HIGH POWER ACCELERATOR DEVELOPMENT PROGRAM AT BARC

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Abstract

The Department of Atomic Energy is planning to build an Accelerator Driven subcritical reactor System (ADS) in connection with its Thorium utilization programme. One of the important components of the ADS is high power proton accelerator which involves development of both normal and superconducting accelerating structures. The hands-on maintenance of the accelerator requires that beam loss, particularly in the high energy sections, should be less than 1 nA/m. One of the sources of this beam loss is halo formation which is normally due to mismatching of the beam parameters at transitions at low energy end. Therefore front-end of the accelerator should be carefully designed and parameters at transitions should be properly matched. We have done detailed beam dynamics studies for a 1 GeV, 30 mA proton linac for our ADS programme. The beam will be accelerated to 100 MeV using room temperature structures and from 100 MeV to 1 GeV by superconducting elliptical cavities. The beam transmission is calculated to be about 97%. It is proposed to build the accelerator in 3 phases. In the first phase, a low energy high intensity proton accelerator (LEHIPA) is under construction at BARC. In LEHIPA, a 50 keV proton beam from an ECR ion source will be accelerated to 3 MeV by an RFQ and then to 20 MeV using a Drift Tube Linac. Both the structures, RFQ & DTL, will operate at 352.21 MHz in CW mode. Permanent Magnet Quadrupoles (PMQ) will be used in DTL for focusing the beam. Prototypes of ion source, LEBT, RFQ, DTL and PMQ have been fabricated and characterized. RF sources have been procured and the tunnel which will house the LEHIPA is ready.

In this talk, details of the project, its present status and future plans will be discussed.

INTRODUCTION

Accelerator Driven Systems [1] are attracting worldwide attention due to their capability to incinerate minor actinitides (MA) and Long-lived fission products (LLFP) and to utilize Thorium as a nuclear fuel for the production of energy without much radioactive waste. Indian interest in ADS is related to the planned utilization of our large thorium reserves [2] for future nuclear energy generation. The ADS mainly consists of a High Power proton accelerator (1 GeV, 10's of mA current), Spallation target and the Sub-critical reactor.

It is planned to develop the High Power Accelerator for ADS in 3 phases, namely, 20 MeV, 100 MeV and 1 GeV. The most challenging part of this accelerator is the development of low energy injector, because the space charge effects are maximal at low energies. Therefore, BARC has initiated the development of a 20 MeV, Low energy high intensity proton accelerator (LEHIPA) as the front-end injector for 1 GeV accelerator for ADS in first phase.

The major components of the LEHIPA [3] are a 50 keV ECR ion source, a 3 MeV Radio-frequency quadrupole (RFQ) and a 20 MeV drift tube Linac (DTL). The schematic layout of the 20 MeV Linac for LEHIPA is shown in Fig. 1. In this paper, the status of components of LEHIPA is discussed.

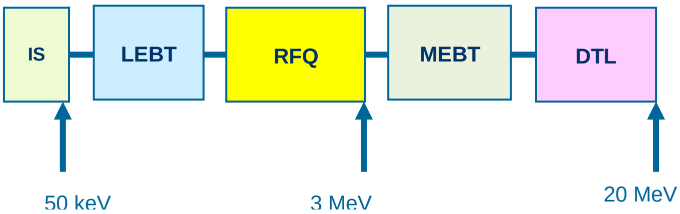

Fig. 1. Layout of the 20 MeV Linac for LEHIPA.

ECR ION SOURCE

The 50 keV, 60 mA ECR ion source for LEHIPA is being developed by the Accelerator and Pulsed Power Division, BARC [4]. In order to optimize the beam emittance, a five electrode extraction geometry has been used. An ion source with three electrode extraction geometry has been fabricated. A 42 mA beam (unanalysed total current) has been extracted from this source at 40 kV. The source is now being optimized for reliable and long time operation. Beam diagnostic for characterization of beam emittance and proton fraction are under progress.

LOW ENERGY BEAM TRANSPORT LINE (LEBT)

A solenoid based magnetic LEBT line is being used to match a 50keV, 30 mA proton beam from ECR ion source to the RFQ. The LEBT is about 3 m long. The LEBT design has been done and the optimized parameters are given in Table 1. Based on these simulations, the two solenoids for LEHIPA have been designed for a maximum field 3.5 kG and effective length of 30 cm, at BARC and fabricated and tested at RRCAT. The results of the measurements are in good agreement with simulations. The LEBT line also consists of the beam diagnostic elements like beam profile monitors, DCCT, ACCT etc.

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Table 1: LEBT Parameters

Element	Length (cm)	Strength (kG)
Drift	90	
Solenoid	30	1.6
Drift	90	
Solenoid	30	1.9
Drift	18	

Streering magnets have been designed to steer the beam by ±3 cm in both X and Y directions from the axis of the beamline at a distance of 75 cm from the entrance of the steering magnet. The details of the designs are given in Ref [5]. The procurement of the various diagnostic elements is in progress.

