

AN EQUIVALENT CIRCUIT FOR POST COUPLER STABILIZATION IN A DRIFT TUBE LINAC

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Abstract

Post Couplers (PCs) are devices used in order to reduce the effect of perturbations on the operating mode of a Drift Tube Linac (DTL), using the resonant coupling stabilization method. In this paper an equivalent circuit for a DTL equipped with PCs is presented, together with a 3D simulation analysis, which can explain the principle of post coupler stabilization and define a new tuning strategy for DTL cavities. The PC tuning procedure based on the equivalent circuit and on frequency measurements has been tested and validated with measurements on the Linac4 DTL aluminium model.

INTRODUCTION

PCs are the solution used for stabilization of the accelerating mode (the TM_{010} mode) in DTL cavities, by applying the resonant coupling method [1]. In this case the resonant coupling elements are internal metallic rods (the PCs), which extend from the outer cylinder towards the drift tube (DT), without touching the latter (Fig. 1).

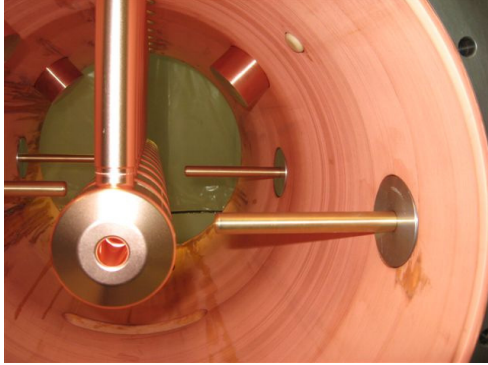


Figure 1: DTL cavity inside view, with PCs in both sides.

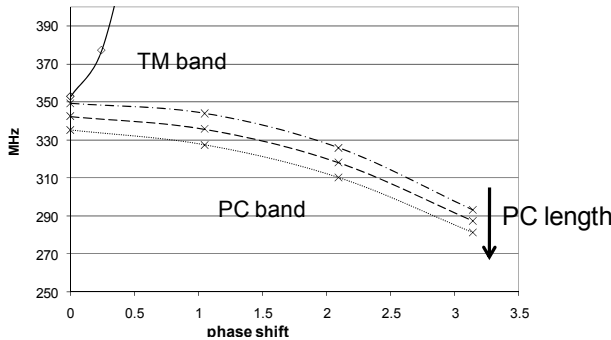


Figure 2: TM and PC band of a DTL cavity.

The system, composed of two chains of coupled resonators, has two bands of frequencies: the TM band, associated to the accelerating cells, and the PC band, associated to the PC resonator chain. PC frequencies are sensi-

tive to the length of the rods, so that longer rods correspond to lower frequencies (Fig. 2).

EQUIVALENT CIRCUIT

An equivalent circuit for a DTL cell equipped with PCs is shown in Figure 3 [2]. In this circuit C_0 represents the gap capacitance, $L_0/2$ represents the inductance of half drift tube, C is the capacitance of a DT to the tank wall, represented by the ground conductor. C_p is the capacitance between PC and DT and L_p the inductance of a PC, in parallel with the shunt capacitance C . The mutual inductance M_p represents the nearest neighbor magnetic coupling between PCs at the opposite sides of the tank, and M_{p2} is the next nearest neighbor coupling factor, acting between PCs placed at the same side of the DTL tank. M_{p2} has an opposite sign with respect to M_p .

The system of equations of this circuit can be put into a matrix form $\underline{M} \cdot \underline{i} = \omega^2 \cdot \underline{i}$ to be solved as an eigenvalue problem. Matrix eigenvalues correspond to the mode frequencies and the eigenvector components correspond to the currents through C_0 and C_p capacitances. The average electric field on axis E_0 is proportional to the currents flowing through C_0 gap capacitances. Figure 4 shows the circuit matrix, where $\omega_0^2 = 1/(2 \cdot L_0 \cdot C_0)$ is the operating mode frequency, and we define a PC frequency $\omega_p^2 = 1/(L_p \cdot C_p)$. PC coupling coefficients are defined as $k_{pi} = -(M_{pi}/L_p) \cdot \omega_0^2$. A comparison between dispersion curves measured on the DTL aluminium model [3] and dispersion curves calculated with the equivalent circuit shows that the circuit precisely reproduces the cavity topology (Fig. 5).

