# ESS DTL RF MODELIZATION: FIELD TUNING AND STABILIZATION

R. De Prisco*, ESS, Lund, Sweden and Lund University, Lund, Sweden
M. Comunian, F. Grespan, A. Pisent, INFN/LNL, Legnaro, Italy
A. Karlsson, Lund University, Lund, Sweden

*Abstract*

The Radio Frequency (RF) design of Drift Tube Linac (DTL) of the European Spallation Source, ESS, has been defined in order to satisfy the accelerating field requirements of beam dynamic studies and to reduce peak field levels in the critical areas. The electro-magnetic field is stabilized with post-couplers. The cells geometries of the DTL are optimized to accommodate permanent magnet quadrupoles (PMQ), to get maximum shunt impedance, to meet the Moretti criterion at the low energy part and to facilitate the mechanical construction.

## INTRODUCTION

The linac of the ESS will accelerate 50 mA of $H^-$-ions at 352.21 MHz up to 2.5 GeV. The pulses are 2.86 ms long with duty cycles of 4%. The average beam power on the target will be 5 MW and the peak power 125 MW. The linac will have a normal-conducting front-end up to 77.7 MeV followed by three families of superconducting cavities and a high-energy beam transport to the spallation target [1].

In particular the DTL of the ESS accelerator will accelerate the beam from 3.0 to 77.7 MeV. Permanent Magnet Quadrupoles (PMQs) are used as focusing elements in a FODO lattice.

The main properties of the ESS DTL are summarized in Table 1 [2].

Table 1: Tank Properties of the ESS DTL

| **Parameter/Tank** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| Cells | 66 | 36 | 29 | 25 |
| $E_0$ [MV/m] | 2.8 to 3.2 | 3.16 | 3.16 | 3.16 |
| $E_{MAX}/E_{Kilp}$ | 1.4 | 1.43 | 1.39 | 1.37 |
| $\phi_S$ | -35 to -24 | -24 | -24 | -24 |
| $L_T$ [cm] | 7.95 | 7.62 | 7.76 | 7.72 |
| $R_b$ [mm] | 10 | 10 | 11 | 12 |
| PCs [#] | 23 | 25 | 28 | 24 |
| Tuners [#] | 24 | 24 | 24 | 24 |
| Modules [#] | 4 | 4 | 4 | 4 |
| $P_{Cu,MAX}$ [MW] | 0.91 | 0.91 | 0.92 | 0.95 |
| $E_{OUT}$ [MeV] | 21.4 | 41.0 | 60.0 | 77.7 |
| $P_{TOT}$ [MW] | 2.06 | 2.12 | 2.10 | 2.07 |

Slug tuners in a DTL should compensate the frequency effects due to construction errors. The evaluation of the static frequency error is done by applying realistic tolerances on the important dimension of the cavity (tank diameter, drift-tube lengths, drift tube diameter, face angles). The tuners have diameter of 90 mm, are distributed uniformly every 30 cm along the tank and are located at 45°with respect to the stem axis in order not to influence the frequency of the PC 0-mode by tuner penetration. The tuner sensitivity is 6.98 (kHz/mm)×m, linear around 50 mm of penetration.

* renato.deprisco@esss.se

## TUNING OF ACCELERATING FIELD

Let the $z$-axis be the symmetry axis of the tank, its origin be on the low energy end wall and the pulsation, or angular resonance frequency, $\omega(z)$ be constant along $z$ and equal to $\omega_0$. The effects of a variation of the cell geometries on the pulsation in a DTL can be described by waveguide theory. Then the DTL is replaced by an empty ***equivalent tank*** in which the geometric variation of the cells changes the resonance frequency, $\omega_0$, along $z$ such that $\omega(z) = \omega_0 + \Delta\omega(z)$.

