SRF ACCELERATOR FOR INDIAN ADS PROGRAM: PRESENT & FUTURE PROSPECTS

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Abstract

Accelerator Driven Systems (ADS) have evoked lot of interest the world over because of their capability to incinerate the MA (minor actinides) and LLFP (long-lived fission products) radiotoxic waste and utilization of Thorium as an alternative nuclear fuel. One of the main sub-systems of the ADS is a high energy and high current CW proton Accelerator. The accelerator for ADS should have high efficiency and reliability and very low beam losses to allow hands-on maintenance. With this criteria, the physics studies has been done for a 1 GeV, 30 mA proton Linac, using NC structures upto 100 MeV followed by Superconducting elliptical cavities, which accelerate the beam from 100 MeV to 1 GeV. We have also studied the configuration where superconducing spoke resonators are used to accelerate the proton beam from 3-160 MeV followed by elliptical cavities for 160 MeV to 1 GeV. The details of these studies are presented in this paper.

INTRODUCTION

Today most energy requirements including electricity generation are met by burning fossil fuel and hydroelectricity generation. However, with increase in the demand for energy, especially in the developing nations, nuclear power appears to be an attractive option for electricity generation. Presently, nuclear power constitutes about 17% of the total electric power generation in the world from about 430 operating reactors. Fission chain reaction is the only way known to harness nuclear energy, while the naturally occurring uranium and the man-made plutonium are the two key elements that are serving as nuclear fuel. In recent times, Accelerator Driven Systems (ADS) [1] are attracting increasing worldwide attention because of their capability to incinerate the minor actinides (MA) and long-lived fission products (LLFP) radiotoxic waste and utilization of Thorium as an alternative nuclear fuel. Due to its vast resources of Thorium in India, ADS is particularly important as one of the potential routes for large-scale Thorium utilization.

In ADS, a high-energy proton beam from an accelerator strikes a heavy element (e.g.; Pb, W, U, Th etc..) target which yields neutrons by (p, xn) spallation reaction. These neutrons can multiply in a sub-critical core through self terminating fission chains. It can be shown that total fission energy released in the multiplying medium is many folds larger than the energy of input proton beam. Thus such a system acts as an energy amplifier. The accelerator for such a system is required to deliver proton beams at energy typically around 1 GeV and operate in CW mode. For accelerator driven systems it is necessary that the accelerator is reliable, rugged and stable with very low number of beam interruptions, which could affect the lifetime of key components such as windows, reactor parts and structure, as well as the ADS operation.

DESIGN OF THE ACCELERATOR

Several countries are working towards making a demonstration system for ADS. In India too, efforts have started in designing and building a proton linac for ADS. The primary concern in building such high-power linac is the minimization of beam losses, which could limit the availability and maintainability of the linac and various subsystems due to excessive activation of the machine. A careful beam dynamics design is therefore needed to avoid the formation of beam halo that would finally be lost in the linac or in transfer lines. An accelerator configuration for a 1 GeV, 30 mA linac has been worked out and the physics design studies have been done in detail [2]. It consists of a 50 keV ion source, 4 vane 3 MeV Radio Frequency Quadrupole (RFQ), Drift Tube Linac (DTL) upto 40 MeV, Cavity Coupled DTL(CCDTL) upto 100 MeV and 5 cell Superconducting elliptical cavities to accelerate the beam to 1 GeV.

In our design of superconducting cavities, we have taken a value of 15 MV/m for accelerating gradient. The SC cavities are designed to perform over the given velocity range and are identified by a design velocity called the geometric velocity, $\beta_{G.}$ This design approach takes advantage of the large velocity acceptance of the superconducting cavities. The transverse and longitudinal phase advances per unit length are maintained constant at all transitions between the structures to provide a current independent match into the next structure. While the RFQ and DTL will operate at 352.21 MHz, the operating frequency of CCDTL and SC linac is 704.42 MHz. The total length of the designed accelerator is about 400 m and the overall beam transmission is 98%. The 2% beam loss takes place in RFQ during bunching of the beam at low energies; and hence poses no serious radiation problem. The total length of the designed accelerator is about 410 m and the RF requirement is about 38 MW.

