Electromagnetic design and development of quadrupole focussing lenses for drift tube linac

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1.0 Abstract :

A linear accelerator comprising of a radio frequency quadruple (RFQ) and drift tube linac (DTL) is being developed at BARC . The alvarez type post-coupled cw DTL accelerates protons from an energy of 3 MeV to 20 MeV. The drift tube linac is excited in TM010 mode, wherein the particles are accelerated by longitudinal electric fields at the gap crossings between drift tubes. The particles are subjected to transverse RF defocusing forces at the gap crossings due to the increasing electric fields in the gap. This transverse defocusing is corrected by housing magnetic quadrupole focussing lenses inside the drift tubes. The permanent magnet quadrupoles are placed inside the hermetically sealed drift tubes and provide constant magnetic field gradient in the beam aperture.

The drift tubes are mounted concentrically inside the resonating DTL tank and are connected to the tank body with stems. Rare earth permanent magnets have been used to achieve the high field gradients in the aperture. The drift tube body is subjected to RF heating due to eddy current losses and hence the sealed drift tubes are required to be cooled from inside. The temperature rise of the drift tube assemblies has to be limited to avoid degradation of permanent magnets and also to limit thermal expansion of the tubes. This paper discusses various aspects of magnetic design, selection of magnetic materials and the engineering development involved in the assembly of the drift tubes.

2.0 The drift tube Linac for LEHIPA

The 3 MeV beam from the RFQ will be coupled to the drift tube linac through the medium energy beam transport line. The alvarez DTL is most efficient structure for accelerating protons in the low to medium energy range. We have based our DTL design on the alvarez type structure which has many advantages in this energy range.

The alvarez DTL comprises of a resonating tank, and a number of drift tubes mounted concentrically to this tank. The drift tubes are connected to the tank using stems. The drift tubes are separated from each other by a small accelerating gap g . The length of the drift tubes is w .A cell comprises of half-lengths of two adjacent drift tubes and the separation gap g. The length of each cell in the alvarez DTL is equal to $\beta\lambda$. This is an important condition to maintain longitudinal phase stability. The particles always arrive for acceleration in one RF time-period. The increasing electric field in the gap imparts longitudinal acceleration to the particles and the particles are shielded from the electric field when the direction of the electric field is opposite to desired particle direction.

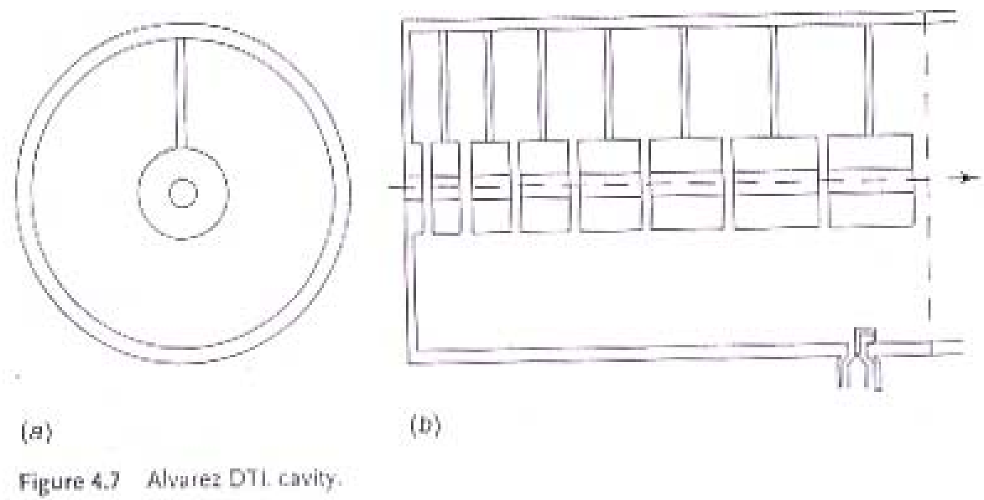

Fig 1 : Alvarez Drift Tube Linac

Each cell length of the DTL acts as a resonating cavity, where in the electric field E is applied longitudinally and the magnetic field is in the azimuthal direction. The drift tubes and the tank wall carry the longitudinal conduction currents which become displacement currents in the cavity gap and complete the circuit. As the particles gain momentum, the cell lengths increase and hence the inductance increases due to increased area of the circulating current path. To keep the structure in synchronism with the resonant frequency, the capacitance of the structure should be decreased, by increasing the gap between the two drift tubes. This results in a reduced transit time factor and lower shunt impedance. Hence the alvarez DTL structures are not efficient beyond beta values of 0.3.

