MULTI-PHYSICS ANALYSIS OF A CW IH-DTL FOR CIFNEF

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Abstract

The Compact Intense Fast NEutron Facility (CIFNEF) project aims to produce high intense neutrons via the ^{7}Li (d, n) ^{8}Be reaction using a 5 MeV, 10 mA deuteron linac. The main components of the linac are an ion source, a short radio frequency quadrupole (RFQ) and an interdigital H-mode drift tube linac (IH-DTL). The IH-DTL will accelerate the continuous wave (CW) deuteron beam from 1 MeV to 5 MeV with a total cavity length of 1.25 m using Kombinierte Null Grad Struktur (KONUS) design, achieving an accelerating gradient of 3.2 MV/m. The RF power loss for the whole cavity is estimated to be 85 kW. This high power loss is a significant challenge to the cooling design, as it could cause large rises in temperature, thermal deformation and frequency drift. A detailed multi-physics analysis of the CW IH-DTL is presented in this paper.

INTRODUCTION

The study of fast neutron radiation effects in materials and the assessment of anti-radiation ability to fast neutron are of great concern in material research. However, at present the high intense fast neutron sources suitable for laboratory research are scarce all over the world. In this case, to produce high intense fast neutron, the CIFNEF project is proposed in Peking University, China. As a part of the project, the IH-DTL will operate in CW mode to accelerate the deuteron beam from 1 MeV to 5 MeV. The specification of the IH-DTL is listed in Table 1.

Table 1: The Specification of the IH-DTL

Parameters	Value
Ion species	Deuteron
Resonant frequency	162.5 MHz
Total length	1.25 m
Accelerating gradient	3.2 MV/m

High intensity CW accelerators produce much higher power loads than pulsed machines, leading to significant heating within the DTL cavity, which can cause thermal deformation and frequency shift. Therefore, it is necessary to develop an effective cooling system. To verify the validity of the system, multi-physics analysis has been performed.

KONUS BEAM DYNAMICS

The design of the IH-DTL is based on KONUS beam dynamics [1]. Unlike conventional Alvarez-type DTLs designs, H-type DTLs using KONUS beam dynamics consists of three sections; the accelerating, transverse focusing, and rebunching sections. The acceleration efficiency is

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improved because of the 0 degree RF phase acceleration. By separating the transverse focusing section and accelerating section, the H-type DTL using KONUS beam dynamics can use slim drift tubes without internal focusing elements. Reference [2] gives the detailed beam dynamics design of the CIFNEF IH-DTL.

EQUIVALENT CIRCUIT OF IH-DTL

In DTL designing, the construction of equivalent circuit is necessary. The equivalent circuit of IH-DTL are illustrated in Fig. 1. L' is the inductance excluding the segment with $r<R_1$. L_{IHD} is the inductance of complete cavity. The capacitance of IH-DTL contains two parts. One is the distributed capacitance between the stems, cavity walls and girders named C'. The other one is the capacitance between the drift tubes named C_d. They can be calculated by the following formulas [3]:

$$C_d = \frac{\varepsilon_0 \pi r_a^2}{2 g_e (g+d)} \left[2 + \frac{4 g_e}{\pi r_a} (\ln 2 + F_d(x)) \right]. \quad (1)$$

$$\text{with } F_d(x) = (1+x)\ln(1+x) - x\ln x; \ x = \frac{d_e}{2 g_e}. \quad (1a)$$

$$C' = \varepsilon_0 \frac{R_2^4 \left(\ln \frac{R_2}{R_1} + \frac{2F-3}{4} \right) + R_2^2 R_1^2 (1-F)}{\left(R_2^2 - R_1^2 \right)^2 (\varphi_2 - \varphi_1)}. \quad (2)$$

$$C_{IHD} = 2C' + C_d \quad (3)$$

$$L' = \frac{\mu_0 \left(R_2^2 - R_1^2 \right)(\varphi_2 - \varphi_1)}{2} \quad (4)$$

$$L_{IHD} = \frac{L'}{2} \cdot \left(\frac{R_2^2}{R_2^2 - R_1^2} \right) \quad (5)$$

The parameters is shown in the Fig. 2. F is the area correction factor in the segment with $r<R_1$. So the frequency of the cavity is:

$$\omega_{IHD} = 2c \sqrt{\left(\frac{R_2^2 - R_1^2}{R_2^4 \left(2\ln \frac{R_2}{R_1} + \frac{2F-3}{2} \right) + 2R_2^2 R_1^2 (1-F)} \right) \left(\frac{2C'}{2C' + C_d} \right) \left(\frac{R_2^2 - R_1^2}{R_2^2} \right)} \quad (6)$$
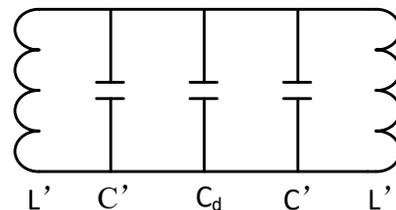

Figure 1: The equivalent circuit of a typical IH-DTL.
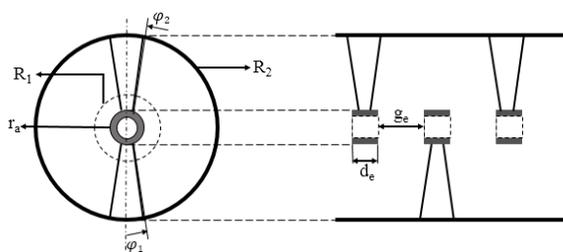
Figure 2: The schematic of a typical IH-DTL.

