The Project X Energy Station as a Candidate Fusion Materials Facility
David Asner – Pacific Northwest National Laboratory

The ability to contribute to world-leading science in the next decade

Project X is a high intensity proton accelerator that will support a world-leading program of Intensity Frontier physics over the next several decades at Fermilab. Project X is completely unique in its ability to deliver, simultaneously, up to 6 MW of site-wide beam power to multiple experiments, at multiple energies, and with flexible beam formats. The primary driver for development of Project X is high energy physics research; however, the high beam power and intensity offers the potential for separate target stations to address important questions in other fields including fusion materials science. Accordingly, the Project X Energy Station concept has been developed to evaluate the ability of this unique accelerator facility to pursue world-leading materials science research.

A complete concept for Project X has been developed and is documented in the Project X Reference Design Report.[1] The Reference Design is based on a continuous wave (CW) superconducting 3 GeV linac providing up to 1 and 3 MW of beam power at 1 and 3 GeV, respectively. Project X represents a factor of three increase, over current capabilities, in proton beam power at 60 to 120 GeV. Project X is an integral part of the U.S. Intensity Frontier Roadmap[2] and within the Fermilab Strategic Plan.[3] Recent reviews have endorsed the use of next-generation accelerators to enable technological breakthroughs needed for future fission and fusion energy applications.[4]

The notional concept for the Project X Energy Station is a beam line of 1 MW power directed to a 10-cm diameter liquid lead or lead-bismuth spallation target. The spallation target produces copious neutrons at fusion-relevant energies. Neutrons produced in the spallation region escape into the surrounding target region, which contains several test modules with independent coolant loops. These test modules could be interchangeable, allowing the facility to accommodate multiple users. The neutron spectra in the test modules could be tailored by using moderating or filtering assemblies, as necessary. Preliminary calculations indicate that large volumes are available (~300 liters with neutron flux $>10^{14}$ n/cm^2/sec) that rival or surpass the limited test volumes in existing high power test reactors.[5] Further, unlike fission reactors, the Project X Energy Station provides significant high-energy neutron flux at positions within and near the spallation target to achieve high dose rates (20-40 dpa per 365 operating days at 1 MW beam power)

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1 Holmes, SD. 2013. "Project X – Reference Design Report: V1.0." Batavia, IL: Fermi National Accelerator Laboratory.

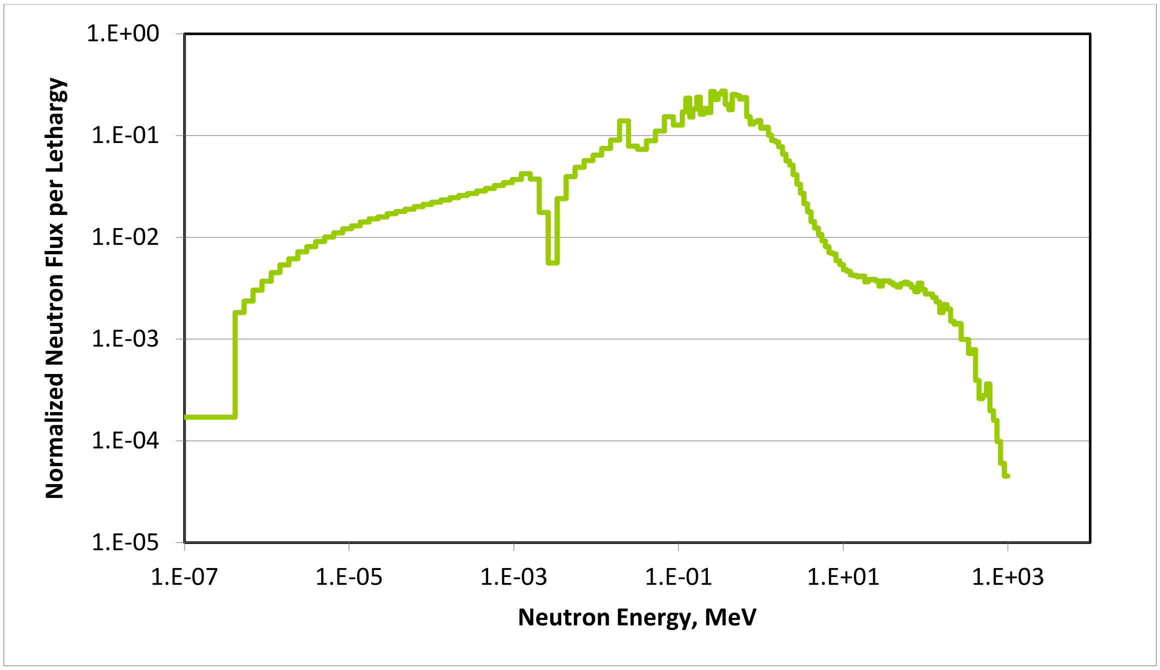
2 Particle Physics Project Prioritization Panel. 2008. "US Particle Physics: Scientific Opportunities, A Strategic Plan for the Next Ten Years." Washington, DC: US Department of Energy.

3 Fermi National Accelerator Laboratory. 2011. "Fermilab: A Plan for Discovery." Batavia, IL: Fermi National Accelerator Laboratory.