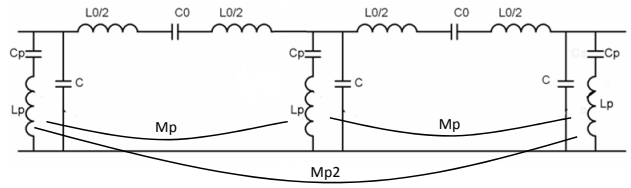


Figure 3: equivalent circuit including nearest and next nearest coupling between PCs.

$$\begin{bmatrix} C_0 \omega_0^2 \left(\frac{1}{C} + \frac{1}{C_0} \right) & -\frac{C_p \omega_p^2}{C} & -\frac{C_0 \omega_0^2}{C} & 0 & 0 & 0 & 0 \\ -\frac{C_p \omega_p^2}{C} & C_p \omega_p^2 \left(\frac{1}{C} + \frac{1}{C_p} \right) & \frac{C_p \omega_p^2}{C} & k_{p1} & 0 & k_{p2} & 0 \\ -\frac{C_0 \omega_0^2}{C} & \frac{C_p \omega_p^2}{C} & C_0 \omega_0^2 \left(\frac{2}{C} + \frac{1}{C_0} \right) & -\frac{C_p \omega_p^2}{C} & -\frac{C_0 \omega_0^2}{C} & 0 & 0 \\ 0 & k_{p1} & -\frac{C_0 \omega_0^2}{C} & C_p \omega_p^2 \left(\frac{1}{C} + \frac{1}{C_p} \right) & \frac{C_0 \omega_0^2}{C} & k_{p1} & 0 \\ 0 & 0 & -\frac{C_0 \omega_0^2}{C} & -\frac{C_p \omega_p^2}{C} & C_0 \omega_0^2 \left(\frac{2}{C} + \frac{1}{C_0} \right) & -\frac{C_p \omega_p^2}{C} & -\frac{C_0 \omega_0^2}{C} \\ 0 & k_{p2} & 0 & k_{p1} & -\frac{C_0 \omega_0^2}{C} & C_p \omega_p^2 \left(\frac{1}{C} + \frac{1}{C_p} \right) & \frac{C_p \omega_p^2}{C} \\ 0 & 0 & 0 & 0 & -\frac{C_0 \omega_0^2}{C} & \frac{C_p \omega_p^2}{C} & C_0 \omega_0^2 \left(\frac{1}{C} + \frac{1}{C_0} \right) \end{bmatrix}$$

Figure 4: DTL equivalent circuit matrix.

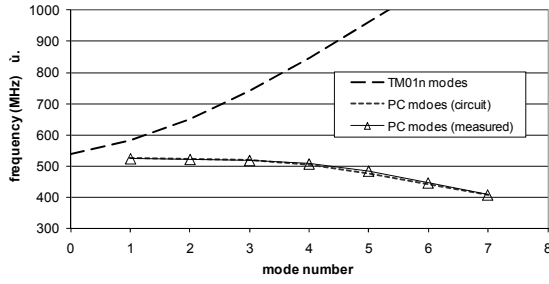


Figure 5: Calculated and measured dispersion curves for the Linac4 DTL aluminium model.

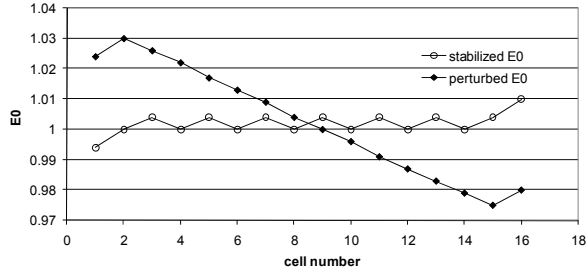


Figure 6: perturbed and stabilized average field E_0 , computed by equivalent circuit.

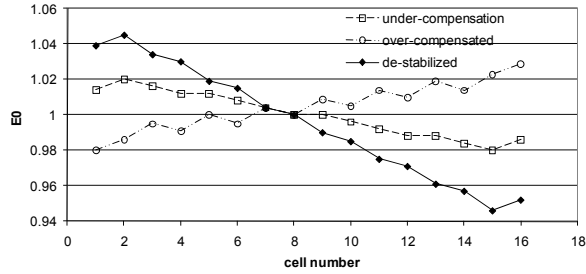


Figure 7: PC effect in a perturbed field with gap PC-DT at 3 different configurations.

