TUNING AND FIELD STABILIZATION OF THE CERN LINAC4 DRIFT TUBE LINAC

M.R. Khalvati*, CERN, Geneva, Switzerland and IPM, Tehran, Iran
S. Ramberger, CERN, Geneva, Switzerland

Abstract

The Drift Tube Linac (DTL) for the new linear accelerator Linac4 at CERN will accelerate H^--beams of up to 40 mA average pulse current from 3 to 50 MeV. The structure consists of three cavities. The first cavity (Tank1) is a 3.9 m long tank containing 38 drift tubes, 10 fixed tuners, 2 movable tuners and 12 post-couplers, operating at a frequency of 352.2 MHz and an average accelerating field of 3.1 MV/m. This paper reports on the results and procedures used for the low–power tuning, stabilization and power coupler tuning carried out on the first Linac4 DTL tank. The upgrade of the bead pull measurement system and twists to the well-known tilt sensitivity technique are discussed.

INTRODUCTION

The low power RF tuning and field stabilization of Tank1 of the Linac4 DTL has been accomplished. Considerable improvements on the precision of the electric field measurement system have been undertaken as errors could affect tuning and stabilization. In the present work the peak field method is used to extract the average axial electric field E_0 [1]. This method allows reducing the relative standard deviation down to 0.25% in our measurement setup, compared to typically 1..2% in the traditional direct integration method. In an analytical approach the initial set of tuner lengths has been found, bringing fields and frequency close to target. Small individual changes in tuner length lead to the desired field flatness of around ±1.3%. Post-couplers (PCs) are used to stabilize the fields inside the structure. The PC lengths are found by minimizing the tilt sensitivity (TS) slope. The paper reports a modification of the traditional procedure of TS measurements which overcomes a deliberate limitation in the mechanical options for applying a perturbation [1]. By simulation, a good agreement between these two approaches has been found. The TS slope has been reduced 28-fold using PCs.

BEAD PULL MEASUREMENT

The purpose of tuning of the Linac4 DTL cavity is to reach the operating frequency with uniform average electric field in all accelerating cells. Beam dynamics simulation show that the maximum acceptable error in average accelerating field between cells is ±2% [2]. The measurement system thus needs to achieve an accuracy that is a good factor better than that. In this work, the well-established bead pull measurement technique is employed for measuring the axial electric field along the structure [3].

In the current setup, a metallic bead of 6 mm length and 0.8 mm diameter on a thin plastic wire traveling at constant speed along the cavity axis causes a frequency perturbation that can be quantified according to the Slater perturbation theorem as

$$\frac{\Delta f}{f} = \frac{\Delta W_m - \Delta W_e}{U} \tag{1}$$

where ΔW_m and ΔW_e are the changes in the stored magnetic and electric energies respectively and U is the total stored energy.

The wire tension is adjusted such that the effect of wire sag on measurements gets less than 0.1%. Instead of a direct measurement of the variation of the resonance frequency, the phase shift is sampled every 0.002 ms at a constant excitation frequency f_0 and the phase shift is converted to frequency shift using

$$\frac{\Delta f}{f_0} = \frac{tan(\Delta\varphi(f_0))}{2Q} \tag{2}$$

where Q is the loaded quality factor [4]. The average axial electric field E_{0i} for the i^{th} cell can be calculated by direct integration over the localized electric field distribution $E(z)$.

More accurate values E_{0i} can be obtained by comparing measurements with SUPERFISH simulations using the peak field method [1]. The change in stored energy due to the bead located at the field maximum and the field integral are found in single cell SUPERFISH simulations from the electric field along the axis of the cavity. The peak field coeffient for the bead located at the centre of the i^{th} cell gap is defined as

$$pfc_i = \frac{1}{E_{0i}^2 L_i^2} \int_{z-l/2}^{z+l/2} E(z)^2 dz \bigg|_{z=\text{gap center}} \tag{3}$$

where l is the bead length.

The values pfc_i are insensitive to any variation in cavity shape outside the gap area. The measured average axial field is $E^i_{0m} \propto (\Delta\varphi^i_m / pfc_i)^{0.5} / L_i$ Where $\Delta\varphi^i_m$ is the measured maximum phase-shift, and L_i the lengths of the i^{th} cell. Finally, the measured E_{0i} are normalized to 1. The peak field method has further advantages compared to direct integration. First, the effect of the bead length is taken into account intrinsically. Secondly, wire slippage that is difficult to tackle does not particularly affect measurements. Wire slippage usually causes sudden bead movements by few steps – usually less than 4 steps in our setup – which ,when uncompensated, leads to a reduction in the measurement accuracy in direct integration. In our bead pull measurement setup, the reproducibility has been determined to be around ±1.5% for direct integration compared to ±0.25% for the peak field method.

