

# THE DTL POST COUPLER – AN INGENIOUS INVENTION TURNS 50

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## Abstract

In September 1967, the patent for "A method and device for stabilization of the field distribution in drift tube linac" has been filed by Edward A. Knapp, Donald A. Swenson, and James M. Potter of Los Alamos National Laboratory [1]. It is this invention which to a good part led to the success of highly efficient Alvarez drift tube linacs (DTLs) in that it considerably reduces field errors. The explanation for why the post coupler when tuned correctly has such a strong stabilizing effect has been given at the time in an accompanying paper by describing the modal confluence of the accelerating mode band with the post-coupler mode band, turning a comparatively sensitive 0-mode structure into a stable  $\pi/2$ -mode like structure. As ingenious as the invention of the post coupler appears, as poor has been the way of finding its optimum length by relying mainly on trial and error. With the design of the Linac4 DTL at CERN, a new technique has been derived by a DTL equivalent circuit model. Understanding stabilization on an almost cell by cell level provides a new way of optimizing post couplers of an entire structure with few measurements and even without the extraction of the circuit model itself. Previous approaches to post-coupler stabilization are reviewed and the new, straightforward and accurate technique is described and demonstrated in the stabilization of the Linac4 DTL structures.

## INTRODUCTION

Within two years after WWII, Luis Alvarez developed the first Drift Tube Linac (DTL) based on ideas of Ising and Widerøe [2]. While beams of ions had been accelerated by RF power before, it was with the availability of strong RF sources at 200 MHz that had been developed for radar applications during the war that such a structure could be built with reasonable dimensions as necessary for the acceleration of proton beams. In order to achieve sufficient acceleration, high gradients were required, that could only be maintained in cavities. Alvarez had the idea to attach one cavity to the next and to suppress end walls in order to reduce losses. He built the first DTL empirically from model cavities that he excited in the  $TM_{010}$  mode and he adjusted the dimensions in order to find the proper drift tube and resonator length.

In the following years, the theory of RF acceleration was further developed and beams of ever higher intensity could be accelerated. The invention of strong focusing in the early 1950s sorted out the issues with grid focusing [3] and soon after, new drift tube geometries were found analytically which lead to higher shunt impedances [4]. Already at that time, permanent magnet quadrupoles have been considered as fo-

cuscing elements and computers were used to optimize the RF design.

## EQUIVALENT CIRCUIT MODEL

For the injection into synchrotrons, effective beam transport and beam quality were of particular importance and in the 1960s with new machines just having come on-line, it became clear that field stability and beam loading needed to be better understood. It turned out that beam loading not only had an influence on the absolute field level but also on the variation of fields within the cavity. Modal analysis and equivalent circuits were used for a better understanding of the cavity behavior [5].

The equivalent circuit of yet unstabilized drift tube cells has been developed in [6] that topologically is that of a transmission line with series resonators  $Z_n$  and shunt elements  $Y'_n$  (Fig. 1):

$$Z_n = j\omega L_n + \frac{1}{j\omega C_n} \tag{1}$$

$$Y'_n = j\omega C'_n + \frac{1}{j\omega L'_n} \tag{2}$$

where  $L_n$  and  $C_n$  represent the equivalent circuit elements for drift tube  $n$ , and  $L'_n$  and  $C'_n$  are the elements of the stem and the shunt capacitance between drift tubes and tanks respectively. Certainly, the elements when extracted do not fully scale with cell lengths as they are the result of a quasi-static approximation and also contain other stray contributions. Note that losses have been neglected.

Infinite circuit structures can be analyzed by transmission line theory in order to get an idea about the average wave transmission on fully distributed elements or more correctly by Floquet's theorem thus representing an infinite chain of equal basic cells (Fig. 1) [7]. The propagation constant and thus the dispersion diagram can be directly extracted from  $Z$  and  $Y'$ . When using transmission line theory, the  $\pi$ -mode is not represented.

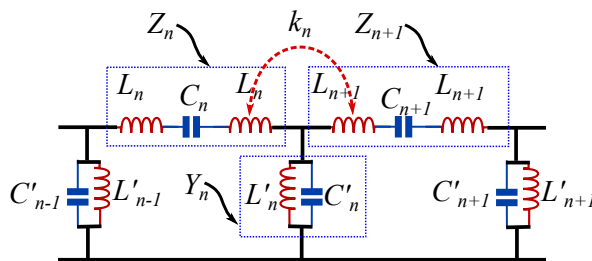


Figure 1: DTL equivalent circuit without post couplers.

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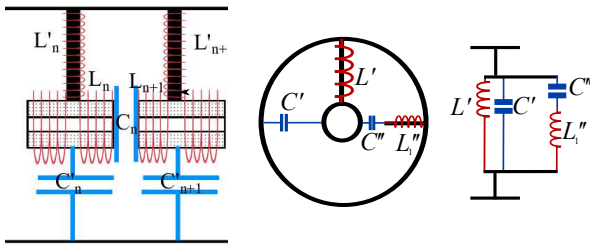


Figure 2: Left: the equivalent circuit represents the cavity elements. Right: post couplers add further circuit elements.

