Title: High-Power Proton Accelerators for Transformational Energy Technologies

Lead proponent: Muons, Inc. (http://muonsinc.com/)
Proposed partners: Fermilab, Jefferson Lab, and Oak Ridge/SNS

• ***Abstract*** *(limited to 150 words or less) - The abstract should summarize your concept paper, giving the essence of your transformative concept, how your proposed research plan would develop this concept and what the potential impact of this applied research is likely to be.*

Accelerator-driven subcritical (ADS) nuclear power stations operating at 5 to 10 GW in an inherently safe region below criticality without generation of greenhouse gases, producing minimal nuclear waste and no byproducts that are useful to rogue nations or terrorists, incinerating waste from conventional nuclear reactors, and efficiently using abundant thorium fuel that does not need enrichment, are the ultimate goal. First, the feasibility of the accelerator technology must be demonstrated. Fermilab has already proposed a $1B to $1.5B 8-GeV super-conducting RF (SRF) linear accelerator called Project-X for particle physics at the intensity and energy frontiers. Muons, Inc. proposes to work with Fermilab and SBIR-STTR partners TJNAF and ORNL to extend this linac design to become also a prototype for a practical accelerator for ADS reactors and to provide beams for reactor development.

• ***Technical Section*** *- In this section (suggest 3 - 4 pages), describe the essence of the technical breakthrough, discovery, invention, or concept on which you will base your proposed applied research. Outline the key technical areas which must be explored and how you will approach this research. Identify the current TRL level (Appendix 4) of the technology and the level you propose to reach when the project is completed. This section is intended to give the reviewers the kernel of your proposed R&D; it is not supposed to document all technical assertions. Focus on what is new and innovative about your concept and proposed R&D. Distinguish your proposed work from other R&D in substantively similar areas, especially if DOE is funding efforts that appear to be similar.*

Recent developments in accelerators and emphasis on green energy technologies are generating renewed interest in two closely related ideas: accelerator-driven subcritical (ADS) reactors and accelerator transmutation of nuclear waste (ATW). The Department of Energy has recently announced a shift away from the single-pass approach to nuclear energy that would require vast amounts of nuclear waste to be stored at repositories such as Yucca Mountain for geological periods of time. This leaves only two options to deal with nuclear waste: fast reactors or accelerator driven sub-critical systems. Fast reactors operate at criticality and are inherently less safe than the ADS approach. An ADS reactor would use an accelerator to produce a copious supply of fast neutrons to burn abundant fuels like thorium and ordinary uranium in a power plant. Switching off the accelerator brings the reactor to a halt. Expansion of conventional types of nuclear reactors employing the single pass approach would exhaust conventional sources of U235 in about a century. ADS and fast reactors, on the other hand, convert plentiful actinides such as Thorium 232 and Uranium 238 into fissile materials while at the same time burning existing nuclear waste to produce energy. ADS has been shown to be more efficient at burning nuclear waste than fast reactors.

A commercial GW-scale ADS power plant requires a proton accelerator with a beam power of about 10 MW. Recent accelerator developments promise to make such powerful accelerators feasible. There is a particular opportunity to explore the relevant concepts in concert with another project, thereby achieving considerable synergies and cost savings. Namely, Fermilab is proposing Project X, a $1B to $1.5B facility whose initial configuration document calls for an 8-GeV superconducting RF linac that can be upgraded to a few megawatts of beam power for particle physics at the intensity and energy frontiers. One of the steps in proceeding through the Department of Energy's critical decision process from CD0 to CD1 is to look at alternative designs. In that spirit, Muons, Inc. proposes to use ARPA-E funds to work closely with Fermilab and with its other SBIR-STTR partners Jefferson Lab (NP) and Oak Ridge/SNS (BES) to examine alternative designs for Project X that would be consistent with the needs of ADS and ATW. For example, the use of continuous-wave (CW) RF may enable production of tens of MW of beam power, considerably more than what is required for the future HEP program at Fermilab, at a modest incremental cost relative to the baseline Project-X. The linac could serve as a prototype device that could drive more than one ADS reactor.

