \mu\text{s}$ RF pulse setup for all beams, which translates into a CCL RF duty factor of 11.4%. Because the DTL duty factor limit is 15% and that of the CCL is 12%, the proposed setup is within the acceptable limits. Tables 7 and 8 contain RF parameters of DTL and CCL with FPNS proposed beam setup.

The only possible limitation in RF operation at higher power comes from the DTL vacuum windows. These windows are water cooled and have a large voltage across them, with highest field

Table 7. RF Parameters of Drift Tube Linac (T1=Tank 1, T2= Tank 2, T3= Tank3, T4=Tank 4).

Parameter	Value
RF duty factor, %	12.4%
Duty factor limit, %	15.0%
Nominal power (T1/T2/T3/T4)	0.322 / 2.60 / 2.22 / 2.68
Beam loading (T1/T2/T3/T4), MW	0.087 / 0.678 / 0.592 / 0.515
Total power (T1/T2/T3/T4), MW	0.409 / 3.278 / 2.812 / 3.195
Peak power limit (T1/T2/T3/T4), MW	0.425 / 3.60 / 3.60 / 3.60
RF FPNS pulse length, ms	1.1

Table 8. RF Parameters of Coupled Cavity Linac.

Parameter	Value
RF duty factor, %	11.4
Duty factor limit, %	12.0
Nominal klystron peak power, MW	0.75
Beam loading, MW	0.245
Total power, MW	0.995
Klystron power limit, MW	1.25
RF FPNS pulse length, ms	1.1

gradient in the middle, around the coaxial central conductor. Temperature sensors of the windows are on the outer edge of the flange, not in the region of highest field near the center. Windows presently get about 45 °C on the window for module 4, which seems to be the warmest of all. Concerns exist of operating above 50 °C as the polymer used has a glass transition temperature that is low. There is a window cooling at the center as well as at the edges. Construction of a window test bench is scheduled for FY2020, which should lead to improved window designs.

3.2.3 IPF Kicker Magnet Modulator

For the FPNS to share H⁺ beam with the IPF beam, the IPF kicker-magnet modulator IPMP10 must be operational. This device will enable the kicker magnet (IPKI01) to deflect H⁺ beam pulses into the IPF beam line from their normal path through the Transition Region. Undeflected H⁺ beam pulses would continue to the FPNS.

The IPMP10 was thoroughly tested during summer 2001 using short-drive cables and a test load similar in electrical characteristics to the actual kicker magnet. It was then transported from the LANSCE magnet test area to the newly constructed IPF building. Drive cables were installed between the magnet on the beamline and a junction box atop IPMP10, allowing either the kicker modulator or a DC supply to drive the magnet. Because pulsed operation was not required at that time, no further connections were made. The modulator has been idle since.

To return IPMP10 to service, several issues must be addressed. There are few risks involved, as most work will be performed before the system is energized. This system has already operated for several hundred hours and hazards are well understood. Hazards are electrical in nature; there are no radiation concerns. Complete safety procedures and documentation, developed at LANSCE during initial test and acceptance, will be reviewed and updated before IPMP10 is energized.

The tasks to be performed to restart the pulsed system operational include connecting the 480VAC/3Ø input power, connecting the de-ionized cooling water supply and return, identifying and purchasing additional spare components, and recommissioning the complete IPF kicker modulator system. Electrical crafts personnel will connect the 480VAC/3Ø input power. An appropriate circuit and breaker are already in place. Electricians will need to install conduit between the existing circuit box (currently outfitted with a 480VAC/3Ø socket) and the IPF kicker disconnect switch, located on the west end of the IPF kicker cabinet.

Plumbing crafts personnel will connect the de-ionized cooling water supply and return. Plumbers will need to install pipe between the existing cooling water circuit and the supply and return line connections on the west side of the IPF kicker cabinet. This installation may also require the installation of a pressure-reducing valve, gauges, etc.

To identify and purchase additional spare components, the Accelerator Operations and Technology (AOT) Pulsed-Power Team will inventory spares on hand and develop a list of additional spares that are required for reliable, long-term operation of the IPF kicker modulator. The Pulsed-Power team will thoroughly inspect the completed system, including the transmission lines, the kicker magnet, and all connections as part of the recommissioning process for the complete IPF kicker modulator system. A low-impedance ground connection between the modulator cabinet and the building ground may need to be installed. The team will then test the completed system to validate correct and reliable operation at required peak current and repetition rate.

The IPF currently runs at 100 Hz repetition rate. Under this proposed scheme for FPNS operation, IPF would operate at 20 Hz, which will increase cyclic thermal stresses in their targets. This could result in higher failure rates of the target canisters, which contaminates the cooling water and can lead to significant down times and cleanup costs. For FPNS to operate at 1 MW beam power, the IPF program will need to understand and concur with this proposed beam delivery scheme.

3.2.4 Accelerator Misalignment and Beam Loss

Misalignment of accelerator components is one of the main phenomena that restricts performance of the linear accelerator. Disruption of focusing and accelerator structures results in an increase of effective beam emittance and formation of beam halo. Small beam losses in the linac produce radio-activation, which degrades accelerator components and therefore reliability, as well as hinder hands-on maintenance. Much of the beam loss is due to the formation and interception of a low-density beam halo at a large radial distance (4 or more times the rms beam radius) from the beam core.

Recent laser tracking of beam elements indicated displacements of the accelerator components within ± 1 mm (see Figure 15). Long-term operation of 800-MeV, 80-kW H^- beam indicates that summed losses of that beam in the high-energy part of the linac do not exceed 200 nA (see Table 9). Losses of H^- beam are mostly determined by stripping of H^- ions on residual gas, intra-beam stripping, and Lorentz stripping. H^+ beam loss is typically one order of magnitude smaller

Figure 15. LANSCE accelerator misalignment.

Table 9. Integral H^- beam losses in the LANSCE accelerator.

Year	Pulse Rate (Hz)	Summed Losses in CCL (nA)
2018	120/60	180
2017	120	150
2016	120	190
2015	120	135
2014	60	211
2013	60	190
2012	60	183
2011	60	167

than that of the H^- beam at the same current due to the absence of stripping mechanisms (see Figure 16). Therefore, we can expect that losses of 1-MW H^+ beam will not exceed losses of 80-kW H^- beam. Previous operation of the accelerator facility at 0.8 MW indicated that losses of H^+ beam were significantly smaller than that of H^- beam.

Figure 16. Measured beam loss relative to peak current for H^+ and H^- beams (from ref. 30).

3.2.5 Beam Loss Control

Beam losses at LANSCE are controlled by various types of loss monitors. The main control is provided by Activation Protection (AP) detectors, which are one-pint size cans with a photo-multiplier tube immersed in scintillator fluid. The AP detectors integrate the signals and shut off the beam if the beam losses around an AP device exceed 100 nA of average current. The same devices are used as beam loss monitors (LM), where the signal is not integrated and therefore one can see a real-time of beam loss across the beam pulse.

Another type of loss monitor is the Ion Chamber (IR) detector. These are used in the high energy transport lines. They are usually located in parallel with Gamma Detectors (GDs) that feed into the Radiation Safety System. An advantage of the IRs is that they do not saturate at high loss rates like the AP devices.

The third type of beam loss monitor is the Hardware Transmission Monitor (HWTM). The HWTM system measures the beam current losses between current monitors and terminates operation if a difference between current monitors exceeds a threshold value. The HWTM system and the activation protection system incorporated with the fast protect system provide a means to minimize activation to areas that require “hands on” maintenance. The current monitor toroids are usually a one hundred or a two hundred turns toroid influenced by the charged particle beam. A single turn loop is included to send a calibrate pulse through to make sure the current monitor is operational. The transmission data differences derived from the toroid signals provides information on the beam losses. The typical constraints result in average current losses of less than 10 nA/m of accelerator length.

3.2.6 Run Permit

Run Permit (RP) is a series of relay inputs designed to interpret the condition the beamline hardware should be in to allow beam to be transported into the area. The input ready on the final RP panel is a summation of all conditions necessary for the accelerator, beamline, and experimental areas. The Run Permit panel shows at a glance the condition or status of the run system for H^+ beam to an area. The RP system operates by the component and/or system completing a 24V DC ready circuit and energizing its associated indicator module relay. The indicator module relay makes up the associated ready chain contact and the contacts to light the corresponding lights on the indicator module and the Ready Chain panel. Examples of RP input are water flow in magnets, magnet temperature, magnet ground fault current, and power supplies on, making sure that the system is ready for operation.

