

## SOLID-STATE HIGH VOLTAGE PULSE POWER IN THE 10-100 NANOSECOND REGIME

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### Abstract

New and proposed particle accelerators, employing storage rings and damping rings as sources for charge packets, require ever faster kickers for charge packet insertion and extraction. Fast strip-line deflectors with voltages exceeding 10 kV and drive currents exceeding 200 A demand pulsed power with pulse durations in the 10-100 ns range and pulse burst rates of 3 MHz or more. Similar levels of pulse performance are needed for state-of-the-art excimer laser systems, impulse radar transmitters, particle accelerators for medical therapy, and food processing using pulsed electric fields. Current research at Diversified Technologies, Inc. (DTI) is exploring the use of IGBTs and MOSFETs in solid-state pulse power systems capable of delivering high-voltage, high-current pulses with 10-100 nanosecond pulse duration for these applications.

### BACKGROUND/INTRODUCTION

Every particle accelerator uses electromagnetic “kickers” to serve two purposes: (1) selective deflection of circulating electron (positron) bunches from the damping ring into the entry aperture of the linear accelerator without disturbing the trajectories of the other circulating bunches, and (2) selective injection of bunches into the damping ring, again without disturbing the trajectories of the other circulating bunches. The ultimate size, and hence cost, of each damping ring is influenced greatly by the speed of the kickers.

Kickers must operate very fast, typically at speeds measured in nanoseconds. Kickers reach their desired field strength between the arrival of particle packets, maintain the field for a finite time, and return to zero field

before the next particle bunch arrives. The drivers of these kicker deflectors, therefore, must be capable of operating on similar timescales.

### IGBT-BASED SWITCHES FOR 25-100 NS RISETIMES

DTI's IGBT-based high voltage switches demonstrate risetimes between 50 – 100 ns, and, when used in our high power modulators, typically achieve risetimes of approximately 1  $\mu$ s. Through our ongoing solid-state device research for the U.S. Department of Energy, we have developed a new topology that extends the switching performance achieved with IGBTs. This switch has the following features:

- Extremely low interconnect inductance between ranks (series stages),
- Provision for up to six parallel TO-247 package IGBTs per rank,
- Independent magnetic coupling of the gate drive for each rank,
- A flat configuration conducive to assembly close above the image ground plane to reduce inductance further.

A prototype of a 10 kV IGBT switch is shown in Figure 1. with four parallel devices used per rank. Measurements confirm that the performance is very good for an IGBT-based system. Figure 2 shows a 6.2 kV pulse into a 100  $\Omega$  load. Risetimes of 25-30 ns were consistently obtained. Some ringing of the leading edge is characteristic of the fast timescale performance of this type of switch array. The ringing is easily remedied by insertion of a small  $LR$  tuned snubber midway through the array.



Figure 1. Assembly of the 10 kV high-speed switch prototype. 18 series stages of four parallel IGBTs per stage were used, and an image ground plane directly underneath the assembly reduces the already low system inductance.

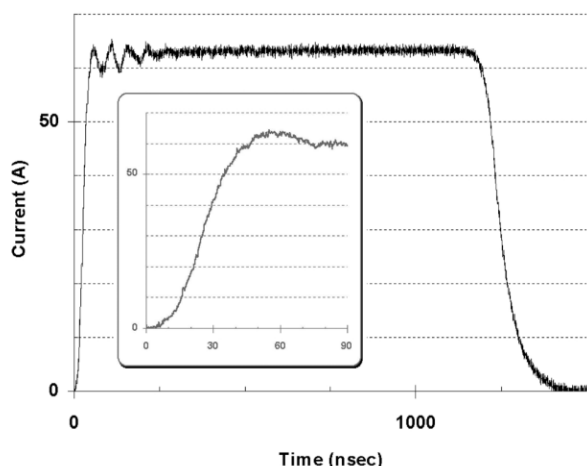


Figure 2. Testing of the 10 kV fast switch assembly shows risetime of  $\sim 26$  ns (10%-90%). A 6.2 kV pulse into a  $100 \Omega$  load is shown. The inset shows the detail of the risetime. (A Pearson 110A current transformer was used to measure the pulse current. Independent voltage risetime was measured with a Northstar 2000:1 high voltage probe, with confirming results).

