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A 50 kV PULSE GENERATOR FOR FAST KICKERS*

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Abstract

Brookhaven National Laboratory has recently been selected as the site for the Electron-Ion Collider (EIC). The EIC will consist of two intersecting accelerators, one producing an intense beam of electrons, the other a high-energy beam of protons or heavier atomic nuclei, which are steered into head-on collisions. One of the sections of the EIC beamline will require a hadron injection fast kicker system. RadiaBeam is developing GaN-based pulser with ±50 kV voltage amplitude, <4 ns rise and fall times, 40 ns pulse width. In this paper, we discuss the development progress.

INTRODUCTION

Stripline kickers are vacuum devices that are driven with a pair of rectangular pulses with opposite polarities to provide transverse kick to the bunched particle beam. To drive strip-line kickers, powerful flat-top pulse generators (pulsers) with nanosecond edges and durations up to tens of nanoseconds are required. The injection kicker system for EIC will be required to support single bunch transfers with a bunching frequency of 24.6 MHz. As a result, this kicker system must provide rise, flat-top and fall times which cumulatively add to no more than 40.7 ns (in comparison, the current RHIC bunching period is about 107 ns). The entire system will consist of 20 kicker units and will span a length of ~25 m [1]. Table 1 summarizes the requirements for the fast kickers pulse generators planned in the EIC.

Table 1: High-Voltage Pulser Specifications for the EIC Kicker Systems

Parameter	Value
Pulse Voltage	+/-50 kV
Load Impedance	50 Ohm
Pulse Width	40 ns including transition times
Rise/fall times	<10 ns each
Repetition rate	20 Hz normal operation, up to 100 Hz for lifetime test

To achieve short pulses with nanosecond edges, gas-discharge switches were traditionally used with pulse shaping lines. However, the low stability of gas-discharge devices over temperature and time, along with their limited service life, fails to meet the requirements of modern systems. Pulse generators based on semiconductor switches, such as Si or SiC MOSFETs, can meet these requirements. Nonetheless, the power of a single device is insufficient (a few kV and tens of amps), necessitating circuit designs that combine many switches in series and parallel circuits to increase the total voltage and current. To further meet design requirements, the development of control circuits capable of providing high synchronization, stability over time, high switching speed, and galvanic isolation for each switch is also necessary. Additionally, it is essential to address the issue of balancing voltages and currents during switching and pulses to ensure the reliable operation of the generator.

In response to these challenges and the demand for a commercial solution for EIC kicker drivers, RadiaBeam proposed building a pulse generator based on distributed pulser topology utilizing modern GaN transistors as switching devices. GaN technology is rapidly advancing, enabling both high peak and average power operation, along with extremely short switching times on the nanosecond scale. The novelty of our approach lies in the combination of power modules based on Marx topology with an inductive adder, as shown in Figure 1.

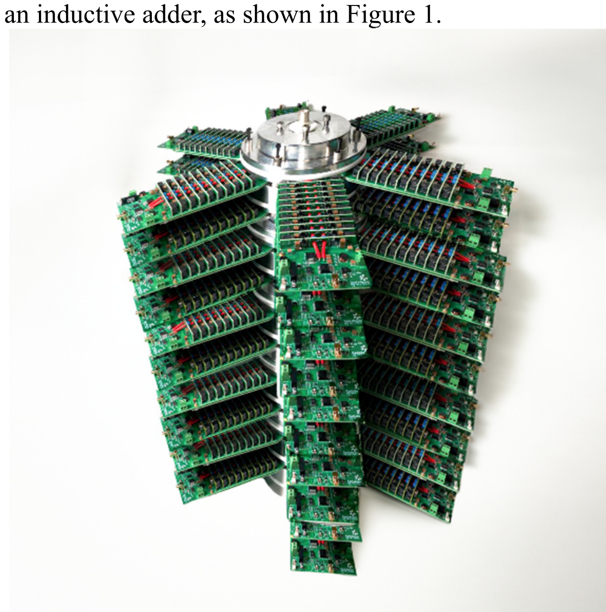

Figure 1: Conceptual design of a 50 kV pulser (single channel), based on Marx modules and inductive adder.

PULSER DEVELOPMENT

The pulser development is being carried out in sequential stages. First, a single GaN transistor was tested to validate the optimal di/dt. Second, transistors were arranged in Marx modules with iterative optimization of switching elements (serial and parallel configurations) and their driver circuits. We aimed to achieve several kV and 100s of A at the output of each module, in order to keep the total number of modules <100. Third, the Marx modules are combined into a single output channel, and their number

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was scaled to achieve a total combined pulsed output of 50 kV and 1 kA.

GaN Transistor Study

We first performed thorough characterization of the GaN transistor to study its performance and extract the optimum d*i*/d*t*. We built a tested a separate board to drive a single transistor at 500V with a low-impedance load (7.5-10 Ohms) at 40ns pulse duration. Figure 2 shows the fabricated test board.

