OPTIMISATION OF THE 3-STUB TUNER FOR MATCHING THE DIAMOND SCRF CAVITIES

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Abstract

The Diamond Storage Ring cavities are aperture coupled, resulting in a fixed external Q. This results in the cavities being matched under certain conditions depending on the loss per turn, the beam current and the accelerating voltage. Operationally, there are advantages to limiting the accelerating voltage to improve reliability, which at high beam current results in a mismatch and high reflected power. To match the cavities under such non-optimum operating conditions we use 3-stub tuners in the waveguide feeds as have been used at many places [1, 2]. It has been observed, that certain configurations of the 3-stub tuners can improve the match of the cavity but result in strong heating of the waveguide in the cryostat. Numerical simulations of the cavity along with the coupling waveguide and 3-stub tuners have been carried out using CST Studio for different beam loading conditions to optimise the 3-stub tuners for acceptable match and heating. In this paper we present the results of our simulations and comparisons with measurements for operation with different beam currents and cavity voltages.

INTRODUCTION

For safe cryogenic operation, Diamond SCRF cavities are equipped with several Cryogenic Linear Temperature Sensors (CLTS). These temperature sensors are distributed on cavity cell, beam tubes and on the coupling waveguide etc. The cavities are generally operated at lower voltage compared to the optimum condition. Also, to improve the reliability, one of the cavities was operated at lower voltage than the other (Cavity-1 at 1.1 and Cavity-3 at 1.4 MV). Therefore, it was required to lower the Q_{ext} of the cavities with the help of 3-stub tuners in order to match the cavities under such non-optimum conditions. With the aim of splitting the total beam power almost equally between the two cavities, cavity-1 required to have lower Q_{ext} than that of cavity-3. So, the Qext on Cavity-1 and Cavity-3 were adjusted to ~9.5E+04 and 1.43E+05 respectively. Following increase in stored current from 200 mA to 250 mA, during mid 2011, it was observed that the temperature sensor on the far end of the waveguide elbow on Cavity-1, showed considerable increase in temperature (338° K) causing increase in the pressure in the waveguide / pump-out-box region. Subsequently, one of the stubs was retracted fully to increase Q_{ext} ~ 1.47E+05. This resulted in increased reflected power but a significant drop in the elbow temperature (by almost 100°) and also in the pressure in the waveguide. It is obvious that the desired Q_{ext} can be obtained with many different settings of the 3-stub tuner. Some of these settings can result in strong Standing Wave (SW) pattern especially in the reduced height waveguide inside the cryostat causing significant heat dissipation. This motivated us to undertake a detailed numerical study of the cavity-coupling waveguide system with 3-stub tuner included.

We used CST Studio [3] to simulate the steady state behaviour of a beam loaded cavity.

CAVITY PARAMETERS Q_0, Q_{ext} AND β

The cavity parameters Q_0, Q_{ext} and coupling coefficient β are defined as follows [4, 5]

$$Q_0 = \frac{\omega \cdot EnergyStored}{PowerDissipationinCavityWalls} = \frac{\omega U}{P_C}$$

$$Q_{ext} = \frac{\omega \cdot EnergyStored}{PowerRadiationThroughtheCouplingNetwork} = \frac{\omega U}{P_{RAD}}$$

$$\beta = \frac{PowerradiatedThroughtheCouplingNetwork}{PowerDissipationinCavityWalls} = \frac{Q_0}{Q_{ext}}$$

where ω, U, P_c and P_{RAD} are resonant frequency, energy stored, power dissipated in cavity walls and power radiated respectively.

