FIELD STABILITY IN TWO-STEM DRIFT-TUBE LINACS*

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Abstract

Drift tubes supported by two stems have been considered for cryogenic drift-tube linacs (DTLs) to reduce vibrations and to minimize drift-tube deflections upon cool down. We investigated rf properties of two-stem DTL structures at room temperature and low power. Even without resonant stabilizers, a DTL with two stems 180° apart is inherently more stable against tuning errors than a similar structure with single stems. The increased stability is higher for DTLs with shorter drift tubes. Ordinary quarter-wavelength-long post couplers actually destabilize the two-stem DTL fields: the extra stem raises the post coupler frequency compared to the frequency of the same post coupler in a single-stem structure. Stabilization occurs with post couplers extended beyond the tank wall into coaxial stub tuners. Adjustment of the stub lengths tunes the post-coupler frequencies, but post-coupler lengths in the tank have no effect, which suggests a field pattern different from traditional post couplers. The stabilized DTL resembles multiple-stem DTLs in which the angle between stems is varied to achieve stabilization. Adjusting the coaxial stub length is mechanically simpler than changing the stem azimuth angle.

Experimental Apparatus and Tilt Sensitivity

For these measurements, we used a 425-MHz aluminum model configured with either 40 identical 2-MeV cells or 16 identical 50-MeV cells. Energies of 2 MeV and 50 MeV refer to proton energies and correspond to cell lengths of 4.60 cm and 22.15 cm, respectively. We measured the axial electric field distribution with the bead-perturbation technique.[1] Tilt sensitivity (TS) measurements consist of two such field distributions for different detunings of the end cells. For the first measurement, we lower the TM_{010} frequency -100 kHz by decreasing the cell-1 gap. Increasing the gap in the last cell restores the correct mode frequency. This type of detuning of the end cells tends to "tilt" the field toward cell 1, resulting in higher field in cell 1 and lower field in the last cell. The second measurement corresponds to opposite sign perturbations to the end cells, which tend to tilt the field in the opposite direction. TS is the cell-by-cell percentage difference between these two field measurements divided by the net end-cell frequency perturbation. A stabilized field distribution is one for which the TS slope is zero over the entire length of the DTL.

Tilt Sensitivity Without Post Couplers

Figure 1 shows two TS measurements, one with single and one with double stems on each drift tube for the 40-cell structure. No post couplers were installed for either of these measurements. The extra stem on each drift tube increased the cavity TM_{010} operating mode resonant frequency by only 1.444 MHz, but resulted in an almost fourfold reduction in the TS slope. This higher stability with double stems is consistent with the observed large increase of 15.99 MHz in the TM_{011} mode frequency. A tilt in the field at the operating mode frequency can be understood in terms of an admixture of higher order longitudinal TM_{01X} modes with the TM_{010} mode. The TM_{011} mode with one zero longitudinally is nearest in frequency to the constant-amplitude TM_{010} mode and, hence, contributes most strongly to the field tilt. The larger the frequency difference between the TM_{010} and

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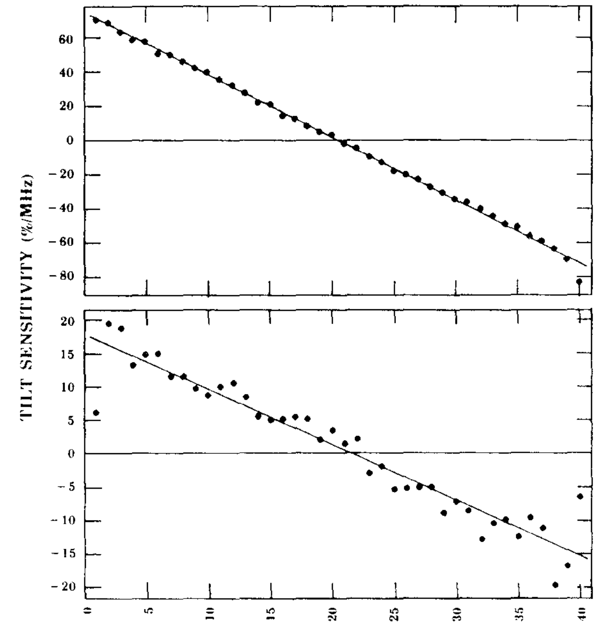