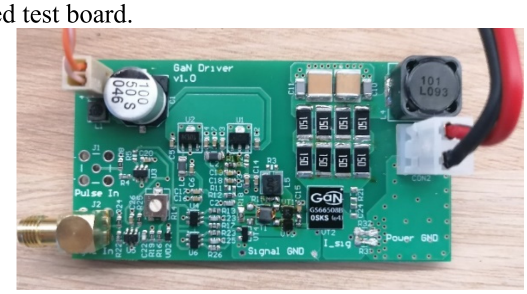

Figure 2: Single GaN chip test board.

The circuit includes a precise pulse forming network, supply line stabilizers and a separate 2-stage transistor driver. The output stage is arranged in a push-pull topology. The circuit has been fabricated, and the test results are plotted in Figure 3.

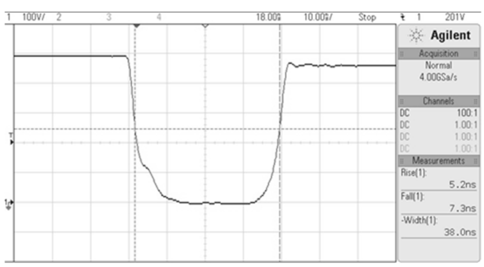

Figure 3: Output waveform of a single GaN transistor with, showing 500 V amplitude with a 7.5 Ω load.

These tests revealed that with proper management of parasitic parameters and instabilities of the driver and supply circuits, the transistor can provide the commutation rate d*i*/d*t* =10 A/ns.

Marx Module Optimization

The next step was to design the Marx module. We followed the following considerations: a) introduce push-pull gate driver topology for better symmetry of the pulse edges and stabilize the on-time duration along with the control pulse amplitude; b) minimize the parasitic parameters of the Marx stage circuits, especially on the high-power side. This can be achieved by reducing the conductors' lengths, increasing their widths, using low loss charging capacitors etc; c) place the gate driver transformers on individual PCBs and orient them orthogonal to the cells' PCBs in order to simplify the assembling process.

The higher the number of transformers for controlling the transistors of the cells, the higher the leakage inductance, making it more challenging to provide the required edges to control the transistor gates in each cell. An increase in the number of transformers in the control circuit leads to an increase in the control voltage in the primary winding, which cannot exceed approximately 500 V. This is due to the limiting operating voltage values of the transistors used in the cell control circuit (driver). Therefore, the maximum number of cells in one module is limited to 10-15, allowing for pulses with a voltage amplitude of 4 to 6 kV from one module (with an input voltage of about 400 V). These considerations were implemented in the following functional schemes of the Marx cell, see Figure 4.

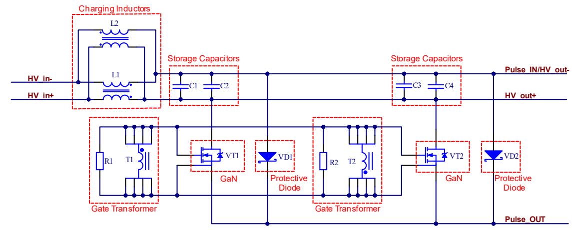

Figure 4: Marx cell diagram.

The module is comprised of a gate driver and 10 Marx cell boards as shown in Figure 5. The transistor driver is of a push-pull type and is made as a half-bridge circuit, which makes it possible to supply bipolar current pulses to control the gates of transistors, improving the trailing edge of the generated high-voltage pulse and re-magnetizing the core.

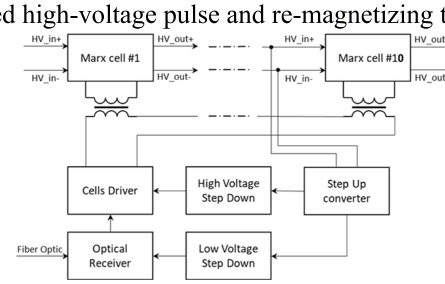

Figure 5: 10-cell module diagram.

All cells are located at a minimum distance from each other, which reduces the parasitic inductance of the power circuit and the loop of the primary winding of the control transformers. This module was fabricated and tested at high-power, see Figure 6.

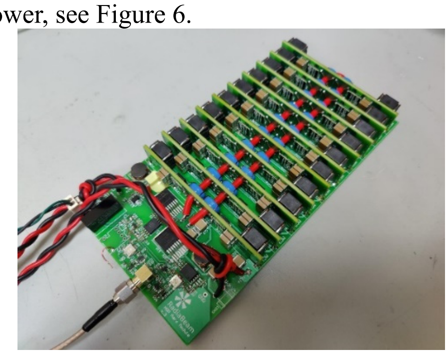

Figure 6: The fabricated 10-cell Marx module.

During the tests, we gradually increased the input voltage and measured the output waveform across a 30 Ohm load. The maximum achieved voltage amplitude was 5.1 kV, corresponding to ~170 A peak current, see Figure 7. With this output level, rise and fall times of 4.4/4.7 ns at 30ns flat-top duration are achieved.

