3D THERMAL STRESS ANALYSIS FOR THE CDS STRUCTURE

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Abstract

The Cut Disk Structure (CDS) has been proposed for high energy linacs as an accelerating structure with high coupling coefficient. This structure was studied for applications both in proton and electron linear accelerators. An important point for the stable structure operation is a cooling capability. Real 3D thermal stress analysis has been performed by coupled simulations with MAFIA and ANSYS codes. For this purpose a special interface code was developed. The temperature and thermal stress distributions, operating and coupling modes frequency shifts for different operating regimes and cooling schemes were studied. Results of the study are presented. For moderate and high heat loading the drift tube region is necessary. Special coupling windows shape is proposed to simplify CDS cooling for operation with high (more than 15 kW/m) heat loading.

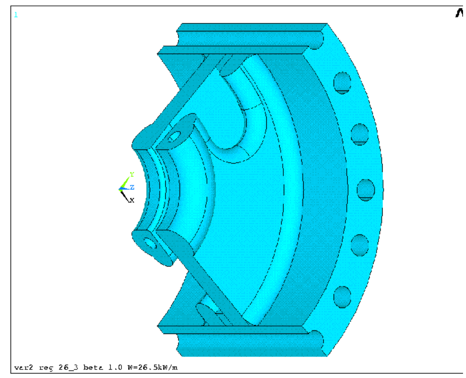

Figure 1. A general view and a cooling scheme for the CDS $\beta = 1.0$ option (h).

1 INTRODUCTION

CDS looks similar to the well known On-axis Coupled Structure (OCS) but realize a different idea in the design of the coupling cell, resulting in an increased coupling coefficient value $k_c \approx 20\%$ without drop of an effective shunt impedance Z_e [1]. A cooling capability is an important structure parameter, especially for a application in modern high intensity proton and electron linacs and a careful thermal stress analysis is important to ensure stable structure operation and reproducibility of parameters.

The power handling capability for OCS was studied [3] during the development of cw electron linacs for industrial purpose [2]. The possibility of a power handling of $P_h \approx 150kW/m$ has been shown (but with solutions rf and cooling systems which are not applicable for scientific multi-cavity linacs).

For the CDS structure a thermal stresses study has been performed by direct 3D simulation of the coupled field problem, both for the CDS option for the proton linacs ($\beta = 0.5$) and for L-band electron ones ($\beta = 1.0$) [4].

2 PROCEDURE OF SIMULATIONS

Because MAFIA and ANSYS use different grids (FIT and FEM respectively), a direct data exchange is not possible. A special set of interface codes has been developed to extract fast and interpolate 3D distribution of electric E_a and magnetic H_a fields. After scaling to real P_h value, the power loss density $R_s H_a^2/2$, where R_s is the surface resistance, is used as input data (boundary condition) for the temperature and stress calculations with ANSYS. The frequency shift due to the surface deformation was estimated for the accelerating (operating) mode frequency and for coupling mode frequency by using perturbation theory:

$$\frac{\delta f_{a,c}}{f_{a,c}} \approx \frac{\int_S (\mu_0 H_{a,c}^2 - \epsilon_0 E^2 a, c)\vec{n} d\vec{S}}{4W_{a,c}}, \qquad (1)$$

where $f_{a,c}, W_{a,c}, E_{a,c}, H_{a,c}$ are frequency, stored energy, electric and magnetic fields distributions for accelerating mode and coupling mode respectively.

Due to the 3D problem complication, a mesh were $\approx 2.5 \cdot 10^6$ mesh-points for MAFIA and ≈ 20.000 nodes for ANSYS, limited by computer resources.

The material characteristics are usual for OFC copper. The study has been performed for several values for the heat transfer constant $\eta[W/(m^2C^o)]$, corresponding to a water flow velocity of $1.0 \div 3.0m/s$. At first, the usual scheme for cooling - two web channels and several circumferential channels (the same as in [2]) has been considered. The CDS options for proton linacs ($\beta = 0.5$) has been considered assuming operating frequency $f_0 = 972MHz$, usual aperture diameter $2a = 30mm$ and accelerating gradient $E_0T \sim 3MV/m$ (the last defines the drift tube dimensions). For L-band ($f_0 = 1300MHZ$) electron linacs a special CDS options with strongly enlarged aperture diameter ($2a = 52mm$) and moderate accelerating gradient ($E_0T \approx 8.5MV/m$, option 1.0 (l)) and high one ($E_0T \approx 14.0MV/m$, option 1.0 (h)) were considered (considering the CDS application in the TESLA Positron Pre-Accelerator linac (PPA)[4]). A general CDS view and

