SLAC-PUB-11945
July 2006

AMPLITUDE LINEARIZERS FOR PEP-II 1.2 MW KLYSTRONS AND LLRF SYSTEMS*

Daniel Van Winkle#, Mike Browne, John Fox, Themis Mastorides, Claudio Hector Rivetta, Dmitry Teytelman SLAC, Menlo Park, California

Abstract

The PEP-II B-factory has aggressive current increases planned for luminosity through 2008. At 2.2A (HER) on 4A (LER) currents, we estimate that longitudinal growth rates will be comparable to the damping rates currently achieved in the existing low level RF and longitudinal feedback systems. Prior to having a good non-linear time domain model [1] it was postulated that klystron small signal gain non-linearity may be contributing to measured longitudinal growth rates being higher than linearly predicted growth rates. Five prototype klystron amplitude modulation linearizers have been developed to explore improved linearity in the LLRF system. The linearizers operate at 476 MHz with 15 dB dynamic range and 1 MHz linear control bandwidth. Results from lab measurements and high current beam tests are presented. Future development plans, conclusions from beam testing and ideas for future use of this linearization technique are presented.

INTRODUCTION

The PEP-II RF systems incorporate 1.2 MW CW klystrons inside direct and comb impedance control loops [2]. Figure 1 shows the power input/output characteristic for a typical klystron. Due to the saturating gain slope as the klystron is operated at higher drive levels the small-signal gain (dPout/dPin) can be reduced by factors or 5 to 20 from the large-signal value. With such compression modulations in the direct/comb feedback paths have different gain than the high power carrier signal. This reduction in loop gain had been implicated in reduced impedance control for the direct and comb loops, and in operation the PEP-II HER and LER rings have exhibited much faster low-mode coupled bunch instability growth rates than predicted from a purely linear klystron and impedance control loop model.

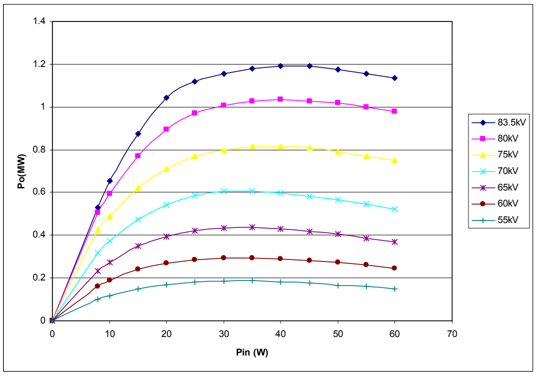

Figure 1 SLAC Klystron Power Curves

To address this difficulty, and concerns that growth rates at higher current might exceed the capabilities of the Low Group Delay Woofer and broadband longitudinal feedback channels [3] our group has investigated several techniques to improve the effectiveness of the impedance control loops. These efforts include modeling of the nonlinear RF systems interacting with the beam and hardware efforts including the klystron linearizer.

The linearizer implements an amplitude control loop around the klystron, and uses a feedback technique to enforce a fixed input/output gain so that small-signal and large signal gains are equal (Figure 2).

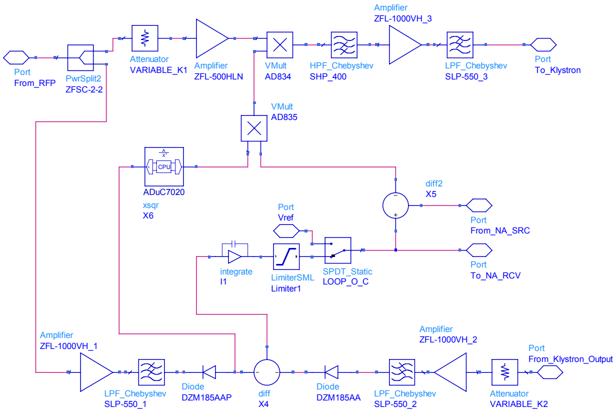

Figure 2 Linearizer Block Diagram

Such amplifier linearization techniques are of increasing interest in the communications area as well. Our earlier paper details the technology of the linearizer, implementation details and initial high-power tests with a PEP-II klystron [4].

LAB TESTS

Before installing the linearizers into the PEP-II LLRF systems for testing with beam, extensive testing was completed both in the lab with a klystron model and on the high power test stand with a full power 1.2 MW klystron. Three main test stand measurement techniques were used: input power sweeps, closed and open loop bandwidth sweeps and AM sideband tests.

Test Stand Measurement Techniques

Input power sweeps of the linearizer/klystron system were taken at 11 data points for output powers from 80 to 90 dBm (1MW). The data shows excellent gain linearity across the 10 dB range available in the test stand.

Measurements are made using an in circuit closed loop measurement function which injects a test signal into the loop and measures the loop response [5]. Because the linearizer loop gain scales as Vin^2, the linearizer implements a digital $1/vin^2$ gain compensation to keep the

---

*Work supported by the U.S. Department of Energy under contract #DE-AC02-76SF00515

#dandvan@slac.stanford.edu

Presented at European Particle Accelerator Conference (EPAC 06) ,
26-30 June 2006, Edinburgh, Scotland

loop frequency response well controlled over the 1 MHz bandwidth [4]. The loop bandwidth response had excellent control over the full power range for the idealized klystron model in our lab. However, when tested with a real klystron on the high power test stand, significant deviation occurred from the expected bandwidth control (Figure 3).

