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BEAM DYNAMICS OPTIMIZATION IN DRIFT TUBE LINEAR ACCELERATOR WITH PERMANENT QUADRUPOLE MAGNETS

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Abstract

The research concerns the design of a drift tube linear accelerator (DTL) with permanent quadrupole magnets (PMQ) placed inside some of the drift tubes for focusing. The study was conducted using Comsol Multiphysics software, where electromagnetic fields and particle dynamics in the cavity were calculated. The proton beam is accelerated up to 10 MeV. Initial beam is assumed to come from Radio Frequency Quadrupole accelerator (RFQ). Mathematical methods of control theory are used for particles dynamics optimization. Different focusing lattices are examined and variations of the gradient of the magnetic lenses are analyzed with respect to output beam parameters. Effectiveness of the optimization is estimated by the transmission rate and the emittance growth.

INTRODUCTION

The tandem of Radio Frequency Quadrupole (RFQ) and drift tube linear accelerators is often used in ion linacs in a wide range of output energies: in high ones (for instance 1 GeV SNS [1]) and in low ones (for instance 8 MeV Tsukuba University linac for BNCT [2]). Both cases need precise beams on output installation. Using RFQ of P-diapason frequencies and permanent magnetic lenses in drift tubes in DTL helps to solve the problem of compactness and narrow spectrum of output energy. The modelling of the structure and beam dynamics was conducted using Comsol Multiphysics software. This package enables the calculation of the 3D RF-field and beam dynamics. The magnetic field of quadrupole lenses along the axis is assumed to be as proposed in paper [3]. The beam dynamics optimization is conducted by gradient methods.

Initial Parameters

The drift tube linear accelerator consists of 2 tanks. Structure parameters are presented in Table 1.

Table 1: DTL Tanks Parameters

Parameter	Tank 1	Tank 2
Input Energy [MeV]	2.5	6
Output Energy [MeV]	6	10
Number of drift tubes	34	22
Length [m]	2.116	1.86
Channel diam. [mm]	16	16
Cavity diam. [cm]	50	49.6
Pulse current [mA]	10	10

The input beam coming from RFQ has characteristics, described in Table 2. This provided data was calculated using LIDOS.RFQ software [4].

Table 2: RFQ Output Parameters

Parameter	X	Y
Twiss param. α	1.39	-1.49
Twiss param. β [m/rad]	0.15	0.17
Emittance [cm*mrad]	0.105	0.105
Phase spread [deg]	40	
Energy spread [%]	2.6	
Output energy [MeV]	2.5	

Electric RF-Field Computation

The structure was designed to work at the frequency of 432 MHz. The diameter of the cavity as well as drift tube inner and outer diameters were selected so that the resonant frequency of the cavity would match the desired one. Comsol Multiphysics software was used to determine the distribution of the RF-field inside the cavity. It uses finite-element method to solve the Helmholz equation for the electric field vector. The mesh of approximately 100 000 elements is set up in the volume of the cavity. Normalized electric field distribution along the axis in tank 1 is presented below (Fig. 1).

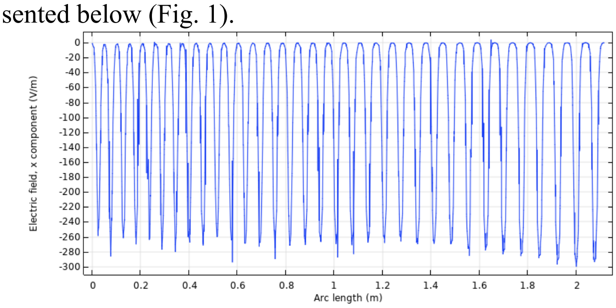

Figure 1: Electric field distribution along the axis, tank 1.

