A CW SRF LINAC TO DRIVE SUBCRITICAL NUCLEAR REACTORS*

Milorad Popovic#, Fermilab, Batavia, IL U.S.A.
Rolland Johnson,Charles Ankenbrandt, Muons, Inc. Batavia, IL U.S.A.

Abstract

Fermilab is developing concepts for Project X [1], which would use a CW superconducting RF (SRF) linear proton accelerator to provide beams for particle physics at the intensity and energy frontiers. We propose to extend this linac design to also serve as a prototype for a practical accelerator to drive several Accelerator-Driven Subcritical Reactors (ADSR) at once. Here we propose to use a multi-GeV linac instead of one having only one GeV, the minimum for efficient neutron production. This will allow most of the power needed for the ADSR applications to be generated by the intrinsically redundant and efficient beta=1 part of the Linac, leading to lower costs and higher reliability. Multiple proton beams will be independently controlled and delivered to their own reactors. The reactor designs should be minimally impacted by the higher energy of this proposed approach since the size of the neutron showers only increases slowly with incident beam energy. To facilitate the R&D necessary for this higher energy driver approach, a new company has been formed to raise private capital.

OVERVIEW

The goals of this project are accelerator-driven subcritical nuclear power stations that

- provide 5 to 10 GW to the power grid,
- in an inherently safe region below criticality,
- without generation of greenhouse gases,
- producing minimal nuclear waste,
- no byproducts useful to rogue nations or terrorists,
- incinerating conventional reactor waste (ATW), and
- efficiently using abundant thorium fuel,
- which does not need enrichment.

A commercial GW-scale ADSR power plant requires a proton accelerator with a beam power of at least 10 MW. Recent accelerator developments promise to make even more powerful accelerators feasible. There is a new 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.

In that spirit, Muons, Inc., Fermi National Accelerator Laboratory (Fermilab, High Energy Physics), Thomas Jefferson National Accelerator Facility (JLab, Nuclear Physics), and the Oak Ridge National Laboratory Spallation Neutron Source (SNS Basic Energy Sciences) have proposed to examine alternative designs for Project X, consistent with the needs of ADSR and ATW.

*Work supported in part by Accelerator Technologies Incorporated.
#popovic@fnal.gov

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 in parallel 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 ADSR and ATW development needs. The planning, component development, construction, and operation of the machine will be the first step toward a practical accelerator for ADSR 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 national energy and environment goals 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.

Figure 1 shows the beam power of present and planned accelerators compared to the potential of a CW Project-X.

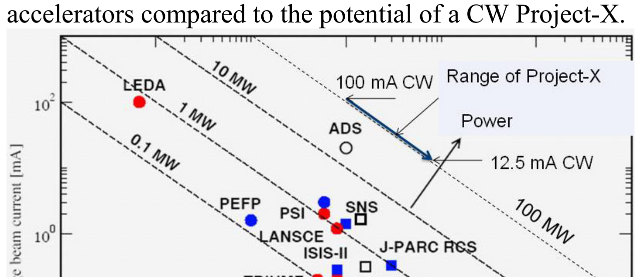

Figure 1: Present and planned high-intensity proton accelerators [2]. The present power record is held by the ORNL SNS. A range of parameters that could be explored by Project-X is indicated on the 100 MW line.

In ADSR 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). Additional neutrons induce fission to produce power.

As discussed below, neutron production increases almost linearly with proton energy above ~1 GeV so that beam power is the relevant parameter 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 drive several ADS/ATW reactors simultaneously compared to one accelerator for each reactor include better efficiency, higher reliability, 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. The velocity of the protons (or H^- ions in the case of Project-X) travelling through the cavities in the low energy part of the linac is much different than the velocity of the RF electromagnetic accelerating voltage waves of the cavities. This decoupling means that intrinsic efficiency of an RF cavity is a strong function of the beta of the proton traveling through it. Figure 2 shows the optimized energy gain for the RF cavities for one proposed version of the Fermilab Project-X CW SRF Linac [3].