Fig. 1. Tilt sensitivity without post couplers for the 1.84-m-long, 40-cell DTL. The upper plot corresponds to single stems and has a slope of $-80\%/\mathrm{MHz/m}$. The lower plot corresponds to double stems 180° apart, with a slope of $-18\%/\mathrm{MHz/m}$.

TM_{011} modes, the harder it is to achieve an appreciable admixture, and therefore, the more stable the field distribution. Table I shows the measured frequency difference between these modes for single- and double-stem configurations. The frequency difference is more than three times greater with double stems than with single stems.

TABLE I. MODE FREQUENCIES FOR THE 40-CELL, 1.84-m-LONG DTL

	TM_{010} Frequency (MHz)	TM_{011} Frequency (MHz)	Frequency Difference (MHz)
Single stem	426.287	432.940	6.653
Double stem	427.731	448.930	21.199

Characteristics of Post-Coupler-Stabilized DTLs

Figure 2 illustrates several features of single-stem DTLs stabilized by post couplers.[2] The structure used for these measurements consisted of sixteen 50-MeV cells equipped with either 7 or 15 post couplers. The quantity plotted is the average TS slope versus the post-coupler length. Stabilization occurs on the upper branch of the curve where it crosses zero TS slope. The discontinuity is near the point where the highest post-coupler mode crosses the TM_{010} mode frequency. Two quantities change simultaneously as a post-coupler length varies: the resonant frequency of the post coupler and the capacitive coupling of the post-coupler resonator to two adjacent cells of the DTL. A longer post coupler has a lower resonant frequency and larger coupling to the DTL cells. Because the post coupler is a quarter-wave resonator whose frequency is lowered by the capacitance between the tip and the drift tube, the spacing between the drift tube outer radius and tank inner space wavelength for the TM_{010} frequency. This constraint ensures adequate coupling when the post-coupler length is adjusted for the proper frequency.[3]

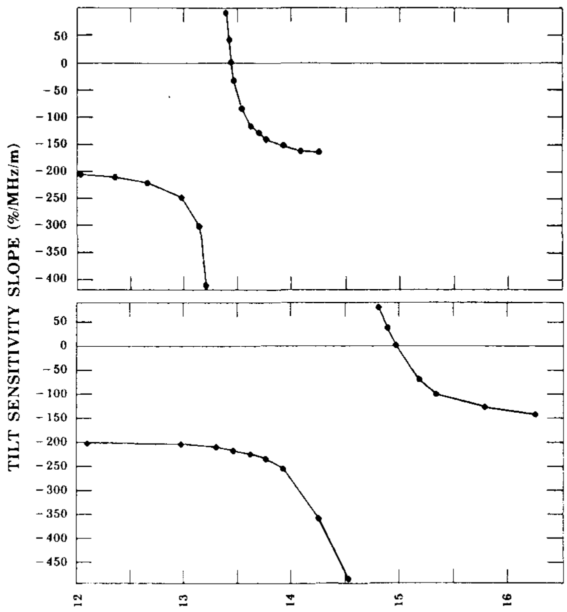

Fig. 2. Tilt sensitivity slope versus post-coupler length for the 3.54-m-long, 16-cell DTL equipped with single stems. The upper plot corresponds to seven post couplers, one every other drift tube. Stabilization (zero TS slope) occurred for a post-coupler length of 13.4 cm. The lower plot corresponds to 15 post couplers, one every drift tube. Stabilization occurred at 15.0 cm.

