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Test of TESEQ CBA 1G-150 wide band 150-Watt amplifier

As a Project X Chopper Kicker Driver

Introduction:

The chopper kicker is a part of the Project X Medium Energy Beam Transport (MEBT) chopping system, which will prepare a pre-specified bunch structure of the 2.1 MeV H minus beam. At least 80% of the beam bunches are directed to the absorber, and the remaining 1 mA average beam current is directed to subsequent linear accelerator structures. The bunch deflection is executed by two 50-ohm 50-cm long travelling-wave synchronized kickers; each providing a 3.7 mrad angle kick.

The kicker electric field is generated by applying equal and opposite polarity voltage to the two opposing electrodes of each kicker structure. One amplifier will drive one electrodes resulting in a total of two amplifiers per kicker. (Figure 1) The drive signal will be an AC coupled phase continuous arbitrary waveform with a bunch spacing of 162.5 MHz, the operational frequency of the Radio Frequency Quadrupole (RFQ), the first RF accelerating structure of Project X.

Chopper kicker requirements:

1. Any bunch of the 162.5 MHz continuous train can either pass to or be removed from the subsequent acceleration.
2. Flattop voltage to kick the beam is defined by two parameters being met simultaneously:
   a. A minimum voltage to kick the bunch by a specified amount.
   b. A minimum length of time of ±0.65 ns with respect to the bunch center.
3. Minimum differential voltage flattop between upper and lower kicker structure for kicking the beam out/in (for the kicker gap of 16 mm): 500 V.
4. Voltage tolerance for bunches passing through: ±50 V flattop voltage on each electrode for the duration of the flattop.
5. The voltages specified above are for the ideal case of two long parallel plates. Any reduction of the integral kicker strength caused by gaps between the kicker plates is to be compensated by increasing the applied voltage by the corresponding amount.
6. Any difference between kicker phase velocity and beam velocity is to be corrected by widening the flattop width by a corresponding amount. For the 50 cm structure, the correction is 0.13 ns per 1% of the velocity error.
7. Uniformity of the kicker electric field in the horizontal direction shall be adequate to the kick applied to the particles within 6 sigma of the bunch, i.e. over the horizontal beam size $\Delta X = \pm 8$ mm, should not differ by more than 5%.
8. If necessary, additional limitations can be applied:
   a. Beam removal for longer than 200 ns gaps in the beam bunch train is made by the Low Energy Beam Transport (LEBT) kicker

b. During 1 μs element of periodicity, the total number of alterations (pass-> remove) or (remove->pass) is not more than (2·162.5/5) = 65, i.e. the maximum average frequency of switching cycles is 33 MHz.

Nominal specifications for an amplifier to drive the above mentioned kicker:

Input Impedance	50 Ohms
Input VSWR	1.2:1
External Load impedance	50 Ohms
External Load VSWR	1.2:1
Bandwidth 3 dB	20-1000 MHz
Bandwidth 1 dB	50-500 MHz
Gain	65 dB minimum
Gain flatness	+/- 1 dB across full bandwidth
Amplitude to phase distortion	not to exceed+/- 10 degrees across small signal to 1 dB compression
Peak to peak output voltage	500 V +/- 50 V
Output average power minimum	1000 Watts
Frequency of incoming bunches	162.5 MHz
Input drive signal	0.6 V p-p

Figure 1 depicts the test setup for the measurements as well as a potential configuration for the actual chopper kicker. The first test performed on the Teseq CBA 1G-150 amplifier was a transfer function test utilizing a network analyzer for the drive signal. The attenuator loads, cable, and splitter were measured and shown to be flat in both amplitude and phase across the test bandwidth of 1-1500 MHz, figure 2. The correction factor that must be added to all of the network and spectrum analyzer measurements is of order 56.5 dB. The readings from the power meter for the transfer functions are approximate values for the frequencies at midband where the amplitude response is flat, Figures 3 through 6. The sweep time of the network analyzer was set to 20 seconds to facilitate the reading of the power meter. Figure 7 is a measurement of the 1 dB compression point of the amplifier.

The second measurement involves the high-speed arbitrary function generator (ARB). This Chase unit is able to generate a waveform that is commensurate with the needs of the Fermilab chopper kicker for Project X. The first test consists of a single sinusoid at 162.5 MHz followed by two periods of zero volts. Due to the limited memory of the ARB, the repetition rate is not one third of the fundamental, but harmonics of 62 MHz. Figures 8 through 11 show the input drive waveform measured separately on the scope with different values of fixed attenuator pads. Figures 12 through 15 are the amplifier output for the respective drive levels. Note the gain measured is lower than the swept network analyzer measurement due to the ripple in the low frequency portion of the pass band. (The pulse is harmonically rich.)

Figures 16 and 17 are the input and output spectrum with 0 dB attenuation on the ARB drive. The marker tables indicate ratio of the first four output harmonics are linear to within a fraction of a dB to the input.

It was observed that the Teseq amplifier, while exhibiting nonlinear phase performance at the low frequency end of the band, did not show excessive amplitude to phase distortion, i.e. AM to PM, suggesting signal pre-distortion could be employed to obtain the desired response. By measuring the impulse response of the amplifier using the Chase ARB as the impulse generator, tap coefficients of an FIR filter to model the amplifier were synthesized. National Instruments LabVIEW Adaptive Filter Toolkit is utilized to run a Least Mean Squares algorithm to determine the best coefficients for the inverse FIR filter to undo the amplifier distortion. The desired output waveform is applied to the inverse FIR filter and the resulting pre-distorted waveform was down loaded to the ARB. Figure 19 shows the pre-distorted input and resulting output. Figure 20 depicts additional outputs at various drive levels.

In an attempt to increase the flat top portion of the kick while keeping within the bandwidth limits of the amplifier, a modified single pulse waveform was synthesized via band limited Fourier transforms yielding the input pulse responses shown in figures 21 and 22. Figures 23 and 24 are the spectra of this input drive signal. Figure 25 is the resulting single pulse amplifier output with a wider flattop region. Adding multiple instances of this single pulse drive developed a waveform more representative of the desired kicker pulse, figure 26. Spectra of the multi bunch drive signal shown in figure 27. The resulting amplifier output waveform provides kicker drive signal that satisfies the requirement to remove four out of five bunches in an arbitrary pattern, figure 28.

Conclusions:

With a pre-distorted drive, the Teseq 150 watt amplifier looks to meet the performance specifications for the 50-ohm Project X chopper kicker. Teseq also makes higher power units that would be more suitable to the final application. It is believed that vector network analyzer transfer function measurements as performed on this amplifier would be the first step in characterizing the higher power amplifiers in the Teseq product line. Before procurement some additional pulse testing is warranted.

References:

•Project X

http://projectx.fnal.gov/

•Chase Scientific

http://www.chase2000.com/da14000.shtml

•Teseq

http://www.teseq.us/com/en/products_solutions/emc_radio_frequency/power_amplifiers/CBA_1G-150_e.pdf