3.3 Beam Transport System

The beamline from the LANSCE switchyard to the FPNS target is composed of existing beamline and additional beamline located in Area A (see Figure 17). The major DC magnetic elements of the beam-transport system (dipoles and quadrupoles) are all available from the present Line A and the LANSCE magnet pool, but the steering and raster magnets will need to be manufactured. The magnet power supplies will also need to be procured. The FPNS target will be located near the center of Area A, some 100 m downstream of the end of the 800-MeV accelerator. Figure 17 shows a sketch of the beamline that will deliver 800-MeV protons from the accelerator to the FPNS target.

Presently, Line A transports H^- particles bound for PSR and WNR through quadrupole doublet LAQM01, LAQM02 into Line D (see Figure 13). In the past, protons were transported to Area A, and the H^- particles and protons were separated in bending magnet LABM01. This will again be the case when FPNS comes on line. Thus, the settings of the first two quadrupoles of Line A are determined by Line D requirements and cannot be adjusted. The present Line A is preserved in magnetic-element placement through LAQM06. The new beamline in Area A has the minimum number of quadrupoles (LAQM07 - LAQM08) necessary to meet all beam-optics requirements (beam parameters at the target, and beam-centroid excursions at the target). The raster-magnet section has two raster magnets LAHR01, LAVR01. An additional beam optics requirement is

Figure 17. Beamline from the end of accelerator to FPNS target.

driven by the need to shield the upstream beamline from backstreaming neutrons. It is achieved by placing a shield wall with a small aperture upstream of the target. There is also a beamline spur, composed of two 15° dipoles (LABM05 and LABM06), leading to a tune-up beam dump.

3.3.1 Beam Optics Requirements

The beam-at-target requirements are dictated by neutronics considerations. A round beam spot with 2.3 mm FWHM (1 mm rms) is painted onto an annular target. Beam-centroid jitter is expected to be at the level of 0.5 rms of beam size. The raster scheme is sufficiently flexible to accommodate changes in the size of the painted annular spot as the design of the FPNS target evolves. For example, a ring with minimum radius of $R_{\min} = 5.5$ cm and maximum radius of $R_{\max} = 6.9$ cm has been assumed in developing the beam optics design presented here, but this design can easily be adjusted to paint a ring with $R_{\min} = 3.2$ cm and $R_{\max} = 4.3$ cm, as assumed in the neutronics design. To be conservative, the beamline apertures are dimensioned to accommodate beam-centroid excursions at the target of up to 10 cm, both horizontally and vertically.

3.3.2 Beamline Design

Application requires minimization of the rastered beam spot on target, while keeping 7-rms beam size within existing beampipe radius of 7.62 cm (or one-rms beam radius within 1 cm). The target area will be surrounded with shielding to prevent irradiation of upstream equipment by backscattered neutrons. The distance from the upstream shield wall to the target is selected to be 10 m. An additional 4 m of beamline is selected for placement of raster magnets. Therefore, the

total distance from the exit of the last quadrupole to the target is 14 m. Evolution of beam size in the drift space, R , is determined by the beam envelope equation:

$$\frac{R}{R_t} = \sqrt{\left(1 + \frac{R'_t}{R_t} z\right)^2 + \left(\frac{\mathfrak{A}}{R_t^2}\right)^2 z^2}, \quad (3.1)$$

where R_t, R'_t are beam envelope size and slope at the target, $\mathfrak{A}$ is the unnormalized beam emittance, and z is the drift space. To minimize beam size at the drift, the slope of beam envelope at the target should be

$$R'_t = -\frac{R_t}{z}. \quad (3.2)$$

Selecting rms beam size and slope at the target as $R_t = 1$ mm, $R'_t = -7.14 \cdot 10^{-5}$ with typical unnormalized rms beam emittance after linac $\mathfrak{A} = 0.05 \pi$ cm mrad, beam size upstream of target at the distance of $z = 14$ m, is $R = 7$ mm. An additional quadrupole doublet LAQD07 - LAQD08 is placed as the last doublet before beam expansion to the target. We assume to place a quadruplet at the distance of 14 m after exiting the wall separating the Switchyard and Area A, which will allow the placement of a separator for future proton radiography double-axis beamline in Area A, and bending magnets LABM05-06 for a beam stop for beam tuning. Geometrical parameters of LAQD07 - LAQD08 doublet are the same as other Line A doublets with effective length of each quadrupole of 60 cm, and distance between quadrupoles 49.88500 cm. Total distance of the beam transport in Area A is around 30 m.

Figure 18 illustrates the beamline design using the beam envelope code TRACE-2D [31]. LANSCE aperture requirements assume that 7-rms beam size should clear the beam pipe aperture radius of 7.62 cm. The quadrupole doublet LAQD01-02 is common for both H^+ and H^- beams. The values of quadrupole gradients in that doublet of 1.5 kGs/cm are selected from a regular run of H^- beam. Four bending magnets LABM01-04 are installed to separate H^+ and H^- beams. They have been used at the time of simultaneous operation of both beams at the energy of 800 MeV. Quadrupole doublets LAQD03-04 and LAQD05-06 were part of 0.8-MW H^+ beam transport to Area A. Those magnets, together with existing beam diagnostics proved to be effective for providing reliable high-energy beam transport. An additional quadrupole doublet LAQD07 - LAQD08 described above provides small beam size at the target. Table 10 lists the beamline elements, in beam-line order, from the downstream end of the vertical bend to the target front face.

Figure 19 illustrates results of 6D beam dynamics study of FPNS beam using the BEAMPATH code [32]. Simulations were performed starting from the exit of the linac with realistic beam parameters. After the linac, the beam is extracted with unnormalized emittance of $\mathfrak{A} = 0.05 \pi$ cm mrad and Twiss parameters $\alpha_{x,y} \approx -0.2 \dots -0.4$; $\beta_{x,y} \approx 1 \dots 2$ cm/mrad. Typical measured FWHM beam energy spread after the linac is $dW/W = 1.8 \cdot 10^{-3}$. Bunch size is measured at the energy 211 MeV to be 25° at 805 MHz. During acceleration the bunched beam size drops due to the phase damping mechanism as

$$\Delta\phi \sim \frac{1}{(\beta\gamma)^{3/4}}, \quad (3.3)$$

TRACE SURE MATCH 24-APR-19 09:29:15 LCS_DATA:[LCSA.TRACE]FPNS_2Q.TRA
N1= 1 N2= 53 I= 0.00 SC=T W=800.000 SMAX= 1.

Figure 18. Beamline design using TRACE-2D code. Presented envelopes are for one-rms beam emittance and one-rms beam size.

and becomes 10° at the energy of 800 MeV. Figure 20 and Figure 21 contain beam distributions in phase space after the linac and at the target.

Table 10. Parameters of beamline quadrupoles.

Quadrupole	z-position (m)	Length (m)	Gradient (G/cm)
LAQM01	0.78542	0.1725	1500.0
LAQM02	1.03924	0.1721	-1500.0
LAQM03	32.21376	0.6	123.8
LAQM04	33.31252	0.6	-117.3
LAQM05	64.00088	0.6	85.9
LAQM06	65.09973	0.6	-100.0
LAQM07	83.02874	0.6	227.8
LAQM08	84.12759	0.6	-228.7

Figure 19. BEAMPATH simulation of FPNS beamline using 6D beam distribution.

Figure 20. Beam distributions after linac.

Figure 21. Beam distributions at the target.

