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STUDYING A PROTOTYPE OF DUAL-BEAM DRIFT TUBE LINAC*

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Abstract

For generating high-intensity ion beams from linear accelerators, a multi-beam acceleration method which involves multiple accelerating beams to suppress the defocusing force from space charge effects, then integrating these beams by a beam funneling system, has been proposed. An Inter-digital H-mode (IH) two-beam type radio frequency quadrupole (RFQ) with accelerating 108 mA (54 mA/channel×2) carbon ion from 5 to 60 keV/u and an IH four-beam RFQ with accelerating 160.8 mA (40.2 mA/channel×4) carbon ion from 3.6 to 41.6 keV/u had been successfully designed for low energy heavy ion acceleration [1]. In order to demonstrate that an IH dual-beam drift tube linac (DB-DTL) is suitable for high-intensity heavy ion beam acceleration in middle energy region, we has been developing a DB-DTL prototype by using three dimensional electromagnetic CST MicroWave Studio (MWS) and using particles tracking Pi Mode Linac Orbit Calculation (PiMLOC) [2-3]. According to the simulation results, the beam dynamics design and electromagnetic design will be presented in this paper.

INTRODUCTION

Shown in Fig.1, with developments of the direct plasma injection scheme (DPIS) and multi-beam linac, new heavy ion inertial fusion (HIF) injector was proposed for inertial confinement fusion drivers [4]. The multi-beam RFQ and the DB-DTL were adopted for suppressing space charge effect of hundreds mA level high intensity heavy ion acceleration during low and middle energy region. The feasibility of multi-beam linac in middle energy region hasn't been studied since the multi-beam RFQ has been successfully designed, thus, an IH DB-DTL prototype with two beam-apertures has been studying. The DB-DTL prototype is about 1 m and operates at 81.25 MHz. After acceleration by an existing prototype of ADS RFQ, the DB-DTL accelerate proton beam from 0.56 MeV up to 2.5 MeV. The method of alternating phase focusing (APF) was applied for beam horizontal focusing and longitudinal bunching in the DB-DTL. The beam transmission of acceleration system is 35% without middle energy transmission beam (MEBT) matching section for shorting founds between ADS RFQ prototype and DB-DTL. But beam transmission of DB-DTL prototype is approximately 94% by adopting 42.5 cm MEBT matching section. The detailed information of the ADS RFQ prototype is presented in Ref [5]. In this paper, the simulation results of beam dynamics of DB-DTL prototype and electromagnetic calculation are presented in detail.

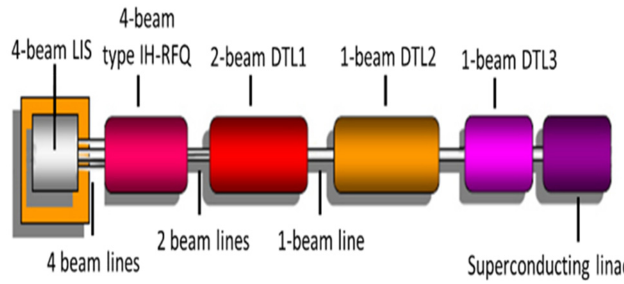

Figure 1: Simple layout of a driver system for 1 GW HIF plant. (Cited from "New development of HIF injector").

BEAM DYNAMICS DESIGN

The beam dynamics design consists of gap voltage designs, synchronous phase designs and particles calculation by using PiMLOC and TraceWin, respectively. The synchronous phase sequence designs are an optimization process. The better phase pattern is judged by higher transmission rate, smaller envelop and better energy spread. Firstly, the gap voltage distribution is fixed and the synchronous phase is varied to obtain higher transmission rate and better energy spread. This DB-DTL prototype design consists of 9 cells and 8 drift tubes. The gap lengths, DT lengths, synchronous phases and gap voltages are created by PiMLOC. Then, based on the PiMLOC calculation, the cavity model is regenerated with the new data. And the field integrated voltage distribution is recalculated and used for beam dynamics calculation. After several a repetitive computation, the synchronous phase sequence and the gap voltage distribution was plotted in Fig. 2. The final parameters of beam dynamics design are outlined in Table 1. The principle of APF is explained by Eq. (1), particles are synchronously bunched (debunched) in longitudinal motion and defocused (focused) in horizontal motion. The longitudinal bunching and horizontal focusing is realized by reasonably setting synchronous phase.

$$\begin{aligned} &\textit{horizontal particles motion}: r'' + k_r^2 r = 0 \\ &\textit{longitudinal particles motion}: z'' + k_l^2 z = 0 \\ &k_r^2 = -\frac{1}{2}k_l^2 = \frac{q\pi E_0 T \sin\phi}{m_0 c^2 \gamma^3 \beta^3 \lambda} \end{aligned} \quad (1)$$

The particle distribution at injection of DB-DTL is illustrated in Fig. 3, namely the particle distribution at exit of the prototype ADS RFQ. The energy spread is approximately 5.35% (± 0.03 MeV) and the maximum horizontal divergence angle is approximately 40 mrad, which

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cause high beam loss, tremendous normalized RMS emittance growth and sharply envelop increasing for shorting focusing force in APF DB-DTL. Finally, the simulation results without MEBT matching section between the ADS RFQ prototype and the DB-DTL prototype show that the transmission of whole beam is 35%, the beam envelop and the emittance diagram at exit of DB-DTL prototype aren't perfect, as illustrated in Fig. 4. The normalized RMS emittance growth is tremendous, seen in Table 1.