•Avtech

http://www.avtechpulse.com/catalog/page102_cat11_avx-sp_rev2.pdf

•Tektronix

http://www.tek.com/datasheet/digital-phosphor-oscilloscopes-0

•National Instruments

http://sine.ni.com/nips/cds/view/p/lang/en/nid/209039

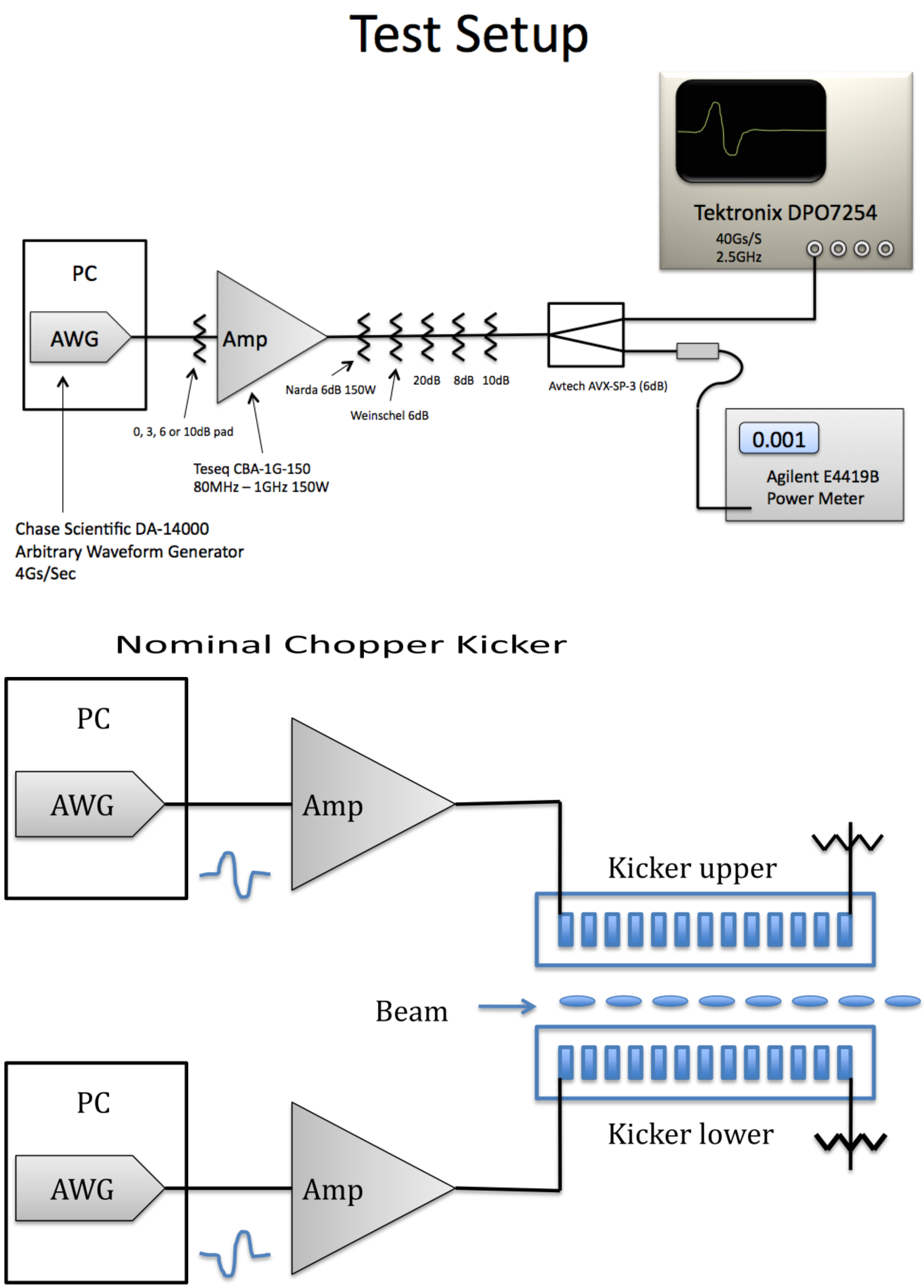


Figure 1. Amplifier Test set up diagram and possible chopper kicker configuration.

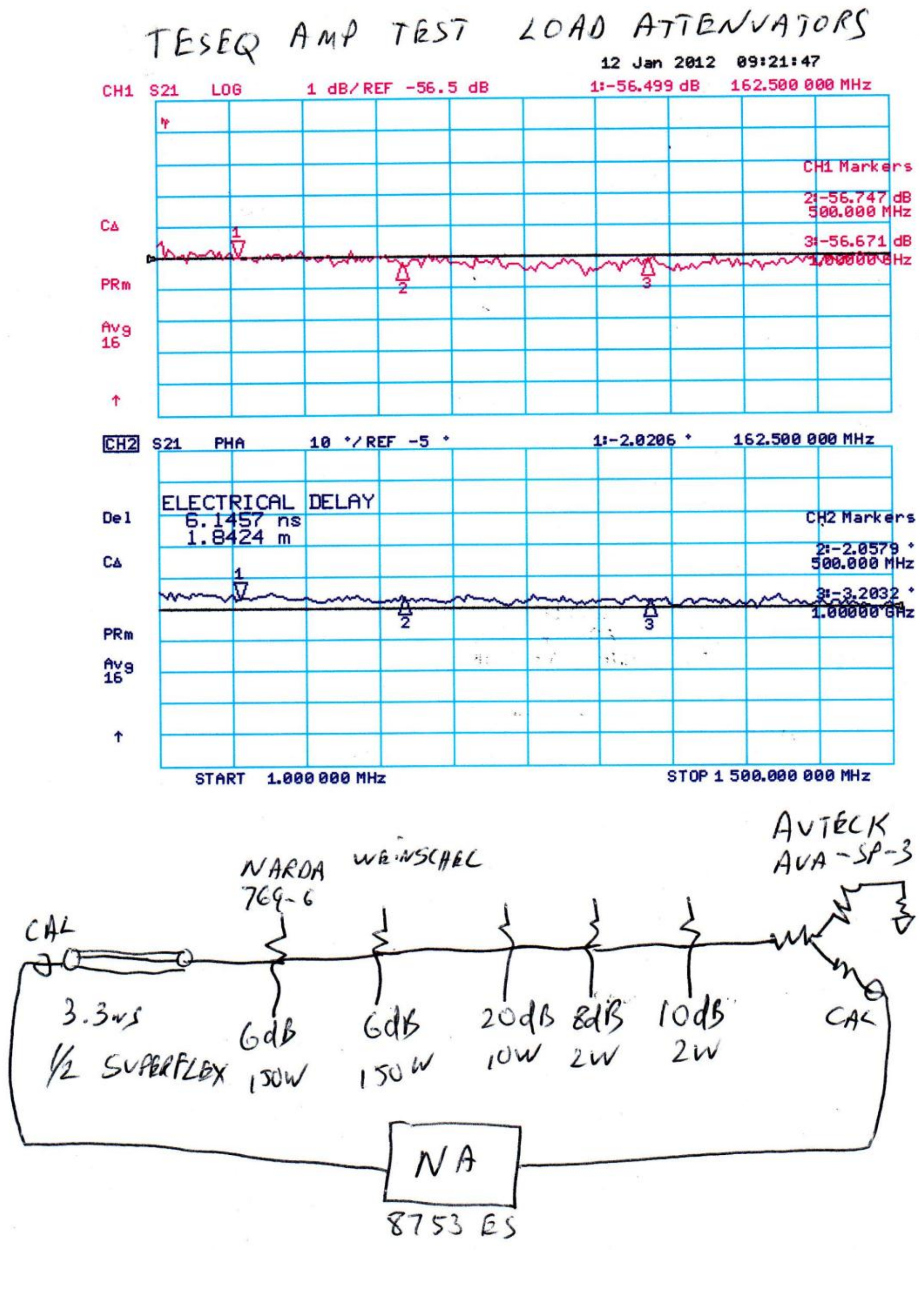


Figure 2. Transfer function of the load cable, attenuators, and splitter. Correction factor is nominally 56.5 dB as the harmonic content of the pulsed measurements is predominantly below 250 MHz.

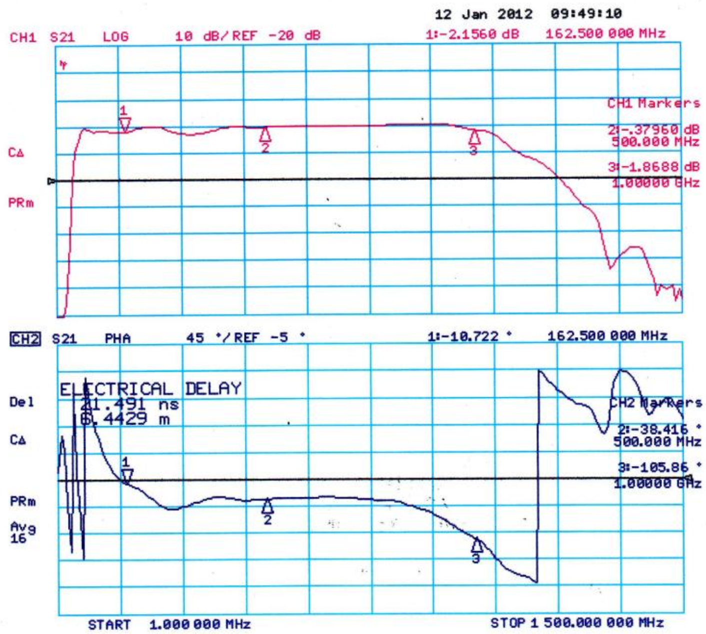


Figure 3. -10 dBm network analyzer drive, average power in pass band ~40 Watts. Gain marker 2 (500 MHz)=56.4 dB. Electrical delay of the amplifier in the pass band is 21.491-6.146=15.345 nanoseconds for all transfer functions. (subtraction of load components)

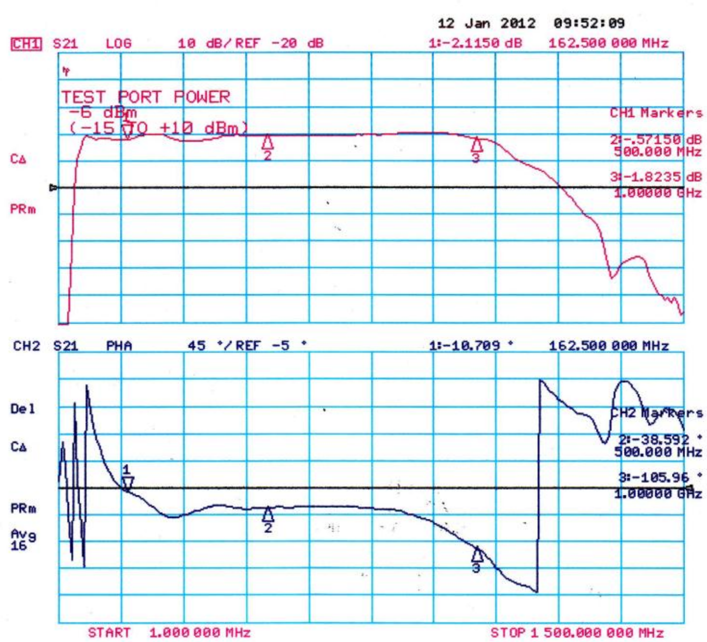


Figure 4. -6 dBm network analyzer drive average power in pass band ~90 Watts. Gain marker 2 (500 MHz)=56.2 dB.

