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The multi-physics field analysis of a dual-beam drift tube linac

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Abstract. An 81.25 MHz dual-beam drift tube linac (DB-DTL) is being designed to prove 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 field analysis of the DB-DTL, including RF electromagnetic simulation, thermal simulation and structural simulation, which is very important for the DB-DTL safe operation. The RF power dissipation will make the cavity temperature rise and cause cavity resonance frequency shifts due to the deformation of cavity structure. The distributions of cavity deformation and stress are calculated according to the cavity temperature map. All the simulation results, including cavity temperature rise, deformation and stress and the frequency shifting, should be within an acceptable range. In this paper, the detailed multi-physics analysis of the DB-TL will be presented.

1. Introduction

The DB-DTL project was proposed to prove the feasibility of multi-beam type linac in middle energy region acceleration [2] [3], which will be applied for high intensity heavy ion beams, such as for heavy ion inertial confinement fusion (HIF) beams [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 cup" for measuring beam transmission, an existing CW RFQ accelerator [5], the DB-DTL and an analyzer magnet for measuring beam energy. The main parameters of the DB-DTL are listed in Table.1. The DB-DTL will accelerate 1 mA proton from 0.56 MeV to 2.5 MeV. Without matching section between the RFQ and the DB-DTL, The transmission rate of the DB-DTL is only 34%. Based on the electromagnetic simulation results, the normalized power dissipation is calculated as 35.83 kW. The DB-DTL will operated at pulse mode with 1/1000 duty.

The RF power dissipated on the internal surface on the DB-DTL will heat the cavity, which cause cavity deformation and resonance frequency shifts. The simulation results of the DB-DTL, including the maximum temperature, the maximum deformation, the maximum stress and the frequency shifts, are carried out systematically. All simulation results are controlled in an acceptable level, which indicates that the DB-DTL could be stably work at pulse mode with 1/1000 duty. The detailed three-dimensional multi-physics analysis of the DB-TL will be presented in this paper, which is a coupled RF electromagnetic, thermal and structural simulation.
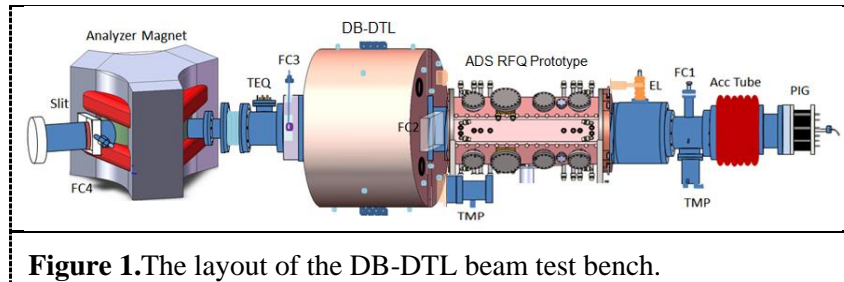
Figure 1. The layout of the DB-DTL beam test bench.

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/total gap voltage (kV)	389/2556
Transmission rate	34%
Operation mode	pulse
Cavity length (mm)	991.43
Quality value	13500
Shunt impedance (MΩ/m)	200.02
Normalized power dissipation (kW)	35.83