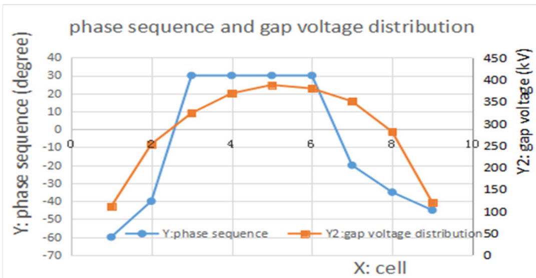

Figure 2: The phase sequence and gap voltage distribution in PIMLOC dynamics design.

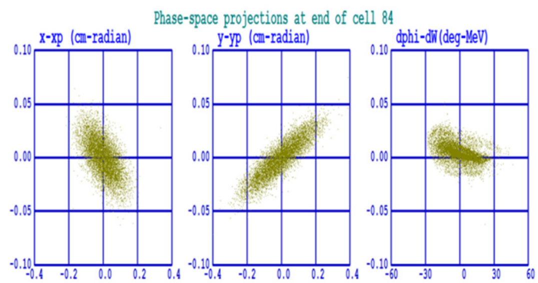

Figure 3: The emittance diagram at injection of DB-DTL.

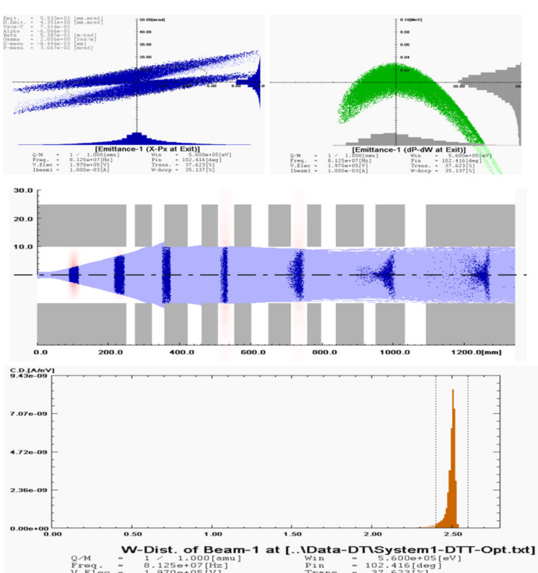

Figure 4: The emittance diagram (up: H/L) at exit of DB-DTL prototype, the beam envelop (middle), the energy spread (down) at exit of DB-DTL prototype in PiMLOC.

But the result of particles calculation in TraceWin show that the beam transmission is 94% by adopting triplet quadrupole magnet between the ADS RFQ prototype and the DB-DTL, as illustrated Fig. 5. The beam transmission of ADS RFQ together with DB-DTL is 35%. The beam transmission, the emittance diagram and the beam envelop are consistent with the simulation results in PiMLOC, as illustrated in Fig. 6.

Table 1: DB-DTL Prototype Main Parameters

Parameters	Value
Particle charge state	H^+
Operation	pulsed
Frequency (MHz)	81.25
Input energy (keV/u)	0.56
Output energy (MeV/u)	2.50
Maximum gap voltage (kV)	387.50
Kilpatrick factor	1.80
Current (mA)	1
Transmission efficiency (%)	35.0
Radius of aperture (mm)	10.0
Normalized RMS eimmtance at injection/exit (mm mrad)	X:0.2864/1.088 Y:0.2840/1.121
Synchronous phase sequence	-60,-40,30,30,~

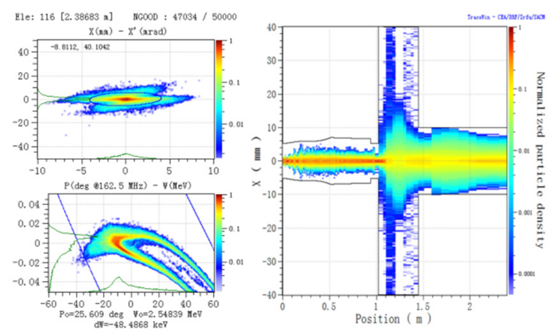

Figure 5: Particles calculation results of ADS RFQ prototype, 42.5 cm MEBT matching section together with DB-DTL prototype.

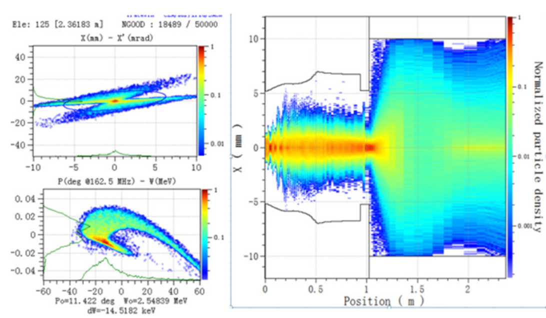

Figure 6: Particles calculation results of ADS RFQ prototype together with DB-DTL prototype.

