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Accelerator development in India for ADS programme

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Abstract. At BARC, development of a Low Energy High Intensity Proton Accelerator (LEHIPA), as front-end injector of the 1 GeV accelerator for the ADS programme, has been initiated. The major components of LEHIPA (20 MeV, 30 mA) are 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 match the beam from the ion source to RFQ and from RFQ to DTL respectively. Design of these systems has been completed and fabrication of their prototypes has started. Physics studies of the 20–1000 MeV part of the Linac are also in progress. In this paper, the present status of this project is presented.

Keywords. High intensity proton Linac; space charge compensation; beam dynamics; radio frequency quadrupole; drift tube Linac; accelerator driven sub-critical reactor system.

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1. Introduction

Accelerator driven sub-critical reactor systems (ADS) [1] have evoked considerable interest in the nuclear community the world over because of their capability to incinerate the MA (minor actinides) and LLFP (long-lived fission products) radiotoxic waste and for converting a fertile material into fissile nuclear fuel. Since India has vast resources of thorium, ADS offers a potential route for accelerated thorium utilization [2].

ADS mainly consists of a sub-critical reactor coupled to a high power proton accelerator through spallation target as outlined in figure 1. The practical realization of ADS requires development of a high energy (∼1 GeV) and high current (>20 mA) proton accelerator to produce the intense spallation neutron source needed to drive the sub-critical reactor assembly. Also, it is necessary that the accelerator is reliable, rugged and stable in order to provide uninterrupted beam power to the

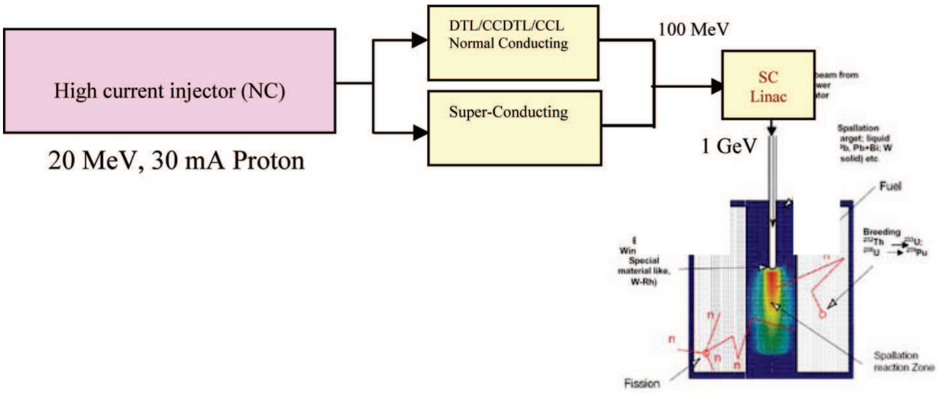

Figure 1. Schematic of ADS.

spallation target, over long periods of time. It should also have a high efficiency (30–40%) for conversion of electric power to beam power. The beam loss in the accelerator must be less than 1 W/m so that hands-on-maintenance of the accelerator subassemblies can be safely done. For ADS, operation of accelerator should be in nearly CW mode to avoid undesirable thermal shocks to the fuel elements.

In high current proton accelerators, the dominance of space charge effect at lower energies causes beam loss and also initiates oscillatory particle motions that appear later as a beam halo in the high-energy sections. The beam halo is the dominant particle loss mechanism resulting in severe activation of components in the Linac and is closely connected to the emittance mismatch in the low energy sections of the accelerating structure. For these reasons, it is very important for beam to smoothly move across segments in the low-energy injector sections. It is envisioned that the 1 GeV accelerator for ADS be pursued in three phases, namely, 20 MeV, 100 MeV and 1 GeV. 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 at low energies.

Therefore, BARC has initiated the development of a low energy (20 MeV) high intensity proton accelerator (LEHIPA) as the front-end injector of the 1 GeV accelerator for the ADS programme.

The major components of LEHIPA are a 50 keV ECR ion source, a 3 MeV radio-frequency quadrupole (RFQ) [3] and a 20 MeV drift tube Linac (DTL) [4]. The LEBT and MEBT lines will match the beam from the ion source to RFQ and from RFQ to DTL respectively. The main criterion for the design of the Linac is to have minimum beam loss. The layout of the 20 MeV accelerator is shown in figure 2. In this paper, the present status of this project is discussed. The activities related to accelerator development for ADS at other centres are also briefly mentioned.

