TECHNOLOGY READINESS LEVELS APPLIED TO CURRENT SRF ACCELERATOR TECHNOLOGY FOR ADS

R. Edinger, PAVAC, Richmond, Canada
R. E. Laxdal, TRIUMF, Vancouver, Canada
L. Yang, TRIUMF/PAVAC, Vancouver, Canada

Abstract

Accelerator Driven Systems (ADS) are comprised of high power accelerators supplying a proton beam to a reactor vessel. The reactor vessel could contain nuclear fuels such as used Uranium or Thorium [1]. The proton beam will be used to produce Neutrons by spallation in the reactor vessel. Technology readiness levels (TRL's) can be used to chart technology status with respect to end goal and as such can be used to outline a road map to complete an ADS system. TRL1 defines basic principles observed and reported, whereas TRL9 is defined as system ready for full scale deployment. SRF technology when applied to ADS reflects a mix of TRL levels since worldwide many SRF Accelerators are in operation [2]. The paper will identify the building blocks of an ADS accelerator and analyze each for technical readiness for industrial scale deployment. The integrated ADS structure is far more complex than the individual systems, but the use of proven sub-systems allows the construction of SRF accelerators that can deliver the beam required. An analysis of the technical readiness of SRF technology for ADS will be presented.

INTRODUCTION

PAVAC and TRIUMF [2] developed an initial plan for a ADS facility named TP-ADS Demonstrator staged in 2 phases with a final goal of a <10mA proton beam with an energy of ~100MeV resulting in up to 1 MW of beam power on a Thorium / target facility. The facility includes a proton source with a normal temperature RFQ. This front end (linac injector) is composed of an ion source and a radiofrequency quadrupole (RFQ) accelerator. The ion source has to deliver high brightness beams (intensity, emittance, stability).

Direct current proton sources using 2.45GHz ECR plasma heating, delivering stable beams with high availability and small emittances are now available as injectors for accelerators. The RFQ, which includes RF electric transverse focusing, bunches and accelerates the beam from about 100 keV to a few (3) MeV. These structures are well suited to keep the beam quality (longitudinal and transverse) at high intensity. Four vane RFQs at 162/325MHz are now in production and testing for high intensity application and therefore for the purpose of this review are not included.

Downstream of the RFQ are six super conducting (SRF) cryomodules, which accelerate the proton beam efficiently to higher energies. Downstream of the last cryomodule is a target facility used as a test bed for future ADS target/reactor systems.

Our focus is on the super conducting accelerator, Proton source and target technology required for a Thorium and related processes will be described later. We will be using technology readiness levels to describe the maturity of the technology similar as being used by NEA [3] for nuclear fuels.

SRF ACCELERATOR CONFIGURATION

The SRF section consists of 6 cryomodules similar in design as shown in Figure 1, named CM0 to CM5. CM0 is considered the injector module capturing the protons coming from the RFQ section and is the only SRF module in Phase 1 of the plan. After CM0 the proton beam can be tested up to <10mA and with an energy of 10MeV. CM1 to CM 5 are accelerating stages with a mix of SRF cavity types, design specs and frequencies for all cryomodules are as shown in Table 1 and a concept shown in Figure 2.

Table 1: TP-ADS Demonstrator Technical Draft Specification

	PHASE 1			GOAL	PHASE 2					GOAL
	PROTON SOURCE	RFQ	CM0		CM1	CM2	CM3	CM4	CM5	
CURRENT	10mA	9.5mA	9.5mA	DEMO OF HIGH BEAM CURRENT ON TARGET	9.5mA	9.5mA	9.5mA	9.5mA	9.5mA	DEMO OF HIGH BEAM CURRENT
NUMBER OF CAVITIES			6		7	7	7	8	8	43
CAVITY TECHNOLOGY		NORMAL CONDUCTING	SRF		SRF	SRF	SRF	SRF	SRF	
TYPE OF CAVITY			HWR		HWR	HWR	HWR	HWR OR SPOKE	HWR OR SPOKE	
ENERGY PER CAVITY (MeV)			1.4		1.4	3.3	3.3	3.7	3.7	
BETA			0.11		0.11	0.24	0.24	0.4	0.4	
RF Power Coupler/kW			14		14	33	33	37	37	
RF (MHz)			162.5		162.5	162.5	162.5	325	325	
Period length/mm			570		570	950	950	1700	1700	
CM length/m			3.42		3.99	6.65	6.65	6.8	6.8	
TOTAL ENERGY (MeV)	0.03	3	9.5		17	35.2	54	76.6	100.7	1 MEGAWATT ON Th TRAGET

TECHNOLOGY READINESS LEVEL

In order to estimate the SRF maturity the technology readiness level process (TRL) can help to identify risks and take corrective action early. TRL's will be used from 1 to 9 as outlined in Table 2 in order to define the readiness level.