<u>The first major milestone of the project proposed here is to produce an enhanced or alternative design for the Project-X CD1 document that includes ADS and ATW development needs.</u>

The planning, component development, construction, and operation of the machine will be the first step toward a practical accelerator for ADS and ATW based on SRF. Once constructed, the proton beam would allow tests and development of reactor components. Combining the goals of the High Energy, Nuclear Physics, and Basic Energy Sciences communities of DOE with those of ARPA-E will lead to many desirable outcomes including lower costs, better technology, faster implementation, and the synergies that come from talented people working together to solve critical national and global problems.

History and Present Status

The origin of the idea that is the basis for the concept we wish to pursue is described in the presentation [1] to Glenn Seaborg and Edwin McMillan of the 1951 Nobel Prize in chemistry: "During his studies on the reaction of slow neutrons with thorium, Seaborg and his colleagues made a discovery which opened important technical prospects. They obtained a uranium isotope U 233, which gives off alpha-rays and has a half-period of 120,000 years. This isotope, like U 235, can be used as an atomic fuel. Thorium, which is more plentiful in nature than uranium, will therefore probably play a role as a basic material in the production of atomic energy."

In 1976, Robert Wilson, then the director of Fermilab and an alumnus along with Seaborg and McMillan of E. O. Lawrence's Berkeley Radiation Laboratory, proposed using the high energy of the machine that became the Tevatron to exploit this concept to produce energy [2].

An important paper in 1993 by F. Carminati, R. Klapisch, J.P. Revol, Ch. Roche, J. A. Rubio, and C. Rubbia [3] discussed details of the design of “Energy Amplifiers” or thorium reactors including the use of either an isochronous cyclotron or a linac to generate the neutron flux. Although the linac parameters they assumed have been considerably exceeded since then, they pointed out that an “accelerator complex could in principle feed more than one Energy Amplifier,” a concept that is used in this proposal.

A subsequent paper by Rubbia et al. [4] carried the studies of the reactors and accelerators even further with a proposed scheme to use three sequential cyclotrons to produce the drive beam.

In these schemes, spallation neutrons are produced by a 10 MW beam of protons on a high Z target. The fast neutrons (1-10 MeV) interact with Thorium 232 (fertile nucleus) to convert it to Protactinium which in turn decays into Uranium 233 (Fissile nucleus). (Similarly for U238, one can make Plutonium 239 which is fissile).

Work in Europe (EUROTRANS), Japan (JAERI/JPARC), Korea (PEFP) and in the US on similar ideas has focused on generating beams of 10 MW with rapid cycling synchrotrons (RCS), cyclotrons, or fixed field alternating gradient (FFAG) synchrotrons with energies near 1 GeV and beam currents around 10 mA. While progress is expected, these challenging parameters have not yet been achieved. A recent discussion of work related to these machines can be found in a lecture at Erice [5].

Figure 1 below, taken from that reference, shows that the neutron production from a proton beam increases roughly linearly with proton energy for energies above 1 GeV. Consequently, it is reasonable to consider beam power as the relevant variable such that a lower beam current accelerated to higher energy can provide the needed beam power.

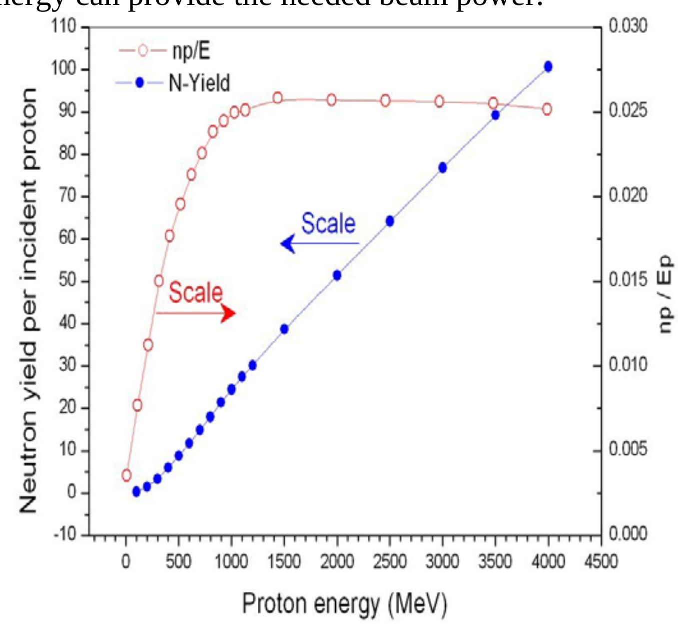

Figure 1: Neutron yield as a function of proton energy for one set of target and moderator conditions.

