LONGITUDINAL BEAM DYNAMICS OF A 5-MeV DTL A COMPARISON OF THEORY AND EXPERIMENT*

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Abstract

A detailed comparison of theory and experiment concerning the longitudinal beam dynamics of a 2- to 5-MeV drift-tube linac (DTL) was carried out. Beam output energy and phase were measured as a function of DTL rf field amplitude and phase. Comparison between experimental data and theory was found to be in good agreement.

Introduction

One can hypothesize that internal space charge forces of an intense, bunched particle beam would not affect the average dynamic longitudinal parameters, beam energy, and phase. To test such a hypothesis, one can calculate single-particle longitudinal motion for given accelerator fields as a function of space and time. Attendantly, average output beam energy and phase are directly measurable by the experimentalist and thus can be compared with single-particle prediction. Agreement is an indication that the hypothesis is correct; consequently, accelerator operational parameters, such as cavity field amplitude and phase, can be selected by searching for best agreement between single-particle prediction and measured average longitudinal-motion dynamic variables. This paper reports the results of such an investigation carried out on the Accelerator Test Stand (ATS) at Los Alamos National Laboratory.

Experimental Setup

Important elements of the ATS configuration for these experiments consisted of a 100-keV H^- ion source, a 0.1- to 2-MeV radio-frequency quadrupole (RFQ), and a 2- to 5-MeV (2 MV/m) DTL. The operational frequency for the ATS is 425 MHz, and a nominal beam current of 30 mA was used during the experiment.

The experimental, independently variable parameters were relative RFQ-DTL phase and DTL field amplitude. Varying the RFQ-DTL phase is equivalent to varying the injection phase of the RFQ output beam bunches into the DTL. Average output beam energy and phase were the experimentally measured dependent variables. The DTL output beam energy distribution was measured with a 60° magnetic spectrometer. Distributions were nominally sharply peaked ($\Delta W/W < 1\%$) with the average energy being used in the data analysis. Output phase of the beam microbunches are measured with a wide-band strip-line diagnostic, located 29.8 cm downstream of the DTL output. As with the output energy, the average phase of the microbunch is used in the data analysis. An example of the strip-line data is shown in Fig 1. A single bipolar-doublet signal is generated at the strip-line output for each microbunch detected. Relative changes to the average bunch output phase are measured using the peak of the first positive-going pulse. Data were obtained using an Tektronix 7854 oscilloscope with an S-6 sampling head and an S-53 trigger recognizer. Reliable low-jitter triggering was provided by a Nanofast timer, which itself was triggered by an rf reference signal.

Theoretical data were single-particle predictions provided by the computer program PARMILA.[1] Input to the code for the ATS DTL was injection phase and energy and relative DTL field amplitude (1.00 being the design value). The code predicts output energy and phase.

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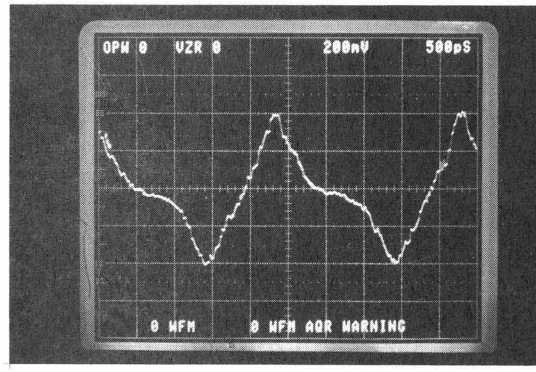

Fig. 1. Typical strip-line data obtrained with a sampling oscilloscope (200 mV/division, 500 ps/division).

Data Analysis

Two important but rather simple analysis procedures were performed on the strip-line raw data before they could be directly compared with theory. The phase reference used for strip-line data was not the DTL cavity field, but rather a signal whose phase remained fixed in relation to the RFQ. Therefore, measured phase shift of the DTL output bunch is a sum of two parts: that resulting from a relative shift of the bunch with respect to the DTL field plus that caused by the fact that the relative phase of the RFQ-DTL was being varied to obtain the data. Because the simulations predict the output phase relative to the DTL field (and not the RFQ), the needed RFQ-DTL phase difference was to be subtracted from the measured phase shifts.

The second analysis procedure pertains to an artificial phase shift resulting from the varying output particle energy and the drift space between the end of the DTL and the strip line. For each data point where output bunch phase was recorded, the average output particle energy was also measured. Thus, knowing the drift length and the particle energy, the phase of the microbunch at the end of the DTL is easily calculable.

