Developmental Studies of High Current Proton Linac for ADS Program

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Abstract: One of the main sub-systems of ADS is a high energy (~1 GeV) and high current (~30 mA) CW proton linac. It is planned to take a staged approach towards development of the requisite accelerator technology, dividing it into 3 sections: namely, 20 MeV, 100 MeV and 1 GeV. One of the most challenging parts of such a CW proton accelerator is development of the low-energy injector, typically up to 20 MeV, because the space charge effects are maximal at these energies. BARC has initiated the development of Low Energy (20 MeV) High Intensity Proton Accelerator (LEHIPA) as front-end injector of the 1 GeV accelerator for the ADS program. Physics design studies have also been done for a 1 GeV proton linac for our ADS program. Proton beams are accelerated upto 100 MeV using normal conducting and then upto 1 GeV using superconducting elliptical cavities with a gradient of ~15 MV/m. The overall beam transmission is calculated to be 98%. In this paper, salient features of these studies are discussed.

1. Introduction:

During the last few years, Accelerator Driven sub-critical reactor Systems (ADS) have evoked considerable interest the world over because of their advantages over conventional reactors in terms of safety, better neutron economy and possible application in greatly reducing unwanted long-lived radioactive materials inventory by incineration. In India, ADS will provide an additional route to an efficient and economic nuclear power generation with its abundant Thorium resources.

An important sub-system of ADS is a high energy (~1 GeV) and high current (>20 mA) CW proton accelerator. In contrast to the high-energy particle accelerators in use hitherto, the electrical efficiency, reliability and beam loss rate for such a system needs to be improved to a great extent. One of the most challenging parts of such a CW proton accelerator is development of the low-energy injector, typically up to 20 MeV, because the space charge effects are maximal at lower energies. It is, therefore, planned to develop the accelerator in 3 phases; namely, 20 MeV, 100 MeV and 1 GeV. With this challenge in mind, a low energy (20 MeV) high intensity (30 mA) proton accelerator (LEHIPA) is being built at BARC [1,2]. It consists of a 50 keV ECR ion source, a 3 MeV Radio Frequency Quadrupole (RFQ) and a 20 MeV Drift Tube Linac (DTL). The Low Energy Beam Transport (LEBT) and Medium Energy Beam Transport (MEBT) lines are used to match and transport the beam from the ion source to RFQ and from RFQ to DTL respectively. The configuration of the 20 MeV accelerator is shown in Fig.1.

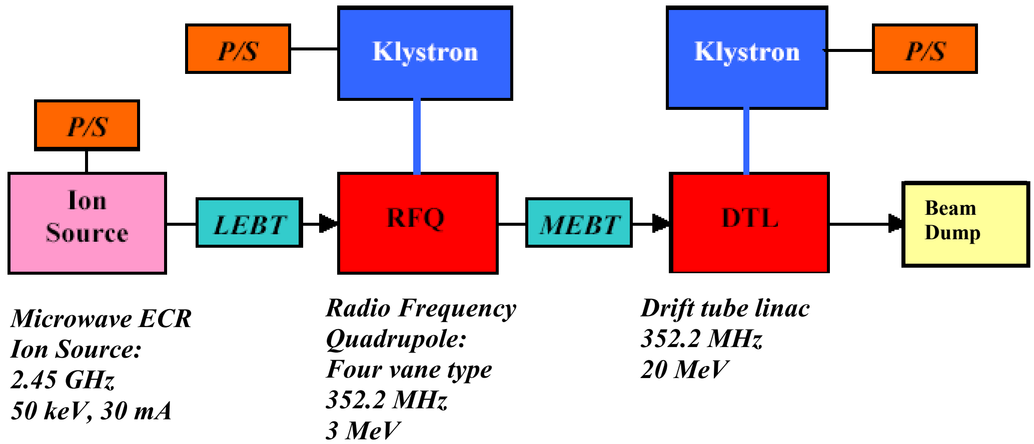

FIG. 1. Configuration of the 20 MeV linac for LEHIPA.

An accelerator configuration for a 1 GeV, 30 mA linac has been worked out and the physics design studies for the same have been done in detail [3,4]. It consists of a 50 keV ECR 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. Earlier, Superconducting linacs have been designed for an accelerating gradient of 5 MV/m. With the recent development in SC technology, accelerating gradients of ~ 25-30 MV/m have now been considered. In our design of superconducting cavities, we have taken a conservative value of 15 MV/m for the accelerating gradient. By increasing the accelerating gradient from 5 to 15 MV/m, the length of the 1 GeV linac has reduced from about 880 to 400 m. 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 activation problem. The proposed layout of 1 GeV linac for the ADS is shown in Fig.2.

