ELECTROMAGNETIC MODELING OF RF DRIVE IN THE LANSCE DTL

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Abstract

A 3D electromagnetic model of the RF drive module in the LANSCE DTL tank 4 has been developed with the CST MicroWave Studio. The model is explored both with eigensolvers and in time domain to evaluate maximal fields in the drive module and RF coupling. Here we describe the model and present simulation results.

INTRUDUCTION

The drift-tube linac at the Los Alamos Neutron Science Center (LANSCE) has recently been experiencing RF problems in its tank 4, in particular, frequent breaks of RF windows. One of possible reasons may be a replaced RF coupler in the tank. This situation stimulated a request by our RF group to provide EM modeling of the RF drive in the DTL tank 4 (T4). A CAD model of the drive was imported into the CST Microwave Studio (MWS) [1] and after some modifications became a part of a simplified MWS model of the T4 RF drive.

MWS MODEL OF RF DRIVE

The model of the T4 RF drive is shown in Fig. 1. Instead of the 19.7-m-long resonator cavity of the DTL tank 4, the drive is connected to a short model cavity. This cylindrical cavity has the same inner radius as the T4 resonator, 44 cm, but its length along the *z*-axis is only 41 cm. The frequency of the TM_{010} mode in the model cavity without coupler is tuned to 201.25 MHz by two coaxial inserts on the cavity end walls; the end walls are not displayed in Fig. 1. The tip of the drive loop (its "foot") is colored metal-grey. The red square on the left indicates the location of a 14″ coaxial waveguide port.

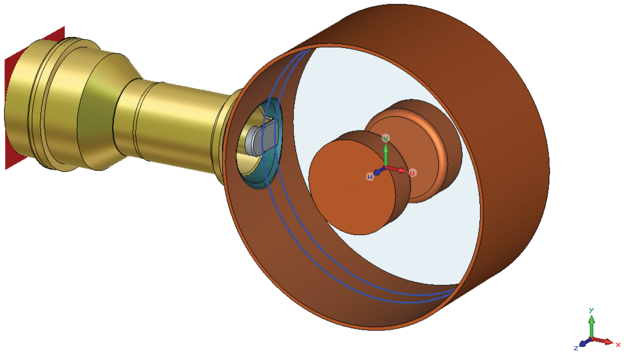

Figure 1: MWS model of the T4 RF drive (copper color) attached to a short cavity (brown).

A longitudinal cross section of the coaxial RF drive is shown in Fig. 2. For EM analysis, the imported CAD model was simplified by excluding external engineering details and filling the hollow inner coax with "metal." Elimination of the extraneous features is essential for MWS simulations; otherwise the MWS mesh routine tries to resolve them in detail. One can notice in Fig. 2 two remaining water-cooling channels in the RF loop foot. The RF drive is mated to the cavity cylindrical wall with a chamfered collar (shown in teal). The exact location of the coupler loop with respect to the cavity wall defines the RF coupling.

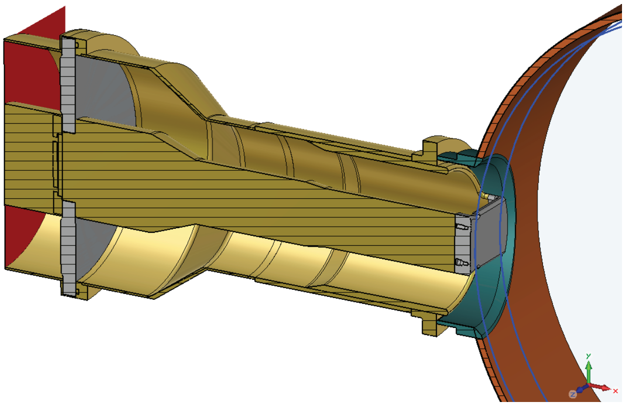

Figure 2: MWS model cut; RF window is shown in grey.

The RF window made of Rexolite [2] is modeled as a dielectric with ε = 2.53; small dielectric losses are neglected. A short section of the 14″ rigid coaxial line is attached to the receiving end of the RF drive assembly, behind the RF window; see in Figs. 1-2.