3.3.3 Beam Rastering

The purpose of beam rastering is to uniformly irradiate the target within a ring area of 5.5 cm $<R<$ 6.9 cm. Rastering is achieved through sinusoidal variation of a set of raster (steering) magnets in horizontal and vertical directions. Fields in the magnets are shifted by 90° to perform circular irradiation. Amplitudes of the fields are changing as the square root with time to assure beam centroid variation as:

$$\begin{pmatrix} R_x \\ R_y \end{pmatrix} = R_{\min} \sqrt{1 + \left(\frac{R_{\max}^2}{R_{\min}^2} - 1 \right) \frac{t}{\tau}} \begin{pmatrix} \cos(\omega t + \varphi_o) \\ \sin(\omega t + \varphi_o) \end{pmatrix}, \quad (3.4)$$

where $\tau = 850 \mu\text{s}$ is the beam pulse length, and ω is the raster frequency. In this case, an increment of irradiated area after each turn, dS , is kept constant which assures uniform target irradiation [33]:

$$dS = 2\pi R dR = \text{const}. \quad (3.5)$$

Uniform irradiation is achieved by overlapping of the beam performing circular sweeping over the target. Figure 22 illustrates the beam-centroid excursions at the target and beam centroid radii after 17 beam revolutions (see Eq. 3.4). The beam deflection angle after crossing the raster magnet of

Figure 22. (a) Uniform irradiation of target by beam spiral rastering, (b) beam centroid radii after 17 beam revolutions.

length L and transverse field B is given by $dR_{axis} / dz = eBL / (mc\beta\gamma)$. Taking into account variation of the beam centroid at the target $5.5 \text{ cm} < R_{axis} < 6.9 \text{ cm}$ and distance from the raster magnets to the target as $z = 11 \text{ m}$, the beam deflection angle is varied within an interval

$$\frac{dR_{axis}}{dz} = (5.0 \dots 6.27) \cdot 10^{-3}. \quad (3.6)$$

Figure 23 illustrates the instantaneous beam density at the target and that after overlapping of 17 beam circles, which requires raster frequency of $\omega = 20.0 \text{ kHz}$. Non-uniformity of the irradiated area after overlapping of 17 beam circles is $\Delta I / I = 0.35\%$. Figure 24 illustrates variation of field amplitude of raster magnets within the $850\text{-}\mu\text{s}$ beam macropulse. The distance between dots corresponds to one cycle of rastering (one beam revolution).

Figure 23. (a) Instantaneous beam distribution with the FWHM x-y beam size at the target 2.0 mm, (b) beam density the target after overlapping of $N = 17$ circular patterns.

Figure 24. Variation of raster magnets field amplitude within the beam macropulse.

3.3.4 Beam Sizes and Aperture of Shield Wall Beam Pipe

The target shield wall is placed 10 m upstream of target to prevent beamline components from activation by backscattered neutrons. In keeping with LANSCE standard requirements, the apertures were dimensioned such that at least 7 rms of the deliberately deflected beam clears the beam pipes. Figure 25 illustrates FPNS beam setup using rasters in front of shield wall. For simplicity, we assume that raster magnets are placed in the same position, while realistically they are supposed to be separated by the distance of 1 m. The distance from rasters to wall is 1 m, and

Figure 25. Beam rastering in front of shielding wall.

from the wall entrance to target 10 m, with wall thickness of 2 m. The shield wall pipe diameter is determined as

$$D(z) = 2 \left[\left(\frac{dR_{axis}}{dz} \right)_{\max} (z - z_{raster}) + 7 R_{rms}(z) \right], \quad (3.7)$$

where $(dR_{axis} / dz)_{\max} = 6.27 \cdot 10^{-3}$ is the maximal raster angle of central trajectory, $z - z_{raster}$ is the distance from raster magnet, and $R_{rms}(z)$ is the rms beam size. For the entrance to shielding wall, $z - z_{raster} = 100$ cm, and $R_{rms} = 0.5$ cm, which gives for entrance diameter of the pipe

$$D_{entrance} = 8.25 \text{ cm}. \quad (3.8)$$

For the exit of shielding wall, $z - z_{raster} = 300$ cm, and $R_{rms} = 0.415$ cm, which gives for exit diameter of the pipe

$$D_{exit} = 9.57 \text{ cm}. \quad (3.9)$$

3.3.5 Beam Emittance Measurement

Emittance measurements are made using wire scanners installed at modules 39-48 of the CCL linac. Figure 26 and Figure 27 illustrate measurements of 800-MeV H^+ beam with peak current of 18 mA performed on 06/24/1993. Program WSLIN executes simultaneous measurements of beam profiles using installed wire scanners (see Figure 26). Program WSMATCH reads results of measurements and calculates emittance using the matrix method incorporated in the TRACE program. Figure 27 illustrates typical values of Twiss parameters ($A = \alpha$, $B = \beta$ in cm/mrad) and unnormalized rms emittance E/PI (cm mrad) measured after the linac.

Figure 26. Profile measurements of H^+ beam using wire scanners of modules 39-48 of CCL linac.

3.3.6 Beam Steering

Steering magnets in combination with beam position monitors (BPM) are required to bring the beam centroid to the axis. Usually two steering magnets (horizontal and vertical) are placed close to each other to provide simultaneous control of beam trajectory in both directions. Typically the steering magnets will have to provide a deflection angle within 2.0 mrad. Currently, Line A contains 4 steering magnets: LASM01-X before LABM01 bending magnet, LASM03-X-Y before LABM03 bending magnet, LASM04-X-Y after LAQM03-04 quadrupole doublet, and 1ASM01-

WSMAT 4-JUN-93 02:28:35 LCS_DATA:[LC TRACE]ML805.TRA
ESTIMATED EMITTANCE at END OF 805 (41WS1 to END OF 805)

Figure 27. H^+ Beam emittance measurements at the end of linac using 39-48 wire scanners.

X-Y after LAQD05-06 quadrupole doublet. Placement of an additional steering magnet LASM06-X-Y after LAQD07-08 quadrupole doublet is required. Four beam position monitors will need to be installed along the beamline: LAPM01 after quadrupole doublet LAQD03-04; LAPM02 before quadrupole doublet LAQD05-06, LAPM03 before the beamline spur, and LAPM04 in front of the target shield. This combination of steering magnets and BPMs will provide careful control of the beam centroid from the end of the linac up to the target.

3.4 Magnets

The design of the FPNS beamline requires a minimum number of magnets that must be fabricated. Table 11 provides a summary of the needed magnets and the status of each type. The Line A quadrupoles (LAQM03 through LAQM06) still reside in Line A; their strengths and 3-in-radius apertures are adequate for use in the new beam line. An additional pair of quadrupoles LAQM07-LAQM08 is new. Their parameters are the same as that of the other Line A magnets. A pair of raster magnets LAHR01-LAVR01 are also new and must be fabricated and installed. Four bending magnets LABM01-04 were damaged by fire during the 2018 run cycle and must be replaced. The dump-line dipoles (LABM05 and LABM06) are available from the LANSCE magnet pool.

The six quadrupole magnets required for the new FPNS beamline are available. These existing magnets will be refurbished, tested, and mapped prior to their use in the FPNS beam line. These magnets can provide gradient-length products somewhat in excess of the nominal values. These existing magnets LABM05 and LABM06 will be refurbished, tested, and mapped prior to their use in the FPNS beam line. The new dual-axis steering magnet will be a copy of an existing LANL design and should not present any fabrication, cost, or schedule problems. The raster magnets will

Table 11. Requirements for the FPNS beamline magnets.

Beamline Designation	Type	Number Needed	ID or Gap (cm)	Effective Length (cm)	Status
LAQM01-06	Quadrupole	6	15	60	Existing
LAQM07-08	Quadrupole	2	15	60	To be fabricated
LABM01-04	Dipole	4	15	101.2	To be replaced
LABM05-06	Dipole	2	15	107	Existing
LASM01,03,04X-Y, 1ASM01-X-Y	Dual-axis steerer	4	15	35	Existing
LASM06 X-Y	Dual-axis steerer	1	20	35	To be fabricated
LAHR/VR01	Raster	2	15	50	To be designed and fabricated

need to be designed as well as fabricated. To simplify matters, the same design will be used for the vertical and horizontal raster magnets. The requirements of the FPNS raster magnets are relatively modest, hence no difficulties are anticipated.

3.5 Magnet Power Supplies

Since Line A has not been operated since 1999, all of the existing power supplies must be replaced with modern versions that are compatible with the current instrumentation and control system. Almost all of these will need to be purchased. Table 12 summarizes the parameters for all of the supplies detailed below.

Table 12. Magnet power-supply requirements.

Parameters	Quadrupole Magnets	Dipole Magnets	Steering Magnets
Max DC Current Output Required (A)	120	300	150
Max DC Voltage Output Required (V)	46	100	135
Max Output Power Required (kW)	5.5	30	20.25
Output regulation errors, %	0.01	0.001	0.1
Output ripple, %	0.01	0.005	0.1

3.5.1 Quadrupole Magnet Power Supplies

The quadrupole magnets are used to focus and confine the proton beam along the beam line. The FPNS beamline contains eight quadrupole magnets LAQM01 – LAQM08. The power supplies for these magnets must be current controlled and must be adjustable from full positive output to zero output without discontinuities. Parameters of power supplied for quadrupole magnets are presented in Table 12. A single commercially available power supply can drive each quadrupole magnet.

