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THE MULTI-PHYSICS ANALYSIS OF A DUAL-BEAM LINAC *

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Abstract

A prototype 81.25 MHz dual-beam drift tube linac (DB-DTL) is being designed to proof the feasibility of multi-beam type linac. The beam dynamics design and electromagnetic calculation have been completed [1]. The following step is the multi-physics analysis of the DB-DTL. The three-dimensional multi-physics analysis is very important for the design of the DB-DTL. The RF dissipated power will make the cavity temperature rise and cause cavity resonance frequency shifting due to the deformation of cavity structure. The distributions of cavity deformation and stress are calculated according to the cavity temperature distribution. All the simulation results, including cavity temperature rise, deformation and stress and the frequency shifting resulted in cavity deformation, should be within an acceptable range. The designing goal is to design the DB-DTL operated in pulse model with 1/1000 duty factor. The detailed multi-physics analysis of the prototype DB-TL will be presented in this paper.

INTRODUCTION

The DB-DTL project has been proposed to proof the feasibility of multi-beam type linac in middle energy region acceleration [2] [3], which will apply to the design of new heavy ion inertial confinement fusion (HIF) facility [4]. The layout of the DB-DTL test bench is shown in Fig. 1, which include a 1mA permanent magnet type PIG ion source, faraday cups for measuring beam transmission, an existing CW 162.5 MHz RFQ accelerator [5], the prototype DB-DTL and an analyzer magnet for measuring beam energy. The DB-DTL is able to accelerate 1 mA proton from 0.56 MeV to 2.5 MeV. The normalized power dissipation of the DB-DTL is 35.83 kW according to the electromagnetic calculation results of the DB-DTL [1]. The main parameters of the DB-DTL are listed in Table 1. The DB-DTL will be operated in room temperature. The power dissipated on the internal surface on the DB-DTL will make cavity temperature rise, which also result in structure deformation and resonant frequency shifting. It is important to simulate the temperature rise, deformation and frequency shifting of the DB-DTL cavity. Actually, the DB-DTL will be operated in pulse mode with a duty of 1/1000, with cooling-water channels but without cooling-water because of the limitation of funds. The multi-physics analysis is performed to explore the maximum operating pulse duty factor, which will apply to the beam experiment. The detailed three-dimensional multi-physics analysis of the DB-TL will be presented in this paper, which is a coupled electromagnetic, thermal and structural analysis.

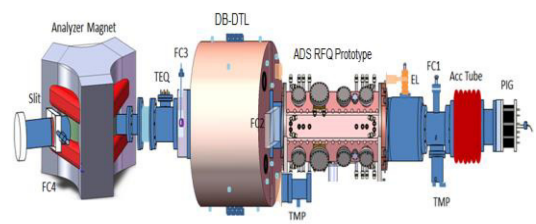

Figure 1: The layout of the DB-DTL beam test bench, which include a PIG ion source, faraday cups, the Prototype ADS RFQ, the DB-DTL and analyzer magnet.

Table 1: Main Parameters of the DB-DTL

Parameters	Value
Charge to mass ratio q/A	1
Frequency (MHz)	81.25
Beam current (mA)	1
Input/output energy (MeV)	0.56/2.5
Radius of beam-aperture (mm)	10
Maximum gap voltage (kV)	389.06
Transmission rate	34%
Operation mode	pulse
Cavity length	991.43
Shunt impedance (MΩ/m)	200.02
Normalized power dissipation (kW)	35.83

THE PROCEDURES AND GOAL OF MULTI-PHYSICS ANALYSIS

As shown in Fig. 2 [6], the procedures of multi-physics analysis include electromagnetic, thermal, structural and frequency shifting analysis. The ANSYS workbench [7] and CST Microwave Studio (MWS) [8] are utilized in the simulation. Firstly, the high frequency electromagnetic simulation is performed with the MWS and the distribution of RF thermal loss is simulated with ANSYS High Frequency Structure Simulator (HFSS) code. Based on the simulation results, the normalized cavity power dissipation is calculated, which is applied to the thermal analysis. The thermal analysis generate cavity temperature map according to the cavity internal surface heat flux. According to the distribution of cavity temperature, the distributions of structural stresses and deformations of the DB-DTL are calculated in structural analysis. Finally, the resonant frequency shifts, resulted in cavity the deformation, is simulated in HFSS code. The frequency sensitivity of cooling-water temperature and velocity are also

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simulated by using ANSYS. Through multi-physics analysis, appropriate parameters of cooling-water are chosen to satisfy the requirement for DB-DTL cavity operation. The deformation and stress of cavity and corresponding resonant frequency shifting of the DB-DTL should be within a proper range.

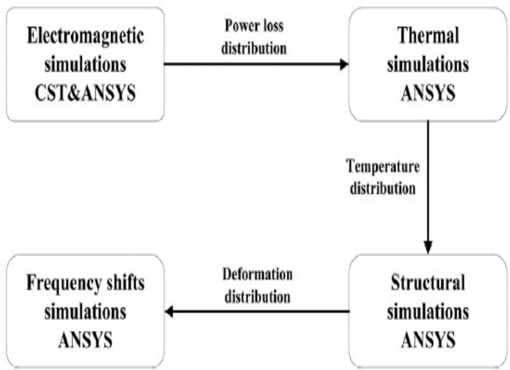

Figure 2: The multi-physics analysis scheme with MWS and ANSYS (Cited [6]).

