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Design of a 10 MeV, 352.2 MHz drift tube Linac

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Abstract. A conventional 10 MeV drift tube Linac is designed as a part of the H^- front end accelerator system for the future Indian Spallation Neutron Source. The front end Linac consists of a 50 keV H^- ion source, low energy beam transport (LEBT), a 3 MeV radio frequency quadrupole (RFQ), and a 10 MeV drift tube Linac (DTL), which will be operated at 1.25% duty factor. Cell geometry of the DTL is optimized to house quadrupole magnets and to get maximum effective shunt impedance. Transmission efficiency and various other output parameters depend on the input design parameters. Beam dynamic studies are done to maximize the transmission efficiency with minimum emittance growth. Errors in the alignment of the quadrupoles inside the drift tubes or the DTL tank alignment with respect to transport line will degrade the beam quality and may reduce the transmission efficiency. Error study is performed to assess the acceptable tolerances on various parameters. This paper describes the 2D and 3D electromagnetic and beam dynamics simulations of the 352.2 MHz, 10 MeV drift tube Linac. Details of the DTL design are reported in this paper.

Keywords. Drift tube Linac; electromagnetic simulations; beam dynamics simulations.

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1. Introduction

It was proposed to develop a low-energy front end accelerator system for high power pulsed H^- injector Linac for the future Indian Spallation Neutron Source. The basic layout of the DTL which is a part of the injector Linac is shown in figure 1. It consists of a 50 keV, 35 mA multicusp H^- ion source, a low energy beam transport (LEBT) system that will transport the beam from the ion source and match it to the 3 MeV radio frequency quadrupole (RFQ), and a 10 MeV DTL. This report describes the design aspects of a 10 MeV drift tube Linac.

DTL is an Alvarez-type structure, where we have a cavity operating in TM_{010} mode loaded with drift tubes, each of length $\beta\lambda$, which increases with an increase of energy along its axis to maintain synchronism between the particle and the RF wave. Each drift tube is supported by a radial stem. The drift tubes house the quadrupole magnets for focussing. The phase difference between successive cells is termed as coupled cavity

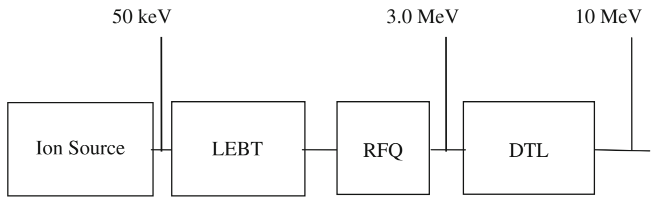

Figure 1. Schematic of the project.

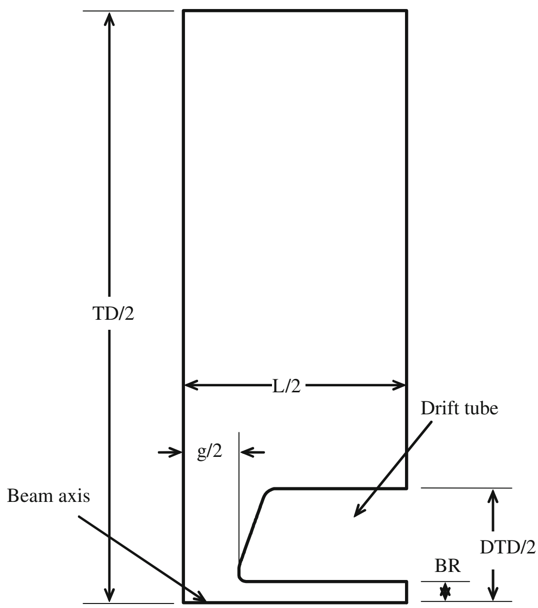

Figure 2. 1/4th unit cell drift tube geometry. TD – tank diameter, DTD – drift tube diameter, BR – bore radius, g – gap length, L – cell length.

mode, i.e. the Alvarez Linac operates in zero mode. This structure is quite efficient at low energies, typically from 3 to 50 MeV, where the space charge forces are considerable. Details of a representative 1/4th unit cell is shown in figure 2.