Thus the lower energy parts of the linac require more components such as RF cavities, power supplies, and RF couplers in order to produce a given amount of beam power. This larger component count of the early linac stages also implies that they will be less robust for a given output power than the beta=1 stages. The beta=1 cavities are all similar to each other such that if one cavity fails, others can be rephased to compensate for the lost accelerating gradient. The early stages are more difficult to rephase in the case of a cavity failure.

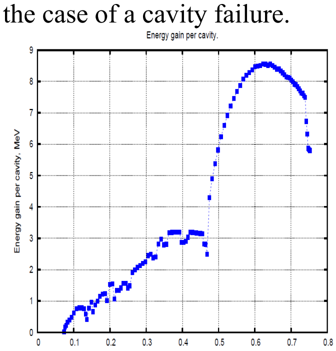

Figure 2: Energy gain for the initial cavities of the proposed Fermilab SRF Project-X CW Linac. The beta=1 part of the linac would have ~17 MeV/m.

For optimum availability and reliability, several parallel, redundant beta<1 sections can feed the beta=1 linac as shown in figure 3.

One of the most attractive concepts for an ADS Reactor is that of the Energy Amplifier (EA) [4] from Rubbia et al. which would use thorium as its fuel. Concepts for ADS Reactors have used the fact that the spallation neutron flux becomes optimal for proton energies above 900 MeV, as shown on figure 5 by Rubbia et al. both by simulations and measurements.

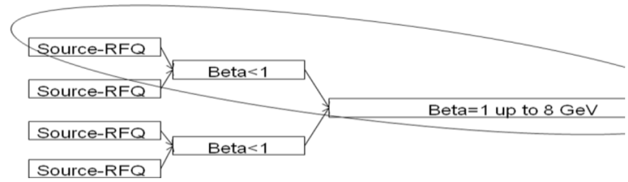

Figure 3: Schematic of an accelerator with sufficient redundancy to serve as a practical driver for ADSR. The ellipse encloses basic Project-X components.

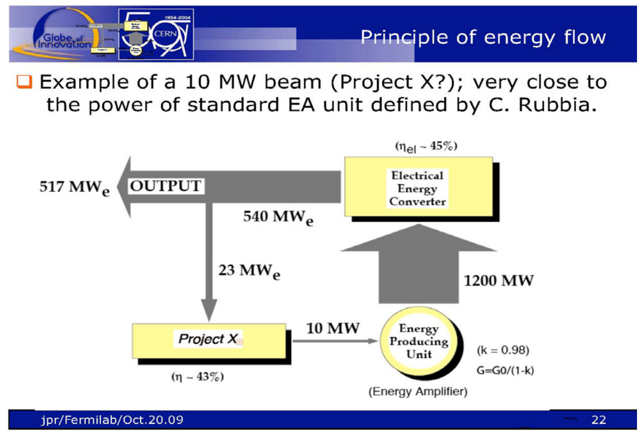

Figure 4: Overview of the Energy Amplifier concept.

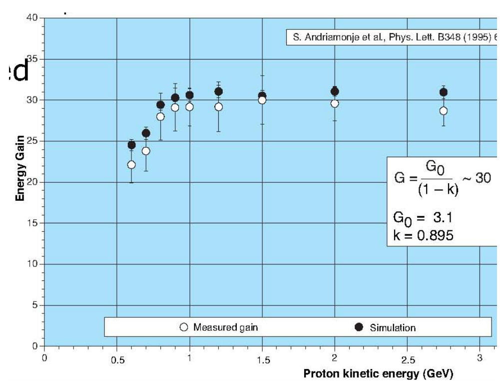

Figure 5: Calculations and measurements showing that spallation neutron production is proportional to incident proton energy for E>900 MeV.

Combining these concepts we propose to have an SRF linac where most of its power is generated from the efficient, reliable beta=1 that could drive many reactors, as shown schematically in figure 6.

Transversely-kicking SRF can be used to combine the pulses from the parallel beta<1 sections to feed the beta=1 high energy linac and also to split the beams to feed the separate reactors. A control system can be constructed to allow each reactor to have proton drive power independent of the other reactors and to quickly reconfigure the beam distribution parameters in the case of component failure fast enough that power station output is uninterrupted. The CEBAF racetrack RLA at JLab delivers beam to experimental halls using transversely-kicking SRF cavities to distribute the electron beam as we propose to do for a proton driver for several ADS Reactors.