### *From Continuous to Discrete Tuning*

Even if it is possible to define a continuous function $\omega(z), \forall z \in [0, L_T]$, where $L_T$ is the tank length, it is convenient to define $\omega(z)$ as piecewise constant function. Let suppose that the tank is composed of $N$ cells, each of length $L_n, \forall n \in [1, N], n \in \mathbb{N}$. Let define $\Delta\omega_n = L_n^{-1}\int_{L_n}\omega(z)\,dz - \omega_0$. It is possible to show that if $\Delta\omega_n \ll \omega_0$ in each cell, then the electric field along $z$-axis, $E_z(z)$, must satisfy the following equation [4]:

$$\frac{d^2E_z(z)}{dz^2} \approx \frac{2\omega_0}{c^2}\Delta\omega_n E_z(z), \forall z \in [0_n, L_n], \quad (1)$$

where $0_n$ is the relative origin, along $z$-axis, of the $n$-cell.

### *Boundary and Continuity Conditions*

Let define the piecewise constant electric fields $E_{0_n} = L_n^{-1}\int_{0_n}^{L_n} E_z(z)\,dz$. Assume that the beam dynamic requirements imply the constraints $E_{0_n}, \forall n \in [1, N]$. It is, now, assumed that the total stored energy in RF fields is constant.

The knowledge of $E_{0_n}$ gives the possibility to define $E_z(0)$, $E_z(L_T)$ and $dE_z(z)/dz, \forall z \in [0, L_T]$. By knowing $E_z(z)$, utilizing the boundary conditions for TM modes ($dE_z/dz = 0$ in 0 and $L_T$) and by imposing the continuity conditions between adjacent cells it is possible to solve the equation (1), cell by cell, and to find $\Delta\omega_n, \forall n \in [1, N]$. In the following the $z$-dependence of $E_z$ and its derivatives are omitted.



ISBN 978-3-95450-122-9

### *The Implicit Slope*

As a first tuning step the RF cavity computer code, SUPERFISH (*DTLfish*), has been used to change the face angle, $\alpha_f$, in order to reach the target pulsation $\omega_0$ in all cells of the tank. The details of the drift tube section is shown in Fig. 1. The second step is to assembly all cells of

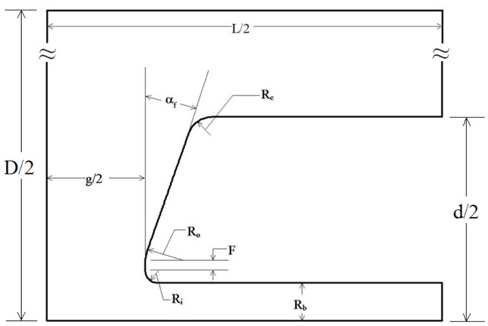


Figure 1: Representative half unit cell geometry longitudinal section: Tank *D*iameter, D; cell *L*ength, L; *g*ap length, g; *d*rift tube diameter, d; *b*ore *R*adius, R$_b$; *F*lat length, F; *i*nner nose *R*adius, R$_i$; *o*uter nose *R*adius, R$_o$; face angle, $\alpha_f$.

the tank and simulate the entire structure in SUPERFISH (*MDTfish*). Even if all the cells, different in length, have the same pulsation, $\omega_0$, the accelerating field is not constant as we can expect from equation (1). This is due to the fact that there is not a perfect mode matching between the adjacent cells built, individually, by DTLfish. The mismatch produces a natural tilt of the accelerating field that must be compensated; from now this tilt is denoted *implicit slope*. In a ramped gradient tank the implicit slope must be properly added to the desired one to compensate it. In a constant gradient tank the implicit slope is the only one to compensate since the desired one is zero. We denote the sum of the implicit slope and the desired one the *total slope*, $S_T$.

### *Macrocells*

It is useful to divide the tank into three parts, *macrocells*, each one composed of one or more cells. The first macrocell satisfies the boundary conditions on the end wall. It ramps the accelerating field and compensates for the implicit slope caused by the $F$ cells with total length $L_F = \sum_{n=1}^{F} L_n$. The second macrocell adjusts the slope to match to the boundary conditions at the other end wall. It is composed by $L$ cells with total length $L_L = \sum_{n=N-L+1}^{N} L_n$. The third one is located between the first two and composed by $(N-L)-(F+1)$ cells with total length $L_L = \sum_{n=F+1}^{N-L} L_n$. Instead of solving the equation (1), cell by cell, it is convenient to solve this equation for the macrocells. To do this the the constant $C = \sqrt{2\omega_0}/c$ is introduced.

