A LINEAR HYBRID KICKER MODULATOR FOR ETA-II

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A new type of pulse modulator is being developed at Livermore that will rapidly split a high current electron beam into two halves, enabling each half to proceed along separate pathways. Each modulator will be capable of applying a ±10kV, 200A pulse onto a transmission line electrode structure with a rise time less than 10 ns, a pulse repetition frequency greater than 1 MHz, and a maximum pulse duration of 400 ns. The electrode structure, located inside the beam-transport pipe, generates an electromagnetic field that acts on part of the original beam to "kick" it in another direction.

The true merit of this high-speed modulator will be its flexibility in pulse duration and shape. The electrodynamics involved in altering the beam's trajectory require the modulator to generate a time-varying pulse that is precisely tailored in amplitude. Consequently, the modulator is driven by an arbitrary waveform generator and must act more as a linear amplifier than as a simple switch. The requirements of high peak power and wide analog bandwidth (about 50 MHz) will be addressed by merging a solid-state driver with an output stage of high-power vacuum tubes. Modulator development and performance data will be presented as will the issues of beam-induced voltage and transit-time isolation that are considered when driving a beam load.

Introduction

The Department of Energy is considering LLNL's induction linac technology as the driver for a multiple-pulse, multiple-line-of-sight induction accelerator. The Engineering Test Accelerator (ETA-II) at LLNL has been recommisioned as a test bed for proving the new technologies being developed for this accelerator. One of these core technologies, the focus of this paper, is the beam kicker. The ETA-II accelerator and its ongoing experiments, including the kicker concept, are described by Weir, et al.[1] Figure 1 shows the kicker operation. A single long-pulse beam (200 ns – 1 μs) passes through a stripline BPM-type electrode structure. The modulators apply a time-varying pulse to the stripline and chop the beam into various shorter pulses (50 ns), sending them on separate paths to converge simultaneously at a target.

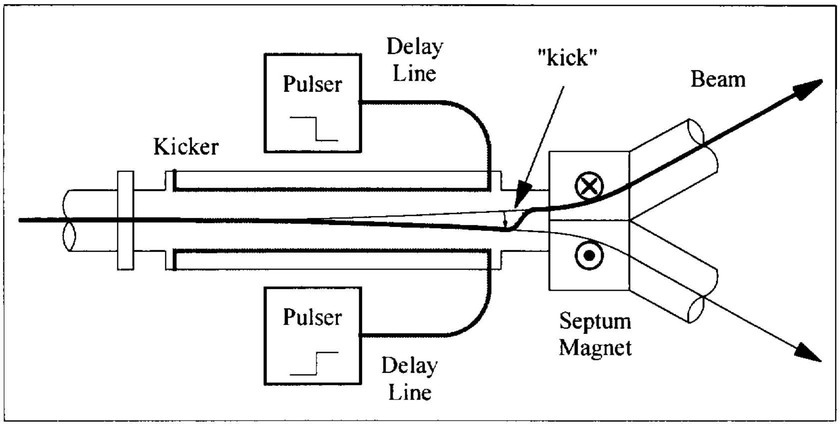

Figure 1.
The beam switches trajectories when electrodes are pulsed. (Kick is exaggerated.) In this manner, multiple beamlets can be generated from a single long beam pulse.

Despite the simplicity of the kicker concept, the electrodynamics are rather complex. Caporaso et al.[2] have analytically investigated

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14. ABSTRACT

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high-current relativistic beam deflection. The wake fields from the beam induce a large voltage on the electrodes due to the high current (> 2kA). Therefore the pulser must supply a nulling modulation to keep the beam on its proper course. At the right moment, the modulator must rapidly apply a high voltage pulse (10 kV) to deflect the beam into the other channel, as well as continue to compensate for the wake fields.

Design Constraint	Desired Goal
Max. Output Voltage	$\geq$ 10 kV
Max. Required Current	$\geq$ 200 A into 50 ohms
Full-Scale Risetime, t_r	< 10 ns
Max. Pulse Length	$\geq$ 1 μs with droop < 5%
Max. Pulse Rep Rate, prf	$\geq$ 1 MHz
Analog Bandwidth ($.35/t_r$)	$\geq$ 35 MHz, full amplitude $\geq$ 100 MHz, small signal
Linearity	as linear as possible[*]
Distortion	as small as possible[*]

Table I. Design Goals of Analog Pulser

The necessary power and agility of such a pulse modulator is demanding. Details of the required waveform will not be absolutely known without experimentation, and depend highly on beam energy and current. Therefore, such a modulator must provide an arbitrary, linear waveform. Table 1 displays the design goals for this analog modulator.