The quadrupole-magnet power supplies must have low output-regulation errors and low output ripple to prevent the beam from being poorly focused and going off target. Commercially available power supplies that exceed these performance requirements are available. A single spare of each type of power supply will be purchased to minimize downtime if any operating power supply should fail. The quadrupole-magnet power supplies require new DC magnet cables and new AC power connections. They will also require new control lines to be connected and new run-permit interfaces to be installed.

3.5.2 Dipole Magnet Power Supplies

The dipoles are used in the beamline to make large-angle changes to the proton beam direction. The FPNS beamline spur contains two dipole magnets. The power supplies for these magnets must be current-controlled and must be adjustable from full positive output to zero output without discontinuities. The supplies must be capable of producing 300 A at 100 V. A single spare of this type of power supply will be purchased to minimize downtime if the power fails.

The requirements on the dipole-magnet current regulation and ripple are stringent. The dipole-magnet power supplies must have output-regulation errors less than 0.001% and an output ripple of less than 0.005% to keep the beam from missing the beam dump. Custom-built special-order power supplies that meet these requirements are available. Multiple commercially available power supplies wired in series may also meet these requirements.

The dipole-magnet power supplies require new DC magnet cables and new AC power connections. They will also require new control lines to be connected and new run-permit interfaces to be installed.

3.5.3 Steering Magnet Power supplies

The steering magnets are used to make fine adjustments to the proton-beam direction. Steering magnets power supplies are adjusted slowly, unlike the power supplies to the raster magnets. The power supplies must be capable of bipolar operation (both positive and negative outputs). The power supplies must be current-controlled and must be adjustable from full positive to full negative output without discontinuities.

The upstream end of Line A currently houses seven single-axis steering magnets (LASM1X, LASM3X, LASM3Y, LASM4X, LASM4Y, 1ASM1X, 1ASM1Y). These all require new power supplies. In addition, the dual-axis steering magnet LASM6XY is planned for the new beam line. Parameters of power supplies for steering magnets are provided in Table 12.

The DC magnet cables and AC power connections for seven available steering-magnet power supplies currently exist in the LANSCE accelerator. New serial control lines will need to be pulled. A single spare of this type of power supply will need to be purchased to minimize downtime in the event of a power-supply failure. The steering-magnet power supplies must have low output regulation errors and low output ripple to keep the beam from going off-target. Commercially available power supplies that exceed these performance requirements are available.

3.5.4 Raster Magnet Power Supplies

Two raster magnets (horizontal and vertical) are used in the beamline to move the beam spot around the target. The raster magnet parameters are presented in Table 13. The magnet current

must produce sinusoidal variation with adjustable amplitude within the beam pulse of $\tau = 850 \mu\text{s}$ according to the law:

$$I(t) = I_o \sqrt{1 + \left(\frac{R_{\max}^2}{R_{\min}^2} - 1\right) \frac{t}{\tau}} \sin(\omega t + \varphi_o), \quad (3.10)$$

where $I_o = 100\text{--}150 \text{ A}$ depending on final design of the raster magnet, and $\omega = 20 \text{ kHz}$. Their waveforms repeat every 8.333 ms. The raster-magnet power supplies require new DC magnet cables and new AC power connections. They also require new control lines to be connected and new run-permit interfaces to be installed. A single spare of this type of power supply will be purchased to minimize downtime if one of the in-service power supplies fails.

Raster-magnet power supplies in use at the IPF are capable of producing this waveform in excess of 156 A and 135 V and are commercially available. Similar magnet power supplies will be used for FPNS raster magnets.

Table 13. Raster magnets parameters.

Raster frequency	20 kHz
Field Strength BL	0.245–0.31 kGs·m
Beam gate	78 Hz $\times$ 850 μs
Magnet length L	0.5 m

3.6 Beamline Vacuum System

The FPNS-beamline vacuum system consists of the equipment necessary to meet two goals. First, it must provide a level of 5×10^{-8} Torr in the upstream portion of the beam line, in the vicinity of the LANSCE switchyard, so that there is no impact to the linac vacuum due to the project. Second, it must provide the ability to protect the linac from a pressure excursion in the FPNS target.

3.6.1 Description

The FPNS vacuum system will be integrated into the 65 m of beamline starting at LABM04 and ending at the shielding of the FPNS target and the beamline spur that will be used for beam tuning. The majority of the beam pipe is 6-in diameter. The beam pipe diameter is driven by the beam-physics design. For maintenance work, the beamline is divided into six different sections through the use of isolation valves. These valves allow work on individual sections of the beamline without disturbing the vacuum in the other sections. A number of ion pumps are placed along the beamline to provide distributed pumping. A set of turbo pumps will need to be deployed at the end of the beamline to pump any gas escaping from the FPNS target, which will likely operate at higher pressure than the beamline. Two fast-acting valves, which are designed to close within 23 ms from the time they receive a signal, are placed near the upstream end of the new FPNS beam line. The sensor that sends a signal to the fast valves is placed near the downstream end of the beamline so there is as much time as possible for the valves to close if there is a pressure excursion in the FPNS

target. A series of ion gauges will be placed throughout the beamline to monitor the vacuum level in the beamline.

3.6.2 Design

Seven ion pumps and two turbo pumps backed by dry-scroll-pump packages are currently considered to meet the goal of maintaining 5×10^{-8} Torr at the upstream end of the FPNS beam line. It is important to note that the assumption with the largest uncertainty is the assumed leak rate into the FPNS beamline from the FPNS target. The desire to *not* have a vacuum window at the end of the beam line, where the beamline enters the target cell, raises the level of uncertainty about the leak rate into the FPNS beam line. The uncertainty arises from the fact that the quality of the vacuum seal around the target chamber is not well known at this time. To be able to predict the vacuum-system performance, a range of pressures was assumed to exist in the beam tube on the target side of the shielding. Consistent with aperture requirements in the shield wall, the conductance through the shielding was calculated assuming a 2-m long, 3-in diameter tube. This information was used to calculate a range of leak rates through the shielding. The model showed that if the pressure near the target chamber was as high as 1×10^{-3} Torr, then the vacuum system would still be able to meet the goal of 5×10^{-8} Torr at the switchyard. However, this is an area where further analysis is required.

The fast-valve system has also been studied. A calculation was made to determine how long it would take a burst of helium gas to go from the shielding through the FPNS beamline and into the switchyard. Assuming the shielding tube acts as a nozzle, the flow of atmospheric helium through the tube would become choked at a velocity of mach 1. For helium, this is approximately 900 m/s. For the gas to reach the switchyard it would need to travel 65 m, which would take 0.074 seconds. The selected valve is designed to close in 0.023 seconds, which should provide enough time to prevent damage to the upstream accelerator. Two fast valves will be installed for redundancy.

3.6.3 Fabrication and Procurement

There will be little fabrication effort associated with the vacuum system. The various vacuum beam boxes will be fabricated along with other beam line-system components. Essentially all of the vacuum equipment is commercially available and, therefore, will be specified and purchased.

3.6.4 Status of the Design

Much of the vacuum-system equipment has been initially identified to a level that should provide a good basis for cost estimating. A mathematical model indicates the system should be able to meet the stated goal of 5×10^{-8} Torr in the LANSCE switchyard. There are still questions remaining about the leak rate from the FPNS target into the FPNS beam line. Additional or alternative pumping may be required at the shield wall. Further analysis will be required if this project moves forward.

3.7 Diagnostics

The diagnostics must provide sufficient beam information for commissioning and allow monitoring of key beam parameters under normal beam-delivery and abnormal operations. These diagnostics include wire-scanners, harps, a camera profile monitor, beam-position monitors, guards, loss monitors, and current monitors.

Sufficient spare parts will also be procured to ensure operation if equipment fails. The guards must be very robust, because their replacement would be a complex operation. As the most essential piece of instrumentation, there will be a complete duplicate (mirrors and camera) for the IR-camera profile monitor. For the wire-scanners and harps, there will be one actuator spare and one fork spare for each diameter beam pipe. There also will be a spare BPM for each size beam pipe, as well as a spare loss monitor and a complete current-monitor-system spare. Parameters and status of FPNS beam diagnostics instrumentation are summarized in Table 14.

Table 14. FPNS beam diagnostics instrumentation and their functions.