For the first macrocell the $\Delta\omega_F$ must satisfy the equation (2):

$$C\sqrt{\Delta\omega_F}\sinh\left(C\sqrt{\Delta\omega_F}L_F\right)E_z(0) = S_T. \quad (2)$$

For the second macrocell the $\Delta\omega_L$ must satisfy the equation (3):

$$-C\sqrt{-\Delta\omega_L}\sin\left(C\sqrt{-\Delta\omega_L}L_L\right)E_z(L_T - L_L) + \\ +\cos\left(C\sqrt{-\Delta\omega_L}L_L\right)S_T = 0. \quad (3)$$

### *Tuning of the ESS DTL*

For the ESS DTL the desired electric field $E_{0_n}$ goes from 2.8 MV/m to 3.2 MV/m in the first tank. It is constant and equal to 3.16 MV/m in the last three tanks. In Fig. 2 the desired $E_{0_n}$ are shown. The accelerating field is calculated by MDTfish, after the tuning of the two macrocells by using equations (2) and (3). Specifically the first three and the last three cells have been used to reach the total slope in the first tank. The first two and the last two cells are used to compensate the implicit slope in the second tank. The first and the last cells are used to compensate the implicit slope in the third and fourth tanks.

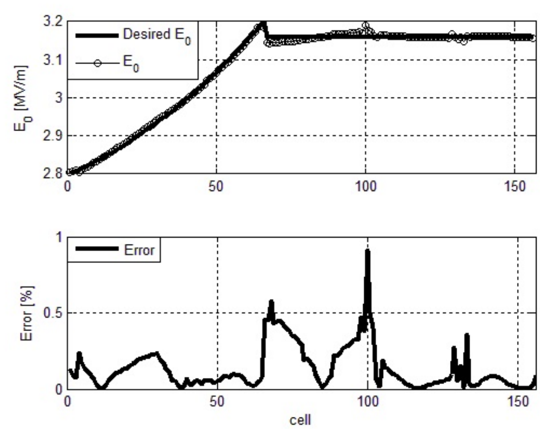


Figure 2: Desired E$_0$, E$_0$ and percentage Error.

### *Compensation of Stems Effect*

Stems connect drift tubes with the inner lateral wall of each tank. They break the $z$-axial cylindrical symmetry. SUPERFISH can only handle axially symmetric structures. However, the code treats the stem as a volume perturbation and by using the Slater theorem it is possible to calculate, cell by cell, the pulsation shift, $\Delta\omega_{Stem,n}$, $\forall n \in [1, N]$ induced by them. To compensate this perturbations one strategy is to introduce volume perturbations (in the ESS DTL case the face angles have been changed) that induce a pulsation shift $\Delta\omega_{Comp,n} = -\Delta\omega_{Stem,n}$, $\forall n \in [1, N]$. This strategy has been validated by COMSOL [5] 3*D*-simulation in a representative tank with 20 cells, from the first to the twentieth cell of the second tank, and long


ISBN 978-3-95450-122-9

1.921 m. In Fig. 3 the stems effect and the face angles compensation are shown.

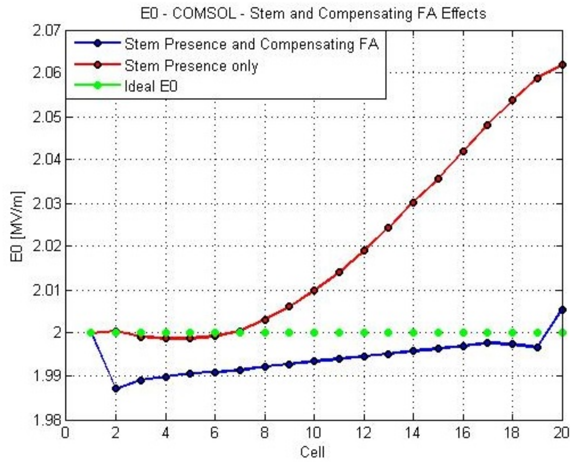


Figure 3: Effects of stems and compensative face angles on $E_0$.