"This Old Pulser"

There is a history to our analog pulser development. We have a few working pulsers designed over a decade ago by developers at LLNL. Figure 2 shows a simplified circuit diagram. A parallel array of 16 Eimac/CPI Y-820 planar triodes was chosen for the output, with a daisy chain of 8 identical driver boards, each board driving a pair of output tubes.

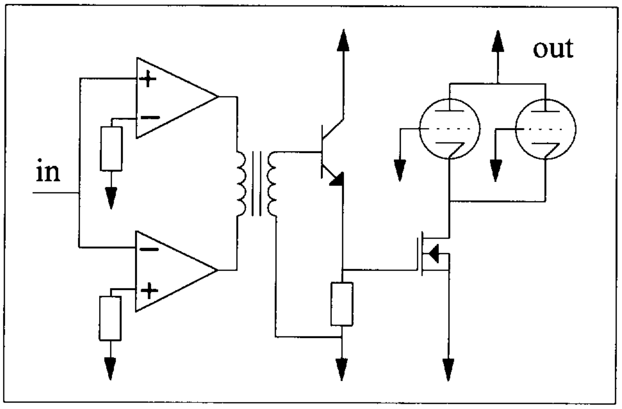

Figure 2. "Old Pulser" simplified schematic.

The front end is a pair of differential transconductance op-amps coupled through a transformer for single-ended drive into a RF transistor for current gain. It is followed by a power MOSFET coupled to two planar triode cathodes in a grounded grid configuration.

After much redesign effort, it was concluded that the MOSFET was not suitable to meet the kicker pulser design goals. Typically, power MOSFETs are used in switching applications and have a gate capacitance of several hundred picofarads. Applying a voltage to the gate will control a certain current, but with a rise time of more than a hundred nanoseconds. It takes time for the channel to open and conduct, and for the gate-drain capacitance to discharge (Miller effect: $dV_{gd}/dt=I_g/C_{gd}$). One may obtain a fast switching response (risetime less than 25 ns) by driving the gate non-linearly.

Some circuit simulations were performed using Electronics Workbench®[3] on how to get a desired linear response with a fast risetime by driving the gate in a non-linear manner. SPICE®

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[*] While linearity and distortion are very important, the power components are inherently nonlinear. Feedback within the circuitry (which may degrade performance) is nonexistent, but is performed in a delayed manner through software algorithms. So, within the capability of the generator, this constraint is somewhat relaxed.

models agreed with device performance. Figure 3 shows the results. Basically, the gate has to be over-driven (about 5 times the threshold voltage) and quickly discharged down to the desired driving voltage. The transferred charge, or ampere-seconds has to be tightly controlled else the MOSFET goes into saturated turn-on.

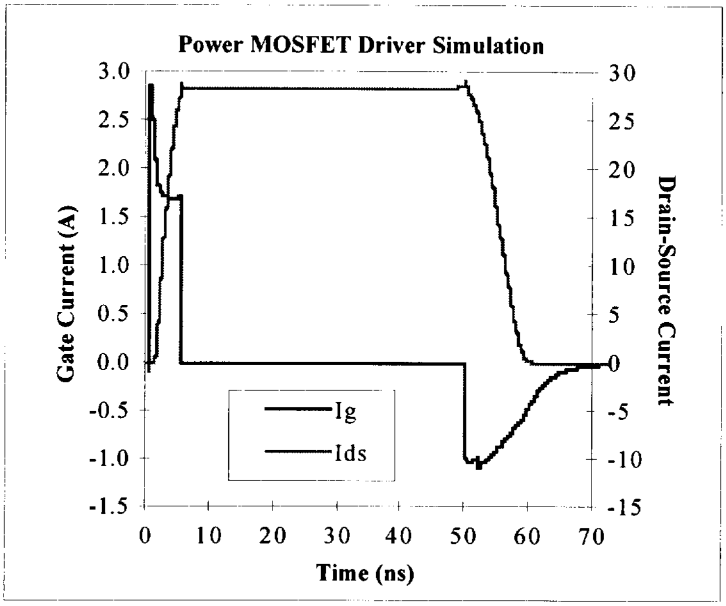

Figure 3. Simulation of MOSFET driver, showing non-linear gate drive. The sharp current spike initiates a fast turn-on. Amplitude and width has to be controlled for fast-rise linear response.[*]