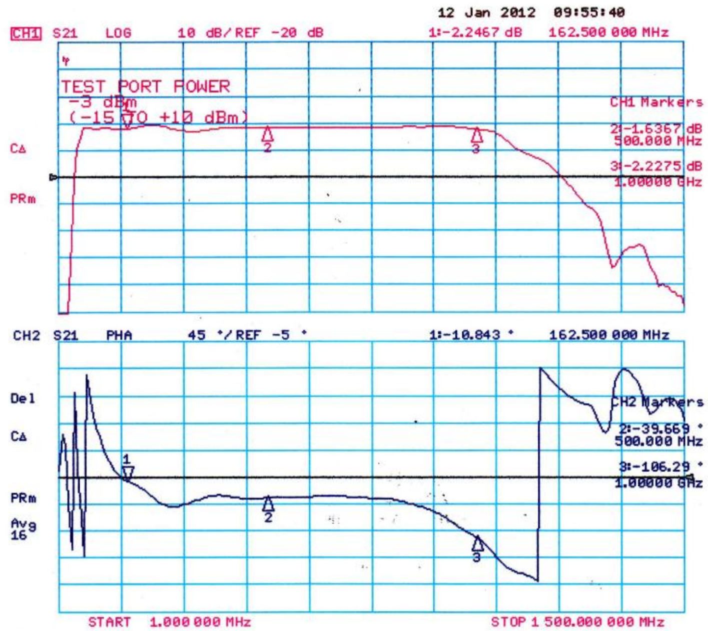


Figure 5. -3 dBm network analyzer drive average power in pass band ~130 Watts. Gain marker 2 (500 MHz)=55.2 dB.

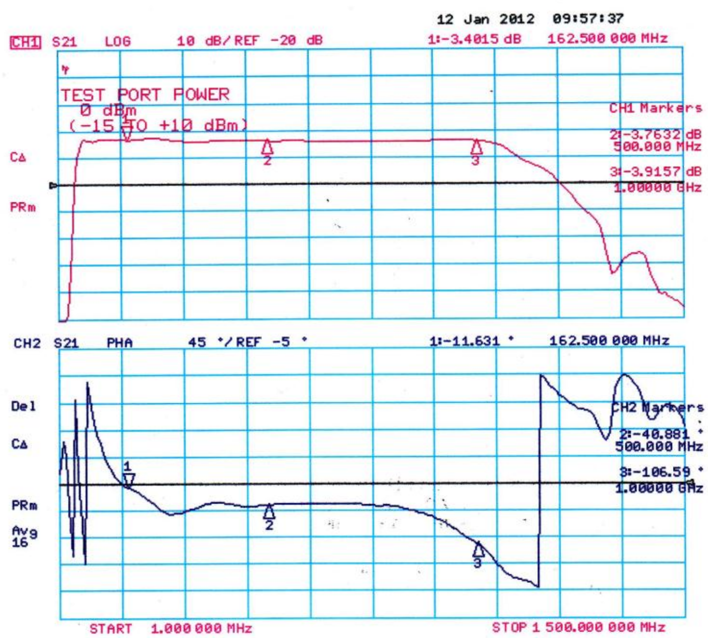


Figure 6. 0 dBm network analyzer drive average power in pass band ~150 Watts. Gain marker 2 (500 MHz)=53.0 dB. Amplifier is in compression.

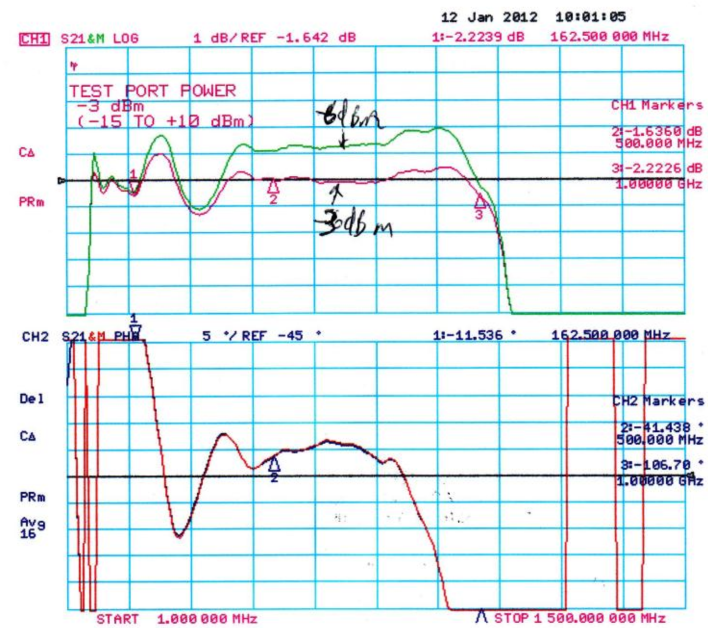


Figure 7. 1 dB compression measurement with -6 dBm and -3 dBm drive from the network analyzer. Gain marker 2 (500 MHz)=55.2 dB @-3dBm; 56.2 dB@-6dBm

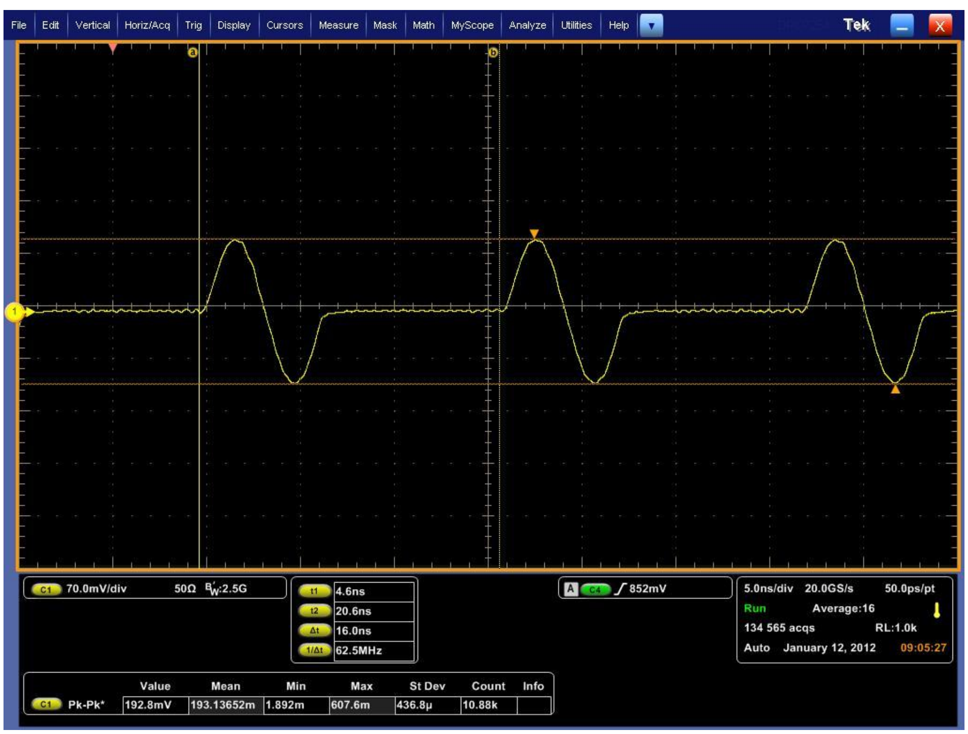


Figure 8. ARB drive with 10 dB of attenuation. Peak to peak voltage is 0.193 volts.

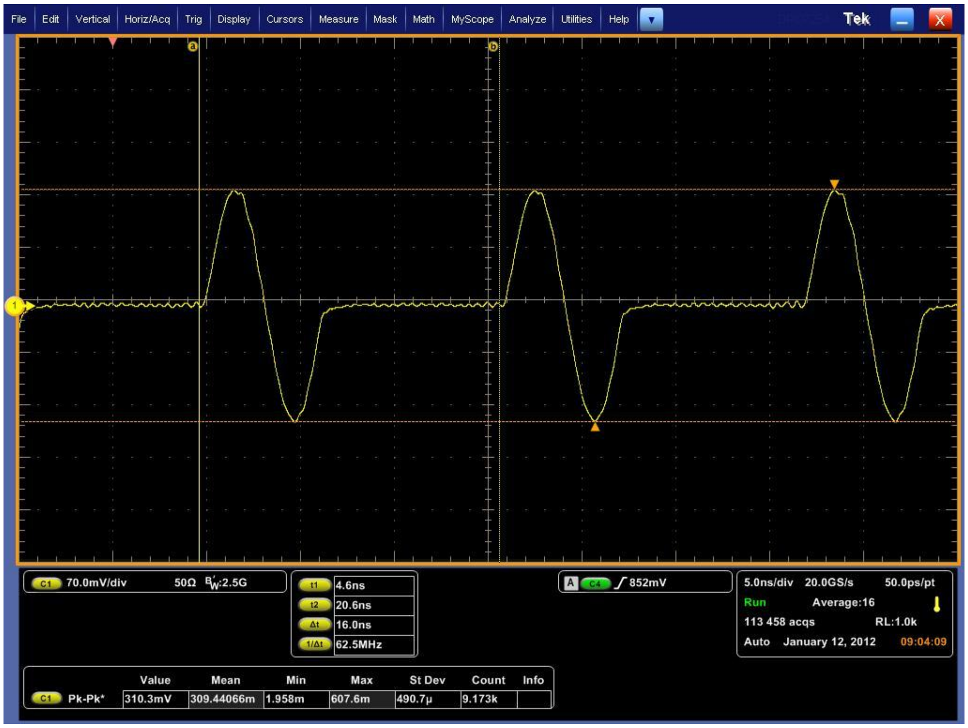


Figure 9. ARB drive with 6 dB of attenuation. Peak to peak voltage is 0.310 volts.

