High-power proton linacs have various applications such as Accelerator Driven Systems (ADS) for transmutation or energy production, neutron spallation source for condensed matter studies, neutrino factories and muon colliders, production of rare isotope beams for nuclear physics studies, etc. These linear accelerators are required to deliver proton beams of up to several MW to several tens of MW power and operate with CW or pulsed high intensity beams. In particular, Accelerator Driven Systems (ADS) [1] have evoked considerable interest in the nuclear community the world over because of their capability to incinerate the MAs (minor actinides) and LLFPs (Long-lived Fission Products) radiotoxic waste and utilization of Thorium as an alternative nuclear fuel. Since India has vast resources of Thorium, ADS is particularly important as one of the potential routes for accelerated thorium utilization [2]. An ADS consists of a sub-critical reactor coupled to a high power proton accelerator through spallation target as shown in Fig. 1. 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 have been done, the details of which are presented in this paper. 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 [3].

Introduction

The 1 GeV linac consists of a 3 MeV RFQ, DTL upto 50 MeV, CCDTL upto 100 MeV and 5 cell superconducting elliptical cavities to accelerate the beam to 1 GeV. While the RFQ and DTL operate at 352.21 MHz, the operating frequency of CCDTL and SC linac is 704.42 MHz. The layout of the proposed 1 GeV accelerator is shown in Fig. 2. 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 [4]. For this, the quadrupole gradients and accelerating electric fields are varied between the structures. The various accelerating structures are described below.

It is planned that the development of the 1 GeV accelerator for ADS will be pursued in three phases, namely, 20 MeV, 100 MeV and 1 GeV [2]. The most challenging part of this CW proton accelerator is development of the low-energy injector, typically up to 20 MeV, because the space charge effects are maximal here. Therefore, BARC has initiated a programme for the development of a Low Energy (20 MeV) High Intensity Proton Accelerator (LEHIPA) as front-end injector [5] of the 1 GeV accelerator for the ADS programme. The major components of LEHIPA are a 50 keV ECR ion source [6], 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 [5,7], DTL [5,8] and low energy and medium energy transport lines LEBT [9, 10] and MEBT [11] respectively.

RFQ

The RFQ operating at 352.21 MHz accelerates the 30 mA proton beam from 50 keV to 3 MeV. The RFQ has been designed with a varying vane voltage keeping the peak electric field less than 1.8 times the Kilpatrick limit.
The parameters of the RFQ are shown in Table 1. The total length of the RFQ is 3.45 m and the total rf power requirement is 500 kW.

**DTL**

The beam from the RFQ is accelerated to 50 MeV using a 352.21 MHz DTL. This 3 MeV beam is matched into the DTL using a matching line (MEBT), which consists of 4 quadrupoles for transverse matching and 2 rf gaps for longitudinal matching. The DTL cavity has been designed using **SUPERFISH** [12]. The parameters of the DTL cavity are listed in Table 2. The face angle in the drift tubes is kept 0° from 3 MeV to 20 MeV where the drift tube lengths are small and increased to 10°(#) beyond 20 MeV where the drift tubes become long enough to accommodate the quadrupoles. This increases the effective shunt impedance at 20 MeV as can be seen in Fig. 3. Fig. 4 shows the electric fields in the half cells of the DTL cavity at 3 MeV, 20 MeV and 50 MeV respectively.

**Table 2 : Cavity parameters of the DTL**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>3-50 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>352.21</td>
</tr>
<tr>
<td>Tank Diameter (cm)</td>
<td>52</td>
</tr>
<tr>
<td>Drift Tube Diameter (cm)</td>
<td>12</td>
</tr>
<tr>
<td>Bore Radius (cm)</td>
<td>1.0</td>
</tr>
<tr>
<td>Face Angle (degrees)</td>
<td>0°/10°(#)</td>
</tr>
<tr>
<td>Corner Radius (cm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Inner Nose Radius (cm)</td>
<td>0.5</td>
</tr>
<tr>
<td>Outer Nose Radius (cm)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Table 1: Parameters of the RFQ**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>352.21 MHz</td>
</tr>
<tr>
<td>Input energy</td>
<td>50 keV</td>
</tr>
<tr>
<td>Output energy</td>
<td>3 MeV</td>
</tr>
<tr>
<td>Input current</td>
<td>30 mA</td>
</tr>
<tr>
<td>Transverse emittance</td>
<td>0.02/0.0217 ( \mu \text{cm-mrad} )</td>
</tr>
<tr>
<td>Synchronous phase</td>
<td>-30°</td>
</tr>
<tr>
<td>Vane voltage</td>
<td>82-111.58 kV</td>
</tr>
<tr>
<td>Peak surface field</td>
<td>32.8 MV/m</td>
</tr>
<tr>
<td>Avg. aperture R0</td>
<td>3.63-3.53 mm</td>
</tr>
<tr>
<td>Length</td>
<td>3.45 m</td>
</tr>
<tr>
<td>Total RF power</td>
<td>500 kW</td>
</tr>
<tr>
<td>Transmission</td>
<td>97 %</td>
</tr>
<tr>
<td>Focusing parameter</td>
<td>4.07 - 4.8</td>
</tr>
<tr>
<td>Max. modulation</td>
<td>1.95</td>
</tr>
</tbody>
</table>
A FODO 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 100 T/m. This can be achieved by permanent magnet quadrupoles placed inside the drift tubes. The focusing lattice period is 2βλ throughout the DTL. The total length of the DTL is 28 m and the RF power required is 4 MW. The DTL will be built in 5 tanks. The axial electric field is kept constant at 2.58 MV/m in all the tanks. The main parameters of the DTL are shown in Table 3.