We use a short cavity instead of the long T4 cavity to better resolve the RF driver details in simulations while keeping MWS meshes within reasonable size. Obviously, the coupling to this cavity is different from that to the tank 4. However, we have previously developed a method [3, 4] for recalculating the MWS RF-coupler model results to real (usually much larger) cavities.

SIMULATION RESULTS

Both eigensolver and time-domain simulations of the RF-drive model were performed with MWS. In **eigensolver calculations**, closed boundary conditions (BCs), electric or magnetic, must be imposed at the waveguide port at the entrance of the 14″ coaxial line. This changes the fields in the vicinity of the port but still allows finding correct fields in the cavity and at the coupler. The eigensolver calculates the external quality factor Q_{ext} due to energy radiated into the coax: the modes in the coaxial port are calculated separately, with open BC. This restriction is removed in time-domain calculations where the BC at the coaxial port is set to "open". The cavity mode at 201.25 MHz is TM_{010}-like, with the longitudinal electric and azimuthal magnetic field. The fields in the RF drive are small compared to those in the cavity. The eigensolver-calculated value $Q_{ext} = 901$ is much smaller than the unloaded cavity quality factor, $Q_0 \approx 39300$, which was found assuming idealcopper cavity walls with conductivity $\sigma = 5.8 \cdot 10^7$ S/m. Obviously, the small model cavity is significantly over-coupled: the coupling coefficient $\beta_{pb} = Q_0 / Q_{ext} \approx 43.6$ (subscript *pb* for "pill-box"). This is not surprising since the coupler was designed for the much larger T4 cavity.

The mode magnetic field is disturbed near the coupler; it is clearly seen when the magnetic field is plotted on the circular curves located in the cavity near its wall and shown in blue in Fig. 1. The tangential component (red) and absolute value (green) of the magnetic field on the circle in the cavity central cross section is plotted in Fig. 3. The field is constant and purely azimuthal far from the coupler, and noticeably modified near the coupler, with small transverse components present. The fields are in the MWS default normalization, with the total field energy in the mode equal to 1 J. The maximal current density is 6.7 kA/m in this normalization; it is achieved on the inner side of the coupler-loop bend.

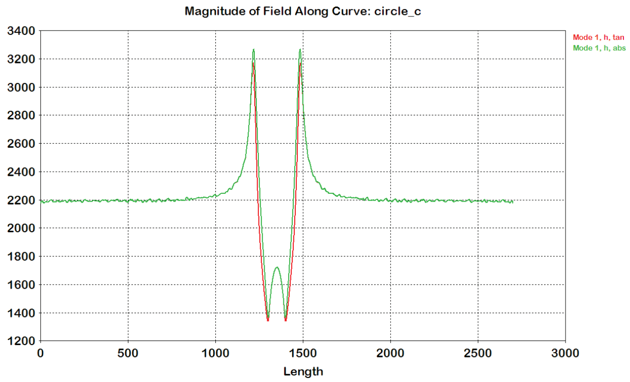

Figure 3: Magnetic field H (A/m) on the central circle in the cavity versus the curve coordinate (mm).

Time-domain MWS simulations have been performed by exciting the structure through the coaxial-port TEM mode with two different excitation pulses. First, a short Gaussian pulse in time domain corresponding to the frequency range from 190 to 212.5 MHz, centered around 201.25 MHz, was applied to excite the structure and then find resonances from *S*-parameters (S_{11} in this case). This short input pulse is almost completely reflected but still excites some fields in the cavity, which then start to decay by radiating energy back through the drive. The Q_{ext} calculated directly from the energy decay curve is 904.5, very close to the value found by the eigensolver.

The second set of time-domain computations was performed with a sin-step input pulse: a sinusoidal signal at the loaded-cavity frequency 200.672 MHz with the amplitude that increases from zero to a maximal value within 150 ns and then remains constant, as shown in Fig. 4 (in red). The output signal (green in Fig. 4) initially increases due to reflection but then, as the fields in the cavity build up, it starts to decrease. The decrease occurs due to cancellation of two waves: one is reflected from the input port and the other one is radiated from the cavity. These two waves have opposite phases; the reflected-wave amplitude remains constant as long as the input is constant, but the radiated-wave amplitude increases because the cavity fields grow at constant input RF power, cf. [3, 4]. One should clarify that the surface losses in the cavity and drive walls are neglected in this simulation.