3.0 The de-focussing effect of the accelerating electric field

The requirements for longitudinal stability of the beam, results in a net transverse electric field in the gap , which thereby defocusses the beam as it crosses the gap . As can be seen from fig-2 the electric field lines at the gap crossing follow a contoured path, resulting in a radial (transverse) component of the electric field. Hence the off-axis particles experience radial electric forces. The radial component in the two longitudinal halves of the gap are unequal, owing to the increasing electric field in the gap . This results in a net radial kick imparted to the particles while they traverse the gap.

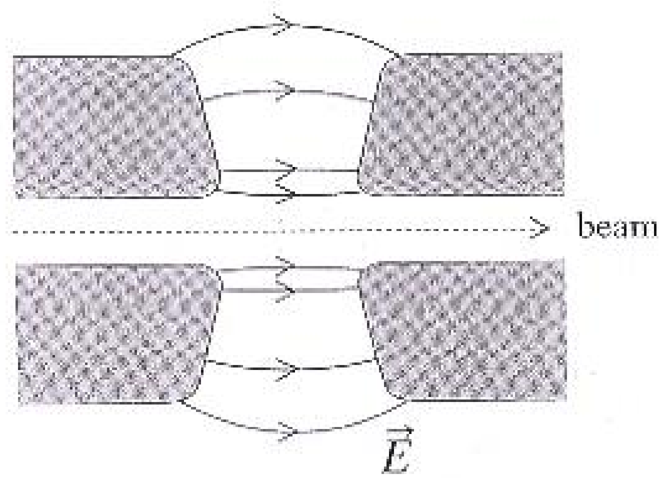

Figure. 9.8 Electric field lines between the ends of two drift tubes in a DTL.

Fig-2 : Electric Field lines in the gap

This defocusing effect is corrected by placing a periodic lattice of quadrupole focussing lenses mounted concentrically inside the drift tubes. These magnets set up a constant gradient quadrupolar field in the beam aperture . Depending on the charge of the particles there is a focussing force exerted on the particles in one transverse axes of the beam aperture.

Conversely, the particles on the other transverse axes of the beam aperture are subjected to defocussing forces. By azimuthal rotation of the magnets, alternately by 90 degrees, we can have a set of focussing / defocusing lenses. This results in a net focussing of the particles, as they travel longitudinally in the beam aperture, and keeps the beam size small.

4.0 Electromagnetic design of the quadrupoles :

A typical quadrupolar magnet is shown in fig-3 . As explained above the 2-dimensional fields in the quadrupole magnet aperture is defined by

$$By = Kx \qquad \text{-------------} \qquad (1)$$

and

$$Bx = Ky \qquad \text{-------------} \qquad (2)$$

Where Bx and By are the x and y-components of the magnetic field in the aperture and K is the magnetic field gradient (T/m) in the aperture. To get a constant K in the aperture the pole faces have to be made in hyperbolic shape.

Ampere-turns (NI) required for establishing a constant gradient K in an aperture of radius r is

$$NI = kr^2 / 2\ \mu_0 \text{ -------------- } (3)$$

The above equation (3) clearly shows that for a given ampere-turns the field gradient is inversely proportional to the square of the aperture radius. This is in contrast to dipoles where the ampere-turns required for the given air-gap field is proportional to the radius of the aperture.

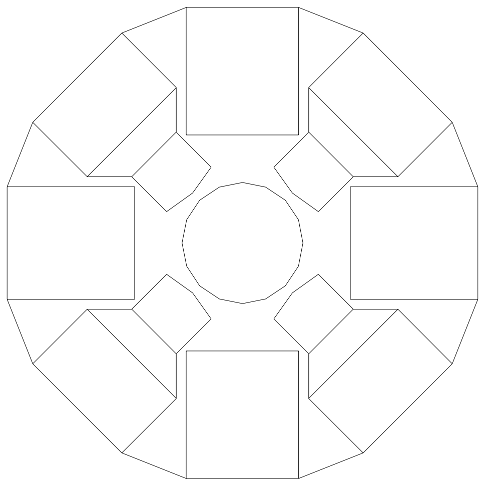

Fig-3: The quadrupole focussing magnet

There is now lesser space to accommodate the coils as we have four hyperbolic poles for the quadrupole. The coils terminate the hyperbolas , thus causing higher order field terms. Hence the normal-conducting electromagnetic quadruples or the EMQs are required to operate at high current densities thus necessitating additional cooling requirements . Also the coil overhangs need additional longitudinal space. Considering the small inner volume of the drift tubes, the use of EMQs inside the drift tubes, at least for initial lower velocities is virtually ruled out.