One of the most challenging parts of such a CW proton accelerator is the low-energy injector, typically up to 10-20 MeV, because the space-charge effects are maximal at lower energies. With this challenge in mind, a low energy (20 MeV) high intensity (30 mA) proton accelerator (LEHIPA) [3] is being built at BARC as a front-end injector for the 1 GeV linac for ADS. It consists of a 50 keV ECR ion source, a 3 MeV, 4-vane Radio

Frequency Quadrupole (RFQ) [4] followed by Drift Tube Linac (DTL) up to 20 MeV. The layout of LEHIPA is shown in Fig. 1.

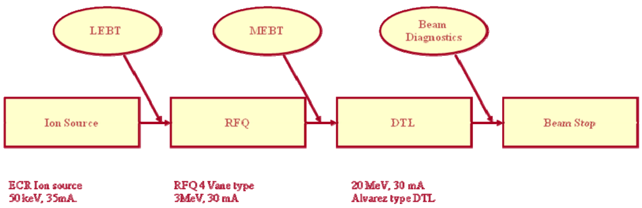


Figure 1: Layout of LEHIPA..

Several prototypes of RFQ and DTL (Fig. 2) have been fabricated and cold tested. Based on these measurements the actual RFQ and DTL are being fabricated.

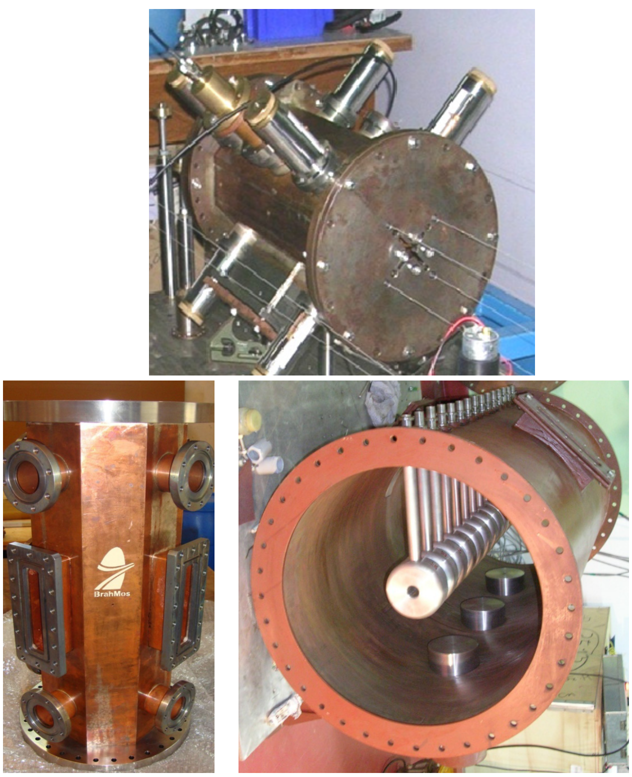


Figure 2: Prototypes of RFQ and DTL for LEHIPA.

A LEBT test bench (Fig. 3.) has also been setup at BARC to validate the LEBT simulations. It consists of an Alphatros ion source, Einzel lens, DC accelerating column, two solenoids, two BPMs and two Faraday cups. Emittance measurement using solenoid scan method was done for Helium beams and measurements for deuteron beam using pepper pot method and solenoid scan method are in progress.

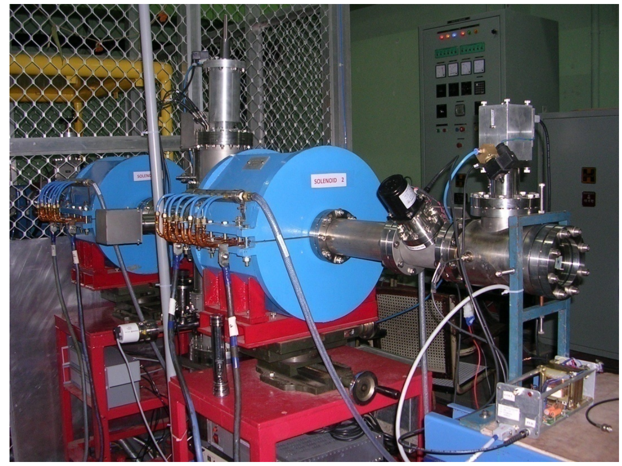


Figure 3: LEBT test bench at BARC.