For data in the upper plot of Fig. 2, the DTL was equipped with seven post couplers, one adjacent to every other drift tube. The fields stabilized for a post-coupler length of 13.4 cm corresponding to a 3.7-cm spacing between the drift tube and the post-coupler tip. For the lower plot, the DTL had 15 post couplers, one adjacent every drift tube. This time, the fields stabilized for a post-coupler length of 15.0 cm, corresponding to only 2.1 cm between the drift tube and the post-coupler tip. In both cases, the TS slope approaches −200%/MHz/m if the post couplers are either too long or too short. This is the slope observed with no post couplers in the tank.

Figure 2 also shows that if the post couplers are tuned high in frequency (shorter than optimum length), they destabilize the field. That is, the TS slope can be made even more negative than it is without post couplers at all. In this case, the highest-frequency mode of the post-coupler passband is above the TM_{010} mode frequency. Similarly, the post couplers can also overstabilize the field, resulting in a positive TS slope. The steepness of the TS slope where it crosses zero is an indicator of the coupling. Lower coupling corresponds to a steeper zero crossing and requires more critical tuning. The lower plot in Fig. 2 shows higher coupling because of the smaller spacing between post-coupler tips and drift tubes.

Figure 3 shows data similar to Fig. 2 but for a 40-cell structure made up of 2.0-MeV cells. This single-stem DTL was stabilized by 19 post couplers, all 15.3 cm long, which corresponds to 1.8 cm between the drift tube and post-coupler tip. This configuration has even more stability than the 50-MeV, 15-post-coupler configuration because there are more post couplers per unit length, one every 9.2 cm compared to one every 22.15 cm. For such short cells, there is no need to use post couplers adjacent to every drift tube. Compared to Fig. 3, Fig. 2 shows a pronounced difference in the asymptotic behavior (that is, in the TS without post couplers). The curves for the 16-cell structure approach −200%/MHz/m, whereas for the 40-cell structure, the TS slope approaches −80%/MHz/m. This difference is related to the structure length and the corresponding proximity of the TM_{011} and TM_{010} modes. According to Table I, this frequency difference is corresponding difference is about 4.5 MHz for the 3.54-m-long, 16-cell structure, and thus the end-cell perturbations more easily mix the pure TM_{010} fields with higher order TM_{01X} modes (chiefly the TM_{011} mode). The longer 16-cell structure is less stable than the shorter 40-cell structure.

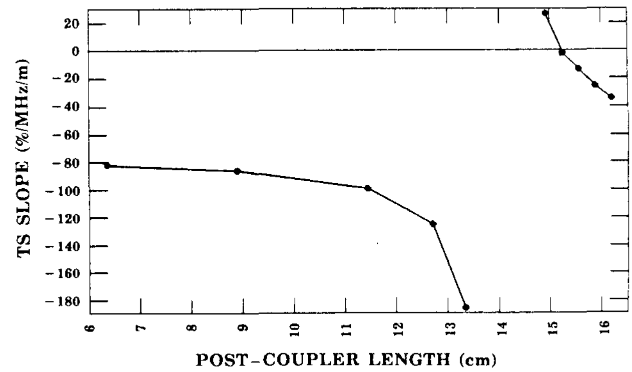

Fig. 3. Tilt-sensitivity slope versus post-coupler length for the 1.84-m-long, 40-cell DTL equipped with single stems and 19 post couplers. Stabilization occurred at 15.3 cm.

Stabilization of the Two-Stem DTL

The two DTL structures differed in some respects when two stems were installed. The 50-MeV, 16-cell structure stabilized with post couplers, but the post couplers were longer than they were in the single-stem DTL. For 15 post couplers, the length was 16.63 cm, leaving a tip-to-drift-tube space of only 0.48 cm. The 2-MeV, 40-cell structure could not be stabilized at all with ordinary post couplers. For the longest post couplers that would fit in the space between the drift tubes and the tank wall, the TS slope was +158%/MHz/m. A positive slope indicates that the post-coupler frequency is too high and, if possible, the post couplers should be lengthened for zero TS slope. Figure 4 shows the TS slope versus post-coupler length for the 40-cell double-stem DTL equipped with 19 post couplers. The higher stability without post couplers mentioned earlier is illustrated by the smaller asymptotic value of the slope. The asymptotic slope is the same as the TS slope for no post couplers (see Fig. 1), −80%/MHz/m for single stems and −18%/MHz/m for double stems.