TRANSVERSE DYNAMICS

Magnetic Field

The focusing in the accelerator is achieved by the use of permanent magnets installed inside drift tubes. Magnets are considered to be of the same length of 5 cm in the axis direction. Their centers coincide with centers of drift tubes. In this study particles should occupy no more than 75% of the aperture. In this case it seems reasonable to use ideal approximation of the magnetic forces in the crossection plane [5]:

$$F_x = -qvGx,\ F_y = qvGy$$

q [C] is a particle charge, v [m/s] is longitudal velocity, G [T/m] is magnetic field gradient.

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Magnetic Lattice

The magnetic lattice types that were examined in the study: FDFD, FF0DD0, F0D0 (F - Focus, D – Defocus, 0 – empty). Initially, the gradient of the magnetic lenses remained the same for all types – 30 T/m. This initial value was chosen based on the parameters used for the similar structure [1]. At first, only tank 1 was tested. The efficiency of the lattice was estimated by transmission rate and maximum beam radius (Table 3).

Table 3: Different Magnetic Lattices in Tank 1

Lattice	Transmission (%)	R(mm)
FDFD	95	8
F0D0	100	6
FF0DD0	100	4.5

Both F0D0 and FF0DD0 lattices showed 100% transmission rate, but maximum radius of the bunch was smaller for FF0DD0. So FF0DD0 lattice was chosen for the first tank. The output beam radius was 2.5 mm in both transverse directions and divergence was 14 and 6 mrad for two directions.

The simulation of beam dynamics in tank 2 showed that with the magnetic field gradient of 30 T/m all particles are transmitted for every type of the lattice (Table 4). But smallest maximum radius among 3 types of the lattice was 6.5 mm. Since the channel radius is 8 mm this value was still too high. So the next step was to determine whether a smaller gradient could be used while having a good transmission rate and smaller beam radius. It was found out that the gradient of 25 T/m gives full transmission and smaller maximum radius of the bunch (5 mm). These results were provided by FF0DD0 lattice (more specifically DD0FF0 here). Fig. 2 and Fig. 3 show X and Y coordinates of particles with respect to time. Figure 4 represents input for tank 1 and output tank 2 transverse emittances.

Table 4: Lattice Study Results

Lattice	G[T/m]	Transmission	R[mm]
FDFD	30	100	7.5
F0D0	30	100	6.5
FF0DD0	30	100	7
FDFD	25	99	8
F0D0	25	96	8
FF0DD0	25	100	5

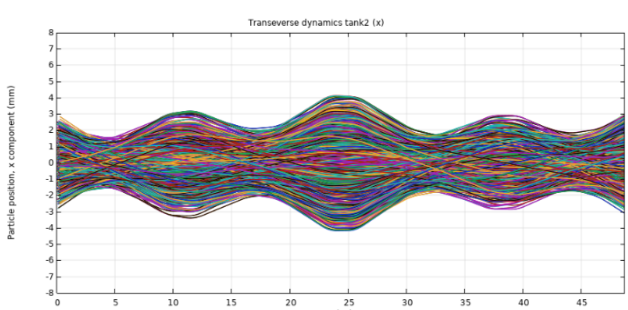

Figure 2: Transverse dynamics (X), FF0DD0 lattice, 25 T/m magnetic lenses gradient.

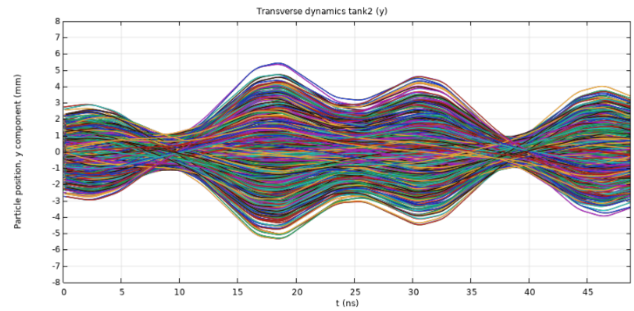

Figure 3: Transverse dynamics (Y), FF0DD0 lattice, 25 T/m magnetic lenses gradient.