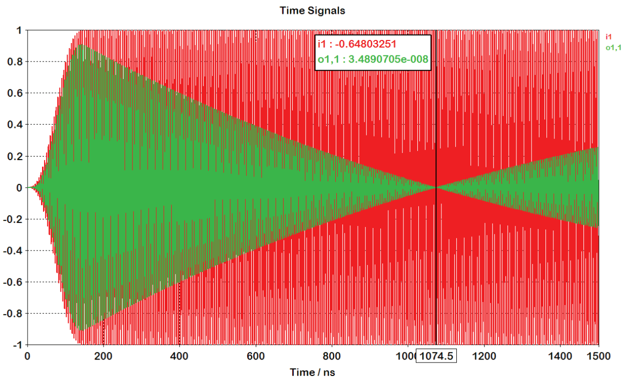

Figure 4: Time signals (in – red, out – green) from time-domain simulations with a long sin-step input pulse.

At some point (marked in Fig. 4, $t = 1074.5$ ns), the two waves completely cancel each other. The field pattern at this moment is exactly the same as a perfect match: no net RF power is reflected back into the coax. The fields at this moment are recorded using a time field monitor; another, frequency field monitor records fields at the main excitation frequency 200.672 MHz. The surface-current distribution from time-domain calculations is similar to that found by eigensolver, see in Fig. 5: the maximal surface current is near the coupler loop bend. This maximal current value is different for the time and frequency field monitors, 4.58 and 3.33 A/m, respectively, and corresponds to the MWS default time-domain normalization, 1 W peak input power.

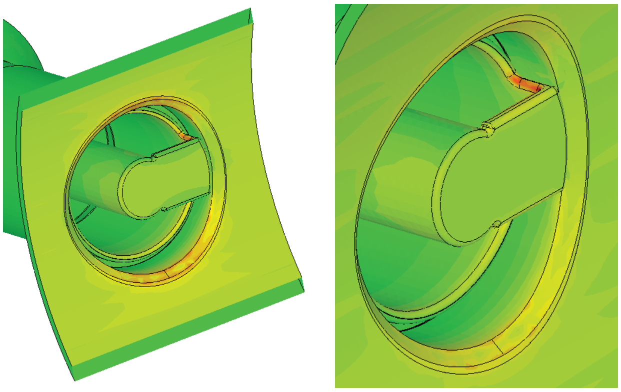

Figure 5: Surface-current magnitude distribution near the RF drive loop from eigensolver (left) and time-domain (right) calculations: red indicates high values, green low.

The magnetic-field plots on the circular curves look very similar to that from the eigensolver, Fig. 3, except for the field scale: for the time monitor, the flat-part value (far from the coupler) is $H_c = 1.32$ A/m; for the frequency monitor, $H_c = 0.962$ A/m. It is important, however, that the ratio of the maximal surface current $J_{\max}$ to the field H_c far from the coupler is almost the same for both monitors: 3.47 and 3.46, correspondingly. Also, the fraction of the surface loss deposited on the RF drive to the total surface loss is about 5%, close to the result of 4% from the eigensolver.

RESULTS FOR DTL TANK 4

We can now rescale the above results for the DTL tank 4 by comparing the magnetic field values far from the coupler. At the accelerating gradient E_0 = 2.4 MV/m in T4, the magnetic field near the tank cylindrical wall is approximately $H_c \approx 3$ kA/m, e.g. [5]. From time-domain results, the ratio of the maximal surface current to the field far from the coupler is $J_{\max} / H_c = 3.47$. Therefore, the maximal surface current near the T4 coupler is $J_{\max} \approx$ 10.4 kA/m. The averaged CW power density dP/ds at a surface point is related to the peak surface current at the same point J_{surf} as dP/ds (W/cm^2) = 0.185 (J_{surf} (kA/m))^2 for copper walls with conductivity $\sigma = 5.8 \cdot 10^7$ S/m at frequency 201.25 MHz. This leads to an estimate of maximal power density dP/ds of 20 W/cm^2 at 100% duty. For a typical high-power operation at 10% duty, the value is reduced to rather reasonable 2 W/cm^2. This power flux is still about 12 times higher than the flux far from the coupler.