2. Ion source

The 50 keV, 60 mA ECR ion source for LEHIPA is being developed by the Accelerator and Pulsed Power Division, BARC [5]. In order to optimize the beam

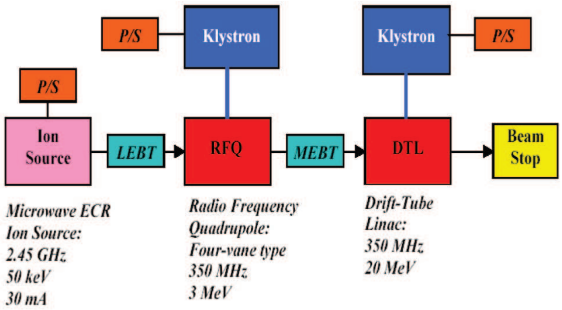

Figure 2. Layout of LEHIPA.

emittance, a five electrode extraction geometry has been used. For the design of subsequent systems a normalized rms emittance of 0.02π cm mrad has been used.

3. Low energy beam transport line (LEBT)

The main criterion for the design of the LEBT is to match the phase space ellipses of the DC proton beam from the ECR ion source to RFQ with minimum emittance growth. This matching has been done using two solenoids ($\sim$3 kG). At lower energies, space charge forces are very strong and cause increase in the size and emittance of the beam. In order to reduce these effects, space charge compensation [6] is done by introducing a residual gas like hydrogen or inert gases in the LEBT. Due to ionization of the residual gas atoms by the proton beam, electrons and ions are created. The ions are repelled radially outward from the beam while the electrons are trapped by the beam potential. So the effective space charge of the beam is gradually reduced until it reaches a stationary degree of compensation. Simulation studies show that there is no emittance growth in the LEBT when the beam is more than 95% space charge compensated [7]. Also the maximum beam radius is restricted to less than 3.4 cm as compared to 6.5 cm in an uncompensated LEBT.

4. Radio frequency quadrupole accelerator (RFQ)

The RFQ is a high-current linear accelerator with high capture efficiency for low-velocity ions. It focuses, bunches and accelerates the beam simultaneously. The physics design of the 350 MHz, 3 MeV, four vane RFQ has been done. The input and output parameters of RFQ are listed in table 1.

The geometry of the vanes of the RFQ for a resonant frequency of 350 MHz was optimized using the 2D electromagnetic code SUPERFISH [8]. The RFQ is operated in the TE_{210} mode, which cannot be excited in a closed cavity. In order to excite the RFQ in a TE_{210}-like mode, the vane ends are provided with undercuts as shown in figure 3 to satisfy the required boundary conditions. The vane undercuts have been

Table 1. Parameters of the RFQ.

Parameter	Value	Unit
Input energy	50	keV
Output energy	3	MeV
Frequency	350	MHz
Beam current	30	mA
RMS emittance	0.02	π cm-mrad
Vane voltage	81.5	kV
Average aperture (R_o)	3.66–4.37	mm
Transmission efficiency	97	%
Length	3.62	m
Total RF power	430	kW
Peak electric field	32.96	MV/m

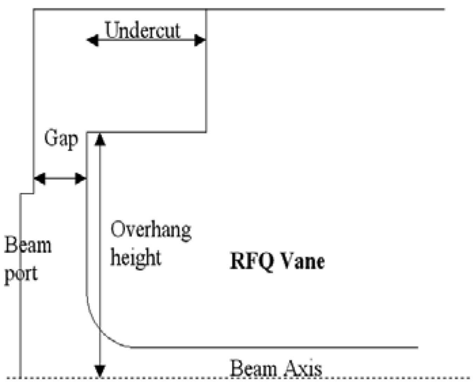

Figure 3. Longitudinal profile of the beginning/end cell.

Table 2. Parameters of beginning and end cell.

Parameter	Beginning cell (mm)	End cell (mm)
Overhang height	60	60
Undercut length	36.5	35
Beam port radius	45	55
Gap between vanes and end walls of the cavity	11	5

optimized using 3D electromagnetic code MAFIA [9]. The optimized parameters of the vane undercuts are listed in table 2.

The mode separation between the operating mode (TE_{210}) and the nearest higher order longitudinal mode (TE_{211}) in a 3.62 m long RFQ is relatively small as can be seen in figure 4. Hence, it is proposed to fabricate the RFQ in smaller sections, which will be coupled resonantly using coupling cells as shown in figure 5.