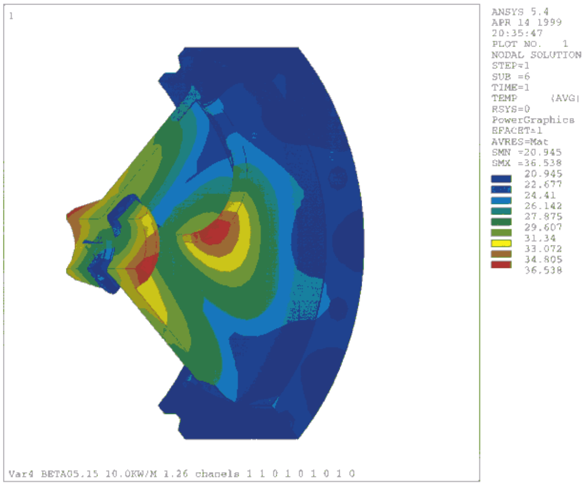

Figure 2. Temperature distribution of the CDS surface at $P_h = 10kW/m, \beta = 0.5$.

cooling scheme for $\beta = 1.0(h)$ option is shown in Figure 1.

3 THERMAL STRESS ANALYSIS

A typical temperature distribution is shown in Figure 2 for $\beta = 0.5, P_h = 10kW/m, \eta = 12600$ option with web channels cooling (The water flow in these channels has opposite direction). There are "hot" regions at the structure surface - at the drift tube (between the web channels) and at the ends of the coupling windows. The overheating value t_h - the difference between maximal local surface temperature and cooling water temperature - is of $t_h \approx 16.5C^o$ for $P_h \approx 10kW/m$. The CDS web cooling is necessary for moderate and high heat loading. With only circumferential channels the drift tube temperature will be $\approx 250C^o$ for $P_h \sim 10kW/m$ and any CDS option. The typical rf losses distribution at the CDS surface is shown in Figure 3. With a correct choice of the coupling window shape and dimensions there are no regions with high rf current density at the ends of the coupling windows (as compared to another slot-coupled structures). This CDS property ensures an enlarged k_c value without Z_e reduction. Nevertheless, about 50% of a total rf losses at $\beta = 1$ and $\approx 65\%$ at $\beta = 0.5$ take place in the web (including drift tube) below the upper window radius. With a significant P_h value the heat conductivity of copper is not sufficient to transfer a large heat flow from the drift tube region to circumferential channels. Without the web cooling the CDS can be applied (assuming a reasonable $t_h \approx 20C^o$) only with low heat loading $P_h \sim 0.5 \div 1kW/m$. Overheating leads to the R_s increasing (and Z_e reduction), to nonuniform surface deformation, and to development of internal stresses S_{st}.

Some results of simulations for the temperature and stress distributions are summarized in Table 1. Due to the relatively small overheating a linear approximation of the results is valid and $t_h, \delta f_{a,c}/f_{a,c}, S_{st}$ values for fixed η and

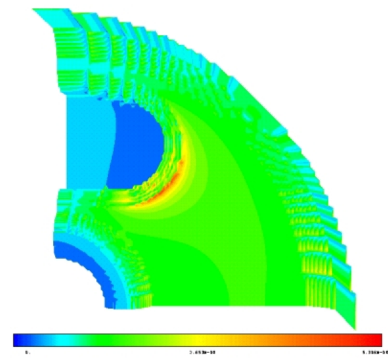

Figure 3. RF losses distribution on the CDS surface.

Table 1. The results of the thermal stress simulations.

β	P_h	η	t_h	$\delta f_a/f_a$	$\delta f_c/f_c$
	kW/m		C^o	10^4	10^4
0.5	10.0	7250	19.76	-2.37	-2.32
0.5	10.0	12600	16.54	-1.86	-1.84
0.5	10.0	17950	15.47	-1.64	-1.63
1.0 (l)	6.0	7250	18.55	-0.58	0.70
1.0 (l)	6.0	9000	17.44	-0.52	0.64
1.0 (h)	26.0	9000	47.30	-1.96	2.08
1.0 (h)	26.0	12600	44.16	-1.61	2.04

CDS geometry are proportional to the heat load P_h.

Results don't depend strongly on η, because η value defines the temperature distribution only in a small vicinity of the cooling channel. Moreover, increasing η is limited by the water flow velocity ($\leq 2m/s$ to preserve channel erosion).

As one can conclude from results, the temperature distribution and related deformation are nonuniform and strongly depend on the geometry details. With the same heat loading the CDS $\beta = 1(l)$ option has a higher overheating value t_h but lower "equivalent" temperature t_e, which can be estimated as $t_e = \delta f_a/f_a/\alpha$ than CDS $\beta = 0.5$ ($\alpha = 1.6 \cdot 10^{-5}$ - is the linear expansion coefficient).

