FIELD UNIFORMITY PRESERVATION STRATEGIES FOR THE ESS DTL: APPROACH AND SIMULATIONS

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Abstract

The Drift Tube Linac (DTL) of the European Spallation Source (ESS) is designed to operate at 352.2 MHz with a duty cycle of 4 % (3 ms pulse length, 14 Hz repetition period) and will accelerate a proton beam of 62.5 mA pulse peak current from 3.62 to 90 MeV. This paper presents the approach taken in order to preserve field flatness of DTL Tanks. This strategy required a set of simulations and consequent choices about RF design of DTL cells, RF coupler tuning and compensation, cooling of the DTL cells. Outcomes of these simulations and the experimental verifications of this approach are then explained.

INTRODUCTION

The introduction of local frequency detuning in a long resonant cavity like a DTL causes field perturbation. There are some elements which are necessary for the DTL construction and functionality, but that lead to local frequency perturbation: stems, post couplers and power couplers. In this paper we are going to verify the opportuneness of their compensation by introducing small modification on the design (face angles, presence of tuners).

In presence of RF power, thermal distortions caused by RF heating result in a frequency shift. In particular, since the shape and the heat load of each cell are different, the frequency shift will be not constant along the tank. We evaluate the importance of this difference and the opportuneness of introducing an appropriate cooling scheme to compensate it.

STEM EFFECT COMPENSATION

In the design phase of ESS DTL, face angles have been already used for stem effect compensation [1]. In this section we propose a verification of this compensation by 2D and 3D simulations. In the process of tuning the single cells and the entire tanks, Superfish makes a revolution solid around beam axis from the 2D cell. Elements such as stems and post couplers are taken in account only for their frequency perturbation effect. Using Slater perturbation theorem, the simulator calculates the corrected frequency, $f_{stems\ +\ posts}$, comprehensive of the perturbation applied [2]. Thus, there is not any information given about the field perturbation due to the stem presence. A way to study the presence and the effects of stems also on fields is the subtraction of a stem–proportional volume from the cell volume [3]. Once one knows the stem corrected frequency for each cell, this could be done by modifying the geometry of the single cells through subtraction of a volume in the way to tune the cell and reach the stem corrected frequency. Then the entire tank can be assembled and field and resonant frequency can be observed.

The discussed "volume subtraction method" is shown in Figure 1, where a detail of tank 4 created is presented.
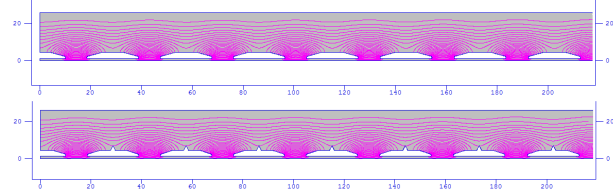

Figure 1: Detail of SF's first cells of tank 4 with and without the "stem volume" subtraction.

In order to verify the consistency of volume subtraction method, the E_0 field of the DTL without stems is compared with the E_0 field of the DTL with stems (use of α_{stems}). Figure 2 shows tank 4 E_0 field, computed in the original geometry without stems and in the geometry with α_{stems} + volume subtraction method.
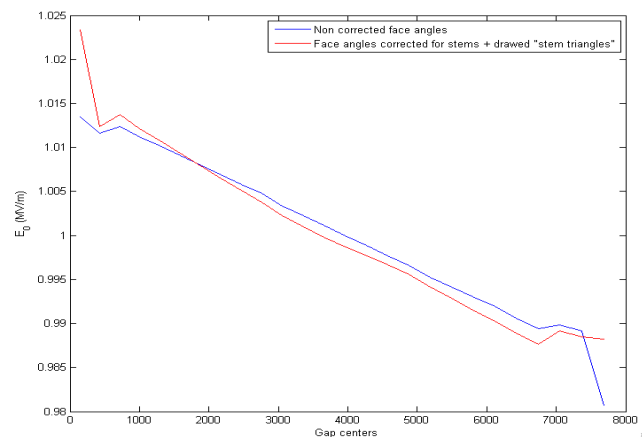

Figure 2: E_0 field for tank 4 obtained in Superfish using original geometry and geometry with α_{stems} + volume subtraction method.