The detailed view of the drift tube is shown in figure 3. The design input parameters of 10 MeV DTL are given in table 1.

2. Choice of the structure

The DTL structure has a reasonable value of effective shunt impedance in the medium energy range, i.e. 3–50 MeV, thus avoiding excessive power dissipation. At higher energies, the DTL structure becomes inefficient due to the decrease in effective shunt impedance (ZT^2) and is taken over by other structures like separated function drift tube Linac (SFDTL), coupled cavity drift tube Linac (CCDTL), etc. In the low-energy regime, inter-tank focussing in SFDTL leads to inferior beam quality which may lead to

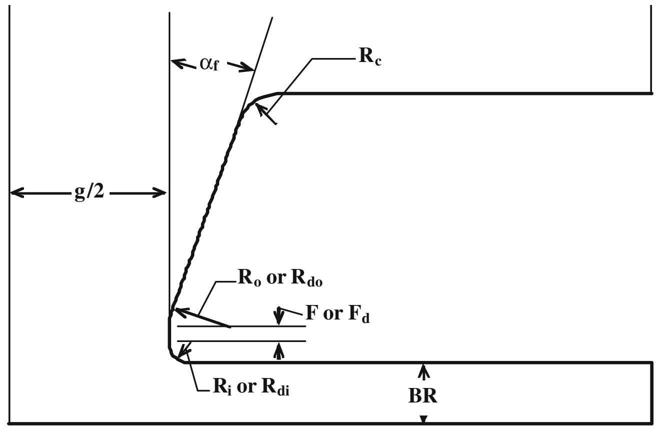

Figure 3. Detailed view of the drift tube. R_i – inner nose radius, R_c – corner radius and α_f – face angle.

Table 1. Design details of the DTL tank.

Particles	H^-
Injection energy	3.0 MeV
Output energy	10.0 MeV
RF Frequency	352.21 MHz
Peak current	30 mA
Pulse duration	500 μs
Pulse repetition rate	25 Hz
Accelerating structure	Alvarez
Field flatness	Post couplers
Focussing	Quadrupoles (FOFODODO)

beam loss. Also small tanks lead to additional power loss and hence to reduced effective shunt impedance. CCDTL is less efficient at lower energies because of additional power loss on end walls. Intercell coupling makes the CCDTL difficult to fabricate and cool.

3. Selection of the parameters

The geometrical parameters are to be selected as a compromise between maximum shunt impedance (Z), freedom from voltage breakdown, provision for housing the focussing quadrupoles inside the drift tubes, ease of structure fabrication etc.

(i) *Resonant frequency (f)*: At higher frequencies, problems of mechanical fabrication multiply rapidly and the tolerances become quite stringent. Also the cell size decreases making it difficult to house the quadrupoles and accommodate the cooling channels. At the same time higher frequency allows higher gradients thus reducing the length of the structure. Typical frequencies vary from 200 to 400 MHz. We have chosen the frequency as 352.21 MHz based on the availability of power source.

(ii) *Bore radii (BR)*: The transit time factor as a function of radius is given by

$$T(r) = \frac{I_0(kr)\sin(\pi g/L)}{I_0(ka)\pi g/L}, \tag{1}$$

where $k = 2\pi/\beta\lambda$, I_0 is the modified Bessel's function, g/L is the gap-to-cell length ratio and a is the bore radius. It can be seen from eq. (1), that the transit time factor decreases as the bore radius increases. Hence a smaller bore radius is preferred. However, the bore radius has to be chosen in such a way that (1) there should be enough transverse room for the particles to avoid beam loss and (2) transit time factor should be close to unity. The bore radius should be about 5–7 times the maximum rms beam radii for the efficient transmission through the DTL to be possible.

(iii) *Tank diameter (TD)*: Tank diameter is selected independent of the velocity of the particle (β) and gap-to-cell length ratio (g/L), and is adjusted to get maximum shunt impedance. The resonant frequency of the structure depends on the tank diameter and drift tube diameter. After optimizing for shunt impedance, the drift tube diameter should be selected in such a way that there should be sufficient space for the focussing quadrupoles. Constant diameter leads to significant saving in the production and fabrication cost.