Beam Instrument	Beam Parameter	Quantity	Status
Wiresscanner X-Y	Slow projection of distribution	5	Existing
Harp: two-axis	Fast projection of distribution	2	To be installed
Beam Position Monitor	Transverse beam centroid measurement	4	To be installed
Guard Ring: four-sided	Beam lost at shielding wall and beam dump	2	To be installed
Guard Ring: double four-sided	Beam lost in front of target	1	To be installed
Loss Monitor	General loss measurements	8	To be installed
Current Monitor	Current measurements	3	To be installed
IR-Camera Profile Monitor	Target rastered beam distribution	1	To be installed

3.7.1 Wiresscanners

A wiresscanner provides a horizontal and a vertical beam profile by slowly scanning a 0.1-mm-diameter silicon-carbon fiber across the beam during 50 to 100 beam macropulses. At LANSCE, this is typically done at low-duty factor, defined throughout the facility as 4 Hz, with a 150- μ s macropulse and at reduced current. The secondary electrons emitted from the fiber due to the beam impingement are detected. The acquired data are proportional to the beam charge as a function of wire location, and thus to the projection of the transverse beam distribution. Because wiresscanners acquire profile information during many macropulses, they do not provide an instantaneous beam-distribution measurement. At a 4-Hz repetition rate, the measurement would be on a one-minute time scale. The five wiresscanners LAWS01, LAWS11, LAWS15, LAWS17, LAWX19 already exist. Wire scanner vacuum ports for wire scanners LAWS05, 07 and 09 are blanked off as these devices were used as spares. Based on long-term experience with existing wire scanners, the expected error in beam size measurements does not exceed 10%.

3.7.2 Harps

Harps provide continuous beam profile measurements and therefore are extremely useful for tuning purposes. The harp profile measurement is accomplished using a set of parallel, 0.1-mm diameter silicon-carbon fibers placed with a >3 -mm fiber spacing. When statically placed in the beam using an actuated mechanism, the secondary-electron emission is simultaneously measured

from each of the wires, resulting in a relatively fast but not very finely resolved spatial measurement. Determination of the instantaneous beam size is possible because each wire secondary emission can be monitored as a function of time. There are two locations in the FPNS beamline where a beam-size measurement should be made: before Area A and before the raster magnets. The first location is a LAHP01 harp, which was removed for cleaning purposes and must be reinstalled, while the second one LAHP02 is new. In both locations the 2-rms beam size is about 1.5 cm, which should be well-determined using harps.

3.7.3 Camera Profile Monitor

As discussed previously, measuring the absolute position of the rastered-beam distribution on the target throughout the life of the FPNS facility will be very difficult. One way to perform this measurement is to view the visible emissions as the beam is painted onto the front surface of the target that has been coated with a luminescent material [34]. The visible emissions are viewed with a camera many meters away in a well-shielded area. Because direct-neutron and other types of radioactivity can damage the camera, this measurement will employ front-surface mirrors that transmit most of the radiation coming from the target. These mirrors will likely have a complex surface shape, so that they de-magnify the image into the camera.

3.7.4 Beam Position Monitors

BPMs are non-interceptive diagnostics that provide transverse beam-position information independent of beam current, with an approximate spatial resolution of $\sim 0.1\%$ of the beam-pipe radius and an accuracy of $\sim 1\%$ of the beam-pipe radius. They can do so over the full peak-current operational range and with bandwidths of greater than a few MHz. The BPMs sense variations in beam motion of < 0.1 mm and in < 1 μ s. The beam-position measurements will give the beam's transverse velocity while the beam is being rastered, with less than a few tenths of a microsecond granularity.

There will be four beam-position monitors placed in the FPNS facility: two in the Swithyard area, one before the tune-up beam stop, and one after the rasters. Each BPM provides x- and y-position of beam centroid with the accuracy 0.1 mm. A central-energy measurement of the H^+ beam is possible using any combination of 2 BPMs separated by the distance larger than 20 m.

3.7.5 Guards

Guards are metal plates that detect errant beam. Their primary mission is to detect unacceptable beam loss. The guards will have sub-microsecond response times, enabling them to turn off beam in less than the required two macropulses. A second mission is to properly center and dimension the beam. These devices will not be movable and will be designed for high reliability through the life of the FPNS. Their signal-detection scheme will be simple secondary-electron-emission current, so they will only need a low potential bias to optimize this emission.

Three locations for guards have been selected. There will be a four-sided guard inside the shielding wall between the Line A beamline and the target vessel. A four-sided guard will be installed in front of the tune-up beam stop. A double four-sided guard will be installed in front of the target. This will allow the facility operators to center the respective beams in the rough center between the edges of the guard. The target guard will also allow adjusting the rastered beam size and

approximate location of the beam at the target. This target guard can be replaced as part of the target if a different footprint is required.

The current actually delivered to the target can be computed by subtracting the current lost on the shielding guard and the target guard from the current measured by the current monitor upstream of the shielding. Concerns include residual background radiation and electromechanical cable connections in a harsh radiation environment.

3.7.6 Beam Loss Monitors

Beam-loss monitors measure beam loss due to operational errors in either beam steering or beam size. Radiation generated when high-energy charged particles interact with beamline components is detected by monitoring electron or ion current in an ionization chamber as some of this radiation traverses the chamber. This measurement will use eight ionization chambers placed throughout the FPNS. The information is reported to the facility operators and monitored by the equipment fast-protection system, but is not used to protect personnel. The ionization-chamber loss monitors can respond relatively fast so that they can report losses to the fast-protection system within 10 μ s after a loss condition occurs. They will be placed in the beamline where losses are likely to occur, such as downstream of dipoles, steering magnets, and limiting apertures.

3.7.7 Beam Current Measurements

Beam-current measurements give the most accurate measure of the beam delivered to the target. Fast machine protection will be activated in cases where there are dissimilar current values in two monitors at different locations in the beam line. These toroidal transformer-based current measurements can detect the beam current independent of the beam's transverse position.

Three beam-current measurements will be made in the FPNS beam line: one at the upstream end of the new beamline (upstream of LAQM03), one in the beamline spur to the tune-up beam stop, and one at the downstream end of the beamline just upstream of the shielding wall. Transmission measurements between these toroidal current measurements are used in the beam run permit systems.

3.8 Upgrades to Deliver 1.8 MW Beam Power

Upgrading the existing LANSCE accelerator facility for beam power of 2 MW and beyond has been considered by Rybarczyk et al. [35] and Garnett [36]. To provide Area A with beam power in excess of 1 MW will require increasing either the beam duty factor, beam peak current, beam energy, or some combination thereof. Increasing the RF duty factor beyond historical averages raises concerns about the maximum operating duty factor that the structures can safely handle. For the DTL, the weakest link is very likely to be the indirectly-cooled copper bellows that are located at the top of every drift tube stem inside the tanks, and post-couplers. The DTL duty factor limit is estimated to be 15.0%. For the CCL, which is cooled through water channels external to the cavities, the duty factor must stay well below that point where thermally induced stresses result in plastic deformation of the accelerator and coupling cells. The CCL duty factor limit is estimated to be 12.2%. As discussed in Section 3.2.1, acceleration of proton beam with peak current of 18.87 mA to provide an average beam power of 1 MW is within operation limits.

Delivering beam with average power of 1.8 MW would need an average beam current of 2.25 mA, which requires operating the existing RF amplifiers and high-voltage systems outside their rated

duty factor and peak power capacity. Possible options of upgrade of accelerator facility for this purpose are discussed in detail in references 35 and 36. Here we briefly review the results of those studies.

3.8.1 Maintain Existing DTL and CCL with Replaced Klystrons

The vintage klystrons, originally manufactured back in the 1970s, would not be able to support the required peak and average power and would need to be replaced. The preferred approach would be to replace all existing klystrons with units capable of providing the RF power requirements with reasonable operating margin. The HVDC power systems that provide the cathode voltage to the klystrons would also need to be improved to support operation at the higher peak and higher average current. Two approaches would be considered. The first approach would be to replace the existing HV equipment with similar equipment designed for higher-power operation. The second approach would be to divide the high voltage in a sector in half, and operate half the sector from the existing power supplies and power the other part of the sector from an additional supply. For the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory, Los Alamos developed a new type of compact high-voltage power system called a converter modulator that directly pulses the cathode of the klystrons. This compact unit would fit in the existing sector buildings and could reliably power half of the klystrons in the sectors. One additional advantage of this approach is that we could increase the voltage rating for the portion of the sector powered from a converter modulator. This higher voltage would allow us to implement high efficiency klystrons in the portion of the sector being powered from the converter modulator.