Table 2: TRL's as per U.S DoE Definitions Applied to this Study

TRL-Level	Description as per DoE
1	Scientific research begins translation to applied R&D - Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Invention begins - Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Active R&D is initiated - Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Basic technological components are integrated - Basic technological components are integrated to establish that the pieces will work together.
5	Fidelity of breadboard technology improves significantly - The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6	Model/prototype is tested in relevant environment - Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7	Prototype near or at planned operational system - Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment.
8	Technology is proven to work - Actual technology completed and qualified through test and demonstration.
9	Actual application of technology is in its final form - Technology proven through successful operations.

The TRL's are further sub-divided in scales starting from a bench-scale (<1 kW beam), a laboratory-scale (<1 MW beam), an engineering scale (1-10 MW beam) and a commercial-scale (>10 MW beam). The proposed project is considered an engineering scale since it could reach up to 1 MW in beam power.

SRF CRYOMODULE

The Cryomodule technology proposed will hold between 6 to 8 jacketed Niobium SRF cavities. The cavities each have one RF power coupler, RF pick-up and are packaged together in a hermetically sealed unit containing the beam/RF volume. The hermetic sealed unit contains inter-cavity transitions (ICT), warm-cold transitions (WCT), cold BPMs and focussing SC solenoids. The jacketed cavities are surrounded by a cold Mu metal layer for suppression of the background magnetic field.

The cavities are individually maintained at frequency by tuners with warm motors in air on the top of the cryomodule. The hermetic unit is secured to a strong-back support frame and this structure defines the 'cold mass' of the SRF cryomodule. The cold mass is surrounded by a multilayer insulation (MLI), which reduces the heat radiation from the vacuum chamber to the LN2 cooled copper shielding.

The cold mass and all thermal shielding is suspended, hanging from the upper module plate from thin walled struts. Four independent positioning units can adjust the cold mass as a whole in order to align the cavities. The whole top assembly is surrounded by a multilayer insulation and lowered into the stainless steel vacuum chamber, which contains a warm Mu metal shielding for further magnetic shielding. Each module has cryogenic diagnostics and a 4K-2K cryogenic insert that receives 4K 1.2Bar LHe from the distribution line (customer scope) into a 4K reservoir and uses a heat exchanger with JT valve, to efficiently produce 2K LHe to 2K phase separator and cavities.

3-17 MeV SECTION - CM0 & CM1

The SRF cryomodules CM0 & CM1 are positioned downstream of the normal temperature RFQ. CM0 accelerates the beam from 3 MeV to approximately 9.5 MeV and CM 1 from 9.5 to 17 MeV. Both modules utilize half wave resonators (HWR) with a beta of 0.11 and a frequency of 162.5 MHz. The cavities are designed to each provide 1.4MeV of effective voltage. This section of the linac will require 13 20kW RF power systems at 162.5MHz.

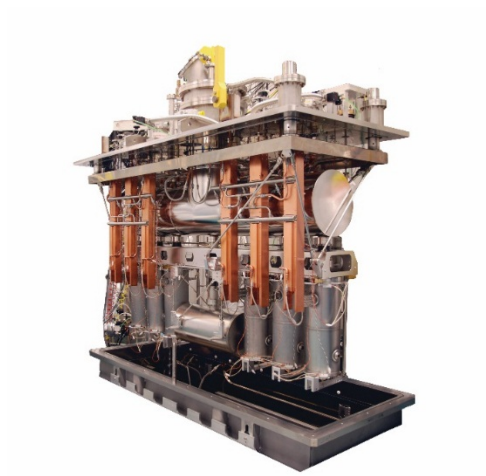

Figure 1: TRIUMF Cryomodule for Half and Quarter Wave SRF cavities.

The TRL matrix for Modules CM0 & CM1 is shown in Table 3 and the concept is illustrated in Figure 3. The main focus on technology viability is for the Engineering Scale which could produce beam power of up to 1 MW at energies of 100 MeV.