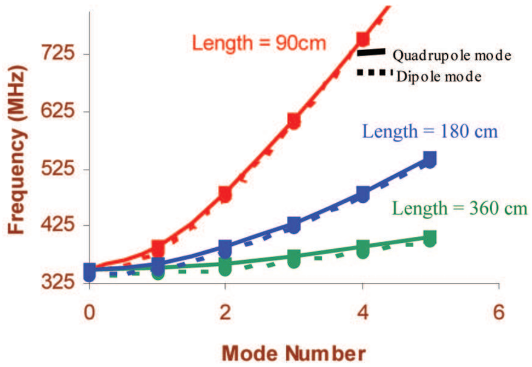

Figure 4. Variation of higher order dipolar and quadrupolar frequencies with RFQ length.

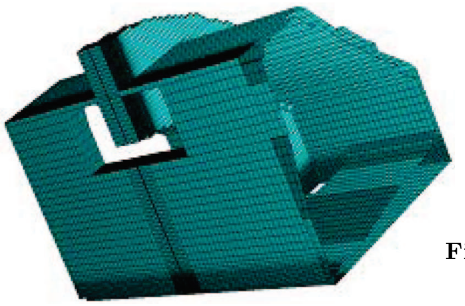

Figure 5. MAFIA model of the coupling cell.

Table 3. Parameter of the coupling cell.

Parameter	Value (mm)
Overhang height	60
Undercut length on each side	35.5
Width of coupling plate	20
Inner radius of coupling plate	70
Outer radius of coupling plate	100

The coupling cell dimensions were optimized to obtain longitudinal stability in the RFQ. The parameters of the coupling cell are shown in table 3.

In RFQ design, it is important to study the effect of errors on the beam dynamics. Therefore, the effect of errors like beam misalignments, vane voltage tilts etc. have been studied. Based on these error analyses, the following tolerances are specified:

1. Alignment of the RFQ: 50 μm,
2. Beam tilt: 5 mrad,
3. Energy spread of the beam: 1%,
4. Tolerance on incoming proton beam energy: 0.5 keV.

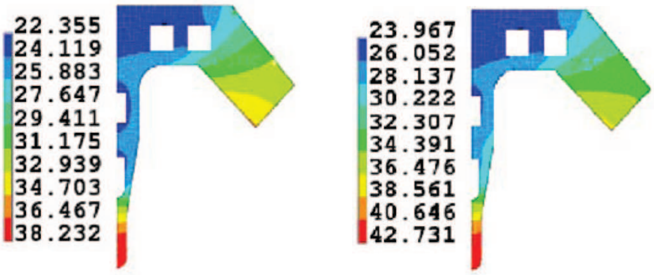

Figure 6. Temperature distribution in the vane at the inlet and the outlet.

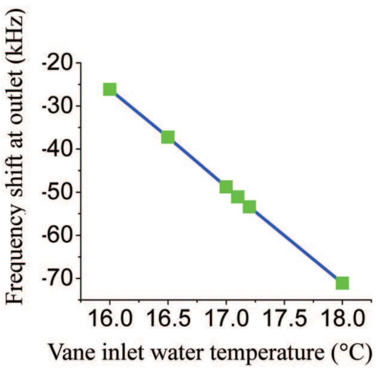

Figure 7. Dependence of frequency shift on inlet water temperature.

The integrated thermal/structural analysis of an RFQ is crucial to its design and operation. The total power dissipated in the RFQ structure is estimated to be 342 kW. This power dissipation can cause large temperature gradient in the RFQ structure along with distortion in the vane, which leads to de-tuning of the structure. The cooling scheme is designed to minimize temperature rise in the RFQ and control the de-tuning to less than 80 kHz. The inlet coolant water temperatures are chosen to be 16°C (vane tip) and 20°C (outer). The temperature distribution in the vane at the inlet and the outlet are shown in figure 6.

The vane tip deflection at the inlet and outlet are 0.03 μm and 2.4 μm respectively, which corresponds to the de-tuning of +30 kHz and +65 kHz respectively. The variation of frequency shift at the outlet as a function of vane inlet water temperature is given in figure 7. The tolerance on the inlet coolant water temperature is estimated to be ±0.1°C for correction of the resonant frequency during operation.

