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Citation for the original published paper (version of record):

Hoang Duc, L., Bhattacharyya, A., Goryashko, V., Ruber, R., Olsson, J. et al. (2018)
Time Domain Characterization of High Power Solid State Amplifiers for the Next
Generation Linear Accelerators.

Microwave and optical technology letters (Print), 60(1): 163-171

<https://doi.org/10.1002/mop.30926>

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Journal:	<i>Microwave and Optical Technology Letters</i>
Manuscript ID	Draft
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	n/a
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Keywords:	particle accelerator, solid state amplifiers, LDMOS, nonlinear circuit envelope, time domain envelope measurements,pulse profile

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Time Domain Characterization of High Power Solid State Amplifiers for the Next Generation Linear Accelerators

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Abstract

This paper presents the time domain characterization of high power pulsed solid state amplifiers to be used for linear accelerator applications. The study comprises nonlinear circuit envelope simulations and time domain envelope measurements. Measurements and simulations are performed under the pulsed conditions (3.5 ms pulse width, 5% duty cycle) specific to the European Spallation Source (ESS) high intensity proton accelerator. We measure the characteristics of pulsed LDMOS based power amplifiers such as: pulse droop along the pulse, efficiency, average envelope pulse amplitude and phase, pulse drain current waveform, pulse drain voltage waveform, etc. A comparison between the measured results and the simulated results is also presented. In addition to the pulse profile characterization, the pulse to pulse (P2P) stability of the presented solid state power amplifier (SSPA) is investigated as variations of amplitude and phase. The P2P stability simulations are introduced as a combination of the Monte-Carlo simulations and the nonlinear circuit envelope simulations. The simulated results are used for fitting the P2P measurements to give an early insight of causes of instabilities of the nonlinear LDMOS models.

1. Introduction

Superconductivity has become a key technology for particle accelerators [1]. Superconducting radio frequency (SRF) cavities have been adopted as the heart of next generation linear accelerators such as: the European Spallation Source (ESS) [2], the International linear collider [3], and the Oak Ridge Spallation

Neutron Source [4]. The use of the SRF cavities results in a dramatic increase of accelerator efficiency and a great reduction of accelerator size and construction cost. Due to extremely low wall losses the required power usage drops by a factor of several hundred to a thousand in SRF cavities. In CW operation, this means a great reduced power and high accelerating gradients. In pulsed operation, SRF cavities offer long pulse and high duty cycle in comparison to normal conducting cavities [5]. RF power amplifiers deliver the required power to the cavities through high power couplers. Typically, the RF power sources employ either vacuum tube (Klystron, Inductive Output Tube) or solid state technology. In this paper, we focus on the characterization of solid state power amplifiers to be used for SRF cavities.

The solid state power amplifiers (SSPAs) are ever growing in kW regime for both wireless and accelerator applications [6]-[7]. Their benefits are modularity, scalability, reliability, life-time, reduced maintenance, and cost. The synchrotron SOLEIL was the first to make use of SSPAs for its booster and storage ring by combining a few hundred of 330W elementary modules [8]. Following this development, a number of developments have been carried out for several accelerators [9]-[13]. However, it remains unclear whether such technology could be feasible and reliable to be used for long pulse and high duty cycle SRF cavities as required in high power proton linac [14].

The pulsed SRF cavities need to be charged to nominal voltage prior to beam arrival using a RF power station, as shown in Fig. 1. The RF power required to charge the SRF cavities is in the order of 400 kW. At the FREIA laboratory, the focus is on developing alternative RF power sources such as SSPAs and evaluating their use in combination with the performance of SRF spoke cavities for high power particle accelerators [15] –[17]. Recall that the ESS will accelerate well-defined proton beam up to 2 GeV. The proton beam is a pulsed beam consisting of bunches of protons, and spreads over 2.86 ms at bunch frequency of 352 MHz. The SRF cavities are required to establish a stable accelerating voltage in order to supply the same energy to all particles, as can be seen in Fig. 1.

An issue with solid state devices is that they exhibit a pulse droop in which the amplitude of a pulse trails off over time [18]. Such pulse droop can lead to a non-constant cavity field along the flat top of the pulse, and thus causes instabilities. As a consequence, it is vital to extensively characterize the flat-top profile of RF fields during the time of beam injection. Another cause of instabilities is the variations of RF fields from pulse to pulse (P2P). The P2P errors should be addressed to the same extent as the pulse profile characterization. The major

sources of RF field disturbance are cavity detuning caused by microphonics, Lorenz force, and beam loading effects.