3.8.2 Replacing Sections of the CCL with Superconducting Linac

An alternative option would be to replace a portion of the linac structures with more modern counterparts that can improve beam quality and provide higher beam energies (1.5 GeV). This would be accomplished by removing some number of CCL modules at the downstream end of the linac and replacing them with collections of superconducting (SC) cavities which have a much higher real-estate gradient of several MV/m compared with ~ 1 MV/m for the existing CCL. An example of this option would be where each of the 18 CCL modules located in Sectors F, G & H are replaced with a SNS high- β SC linac (SCL) cryomodule. The SNS accelerator uses two different 805-MHz cryomodule configurations. The first cryomodule configuration (medium- β) has 3 cavities per cryomodule with 6 cells per cavity each having a geometric- β of 0.61. The second type of cryomodule configuration (high- β) has 4 cavities per cryomodule, also with 6 cells per cavity, but with a geometric- β of 0.81. They were designed to operate at an accelerating gradient $E = E_0 T$ of 10.1 MV/m (at $\beta = 0.61$) and 15.8 MV/m (at $\beta = 0.81$) for the medium- and high- β cavities, respectively. Using the SNS design energy gains versus particle β (normalized velocity), a simple layout was developed to demonstrate a final accelerator energy of ~ 1.5 GeV. Since each of the multi-cell cavities in these high- β cryomodules requires a separate klystron to provide a stable accelerating field, the HPRF systems that feed the SCL linac would need to be replaced with 18×4 lower-power klystrons to provide the requisite power. The existing HPRF systems at each module in the CCL would be sufficient for the remaining CCL structures.

To continue to meet the requirements of the existing user programs, a special transport section will need to be added at the 800-MeV point within the SC linac in this case. This transport would allow H^- beams for Line D (Lujan and WNR) and Line X (pRad and UCN) to be extracted and drifted to their destinations without the additional energy gain. This would also require reconfiguring or

rebuilding the Switchyard (SY) beam-transport system to accommodate the split beam lines as well as the higher-energy H^+ beam. A special transport “spur” would be needed within the SC linac to allow extraction of the 800-MeV H^- beams to Line D and Line X. The Switchyard would also need rebuilding to accommodate these changes, i.e. the higher momentum H^+ beam to Area A and the different injection point for the H^- beams. An alternative variation would be to accelerate the Line X beams to 1.5 GeV, thereby providing higher-energy beam to pRad, which would improve their resolution and to UCN for increased neutron production. This would simplify the Switchyard design but would require additional changes in Line X to accommodate this higher beam energy. The special 800-MeV transport section for Line D would still be needed.

4 Needed Infrastructure

The LANSCE facility started routine operations in 1972. It has evolved from conducting primarily meson physics research to a neutron science facility with currently five operating targets serving a variety of applications that includes radioactive isotope production, ultra-cold neutron production (both funded by the Office of Nuclear Physics), proton radiography, and two neutron time-of-flight facilities (Lujan Center and Weapons Neutron Research) where neutron scattering and neutron-induced reaction research is conducted for the National Nuclear Security Administration (NNSA).

There is substantial existing infrastructure that can be made available for use by the FPNS should the facility be sited at LANSCE. These include the so-called “Area A” experimental hall where 800-kW beam was routinely delivered to two pion production targets for a quarter century, with two adjacent unused hot cells. There are many hundreds of tons of steel and cast-iron shield blocks that are available to construct beam line and target station shielding in Area A. The LANSCE facility has in place all of the needed expertise required to license and operate a high-power spallation target station, including safety basis experts, a target operations group that currently operates two spallation targets, and a facility operations organization with expertise in industrial hygiene, radiation protection, waste management, and environmental protection.

4.1 Area A Experimental Hall

The Area A experimental hall, shown in Figure 28, is a 30,000-sq.ft. building originally built for meson physics research. About a decade ago, most of the legacy equipment and shielding was removed from the hall, with the exception of some portion of one of the old targets and associated shielding, which still remains. Presently, the hall is largely used for storage, staging equipment,

Figure 28. View of the Area A experimental hall upon completion of its construction in 1971. Beam enters from the switchyard through the large hole at floor level in the far left wall.

and a few small non-beam experiments. Beam has not been transported to Area A since 1999, and the ability to transport beam will require reconstitution of some portion of the “Line A” beam line from the LANSCE switchyard to Area A, details of which are provided in Section 3.3.

Currently, a dual-axis proton radiography station is planned for Area A. This station will augment the experimental program currently conducted at the existing proton radiography station in Area C. Funding has yet to be secured for this project, but the plan is that it will occupy the north half of Area A, leaving the south half of the hall available for other projects. If FPNS were to be sited at LANSCE, it will require coordination and integration into the long-range plan for the utilization of Area A for multiple missions. As detailed in the next section, the FPNS layout proposed here is inconsistent with the current vision of two-axis proton radiography station occupying the north half of Area A.

The experimental hall has plenty of installed electrical (6 MW) and water-cooling capacity that can be allocated to an FPNS station. The station will require a dedicated ventilation system with its own fans and high-purity filtration, but may be able to use some existing subfloor ductwork in Area A, as well tie into the existing exhaust stack.

4.2 Target Station

A logical layout of the FPNS target station in Area A would be along a straight path from the switchyard, as shown in Figure 29 (note this layout potentially conflicts with the current vision of using the north half of Area A for a dual-axis proton radiography station). “Line A” transports the 1-MW proton beam from the switchyard to Area A. As described in Section 3.3, the beam transport line would extend into Area A along a straight path. A backstreaming neutron shield wall would

Figure 29. Conceptual layout of FPNS in the Area A experimental hall.

protect the beamline magnets, vacuum equipment, and beam diagnostics from becoming activated by neutrons backstreaming from the spallation target, thereby allowing hands-on maintenance of all active systems. A likely concept for the target servicing is to mount it on a trolley that can be extracted in the downstream direction into a service cell. This is a commonly used arrangement, demonstrated successfully at both target stations of the ISIS facility at the Rutherford Appleton Laboratory, the Materials and Life Science facility at the Japan Particle Accelerator Research Complex, and the Spallation Neutron Source at the Oak Ridge National Laboratory. The service cell would have remote manipulator stations on either side of the target trolley, allowing highly activated components to be serviced remotely. Downstream of the service cell is the equipment room that houses the various cooling systems and ancillary equipment.

4.3 Hot Cells and PIE Capability

Adjacent to Area A are two unused hot cells (see Figure 30). The south hot cell has four remote manipulator stations (8 manipulators in all), while the north hot cell has two (6 manipulators). These could be made available for performing post-irradiation examination (PIE) of irradiated samples. Access to the hot cells is accomplished through transfer hatches on the roofs. For items too large to fit through the transfer hatches, the roofs can be rolled southward.

4.3.1 Hot Cells

Currently, the south hot cell is clean and can be entered without restrictions. The north hot cell contains legacy radioactive items that must be removed and disposed of. The manipulators are in various states of disrepair, and must either be refurbished or replaced. One option for replacement

Figure 30. Hot cells adjacent to Area A (from ref. 37).

is to acquire manipulators from LANL's Wing 9 hot cells that are slated to be taken out of service in the near future. These are the same manipulator models as are currently installed in the LANSCE hot cells, and this result in significant savings as compared to purchasing new ones. There are nine oil-filled lead glass windows. They require hot-side cover plate removal and all surfaces cleaned and remounted with new air-sealing gaskets. Some new cover plates may be required. At least one window is leaking oil on the hot side, so that window needs to be drained, and a new oil-sealing gasket installed. The work space around the hot cells and the mezzanine area at the level of the hot cell roofs have legacy material that should be cleaned out. Estimates for this work have been made and details are provided in Chapter 5.