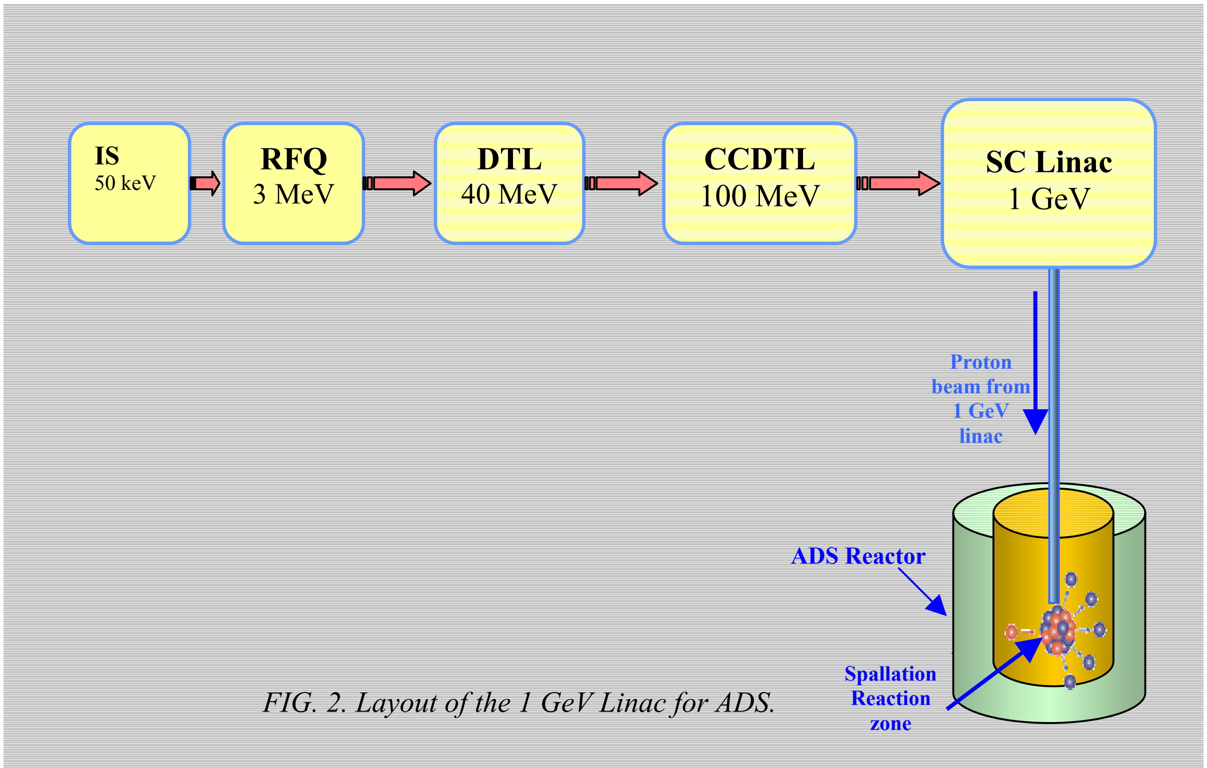

FIG. 2. Layout of the 1 GeV Linac for ADS.

In the following sections details of some of the sub-systems are given.

2. Low Energy Beam Transport line (LEBT):

The DC beam from the ECR ion source, being developed at BARC, is matched to the RFQ using LEBT. The main criterion for the design of the LEBT was to minimize the emittance growth with minimum beam loss. Matching was done using 2 solenoids (~3 kG) and 3 drift spaces. Solenoids are preferred over quadrupoles as they focus in both transverse dimensions, and reduce aberrations. The solenoids designed at BARC were fabricated and tested at RRCAT. The performance was found to be as specifications. Space charge forces are mainly responsible for increase in beam size and emittance. In order to reduce these effects, space charge compensation technique is employed. Simulation studies show that there is no emittance growth in the LEBT when the beam is more than 95% space charge compensated [5,6]. Also the maximum beam radius reduces from 6.5 to 3.4 cm.

