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Fermilab Project-X Nuclear Energy Application: Accelerator, Spallation Target and Transmutation Technology Demonstration

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The recent paper "Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production"[1] and report "Accelerators for America's Future"[2] have endorsed the idea that the next generation particle accelerators would enable technological breakthrough needed for nuclear energy applications, including transmutation of waste. In the Fall of 2009 Fermilab sponsored a workshop on Application of High Intensity Proton Accelerators [3] to explore in detail the use of the Superconducting Radio Frequency (SRF) accelerator technology for Nuclear Energy Applications. High intensity Continuous Wave (CW) beam from the Superconducting Radio Frequency (SRF) Linac (Project-X) at beam energy between 1-2 GeV will provide an unprecedented experimental and demonstration facility in the United States for much needed nuclear energy Research and Development. We propose to carry out an experimental program to demonstrate the reliability of the accelerator technology, Lead-Bismuth spallation target technology and a transmutation experiment of spent nuclear fuel. We also suggest that this facility could be used for other Nuclear Energy applications.

I. INTRODUCTION

Particle accelerators have become an integral part of our lives spanning from health care to national security. Over the last two decades in the United States we have studied the feasibility of an accelerator driven systems (ADS) for nuclear application. In coming decades, United States along with the rest of the world must address the growing environmental and energy issues, with a renewed focus on safer and cleaner energy production and practical methods of handling and reducing nuclear spent fuel from the nuclear reactors. There are several programs being developed in the world to demonstrate and utilize ADS technology for the transmutation of spent nuclear fuel and power generation. ADS has the potential to effectively burn minor actinides from spent nuclear fuels and also utilizing fertile material like thorium that cannot be directly used in conventional reactors. An ADS consists of a heavy metal neutron spallation target coupled with a high-power proton accelerator and a sub-critical core. Only in recent years with the advancement in and cost effectiveness of Superconducting Radio Frequency (SRF) linear accelerator technologies, it appears that the United States could undertake a demonstration study for ADS as a significant part of other national programs, such as Project-X at Fermilab.

Project-X is a high intensity continuous wave proton beam accelerator proposed to be built at Fermilab in the next decade. We propose to develop one beam line at this facility for nuclear energy related R&D. A small scale demonstration project supported by the Project-X linac could also enhance public acceptance of the accelerator-driven systems and nuclear energy.

The issue of high radiotoxicity and lifetime of spent nuclear fuel is a challenge facing the nation today. Either fast reactors or subcritical accelerator-driven systems can be used for the transmutation of the spent nuclear fuel from the US light water reactors. The near-term problem is that the US industry is unlikely to build enough fast reactors for the utilization of the spent fuel. Hence, it is crucial to develop alternate technologies using accelerators. It is proposed that spent nuclear fuel processing followed by accelerator based transmutation could significantly reduce the lifetime and amount of nuclear waste the United States has to put in geological disposal. At the same time this process could also be used to produce clean electricity (nuclear energy). The program would include demonstrations of reliable accelerator technology, operation of spallation target and transmutation of spent nuclear fuel from the nuclear power reactors.

One common need for all the nuclear reactor designs (fission or fusion reactors) is the understanding and development of the materials and structure capable of functioning reliably for a long time in environments with high temperatures, reactive chemicals, high stresses and high radiation. The steady-state operation of fission and fusion reactors can be well simulated by the radiation conditions from a CW proton linac coupled to a spallation neutron target. A high intensity neutron source produced with a high power CW proton beam from Project-X would enable aforementioned materials R&D.

Accelerators can also be used to produce fissile materials from elements such as thorium. Using the thorium fuel cycle instead of uranium to fuel the nuclear reactors reduces the production of actinides and increases significantly the clean nuclear energy contribution. Current advances in accelerator technologies, essentially driven by basic science research, enable us to realize a basic idea [4] that would make nuclear power abundant and cleaner with far less nuclear waste. These reactors would produce much less transuranics and the enhance proliferation resistance of the fuel cycle. Accelerator driven reactors, by design, run in the subcritical mode, hence would be safe to operate. Although this idea could be tested with the Project-X accelerator at present we do not envision a full-blown reactor during the 1st stage of this experimental program.

Our proposal is to create a joint facility with shared infrastructure to address some important engineering demonstrations related to disposal of radioactive waste and nuclear energy, as well as, carry out experiments in the area of nuclear physics that would address the "Physics Beyond the Standard Model".

II. THE NUCLEAR ENERGY FLAGSHIP EXPERIMENT WITH PROJECT-X: TRANSMUTATION OF NUCLEAR WASTE

The half life of the spent nuclear fuel from the current operation light-water-reactors is more than hundreds of thousands of years. The United States has been considering geological repositories to dispose of spent nuclear fuels. Just removing the uranium isotopes for recycling in fission reactors and the transuranic elements from spent nuclear fuels would change this requirement dramatically. Roughly 300,000 years must pass for the spent fuel from a light-water reactor to achieve the toxicity level of the natural uranium. However, transmuting these isotopes, using spallation neutrons produced from a particle accelerator, would reduce this time to less than 500 years.