4 Henning, W and C Shank. 2010. "Accelerators for America's Future." Washington, DC: US Department of Energy.

5 Wootan, D and D Asner. 2012. "Project X Nuclear Energy Station," *PNNL-21134*. Richland, WA: Pacific Northwest National Laboratory.

with fusion-relevant He generation rates. The highest dose rates would be associated with sample volumes on the order of a few liters. The figure below shows a representative neutron spectrum with a significant population of fusion-relevant 14 MeV neutrons that cannot be achieved in a fission reactor.



Project X Energy Station Spallation Neutron Spectrum with 1 GeV Incident Proton Beam (After Wootan and Asner 2012).

Readiness of the Facility for Construction

The Project X R&D Program is being undertaken by a collaboration of twelve national laboratories and universities, and four Indian laboratories (Project X Collaboration). R&D assignments of the collaborating institutions are made on the basis of unique skills and competencies, with the assumption that these assignments will continue into the construction phase. A very significant in-kind contribution to Project X is currently under discussion between the U.S. Department of Energy and the Indian Department of Atomic Energy.

A comprehensive R&D program is underway, aimed at mitigating the primary technical and cost risk associated with Project X. The existing Reference Design is supported by comprehensive electromagnetic and beam dynamics modeling and simulations, and provides the context for the R&D program. The primary supporting technologies required to construct Project X exist today. Fermilab, with national and international collaborators, has an extensive development program in superconducting radio frequency acceleration. This program has produced both spoke resonator and elliptical accelerating structures that meet the requirements of Project X. The Project X Front End breaks new ground technically and is the focus of an intensive development and systems testing program. Proof-of-concept components exist. Project X is pre-CD-0. However, a preliminary, bottoms-up, cost estimate exist and the state of development is sufficient to support an expeditious move to construction (CD-3), in parallel with ongoing development, over the next three-four years. The Project X accelerator is ready to construct. The Project X Energy Station is currently in the pre-conceptual design phase, but no significant technological challenges have been identified and a definition of mission and technical requirements is currently underway.

A preliminary estimate of rough order of magnitude cost for the Project X Energy Station is $150-200M, based on comparisons to the proposed Materials Test Station (MTS) at Los Alamos National Laboratory, and allowing for the larger irradiation volume of the Energy Station. A similar comparison for operating costs yields an estimate of $20-25M per year.[6] The Energy Station would operate as a national user facility, presumably with the cost shared between organizations that utilize the target station to the greatest extent.

Scientific Community Considerations

A workshop was recently held at Fermilab to identify and evaluate unique applications for the Project X Energy Station concept.[7] Workshop participants included accelerator physicists and engineers, but also nuclear materials experts from the fission and fusion communities. The most compelling application identified for the notional target station is irradiation of fusion reactor structural materials. There currently is no facility available anywhere in the world that can provide fusion-relevant neutron flux and achieve a minimum of 20 dpa per calendar year in a reasonable irradiation volume.

To ensure maximum relevance to the fusion materials community, the notional Project X Energy Station can accommodate a range of sample sizes for structural materials of interest, from very small (mm-scale) to relatively large (maybe 10 cm). The smaller end of the size range is appropriate for fundamental studies of irradiation damage mechanisms, while the larger end of the range is appropriate for bulk samples needed for engineering property measurements. Because of its ample irradiation volume (due to the intensity of the incident proton beam) the Project X Energy Station can accommodate the full range of sample sizes. Further, the target and incident beam can be designed to ensure there are areas of relatively uniform (and high) flux over cm-scale dimensions. At the same time, the irradiation facility can include not only replaceable large modules as described above, but also fixed, irradiation positions to accommodate specimens for long-term irradiations to achieve high dose (150+ dpa).

One question that must be addressed to further evaluate the feasibility of performing fusion materials irradiation tests are the effects of beam transients. For any irradiation experiment, active temperature control of test specimens during irradiation is an absolute requirement. While relatively straightforward during steady-state operation, the issue of

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[6] Pitcher, EJ. 2008. "The Materials Test Station: A Fast-Spectrum Irradiation Facility," *Journal of Nuclear Materials*, 277:17-20.

[7] Peterson, M, et al. 2013. "Project X Energy Station Workshop Report," *in press*. Richland, WA: Pacific Northwest National Laboratory.

incident proton beam trips and downtime (both planned and unplanned) must be addressed. These transients exist on both short time scales (beam trips and downtime during normal operation) and longer time scales (planned and unplanned extended outages). It is possible that some of the events could have consequences for irradiation damage mechanisms (e.g. cascade annealing, atomic diffusion, phase transformations), particularly for samples located in the highest-flux regions adjacent to the proton beam and spallation target. Recent experience at SNS provides examples of real-world accelerator operation that offer an indication of the degree of reliability to be expected in such a system.

As shown in the figure above, there is a high-energy tail resulting from spallation that is not prototypic of a fusion neutron spectrum. This is an issue that will require further consideration, but there are potentially good as well as bad implications. For fusion materials, the high-energy tail offers the potential to achieve a variety of dose and He generation rates in irradiation experiments, which could significantly enhance the understanding of irradiation damage mechanisms and effects in a regime that has received very little attention (due to lack of fusion-relevant neutron sources with high dose rates).