RADIO FREQUENCY QUADRUPOLE (RFQ)

The RFQ is a high-current linear accelerator with high capture efficiency for low velocity ions. The physics design of the 352.21 MHz, 3 MeV four vane RFQ has been done. We have employed the conventional design procedure where the RFQ has been divided into 4 sections: Radial matcher section, shaper, Gentle buncher and Accelerator. This procedure makes the fabrication and tuning of the RFQ cavity easier. The optimized parameters of the RFQ are given in Table 2.

Table 2: Optimized Parameters of RFQ

Parameters	Values	Units
Ions	H+	
Frequency	352.21	MHz
I/O energy	0.05/3.0	MeV
Current	30	mA
Vane voltage	85	kV
Peak field	32.5	MV/m
Modulation	1.96	
Average radius	0.3556	cm
I/P Norm. RMS emittance	0.02	π cm-mrad
O/P Norm. RMS emittance	0.02	π cm-mrad
Long. Norm emittance	98.13	deg-keV
Length	4	m
Transmission	99.2	%
RF Power	550	kW

A single segment of the 4 m long RFQ will be very unstable because the longitudinal higher-order modes (HOMs) are very close in frequency to the accelerating mode. The cavity has therefore been split into four 1 m sections. These four sections are made into two 2 m long segments and the LEDA resonant coupling technique [6] will be followed to make the structure insensitive to the mechanical errors. The detailed 2D and 3D electromagnetic design of the RFQ has been done [7].

The 3D CAD model and the mechanical drawings of the LEHIPA RFQ have been prepared. Each RFQ section will be made of four OFE copper vanes; two major and two minor vanes. We are following the two step brazing process, where in the first step the two major and minor vanes are brazed to make the RFQ cavity assembly. In the second brazing step various ports and flanges are brazed at marginally lower temperature.

MEDIUM ENERGY BEAM TRANSPORT LINE (MEBT)

The Medium energy beam transport line is used to match the beam from RFQ to DTL. It consists of four quadrupoles and two RF gap for matching the beam in transverse and longitudinal direction respectively. We have given a provision for placing a BPM and wall current monitor at the beginning and at middle of the MEBT line. The effective voltage seen by the particle in the RF gap is around 0.13 MV and the quadrupole field gradients are in the range of 30-48 T/m. The total length of the MEBT line is about 1 m.

DRIFT TUBE LINAC (DTL)

The DTL can accelerate a high intensity proton beam very effectively in the energy range 3 to 50 MeV. For LEHIPA, an Alvarez type DTL has been designed to accelerate the proton beam from 3-20 MeV. The optimized parameters of the DTL are given in Table 3. In order to have current independent matching between the RFQ and DTL, the quadrupole gradients for FD focusing lattice is ~ 80 T/m However, if FFDD lattice is considered, the required quadrupole gradient is 46.5 T/m. The design of permanent magnetic quadrupole (PMQ) has been done and prototype PMQs have been fabricated by the Control and Instrumentation Division, BARC. Field gradients of 50 T/m have been measured which are in good agreement with the simulations.

Table 3: Optimized parameters of DTL

Parameter	Value	Units
I/O energy	3/20	MeV
Frequency	352.21	MHz
Current	30	mA
No. Of Tanks	4	
Total length	12.86	m
Total RF power	1.3	MW

Type of quadrupole	PMQ	
Focussing Lattice	FFDD	
Norm.RMS emittance	0.021	π cm-mrad
Long. Emittance	115.36	deg-keV

The total length of the DTL is 12.86 m. So for the ease of fabrication it will be built in four tanks, each of length about 3.2 m. The 3D electromagnetic design of DTL cavity [8] has been done using CST Microwave studio.

PROTOTYPE DTL CAVITY

Based on these simulations, a prototype DTL cavity of 1.2 m long (Fig. 2) has been fabricated [9]. This prototype contains 17 drift tubes, 3 tuner ports, 2 RF ports and 1 vacuum port.

Fig. 2. Prototype DTL cavity.

The RF characterization of prototype cavity has been done. The resonant frequency was measured to be 349.9 MHz, which is only 1 MHz off from the simulated value. The field distribution has also been measured using bead pull measurement (Fig. 3) setup and with the help of 3 tuners the field uniformity was obtained within ±2% except in the end cells.

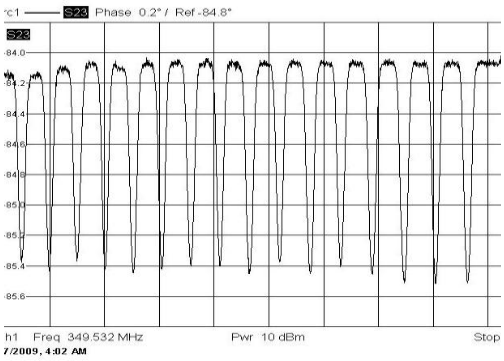

Fig. 3. Phase of S_{23} along the DTL axis.

In the actual DTL cavity, the PMQs are housed inside the drift tubes. Housing the PMQs inside the Drift tubes of the DTL and maintaining the vacuum tight metal joints is a tedious job. Laser welding seems to be best option for these types of joints. However, high thermal conductivity of copper makes the laser welding difficult. In order to see the complexities involved in the laser welding, trials were initiated at RRCAT, Indore. A Nd-Yag pulsed laser, of wavelength 1064 nm, with a peak power of 7 kW and average power of 500 W was used for these trials.