For a moderate heat loading $P_h \leq (10 \div 15)kW/m$ the usual cooling scheme ensures reliable structure operation. The operating frequency shifts due to the surface deformation are within tolerable limits to be removed by the frequency control system. The internal stress values S_{st} are below the yield strength $S_{stlim} \approx 530kg/cm^2$ of OFHC copper and the total reduction of the shunt impedance $\approx (2 \div 6)\%$ is not dangerous.

The surface displacement distribution, which defines the frequency shifts, is rather complicated (Fig. 4). For CDS $\beta = 1.0$ options the frequency shifts for the accelerating mode and the coupling mode have different signs, leading to a stop-band opening during the structure heating (the

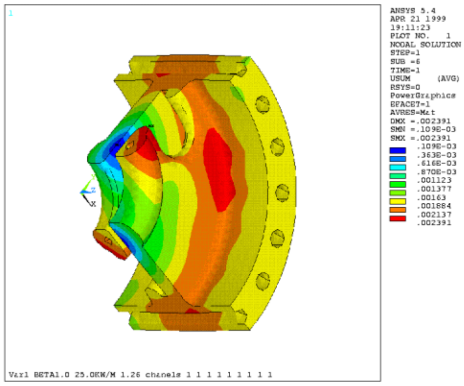

Figure 4. Deformation of the CDS surface for $\beta = 1(h)$ option, $P_h = 30kW/m$.

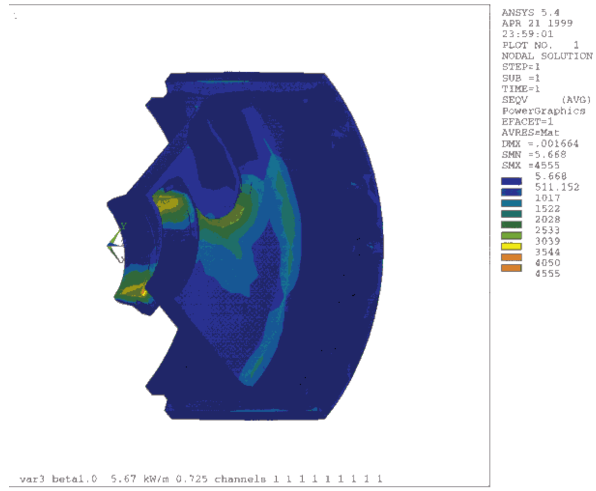

Figure 5. Von Miss thermal stress distribution for $\beta = 1(l)$ option.

same as for OCS - well known behavior). The structure should be tuned at normal temperature with some stop-band width, with the purpose to close the stop-band in the operating regime. But for CDS $\beta = 0.5$ option the same signs and practically the same values were founded for frequency shifts (see Table 1). This fact has been checked but not understood completely - the deformation distribution is rather complicated.

For high heat load $P_h \geq 15kW/m$ with the usual web channel scheme the limitation come from the internal stress value - S_{st} may exceed the yield strength of OFHC copper. S_{st} also doesn't depend strongly on η. The maximum value of the internal stress all time takes place at the surface. Typical von Miss thermal stress distribution is shown on Fig. 5 for $\beta = 1(l)$ option.

There are two specific regions for a high stress value. The first one is the inner drift tube surface opposite to the coupling window, in spite of a web channel is at very short distance. At this place the deformations (see Fig. 4) have a large value due to pressure from expanding "hot" regions at the drift tube between channels and the rigidity of this region is reduced by window (as compared to OCS). To restrict a stress value in the first region, one needs in a more uniform nose cone area cooling and circular channel should be placed in drift tube.

The second dangerous place are the windows ends. The large stress value in this region is due to interruption of a continuous web body by coupling window. To diminish a stress value in this region, one needs a large radius of the window ends. The window opening angle should be reduced and the window should be extended in radial direction as possible. In all CDS options, considered here, the window shape satisfies to this recommendation (see, for example, Fig. 2). Two parallel web channels should be replaced by four radial ones, from outer circumferential channels to the circular channel in the drift tube. With the restriction for the window shape the k_c value isn't maximal possible ($\approx 80\% k_{cmax}$), but it is a price for high power capability.

Such cooling scheme is foreseen for high accelerating gradient $E_0T \sim 14.5MV/m$ PPA accelerating cavities, resulting in a more uniform temperature distribution, acceptable internal stresses and lower frequency deviations.

4 CONCLUSION

The procedure and an interface code for a thermal stresses study by direct 3D simulation of the coupled field problem with MAFIA and ANSYS codes have been developed. The thermal stresses study has been performed for different CDS options.

Without the web cooling the CDS can be recommended only for low heat loading $P_h \sim 0.5 \div 1kW/m$. The simple cooling scheme with two straight web channels and several circumferential ones ensures the stable operation for moderate heat loading $P_h \sim 10kW/m$. For high heat loading $P_h \geq 20kW/m$ a circular drift tube channel and "smooth" coupling windows are recommended.

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