Risetimes (10%-90%) for IGBT switches depend on the load impedance, or more precisely, on the pulse current. Generally, risetime will be faster at lower currents, and slower at higher currents. Figure 3, for example, shows the same test circuit, but at 9 kV (hence 50% higher pulse current). The 10-90% risetime increases to about 30-35 ns. 10 kV pulses into  $59 \Omega$  show about 45-60 ns risetime, and a  $20 \Omega$  load shows about 130 ns risetime. These results appear to represent the practical limits of the speeds achievable with IGBTs.

### FAST KICKER SWITCHES FOR 3-25 ns RISETIMES

DTI's research focus is the development of solid-state kicker drivers that can meet the very demanding requirements of the International Linear Collider.

The DOE kicker driver specification is evolving as the ILC design effort proceeds. One specification calls for the rise and fall times of the deflection voltages at 3-20 ns, with a preference for 3-4 ns. The speed parameter of interest to the accelerator community is termed "bunch spacing" which is the full duration of a pulse. These rise and fall times are understood to relate to a rise to 98 per cent and a fall to 2 per cent of flat-top voltages. Further, the pulse rate may be 3 MHz for a burst duration of one millisecond, and such bursts repeat at a rate of 5 Hertz (i.e. the average PRF is 15,000 Hertz). Overall, multiple kicker modules will be required to deflect the 5 GeV beam by 0.6 mrad. In addition, it is apparent from consideration of the highly periodic character demanded of the bunch cycling in the damping ring that pulse jitter

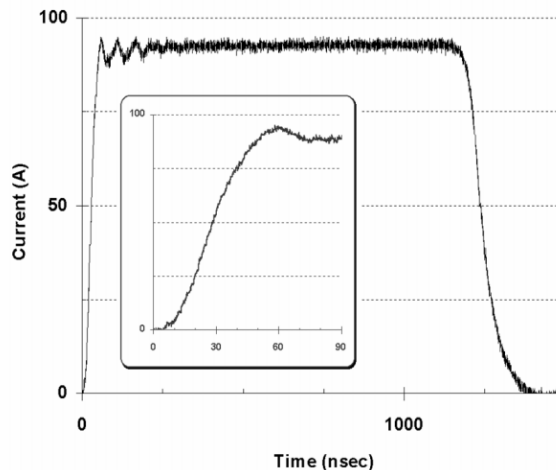


Figure 3. Higher voltage (and current) test of the same switch and load as in Figure 2 shows that the risetime increases to  $\sim 33$  ns (10%-90%). DC voltage was 9 kV, and load impedance was  $100 \Omega$ .

exceeding  $\pm 3$  per cent of the bunch spacing would be unacceptable.

We are researching two approaches to driving the stripline deflectors of a kicker module: The first approach is the application of commercial high voltage MOSFETs arranged in an array to achieve pulses of approximately 5-nanosecond rise and fall times of 200 A to a 50 Ohm load (i.e. to deliver 10 kV pulses to such a load).

The second approach is to exploit the Drift Step Recovery Diode (DSRD) technology advocated by Dr Alexei Kardo-Sysoev and Dr Anatoly Krasnykh. This second approach has considerable promise for delivery of 5 kV, 2 ns-to-6 ns flat-topped pulses to a 50-Ohm load with exceptionally fast (sub-nanosecond) rise and fall times.

### High Voltage MOSFET Array

Several key considerations are important to successful use of MOSFETs:

- the component high voltage MOSFETs must exhibit exceptional switching speed in their own right,
- the circuit layout must eliminate series inductance to the extent possible, especially on the SOURCE side of the MOSFET,
- fall times are strongly affected by distributed capacitance within a high voltage switch array, especially capacitance between switch modules and the ground surround,
- means for achieving ultra-fast gate drive performance are required,

- switch arrays must be designed and built for reliability.

In practice, the achievement of robust electronics capable of 5 ns rise and fall times for 200 A pulses driving into a 50 Ohm load is an enormous challenge. One high voltage MOSFET is specified by the manufacturer, Directed Energy, Inc., to exhibit a rise time of 5 ns. Kickers require multiple switching devices arranged in series. Simply stated, our challenge is to build a robust high-voltage 5 ns system from 5 ns parts.