The upper branch of the curve in Fig. 4 apparently would cross zero if only the post couplers could be lengthened. We lengthened the post couplers by extending each one beyond the tank wall into a coaxial line. Such a geometry has been used previously[4] to stabilize a DTL with the $3\lambda/4$ post-coupler mode. For the present tests, the coaxial line had inner and outer diameters of 1.27 and 2.54 cm, respectively. The overall post-coupler length equals the coaxial-line length plus the inner length, that is, the portion inside the tank radius. The coaxial-line length could be varied continuously from zero to 18 cm. Figure 5 shows the results of four series of measurements with different post-coupler lengths measured inward from the tank inner radius. The inner lengths were 13.30, 14.57, 15.84, and 17.11 cm, corresponding to spaces of 3.81, 2.54, 1.27, and 0.0 cm, respectively, between the post-coupler tip and the drift tube. Stabilization (zero TS slope) occurred for a coaxial-line length of 14.5 cm and was nearly independent of the inner post-coupler length, a surprising result because we expected the coaxial-line length to merely compensate for changes in the overall length of the post coupler. Instead, the measurements seemed to indicate that the system does not behave at all like the traditional post coupler in a single-stem DTL.

The stabilizing mode of the traditional quarter-wave post coupler has a voltage maximum at the tip and a current maximum at the tank wall. Contact with the drift tube would short out this mode of excitation rendering the post coupler useless in stabilizing the fields. For 17.11-cm post-couplers (see Fig. 5), the tip of the post coupler was actually in good rf contact with the drift tube and yet stabilized the fields for the same coaxial line length as the

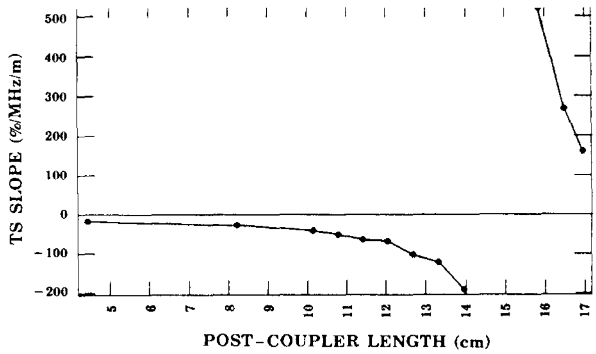

Fig. 4. Tilt-sensitivity slope versus post-coupler length for the 1.84-m-long, 40-cell DTL equipped with double stems and 19 post couplers. There is no stabilization point below 17 cm.

other inner post-coupler lengths. Thus in the new configuration, the end of the post near the drift tube is not a voltage maximum for the stabilizing mode. The configuration resembles the three-stem DTL of Giordano and Hannwacker.[5] They investigated several multiple-stem configurations and demonstrated stabilization of the TM_{010} fields. Stabilization depended upon the angle between stems as controlled by the installation of flared vanes on the stems. Adjustment of the angle changed the inductance of transverse stem resonances and, hence, tuned the modes for stabilization. These stem-mode frequencies also depend upon the cell length; thus, the angle changes continuously along the length of a graded-β DTL.