This can probably be done utilizing a controllable impulse source but is beyond the scope of this pulser effort and is yet to be developed. As it stands, the old pulser driver sources enough gate drive to get about 25 ns full-amplitude risetime, without saturating the gate. It is capable of 10 ns risetime with overdrive, but without the tight control as seen in figure 3. Bandwidth and linearity suffer. It was concluded a new pulser, one which avoids the huge capacitive drive requirements and channel dynamics, must be designed,. A vacuum tube would offer much better performance.

The Vacuum Tube

Although research and development is continually pushing the frontier of solid-state pulsed-power systems[4], (which is great for switching power on and off in nanosecond time) FETs still cannot deliver high power (2 MW pulsed) with the linearity and bandwidth (50 MHz) required for this analog pulser. Vacuum tubes have the power and bandwidth required, and the large selection of power tubes on the market meets the needs of most applications.

The vacuum tube is a transconductance device, similar to a field-effect transistor. Applying a voltage to the grid controls the current flow from anode to cathode. Like the FET, the grid also has a capacitance to anode and cathode, but it is a hundred times smaller. Nevertheless, there is still considerable transient current drive. Unlike the FET, the vacuum tube grid intercepts some of the output current, in which case, the driver has to be able to sink (or source as the case may be) the extra current.

Optimizing for the right tube is an iterative process. There's a tradeoff in power output versus the ability to drive it. There are two basic configurations for power tube operation: grounded grid or grounded cathode.

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[*] Device modeled is DE150-201N09 power MOSFET, Directed Energy Incorporated, Fort Collins, CO. Gate capacitance is 600 pF.

- In a grounded grid configuration, the cathode is driven with a negative (current sinking) pulse, circumventing the Miller effect. However, driving the cathode also means the driver has to sink all the output current.
- Grounding the cathode and driving the grid with a positive (current sourcing) pulse reduces the current requirements. However, the transient current demand of the Miller effect usually rules out this configuration.

Vacuum tubes have a response of several gigahertz bandwidth, so the onus is on the driver to provide modulator performance. Since semiconductors generally tend toward lower power for higher frequency, a compromise exists between the tube power, and driver speed. In designing the tube configuration, one seeks to minimize driver power requirements.

The Analog Pulser - A Linear Hybrid Video Amplifier

In the last few years, various semiconductor manufacturers, including Philips and Motorola, have developed fast linear hybrid microcircuits (video CRT amplifiers) which are mounted directly on the cathode of high-resolution picture tubes. These typically drive 40-80 volt video analog signals into 8-12 pF load with a risetime under 3 ns (CdV/dt ≈ 200 mA of drive current), and do so with high stability and linearity.[5]

After comparison of vacuum tubes, development of a planar triode SPICE® model, and performing circuit simulations using Electronics Workbench,® it was clear that a hybrid video CRT amplifier could function as the driver for a planar triode. (Figure 4.) Hence the title of this paper: A Linear Hybrid Kicker Modulator. However, some modifications were needed to match the video amplifier with a compatible planar triode. We settled on the CPI/Eimac YU-176, a low-voltage (only 12 kV), high-current (40 A) planar triode. The YU-176 is an ideal choice due to its large cathode (3 cm^2) and optimum cutoff voltage (-50 V). It can be operated below zero-bias[*] and still have a large output current (6 A at zero bias). Therefore, the 50 V swing of the video amp is perfect for driving the tube from cutoff to zero bias, while never having any current drive demand other than capacitive charging. The first tube output is 6 A into an arbitrary load. This in turn drives an array of output tubes, still using the Y-820 for the final voltage.

Incidentally, the transient current necessary to charge/discharge the tube capacitance is about 2 amperes. It is necessary to amplify the current output of the hybrid video amp. Using discrete video transistors (the same type existing internally on the hybrid microcircuit). A bipolar emitter follower totem-pole structure was added to achieve more than 5 amperes of transient current to drive the YU-176 grid.