5. Medium energy beam transport line (MEBT)

The MEBT is used to match the beam from RFQ to DTL. It consists of four quadrupoles and one RF gap for matching the beam in transverse and longitudinal direction respectively. The effective voltage seen by the particle in the RF gap is

0.2 MV and the quadrupole field gradients are in the range of 10–58 T/m. The total length of the MEBT is about 70 cm.

6. Drift tube Linac (DTL)

The DTL can focus and accelerate a high intensity proton beam very effectively in the energy range 3 to 50 MeV, where the space charge forces are considerable. In LEHIPA, an Alvarez-type DTL operating in the TM_{010} mode is chosen to accelerate the beam from 3 to 20 MeV. The transverse geometry of the DTL cavity was optimized to maximize the effective shunt impedance at 350 MHz using SUPERFISH. The variation of effective shunt impedance with energy is shown in figure 8. The parameters of the DTL cavity are shown in table 4.

It is proposed to make the DTL in two tanks which will accelerate the beam from 3–10 MeV and 10–20 MeV respectively. The axial electric field will be ramped in the first tank from 1.38–3.00 MV/m and kept constant at 3 MV/m in the second tank. The beam dynamics of the DTL using FD lattice has been studied using PARMILA [10] code. The input and output parameters of the DTL are shown in table 5.

The transverse phase advance per unit length in the RFQ and DTL should be the same for current independent matching. This requires very high quadrupole

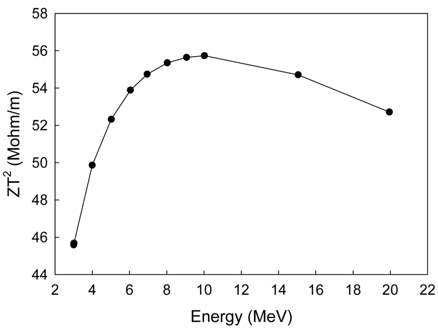

Figure 8. Variation of effective shunt impedance with energy.

Table 4. Parameters of DTL cavity.

Parameter	Value	Unit
Cavity diameter	54	cm
Drift tube diameter	11	cm
Aperture	1.6	cm
Corner radius	1.5	cm
Nose radius	0.5	cm
g/L	0.26–0.36	
$E_{\max}$	6.54–12.71	MV/m

Table 5. Parameters of the drift tube Linac.

Parameter	Value	Unit
Input energy	3	MeV
Output energy	20	MeV
Frequency	350	MHz
Beam current	30	mA
Total length	9.51	m
Beam power in DTL	510	kW
Beam transmission	100	%
Effective length of quad.	4.41	cm
Quadrupole gradient	80.0	T/m
Total power (dissipated+beam)	1.36	MW

Figure 9. Conical target for beam dump.

gradients in the DTL if FD lattice is considered, making the design of electromagnetic quadrupoles (EMQs) difficult at the low-energy end. However, if FFDD lattice is considered, the required quadrupole gradient is 46.5 T/m [11], making the design of EMQs comparatively easy.

7. Beam dump

A target for beam dump of 600 kW proton beam from LEHIPA has been designed covering thermal and structural requirements. A conical shape and nickel bulk was chosen for preliminary analysis of this target (figure 9) and design of the water-cooling system has been finalized.

8. 400 keV RFQ

The 20 MeV Linac involves handling of large RF power at 350 MHz and fabrication of complex structures like RFQ. Presently, no experience exists in building long and complex structures such as CW RFQs, handling high RF power. It was therefore

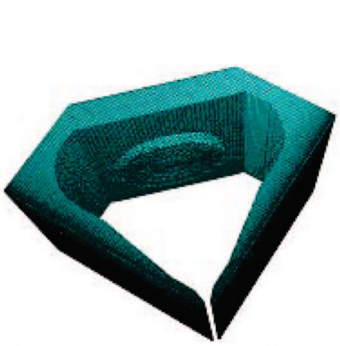

Figure 10. RFQ cavity with tuner.

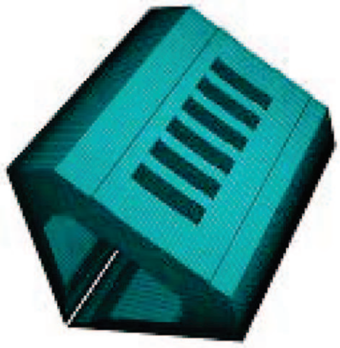

Figure 11. RFQ cavity with vacuum port.

thought prudent to develop a small RFQ, which will also be useful to our department's programme. So it has been decided to develop a 400 keV, 1 mA deuteron RFQ at the same frequency of 350 MHz. This RFQ will replace an existing 400 kV DC accelerator for deuteron at PURNIMA facility at BARC, which is used as a neutron generator [12].