HEAT TRANSFER THEORY OF COOLING-WATER

According to the heat conduction formula [9], the heat transfer coefficient h_c of cooling-water can be calculated.

$$h_c = \frac{KN_u}{D} \quad (1)$$

Here D and K is the diameter and the thermal conductivity of cooling-water, respectively. The value of K is 0.63 W/m/^{0}C. The parameter N_u is the Nusselt number of cooling-water [10].

$$N_u = 0.023 R_e^{0.8} P_r^{0.8} \quad (2)$$

The P_r represents the Prandtl parameter of cooling-water, where μ and C_p is dynamic viscosity coefficient and specific heat capacity of cooling-water, respectively.

$$P_r = \frac{\mu C_p}{K} \quad (3)$$

The Re is the Reynolds number, here ρ and v is the density and average velocity of cooling-water, respectively.

$$R_e = \frac{\rho v D}{\mu} \quad (4)$$

In thermal analysis, the ambient temperature and cooling-water temperature are both set to be 20 ^{0}C.

STRUCTURE MODEL AND LAYOUT OF COOLING-WATER CHANNELS OF THE DB-DTL

In multi-physics simulation, a half model of the DB-DTL cavity with the cooling-water channel is utilized, as illustrated in Fig. 3. The copper cavity model will be applied in thermal and structural analysis by using ANSYS. The octahedron structure shell of DB-DTL is applied for good stability and easily assembling. There are eight cooling-waterway channels for ridge and ten cooling-waterway channels for wall. The interface of coupler, Pickup and observing window is located at another surface of the octahedron cavity. The main parameters of cooling-water are plotted in Table 2. Considering the limitation of water-supply machine, the velocity of cooling-water for ridge and wall are both set to be 2 m/s. The diameter of cooling-water channel is 15 mm. Therefore, the heat transfer coefficient h_c can be calculated by using the heat transfer theory of cooing water in chapter 3.

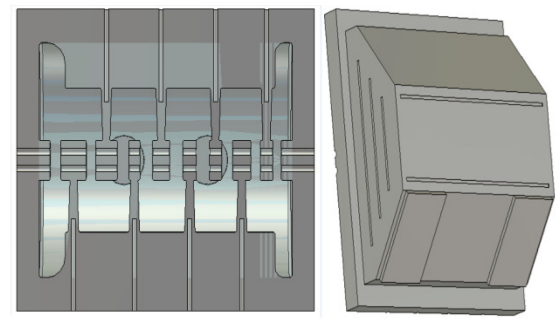

Figure 3: The cooling-water layout and structure model of the DB-DTL.

Table 2: Main Parameters of Cooling-Water

Parameters	Ridges Cooling-water	Walls Cooling-water
D (mm)	15	15
v (m/s)	2	2
R_e	30000	30000
P_r	6.6349	6.6349
N_u	187.14	187.14
h_c (W/m^2/^{0}C)	7860	7860

RF SIMULATION

The electromagnetic simulation is firstly performed by using MWS. Then, verification of electromagnetic calculation is simulated by using ANSYS HFSS. Table 3 gives a comparison of electromagnetic simulation between the MWS and ANSYS. The simulation results show that the difference between the two codes is enough small to ignore. The power dissipation of the DB-DTL is calculated with MWS and the surface loss density is simulated with ANSYS HFSS, as illustrated in Fig. 4, which will be applied to following thermal simulation. The normalized power dissipation of the DB-DTL cavity is calculated to be 35.83 kW. The beam power is 2 kW. According to the experience, the practical power loss is 1.2 times the simulated value [11]. The half model of the DB-DTL will dissipate 18.915 kW in multi-physics simulation

Table 3: The RF Simulation Results Comparison Between the MWS and the ANSYS HFSS

Parameters	MWS	ANSYS
F (MHz)	81.24993	81.9050
Q	13514	12860

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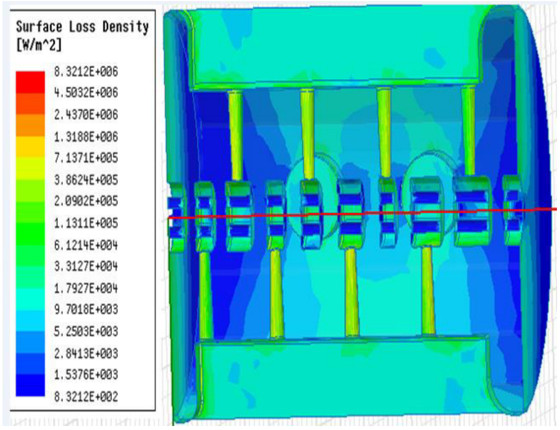

Figure 4: The power loss distribution on the internal surface of DB-DTL cavity.