ELECTROMAGNETIC SIMULATIONS

Based on calculation results of DB-DTL in PIMLOC, cavity structure is modelled using the CST Micro Wave (MW) Studio. The electromagnetic calculation and the resonance frequency depend on the entire structure of DB-DTL cavity, therefore, the detailed of overall structure should be incorporated in the calculation model. The

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relationship between mesh, resonance frequency and power dissipation was firstly simulated and an optimal tetrahedron mesh number of 1 million was chosen for all other models. Then, the relationships between radius of cavity, radius of drift tube, undercut, plunger tuner and frequency and power dissipation were characterized, respectively. The cavity of IH DB-DTL operates at TE110 model and the electrical field drops along the beam-aperture axial direction. The electrical field flatness tuning by undercut tuning and tube tuning is achieved to increase the shunt impedance and decrease the power dissipation, as illustrated in Fig. 7 [6]. The field distribution of up aperture is approximately identical with the field distribution of down aperture. The corresponding field integration gap voltage distribution is consistent with the gap voltage distribution in PIMLOC, which means the field distribution of cavity is agreement with the field distribution in beam dynamics. Finally, the IH DB-DLT cavity parameter is shown in Table2 and the cavity structure model is shown in Fig. 8 after the completion of all simulation and design process. The resonance frequency of cavity is 81.2432 MHz, the calculated shunt impedance is 94.85 MΩ/m, the maximum surface electric field is 18.752 MV/m (1.8 Ekilpatric), and the normalized power dissipation is 37.51 kW. The cavity surface current distribution is shown in Fig. 9, the dissipation is mainly focus on stems and undercut, and the further multi-physics field simulation is being carried on.

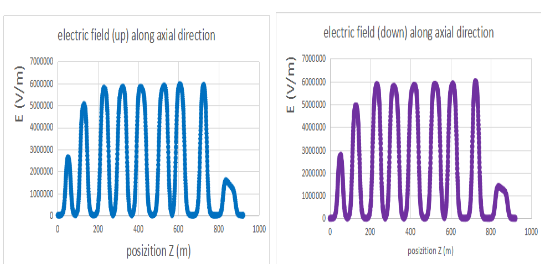

Figure 7: Electric field distribution of up/down aperture (left/right) along the cavity. With field tuning, uniform distribution is achieved.

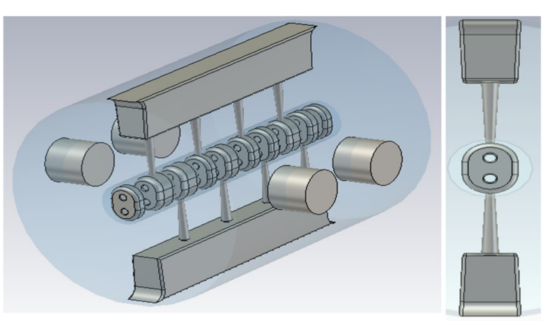

Figure 8: The structure model of IH DB-DTL, arbitrary view (left) and front view (right).

Table 2: DB-DTL Prototype Cavity Parameters

Parameters	Value
Length of cavity (mm)	922.36
Radius of cavity (mm)	355.25
Horizontal size of DT (mm）	90
Vertical size of DT (mm)	120
Radius of tuner (mm)	100
Radius of stem (mm)	10
Undercut (mm)	30
Size of ridge.up (mm）	100
Size of ridge.down (mm)	90
Frequency (MHz)	81.2432
Shunt impedance (MΩ/m)	94.85
Normalized power dissipation (kW)	37.51
Maximum surface field (MV/m)	18.75

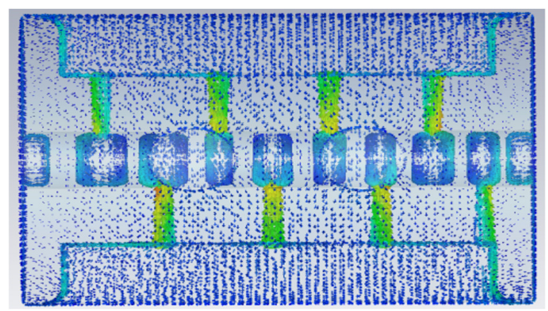

Figure 9: The surface current distribution of the cavity.

CONCLUSION

An APF IH DB-DTL prototype is designed with 35% transmission rate without MEBT matching section for shorting founds. But the beam transmission of the whole beam system in TraceWin, including ADS RFQ prototype, triplet quadrupole MEBT matching section and DB-DTL, is 99%. The resonance frequency is 81.25 MHz, the calculated shunt impedance is 94.85 MΩ/m, the power loss is 37.51 kW and the maximum surface electric field is 1.8 Ekilpatric. The further multi-physics field calculation and particles simulation will be performed and reported later.

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