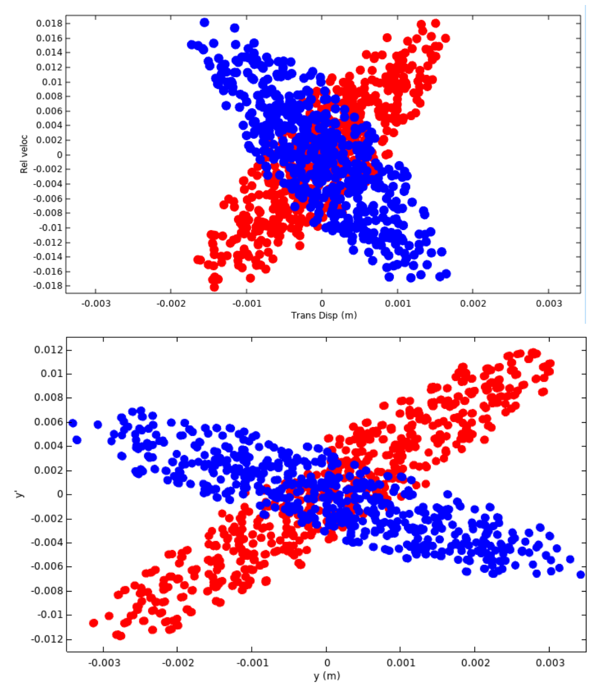

Figure 4: Transverse dynamics, FF0DD0 lattice, 25 T/m magnetic lenses gradient.

LONGITUDAL DYNAMICS

The object of optimization was to minimize an output energy range. The control parameters are magnitude of the electric field and initial phase. The initial phase here is a phase of the electric field when first particle of the bunch enters the accelerator.

In case of one or two varied parameters different gradient methods are commonly used for optimization [6]. In this study steepest descent method was used due to its uncomplicated implementation:

1. One of two parameters is fixed. Varying the other one until obtaining the smallest value of fit function. The value of the parameter is according to the direction of fit function anti-gradient. Fix this parameter.
2. Varying the second parameter find the smallest value of fit function. Fix this parameter.
3. Varying again the first parameter find the smallest value of fit function. Fix this value.
4. Continue this cycle until the decrease of fit function on the next step is negligible.

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The relative initial energy spread of the beam coming from RFQ was 2.6% total (taking into account 90% of particles). After the optimization the output energy range was 1.9%, which represent 27% of improvement (Fig. 5). These parameters were achieved with the initial phase of 1.2 radian and electric field amplitude of 36 kV/m.

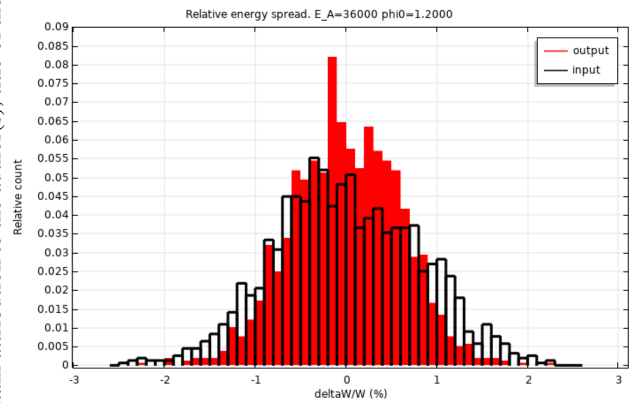

Figure 5: Energy distribution.

Output proton beam with the energy of 10 MeV when hitting the target could provide a neutron flux of 10^{13} n/mC from Berrilium target[2], which is a high enough to conduct radiation therapy.

CONCLUSION

The problem of the design of drift tube accelerator with permanent quadrupole magnets was considered in the paper. Magnetic lattice types were studied in detail and FF0DD0 lattice was proved to have advantage over other types with respect to the output beam emittance and channel filling. The minimization of output energy range was achieved by the variation of magnitude of the electric field and initial phase. The proposed design of RFQ and DTL tandem could provide a proton beam for a neutron flux from Berrilium target, which is sufficient for accelerator-based BNCT facility.

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