Another check of the volume subtraction is a comparison of the five tanks resonant frequencies obtained by the two methods: SF frequency calculation by Slater's theorem (method 1) and SF frequency calculation with volume subtraction (method 2). Results are shown in Table 1.

Table 1: Tank Resonant Frequencies Obtained using Method 1 and Method 2

	f_{STEMS} – method 1 (MHz)	f_{STEMS} – method 2 (MHz)
Tank 1	351.30	351.34
Tank 2	351.31	351.30
Tank 3	351.29	351.28
Tank 4	351.28	351.29
Tank 5	351.29	351.29

3D Simulations

Figure 3 shows the 3D polygon that HFSS uses to represent tank cylindrical structure. γ is the "normal deviation angle", a parameter set in simulation that affects the precision of the circular surface approximation.
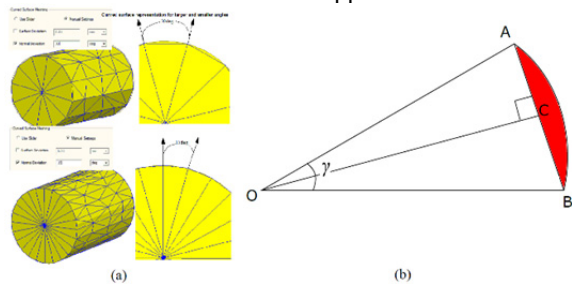

Figure 3: (a) HFSS curved surface approximation; (b) difference between real and simulated model (red highlight).

Due to the model representation in simulation, a smaller volume is simulated compared to reality or 2D axial symmetric simulation, so that a frequency shift Δf_0 occurs from the tank nominal frequency f_0. This Δf_0 is related to the difference in volume ΔV between real and simulated geometry via Slater perturbation theorem [4].

$$\frac{\Delta f_0}{f_0} = \frac{\Delta V}{4U}(\mu_0 H^2 - \varepsilon_0 E^2)$$

where U is the total electromagnetic energy stored inside the tank. Since inside a DTL the tank outer wall is interested by a predominance of magnetic field, after some trigonometric manipulations one can write:

$$\frac{\Delta f_0}{f_0} \simeq \frac{1}{4U}\mu_0 H^2 \frac{R^2}{2}(\gamma - \sin\gamma)b_{tot}L$$

The term b_{tot} is introduced to take in account the entire tank front face area and it depends on the γ chosen. Taking as example tank 4 with length $L = 7.84\ m$, stored energy $U = 22.431\ J$, tank radius $R = 0.2605\ m$, average magnetic field on tank outer wall $|H| = 3719.38\ A/m$ and working frequency f_0=351.28 MHz, choosing $\gamma = 10°$ a $\Delta f_0 = 586\ KHz$ is obtained, choosing $\gamma = 5°$ a $\Delta f_0 = 143\ KHz$ is obtained. In Table 2 frequencies obtained in HFSS are shown. Simulation results are in agreement with analytically calculated values.

Table 2: Tank 4 frequency results: Superfish vs analytical method vs HFSS.

f_0 (MHz) Superfish	f_0 (MHz) analytical $\gamma = 5°$	f_0 (MHz) HFSS $\gamma = 5°$	f_0 (MHz) analytical $\gamma = 10°$	f_0 (MHz) HFSS $\gamma = 10°$
351.28	351.42	351.30	351.86	351.70