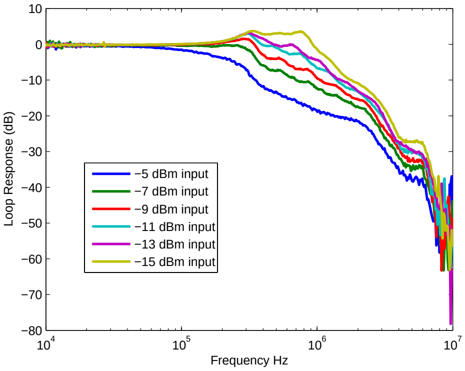

Figure 3 Closed loop frequency vs. drive level

The main reason this distortion occurs is that the klystron curves are not simply scaled versions of each other. Figure 4 shows the scaled version of the power curves (vs. HV power supply) normalized to 26W drive. It is clearly seen that the gain compression at a high voltage power supply settings of 75 and 80 kV is much higher than at 50 kV.

This gain variation makes the bandwidth compensation a much more complicated problem than the originally implemented $1/vin^2$ compensation. It is also seen that the inflection point (the top of the saturation curve) varies with the DC power supply setting (moving lower in input power with increasing DC HV operating point). Some klystrons show the opposite effect (i.e. the inflection point moves higher with higher DC power supply setting) compounding the overall complexity of compensating this effect. This additional compensation must be klystron specific and operating point specific.

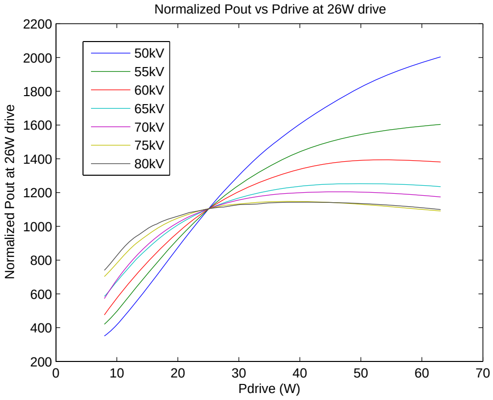

Figure 4 Normalized Power Plots

When an AM signal is passed through a compressed amplifier, the AM depth is reduced by the level of compression. This effect can be measured by measuring the AM sidebands on the output and input of the system. Figure 5 shows the result of one such test with 2% AM modulation at 100 KHz. It is seen that the input to the linearizer and the linearized output of the klystron are in close agreement. Also from this plot it can be seen that the klystron is compressing the AM sidebands by about 5 db. The pre-distortion created by the linearizer is clearly seen in the linearizer output (2^{nd} Harmonic).

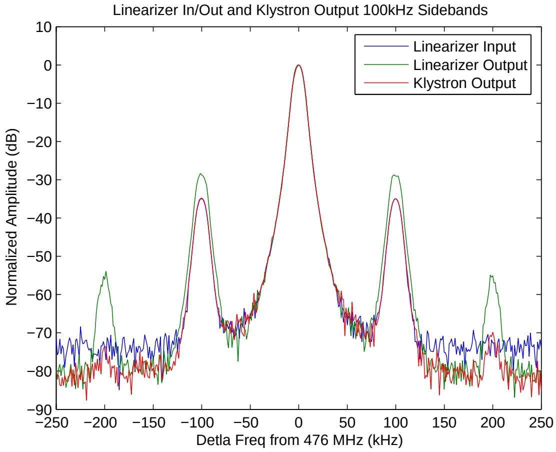

Figure 5 AM sideband test results

PEP-II machine test results

The real test of the linearizer was to measure the effect of the linearizer on the longitudinal growth rates.

One of the key obstacles encountered was excess noise in the LLRF processing channel. Successfully running the prototype linearizers required repartitioning the gains in the RFP and GAP modules to minimize the noise floor in the klystron signal, as the noise from the processing functions was sufficient to overdrive the klystron at the nominal operating points. Because of the klystron inflection point (small signal gain sign reversal), the operating point was very susceptible to being sent “over the top” of the klystron power curve.

Another challenge was the variation among stations in group delay due to cabling and physical layout issues. This limited our ability to set up the linearizer on one station and eventually led to the station being parked (klystron off with cavities parked +/- 2.5 revolution harmonics) for these linearizer tests. Impedances caused by symmetries in the parking positions of the idle cavities can increase growth rates. Careful parking of these cavities was required to insure they did not affect the measured growth rates.

To accurately compare growth rates for linearized and saturating stations, each must be configured at nearly identical operating points (e.g. identical direct and comb loop gains). If two different operating points are studied, the variation in impedance control from the differing operating points masks the effect of the linearizer.