A simplified circuit, without mutual inductances M_p and M_{p2} , explains the PC stabilization mechanism and leads to an expression for the optimum PC frequency ω_p , which stabilizes the field. The stabilized field E_0 , here artificially perturbed by a displacement of the two end gaps, results in the characteristic saw-tooth pattern (Fig. 6). The optimum conditions for the PC frequency and for the PC capacitance (more directly related to the gap PC-DT), are

$$\left(\omega_p^{stab}\right)^2 = \frac{\omega_0^2}{1 + n \cdot k_p} \text{ and } C_p^{stab} = \frac{C}{CL_p \omega_0^2 - n},$$

where $k_p = C_p/C$ is a coupling coefficient and n is the number of PCs per cell.

The circuit analysis of the stabilization distinguishes 3 main conditions for the field as a function of the gap between PC and DT (Fig. 7):

- under-compensation: if the gap is too short ($C_p > C_p^{stab}$), PCs cannot completely compensate the perturbation;
- over-compensation: if the gap is slightly larger than the stabilizing condition ($C_p < C_p^{stab}$ with $\omega_0 > \omega_p > \omega_p^{stab}$), the E0 field crosses the stabilization point and there is a change of slope with respect to the perturbed field;
- de-stabilization: if the gap is much larger than the stabilizing condition ($C_p \ll C_p^{stab}$ and $\omega_p > \omega_0$), the PC effect increases the field tilt.

3D SIMULATIONS AND CIRCUIT PARAMETERS

3D HFSS [4] simulations have been used in order to obtain values of the PC mode frequencies as a function of the number of PCs per tank unit length, as well as a function of the gap between PC and DT. Taking a very small gap between PC and DT (gap PC-DT $\ll \lambda/4$) the PC mode electric field is concentrated in the gap area, so it is possible to apply the quasi-static approximation to the simulation results and calculate values for L_p and C_p .

Starting from magnetostatic and electrostatic considerations, we obtain empirical formulas for L_p and C_p , based on geometrical dimensions of the DTL cavity:

$$L_p = \frac{\mu_0}{2\pi} \ln\left(\frac{D_{eq}}{d_{PC}}\right) \cdot l_{PC} \text{ and } C_p = \epsilon_0 \frac{A_Q}{g_{av}}$$

where D_{eq} is the external diameter of an equivalent coaxial inductor, the PC is the coaxial inner conductor of diameter d_{PC} ; A_Q is the area where the surface charge density, induced by the electric field of the PC mode, is distributed and g_{av} is the average integral path of the electric field [2].

Figure 8 and Figure 9 show curves given by the formula compared with values calculated from simulations. Formulas and simulations show that inductance L_p strongly depends on the number of PCs per unit length of the tank, while the capacitance C_p is mainly a function of the gap between PC and DT.

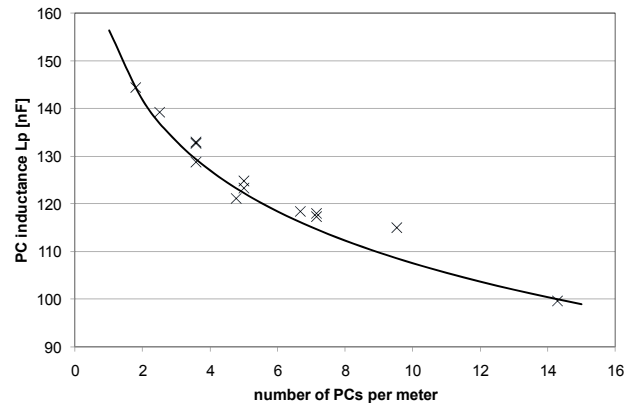


Figure 8: PC inductance as function of the number of PCs per meter.

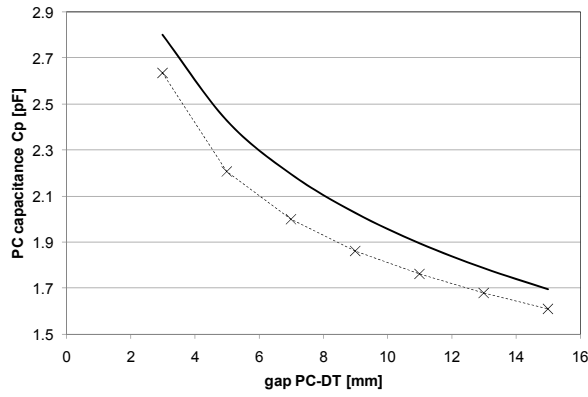


Figure 9: PC capacitance as function of the gap PC-DT.

PC TUNING PROCEDURE AND MEASUREMENTS

Quantities used to evaluate the field in a DTL are the Tilt Sensitivity, defined as

$$TS_i = (E0_i^{pert} - E0_i^{unpert}) / E0_i^{unpert} \cdot (1/\Delta f)$$

and the Tilt Sensitivity Slope (TS_Slope), i.e. the slope of the linear interpolation of the Tilt Sensitivity curve.