Figure 2 shows the spectrometer data plotted for three different DTL amplitudes as a function of RFQ-DTL relative phase. The dashed line at 5.055 MeV indicates the design output energy when the input energy, DTL phase, and DTL amplitude are all set at their respective design values. Relative measured DTL amplitudes are expressed in terms of a crystal-diode detected cavity field, sampled by an rf pickup loop. For unknown reasons, the DTL output energy is 45-keV high when all other indications are that the accelerator is being operated at the design set points. Therefore, instead of plotting the absolute value of the output energy, the difference between the measured energy and that of the synchronous particle is plotted in subsequent figures. For the experimental data, the synchronous particle energy is 5.099 MeV. The results emphasize scaling of the output energy and phase with input phase and field amplitude; thus, plotting the energy data in terms of ΔW makes for easier comparison.

Results and Discussion

Figure 3 shows both theory and experiment indicating the dependence of the bunch output phase with varying input phase. Simulation predicts that the synchronous phase is -40°, and, as expected, the theoretical curve passes through the point (-40°, -40°). Note that the sign of the slopes of these curves indicates that a particle (or bunch) entering the DTL early (relative to the synchronous

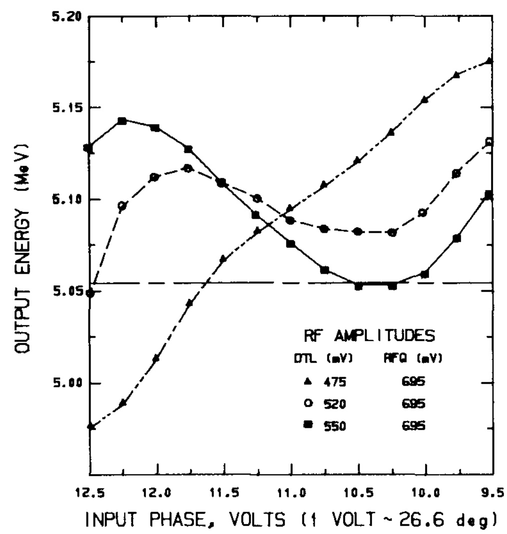

Fig. 2. Dependence of DTL output energy on injection phase for three different DTL amplitudes. Nominal set points for ATS operation are 520 mV, 695 mV, and 11.25 V for the DTL amplitude, RFQ amplitude, and RFQ-DTL relative phase, respectively.

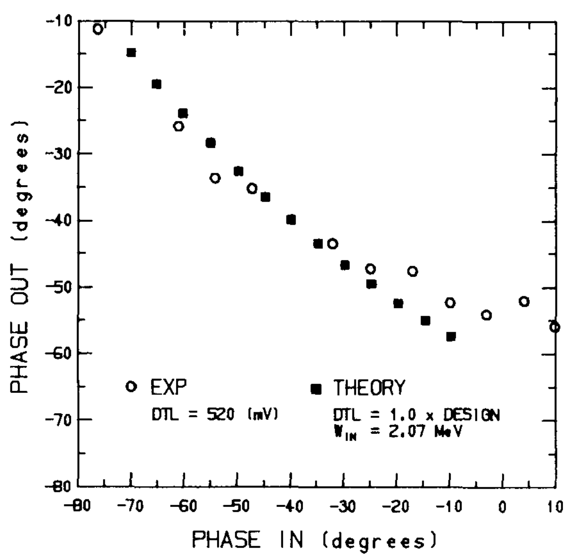

Fig. 3. Phase advance at DTL output for various injection phases. Theoretical synchronous phase for DTL design amplitude is $-40°$.

particle) leaves late. The theoretical curve uses the design input energy (2.07 MeV) and the design DTL field amplitude. Experimental data were taken for a DTL amplitude setting of 520 mV, the nominal set point for the ATS-DTL amplitude. As mentioned above, the experimental input variable is the RFQ-DTL relative phase, which equivalently varies the bunch injection phase. An absolute evaluation of this relative phase is determined by shifting the axes for the experimental data to get best alignment with the theoretical curve. Of course, this procedure does not affect the slope of the experimental data.