A low level RF (LLRF) control system is used to compensate the RF instabilities [19]-[20]. The LLRF system configures the digital Proportional-Integral (PI) controller together with adaptive feed-forward compensation, to automatically stabilize the cavity voltage and phase within each RF pulse. As required in [14], the RF voltage amplitude and phase errors do not exceed 0.5% and 0.5° respectively while using the LLRF control system. Because of such stringent demands, it is required to assess the amplitude and phase stabilities of the RF power system. The pulse-to-pulse (P2P) stabilities are calculated to quantify the errors in the time domain, which can be compensated by the LLRF. To the authors' knowledge, no study has been carried out to characterize solid state amplifiers delivering high output power for particle accelerators in the time domain.

In this paper, we present a measurement system enabling the characterization of high power solid state amplifiers in time domain, as required for accelerator applications. We also propose a non-linear modeling approach capable of simulating the achieved measurements. Specifically, we study such characteristics of the SSPAs as: pulse profile, drain voltage waveform, pulsed drain current waveform, efficiency, P2P amplitude stability, and P2P phase stability, delivering kilowatt-level output power.

2. Amplifier Design

The SSPA module uses the BLF188XR LDMOS transistor, which features high-efficiency, thermal stability, excellent ruggedness, high output power up to 1500 W and is capable of handling a high load mismatch [21]. In the amplifier design, we implement matching networks based on the single-ended architecture in order to avoid using baluns, as compared to a push-pull configuration at kilowatt-level output power. In addition, the matching networks are realized by using a two-step microstrip line transformer to match the transistor's impedances, $Z_{IN} = 0.36 - j0.72\Omega$ and $Z_{OUT} = 0.35 + j0.37\Omega$. The input network includes: three micro-strip transmission lines TL₁, TL₂, TL₃; DC coupling capacitors C₁, C₂, C₃; matching capacitors C₄, C₅; SMD resistor R₁ to inject bias voltage for the transistor V_{bias} as shown in Fig. 2. In this network, TL₁ and TL₂ have the same impedance and the matching capacitors provide good performance regarding the input return loss (RL), as shown in [22]. The output network used in this amplifier is also shown in Fig. 2. A two-step transformer including: TL₄, TL₅, TL₆, TL₇, performs the load impedance transformation in order to deliver as high output power as possible. The

matching capacitors C_{10} , C_{11} , C_{12} , are chosen for optimum drain efficiency at the expense of output power and vice versa. An RF choke is used for DC drain voltage injection. The details of the design and implementation can be found in [22]-[23]. The amplifier can operate in both continuous wave (CW) and pulsed modes at 352 MHz. The SSPA module is operated in class B at a bias of 80-mA quiescent drain current and 50V drain voltage, along with a continuous pulsed RF signal of 3.5 ms pulse width and 5% duty cycle at 352 MHz. In the following section, we introduce a measurement setup used for time domain characterization of the SSPA modules.

3. Measurement Setup

The block diagram of the measurement setup is presented in Fig. 3. The pulse waveform is generated by the function generator (HP3320A), modulated by a signal generator (ESG-E4400B). The pulsed RF signal is linearly amplified by a 50-dB driver amplifier before feeding the power amplifier (PA) module. Two bi-directional couplers are connected to the input and output of the module in order to determine the voltage waveforms at the module's terminals. Two power meters (N1912A) are used to measure the average envelope power of the PA at the input (π_{in}) and output (π_{out}) reference planes as can be seen in Fig. 3. The oscilloscope (RTO1024) is used to capture the envelope of the pulsed RF signals and analog signals sensed from a monitoring circuit, as described in [24]. The oscilloscope enables to perform a hardware based down conversion [25], which uses the same local oscillator (LO) frequency at both transmitter and receiver in order to measure the baseband signal. We can take advantage of a reduced Nyquist sampling rate, and eliminating degradations of the stability due to the phase noise of the LO source. The monitoring signals, including the pulsed current waveform and the drain voltage waveform, are available as baseband signals. To capture all necessary envelope pulsed signals and monitoring signals simultaneously, a trigger strategy is implemented. A digital control signal starts the data acquisition. The data acquisition is then implemented continuously for studying the stability of the PA module, i.e. variations of the amplitude and phase from pulse to pulse are monitored in time domain. For our time domain measurements, N pulses are captured at the same sample rate 500 kSamples/s with a recording time of 10 ms for each data acquisition. A script remotely configures and implements the retrieval of the sampled IQ data from the oscilloscope along with P2P stability calculations. The time domain measurement setup also allows the characterization of any kinds of high power amplifiers combined with the varied duty cycle, pulse width, or even complex pulsed radar signals.