4.3.2 Post-Irradiation Examination Capability

For post irradiation examination after an irradiation campaign, hot cells will need to be capable of disassembling the specimens from their holders, cleaning and examination of specimens, metallurgical preparation and mechanical testing. Thus, the following equipment would be needed:

1. Large scale machining to remove specimens: A milling machine is typically used for this operation. Generally specialized fixtures are also created tuned to the needs of the holder design.
2. Cleaning and examination of specimens: This is easily performed by having a Koll-Morgan to view specimens and an optical microscope. Cleaning is performed with ultrasonic cleaning equipment.
3. Metallurgical preparation: Equipment would be needed for cutting specimens, mounting and metallurgical preparation. Typically this is done with a slow speed cutting saw, epoxy mounting and a polishing machine for remote polishing of specimens.
4. Mechanical testing: Equipment required for mechanical testing would include two or three mechanical test machines with furnaces on them for performing tensile testing, compression testing, bend testing, shear punch testing and fracture toughness testing. In addition, a hardness tester would be useful for microhardness testing.

Because of the cost and time required for testing in hot cells, it would also be useful to have some test machines in a low rad area and one test machine in the hot cells. Thus, the hottest specimens could be tested in the hot cells but cooler specimens or smaller specimens could be tested in a low radiation area near the hot cells.

5 Cost Range and Schedule

Cost range and schedule for the design, fabrication, installation and commissioning of an FPNS at LANSCE are detailed here.

5.1 Cost Range

At this pre-conceptual design stage, a Class 5 cost range has been generated, consistent with guidance from the DOE Cost Estimating Guide [38]. Costs are largely predicated on the Class 3 cost estimate produced in 2012 for the MTS project as part of its CD-1 package. This has been adjusted for escalation (assuming 2% per year for nonlabor and 3% per year for labor, cumulative over the past eight years, to 2020), and for known differences in project scope. The point cost estimate derived in this manner forms the basis for a Class 5 cost estimate for an FPNS at LANSCE by the application of a cost range that is 25% below and 100% above the point estimate.

Table 15 shows the MTS cost estimate by Work Breakdown Structure (WBS) element as estimated at the end of Conceptual Design, and the anticipated cost for FPNS when accounting for differences in scope and escalated from 2012 to 2020. Summed over all WBS elements, the FPNS cost comes to \$78.2M. Assuming equivalent percentage contingency (31.0%) as derived for the MTS project, the FPNS point cost estimate is \$103M, which is 24% greater than the MTS point cost estimate from 2012. The FPNS Class 5 cost range is then \$77M to \$206M.

The remainder of this section provides details for each WBS element on the anticipated differences between MTS scope and FPNS scope, and the cost estimate associated with those differences.

Table 15. Summary of PFNS point cost estimate, scaling from MTS WBS elements from ref. 27.

MTS WBS Element	MTS WBS Title	MTS Cost	FPNS Cost	Ratio (FPNS/MTS)
	Conceptual Design	\$2,908,558	\$3,684,474	1.27
MTB7.01	Project Management	\$3,795,684	\$6,200,000	1.63
MTB7.02	Neutronics	\$953,640	\$1,208,043	1.27
MTB7.03	Target Assembly	\$5,811,289	\$8,168,117	1.41
MTB7.04	Target Assembly Services	\$10,351,363	\$13,022,085	1.26
MTB7.05	Accelerator Systems	\$20,286,349	\$18,866,999	0.93
MTB7.06	Shielding and Structures	\$5,064,720	\$6,290,592	1.24
MTB7.07	Instrumentation & Controls	\$5,912,915	\$7,315,966	1.24
MTB7.08	Area A Preparation	\$3,534,545	\$8,297,072	2.35
MTB7.09	Safety and Permitting	\$2,575,738	\$2,936,581	1.14
MTB7.10	Commissioning and Closeout	\$1,997,219	\$2,530,017	1.27
MTB7	Sum	\$63,192,020	\$78,159,947	1.24
	Contingency	\$19,602,374	\$24,357,148	1.24
TOTAL		\$82,794,394	\$102,877,094	1.24

5.1.1 Conceptual Design

The MTS Class 3 point cost estimate was developed at the completion of conceptual design. Total costs accumulated at that point constitutes the cost of conceptual design, which was \$2.91M. Assuming FPNS conceptual design has equivalent scope as MTS had, and conservatively assuming that all conceptual design costs were labor, the MTS value was escalated by 3% per year for eight years to an estimated cost of \$3.68M.

5.1.2 Project Management

This WBS element includes all costs to perform project management and integration activities that are not specific to a particular hardware work scope. It consists of project scheduling, project controls, systems engineering, design integration, quality assurance, records management and document control, dedicated procurement support, and risk management. Also included in this element are interactions with the program sponsor, project reporting, preparation of project-level documents as required by DOE O413.3B, and execution of project reviews.

While management of the two projects (MTS and FPNS) is anticipated to be substantially similar in scope, the FPNS estimate for project management is based on anticipated level of effort for the tasks detailed above. This budget must cover labor for approximately 3.5 FTEs for 4 to 5 years (conceptual design costs are considered separately), or 14 to 17.5 FTE-yr. Taking 15 FTE-yr as the labor effort and assuming an average burdened labor cost of \$400K/yr, and adding \$200K for nonlabor (travel, etc.), an estimate of \$6.2M is derived for FPNS project management. This represents 8.3% of the point cost estimate when contingency and conceptual design costs are subtracted.

5.1.3 Neutronics

The neutronics effort covers neutronic optimization as well as support for the mechanical design of the target assembly and other components (energy deposition by radiation, radiation damage in structural components, decay heat). It also includes the calculation of nuclide inventories that support safety and permitting activities, and radiation shield design.

For MTS, this effort had an estimated cost of \$1.0M, essentially all of which was labor. As FPNS and MTS are expected to be substantially similar in the neutronics effort, the MTS cost was escalated by 3% per year for eight years to arrive at an estimate of \$1.21M for FPNS.

5.1.4 Target Assembly

This element covers the design, fabrication, and installation of the target assembly, which consists of an integrated target housing, spallation target, sample can and mask, reflector, mounting system, instrumentation, and primary cooling systems. Activities include mechanical design, thermal hydraulic and stress analyses, fabrication prototyping, safety analysis support, cost and schedule estimating, materials procurement, fabrication, assembly, and installation.

For MTS, the target assembly estimated cost was \$5.8M, of which \$3.8M was labor and \$2.0M was nonlabor. For FPNS, these costs were escalated and another \$1M was added to nonlabor to account for the higher cost of a helium circulator compared to an electromagnetic pump for the lead-bismuth eutectic primary coolant in MTS. This results in a total FPNS cost estimate for this element of \$8.2M.

5.1.5 Target Assembly Services

This WBS element covers the remote servicing of the target assembly and associated ancillary equipment (e.g., primary cooling loops, instrumentation, trolley), as well as the remote handling activities associated with the removal of irradiated material samples, and insertion of fresh samples. This activity will have design authority over the hot cell layout, remote manipulators, hot cell windows, and the types of fittings, fasteners, etc., that must be serviced remotely. Activities include remote handling design and optimization, cost and schedule estimating, procurement, assembly, and installation.

For MTS, the target assembly estimated labor cost was \$4.1M and nonlabor cost was \$6.2M, for a total cost of \$10.4M. For FPNS, these costs were escalated to 2020 dollars and another \$0.5M was added to nonlabor to incorporate an inflatable seal in the design. The inflatable seal is a feature that has been employed successfully at several facilities, but was not included in the MTS design. This brings the FPNS total for this work element to \$13.0M.

5.1.6 Accelerator Systems

Accelerator Systems consists of beam diagnostics (harps, beam loss monitors, beam position monitors, imaging cameras, wire scanners and guard rings), vacuum systems, magnets and associated power supplies, beam plugs, low-power beam dump, ion source, spare radiofrequency power systems. Activities include beam transport design and optimization, cost and schedule estimating, procurement, assembly, and installation.

FPNS is expected to have the same magnet, vacuum system, and protective systems scope as MTS, so for FPNS these elements were taken directly from MTS, escalated to 2020 dollars. FPNS is estimated to require two-thirds the number of magnet power supplies as MTS (24 vs. 36), so a factor of 0.7 has been applied to this scope. The MTS project included the purchase of two 805-MHz klystrons at \$160K each (\$320K total), whereas FPNS assumes the purchase of 15 klystrons at \$200K each (\$3M total). The FPNS beamline design includes half the number of beam diagnostics as that proposed by the MTS project, so the diagnostics costs were estimated by halving the MTS cost estimate and escalating to 2020 dollars. No budget for alignment has been included in the FPNS cost estimate, whereas MTS assumed a labor cost of \$0.66M for this effort. The reason for not including alignment costs is that recent measurements is currently adequately aligned (for details, see Section 3.2.4). With these adjustments, FPNS labor and nonlabor are estimated to be \$8.8M and \$11.1M, respectively, for a total Accelerator Systems cost of \$18.9M.