(iv) *Gap-to-cell length ratio (g/L)*: For a given average gradient E_0, the gap length should be small so as to maximize the transit time factor. But if g/L is too small, it leads to excessive surface electric field on the drift tubes leading to sparking. A compromise between the two is needed. Thus generally, g/L ratio is selected to be between 0.2 and 0.4. To ease fabrication and alignment, tank diameter, drift tube diameter and the bore radius are held constant with g/L changing along the Linac.

(v) *Accelerating field gradient (E_0)*: This is to be close to the maximum limit set by the breakdown. At 352.21 MHz, the Kilpatrick limit [1] is 18.437 MV/m. With modern fabrication methods and better handling techniques, the maximum electric field possible today is about 0.9 times Kilpatrick.

4. Cavity design

4.1 *2D Electromagnetic simulation*

The individual cells in a tank have been tuned to generate the cell geometry using SUPERFISH [2]. Additionally, Q factor, power loss on various surfaces, surface electric fields etc. were calculated, apart from the resonant frequency and the field distribution. The electromagnetic design aims at acceleration with ramped accelerating field gradient (E_0) with high effective shunt impedance per unit length. A particular advantage of ramping E_0 is the lower peak fields at lower beam energies with reduced risk of breakdown [3]. The electric field profile at 10 MeV is shown in figure 4.

4.1.1 *Drift tube optimization.* The effective shunt impedance was calculated as a function of β along the length of the beam axis, by varying each of the cavity parameters [4]. The design of the drift tubes was constrained by several interrelated factors: (a) desire

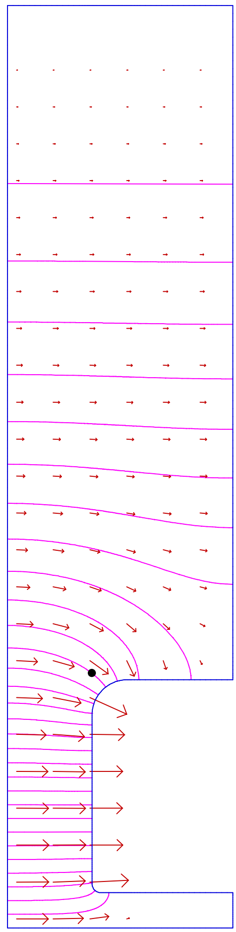

Figure 4. Electric field profile at 10 MeV.

to have a large bore size, (b) peak surface field less than 0.9 times Kilpatrick field, (c) strength and housing of qudrupoles etc. It is seen that for a given value of β, the value of transit time factor (T) decreases while Z increases, with increasing tank diameter. Thus an optimized value of tank diameter was chosen to get a high T and Z, both simultaneously. Thus, as a compromise, 52 cm is chosen as the most suitable tank diameter. The plot of ZT^2 vs. β for 52 cm TD is shown in figure 5. It is found that for all the tank diameters, lower drift tube diameter (DTD) gives the highest values of T for a given BR. But DTD of 14 cm is selected as the most appropriate value keeping in mind the space needed to install quadrupoles. Table 2 lists the optimized structure parameters of DTL.

4.2 *Beam dynamic studies*

At low energy, the main considerations will be to control the emittance growth, higher transmission efficiency to reduce the risk of structure activation. Detailed simulation