Figure 4 shows E_0 plot for tank 4. Curves were obtained in Superfish and in HFSS. In particular for HFSS the field curve relative to a 10° surface approximation and the field curve relative to a 5° surface approximation are reported. The use of a good surface approximation determines a field curve comparable between HFSS and Superfish, which confirms the field flatness obtained with the face angle compensation.
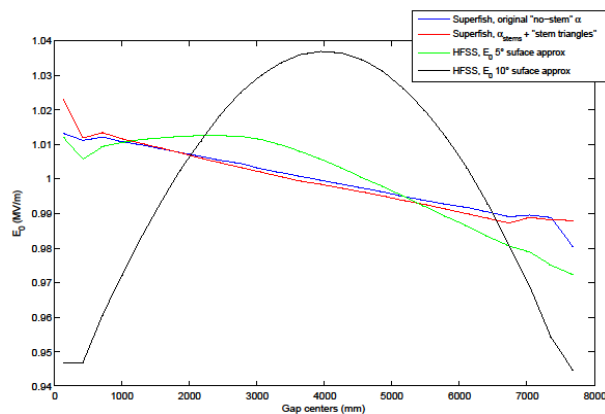

Figure 4: E_0 field curves (a) SF with original no-stem model, (b) SF with corrected α and volume subtraction method, (c) HFSS with $\gamma = 5°$, (d) HFSS with $\gamma = 10°$.
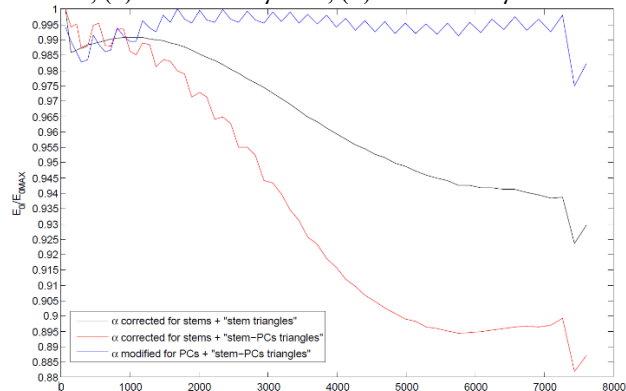

Figure 5: Superfish E_0 results for tank 1.

POST COUPLERS COMPENSATION

Post couplers are used to stabilize the accelerating fields of DTLs against tuning errors [5]. As for stems, PCs induce a local frequency variation and a consequent field perturbation. Moreover, differently than stem, for the first two tanks post couplers are unevenly disposed along the cells. Post coupler length is finely adjusted with bead pull measurements, but for simulation purposes we set an average length of 19 cm for all post couplers, which corresponds to confluence point for similar structures [6]. Post couplers insertion shift up every tank frequency of a value between 200 and 300 KHz. The volume subtraction method is used for model PCs in Superfish to study the appropriate α modification to recover the local detuning of PCs, and results are summarized in Table 3.

Table 3: Superfish Frequency Results for PCs

	f_{STEMS} (MHz)	$f_{STEMS+PCs}$ − old α (MHz)	$f_{STEMS+PCs}$ − new α (MHz)
Tank 1	351.30	351,48	351.29
Tank 2	351.31	351,53	351.25
Tank 3	351.29	351,61	351.26
Tank 4	351.28	351,60	351.25
Tank 5	351.29	351,61	351.23

The compensation recovers the original tank resonant frequencies, which is a benefit for frequency budget. Figure 5 shows a comparison of E0 fields inside the tank

1; with the volume subtraction and α modification methods applied, the field flatness is improved (blue curve).

POWER COUPLER COMPENSATION

Power couplers are iris type located approximatively at L/4 and ¾ L. The fine tuning of the coupling coefficient β will be provided by a dedicated post located on the waveguide, just under the iris aperture [7]. This solution simplifies the coupler adjustment process and allows to increase the coupling factor by more than 60% respect to the maximum without post.