5.1.7 Shielding and Structures

This WBS element covers design, fabrication and installation of shield structures to protect personnel from both prompt and decay radiation, which includes extension of the beam line tunnel into Area A, the target bulk shield (including the He tank and its internals), and the service cell.

The FPNS cost estimate for this element is taken directly from MTS, escalated to 2020 dollars, which amounts to \$6.3M.

5.1.8 Instrumentation & Controls

This WBS element covers design, fabrication, installation and testing of the instrumentation and control systems required to operate the MTS. Included in this element are safety and protection

systems (including the Fast Protect, Run Permit, and Radiation Safety systems), controls hardware and software, and target instrumentation. Activities include I&C design and optimization, cost and schedule estimating, procurement, assembly, and installation.

The FPNS cost estimate for this element is taken directly from MTS, escalated to 2020 dollars, which amounts to \$7.3M.

5.1.9 Area A Preparation

This element covers the preparation of the experimental hall where the FPNS will be installed. Included are the facility condition assessment and refurbishment, structural analysis, utilities refurbishment or replacement, and re-commissioning of the secondary cooling systems. Also included is the removal and storage or disposal of existing equipment, including steel and concrete shielding, within the experimental hall that interferes with the installation of the beam line and target station. In addition, this element includes the refurbishment of the adjacent hot cells and outfitting them with equipment needed to perform PIE on irradiated samples.

To estimate the cost, the MTS labor cost estimate of \$0.57M was escalated by 3% per year for eight years, and \$2M was added to cover labor costs associated with cleaning out and refurbishing the hot cells. The MTS nonlabor cost estimate of \$3.0M was escalated by 2% per year for eight years, which comes to \$3.5M. Added to this are \$1.6M for nonlabor costs associated with hot cells refurbishment (of which \$1M is allotted to the refurbishment or replacement of nonfunctioning manipulators), and \$0.5M for PIE equipment. The FPNS total for this element comes to \$8.3M.

5.1.10 Safety and Permitting

This element is comprised of efforts required to ensure that the FPNS will comply with applicable laws, rules, orders, and guides pertaining to the safe and environmentally compliant installation and operation of the FPNS. Included in this element are the production, review, and defense of hazards analyses and safety assessment documents, and NEPA assessment and compliance.

The MTS project included the irradiation of nuclear reactor fuel that brought with it a larger at-risk radionuclide inventory and the need for a nuclear criticality assessment. For FPNS, the nuclide inventory is smaller, there are no actinides, and there is no potential for nuclear criticality. Therefore, the safety and permitting effort for FPNS is expected to be smaller than for MTS. To account for this smaller effort, the MTS cost estimate was multiplied by 0.9 after escalation to 2020 dollars, which amounts to \$2.9M.

5.1.11 Commissioning and Closeout

This element provides labor, supervision and consumables to support the accelerator readiness review, and integrated startup and testing of the FPNS. Also included is the preparation of turnover packages, and project closeout documentation.

The FPNS cost estimate for this element is taken directly from MTS, escalated to 2020 dollars, which amounts to \$2.5M.

5.2 Schedule

The project phases include conceptual design, preliminary design, final design, construction, and commissioning. Assuming a technically driven schedule that is adequately funded on time (e.g.,

not negatively impacted by Continuing Resolutions), receives timely Critical Decision approvals to proceed to the next phase, with the ability to onboard capable staffing when needed and as needed, the total project schedule is estimated to take five to six years from approval of mission need (CD-0).

Conceptual design is expected to take 12 months, followed by 18 months for preliminary design and 12 months for final design. To keep the schedule as short as possible, CD-3 approvals may be staged to allow for the clearing of Area A, refurbishment of the hot cells, or long-lead procurements prior to completing the final design of all elements of the project. Construction is estimated to take 18 months to 24 months, which is relatively short due to the use of an existing experimental hall and a prodigious quantity of cast iron and steel shielding already on hand and available for use by this project. Finally, the commissioning phase is expected to take three months.

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APPENDIX: Author Biographies

Eric Pitcher

Eric graduated magna cum laude from Mississippi State University with a B.S. in nuclear engineering. He went on to earn M.S.E. and Ph.D. degrees in nuclear engineering from the University of Michigan. His area of expertise is spallation source design and operation, and he has authored more than 100 articles in peer-reviewed journals and conference proceedings. In the late 1990s, Eric served as Physics Task Leader for the Accelerator Production of Tritium project (a 100-MW-class accelerator driving a spallation source to produce tritium for the nation's nuclear stockpile). In this capacity he led a team of researchers from multiple institutions performing the neutronics design and assessment for the project. In the mid-2000s, Eric was named Deputy Group Leader of LANL's theoretical nuclear physics group, a leading contributor of evaluated nuclear data to the US Evaluated Nuclear Data File (ENDF). Following this, Eric served as Project Leader for the Materials Test Station project, whose goal was the construction of a 1-MW irradiation station at LANSCE for rodlet-scale fast reactor fuels and materials testing. In the mid-2010s, Eric took a four-year leave of absence from LANL to serve as Deputy Head, and later Head, of the Target Division for the European Spallation Source project, a 5-MW spallation source facility currently under construction in southern Sweden. Eric then returned to LANL to lead the group that operates and conducts nuclear physics research on the unmoderated (WNR) and moderated (Lujan Center) spallation neutron sources at LANSCE. Eric currently serves as the Deputy Division Leader for the Physics Division, with a staff of 250 and annual budget exceeding \$100M. This division operates and leads the research conducted at four of the five facilities served by the LANSCE accelerator.

Yuri Batygin

Dr. Yuri Batygin is an internationally recognized expert in accelerator physics with over 40 years of experience in the field. His expertise includes physics and design of charged particle accelerators and beamlines, operation and experimental study of particle beams, radiation phenomena and polarization effects in particle beams, nonlinear dynamics, as well as large-scale numerical simulations of particle tracking with collective effects. Dr. Batygin graduated from Moscow Engineering Physics Institute (Moscow, Russia) in 1977 with a degree in Engineering Physics. He received his PhD in Accelerator Physics from the same Institute in 1984. In 1998 he received a higher-level academic degree of Doctor of Science in Accelerator Physics from Joint Institute for Nuclear Research (Dubna, Russia). Between 1994 and 1999, he worked in the Institute of Physical and Chemical Research (RIKEN, Japan) on Radioactive Isotope Beam Factory accelerator project, a next-generation heavy-ion research facility which commenced operation in 2006. Between 2000 and 2007, Dr. Batygin worked at Stanford Linear Accelerator Center on the International Linear Collider project, which is expected to become the next high-energy accelerator facility for discovery of new physics beyond the Standard Model. From 2007 to 2009, he worked at Michigan State University on the Facility for Rare Isotope Beams (FRIB) project, which is now under construction. Batygin joined Los Alamos National Laboratory in 2009, specializing in operation of the LANSCE accelerator facility, in conjunction with various other research projects. To date, Dr. Batygin has authored more than 200 publications, and served as an editor of the International Symposium on Space Charge Dominated Beam Physics for Heavy Ion Fusion, Saitama, Japan (American Institute of Physics Proceeding Series, Volume 480, 1999).

Stuart Maloy

Stuart Maloy is Deputy Group Leader for MST-8 (materials at radiation and dynamic extremes) at Los Alamos National Laboratory (where he has worked for 30 years) and is the advanced reactor core materials technical leader for the Nuclear Technology Research and Development's Advanced Fuels campaign. He has a Bachelors ('89) Masters ('91) and PhD ('94) in Materials Science from Case Western Reserve University and is a registered PE in Metallurgy. He has applied his expertise to characterizing and testing the properties of metallic and ceramic materials in extreme environments such as under neutron and proton irradiation at reactor relevant temperatures. This includes testing the mechanical properties (fracture toughness and tensile properties) of Mod 9Cr-1Mo, HT-9, 316L, 304L, Inconel 718, Al6061-T6 and Al5052 after high energy proton and neutron irradiations using accelerators and fast reactors. Characterization of materials after testing includes using transmission electron microscopy for analyzing defects such as dislocations, twins and second phases, using high resolution electron microscopy to characterize defects at an atomic level and nanoscale mechanical testing. Stuart has >200 peer reviewed technical publications (>4500 citations, H-index of 36) and numerous presentations.