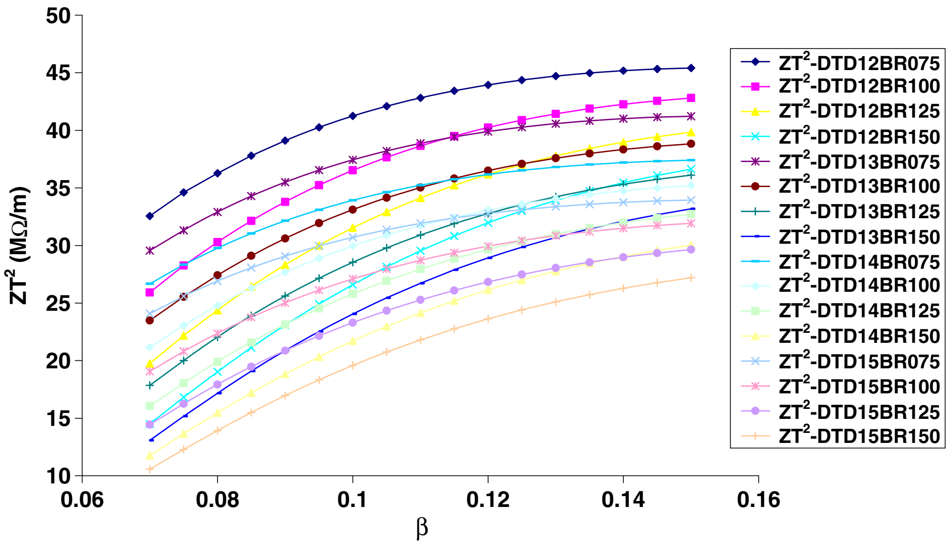

Figure 5. Plot of ZT^2 vs. β for a TD of 52 cm.

Table 2. Parameters of DTL.

Tank diameter	52.0 cm
Drift tube diameter	14.0 cm
Bore hole radius	1.0 cm
Corner radius	1.0 cm
Inner nose radius	0.25 cm
DT stem diameter	2.6 cm
Post coupler diameter	2.6 cm
Cavity loss @ 1.25%	6.914 kW
Total power loss @1.25%	9.539 kW

studies were performed to evolve the optimized design with transmission efficiency close to 100% keeping minimum emittance growth, transverse zero current phase advance per focussing period less than 90° for stability reasons and ratio of aperture-to-rms beam size around 7 etc. Detailed studies with different accelerating field gradients, synchronous phase and quadrupole gradients were performed to evolve the optimized design. Input to PARMILA [5] includes transit time data T, T' etc. other than g/L and Z for a sample set of cells in the accelerating energy range obtained from SUPERFISH. The cell is regarded as the sum of 2 half-cells for beam dynamics and cell length calculations in PARMILA. With FODO lattice, the quadrupole gradient required comes out to be 95 T/m which is very high [6] making the design of electromagnetic quadrupoles difficult, while for FOFODODO lattice the required quadrupole gradient is reduced to 55 T/m with marginal increase in beam size. Both the lattices have been studied and FOFODODO lattice is selected to overcome the limitation on quadrupole. The output beam parameters are given in table 3. Figure 6 shows the phase space plots for the 60th cell. Transverse and longitudinal profiles, i.e. beam size and beam divergences in both the transverse planes and phase and energy variation along the length is as shown in figure 7.

4.2.1 *Error analysis.* Transmission efficiency and various other output parameters depend on the input design parameters. It is important to study the effect of small variations of input parameters on beam dynamics of the structure as errors in alignment will degrade the beam and may reduce the transmission efficiency. Error study is performed

Table 3. Output beam dynamics parameters.

Total length	562.3 cm
No. of cells	60
Cell length	6.81–12.28 cm
Avg. accelerating field	1.8–2.2 MV/m
Synchronous phase	−45 to −30 deg
Quadrupole length	3.5–5.5 cm
Quadrupole gradient	55–35 T/m
Transmission efficiency	100%
Transverse rms normalized emittance	0.023 cm mrad
Longitudinal emittance	0.1148 deg MEV