3. Radio Frequency Quadrupole (RFQ):

Proton beam extracted from the ECR ion source is injected into RFQ through a Low Energy Beam Transport System (LEBT). The parameters of the RFQ are shown in Table I.The RFQ design has been done using the equi-partitioning [7] scheme, where the longitudinal and transverse temperatures of the beam should be equal. By using this technique the emittance growth was observed to be less than 2%. In this design the vane voltage has been kept constant, keeping the peak surface field less than 1.8 times the Kilpatrick limit. The total length of the RFQ is 4 m and it will be built in 4 segments, which will be coupled with coupling cells. The total RF power requirement is 500 kW which includes 88.5 kW of beam power. The LEHIPA project involves handling of very large RF power at 352.21 MHz and fabrication of long complex structures like the RFQ. In order to understand these accelerator technologies it is planned to build first a 400 keV D^+ RFQ which will replace an existing 400 kV dc accelerator at PURNIMA facility in BARC. So, this system consisting of a 50 keV, 1 mA dc deuteron source, a LEBT line and a 400 keV CW RFQ has been designed. A 1.2 m long prototype of the 400 keV RFQ has been fabricated and its characterization is in progress at BARC.

TABLE I: PARAMETERS OF THE RFQ.

Parameters	**Value**
Frequency	352.21 MHz
Input energy	50 keV
Output energy	3 MeV
Input current	30 mA
Transverse emittance	0.02/0.0204 π cm-mrad
Synchronous phase	-30^0
Vane voltage	80 kV
Peak surface field	32.8 MV/m
Length	4 m
Total RF power	500 kW
Transmission	98 %

An indigenous power coupler development program has been initiated at the Nuclear Physics Division, BARC. Two 50 kW CW coaxial couplers are presently under fabrication. The design incorporates disc type alumina windows with double barrier for better mechanical stability and reliability of the coupler. A shorted stub will provide RF matching along with providing support for central conductor and cooling channels. The 250 kW iris type coupler for the 3 MeV RFQ, with tapered transition to WR 2300 half height wave-guide, is presently in RF design stage [8,9]. The thermal loss estimation and mechanical tolerance level requirements are being worked out.

4. Medium Energy Beam Transport line (MEBT):

The Medium Energy Beam Transport (MEBT) system is used to transport the 3 MeV, 352.2 MHz proton beam from RFQ to DTL. It was designed using TRACE3D and consists of 4 quadrupoles and two RF gap for matching the beam in transverse and longitudinal direction respectively. The total length of the MEBT is about 1.21m.

5. Drift Tube Linac (DTL):

The DTL has high shunt impedance at low energies. It can focus and accelerate a high intensity proton beam very effectively at these energies, where the space charge forces are considerable. In LEHIPA, an Alvarez-type DTL is used to accelerate the beam from 3-20 MeV and its parameters are given in Table II. It is proposed to make the DTL in four tanks. The axial electric field is kept constant at 2.14 MV/m in all the four tanks. For minimum emittance growth, it is necessary to match the transverse phase advance per focusing period in the RFQ and DTL. This requires very high quadrupole gradients in the DTL if FODO (FD) lattice is considered, making the design of such compact quadrupoles very difficult at low-energy end [10]. However, if FOFODODO (FFDD) lattice is considered, the required quadrupole gradient is 46.5 T/m; making the design of EMQs easier. Hence, studies are being done to design the DTL with smaller tanks having FFDD lattice. The electromagnetic design of the cavity has been done to get the parameters of the tuners, post couplers and vacuum ports [11]. As a first step in the development of the DTL we are building a 1.2 m long physics prototype and the RF measurements on this prototype are planned.

TABLE II: PARAMETERS OF THE DTL.

Parameter	**Value**
Resonant frequency	352.21 MHz
Input energy	3 MeV
Output energy	20 MeV
Beam current	30 mA
Diameter of cavity	52 cm
Diameter of drift tube	12 cm
Bore radius	1.2 cm
Axial electric field	2.14 MV/m
Total length	12.86 m
Beam transmission	100%
Type of lattice	FFDD
Effective length of quad.	4.72 cm
Quadrupole gradient	46.5-43.6 T/m
Total power (dissipated+beam)	1.34 MW
Maximum surface field	0.53 Kilp.