To measure the growth rates, we use a technique which involves opening the longitudinal feedback loops for a brief period [6]. When the feedback control loops are opened, unstable motion may grow while time domain bunch oscillation data is recorded. The analysis technique transforms the data to a modal domain, and fits complex exponentials to the fasting growing modes. This data is taken multiple times at each of several different currents to give insight into the change of growth rates vs. beam current. We performed these growth rate measurements both with and without the linearizer and the results are presented in figure 6.

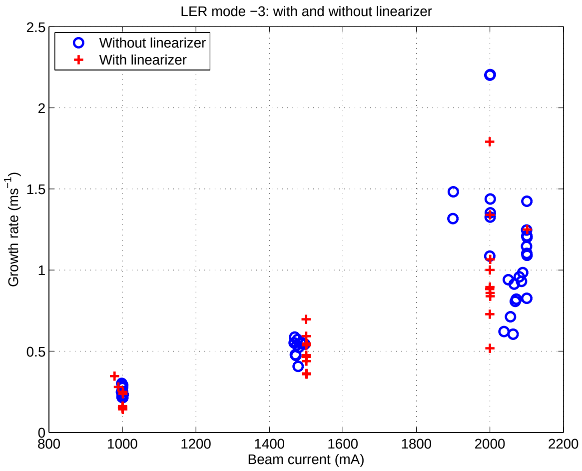

Figure 6 Growth rate measurements

From this data, no clearly definable reduction in growth rates is seen. After further analysis and a convergence with the modeling effort we have concluded that our earlier estimates of the impact of klystron non-linearity were in error and that when comparing identical comb and direct loop small signal gain operating points, the impact of the klystron nonlinearity is small compared with other factors.

We still measure growth rates that are faster than expected from a purely linear system model, and we now understand, via more developed time domain system modeling, that a combination of several factors play together to reduce the effectiveness of the impedance control loops.

We now better understood the impact of imperfections in the klystron frequency response. These simulation efforts are now converging to close agreement with our beam measurements and offer insight into alternative control strategies. [1]

CONCLUSIONS

The linearizers worked as designed and helped provide insight into the non-linear behavior of the PEP-II RF systems. While we have demonstrated operation of this linearizer inside the multiple LLRF feedback loops in PEP-II, the complexities of integrating this function, and the limited benefit in growth rate reduction, have led us to hold off on full integration and installation of this technique for routine use in PEP-II. Instead, we have used the understanding of the non- linear dynamics to focus on the “comb rotation” technique as a means of reducing the low mode growth rates [1].

Our beam studies of the linearizer have required us to better understand the impact of klystron frequency response, and have led to a control technique trading off stability of the LLRF system in exchange for better impedance control and lower low mode growth rates. One possible use of the linearizer technique is to allow for better LLRF loop stability when using this comb rotation technique. Because the linearizer and an improved phase control loop can contribute to reduced amplitude and phase response variations in the klystron, the comb rotation technique might achieve best results in conjunction with the linearizer. Studying the comb rotation technique using the non-linear modeling, as well as additional beam testing focused on the combination of the linearizers and the comb rotation technique, should help us to better understand the options to moderate and control the low mode growth rates.

Another possible application of the linearizer technique is to improve low-frequency amplitude modulations of the RF output due to power supply ripple. Such RF output ripple may be of concern to light sources, and such studies are planned for SPEAR 3 (the SPEAR 3 RF system shares most components with PEP-II and the linearizer can be easily configured in this system). In these studies both the klystron linearizer and new DSP phase ripple code will be evaluated and the impact on the driven low frequency longitudinal beam motion will be studied.

This linearizer technique, and these prototype linearizers, may yet have a role in reducing power supply ripple or in improving the responses of direct and comb loop feedback around a klystron.

REFERENCES

[1] C. Rivetta, T. Mastorides, J.D. Fox, D. Teytelman, D. Van Winkle, “Modeling and Simulation of Longitudinal Dynamics for LER-HER PEP II Rings”, EPAC 2006.

[2] F. Pedersen, “RF Cavity Feedback”, B Factories, The State of the Art in Accelerators, Detectors and Physics, SLAC-400, pp. 192 – 207

[3] D. Teytelman, D. Van Winkle, J. Fox, “Operating Performance of the Low Group Delay Woofer Channel in PEP-II”, PAC-2005-MPPP007, May 2005. 3pp.

[4] J. Fox, T. Mastorides, D. Teytelman, D. Van Winkle, Y. Zhou, “Klystron Linearizer for Use with 1.2 MW 476 MHz Klystrons in PEP-II RF Systems”, PAC-2005-WPAT041, Jun 15, 2005. 4pp.

[5] K. Johnson, “Measure PLL Open-Loop Response with the Loop Closed”, Electronic Design November 22, 1990 p. 79-85.

[6] S. Prabhakar, R. Claus, J. Fox, H. Hindi, I. Linscott, J. Olsen, W. Ross, D. Teytelman, “Observation and modal analysis of coupled bunch longitudinal instabilities via a digital feedback control system”, Published in Part.Accel.57:175-187,1997