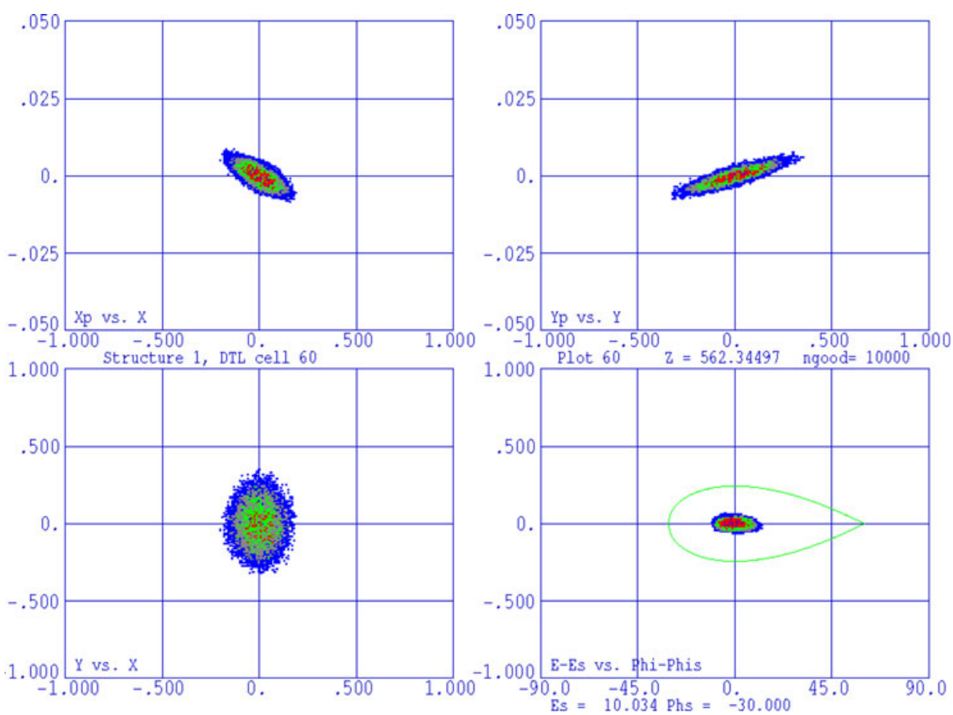

Figure 6. Phase space plots for x vs. x', y vs. y', x vs. y and $E - E_s$ vs. $\varphi - \varphi_s$ for the 60th cell.