Better agreement is seen in Fig. 4, which compares the same experimental data with theoretical data that have the DTL amplitude set 5% higher than design. The slope of the theoretical data decreased by -20% when the DTL amplitude was changed by a relatively lesser amount from 1.00 (Fig. 3) to 1.05 (Fig. 4) times the design value. Therefore, bunch output phase versus input phase is a sensitive measurement of changes to DTL field amplitude.

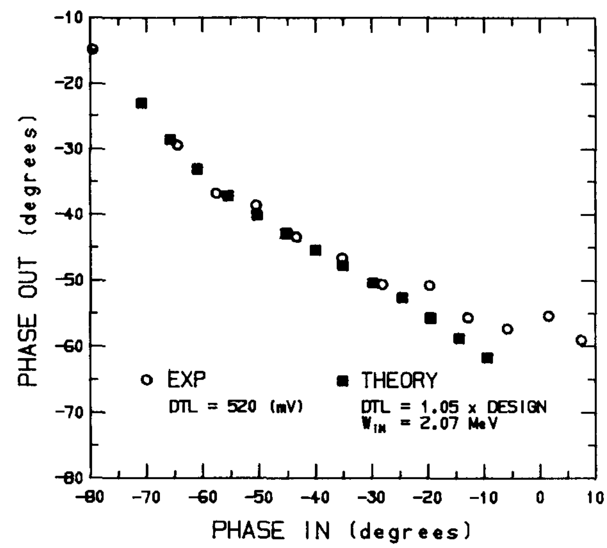

Fig. 4. Better agreement is observed when data are compared with theoretical prediction for a DTL amplitude 5% greater than design.

The better agreement indicates that a DTL amplitude setting of 520 mV is a few percent higher than design.

Figure 5 shows the theoretical and experimental dependence between the output energy and output phase. The qualitative properties of two curves are in excellent agreement. Peaks and zero crossings of ΔW occur for experiment and theory at the same output phase angles. The energy excursion away from that of the synchronous particle is slightly greater for the experimental data. Figure 6 compares the experimental data with the 5%-higher DTL amplitude theoretical case. Note that now the energy excursion for the theory is greater than that of the experiment, an opposite circumstance to that in Fig. 5. Therefore, Figs. 5 and 6 indicate that a DTL amplitude of 520 mV is slightly higher than design. The same conclusion was arrived at earlier after analysis of the phase-in versus phase-out data.

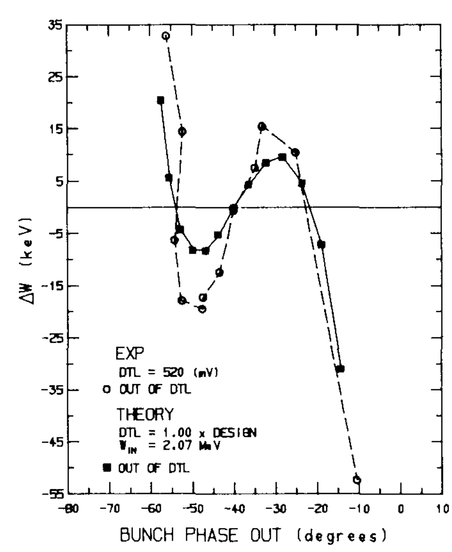

Fig. 5. Comparison of design simulation and experimental data for nominal ATS operating conditions. Excellent qualitative agreement is observed.

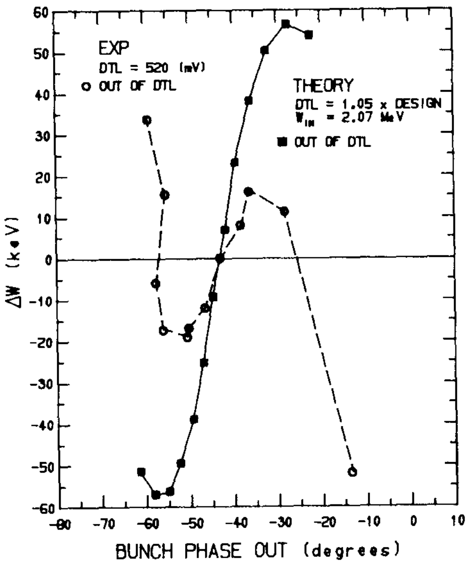

Fig. 6. Energy excursions predicted by simulation for a 1.05 × design DTL amplitude are much larger than measured with the DTL set at its nominal value (520 mV).