6. Beam Dump:

A beam dump has been designed to dissipate 600 kW (20 MeV, 30 mA) proton beam power (Fig. 3). The beam will be stopped on a beam dump during commissioning and on a suitable neutron converter target to produce neutrons during utilization stage for which a Beryllium target will be used. In addition to neutron yield, the designed target should also have good heat removal capability. To reduce the peak power density one needs to extend the operational area of the target. Hence a conical shape of the target has been chosen.

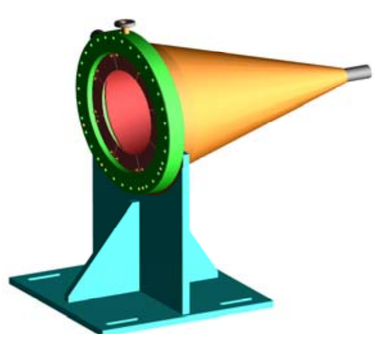

FIG. 3. Beam dump for the 20 MeV LEHIPA.

7. Beam dynamics for 1 GeV Linac:

The linac for an Accelerator Driven System is required to deliver a 1 GeV proton beam at tens of milliamperes of current. The main design criterion for such a linac is low beam loss in the accelerator to allow hands-on-maintenance of the entire linac. With this criteria, the beam dynamics simulations for a 1 GeV, 30 mA proton linac has been done. The linac consists of an ECR ion source, a normal-conducting Radio-Frequency Quadrupole (RFQ), Drift Tube Linac (DTL) and Coupled Cavity Drift Tube Linac (CCDTL) structures that accelerate the beam to about 100 MeV followed by Superconducting (SC) elliptical cavities, which accelerate the beam from 100 MeV to 1 GeV.

The RFQ operating at 352.21 MHz accelerates the beam from 50 keV to 3 MeV. The 3 MeV beam from the RFQ is then matched into the DTL using the medium energy beam transport (MEBT) line, which consists of 4 quadrupoles for transverse matching and 2 rf gaps for longitudinal matching. The DTL cavity has been designed with SUPERFISH. The FFDD lattice is used in the DTL for transverse focusing. For this lattice the quadrupole gradient required to match the transverse phase advance between RFQ and DTL, for current independent matching, comes out to be ~ 43 T/m. This can be achieved by permanent magnet quadrupoles placed inside the drift tubes. The focusing lattice period is $4\beta\lambda$ throughout the DTL. The total length of the 40 MeV DTL is 22.7 m and the RF power required is 3.02 MW. The 40 MeV beam from the DTL is then accelerated to 100 MeV using 2 gap CCDTL cavities at 704.42 MHz. Each cavity contains a single drift tube inside mounted by stems and electromagnetic quadrupoles are mounted between two CCDTL cavities for transverse focusing. The transverse focusing lattice is FODO and the focusing period is $5\beta\lambda$ at this frequency. The beam from the DTL is transversely matched into the CCDTL by using the first four quadrupoles in the CCDTL. The accelerating gradient is kept constant in the CCDTL at 1.37 MV/m. Its total length is 70 m and the RF power requirement is 6.45 MW.

Multi-cell superconducting (SC) elliptical cavities at 704.42 MHz are used to accelerate the beam from 100 MeV to 1 GeV using 15 MV/m accelerating gradient. The cavities are designed to perform over the given velocity range and are identified by a design velocity called the geometric velocity, $\beta_{G.}$ The design approach takes advantage of the large velocity acceptance of the superconducting cavities. 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. In order to efficiently design a linac it is necessary to divide it in sections, each using a different cavity geometry in a given energy range. To begin with, the β_G values for the cavities, the number of constant β_G sections and the beam velocity limits for each section have to be determined. Based on velocity acceptance, the entire energy range from 100 MeV to 1 GeV is divided into 3 sections of constant beta cavities as shown in Fig. 4.

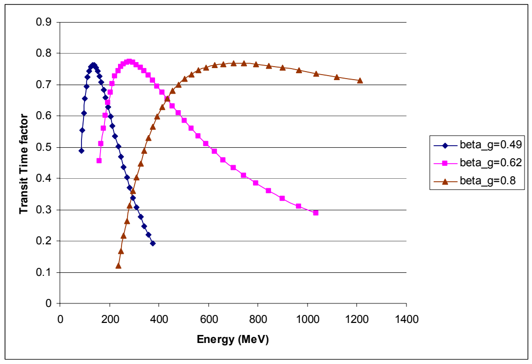

FIG. 4. Transit time factor curves for 3 constant beta cavities.