Many people believe that the ideal proton energy is near 1 GeV since the spallation generation of neutrons is good and it seems to require the least of the proton driver. In the case of SRF, for reasons above, higher energy can be more efficient and more reliable. Also it might be thought that the dimensions of the reactors will have to be enlarged to contain the beam interaction products of incident protons with much higher energy. As is well known from high-energy physics particle beam calorimetry, the dimensions of a hadronic shower only weakly depend on the energy of the incident particle. Figure 7 is such an example, showing longitudinal shower profiles from 1 to 100 GeV protons.

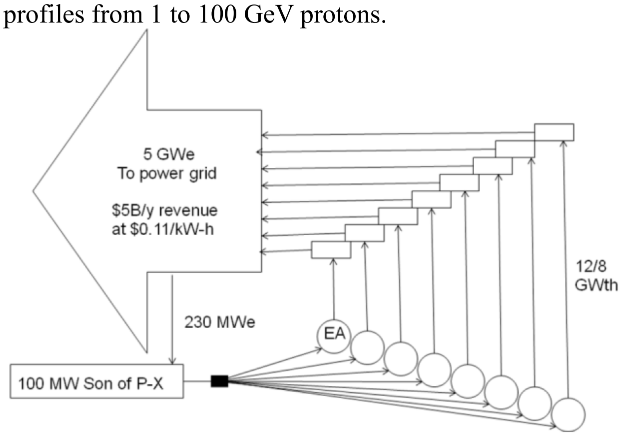

Figure 6: Schematic of a large power station that is driven by an SRF proton linac that could be developed using the proposed Fermilab Project-X. The 100 MW beam is distributed to 8 thorium-burning Energy Amplifiers (EA) as in Figure 4 above. Each EA feeds a steam turbine to provide power to the national grid.

HIGHER-ENERGY SRF LINACS

Since the 1993 study by Carminati et al., 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 ADSR 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 ADSR. Free Electron Lasers and synchrotron light sources that are based on CW SRF are likewise becoming commonplace.

The special additional requirement for ADSR uses, and an important reason to have an ADSR 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, where Figure 3 indicates how Project-X can be used for this development. 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.

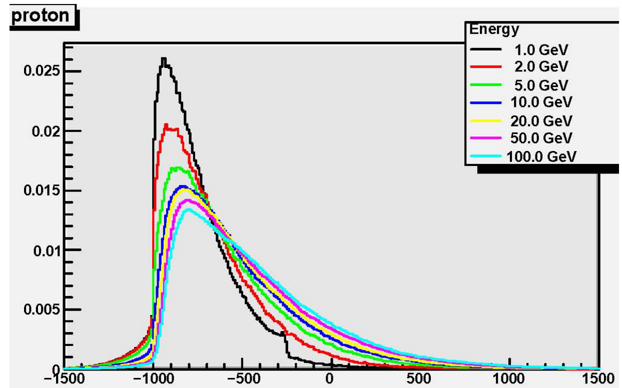

Figure 7: Hadronic shower energy deposition as a function of longitudinal position (in mm) and incident proton energy, from a calorimetry study by A. Para [5].

USE OF PRIVATE CAPITAL

In order to finance studies of the ADSR concepts described above, a company [6] has been formed to raise money from the private sector. Many government activities are partnerships with private industry. For example recent ARPA-E funding opportunity announcements have required at least 20% cost sharing from the proposing company.

We are advocating a one to two billion dollar class accelerator, which can be justified by the extremely large power it can generate. The benefits of this approach include considerable synergies with the interests of the world's particle accelerator community. Not the least of which is a great desire to contribute to solving the energy, environmental, and security challenges or our time.

REFERENCES

[1] http://projectx.fnal.gov/index.shtml
[2] Original data compiled by J. Wei and S. Henderson.
[3] N. Solyak, V. Yakovlev, unpublished.
[4] F. Carminati, R. Klapisch, J.P. Revol, Ch. Roche, J.A. Rubio, and C. Rubbia, CERN-AT-93-47.
[5] Adam Para, private communication.
[6] Accelerator Technologies Inc. http://acceltech.us