400 keV DEUTERON ACCELERATOR

In order to gain experience regarding the fabrication of CW RFQs and handling of high RF power, it was planned to develop a 400 keV, 1 mA deuteron RFQ, which will replace an existing 400 keV DC accelerator for deuteron at PURNIMA facility at BARC. The detailed physics and cavity design of the entire 400 keV accelerator have been done. The total length of the entire Linac including its LEBT is about 2.25 m.

LEBT TEST BENCH

In order to validate the simulations and to see the focussing action of solenoids, an LEBT test bench has been setup at BARC using an existing Alphatros ion source. The test bench (Fig. 4) consists of an ion source, Einzel lens, accelerating tube and 2 solenoids. In order to measure the beam current and size we have used 2 Faraday cups and 2 BPMs. He^+ beam of current 100 µA has been extracted from the ion source and accelerated to 50 keV.

Fig. 4. LEBT test bench at BARC.

The emittance of He^+ beam at the end of the LEBT test bench has been measured using the solenoid scan method [10]. The horizontal and vertical beam profiles are measured using the BPMs. The normalized RMS emittance is calculated to be 1.8 π mm-mrad.

RFQ PROTOTYPE

In order to validate the simulations, two 400 keV RFQ prototypes of length 50 cm (without modulations) and 60 cm (with modulations) have been fabricated simultaneously at two different vendors. The RF characterization of these prototypes has been done. The resonant frequencies are observed to be 344, 353 and 356 MHz respectively. By S_{21} phase measurements we have identified the modes. We found that the lowest mode is the quadrupole mode and other higher frequencies are the dipole modes. The field distribution for the quadrupole frequencies has been done using the bead pull measurement setup as shown in the figure 5.

Fig. 5. Bead pull measurement setup.

The field distribution of the lowest mode frequency is shown in Fig. 6. From these measurements we have found that the dipole contribution is nearly 40% of the quadrupole component.

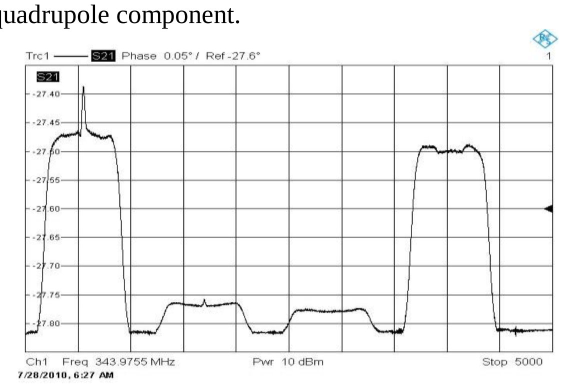

Fig. 6. Magnetic field distribution in all the four quadrants.

The fabrication of third prototype of length 1.02 m is in progress at BATL, Trivandrum. The four vanes have been machined and the machining tolerances that were achieved are listed in Table 4.

Table 4: Machining tolerances achieved on the Vanes

RFQ Tolerances	Value	Units
Machining error	± 20	µm
Vane modulation error	± 20	µm
Vane thickness error	± 10	µm
Vane Flatness error	± 50	µm

RF COUPLER

For LEHIPA project, the RF power requirement is around 1.9 MW. So it is planned to use 10 wave guide couplers (2 for RFQ and 8 for DTL) with a power ratings of 275 kW each.

The power requirement for the 400 keV RFQ is only around 70 kW. We plan to use two coaxial loop couplers with power ratings of 35 kW each. The design of these wave guide and coaxial couplers have been done [11]. The design of a 50 kW, 350 MHz pulsed power coupler [12] for RFQ conditioning has been done at BARC and fabrication is in progress at CEERI, Pilani. A prototype of this power coupler has been fabricated (Fig. 7) with a leak rate of 5e-10 in RF window of pulsed power coupler.

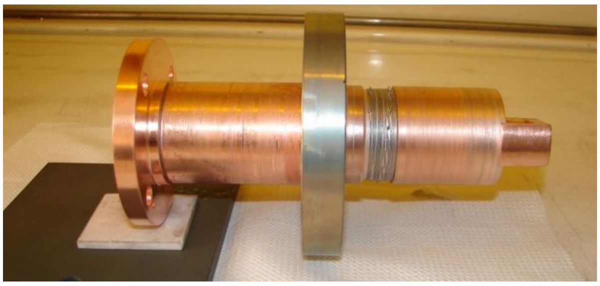

Fig. 7. Prototype RF Coupler.

BEAM DYNAMICS OF 1 GeV ACCELERATOR

The beam dynamics of 1 GeV accelerator for ADS has been done. Normal conducting structures will be used upto 100 MeV and for 100-1000 MeV, superconducting elliptical cavities with gradients of 15 MV/m have been designed. The overall length of the Linac comes to be 650 m. In view of the advancement in SC technology, it is planned to design the Linac by considering other structures like spoke cavities.

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