4. Time domain simulated and measured results over a single pulse

In this section, we present the nonlinear circuit envelope (CE) simulation of the pulsed power amplifier module at circuit level. The CE method has been developed over the past decade [26]. The CE simulation is a combination of the transient simulation and the harmonic balance (HB) simulation in frequency domain. Instead of sampling the RF carrier frequency as in the classical time-domain simulation, it samples the time-varying modulation envelope. We then capture the spectral content of each time point based on the time step of the simulation. Afterwards, the HB analysis is performed at each time sample in order to recreate the time-varying spectrum. Therefore, the CE simulation is highly efficient to analyze a variety of data over time such as: amplitude, phase, frequency, and harmonics [27]. The simulated results will be compared to the measured results in the following sub-section.

a. Average envelope measurements

Average envelope power measurements at the input and output of the PA module in Fig. 3 are performed using two power meters. The uncertainty of the measurements is $\pm 0.65\%$, which is determined by the uncertainty of the power sensors [28]. The PA module is driven into compression region in order to optimize the efficiency as delivering kilowatt-level power at 352 MHz. At 1.5-dB compression point, the PA delivers 1.25-kW output power with 70% drain efficiency, see Fig. 5. Fig. 6 shows the change of the insertion phase is as a function of output power. The output phase varies from -129.12° at 200W output power to -155.94° at 1300W output power as the SSPA is operated at 1.5-dB compression point.

b. Time domain measurement results over a single pulse

For the pulsed high power operation, the DC current drawn by the transistor is in the form of current pulses, which have rise time, fall time, and duty cycle of the pulsed RF envelope. An energy storage capacitor is required in order to supply the energy for a single pulse and the power supply then provides a recharge current to the capacitor during the silence between pulses. A 68-mF capacitor is selected to keep the voltage droop to less than 1V from the drain operating voltage 50V. The drain voltage is measured 49.25V instead of 50V due to loss of cables from the mains and the equivalent series resistance (ESR) $7\text{m}\Omega$ of the capacitor bank. During the RF pulse, the capacitor voltage droop is measured around 1 V or 2% of the drain voltage after 3.5 ms whereas the PA delivers 1.25 kW output power, see Fig. 7. The capacitor is then recharged fully after approximately 5 ms for the next pulse with a 14-Hz repetition rate. The simulated and measured drain current waveforms are

performed at 1.25 kW output power as shown in Fig. 8. The measured current waveform increases by 0.3A as compared to the simulated one due to the uncertainty of the current sensor, which is 1%. The droop over the pulse is measured 0.5A and 0.7A, respectively for the measured and simulated current waveforms. No overshoot is observed in the simulated pulse current because of using an ideal current probe. Meanwhile, a transient overshoot was measured at the beginning of the pulsed current waveform in response to a fast-rising pulse of the drain current. The amplitude of the overshoot is 5% higher than the average value of 35.4A. As the measured results in terms of the drain voltage and the current waveform, the DC power consumption can be computed in order to evaluate the DC-to-RF efficiency performance of the PA module. The output power of the RF pulsed signal is averaged over 1000 pulses, and is presented in Fig. 9. A slight difference between simulation and measurement is observed over the flat-top of the pulse. As the output power is proportional to the square of the capacitor drain voltage, a droop is measured 0.2 dB corresponding to 4% in amplitude. The measured droop agrees well with the simulations. The drain efficiency is about 70% along the 3.5 ms pulse width. The insertion phase of the PA module is determined by comparing the phase between the input and output measured planes. As parasitic junction capacitor of the transistor varies as a function of the output power, 4% droop in the output power causes a droop of the insertion phase. A small phase offset between the simulation and measurement occurs which may be due to inaccurate model of N-type connectors, see Fig. 10. The average insertion phase over 1000 pulses is measured -149.7° and drops by 1.2° in comparison with 1° of droop in simulated results.

5. Time domain pulse to pulse (P2P) stability measurement results

a. Pulse to pulse (P2P) stability definition

The envelope diagram of the RF pulsed signal is shown in Fig. 11. From the N captured pulses, there are N sampled points at a sampling time t_k along the pulse, see Fig. 11. The standard deviation is then calculated among the N samples to obtain the P2P stability at the single sampling time t_k . As a result, the P2P stability is composed of individual standard deviations estimated at each sampling time t_k along the pulse. The standard deviation P2P stability at the sampling time t_k is given as:

$$\overline{Stability}(t_k) = 10 \times \log \left[\frac{1}{N} \sum_{i=1}^N \left(V_{out_i}(t_k) - \bar{V}_{out}(t_k) \right)^2 \right] \quad (1)$$

$$\bar{V}_{out}(t_k) = \frac{1}{N} \sum_{i=1}^N V_{out_i}(t_k) \quad (2)$$

where the index i refers to the i_{th} pulse in the sequence. The value V_{out_i} can be either amplitude or phase in case of amplitude stability or phase stability measurements.