The power dissipated in the cavity walls depends on the conductivity of the material whereas the power radiated and so the Q_{ext} depends only on the geometry of the coupling device (a probe or an aperture etc.). The skin depth and surface resistivity are given by;

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\pi f \mu}{\sigma}} \quad (1)$$

We know

$$P \propto R_s$$

Observing the expression for R_s, we see that

$$P \propto \frac{1}{\sqrt{\sigma}}$$

at a fixed frequency f. If we build exactly similar cavities out of two different materials with conductivities σ1 and σ2 or if the conductivity of the cavity material changes from σ1 to σ2 (e.g. on cool down in a Nb cavity and neglecting the deformations), the ratio of Quality factors at two conductivities can be written as

$$\frac{Q_{01}}{Q_{02}} = \frac{P_2}{P_1} = \sqrt{\frac{\sigma_1}{\sigma_2}}$$

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We know

$$Q_0 = \beta Q_{ext}$$

$$\frac{Q_{01}}{Q_{02}} = \frac{\beta_1}{\beta_2} = \sqrt{\frac{\sigma_1}{\sigma_2}} \qquad (2)$$

From the last equation, we can estimate Q_{02} or β_2 at any conductivity σ_2 if Q_{01} is known at conductivity σ_1. Or we can estimate the conductivity σ_2 in order to get a desired value of Q_{02} or β_2.

SIMULATION OF STEADY STATE BEAM LOADED CAVITY

We can make use of the fact that the Qext is independent of conductivity to simulate the operation of a cavity under steady state condition. Let us consider a cavity operating with some reflection or which is not matched to the generator so well. In this situation, the total generator power (P_f) being transferred to the cavity is divided into three parts (i) power dissipated in the cavity walls (P_c) (ii) power transferred to the beam (P_b) and (iii) power reflected (P_r). We calculate the magnitude of the reflection coefficient as

$$|\rho|^2 = \frac{P_r}{P_f} = |S_{11}|^2 \qquad (3)$$

And the VSWR

$$S = \frac{1+|\rho|}{1-|\rho|} \qquad (4)$$

We also know that [4],

$\beta = S$ for an over-coupled cavity (5)

and $\beta = 1/S$ for an under-coupled cavity (6)

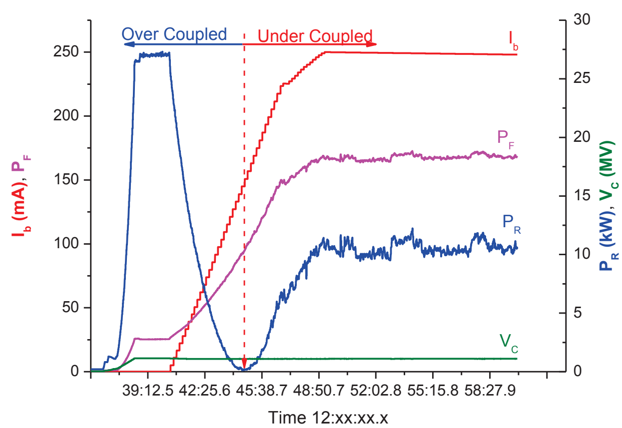

Figure 1: Typical measured operating parameters of Cavity-1during an injection cycle.

Depending on whether the cavity is operated below optimum or over the optimum condition (corresponding to P_r = 0), the cavity will appear to be over-coupled or under-coupled respectively. Figure 1 shows the forward and reflected power along with the beam current for cavity-1 during filling of the storage ring for a certain setting of the 3-Stub tuner. The voltages across cavity-1 and cavity-3 are 1.1 and 1.4 MV respectively. Initially when there is no beam in the storage ring, almost all of the power is reflected. As the beam current increases, the reflected power starts dropping and passes through a minimum almost equal to zero. This minimum corresponds to the optimum coupling condition at a particular voltage given by [6],

$$\beta_0 = \frac{Q_0}{Q_{ext}} = 1 + \frac{P_b}{P_c}$$

$$(\beta_0 - 1)P_c = P_b. \qquad (7)$$

For Diamond cavities (without 3-Stub tuner), $\beta_0 = Q_0/Q_{ext} \cong 2500 >> 1$; or $\beta_0 P_c \cong P_b$. In figure 1, the cavity is over-coupled towards the left of the red vertical dotted line and under-coupled towards its right. To simulate the operation of a cavity at one particular instant, we require 3 cavity parameters P_f, P_r, V_c at that instant and which side of the optimum condition the cavity is being operated. We calculate $|\rho|$ and S from equations (3) and (4) respectively. The effective β or Q_{ext} can be estimated from Eq. (5) when the cavity is operated below the optimum condition and Eq. (6) above it. We consider three cases corresponding to critically coupled (β =1), over-coupled (β >1) and under-coupled (β<1) cavity.