ISBN 978-3-95450-178-6

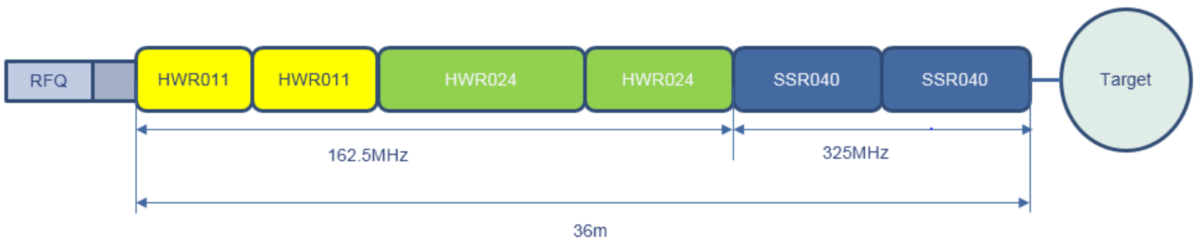

Figure 2: TP-ADS Demonstrator Outline.

A periodic unit inside the cryomodule consists of one cavity, one cold BPM and a high field superconducting solenoid. With corresponding drifts the unit is ~570mm long. Six such units comprise one cryomodule. The technology for this type of cryomodule is well understood in many laboratory scale facilities and therefore is a low risk to scale later to a commercial facility. The beam intensity presents a challenge. Projects like SARAF, SNS, ESS and PIP-II are giving insight to industry on how to construct robust, reliable technology for high intensity proton acceleration.

Table 3: TRL Matrix for CM0 and CM1

	TRL Level CM0 & CM1				
Cavity design	9	9	8	8	8.5
Cryogenics	9	9	6	4	7
Power Systems	9	9	3	3	6
Beam Dynamics/ Characteristics	9	9	8	2	7
ADS- Compatibility	8	8	6	4	6.5
	8.8	8.8	6.2	4.2	
	Bench-Scale (< 1kW)	Laboratory-Scale (<1MW)	Engineering-Scale (1-10 MW)	Commercial-Scale (>10MW)	

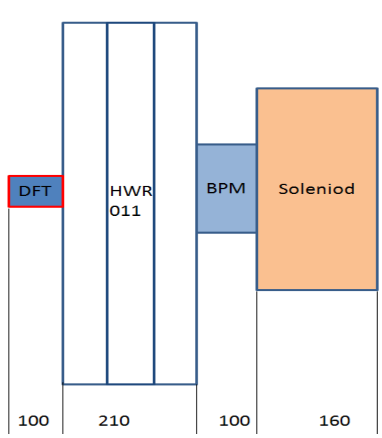

Figure 3: A periodic section for CM0 and CM1.

17 – 55 MeV SECTION - CM2 & CM3

Following the section 1, the CM2 and CM3 module will accelerate the beam to 35 MeV and 54 MeV respectively. Similar to the first modules the modules hold half wave designs with a beta of 0.24 and a frequency of 162.5 MHz. Both modules follow the same basic design as previous modules. At peak beam loading the cavities will require 35kW of rf power. The periodic unit for CM2 and CM3 is shown in Figure 4. This section of linac will require 14 40kW RF systems at 162.5MHz TRL is shown in table 4 and concept illustrated in Figure 5.

Figure 4: QWR cavity fabricated by PAVAC for the ISAC-II project at TRIUMF.

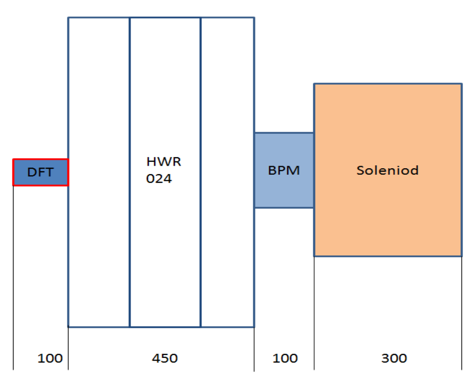

Figure 5: A periodic section for CM2 and CM3.

ISBN 978-3-95450-178-6

The module technology is considered straightforward since many are in use or development for other hadron accelerators such as FRIB, TRIUMF (see Figure 4), PIP-II, ESS [4].

Table 4: TRL Matrix for CM2 and CM3

	TRL Level CM-2 & CM3				
Cavity design	9	9	8	8	8.5
Cryogenics	9	9	6	4	7
Power Systems	9	9	3	3	6
Beam Dynamics/ Characteristics	9	9	8	2	7
ADS- Compatibility	8	8	6	4	6.5
	8.8	8.8	6.2	4.2	
	Bench-Scale (< 1kW)	Laboratory-Scale (<1MW)	Engineering-Scale (1-10 MW)	Commercial-Scale (>10MW)	

55 – 100 MeV SECTION - CM4 & CM5

CM4 and CM5 modules require different cavity characteristics, which are adjusted to the higher energies of the beam. Therefore cavity frequencies and beta are adjusted to beta of 0.4 and a frequency of 325 MHz. For this module two cavity designs are available and could be used: HWRs and Spoke [5] cavities as shown in Figure 6 can be used for this stage of the beam acceleration. This section of the linac will require 16 50kW rf power systems at 325MHz.