### Table 3: Parameters of each DTL tank

<table>
<thead>
<tr>
<th>DTL Tank No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Energy (MeV)</td>
<td>3.0</td>
<td>11.48</td>
<td>20.11</td>
<td>30.58</td>
<td>40.52</td>
</tr>
<tr>
<td>Output Energy (MeV)</td>
<td>11.48</td>
<td>20.11</td>
<td>30.58</td>
<td>40.52</td>
<td>50.10</td>
</tr>
<tr>
<td>No. of Cells</td>
<td>51</td>
<td>33</td>
<td>31</td>
<td>26</td>
<td>23</td>
</tr>
<tr>
<td>Synch. Phase (deg)</td>
<td>-30</td>
<td>-30</td>
<td>-30</td>
<td>-30</td>
<td>-30</td>
</tr>
<tr>
<td>Accelerating field gradient (MV/m)</td>
<td>2.58</td>
<td>2.58</td>
<td>2.58</td>
<td>2.58</td>
<td>2.58</td>
</tr>
<tr>
<td>Total Power (kW)</td>
<td>732.2</td>
<td>708.9</td>
<td>838.7</td>
<td>818.3</td>
<td>804.0</td>
</tr>
<tr>
<td>Tank Length (m)</td>
<td>5.07</td>
<td>5.04</td>
<td>5.98</td>
<td>5.91</td>
<td>5.86</td>
</tr>
<tr>
<td>Norm. rms trans. Emitt. (σ cm-mrad)</td>
<td>in x 0.0233</td>
<td>0.0233</td>
<td>0.0231</td>
<td>0.0230</td>
<td>0.0230</td>
</tr>
<tr>
<td></td>
<td>in y 0.0222</td>
<td>0.0225</td>
<td>0.0228</td>
<td>0.0230</td>
<td>0.0230</td>
</tr>
<tr>
<td>Long. Emitt. (deg-MeV)</td>
<td>0.1167</td>
<td>0.1190</td>
<td>0.1206</td>
<td>0.1189</td>
<td>0.1261</td>
</tr>
</tbody>
</table>
The 3D design of the DTL tanks to include post couplers, tuners and vacuum ports is also being done. Figs. 5 and 6 show post couplers and tuner modelled in CST Microwave Studio respectively, in a single DTL tank.

![Fig. 5: Model of post couplers in DTL](image)

![Fig. 6: Model of tuner in DTL](image)

**CCDTL**

The 50 MeV beam from the DTL is then accelerated to 98.6 MeV using 2 gap CCDTL cavities at 704.42 MHz as shown in Fig. 7. Each cavity contains a single drift tube inside mounted by stems and electromagnetic quadrupoles are mounted between two CCDTL cavities for transverse focusing. The CCDTL cavity is designed in SUPERFISH and the cavity parameters are shown in Table 4. The transverse focusing lattice is FODO and the focusing period is 5bl 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 at 1.6 MV/m in the CCDTL. Its total length is 75 m and the RF power requirement is 5 MW. The beam dynamics parameters of the CCDTL are shown in Table 5.

The 3D design of the DTL tanks to include post couplers, tuners and vacuum ports is also being done. Figs. 5 and 6 show post couplers and tuner modelled in CST Microwave Studio respectively, in a single DTL tank.