The physics design of the 400 keV RFQ for deuteron beam has been completed [13]. The total length of this Linac including its LEBT section is about 2.25 m. The transmission at the end of the Linac is 95%. The detailed 3D design of this RFQ has been done, which includes the design of beginning and end cells, tuners and vacuum ports. The tuning range of all the 16 tuners (each of diameter 4.5 cm) is found to be (−2.1 MHz, 4.29 MHz) for a penetration of (−15 mm, 10 mm). The de-tuning due to all the 8 vacuum ports is 900 kHz, which can be compensated by inserting the vacuum port assembly in the volume of the RFQ by 3 mm. The MAFIA model of the tuner and the vacuum port are shown in figures 10 and 11 respectively. Thermal analysis of this RFQ has also been done.

RF design of inductive couplers (40 kW each) has been completed and its complete assembly is shown in figure 12a.

Coupling coefficient can be varied from 0 to 1.5 by rotating the coupler inside the cavity. Resonant frequency shift of the quadrupolar mode of RFQ cavity with four loop couplers has been kept within 2 MHz. The maximum power loss density estimated on the coupler using MAFIA code is about 56 W/cm^2 as shown in figure 12b. Cooling arrangement and its final mechanical design are being worked out.

To validate the simulations, a 50 cm aluminium model has been fabricated without modulation. The RF characterization of this cavity is under progress. The complete CAD and aluminium models of 400 keV RFQ are shown in figures 13a and 13b. The resonant frequencies of different modes have been measured with VNA. Inductive couplers of different sizes have been used for RF measurements to study the variation of coupling coefficient. The results are being compared with the EM simulations using MAFIA.

A preliminary design of the 100 MeV Linac using DTL has also been done. The transmission efficiency through the DTL is 99%. The total length of the 3–100 MeV Linac is about 60 m and the total power required is 9.6 MW. The input and output parameters of the 100 MeV Linac is listed in table 6.