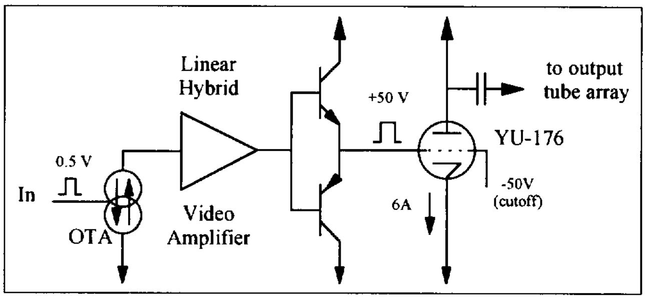

Figure 4. Simplified schematic of linear hybrid driver with zero-bias tube. The grid is biased at -50V just below cutoff. The video amp drives grid +50V up to zero bias and the tube conducts 6 amps.

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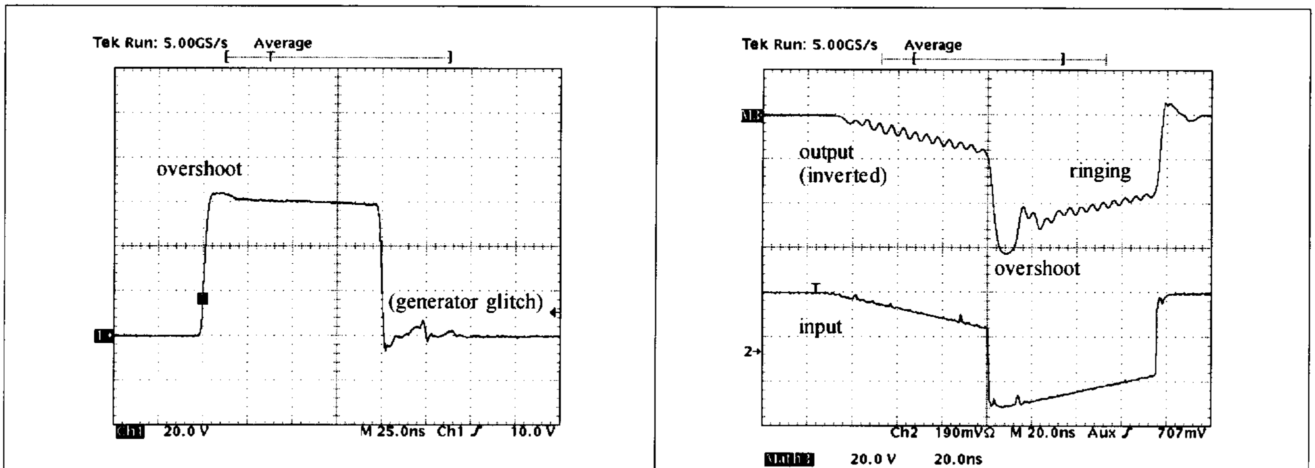
[*] With a zero-bias tube, current flows at grid-cathode potential of zero volts, with cutoff at some negative voltage, just like a depletion-mode FET. Between cutoff and zero bias, the grid is at a lower potential than the cathode, so electrons pass through the grid with very few of them striking it. Grid current is essentially nil below zero-bias.

Driver Performance - Risetime, Distortion, Linearity

Figure 5(a-d) show the performance of this analog pulser driver. Figure 5a is simply a square wave demonstrating pulse flatness and a full-amplitude risetime agility of 4 ns. The only distortion is the overshoot of the fast rise and fall, with a settling time less than 10 ns. The second shows a simple representation of the type of waveform needed for driving the kicker, a slow ramp up, fast rise, and slow ramp down. Figure 5d shows burst pulse schedules of small, 100 MHz and full amplitude, 50 MHz pulses. In all the figures 5a-d, the output amplitude is highly linear. However, there is quite a lot of distortion (overshoot and high-frequency ringing) that should disappear with more attention to board layout and EMI shielding.

