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Authors: J. Delayen*, Y. Gohar#, R. Raja+, and Alex Stanculescu§

*Old Dominion University, Norfolk, and TJNAF, Newport News, Virginia
#Argonne National Laboratory, IL
+Fermi National Accelerator Laboratory, IL
§IAEA, P.O.Box 100, 1400 Vienna, Austria

Working Group: Energy & Environment

SRF Linacs and Accelerator Driven Sub-Critical Systems[1]

Summary Working Groups 3 & 4 of the Fermilab Workshop AHIPA09

Abstract

We describe here the findings of two working groups on SRF linacs and Accelerator driven subcritical systems (ADS) that met at Fermilab during October 19-21, 2009 at the workshop on Applications of High Intensity Accelerators, AHIPA09.

INTRODUCTION

Most of the energy consumed today comes from oil (37%), coal (25%) and natural gas (23%), with nuclear energy making up only 6% of the total. Thus 85% of the energy production is from non-renewable sources that are a leading cause of global warming. Currently the world emits 7 billion tons of carbon into the atmosphere every year. This figure is expected to double by the year 2055 if nothing is done to change the mix of energy production. If we increase nuclear energy production to offset just one seventh of the rate of increase in carbon emission, using solar, wind, geothermal and other technologies to offset the remainder, we will have to double the number of nuclear reactors by the year 2055.

Conventional nuclear reactors use less than 0.7% of the mined Uranium. After a single pass through a nuclear reactor, the U.S stores away the waste. This waste has to be stored for geological periods of time (>100,000 years) to decay away the residual radio-activity in the long-

[1] Further details of the AHIPA09 workshop may be found at at http://conferences.fnal.gov/App-Proton-Accelerator/index.html

lived actinide waste. The residual fission energy in the nuclear waste remains largely untapped, some of it is wasted as the decay processes heat up the storage facility over geological periods of time. There are two known ways to solve the waste problem and to utilize more sources of fuel such as Thorium 232 and Uranium 238. Both involve bombarding the fuel mix with fast neutrons. The first method uses fast critical reactors that produce fast neutrons using an un-moderated core of plutonium. The second uses a proton accelerator that directs a beam of protons (10mA current, 1GeV proton energy, 10MegaWatts of power) at a spallation target made of high atomic weight (e.g lead, lead/bismuth eutectic, tungsten, Uranium). The neutrons thus produced are directed at the fuel (or fuel/waste mix), that is operated well away from criticality (typical criticality factors k range from 0.95-0.98). This second method is collectively called Accelerator Driven Sub-Critical Systems (ADS). One of the main reasons such systems have not been built since the method was proposed by Rubbia et al in the early 1990's is that the accelerator of requisite power was deemed too expensive to build. The advent of super-conducting radio frequency (SRF) cavities has made building such accelerators easier and more cost effective and the use of SRF for ADS systems will be the subject of this paper.

ADS Efforts Worldwide

The workshop heard reports on the status of ADS research in Europe (EUROTRANS /MYRRHA), Japan (JAEA/JAERI), China (CSNS) and India (BARC, RRCAT). The MYRRHA effort in Belgium plans to have an experimental demonstration of an ADS system (SRF Linac and reactor) by 2020. The Japanese design efforts are well advanced and the Chinese spallation neutron source (CSNS, 2016 completion) plans to upgrade its accelerator to facilitate an ADS effort. In India, there is vigorous research into advanced reactors, with fast breeder reactors being in phase 2 and ADS is expected to be part of phase 3.

In the U.S, the ADS effort suffered from a 1996 National Research Council study, which was predicated on assumptions that no longer hold. The study considered costs associated with building a 250mA, 1.6 GeV 1MV/m room temperature accelerator that was shown to be too expensive. The advent of SRF has made the conclusions of this study subject to re-examination. In 2004, DOE-NE dropped ADS research in favor of solely utilizing fast reactors. It can be shown that ADS is capable of deep burning of minor actinide waste, since it is less dependent on the abundance of delayed neutrons for its safe operation. ADS is also effective in utilizing Thorium to breed U-233 fuel. Given these considerations and the intense activity abroad into ADS research, it is perhaps appropriate to restart ADS research in the U.S.

Feasibility of building a 10MW proton SRF Linac in the 1- 2GeV energy range

The overall conclusion of WG3 was that there are no show-stoppers in building such a machine. Most of the hardware required to make a CW linac of the requisite power exists already. Vintage designs (LANL, 1999) were shown for building a 1.5 GeV SRF CW linac of adequate power. A

general comment was that the optimized RF frequency should be significantly lower than 1GigaHz below 2 GeV proton energies. Designs were shown that used 350MHZ rf below 130MeV and 700MHz rf below 1.5 GeV. This was mainly motivated by the desire for larger apertures to reduce beam losses. The main challenges in a final design may well be the fraction of halo in the high-power proton beam and the associated beam losses and trips. These issues can be studied and controlled at a low energy front-end to the linac that delivers CW high current (30mA) and few tens of MeV energy. The critical accelerator physics related to beam quality is below 50 MeV. The Fermilab project HINS can play an important role here.