## POST COUPLERS

At the time, various RF structures were analyzed for their quality in beam stability. The disadvantage of the 0 and  $\pi$ -modes became evident in that they have zero group velocity along the cavity axis in the lossless limit, corresponding to cut-off in the modal spectral diagram, and that this mode thus is sensitive to field errors [6, 8]. As an alternative, several structures with coupling cavities operating in the  $\pi/2$ -mode were analyzed at the time. Efforts finally lead to the development of the side-coupled linac and a full theory of modal coupling [9]. At the same time, analysis of multistem DTL structures showed that the stopband between the modal bands of stems and drift tubes can be closed [10].

On the basis of the work on  $\pi/2$ -mode structures, the inventors of the post couplers found that transforming the 0-mode Alvarez DTL into a quasi  $\pi/2$ -mode structure might be possible in a more elegant way similar to the way how coupling cells transform a  $\pi$ -mode structure into the  $\pi/2$ -mode side-coupled linac. The idea that additional resonators that are resonant at about the same frequency and that get tightly coupled to the chain of accelerating cavities therefore was tried in the DTL with the introduction of post couplers that were tailored to the right frequency [11]. The respective equivalent circuit is shown in figure 2 and the shunt admittance is

$$Y'_n = j\omega C'_n + \frac{1}{j\omega L'_n} + \frac{j\omega C''_n}{1 - \omega^2 L''_n C''_n} \quad (3)$$

## TILT SENSITIVITY SLOPE

With all the work on cavity stabilization, also tilt sensitivity was introduced as a measure for field stability [10, 11]. Global as well as local tilt sensitivity are mentioned in the original post-coupler article which showed that there was some clear understanding in how to measure the quality of stabilization. In the interest of limiting the number of time consuming bead-pull measurements, a modern and most practical way to define tilt sensitivity is

$$TS_n = \frac{2\pi}{\Delta\omega} (E_{0n}^{he} - E_{0n}^{le}) \quad (4)$$

where  $E_{0n}$  is the average axial electric field in cell  $n$ .  $le$  indicates that the first gap at the low-energy end is perturbed.  $he$  refers to the case of perturbing the high-energy end. All

perturbation measurements are undertaken at the same operation frequency  $\omega^{he} = \omega^{le} = \omega_{op}$  and require the compensation of the end perturbation by an average tuner shift.

Since the invention of post couplers, close to 50 years ago, considerable literature on the strategy for stabilization accumulated with various approaches that saw equivalences in other parameters that actually do not exist. While e.g modal spectra do show if some average overall stabilization has been reached, they do not suffice for finding proper stabilization in all cells. Also the similarity of accelerating modes with post-coupler modes has turned out not to be an absolute requirement for finding the optimum stabilization everywhere in a tank. What remained over the years was that tilt sensitivity is the right parameter to look at globally and locally, and that post couplers as local resonators have a resonance at which currents on either side of a drift tube can be made the same independent of the perturbation.

Applying the idea of flat tilt sensitivity strictly means that in the very limit the tilt sensitivity of adjacent cells needs to be the same. Said differently, the difference or slope in tilt sensitivity of adjacent cells shall be zero:

$$TS'_n = TS_{n+1} - TS_n \quad (5)$$

Applying the criterion of tilt sensitivity strictly together with the finding that the tilt sensitivity is proportional to the shunt admittance  $TS'_n \propto Y'$  brought a turning point in the quest for optimum stabilization [12].

## UNDERSTANDING STABILIZATION

Stabilization does the trick to compensate the shunt capacitors at the operation frequency. The post couplers add a resonator that can be represented by an inductance  $L''_n$  for the post-coupler post of about  $\lambda/4$  in length and a capacitor  $C''_n$  for the capacitance between the post-coupler tip and the drift-tube. This resonator is in resonance with the shunt capacitor at the operation frequency turning the shunt admittance  $Y'$  effectively to zero. While in a non-compensated structure, slight frequency errors result in a current over the shunt branches and thus a voltage error, in virtual absence of these branches a stabilized structure will not be perturbed by such an error [13, 14].

Nevertheless when setting out to stabilize the Linac4 DTL, the authors still faced an unbearable situation. It was not clear how to get to the optimum without loosing much time. Precise tilt sensitivity measurements are time consuming and without a clear strategy one can spend days in moving post couplers around. Neighboring post-couplers turned out not to be independent and in the effort of improving field quality at one cell, it degraded in the next. By chance however, when checking the second-next post-couplers, almost complete independence was found which by closer inspection is not surprising as the coupling to the next post-coupler is much tighter and compensation currents flow almost exclusively between neighboring post-couplers.