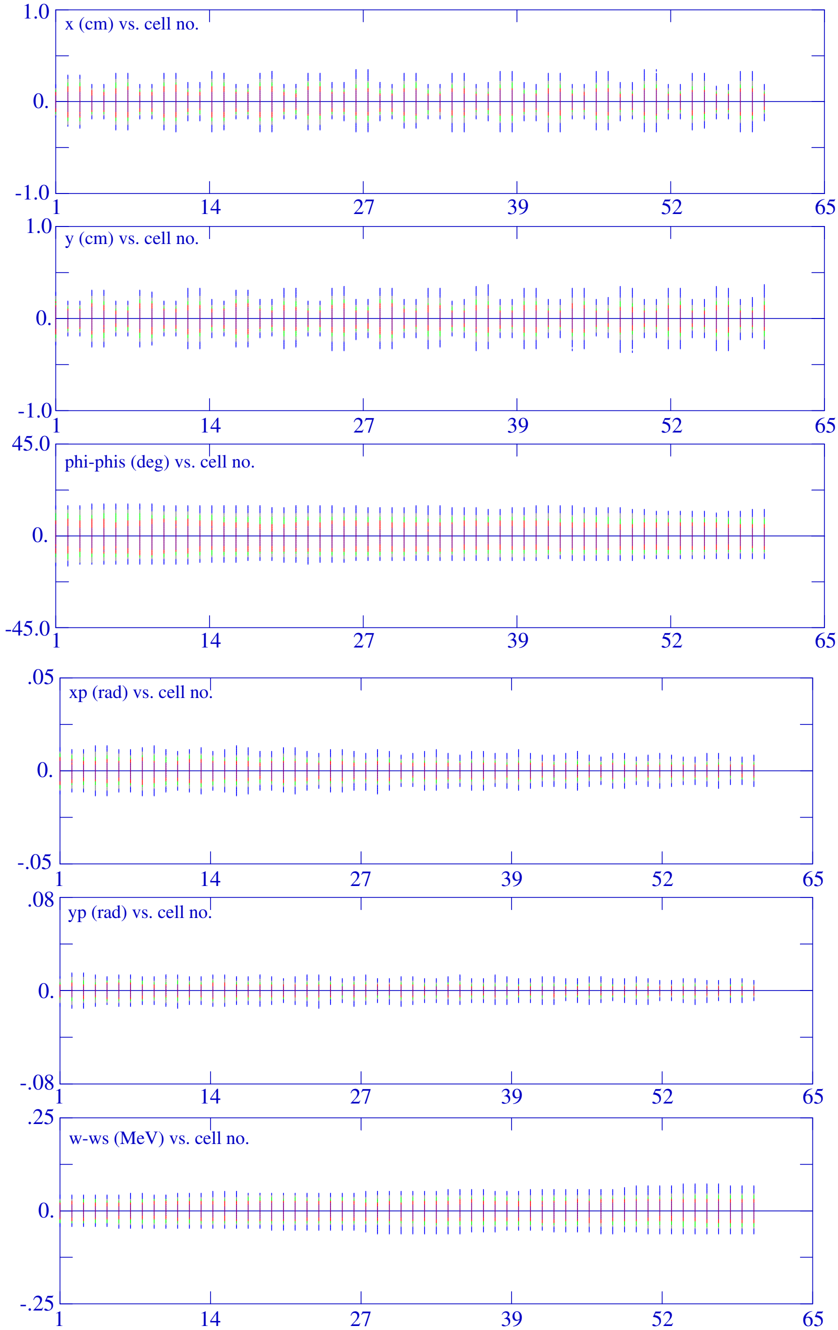

Figure 7. Transverse and longitudinal profiles along the length of the DTL.

to assess the tolerances on various parameters. Two kinds of errors are analysed using PARMILA. Alignment errors affect the transverse dynamics and RF phase and amplitude errors affect the longitudinal dynamics. Errors are modelled on quadrupole transverse translations, quadrupole rotations in all the three axes and quadrupole excitation error and Klystron field and phase. With different quadrupole errors applied on all the cells, the beam is traced with 10,000 particles, and no loss is detected. Effect on the emittance of the beam due to off-axis injection and beam tilt are also studied [7]. The tolerances are based on the requirement to avoid beam losses and to limit the increase in emittance to about 5% with errors. This acceptance criterion is met with misalignments of about 1 mm of the input beam and angular misalignment upto 5 mrad.

4.3 *3D Electromagnetic modelling*

To include features that break the 2D symmetry, a 3D design of the DTL tank was done, using CST microwave studio (CST MWS). Four centre cells are modelled in CST MWS and the effect of the tuners, post couplers and vacuum ports on the field and frequency of the structure was studied. Figure 8 shows tuner, vacuum port and post couplers modelled in CST MWS. The post coupler gives rise to a TE mode band. Figure 9 shows the field configuration for the fundamental as well as the post coupled mode.

Vacuum port: Vacuum port is slotted in order to attenuate the RF power leaking out and to reduce the surface currents at the port corners, thus reducing the heat dissipation at these locations. The slots are oriented in the direction of the RF current to have minimum perturbation to the RF currents. A vacuum port was simulated with a total of five slots. The frequency shift due to one vacuum port is 13 kHz which is negligible and six ports will be located along the entire DTL tank.

Tuners: Mechanical fabrication errors may lead to a change in design frequency and to compensate for this, a total tuning range of 2.5 MHz will be provided. Slug tuners when pushed inside the DTL cavity, perturbs the magnetic field in the cavity leading to an increase in the resonant frequency as suggested by Slater's perturbation theorem [8]. The effects of tuner depth and tuner diameter on the resonant frequency have been studied and are shown in figure 10. As the tuner is penetrated deeper into the cavity, the resonant frequency rises linearly, because the magnetic field is large at the location where the tuners are pushed in. The rise becomes slow as the tuner is penetrated deeper, since the tuners start perturbing the electric field. In the simulation, one tuner is modelled and

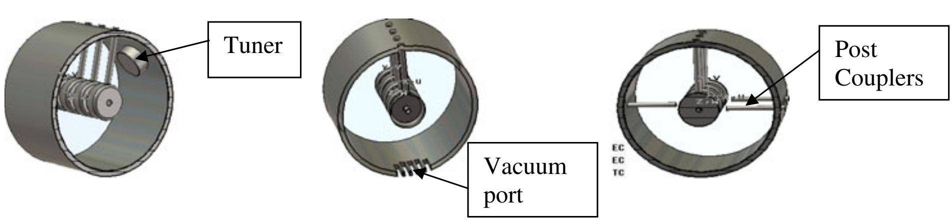

Figure 8. 3D Plots showing tuner, vacuum port and post couplers.