A continuous wave high-power proton beam from the Project-X SRF linac will be used to generate spallatiion neutrons from interactions with a lead-bismuth target. The spallation target will be surrounded by transuranic material from spent nuclear fuel. The target assembly will be designed to operate as long as possible between replacements for driving the transmutation reaction of the transuranic elements. The energy produced by the transmutation reaction will be measured and removed by the coolant material.

III. ACCELERATOR REQUIREMENTS

The neutron production per proton increases almost linearly with proton energy as shown in Figure 1. However, the neutron yield per unit proton energy saturate at about 1 GeV. Increasing the proton energy much above 1 GeV can complicate the target and the transmuter design.

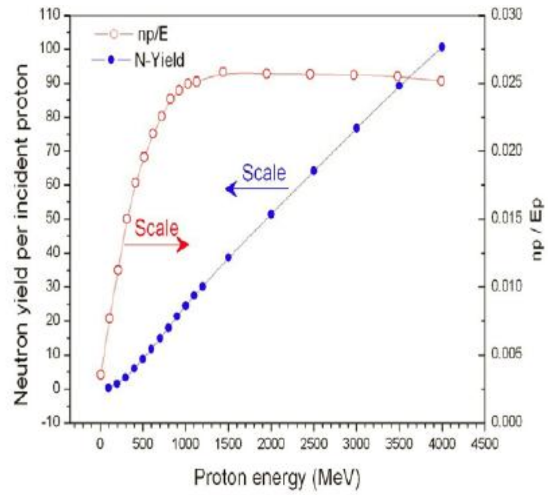

Figure 1. Neutron yield as a function of proton energy for one set of target and moderator condition [5]

An Accelerator Driven Systems (ADS) would require beam energies near 1 GeV to maximize the neutron yield per unit proton beam power. The most suitable proton energy and beam power for this demonstration project should be decided by weighing in different trade-offs including technical issues, cost, and other utilizations of the facility. A transmutation demonstration and research facility would require a beam power of 1-2 MW to deliver a thermal power of 50-100 MW. We propose a joint nuclear physics and nuclear energy experimental beam line with the Project-X accelerator. Figure 2 shows the beam power as a function of the proton energy needed to drive a 0.8 GW transmuter. One MW beam power should be sufficient for this transmutation demonstration experiment.

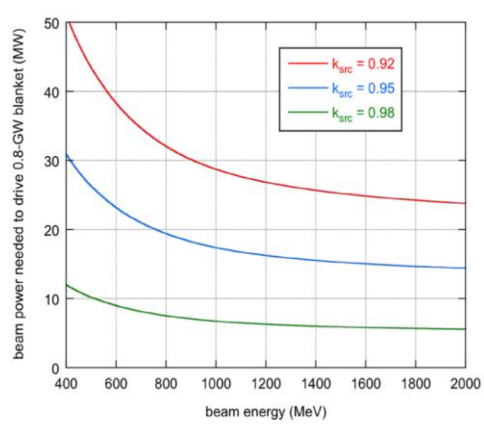

Figure 2: Beam power needed to drive a 0.8 GW ADS sub-critical core as a function of k_{src}, the effective neutron multiplication factor.

The proposed concept is to share this beam with the Nuclear Physics group on the time-scale of months, i.e. alternating a few months of beam for the Nuclear Application demonstrations with a few months of beam for Nuclear Physics research. The accelerator design should provide for a high power (~1 mA) continuous beam with proton energy of 1-2 GeV. This beam energy requirement is essentially driven by the spallation target length, the engineering requirements for a satisfactory target and transmuter operating performance, and the shielding requirement. Average power required for these experiments is about 1 MW.

The current concept for the Joint Nuclear Physics and Energy Experimental Area is that they will share a common facility due to similar beam and material handling requirements. Although the Nuclear Physics program could utilize higher proton energy, the primary beam energy selected for both programs is approximately 1 GeV +/- 200 MeV. Experiments in both areas require 1 MW beam power delivered to one of the experimental halls at a time. This simplifies the sharing of the beam between the experiments since an RF separator for directing beams in the transport line will not be required. It is expected that all switching between experimental areas will be accomplished with simple DC dipole switches.

The current assumption is that the primary beam delivered to this joint facility should be protons. This has been motivated by the limited magnetic field required to extract and transport the H- without Lorentz stripping and potential vertical targeting for the transmutation demonstration experiment. At 1 GeV the magnetic field is limited to approximately 2.5 kG for H- transport to minimize beam loss through Lorentz stripping, which will increase the length of the extraction insert and limit the trajectories of the downstream transport line.