The Model

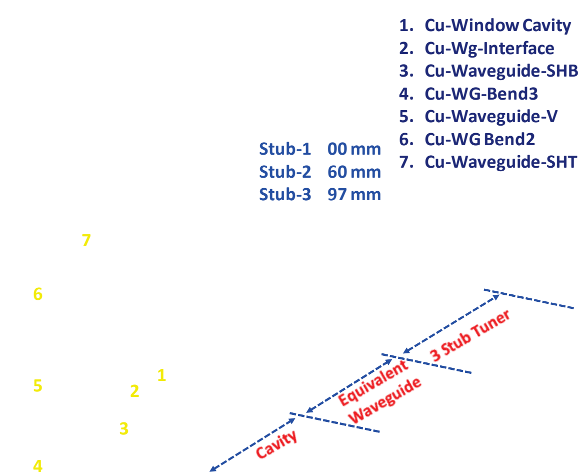

Figure 2: CST Studio model of the Diamond storage ring cavity and the coupling waveguide. The stub insertions are shown to be 0, 60 and 97 mm.

Figure 2 shows the CST Studio model of the storage ring cavity along with the coupling waveguide. The Niobium parts which are in the LHe bath are represented in bluish colour. Reddish brown colour represents the waveguide and window cavity parts which are made from stainless steel and are plated internally with copper. The rest of the waveguide parts are shown in grey. The cavity is simulated as a *one port* device. In order to calculate Q_{ext}, the Frequency Domain (FD) or Time Domain (TD) simulations can be performed considering the material losses. Since DLS cavity is excessively over-coupled, the

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computed S11 or SWR will be extremely high if conductivity of SC niobium is used. The impedance varies very fast about the resonant frequency and S11 or SWR values are generally too inaccurate to estimate the Q_0 or Q_{ext}. Instead we use a smaller value for the material conductivity (e. g. that of copper) to get S11 typically below 0.95. Here we assume that the net power being delivered to the cavity, $P_f - P_r = P_b + P_c$ is being dissipated in the cavity walls.

Perfectly Matched Cavity (β = 1)

We make use of the fact that for a perfectly matched cavity, $Q_{ext} = Q_0$. The conductivity of the cavity material which will give $Q_0 = Q_{ext}$, can be estimated from Eq. (2).

For this we can first compute cavity Q_0 either with the help of Eigen mode solver or FD solver assuming conductivity of material to be known e.g. copper with σ_{Cu} = 5.8E+07 S/m. From a FD run with this conductivity, we can estimate both Q_0 and Q_{ext} and thus β.

We can estimate the conductivity which will give perfect match i.e. $Q_0 = Q_{ext}$ or β = 1 from Eq. (2). Let $Q_{0\text{-}Cu}$ be the Q_0 computed in Step 1 above. We should look for σ_{New} which will give $Q_{0\text{-}New} = Q_{ext}$.

$$\frac{Q_{0-Cu}}{Q_{0-New}} = \sqrt{\frac{\sigma_{Cu}}{\sigma_{New}}} \quad \text{or}$$

$$\sigma_{New} = \sigma_{Cu}\left(\frac{Q_{0-New}}{Q_{0-Cu}}\right)^2 = \sigma_{Cu}\left(\frac{Q_{ext}}{Q_{0-Cu}}\right)^2$$

(as we know Q_{ext} from step 1)

In a subsequent run either in TD or FD, we use σ_{New} to compute S11. This run will give us Q_0, Q_{ext}, VSWR or β. As we are simulating a matched ($Q_0 = Q_{ext}$) case, we can check the validity of the simulation results against following conditions

1. S11 should be as close as possible to 0 (S11 ≤ 0.02 would be a good and acceptable result) OR
2. VSWR as close as possible to 1
3. $Q_{ext} = Q_0/\beta$ as both Q_0 and Q_{ext} can be computed from the same run.
4. Q_{ext} can be compared with the experimentally measured value.