2. The procedure and goal of multi-physics field analysis

As shown in Fig. 2 [6], the procedures of multi-physics analysis include RF electromagnetic, thermal, structural and frequency shifts simulation. Firstly, the RF electromagnetic simulation is performed with the MWS [7] and ANSYS code [8]. The RF power dissipation is calculated to the normalized value, and the distribution of RF thermal loss is applied to the thermal analysis. The thermal simulation will generate cavity temperature map. According to the distribution of cavity temperature, the cavity stresses and deformations are calculated in structural simulation. Finally, based on the displacement of the DB-DTL, the resonant frequency shifts is calculated. Through the multi-physics field analysis, the cavity temperature and resonant frequency shifts should be within an acceptable range to satisfy the requirement for DB-DTL cavity operation.
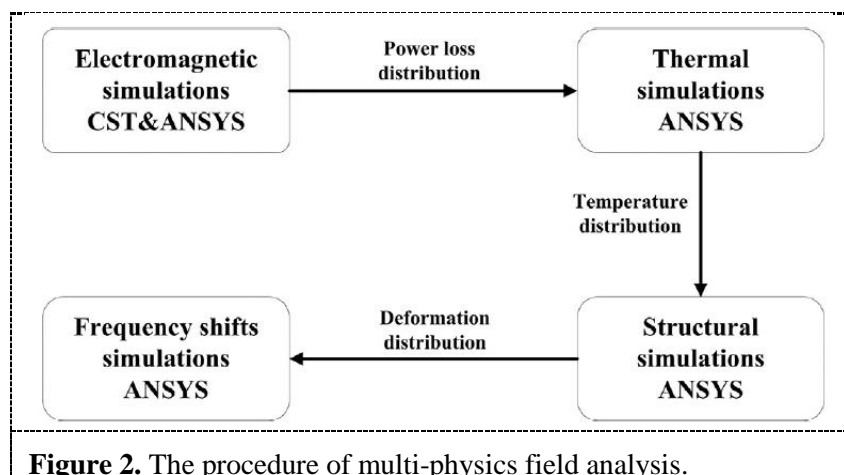

Figure 2. The procedure of multi-physics field analysis.

3. 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. Here D and K are 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]. 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. The Re is the Reynolds number, here ρ and v is the density and average velocity of cooling-water, respectively. In thermal analysis, the ambient temperature is set to be 20 ^{0}C.

$$h_c = \frac{KN_u}{D} \tag{1}$$
$$N_u = 0.023R_e^{0.8}P_r^{0.8} \tag{2}$$
$$P_r = \frac{\mu C_p}{K} \tag{3}$$
$$R_e = \frac{\rho v D}{\mu} \tag{4}$$

4. Structure mode and layout of cooling-water channels

In the multi-physics field analysis, a half model of the DB-DTL cavity with cooling-water channels is utilized, as illustrated in Fig. 3. The copper cavity model will be applied in thermal and structural simulation by using ANSYS. There are eight cooling-waterway channels for ridge and ten cooling-waterway channels for wall. 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 channels is 15 mm. Thus, the heat transfer coefficient h_c can be calculated as 7860 W/m^2/^{0}C by using the theory in chapter 3. The temperature of cooling-water is set to be 20 ^{0}C.
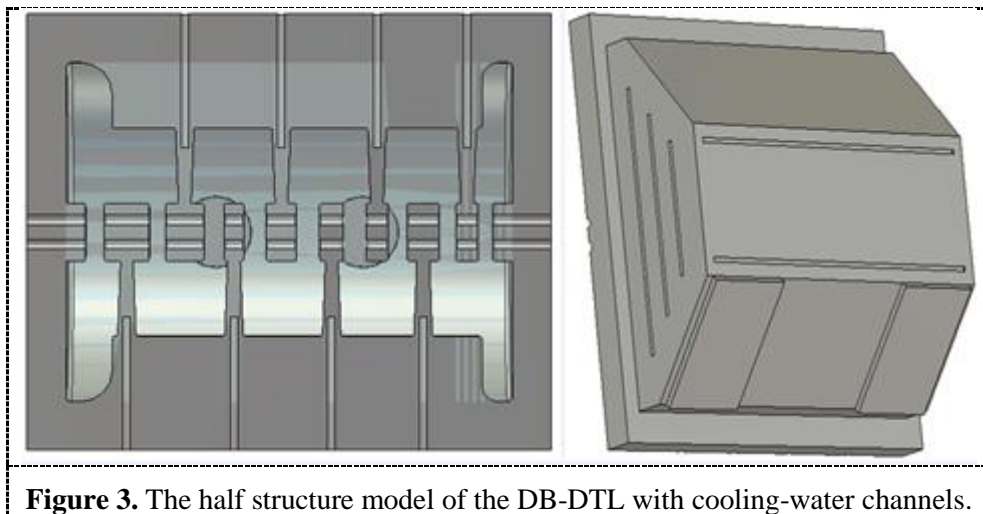

Figure 3. The half structure model of the DB-DTL with cooling-water channels.