Higher-Energy SRF Linacs

Since the 1993 study described above, SRF has become much more mature, with many examples of successful projects. The 6 GeV CW Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab has demonstrated reliable SRF operation, while advances in cavity construction and processing have shown higher gradients and quality factors that will lead to lower construction and operating costs for future machines. The 1 GeV SRF linac at the Spallation Neutron Source at ORNL, while operating in 60 Hz pulsed mode, is being used to explore many of the issues relevant to reliable operation and control of losses at high beam power that will be essential for ADS applications. A proton beam power near the MW-level has already been achieved at SNS, thereby demonstrating the feasibility of one of the key technologies required for ADS. Free Electron Lasers and synchrotron light sources that are based on CW SRF are likewise becoming commonplace.

The Initial Configuration Document (ICD) for the Project-X 8-GeV SRF linac, submitted to the DOE as part of the Critical Decision 0 (CD0) process, is based on the parameters of the International Linear Collider (ILC). The ILC is a continuation of the TESLA project that also generated the European XFEL project [6]; all three are based on 1300 MHz SRF operating at a relatively low pulse repetition frequency of 5 to 15 Hz. This low repetition rate precludes achieving high enough beam power at 8 GeV to be useful for many essential ADS studies.

However, we have already proposed an alternative scheme to operate the SRF continuously [7], as is done for CEBAF and many other FEL and light sources, rather than in pulsed mode as is necessary for the ILC. For high-energy physics purposes, the CW beam would be accumulated and bunched in 8-GeV storage rings to then produce beams appropriate to the experimental program, either directly onto production targets or to feed the 150-GeV Main Injector synchrotron. The original motivation for this proposal to operate Project-X as a CW machine was to make sure that there would be sufficient 8-GeV beam to satisfy future needs that might not yet be known. It seems unlikely, for example, that an energy frontier muon collider could achieve optimum luminosity with the beam that a pulsed rather than CW Project-X could provide. Considering that the present Booster synchrotron will have operated more than 40 years by the time it is replaced by Project-X, it seems also likely that there will be intensity needs that are yet to be imagined in the lifetime of Project-X.

Developing beams for ADS reactors may be the first example of an otherwise unanticipated reason to have a generous supply of 8-GeV protons at Fermilab. Potential high energy physics beneficiaries of such a proton source include a muon factory and a neutrino factory [8].

The changes to the initial configuration document that optimize Project-X for CW operation include rethinking the basic parameters such as the operating cavity gradient, the RF power sources, the power couplers, and refrigeration loads. One of the key motivations is to demonstrate advanced-control algorithms that will be required to achieve an acceptable trip-rate.

The special additional requirement for ADS uses, and an important reason to have an ADS prototype, is that the accelerator must be extremely reliable. This requirement is motivated not so much by the desire for steady power output but by the concern that reactor components might be damaged by sudden changes. We will propose to demonstrate this reliability by invoking a combination of component selection and redundancy. For example, instead of fanning out power from one klystron to many RF cavities we can use individual power sources for each cavity [9]. A power source failure in this latter case can be compensated by adjusting the synchronous phase of the other cavities in the linac.

We note that each of our research partners, from three different programmatic branches of the DOE Office of Science, has expertise to carry out the R&D that will be essential to achieving the timely and successful design for a CD1 design that can be considered in the larger picture of DOE and national goals. For example, Jefferson Lab, from Nuclear Physics, has unique knowledge of SCRF technology, CW operation, and CEBAF experience, SNS, from Basic Energy Sciences, has unique knowledge of high-power linac operational reliability, beam loss control, and spallation production of neutrons, and Fermilab, from High Energy Physics, has the wherewithal to put it all together.

Present Technology Readiness Level: From the standpoint of whether a high-current, high-energy CW SRF linac is possible and whether it can be used for an ADS, we believe that calculations have shown that all the pieces can work. This can be characterized by TRL 3.

Expected Technology Readiness Level: After 2 years, we will show that all the pieces will work together to achieve TRL4. If the corresponding CD1 with CW linac is approved, then, with appropriate funding, the linac can be built as a prototype to achieve TRL7. We expect that a prototype reactor can be ready at the same time.