The transverse focusing is achieved by using room temperature electromagnetic quadrupole doublets in between the cryomodules containing the superconducting cavities. The focusing doublets are placed after every 2 cavities in the first section, having 12 cryostats, after every 3 cavities in the second section having 15 cryostats and after every 4 cavities in the third section having 23 cryostats. To obtain a current independent match between the normal conducting linac and superconducting linac, which has a weaker focusing, the quadrupole gradients in the CCDTL are gradually reduced with energy. Transverse matching is done using the last 2 quadrupoles in the CCDTL and the first 2 quadrupoles in the superconducting linac. The beam dynamics parameters of the RFQ, DTL, CCDTL and Superconducting Linac are shown in Table III.

TABLE III: PARAMETERS OF RFQ, DTL, CCDTL AND SC LINAC.

Parameters		**RFQ**	**DTL**	**CCDTL**	**SC linac**
Input Energy (MeV)		0.05	3.0	40.12	100.24
Output Energy (MeV)		3.0	40.12	100.24	1016.5
Frequency (MHz)		352.21	352.21	704.42	704.42
Synch. Phase (deg)		-30	-30	-30	-30/ -35
Accelerating field gradient (MV/m)		-	2.5	1.37	15
Total Power (MW)		0.5	3.0	6.4	26.9
Total Length (m)		4.0	22.7	69.6	306.2
Norm. rms trans. Emitt. (π cm-mrad)	In x	0.0204	0.0233	0.0232	0.0351
	In y	0.0204	0.0242	0.0236	0.0313
Long. Emitt. (deg-MeV)		0.10432	0.1150	0.2373	0.2549

The computer code PARMILA was used to do the end-to-end beam dynamics simulations from 3 MeV to 1 GeV. The maximum beam radius never exceeds 1.1 cm in the entire linac. The aperture is ~10 times the rms beam size in the normal conducting linac and is more than 16 times the rms beam size in the superconducting linac where the risk due to activation is more. The beam transmission is 100% from 3 MeV to 1 GeV. The variation of transverse and longitudinal emittance through the linac is shown in Fig. 5.

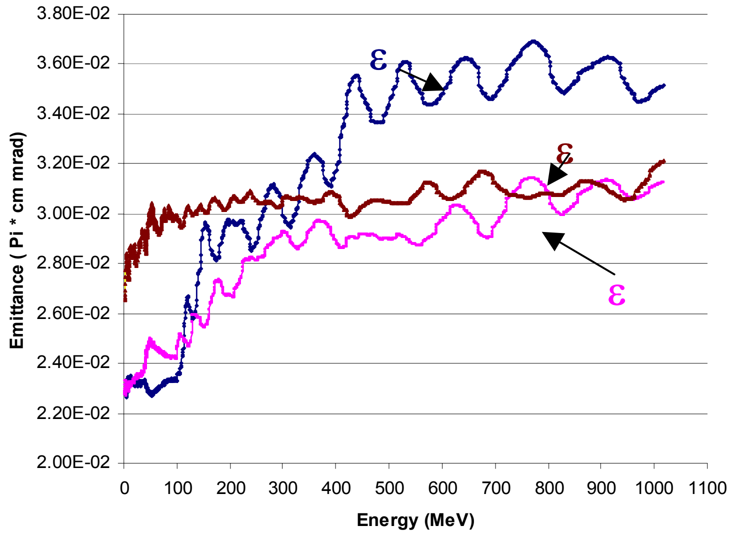

FIG. 5. Variation of transverse (ε_x, ε_y) and longitudinal (ε_z) emittances with beam energy.

8. Summary and Conclusions:

At BARC, development of a Low Energy (20 MeV) High Intensity Proton Accelerator (LEHIPA) as front-end injector of the 1 GeV accelerator for the ADS programme is in progress. The major components of LEHIPA are a 50 keV ECR ion source, a 3 MeV Radio-Frequency Quadrupole (RFQ) and a 20 MeV Drift Tube Linac (DTL). Extensive studies related to LEHIPA have been done to design the RFQ, DTL and low energy and medium energy transport lines LEBT and MEBT respectively. The fabrication and procurement of various subsystems is in progress. A linac based 1 GeV accelerator has been designed for the Indian ADS programme and its beam dynamics studies, with accelerating gradient of 15 MV/m in superconducting cavity section (0.1-1 GeV), have been done.

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