A special insert will be installed at an optimal location in the 1 to 2 GeV section of the 3 GeV CW linac. The insert will select specially prepared bunches from the 325 MHz bunch train to be extracted to the joint Nuclear Facility. The 2.5 MeV chopper and ion- source will prepare the bunch train in a similar fashion to the bunch train for the 3 GeV experiments. The insert will be required to match bunches both longitudinally and transversely for acceleration to the final 3 GeV energy. Although the required bunch frequency is of the order of a few kilohertz due to thermal time constants, it is expected that the delivered bunch frequency will be 20 to 80 MHz bursts with increased bunch intensity.

Extraction of H- from the linac would require a downstream stripping station for conversion to protons. This facility would be required to strip the 1 MW of beam current in the transport line. The option of accelerating protons along with H- has been previously investigated. This method of accelerating, extracting, and transporting protons to the Nuclear Facility has advantages of a shorter extraction insert, a more compact transport line and the option of vertical targeting for the transmutation demonstration experiment, if required.

The schematic layout of the Nuclear Facility is shown in Figure 3. A preliminary dipole may be energized to send the beam to either the Nuclear Transmuter or the Nuclear Physics experimental areas.

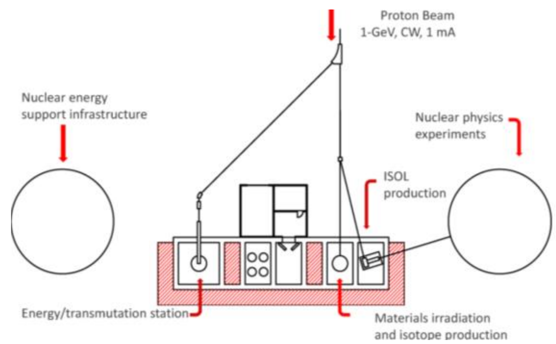

Figure 3. Schematic layout of the Joint Nuclear Facility

A second dipole is utilized to select between ISOL production target or the material irradiation and isotope production target. Included in the layout are dedicated areas for Nuclear Physics experiments and Nuclear Transmuter support infrastructure.

The beam spot size required for this experiment is 5 cm X 5 cm with an additional requirement that such a spot is achieved by beam painting with a beam of about 40 μAmp/cm^2. Stability of beam power is +/- 1% on average.

This demonstration facility would couple the R&D in several areas including the demonstration of the reliability of the SRF accelerator for a possible future utilization of this technology, a spallation target, and transmutation station. The beam trip rate requirements follow from thermo-mechanical consideration of the spallation target, the subcritical assembly, and the requirements set by the electrical grid. We also propose to operate the Project-X linac in a high availability mode to reduce the fatigue in the structural materials of the different components. The beam parameters for this demonstration project are summarized in Table 1.

TABLE 1. The main beam parameters required for the demonstration experiment using the Project-X linac.

Beam Parameter	Parameter Range
Beam Power	1-2 MW
Beam Energy	1-2 GeV
Beam Time Structure	Continuous Wave
Beam trips (1<t<10 Sec)	< 5000 per year
Beam trips (10 sec < t < 5 mins)	< 2500 per year
Beam trips (t > 5 mins)	< 50 per year
Availability	➢ 50%

IV. MEASUREMENT AND DEMONSTRATION (PHYSICS OPPORTUNITIES)

The flagship experiment proposed for the Nuclear Energy application is the transmutation of nuclear fuel coupled with reliable accelerator operation. These studies are focused primarily on a feasibility demonstration for this transmuter. We plan to couple the transmutation demonstration studies with the development and operation of a highly reliable SRF accelerator technology. The ADS accelerator technology development would include 1) beam dynamics modeling and benchmarking of beam loss and halo mechanisms, 2) front-end systems, 3) robust SRF linac technology including RF power generation and delivery and 4) beam instrumentations needed to support this high power and reliable operation.

In this demonstration experiment, the experimental setup will use a simple configuration. We propose to use continuous wave high intensity proton beam from the Project-X linac on a liquid lead-bismuth target, configuration of accelerator and target need studies and optimization for producing spallation neutrons. The target will be surrounded by another enclosure containing transuranic materials with a coolant for removing the generated heat.

We propose to measure the neutron flux, the neutron spectrum, the composition of spent nuclear fuel before and after radiation, and the heat generated due to the beam induced fission.

The study will focus on accelerator, target demonstration for neutron production and transmutation efficiency and related measurements. We do not propose to use the generated heat for the electricity production.

V. SUMMARY

The continuous wave, 1 MW beam power with1-2 GeV, proton energy from the Project-X SRF Linac provides unprecedented opportunities for nuclear R&D in the United States. The storage of spent nuclear fuel for the US reactor poses a significant environmental problem. We propose to carry out a demonstration experiment focused on transmutation of spent nuclear fuels using the Project-X linac. This experiment could address some of the crucial questions related with low loss accelerator design, accelerator reliability, targeting, material and future fission energy.

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