Considering the above factors permanent magnet quadrupoles or the PMQs are used. Some of the advantages of using the permanent magnet quadrupoles are :

- No additional power requirement
- No power consumption, hence no joule losses inside the tube
- No additional cooling burden
- High energy densities in the rare earth magnets result in compact sized drift tubes
- High shunt impedance owing to small sizes

The magnetic design of the quadrupoles follows the well known law of split-pole mulipole lenses viz the magnetisation vector (as we move in the azimuth direction) is rotating around the radial unit vector with twice the frequency. The electromagnetic design and analysis of the permanent magnet quadrupoles was carried out using finite element analysis software Opera3D. Various magnets and pole configurations were tried out to get the requisite field gradient in the large beam aperture. Rare earth neodymium-iron boron magnets permanent magnets have been used in the assembly. These magnets have the highest energy densities among all permanent magnets and hence 8 nos. of such magnets have been fitted in each assembly.

Some of the important comparative parameters of permanent magnets are compiled in Table-1 as shown below :

Material	B_r (KG)	H_c (KA/m)	H_{ci} (KA/m)	Curie Point (°C)	Maximum Working Temperature (°C)	Temperature coefficient B_r %/ °C	Temperature coefficient H_c %/ °C	Maxim um Energy product (KJ/m^3)	Densi ty (g/cc)
Ferrites	3-4	300	400	450	200	-0.2	0.4	36	4.8
Alnico	11-12.5	48	50	750-900	250	-0.02	0.02	44	7.3
$SmCo_5$	10	756	1700	740	250	-0.045	-0.25	192	8.2
Sm_2Co_{17}	11.5	820	1592	>850	350	-0.035	-0.2	248	8.3
Sm_2Co_{17} (low Temp. coeff. grade)	10.4	756	1194	>850	350	-0.01	-0.2	208	8.4
NdfeB	12.8-13.2	995	1592	300	150	-0.12	-0.70	340	7.4

Table 1 : Important Properties of various Permanent Magnets

Higher-order harmonics in the quadrupole magnets

As per the in-built symmetry of the quadrupole magnet , we must have vanishing normal coefficients for sextupole , 14-poles and 22-pole component .Also we get vanishing skew dipole, decapole and 18-polar components in the beam aperture. . Our analysis confirmed the above findings on the harmonic components.

5.0 Engineering development of the drift tube assembly :

Some of the important geometrical parameters of the drift tube assembly for LEHIPA are listed below in Table-2.

Parameters	Units	Value
Drift tube length ($\beta\lambda$)	mm	60
Quadrupole magnet length	mm	32
Quadrupole magnet O.D	mm	96
Quadrupole magnet I.D	mm	28
Drift tube outer diameter	mm	120
Beam aperture diameter	mm	24
Outer corner radius R_0	mm	15
Inner corner radius R_i	mm	5
Drift tube tank ID	mm	520
Quadrupole gradient	T/m	46.5

Table-2 Geometrical dimensions of drift tube

As can be seen from the above table, the overall inner volume available in the drift tubes is very small .Inside this small volume , permanent magnets as well as coolant channels have to be installed . The permanent magnets have to be sealed to avoid any contact with water. The drift tube assembly has to be hermetically sealed, with magnets entombed. This is an extremely critical operation as it involves precise welding on thin sections. The welding operation is also critical, due to the low working temperature limit of the rare earth NdFeB magnets. The maximum working temperature of the neodymium-iron-Boron magnets used by us is limited to 150 deg celsius . Any increase in temperature beyond this point leads to a permanent demagnetisation of the magnets. This renders the complete drift tube assembly useless, since the equatorial welding on the drift tube outer wall is the last operation in the fabrication of the drift tubes.

A set of drift tube assembly with all the fabricated components is shown in Fig 4 . All the components except the magnets and the pole shoes are made from austenitic stainless steel 304 L in the present development. The front and rear face cups have contoured corner edges, in order to avoid peak electric stress buildups at the corners. The welding operation has to be carried out in the presence of strong magnetic field from the permanent magnets. Pulsed laser beam welding technique has been chosen over electron beam welding technique to avoid beam distortion in presence of strong magnetic fields from the PMQs.

The successful completion of the engineering development of above drift tubes assembly has given us the confidence for making similar assemblies in oxygen-free copper. All the components that were fabricated in austinitic stainless steels will be replaced by OFE copper for the final assembly.

6. Thermal – Hydraulics of the drift tube assembly :

CFD analysis of the drift tube assembly with cooling channels has been done. A heat flux of 22,200 W/sq. meter has been applied on the outer surface of the cavity . For a flow rate of 7 liters per minute of water inside the DTL assembly, we are able to limit the peak temperature in the cavity walls to about 32 degrees celsius. The pressure drop across the drift tubes at the flow rate of 7 lpm is a modest 12000 pascals .

Fig-4 : Exploded view of the drift tubes

7. Acknowledgements:

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8. References :

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