Figure 10. ARB drive with 3 dB of attenuation. Peak to peak voltage is 0.438 volts.

Figure 11. ARB drive with 0 dB of attenuation. Peak to peak voltage is 0.605 volts.

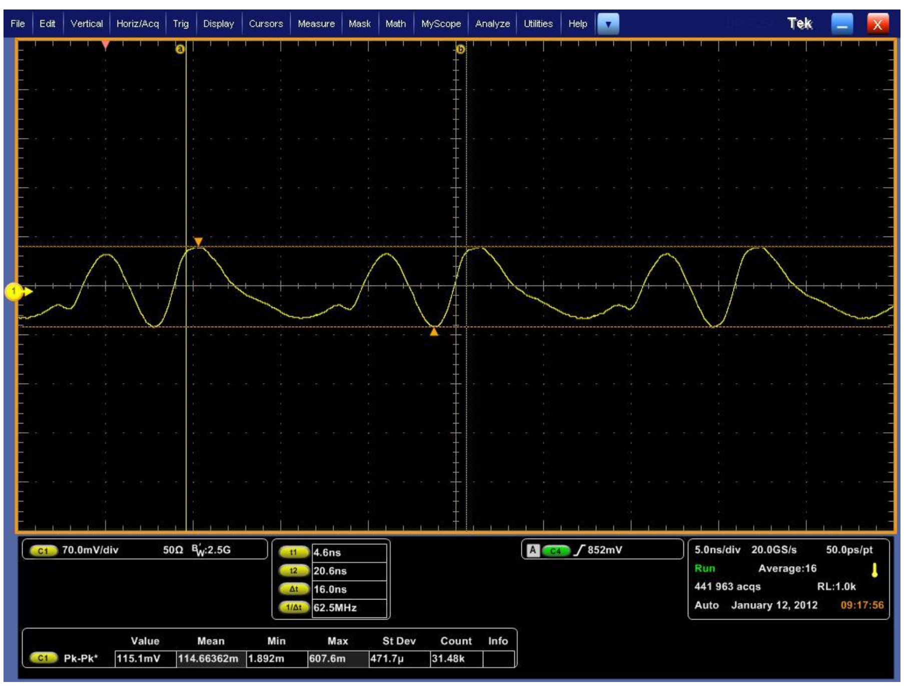


Figure 12. Amplifier output with 10dB on ARB drive average power 11 Watts. Peak to peak voltage is 0.115 volts * 56.5 dB correction=77 volts p-p, gain=52.0 dB

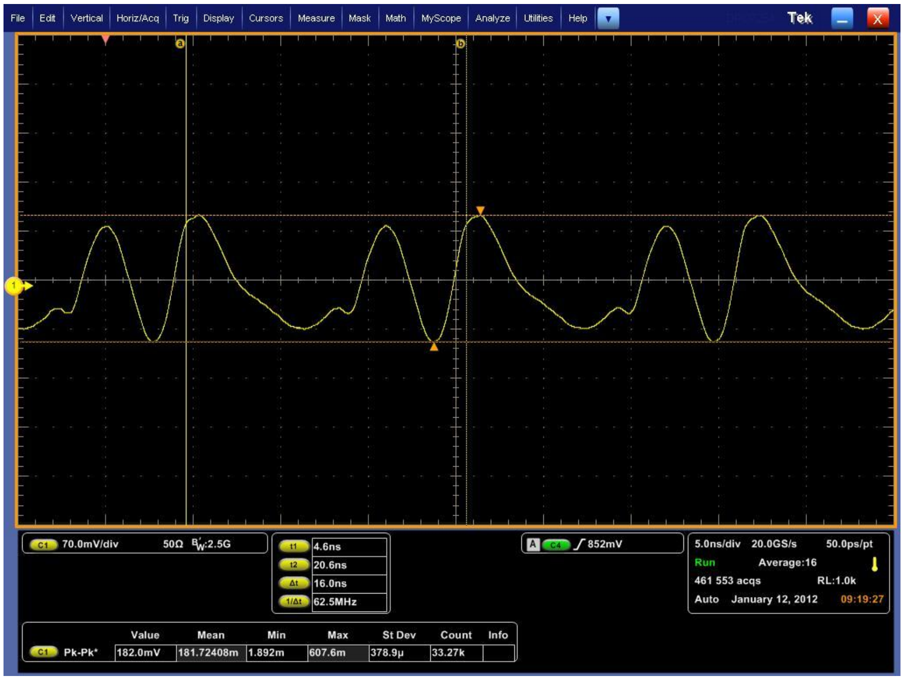


Figure 13. Amplifier output with 6dB on ARB drive average power 28 Watts. Peak to peak voltage is 0.182 volts * 56.5 dB correction=122 volts p-p, gain=51.9 dB

Figure 14. Amplifier output with 3dB on ARB drive average power 52 Watts. Peak to peak voltage is 0.251 volts * 56.5 dB correction=168 volts p-p, gain=51.7 dB.

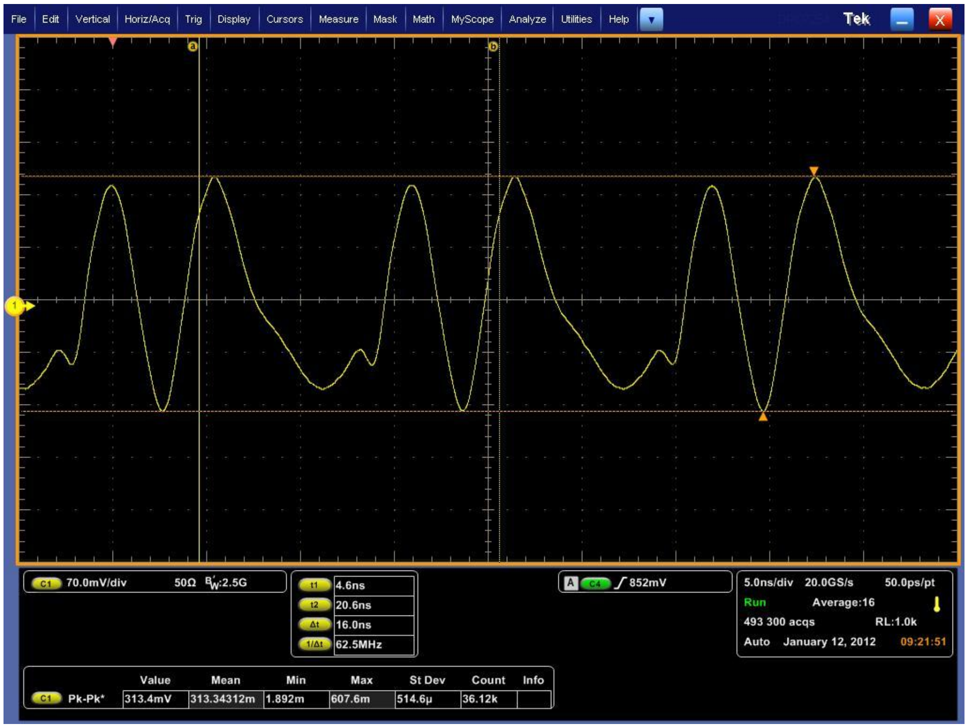


Figure 15. Amplifier output with 0dB on ARB drive average power 83 Watts. Peak to peak voltage is 0.313 volts * 56.5 dB correction=209 volts p-p, gain=50.8 dB. The amplifier is showing 1 dB compression at this drive level.

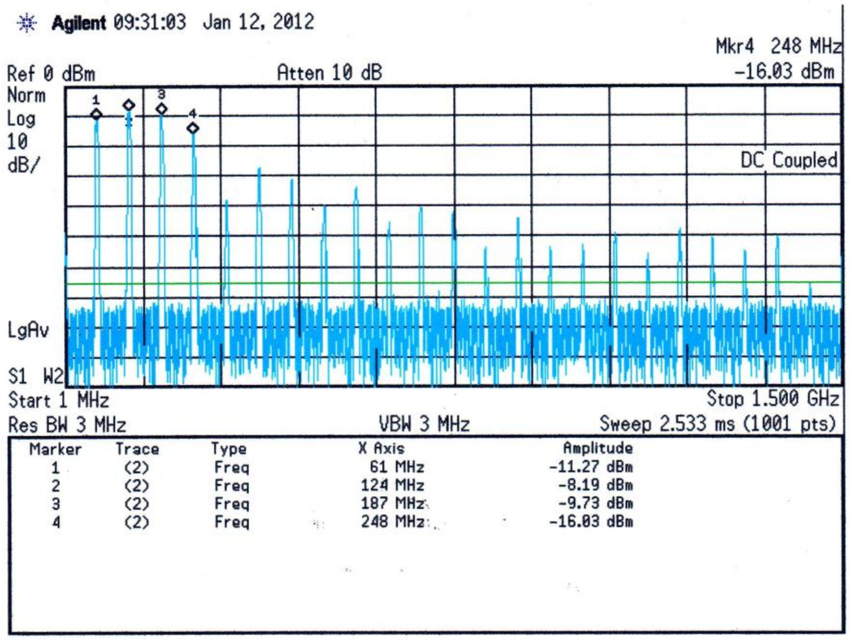


Figure 16. Input spectrum from ARB with 0 dB attenuator.