As per the original roadmap, we have done the physics design of a 1 GeV linac using normal conducting cavities in the medium energy range (upto 100 MeV) and superconducting elliptical cavities for higher energies (100 MeV - 1 GeV). However, in recent times, several superconducting structures like the spoke resonators are being considered as options for the medium energy superconducting linac, in the range 5-150 MeV. Superconducting spoke resonators are relatively new type of accelerating structures and could be a good choice for accelerating high current beams. The CW accelerating gradients that have been achieved with these SC structures today are of the order of 6-10 MV/m, with a quality factor of $1.0\text{x}10^{10}$ as compared to the accelerating gradients of 2-3 MV/m with normal conducting (NC) structures at these energies. With these gradients, shorter overall length of the linac will be possible. Also, for CW structures lot of RF power is dissipated in the structures and removing this dissipated heat is a major challenge. This also leads to wastage of RF power which is very expensive. Use of superconducting technology will make the linac compact and cost effective. With SC cavities, we can have larger apertures; hence probability of beam loss also reduces. So for high current linacs operating in CW mode, SC option is the best. Due to these advantages, we are now designing the linac for ADS where we will inject the beam in the SC structures at 3 MeV itself. Also in view of collaboration with Fermilab on Project X, the operating frequency has been changed to 325 MHz and its harmonics from the earlier frequency of 352 MHz. The modified linac configuration for ADS is shown in Fig. 4. It consists of a 35 keV ion source, a 3 MeV Radio Frequency Quadrupole (RFQ) at 325 MHz, 3 sections of Single Spoke Resonators (SSR) at 325 MHz to accelerate the beam to 160 MeV and 5 cell Superconducting elliptical cavities at 650 MHz to accelerate the beam to 200 MeV and finally to 1 GeV. Option to use half wave resonators at low energies (3-20MeV) is also under consideration.

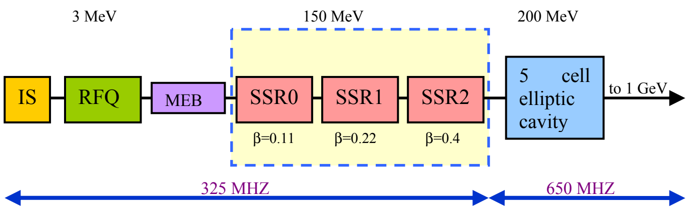


Figure 4: Modified layout of the 1 GeV Linac for ADS.

The RFQ operating at 325 MHz which will accelerate protons from 35 keV to 3 MeV has been designed using LIDOS and TRACK codes. The parameters have been listed in Table 1 and the beam profile is shown in Fig. 5.

Table 1: Parameters of the RFQ

Parameters	Value
Frequency	325 MHz
Input energy	35 keV
Output energy	3 MeV
Input current	30 mA
Transverse emittance	0.02/0.02 π cm-mrad
Synchronous phase	-30^0
Vane voltage	78 kV
Peak surface field	29.4 MV/m
Length	4.15 m
Transmission	98 %

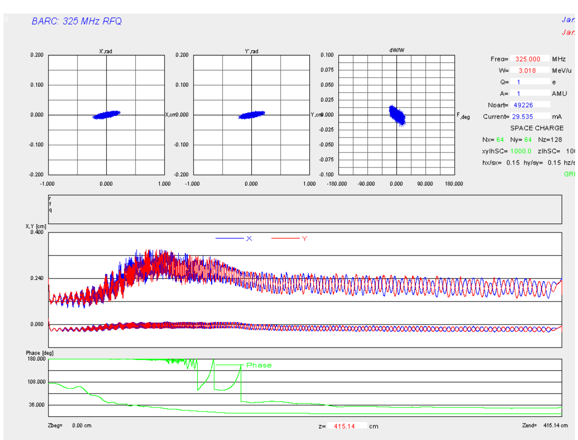


Figure 5: Beam envelop in the RFQ.

A preliminary design of the single spoke resonator cavities for $\beta_G = 0.11$ and 0.40 has been done using CST Microwave Studio. Fig.6 (a) shows the SSR2 cavity modeled in CST Microwave Studio and Fig.6 (b) shows the electric field profile in the cavity. The parameters of SSR2 are shown in Table2.