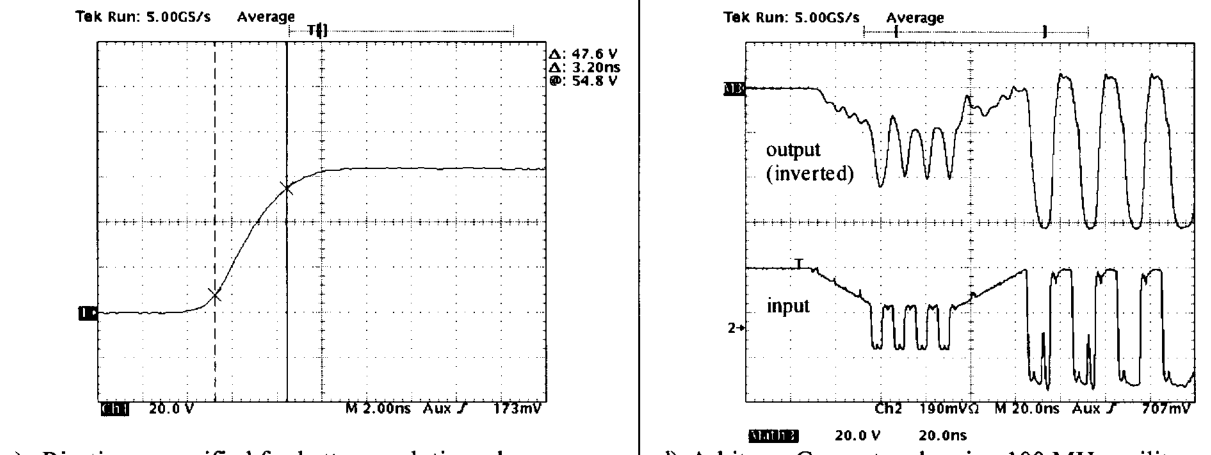
The absence of feedback circuitry in the modulator may cast doubt on its expected performance. Although the driver is fairly linear because of its linear hybrid amplifier, planar triodes are not. The transconductance of a vacuum tubes is governed by the Child-Langmuir relation which states that current is proportional to $V_{gc}^{3/2}$. Therefore, a distortion compensation technique is required to tailor the arbitrary waveform generator input to obtain the "linear" output from the pulser. So, although the analog pulser is not a linear system in a true sense, the

Figure 5. Driver characteristics into YU-176 grid.



a) square pulse response (tr=0.7 ns)

b) Typical kicker pulse from arbitrary waveform generator



c) Risetime magnified for better resolution, shows 3.2 ns risetime of driver.

d) Arbitrary Generator showing 100 MHz agility of the driver. Generator capability is strained.

desired output is still obtained. A delayed feedback system can be used to adjust the arbitrary generator between pulses. All the processing and control is done "on the fly" with interface hardware and computer algorithms. Such a method is already employed in the ETA-II timing system. Developers are already working on the algorithms and control interface.

Work to be Completed - Future Developments

Work is still underway to assemble the output array of twenty Y-820 planar triodes. These are necessarily operated in a grounded grid configuration to circumvent the Miller effect. The present design includes four YU-176 tubes driving the twenty Y-820 output tubes. Mechanical design is important to maintain the proper characteristic impedances of the structure. More circuit simulation is needed to firm up confidence in the design.

As just stated, a distortion compensation algorithm and control interface is being completed. This and various other interface issues with ETA-II operations, such as timing and safety interlocks are in progress.

Despite the promising results of the driver, it is still in the prototype stage. A finished circuit board with a clean RF layout needs to be manufactured. The ringing seen in the figures is evident. Optimally, all of the solid-state components can be reduced to a single hybrid microchip, all on the same substrate. Such work with Allied Signal is currently underway.

Work is continuing to expand this linear hybrid modulator to long pulse (100 μs) operation, and full-amplitude modulation in excess of 35 MHz analog bandwidth.

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[1] J. T. Weir, et al., "ETA II Experiments for Determining Advanced Radiographic Capabilities of Induction Linacs", Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-126072, April, 1997. (Published in Proceedings of the 1997 Particle Accelerator Conference, Vancouver, B. C., Canada, May 1997.)

[2] G. Caporaso, et al., "Transmission Line Analysis of Beam Deflection in a BPM Stripline Kicker", Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-126073, April, 1997. (Published in Proceedings of the 1997 Particle Accelerator Conference, Vancouver, B. C., Canada, May 1997.)

[3] Electronics Workbench® is an electronic circuit analysis program published by Interactive Image Technologies Ltd., 111 Peter St., Toronto, Ontario, Canada.

[4] H. Kirbie, et al., "Development of Solid-State Induction Modulators for High PRF Accelerators," Proceedings of the 10th IEEE International Pulsed Power Conference, Albuquerque, NM, July 3-6, 1995, p. 441.

[5] C. Henn, "Driving Video Output Stages with Monolithic Integrated Amplifiers", Application Bulletin-184, Burr-Brown International GmbH, 6730 S. Tuscon Blvd., Tuscon, AZ 85706, 1993.