* khalvati@ipm.ir

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TUNING OF THE STRUCTURE

As has been mentioned earlier, the Linac4 cavities are designed to operate at 352.2 MHz and Tank1 of the DTL has a uniform average axial field for all of the accelerating cells of 3.1 MV/m. After assembly, initial field measurements with all tuners out showed a field flatness of around ±6% (Fig. 1) and a resonant frequency around 1 MHz below. The cavity is equipped with 12 slug tuners to adjust the field flatness and the resonance frequency. The initial set of tuner lengths has been determined by an analytical approach from measurements of the individual tuner sensitivities to penetration length. Under the rough assumption that each tuner changes the fields and the resonance frequency linearly, one can calculate the set of tuner lengths by linear regression. Applying the desired relative tuner positions to the tuners, fields and resonance frequency can be brought near target. With some further small corrections of the tuner lengths, field flatness of stabilized DTL Tank1 is achieved as shown in Fig. 1 with errors within ±1.3%.

DTL STABILIZATION

DTL cavities operate in the TM zero mode. Fields are thus known to be sensitive to tuning errors. In order to stabilize the structure against such errors post-couplers are employed [3]. One can adjust the resonant characteristics of the PCs by changing their length such that the fields of accelerating cells get insensitive to tuning errors.

In Tank1, a strong dependency of the electric field on the individual PC length is observed. This is not too surprising as the purpose of PCs is to make the structure insensitive to tuning. Regions between two PC locations that without PCs might see an influence of tuning from adjacent regions, will not see much of an effect as soon as the structure is stabilized. In consequence, stabilization must be undertaken before the tuning of the cavity.

Tilt sensitivity is the criterion for measuring how stable the electric fields are against tuning errors. Usually TS is measured by counter-perturbing the cavity on either end. In a non-stabilized cavity, this perturbation propagates over the whole tank and results in an approximately linear variation of field levels (Fig. 2). The resonant frequency is lowered by $-\Delta f$ by decreasing the cell's gap length, and the resonant frequency is restored to the initial value by adjusting the gap at the other end of the tank. The electric fields along the axis are measured by the bead-pull method. Repeating the same procedure starting from the other end and subtracting the fields of these two measurements divided by frequency perturbation Δf yields the TS value. In this procedure, the perturbation is symmetric and it causes a tilt in average axial electric field along a cavity in each measurements [1, 5].

In our measurements, we decided to avoid mechanical means for changing the end-cell gap by movements of the half drift tubes. In consequence, no mechanical means to increase the gap size is available for restoring the resonant frequency. In consequence, the TS measurement procedure had to be modified. In our approach, the low energy end is perturbed by $-\Delta f$ by sliding a hollow metallic pipe in the first cell gap, and the fields are measured in this setup. In the next step, the perturbation at the low energy end is removed and the high energy end is perturbed by the same pipe such that the frequency shift becomes the same. Fields are measured again. The TS is defined as the difference of the two measured field levels divided by the frequency perturbation Δf. The knowledgeable reader will note that the latter technique can be considered as applying the former at a frequency $f + \Delta f$ with half the perturbation. The unperturbed case would be the one where the end cells have frequency errors of $\Delta f/2$.

Simulation shows that these two techniques of measuring TS are in agreement within few percent. This difference originates from the different shape of the perturbation in the two methods. It does not affect final results because the non-stabilized and stabilized cases are compared using the same procedure. In the present work, the perturbation has been set to 120 kHz for all TS measurements. In Fig. 2 the initial TS of the first DTL cavity is plotted. The non-stabilized TS has a slope of around 36.5%/MHz/m.

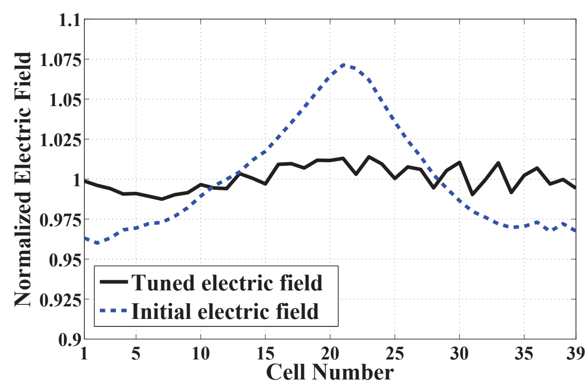

Figure 1: The initial (blue - without tuners and PCs) and the final (black) average electric field E_0 of Linac4 DTL Tank1.

The numerical target in the stabilization of the DTL structure is to optimize TS slope so that it gets close to zero. As a starting point all PCs are adjusted with the same length such that the PC_1 mode is located just below the accelerating TM_{010} mode and the stop band between the TM and PC bands disappears. The resonant frequency spectrum of TM and PC modes for different initial lengths of PCs are plotted in Fig. 3. The PC length of 217.9 mm results in the best confluence. All the PCs are set to the same length and the final set of PC lengths is distributed around this initial length. The measurements show that for the DTL tank1 this is ±10 mm around the initial value for all PCs. Using this starting value helps converging to the desired target.

The shape of the PC no. 7 has been modified. According to the Fig. 1, electric fields peak around the 23rd cell due to a strong influence of the power coupler. The compensation for the power coupler is mostly on tuner no. 6 but in order to provide more compensation and preventing Tuner6 from getting too close to drift tubes, PC7 – which is longitudinally approximately at the same place as Tuner6 – has been modified with a thicker copper cylinder with 50 mm extra length and a tuner diameter. Fig. 2 shows that the stabilized TS is reduced to 1.3%/MHz/m which corresponds to a 28-fold reduction compared to the non-stabilized TS.