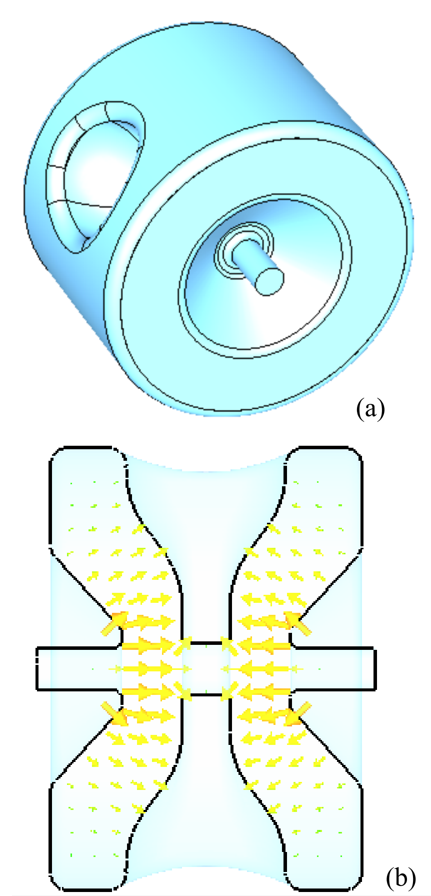


Figure 6: (a) Spoke resonator designed in CST Microwave studio (b) Electric field profile in the spoke resonator.

Table 2: Parameters of SSR2.

Parameter	Values
Geometrical beta	0.40
frequency	323.92 MHz
Peak electric field	9.15 MV/m
Peak Magnetic Field	13.66 A/m
Radius	26.13 cm
Cavity Length	36.81 cm

At higher energy, elliptic superconducting cavities are preferred. The transition from the front-end operating at 325 MHz based on single-spoke cavities to the 650 MHz section based on elliptical cavities is chosen at the energy 160 MeV, because for lower energies elliptical cavities lose efficiency. In order to choose the number of cells per cavity, a compromise must be made between many competing effects. The transit time factor is calculated for varying no. of cells/cavity in the energy range 100 MeV-1000 MeV using SUPERFISH for β_G = 0.6. The results are plotted in Fig. 7. As can be seen in the figure a small number of cells/cavity provides a large velocity acceptance. On the other hand, using a larger number of cells/cavity has the advantage of reducing the overall number of system components, system size, and system complexity. As a compromise between the two, in our design, we have chosen 5 cells/cavity.

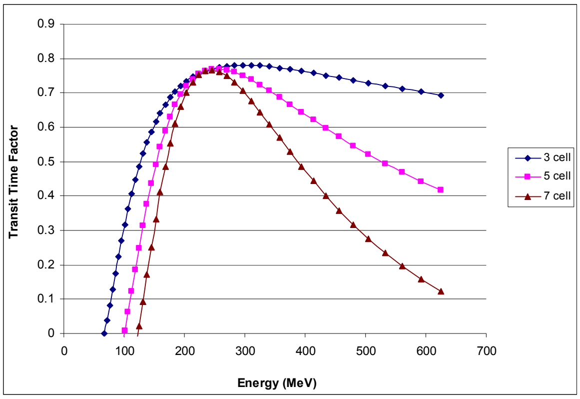


Figure 7: Variation of TTF with energy for different no. of cells/cavity for β_G = 0.6.

We have designed 5 cell elliptical at 650 MHz for β_G = 0.6, and 0.8 using SUPERFISH. The parameters are shown in Table 3.