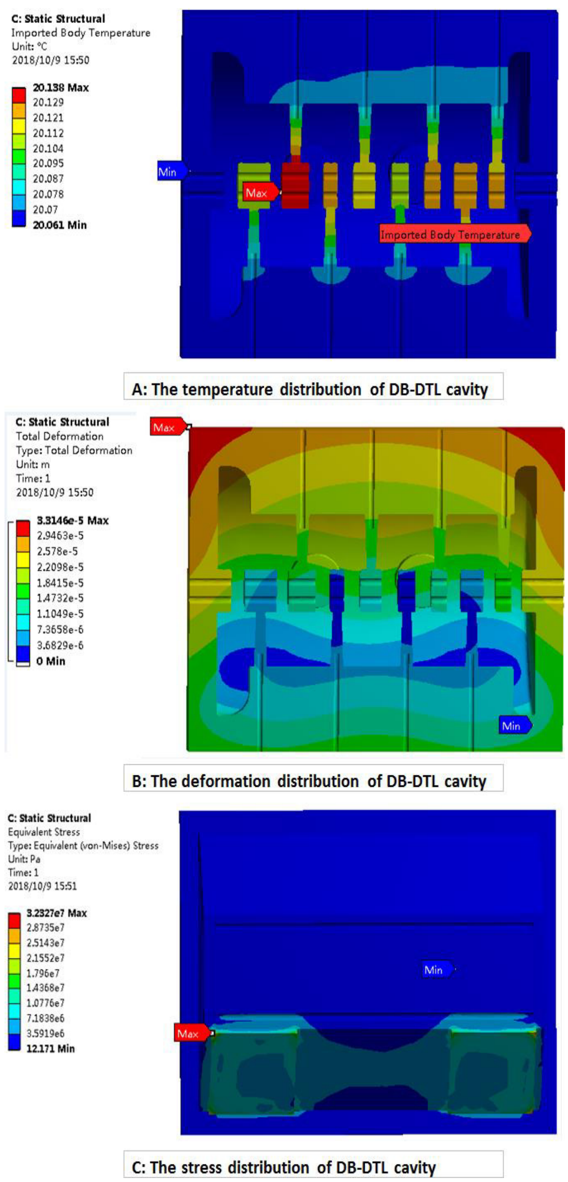

Figure 5: When the duty factor is 1/1000, the temperature (A), deformation (B) and stress (C) deformation distribution of the DB-DTL without cooling-water system.

THERMAL AND STRUCTURAL SIMULATION AND FREQUENCY SHIFTING CALCULATION

The thermal simulation is performed with the ANSYS Steady-State Thermal code, which generate the temperature map of the DB-DTL cavity. The cooling system and power dissipation is very important to simulate the temperature distribution of the DB-DTL. The cavity temperature distribution is applied to structural analysis in ANSYS Static Structural code for simulating the deformation and stress distribution of DB-DTL cavity.

The designing goal is that the DB-DTL operates in pulse model with a duty of 1/1000. In addition, there isn't cooling-water in the cooling-water channels because of the limitation of funds. Therefore, the power dissipation on the internal surface of the half model of the DB-DTL is firstly set to be 18.915*1/1000 kW in thermal simulation. The simulation results show that the maximum temperature is 21.38 ^{0}C located at drift tube, the maximum deformation is 23.4 um located at upper cavity edge and the maximum stress is 22.942 MPa located at fixed supporting plane edge, as illustrated in Fig. 5. The deformation of the DB-DTL cavity will cause frequency shifting. Based on the displacement result of the cavity, the frequency shifting is calculated with ANSYS HFSS code. The frequency shifting is 0.9 kHz. The frequency tubing ability of tuners is 9.65 kHz/mm, as shown in Fig. 6, which is applied in frequency tubing. All the simulation results are within an acceptable range, which meet the designing goal of the DB-DTL operated in pulse mode with a duty of 1/1000.

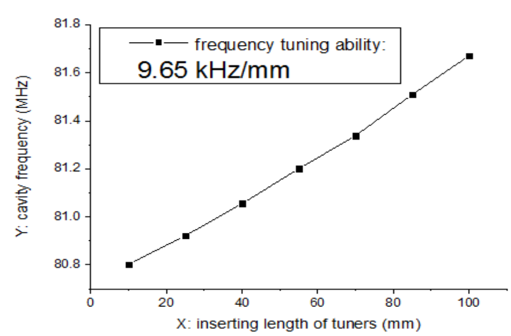

Figure 6: The frequency tubing capacity of tuners.

CONCLUSION

The designing goal is that the DB-DTL is operated in pulse model with a duty of 1/1000. There isn't cooling-water in the cooling-water channels of the DB-DTL for the limitation of funds. The multi-physics analysis results of the DB-DTL show that the maximum temperature is 21.38 ^{0}C located at drift tube, the maximum deformation is 23.4 um located at upper cavity edge, the maximum stress is 22.942 MPa located at fixed supporting plane edge and The frequency shifting is 0.9 kHz caused by the cavity deformation. All the simulation results are within an acceptable range, which indicate that the designing goal of DB-DTL is achieved.

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