A schematic representation of the proposed 10 kV, 200 A ILC kicker pulser employing parallel MOSFETs is shown in Figure 4. It displays a low-inductance, low-capacitance series configuration of 16 modules. Within each module we envision 8-to-10 high-voltage MOSFETs in parallel. Because even miniscule amounts of parasitic capacitance to ground will undermine pulse performance, the modules must receive their working power from internal storage means (e.g., capacitors or rechargeable batteries), or by radiation transfer across open space (e.g. by rf horn antennae, or by optical pumping) from remote sources. Furthermore, because this kicker driver is required to perform at an average continuous pulse repetition rate of 3,000 Hertz, dissipation within each module is likely to exceed 50 Watts. To remove this heat effectively, we plan to circulate an acceptable fluorocarbon through the modules. One single-mode optical fiber will be employed for triggering each of the modules.

### *DSRD Array*

The second approach is more complex. The Drift Step Recovery Diodes (DSRDs) which underpin it are more fundamentally capable of supporting sub-5-nanosecond switching speeds. DSRDs are essential elements in ultra-wide-band (UWB) radar systems, and have been available for a number of years. In their earliest incarnation such devices were known as “step recovery diodes”. Refinements, especially by modifying the drift region in such diodes, permitted sharpening of the waveforms they generated. Hence, the name “Drift Step Recovery Diodes”.

The fabrication and application of such devices is described in detail in Chapter 9 of “Ultra-Wideband Radar Technology” (editor James D. Taylor, CRC Press, 2001) authored by Alexei F. Kardo-Sysoev. In one radar application, DSRDs are used to produce triangular pulses of 2 ns duration.

Although 5kV, 10kHz, 1nsec risetime, DSRD based devices exist in the marketplace (e.g. FID Technology, Burbach, Germany) extending the operational voltage to 10kV, adequately flattening of the pulse top for 2 nanoseconds, increasing the average PRF to 22.5kHz, and effectively eliminating after-pulse tails that reach beyond

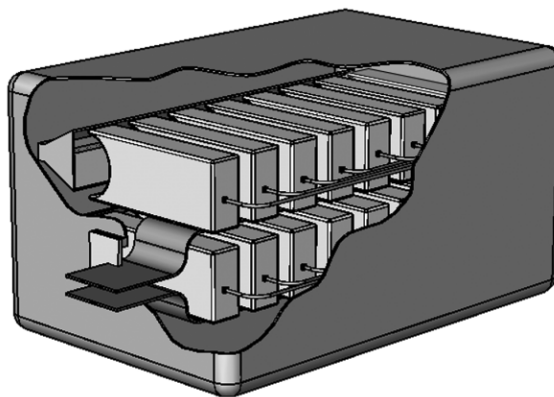


Figure 4. Cutaway solid model of proposed 10 kV ILC kicker driver, showing arrangement of MOSFET-based solid-state switches. The entire driver has 16 MOSFET modules in series. Also shown are two remote RF radiators for supplying working power to modules. Dimensions are approximately 15" x 18" x 28".

6 nsec, all required for the ILC strip-line kicker, remain challenges.

## **BENEFITS**

The International Linear Collider is a multibillion dollar, multinational system for generating extremely energetic particles thought to have existed only during the formation of the universe. Its purpose is to extend humankind's understanding of the universe and the dynamics of its creation. The major thrust of DTI's research is to develop and demonstrate the technologies which will help bring the ILC into reality by enabling the precise kicker operation needed to handle the specified ILC bunch spacing and energy.

The research will also yield reliable, solid-state kicker pulsers to meet the needs of other existing and planned accelerators and colliders throughout the world. With ILC representing the apex of kicker requirements, focusing on the ILC will certainly enable DTI to develop kicker drivers which are readily applicable to these programs as well. As DTI develops kicker drivers which exceed the performance of these existing systems, it may also open opportunities for enhanced ranges of operation in these machines – at very small incremental investments.

Finally, faster and less expensive high-voltage modulators are constant objectives of industry worldwide. High voltage modulators are used in (a) medical particle accelerators for therapeutic treatment and for generating useful radioactive isotopes, (b) radar systems, (c) a variety of scientific accelerators, and even (d) food processing. Improvements in these high voltage modulators and reductions in their cost of manufacture will benefit all of these applications.