- ***Mission Impact Section*** - *In this section (suggest 3 - 4 pages), address why your proposed project is transformational. Will the outcome of your applied research lead to new energy-related applications? How will it revolutionize one or more energy-related field(s)? What potential impact (both quantitatively and qualitatively) on the ARPA-E Mission Areas and the Administration's Energy and Environment Agenda do you foresee arising from further development of the technology project you propose? Justify briefly how you derived the quantitative impact. If your technology might be interpreted as supporting one of the ARPA-E Mission Areas while being detrimental to another, please explain why this is not so. Briefly describe how the results of your R&D will be made available for further development after the end of your proposed effort.*

We plan to develop technology for a 5 to 10 GW accelerator-driven subcritical (ADS) nuclear power station that operates without generation of greenhouse gases, produces minimal nuclear waste, incinerates nuclear waste from conventional nuclear reactors [10], efficiently uses abundant thorium fuel that does not need to be enriched, is inherently safe since it operates below criticality and can be quickly switched off, and has no byproducts that are useful to rogue nations or terrorists.

We believe this transformational project addresses each of the ARPA-E mission areas:

1) We will reduce GHG emissions by creating power without them. Although the thorium that will be used is not renewable, the high efficiency for ADS and thorium's natural abundance implies that there is enough to supply mankind's needs for several thousand years.

2) Enhance Energy Security: We believe that large power stations will become even more attractive as very efficient high-temperature superconducting power transmission lines are put in place, allowing power plants to be located in remote areas. The abundant availability of safe nuclear power will practically eliminate the need for foreign oil and gas for power generation and, to the extent that electric vehicles are developed, for much of local transportation.

3) Restore Science Leadership: Strengthen America's role as the world leader in science and technology. This high-tech project builds on work that has been done by DOE scientists and engineers, and will in itself be a driver for even more innovation. While achieving the accelerator goals, we will partner with other labs with reactor knowhow (e.g. Argonne, LANL, BARC India, PNL) to obtain a reactor design compatible with ADS.

4) Quickly Implement the Economic Recovery Package: Create millions of new green jobs and lay the foundation for the future. To the extent that the project can be done well and quickly, the construction of the Fermilab prototype linac will soon demand the efforts of our best scientists and engineers.

The significant obstacle to this development is that there is no accelerator in the world with the required beam power. We believe that such a machine is possible based on the use of SRF that has been developed within the DOE community.

Pursuing such a generally useful device may also foster closer cooperation among various entities within the DOE Office of Science. This includes HEP (which would gain by improving capabilities for basic research), BES and NP (both of which could help develop, provide, and use the accelerator technology implicit in the project). This cooperation is essential because the development of these technologies requires expertise and technologies that cut across Office of Science programs.

- ***Cost Summary** - Include a one (1) page summary of direct costs. Identify the general number, types, and percentage of time anticipated to be work for people funded under the project. Identify any major equipment purchases. If multiple team members are proposed, include a top-level break-down of costs by team member. Note that the cost summary is not binding. It is merely included to give reviewers a sense of how the applicant proposes to spend funds to accomplish its tasks.*

We have discussed the participation of our proposed National Laboratory collaborators with the leadership of those laboratories. The following leaders have agreed to help develop the proposal should we be invited to submit one:
Dr. Stephen Holmes, Associate Director of Fermilab
Dr. Stuart Henderson, Head of the SNS Accelerator Division at Oak Ridge
Dr. Robert Rimmer, Head of the Jefferson Lab SRF Institute.

A level of effort corresponding to the $5M request and other guidelines from the FOA is:

Effort/Costs:	Muons, Inc. + non-FFRDC subcontracts,	12 FTE-years	$2.50 M
	Fermilab	4 FTE-years	$1.00 M
	JLab	3 FTE-years	$0.75 M
	ORNL (SNS)	3 FTE-years	$0.75 M
Total (to be completed in 24 months)		22 FTE-years	$5.00 M

This study would directly further the goals of DOE and, in particular, ARPA-E; those goals motivate Muons, Inc. to propose this activity. Since no financial advantage would accrue to Muons, Inc., the company cannot responsibly justify a cost-sharing contribution; hence the company may request a waiver of that requirement. However, it would be beneficial to Illinois, and we will solicit cost-sharing support from the state's Department of Commerce and Economic Opportunity (which has previously supported the company's activities).

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