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Project X, SRF, and Very Large Power Stations

• *Abstract*

We seek to develop accelerator-driven subcritical (ADS) nuclear power stations operating at more than 5 to 10 GW in an inherently safe region below criticality, generating no 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. First, the feasibility of the accelerator technology must be demonstrated. Fermilab is developing concepts for Project X, which would use a superconducting RF (SRF) linear proton accelerator to provide beams for particle physics at the intensity and energy frontiers. Muons, Inc. proposes to work with its SBIR-STTR partners Fermilab, JLab, and SNS to extend this linac design to also serve as a prototype for a practical accelerator to drive several ADS reactors at once and to provide beams for reactor development.

Overview

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 unenriched 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 even more 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 developing concepts for Project X, which would use a superconducting RF (SRF) linear accelerator that could deliver megawatts of beam power to provide beams for particle

physics at the intensity and energy frontiers. One concept calls for an 8-GeV pulsed SRF linac; another calls for a CW linac with a lower initial energy of about 2 GeV. 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 work closely with its SBIR-STTR partners Fermi National Accelerator Laboratory or Fermilab (High Energy Physics), Thomas Jefferson National Accelerator Facility or JLab (Nuclear Physics), and the Oak Ridge National Laboratory Spallation Neutron Source or SNS (Basic Energy Sciences) 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 intermediate-term HEP program at Fermilab, at a modest incremental cost relative to the baseline Project-X. The linac could serve as a prototype of a device that could drive several ADS reactors at one location, an approach which will become increasingly attractive with the development of the national power grid using low-loss transmission lines based on new superconductors.

The first major milestone of the project discussed here is to produce an enhanced or alternative design for Project X that includes ADS and ATW development needs.

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](#) 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](#). An important paper in 1993 by F. Carminati, R. Klapisch, J.P. Revol, Ch. Roche, J. A. Rubio, and C. Rubbia 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. 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 U 238, 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, where it is shown that 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. Or, as we propose here, a large current at higher energy can supply several ADS reactors in parallel.

Essential advantages of using a higher-power higher-energy machine to simultaneously drive several ADS/ATW reactors compared to one accelerator for each reactor include better efficiency and lower cost. By creating most of the beam power with higher-gradient, more-efficient SRF cavities operating where the proton velocity is close to the speed of light ($\beta=1$), capital and operating costs are reduced.

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 JLab 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 Project X SRF linac 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](#); 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 makes it difficult to achieve 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, 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 beam power to satisfy future needs that might not yet be known. 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 several-GeV protons at Fermilab. Potential high energy physics [beneficiaries](#) of such a proton source include a muon factory and a neutrino factory.

The changes 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 in power level. 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. A power source failure in this latter case can be compensated by adjusting the synchronous phase of the other cavities in the linac.

Each of the research partners of Muons, Inc., 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 that can be considered in the larger picture of DOE and national goals. For example, JLab, from NP, has considerable knowledge of SRF technology, CW operation, and its unique CEBAF experience; SNS, from BES, has unique knowledge of high-power linac operational reliability, beam loss control, and spallation production of neutrons; and Fermilab, from HEP, has the wherewithal to put it all together.

Muons, Inc., is a relatively young company that has worked within the framework of the DOE SBIR-STTR program to help that agency to achieve its programmatic goals. With an experienced staff of 17 Ph.D. accelerator scientists and a track record of innovation and successful collaboration with national laboratories and universities, Muons, Inc. is very well positioned to coordinate the project that is discussed here. We note that many accelerator experts from laboratories and universities have asked to participate in this project; their desire to contribute to solving the most pressing and important technological problems facing humanity is large and their expertise is a compelling resource.