5. RF simulation

The RF electromagnetic simulation is firstly performed by using MWS. Then, verification of electromagnetic calculation is simulated by using ANSYS HFSS. Table.2 gives a comparison of electromagnetic simulation results between the MWS and ANSYS. The simulation results show that the difference between the two codes is enough small to ignore. The surface loss density is simulated with ANSYS HFSS, as illustrated in Fig. 4, which will be applied to the 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 DB-DTL will operated at pulse mode with 1/1000 duty, thus, the half mode of the DB-DTL will dissipated 22.5 W in thermal simulation.
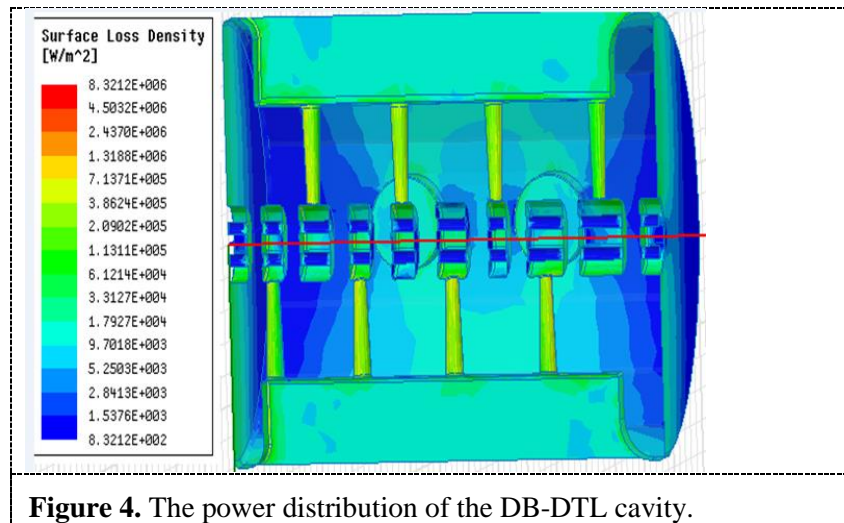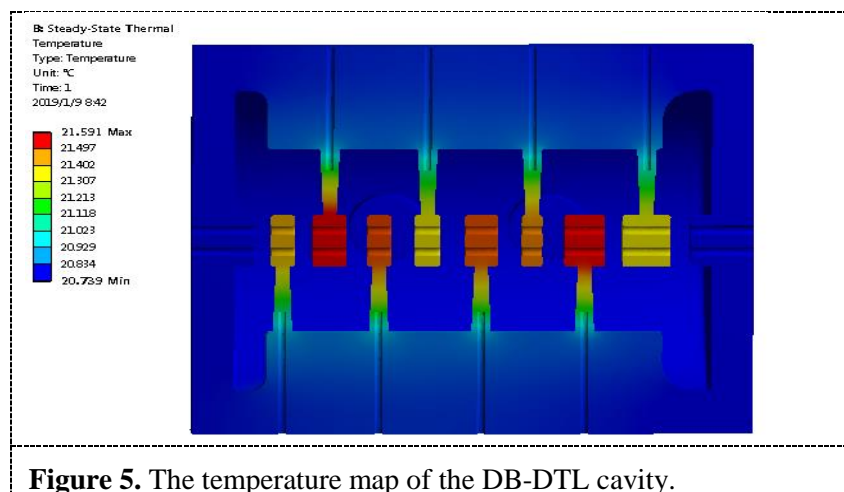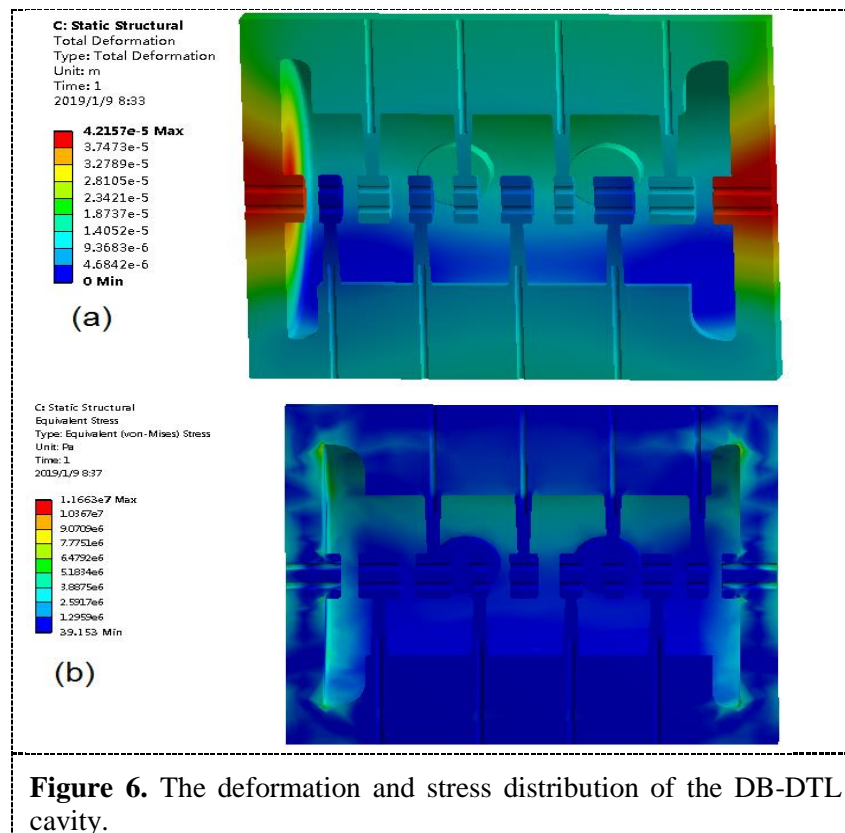
Figure 4. The power distribution of the DB-DTL cavity.