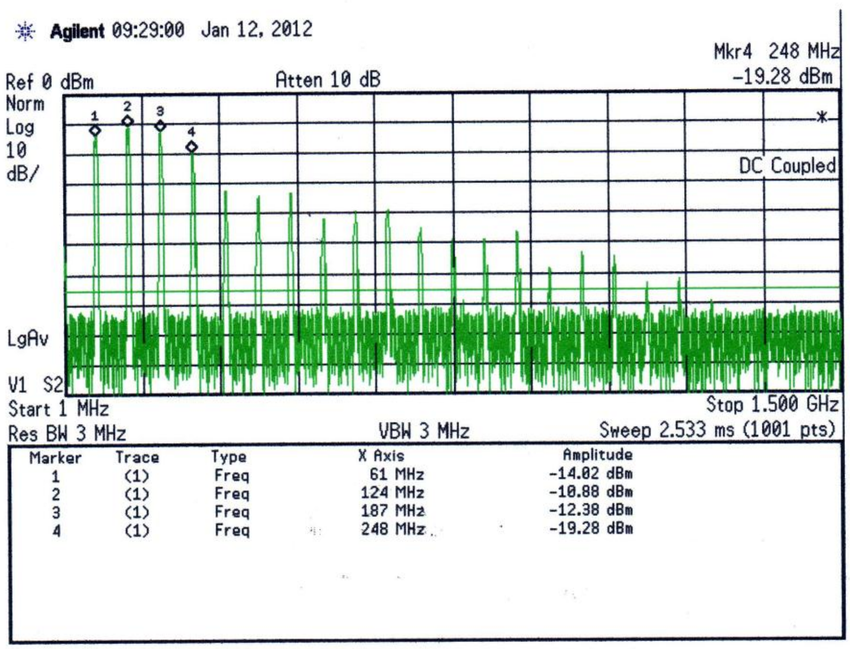


Figure 17. Amplifier output spectrum with 0 dB on ARB drive. Add 56.5 dB to each value for the calibration of the load attenuators.

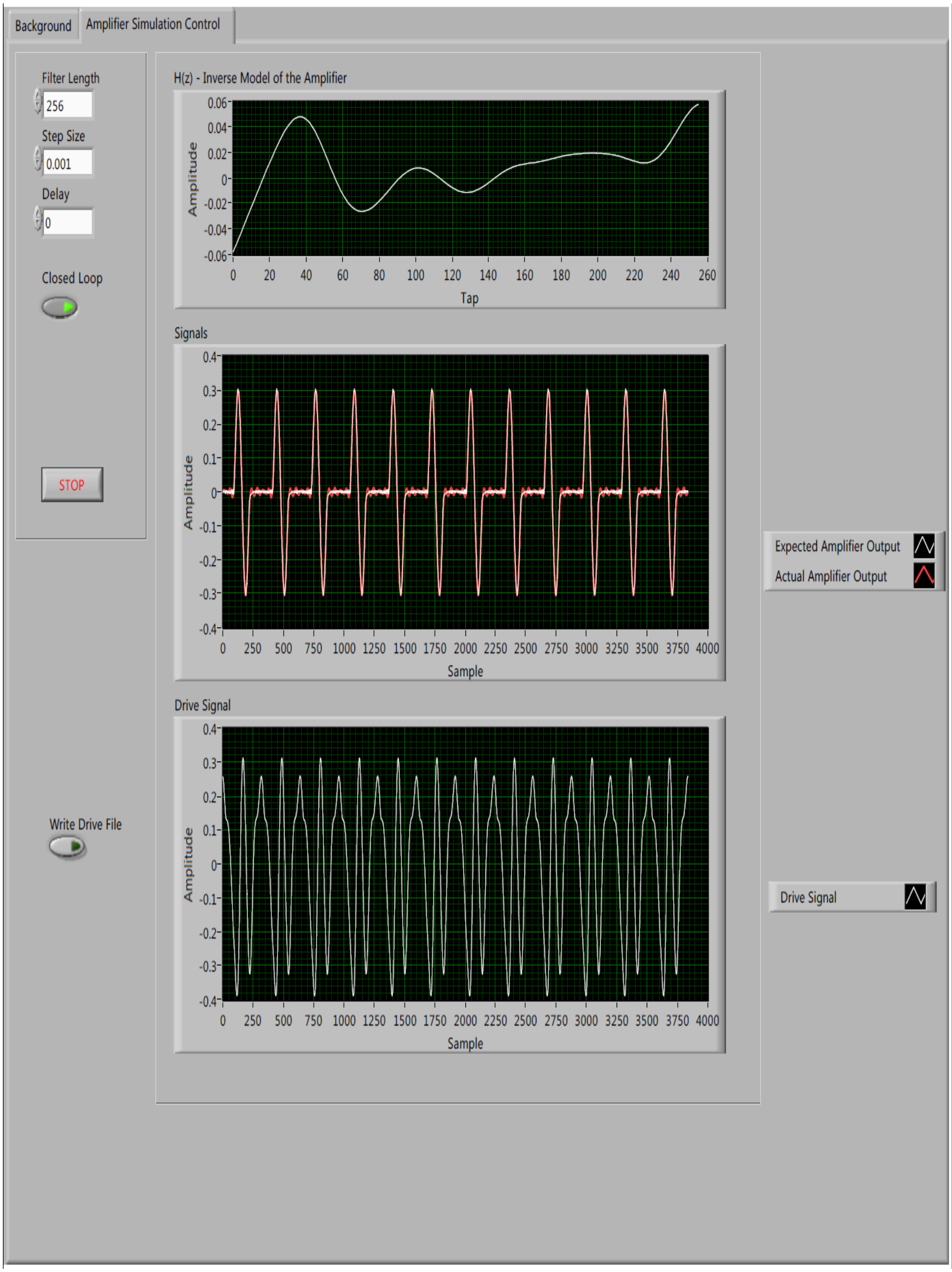
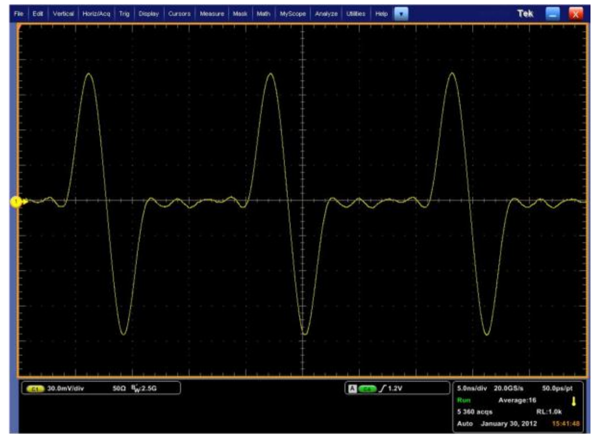


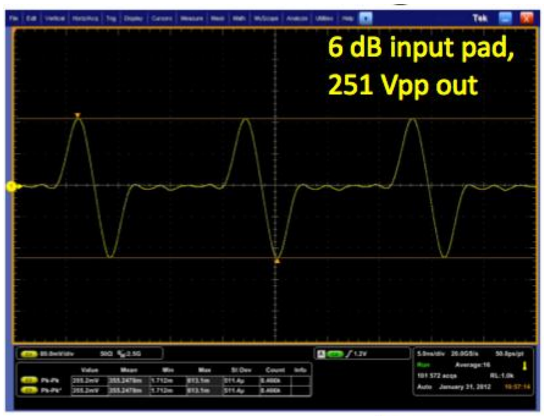
Figure 18. Labview results of an adaptive FIR filter for pre-distortion.

New predistorted input signal



Amplifier Output

Figure 19. Teseq amplifier response for pre-distorted input wit 10 dB pad.



The output of the AWG is 0.611 Vpp.
This is well within the input drive limits of the Teseq amplifier.