![Fig. 7: Two cell CCDTL cavity designed in SUPERFISH](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>704.42</td>
</tr>
<tr>
<td>Diameter (cm)</td>
<td>24</td>
</tr>
<tr>
<td>No. of gaps</td>
<td>2</td>
</tr>
<tr>
<td>Drift tube diameter (cm)</td>
<td>5</td>
</tr>
<tr>
<td>Bore radius (cm)</td>
<td>1.2</td>
</tr>
<tr>
<td>Equator flat (cm)</td>
<td>3</td>
</tr>
<tr>
<td>Cone angle (Deg)</td>
<td>10</td>
</tr>
<tr>
<td>Drift tube face angle (deg)</td>
<td>70</td>
</tr>
<tr>
<td>Inner corner radius (cm)</td>
<td>0.25</td>
</tr>
<tr>
<td>Outer nose radius (cm)</td>
<td>0.05</td>
</tr>
<tr>
<td>Inner nose radius (cm)</td>
<td>0.2</td>
</tr>
<tr>
<td>Drift tube outer nose radius (cm)</td>
<td>0.6</td>
</tr>
<tr>
<td>Drift tube inner nose radius (cm)</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Superconducting linac

Superconducting elliptical cavities at 704.42 MHz are used, to accelerate the beam from 100 MeV to 1 GeV. 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. For a cavity with N identical cells, the transit time factor $T$ can be expressed as a product of two separate factors $T = T_{GS} \times T_{S}$ [13]. In order to choose the number of cells per cavity, a compromise must be made between many competing effects. 

SUPERRFISH is used to compute the gap factor $T_{GS}$ and the synchronism factor $T_{S}$ is computed analytically for varying no. of cells/cavity. The results are plotted in the Fig. 8. As can be seen from 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.

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 $\beta_G$ values for the cavities, the number of constant $\beta_G$ 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. 9. The cavity parameters of the 3 sections are shown in Table 6. The parameters of the elliptical cavity are shown in Fig. 10(a) and the 5 cell elliptical cavity for $\beta_G = 0.47$ is shown in Fig. 10(b).
The transverse focusing is achieved, by using room temperature electromagnetic quadrupole doublets in between the cryomodules containing the superconducting cavities. The focussing doublets are placed after every 2 cavities in the first section, which will have 35 cryostats, after every 3 cavities in the second section having 40 cryostats and after every 4 cavities in the third section having 51 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. Transverse matching between two superconducting sections was done, by making small adjustments to the quadrupole gradients at the transition between the sections.
Longitudinal matching was achieved, by adjusting the synchronous phase $\phi_s$ in the superconducting cavities to maintain constant longitudinal phase advance per unit length on both sections and maintaining a constant energy gain in each cavity. This was done by keeping $(\Delta W \tan \phi_s/L)$ constant on both sides of the transition, where $\Delta W$ is the energy gain per cryomodule and $L$ is the length of the focusing period. The parameters of the SC linac are shown in Table 7.

The computer code PARMILA [14] was used to do the end-to-end beam dynamics simulations from 3 MeV to 1 GeV. Fig. 11 shows the beam at the end of the DTL, CCDTL and the SC linac and the $x$, $y$ and phase profiles of the beam from the DTL through the superconducting linac for a beam current of 29.3 mA. The maximum beam radius never exceeds 1.1 cm in the linac as can be seen from Fig. 12. The aperture is 10-12 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 emittance through the linac is shown in Fig. 13.

### Table 7: Parameters of the superconducting linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\beta_0 = 0.47$</th>
<th>$\beta_0 = 0.62$</th>
<th>$\beta_0 = 0.80$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range (MeV)</td>
<td>98.6-198.3</td>
<td>198.3-498.3</td>
<td>498.3-1008.3</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>704.42</td>
<td>704.42</td>
<td>704.42</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>29.3</td>
<td>29.3</td>
<td>29.3</td>
</tr>
<tr>
<td>Trans. focusing lattice</td>
<td>Doublet</td>
<td>Doublet</td>
<td>Doublet</td>
</tr>
<tr>
<td>Lattice period (cm)</td>
<td>300.1</td>
<td>608.0</td>
<td>810.7</td>
</tr>
<tr>
<td>Quad. gradient (T/m)</td>
<td>5.8-5.37</td>
<td>4.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Eff. length of quad. (cm)</td>
<td>35</td>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>Synchronous phase</td>
<td>-30</td>
<td>-23.44</td>
<td>-23.44</td>
</tr>
<tr>
<td>Cavities/cryomodule</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>No. of cryomodules</td>
<td>35</td>
<td>40</td>
<td>51</td>
</tr>
<tr>
<td>Aperture radius (cm)</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Total length (m)</td>
<td>105.04</td>
<td>243.2</td>
<td>413.46</td>
</tr>
<tr>
<td>Norm. rms trans. Emitt. ($\pi$ cm-mrad)</td>
<td>0.0236-0.0253</td>
<td>0.0253-0.0285</td>
<td>0.0285-0.0299</td>
</tr>
<tr>
<td></td>
<td>0.0237-0.0251</td>
<td>0.0251-0.0276</td>
<td>0.0276-0.0271</td>
</tr>
<tr>
<td>Long. Emittance (deg-MeV)</td>
<td>0.3270-0.4440</td>
<td>0.4440-0.4820</td>
<td>0.4820-0.4990</td>
</tr>
</tbody>
</table>
Fig. 11: Beam at the end of (a) DTL (b) CCDTL (c) SC Linac and (d) Beam profile through the entire linac