A critical need in studying the halo problem is the development of better diagnostics to measure the halo. Better simulation tools to predict and study the halo problem are also called for, where we include all the associated accelerator errors (both static and dynamic).

Reactor Beam requirements

ADS neutron multiplication varies as $1/(1-k_{eff})$, where k_{eff} is the effective criticality factor. Figure 1 shows the beam power in MW needed to power a reactor of 3GW (thermal) energy output as a function of beam proton energy (LANL study). It can be seen that all the curves flatten out above 1 GeV proton energy. However, the reactor designers prefer beam energies in the 1-2 GeV range and not higher in order to keep the length of the target as small as possible., to reduce the structural material damage from high energy neutrons and to reduce the required shielding volume.

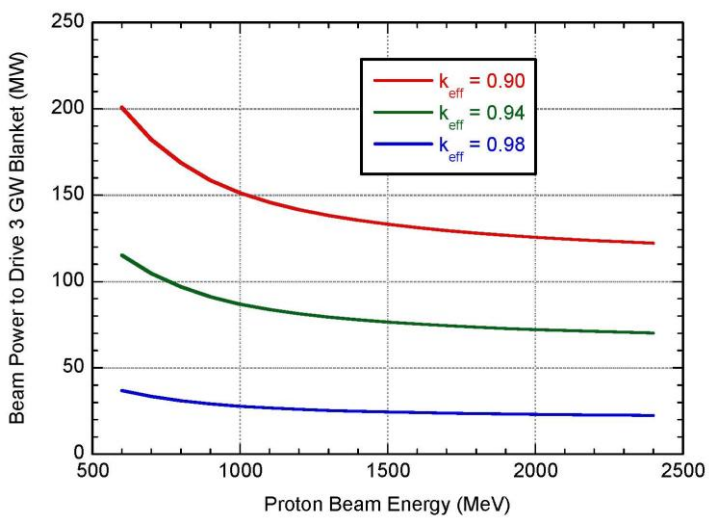

Figure 1 Shows the dependence of the beam power in MW needed to produce 3 GW_{th} ADS reactor as a function of proton energy and the effective criticality factor k_{eff}.

The beam power needed for other thermal outputs can be obtained by scaling the above curves for the appropriate k_{eff} factor.

Tolerable beam trip rates

A Japanese study (JAEA) showed that the target window can tolerate 10^5 beam trips of <1 sec per 2 years. The reactor vessel can tolerate 10^4 trips per 40 years of duration 1sec to 5 minutes. The system availability requirements will not permit downtimes of > 5 mins once per week. A European study has even more stringent requirements on beam trips (>1sec to a few mins) of less than 3 per year. These requirements are motivated to try and minimize the thermal stresses on the fuel rods as well as the stability of power output from the reactor. The thermal stress requirement may be relaxed in future with progress in fuel structure and the stability requirement may be ameliorated by the development of energy storage devices such as superconducting coils or pumping water uphill.

Potential of Project-X to contribute to ADS research

The design of Project-X has evolved to an extent that ICD-2 design provides for a CW SRF linac to 2 GeV. This linac can be designed in such a way as to permit intensity upgrade to 10MW (5mA current at 2 GeV), should the U.S decide that ADS research is a national priority. The 10MW beam can be dumped on to a target station that can be used for muon collider/neutrino factory pion production. This technology can then be transferred to a partner laboratory that has nuclear reactor expertise (Argonne, ORNL , BARC) and a full demonstration system can be put together. No attempt should be made to require super-stable beams at Fermilab short of trying to limit halos. This work can be done for the final demonstration machine. Table 1 shows the power requirements of various possible uses of Project-X beams. The total requested equivalent power budget at 2 GeV excluding ADS is (as of AHIPA09) is 10.417MW. So having an ADS class machine will help power the rest of the physics. Project-X can come online at 2MW with an upgrade path to 10MW.

Project-X user	Power need	Equivalent Power at 2 GeV
Muon Collider/Neutrino factory	4 MW each @ 8 GeV	2 MW
ADS	--	10MW
Main Injector Neutrinos	2 MW @ 60GeV	0.067MW
Low Energy Neutrinos	1 MW @ 8GeV	0.25MW
Rare Kaon Decays K^+ ,K^0_L decays		2+2 = 4MW
Rare Muon decays mu2E,g-2, muon EDM		0.2+0.4+2= 2.6MW
Material Science and Nuclear science		1.5 MW

Table 1 Shows the power budget of Project-X for various activities discussed at AHIPA09. Rare Kaon decays (K^+ and K^0_L) each demand 2 MW at 2 GeV, yielding a demand for 4 MW. Similarly for rare muon physics.