Computation for DLS Cavity-1: As an example, we first compute Q_{ext} for the cavity with waveguide without the 3-stub tuner (as shown in Fig. 2 with all the 3 stubs fully retracted). The results are summarised in Table 1 below. First step results of a FD run are listed 2nd column and second step results are listed in 4th column. The computed values of $Q_{0\text{-}New}$ and Q_{ext} agree well with the experimentally measured value of Q_{ext} = 2.35E+05 to validate the procedure.

Unmatched Cavity (β ≠ 1)

A fractional length of guide wavelength (λ_g) can be used as 'equivalent waveguide' in the simulation to represent the whole run of waveguide between the window and the 3 stub tuner. This can be obtained by subtracting the largest integral multiple of $\lambda_g/2$ from the total length of waveguide. It is straight forward to simulate the cavity without 3-stub tuners. Any arbitrary length of the waveguide between the cavity (RF window) and the input port can be used. If the cavity operated with Q_{ext} modified with the help of 3 stub tuner is to be simulated, the correct (electrical) length of waveguide between cavity and the 3 stub tuner should be used. A deviation of few mm's can cause significant deviation or error in computed S11 or VSWR and thus the SW pattern. The correctness of the length of the equivalent waveguide can be verified by comparing the S11 or VSWR (or Q_{ext}) values computed by CST Studio with those calculated from P_f, and P_r data for known 3 stub tuner settings at a known cavity voltage.

Table 1: CST Studio Results for Matched ($Q_0 = Q_{ext}$) Case of DLS Cavity without 3 Stub Tuner

Parameter	CST Studio	Parameter	Computed
σ	5.8e+07	σ_{New}	1.81948e+09
$Q_{0\text{-}Cu}$	4.1389e+04	$Q_{0\text{-}New}$	2.3183e+05
S11	0.697012248	S11	0.011
VSWR	5.601	VSWR	1.022
Coupled	Under	Coupled	Under
β	0.178542	β	0.98
Q_{ext}	2.318165e+05	Q_{ext}	2.3453e+05
σ_{New}	1.81948e+09	$Q_{ext\text{-}meas}$	2.35e+05
$Q_{0\text{-}New}$	2.318165e+05		
Desired β	1.0		

The length of equivalent waveguide needs to be adjusted to get a good agreement between the computed and the measured value of Q_{ext} from machine data. This is necessary as the electrical length of certain waveguide components (such as mitres etc.) differ from the physical length. Once the correct length of equivalent waveguide (correct phase of the reflected wave from the cavity) is established, SW pattern and power dissipation in the waveguide corresponding to any operating condition of the cavity can be obtained.

To obtain the representative field configuration corresponding to any operating condition of the cavity, we calculate the conductivity which gives the desired value of Q_0 or β or S11 (as Q_{ext} is fixed for one particular 3 stub tuner setting) with the help of Eq. 2 as we already know Q_0 and σ. Figure 3 shows measured values of S11 during an injection cycle compared with those computed with CST Studio. The storage ring is operated with a single cavity (cavity 1) at 1.2 MV with stubs 1 – 3 set at 0, 60, and 97 mm respectively (as shown in Fig. 1). Cavity 3 was detuned sufficiently so that it interacts least with the beam. This was confirmed by negligible voltage

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measured on cavity 3 when sufficient beam was stored in the storage ring. At the point corresponding to Pr ≅ 0 (perfect match), for the estimated Q_0 = 8.67E+04 from Eq. 2, the CST computed values of Q_0, S11 and Q_{ext} are 8.56E+04, 0.00166 and 8.53E+04 respectively. This confirms the validity of the simulation results.