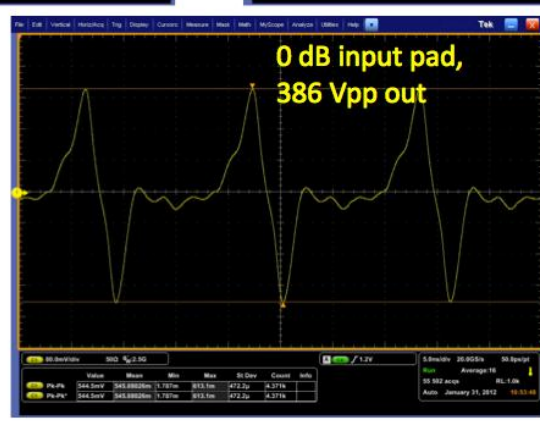
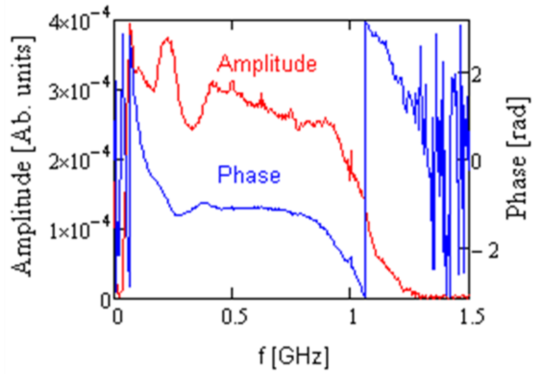
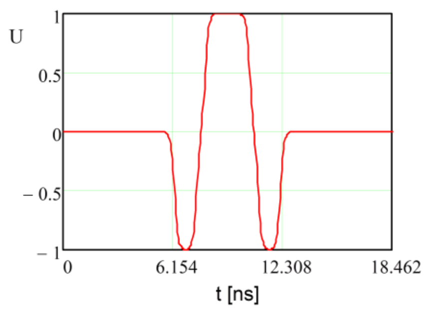
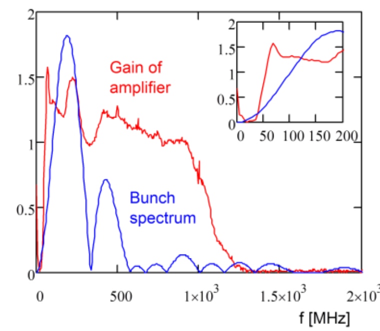


Figure 20. Output waveforms for various input drive levels. The amplifier input attenuator was changed to adjust the drive from the ARB.

- The amplifier bandwidth is 0.05 – 1 GHz (at half maximum)
- To reduce coupling between nearby pulses a single bunch spectrum has to have a small content at low frequency
- High frequency of upper band boundary allows one to have fast transition between positive and negative voltages and makes triple pulse as a good candidate
- Rise and fall time were chosen so that the single bunch spectrum would be inside amplifier band







- Desired dependence of voltage on time at the amplifier input (for one pulse) was obtained from the desired signal shape making following transformations
  - FFT of desired pulse
  - Removing content outside of amplifier band
  - Multiplying obtained spectrum by inverse of amplifier gain
  - Performing inverse FFT
- The dependence of voltage on time for multiple pulses (bunches) was obtained by summing signals of single pulse with 1 bucket delay time for each next pulse
  - The signal polarity was not changed for bunches to be killed
  - The signal polarity was changed for pulses assigned to pass

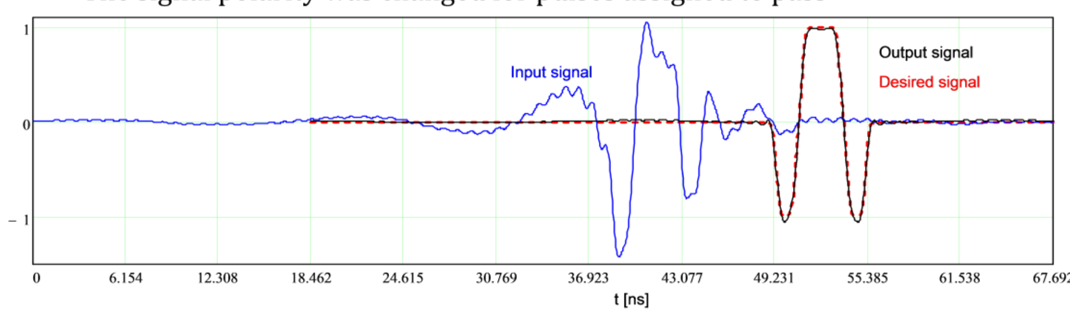


Figure 21. Method of synthesizing wider flattop single pulse.

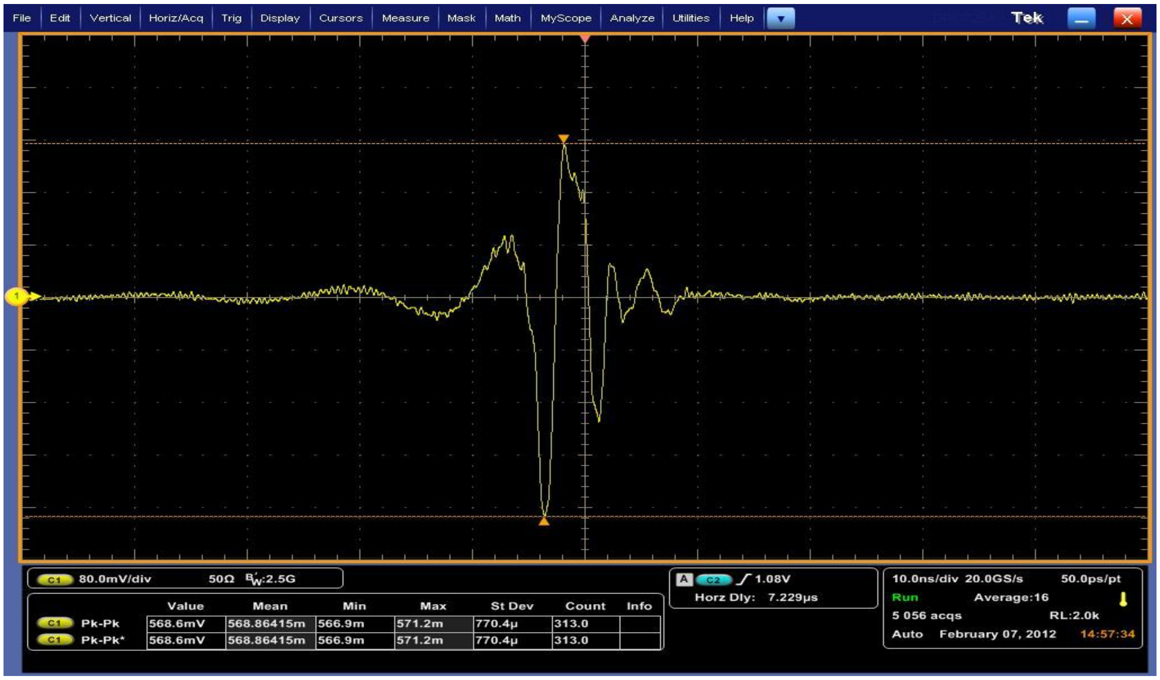


Figure 22. ARB generated pre-distorted input pulse for wider flat top single pulse.

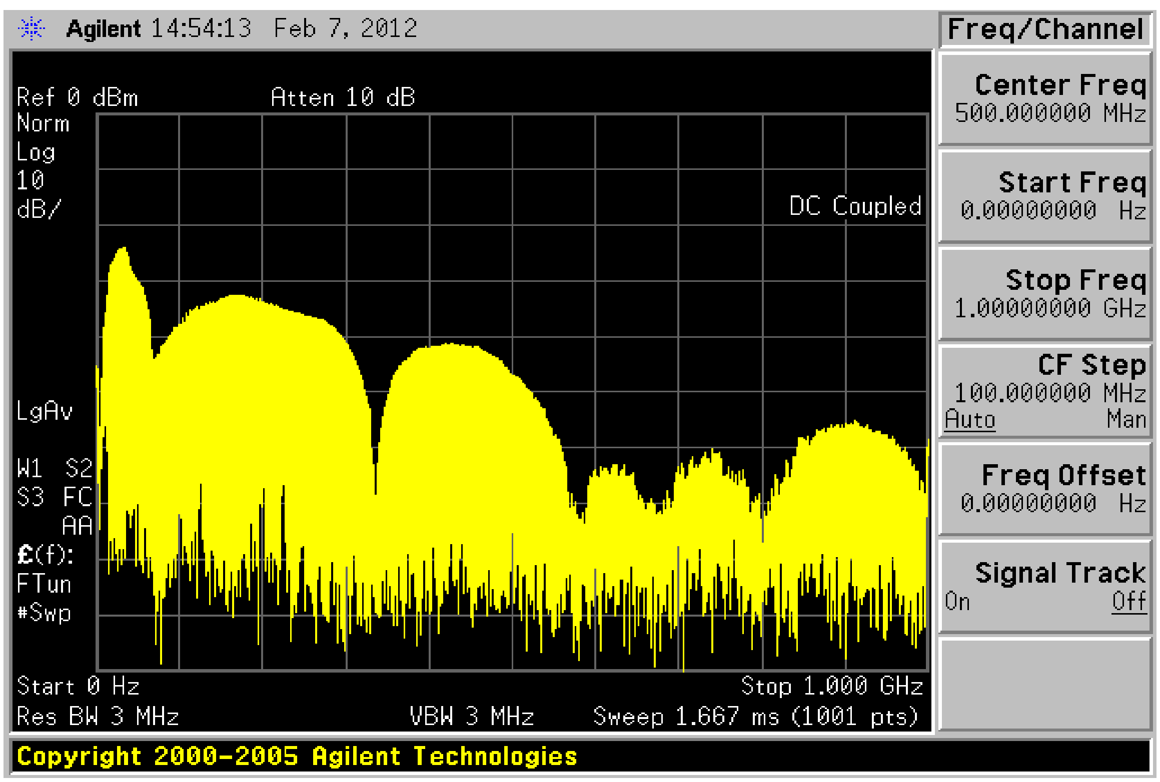


Figure 23. Broad band spectrum for input pulse in figure 22.