The presence of the aperture provokes a local frequency detuning on the DTL cells of about - 3.2 MHz, and thus influences the field flatness along the tank of ± 5% (Figure 6). The field perturbation is minimizes by the position of the couplers themselves, which corresponds to zeros of the 2nd superior mode. Moreover, in order to compensate for such detuning, two tuners per each coupler are foreseen to be placed at the same longitudinal position (Figure 7).
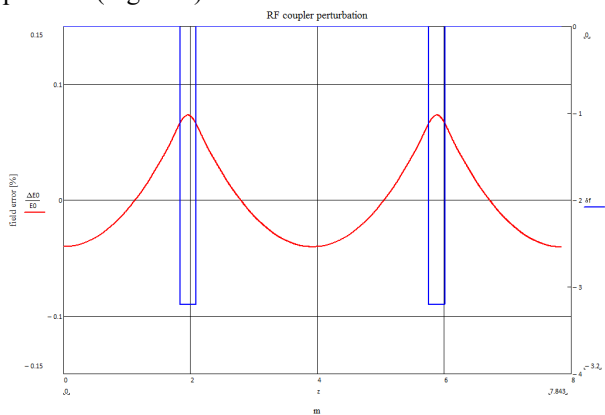

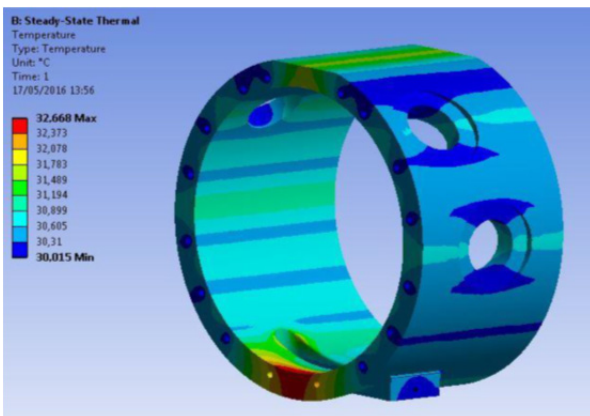Figure 6: Field perturbation due to power coupler local detuning.

Figure 7: thermal simulation of the power coupler section. The second tuner port is here shown.

COMPENSATION OF HIGH POWER RF THERMAL EFFECT

3D simulations have been performed as well in order to evaluate local and global perturbation due to RF power heat load in operation [8]. As an example in Tank 1, the 1st cell present a detuning of – 15 kHz, the last 61 cell of -

33 kHz, the rest will be almost linearly in between [8]. The effect of such a perturbation, when applied to a circuital model of Tank 1, is a global frequency shift of - 24 kHz and an induced field perturbation of ±1.5% (Figure 8). This small perturbation could be further reduced by a flow modulation of the drift tube cooling: if 1st cell is cooled with h = 4000 W/m^2/K and the last with h = 10000 W/m^2/K the frequency perturbation range is halved as well as the field perturbation.
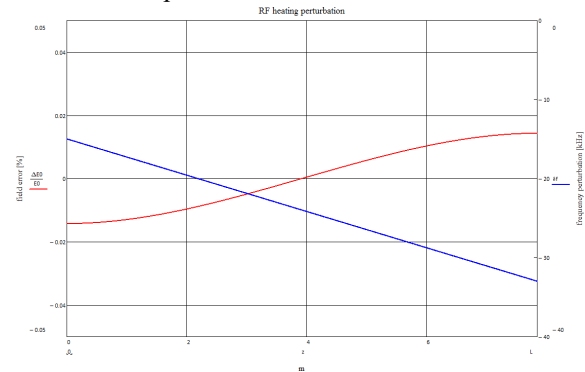

Figure 8: circuital model estimation of the field perturbation induced by differential thermal deformation of Tank 1 cells.

CONCLUSIONS

This paper presents a series of design choices aimed to preserve the field uniformity in the ESS DTL tanks. The local perturbations of stems and post couplers are recovered by an appropriate modulation of DT face angles. The big perturbation due to the power coupler iris will be recovered by a second tuner at this section. Finally, since the frequency shift due to RF heating is not constant along the cells of a single tank, we propose a compensation of this effect by a modulation of cooling flow along the drift tubes.

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