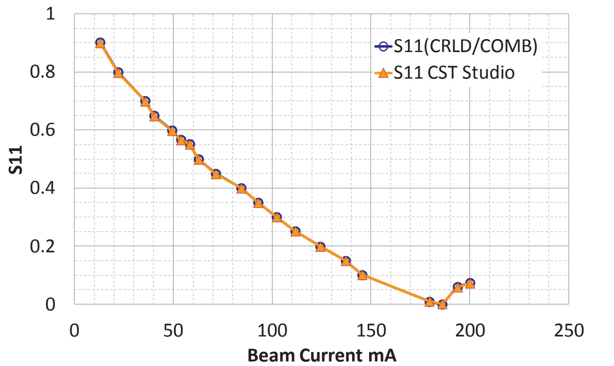

Figure 3: S11 values from CST Studio (orange triangles) compared with those measured (empty circles) during injection into storage ring operated with cavity1 alone and 3 stub setting of 0, 60 and 97 mm.

Q_{ext} VS STUB POSITION

Detailed simulations were performed for systematic variations of all the 3 stub positions individually and together in combination.

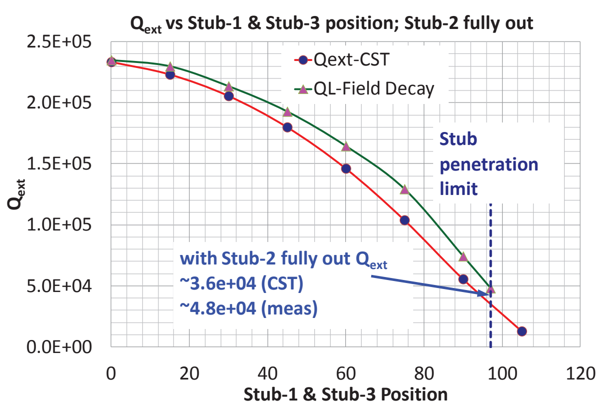

Figure 4: Q_{ext} vs stub-1 and stub-3 positions. Both stubs are moved together with stub-2 fully out.

Figure 4 shows Q_{ext} values computed by CST (blue dots) compared with measured values (pink triangles) when stub 1 and stub 3 are moved together with stub 2 fully out. Figure 5 shows Q_{ext} vs stub 2 positions with stub 1 and 3 fully out. It is seen that Q_{ext} decreases as stub 1 and 3 are moved in individually and together whereas it increases as stub 2 is moved in. Figure 6 – 8 show carpet plots for Q_{ext} for various combinations of the three stubs. It can be seen that Q_{ext} values as low as 5.0E+04 can be obtained with the help of stub 1 and stub 3 and can be used for matching heavy beam loading conditions. Stub 2 however can be used to get higher Q_{ext} values which can be useful to match the cavity during low current operation e.g. during low-α run etc.

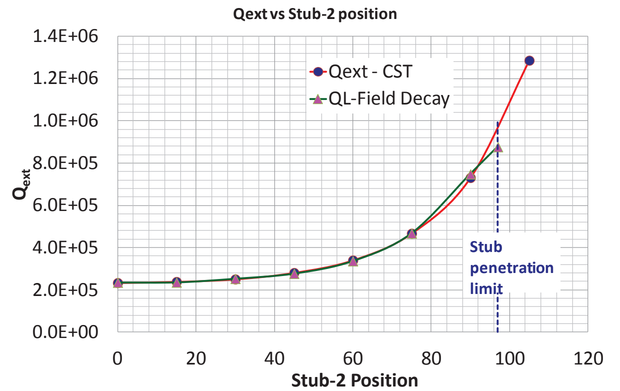

Figure 5: Q_{ext} vs stub 2 positions. Blue dots – CST, pink triangles –measured values.