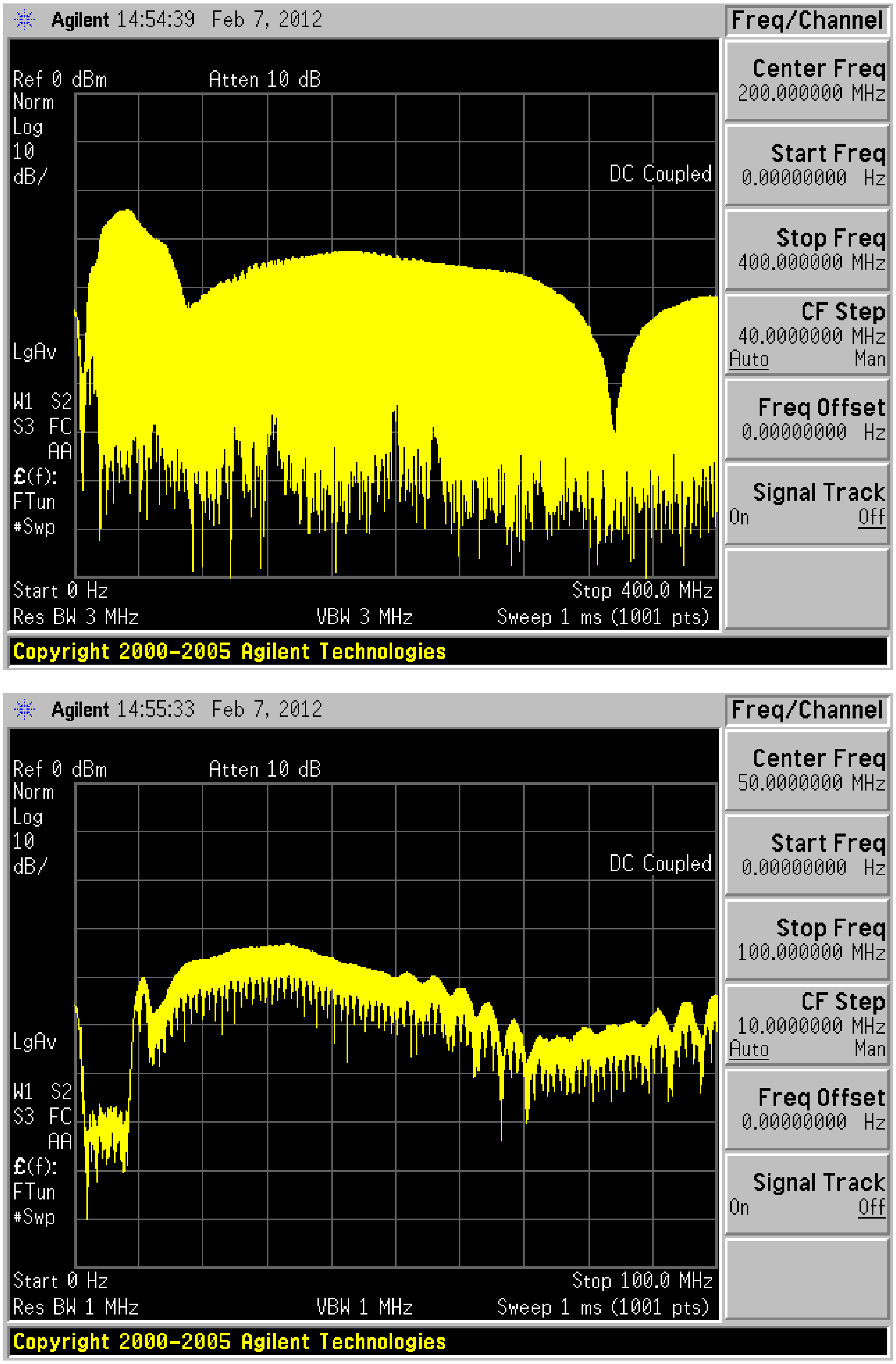


Figure 24. Close up spectra of input pulse in figure 22.

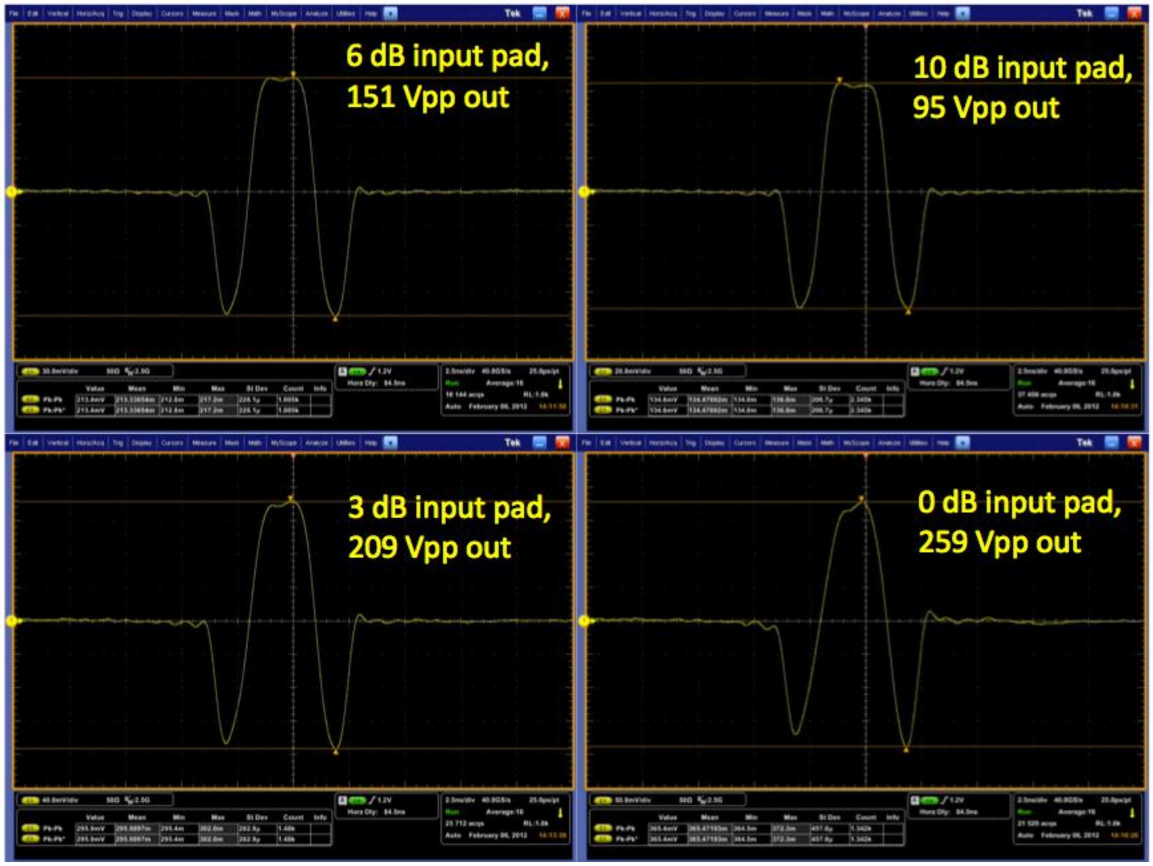


Figure 25. Output for modified single pre-distorted input of figure 22.