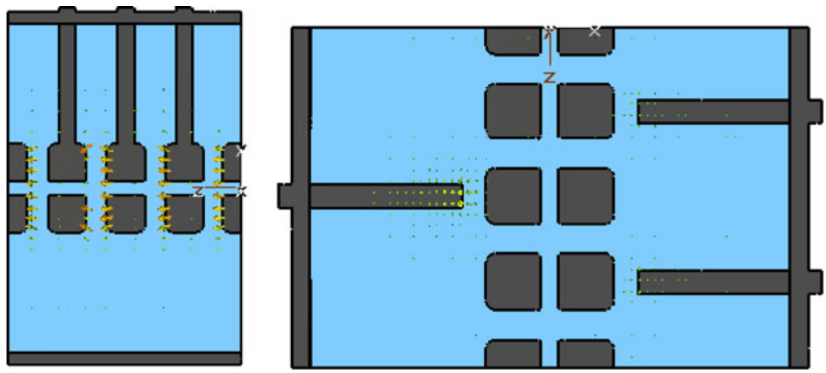

Figure 9. Field configuration for the fundamental mode and the post coupled mode.

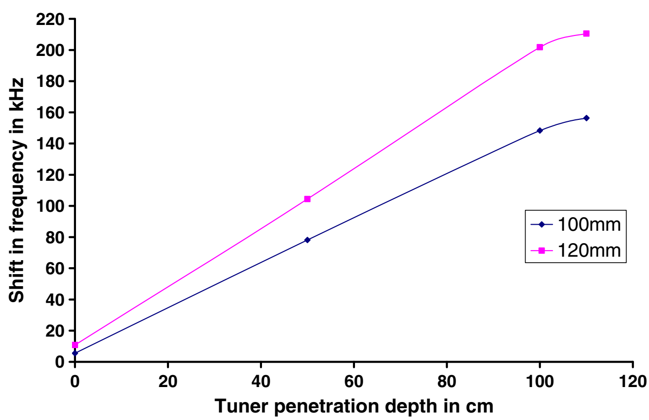

Figure 10. Tuner penetration depth vs. shift in resonant frequency.

the frequency shift due to all the tuners is obtained by summing up the effect of each. The number of tuners is evaluated based on the total tuning range required and the shift in frequency per tuner. Slug tuners of 12 and 10 cm diameter are modelled with a maximum penetration depth of 11 cm.

Post coupler studies: The DTL operates in zero mode where the electric field distribution is very sensitive to perturbations and slight perturbation may lead to mode mixing. To make the operating mode more stable, post couplers are inserted in the horizontal plane at the drift tube centres. Maximum stabilization and significant improvement in mode spacing are obtained at confluence, i.e. when the frequency of the highest mode of the lower pass band (TE mode) coincides with the lowest mode (TM_{010}) of the higher pass band of these two resonant systems. The effect of post couplers on frequency and field was studied with the help of CST MWS code. 3D simulation was done with post couplers on every cell located alternately on opposite sides of the drift tubes. The effect of post coupler on the fundamental resonant frequency and post coupled mode frequency was studied for different radii and the penetration depth for each was found, to achieve confluence. The