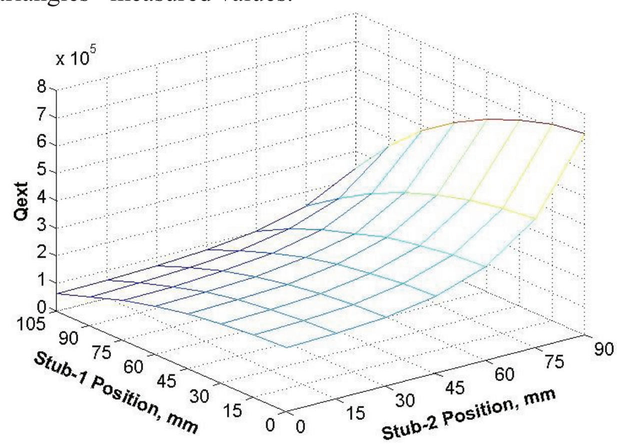

Figure 6: Q_{ext} vs stub 1 and stub 2 positions. Stub 3 is fully out.

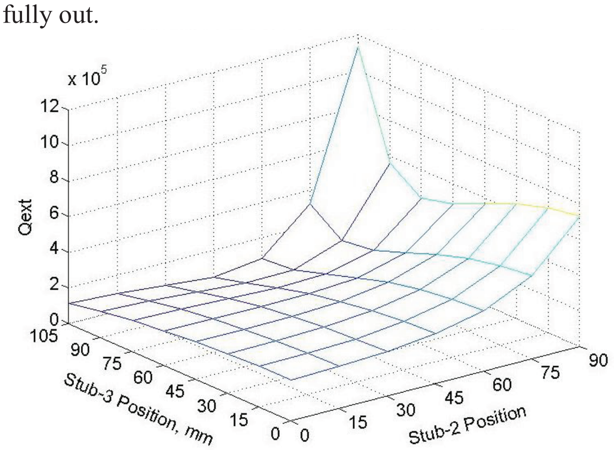

Figure 7: Q_{ext} vs stub 2 and stub 3 positions. Stub 1 is fully out.

The two cases of 3 stub tuner settings mentioned above, one with 79-47-85 which resulted in heating in the reduced height waveguide and another with 00-47-85 were investigated with CST studio. The Q_{ext} values estimated from archived data corresponding to P_r = 0 are 9.5E+04 and 1.47E+05 respectively. The simulation results are summarised in Table 2. First two rows show the estimated values of Q_0 and σ from Eq. 2 for matched operation (Q_0 = Q_{ext}). It is seen from the results that the computed values of Q_0 and Q_{ext} agree well with the estimated values.

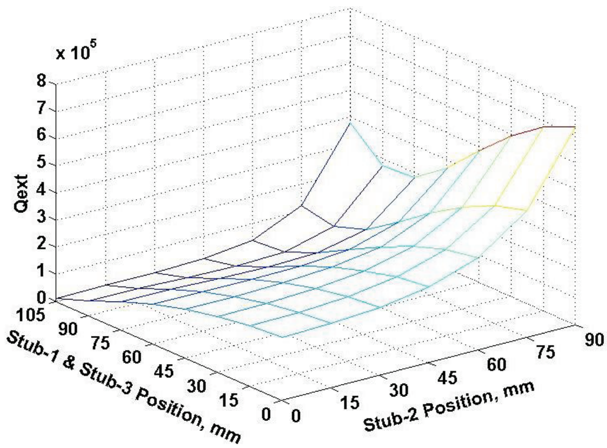

Figure 8: Qext vs stub 1 and 3 (together) and stub 2 positions.

Table 2: Summary of CST Simulations for two Configurations of 3 Stub Tuner Matched Cases.