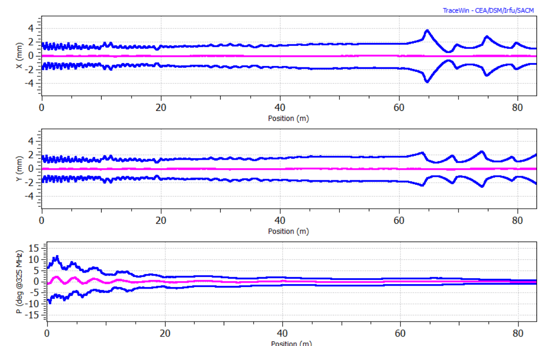
Table 3. Parameters of elliptical cavity

Parameters	βG = 0.6	βG = 0.8
No. of Cells	5	5
Diameter (cm)	39.34	38.54
Dome B (cm)	2	2
Dome A/B (cm)	1.9	2.4
Wall Angle (deg)	8	7
Iris a/b (cm)	0.8	0.6
Bore Radius (cm)	4.0	4.0
Equator Flat (cm)	0.5	1.2
Acc. Gradient (MV/m)	15	15

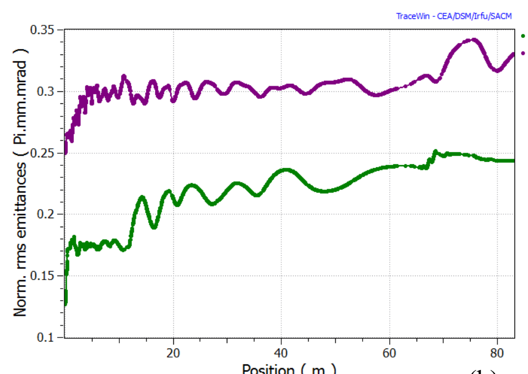
Preliminary studies have been done using Tracewin in collaboration with Fermilab to see the beam dynamics in the spoke resonators that will accelerate the beam from 3 MeV to 150 MeV and 5-cell elliptical cavity (β_G=0.61) that will accelerate the beam to 200 MeV. The first iteration for lattice design was performed with 30 mA beam current. No beam losses are seen. The lattice for the 200 MeV section is summarized in Table 4. Figs. 8(a) & (b) show the beam profile and emittance along the linac. The evolution of the synchronous phase and the energy gain per meter is shown in Figs. 8(c) & (d). Further detailed studies are in progress.

Table 4: Summary of lattice for the 200 MeV linac

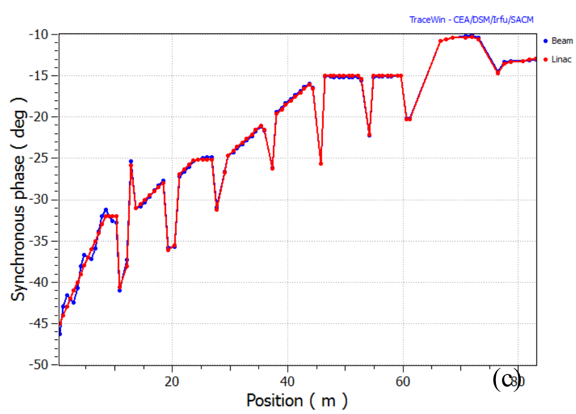
Sections	Cavities	Cryomodule	Final Energy (MeV)
SSR0	18	1	10.98
SSR1	20	2	42.57
SSR2	40	4	160.53
Beta =0.61	12	2	268.41



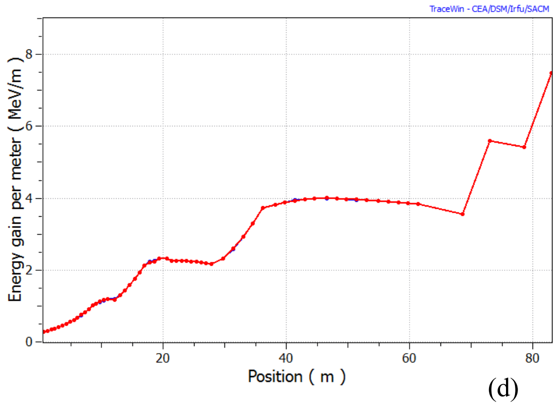
(a)



(b)



(c)



(d)

Figure 8: (a) Beam profile along the linac (b) Evolution of emittance along the linac (c) synchronous phase along the linac (d) Energy gain per meter along the linac.

SUMMARY AND CONCLUSIONS

A high intensity proton accelerator is being built for Indian ADS program. Presently, we are constructing a low energy high intensity (20 MeV, 30 mA) proton accelerator (LEHIPA) at BARC. We are also investigating possibility of using SC spoke resonators from 3 to 150 MeV and analysis for this is in progress.

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