## DTL TRANSMISSION LINE MODEL

In the neighborhood of $TM_{010}$ mode the electromagnetic field, in each tank of the DTL, can be approximate by the electromagnetic field of a circular cavity filled by anisotropic media [3] ($\mu$ is constant and $\underline{\epsilon} = \hat{z}\hat{z}\epsilon_z + \hat{r}\hat{r}\epsilon_t$). The equivalent cell of the transmission line is shown in Fig. 4 with:

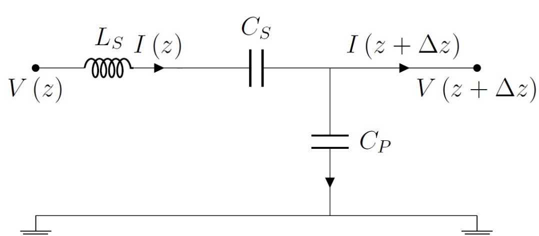


Figure 4: Equivalent DTL cell of the transmission line DTL model.

$$L_S = \frac{\pi\omega_{011} \left|\underline{E}_t(D/2)\right|_{MAX} \Delta z}{(\omega_{011}^2 - \omega_{010}^2)\left|\underline{H}_t(D/2)\right|_{MAX} L_T}; \quad (4)$$

$$C_S = \frac{1}{\omega_{010}^2 L_S}; \quad (5)$$

$$C_P = \frac{\pi\left|\underline{H}_t(D/2)\right|_{MAX} \Delta z}{\omega_{011} L_T \left|\underline{E}_t(D/2)\right|_{MAX}}, \quad (6)$$

where $\omega_{010}$ and $\omega_{011}$ are the pulsations of the $TM_{010}$ and the $TM_{011}$ mode respectively, $\underline{E}_t(D/2)$ and $\underline{H}_t(D/2)$ are the electric and the magnetic transverse fields evaluated in the inner neighborhood of the cavity lateral wall respectively.

The field stabilization is achieved by utilizing Post Couplers (PC). COMSOL has been used to design the PC. PCs can be introduced as series of inductance, $L_{PC}$, and capacitance, $C_{PC}$, in parallel with the capacitance $C_P$ positioned in the longitudinal center of the drift tubes. The values of $L_{PC}$ and $C_{PC}$ must be choosen in order to stabilize the accelerating field. It is possible to outdistance the PCs until the $E_0$ is within the 1% of the desired value.

The results are confirmed by COMSOL $3D$-simulations in a representative tank of 20 cells. In Fig. 5 the transmission line model and COMSOL result are shown with their relative error in the case of stabilization achieved by using one PC every two cells.

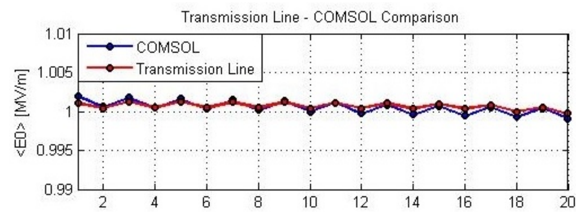


Figure 5: Stabilized field with one PC every two cells obtained by transmission line model and COMSOL.

Fixed the number of PCs and their radius in the case of constant gradient tanks the post length are then adjusted such that the frequency of the PC 0-mode is close to the operation frequency of 352.21 MHz (*confluence*). After reaching of the confluence, the posts in the first tank have been bent, without changing the PC length along its cylindrical symmetry axis, to equalize the product of capacitive coupling (to drift tube) times the field level on both sides of each PC.

The compensation of the PC is done with the same strategy that was used for the compensation of the stems.

## CONCLUSION

To design the ESS DTL was implemented a software to automatically tune the accelerating field, compensate the stems and the PCs effect, determine the PCs numbers and their optimum length, define the minimum numbers of tuners, that allows to obtain a really exhaustive RF DTL design.

## REFERENCES

[1] H. Danared, "Design of ESS accelerator," IPAC'12, New Orleans, May 2012, THPPP071, p. 3904.

[2] M. Comunianet et al., "DTL Design for ESS," LINAC'12, Tel-Aviv, September 2012.

[3] M.K. Ke et al., "Continuous transmission line modeling of a DTL including beam loading and other perturbations," Particle Accelerators, p. 109 (1994).

[4] Z.R. Sun et al., "Trasfer matrix method used in rf tuning on DTL for CSNS," PAC'09, Vancouver, May 2009, TU5PFP005.

[5] `http://www.comsol.com`