Parameter	79 – 47 - 85	0.0 – 47 - 85
$Q_0 = Q_{ext}$	9.5284e+04	1.47239e+05
σ	3.03e+08	7.237e+08
S11	0.0052	0.0085
β	1.01	1.017
Q0	9.47e+04	1.465e+05
Q_{ext}	9.376e+04	1.440e+05

Figure 9 (a) and (b) shows power loss density for the above mentioned two cases with conductivities adjusted to have S11=0.2 and 0.253 to represent operation at 1.1 MV with P_f = 175 and 167 kW respectively with stored current of 250 mA in both the cases. A plot of |E| along the waveguide axis is shown in Fig. 9(c). The SW corresponding to stub setting 79-47-85 is shown by green curve and the one for 00-47-85 is shown by purple curve. The power dissipation in the copper plated part of the reduced height waveguide estimated from CST results is shown in Fig. 9(d). The high temperature recorded on the elbow far end (lower end of part 5 in Fig. 2) could be due to the higher dissipation in the waveguide part itself and also due to heat conducted from the window cavity side. Parts closer to the He vessel will be at lower temperature and may have lower dissipation owing to higher conductivity of copper at lower temperature.

SUMMARY

It is seen that CST Studio can be used to simulate steady state operation of a beam loaded cavity when losses are taken into account. The simulation results show good agreement with the measured values of S11 or Q_{ext} for matched or unmatched conditions. The simulations can be used to compute the power dissipation in different parts of the waveguide. The difference in computed power dissipation explains the observed differences in temperatures recorded on the waveguide due to varying configurations of 3-stub tuner.

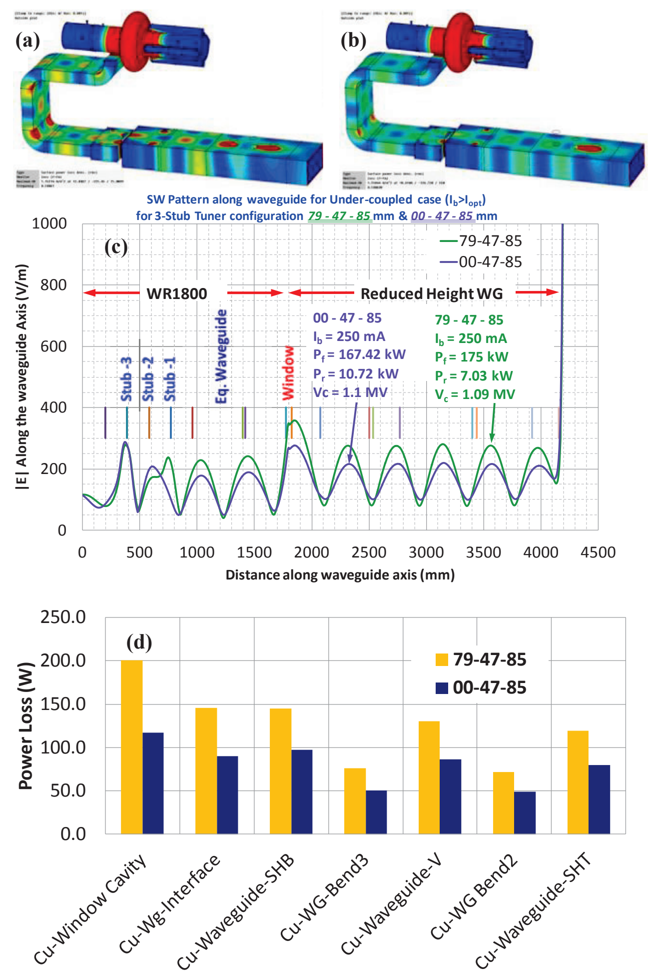

Figure 9: (a) and (b) Power loss density in W/m^2 for stub configurations 79-47-85 and 00-47-85 respectively. The results shown are for 1 W peak power input with maximum clamped to 0.001 W/m^2. (c) |E| along waveguide axis showing Standing Wave pattern for two cases 79-47-85 (green) and 00-47-85 (purple). (d) Power dissipated in copper plated reduced height waveguide in two cases (refer to Fig. 2 for nomenclature).

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