We can also estimate the coupling coefficient for the DTL T4. The coupling coefficient for the model cavity $\beta_{pb} = Q_0 / Q_{ext}$ = 43.6, found in eigensolver calculations, can be used to calculate the coupling coefficient β_c for the T4 cavity. The relation is given by

$$\beta_{pb} = \beta_c \frac{W_c}{W_{pb}} \left(\frac{H_{pb}}{H_c} \right)^2 \frac{Q_{pb}}{Q_c}, \qquad (1)$$

where W_i, H_i, Q_i are the stored energy, magnetic field at the coupler location (without coupler), and unloaded quality factor for the cavity with subscript i = *c, pb*; details can be found in [3, 4]. Here subscript *c* is used for the T4 cavity, and *pb* is for the model (pill-box) cavity. In Eq. (1), we can use eigensolver results Q_{pb} = 39300, H_{pb} = 2.2 kA/m, and W_{pb} = 1 J for the model cavity, and Q_c = 57780, H_c = 3 kA/m for the T4 cavity [5]. The stored energy W_c for the T4 resonator can be estimated based on power-loss and Q-factor results in Ref. [5] as W_c = 102 J. In our case, however, it is more convenient to rewrite (1) using the Q-factor definition, $Q = \omega W/P$, in terms of the total surface-loss power P in the corresponding cavity. Since $\omega_c = \omega_{pb}$, this leads to the equation

$$\beta_c = \beta_{pb} \frac{P_{pb}}{P_c} \left(\frac{H_c}{H_{pb}} \right)^2, \qquad (2)$$

where we can directly use the value for the power loss in T4, P_c = 2.24 MW at 2.4 MV/m [5], and only need P_{pb} = 32.1 kW from the MWS eigensolver calculations. With this input, Eq. (2) gives an estimate for the coupling coefficient of the T4 cavity, $\beta_c \approx 1.16$. One should emphasize that the coupling depends on the exact position of the coupler loop with respect to the resonator wall.

We performed similar computations with the old drive loop of the tank 4 for comparison. The old "foot" was just slightly thinner in the coupler axial direction: 3/8″ vs. 1/2″ for the new loop. The encircled tank cross section within both loops is the same. Our simulations found only one small difference: the coupling with the old loop was about 5% lower. This is because the thicker new foot protrudes into the tank by 1/8″ deeper, which forces some extra flux through the loop. In both cases, the total power deposited at the RF drive is 2.4 kW at 100% duty, out of which 400 W is deposited in the "foot" and 900 W in the collar.

In addition, we explored higher-order modes (HOM) in the drive model to see if higher RF harmonics can excite them. The HOM are practically identical with the new and old loop. One needs to study the full tank model to evaluate realistic HOMs. It would also be interesting to calculate effects of arcs in the tank on the RF drive and window; however, it is unclear how to model that.

SUMMARY

A simplified 3-D MWS model for the RF drive in the LANSCE DTL tank 4 (T4) has been constructed using CAD import for the drive. Both eigensolver and time-domain calculations with the model have been performed to evaluate maximal fields in the drive module and RF coupling. The maximal power flux on the coupler loop was calculated, 20 W/cm^2 at 100% duty. The electric fields inside the coupler are low compared to the values near the tank drift tubes. The RF coupling coefficient to the T4 cavity was estimated as $\beta_c \approx 1.16$. Overall, our simulations of the RF coupler do not indicate any reasons that could be related to the recent RF problems in the DTL T4. More details can be found in [6].

Obviously, the present model is simplified. It does not include details of the 14″ coaxial RF guide and its 45° bend; the RF window is also simplified and its dielectric losses are neglected. These or other details can be added as needed in future developments. Still the model as is can be useful to evaluate sensitivity of the coupling to the coupler-loop displacements or rotations.

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