Until now, experimental data for only one DTL amplitude have been presented. Figures 7, 8, and 9 investigate the scaling of the output beam energy and phase with DTL amplitude. Figure 7 shows theoretical scaling for two different DTL amplitudes, 1.00 and 1.05 times design. Note that for the 1.05 case the synchronous phase has shifted to -43°, consistent with the well-known condition that V cos θ_S = const. Figure 8 exhibits similar experimental data. The DTL fields are 4% higher for the 550-mV case as compared with the 520-mV curve. Note the shift in synchronous phase consistent with the increased field amplitude. Finally, Fig. 9 illustrates all four curves, experiment and theory, on one plot for easier comparison. The observed dependence of the beam energy and phase centroids on DTL rf parameters is in good agreement with the single-particle simulations.

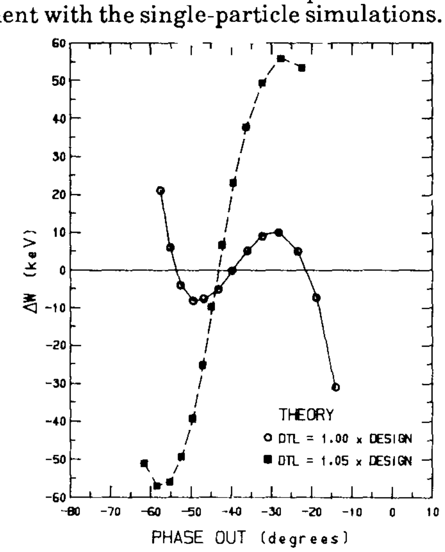

Fig. 7. The ΔW scaling, as a function of output phase, with DTL amplitude as predicted by theory.

Conclusion

An initial but detailed comparison of theory and experiment concerning the ATS-DTL longitudinal beam

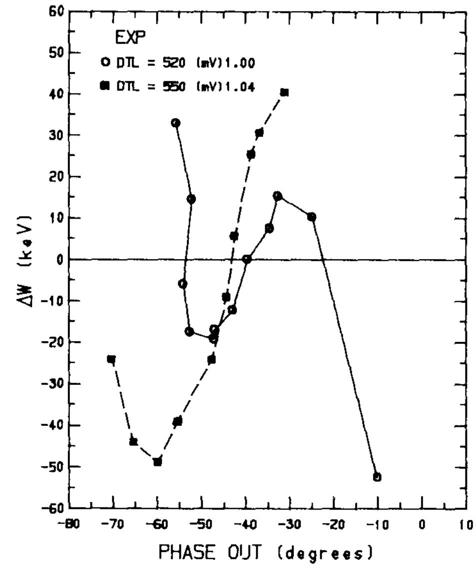

Fig. 8. Experimentally observed scaling of ΔW as a function of output phase for two different DTL amplitudes.

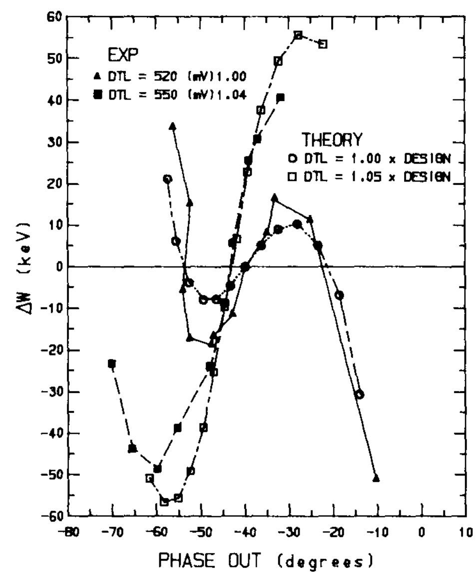

Fig. 9. Figures 7 and 8 overlaid to illustrate a comparison between theory and experiment. Note the excellent agreement regarding a shift in the synchronous phase.

dynamics has been performed and good agreement is observed. Phase advance and output energy through the DTL as functions of injection phase and DTL relative amplitude appear to be sensitive measures of DTL amplitude. Changes in synchronous phase have been observed and agree quantitatively with theory. For the ATS, DTL single-particle theory seems adequate for modeling the average longitudinal bunch parameters. Furthermore, comparing the observed longitudinal centroids with the single-particle simulations is a useful technique for determining the accelerator operational set points.

Reference

1. K. Crandall, AccSys Technologies, Pleasanton, California, 1987, private communication.