MULTI-PHYSICS ANALYSIS

The multi-physics analysis process includes coupled RF electromagnetic, thermal and mechanical analyses. The RF electromagnetic analysis is used to determine the high frequency field and to obtain the power loss. The thermal analysis can evaluate the temperature rise with the power loss obtained in the RF analysis. Then, the results of thermal analysis including a temperature field map are read into the mechanical model to calculate the structural deformation and stress. Finally, the mechanical results are coupled back to the RF model to determine the frequency shift. Figure 3 shows a simplified flow chart of the analysis procedure. In this case, CST [4] was used to perform the multiphysics analysis.
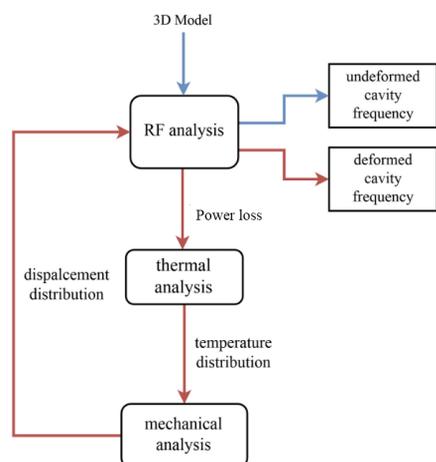

Figure 3: Simplified analysis procedure.

RF analysis

The model of the cavity is illustrated in Fig. 4. This cavity contains 20 accelerating gaps. The triplet lens is used to transversely focus the beam with three quadrupole magnets inside it.
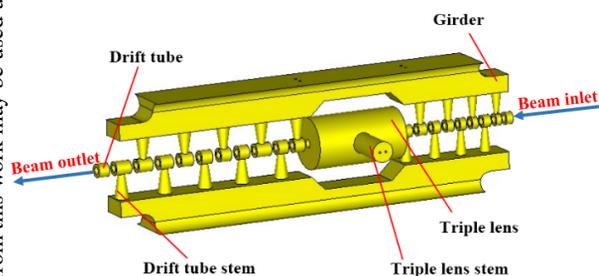

Figure 4: The model of the IH-DTL.

As shown in Table 2, the dimensions of the cavity have been optimized using CST MWS. Though the RF analysis, the cavity frequency and quality factor are 162.47 MHz and 14112, respectively. The frequency is close to the design frequency of 162.5 MHz, with a difference of only 0.018%. The power loss is estimated to be 85 kW.

Table 2: The Parameters of the IH-DTL

Parameters	Value (mm)
Cavity length	1248.2
Cavity width	325.6
Cavity height	375.6
Girder height	100.0
Girder width	80.0