Table 2: The RF Simulation Results Comparison between the MWS and the ANSYS HFSS

Parameters	*MWS*	*ANSYS*
F (MHz)	*81.24993*	*81.8657*
Q	13514	12820

6. Thermal, structural and frequency shifts simulation

The thermal simulation is performed with the ANSYS Steady-State Thermal code, which generate the temperature map of the DB-DTL cavity. The cavity temperature map shows that the maximum temperature is 21.59 ^{0}C located at drift tube. The cavity temperature distribution is applied to structural analysis in ANSYS Static Structural code. The simulation results show that the maximum deformation is 42.16 μm located at outside of cavity end-cup and the maximum stress is 11.66 MPa located at fixed supporting plane edge, as illustrated in Fig. 5. Based on the displacement result of the cavity, the frequency shifts is calculated with ANSYS HFSS code. The frequency shifting is 0.9 kHz. All the simulation results are controlled in an acceptable level, which indicate that the DB-DTL will safely operate at pulse mode with 1/1000 duty.

Figure 5. The temperature map of the DB-DTL cavity.

Figure 6. The deformation and stress distribution of the DB-DTL cavity.

7. Conclusion

The multi-physics field analysis of the DB-DTL, including RF electromagnetic simulation, thermal simulation, structural simulation and frequency shifts simulation, are carried out systematically. Our simulation results show that the maximum temperature is 21.59 ^{0}C located at drift tube, the maximum deformation is 42.16μm located at upper cavity edge, the maximum stress is 11.66 MPa located at fixed supporting plane edge and The frequency shifting is 0.9 kHz due to the cavity deformation. All the simulation results are controlled in an acceptable level to ensure the DB-DTL safe operation.

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