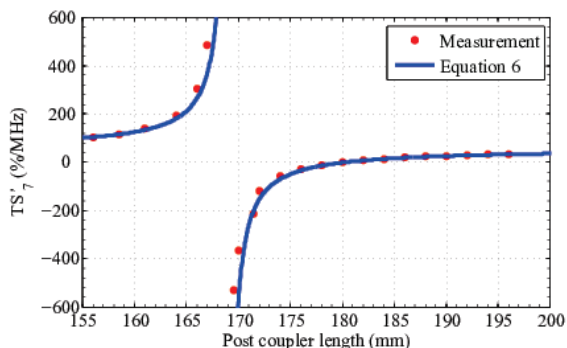


Figure 3: Curve fitting of the tilt sensitivity slope  $TS'_7$ .

### STABILIZATION TECHNIQUE

Even without an extraction of the exact circuit parameters, the shunt admittance behavior versus the post-coupler length can now be extracted (Fig. 3), and the optimum point at the zero crossing  $Y'_n(\omega = \omega_{op}) = 0$  can be found with few measurements. The capacitance  $C''_n$  of the post coupler depends strongly on the distance  $d_n = R_c - R_d - l''_n$  between the post-coupler tip and drift tube surface with  $R_c$  and  $R_d$  the cavity and drift tube radii respectively. It is approximated with a two plate capacitor  $C''_n = \epsilon_0 A / d_n$  with  $A$  being an equivalent post-coupler tip area.  $TS'_n$  can be fitted by the following function:

$$TS'_n = \alpha_n + \beta_n \frac{1}{l''_n - l^r_n} \quad (6)$$

with the fitting parameters  $\alpha_n$  and  $\beta_n$ , where  $l''_n$  is the post-coupler length and  $l^r_n = R_c - R_d - (\epsilon_0 A \omega^2 L''_n)$  is a reference length for the post coupler. In cavity measurements, the self-resonance  $Y'_n = \infty$  at  $\omega'' = 1/\sqrt{L''C''}$  can be used for extraction.

As neighboring post couplers on opposite sides show a dependency in parameters, only every second post couplers - those on one side of the cavity - can be adjusted together. After adjusting post couplers on one side, however, those of the other side can also be adjusted together, and the DTL is fully stabilized in just 4 tilt-sensitivity measurements. Admittedly, depending on the starting point of post-coupler adjustment, an asymmetry can be found. For this reason, it is important to first seek a starting point at modal confluence. In case that a more symmetric setting is sought, averaging of post-coupler distances on one side  $d_n^{new} = d_n/2 + 1/(d_{n-1}^{-1} + d_{n+1}^{-1})$  and repetition of the procedure starting at the other side can be considered. For a detailed description of the stabilization technique with proofs of the equations, the interested reader is referred to [12]. The technique has been applied to the stabilization of the Linac4 DTL at CERN (Fig. 4).

### OUTLOOK

Stabilization of DTL cavities is not only beneficial for beam loading, it serves also the equalization of field errors introduced by manufacturing errors as well as thermal variation during operation. Today's manufacturing techniques are

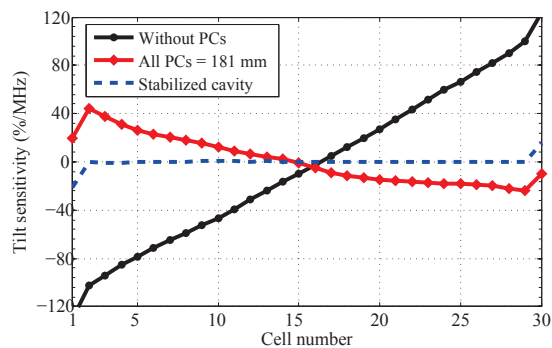


Figure 4: Results of the post-coupler optimization for the Linac4 DTL Tank 3. The initial tilt sensitivity is reduced by a factor of 100.

able to achieve tolerances that are sufficient for building DTL structures that do not require much tuning. This has been shown in the manufacturing of the Linac4 DTL at CERN in recent years, in a design which did not foresee adjustment mechanisms to position drift tubes inside cavities [15, 16]. And today's 3d field simulation codes are already capable of simulating complete DTL cavities. The stabilization technique outlined above applied right in the simulation stage, new DTL structures can be manufactured at lower cost and with considerably less effort at the assembly stage.

### CONCLUSIONS

50 years from the invention of post couplers to a straightforward stabilization technique is a long time when put in perspective with the about 20 years from the invention of Ising and Widerøe of the first ion linear accelerator to the first Alvarez DTL, and the about 20 years from there to the invention of post couplers. Apparently the rough advice on the final result of stabilization was sufficient over the years and even if not followed closely, the defects of an incompletely stabilized DTL are not severe. However it is felt that having a clear stabilization technique is not only of academic interest but closes a gap in the assembly stage that has led to some confusion. Last but not least the new stabilization technique lends itself to an implementation at the design stage which could further develop the way we build modern DTLs.

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