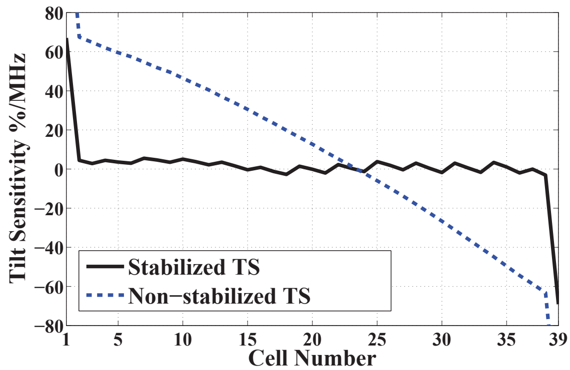

Figure 2: Comparison of stabilized (black) and non-stabilized (blue) TS of Linac4 DTL Tank1. The TS slope is reduced by factor of 28 using PCs.

The final dispersion diagram for the stabilized DTL Tank1 is plotted in Fig. 3. For the DTL Tank1, The difference between the accelerating TM_{010} mode and the TM_{011} and PC1 modes are respectively 3.59 and 4.44 MHz.

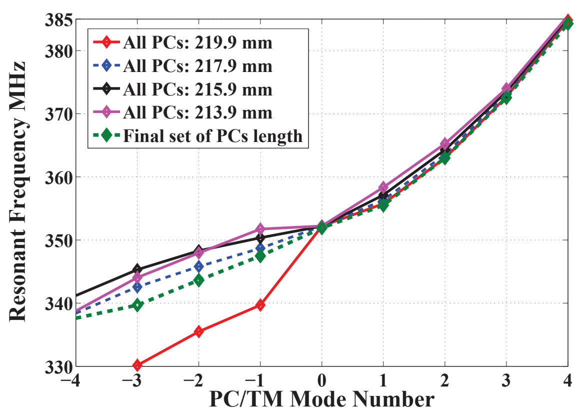

Figure 3: The measured dispersion diagram of PC_{-p} and TM_{01p} modes for different set of PCs length. The best confluence for constant PC length is at 217.9 mm.

The final tuner and PC lengths are plotted in Fig. 4. Note that the PCs employed in the Linac4 DTL cavities do not have any asymmetry like a bend or tap and are not used for tuning. The PC lengths decrease toward the high energy end of the cavity. Tuners 4 and 9 have been chosen as movable tuners. Their nominal length is 54 mm and they can vary between 0 and 104 mm providing a tuning range of -64..200 kHz while field flatness varies between ±1.25% and ±1.67%.

POWER COUPLER TUNING

The Linac4 DTL Tanks are fed by TaCO power couplers [6]. It is a waveguide coupler with a race-track shaped coupling iris, which has a piston tuner close to the cavity iris to adjust the coupling factor to the cavity in order to make sure that the maximum power is transferred to the cavity with beam. Without beam, the coupling factor β is adjusted to 1.6. For measurements of β and the unloaded quality factor Q_0, the reflection-type method is used [7]. Q_0 of the first DTL tank is 42200 which is 86% of the simulated value which reflects the quality of the mechanical design in terms of surface roughness, copper plating and RF sealing technique.

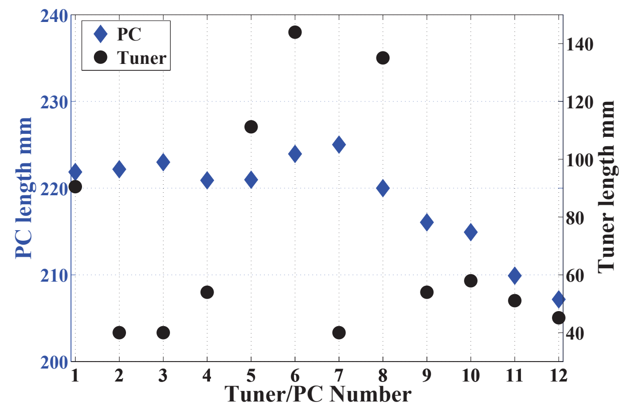

Figure 4: Final tuners and PCs length. The final PCs length are distributed ±10 mm around the initial PCs length.

CONCLUSION

Tank1 of the Linac4 DTL has been tuned and stabilized. In order to be able to measure a 3.9 m long structure with 39 gaps with the required precision, the bead pull measurement system has been improved to a reproducibility error of E_0 of 0.25%. The procedure for tuning and stabilization has been described. For practical reasons a modified procedure for tilt sensitivity measurements has been introduced that is in agreement with the traditional approach. The final field flatness error is ±1.3%, which correspond, to a TS slope reduction by a factor of 28. The power coupler is adjusted to a coupling factor β of 1.6, and Q_0 is 42200 which is 86% of the simulated value.

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