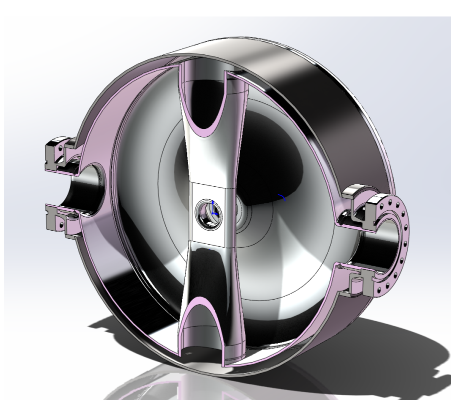

Figure 6: PAVAC model on Spoke cavity.

Considering a new cavity design the TRL level as shown in Table 5 will be lower than the previous modules. The main reason is the lack of long term operation at the laboratory scale. The conceptual periodic unit for this CM are shown in Figure 7.

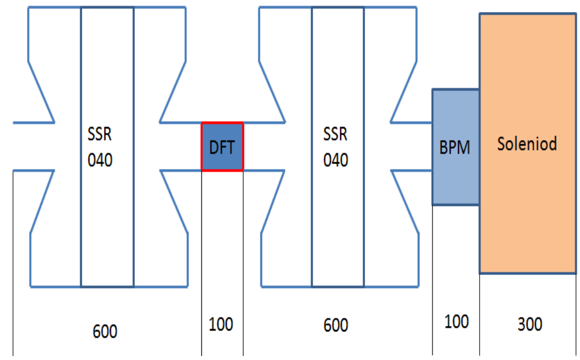

Figure 7: Periodic unit for CM4 and CM5.

Table 5: TRL Matrix for CM4 and CM5

	TRL Level CM-4 & CM5				
Cavity design	9	9	6	8	8
Cryogenics	9	9	6	4	7
Power Systems	9	9	3	3	6
Beam Dynamics/ Characteristics	9	9	6	2	6.5
ADS- Compatibility	8	8	6	4	6.5
	8.8	8.8	5.4	4.2	
	Bench-Scale (< 1kW)	Laboratory-Scale (<1MW)	Engineering-Scale (1-10 MW)	Commercial-Scale (>10MW)	

CONCLUSION

Accelerator Driven Systems (ADS) in combination with thorium or other advanced nuclear fuels are very real options to be considered to provide electrical energy with a reduced CO2 footprint. In addition new advanced nuclear system such as ADS have the energy density that allows a small enough facility size when we consider highly populated countries with little free land available. In addition this technology will allow new options in fuel recycling and end storage, largely reducing the issues that conventional nuclear facilities have when using Uranium. SRF accelerators could be used directly to destroy very long lived isotopes with the proton beam using either fission or transmute them via neutrons into a martial with much shorter half-life.

ISBN 978-3-95450-178-6

We recognize that for a full scale ADS beam energies of 600MeV to 1GeV will be required. The proposed project is a base line system that will benchmark industrial superconducting linac technology and provide a beam for target/reactor development while focusing on building future systems for the power generation sector. It is envisioned to add further section to such a baseline system in order to increase the beam energies.

ACKNOWLEDGMENT

We would like to thank TRIUMF, Fermilab and Michigan State University in supporting us with their research and active collaboration in the field of Superconducting Radio Frequency (SRF) technology.

REFERENCES

[1] Nuclear Energy Agency, Organisation For Economic Co-Operation And Development; "Introduction of Thorium in the Nuclear Fuel Cycle, Short- to long-term considerations", OECD 2015 NEA No. 7224.

[2] R.E. Laxdal, TRIUMF, Vancouver, B.C., Canada, "Operating Experience of the 20MV Upgrade Linac", Proceedings of Linear Accelerator Conference LINAC2010, Tsukuba, Japan.

[3] Nuclear Energy Agency, Organisation For Economic Co-Operation And Development; "State-of-the-art Report on Innovative Fuels for Advanced Nuclear Systems", OECD 2014 NEA No. 6895.

[4] M. Leitner, Michigen State Universtity, Lasing, MI, U.S. "THE FRIB PROJECT AT MSU", Proceedings of SRF2013, Paris, France, MOIOA01.

[5] G. Lanfranco, Fermi National Accelerator Laboratory, Batavia, IL 60510, U.S., "Design of 325MHz Single and Triple Spoke Resonators at FNAL", FERMILAB-CONF-06-307-TD.