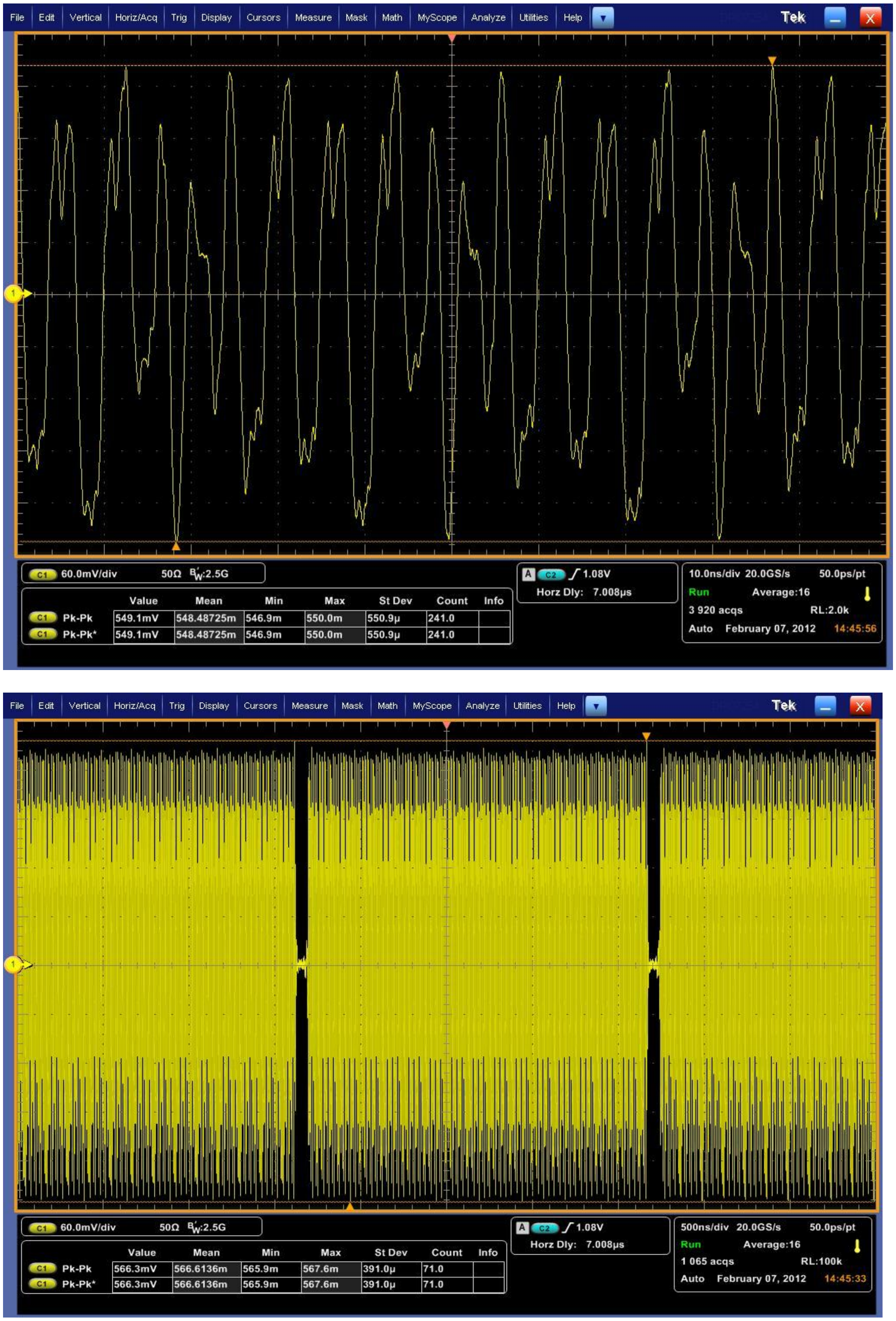


Figure 26. Input signal time domain for multi-pulse amplifier drive signal. Top close up of five-bunch rep rate 10 ns/div., bottom full pulse structure with high duty cycle 500 ns/div.

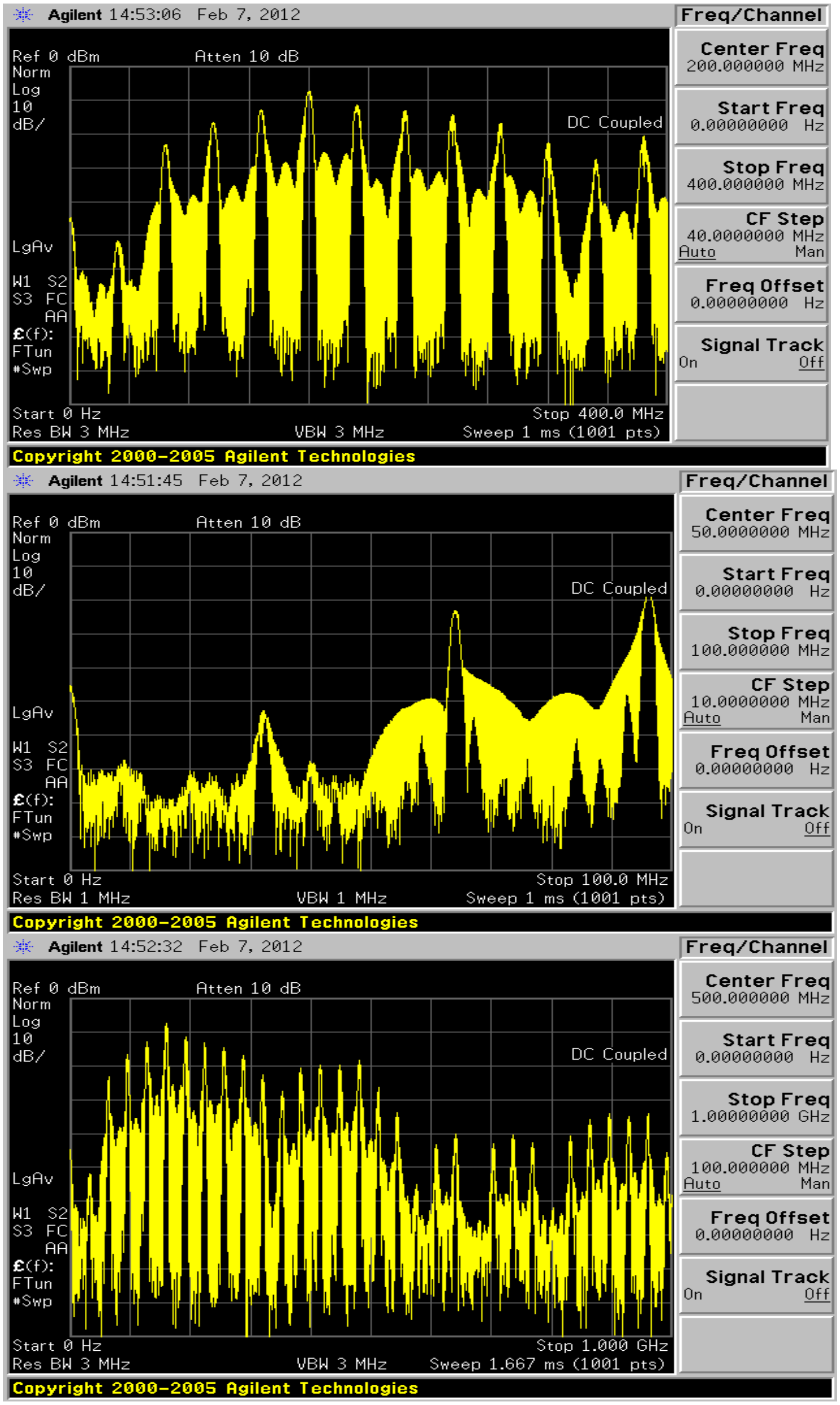


Figure 27. Spectra of input signal multi-bunch from figure 26.

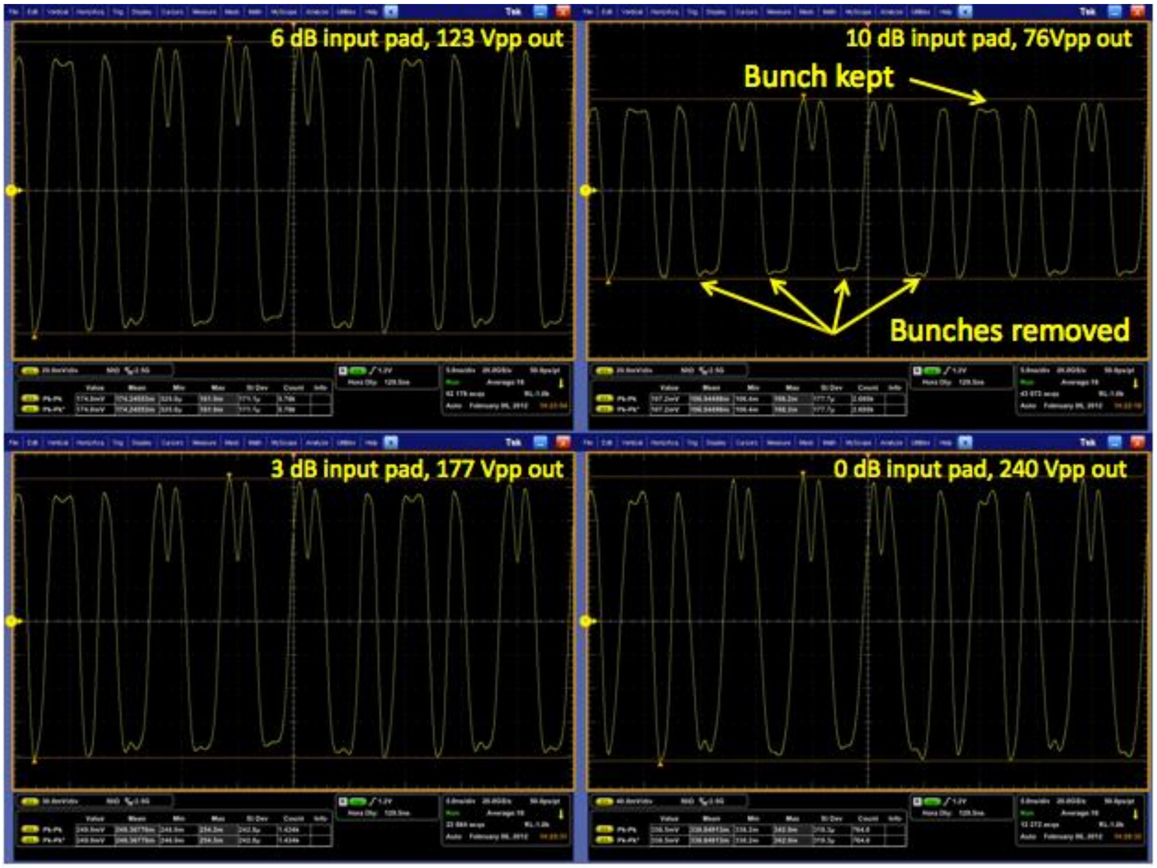


Figure 28. Output for multiple bunch kicking. This pattern shows four consecutive kicks to remove beam bunches followed by a one-bunch kick to retain the fifth bunch at various output powers. It should be possible to synthesize any arbitrary pattern. Additional pre-distortion can be utilized to remove ripple and flatten the amplitude response for all kicks.