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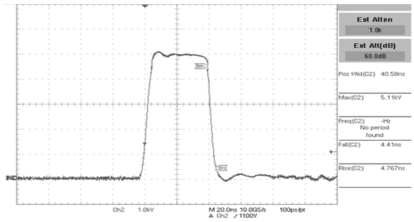

Figure 7: Measured output voltage of a single module with a 30 Ohm load.

The module showed good reliability and stability. Later, we made small modifications to it, which were focused on rearranging the output HV connections for compatibility with the inductive adder.

INDUCTIVE ADDER DESIGN

Combining power from many Marx modules can be done in different ways, but the most practical in terms of adding currents from multiple modules and matching with a load is the inductive adder, see Figure 8. It provides the most axially symmetric and compact connection of the modules to the common load.

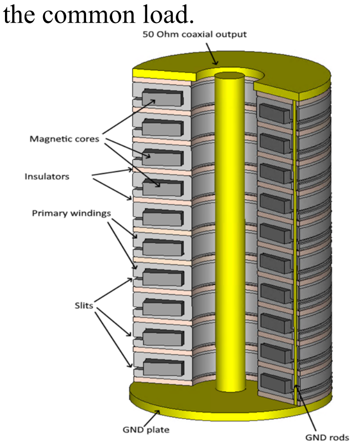

Figure 8: Sectional view of an inductive adder. 60 modules connected in 10-by-6 configuration (10 stages with 6 modules per stage). The modules are inserted into the radial slits in each stage.

Having Marx module with demonstrated output of 5 kV (170 A), the adder must, therefore, consist of 10 stages with 6 modules in each stage to combine to a total of 50 kV (1000 A). Initial modeling and optimizations of the full-scale inductive adder were performed in CST using time-domain solver. The optimized inductive adder with reduced parasitics slows to the rising edge by only ~1ns and does not distort the flat-top, as shown in Figure 9.

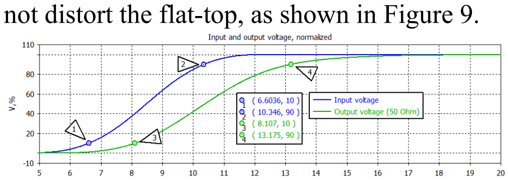

Figure 9: Inductive adder transient simulation results: normalized waveforms of the input pulse (blue) and the combined output pulse (green). The results are plotted for the rising edge only.

We fabricated a scaled-down prototype of the adder consisting of 3 stages and tested it with 6 available Marx modules, see Figure 10.

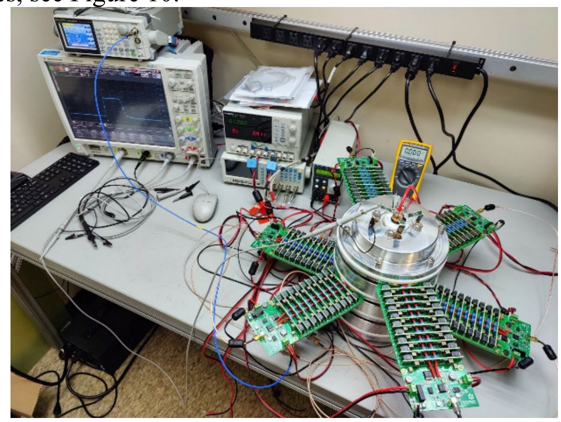

Figure 10: 3-stage inductive adder under high-power testing.

The output waveform is shown in Figure 11. These tests demonstrate the successful operation of the inductive adder in conjunction with Marx modules.

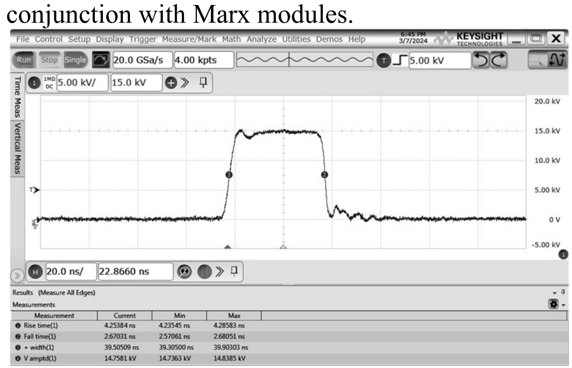

Figure 11: Measured combined output from 6 Marx modules with an inductive adder. Load impedance 50 Ω; pulse amplitude 15 kV, rise/fall times 4.2 ns / 3 ns.

CONCLUSIONS

In this paper, we presented a high voltage pulser design based on GaN technology. We reached 15 kV with a scaled-down version of the pulser which proves the applicability of Marx topology with inductive adder and demonstrates scalability to different output power levels.

In addition to being an enabling technology for EIC, the proposed system or its constituent blocks may find various uses in HV switching applications, including fast beam choppers for injector test facilities, the next generation FELs.

REFERENCES

[1] https://wiki.bnl.gov/eic/upload/EIC.Design.Study.pdf