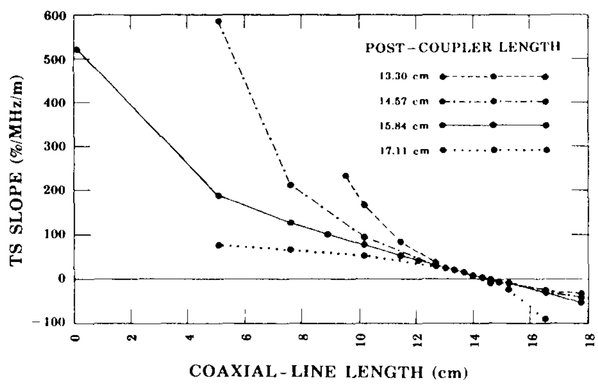

Fig. 5. Tilt-sensitivity slope versus post-coupler coaxial-line length for the 1.84-m-long, 40-cell DTL with double stem and 19 coaxial post couplers. The four post-coupler lengths refer to inner lengths, that is, inside the tank radius.

The present design with two stems 180° apart and the coaxial post couplers at right angles to the stems is equivalent to the multistem arrangement. Here, instead of changing the angles between stems for tuning one varies the length of the coaxial line. This system has several potential advantages over the earlier multistem configuration. First, the tuning adjustment is simple and can be done outside the tank without disassembly. Second, in contrast to flared vanes, little extra material need be immersed in the TM_{010} magnetic fields, thereby reducing power losses from eddy currents. Third, the mechanical design can incorporate either a solid connection to the third stem (or post) or no connection at all. Stabilization can be achieved for either case, so the choice can be based on mechanical considerations.

We also studied the stability of the 50-MeV, 16-cell DTL equipped with 15 coaxial post couplers. Figure 6 shows the results for three post-coupler inner lengths of 12.03, 14.57, and 15.84 cm corresponding to spaces of 1.08, 2.54, and 1.27 cm, respectively, between the tip and the drift tube. Stabilization occurred for a different length of coaxial line for each post-coupler length. Longer post couplers required shorter coaxial lines.

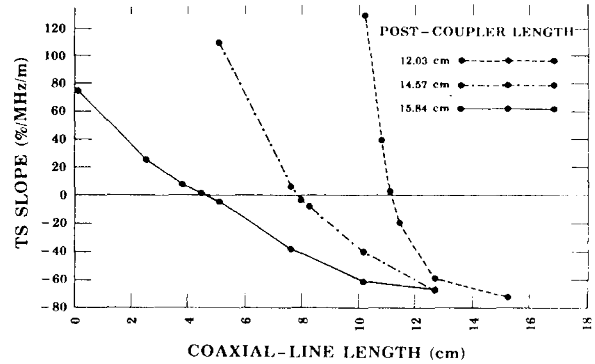

Fig. 6. Tilt-sensitivity slope versus post-coupler coaxial-line length for the 3.54-m-long, 16-cell DTL with double stems and 15 coaxial post couplers. The three post-coupler lengths refer to inner lengths, that is, inside the tank radius.

Ramped-Field Distributions

The accelerator design for which the two-stem DTL was originally considered also incorporated a longitudinally ramped distribution of the accelerating gradient. After the 40-cell, 2-stem structure had been stabilized, we tried to ramp the axial field in the manner used for a conventional single-stem structure.[1] In the single-stem DTL, a bend in the post coupler toward the low-field end of the tank provides for such a ramped field. Attempts to ramp the field using this method in the two-stem DTL were not successful. The largest observed end-to-end difference in the axial electric field was ~2% (or about 0.05% per cell). Ramped (stabilized) fields with slopes >8%/cell are easily achieved in single-stem DTLs with comparable cell lengths. This marked difference provides additional evidence that, in the low-β 40-cell DTL, the tip of the post is actually a voltage minimum unlike the traditional quarter-wave post coupler. In the high-β 16-cell DTL, we achieved ramped-field distributions as large as 4.7%/cell.

Conclusion

The two-stem DTL for low-β cells is not stabilized by traditional quarter-wave post couplers. A stabilized field distribution is possible using a third stem or post that extends beyond the tank wall into a coaxial line. The structure is similar to older three-stem configurations, but offers advantages in tuning, power consumption, and mechanical design. In its present form, the two-stem structure is inappropriate for DTLs with a ramped field gradient. However, it is an attractive alternative to the single-stem DTL for applications with a constant-field gradient.

References

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