HIGH POWER SRF LINACS FOR ADS REACTORS*

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Abstract

We discuss plans to develop Accelerator-Driven Subcritical Reactor (ADSR) nuclear power stations producing more than 5 to 10 GWe 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. Fermilab is developing concepts for Project X [1], which would use a 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 serve as a prototype for a practical accelerator that can drive several nuclear reactors at once and also provide beams for reactor development. We also propose that a Recirculating Linear Accelerator be developed for ADSR applications by extrapolating from techniques developed for the CEBAF machine.

OVERVIEW

A commercial GW-scale ADS 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. One concept calls for an 8-GeV pulsed SRF linac; another concept is for a CW linac with a lower initial energy of about 3 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., 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 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 the 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.

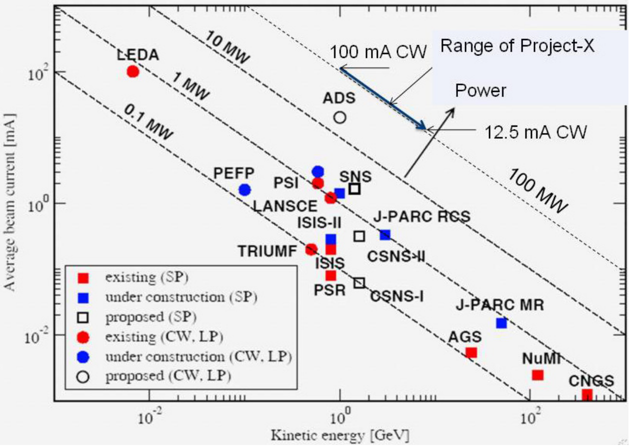

Figure 1: Present and planned high-intensity proton accelerators [2].The present power record is held by the ORNL SNS. A range of parameters that could be explored by Project-X is indicated on the 100 MW line.

In ADS 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 such that beam power is the relevant parameter; 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

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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 rephrased to compensate for the lost accelerating gradient. The early stages are more difficult to rephase in the case of a cavity failure.

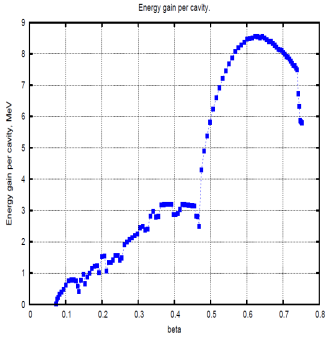


Figure 2: Energy gain for the initial cavities of the proposed Fermilab SRF Project-X CW Linac. The beta=1 part of the linac would have ~17 MeV/m.

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

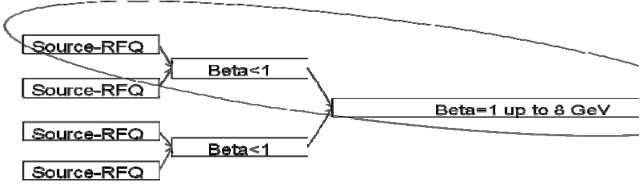
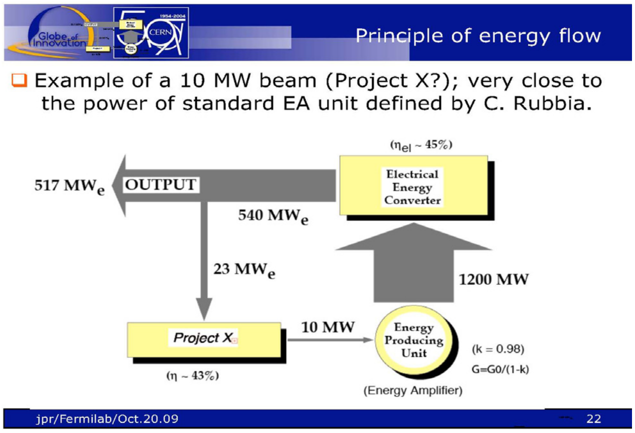


Figure 3: Schematic of an accelerator with sufficient redundancy to serve as a practical driver for ADSR. The ellipse encloses basic Project-X components.

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.


Principle of energy flow

❑ Example of a 10 MW beam (Project X?); very close to the power of standard EA unit defined by C. Rubbia.

Figure 4: Overview of the Energy Amplifier concept.

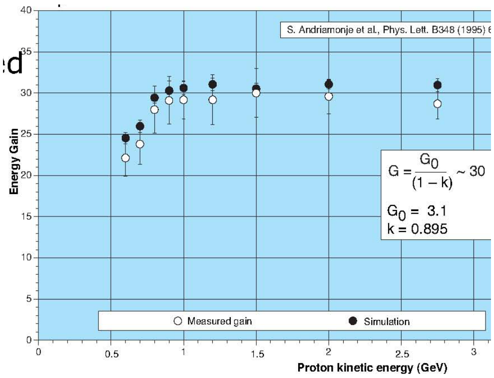


Figure 5: Calculations and measurements showing that spallation neutron production is proportional to incident proton energy for E>900 MeV.