Thermal Analysis

Results obtained in the RF analysis have been coupled into the thermal analysis to simulate the expected temperature rise. The power loss of the whole cavity is estimated to be 85 kW (68 kW/m) in the RF analysis. Such high power loss and CW operation make it a significant challenge to design a cooling system. Figure 5 shows the cooling system layout. The cooling system contains the girder water tanks, stem cooling pipes, drift tube cooling channels, and a triplet lens cooling pipe. As shown in Fig. 5 (a), there are two girders. Each girder has four water tanks. Two tanks with adjacent parts comprise a cooling cycle. Figure 5 (b) is one such cooling cycle, which is an enlarged view of the top left section of Fig. 5 (a). The red arrows indicate the flow path of the water. The yellow part in Fig. 5 (b) is the cross-section of a drift tube's cooling channel. The cooling channel extends down the drift tube stem and circles inside the walls of the drift tube itself.
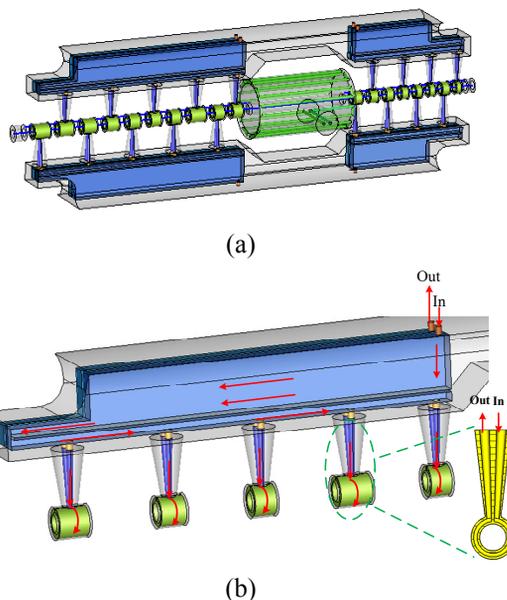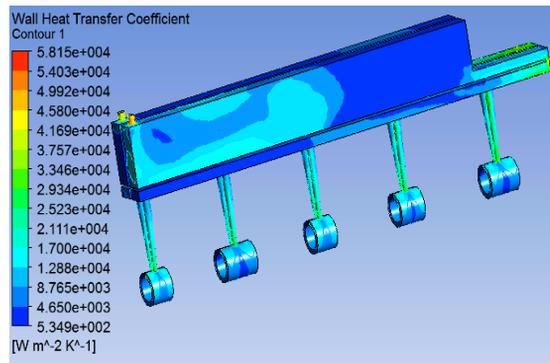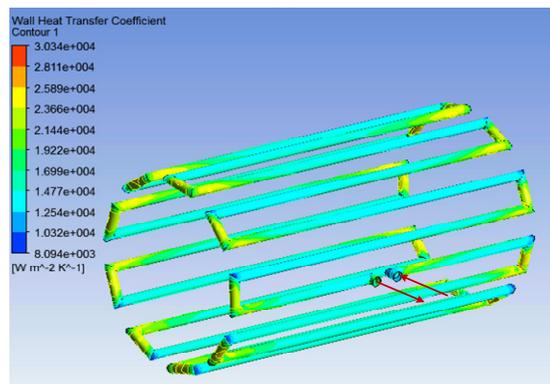

(a)

(b)

Figure 5: The cooling system. (a) Overview. (b) Enlarged view of cooling path.

(a)

(b)

Figure 6: Heat transfer coefficients for the cooling system. (a) Girder water tank, stem and drift tube cooling channels. (b) Triplet lens cooling pipe.

The heat transfer coefficient between water and the cavity was simulated using ANSYS CFX [5]. The velocity and temperature of the cooling water at the inlet are set to 3 m/s and 291 K respectively. Figure 6 illustrates the heat transfer coefficient simulation results. The heat transfer coefficients of different parts of the cavity are listed in Table 3. Since the distribution is not uniform, the average value is given.

Table 3: The Heat Transfer Coefficients of Different Sections

Parts	Heat transfer coefficient (W/m^2/K)
Girder tank	8000
Stem cooling pipes	15000
Drift tube cooling channels	8000
Triplet lens cooling pipes	16000

After applying the power loss and heat transfer coefficients to the thermal model as boundary conditions, the temperature rise has been calculated. Figure 7 shows the temperature distribution of the cavity after this thermal analysis. The maximum temperature is 347 K, located at the undercut. As the initial temperature is set to 291 K, the maximum temperature rise is 56 K.
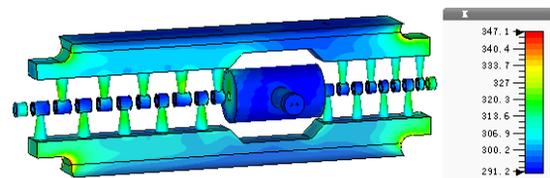

Figure 7: The temperature distribution of the whole cavity.

Mechanical Analysis and Frequency Shift

The temperature distribution field obtained in the thermal analysis is passed to mechanical analysis to determine the thermal deformation. The displacement distribution is illustrated in Fig. 8. The maximum displacement is 0.163 mm, located at the second drift tube. The maximum stress is 94.7 MPa.
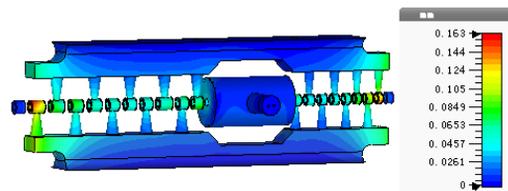

Figure 8: The displacement distribution of the whole cavity.

At the last step, the mechanical result is coupled back to the RF electromagnetic analysis to calculate the deformed cavity frequency. The frequency shift is about -0.086 MHz. The change percentage is 0.05%. The frequency shift is in the reasonable range, but the maximum Von Mises stress is simulated to be 94.7 MPa, which is quite large for copper [6]. Such large stresses may cause abnormal operation. More work is required to further reduce these stresses.

CONCLUSION

An IH-DTL has been designed for the CIFNEF project. The processes of the multi-physics simulations are presented in this paper. A cooling system is designed for the cavity to counteract joule heating from the high intensity CW deuteron beam. The frequency shift is only 0.05%. The thermal deformation and Von Mises stress exceed the recommend limit. Further work is required to improve the cooling system to ensure normal operation.

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