The following procedure for PC tuning in a DTL, based on the equivalent circuit, considerably reduces the number of field bead-pull measurements necessary to set the optimum PC length:

- Calculation of the gap capacitance C_0 from a 2D or 3D simulation, using the formula $1/2 \cdot C_0 V^2 = U$.
- Measurement of the TM_{010} and TM_{011} mode frequencies without PCs to calculate the coupling capacitance C between tank and drift tubes.
- Measurement of the PC frequency band (at least 3 modes, for example $PC_{highest}$, PC_{lowest} , $PC_{central}$ modes) and measurement of the TM_{010} and TM_{011} modes at different length of the PCs.
- Fitting of the measured frequencies with dispersion curves computed by the circuit, by adjusting the circuit parameters $\omega_0, \omega_p, C_p, k_{p1}, k_{p2}$.
- Insertion of a perturbation δC_0 in the end capacitances C_0 of the circuit, which simulates the displacement of the two end gaps.
- Looking at the fields given by the previously fitted circuits: the goal is to minimize the Tilt Sensitivity.
- Extrapolation of the optimum PC length from the parameter curves, looking at the zero of TS_Slope curve (Fig. 11).
- Adjusting all PCs at optimum gap PC-DT given by the circuit and measurement of the E0 field.

One can see the TS curve approaching to zero, except that for the cells close to the tank ends (Fig.12). This effect can be mitigated by adjusting the gap PC-DT in order to take into account the increasing cell length in DTL cavities. What we expect is an optimum PC configuration where the central PC is kept at the computed gap PC-DT but with smaller gap PC-DT at the low energy side, and larger gap PC-DT at the high energy side.

This method for PC tuning has been validated with measurements on the Linac4 DTL aluminium model [3] equipped with 5 and 7 PCs. Figure 10 shows the extrapolation of the optimum gap PC-DT by the circuit analysis and Figure 11 and 12 show the average field E0 measured before and after stabilization by 7 PCs.

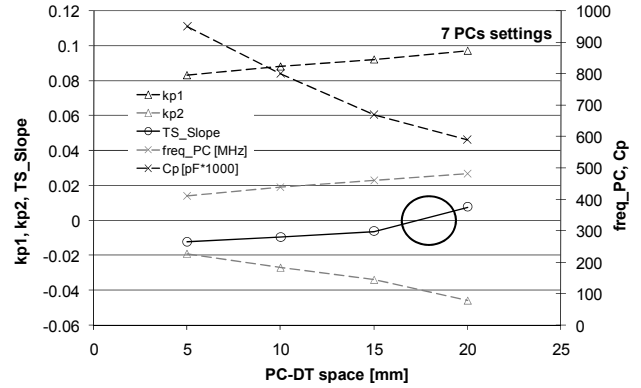


Figure 10: Circuit parameters and TS_Slope for the DTL aluminium model. The TS_Slope zero point is marked.

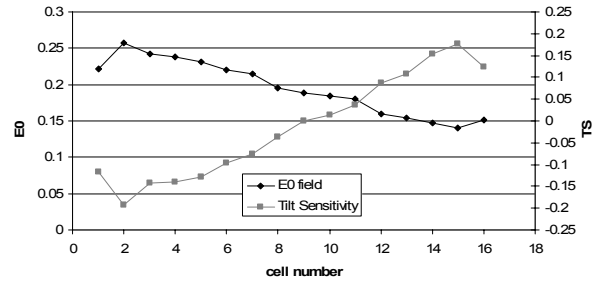


Figure 11: Perturbed field and tilt sensitivity.

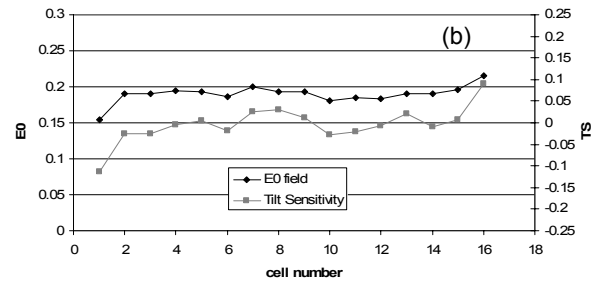


Figure 12: Stabilized field and tilt sensitivity.

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- [2] F. Grespan et al. "Circuitual Model for Post Coupler Stabilization in a Drift Tube Linac", sLHC Project Note 0014, 2010.
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