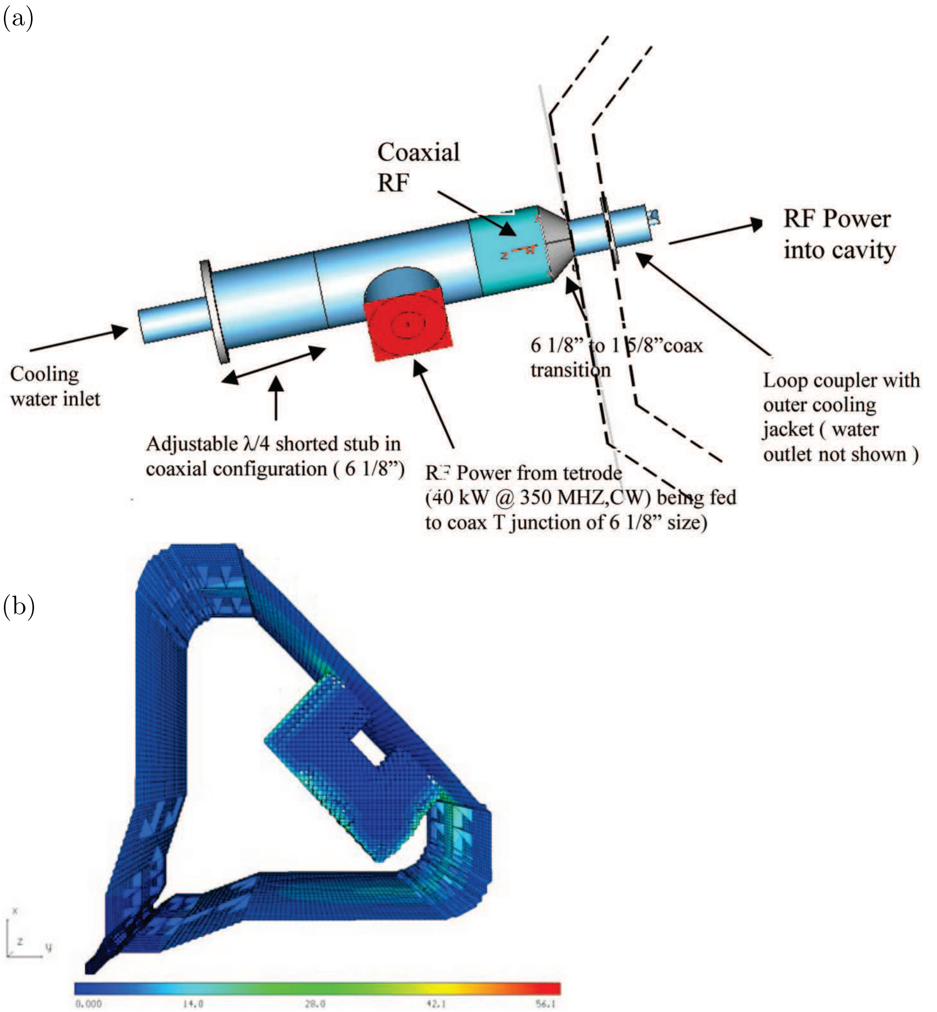

Figure 12. (**a**) Schematic of 40 kW RF loop coupler assembly. (**b**) Power loss density distribution on loop coupler in W/cm^2.

The Linac for accelerating proton beam from 100 MeV to 1 GeV will be of superconducting type. Design and development of superconducting cavities at 700 MHz for this energy range is also in progress at BARC [14,15]. Depending upon the experience gained during these developments, the 20–100 MeV section of the accelerator could also be of superconducting type. As part of the Indian ADS programme, development of a 10 MeV high current cyclotron is in progress at VECC, Kolkata [16]. Also design studies of a 100 MeV high current, normal conducting Linac have been taken up at RRCAT, Indore [17] which will be used as an injector to the 1 GeV rapid cycling synchrotron (RCS) for spallation neutron source.

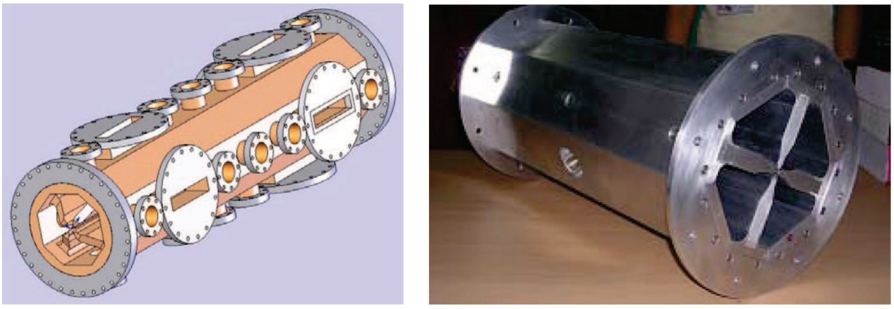

Figure 13. (**a**) CAD model of 400 keV RFQ. (**b**) Aluminium model of RFQ.

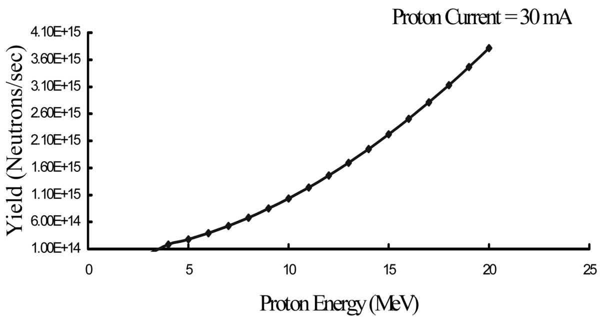

Figure 14. Neutron yield vs. proton energy for beryllium target.

Table 6. Parameters of 100 MeV Linac.

Parameter	Value	Unit
Resonant frequency	350	MHz
Input energy	3	MeV
Output energy	100	MeV
Beam current	30	mA
Beam transmission	99	%
Total length	59.6	m
Total power	9.6	MW
Type of lattice	FD	
Quadrupole gradient	80	T/m
Effective length of quad.	4.41	cm

9. Applications of LEHIPA

The beam from LEHIPA will be used to produce neutrons via ^{9}Be(p,n)^{9}B reaction. A neutron yield (figure 14) of 4.0×10^{15} n/s will be obtained from 20 MeV proton beam of 30 mA current [18]. These neutrons can be used for both basic and applied research. In future, the proton beam from LEHIPA can also be injected into AHWR in order to perform ADS related experiments.

10. Summary and conclusions

The physics design of LEHIPA, a 20 MeV, 30 mA proton Linac has been completed [4] and the beam dynamics studies for the entire 1 GeV Linac is in progress [15]. In order to get hands-on experience in handling high power at 350 MHz, a 400 keV deuteron RFQ, for neutron generation at PURNIMA facility, has been designed [13] and is being fabricated. This facility will be used for studying neutron multiplication in a sub-critical assembly.

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