Fig. 12: Variation of beam size and aperture with beam energy
Present status and future studies

The design of the 20 MeV, 30 mA proton accelerator (LEHIPA), being built in connection with our ADS programme, is complete. The fabrication and procurement of various subsystems are in progress. The Low Energy Beam Transport line (LEBT) uses two solenoids for focusing the diverging beam from the ion source. The beam dynamics of LEBT was studied using ‘TRACE 2D” code and its layout is shown in Fig. 14. Fabrication of the LEBT solenoids is in progress at RRCAT, Indore.
The CAD model of the 3 MeV RFQ for LEHIPA is shown in Fig. 15. This 3.45 m long RFQ will be made in 4 sections, resonantly coupled using coupling cells [15]. The fabrication of the RFQ is in progress at M/s KELTEC, Thiruvanathapuram.

References

1. F. Carminati, R. Klapisch, J.P. Revol, J.A. Rubio and C. Rubbia CERN/AT/93-47 (ET); C. Rubbia et al; CERN/AT/95-44 (ET); CERN/LHC/96-01 (EET); CERN/AT/95-53 (ET); CERN/LHC/97-01 (EET).


The current design of the 1 GeV linac has been done using modest gradients of about 5 MV/m in the superconducting cavities. Because of the high beam current, the major design issue is not attainment of high cavity gradients, but high power rf coupler capability [16]. In view of advancement in SC technology and higher gradients achievable that have been demonstrated at various labs around the world, it is planned to design the linac with higher accelerating gradients and also considering other structures like the spoke cavities. It is also planned to incorporate equipartioning in the design in future, to avoid beam halo formation in the linac.

Acknowledgement

We thank Dr V.C. Sahni, Dr S. Kailas and Dr R.K. Choudhury for their keen interest in this work.


About the Authors

Ms. Rajni Pande is from the second batch of RRCAT Training School and is working in Nuclear Physics Division since 2002. She did her M.Sc. in Physics from Lucknow University. Ms. Rajni Pande is involved in Physics Studies of the 20 MeV High Intensity Proton Accelerator being developed for ADS Programme.

Ms. Shweta Roy is working in Nuclear Physics Division, BARC since 2003. She is from the 46th batch of BARC Training School. She did her Masters in Physics from IIT, Delhi. Ms. Shweta Roy is involved in Physics Studies of the 20 MeV High Intensity Proton Accelerator being developed for ADS Programme.
Dr Pitamber Singh, a graduate of the 19th batch of BARC Training School, joined Nuclear Physics Division, BARC in 1976. He received his Ph.D. degree in Physics from Mumbai University in 1983. In addition to designing and building the first 2 MV Tandem Accelerator, he has made an outstanding contribution in setting up the 6 MV Foded Tandem Ion Accelerator (FOTIA) facility at BARC. He was conferred DAE’s Technical Excellence Award for the year 2000 for his contributions towards indigenous development of accelerator technology in the country. He is a life member of “The National Academy of Sciences, India”. Dr. Singh is working on the development of High Intensity Proton Accelerators for the ADS programme of DAE. Presently, he is Head, FOTIA Section of the Nuclear Physics Division, BARC.

Ms. T. Basak was working in Nuclear Physics Division, BARC as a Ph.D. student since 2002. She did her Masters in Physics from University of Mumbai. Ms. Basak is involved in Physics Studies of the 20 MeV High Intensity Proton Accelerator being developed for ADS Programme.

Mr. S.V.L.S. Rao did his Masters in Physics from University of Hyderabad in 2000 and joined Nuclear Physics Division in 2001 after one year of Orientation programme at BARC. Mr Rao is presently involved in development of High Current Accelerator for ADS.