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.

Many people believe that the ideal proton energy is near 1 GeV since the spallation generation of neutrons 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.

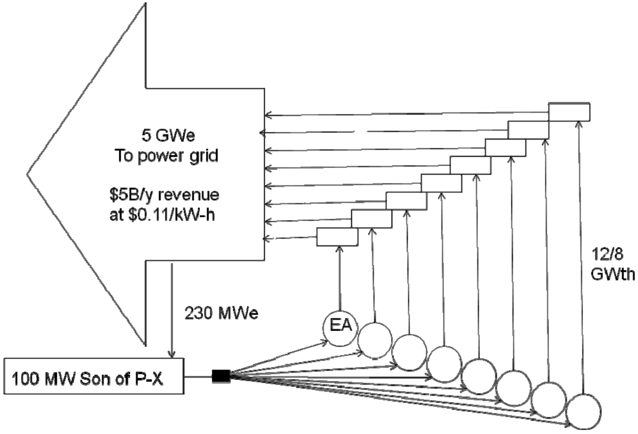


Figure 6: Schematic of a large power station that is driven by an SRF proton linac that could be developed using the proposed Fermilab Project-X. The 100 MW beam is distributed to 8 thorium-burning Energy Amplifiers (EA) as in figure 4 above. Each EA feeds a steam turbine to provide power to the national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

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, 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 8 is a picture of the CEBAF racetrack RLA at JLab showing the general size and shape of what will be a 12 GeV CW SRF RLA. Also seen are the three (green circular) experimental halls at the bottom of the picture that are fed by transversely-kicking SRF cavities that distribute the electron beam as we propose to do for a proton driver for several ADS Reactors. Similar cavities can also be used to merge beams from several parallel beta<1 sections before they are injected into the RLA.

For ADSR, a 12 GeV RLA proton driver could be physically smaller using today's higher gradient RF cavities as well as stronger bending arc magnets, now limited at CEBAF by synchrotron radiation. The difference in transit time for the lowest energy and the highest energy passes through one linac section (and corresponding phase shift) determines the minimum beta of the protons that can be injected into the RLA. Ways to lower the minimum RLA injection beta are being studied.

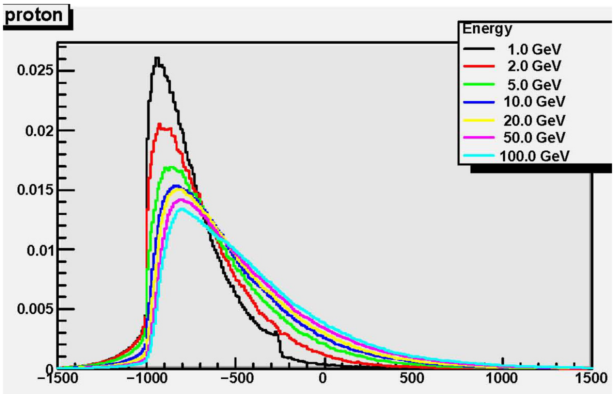


Figure 7: Hadronic shower energy deposition as a function of longitudinal position (in mm) and incident proton energy, from a calorimetry study by A. Para [5].

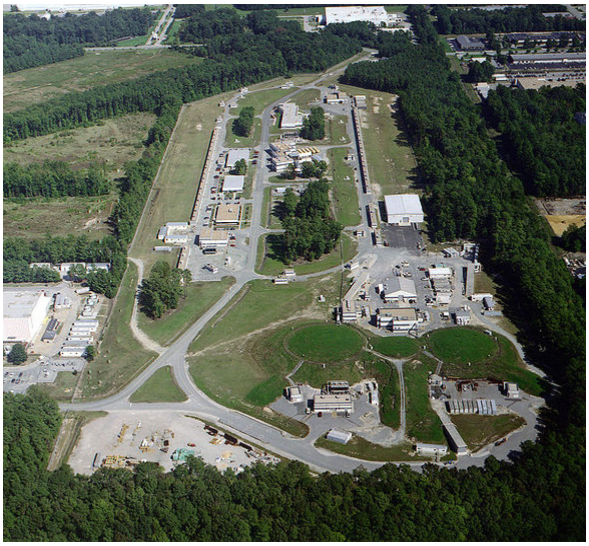


Figure 8: CEBAF Aerial View.

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[2] Supplied by J. Wei and S. Henderson.
[3] N. Solyak, V. Yakovlev, unpublished.
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[5] Adam Para, private communication.