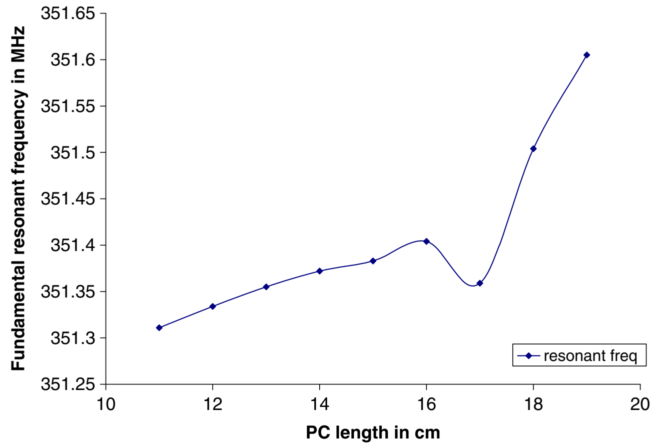

Figure 11. Resonant frequency vs. length of the post coupler for a post coupler radius of 1.3 cm.

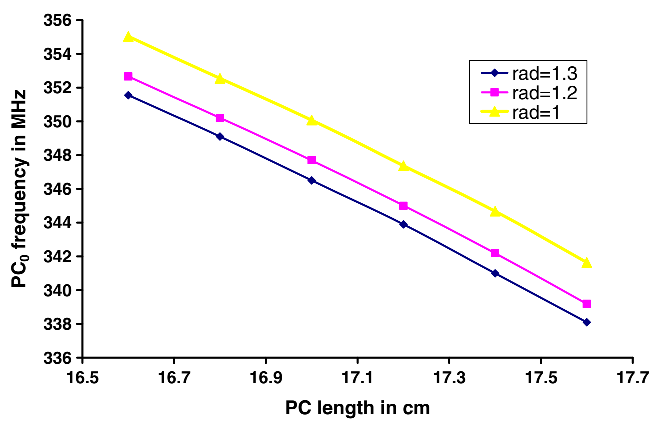

Figure 12. TE mode frequency as a function of post coupler length and radius.

shift in the fundamental frequency is found to be very less except near the confluence where a sharp dip in resonant frequency is observed. The plot of fundamental frequency vs. the length of the post coupler for a post coupler radius of 1.3 cm is shown in figure 11. The post coupler mode frequency as a function of post coupler length and radius is shown in figure 12.

5. Summary and conclusion

The 2D electromagnetic design, beam dynamics simulation and 3D electromagnetic simulation of the 352.2 MHz, 10 MeV drift tube Linac is done. Cell geometry of the DTL is optimized using SUPERFISH to house quadrupole magnets and to get maximum effective shunt impedance by varying the gap-to-cell length ratio (g/L). Thus, after the optimization, a combination of tank diameter of 52.4 cm, drift tube diameter of 14 cm, bore radius of 1 cm is arrived at as one of the choices. Beam dynamic simulation and cell length computations are done using PARMILA. The total length of the DTL is 5.62 m with 60 cells and the RF power required is 12 kW. Transmission efficiency of 100% is obtained without much increase in output emittances. The transverse rms normalized emittance is 0.023 cm mrad and the longitudinal emittance is 0.1148 deg MeV. The ratio of aperture-to-rms beam size is around 7. Error analysis is done on the designed structure with errors applied on each cell of the Linac. It is observed that the acceptance criterion of 100% transmission with 5% increase in the normalized rms emittance is met with misalignments of about 1 mm of the input beam and angular misalignment upto 5 mrad. Tuners, post couplers and vacuum ports have been modelled in 3D code CST MWS. With 12 cm tuner and 11 cm penetration depth, the shift in frequency is evaluated to be 210 kHz. A total of 14 tuner ports with 12 cm diameter tuners will be provided. Slater's perturbation theorem is also used to calculate the tuning range theoretically and the shift in frequency is found to be 195 kHz, which is very close to the shift found from the simulation in CST MWS. Post coupler of 1.3 cm radius at a penetration depth of 16.62 cm leads to confluence with a frequency separation of 17 kHz between the fundamental and the post coupled mode. It is concluded that as the radius of the post coupler decreases, the penetration depth has to be increased to maintain the point of confluence.

Based on this physics design, engineering design and fabrication are being taken up. Heat calculations are done using which cooling channels will be designed taking into account the thermal considerations.

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