b. P2P measurement results in time domain

Beam loss is important for high power accelerators with pulsed high power RF system, and is caused by RF jitter in amplitude and phase. Therefore, it is required to characterize the variations of the RF amplifiers within the pulse. Recall that 400-kW RF power station results from the combination of individual 1.25 kilowatt-level SSPA modules. To evaluate the RF errors, P2P stability measurements are performed over SSPA module at 1.25 kW. In this section, we present the measured and simulated results regarding the P2P stability for pulsed RF signals. Simulations of the amplifier's behavior are realized by combining the non-linear circuit envelope simulations and Monte Carlo analysis. The Monte Carlo simulations are used to estimate quantitatively the behavior of the SSPA in presence of a variable input with a known Gaussian distribution. Each trial in the Monte Carlo simulations, which is equivalent to each captured pulse, is simulated in time domain using the non-linear CE simulation, as described in Section 4. The simulated results are recorded and then the time-domain P2P stabilities are extracted using (1). Such combination can be used to assess the nonlinear models to match the P2P stabilities in time domain. Fig. 12 compares the measured and simulated time domain amplitude stabilities in the case of 1000 captured pulses. There is a slight difference at the beginning of the pulse due to the uncertainties of the measurements. However, the simulated level of amplitude P2P stability is in good agreement with the measurements. The variation in amplitude is measured around -80 dB. The standard deviation in phase is measured about -24 dB, which is equivalent to 0.05° along the pulse, see Fig. 13. A slight discrepancy is measured 0.6 dB between the simulated and measured variation of the phase P2P stabilities over the first half of the entire pulse width and 0.3 dB is measured afterwards. Regarding the P2P phase stability measurements, the uncertainty is related to the time base error of the oscilloscope, which is equivalent to ± 5 ppm according to [25].

Using an accurate nonlinear model, the P2P stability measurements can be reproduced by the proposed simulations. In addition, the variations of the RF amplifiers in amplitude and phase cause instabilities in the RF accelerating field of the SRF cavities. The time domain characterization of these variations should be considered for the design of the LLRF. The LLRF then could compensate predictable variations of SSPAs for use in particle accelerators.

6. Conclusion

The presented SSPA is fully characterized in time domain in terms of envelope pulse profile and pulse-to-pulse stabilities in amplitude and phase as delivering 1.25 kW output power with 70% drain efficiency. The P2P stabilities of -80 dB in amplitude and -24 dB in phase are obtained. A combination of the non-linear circuit envelope method and the Monte Carlo method is implemented in order to simulate the performance of the SSPA at the circuit level. Amplitude and phase droop along the pulse, pulsed current waveform, insertion phase as a function of output power, P2P variations over the flat-top of the pulse are simulated and are in good agreement with the measurements. The time domain characterization is very important for the high power SSPA to be used for next generation accelerators.

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Figure 1: The RF system profile for a pulsed superconducting cavity.

Figure 2: Schematic and layout (top) and a prototype of the single-ended power amplifier (bottom).

Figure 3: The block diagram of the time domain measurement setup.

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Figure 4: Photograph of the measurement setup.

Figure 5: Gain and efficiency traces are measured as a function of output power. The drain efficiency of the PA reaches 70% as delivering 1.25 kW output power..

Figure 6: Insertion phase is measured as a function of output power.

Figure 7: Drain voltage is measured as delivering about 1.25 kW output power. The droop voltage is around 1V along the pulse width 3.5 ms.

Figure 8: Simulated and measured current waveforms are captured at 1.25 kW output power over 1000 pulses.

Figure 9: Average output power for simulation and measurement are obtained at 1.25 kW after 1000 pulses.

Figure 10: Simulated and measured average insertion phase is measured after 1000 captured pulses. The measured insertion phase drops by 1.2° while a drop of simulated phase response is observed 1° .

Figure 11: Time domain envelope diagram of the pulsed signal along with arbitrary pulse width (PW) and repetition rate period (PRP).

Figure 12: Comparison of measured (red crosses) and simulated (blue asterisk) amplitude stabilities along the pulse width over 1000 pulses.

Figure 13: Comparison of measured (red crosses) and simulated (blue asterisk) phase stabilities along the pulse width over 1000 pulses.